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作 者 姓 名	王昱昊
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导 师 姓 名	张雷 教授

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答辩委员会主席	陈申见 教授
评 阅 人	陈明水 教授
	顾嘉荫 研究员
	李强 教授
	刘衍文 教授

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研究生签名：

导师签名：

The beauty and charm of Higgs: Search for Higgs Boson decays to charm quarks with the ATLAS experiment and search for new physics with combined measurements

by
Yuhao Wang

Supervised by
Professor, Lei Zhang

A dissertation submitted to
the graduate school of Nanjing University
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in

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School of Physics
Nanjing University

南京大学研究生毕业论文中文摘要首页用纸

毕业论文题目: ATLAS 实验中寻找希格斯玻色子衰变到粲夸克过程及通
过联合测量寻找新物理

粒子物理与原子核物理 专业 2019 级博士生姓名: 王昱昊

指导教师 (姓名、职称): 张雷 教授

摘 要

在标准模型中,希格斯玻色子通过自发对称性破缺机制赋予其他基本粒子质量。2012年,大型强子对撞机上的 ATLAS 和 CMS 实验同时宣布发现了希格斯玻色子,进一步验证了标准模型的正确性。自此之后,对希格斯玻色子性质的测量日益精细,并且其结果与标准模型的预测一致。然而,标准模型仍有着无法解释的理论问题,例如希格斯玻色子质量的精细调节问题以及费米子质量的等级问题,因此被认为不是描述自然界的终极理论。为了解决这些问题,许多超出标准模型理论被提出,其中的不少模型都预言了额外的希格斯粒子,并对于当前观测到的希格斯玻色子的性质给出了不同于标准模型的预测。所以,研究希格斯玻色子的性质,包括其与费米子及与矢量玻色子的耦合强度,以及其自相互作用,能够帮助进一步理解标准模型以及寻找新物理,是大型强子对撞机上的重要课题。本论文展示了两项关于希格斯玻色子性质以及寻找超出标准模型新物理的研究,其一是测量希格斯玻色子与粲夸克及与底夸克的耦合强度,其二是通过联合分析多个物理过程的实验测量数据以寻找超出标准模型理论的迹象。

论文展示的第一项研究是利用希格斯衰变到粲夸克对和希格斯衰变到底夸克对过程,来测量希格斯玻色子与粲夸克及与底夸克的耦合强度。希格斯玻色子与费米子的耦合由汤川机制描述,标准模型中希格斯玻色子通过汤川耦合赋予费米子质量,其耦合强度与费米子质量成正比,是只能通过实验测量得到的自由参数。迄今为止,希格斯玻色子与第三代费米子以及与矢量玻色子的耦合都已经被发现,而希格斯与第二代费米子的耦合却还没有被证实。测量希格斯衰变到费米子对的分支比是研究希格斯与费米子耦合强度的最好途径之一。而希格斯衰变到粲夸克对是目前还没有发现的标准模型希格斯衰变模式中分支比最大的一个,约为 2.9%。于是,寻找希格斯玻色子衰变到粲夸克的研究是近年来 ATLAS 的重点研究课题之一。本论文利用 ATLAS 实验在大型强子对撞机 (LHC) 第二期运行中收集的质心能量为 13 TeV,积分亮度为 140 fb^{-1} 的质

子-质子对撞数据，通过伴随矢量玻色子产生的希格斯产生模式 (VH) 寻找希格斯衰变到粲夸克对的过程。由于希格斯衰变到粲夸克对和希格斯衰变到底夸克对的过程非常相似并且拥有相同的本底过程，本论文同时测量了希格斯衰变到底夸克对过程。通过数据分析，本论文对希格斯-粲夸克耦合强度 $|\kappa_c|$ 进行了约束，将其观测取值范围在 95% 置信度下限制到了 4.2 倍于标准模型预测值以内，并将希格斯-粲夸克耦合强度与希格斯-底夸克耦合强度之间的比值在 95% 置信度下限制到了 3.6 以内。得益于特别优化的喷注鉴别方式，使用增强决策树来区分信号和本底等手段，这些结果是迄今为止对于希格斯-粲夸克耦合强度最精确的测量。本论文同时给出了对于通过 VH 产生的希格斯衰变到底夸克对的简化模版产生截面 (STXS) 的测量，其结果与标准模型一致。本论文还测量了双玻色子 (VZ) 产生过程作为交叉检查，以保证分析策略的合理性，并首次在 ATLAS 实验中以超过五倍标准偏差的显著性发现了 $VZ(\rightarrow c\bar{c})$ 过程。

本论文展示的第二项研究是通过联合分析多个物理过程的实验测量数据直接或间接寻找超出标准模型的新物理。本论文一共展示了三项利用联合分析数据所展开的搜寻，利用了不同能标下新物理模型可能带来的可观测效应，分别为：通过标准模型希格斯玻色子产生和衰变模式联合测量以间接寻找新物理，通过联合直接寻找超出标准模型的新粒子共振态产生衰变到希格斯玻色子对过程直接寻找新物理，以及通过联合对于电弱过程的精确测量间接寻找新物理。

对于特定的希格斯玻色子产生过程和衰变模式，其产生过程较小的截面以及衰变时较小的分支比，使得对于希格斯玻色子性质的精确测量很有挑战性。通过联合各类产生过程以及衰变模式的测量（常被称为希格斯联合测量），可以得到更多的测量数据，从而得到更为精确及全面的性质测量，对希格斯玻色子性质由于新物理而产生的改变也更为敏感。联合测量能够同时研究希格斯与各个粒子的耦合，减少模型依赖，得到对于希格斯性质的更为全面的了解。本论文展示了利用希格斯性质的联合测量寻找超出标准模型的新物理的研究。这些测量结果被用于检验双希格斯二重态模型 (2HDM) 和最小超对称标准模型 (MSSM) 的一些特定参数空间，也被用于探测有效场论 (EFT) 方法中的一些新物理算符。

希格斯玻色子的自耦合源自于希格斯标量势函数，其强度决定了标准模型希格斯标量势函数的形状。标量势函数的形状与宇宙早期发生的电弱相变以及与真空稳定性等问题有着深刻的联系。当前，测量希格斯自耦合的最有效的手段是测量希格斯成对产生过程，希格斯成对产生过程的振幅不仅对希格斯自耦合强度非常敏感，也能被新粒

子产生后衰变到两个标准模型希格斯玻色子过程（共振态产生）大大增强。本论文展示了利用希格斯成对共振态产生过程的联合测量来寻找超出标准模型的新物理的研究，考虑了最为敏感的三个衰变道： $b\bar{b}b\bar{b}$, $b\bar{b}\tau\tau$ 和 $b\bar{b}\gamma\gamma$ 。其结果被用于检验多个新物理模型的参数空间，包括双希格斯双重态模型，最小超对称标准模型，额外希格斯单重态模型（Singlet）。

对于电弱过程的测量常被用于在有效场论框架下寻找高能标新物理对低能过程的细微改变，与希格斯玻色子过程的测量相互补充，对于特定的新物理效应有特别的敏感度。电弱测量的优势在于其高精度，这些过程在大型正负电子对撞机（LEP）以及 PVDIS 等低能深度非弹性散射实验上得到了极为精确的测量。然而，由于有效场论中的顶夸克算符对于顶夸克对产生能量下的电弱过程没有树图阶贡献，在只考虑树图贡献的情况下，这些算符很难受到电弱精确测量结果的限制。本论文研究了这些算符对于电弱过程的圈图贡献，发现了其大小不可忽略，并且探讨了电弱精确测量对于这些顶夸克算符的限制。本论文还研究了在规划中的 CEPC 及 FCC-ee 对撞机能够探寻到这些算符对应的新物理能标，展现了未来对撞机在电弱过程测量上的进步和对于搜寻新物理的优势。该研究是与数名理论物理学家合作完成的，独立于 ATLAS 合作组的工作。

综上所述，本论文展示了关于希格斯玻色子性质以及寻找超出标准模型新物理的研究。第一项研究是对希格斯玻色子与粲夸克及与底夸克汤川耦合强度的联合测量。通过多种优化的分析手段，信号显著度大幅提升，得到了迄今为止最精确的对于希格斯玻色子与粲夸克汤川耦合强度的限制。该研究对于理解希格斯玻色子汤川耦合结构以及费米子质量等级问题有着重要意义。第二项研究是联合利用多个物理过程的实验测量数据以直接或间接寻找超出标准模型新物理，分为三个部分：其一是利用对标准模型希格斯玻色子性质的联合精确测量来间接寻找新物理，其二是利用超出标准模型的新粒子共振态产生衰变到希格斯玻色子对过程的联合寻找来直接寻找新物理，其三是利用电弱精确测量间接寻找顶夸克相关新物理。这些结果被用于检验多个新物理模型的参数空间，也被用于探测有效场论方法中的新物理算符。这项研究展现了标准模型中希格斯，电弱和顶夸克过程之间深刻的联系，对于理解超出标准模型的新物理在电弱能标的影响以及探寻新物理能级有着重要意义，并且对于未来更高能级对撞机上开展的物理研究有一定的指导作用。

关键词：ATLAS 实验；希格斯玻色子；汤川耦合；粲夸克；底夸克；希格斯玻色子联合测量；超出标准模型新物理；有效场论

南京大学研究生毕业论文英文摘要首页用纸

THESIS: The beauty and charm of Higgs: Search for Higgs Boson decays to charm quarks with the ATLAS experiment and search for new physics with combined measurements

SPECIALIZATION: Particle Physics and Nuclear Physics

POSTGRADUATE: Yuhao Wang

MENTOR: Professor, Lei Zhang

ABSTRACT

Since the discovery of Higgs boson in 2012, its properties are measured with increasing details and the results are in good agreement with the prediction of Standard Model (SM) of particle physics so far. However, the SM is believed not to be the ultimate theory due to its deficiencies, such as difficulty in explaining Higgs mass hierarchy problem and missing candidate for dark matter. Numerous models have been raised to solve these issues and several of them predicts additional Higgs bosons and a different behavior of SM Higgs, including Yukawa coupling and Higgs self-coupling strength. Thus, the measurement of Higgs properties is crucial to test the SM and search for new physics. This thesis presents two works concerning the Higgs properties and new physics searches: The simultaneous measurements of Yukawa coupling of charm and bottom quarks and the searches for physics beyond Standard Model (BSM) by combining various measurements of different processes.

The Higgs couplings with third generation fermions and with vector bosons are well established. However, it's coupling with the second generation of quarks is still not discovered yet. The search for Higgs decay to charm quarks is the next most promising decay mode to probe given its relative sizable branching ratio. It is also a good portal to search for new physics as any small deviation of Higgs-charm coupling will lead to a significant change of the Higgs phenomenology. In the first part of the thesis, the search for $H \rightarrow c\bar{c}$ decay in the vector boson associated production mode is presented. It also simultaneously measures $H \rightarrow b\bar{b}$ decay at the same time due to their similar topology and common backgrounds. The analysis use the

proton-proton collision dataset with an integrated luminosity of 140 fb^{-1} at 13 TeV collected by ATLAS during LHC Run-2. The searches for $H \rightarrow c\bar{c}$ yields in an observed (expected) upper limit of 11 (10) times the Standard Model prediction on the signal strength, which is the best observed results up to now. The results are also used to put constraints on a charm Yukawa coupling modifier $|\kappa_c| < 4.2$ at the 95% confidence level. The simultaneous measurements provide constraint on the ratio of Higgs-charm coupling and Higgs-bottom coupling (κ_c/κ_b) to be less than 3.5 at the 95% confidence level. The analysis method is validated with the measurement of the VZ process where V is a W or Z boson. For the first time in ATLAS, the $VZ(\rightarrow c\bar{c})$ process is observed with a significance larger than 5 standard deviation. This study is crucial for the understanding of the Yukawa coupling structure and the hierarchy problem of fermion mass.

In the second part, the thesis presents several studies that utilize statistical combination of measurements on different processes to search for the physics beyond SM. The first study searches for new physics beyond Standard Model using the combined measurement of SM Higgs production and decay. The results are interpreted with Two Higgs Doublet Models (2HDM) and dedicated scenarios of the Minimal Supersymmetric Standard Model (MSSM), as well as the Effective Field Theory (EFT) framework. The second study combines the search for Higgs pair production via a new resonance, and the results are interpreted in 2HDM and MSSM scenarios. In complementary to the Higgs measurement, the electroweak measurements provides unique sensitivity to specific BSM effects. The third study probes the Top EFT operators using electroweak measurements. These operators are found to have sizable loop contribution to electroweak process and thus can be constrained using the precision measurements made by LEP and various low energy experiments like PVDIS. The study also makes the prediction of the constraint on these operators with the CEPC and FCC-ee, which shows significant advantage over the current ones. For all interpretations, no significant deviation from Standard Model is observed. These studies reveal the interplay between the Higgs, electroweak and top sector, help the understanding of the behavior of new physics at the electroweak energy scale and probe the energy scale of new physics exists. They also provide useful hints for the construction and operation of future colliders.

KEYWORDS: ATLAS Experiment; Higgs Boson; Yukawa coupling; charm quark; bottom

quark; Combined Higgs measurement; BSM Search; Effective Field Theory

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Personal Contribution

$VH(\rightarrow b\bar{b}, c\bar{c})$ Analysis

The analysis is the simultaneous measurement of $VH(\rightarrow b\bar{b})$ and $VH(\rightarrow c\bar{c})$ process. I have made significant contribution to both regimes, mainly including:

- b -jet calibration for the Pseudo Continuous tagger
- background validation of $VH(\rightarrow c\bar{c})$ 2-lepton channel
- Jet energy correction study: Introducing kinematic fit to $VH(\rightarrow c\bar{c})$ 2-lepton channel and update the implementation in $VH(\rightarrow b\bar{b})$ 2-lepton channel
- Machine Learning model training, including MVA model for $VH(\rightarrow c\bar{c})$ 2-lepton channel and CARL model for the assessment of $VH(\rightarrow b\bar{b})$ $t\bar{t}$ background shape uncertainties
- Fit study: Fit correlation scheme study, assessment of the impact from potential mis-modelling and the development of fit framework
- Production of final fit results and kappa interpretation
- Presented the analysis for the unblinding closure
- Internal note editor

This analysis is public as a conference note, ATLAS-CONF-2024-010, and have been submitted to JHEP (arXiv:2410.19611).

Searches for BSM with Combined Measurements

This work includes several individual studies, and I have made major contribution to them in the following aspects.

For the interpretation of combined measurements of Higgs properties, the contribution is as follows:

- BSM UV model interpretation using h MSSM, 2HDM and MSSM benchmarks.
- Develop GRID submission framework to allow running container image on the GRID system, which ensures the on-time delivery of results for several publications.
- Validated the $VH(\rightarrow b\bar{b})$ analysis and maintain the fit framework.
- Internal note editor and gave ATLAS approval talk for one conference note
- Presented the results to the public in a global conference (Higgs2023).

This study has published a series of conference note, including ATLAS-CONF-2020-053, ATLAS-CONF-2021-053, ATLAS-CONF-2023-052, and published two papers, the coupling measurements results on Nature^[1] and the interpretation results on JHEP^[2].

For the interpretation of combined search for Di-Higgs resonant production, I was the internal note editor, introduced a new interpretation strategy which makes use of the BSM models feature and significantly cut down the computing resources consumption, and perform the interpretation in h MSSM and 2HDM. The result is published on Physics Review Letter^[3].

The Top EFT study utilizing the electroweak precision measurements is outside the ATLAS scope. I have the following contributions:

- Main editors of the paper.
- Produced the Monte Carlo samples and calculated the impact of the operators.
- Studied the effect of experiment acceptance.
- Developed the fit framework and produced fit results
- Made prediction with projections from future colliders

The paper is published on Chinese Physics C^[4] (Chinese Phys. C, 46 113105).

Chapter 1

Introduction

The Standard Model of Particle Physics (SM) describes the elementary particles and their interactions, unifying three out of four fundamental forces: electromagnetic, weak and strong forces. It has been tested by numerous experiments and shows good agreements. In 2012, the Higgs boson was discovered by ATLAS and CMS at LHC, which marks a milestone that further confirm the validity of Standard Model. The Higgs boson plays a special role in the SM, that is responsible for the generation of particle mass via the Brout-Englert-Higgs mechanism. After its discovery, the properties of Higgs boson have been studied in increasing details and the experiment results show good agreement with the SM prediction. However, some of its couplings predicted by SM haven't been observed so far, for example, the Higgs couplings to first and second generation fermions and Higgs self couplings. Additionally, a lot of BSM theories predicts a different behaviors of the Higgs, and with current measurements these possibilities can not be excluded. Thus, the measurement of Higgs boson properties is crucial to understand the Standard Model and search for new physics, making it a focus of the LHC program. This thesis present two works concerning the Higgs boson and searches for BSM physics. The first work is the simultaneous measurements of Higgs Yukawa coupling strength to charm quarks and to bottom quarks. The second work is the search for the BSM using three kinds of combined measurements respectively.

The fermions acquire their mass through interaction with Higgs boson, described by Yukawa mechanism. The Yukawa coupling is predicted to be proportional to the fermion mass in the SM. It is not controlled by any symmetry principle, resulting in a large number of free parameters that can only be measured by experiments, and with sizes varying from 10^{-6} (for electron) to 1

(for top quark). This is known as the fermion hierarchy problem which also lacks explanation from SM. Thus, the measurement of Yukawa coupling strength is essential for the understanding of flavor structure of fermions and any deviation from SM would be the sign of new physics. The Yukawa coupling of Higgs to the third generation of quarks (top and bottom quark) and charged lepton (tau lepton) have been confirmed and measured to be in agreement with SM prediction. However, the coupling of Higgs to first and second generation of quarks has never been discovered as their expected branching ratios are much smaller. Thus, it is of particular interest to search for the Higgs coupling to first and second generation quarks for complete understanding of the properties of Higgs. Among all the decay channels, Higgs decaying to charm quarks ($H \rightarrow c\bar{c}$) is the most promising decay mode to investigate as it is the largest undiscovered decay modes. It is also a perfect portal of the search for the physics beyond SM as in many BSM models, the Higgs-charm coupling is predicted to be significantly altered compared with its SM prediction^[5]. At LHC, the large multi-jet background from the proton-proton collision makes the search of physics process with quark final states very challenging. As a result, the $H \rightarrow c\bar{c}$ is searched in the vector boson associated production mode, with the vector boson decay leptonically. The $H \rightarrow b\bar{b}$ decay was also firstly discovered in this production mode. By utilizing VH production mode, the multi-jet background can be greatly suppressed. The identification of c -quark initiated jet is crucial for the search. Due to the similarity of jet structure of c -jet and b -jet, a harmonized identification tool is developed for better separation of two kinds of jets. Given the similar topology of $VH(cc)$ and $VH(bb)$ processes, there is significant benefit on physics output and background control to study these two decay modes simultaneously. This simultaneous measurement is presented in this thesis.

So far, there is no obvious deviation from the SM observed by experiments. However, despite its success, the SM is still believed not to be the ultimate theory due to its limitations. For instance, the Higgs hierarchy problem that raises question to the fine-tuning cancellation between quadratic radiative corrections and the bare mass of Higgs to obtain the current measured mass of Higgs. There is also the existence of dark matter that is well-known from astrophysical observation, but the SM has no candidate particle for it. In order to solve these issues, a lot of beyond Standard Model (BSM) theories have been proposed, and many of them extend the Higgs sector of SM. For example, the Minimal Supersymmetric Model (MSSM) extends the Higgs

sector with an additional scalar. These BSM theories will result in the different phenomena than SM, which could be probed with current experiments. The search for new physics can be performed through two approaches: the direct search that targets the new particles or processes which is not presented in the SM; The indirect search that targets the deviation on the SM process brought by the new physics. These two approaches are complementary to each other and provide competitive sensitivity in specific BSM theories. In this thesis, either two approaches are presented, using three sets of combined measurements that include the current most precise measurements of different processes, targeting different phase space of BSM theories: the indirect search using combined Higgs measurements, the direct search using combined resonant Di-Higgs production and the indirect search using combined electroweak precision measurements. They are briefly introduced in the following paragraphs.

The measurement of Higgs property in single channel could provide information of Higgs couplings to the given particles. However, it hardly provides full picture of Higgs properties. For example, through $VH(\rightarrow c\bar{c})$ production measurement, it is possible to constrain the Higgs-charm coupling. Yet, the process is also affected by the coupling of Higgs to vector bosons, but due to the overlap of its impact with charm Yukawa coupling, it is difficult to entangle the HVV and Hcc couplings in this single measurement. Therefore, a combined analysis that utilizes all the Higgs measurements will be beneficial. It allows the measurement of various Higgs couplings at the same time without additional assumptions. Several Higgs production and decay modes are considered for the latest ATLAS combined Higgs analysis, including: multiple production mode for $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ$, $H \rightarrow WW$, $H \rightarrow \mu\mu$, $H \rightarrow \tau\tau$ and $H \rightarrow b\bar{b}$ decay channels; $H \rightarrow Z\gamma$ decay in inclusive production mode. The combined analysis not only benefit from the increase of statistic by adding up all the measurements, but also the coherent treatment of uncertainties will further improve the precision on the measurements, which makes it easier to search for the deviations brought by the physics beyond SM. The potential deviation is interpreted in several frameworks: framework of multiplicative modifiers κ which directly apply to the SM coupling strength (κ framework), effective field theory framework (EFT) and UV-complete BSM theories. This thesis presents the interpretation results of the recent combined Higgs measurements using EFT and BSM models.

In addition to the coupling of Higgs with other massive particles, the self-coupling of Higgs

is also a crucial topic to study. In the Standard Model, the self-coupling is originated from the potential of Higgs field after the simultaneous symmetry breaking. The size of self-coupling will decide the shape of the Higgs potential, which has important cosmological implications, involving the vacuum stability. Any deviation from SM would open a new window for new physics. It can be probed through the pair production of Higgs (so-called DiHiggs production). The DiHiggs production can be greatly enhanced through the production of a new resonance that decays to a pair of SM Higgs, which is a commonplace signature for almost all BSM models that extend the Higgs sector. Thus, a combined analysis that utilizes three most sensitive channels: $bbbb$, $bb\tau\tau$ and $bb\gamma\gamma$, is performed to search for such resonance. The results are interpreted in popular BSM models, including 2HDM, h MSSM and singlet model. The analysis are shown in this thesis.

The electroweak measurements, which refers to the measurements of vector boson properties, is also a good portal to search for hint of new physics thanks to the high precision, and it is natural to use the EFT framework to search for the hints as the process happens at low energy. In many BSM models, the third generation quarks often play a special role that have interplay with BSM particles, which can be captured by the EFT operators involving the third generation quarks. As a result, it is important to probe them using the electroweak process. In this paper, a study that probes the top quark EFT operators using electroweak precision measurements is presented. These top quark EFT operators contribute to the electroweak process whose energy is lower than $t\bar{t}$ threshold via loop, making it difficult to constrain them at tree-level. However, it is found that these loop contribution is comparable with that from tree-level operators, and it is possible to constrain the top operators using electroweak data. Finally, the study makes the prediction of the constraining power using future colliders that have significant advantage over the current constraint.

Structure of the thesis

The thesis is structured as follows. Chapter 2 provides a brief overview of theoretical background about the Standard Model and Higgs phenomenology at LHC. Chapter 3 gives an introduction on LHC and ATLAS experiment, together with basic physics object definitions used in the physics analysis. The details of the simultaneous measurement of Higgs decay to charm

quarks and bottom quarks in VH production mode is shown in Chapter 4. Chapter 5 presents the three analyses that search for new physics using combined measurements, including Section 5.2 for combined Higgs measurements, Section 5.3 for combined measurements of Higgs pair production and Section 5.4 for electroweak measurements. Finally, Chapter 6 gives a brief summary and outlook.

Chapter 2

Theoretical Background

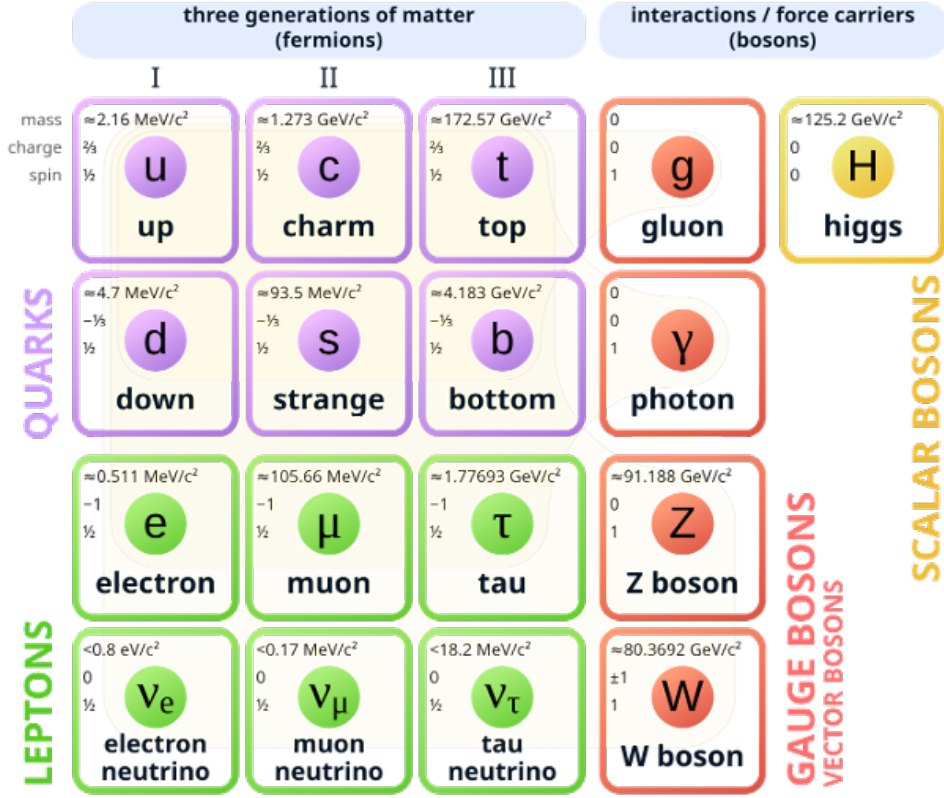
Up to now, our best understanding of the elementary particles is described by the Standard Model (SM). This chapter gives an overview of the SM, especially focus on the Higgs sector. Furthermore, several popular models that predict physics beyond standard model (BSM) are introduced.

2.1 The Standard Model

The SM provides fundamental description of the elementary particles and the interaction between them, through electromagnetic, weak and strong interactions in a unified picture^[6-8]. It has been tested in high precision in the past decades, resulting in a good agreement between the experiment and the theory.

2.1.1 Particles and Interactions

Figure 2-1 shows the elementary particles in SM. They can be classified by the intrinsic angular momentum, i.e. spin. Particles with half-integer spin follow the Fermi-Dirac statistics and named as fermions. Particles with integer spin follow the Bose-Einstein statistics and named as bosons. The fermions are further classified into two categories: quarks and leptons. The quarks carry the colour charge, which is the quantum number for strong interaction. Up-type quarks have the charge of $\frac{2}{3}e$ and have three generations: up (u), charm (c) and top (t). Down-type quarks carry charge of $\frac{1}{3}e$ and also have three generations: down (d), strange (s) and bottom (b). The leptons do not have colour charge and carry the integer charge of e or no charge. The


 Figure 2-1: Elementary particles in Standard Model. Data from Ref^[9].

charged leptons are electron (e), muon (μ) and tau (τ). Each of them has a neutral counterpart, referred to the neutrinos and denoted as ν_e , ν_μ and ν_τ .

The elementary particles interact via the four fundamental forces: strong, weak, electroweak and gravity forces. The gravity interaction between massive particles has a tiny strength in the micro scope, and it has not been unified with other forces, thus is excluded in following discussions. The rest fundamental interactions are constructed in the non-Abelian gauge group:

$$SU(3)_C \times SU(2)_L \times U(1)_\gamma \quad (2-1)$$

According to the Yang-Mills theory^[10], it gives rise to twelve vector fields. The excitation of these fields are known as gauge bosons that propagate the interactions. The strong force is propagated by eight gluons that carry two colour charges, weak interactions is propagated by the $W^\pm$ and Z bosons and the electromagnetic interaction is carried by the photon (γ). The $W^\pm$ and Z bosons are initially massless but require their mass through electroweak symmetry breaking (EWSB).

The Higgs boson arises from the EWSB. It is the only scalar boson in SM, which carries no spin. The details of EWSB and Higgs boson will be discussed later.

In the following sections, a brief review of the strong interaction and the electroweak interactions will be presented, followed by an overview of the electroweak symmetry breaking.

2.1.2 Strong Interactions

The interactions between quarks and gluons is described by quantum chromodynamics (QCD). Quarks carry a quantum number named colour charge and each quark flavor carries either a red (r), a green (g) or a blue (b) charge. Anti-quarks carry the anti-colours and any bound state of quarks is required to be colour neutral. As a result, it is impossible to find a stable state with single quark, and therefore the quarks and gluons will go through the hadronization after their production in LHC.

QCD is a non-Abelian gauge theory that is invariant under $SU(3)_C$ group transformation. The QCD Lagrangian given by a Dirac- and a kinematic term is

$$\mathcal{L}_{QCD} = \sum_q \bar{\psi}_q (i\gamma^\mu D_\mu - m_q) \psi_q - \frac{1}{4} G_{\mu\nu}^a G_a^{\mu\nu} \quad (2-2)$$

where q corresponds to the sum over the quarks and ψ_q indicates the spinor triplet. The covariant derivative D_μ is given by

$$D_\mu = \partial_\mu + ig_s \frac{\lambda^a}{2} G_\mu^a \quad (2-3)$$

where G_μ^a are the eight gluon vector field. The gluon tensor field $G_a^{\mu\nu}$ is given as

$$G_{\mu\nu}^a = \partial_\mu G_\nu^a - \partial_\nu G_\mu^a - g_s f^{abc} G_\mu^b G_\nu^c \quad (2-4)$$

where f^{abc} are the $SU(3)_C$ structure constants. g_s is the coupling constant, which is more commonly used as strong interaction $\alpha_s = \frac{g_s^2}{4\pi}$. It is dependent on the energy scale of the interaction. At high energy, α_s is small enough so that the perturbation calculation is valid, known as asymptotic freedom.

2.1.3 Electroweak Interaction

Electromagnetic interaction and weak interaction are described jointly within the Glashow-Salam-Weinberg (GSW) model^[6,8,11]. This model is constructed with the symmetry group $SU(2)_L \times U(1)_Y$. The first part comes from the $SU(2)$ invariance of weak charged current interaction, which has the $V - A$ structure that only couples to the left-handed fermions. The second part incorporates the weak neutral current interaction and electromagnetic interaction, with Y stands for weak hypercharge. Fermionic fields are split into left- and right-handed components using the projection operators P_L and P_R by:

$$\psi = P_L \psi + P_R \psi = \frac{1 - \gamma^5}{2} \psi + \frac{1 + \gamma^5}{2} \psi = \psi_L + \psi_R \quad (2-5)$$

The left-handed field can be termed as weak isospin doublet:

$$\begin{pmatrix} \nu'_e \\ e \end{pmatrix}_L, \begin{pmatrix} \nu'_\mu \\ \mu \end{pmatrix}_L, \begin{pmatrix} \nu'_\tau \\ \tau \end{pmatrix}_L, \begin{pmatrix} u' \\ d' \end{pmatrix}_L, \begin{pmatrix} c' \\ s' \end{pmatrix}_L, \begin{pmatrix} t' \\ b' \end{pmatrix}_L \quad (2-6)$$

In the SM, there is no right-handed neutrinos or LH anti-neutrinos. The right-handed field can be termed as weak isospin singlet:

$$e_R, \mu_R, \tau_R, u'_R, c'_R, t'_R, d'_R, s'_R, b'_R \quad (2-7)$$

Note that the prime indicates that the spinor field is weak interaction eigenstate instead of mass eigenstate. The Lagrangian of EW interaction can be written as

$$\mathcal{L}_E W = \bar{\psi}_L i \gamma^\mu D_\mu \psi_L + \bar{\psi}_R i \gamma^\mu \psi_R - \frac{1}{4} W_{\mu\nu}^a W_a^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} \quad (2-8)$$

with covariant derivation D_μ defined as

$$D_\mu = \partial_\mu + ig \frac{\sigma_a}{2} W_\mu^a + ig' \frac{Y}{2} B_\mu \quad (2-9)$$

The vector gauge field W_μ^a ($a = 1, 2, 3$) originates from the $SU(2)$ group, with W_μ^1 and W_μ^2 being charged and W_μ^3 being neutral. B_μ comes from the $U(1)$ group and is a neutral gauge

field. In the GSW model, the physical field, electromagnetic photon A_μ and Z boson field Z_μ result from the rotation of B_μ and W_μ^3 by a mixing angle θ_W (Weinberg angle):

$$\begin{pmatrix} A_\mu \\ Z_\mu \end{pmatrix} = \begin{pmatrix} \cos \theta_W & \sin \theta_W \\ -\sin \theta_W & \cos \theta_W \end{pmatrix} \begin{pmatrix} B_\mu \\ W_\mu^3 \end{pmatrix} \quad (2-10)$$

The coupling strength of weak interaction g (or denoted as g_W) and electromagnetic interaction e are related as:

$$e = g_W \sin \theta_W \quad (2-11)$$

However, the local gauge invariance can only be satisfied if all the bosons are massless. Experimentally the W and Z bosons are observed to have mass. As a result, additional mechanism needs to be included in the electroweak sector of SM: the Brout-Englert-Higgs (BEH) mechanism.

2.1.4 The Higgs Mechanism

The Brout-Englert-Higgs mechanism describes how the gauge bosons acquire mass through interaction with the Higgs field^[7,12-14]. Considering a complex scalar doublet ϕ that can be used to describe the weak isospin field

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} \quad (2-12)$$

with four degrees of freedom $\phi_i (i = 1, 2, 3, 4)$. The corresponding Lagrangian is

$$\mathcal{L} = (D_\mu \phi)^\dagger (D_\mu \phi) - V(\phi) \quad (2-13)$$

The first term is the kinematic term of the field, D_μ is the covariant derivative defined as Equation 2-9. The second term is the Higgs potential.

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2 \quad (2-14)$$

where μ and λ are scalar constants. The first term is the mass term and second term describe the self-coupling of the field. If $\mu^2 > 0$, the Higgs potential has its minimum at $\phi = 0$, which does not have the spontaneous symmetry breaking and the gauge bosons remain massless. As a result, the parameters are chosen such that $\mu^2 < 0$ and $\lambda > 0$, which yields the Mexican-hat potential as displayed in Figure 2-2. The minimum of the potential corresponds to the case of

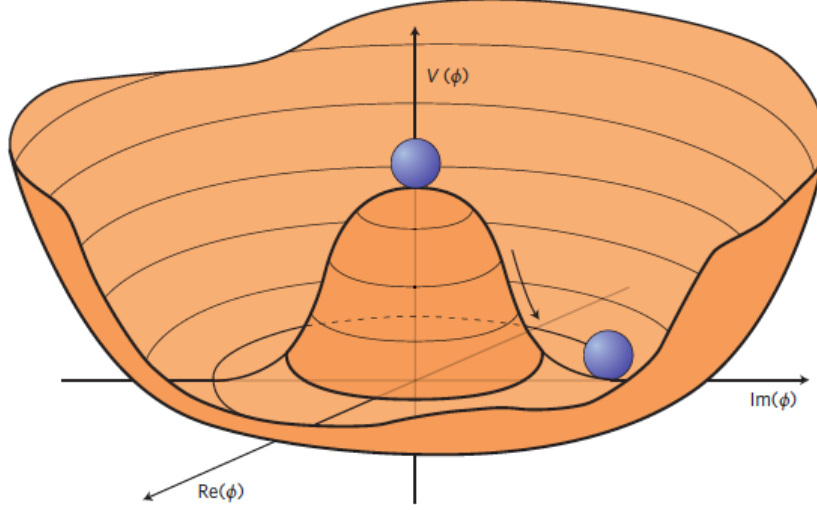


Figure 2-2: Illustration of the Higgs potential as a function of the real and imaginary part of complex singlet field.

$$\phi^\dagger \phi = -\frac{\mu^2}{\lambda} = \frac{v^2}{2} \quad (2-15)$$

The parameter $v = \sqrt{\frac{-\mu^2}{2\lambda}}$ is known as the vacuum expectation value. All the minima are equivalent and can be connected by an $SU(2)$ transformation. Therefore, the vacuum expectation state is chosen to be

$$\langle 0 | \phi | 0 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \quad (2-16)$$

The expansion around this vacuum expectation state can be written As

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ v + i\eta + i\phi_4 \end{pmatrix} \quad (2-17)$$

The field ϕ is described by one real physical field η and three Goldstone fields $\phi_{1,2,4}$. By applying the unitary gauge, the Goldstone fields can be absorbed by vector field. In this case,

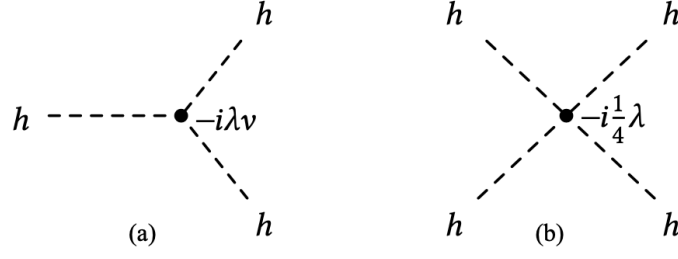


Figure 2-3: Feynman diagram for the trilinear (left) and quartic (right) self-coupling of Higgs boson.

the expansion can be simplified to:

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix} \quad (2-18)$$

where $h(x)$ is the Higgs field. Now it is possible to extend the Lagrangian as:

$$\begin{aligned} \mathcal{L} = & \frac{1}{2}(\partial_\mu h)(\partial^\mu h) - \lambda v^2 h^2 - \lambda v h^3 - \frac{\lambda}{4} h^4 \\ & + \frac{v^2 g^2}{4} W_\mu W^{\dagger\mu} + \frac{v^2 g^2}{8 \cos^2 \theta_W} Z_\mu Z^\mu \\ & + \frac{v g^2}{W_\mu W^{\dagger\mu}} H + \frac{v g^2}{4 \cos^2 \theta_W} Z_\mu Z^\mu H + \frac{v g^2}{4} W_\mu W^{\dagger\mu} H^2 + \frac{v g^2}{8 \cos^2 \theta_W} Z_\mu Z^\mu H^2 \end{aligned} \quad (2-19)$$

The first term of the first line is the kinematic term of Higgs field and second term gives the mass of Higgs:

$$m_H = \sqrt{2\lambda v^2} = \sqrt{-2\mu^2} \quad (2-20)$$

The third and fourth term are the trilinear and quartic coupling of Higgs field, as illustrated in Figure 2-3. The second line of Equation 2-19 gives the mass of W and Z boson:

$$m_W = \frac{vg}{2}, \quad m_Z = \frac{vg}{2 \cos \theta_W} \quad (2-21)$$

They have the relation of $m_W = m_Z \cdot \cos \theta_W$. The third line of Equation 2-19 describes the coupling of Higgs boson with the gauge bosons, including WWH , ZZH , $WWHH$ and $ZZHH$ couplings.

The Higgs mechanism also gives rise to fermion mass by the Yukawa terms. The Yukawa

term describes the coupling of fermions with Higgs, which is invariant under $SU(2)_L \times U(1)_Y$ transformation. It can be written as

$$\mathcal{L}_{Yukawa} = \sum_f -\frac{y_f v}{\sqrt{2}} \bar{\psi}_f \psi_f - \frac{y_f}{\sqrt{2}} \bar{\psi}_f \psi_f h \quad (2-22)$$

where the coupling parameters y_f are known as the Yukawa coupling, which can be parameterized as

$$y_f = \sqrt{2} \frac{m_f}{v} \quad (2-23)$$

The coupling strength of fermion with Higgs boson is proportional to the mass of the fermions, which is an important feature to be checked in the $VH(\rightarrow b\bar{b}, c\bar{c})$ analysis. The fermion field used in Equation 2-22 is the mass eigenstate. As a result, a rotation matrix needs to be introduced to translate the mass eigenstate basis to weak interaction eigenstate basis. The transformation matrix in quark sector is called the Cabbibo-Kabayashi-Maskawa (CKM) matrix^[15], in neutrino sector is called Pontecorvo-Maki-Nakagawa-Sakata matrix^[16].

2.2 Higgs Phenomenology at LHC

One of the primary goal since the operation of LHC is the observation of Higgs boson. In 2012, ATLAS^[17] and CMS^[18] reported the discovery of a particle at 125 GeV. Further studies confirmed that the property of this particle is in line with the predicted Higgs boson of SM.

2.2.1 Production of Higgs at LHC

At LHC, there are four main Higgs production modes: gluon-gluon fusion (ggF), vector boson fusion (VBF), associated production with a vector boson (VH) and associated production with top quarks ($t\bar{t}H$). The Feynman diagrams of these production modes are illustrated in Figure 2-4. Their cross-section depends on the centre-of-mass of the proton-proton collision, as shown in Figure 2-5. Some other production modes are also shown in the figure such as $b\bar{b}H$ and tH .

ggF is the most common Higgs production mode at LHC, with a cross-section of $\sigma_{ggF} = 48.6 \pm 2.4$ pb at 13 TeV^[19]. The relative large production cross-section comes from the significant portion of gluon in parton distribution function. The gluon does not couple to Higgs

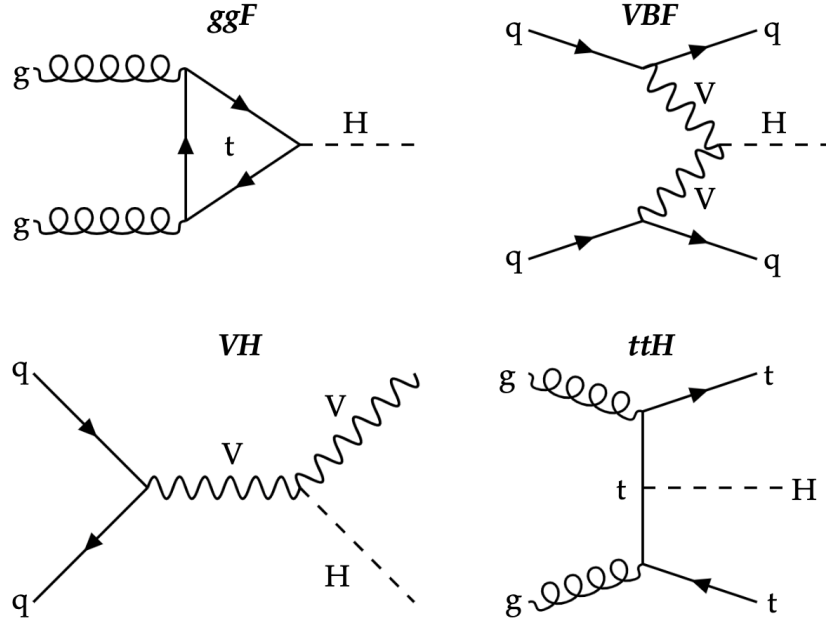
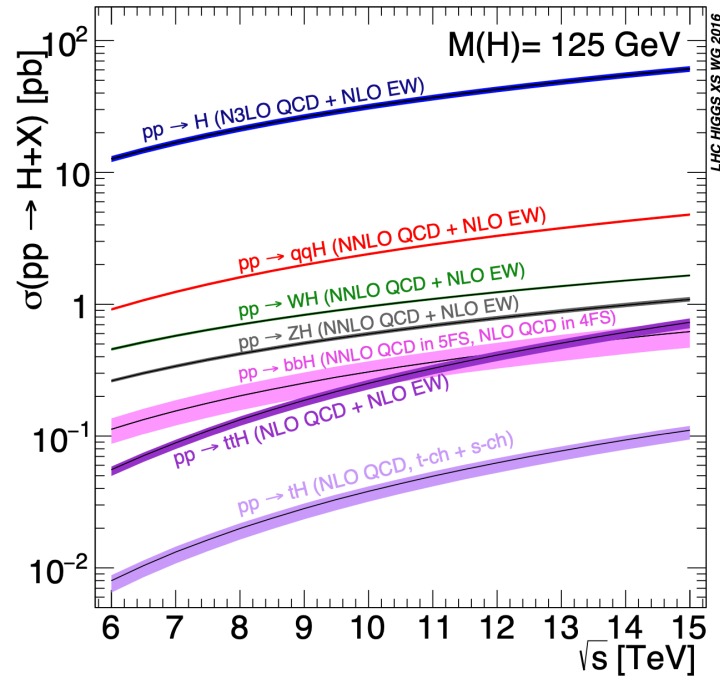


Figure 2-4: Four main production modes of Higgs at LHC.

Figure 2-5: Higgs production cross-section as a function of LHC centre-of-mass energy^[19].

boson, so the Higgs boson is produced via quark loop, where top quark contributes most since it is the heaviest quark. Though ggF is the most common production mode, it is extremely hard to search for $H \rightarrow c\bar{c}$ and measure $H \rightarrow b\bar{b}$ due to the large multi-jet background.

VBF is the second most common Higgs production mode, with a cross-section of $\sigma_{VBF} = 3.77 \pm 0.09$ pb. Two quarks mediate two off-shell vector bosons and then produce a Higgs boson. This production mode is easy to be identified in experiment as it is characterized by two forward jets originated from the two scatter quarks.

VH production has a smaller cross-section of $\sigma_{VH} = 2.24 \pm 0.14$ pb, yet it provides a very clean signature in the detector when the vector bosons decay leptonically. The lepton requirements can significantly reduce the multi-jet background. As a result, VH is the golden production mode for the measurement of $H \rightarrow b\bar{b}$ and $H \rightarrow c\bar{c}$.

The ttH production mode have an even smaller cross-section of $\sigma_{ttH} = 0.51 \pm 0.04$ pb. It offers a chance to measure the top quark Yukawa coupling at tree-level.

2.2.2 Decay of Higgs

The width of Higgs boson is estimated to be around 4 MeV, which implies a very short lifetime at $O(10^{-22}s)$. It means that Higgs will decay immediately once it is produced, and the detector can only capture the signals from its decay products. Relative decay rate of the particle is described by branching ratio(BR), which represents the probability of the parent particle decaying to the given final states. As the Yukawa coupling strength is proportional with the fermion mass, the Higgs decaying to heavy particles are preferred, especially $H \rightarrow b\bar{b}$. Besides the Higgs decay to quark pairs, it can also decay to vector boson pair with one boson off-shell and to neutral boson pair (gluons, photons) via quark loop. It is defined as the ratio of partial width in the total decay width. The dominant Higgs decay mode is $H \rightarrow b\bar{b}$, taking up to 58% of BR. The second most common decay into quarks is $H \rightarrow c\bar{c}$, with a BR of 2.9%. Other common decay channels (corresponding BRs) include $H \rightarrow WW$ (22%), $H \rightarrow gg$ (8.2%), $H \rightarrow \tau\tau$ (6.3%), $H \rightarrow ZZ$ (2.6%), $H \rightarrow \gamma\gamma$ (0.23%) and $H \rightarrow Z\gamma$ (0.15%)^[19].

The discovery of Higgs boson in 2012 exploited the decay mode of $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ \rightarrow 4l$ and $H \rightarrow WW \rightarrow l\nu l\nu$. They do not have the largest BRs but have a clean background. After the discovery, more decay channels and production modes have been measured and show good

consistency with the SM expectation.

2.2.3 Di-Higgs Production

The Higgs can also be produced in pair (Di-Higgs production) via several processes. The leading production modes are gluon-gluon fusion (ggF) and vector boson fusion (VBF). The gluon-gluon fusion accounts for about 90% of the Di-Higgs production. It proceeds through two diagrams at tree level, as shown in Figure 2-6, the so-called triangle diagram and box diagram. The triangle diagram is sensitive to Higgs trilinear self-coupling while the box diagram is sensitive to the Higgs-top Yukawa coupling. The two diagrams interfere destructively, leading to a small cross-section. For $m_H = 125$ GeV and $\sqrt{s} = 13$ TeV proton-proton collision, the predicted cross-section is^[20]

$$\sigma_{ggF} = 31.1^{+1.9}_{-7.1}(\text{scale}+m_{top}) \pm 0.9(\text{PDF}+\alpha_S) \text{ fb} \quad (2-24)$$

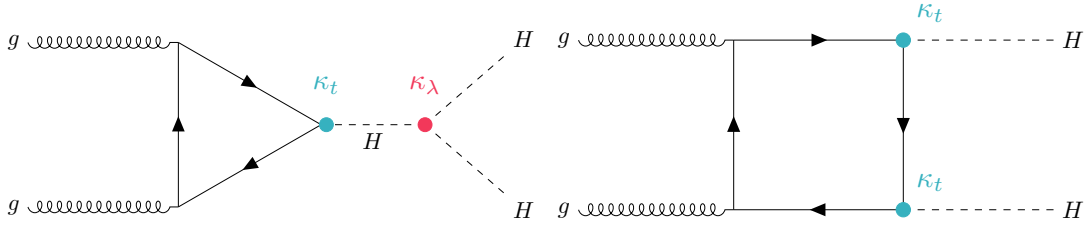


Figure 2-6: Leading-order Feynman diagrams of gluon-gluon fusion Di-Higgs production in standard model, left is called triangle diagram and right is called box diagram.

The Feynman diagrams of vector boson fusion production mode are shown in Figure 2-7, which has an even smaller cross-section^[21]

$$\sigma_{VBF} = 1.73 \pm 0.04 \text{ fb} \quad (2-25)$$

The cross-section of Di-Higgs production is about three orders of magnitude smaller than the single Higgs production, makes the search very challenging. The latest results from ATLAS using the Run-2 dataset set the observed (expected) upper limit at 95% CL on Di-Higgs production cross-section of 2.9 (2.4) times the SM prediction by combining the main decay channels^[22].

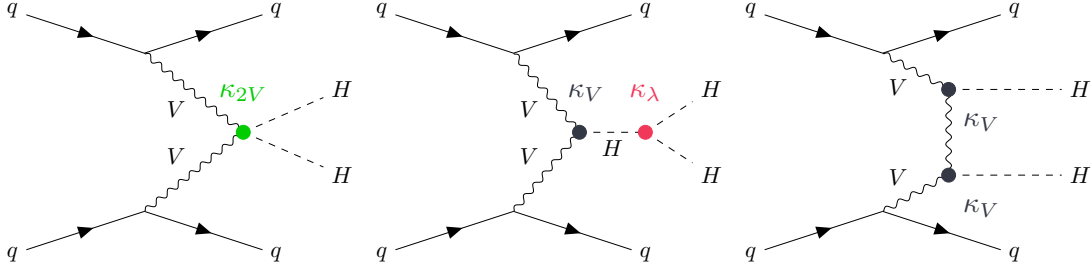


Figure 2-7: Leading-order Feynman diagrams of vector boson fusion Di-Higgs production in standard model.

2.3 Beyond the Standard Model

The SM has been proved to be an incredibly successful theory, with its predictions to the behaviors of subatomic particles being verified experimentally in unprecedented precision. However, the SM still has substantial shortcomings that suggest it is not the final theory of nature. For example, the "fine tuned" description of Higgs boson mass and omission of the description of dark matter.

The Higgs mass is a free parameter in the SM, which means no prediction can be made and can only be measured by experiment. The measured mass of Higgs is a combined result from the bare mass of Higgs boson and sum of corrections from the interaction between Higgs and other particles. The heavier particle will bring a larger correction to Higgs mass. For top quark, the heaviest SM particle, it brings such a large correction to the Higgs mass that it requires the bare mass of Higgs to be very large to cancel the corrections and results in a relative small measured mass. This exquisitely precise cancelation between two very large numbers to yield a single small number is known as "fine tuning". Fine tuning has historically been a sign that the cancelation is not coincidental, but there is an additional unknown mechanism that naturally requires the cancelation to occur.

Dark matter was established to explain the observation that rotational velocity of certain galaxies requires more matter than is visible, and further described quantitatively through the precision measurements of Cosmic Microwave Background radiation. These evidences indicate that the dark matter is potentially a weakly interactive massive particle (WIMP), for which there is no candidate in the SM.

Besides these two compelling shortcomings of SM, there are some other phenomena, such

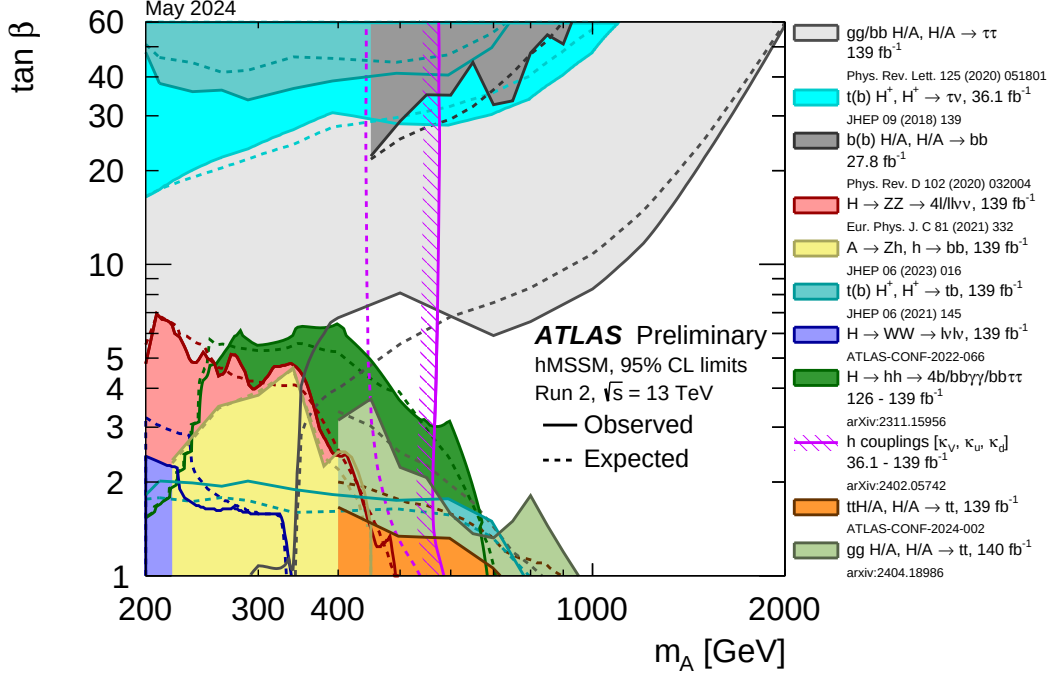


Figure 2-8: Regions of the $[m_A, \tan \beta]$ plane excluded in the hMSSM via direct searches for heavy Higgs bosons and fits to the measured rates of observed Higgs boson production and decays. Limits are quoted at 95% CL and are indicated for the data (solid lines) and the expectation for the SM Higgs sector (dashed lines).

as the matter-antimatter asymmetry and neutrino oscillations, that can not be explained by the SM. In addition, the SM has difficulty to harmonize with the general relativity. One or both theories will break down under certain conditions. As a result, various theories have been developed to explain the deficiencies of the SM, such as Two Higgs doublet Model (2HDM) and supersymmetric standard model (SUSY). And these theories are the so-called BSM ultra-violet complete model, which are renormalizable at UV limit. In practice, because the new physics in these models are at high energy scale, the effective field theory (EFT) is often used as a low energy approximation to simplify the calculation at the electroweak energy scale. These theory frameworks are among the ones that is popular used in the ATLAS searching for BSM, due to their rich phenomenology brought at LHC. As indicated in Figure 2-8 by using hMSSM model as an example, which shows the exclusion region in hMSSM phase spaces by different channels, a lot of final states are targeted in ATLAS searching for BSM, and they provide competitive and comparable sensitivity. A brief introduction of the theories that included in the thesis are given below, and more details can be found in the corresponding chapters.

2.3.1 Two Higgs doublet Model

2HDM is one of the simplest extensions of SM, built by adding one more scalar doublet to the SM Higgs sector. It was firstly raised by T.D. Lee^[23] to provide extra source of CP-violation to explain the matter-antimatter asymmetry. Let Φ_1 and Φ_2 denote the two complex doublet scalar fields, the Higgs potential can be written as:

$$\begin{aligned} \mathcal{V} = & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - [m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.}] \\ & + \frac{1}{2} \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2} \lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1) (\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2) (\Phi_2^\dagger \Phi_1) \\ & + \frac{1}{2} \lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \lambda_6 (\Phi_1^\dagger \Phi_1) (\Phi_1^\dagger \Phi_2) + \lambda_7 (\Phi_2^\dagger \Phi_2) (\Phi_1^\dagger \Phi_2) + \text{h.c.} \end{aligned} \quad (2-26)$$

The m_{12}^2 and $\lambda_{5,6,7}$ can be complex while other parameters have to be real to make the potential hermitian. In many discussions of 2HDM, an additional $\mathbb{Z}_2$ symmetry ($\Phi_1 \rightarrow -\Phi_1$) is usually imposed to avoid the flavor changing neutral current happens at tree level, and results in the absence of λ_6 and λ_7 . The scalar field will have non-zero vacuum expectation values if the mass matrix m_{ij}^2 has at least one negative eigenvalue. By choosing the two vacuum expectation values to be real, the 2HDM can be CP-conserving or explicitly CP-violating. Usually the CP-conserving 2HDM is used for the interpretation of Higgs measurements in ATLAS. Thus, in the following context, only the CP-conserving 2HDM will be discussed. Then the scalar field vacuum expectations can be expressed in the form

$$\langle \Phi_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \quad \langle \Phi_2 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_2 \end{pmatrix} \quad (2-27)$$

with the relation of $v^2 = v_1^2 + v_2^2 = (246 \text{ GeV})^2$ due to the requirement of gauge bosons mass.

The doublets can be thus written as

$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ (v_i + \rho_i + i\eta_i)/\sqrt{2} \end{pmatrix}, \quad i = 1, 2 \quad (2-28)$$

Two most important parameters of 2HDM is $\tan \beta \equiv \frac{v_2}{v_1}$ and α . β is the rotation angle that diagonalizes the mass matrix of charged scalars and pseudoscalars, while α is the rotation angle diagonalizes the mass matrix of scalars. These two parameters decide the interactions of various Higgs fields with the vector bosons and fermions. The couplings of the scalar with bosons and

fermions are discussed in detail in Section 5.2.3.

Of the original eight scalar degrees of freedom, three Goldstone bosons are absorbed by the $W^\pm$ and Z bosons. The remaining five degrees of freedom correspond to five Higgs particles: two CP-even scalar h and H , two charged Higgs $H^\pm$ and one CP-odd scalar A . The pseudoscalar A can be obtained from the linear combination of η_1 and η_2

$$A = \eta_1 \sin \beta - \eta_2 \cos \beta \quad (2-29)$$

The CP-even scalars are a lighter h and heavier H , which are orthogonal combinations of ρ_1 and ρ_2

$$h = \rho_1 \sin \alpha - \rho_2 \cos \alpha \quad (2-30)$$

$$H = -\rho_1 \cos \alpha - \rho_2 \sin \alpha \quad (2-31)$$

and the standard model Higgs boson would be

$$H^{SM} = h \sin(\alpha - \beta) - H \cos(\alpha - \beta) \quad (2-32)$$

In the decoupling limit, where the energy scale of new physics is much larger than the electroweak energy scale, the role of SM Higgs is mostly played by the lighter scalar. The phenomenology of 2HDM at decoupling limit is discussed in detail by Ref^[24-25].

2.3.2 MSSM

Supersymmetry (SUSY) is an extension of standard model by introducing additional symmetry between fermions and bosons. It proposes that for every known particle, there is a superpartner particle with different spin property. The SUSY theory can be used for the explanation of "fine tuning" problem of Higgs mass, by the exact cancelation of loop correction from SM particles and their superpartners. In many SUSY models, there is a heavy stable particle (such as neutralino) which could be the WIMP dark matter candidate. The SUSY can also provide solution to matter-antimatter asymmetry and hierarchy problem^[9].

The Minimal Supersymmetric Standard Model (MSSM) is the minimal supersymmetrical

model as it introduces minimal number of new particles for the realization of supersymmetry. The Higgs sector of MSSM consists two Higgs complex doublets, which is same as 2HDM. Similarly, there are five Higgs particles after the spontaneous symmetry breaking: h , H , A and $H^\pm$. The details of the MSSM benchmark scenarios and their phenomenology at LHC are discussed in detail in Section 5.2.3

2.3.3 Effective Field Theory

The basic idea of effective theory is that the dynamics at low energy scale does not depend on the details of the theory at high energy scale. It means that the low energy phenomena can be described using effective Lagrangian that contains only a few degrees of freedom^[26]. For example, in the Fermi theory of weak interaction, instead of having the W boson propagator, the interactions are described with a four-fermion vertex, which also works well at energy scale well below W mass. For many UV-complete models, including the 2HDM and MSSM mentioned above, with no obvious direct evidence for new physics at current energy scale probed, they usually predict that the new particles will present at high energy scale (usually above 1 TeV), which is highly above the energy scale that LHC can reach. However, by using the effective field theory, it is possible to probe the effect from high energy scale theories with the LHC data.

In the case that the new physics happens at high energy scale, it is enough to describe its phenomenology at electroweak energy scale by using the fields from SM. The standard model effective field theory (SMEFT) discussed below is built from the gauge invariant operators involving the SM fermion, gauge and Higgs field, remaining the $SU(3) \times SU(2) \times U(1)$ symmetry as SM. However, the interactions are no longer renormalizable in EFT, which means that the operators have canonical mass dimension larger than 4. The general form of the EFT Lagrangian can be written as

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i^{(5)}}{\Lambda} O_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)} + \sum_i \frac{c_i^{(7)}}{\Lambda^3} O_i^{(7)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4} O_i^{(8)} + \dots \quad (2-33)$$

where $O_i^{(D)}$ is the operator of Dimension D and the corresponding parameter $c_i^{(D)}$ multiplying the operator is the so-called Wilson coefficient. The leading term in this Lagrangian is the SM Lagrangian with operators up to $D = 4$. All effects of new physics are encoded in operators

with $D > 4$, which are suppressed by the mass scale Λ . When $\Lambda \rightarrow \infty$, the EFT falls back to the SM. All operators with $D = 5$ violate the lepton number conservation and thus stringently constrained by experiment. Operators with $D = 7$ violate the baryon number minus lepton number ($B - L$) conservation which means they will be constrained to the level that makes them unobservable at LHC. For the operators with $D \geq 8$, they are suppressed by the order of $1/(\Lambda)^4$, in most case are negligible. As a result, the following discussion will focus on the operators with $D = 6$.

It is demanded that the $D = 6$ operators need to form a complete, non-redundant set, named as *basis*. Any $D = 6$ operator is either a part of the basis or can be obtained from a combination of operators in the basis. Non-redundant means it is a minimal subset. Several bases are proposed, and have their advantages in different cases. The most popular bases include Warsaw basis, SILH basis and Higgs basis. The Warsaw basis^[27] builds the operators using the fields before the spontaneous symmetry breaking, resulting in 2499 $D = 6$ operators. Warsaw basis is one of the most popular bases, used most commonly for the interpretation of electroweak, top and Higgs measurements.

The contributions from the operators in EFT to amplitudes of electroweak process are at the order of $(v/\Lambda)^4$. With the choice of $\Lambda \gg v$, the EFT typically describes the small deviations from the standard model. By combining different measurements, the EFT operators can be probed more precisely and widely.

Connection between EFT and BSM UV models

The BSM UV models provide the detailed description of the new physics at both high energy scale and low energy scale, but with the cost of too many free parameters and heavy theoretical calculation. While the EFT provides the approach to simplify the calculation without losing the precision of the impact. As a result, EFT is often used as the framework for the indirect search of BSM that happens at relatively low energy. And the Constraints on EFT parameters can be re-interpreted as constraints in many BSM theories, through the procedure named *Matching*. With this approach, the interpretation of experimental measurements as constraints on theoretical framework has to be done only once in the EFT framework, rather than for each BSM model separately. However, since EFT will lose its validity at high energy scale, for example, when

probing the heavy Higgs decay to a pair of SM higgs, it cannot be used for direct search. In summary, these two kinds of theoretical framework which describes BSM phenomenology are complementary with each other, and have advantages in different energy scale, both of them are used in the BSM studies of this thesis.

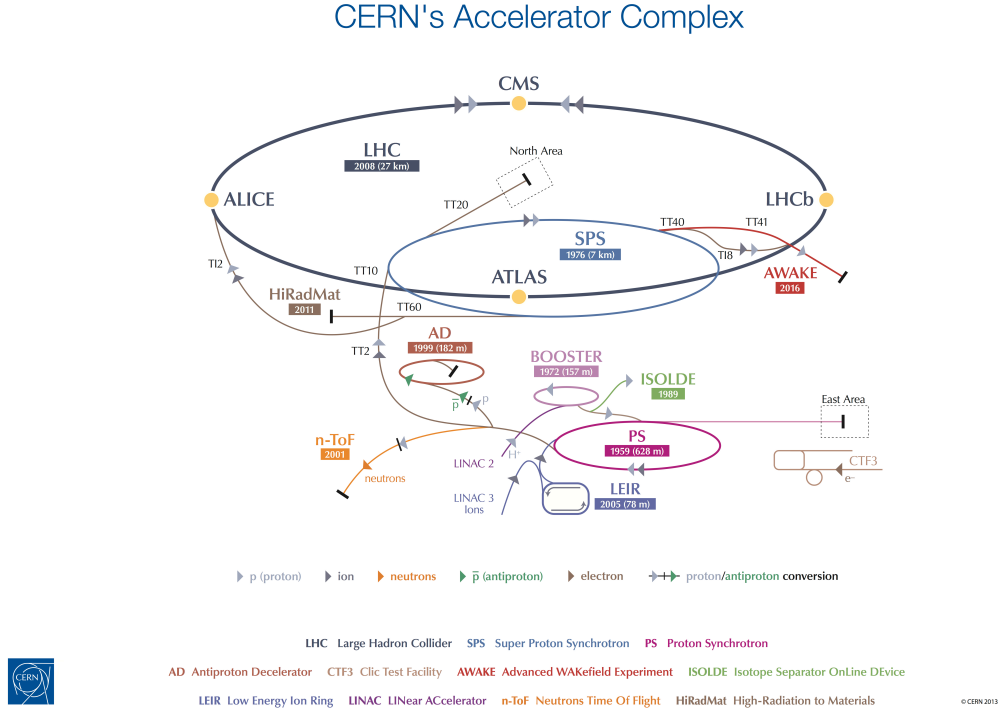
Chapter 3

The ATLAS Experiment

3.1 Large Hadron Collider

The Large Hadron Collider (LHC) at CERN is the world's largest particle accelerator and collider^[28] installed in the 26.7 km tunnel that was constructed for the LEP machine. The tunnel lies between 45 m and 170 m below the surface. The LHC is designed to collide proton beams with a centre-of-mass energy of 14 TeV and the peak luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$. It can also collide heavy ions (Pb).

Before the proton is injected into the main ring, they need to pass through several pre-accelerators, as shown in Figure 3-1. The protons are obtained from hydrogen gas that is ionized using electric field. They are then accelerated by a linear accelerator Linac to the energy of 50 MeV. The beam is then injected to the Proton Synchrotron Booster (PSB) which consists of four stacked synchrotron rings and accelerated to 1.4 GeV. The PSB also shapes the beam into bunches, each bunch contains about 10^8 protons. They are injected into the Proton Synchrotron (PS) that increase the energy to 25 GeV and followed by Super Proton Synchrotron (SPS) that increase the energy to 450 GeV. Finally, the proton bunch are injected into the LHC, where they circulate in two beam pipes in opposite directions. In the main ring, they are accelerated by radio-frequency cavities, kept on the circular path using super conducting dipole magnet which can produce a magnetic field of 8.33 T, shaped and focused using higher-order magnets. Finally, the proton bunches are accelerated to reach the energy of 6.5 TeV (in Run-2, 7 TeV in Run-3), spaced by 25 ns in time, corresponding to a crossing frequency at 40 MHz. The bunches are brought to collision at four interaction points, where locates four main LHC experiments: ATLAS^[29], CMS^[30], ALICE^[31] and LHCb^[32].

Figure 3-1: Illustration of LHC accelerator complex^[33].

ATLAS and CMS are two general purpose detectors, that are designed to explore SM, Higgs boson, supersymmetry and various exotic physics. The details of ATLAS detector will be described in the following section. The ALICE detector is built to study heavy-ion collision. The heavy-ion collision results in events with rich decay products including heavy flavor quarks which is sensitive to probe the quark-gluon plasma. The LHCb detector focuses on the heavy flavor physics (especially B-physics) with an asymmetric design of the detector as the B-meson are produced in the forward direction.

In the first period of LHC operation, known as Run-1, from 2011 to 2012, the protons are collided at centre-of-mass energy of 7 and 8 TeV, delivering an integrated luminosity of 28.3 fb⁻¹ dataset with ATLAS detector. The Higgs is discovered using these data. The Run-2 period lasts from 2015 to 2018. The centre-of-mass energy was increased to 13 TeV, delivering in total of 156 fb⁻¹ integrated luminosity and 140fb⁻¹ of them is recorded by ATLAS and used for physics analysis^[34]. The total average number of interactions per bunch crossing $\langle \mu \rangle$ (or called pile-up) is 34. The pile-up is defined as

$$\mu = \frac{L_{bunch} \sigma_{inel}}{N_b f} \quad (3-1)$$

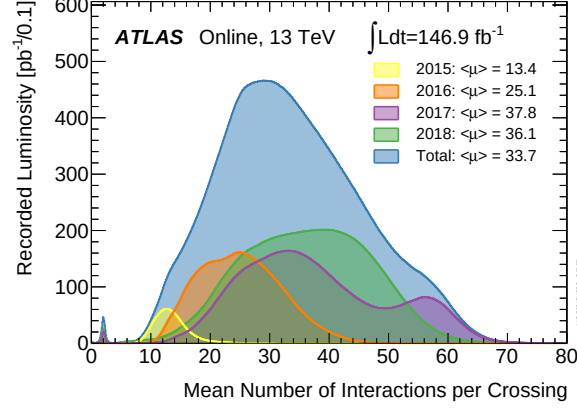


Figure 3-2: Luminosity-weighted distribution of the mean number of interactions per crossing for the Run-2 data recorded by ATLAS^[35].

where L_{bunch} is the instantaneous luminosity per bunch crossing, σ_{inel} is the cross-section of inelastic scattering, N_b is the number of bunches and f is the collision frequency. Figure 3-2 shows the distribution of mean pile-ups for the Run-2 data^[35]. During the Run-2, ATLAS recorded in total of 18 billion complete events.

At the moment, the LHC is in the third running period (Run-3), starting at 2022 and is expected to last about 4 years. The centre-of-mass energy for proton-proton collision has increased to 13.6 TeV. The pile-up also increases to around 50 to produce more events at one collision. It is expected to get twice the size of Run-2 dataset (300 fb^{-1}) till the end of the Run-3.

After the Run-3, LHC will have a long shutdown for the upgrade to High-Luminosity LHC (HL-LHC)^[36]. It is designed to have a collision rate five times greater than the LHC's original design, reaching up to $\langle \mu \rangle = 140$. It is expected to deliver an integrated luminosity of 3000 fb^{-1} dataset.

3.2 The ATLAS Experiments

The ATLAS (A Toroidal LHC ApparatuS) detector^[29] is a general purpose detector that locates at one of the interaction points of LHC. The ATLAS detector is the largest detector at LHC, with a total length of 44 m, a height of 25 m and a weight of 7000 tons. It consists of cylindrical detector layers and endcaps, as shown in Figure 3-3. From inside to outside, there are inner detector, electroweak calorimeter, hadronic calorimeter and the muon spectrometers (or named

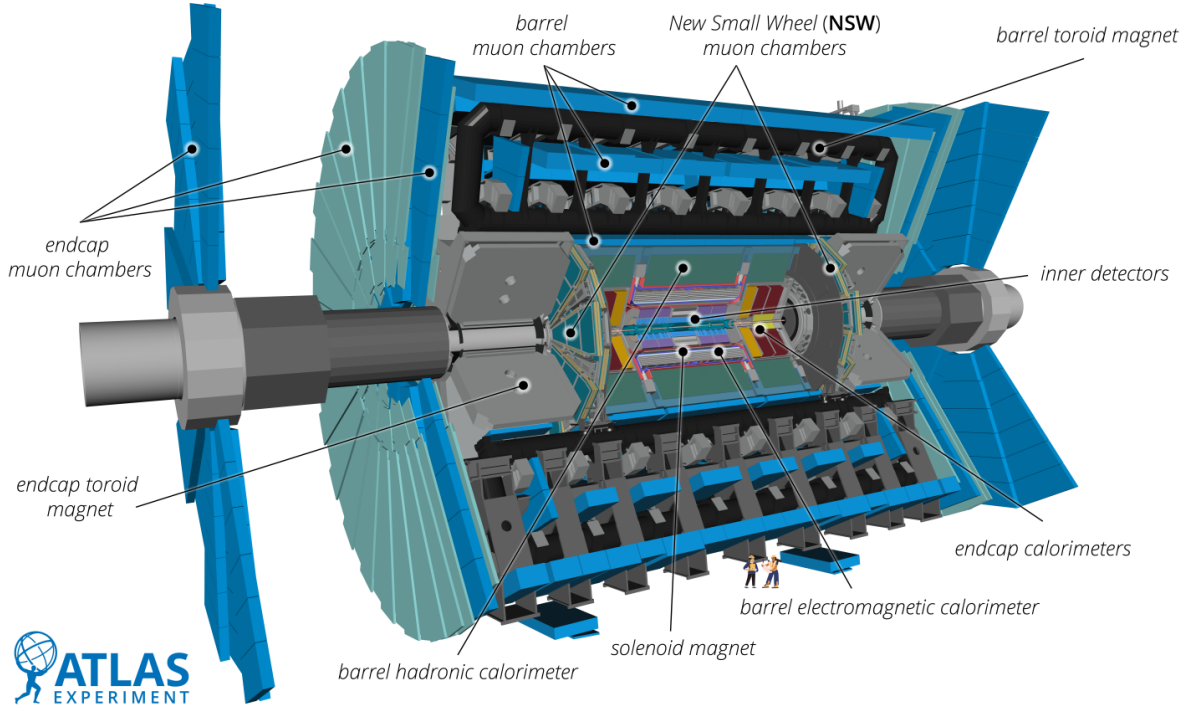


Figure 3-3: Schematic of ATLAS detector.

as muon chambers). Magnet system is also a crucial part for the detector that providing magnetic field for the measurement and identification of the particle. ATLAS has two magnetic system: solenoid system and toroid system. The solenoid system provides the inner detector with a 2 T magnetic field while the toroid system provides 0.5 and 1 T magnetic field for the muon spectrometer in central and end-cap regions respectively.

The right-handed coordinate system is used for ATLAS detector, the z -axis is defined to be the direction of the beam. The x -axis points towards the center of LHC ring and the y -axis points upwards from the interaction point. The azimuthal angle ϕ and polar angle θ are defined in this coordinate system. The pseudo-rapidity $\eta = -\ln(\tan(\frac{\theta}{2}))$ is used as an approximation of the rapidity¹ for the ultra-relativistic particles.

3.2.1 Inner Detector

The Inner Detector (ID)^[37] locates at the most central part of the ATLAS detector. It is used for the tracking of charged particles from the interaction region and measure their momentum. When the charged particles travel through the discrete layers of inner detectors, it will interact

¹ The rapidity y is defined as $y = \frac{1}{2} \ln(\frac{E+p_L}{E-p_L})$ with p_L the longitudinal momentum

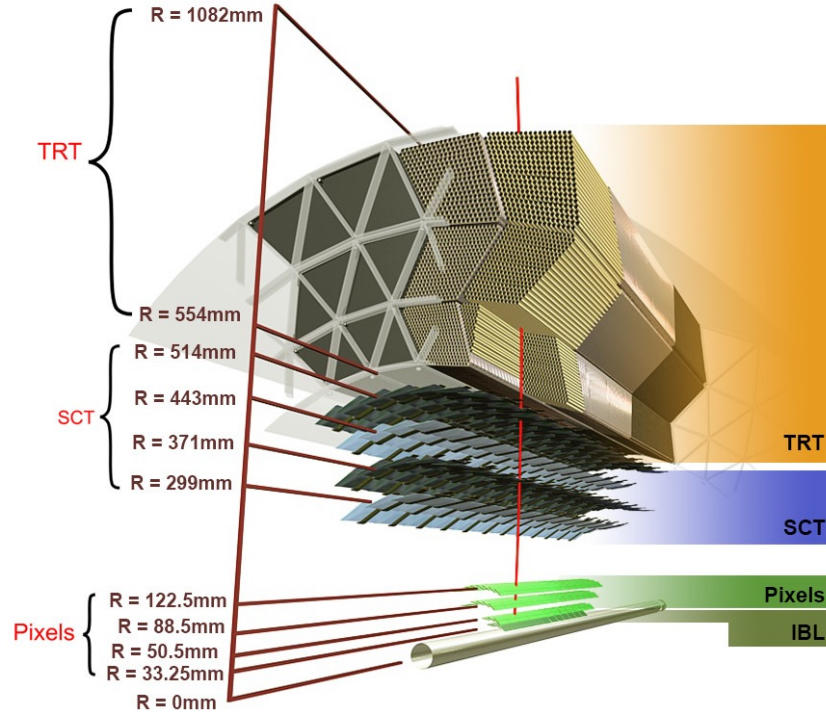


Figure 3-4: Sketch of the ATLAS inner detector^[38].

with the material and leave ionization signals (hits). The hits are collected and linked with the close-by hits as well as the vertex to reconstruct the track of the particles. The curvature of the tracks is used for the measurement of momentum. The ID covers a region of $|\eta| < 2.5$ and a radius between 3 cm and 1 m. The ID consists of three sub-system from inner to outer: the Pixel Detector, the SemiConductor Tracker (SCT) and Transition Radiation Tracker (TRT), as illustrated in Figure 3-4. The Pixel Detector consists of three barrel layers and three endcap layers. During the second long shutdown of LHC (LS1), an additional pixel detector layer named the Insertable B-Layer (IBL) was installed^[39] which significantly improves the tracking robustness and precision as well as flavor tagging performance. The current pixel detector provides a hit position resolution of $10 \mu\text{m}$ in the r - ϕ plane and $67 \mu\text{m}$ in the z -direction.

The SCT consists of silicon microstrip modules that are arranged into four barrel layers and two endcap layers with nine disks each^[40]. Two stripes are combined into a module with a stereo angle of 40 mrad to provide hit reconstruction in two dimensions. The SCT provides a position resolution of $17 \mu\text{m}$ in the r - ϕ plane and $580 \mu\text{m}$ in the z -direction.

The TRT is a straw-tube tracker that consists of 300 thousands cylindrical drift tubes (straws) with a diameter of 4 mm. When the charged particles travel through the straw, it will ionize

the gas inside the straw and produce a detectable signal. Since the straws are aligned with the z axis, it cannot provide information at z direction. The TRT provides a position resolution of $130 \mu\text{m}$ in the r - ϕ plane. The TRT can contribute to not only the momentum measurement but also the particle identification. The space between the straws is filled with polyethylene. When the particle travel the straw boundary, it can emit radiation that is dependent on the Lorentz boost $\gamma \sim E/m$. The amount of the radiation can be used for particle identification.

Combining all the three components of ID, the momentum resolution can reach

$$\frac{\sigma_{p_T}}{p_T} = 0.05\% p_T [\text{GeV}] \oplus 1\% \quad (3-2)$$

The $\oplus$ denotes a sum in quadrature.

3.2.2 Calorimeters

The calorimeters are used for measuring the energy of neutral and charged particles^[41]. All the calorimeters in ATLAS are sampling calorimeter, which consists multiple layers of active and passive material. The passive material is dense material with a high atomic number, which will interact with particles and produce cascaded particles (showers). The active material measure the energy deposition by the showers through ionization or scintillation light. In ATLAS, Liquid Argon (LAr) is mainly used as active material^[42].

Figure 3-5 shows the layout of ATLAS calorimeters. It covers a range of $|\eta| < 4.9$ and is hermetic in ϕ . The electromagnetic calorimeter (ECal) is used to measure the energy deposition by electrons, photons and part of energy carried by jets^[43]. It uses lead as passive material. The radiation length (X_0)¹ of ECal is 14.2 cm and ATLAS ECal have a depth of $22X_0$. The structure of ECal is shown in Figure 3-6. It is designed in accordion shape, which can be segmented into a presampler layer and three ECal layers. The Presampler layer is used for the collection of energy loss ahead of ECal. The first layer of ECal (EM1) is in very fine granularity which can be used to discriminate neutral pion ($\pi^0 \rightarrow \gamma\gamma$) and photons. The second layer of ECal (EM2) is used to collect the majority of the energy deposit and third layer (ECal3) is used to collect tail energy.

¹ X_0 is defined as the average distance over which the energy of electron reduced to $1/e$ of its original value

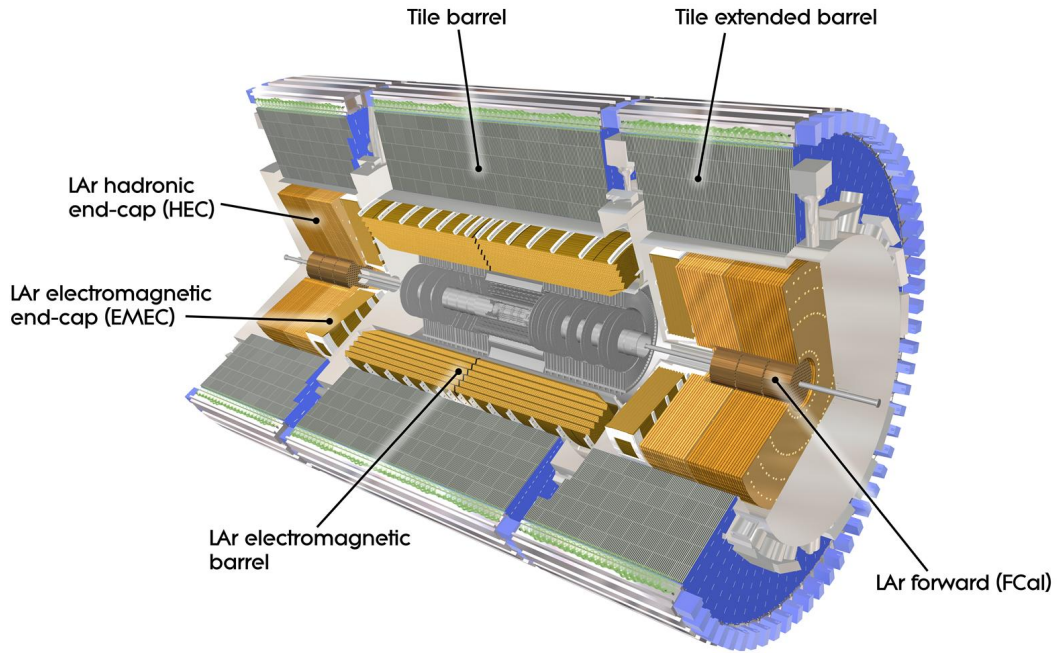
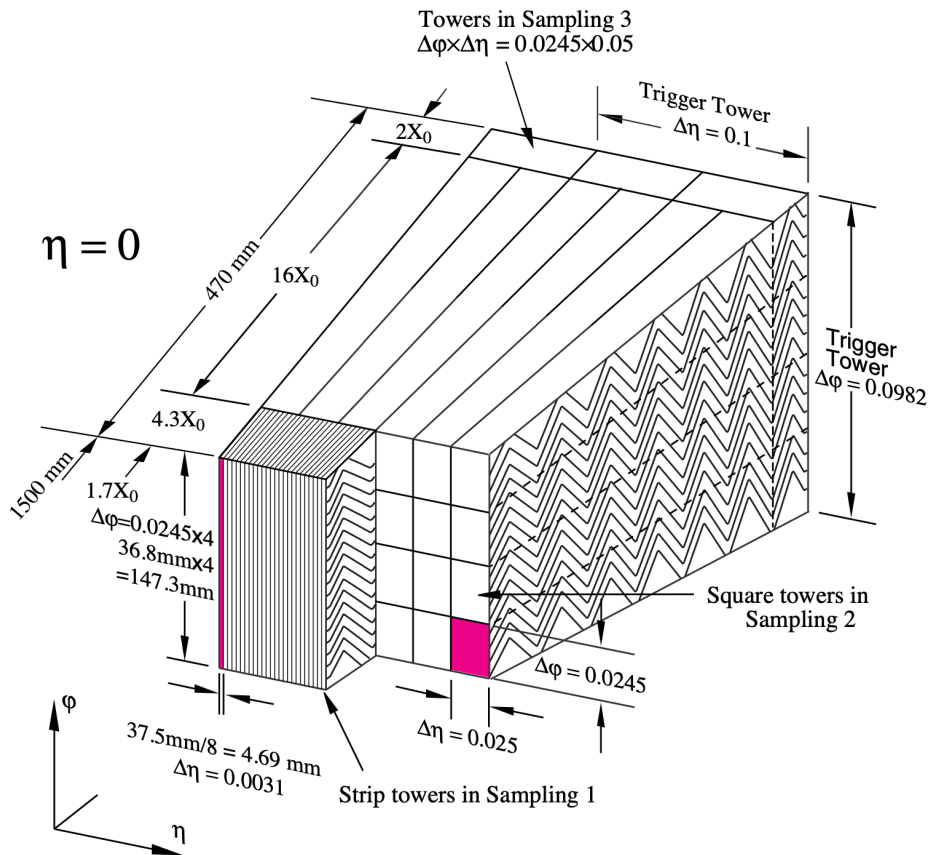


Figure 3-5: Sketch of ATLAS Calorimeters.

Figure 3-6: Sketch of the accordion structure of the EM calorimeter^[42].

The ECal covers the barrel and end-cap in region of $0 < |\eta| < 1.475$ and $1.375 < |\eta| < 3.2$ respectively. The region $|\eta| < 2.5$ is used for precision physics with better resolution. The transition between barrel and end-cap ($1.37 < |\eta| < 1.52$) is called crack region. The resolution of ECal is

$$\frac{\sigma_E}{E} = \frac{10\%}{\sqrt{E}} \oplus 0.7\% \quad (3-3)$$

The hadronic calorimeter is used to measure the energy of hadronic showers. The hadronic end-cap and forward calorimeter use LAr as active material, and copper plates are used as passive material in the end-cap^[44]. The forward calorimeter use copper and tungsten as passive material^[45]. The tile calorimeter in the barrel uses steel as absorbing material and scintillating plastic tiles as active material^[46].

The depth of hadronic calorimeter is around ten times the nuclear interaction length λ ¹. The tile calorimeter has two parts, cover $|\eta| < 1.0$ and $0.8 < |\eta| < 1.7$. The end-cap calorimeter covers $1.5 < |\eta| < 3.2$ and the forward calorimeter covers forward region to $|\eta| < 4.9$. The energy resolution of hadronic calorimeter is larger than ECal due to the complexity of hadron showers, with

$$\frac{\sigma_E}{E} = \frac{50\%}{\sqrt{E}} \oplus 3\% \quad (3-4)$$

3.2.3 Muon Spectrometer

The muon spectrometer (MS) lies in the outermost region of ATLAS detector since the muon is the minimum ionizing particle that hardly interact with the materials of the ID and calorimeter. The toroid magnets bend the trajectories of muon and precisely measure the momentum. The energy resolution of muon spectrometer is 3% for low p_T muons ($2 < p_T < 250$ GeV) and 10% for high p_T muons.

Figure 3-7 shows the layout of muon spectrometer, it consists of two kinds of detectors to perform tracking and trigger function separately. The precision tracking is provided by the Monitored Drift Tube (MDT)^[48] in the barrel region that covers $|\eta| < 2.7$ and the Cathode Strip Chambers (CSC)^[49] in end-cap region that covers region $2.0 < |\eta| < 2.7$. The muon trigger system is supported by Resistive Plate Chambers (RPCs)^[50] at barrel region and Thin

¹ λ is defined as the average distance traveled by a particle before interacting with a nucleus

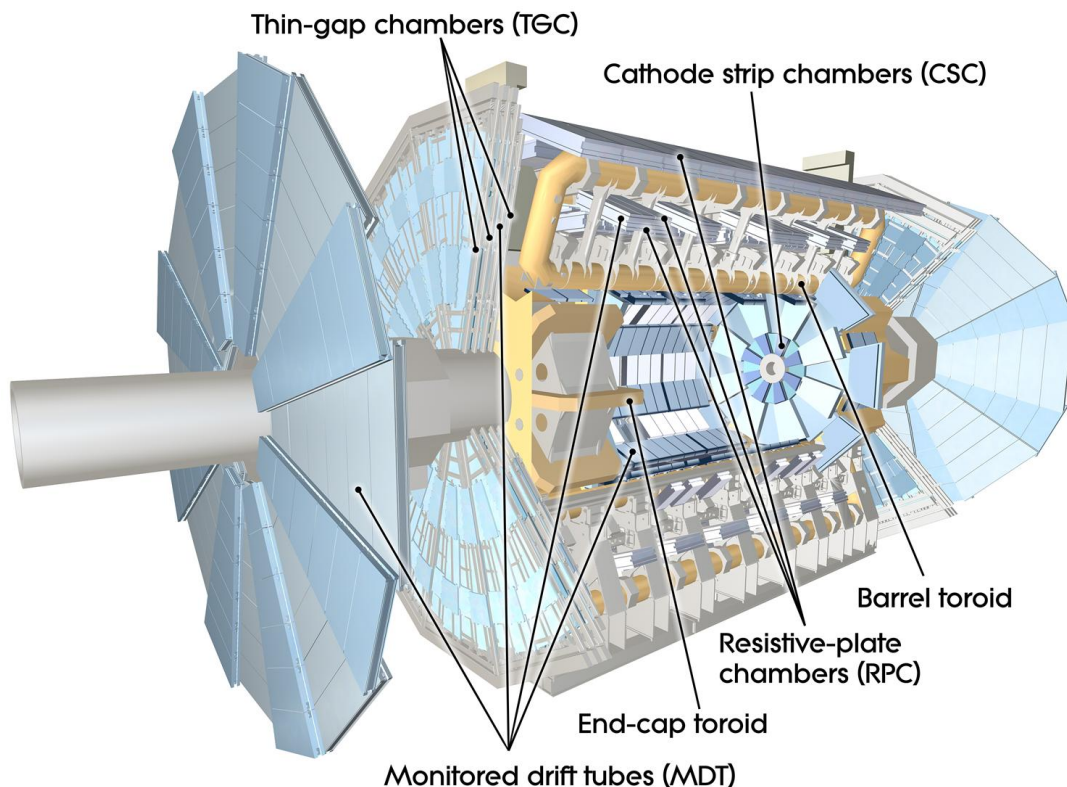


Figure 3-7: Sketch of the ATLAS Muon Spectrometer^[47].

Gap Chambers (TGC)^[51] at end-cap region.

3.2.4 Trigger and Data Acquisition

In the Run-2 of LHC, the proton collision occurred around 40 MHz. Due to the limitation of computing resources, it is impossible to record all the events, only a subset of them can be stored. As a result, ATLAS uses the trigger system^[52] to quickly reject events without hard scattering interactions and only keep events that have the physics process of our interest. It consists of a hardware based Level-1 (L1) trigger and a software based high-level trigger (HLT).

The L1 trigger has two types: calorimeter trigger and muon trigger. The calorimeter trigger uses the information from calorimeter that is processed by Cluster Processor which selects electron, photon and tau lepton candidates, and the Jet/Energy-sum Processor that selects the jet candidates and calculate the sum of transverse energy. The muon triggers uses information from muon trigger chamber. Finally, the decision of whether to keep the event is made by the Central Trigger Processor that combines the input from L1 calorimeter and L1 muon, as well as L1 topological process (L1Topo) and inputs from other systems, in just 2.5 ms. With L1

trigger, data rate is reduced to 100 kHz.

The HLT trigger then makes the decision using the complete detector information from all detector systems. In the HLT, it is possible to identify more complex signatures such as E_T^{miss} and have the preliminary tagging information. This stage is very similar to the offline physics analysis. The decision from HLT can be made in 200 ms and the data rate is reduced to 1 kHz. The events after HLT will be stored for offline analysis.

A trigger menu is used to define selection criteria for L1 and HLT. Different triggers are used depending on the purpose, e.g. for physics analysis, performance measurements or detector calibration.

3.2.5 Upgrade of ATLAS

As mentioned in Section 3.1, the HL-LHC will greatly improve the integrated luminosity by up to 10 times. It will have a larger pile-up, making it more difficult to distinguish the hard scatter events from the inelastic scattering. In addition, the larger luminosity will bring a larger radiation pressure on the detector. In order to cope with these developments, the ATLAS will have a major upgrade during the shutdown after the Run-3 of LHC. The inner tracker (ITk) will be upgraded to have increased η acceptance and better pile-up rejections. It will have less material to reduce the energy loss in the ID, and the pixels will be finer to have better resolution. The EM and hadronic calorimeters, as well as the muon detectors will upgrade the electronics. The DAQ system will have upgrades to reach 1 MHz trigger output at level 0. The new luminosity detector will be able to measure the luminosity at 1% precision. The muon chambers will be updated to improve trigger efficiency and momentum resolution, as well as reduce fake rate. And finally, a new detector will be installed to handle the large increase of pile-up: the High Granularity Timing Detector (HGTD)^[53]. HGTD can provide precise timing measurement of the track, with a resolution of 30 ps, to help disentangle the tracks from hard scatter events in large pile-up backgrounds.

The HGTD will be installed at the gap between the barrel and the end-cap of the calorimeter, which lies outside the ITk and in front of the calorimeters, as shown in Figure 3-8. It covers the region of $2.4 < |\eta| < 4.0$ and has in total of four layers of silicon detector modules. In the design, a bare module is made of two parts: an low gain avalanche detector (LGAD) sensor and

two ASICs. The sensor and the ASICs are connected through a flip-chip bump bonding process called hybridization. The ASICs are then connected to the peripheral electronics through the module flex cable. The size of the bare modules is around $2 \times 4 \text{ cm}^2$ with 450 pads, and the nominal numbers of bare modules is 7984, all of them are identical. The size of the pad is $1.3 \times 1.3 \text{ mm}^2$ and each of the ASIC reads a matrix of 225 pads. The size of the ASIC is about $19 \times 22 \text{ mm}^2$. As a result, the detector has in total of around 3.6 million modules and have very high granularity of $1.3 \times 1.3 \text{ mm}^2$.

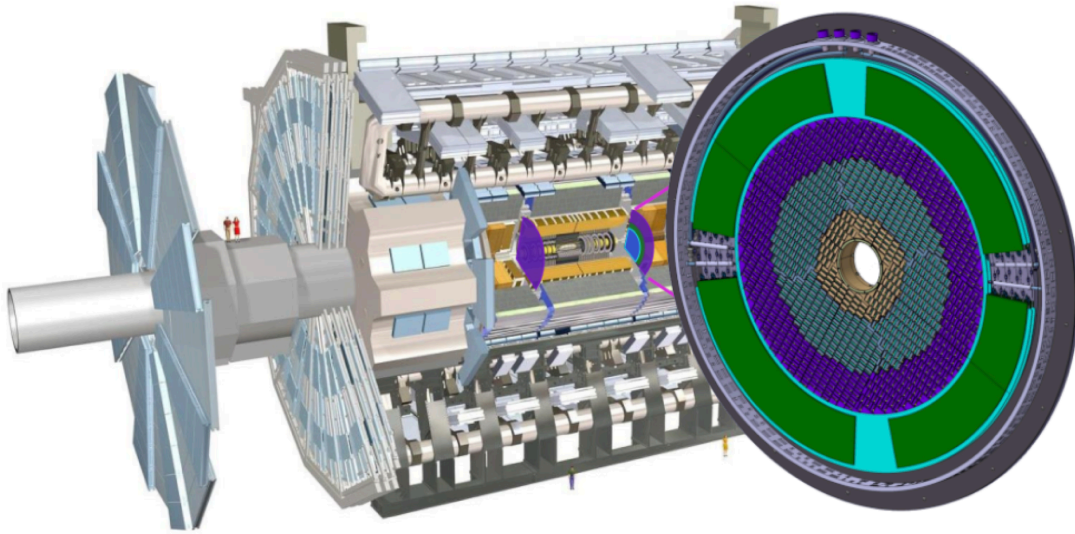


Figure 3-8: Position of the HGTD in ATLAS detector.

One of the key topic in the HGTD sensor is the calibration of the time of arrival (TOA) of the signal, which is crucial to the performance of the timing resolution. A study about the impact of the high voltage connection of the sensor on the calibration is shown in the Appendix 6.

3.3 Object Reconstruction

The collision at the center of ATLAS detector will produce outgoing particles. These final state particles can be probed when they interact with the detectors. Different particles will leave different signatures in the different layers of detectors. Figure 3-9 shows an illustration of the common signatures left by various particles.

The signatures in detectors are first collected and reconstructed to the so-called detector-level objects, such as tracks, vertices and calorimeter clusters. They are then combined to build

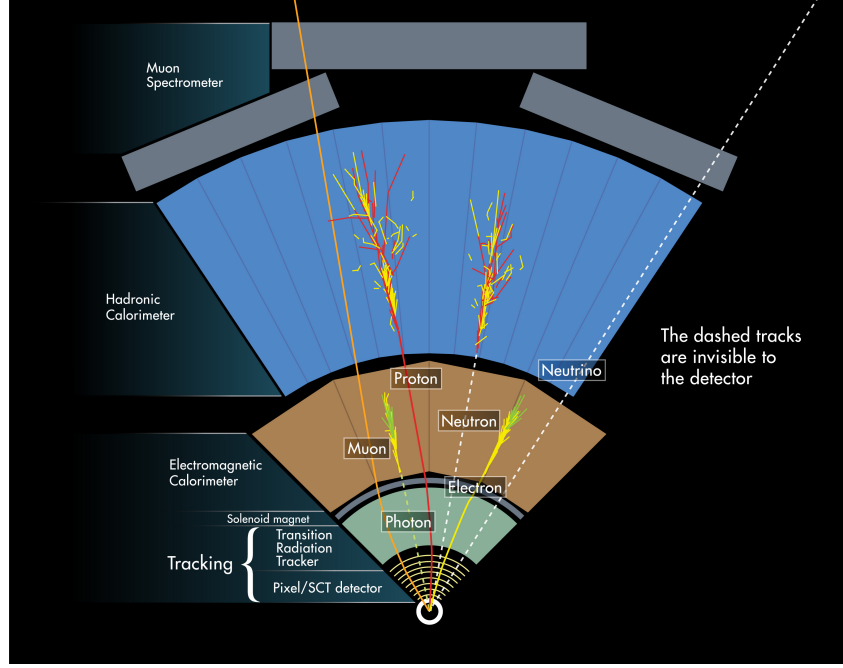


Figure 3-9: Diagrams of particle paths in the detector, credit owned by CERN^[54].

the high-level objects, which can be matched to the particles, for example, electrons, muons, jets and E_T^{miss} .

3.3.1 Detector-level Objects

This section introduces the objects that are reconstructed directly from the signatures of the detector, including tracks, vertices and calorimeter clusters.

Tracks

The curved trajectories of charged particles in the magnet field of ATLAS detector can be reconstructed by the energy deposit left in the inner detector. The reconstruction process^[55] starts with clustering the raw measurements (hits) from the pixel and SCT. After cluster creation, an inside-out algorithm, which starts from the pixel layer and build the tracks outwards, is employed for the reconstruction of prompt tracks (the tracks from hard-scatter or decay of very short-life particles). The seed of the algorithm is the hits in pixel or SCT, and then extrapolated to the end of SCT layer using a combined Kalman filter^[56]. An ambiguity solver is applied in the case of multiple track candidates are considered by comparing the track qualities based on a χ^2 fit. The track candidate with highest score is selected and extend to the TRT layer and con-

duct a re-fit. A complementary outside-in algorithm which starts from TRT hits is also applied for the reconstruction of non-prompt tracks which originate from decay of relative long-life particles (such as b -hadron or c -hadron).

All the tracks reconstructed has to pass the quality criteria^[57], such as the requirement for the number of hits in silicon detectors and the association to the primary vertex. Additional kinematic requirement of $|\eta| < 2.5$ and $p_T > 500\text{MeV}$ is also applied.

Vertices

The vertices indicate the place where the interactions happen, which can be reconstructed by the intersections of the tracks. The primary vertex is of great importance as it shows the place where the pp collision happens, and is reconstructed using an iterative vertex finding and fitting procedure^[58-59]. Firstly, initial vertex locations (seeds) are estimated with high accuracy using a Gaussian resolution model for the track impact parameter. After the seed is found, the nearby tracks are chosen to repeat the fit process and get the new vertex. The iteration repeats until the reconstructed vertex passes the quality requirements. The tracks that are not used in the iterations are used again for the search of additional vertex. The primary vertex is selected to be the vertex that have the highest sum of squared track transverse momentum ($\sum p_T^2$). Figure 3-10 shows the two parameters of tracks, transverse impact parameter d_0 and longitudinal impact parameter z_0 , that are used most frequently for the vertex reconstruction.

Calorimeter Clusters

The particles usually deposit their energies in calorimeter cells. Using clustering algorithm, the energy deposit in the calorimeter cells that come from the same particle can be grouped and form the topological clusters (topo-clusters)^[60]. These topo-clusters are the important inputs for the construction of many high-level objects such as electron and jets. Two types of clustering algorithm are used in the ATLAS. The "sliding-window" algorithm that is based on summing cells within a fixed-size rectangular window, which can be efficient for very precise calibration. As a result, this algorithm is used for the reconstruction of electromagnetic showers and leptonic τ . Another algorithm is topological algorithm. It starts with a seed cell and iteratively adds to

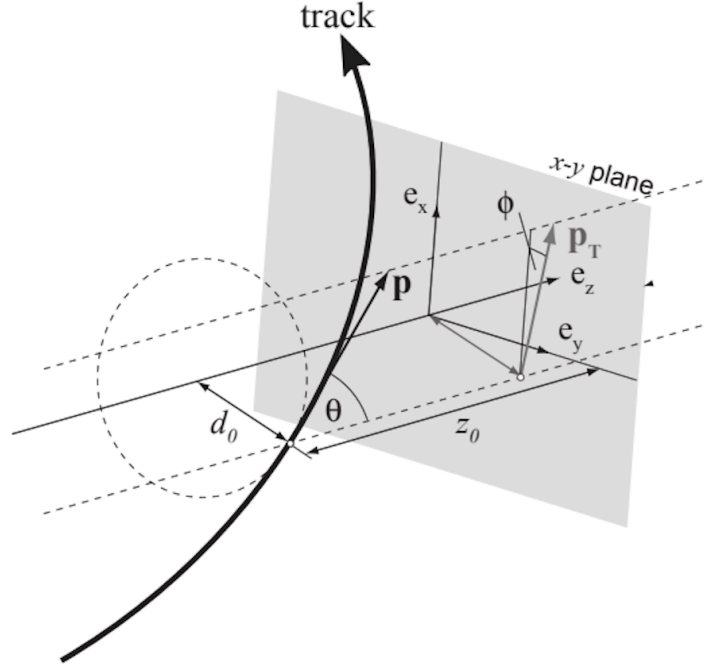


Figure 3-10: Illustration of the track parameters: transverse impact parameter d_0 and longitudinal impact parameter z_0 .

the cluster the neighbor cell if the signal is significant compared the noise. This algorithm is efficient for suppressing the noise and thus used for reconstruction of jets and E_T^{miss} . After the clustering, these energies are calibrated to account for the energy deposit outside the detector and in dead materials.

3.3.2 Electrons

The electrons in the central region ($|\eta| < 2.5$) are reconstructed by combining the tracks from ID and energy deposit in the electromagnetic calorimeter^[61-62]. The forward region is not covered by ID, so the electron in forward region is not usually used in physics analysis. In the following thesis, only the electron in central region is discussed. Figure 3-11 shows how the electron travel in the detector and leave the signatures.

The reconstruction of the electron starts with topo-cluster after calibration. The tracks that compatible with the expected energy loss of electrons in the detector are then matched to the topo-cluster. The selected tracks are refit using the Gaussian Sum Filter^[63] to take into account electron energy loss via bremsstrahlung. When multiple tracks are matched to one topo-cluster, the track closest to the cluster is chosen. An electron candidate is now identified with a combi-

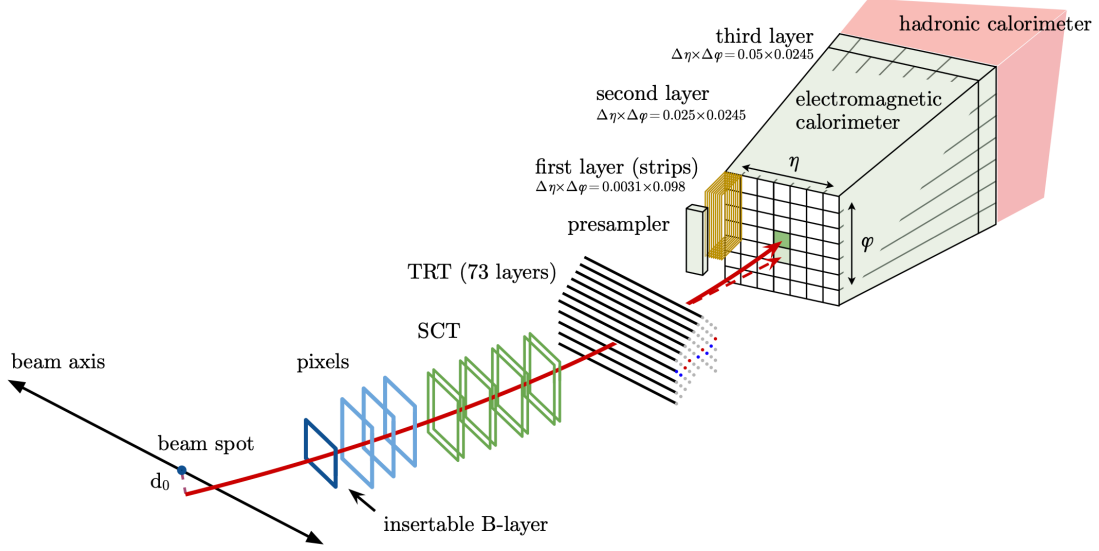


Figure 3-11: A schematic illustration of the path of an electron through the detector. The red trajectory shows the hypothetical path of an electron, and the dashed red trajectory indicates the path of a photon produced by the electron. Figure taken from Ref^[62].

nation of one track and one topo-cluster, and needed to pass the additional quality requirements.

After the reconstruction, additional requirements are placed to identify the electrons from hard scatter (prompt electrons), against the backgrounds. The background contains the jet with high EM fraction, electrons from photon conversion and leptonic decay product of hadrons. A likelihood-based discriminant that combines multiple variables is used for the identification^[62]. Several working points are defined with an increasing selective power: Very Loose, Loose, Medium and Tight.

In addition to the identification, isolation criteria are also used for further rejection of background, which requires the electron candidate to be isolated from other tracks or energy deposits. Several working points are defined with different allowed threshold of energy deposit or p_T in ID in the cone of electron candidate.

The electron energy calibration is determined by using dedicated energy scale and resolution measurements of standard-candle processes, especially the invariant mass m_{ee} of $Z \rightarrow ee$ process. The total electron efficiency, after reconstruction, identification and isolation is calibrated using the $Z \rightarrow ee$ and $J/\Psi \rightarrow ee$ process.

3.3.3 Photons

Photons will also leave energy deposit in the electromagnetic calorimeter that is similar to electrons^[61]. As a result the reconstruction of photons is quite similar to the electrons. Two cases of photons can be distinguished: converted photons that decay to a pair of electrons, which will leave two opposite charged tracks in the ID. Un-converted photons that do not leave track in the ID.

3.3.4 Muons

The muon produced in pp collision is typically the minimum ionising particles. They will leave tracks in ID, travel through the calorimeter leaving a small amount of energy finally create hits in the MS. The reconstruction of MS tracks are built from the combination of hits in different MS stations and a χ^2 fit following. Several methods are used for the reconstruction of muon depending on the detector signatures used^[64-65]:

- *Combined muon* uses the track from ID and MS jointly. If the track in ID matches the one in MS, two tracks are combined and refit to one single track. Combined muons are the purest and the most commonly used type of reconstructed muons.
- *Inside-out muon* that do not depend on the tracks in MS. It only uses the track in ID and some loosely aligned MS hits. This method increase the reconstruction efficiency for low p_T muon and in regions that poorly covered by MS.
- *Muon-spectrometer* extrapolated muons are reconstructed from MS tracks that cannot be matched to an ID track. This method increase the efficiency in the regions that outside of ID coverage $2.5 < |\eta| < 2.7$.
- *Segment-tagged* muons have an ID track associated to at lease one track in MS. The properties of ID tracks are used as the muon properties. This kind of muons usually have low p_T .
- *Calorimeter-tagged muons* are reconstructed by combining ID tracks with the energy deposit in calorimeter. The energy deposit needs to match the expectations from a minimum ionising particle. If such energy deposits are found, the properties of the ID track are used to define the muon. This method is used when the MS information is missing due to the

gap in MS or has poor performance.

Similar to the electron, the identification of muon also aims to select the prompt muon against the backgrounds. The main backgrounds are the muons from decays of pion, kaon or heavy flavor hadrons. The typical characteristic of background muons from pion and kaon is a kink in the track where the decay happens. For the muon from decays of heavy flavor hadrons, their tracks are usually less compatible with the primary vertex. Using these features, a discriminant is built and five WPs are defined: Low- p_T , Loose, Medium, Tight and High- p_T .

Isolation criteria are also used for further rejection of the background. The definition is quite similar as the electron and several WPs are defined.

Two process, $Z \rightarrow \mu\mu$ and $J/\Psi \rightarrow \mu\mu$, are used for the calibration of muon energy and the efficiencies of reconstruction, identification and isolation.

3.3.5 Jets

The quarks and gluons are among the most frequently produced final states in pp collision. After production, they will quickly hadronise to color-neutral hadrons, like pions. These hadrons will continue the fragmentation and hadronisation, producing a bunch of particles and leave large energy deposit in the hadron calorimeter. If the quarks or gluons are Lorentz boosted enough, their decay products will be in a cone, which is named as jets. The jets reconstruction is very challenging due to its complexity. Ideally, the reconstruction of jets give the information about jet momentum, direction and the underlying partons that initiated the jet^[66].

Jet algorithm

In the ATLAS experiment, the *anti- k_T* algorithm is used for the reconstruction of jets^[67]. This algorithm satisfied the so-called infrared and collinear safe, which means the jet definition remain the same when the event is modified with collinear splitting or soft emission. Two kinds of inputs are most commonly used as the input for the jets reconstruction and calibration: the topo-cluster^[68] calibrated at EM scale (EMTopo) and the particle flow (PFlow)^[69].

The PFlow method combines the information from track in ID and topo-cluster. It can

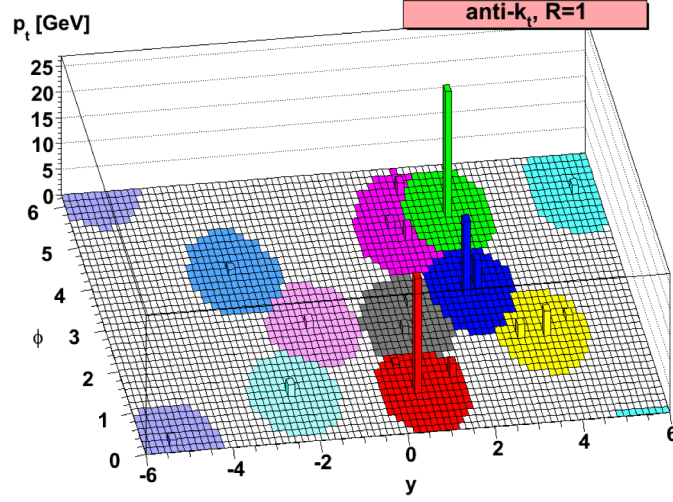


Figure 3-12: Illustration of the $anti-k_T$ algorithm in the $y - \phi$ plane, with the radius parameter $R = 1$.

subtract the energy deposit from different particles in the same topo-cluster based on the information of tracks. This method provides a more precise energy reconstruction.

The inputs to the $anti-k_T$ algorithm provide the 4-vector of objects (topo-clusters or tracks). For each pair of objects i and j , the relative distance d_{ij} between them are defined as:

$$d_{ij} = \min \left(\frac{1}{p_{T,i}^2}, \frac{1}{p_{T,j}^2} \right) \times \frac{\Delta y_{ij}^2 + \Delta \phi_{ij}^2}{R^2} \quad (3-5)$$

where Δy_{ij} is the rapidity difference, $\Delta \phi_{ij}$ is the azimuthal angle difference. The radius R is a free parameter of the algorithm. A larger R indicates a larger radius of the jet cone. The object j will be combined into object i if

$$d_{ij} < d_{iB}, \text{ with } d_{iB} = \frac{1}{p_{T,i}^2} \quad (3-6)$$

And the distance between new object and other objects will be recalculated. If $d_{ij} > d_{iB}$ for all the objects pair, the object i will be identified as a jet.

Figure 3-12 shows an illustration of $anti-k_T$ algorithm with radius parameter $R = 1$. This algorithm will result in a round jet in the $y - \phi$ plane. The R can be adjusted according to the physics purpose. The most commonly used values are $R = 0.4$ and $R = 1$. $R = 0.4$ (small- R) is used for the reconstruction of jets originate from quarks and gluon. $R = 1$ (large- R) is used for

the jets originate from the hadronic decay of massive particles like Higgs boson.

Despite the jets with fixed R parameter, there is another Variable- R (VR) jets which are constructed using the *anti- k_T* algorithm with the radius parameter R dependent on the jet p_T , defining as follows:

$$R(p_T) = \frac{\rho}{p_T} \quad (3-7)$$

The inputs used for the algorithm is the tracks in the ID. The parameter ρ is a free parameter and can be chosen based on the physics purpose. In the boosted $VH(\rightarrow b\bar{b})$ analysis mentioned later in this thesis, the ρ is chosen to be 30 GeV and the $R(p_T)$ is bound to be in the range of $[0.02, 0.4]$. These parameters are optimized for the double b -tag efficiency for the VR jets^[70].

Calibration

The calibration of jet energy scale (JES) corrects for the detector effect such as difference between electromagnetic and hadronic calorimeters response, dead material and missing energy outside the calorimeters. It also corrects the reconstruction effect such as energy deposit outside the jet cone and pile-up contamination^[71]. Figure 3-13 shows different stages of jet energy scale calibration^[72] for small- R jets. The whole flow of these corrections is named as Standard Calibration (GSC).

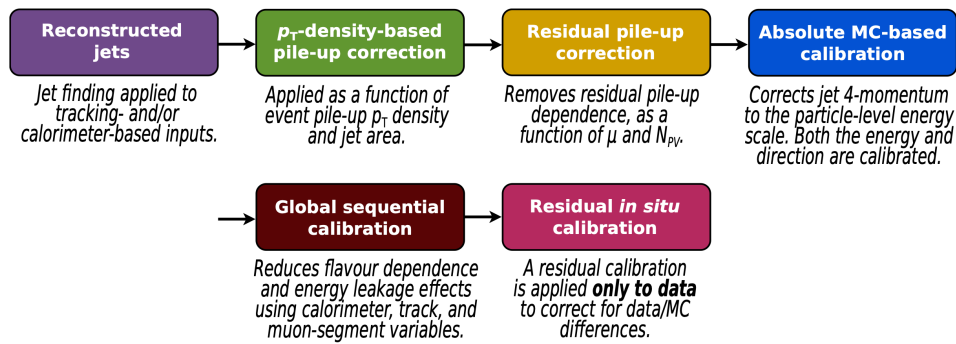


Figure 3-13: Stages of jet energy scale calibrations for small- R jets. Each one is applied to the four-momentum of the jet.

The jet energy resolution (JER) is also an important parameter that gives the uncertainty of the jet energy. It is calibrated using the dijet measurements^[72-73] and evaluated in the form of relative uncertainty $\sigma(p_T)/p_T$ as a function of jet p_T .

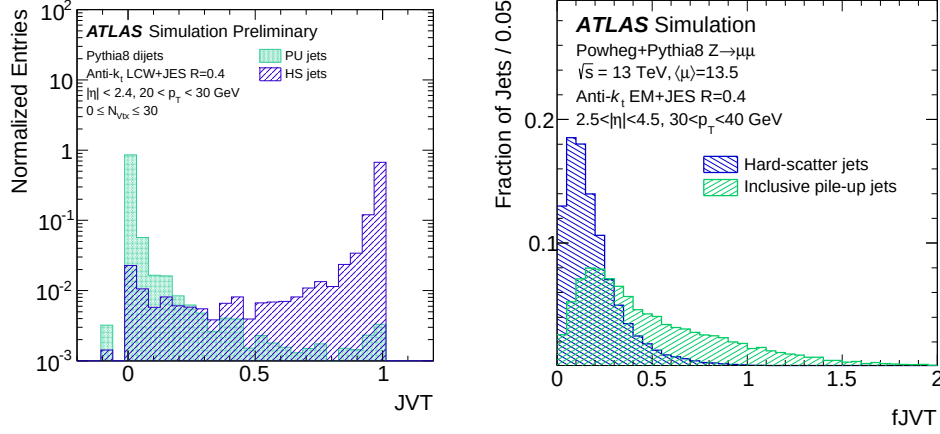


Figure 3-14: Distribution of JVT (left) and fJVT (right) for pile-up jets and hard-scatter jets.

Jet Vertex Tagger

The Jet Vertex Tagger (JVT) is used to further suppress the pile-up jets^[74]. The JVT discriminant is defined as the fraction of scalar sum p_T of jets originate from the hard vertex. The jets with larger fraction are more likely to be the jets from hard-scatter. As the JVT use the track information provided by ID, it can only cover the region $|\eta| < 2.5$. So for the jets in forward region ($2.5 < |\eta| < 4.5$), the forward jet vertex tagging (fJVT) is used, which is defined as the normalized projection of the missing transverse momentum on the forward jet p_T ^[75]. The jet with smaller fJVT value is more likely to be from hard-scatter. The distribution of JVT and fJVT for pile-up jets and hard-scatter jets are shown in Figure 3-14^[74-75].

3.3.6 Taus

Tau is the heaviest lepton, with a mass of 1.78 GeV and lifetime of 290 fs^[76]. It's average travel length in ATLAS detector is around 87 μm before the decay. Around 35% of taus will decay leptonically, to electron or muon plus a pair of neutrinos. The signatures of leptonically decay tau (τ_{lep}) is very similar to the electron and muon, making it difficult to distinguish. The rest (65%) of taus decay hadronically (τ_{had}), to one or three charged particles typically. They are labelled as 1-prong and 3-prong, taking up 77% and 23% of hadronic decay respectively. The identification of τ_{had} use the Recurrent Neural Network (RNN), with information about tracks and topo-clusters as input^[77]. Four WPs are defined for both 1-prong and 3-prong decay mode: VeryLoose, Loose, Medium and Tight.

3.3.7 Missing Energy Transverse

The objects discussed above all leave clear signatures in the detector. However, there are some particles do not interact with the matter in the detector or the interaction is very rare and weak. For example, the neutrinos in SM or some BSM particles (such as dark matter candidates). As a result, the energy carried by these particles will not be detected, and cause the momentum imbalance in the transverse plane of the detector. The momentum along the beam line carried by the partons in the pp collision is unknown, so only the transverse plane can be used. The missing energy transverse (E_T^{miss}) is thus defined as:

$$E_T^{\text{miss}} = - \left(\sum_{\text{hard}} p_T + \sum_{\text{soft}} p_T \right) \quad (3-8)$$

The $\sum_{\text{hard}} p_T$ is the vector sum p_T of all the fully constructed high-level objects including e, μ, τ, γ and jets. The soft term considers all the tracks in ID that is associated to the primary vertex but not related to any object. The uncertainties of E_T^{miss} is estimated from the events where no E_T^{miss} expected, such as $Z \rightarrow ll$ ^[78]. It is estimated to be around 10 GeV in low pile up case ($\mu \sim 5$) and around 20 GeV when $\mu \sim 40$.

3.4 Flavor Tagging

Identifying the quark from which the jet originated, referred to as flavor tagging, is vital for the physics analysis at ATLAS. The identification of jets originated from b -jet is the so-called b -tagging and from c -jet is c -tagging, they are crucial for selecting the signal events and rejecting background in the $VH(\rightarrow b\bar{b}, c\bar{c})$ analysis. Currently, it is possible to perform the b -tagging and c -tagging as b and c quarks has relative long lifetime and leave signatures different from other quarks. It is also possible to identify the jets originated from hadronically decay τ . The following section will introduce the flavor tagging algorithm, and the details of the calibration and its application in $VH(\rightarrow b\bar{b}, c\bar{c})$ analysis will be discussed in Chapter 4.

3.4.1 Signatures of Jets

The distinction between b -jet, c -jet and $light$ -jet is based on the characteristics of different jets. The b -jet is the one that is most different from other jets, resulting in a high tagging efficiency of b -jet. A schematic of the b -jet is shown in Figure 3-15^[79]. After the production of b -quark, it will quickly hadronize into b -hadron and the b -hadron has a relative long lifetime, around 1.5 ps. A typical 50 GeV b -hadron will travel an average of 5 mm distance (L_{xy} shown in figure) in the inner detector after its production, leading to at least one secondary vertex displaced with an impact parameter of few mm. In addition, the b -hadron has a relative high invariant mass compared with other hadrons, around 5 GeV, and carries around 75% of the jet energy. It means that the decay chain of b -hadron will be longer and have high decay multiplicity, also its decay fragmentation will be harder. Most of the b -hadrons will decay into c -hadrons due to the CKM matrix transition value, $|V_{cb}|$ is 100 times larger than $|V_{ub}|$. The c -hadron has a smaller lifetime than b -hadron, but it will leave a second displaced vertex.

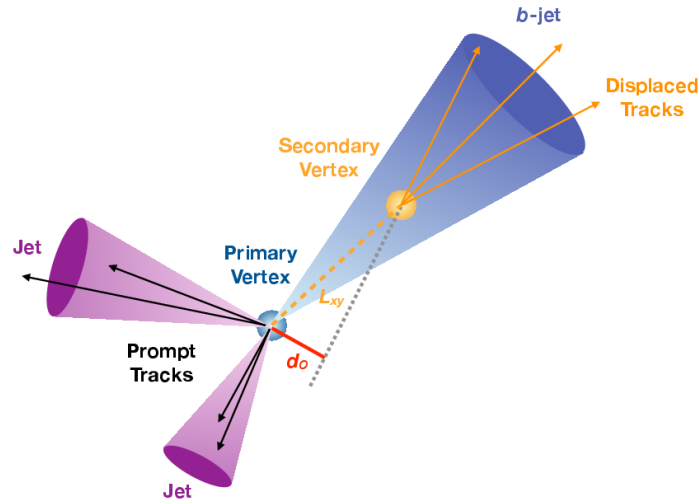


Figure 3-15: Illustration of the b -jet, taken from Ref^[79].

The c -jet originates from the hadronization of the c -quark. The c -quark will usually hadronize into a D -meson, which has a lifetime for about 0.4 – 1 ps. Thus, it will also travel a few mm in the ID, but shorter than the b -hadrons, and leave a secondary vertex as well. Due to the dead-cone effect, which predicts the gluon spectrum emitted by a heavy quark will be suppressed with the

mass and energy of the quark^[80-81], the D -meson will carry about 55% of jet energy and has a mass around 2 GeV, resulting a smaller decay multiplicity and softer decay fragmentation.

The light-jet originates from the hadronization of u, d, s quarks or gluons. The quarks will hadronize instantly into several light-hadrons. Some hadrons can have long lifetime, which is outside the ID. As a result, no secondary vertex can be found in the ID. The gluon-initialed jets also leaves no secondary vertex. It will quickly hardonize and produce various kinds of constitution.

The τ -jet comes from the hadronic decay of τ lepton. The τ lepton has a lifetime of 0.29 ps and mass of 1.8 GeV^[9]. As a result, it will also have a secondary vertex in ID similar to the c -jet. The τ jet share quite some patterns with c -jet, making it challenging to distinguish the two kinds of jets. However, the τ jet are generally narrower than the c -jet.

3.4.2 Flavor Tagging Algorithm

ATLAS uses the patterns of different kinds of jets to distinguish them. The algorithms used can be divided into two levels: the low-level taggers make use of the information in the ID and calorimeter to extract the information that would be helpful to distinguish the jet, like vertex and impact parameter. They match the track in ID and the jet calorimeter by the angular distance between them. The output of the low-level taggers are then combined into a multivariate classifier, called high-level tagger. The common ATLAS high-level taggers use the machine learning techniques, and their output are the final discriminant to perform the tagging of the jets. The following section will introduce the algorithm used in the $VH(\rightarrow b\bar{b}, c\bar{c})$ analysis.

Low-level taggers

The low-level taggers in ATLAS can be divided into two broad categories. The first approach is based on exploiting the large impact parameters of the tracks. It includes the IP2D, IP3D algorithm^[82] and the RNNIP^[83] algorithm. The second approach is based on exploiting the displaced vertices, including the SV1 algorithm^[84] that reconstruct the secondary vertex and JETFITTER algorithm^[85] that reconstruct the whole decay chain.

The IP2D algorithm uses the signed transverse impact parameter significance of tracks to

build the discriminant while the IP3D algorithm uses both the signed transverse and signed longitudinal impact parameter significances together. The b -jet is most likely to have a positive significance, while the c -jet is second likely and the light-jet has the least possibility. The IP-based algorithms assume that the properties of each track in a jet are independent of all other tracks, thus limits the ability of jet modelling. The Recurrent neural networks are then used to overcome this issue, and the algorithm is named as RNNIP. The neural network is fed with signed transverse and longitudinal impact parameter significances, the fraction of transverse momentum carried by the track, the angular distance between track and jet axis and the hit multiplicity of the track in ID. The output discriminant of RNNIP has a better separation power than the IP2D and IP3D.

The second vertex tagging algorithm, SV1, reconstruct a single secondary vertex in the jet. It starts with the by identifying the possible two-track vertices built with all tracks associated with the jet, while rejecting any tracks making two-track vertices compatible with K_0 or Λ decay, photon conversions or hadronic interactions with detector. It runs iteratively on all tracks and perform the χ^2 test of the secondary vertex until the χ^2 reach the threshold and the vertex has at least 6 GeV invariant mass.

The topological multi-vertex finding algorithm, JETFITTER, exploits the topological structure of b -hadron and c -hadron decays in the jet and try to reconstruct the full decay chain. A Kalman filter is used to find a common line on which the primary vertex and the hadron decay vertex lies. It can be used as an approximation of hadron flight path and the vertex position. Based on these information, a set of discriminating variables are built to serve as the input to high-level tagger.

High-level taggers

The high-level taggers make use of the information from the low-level taggers mentioned above and use the machine learning techniques to create a more powerful discriminant. Based on the machine learning technique used, the high-level taggers have several series: the MV2 series that use the boosted decision tree, the DL1 series that use deep neural network and the GN series that use graph neural network. In the $VH(\rightarrow b\bar{b}, c\bar{c})$ analysis, the DL1r algorithm is used.

The DL1 can provide multi-dimensional output, which corresponds to the probability of the

jet to be identified as b -jet, c -jet and light-jet. Since all flavors are treated equally during training, the trained network can be used for both b -tagging and c -tagging. The final discriminant is defined based on the type of jets that would like to tag. For the b -tagging, it is defined as

$$\text{DL1r}_b = \ln\left(\frac{p_b}{f_c \cdot p_c + (1 - f_c) \cdot p_l}\right) \quad (3-9)$$

where the p_b , p_c and p_l are the possibility of the jet tagged as b -, c - and light-jet, respectively. The f_c is the fraction of c -jet in the background, which is calculated as 0.018 from the simulated MC sample provided by the PMG group. This value is chosen to ensure good rejection of both c -jet and light-jet in different analysis. Similarly, the discriminant for c -tagging is defined as

$$\text{DL1r}_c = \ln\left(\frac{p_c}{f_b \cdot p_b + (1 - f_b) \cdot p_l}\right) \quad (3-10)$$

with f_b is usually chosen to be 0.2 in the FTAG recommendations, while in the $VH(\rightarrow b\bar{b}, c\bar{c})$ analysis it is chosen to be 0.3 for a better performance in the specific phase space. Figure 3-16 shows the distribution of DL1r_b and DL1r_c score in the common FTAG recommendation setup^[86].

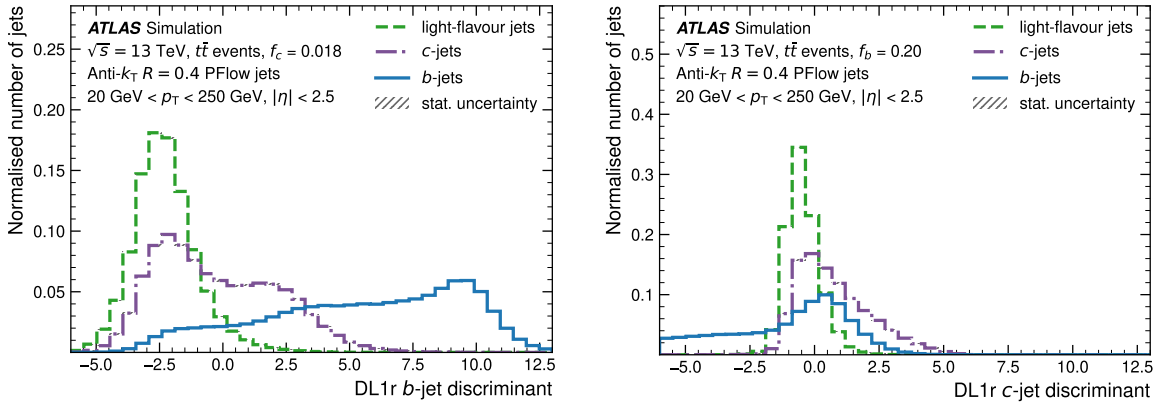


Figure 3-16: Distribution of the DL1r output discriminant: DL1r_b (left) and DL1r_c (right)^[86].

A cut can then be defined on the DL1r score, e.g. if a jet have the DL1r_b score larger than the cut, it will be identified as a b -jet. The cut is also named as Working Point (WP). The WP

always labelled by the tagging efficiency (ϵ_f) of the jet, which is defined as

$$\epsilon_f = \frac{N_{\text{pass sel.}}^f}{N_{\text{tot}}^f} \quad (3-11)$$

where the f denote the flavor that tagged, N_{tot}^f is the total number of the jets with flavor f , and $N_{\text{pass sel.}}^f$ is the number of jets with flavor f that pass the cut. The number of jets is calculated from the MC samples. A larger tagging efficiency will be able to select the jets that have the flavor which is targeted, but also increase the possibility to mis-tag the flavor that is not the target. One of the important criteria to quantify the performance of flavor tagging is the mis-tag rate (or the rejection efficiency, which is the inverse of mis-tag rate). Figure 3-17 shows the c -jet and light-jet rejection efficiency with different b -tagging efficiency^[87]. Since the tagging efficiency

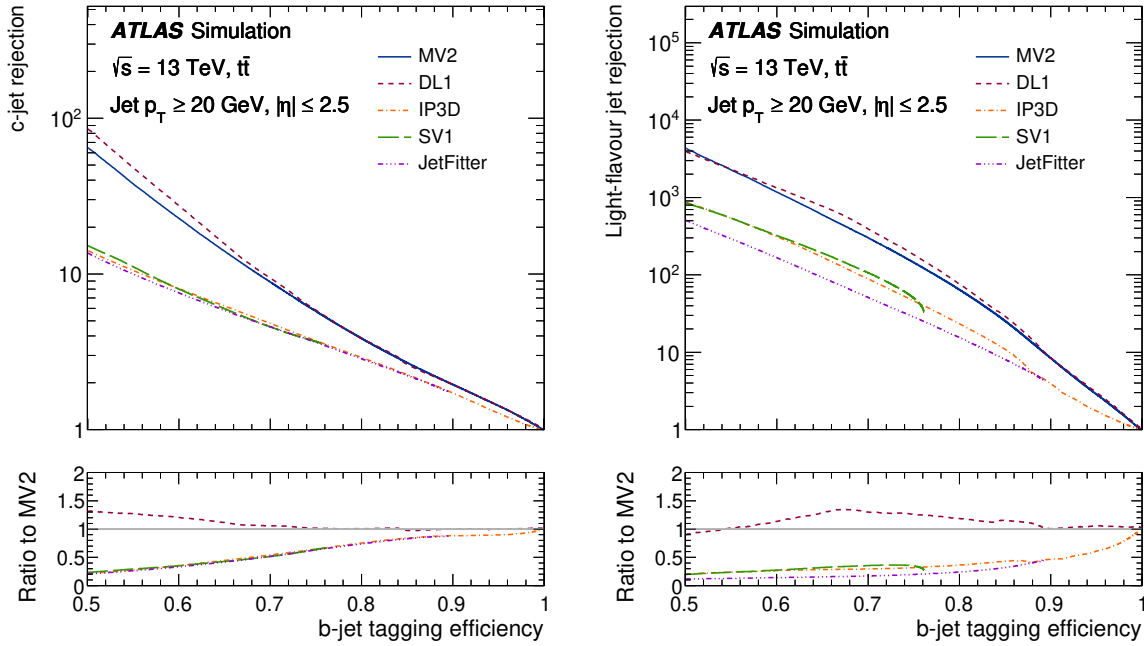


Figure 3-17: c -jet (left) and light-jet (right) rejection efficiency with different b -tagging efficiency using different tagging algorithm^[87].

is derived from the simulation, it needs to be calibrated. The Data-to-MC scale factors are derived in a function of the momentum of jet p_T by comparing the tagging performance in data and MC, usually using a pure process that contain the jets with flavor targeted. The calibration of the tagger used in the $VH(\rightarrow b\bar{b}, c\bar{c})$ analysis is shown in Section 4.3.1.

New Tagging Algorithm

It can be found that the evolution of the flavor tagging algorithm is close related to the development of machine learning techniques. The MV2 series using BDT and the DL1 series that use deep neural network are the most popular algorithms used in the Run-2 analysis of ATLAS. Now, the GN series uses the advanced graph neural network technique, and will be the default recommended flavor tagging algorithm of ATLAS FTAG group.

The Graph neural network^[88] is tailored to handle the so-called *group*, which has a data structure of complex relationship. It uses node to represent the entities and uses edge to represent relationship between entities. The information is passed between nodes via the edges, which allows the GNN to learn the patterns of the information flow.

The first generation of the GN series tagger is the GN1^[89]. Contrary to the MV and DL1 series that use low-level taggers as input, GN1 uses the information of the tracks directly. At the 70% *b*-tagging efficiency, the GN1 tagger improves the *c*-jet rejection by a factor of 2.1 and the light-jet rejection by a factor of 1.8 compared to the DL1r. The GN2^[90] then superseded the GN1 by using the transformer architecture and improvement in the settings of the network. Compared with GN1, GN2 improves the *c*-jet rejection by a factor of 1.5 and the light-jet rejection by a factor of 2.

The development of flavor tagging is crucial to the performance of ATLAS analysis. For example, in the $VH(\rightarrow b\bar{b})$ analysis, one of the major background is the $V + \text{light}$ process, where the *c*-jets and light-jets are mis-identified as the *b*-jet. By improving the rejection efficiency, the $V + \text{light}$ background can be reduced. It can be expected that in the future, more powerful flavor tagging algorithms will be developed and benefit the physics analysis.

3.4.3 Flavor Tagging Calibration

As mentioned above, the working point of the tagger is defined distribution of MC sample, which may have a different behavior than the real case(data), as shown in Figure 3-18. Thus, the scale factors are derived to correct the difference, this procedure is named as calibration. A detailed description about the calibration of the PCFT tagger is presented in the following. This tagger is used in the $VH(\rightarrow b\bar{b}, c\bar{c})$ analysis, defined with in the 2D plane of *b*-tagging

score versus c -tagging score of the jets. It is designed to achieve simultaneous flavor tagging for b - and c -jets, with new working points defined to increase c -jet efficiency. The details of the tagger design can be found in the Section 4.3.1.

The calibration of the PCFT tagger follows the standard FTAG method^[91-93]. The calibration for b -jets, c -jets and $light$ -jets are done separately. However, the efficiency of one kind of jet has non-trivial relation with the efficiency of other kinds of jet, e.g. the efficiency of c -jets can be affected by the number of b -jets and $light$ -jets in the same tagged bin, which will bring a circular dependence of the efficiencies for these three kind of jets. In order to mitigate the dependence and derive reasonable scale factors, the following strategy is used. The b -jet calibration is less dependent on the other two SFs given the high tagging efficiency and relative pure calibration sample, so it is derived with floating SFs for c - and $light$ -jets. The $light$ jet calibration is done similarly, but with the c -jet SFs constrained with a conservative uncertainty. For the c -jet calibration, the b -jet SFs are also floated while the $light$ -jet SFs are set to 1 with an uncertainty derived from the $light$ calibration.

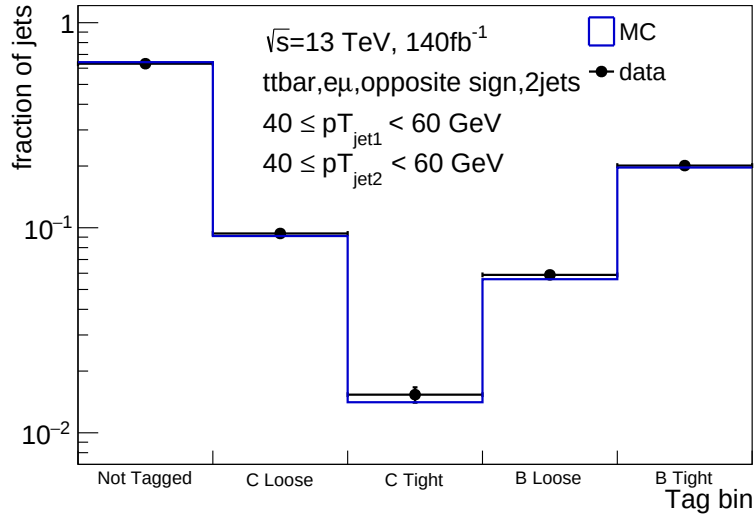


Figure 3-18: Comparison of the fraction of jets being tagged into different bins between Monte Carlo and Data. Examples are taken from the first jet of $t\bar{t} e\mu$, opposite sign, 2jets events.

***b*-jet tagging efficiency**

Almost all the *top* quark will decay to a *W* boson and a *b*-quark, taking a BR up to 99.7%, which is a golden final state enriched with *b*-jets. The *b*-jet calibration of PCFT uses standard FTAG recipe^[92], using the sample enriched with $t\bar{t}$ di-leptonic decay events. By requiring two leptons in the final state, the multi-jet background is highly suppressed. The details of the event selection will be discussed later.

Data and Simulated Sample

Data: The full Run-2 dataset with an integrated luminosity of 140fb^{-1} at centre-of-mass energy of $\sqrt{s} = 13\text{TeV}$ is used. Data events are required to pass the quality check. The dataset was collected using the lepton trigger, requiring the presence of high- p_T electron or muon.

Top pair: The baseline $t\bar{t}$ sample is produced with POWHEG v2^[94-95] generator, interfaced to the PYTHIA 8 for parton shower process. Alternative sample is produced with POWHEG v2 interfaced to HERWIG 7.

One of the major background comes from the 'fake' lepton events. The majority of this kind of events is $t\bar{t}$ with only one top decay leptonically, while another lepton coming from several sources: non-prompt leptons from the decay of bottom or charm hadrons; electrons from photon conversion; jets misidentified as electrons; muons produced from in-flight pion or kaon decays. The 'fake' lepton background is also modelled using the $t\bar{t}$ MC sample. Most of these events have only one 'fake' lepton, events with two or more 'fake' leptons are found to be negligible.

Single-top: Single top production in association with a boson (Wt) process is also a major background. The nominal sample is produced with POWHEG + PYTHIA 8, using the DR scheme to handle the overlap with $t\bar{t}$. The sample using same generator but with DS scheme is used as alternative sample for the impact of interference. Alternative sample produced with POWHEG + HERWIG 7 is also used. The single-top t -channel and s -channel are relative minor background process since there is only one real lepton. Their nominal samples are simulated using the same generator as Wt channel. Their uncertainties are estimated directly from data.

V+jets: The V +jets can be split to Z +jets and W +jets events. In Z +jets events, the Z boson decaying to a pair of leptons, while in W +jets events the W boson decay leptonically and another

lepton candidate is 'fake'. The nominal sample of V +jets is produced with SHERPA 2.2.1. The systematic uncertainties for Z +jets are estimated using the internal weight variation of nominal samples, whereas for W +jets it is evaluated from data.

Diboson: The Diboson production with additional jets can easily pass the selection if at least one of the boson decay leptonically. It is simulated using SHERPA 2.2.1 (for one boson decay leptonically) and SHERPA 2.2.2 (for two bosons decay leptonically). The systematic uncertainties are also estimated using internal weight variation.

Event selection and classification

In order to select events enriched with $t\bar{t}$ events, the event is required to have exactly two lepton candidates. The lepton candidate is defined as below:

- **Electron candidates** are reconstructed from isolated energy deposit in the electromagnetic calorimeter matched to an ID track^[96]. The candidate in the calorimeter barrel/endcap transition region, defined by $1.37 < |\eta| < 1.52$ are excluded for bad quality. It is also required to have transverse energy $E_T > 28$ GeV, $|\eta| < 2.47$ and pass the medium identification criteria to reject the non-prompt candidates.
- **Muon candidates** are reconstructed by combining tracks found in the ID with tracks found in the muon spectrometer^[64]. The muon candidates are required to have $p_T > 27$ GeV, $|\eta| < 2.5$ and pass the tight identification criteria to reject the background.

In order to reject the background with non-prompt electrons, the two lepton candidates are required to have opposite charges. They are further requested that one lepton is electron and the other is muon to suppress the Z +jets background. The event is also requested to have exact two jets. The jets are ranked by their reconstructed p_T .

For the purpose of the calibration method, it is useful to label the events according to the flavor of the two jets in generation level. Events with two b -jets (non b -jets) are labelled as bb (ll). Events with one b -jet and one non b -jets are labelled as bl or lb , depending on which jet has larger p_T .

Figure3-19 shows the prefit agreement between data and MC, which is good in general, indicating a good consistency for the b -tag efficiency in data and MC. However, it can also

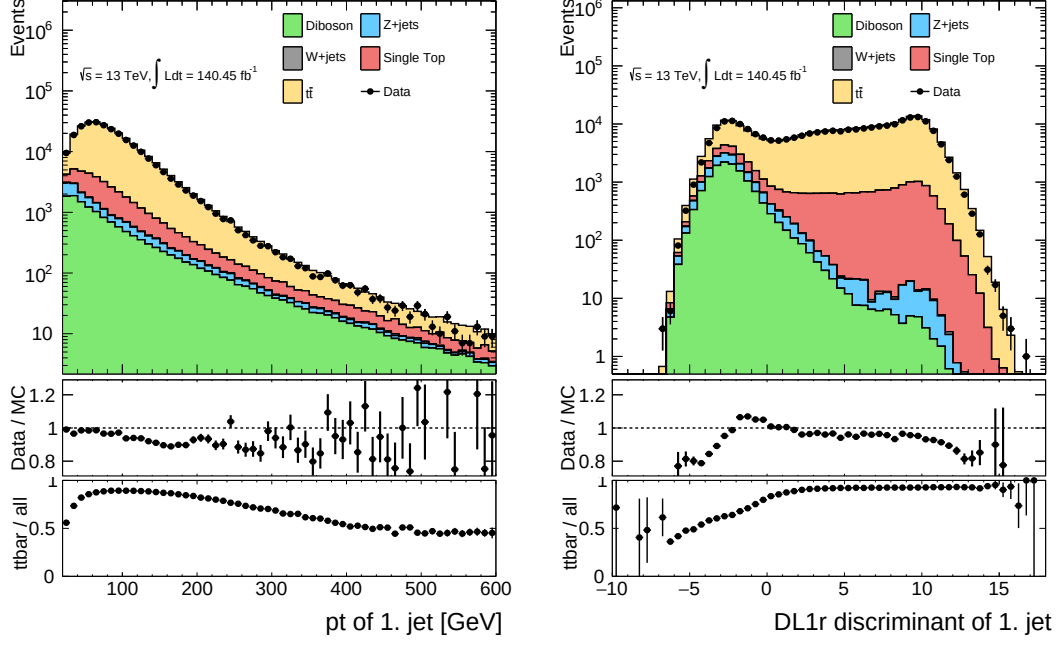


Figure 3-19: Prefit distribution of leading jet p_T (left) and its DL1rscore (right), categorized by the physics process. The ratio panel shows the fraction of $t\bar{t}$ events among all the MC events.

be observed that there is a trend in the p_T distribution that is probably brought by the well known issue of top quark p_T mis-modelling. This motivates the extraction of b -tag efficiency in separate jet p_T bins. The jet p_T is divided to in total of nine bins, with the bin boundary as [20,30,40,60,85,110,140,175,250,400]

Derivation of b -tag efficiency

The b -tag efficiencies in different p_T bins and PCFT bins are derived at same time, by maximizing the joint likelihood function. The general form of likelihood function is defined as:

$$\log \mathcal{L}(v_{tot}, P_b, \theta) = -v_{tot} + \sum_i^N n_i \cdot \log v_i(P, \theta) \quad (3-12)$$

where v_{tot} is the total number of expected events, P_b is the list of parameters of interest (POI), the probability of b -jets being tagged. They are defined as the probability of a b -jet falls into one of the five PCFT bins. θ is the nuisance parameters that also contains the P_c and P_l , which are the probabilities of c -jets and $light$ -jets being tagged respectively. $v_i(n_i)$ is the expected (observed) number of events in the bin i . There is in total of N bins are considered in

the fit.

The probabilities (P) are split by the jet p_T bins. As a result, the probabilities has the following relation:

$$P(b60|T^i) + P(b60 - 70|T^i) + P(N|T^i) + P(C_L|T^i) + P(C_T|T^i) = 1 \quad (3-13)$$

where T^i indicates one of the nine p_T bins. This relation is valid for both b -jet probabilities (P_b), c -jet probabilities (P_c) and *light*-jet probabilities.

In the fit regions, the events are binned according to the b -tagging bins and p_T bins of the two jets. Assuming the $j1$ with p_T in T^m is tagged as O^k and $j2$ with p_T in T^n is tagged as O^p , the expected events in a given (T^m, T^n, O^k, O^p) bin is:

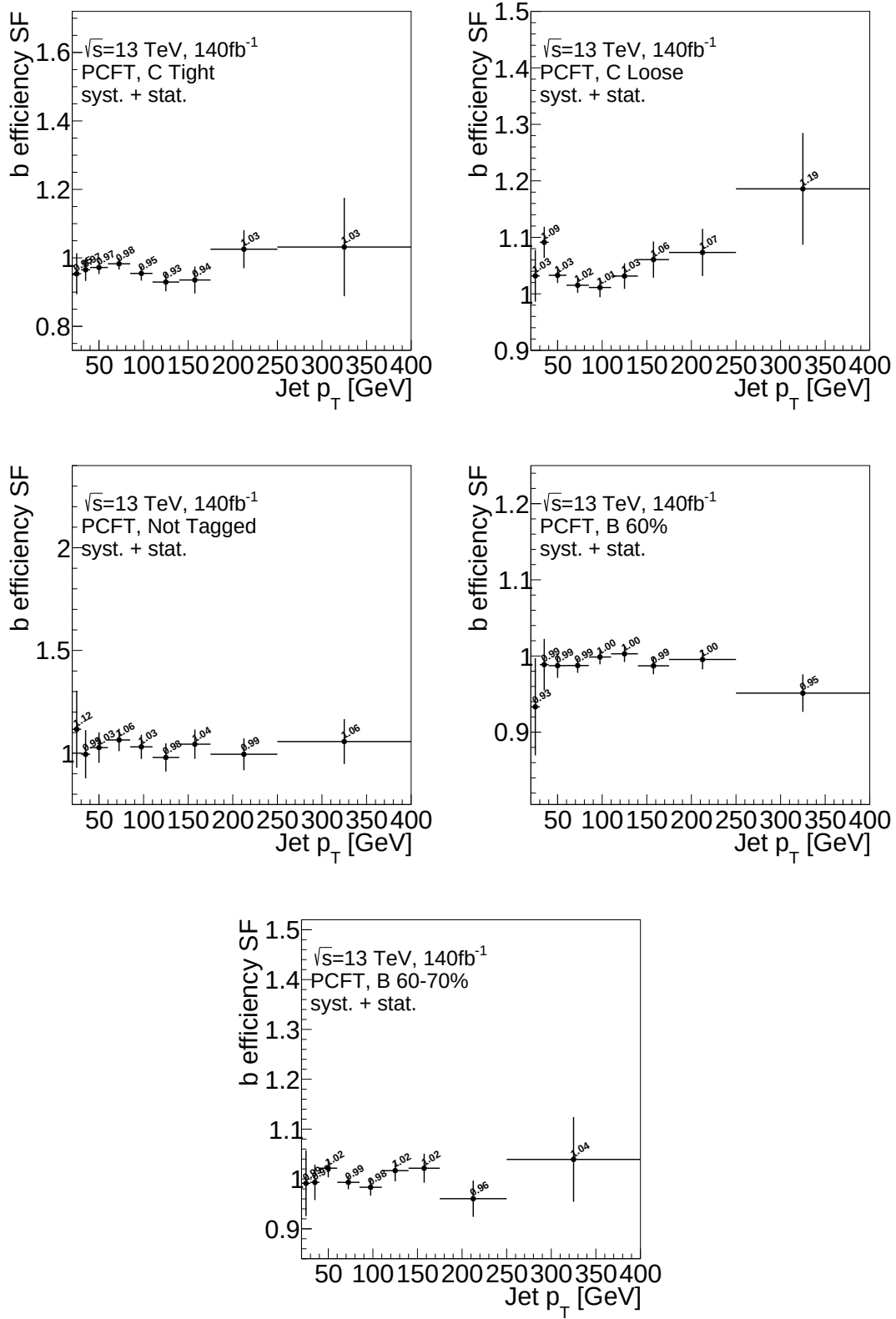
$$\begin{aligned} v(T^m, T^n, O^k, O^p) = & v_{bb}^{m,n} \cdot P_b(O^k|T^m) \cdot P_b(O^p|T^n) \\ & + v_{bl}^{m,n} \cdot P_b(O^k|T^m) \cdot P_l(O^p|T^n) \\ & + v_{lb}^{m,n} \cdot P_l(O^k|T^m) \cdot P_b(O^p|T^n) \\ & + v_{ll}^{m,n} \cdot P_l(O^k|T^m) \cdot P_l(O^p|T^n) \end{aligned} \quad (3-14)$$

Note that for simplicity, here the P_l includes both c - and *light*-jet probabilities, they are separated in the actual fit. In order to mitigate the dependence of b -tag efficiencies on P_l and P_c , they are free floating instead of taking from the other calibration.

Results

The fit results are interpreted with the scale factors, which is the ratio between the fitted efficiencies over the efficiencies derived from the MC. Figure 3-20 shows the scale factors in five PCFT bins.

Cross-check has been done to ensure the reliability of the fit results. The fit to a Pseudo dataset that is built with the nominal MC prediction gives the scale factors very close to unity. Additionally, since the b -tag working point is inherited from the official ones, the SFs in the two b -tagged bins should also be close. The check results are shown in Figure 3-21. The results are compatible within the uncertainties. Some small differences are expected due to the different

Figure 3-20: b -jet tagging scale factors as a function of jet p_T in different PCFT bins.

tagger design and evolution of MC samples.

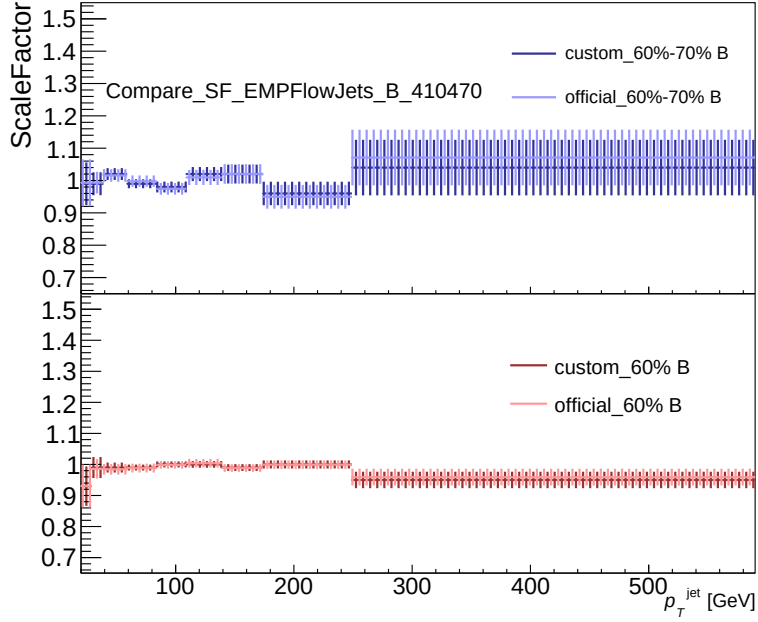


Figure 3-21: Comparison of scale factors of 60%(down) and 60-70%(up) b -tagged bins between FTAG official results and custom results.

c -jets and l -jets tagging efficiencies

c -jet tagging efficiency

The calibration of c -jets use the semi-leptonic $t\bar{t}$ events following the official suggestions. The SFs for b -jets and l -jets are floating in the fit. The events in B 60% bin is split into two, with threshold of $DL1r_c = 8$, to allow for a better constraint on b -jet and c -jet SFs at the same time. For the *light*-jet SFs, due to the very low efficiencies at B 60% bin, the SFs in this bin is set to 1 with the uncertainties taken from fixed cut 70% calibration. Figure 3-22 shows the c -jets scale factors with the POWHEG + PYTHIA 8 samples. In the analysis, there is also a small amount of τ -jets, which use the same SFs as c -jets for simplicity.

l -jet tagging efficiency

l -jet calibration is based on the Z+jets events, using the negative tag method (or named Flipped method). The l -jets SFs in the two b -tag bins have negligible impact on the analysis, so a relative conservative way of estimating uncertainties is applied. The b -jet SFs are free floating in the fit and c -jet SFs are set to 1 with 30% uncertainties. Figure 3-22 shows the l -jets scale factors with the POWHEG + PYTHIA 8 samples.

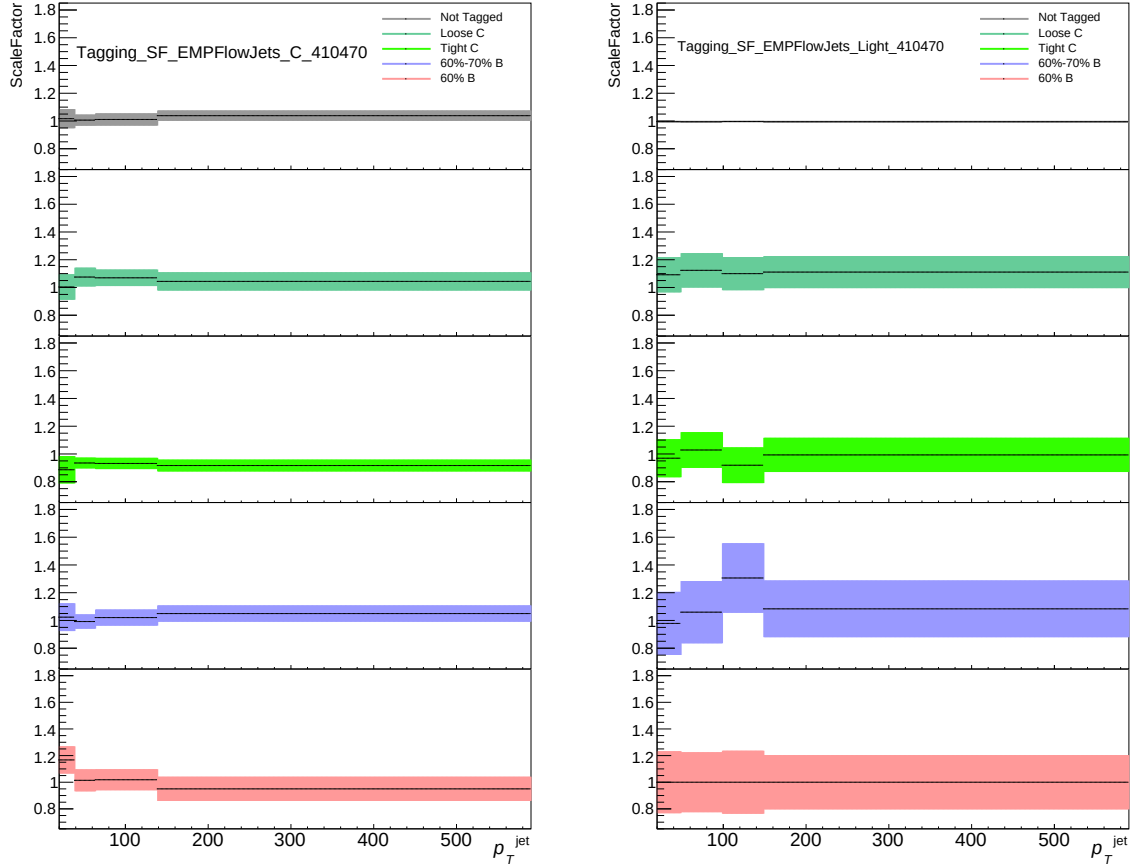


Figure 3-22: Scale Factors for c -jets (left) and l -jets (right) in different PCFT bins.

Chapter 4

Simultaneous Measurements of Higgs to charm and to bottom Yukawa Coupling

4.1 Introduction

The Higgs boson was discovered by ATLAS and CMS^[17-18] in 2012 using the Run-1 data of LHC, mainly through the bosonic decay channel of Higgs boson ($H \rightarrow WW, H \rightarrow ZZ, H \rightarrow \gamma\gamma$). Since its discovery, the properties of Higgs are studied in increasing detail. The SM predicts that the Higgs boson has the Yukawa couplings with the fermions and the coupling strength is proportional to the mass of the fermions. Thus, the discovery and measurements of the Yukawa coupling is of crucial importance to validate the BEH mechanism and understand the fermion flavor structure.

Using the Run-1 dataset, the coupling of Higgs to τ lepton was discovered and measured, with the ATLAS and CMS combined search for $H \rightarrow \tau\tau$ decay, which is the first test of the Yukawa mechanism. With the successful operation of Run-2 of LHC, more data is delivered and the Yukawa coupling of other fermions are discovered, starting with the observation top quark Yukawa coupling via $t\bar{t}H$ production^[97-98] and follows the bottom quark Yukawa coupling. The $H \rightarrow b\bar{b}$ is the most common decay mode in prediction, taking up 58% BR for Higgs mass at 125 GeV^[19]. However, the multi-jet background in hadron collider makes it very challenging to discover. In order to suppress the multi-jet background, the VH production mode is studied, requiring the vector boson (W or Z boson) decay leptonically, which meanwhile allows for a sufficient trigger efficiency using lepton triggers and E_T^{miss} triggers. Utilizing this production

mode, ATLAS and CMS collaboration both observed the $H \rightarrow b\bar{b}$ decay mode^[99-100]. After the discovery, the focus of the study shifted to the measurement with better precision, to better test the SM. Three additional results are published by ATLAS using the full Run-2 data, with an integrated luminosity of 140 fb^{-1} . The first result^[101] focus on the events with relative low Lorentz boost, where the two jets from the Higgs decay can be resolved into two separate small radius (small- R) jets in the detector. This is always referred to the *resolved* regime and will also be used in the following context. Complementary to the resolved regime, the second result^[102] target the events with high Lorentz boost (usually noted as *boosted* regime), where the two jets from the Higgs decay is merged and can be reconstructed as a single large-radius (large- R) jet (with the jet radius parameter $R = 1$). These two results target different kinematic phase space, but still have some overlap with each other. The third results then harmonized and combined these two regimes for a comprehensive understanding of the whole p_T^H spectrum^[103]. The combination introduced a p_T^V split for the switch between *Resolved* and *boosted* region. Below the $p_T^V = 400 \text{ GeV}$, the resolved strategy is applied while above the cut boosted strategy is applied. In the meantime, CMS collaboration also performed a similar combined analysis for $VH(\rightarrow b\bar{b})$ in 2022, using full Run-2 dataset with integrated luminosity of 138 fb^{-1} ^[104]. Both ATLAS and CMS results show a good consistency with the SM prediction.

With the coupling of Higgs to the third-generation fermions well established, efforts are also devoted to searching for the coupling with other fermions, especially second generation, namely c, s quarks and μ lepton. ATLAS has reported a search for the $H \rightarrow \mu\mu$, with an 2 sigma excess over the background hypothesis^[105]. For the $H \rightarrow cc$ and $H \rightarrow ss$ decays, ATLAS also has direct searches that providing the upper limits, but no direct evidence found yet.

Among all the searches for Higgs coupling to the first and second generation quarks, the $H \rightarrow c\bar{c}$ decay is the most promising decay channel to look into. With the branching ratio of 2.89% in the SM prediction^[19], $H \rightarrow c\bar{c}$ is the largest undiscovered Higgs decay channel. In the meantime, due to its smallness (comparing to the major decay modes), it is susceptible and could be significantly affected in some new physics scenarios^[5,106-111]. Similar to the $b\bar{b}$ decay channel, the multi-jet is also the major background. In addition, the c -hadrons has relative shorter lifetimes and smaller masses than the b -hadrons, making it harder to be distinguished from other jets (The details of their tagging performance will be discussed in the later section)

and thus has a worse signal significance. As a result, VH production mode provides the best sensitivity as it has a relative clean background. Both ATLAS and CMS has published results that set upper limit on the VH production mode cross-section times the branching ratio of $H \rightarrow c\bar{c}$. Using the full Run-2 dataset, ATLAS collaboration measured an upper limit of 26 times the signal strength predicted by the SM (31 times SM for expected)^[112], corresponding to a constraint on the charm Yukawa coupling modifier $\kappa_c < 8.5(12.4)$ at 95% confidence level. The CMS collaboration measured an upper limit 14.4 times SM (7.6 times SM for expected), and a constraint on $1.1 < \kappa_c < 5.5$ ($|\kappa_c| < 3.4$ for expected).

Due to the similarity of the $VH(\rightarrow b\bar{b})$ and $VH(\rightarrow c\bar{c})$ process, there are significant benefits to measuring them simultaneously. The first advantage is that it can have an extended physics output. With the combined analysis, it is possible to simultaneously measure the Yukawa coupling modifiers κ_b and κ_c or their ratios κ_c/κ_b , without making any assumption on total width of Higgs. The second advantage is about a more coherent treatment of the background. The main background in both $VH(\rightarrow b\bar{b})$ and $VH(\rightarrow c\bar{c})$ analyses are $V + jets$ and top process. Same control regions can be shared between two analyses to have a better control of these backgrounds. Previously, there are already combinations of resolved+boosted $VH(\rightarrow b\bar{b})$ ^[103] and resolved $VH(\rightarrow b\bar{b})$ + resolved $VH(\rightarrow c\bar{c})$ ^[112].

The analyses presented following aim to combine the resolved $VH(\rightarrow b\bar{b})$, boosted $VH(\rightarrow b\bar{b})$ and resolved $VH(\rightarrow c\bar{c})$ regimes, using an integrated luminosity of 140 fb^{-1} dataset. While the previous combinations demonstrated the feasibility of such combined measurements, they used individual analysis strategies from each published results. This analysis separate the regimes by different requirement for the Higgs candidate and the p_T of reconstructed vector boson (p_T^V), as shown in Figure 4-1. The $VH(\rightarrow b\bar{b})$ regime requires to have exactly two b -tagged jets while the $VH(\rightarrow c\bar{c})$ region requires to have at least one c -tagged jet. The resolved and boosted $VH(\rightarrow b\bar{b})$ regimes are split at the threshold of $p_T^V = 400 \text{ GeV}$ following the previous studies. The Higgs candidate is constructed from two small R jets ($R = 0.4$) below the threshold. Above the threshold, it is built from a large R jet ($R = 1$) with two track jets (ghost-associated to the large R jet).

A coherent analysis strategy is used across the regimes, which is optimized both for $VH(\rightarrow b\bar{b})$ and $VH(\rightarrow c\bar{c})$, and the uncertainties are correlated as much as possible. A cross-check

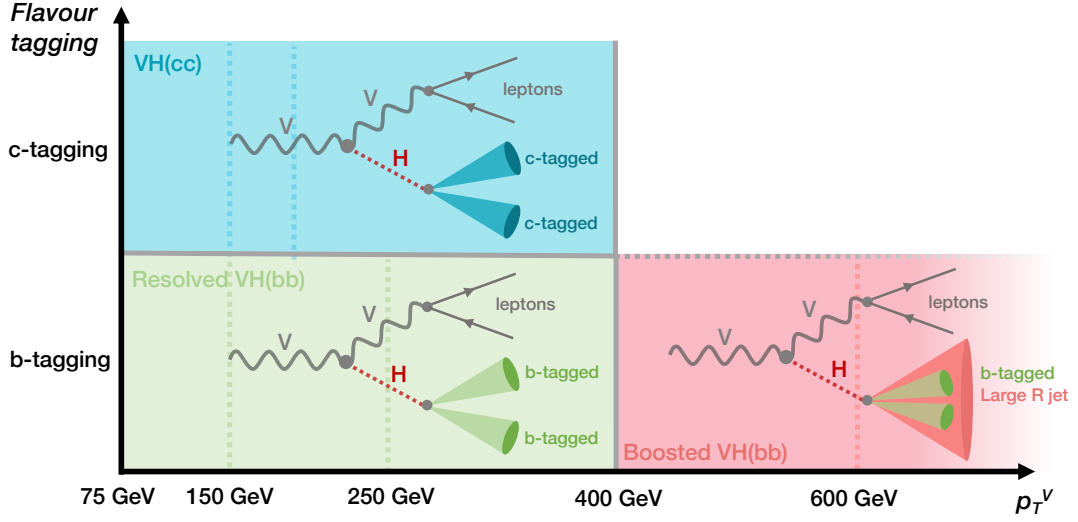


Figure 4-1: Illustration of the analysis regime used in the analysis. The $VH(\rightarrow b\bar{b})$ and $VH(\rightarrow c\bar{c})$ regimes is split by the requirement of b - and c -tagged jets. The boosted and resolved are split by a cut at $p_T^V = 400$ GeV.

that considering the SM $VZ(\rightarrow b\bar{b})$ and $VZ(\rightarrow c\bar{c})$ process as signal is also performed to valid the analysis strategy. In the meantime, with the improved object reconstruction and calibration as well as event classification techniques, especially the flavor tagging techniques and multivariate classifier, the results have a significant improvement compared with the previous ones.

This analysis extract all the results from the combined fit considering all the regimes, delivering the following physics output:

- Inclusive $VH(\rightarrow b\bar{b})$ signal strength and significance
- Inclusive $VH(\rightarrow c\bar{c})$ signal strength and upper limit
- Signal strength and significance for $WH(\rightarrow b\bar{b})$ and $ZH(\rightarrow b\bar{b})$ process, Signal strength and upper limit for $WH(\rightarrow c\bar{c})$ and $ZH(\rightarrow c\bar{c})$ process
- Signal strength and significance for $ZH(\rightarrow b\bar{b})$, $WH(\rightarrow b\bar{b})$, $ZH(\rightarrow c\bar{c})$ and $WH(\rightarrow c\bar{c})$ process
- Reduced Stage1.2 Simplified cross-section measurements (STXS) in p_T^V and jet multiplicity bins
- Constraint on Yukawa coupling modifier κ_b , κ_c , and their ratio $\kappa_c\kappa_b$

This chapter is organized as following. The Section 4.2 describes the Data and Monte Carlo samples used in the analysis. Section 4.3 shows the flavor tagging techniques used in the analysis and will especially show the b -jet tagging efficiency derivation. Section 4.4 and 4.5 summarizes the event selection and categorization, the details of events tagging strategy is also described. Section 4.6 will discuss the jet energy correction applied to improve signal resolution. Section 4.7 shows the multi-variate analysis techniques applied for the separation of signal and backgrounds. The treatments of systematic uncertainties are briefly summarized in Section 4.8.3. Section 4.8 shows the fit model and the treatments of systematic uncertainties, a fit study for the assessment of impact from mismodelling is also shown. The fit results and interpretation will be shown in Section 4.9 and a brief summary will be given in Section 4.10.

4.2 Data and Simulated Samples

4.2.1 Data

The data used in this analysis were collected by ATLAS during the Run-2 proton-proton collision of LHC, corresponding to an integrated luminosity of 140 fb^{-1} at $\sqrt{s} = 13 \sim \text{TeV}$ ^[34]. Data events are required to pass a number of quality requirements. The triggers used in this analysis for data collection will be discussed later in Section 4.4.

4.2.2 Simulated Sample

The main background in both $VH(\rightarrow b\bar{b})$ and $VH(\rightarrow c\bar{c})$ regime comes from the $V + jets$ and top quark process. The $V + jets$ background mainly consists b or c quarks, thus divided based on the flavor composition to $V + hf$ (bb, cc), $V + mf$ (bc, bl, cl) and $V + light$. Similarly, the top process can also be divided to $Top(bb)$ ¹, which is dominant top background in the $VH(\rightarrow b\bar{b})$ regime, and the remaining components are grouped. The minor background processes are single-top, multi-jet and Diboson process. All the simulated sample are passed through the ATLAS detector simulation and reconstructed with ATLAS offline reconstruction software^[113]. Table 4-1 lists the matrix element generators, PDF set and Parton showered used for the nominal

¹ The b/c here in the brackets refer to the flavor composition of the higgs candidate jets

Process	Matrix Element	PDF Set (ME)	Parton Shower	σ order	$\sigma \times \text{Br}$ [pb]
$qq \rightarrow WH \rightarrow \ell \nu b \bar{b}$	PowHeg-Box v2 + GoSam + MinLo	NNPDF3.0NLO	Pythia-8.245	NNLO(QCD)+ NLO(EW)	2.69×10^{-1}
$qq \rightarrow ZH \rightarrow \nu \nu b \bar{b}$	PowHeg-Box v2 + GoSam + MinLo	NNPDF3.0NLO	Pythia-8.245	NNLO(QCD)+ NLO(EW)	8.91×10^{-2}
$qq \rightarrow ZH \rightarrow \ell \ell b \bar{b}$	PowHeg-Box v2 + GoSam + MinLo	NNPDF3.0NLO	Pythia-8.245	NNLO (QCD)+NLO(EW)	2.99×10^{-2}
$gg \rightarrow ZH \rightarrow \nu \nu b \bar{b}$	PowHeg-Box v2	NNPDF3.0NLO	Pythia-8.307	NLO+NLL	1.43×10^{-2}
$gg \rightarrow ZH \rightarrow \ell \ell b \bar{b}$	PowHeg-Box v2	NNPDF3.0NLO	Pythia-8.307	NLO+NLL	4.80×10^{-3}
$qq \rightarrow WH \rightarrow \ell \nu c \bar{c}$	PowHeg-Box v2 + GoSam + MinLo	NNPDF3.0NLO	Pythia-8.245	NNLO(QCD)+ NLO(EW)	1.34×10^{-2}
$qq \rightarrow ZH \rightarrow \nu \nu c \bar{c}$	PowHeg-Box v2 + GoSam + MinLo	NNPDF3.0NLO	Pythia-8.245	NNLO(QCD)+ NLO(EW)	4.42×10^{-3}
$qq \rightarrow ZH \rightarrow \ell \ell c \bar{c}$	PowHeg-Box v2 + GoSam + MinLo	NNPDF3.0NLO	Pythia-8.245	NNLO (QCD)+NLO(EW)	1.48×10^{-3}
$gg \rightarrow ZH \rightarrow \nu \nu c \bar{c}$	PowHeg-Box v2	NNPDF3.0NLO	Pythia-8.307	NLO+NLL	7.10×10^{-4}
$gg \rightarrow ZH \rightarrow \ell \ell c \bar{c}$	PowHeg-Box v2	NNPDF3.0NLO	Pythia-8.307	NLO+NLL	2.38×10^{-4}
$Z \rightarrow \nu \nu + \text{jets}$	Sherpa 2.2.11	NNPDF3.0NNLO	Sherpa 2.2.11	NNLO	10700
$W \rightarrow \ell \nu + \text{jets}$	Sherpa 2.2.11	NNPDF3.0NNLO	Sherpa 2.2.11	NNLO	60200
$Z \rightarrow \ell \ell + \text{jets}$	Sherpa 2.2.11	NNPDF3.0NNLO	Sherpa 2.2.11	NNLO	6300
$t \bar{t}$	PowHeg-Box v2	NNPDF3.0NLO	Pythia-8.230	NNLO+NNLL	832
single-top (s)	PowHeg-Box v2	NNPDF3.0NLO	Pythia-8.230	NNLO	10.32
single-top (t)	PowHeg-Box v2	NNPDF3.0NLO	Pythia-8.230	NNLO	214.2
single-top (Wt)	PowHeg-Box v2	NNPDF3.0NLO	Pythia-8.230	Approx. NNLO	79.3
$qq \rightarrow WW$	Sherpa 2.2.11	NNPDF3.0NNLO	Sherpa 2.2.11	NLO	109.28
$qq \rightarrow WZ$	Sherpa 2.2.11	NNPDF3.0NNLO	Sherpa 2.2.11	NLO	20.85
$qq \rightarrow ZZ$	Sherpa 2.2.11	NNPDF3.0NNLO	Sherpa 2.2.11	NLO	17.51
$gg \rightarrow VV$	Sherpa 2.2.2	NNPDF3.0NNLO	Sherpa 2.2.2	NLO	3.09

Table 4-1: The nominal Monte Carlo samples used in the $VH(\rightarrow b\bar{b}, c\bar{c})$ analysis, and the corresponding process cross-sections at $\sqrt{s} = 13$ TeV. The PDF sets in the table are the ones used for the matrix element. For the signal, the samples are reweighted to the PDF4LHC15NLO PDF set.

MC samples. The corresponding cross-sections are also shown.

Signal

The VH production mode is composed of $qq \rightarrow VH$ and $gg \rightarrow ZH$ process, the Feynman diagrams are shown in Figure 4-2 and 4-3. Both of two processes are taken into account. They are simulated with POWHEG v2^[94-95] generator, interfaced to the PYTHIA 8 for parton shower process. For the matrix elements (ME) process, NNPDF3.0NLO PDF^[114] is used and then reweighted to PDF4LHC15NLO^[115] PDF set. Alternative samples generated with POWHEG + HERWIG 7^[116] are available and used for the assessment of signal modelling uncertainties.

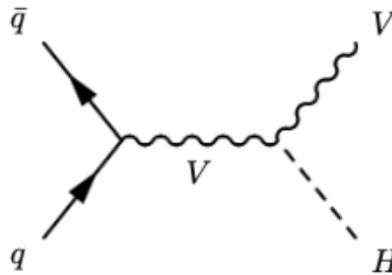
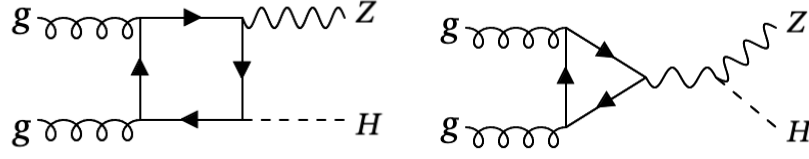
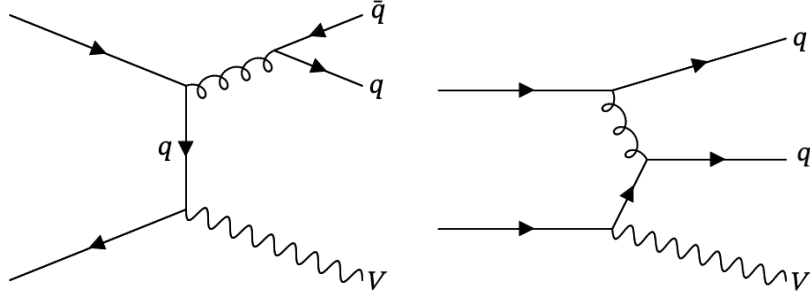


Figure 4-2: LO $qq \rightarrow VH$ process Feynman diagram.

Figure 4-3: LO $gg \rightarrow ZH$ process Feynman diagram.

V+jets

The production of vector boson in association with jets ($V + jets$) is one of the major background for all channels in the analysis. Figure 4-4 shows some example of the Feynman diagrams of $V + jets$ process. Two quarks are generated by the decay of one vector boson or through scattering, which can be misidentified as quarks decaying from Higgs.

Figure 4-4: Some example Feynman diagrams of $V + jets$ process.

The nominal $V + jets$ process is simulated with SHERPA 2.2.11^[117]. The default parton shower and hadronization is simulated with SHERPA. Two sets of alternative samples are used. One is generated with the MADGRAPH FxFx^[118] interfaced to the PYTHIA 8. Another one is generated with SHERPA 2.2.1, which is mainly for assessment of the kinematic (p_T^V) distribution uncertainties which is not fully covered by the scale variation of nominal sample.

Top pair

The top pair production ($t\bar{t}$) is also one of the major background. Figure 4-5 shows the leading order $t\bar{t}$ process. $t\bar{t}$ can enter different channels depending on the decay of W bosons. The two quarks decaying from top quarks can be misidentified as the quarks decay from Higgs. If two W bosons decay hadronically or decay to hadronic τ s, it will enter the 0-lepton channel. If one of the W bosons decay leptonically, it will most probably enter the 1-lepton channel. With

both W bosons decay leptonically, the event will be categorized into 2-lepton channel. $t\bar{t}$ is significant in 0-lepton and 1-lepton channels and has much fewer yields in 2-lepton channel. As a result, the data-driven method is used to estimate the top ($t\bar{t}$ +single-top) background in 2-lepton channel.

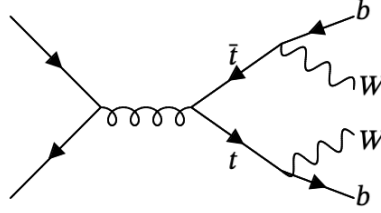


Figure 4-5: LO $t\bar{t}$ process Feynman diagram.

The nominal sample of $t\bar{t}$ is generated with POWHEG using NLO calculation for matrix element and PYTHIA 8 for parton shower and hadronization. Reweighting to NNLO calculation of matrix element is also tried but no major improvement is found, so it is not used. Two sets of alternative samples are generated. A POWHEG + HERWIG 7 sample is used for the estimation of modelling uncertainties related to parton shower. The uncertainties related to the matrix element calculation is estimated from another MADGRAPH + PYTHIA 8 sample.

Single-top

As shown in Figure 4-6, the single-top process can be divided to s -channel, t -channel and Wt -channel. The dominant contribution comes from the Wt -channel. They are generated separately using POWHEG interfaced with PYTHIA 8.

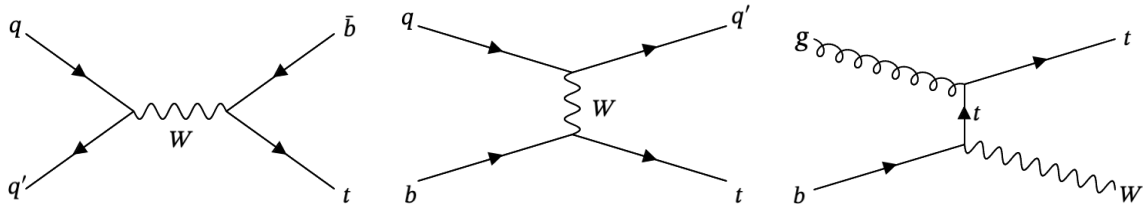


Figure 4-6: LO Feynman diagrams of single-top process in s -channel (left), t -channel (middle) and Wt -channel (right) .

In the case of Wt -channel, there is some overlap with the $t\bar{t}$ process. At NLO in QCD, these processes have common diagrams, and it is impossible to keep them formally apart. The

diagram subtraction (DS) scheme^[119] is used to handle the overlap by removing doubly resonant diagrams from the Wt sample, i.e. where both top quarks are on-shell. Another scheme named diagram removal (DR) is also studied and used as alternative scheme to assess the systematic uncertainties. The DS-DR difference is also expected to take the interference between $t\bar{t}$ and single-top into account. In previous iterations of the analysis, the DR scheme was used as the default. However, in this analysis, the DS scheme showed better agreement of MC with data in the boosted $VH(\rightarrow b\bar{b})$ regime and is thus used as the nominal sample.

Alternative single-top samples are used for t -channel and Wt -channel. POWHEG + HERWIG 7 sample is used as parton shower variation and MADGRAPH + PYTHIA 8 is used as matrix element variation.

Diboson

The Diboson process has a quite similar signature as the signal, the leading order Feynman diagrams are shown in Figure 4-7 (qq-initiated) and Figure 4-8 (gg-initiated). One of the vector boson can decay to a pair of quarks, which is same as Higgs decay.

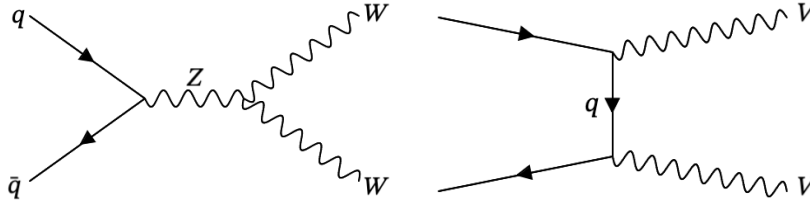


Figure 4-7: LO Feynman diagrams of qq-initiated Diboson process s-channel (left) and t-channel (right).

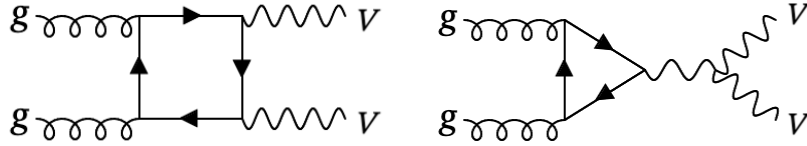


Figure 4-8: LO Feynman diagrams of gg-initiated Diboson process.

The nominal simulation generator for qq-initiated process is SHERPA 2.2.11 and SHERPA 2.2.2 for gg-initiated. The alternative POWHEG + PYTHIA 8 sample is used for the assessment of systematic uncertainties related to matrix element and parton shower. The additional SHERPA

2.2.1 sample is also used, similarly to V +jets, for covering the difference between Data and MC in kinematic distribution.

Multi-jet

The dominant contribution to this background comes from real muons or electrons from heavy-flavour hadrons decaying semi-leptonically or jets faking leptons, which trigger the event. Only a small fraction of these events can pass the selection since the leptons are not expected to be isolated. Given its low efficiency, it is hard to have a reliable MC simulation for multi-jet. Thus, the data-driven method is used to extract its contribution. After the event selection that especially suppress the multi-jet background, its contribution is found to be negligible in the 0-lepton and 2-lepton channel, also in the boosted 1-lepton channel. As a result, it is only considered for resolved 1-lepton channel.

4.3 Flavor Tagging

In the $VH(\rightarrow b\bar{b}, c\bar{c})$ process, the Higgs will decay to a pair of b -quarks or c -quarks, which will undergo fragmentation and harmonization and finally become jets in the detector. By distinguishing b -jets and c -jets from *light*-jets and τ -jets, the events which is more signal-like can be selected. As a result, the performance of flavor tagging plays a crucial role in improving the signal sensitivity.

In ATLAS standard flavor tagging procedure, the tagging of jets is done separately. To be more explicit, the jet go through the b -tagger and c -tagger separately, and each tagger give the evaluation. It means that in some case, the jet could be possible to be b -tagged and c -tagged at the same time. To avoid selecting the same event twice in this case, the previous analysis will only consider the jet to be a c -jet only when it fails the b -tagging requirement. However, the calibration of the taggers are still done separately, which brings difficulty for deriving the scale factors across tag regions.

Following the recommendation from the FTAG group, a custom tagger called Pseudo Continuous Flavor Tagging (PCFT) is built that simultaneously tag the b -jet and c -jet. This tagger is used in the resolved regimes. The basic scheme and the calibration is shown in the following,

especially the b -jet calibration of this tagger will be discussed in detail.

4.3.1 Flavor Tagging in Resolved Regimes

The PCFT aims to provide a harmonized tagger for the analysis and further ensure the orthogonality between regimes and coherent treatment of uncertainties. The jet will be assigned a b -tagging score ($DL1r_b$) and c -tagging score ($DL1r_c$) at the same time. The definition of $DL1r_b$ and $DL1r_c$ follows the standard recommendation from ATLAS . As demonstrated in Figure 4-9, two b -tagging working points (WPs) and two c -tagging WPs divide the 2D plane of b - and c -tagging score to five exclusive bins.

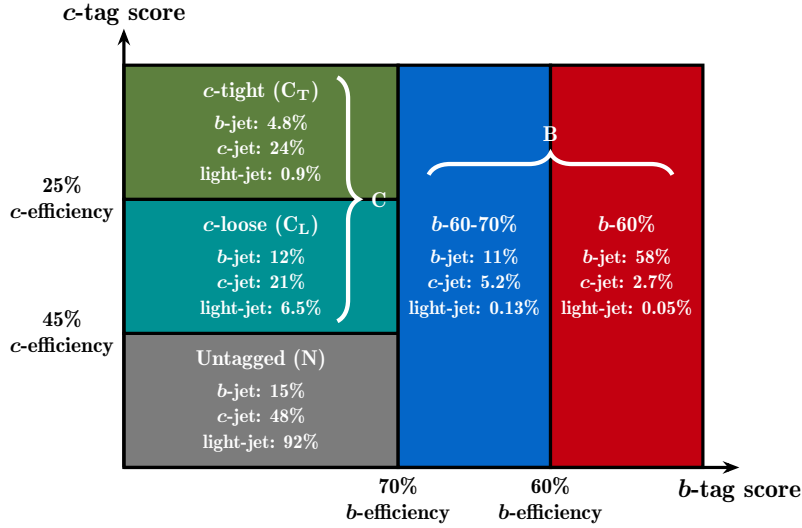


Figure 4-9: Schematic of flavor tagging regions used in the resolved regimes. The efficiencies for the various jet flavors in the various regions are extracted from a simulated $t\bar{t}$ sample following the procedure detailed in Ref. [91].

The $b - 60\%$ bin comprises jet with the b -tagging score larger than the 60% b -tagging efficiency $DL1r_b$ cut value ($DL1r_b > 4.565$). The $b - 60\% - 70\%$ bin comprises jet with the b -tagging score between the 60% and 70% b -tagging efficiency $DL1r_b$ cut values ($3.245 < DL1r_b < 4.565$). The jet that falls into these two bins is classified as b -tagged, labelled as **B**. For the jets that fail the b -tagging requirement ($DL1r_b < 3.245$), they will be classified into the following three bins depending on their $DL1r_c$ score: tight- c tagged jet (labelled as **C_T**) that have the score larger than 25% c -tagging efficiency cut value ($DL1r_c > 1.76$); Loose- c tagged jet (labelled as **C_L**) that have the score between 25% and 45% c -tagging efficiency cut values

($0.67 < \text{DL1}r_c < 1.76$); Not tagged jet (labelled as **N**), which comprises jets that fail all the four above-mentioned bins. The jet that is labelled as **C_T** or **C_L** is classified as *c*-tagged.

The cut values for the 60% and 70% *b*-tagging WPs are inherited from the standard ATLAS FTAG DL1r recommendation, while the tight and loose *c*-tagging WPs are optimized by the analysis team. The tagging efficiency for *b*-, *c*- and *light*- jets of each bin can be found in Figure 4-9. For the τ -jets, the efficiency in the tight and loose *c*-tagging bins are around 20%, while in the *b*-tagged bins are very small (order of 1%). The calibration of the PCFT tagger has already been presented in 3.4.3

4.3.2 Flavor Tagging in Boosted Regime

In the boosted regime, only *b*-tag is needed. So the FTAG standard Pseudo Continuous B Tagging (PCBT) is applied to the VR track jets. PCBT defines four working points depending on the efficiencies of *b*-jet to pass the selection, which are 60%, 70%, 77% and 85%. In order to have more signal events in the boosted regime, the 85% WP is chosen. The details of the PCBT and its calibration can be found in FTAG paper^[91].

4.4 Event Selection

The events used in this analysis are selected based on the criteria described in the following section. The event is required to be triggered by the given triggers. After that, the objects in the event will be reconstructed, and they need to meet certain criteria to be considered as valid objects. Based on the objects that pass the selection, the events are further selected, with different criteria for different regimes and lepton channels. These events selection criteria can be classified into selections related to the vector boson candidate, selections related to Higgs candidate and selections related to suppression of multi-jet background.

4.4.1 Trigger Selection

The trigger used in $VH(\rightarrow b\bar{b})$ and $VH(\rightarrow c\bar{c})$ regimes are harmonized. In 0-lepton channel, events are selected using the lowest un-prescaled E_T^{miss} triggers with online thresholds of 70

GeV for the data recorded in 2015, of 90 and 110 GeV for data recorded in 2016 and 110 GeV for data recorded in 2017 and 2018.

In 1-lepton channel, single electron events are required to be triggered by at least one of the lowest un-prescaled single electron triggers. Single muon events are triggered by lowest un-prescaled muon triggers for $p_T^V < 150$ GeV. For higher p_T^V events, the same E_T^{miss} trigger as 0-lepton channel is used for higher efficiency than single muon trigger.

In 2-lepton channel, similar triggers are used as 1-lepton channel. The only exception is that in the muon channel, the threshold of switch between single muon trigger and E_T^{miss} trigger is 250 GeV.

The scale factors of the triggers are applied. For E_T^{miss} trigger, the efficiency and scale factors are measured independently using three different samples: $W(\mu\nu) + jets$, $Z(\mu\mu) + jets$ and semi-leptonic $t\bar{t}$. In this analysis, the scale factors measured using $t\bar{t}$ are used as it provides better agreement between data and MC. The other two scale factors are included as systematic uncertainties. However, in the 2-lepton channel, since the E_T^{miss} trigger efficiency reaches 100%, no SF is used. For lepton triggers, the SFs are applied following the recommendations.

4.4.2 Object Selection

The object used in the analysis is based on the reconstructed objects mentioned in Section 3.3. The definition and additional criteria used in this analysis is shown in the following.

Primary vertex

Events enter the analysis is required to have at least one primary vertex.

Electrons

All electrons are required to have $p_T > 7\text{GeV}$ and $|\eta| < 2.47$, the track associated needs to pass additional requirement on the impact parameters. Three sets of criteria are considered for the electron selection: VH-Loose, ZH-Signal and WH-Signal, the criteria are listed in Table 4-2. The electron fails these three criteria will not be considered. The electron identification efficiency and energy scale factors are applied following the recommendation.

Electron Selection	p_T	η	ID	d_0^{sig} w.r.t. BL	$ \Delta z_0 \sin \theta $	Isolation
VH-Loose	>7 GeV	$ \eta < 2.47$	Loose	< 5	< 0.5 mm	Loose_VarRad
ZH-Signal	>27 GeV	$ \eta < 2.47$	Loose	< 5	< 0.5 mm	Loose_VarRad
WH-Signal	>27 GeV	$ \eta < 2.47$	Tight	< 5	< 0.5 mm	HighPtCaloOnly

Table 4-2: Electron selection requirements.

Muons

Similar to the electrons, the muons are required to have $p_T > 7\text{GeV}$ and $|\eta| < 2.7$, also with requirements on the tracks associated. All the muons in $|\eta| < 2.5$ are required to pass the additional ID quality check, while the muon in $|\eta| > 2.5$ are reconstructed using standalone algorithm. Three sets of criteria for the muon selection are listed in Table 4-3. The muon fails these criteria will not be considered. The muon reconstruction, isolation and track-to-vertex association scale factors, as well as energy scale factors, are applied following the recommendation.

Muon Selection	p_T	η	ID	d_0^{sig} w.r.t. BL	$ \Delta z_0 \sin \theta $	Isolation
VH-Loose	>7 GeV	$ \eta < 2.7$	Loose	< 3	< 0.5 mm	Loose_VarRad
ZH-Signal	>27 GeV	$ \eta < 2.5$	Loose	< 3	< 0.5 mm	Loose_VarRad
WH-Signal	>25 GeV when $p_T^V > 150$ GeV	$ \eta < 2.5$	Medium	< 3	< 0.5 mm	HighPtTrackOnly
	>27 GeV when $p_T^V < 150$ GeV					

Table 4-3: Muon selection requirements.

Taus

The hadronic taus (τ_{had}) are considered for this analysis. All the hadronic taus are required to have $p_T > 20\text{GeV}$ and $|\eta| < 2.5$. The tau identification is based on the RNN. The τ_{had} candidates need to pass the Loose WP, which corresponds to 85% efficiencies for 1-prong and 75% efficiencies for 3-prong. The requirements are listed in Table 4-4. The reconstruction, identification scale factors and the energy corrections are applied according to the recommendations.

Lepton	p_T	η	n_{trk}	ID
tau	>20 GeV	$ \eta < 2.5$	1 or 3 tracks	Loose

Table 4-4: Hadronic tau selection requirements.

Jets

In this analysis, the Higgs candidate is expected to decay to a pair of b - or c -quarks, which will continue fragmentation and hadronization, becoming the jets in the detector. Consequently, jets play a very important role in identifying event whose topologies and kinematics are consistent with the signal processes.

Three different kind of jets reconstructed with $anti-k_T$ algorithm is used in the analysis:

- Small- R jets: calorimeter jet collection with $R = 0.4$, used to reconstruct the Higgs-candidate in resolved regime and in the event categorization.
- Large- R jets: calorimeter jet collection with $R = 1$, used to reconstruct the Higgs-candidate in boosted regime.
- Variable- R track jets: track jet collection with variable radius, used to reconstruct the b -tagged objects inside the large- R jet and in the event categorization in boosted regime.

Small- R Jets The reconstruction of small- R jets use the particle flow as inputs. They are classified as either "signal" jets ($|\eta| < 2.5$) or "forward" jets ($2.5 < |\eta| < 4.5$). Only the signal jets are used for the reconstruction of Higgs candidate, but both of them are considered for E_T^{miss} reconstruction and event categorization.

The jet vertex tagger (JVT) and forward jet vertex tagger (fJVT) are applied to suppress pile-up jets. The tight JVT WP and loose fJVT WP are used. Additional JetCleaning requirement is applied to help remove the jets from calorimeter noise or beam-induced background fake jets^[120-121].

The jet mass calibration of small- R jets is recommended for jets with mass over 40 GeV, while in this analysis most of the jets have mass scale from 5 to 20 GeV. Thus, the mass calibration is not applied. The JVT and fJVT efficiency scale factors are applied following the recommendation.

The selection criteria for small- R jets are summarized in Table 4-5.

Large- R jets In the $VH(\rightarrow b\bar{b})$ boosted regime, two b -jets from the Higgs decay are very close to each other, and can be reconstructed to one single large- R jet. The reconstruction of large- R jets use the topo-cluster object as inputs. The clustered jets in the reconstruction

Jet Category	Tight Jet Cleaning	p_T	η	JVT/fJVT
Signal Jet	true	$> 20 \text{ GeV}$	< 2.5	JVT >0.5 for $ \eta < 2.4, p_T < 60 \text{ GeV}$ jets
Forward Jet	true	$> 30 \text{ GeV}$	$2.5 < \eta < 4.5$	fJVT <0.5 for $p_T < 120 \text{ GeV}$ jets

Table 4-5: Small- R selection requirements.

algorithm are afterwards "groomed" using the trimming procedure to minimize contamination from pileup and the underlying events^[122]. For the analysis, only large- R jets with $p_T > 250 \text{ GeV}$ and $|\eta| < 2.0$ are considered. The p_T threshold corresponds to the point when two b -jets are separated by $\Delta R = 1$ ¹. Table 4-6 summarize the selection criteria for large- R jets.

Track jets The track jets are reconstructed using the variable radius algorithm with the parameters already discussed in Section 3.3.5. They are used as the inputs for the b -tagging to identify the jets originating from the Higgs decay. They are preferred than the standard $R = 0.4$ jets since it can better separate two b -hadron in high p_T region, and can better suppress pile-up jets by matching the track with primary vertex. The standard tracking quality criteria are applied. The selection criteria are summarized in Table 4-6. Since there is no recommendation for track jets calibration and uncertainties, they are not applied and the flavor tagging uncertainties are expected to cover the effects.

Jet Category	Selection Requirements
Large- R jets	$p_T > 250 \text{ GeV}$ $ \eta < 2.0$
Track jets	$p_T > 10 \text{ GeV}$ $ \eta < 2.5$

Table 4-6: Summary of the large- R jets and VR track jets selections.

Missing Energy Transverse

The missing energy transverse (MET or E_T^{miss}) is used in the 0-lepton and 1-lepton channel as a sign of neutrinos. The E_T^{miss} related variable is also used in the 2-lepton channel for the

¹ The angular distance $\Delta R(i, j)$ between two particles i and j (or objects such as jets) is defined as $\Delta R(i, j) = \sqrt{(\Delta \phi(i, j))^2 + (\Delta \eta(i, j))^2}$ with $\Delta \phi(i, j) = \phi_i - \phi_j$ the azimuthal and $\Delta \eta(i, j) = \eta_i - \eta_j$ the pseudorapidity distances.

suppression of $t\bar{t}$ background. No scale factor is applied to E_T^{miss} , and it is calculated using other objects after applying corresponding SFs.

The variables used in 2-lepton MVA training is named $E_T^{\text{miss}}/\sqrt{S_T}$, defined as:

$$E_T^{\text{miss}}/\sqrt{S_T} = \frac{E_T^{\text{miss}}}{\sqrt{\sum p_T^e + \sum p_T^\mu + \sum p_T^{\text{jets}}}} \quad (4-1)$$

This variable includes the resolution information of E_T^{miss} and the signal process should give a value around zero, thus it can bring improvement for the 2-lepton MVA training.

Aside from the normal E_T^{miss} built from electrons, muons, taus, jets and a track-based soft term, a track-based MET ($E_{T,\text{track}}^{\text{miss}}$) is also used. $E_{T,\text{track}}^{\text{miss}}$ is reconstructed using electrons, muons and tracks based on ID. Since ID only detects charged particles, the $E_{T,\text{track}}^{\text{miss}}$ do not account for the neutral particles.

4.4.3 Vector boson Selection

The leptons (electrons and muons) defined in the Section 4.4.2 are used for the categorization of lepton channels. Events with zero VH-loose leptons are considered for 0-lepton channel. Events with exactly one WH-signal lepton and no additional VH-loose lepton are considered for 1-lepton channel. Events with exactly two VH-loose leptons are considered for 2-lepton channel. Further requirements of each lepton channels are discussed below.

0-lepton channel The vector boson (Z boson) in 0-lepton channel is expected to decay to a pair of neutrinos, which appears as E_T^{miss} in the detector. The transverse momentum of Z boson is thus represented by the E_T^{miss} . In the resolved $VH(\rightarrow b\bar{b})$ and $VH(\rightarrow c\bar{c})$ regimes, the E_T^{miss} is required to be larger than 150 GeV for an efficient reconstruction of Z boson. The E_T^{miss} trigger efficiency is about 90% at 150 GeV, and reaches the plateau at around 200 GeV where the efficiency is near 100%. In the boosted regime, the E_T^{miss} is required to be larger than 200 GeV.

Additional requirements are applied on the scalar sum of jets p_T (S_T). S_T is asked to be larger than 120 GeV in events with 2 jets and 150 GeV for events with 3 or more jets (3- p jets). This requirement is designed to remove the phase space that has the mismodelling issue due to

the non-trivial dependence of trigger efficiency on jet property.

Given that the counting of lepton numbers in lepton channel categorization only consider the electron and muon, there is a special case that the WH process with W decay to $\tau\nu$ and subsequently τ decays hadronically. This kind of events will not have electron or muon and thus have the chance to end up in 0-lepton channel instead of 1-lepton channel. Thus, for events that have hadronic tau reconstructed, they are moved from 0-lepton channel to 1-lepton channel. An additional cut on the transverse mass of reconstructed W boson, asking $m_T^W > 10 \text{ GeV}$ ¹ is applied to these events to mitigate the contamination of fake tau.

1-lepton channel The vector boson (W boson) in 1-lepton channel is expected to decay to one lepton and one neutrino. The transverse momentum of W boson (p_T^W) is thus represented by the sum of lepton p_T and E_T^{miss} . The p_T^V is required to be larger than 75 GeV, for a good trigger efficiency and suppress the multijet background. In the electron channel, E_T^{miss} needs to be larger than 30 GeV to further mitigate multijet background. And for the region of $75 < p_T^V < 150 \text{ GeV}$, the similar cut asking $m_T^W > 20 \text{ GeV}$ is applied to reduce the fake leptons.

One possible background in the 1-lepton channel is $t\bar{t}$, with both top quarks decay to W bosons and b -quarks. One W boson decay to hadronic τ and neutrino. Another W boson decay to e or μ . These events have same signatures as signal process. Thus, a hadronic tau veto is applied in both resolved and boosted regimes to suppress these background.

As mentioned above, the events in muon channel at $p_T^V > 150 \text{ GeV}$ region is triggered by E_T^{miss} trigger. So the same S_T cut is applied for these events.

2-lepton channel The vector boson (Z boson) in 2-lepton channel is expected to decay to a pair of leptons, which means the Z boson can be fully reconstructed from the two VH-loose leptons. The two leptons are required to have same flavor, and at least one of the leptons need to satisfy the ZH-signal requirements listed in Table 4-2 and 4-3. For the di-muon events, the muon are required to have opposite charge. It is not applied to di-electron events since the higher charge mis-identification rate. The invariant mass of di-lepton system needs to be consistent with Z mass: $81 < m(ee/\mu\mu) < 101 \text{ GeV}$ in resolved regimes and $66 < m(ee/\mu\mu) < 116 \text{ GeV}$

¹ m_T^W is defined as $\sqrt{2p_T^l E_T^{\text{miss}}(1 - \cos(\Delta\phi(l, E_T^{\text{miss}})))}$

in boosted regime. Similarly, the p_T^V is required to be larger than 75 GeV to have a good trigger efficiency.

4.4.4 Higgs Candidate Selection

The Higgs candidate is reconstructed from the jets in the events, using two jets in the resolved regime and one large- R jets in the boosted regime. However, in some case there will be additional jets, which could be coming from the radiation of final state particles (FSR), radiation from initial state (ISR), or some other sources. In order to select the two jets that coming from Higgs, and avoid overlap between $VH(\rightarrow b\bar{b})$ and $VH(\rightarrow c\bar{c})$, the following Higgs candidate selection criteria are used.

Resolved Regime

Utilizing the PCFT introduced in Section 4.3.1, the jets are classified into four tags: b -tagged (**B**) jets, Tight- c tagged (C_T) jets, Loose- c tagged (C_L) jets and Not-tagged (**N**) jets. In order to avoid the overlap between $VH(\rightarrow b\bar{b})$ and $VH(\rightarrow c\bar{c})$ regime, only events without any b -tagged jet enter the $VH(\rightarrow c\bar{c})$ regime and events with exactly two b -jets enter $VH(\rightarrow b\bar{b})$ regime. Additional requirement of no C_T jets in $VH(\rightarrow b\bar{b})$ 0-lepton and 1-lepton channel is used for suppression of Top background. For events with either b -jets and C_T jets will be selected into a specific Top control regions, the details will be discussed later.

After the events selection, the second step is to select the two jets used for the reconstruction of Higgs (H_{cand} jets), using the "AllSignalJets" strategy. This strategy consider all the signal jets in the events instead of only considering the leading two jets with highest p_T . For the $VH(\rightarrow b\bar{b})$ regime, since the tagging requirement only allows exactly two b -jets, these two jets will be selected as H_{cand} jets. For the $VH(\rightarrow c\bar{c})$ regime, the jets are firstly prioritized by the tagging: $C_T > C_L > N$. If two or more jets have the same tagging information, they are prioritized by the p_T , the larger p_T ones will have higher priority. After the ranking, the two jets with the highest priority will be selected as H_{cand} jets. For the SRs and High ΔR CRs, the event is required to have at least one H_{cand} jets to be C_T tagged, otherwise it will be used as $V + \text{light}$ CRs with some additional requirements. The details will be discussed in Section 4.5.

For the events with either **B**-jets and **C_T**-jets, they will form the CRs for the control of Top background (TopBC CRs) in the 0-lepton and 1-lepton, which is harmonized between resolved $VH(\rightarrow b\bar{b})$ and $VH(\rightarrow c\bar{c})$. If there are several jets are **B**-tagged (**C_T**-tagged), they are sorted by descending p_T . The **B**-jet and **C_T**-jet will be used for the reconstruction of H_{cand} .

After deciding the H_{cand} jets, the two H_{cand} jets will be re-ranked based on the p_T , the one with higher p_T will be the leading H_{cand} jet. Same p_T ranking will be applied to the non- H_{cand} jets. The leading H_{cand} jet is required to have $p_T > 45$ GeV. Due to the known issue of mis-modelling of gluon splitting in V +jets at low Higgs invariant mass region, the invariant mass of Higgs is required to be larger than 50 GeV ($m_{H_{\text{cand}} \text{ jets}} > 50$ GeV). An upper cut on the ΔR of the two H_{cand} jets at $\Delta R = \pi$ is used to avoid the mismodelling issue of V +jets process observed at high ΔR regions.

Boosted Regime

The H_{cand} in boosted regime is reconstructed from the large- R jets. For events with several large- R jets, the one with highest p_T is selected, and it needs to have at least two ghost-matched track-jets. For the track-jets inside the large- R jets, the three track jets with highest p_T are considered for tagging, and it is required to have at least two of them b -tagged. This strategy is therefore referred to the "*Leading3SignalJets*" strategy. Similar to the resolved regime, the invariant mass of Higgs candidate is required to be larger than 50 GeV.

4.4.5 Multi-jet Suppression Cut

The multi-jet (QCD) background is one of the main background at 0-lepton and 1-lepton channel, and it is hard to estimate with MC generator. In order to suppress the multi-jet background, the following cuts (Also referred as Anti-QCD cuts) are applied.

0-lepton

- $|\Delta\Phi(j_1, j_2)| < 140^\circ$ for the resolved regimes. Here the Φ is the azimuthal angle and j_1, j_2 are the H_{cand} jets
- $|\Delta\Phi(E_T^{\text{miss}}, H_{\text{cand}})| > 120^\circ$

- $\min[|\Delta\Phi(E_T^{\text{miss}}, \text{pre.seljets})|]$ for the resolved region, $> 20^\circ$ in 2-jets region and $> 30^\circ$ in 3-jets regions. For the boosted region, it needs to be larger than 30°

In the $\min[|\Delta\Phi(E_T^{\text{miss}}, \text{pre.seljets})|]$ calculation, only the leading three signal jets are considered for the *pre.seljets*, when no third signal jets are available, a forward jet will be considered. The cut thresholds are defined to result in that the remaining fraction of multi-jet contamination of the total background is at the order of one percent.

1-lepton

- $E_T^{\text{miss}} > 30$ GeV in electron channel for resolved regime and > 50 GeV for boosted regime.

The muon channel has the S_T cut mentioned above that have similar effect.

- $m_T^W > 20$ GeV when the p_T^W is low ($75 < p_T^W < 150$ GeV).

All the selection criteria are summarized in Table 4-7 and 4-8

Analysis regime	resolved $VH(\rightarrow b\bar{b})$	$VH(\rightarrow c\bar{c})$
	Common Selections	
Jets	≥ 2 signal jets	
Candidate jets tagging	2 B -tags	≥ 1 C_T -tags ^a
Leading Higgs candidate jet p_T	> 45 GeV	
Sub-leading Higgs candidate jet p_T	> 20 GeV	
m_{bb} or m_{cc}	> 50 GeV (before correction)	
$\Delta R(\text{jet1, jet2})$	$\Delta R < \pi$	
	0 Lepton	
Trigger	E_T^{miss} triggers	
Jets	≤ 4 jets	≤ 3 jets
Additional jets tagging	no C_T -tag	no B -tag ^b
Leptons	0 VH -loose lepton	
E_T^{miss}	> 150 GeV	
S_T	> 120 (2 jets), > 150 GeV (3p jets)	
m_T^W	> 10 GeV (for events with at least one hadronic τ)	
$ \min \Delta \phi(E_T^{\text{miss}}, \text{jet}) $	$> 20^\circ$ (2 jets), $> 30^\circ$ (3 jets)	
$ \Delta \phi(E_T^{\text{miss}}, H) $	$> 120^\circ$	
$ \Delta \phi(\text{jet1, jet2}) $	$< 140^\circ$	
	1 Lepton	
Trigger	e channel: single electron trigger μ channel: single muon trigger ($p_T^V < 150$ GeV) and E_T^{miss} triggers (above)	
Jets	≤ 3 jets	
Additional jets tagging	no C_T -tag	no B -tag ^b
hadronic τ -veto	no hadronic τ	
Leptons	1 WH -signal lepton	
E_T^{miss}	> 1 VH -loose lepton veto	
p_T^V	> 30 GeV (e channel)	
S_T	> 75 GeV	
m_T^W	> 120 (2 jets), > 150 GeV (3 jets) (μ channel with E_T^{miss} trigger)	
	> 20 GeV ($75 < p_T^V < 150$ GeV only)	
	2 Lepton	
Trigger	e channel: single electron trigger μ channel: single muon trigger ($p_T^V < 250$ GeV) and E_T^{miss} triggers (above)	
Additional jets tagging	-	no B -tag
Leptons	2 VH -loose leptons	
	≥ 1 ZH -signal lepton	
	Same flavour ^c , opposite-charge for $\mu\mu$	
m_{ll}	$81 < m_{ll} < 101$ GeV	
p_T^V	> 75 GeV	

Table 4-7: Event selection in the resolved regime.

^a Except for $V + \text{lights}$ CRs, where exactly one **C_L** jet and no **C_T** jet is required.

^b Except for Top BT CR, where the ≥ 1 **B**-tag jets is required

^c Except for Top $e\mu$ CR, where different flavor is required

Selection	0 lepton channel	1 lepton channel		2 lepton channel	
		e sub-channel	μ sub-channel	e sub-channel	μ sub-channel
Trigger	$E_{\text{T}}^{\text{miss}}$	Single electron	$E_{\text{T}}^{\text{miss}}$	Single electron	$E_{\text{T}}^{\text{miss}}$
Leptons	0 VH- <i>loose</i> lepton	1 WH- <i>signal</i> lepton no second VH- <i>loose</i> lepton no hadronic τ		≥ 1 ZH- <i>signal</i> lepton 2 VH- <i>loose</i> leptons	
$E_{\text{T}}^{\text{miss}}$	> 250 GeV	> 50 GeV	-	-	
p_{T}^{V}	$p_{\text{T}}^{\text{V}} > 400$ GeV				
Large-R jet	at least one large- R jet, $p_{\text{T}} > 250$ GeV, $ \eta < 2$				
Track-Jets	at least two track-jets, $p_{\text{T}} > 10$ GeV, $ \eta < 2.5$, matched to the leading large- R jet				
b -jets	exactly two of the leading three track-jets matched to the leading large- R must be b -tagged				
m_J	> 50 GeV				
$\min \Delta \phi(E_{\text{T}}^{\text{miss}}, \text{jets})$	$> 30^\circ$	-			
$\Delta \phi(E_{\text{T}}^{\text{miss}}, H_{\text{cand}})$	$> 120^\circ$	-			
$m_{\ell\ell}$	-			$66 \text{ GeV} < m_{\ell\ell} < 116 \text{ GeV}$	
lepton flavor	-			two lepton same flavour	
lepton charge	-			opposite sign muons	

Table 4-8: Event Selection for the three channels of the boosted $VH(\rightarrow b\bar{b})$ analysis.

4.5 Event Categorization

In order to maximize the sensitivity of the signal and have a better control of backgrounds, the events are further categorized into different regions. The Signal Regions (SR), which is populated with signal events, are mainly used for the measurements of signal process. The Control Regions (CR) that is populated with background events are mostly used for the control of background process. In this study, the following categorization strategies are used.

4.5.1 Resolved $VH(\rightarrow b\bar{b}, c\bar{c})$

The events in the resolved regime are split by number of selected jets and p_T^V , regardless in signal regions or control regions. The number of jets counts the total number of signal jets and forward jets of the event. The events containing two jets comprise the 2-jets category, three (four) jets the 3- (4-)jets category, three (four) or more jets 3p- (4p-) jets category. In $VH(\rightarrow c\bar{c})$, 0-lepton and 1-lepton channels contain 2-and 3-jets category and reject events with four or more jets due to the high $t\bar{t}$ background contamination, while 2-lepton channel include 2-and 3p-category. In the resolved $VH(\rightarrow b\bar{b})$ regime, 0-lepton includes the 2-, 3-and 4-jets categories, 1-lepton includes the 2-and 3-jets category and 2-lepton includes 2-, 3-and 4p-jets categories. The 4 and

4p-jets regions are included in 0-lepton and 2-lepton to improve the sensitivity in the STXS bins with additional jets. For the 1-lepton channel, the 4p-jets regions overlap the region used for the c -jets calibration of PCFT and has very limited sensitivity due to the large $t\bar{t}$ background, therefore it is not used for the analysis.

As mentioned in Section 4.4.2, the signal jets used in the analysis is required to have p_T larger than 20 GeV. However, some jets are not originated from the hard process, but come from soft emission like FSR, especially for the jets that have relative low p_T . These jets will result in the migration of between STXS bins. In order to mitigate the migration, the p_T threshold of the signal jets except the two H_{cand} jets are raised to 30 GeV. This raised p_T cut only applies to the calculation of number of jets, the jets with p_T within 20 to 30 GeV are still used for the various correction of the H_{cand} mass.

For the p_T^V split, as already discussed, the resolved and boosted $VH(\rightarrow b\bar{b})$ is split by a cut at $p_T^V = 400$ GeV. In the resolved $VH(\rightarrow b\bar{b})$ regime, the 0-lepton is split to $150 < p_T^V < 250$ GeV and $250 < p_T^V < 400$ GeV regions. The 1-lepton and 2-lepton are split to $75 < p_T^V < 150$ GeV, $150 < p_T^V < 250$ GeV and $250 < p_T^V < 400$ GeV. For the $VH(\rightarrow c\bar{c})$, the p_T^V split is similar, with the only difference that the upper threshold at 400GeV is removed. The highest p_T^V bin in $VH(\rightarrow c\bar{c})$ is $p_T^V > 250$ GeV.

Signal Regions Categorization

The resolved $VH(\rightarrow b\bar{b})$ signal regions require exact two **B**-jets, no further split are used. The $VH(\rightarrow c\bar{c})$ signal regions, it is further split to two categories, according to the number of c -tagged jets in the two H_{cand} jets: 2 c -tagged regions, which contains events with two $\mathbf{C_T}$ -jets ($\mathbf{C_T C_T}$ events) or one $\mathbf{C_T}$ -jet and one $\mathbf{C_L}$ -jet ($\mathbf{C_T C_L}$ events); 1 c -tagged regions, which comprises events with one $\mathbf{C_T}$ -jet and one **N**-jet ($\mathbf{C_T N}$ events). The signal region events also need to fail the following ΔR cuts that define the ΔR control regions discussed below.

Control Regions Categorization

Since the MC modelling is not perfect, there will be some discrepancy between the MC and the real data for the background process. The control regions (CRs) are then defined and used for a

better control of the background process. The control regions are usually dominant by the kind of background that needs to be modelled and have almost no signal. All CRs are constructed after the event selection described in Section 4.4.

High ΔR CRs The High ΔR CRs are designed to control the $V + \text{light}$ and $t\bar{t}$ process. The cut is applied on the ΔR between the H_{cand} jets and is dependent on the p_T^V . Larger p_T^V indicates a larger Lorentz boost of the Higgs decay products and thus smaller ΔR of the two jets for the signal process. In the meantime, the jets coming from the $V + \text{light}$ and $t\bar{t}$ process do not have such kinematic relationship. The distributions of signal fraction over the total MC events are shown in Figure 4-10. The cut is defined such that a certain percentage of signal events ends up in the regions below the cuts (95% for the 2-jets category, 85% for 3 or more jets category). The numerical function of the cuts are listed in Table 4-9. The High ΔR CRs in 0-lepton and 1-lepton channel are enriched with Top(bb) process. They are usually fit in a norm-only distribution only with one exception. The High ΔR CRs in $VH(\rightarrow b\bar{b})$ 1-lepton channel are fitted in binned p_T^V distribution to mitigate the mismodelling of $t\bar{t}$ sample.

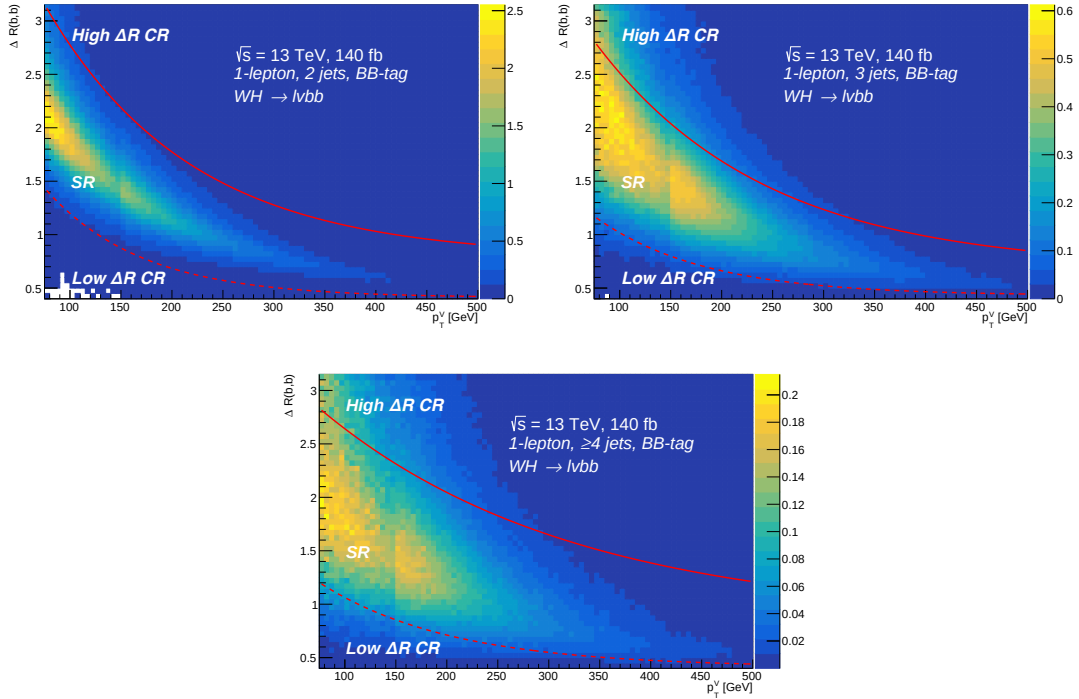


Figure 4-10: Signal distribution of ΔR between the two selected jets as function of p_T^V in the $VH(\rightarrow b\bar{b})$ 1-lepton channel are shown in the 2-tag 2-jet (a), 2-tag 3-jet (b) and 2-tag 4p-jet (c) categories. The solid and dashed lines demonstrate the upper and lower continuous cuts used to categorize the events into the signal and control regions.

Category	Cut
2 - jet	$\Delta R > 0.787 + e^{1.387-0.007 \times p_T^V}$
3 - jet	$\Delta R > 0.684 + e^{1.204-0.006 \times p_T^V}$
4 - jet	$\Delta R > 0.8627 + e^{0.9837-0.004077 \times p_T^V}$
5p - jet	$\Delta R > 1.667 + e^{0.5189-0.005038 \times p_T^V}$

Table 4-9: Cuts defining the high ΔR control region. Events in this region are removed from the signal region.

Low ΔR CRs The low ΔR CRs are only used in the $VH(\rightarrow b\bar{b})$ 1-lepton channel. This region is designed to help control the $W + hf$ process. The cut is defined such that 90% of diboson signals can stay in the signal regions. The numerical cuts are shown in Table 4-10. In the 0-lepton and 2-lepton, the impact of this region is found to be small and thus merged with the signal regions.

Category	Cut
2 - jet	$\Delta R < 0.41 + e^{0.818-0.01056 \times p_T^V}$
3 - jet	$\Delta R < 0.43 + e^{0.399-0.00931 \times p_T^V}$
4 - jet	$\Delta R < 0.4106 + e^{1.204-0.006 \times p_T^V}$
5p - jet	$\Delta R < 0.5009 + e^{1.192-0.00753 \times p_T^V}$

Table 4-10: Cuts defining the low ΔR control region which is used in $VH(\rightarrow b\bar{b})$ 1-lepton category. Events in this region are removed from the signal region, such that the two regions are fully orthogonal.

Top CRs In 0-lepton and 1-lepton channels, besides from the Top(bb) component that is controlled by the High ΔR CRs, the Top(bc) and Top(bl) component are controlled by the TopBC CRs. The TopBC CRs are selected to have at least one **B**-jet and at least one **C_T**-jet. Given the tagging requirement, the TopCR are completely orthogonal with the SRs and other CRs. The TopCRs are shared between the $VH(\rightarrow b\bar{b})$ and $VH(\rightarrow c\bar{c})$ regime.

In the 2-lepton channel, the $t\bar{t}$ background is mainly coming from di-leptonic $t\bar{t}$ events. The TopCR can be selected by requiring a different lepton flavor (one is electron and another one is muon). This requirement will eliminate most of the signal and $Z + jets$ process. The Top $e\mu$ CRs in the $VH(\rightarrow b\bar{b})$ 2-lepton channel are not used as separate regions in the fit but used to derive the $t\bar{t}$ template for the SRs. This data-driven method is not used in the $VH(\rightarrow c\bar{c})$ due to the low statistics and $t\bar{t}$ is a tiny background in $VH(\rightarrow c\bar{c})$. As a result, the Top $e\mu$ CRs are

used as separate CRs in $VH(\rightarrow c\bar{c})$ 2-lepton channel, being comprised with events with at least one C_T -jet and merged into one category. The p_T^V and jet multiplicity split is same as the SRs.

C_L N CRs The C_L N CRs consist of events with one of the H_{cand} jets being a C_L -jet and one being the N-jet (C_L N events). By this tagging requirement, the C_L N CRs are enriched with $V + mf$ and $V + lf$ events and can be used to control the normalization and shape of these backgrounds. It is considered for all three lepton channels. For 1-lepton channel, it is composed of 60% of $W + lf$ component. For 2-lepton channel, it has more than 70% of $Z + lf$ component.

Table 4-11 summarizes the event categorization in the resolved $VH(\rightarrow b\bar{b})$ and $VH(\rightarrow c\bar{c})$ regimes and Figure 4-11 shows an overview of the regions used in the analysis.

Analysis regime	resolved $VH(\rightarrow b\bar{b})$	$VH(\rightarrow c\bar{c})$
	Common Selections	
nJet categorisation	Non Higgs candidate jet $p_T > 30$ GeV	
High $\Delta R(\text{jet1, jet2})$ CR	Continuous $\Delta R - p_T^V$ cut (with cut values depending on p_T^V) separating SR/High ΔR CR, defined as Table 4-9	
	0 Lepton	
p_T^V regions	[150, 250], [250, 400] GeV	[150, 250], >250 GeV
Top(BC) CR	≥ 1 B-Tag, ≥ 1 C_T -Tag	
	1 Lepton	
p_T^V regions	[75,150], [150, 250], [250, 400] GeV	[75,150], [150, 250], >250 GeV
Low $\Delta R(\text{jet1, jet2})$ CR	Continuous ΔR cut (with cut values depending on p_T^V) separating SR/Low ΔR CR, defined as Table 4-10	-
Top(BC) CR	≥ 1 B-Tag, ≥ 1 C_T -Tag	
$V + \text{lights}$ CR	-	no B- and C_T -Tag, exactly 1 L-tag
	2 Lepton	
p_T^V regions	[75,150], [150, 250], [250, 400] GeV	[75,150], [150, 250], >250 GeV
Top $e\mu$ CR	Different flavor leptons ($e\mu$ or μe)	
$V + \text{lights}$ CR	-	no B- and C_T -Tag, exactly 1 L-tag

Table 4-11: Summary of the event categorization in the resolved $VH(\rightarrow b\bar{b})$ and $VH(\rightarrow c\bar{c})$ 0-, 1- and 2-lepton analyses.

4.5.2 Boosted $VH(\rightarrow b\bar{b})$

The events in the boosted regime are categorized into two p_T^V regions, $400 < p_T^V < 600$ GeV and $p_T^V > 600$ GeV.

Signal Regions

To reject the top background, the events in signal regions are required to have no additional b -tagged track jet outside the H_{cand} jet. Previously, the 0-lepton and 1-lepton channel SRs are

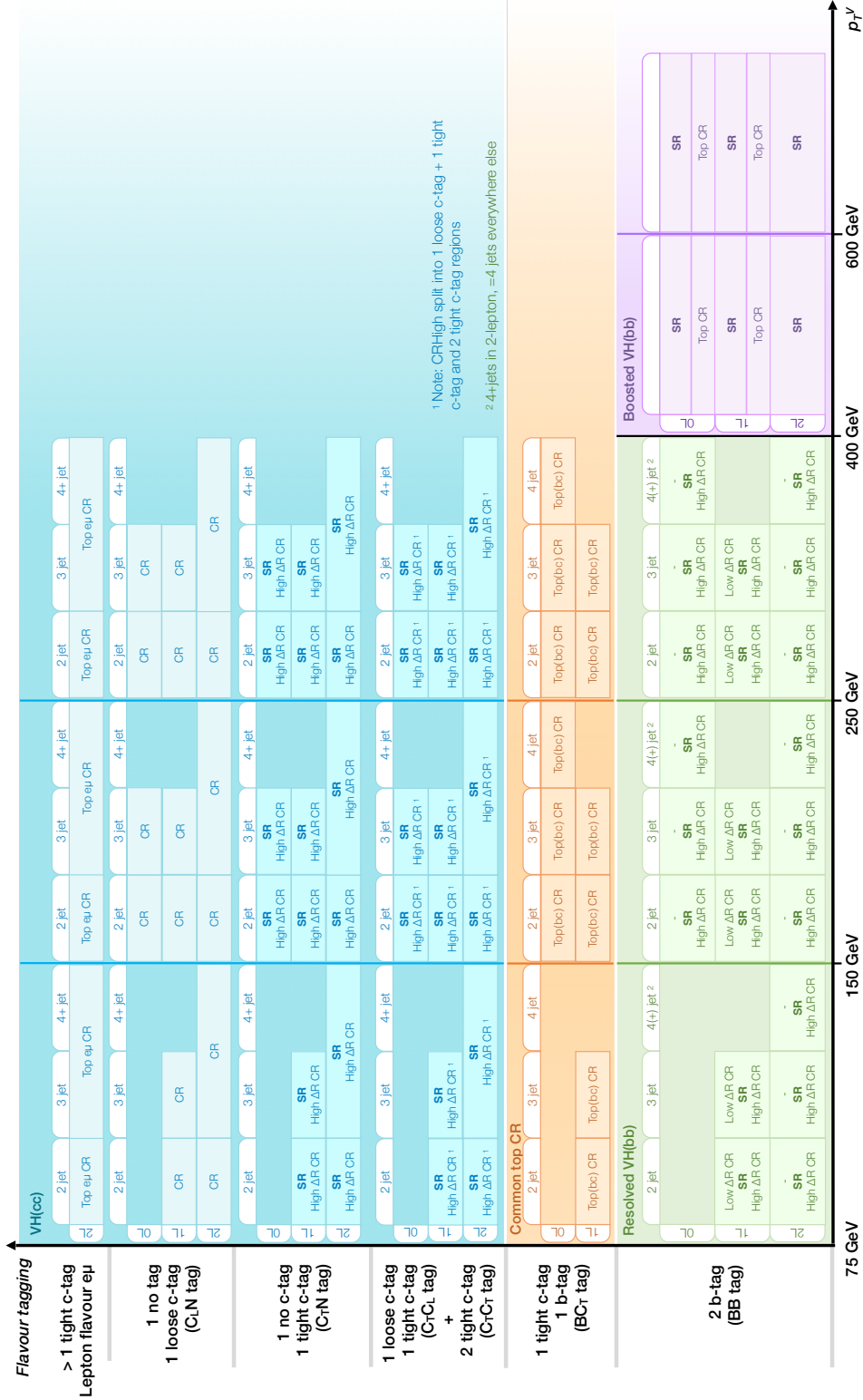


Figure 4-11: Schematic view of all the signal and control regions used in the analysis. The green regions are used in the $VH(\rightarrow b\bar{b})$ category, the blue regions are used in the $VH(\rightarrow c\bar{c})$ category, and the orange regions are used in the Top CRs, as defined in the text.

further split into high purity (HP) and low purity (LP) regions depending on the small- R jets outside the H_{cand} jet. Since this variable is already used in the MVA and the split will bring large acceptance uncertainties, it is not split anymore in this analysis.

Control Regions

The $t\bar{t}$ process is the main background in 0-lepton and 1-lepton channel. As shown in Figure 4-12, the decay product of hadronic decay top quark can be reconstructed as a large- R jet and one stand alone b -jet present outside the large- R jet. The Top CR is thus defined requiring at least one b -tagged track jet outside the H_{cand} jet.

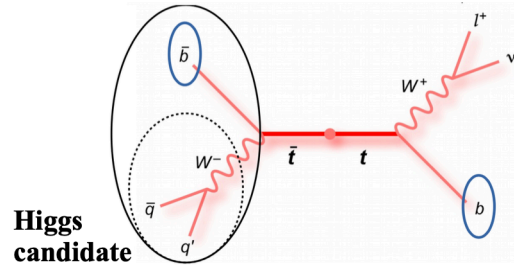


Figure 4-12: $t\bar{t}$ event in which the decay products of one top quark, with a hadronic-decay W , are reconstructed in a large- R jet (left) and an additional b -tagged track-jet is produced in the other top-quark decay.

The signal regions and control regions are also summarized in Figure 4-11. Figure 4-13 shows the background composition in some selected SRs and CRs.

4.5.3 Truth Tagging

The event categorization of tagging regions is heavily based on the flavor tagging results of the H_{cand} jets. And there are several strategies to decide which tagging region that the event are categorized into. The most commonly used tagging strategy is named Direct Tagging. It is a cut-based method, when the jet's flavor tagging score pass the WP cut of the PCFT bin, it will be labelled as the tagged jet of the PCFT bin. In this analysis, the c-tagging has limited tagging efficiency, making a lot of c-jets ends up in the **N** bin. However, the event selection criteria require at least one c-tagged jet, which means that a lot of MC events will be discarded. This will result in the problem that do not have an adequate number of MC events in some phase space, leading to a large MC statistical uncertainty.

In order to solve the problem, different tagging strategies are used, Truth Tagging and its extension Hybrid Tagging. The details will be discussed in the following.

The alternative tagging strategy is named Truth Tagging. It uses all the MC events, and weigh them based on the probability of each event being selected into the required tagging region, using the tagging information of the jets. The weight is calculated with the equation:

$$w = \sum_i^C \epsilon(T_i, \mathbf{x}, \theta) \cdot \epsilon(\mathcal{T}_i, \mathbf{x}, \theta) \quad (4-2)$$

where,

$$\epsilon(T_i, \mathbf{x}, \theta) = \prod_{j \in T_i} \epsilon_j(\mathbf{x}|\theta) \quad (4-3)$$

$$\epsilon(\mathcal{T}_i, \mathbf{x}, \theta) = \prod_{j \in \mathcal{T}_i} (1 - \epsilon_j(\mathbf{x}|\theta)) \quad (4-4)$$

where $\epsilon_j(\mathbf{x}|\theta)$ is the tagging efficiency of jet j parameterized with a set of variables θ . The set of tagged jets is labelled as T_i , while the set of not-tagged jets is labelled as $\mathcal{T}_i$.

One of the key process in Truth Tagging is the calculation of $\epsilon_j(\mathbf{x}|\theta)$. The traditional and straightforward way of doing this is the map based approach. It parameterizes the tagging efficiency in a 2D histogram, with the two most dominant parameters contributing to the trigger efficiency: jet p_T and the pseudo-rapidity of the jet (η). The 2D histogram is referred as an efficiency map. Due to the different jet topologies, the efficiency maps need to be derived for b -, c -, $light$ - and τ -jets separately. This approach is used in the previous $VH(\rightarrow b\bar{b})$ and $VH(\rightarrow c\bar{c})$

analysis, which improves the MC statistics in the analysis regions. However, it is found that there is some non-closure between the direct tagging and map-based truth tagging, and thus additional uncertainties are introduced to fix it. It is understandable since the tagging efficiency is not solely depend on the two parameters, p_T and η . But creating a multi-dimensional map is not possible due to the limitation of statistics, the events in each dimension will not be adequate to get the correct efficiency map.

Neural networks in the other hand are perfect tools to handle the high dimensionality problems. The Graph Neural Network (GNN) is used in this analysis. GNN can take in information between nodes and be flexible in the number of input nodes. The input to the network is a fully connected graph, with each node in the graph represented by a jet. The node features are the parameters of the jets and events. The details of the network can be found in Ref^[123].

Different GNN models are trained independently for samples with different MC generators. For the resolved regime, the models are trained exclusively for different background process. Table 4-12 lists all the GNN models trained in the analysis.

	Resolved regime model	Boosted regime model
$t\bar{t}$	pythia $t\bar{t}$	pythia
single-top	pythia single-top	
signal	pythia signal	
SHERPA 2.2.11 W+jets SHERPA 2.2.11 Z+jets	SHERPA 2.2.11 V+jets	SHERPA 2.2.11
SHERPA 2.2.11 di-boson	SHERPA 2.2.11 di-boson	

Table 4-12: The different GNN models used for truth tagging nominal samples. The models are trained inclusively in all 3 lepton channels.

Performance of Truth Tagging

In the region with adequate statistics, if the efficiency map is accurate, the distribution of truth tagging should be consistent with the distribution of direct tagging. Hence, the performance of truth tagging is evaluated based on this comparison. Figure 4-14 shows some examples of the comparison between direct tagging, map-based truth tagging and GNN truth tagging for the V+jets process in $VH(\rightarrow c\bar{c})$ SRs.

The GNN truth tagged distributions have shapes very close to the direct tagged distributions. For the regions that have limited MC events for direct tagging, the GNN truth tagged distribution

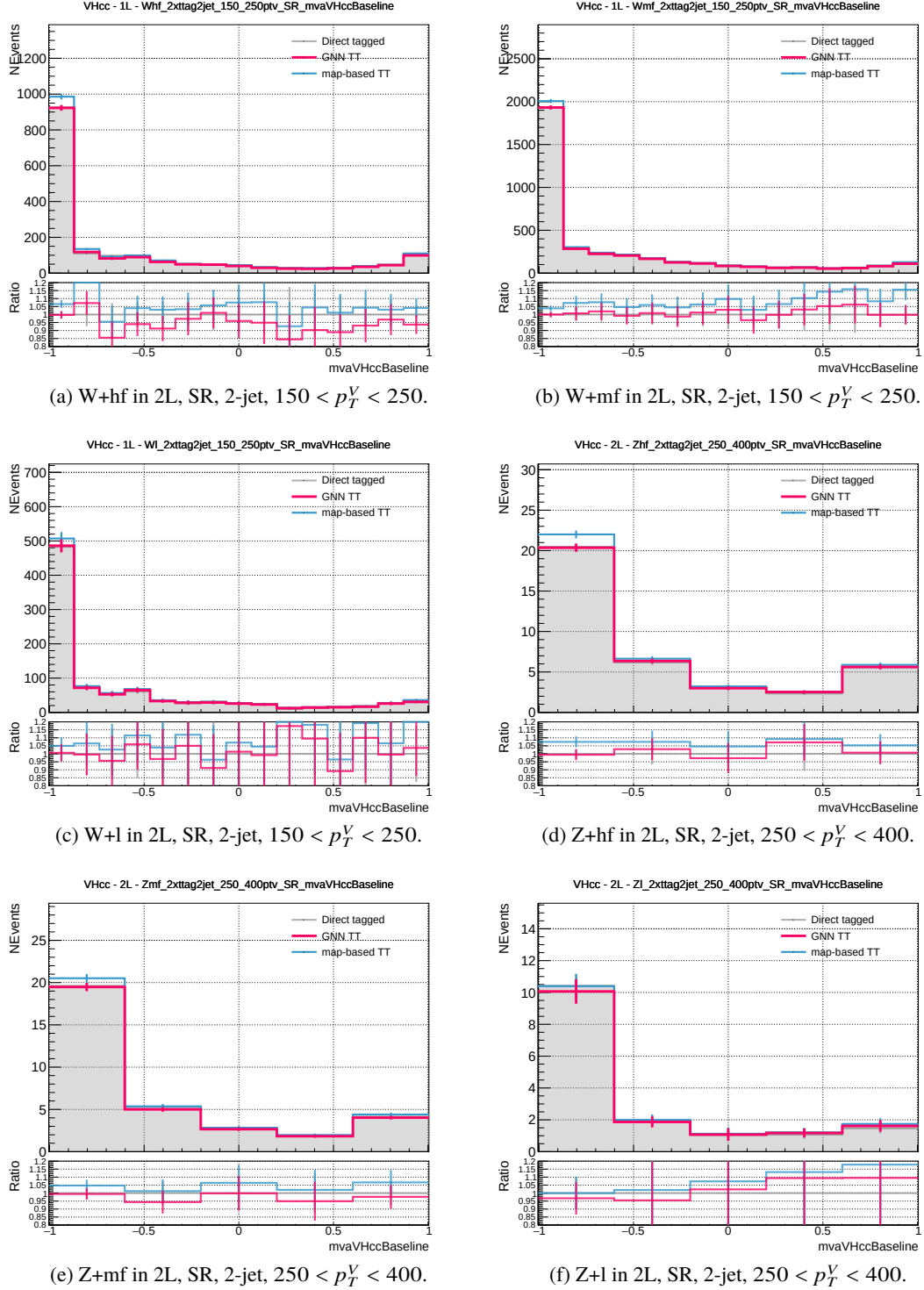


Figure 4-14: The direct tagged, GNN truth tagged and map-based truth tagged mva distributions for SHERPA 2.2.11 V +jets in the $VH(\rightarrow c\bar{c})$ 1-lepton and 2-lepton channel. The first row shows the plots from $150 < p_T^V < 250$ GeV region, and the second row shows $250 < p_T^V < 400$ GeV region.

has a more smooth shape. Other models described in Table 4-12 give a similar performance, in both $VH(\rightarrow b\bar{b})$ and $VH(\rightarrow c\bar{c})$ regimes.

Partial Truth Tagging

In the $VH(\rightarrow c\bar{c})$ regime, the $C_T C_T$ suffers from not having enough MC events due to the low efficiency of tagging. The truth tagging is thus applied to this region to help solve the issue. However, if it is decided to truth tag the $C_T C_T$ region, all the events, no matter what direct tagged regions they will fall into, will be used to fill in this region with the calculated weight. As a result, it is possible that one event entered truth tagged region and the direct tagged region at the same time if $C_T C_T$ region is truth tagged and other regions (e.g. $C_T N$ and $C_T C_L$ regions) are direct tagged. To avoid the overlap that would bring difficulty of systematic treatment, the partial truth tagging that truth tag a specific percent of samples and let the rest of samples being direct tagged. Several numbers of percentage are tested, and relation between the MC statistic errors of several tagging categories and this percentage are shown in Figure 4-15. It is decided to use 8% of all the samples for truth tagging since it can significantly improve the MC Statistics in the two tight-c tagged region (labelled as TT in the figure), which are the most sensitive ones in the $VH(\rightarrow c\bar{c})$ analysis and do not cause large degradation of the MC statistics in other regions.

Hybrid Tagging

Though the GNN Truth Tagging provide a much better performance than the map-based truth tagging, there will still have some potential non-closure, which can be caused by the missing of some variables that impact the tagging efficiencies or the performance of GNN being not perfect. Since the direct tagging efficiency for the b -jet is 70%, the benefits from truth tagging in resolved $VH(\rightarrow b\bar{b})$ regime is limited. To avoid the potential non-closure, the *Hybrid Tagging* is used for some background MC samples (V +jets and single-top s -channel and t -channel) that do not have good performance with truth tagging, which direct tag the b -jet and truth tag the other flavors. This method is also used in previous $VH(\rightarrow b\bar{b})$ analysis, where the truth tagging is done with the map-based approach. In this analysis, the GNN truth tagging method is used.

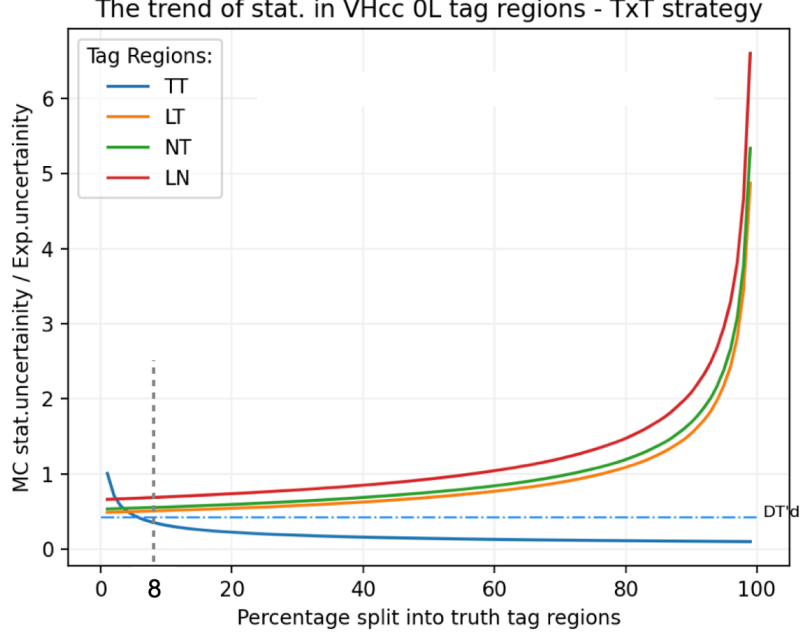


Figure 4-15: The MC Statistic uncertainties of different tagged regions with the varying percentage of events used for 2 tight-c tagged (labelled as TT) regions in $VH(\rightarrow c\bar{c})$.

Truth Tagging Strategy

Considering the size of the MC samples, tagging efficiencies, analysis regions and the performance of the closure for GNN truth tagging, the following tagging strategy is used in the analysis:

- Resolved $VH(\rightarrow b\bar{b})$ regime: The GNN based hybrid tagging is applied to V +jets and single-top s/t channels. The remaining samples are direct tagged since they have enough MC events.
- Boosted $VH(\rightarrow b\bar{b})$ regime: Due to the low MC statistics, the GNN truth tagging is used for all samples except for signal and diboson. The signal and diboson samples are direct tagged to avoid any potential non-closure.
- $VH(\rightarrow c\bar{c})$ regime: The partial truth tagging is applied to V +jets and singlet-top s/t channels. 8% of these MC samples are used for truth tagged into the $C_T C_T$ regions. The remaining 92% of events are direct tagged. The other samples, $t\bar{t}$, single-top Wt channel, diboson and signal, are direct tagged.

The strategy is summarized in Table 4-13. No significant non-closure between the direct tagging strategy and other tagging strategy is found in all distributions.

	VHbb resolved	VHbb boosted	VHcc
Hybrid tagging	Yes (b-jets are DT'd)	No (fully TT'd)	No (fully TT'd)
Truth tag WP	70% b & 70% b	85% b & 85% b	c-tight & c-tight
MC stat. % for TT regions	100%	100%	8%
V+jets	hybrid tagged	truth tagged	truth tagged
single-top s/t	hybrid tagged	truth tagged	truth tagged
single-top Wt	direct tagged	truth tagged	direct tagged
$t\bar{t}$	direct tagged	truth tagged	direct tagged
diboson	direct tagged	truth tagged	direct tagged
signal	direct tagged	direct tagged	direct tagged

Table 4-13: The different strategies used for truth tagging. The abbreviations DT and TT used above stand for direct tag and truth tag respectively. WP stands for working point.

4.6 Higgs Candidate Jet Corrections

The invariant mass of H_{cand} is one of the key variables that can distinguish signal from the background, with signal has the H_{cand} mass around 125 GeV, while the background does not. It is reconstructed from the invariant mass of two H_{cand} jets, so improving the energy of the H_{cand} jets is crucial to the analysis. In total of four kinds of corrections are applied: muon-in-jet, PtReco, Kinematic Fit and FSR recovery. For the signal jets used in these corrections, the p_T is required to be larger than 20 GeV. Table 4-14 shows the corrections used in different regions, the details of each correction are shown in the following.

Scheme	lepton channel	muon-in-jet	PtReco	kinematic fit	FSR recovery
Resolved $VH(\rightarrow b\bar{b})$	0-lepton	✓	✓		
	1-lepton	✓	✓		
	2-lepton	✓	✓ (nJet ≥ 4)	✓ (nJet ≤ 3)	✓ (nJet ≤ 4)
$VH(\rightarrow c\bar{c})$	0-lepton	✓			
	1-lepton	✓			
	2-lepton	✓		✓ (nJet ≤ 3)	✓ (nJet ≤ 4)
boosted $VH(\rightarrow b\bar{b})$	0-lepton	✓			
	1-lepton	✓			
	2-lepton	✓		✓	

Table 4-14: H_{cand} energy correction used in different analysis regions. The number of jets here count the signal jets with p_T larger than 20 GeV and forward jets with p_T larger than 40 GeV.

4.6.1 Muon-in-jet Correction

The decay of b/c quarks will sometimes produce muon, which will leave a track in the MS and reconstructed as a separate muon. Since the muon will not leave much energy deposit in the calorimeter, the measured energy of the quarks will be smaller. Muon-in-jet correction is used to recover this kind of muon. If a muon is found to be in the cone of the reconstructed jet, $\Delta R(jet, \mu) < \min(0.4, 0.04 + 10[\text{GeV}]/p_T^\mu)$, the muon will be added into the jet. It's energy deposit in the calorimeter will be subtracted to avoid double counting of the energy. In the boosted regime, the tagged track jet inside the H_{cand} large- R jet is used to compute the ΔR between the jet and muon. If the muon is found to be inside one of the track jets, it will be added into the large- R jet. In case several muons are found inside the jet, only the one closest to the jet will be added. The muon added into the jet will no longer be considered as a lepton in the event, i.e. will not be counted for the number of leptons. The muon-in-jet correction is applied to all the events as it is a common feature for both b - and c -jet decay. The correction is sometimes also called "OneMu" correction.

4.6.2 PtReco Correction

The b -jets have unique features such as secondary vertex, which can cause the out-of-cone effect, i.e. some energies are not included in the jet cone, especially for the b -jet with lower energy. In the $VH(\rightarrow b\bar{b})$ regime, a p_T dependent correction, PtReco, is applied to all the b -jet to recover the energy out of the cone. The correction factor is derived using the jets after muon-in-jet correction (OneMu) and the truth jets which include truth muon and neutrinos (TruthWZ). The p_T of the jets is divided into several slices, the mean value of the ratio between OneMu p_T and TruthWZ p_T distribution is used as the correction factor. The b -jet with muon and without muon are considered separately since the semi-leptonic decay will produce neutrinos together with muon. The correction factor is derived from nominal sample and applied to all systematic variations.

The c -jet has a similar structure, but since the lifetime of c -quark is much shorter, the out-of-cone effect is much smaller. As a result, the correction is not applied to the $VH(\rightarrow c\bar{c})$ regime.

4.6.3 Kinematic Fit

The kinematic fit (KF) is applied to the resolved $VH(\rightarrow b\bar{b}, c\bar{c})$ 2-lepton channels. In the 2-lepton channel, the Z boson decay to two leptons, and leptons are very well measured in ATLAS. The typical resolution of electron and muon p_T is in the level of 1% while the resolution for jet is 10% level. As a result, by using the balance of energy at transverse plane, the resolution of jets can be improved with the help from the leptons. This can be achieved by maximizing an event-level likelihood built from the signal topology. The likelihood function is defined as following:

$$-2\ln\mathcal{L} = \sum_i \frac{(p_T^i - p_T^{i,fit})^2}{\sigma_i^2} - \sum_j 2\ln\mathcal{L}(p_T^j, p_T^{j,fit}) + \frac{(\sum_n p_x^n)}{\sigma_{bal}^2} + \frac{(\sum_n p_y^n)}{\sigma_{bal}^2} + 2\ln[(m_{ll}^2 - m_Z^2)^2 + m_Z^2 \Gamma_Z^2] \quad (4-5)$$

The first term is the resolution term for the final state objects, including electron, muon, jets excluding the b/c -tagged jets and E_T^{miss} soft term. The energy response of these terms are treated as Gaussian distribution. The E_T^{miss} soft term is included to take account of the ISR in $ggZH$. The ISR will usually produce a soft jet which leave track in the ID but almost no energy deposit in the calorimeter and thus not reconstructed as an object. As mentioned in Section 3.3.7, the resolution of soft E_T^{miss} is estimated to be 10 GeV. The resolutions of other terms are set to the recommendation of ATLAS.

The second term is the resolution term of the b/c -tagged jets. Instead of using the Gaussian distribution, a transfer function is derived. The transfer function is a probability density function of the ratio between the reconstructed jet p_T after the OneMu correction and the truth jet p_T including the muon and neutrinos (TruthWZ). The definition is same as the correction factor used in PtReco Correction, but instead of using a fixed factor, the transfer function here consider the probability distribution. As a result, the events that have kinematic fit should not be corrected again using PtReco. The details of deriving the transfer function will be discussed later. It is only available for the small- R jets. For the large- R jets, it is treated as a Gaussian distribution.

The third and fourth terms are the p_T balance constraint term at the x and y direction. They are also treated as Gaussian distribution. The resolution is estimated from the signal MC events, 12 GeV for the 2-jets events and 15 GeV for the 3-jets events. The fifth term is the Z mass

constraint term. It is expected to follow the Breit-Wigner distribution.

The Kinematic Fit is applied to the 2-jets and 3-jets events in $VH(\rightarrow b\bar{b})$ and $VH(\rightarrow c\bar{c})$ 2-lepton channels. The events with four or more jets are found to have no improvement with Kinematic Fit and thus the PtReco correction is applied (only in resolved $VH(\rightarrow b\bar{b})$). For other lepton channels, as the resolution of E_T^{miss} is not as good as leptons, they can hardly benefit from the Kinematic Fit and thus the correction is not applied.

Transfer function Derivation

The derivation of transfer function is separated for b -jets and c -jets due to the different topology and detector response for the two kind of jets. For b -jet, the $ZH \rightarrow llbb$ samples are used, where the b -jet are the PFlow jet with 70% DL1r b -tagging WP. The transfer function is further divided to different p_T bins: [20,30], [30,40], [40,50], [50,60], [60,70], [70,80], [80,100], >100 GeV, η larger or smaller than 1.2 and with or without muon. The transfer function of b -jets is inherited from the previous analysis since the tagging WP is identical with the previous analysis.

For the c -jet, the kinematic fit is not used in the previous $VH(\rightarrow c\bar{c})$ analysis due to the known issue that it brings mismodelling of the background distribution. In this analysis, the jet collection is updated from EMTopo to PFlow, the new PCFT tagger is used, and the MVA distribution is used as the fit discriminant, the kinematic fit for the $VH(\rightarrow c\bar{c})$ is introduced. The derivation of c -jet transfer function is similar to the b -jet. However, there are several tagging bins are considered in $VH(\rightarrow c\bar{c})$, including C_T , C_L and N . It is found that the C_T , C_L and N jets have similar transfer function. Given the low statistics of C_T and C_L jets due to the low tagging efficiency, they are combined with N for the derivation of transfer function. For the derivation of transfer function, the H_{cand} jets of the C_T $C_T + C_T C_L + C_T N$ 2 and 3 jets events are used. The $p_T > 45$ GeV cut on the leading H_{cand} jet is removed to get more events for the fit.

After selecting the jets, the ratio between the reconstructed p_T after OneMu correction and the truth jet p_T is filled into the histogram. The bin size of the histogram is 0.1. Then a Bukin (NovosibirskA) function, which is a Gaussian-like asymmetry distribution with two sides of tails adjustable, is used to fit the histogram and get the transfer function. Figure 4-16 shows the distribution and the postfit transfer function in different split of $p_T < 30$ GeV jets, the results

of jets in other p_T bins are shown in the Appendix 6. It can be found that the jets with muon has the ratio smaller than one, which is due to the energy loss of neutrino that produce together with the muon.

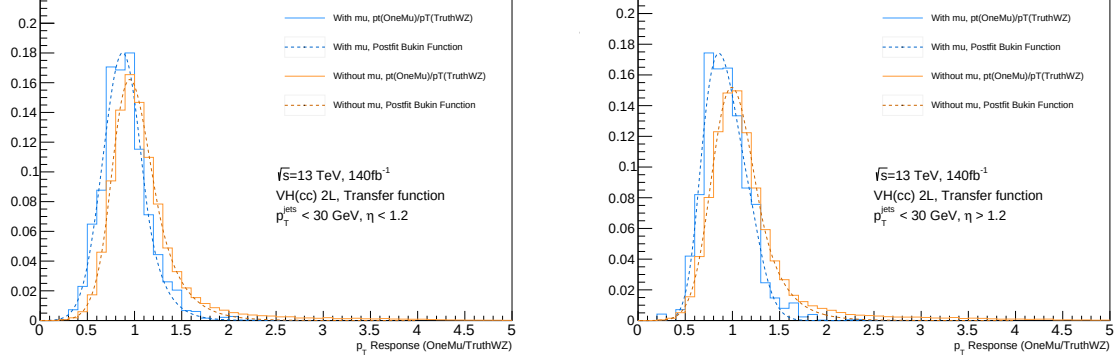


Figure 4-16: The distribution of $p_T(OneMu)/p_T(TruthWZ)$ (solid) and fitted transfer function (dashed) of C_T , C_L and N $p_T < 30$ GeV jets in $VH(\rightarrow c\bar{c})$ 2-lepton 2+3 jets events. Blue indicates the jets has a muon in its decay and orange indicates the jets without the muon. The jets are required to have $\eta < 1.2$ (left) or $\eta > 1.2$ (right).

In this analysis, the kinematic fit is found to have very small impact on the background and significantly improve the signal H_{cand} invariant mass resolution. The distribution after all the corrections can be found in Appendix 6.

4.6.4 FSR Recovery

In the event with three or more jets, the non-Higgs candidate jets have the possibility of coming from:

- Gluon radiation from the H_{cand} jets, known as the Final State Radiation (FSR).
- Gluon or quark radiation from initial incoming partons, known as Initial State Radiation (ISR).
- Other radiation from pile-up

Figure 4-17 shows an example event with one FSR jet and one ISR jet.

FSR will cause a loss of the invariant mass of reconstructed Higgs, since the Higgs is reconstructed from the two tagged jets. As a result, in the case of events that have FSR jet, the invariant mass of two H_{cand} jets and the FSR jet (m_{bbj}/m_{ccj}) should be the Higgs invariant mass.

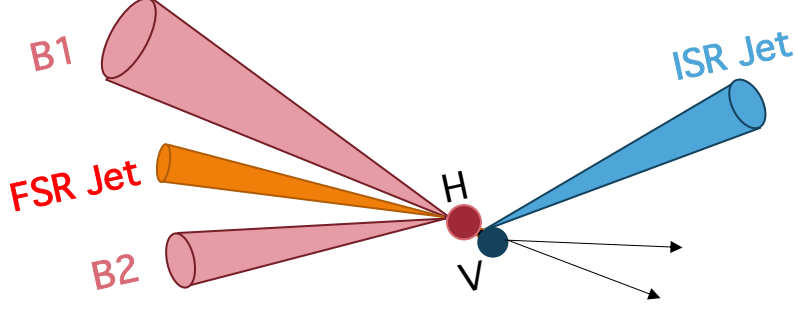


Figure 4-17: Illustration of an $VH(\rightarrow b\bar{b})$ event with one FSR jet and one ISR jet.

The FSR correction aims to identify the FSR jets against the ISR jets and pile up jets, add the FSR jets to the H_{cand} jets that originate the FSR jets. By doing this, the invariant mass of the Higgs system is corrected, and the resolution can be improved. Additionally, the STXS bins are categorized based on the number of additional ISR jets. By removing the FSR jets, the correlation between truth and reconstructed categorization of STXS can be improved.

The identification of FSR jet is done by a cut function:

$$dR_{H_{\text{cand}}jet_{1,j}} + dR_{H_{\text{cand}}jet_{2,j}} < 0.495 + 3.520 \cdot e^{-5.360e-3p_T^V} \quad (4-6)$$

The $dR_{H_{\text{cand}}jet_{1,j}}$ ($dR_{H_{\text{cand}}jet_{2,j}}$) stand for the dR between the leading (subleading) H_{cand} jet and the jet. The cut function is defined to optimize the signal significance in the m_{bb} distribution.

The FSR recovery improves the signal invariant mass resolution and peak, hence improve the performance of signal significance in the MVA discriminant, especially in the resolved 2-lepton channel. However, in the 1-lepton channel, the FSR recovery will result in large migration of $t\bar{t}$ background into the signal sensitive region ($m_{H_{\text{cand}}}$ near 125 GeV). As a result, the FSR recovery is only applied in the $VH(\rightarrow b\bar{b})$ and $VH(\rightarrow c\bar{c})$ 2-lepton channels. In addition, for the events with five or more jets, there is difficulty of the implementation and almost no improvement is expected, thus the FSR is only used in 3-and 4-jets events. Note that here the number of jets count the ones with p_T larger than 20 GeV.

4.6.5 Corrections Application

For these kinds of jet corrections, as some of them will change the number of objects in the events and also the jet p_T , they need to be harmonized in the order of application.

The muon-in-jet is applied first, to all the events. The events after muon-in-jet correction will then be categorized for different corrections. For resolved $VH(\rightarrow b\bar{b})$ 0-lepton and 1-lepton events, together with the 2-lepton events having more than 4 jets, PtReco correction will be applied. For resolved 2-lepton events with less than 4 jets, the kinematic fit will be applied, using the jet 4-vector after the OneMu correction. After the PtReco and kinematic fit correction, the 2-lepton events with less than 4 jets, the FSR recovery is used. The kinematic fit is applied before the FSR recovery due to the reason that the transfer function is derived with the hard jets, which is not applicable to the combined jets (H_{cand} jet+FSR jet).

4.6.6 Performance of the jet correction

The invariant mass of the H_{cand} in resolved $VH(\rightarrow b\bar{b})$, $VH(\rightarrow c\bar{c})$ and boosted $VH(\rightarrow b\bar{b})$ are shown in Figure 4-18 and 4-19

Compared with the standard H_{cand} invariant mass resolution, the muon-in-jet correction brings an improvement about 10% level for all the events of signal process. The PtReco correction brings additional 5% improvement for the events that is applicable. For the kinematic fit, it brings about 20% level improvement in the resolution for $VH(\rightarrow b\bar{b})$ and about 15% in $VH(\rightarrow c\bar{c})$. The FSR correction will bring around 5% more improvement. In some most sensitive regions, like $VH(\rightarrow b\bar{b})$ 2-lepton 2-jets SR, the overall improvement on the $m_{b\bar{b}}$ resolution reaches about 45% compared to the resolution after GSC.

Kinematic fit is further validated using the $ZH \rightarrow llbb/llcc$ MC samples, as shown in Figure 4-20. The plots show the distribution of the ratio between reconstruction level p_T and truth p_T of the b -jets, with different jet energy calibrations. It can be found that after kinematic fit, the reconstructed p_T is closer to the truth value.

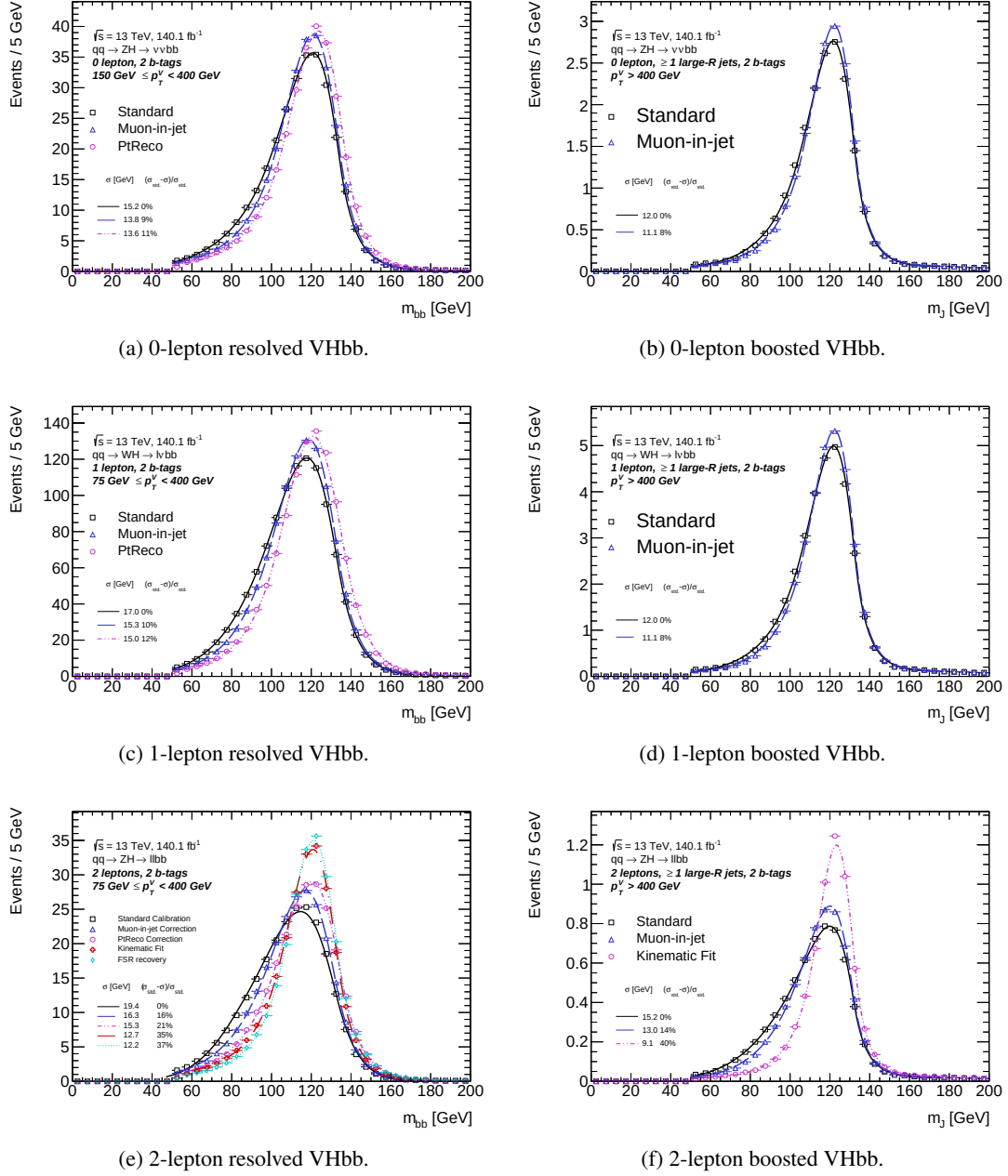


Figure 4-18: Tagged energy correction performance in $VH(\rightarrow b\bar{b})$ different lepton channels. Events in different nJet or p_T^V categories are shown inclusively in resolved and boosted $VH(\rightarrow b\bar{b})$. The events are taken from signal MC samples.

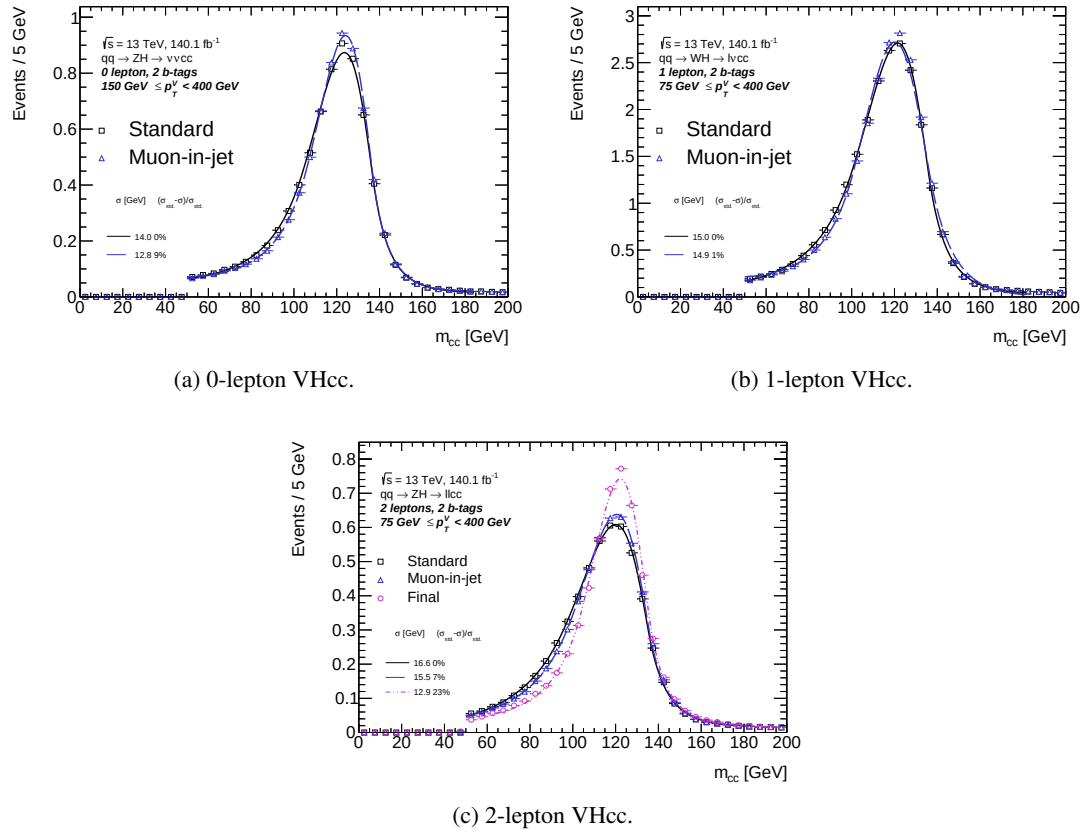


Figure 4-19: Tagged energy correction performance in $VH(\rightarrow c\bar{c})$ different lepton channels. Events in different nJet or p_T^V categories are shown inclusively. The events are taken from signal MC samples.

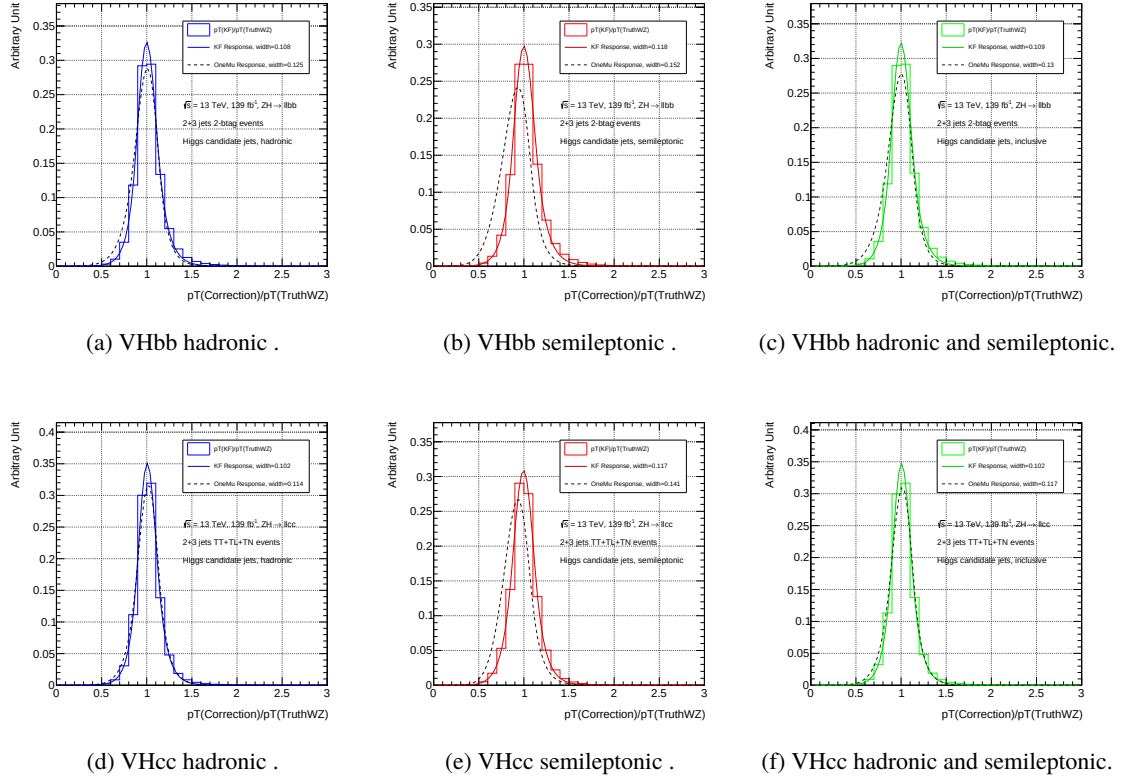


Figure 4-20: Distributions of ratio between reconstruction level p_T and truth p_T of the b -jets, with different jet energy calibrations. The histograms show the p_T ratio distribution after kinematic fit. The dash line and solid line show the Bukin function fitted from the p_T ratio distribution with muon-in-jet correction and kinematic fit.

4.7 Multi-Variate Analysis

Multi variate analysis (MVA) methods are widely used in high energy researches in order to increase signal purity and background rejection. With a set of discriminating input variables as input, the multi variate algorithm is trained to understand the difference between signal and background. The output of MVA is a one dimensional discriminant which is supposed to better discriminant signal from background compared with single variable.

The boosted decision tree (BDT)^[124] is used in this analysis, provided by the TMVA^[125] package of ROOT. The decision is a classifier performing repeated left/right decisions dividing phase space based on the input variables until the stop criterion is fulfilled. BDT is an extension of decision tree^[126] from one to several trees which form a "forest". The trees are trained with the same setup, but with different event weights. The newer tree will use higher weight for the misclassified events in the previous tree. The trees are finally combined into a single classifier which is the weighted average of individual decision trees. This method is the "Boosting". Boosting helps reducing the overfit and prevents sensitivity from fluctuations in the training samples, thus have a better performance than a single decision tree. Two boosting algorithms are used in the analysis: the adaptive boost (AdaBoost) and gradient boost method. The resolved $VH(\rightarrow b\bar{b})$ regime uses the gradient boost while the boosted $VH(\rightarrow b\bar{b})$ regime is using the Adaboost. $VH(\rightarrow c\bar{c})$ regime uses both algorithm in different regimes.

All the objects and events selection criteria are applied before the training of BDT, as well as the jet corrections. The events in the SRs and ΔR CRs are trained inclusively to ensure enough statistics for the training. In the $VH(\rightarrow b\bar{b})$ regime, the BDT is trained using $VH(\rightarrow b\bar{b})$ sample as signal, while for the $VH(\rightarrow c\bar{c})$ regime the $VH(\rightarrow c\bar{c})$ sample is used as signal. In both case, the V +jets, $t\bar{t}$, s-top and diboson samples are used as background. The $VH(\rightarrow c\bar{c})$ sample is not listed in the background sample in $VH(\rightarrow b\bar{b})$ training and vice versa. Studies have shown that the difference between including the $VH(\rightarrow c\bar{c})$ (or $VH(\rightarrow b\bar{b})$) in the background sample did not significantly affect the performance of training and evaluation thus they are excluded. However, the BDT is still expected to have separation power between $VH(\rightarrow b\bar{b})$ and $VH(\rightarrow c\bar{c})$, since the flavor tagging information is used as an input variable. Besides the nominal BDT models, additional BDT is trained for the cross-check analysis using the diboson

samples as signal, in all three regimes. In $VH(\rightarrow b\bar{b})$ ($VH(\rightarrow c\bar{c})$) regime, the $VZ(\rightarrow b\bar{b})$ ($VZ(\rightarrow c\bar{c})$) sample is used as signal for training, and the $VZ(\rightarrow c\bar{c})$ ($VZ(\rightarrow b\bar{b})$) is excluded from the training. The cross-check is essential for the analysis, especially for the $VH(\rightarrow c\bar{c})$ regime, to test the reliability of the BDT method as well as the performance of the fit model.

4.7.1 MVA Training Regions

As mentioned above, the training regions are not identical with the analysis regions since some regions need to be merged to ensure adequate statistics for training. The categorization of training regions is summarized in Figure 4-21.

In resolved regimes, the low/high ΔR regions are merged together with SRs in the training while events in TopCRs are excluded. For $VH(\rightarrow b\bar{b})$, although $p_T^V = 400$ GeV defines the boundary between resolved and boosted, it is not applied in the training, which means the events with $p_T^V > 400$ GeV also enters the training. But the boundary is applied in the evaluation. For $VH(\rightarrow c\bar{c})$, separate training are performed for C_T $C_T + C_L$ region and C_T N region.

- 0-lepton channel: separate BDTs are trained corresponding to the 2-, 3- and 4-jets categories for $p_T^V > 150$ GeV for both $VH(\rightarrow b\bar{b})$ and $VH(\rightarrow c\bar{c})$.
- 1-lepton channel: separate BDTs are trained corresponding to the 2- and 3-jet categories for $p_T^V \in [75, 150]$ GeV and $p_T^V > 150$ GeV for both $VH(\rightarrow b\bar{b})$ and $VH(\rightarrow c\bar{c})$.
- 2-lepton channel: separate BDTs are trained corresponding to the 2- and 3p-jet categories for $VH(\rightarrow c\bar{c})$. Similar case for $VH(\rightarrow b\bar{b})$ except in which the 3p-jet category is further split to 3-jet and 4p-jet categories.

In boosted regime, the topCRs are also excluded from training and separate BDTs are trained per lepton channels corresponding to $p_T^V > 400$ GeV.

4.7.2 MVA Input Variables

The training variables used in the analysis are chosen based on the balance of training performance and simplicity. The variables used for $VH(\rightarrow b\bar{b})$ and $VH(\rightarrow c\bar{c})$ are fully harmonized in each lepton channel. Table 4-15 summarize all the input variables used in the training and the details of the variables will be discussed below.

		75GeV < p _T ^V < 150GeV			p _T ^V > 150GeV		
VH, H → cē	TN	0-lepton	1-lepton 2-jet 3-jet	2-lepton 2-jet ≥3-jet	0-lepton	1-lepton 2-jet 3-jet 4-jet	2-lepton 2-jet ≥3-jet
	TT + TL	0-lepton	1-lepton 2-jet 3-jet	2-lepton 2-jet ≥3-jet	0-lepton	1-lepton 2-jet 3-jet 4-jet	2-lepton 2-jet ≥3-jet
VH, H → bē	Resolved	0-lepton	1-lepton 2-jet 3-jet ≥4-jet	2-lepton 2-jet 3-jet 4-jet	0-lepton	1-lepton 2-jet 3-jet 4-jet	2-lepton 2-jet 3-jet ≥4-jet
	Boosted					0-lepton ≥2-jet	1-lepton ≥2-jet
					p _T ^V > 400GeV		

Figure 4-21: Illustration of the regions used in MVA training, defined in terms of topologies, p_T^V regions and jet multiplicities. For $VH(\rightarrow c\bar{c})$, separate BDTs are trained for C_T $C_T + C_T$ C_L region and C_T N region.

Variable	Name	$VH(\rightarrow b\bar{b}, c\bar{c})$ Resolved			$VH(\rightarrow b\bar{b})$ Boosted		
		0-lepton	1-lepton	2-lepton	0-lepton	1-lepton	2-lepton
$m_{j_1 j_2}$ or m_J	mBB / mJ	×	×	×	×	×	×
$m_{j_1 j_2 j_3}$	mBBJ	×	×	×			
$p_T^{j_1}$ or $p_T^{j_1, \text{trk}}$	pTB1 / pTBTrkJ1	×	×	×	×	×	×
$p_T^{j_2}$ or $p_T^{j_2, \text{trk}}$	pTB2 / pTBTrkJ2	×	×	×	×	×	×
$p_T^{j_3, \text{trk}}$	pTBTrkJ3				×	×	×
$\sum_{i \neq 1,2} p_T^{j_i}$	sumPtAddJets	×	×	×			
$\Delta R(j_1, j_2)$ or $\Delta R(j_1, \text{trk}, j_2, \text{trk})$	dRBB / deltaRbTrkJbTrkJ	×	×	×	×	×	×
$ \Delta \eta(j_1, j_2) $	dEtaBB	×					
$\text{bin}_{\text{DL1r}}(j_1)$	bin_btagB1 / bin_bTagBTrkJ1	×	×	×	×	×	×
$\text{bin}_{\text{DL1r}}(j_2)$	bin_btagB2 / bin_bTagBTrkJ2	×	×	×	×	×	×
p_T^V	pTV	$\equiv E_T^{\text{miss}}$	×	×	$\equiv E_T^{\text{miss}}$	×	×
E_T^{miss}	MET	×	×		×	×	
$E_T^{\text{miss}} / \sqrt{S_T}$	METSig			×			
$ \Delta y(V, H_{\text{cand}}) $	dYVBB/deltaYVJ		×	×		×	×
$ \Delta \phi(V, H_{\text{cand}}) $	dPhiVBB/absdeltaPhiVJ	×	×	×	×	×	×
$\min[\Delta \phi(\ell, j_i)], i = 1, 2$	dPhiLBmin		×				
m_{eff}	MEff	×					
m_T^W	mTW		×				
m_{top}	Mtop		×				
$m_{\ell\ell}$	mLL			×			
$\cos \theta(\ell^-, Z)$	cosThetaLep			×			×
$(p_T^{\ell_1} - E_T^{\text{miss}}) / p_T^W$	lepPtBalance					×	
p_T^{ℓ}	pTL					×	
$N(\text{track-jets in } J)$	NMatchedTrackJetLeadFatJet				×	×	×
$N(\text{add. small R-jets})$	NAdditionalCaloJets				×	×	×
Colour	Colour				×	×	×
$\min\{\Delta R(j_i, j)\}, i = 1, 2$	minDRBjets	×	×				

Table 4-15: MVA variables used for the 0-, 1- and 2-lepton channels in the resolved and boosted topologies for the $VH(\rightarrow b\bar{b})$ and $VH(\rightarrow c\bar{c})$ analyses. The $VH(\rightarrow c\bar{c})$ analysis only probes the resolved topology. The Higgs candidate system, composed of the 2 small- R jets ($b\bar{b}$ or $c\bar{c}$) for the resolved regime or of the leading large- R jet (J) of the event for the boosted regime, is sometimes denoted H_{cand} .

Resolved Regime

Due to the $p_T > 30$ GeV cut for the non- H_{cand} jets mentioned in Section 4.5 to mitigate the STXS migration, the jet multiplicity categorization can not fully reflect the jet activities in an event. In order to avoid this issue in the training, the input variables that are related to the jet activities in the MVA still take the non- H_{cand} jets with $20 < p_T < 30$ GeV into account. The definitions of input variables are described in the following:

Common variables

- p_T^V : transverse momentum of the vector boson. In 0-lepton channel it is equivalent to E_T^{miss} ; in 1-lepton channel it is sum of E_T^{miss} and the lepton p_T ; in 2-lepton channel it is the sum of 2 leptons p_T .
- $p_T^{j_1}$ and $p_T^{j_2}$: the p_T of two H_{cand} jets.
- $m_{j_1 j_2}$: invariant mass of H_{cand} system.
- $\Delta R(j_1, j_2)$: angular distance between two H_{cand} jets.
- $m_{j_1 j_2 j_3}$: invariant mass of H_{cand} jets and the remaining jet with highest p_T . When there is only two jets in the event, $m_{j_1 j_2 j_3} = m_{j_1 j_2}$. When the remaining jet is coming from FSR and it is not recognized in the FSR recovery, this variable represents the true H_{cand} system mass.
- $\Delta\phi(j_1, j_2)$: azimuthal distance between reconstructed vector boson and H_{cand} .
- $\text{bin}_{\text{DL1r}}(j_1)$, $\text{bin}_{\text{DL1r}}(j_2)$: the numerical representative of the PCFT tagged bin of two H_{cand} jets. In total of five possible bins are assigned with different integer values, from 0 to 4: N, 60-70% WP b -tagged, 0-60% WP b -tagged, C_L and C_T .
- $\sum_{i \neq 1, 2} p_T^i$: p_T sum of the non- H_{cand} jets that have $p_T > 20$ GeV.

0-lepton specific variables

- $\Delta\eta(j_1, j_2)$: the pseudorapidity distance between the two H_{cand} jets.
- $\min\{\Delta R(j_i, j)\}, i = 1, 2$: the minimum angular distance between the H_{cand} jets and the non- H_{cand} jets.
- m_{eff} : the scalar sum of p_T of all small- R jets and E_T^{miss} .

- $\min[\Delta\phi(\ell, \mathbf{j}_i)], i = 1, 2$: the minimum azimuthal distance between the leptons and the H_{cand} jets.

1-lepton specific variables

- m_T^W : transverse mass of W boson candidate.
- E_T^{miss} : missing energy transverse.
- $\Delta y(\mathbf{V}, \mathbf{H}_{\text{cand}})$: rapidity difference between the reconstructed vector boson and H_{cand} .
- $\min[\Delta\phi(\ell, \mathbf{j}_i)], i = 1, 2$: the minimum azimuthal distance between the leptons and the H_{cand} jets.
- m_{top} : reconstructed mass of leptonically decaying top quark.

2-lepton specific variables

- m_{ll} : the invariant mass of 2 lepton system.
- $\cos\theta(\ell^-, \mathbf{Z})$: the Z boson polarization sensitive angle. This variable shows the difference in polarization of Z boson between signal and background Z +jets process^[127].
- $E_T^{\text{miss}}/\sqrt{S_T}$: the quasi-significance of E_T^{miss} .
- $\Delta y(\mathbf{V}, \mathbf{H}_{\text{cand}})$.

Boosted Regime

The boosted regime uses a similar set of variables as resolved regime, which in some case have a different definition due to the different topology. In addition, some other variables are also used to improve the performance of BDT.

Common variables

- p_T^V : same definition as resolved regime
- $p_T^{j_{1, \text{trk}}}, p_T^{j_{2, \text{trk}}}$ and $p_T^{j_{3, \text{trk}}}$: transverse momentum of the track jets. j_1 and j_2 refer to the b -tagged track jets and j_3 is the leading non- b -tagged jet.
- m_J : invariant mass of the H_{cand} large- R jet.
- $\Delta R(j_{1, \text{trk}}, j_{2, \text{trk}})$: the angular distance between two b -tagged track jets.

- $N(\text{track-jets in } J)$: number of track jets that are ghost-associated to the leading large- R jets.
- $N(\text{add. small } R\text{-jets})$: number of additional small- R jets that are not matched to the leading large- R jet.
- $\Delta\phi(j_1, j_2)$: same definition as resolved regime.
- Colour: a variable designed to exploit the difference in color flow between gluon splittings and decay from QCD singlets state^[128], which is defined as:

$$\text{Colour} = \frac{\theta_{j_1 j_3}^2 + \theta_{j_2 j_3}^2}{\theta_{j_1 j_2}^2} \quad (4-7)$$

- $\text{bin}_{\text{DL1r}}(j_{1, \text{trk}}), \text{bin}_{\text{DL1r}}(j_{2, \text{trk}})$: the numerical representative of the b -tag bin of two H_{cand} track jets. In total of four possible bins: 85%, 77%, 70% and 60% b -tagging efficiency bin.

1-lepton specific variables

- $E_{\text{T}}^{\text{miss}}$: missing energy transverse.
- $\Delta y(V, H_{\text{cand}})$: same definition as resolved regime.
- p_{T}^{ℓ} : transverse momentum of the lepton
- $(p_{\text{T}}^{\ell_1} - E_{\text{T}}^{\text{miss}})/p_{\text{T}}^W$: proxy for the p_{T} imbalance of the charged lepton and the neutrino of the W decay.

2-lepton specific variables

- $\Delta y(V, H_{\text{cand}})$.
- $\cos(\theta(\ell^-, \mathbf{Z}))$: same definition as resolved regime.

For all the variables, when it is not defined in a certain event (e.g. the variables that require the non- H_{cand} jets, but there is no such jet) a default value will be assigned. The default values are chosen to be close to the distribution of the variables where it is well-defined but not fall into the range. For example, the default value of $\min\{\Delta R(j_i, j)\}, i = 1, 2$ is chosen to be 0.35 and the well-defined value of this variable start from 0.4.

Many distributions have long tails, especially the kinematic variables that can sometimes reach TeVscale. To increase the training stability, an upper limit is set to include 99% of signal events. The events that have values above the limit will be set the maximum value.

The distribution of the variables used in the $VH(\rightarrow c\bar{c})$ 2-lepton channel 2-jets $C_T C_T + C_T C_L$ region are shown in the Figure 4-22 and Figure 4-22.

4.7.3 Training Setup

The BDTs are trained using the nominal MC samples of the analysis. In order to maximize the statistics for the training, all the samples are produced with GNN truth tagging method.

The hyperparameters used in the BDT training are optimized per training channel to maximize the statistics only significance of the BDT output. For the boost method, the Gradient boost is used in the $VH(\rightarrow b\bar{b})$ regime as it is good at capturing the effects outside the bulk of the distributions, and improve the performance in most case. However, the Gradient boost is susceptible to the overtraining, especially when the size of training sample is small. While another boost type, Adaboost, is proved to help avoid the overtraining issue. Thus, in the boosted $VH(\rightarrow b\bar{b})$ regime the Adaboost is used. For $VH(\rightarrow c\bar{c})$, the hyperparameters are mostly inherited from the resolved $VH(\rightarrow b\bar{b})$, which in some case is aggressive. Some fine-tuning is then done to avoid the overtraining and ensure good signal sensitivity of the BDT output. The hyperparameters used in the analysis are summarized in Table 4-16 ($VH(\rightarrow b\bar{b})$) and Table 4-17 ($VH(\rightarrow c\bar{c})$).

Settings	Resolved $VH(\rightarrow b\bar{b})$			Boosted $VH(\rightarrow b\bar{b})$		
	0-lepton	1-lepton	2-lepton	0-lepton	1-lepton	2-lepton
Boost type	Gradient boost	Gradient boost	Gradient boost	Adaboost	Adaboost	Adaboost
Number of trees	200	600	200	800	800	400
Maximum depth	3	4	4	3	3	3
Learning rate (β)	0.5	0.5	0.5	0.5	0.35	0.3
Number of cuts	100	100	100	60	60	100
Minimum node size	5%	5%	5%	2%	2%	7%
Separation method	Gini index	Gini index	Gini index	Gini index	Gini index	Gini index
Pruning method	No pruning	No pruning	No pruning	No pruning	No pruning	No pruning

Table 4-16: BDT hyperparameters used for the 0-, 1- and 2-lepton channels for the $VH(\rightarrow b\bar{b})$ resolved and boosted analyses.

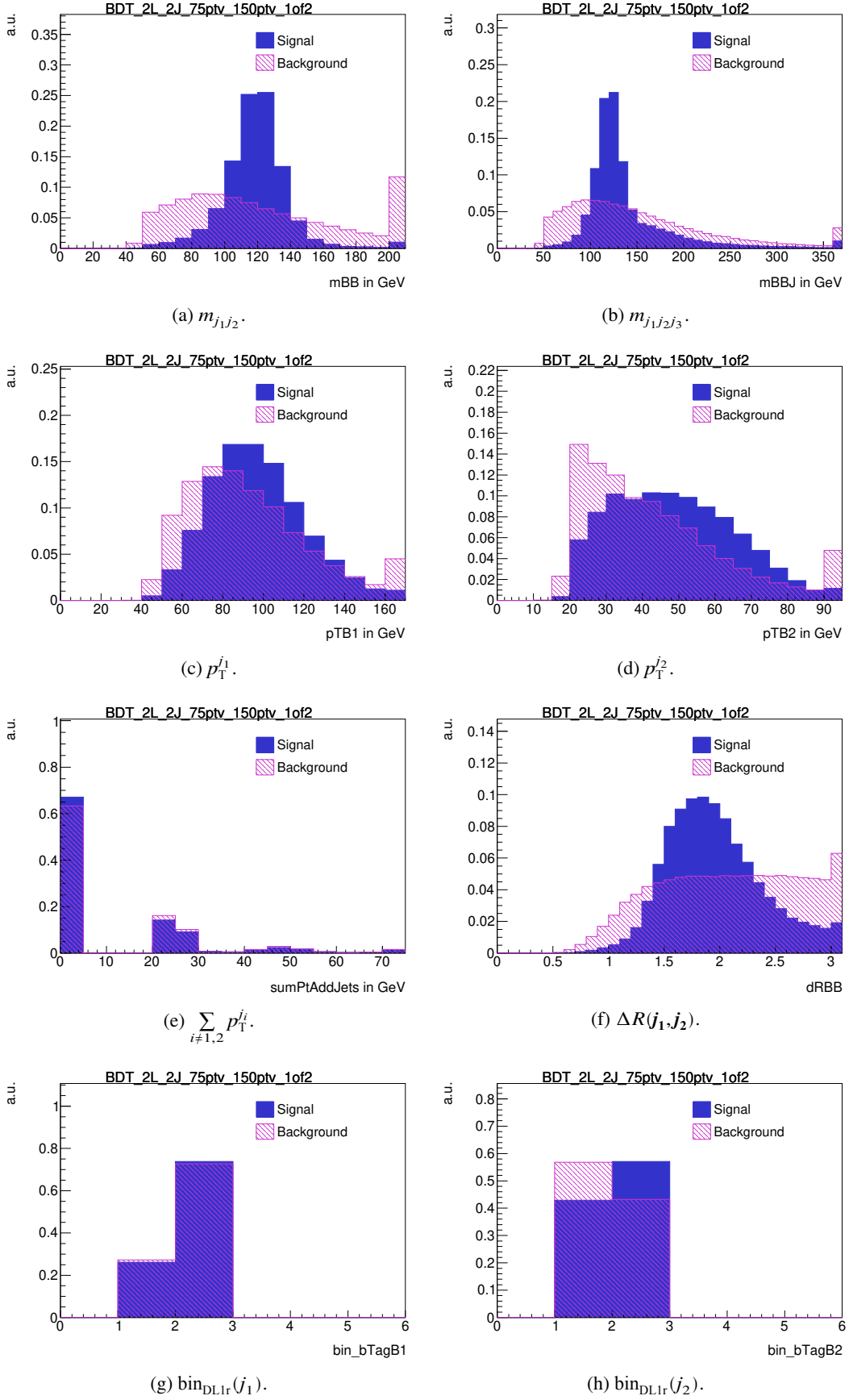


Figure 4-22: Distribution of input variables used in the BDT training for $VH(\rightarrow c\bar{c})$ 2-lepton channel 2-jets $C_T C_T + C_T C_L$ region.

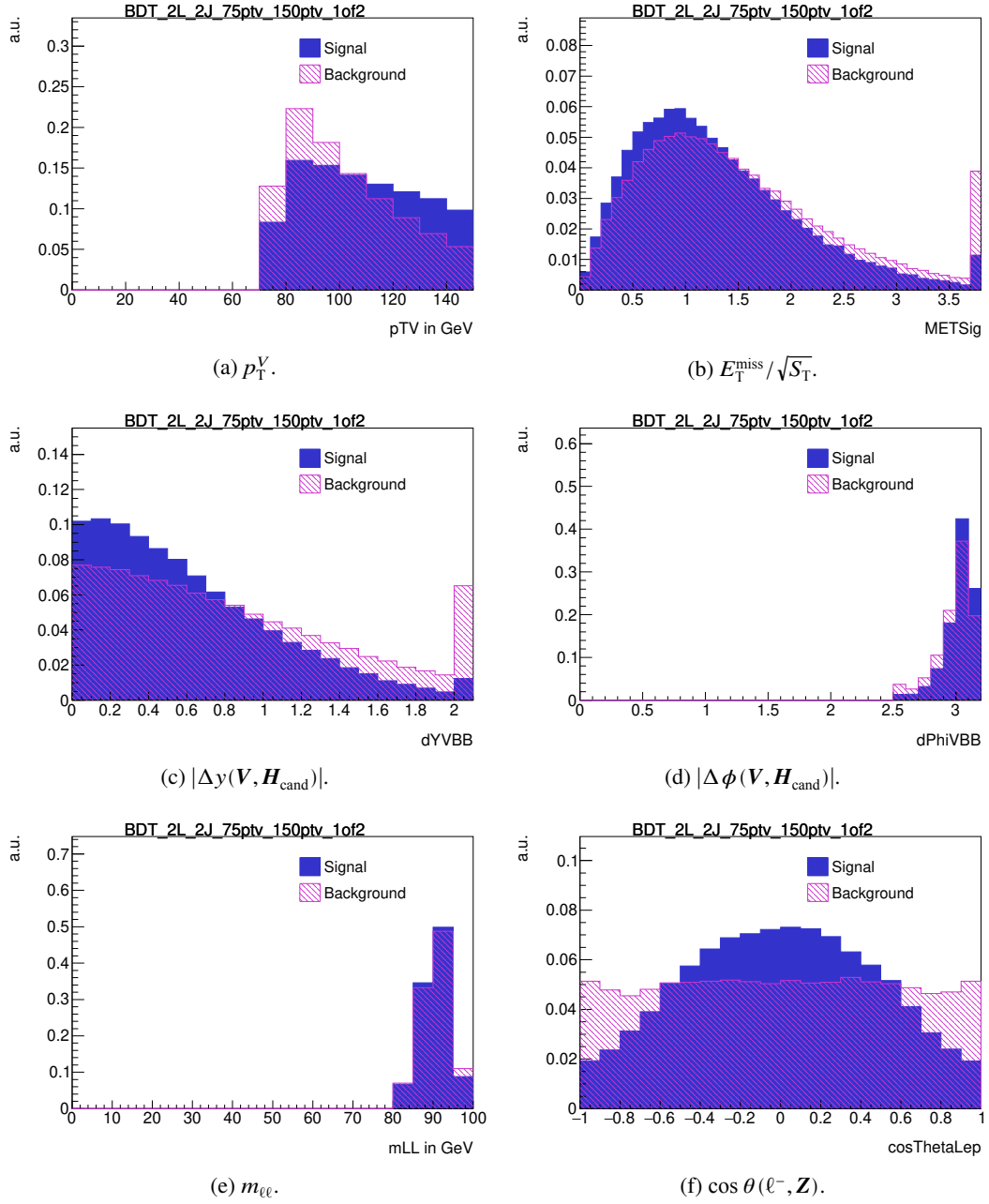


Figure 4-23: Distribution of input variables used in the BDT training for $VH(\rightarrow c\bar{c})$ 2-lepton channel 2-jets $C_T C_T + C_T C_L$ region.

Settings	$VH(\rightarrow c\bar{c})$		$VH(\rightarrow c\bar{c})$, Diboson as signal
	0-, 1- and most 2-lepton regions	2-lepton, 3pJ, low pTV	0-, 1- and 2-lepton
Boost type	Gradient boost	Adaboost	Adaboost
Number of trees	600	200	200
Maximum depth	4	4	4
Learning rate (β)	0.5	0.15	0.15
Number of cuts	100	100	100
Minimum node size	5%	5%	5%
Separation method	Gini index	Gini index	Gini index
Pruning method	No pruning	No pruning	No pruning

Table 4-17: BDT hyperparameters used for the 0-, 1- and 2-lepton channels for $VH(\rightarrow c\bar{c})$ analysis. Notice that for the trainings where $VH(\rightarrow c\bar{c})$ is the signal, most of the regions and channels use the same parameters as in resolved $VH(\rightarrow b\bar{b})$ 1-lepton channel, with the 3p-jet low pTV region ($75 \text{ GeV} < p_{\text{TV}} < 150 \text{ GeV}$) in 2-lepton channel as an exception. This region shows some overtraining issue under the same parameters from other regions, thus a different set of hyper parameters is applied.

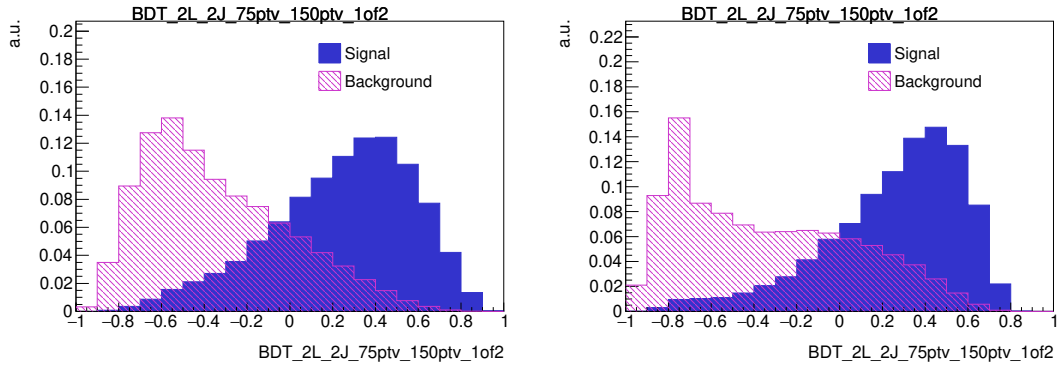


Figure 4-24: Distribution of BDT output of one fold of $VH(\rightarrow c\bar{c})$ 2-lepton $75 < p_{\text{T}}^V < 150 \text{ GeV}$ region training, left is the signal training in $C_{\text{T}} C_{\text{T}} + C_{\text{T}} C_{\text{L}}$ region and right is the diboson cross-check training in $C_{\text{T}} \text{N}$ region .

The k -fold method is used in the training. The training samples are evenly divided to k sets, each time one set is used as the evaluation sample and the rest $k - 1$ sets are used for training. As a result, in total of k BDT models will be trained, and they will be applied to the corresponding evaluation set. By using this method, the samples used for evaluation is fully orthogonal with the training samples. In this analysis, the k is set to 2. The events will be divided based on their MC number to odd and even events. The final discriminant is built by summing the BDT discriminant of even and odd events.

The ROC curve is one of the important curve to evaluate the performance of MVA. The x-axis of ROC is the signal efficiency and the y-axis is one minus background rejection efficiency.

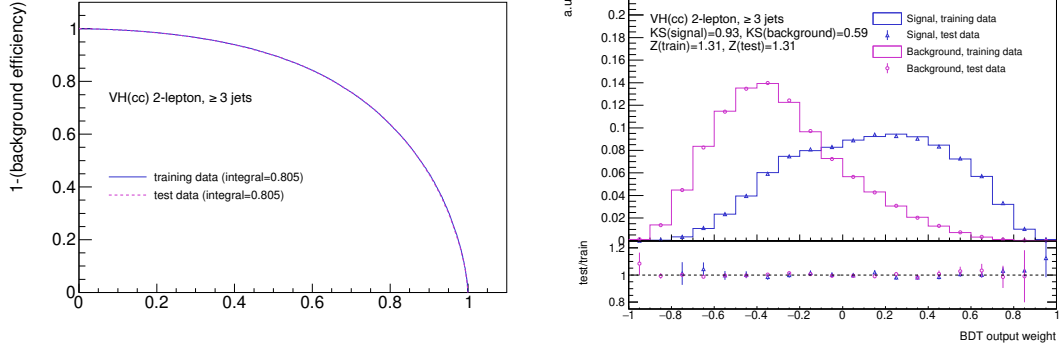


Figure 4-25: ROC curve (left) and BDT output (right) distributions comparison between train sample and test sample for one fold of $VH(\rightarrow c\bar{c})$ 2-lepton $75 < p_T^V < 150$ GeV $C_T C_T + C_T C_L$ region BDT training.

It is plotted by varying the cut on the BDT output. It is also a good distribution of checking the overtraining by comparing the ROC curve for training and evaluation samples. Overtraining will result in different distributions for training and evaluation samples. Similar case can also be found in the distributions of BDT discriminant. A KS test is performed to make sure the BDT output has a similar discriminant power in both samples. Figure 4-25 shows an example of the ROC curves and BDT distributions for $VH(\rightarrow c\bar{c})$ 2-lepton training. No significant overtraining is observed in any BDT model.

The low ΔR CRs in resolved $VH(\rightarrow b\bar{b})$ 1-lepton is aimed for the control of $W + hf$ process. It is expected to be enriched with $W + bb$ events. However, in the low p_T^V , there are also quite a lot of $t\bar{t}$ events in the region, making it harder to control the $W + bb$. As a result, a dedicated BDT training is done in this region using the $W + bb$ as signal. The BDT discriminant is named as $MVACRLow$. The $MVACRLow$ is trained using the GNN truth tagged events that have exactly two b -tagged jets in resolved $VH(\rightarrow b\bar{b})$ 1-lepton channel. The same input variables and hyperparameters as the standard BDT training are used. It is trained separately for $75 < p_T^V < 150$ GeV and $p_T^V > 150$ GeV.

4.7.4 Output transformation

The default binning of BDT output is equidistant and very fine, which may not achieve the optimal sensitivity. So a rebinning technique named Transformation D is applied to optimize the signal sensitivity of BDT output. The details will be discuss in Section 4.8.2

An example of BDT score output distribution before and after transformation can be found

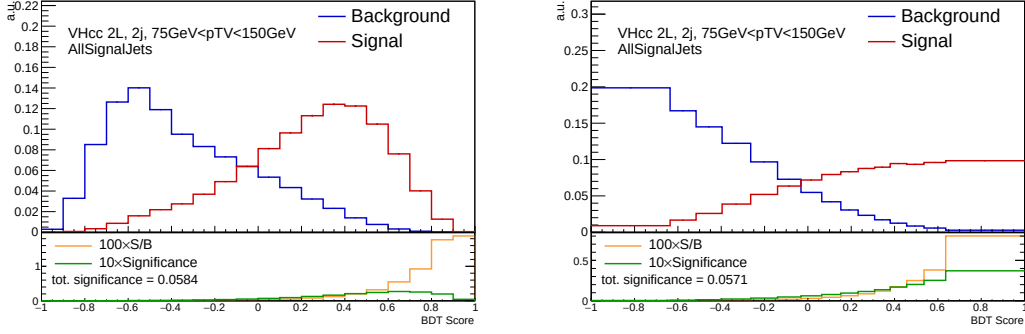


Figure 4-26: Comparison of BDT output before and after Transformation D in $VH(\rightarrow c\bar{c})$ 2-lepton $75 < p_T^V < 150$ GeV 2-jets region.

in Figure 4-26. The distribution after transformation are used for all the evaluation of BDT model performance.

4.8 Statistical description

In order to extract the signal strength for $VH(\rightarrow b\bar{b})$ and $VH(\rightarrow c\bar{c})$ process, the fit is performed by maximizing the likelihood function. All the SRs and CRs in the three lepton channels from resolved $VH(\rightarrow b\bar{b})$, boosted $VH(\rightarrow b\bar{b})$ and $VH(\rightarrow c\bar{c})$ are fitted simultaneously. The parameters of interest is $VH(\rightarrow b\bar{b})$ and $VH(\rightarrow c\bar{c})$ signal strength in the nominal fit, $VZ(\rightarrow b\bar{b})$ and $VZ(\rightarrow c\bar{c})$ signal strength in the cross-check fit. The fit is performed in the WorkspaceMaker framework building upon HistFactory^[129], RooFit^[130] and RooStats^[131]

4.8.1 Likelihood Function Definition

The first part of the likelihood function consists of Poissonian probability terms, based on the expected and observed event yields in all of the bins:

$$\mathcal{L}(\mu) = \prod_{i \in \text{bins}} \text{Pois}(N_i | \mu s_i + b_i) = \prod_{i \in \text{bins}} \frac{(\mu s_i + b_i)^{N_i}}{N_i!} e^{-(\mu s_i + b_i)}, \quad (4-8)$$

where N_i is the number of measured data events in bin i , and s_i , and b_i are expected signal and background counts predicted by simulation. The parameter μ is the signal strength, which is defined as the measured $\sigma \times \text{BR}$ for the signal process divided by the Standard Model expectation.

The second term of likelihood function introduce the systematic uncertainties in the form of

nuisance parameters (NPs) θ , which can modify the signal and background yields in the bins: $\{s_i, b_i\} \rightarrow \{s_i(\theta), b_i(\theta)\}$. They are implemented as a set of Gaussian penalty term, which have a mean value of zero and variation of 1:

$$\mathcal{L}_{\text{Aux}} = \prod_{\theta \in \theta} \frac{1}{\sqrt{2\pi}} e^{-\theta^2/2}. \quad (4-9)$$

The effect of the nuisance parameters is determined in auxiliary measurements, named as *prior*. The deviation of the best fit value of a NP from zero is the *pull* and a decrease in the variance after performing the fit is the *constraint*. The constraint indicates the certainty with which the value of the NP is known.

There are also some NPs do not have priors, named as free-floating parameters. They are used to modify the overall normalization of the background, and determined from the data, e.g. with the help of CRs. The pre-fit values of these free-floating parameters are set to 1.

Finally, the uncertainties related to the limited statistics of MC samples are introduced as γ parameters. One γ parameter is introduced per bin, which can modify the expected background yield: $b_i(\theta) \rightarrow \gamma_i b_i(\theta)$. They are implemented as:

$$\mathcal{L}_{\text{BkgStat}}(\gamma) = \prod_{i \in \text{bins}} \text{Gauss}(\beta_i | \gamma_i \beta_i, \sqrt{\gamma_i \beta_i}), \quad (4-10)$$

with $\gamma_i \beta_i$ is the mean value, $\sqrt{\gamma_i \beta_i}$ is the variance of the Gaussian distribution, and

$$\beta_i = \frac{1}{\sigma_{\text{rel}}^2}, \quad (4-11)$$

where σ_{rel} is the relative statistical uncertainty on the expected total background yield.

The full likelihood can be finally written as:

$$\mathcal{L}(\mu, \theta, \gamma, \tau) = \prod_{i \in \text{bins}} \text{Pois}(N_i | \mu s_i(\theta) + b_i(\theta, \gamma, \tau)) \times \prod_{\theta \in \theta} \frac{1}{\sqrt{2\pi}} e^{-\theta^2/2} \times \prod_{i \in \text{bins}} \text{Gauss}(\beta_i | \gamma_i \beta_i, \sqrt{\gamma_i \beta_i}). \quad (4-12)$$

The fit result is obtained by minimizing the negative log likelihood (NLL): $-\ln L$ with respect to all the parameters μ , θ and γ . A gradient-descent-based method is used for the minimization, implemented in the MINUTE^[132] package.

The likelihood can also be used to test a certain hypothesis for the value of μ (only consider one POI here for simplicity). For example, the SM hypothesis ($\mu = 1$) or background only

hypothesis $\mu = 1$. One can define the profile likelihood ratio:

$$\lambda(\mu) = \frac{\mathcal{L}(\mu, \hat{\hat{\theta}}, \hat{\hat{\gamma}})}{\mathcal{L}(\hat{\mu}, \hat{\theta}, \hat{\gamma})} \quad (4-13)$$

where $\{\hat{\mu}, \hat{\theta}, \hat{\gamma}\}$ are the values that maximize the likelihood overall and $\{\hat{\hat{\theta}}, \hat{\hat{\gamma}}\}$ the ones that maximize $\mathcal{L}$ for a fixed value of μ . The likelihood ratio is defined in the range $[0, 1]$, where a value close to 1 implies good agreement between data and the specific hypothesis. While for larger disagreement, the likelihood ratio value moves toward 0. The test statistic q_μ can be defined^[133]:

$$q_\mu = \begin{cases} -2 \ln \lambda(\mu) & \hat{\mu} \geq \mu \\ 0 & \hat{\mu} < \mu \end{cases} \quad (4-14)$$

In the case of $\mu = 0$, the hypothesis of no signal is tested. It is helpful to define the *p-value* to quantify the compatibility of the data with the background-only hypothesis. The *p-value* is defined as:

$$p_\mu = \int_{q_{\mu, \text{obs}}}^{\infty} f(q_\mu | 0) dq_\mu \quad (4-15)$$

where $f(q_\mu | 0)$ is the probability density function of q_μ under the assumption of $\mu = 0$ and $q_{\mu, \text{obs}}$ is the value of q_μ observed in data. The *p-value* can be interpreted as the probability of finding data incompatible with the given hypothesis $\mu = 0$. From the *p-value*, the significance Z can be calculated which is defined as the number of Gaussian standard deviation above the background:

$$Z = \Phi^{-1}(1 - p), \quad (4-16)$$

where Φ^{-1} is the inverse Gaussian cumulative distribution function.

For the $VH(\rightarrow c\bar{c})$, the upper limit on the $VH(\rightarrow c\bar{c})$ signal strength is calculated, using a modified frequentist CL_S method^[133-134]. The test statistic is defined as:

$$q = -2 \ln \frac{\mathcal{L}_{s+b}}{\mathcal{L}_b} = -2 \ln \frac{\mathcal{L}(\mu, \hat{\hat{\theta}}(\mu), \hat{\hat{\gamma}}(\mu))}{\mathcal{L}(\mu = 0, \hat{\hat{\theta}}(0), \hat{\hat{\gamma}}(0))} \quad (4-17)$$

where $\mathcal{L}_{s+b}$ is the likelihood of the nominal signal model and $\mathcal{L}_b$ is that of the background-only hypothesis. In particular, $\mathcal{L}_{s+b}$ corresponds to the likelihood with a signal strength of μ and $\mathcal{L}_b$ corresponds to that with $\mu = 0$. A 95% CL limit can be calculated from this test statistic, which corresponds to the signal strength μ with a p-value of 0.05.

4.8.2 Fit Model

Fit Inputs

The likelihood function is built from the histograms in the signal regions and control regions of all three regimes: resolved $VH(\rightarrow b\bar{b})$, boosted $VH(\rightarrow b\bar{b})$ and $VH(\rightarrow c\bar{c})$. The regions included have been summarized in Figure 4-11. In the resolved regime, different distributions are used in control regions in resolved regimes, summarized in Figure 4-27. For the signal regions, the BDT discriminant is used. In the boosted regime, the BDT discriminant is used in the SRs and the m_J distribution is used in CRs. Detailed studies on the choice of the fit variables and the size of bins were done to have a good control of the backgrounds and signal sensitivity.

BDT transformation

The original binning of the BDT output is equidistant and very fine, which is not optimized for the signal sensitivity. Given the fact that low BDT output scores are populated by background events and almost no signal events, while high BDT output scores have a good signal-to-background ratio, considering the statistical uncertainty of each bin, the BDT transformation is applied. It is designed to optimize the signal sensitivity and reduce the number of bins. The transformation used in the analysis is named as Transformation D, with the formula defined as:

$$Z = z_s \frac{n_s}{N_s} + z_b \frac{n_b}{N_b}. \quad (4-18)$$

where N_s and N_b are the total number of signal and background events respectively, n_s and n_b are the number of signal and background in the new bin. Before the transformation, the BDT output has 500 bins. The bins are merged from highest to the lower output score, until $Z > 1$ is satisfied with increasing n_s and n_b . This forms one bin in the transformed histogram and the



Figure 4-27: Illustration of the control regions in the resolved $VH(\rightarrow b\bar{b}, c\bar{c})$ fit and the variables fitted in each region.

process restarts from the next unmerged bin. z_s and z_b are adjustable parameters that roughly reflect the number of desired signal-enriched bins and background-enriched bins. Normally, the total number of bins of transformed histogram equals to $z_s + z_b$. They are optimized in each analysis regime to give more bins in regions with higher statistics and fewer bins in regions with lower statistics. The values of z_s and z_b are summarized in Table 4-18 and 4-19.

The signal sample used for transformation is dependent in the region and fit type. For $VH(\rightarrow b\bar{b})$ and $VH(\rightarrow c\bar{c})$ signal regions, the signal used is $VH(\rightarrow b\bar{b})$ for 2 b-tagged SRs and $VH(\rightarrow c\bar{c})$ for c-tagged SRs. In the diboson cross-check fit, the $VZ(\rightarrow b\bar{b})$ or $VZ(\rightarrow c\bar{c})$ samples are used for transformation in their corresponding SRs. For the Low ΔR control regions, the signal sample used for transformation is $W + hf$ to have a better control on it.

Additional protection to avoid empty bins in data is added to require each MVA bin after transformation to have at least 3 signal + background events. For the left two bins, they will be merged in the case of the yield difference between the left two bins is larger than 50%. This protection is added to avoid having a very low statistic bins on the left side in some case (especially when using Adaboost for BDT training).

	$75 < p_T^V < 150 \text{ GeV}$	$150 < p_T^V < 250 \text{ GeV}$	$250 < p_T^V < 400 \text{ GeV}$
$VH(\rightarrow b\bar{b})$ SRs	$z_s = 10, z_b = 5$		$z_s = 5, z_b = 3$
$VH(\rightarrow b\bar{b})$ CRLow	$z_s = 7, z_b = 1$	$\begin{cases} \text{2-jet: } z_s = 2, z_b = 1 \\ \text{Else: } z_s = 5, z_b = 1 \end{cases}$	$\begin{cases} \text{2-jet: } z_s = 2, z_b = 1 \\ \text{Else: } z_s = 4, z_b = 1 \end{cases}$
$VH(\rightarrow c\bar{c})$	$\begin{cases} \text{TT-tagged: } z_s = 5, z_b = 3 \\ \text{Else: } z_s = 10, z_b = 5 \end{cases}$	$\begin{cases} \text{0-/1-lepton} & \begin{cases} \text{TT-tagged: } z_s = 5, z_b = 3 \\ \text{Else: } z_s = 10, z_b = 5 \end{cases} \\ \text{2-lepton} & \begin{cases} \text{TT-tagged: } z_s = 2, z_b = 2 \\ \text{LT-/XT-tagged: } z_s = 5, z_b = 5 \\ \text{Else: } z_s = 10, z_b = 5 \end{cases} \end{cases}$	$\begin{cases} \text{TT-tagged: } z_s = 2, z_b = 2 \\ \text{LT-/XT-tagged: } z_s = 5, z_b = 3 \\ \text{Else: } z_s = 10, z_b = 5 \end{cases}$

Table 4-18: Parameter z_s and z_b settings used in Transformation D for different phase space of Resolved Topology.

$400 < p_T^V < 600 \text{ GeV}$	$p_T^V > 600 \text{ GeV}$
$z_s = 5, z_b = 3$	$z_s = \begin{cases} 3 & \text{for 0-, 1-lepton} \\ 2 & \text{for 2-lepton} \end{cases}, z_b = 2$

Table 4-19: Parameter z_s and z_b settings used in Transformation D for different phase space of Boosted Topology.

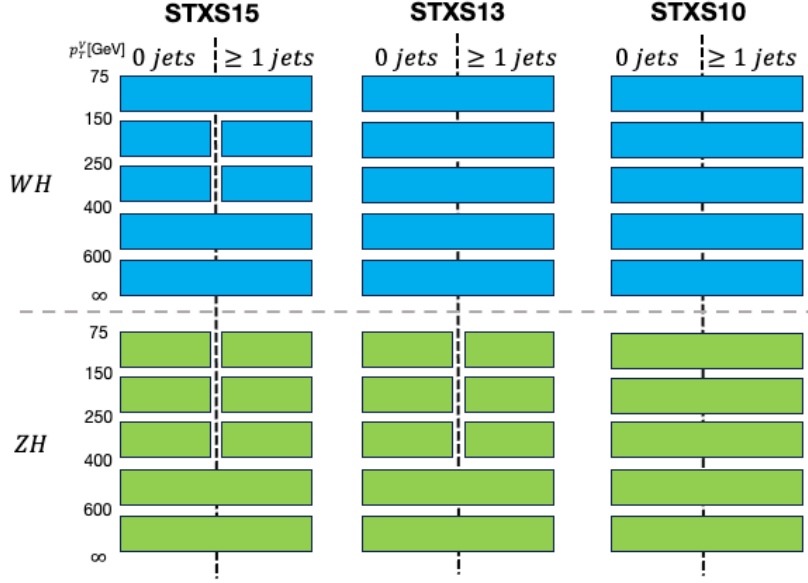


Figure 4-28: Illustration of the STXS schemes used in the $VH(\rightarrow b\bar{b}, c\bar{c})$ fit, split by ZH/WH production mode, p_T^V and number of additional jets, each filled box refer to one STXS bin.

Parameter of Interest

For the normal fit that extract $VH(\rightarrow b\bar{b})$ and $VH(\rightarrow c\bar{c})$ signal strength, several fit schemes are used in the analysis, measuring the $VH(\rightarrow b\bar{b})$ STXS in different granularity. The $VH(\rightarrow c\bar{c})$ signal strength is measured inclusively with one single POI in all the scheme. The scheme that have finest STXS binning is named STXS15, composing 15 POIs for $VH(\rightarrow b\bar{b})$ process, split as mentioned in Section 4.8.3. The other schemes named STXS13 follows STXS15 by merging the jet multiplicity split in WH channel and STXS10 that merge all the jet multiplicity split, as illustrated in Figure 4-28.

There are other schemes that do not split the $VH(\rightarrow b\bar{b})$ in STXS: 2POI scheme that only have 2 POI, one for inclusive $VH(\rightarrow b\bar{b})$ signal strength and one for inclusive $VH(\rightarrow c\bar{c})$ signal strength. $WHZH$ scheme that split the $VH(\rightarrow b\bar{b})$ and $VH(\rightarrow c\bar{c})$ to WH and ZH production.

For the Diboson crosscheck, similar POI schemes are used, except the STXS ones that do not exist for Diboson process.

Asimov Dataset

A common tool to assess the fit performance and estimate the expected sensitivity of analysis is fit to the Asimov dataset. Two kinds of Asimov dataset is used in the analysis: prefit Asimov

and postfit Asimov. The prefit Asimov dataset is built with all NPs set to their central value (expected value). It can be used for the study of the constraints and correlations of NP and POIs. The postfit Asimov is built by profiling the background NPs to the fitted values from an unconditional fit to data, while the signal NPs and POIs are set to their SM prediction. It is used for the calculation of expected significance and limit.

4.8.3 Systematic Uncertainties

Several kinds of uncertainties need to be considered for this analysis to account for the potential discrepancies of modelling. In general, the uncertainties can be divided to the experimental uncertainties and theoretical uncertainties. The experimental uncertainties are the ones related to the detector performance, trigger selection, object reconstruction and flavor tagging. The theoretical uncertainties are the ones related the theory prediction of the physics process, including cross-section calculation, MC modelling and so on. It is sometimes named as modelling uncertainties.

All the experimental uncertainties and modelling uncertainties are introduced in the form of nuisance parameters. The priors of experimental uncertainties follow recommendations and the priors of modelling uncertainties are derived from the MC simulation. They are summarized in the Appendix 6. The following techniques are used for a better description of these uncertainties.

Inter- and Extrapolation The systematic uncertainties are usually saved as separate histogram corresponding to the $\pm 1\sigma$ variation of the nuisance parameters. However, the likelihood function requires a continuous description of the effect. In another word, it requires to have the effect of NP with the NP value corresponding to arbitrary value other than ± 1 . Thus, a polynomial interpolation and exponential extrapolation is used.

Symmetrization For some shape NPs, e.g. the large- R JES uncertainty, only an one-side variation histogram is provided. In these case where only the $+1\sigma$ variation exist, the effect of the NP is symmetrized to obtain the -1σ variation.

Smoothing Since the derivation of the systematic uncertainty is sometimes dependent on the size of MC samples, there is case that the limited statistic results in the fluctuation, which will bring unwanted effect to the fit. To reduce the fluctuation, the smoothing algorithm is applied by using a function to fit the distribution. Two smoothing strategies are used in the analysis: Monotonic and Parabolic, depending on the shape of the systematic uncertainty.

Experimental Uncertainties

All the experimental uncertainties considered in this analysis follow the recommendation provided by the dedicated performance group. A full set of experimental uncertainties are considered in all three regimes, depending on the objects used in the dedicated regime. The uncertainties are kept to be fully correlated wherever possible. All the experimental uncertainties are summarized in Appendix 6.

Luminosity and Pile-up The total integrated luminosity for the full Run-2 data taking period from 2015 to 2018 is 140fb^{-1} with an uncertainty of 0.83% ^[34], obtained using the LUCID-2 detector^[135] for the primary luminosity measurements. The pile-up uncertainties is computed by changing the $\langle \mu \rangle$ (defined in Equation 3-1) from the nominal scale 1.0/1.03 to 1.0/0.99 or 1.0/1.07 to get respectively the up and down variations.

Triggers In this analysis, lepton and E_T^{miss} triggers are used. For the E_T^{miss} triggers, three effects are taken into account as systematic uncertainties. The first part is the SF difference when using different physics process to derive the SFs. Three sets of SFs are derived using W +jets, Z +jets and semi-leptonic $t\bar{t}$ events. The SFs derived with $t\bar{t}$ is used as the nominal and the other two are used as systematic uncertainties. The second part is the statistical uncertainties on the dataset for the derivation of SFs. The third part accounts for the kinematic dependence of the trigger efficiency on the offline p_T sum of all objects.

For the lepton trigger uncertainties, one electron trigger uncertainty is considered, which is supposed to cover systematic and statistical uncertainties on the trigger SFs. For the muon trigger, the systematic and statistical uncertainties are considered separately.

Leptons and E_T^{miss} reconstruction The uncertainties related to the reconstruction of electron and muons are considered following the recommendations of ATLAS. For electron efficiency, the reconstruction efficiency, identification efficiency, isolation efficiency are considered and each of them have one nuisance parameters covering the total uncertainties. The electron energy calibration uncertainties are also considered, including energy scale uncertainty and energy resolution uncertainty. Similar treatment of systematic uncertainties are applied for the muon, with a finer split of systematic uncertainties from different sources. The uncertainties related to the E_T^{miss} reconstruction and scale are also considered.

Jets The systematic uncertainties for small- R jets and large- R jets are considered. For small- R jet, a full set of around 50 systematic uncertainties is derived from jet energy calibration. The baseline set includes uncertainties from *in-situ* analysis, η inter-calibration, high- p_T jets, pile-up, flavor composition, flavor response, b -jets and punch-through jets. The reduced set is used in the analysis, which is derived by principal component analysis. The most prominent sources of jet-related uncertainties are the ones for jet energy scale and jet energy resolution. For the large- R jets, a full set of uncertainties for the jet energy scale, jet energy resolution, jet mass scale and jet mass resolution are considered. For the VR track jets, there is no recommendation available right now thus no momentum or energy uncertainty is considered. However, the tagged track jet has the flavor tagging uncertainties which is expected to cover most effects from reconstruction.

Flavor Tagging The calibration of the PCFT used in the resolved regime is described in Section 4.3.1. The tagging for track jets follows the recommendation. However, the official calibrations have a limited reach in jet p_T , which is lower than the jet p_T used in the analysis. Thus, the uncertainties are extrapolated from the last calibrated bin to beyond. There are quite a lot of individual sources of systematic uncertainties from the calibration, reaching up to around 160 variations for resolved PCFT. In order to alleviate the burden of using so many variations, a principal component analysis is used to reduce the number of variations. The loose reduction scheme results in 105 variations for small- R jets and 110 variations for VR track jets.

For the hadronic tau jet, no independent calibration is available due to its low statistics in

the calibration region. Since the tagging efficiency for c -jet and τ -jet is similar, the same scale factors and variations are applied to c -jet and τ -jet.

Modelling Uncertainties

The signal and background in this analysis are mostly modelled using the Monte Carlo simulation. In order to assess the uncertainties of the modelling, the alternative samples are also generated to compare with the nominal sample or using the internal weight variations of the nominal samples. The idea is to disentangle different sources of uncertainties. So different alternative samples are used to assess the impact of e.g. matrix element or parton shower variations. Since the resolved $VH(\rightarrow b\bar{b})$ and $VH(\rightarrow c\bar{c})$ share similar topology, the modelling uncertainties are correlated as much as possible between two regimes. The uncertainties in boosted $VH(\rightarrow b\bar{b})$ regime are considered separately.

The modelling uncertainties are derived for different process and can be divided to the following categories according to the impact:

Normalization Uncertainties are the ones that alter the overall yield of a process in several or all regions. They can be derived from the simulated samples by comparing the yield difference between generators, or they can also free float in the fit and be constrained by the data.

Acceptance Ratios account for the difference of yield in the specific phase space, due to the different acceptance between generators (or same generator with different setup) after all the samples are normalized to same cross-section. This will result in a change in the ratio between the number of events across the regions. In this case, the acceptance uncertainties are treated as a Gaussian constraint with the prior calculated as double ratios:

$$\frac{\text{Acceptance}[\text{Cat.}^B(\text{alternative MC})]}{\text{Acceptance}[\text{Cat.}^B(\text{nominal MC})]} \bigg/ \frac{\text{Acceptance}[\text{Cat.}^A(\text{alternative MC})]}{\text{Acceptance}[\text{Cat.}^A(\text{nominal MC})]} \quad (4-19)$$

where category A (Cat.^A) is the region with highest purity and category B is the other region under test. In the case of extrapolation accross several regions A, B and C, which have decreasing purity, the acceptance uncertainty is first computed from the purest region to the two less

pure ones, i.e. $A \rightarrow [B+C]$, and then between the two less pure regions, i.e. $B \rightarrow C$. The usage of double-ratios avoid double counting with the normalization uncertainties. The uncertainties from different sources are calculated individually and then added in quadrature:

$$\text{Total acceptance} = \sqrt{\sum_i (\text{Acceptance unc}_{var_i})^2} \quad (4-20)$$

Shape Uncertainties consider the difference in shape of distributions used for fit when comparing different MC samples. The shape uncertainties can be derived by the direct comparison between MC samples after normalized to same yield in the specific phase space. This approach is used for e.g. the shape uncertainties originated from QCD scales and the Parton Shower variations for signal process. This method requires to have enough events for both nominal samples and alternative samples to derive a meaningful shape uncertainty. Thus, it is suitable for the uncertainties assessed from internal weight variation or with large size of MC samples.

However, the MC generation consumes a lot of time and computing resources. In order to solve this problem, a new approach named Calibrated Likelihood Ratio Estimators (CARL) is used. CARL is a reweighting technique based on the deep neural network. The neural network is trained to distinguish the difference between nominal sample and alternative sample using the same input variables as MVA that is described in Section 4.7. The output of CARL for each single event is the probability of the specific event coming from the alternative sample. Applying the probability as an event weight to the nominal sample would hence reweight the nominal sample and make the distribution to follow the shape of the alternative sample. Because of the much larger size of the nominal samples compared to the alternative samples, this reweighting process can smooth out statistical fluctuations and provide shape uncertainties as the CARL-reweighted sample.

In order to have adequate events for a stable training, some regions are merged. For example, in the CARL training for $t\bar{t}$ in $VH(\rightarrow b\bar{b})$ 0-lepton channels. The events are only split by the event flavor to $b\bar{b}$ and non- $b\bar{b}$, merging all the SRs and CRs, jet multiplicity and pTV regions. Figure 4-29 shows the distribution after CARL reweighting and it can be found that the reweighted distribution keeps the shape of alternative sample while smooth out the statistical fluctuations.

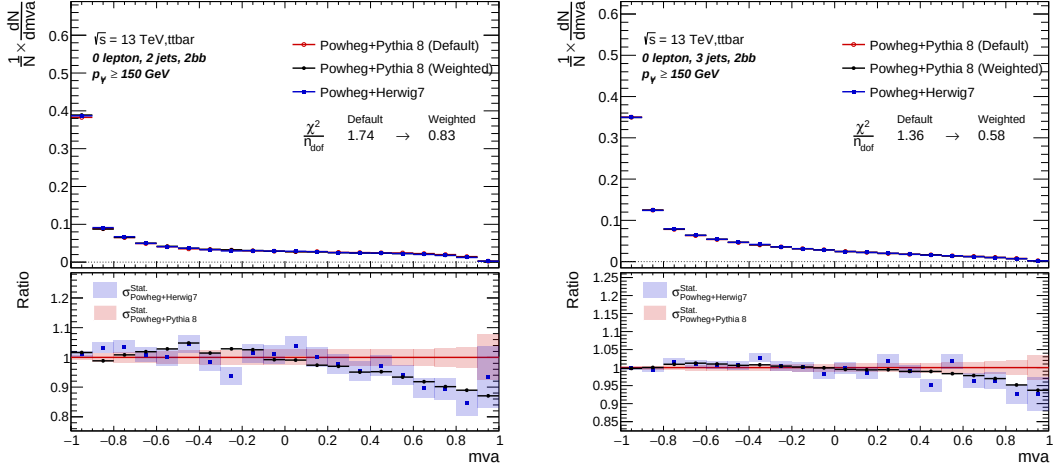


Figure 4-29: Comparison of MVA distribution between nominal sample (red), alternative sample (blue) and nominal sample after CARL reweighting (black) in $VH(\rightarrow b\bar{b})$ 0-lepton 2-jets (left) and 3-jets (right) SR+CR.

Sample	Nominal Generator	Alternative Generators	systematic effectes
$VH(\rightarrow c\bar{c})$	POWHEG + PYTHIA 8	POWHEG + HERWIG 7	$\mu_R, \mu_F, \text{ISR/FSR, PDF}$
$VH(\rightarrow b\bar{b})$	POWHEG + PYTHIA 8	POWHEG + HERWIG 7	$\mu_R, \mu_F, \text{ISR/FSR, PDF}$
Diboson	SHERPA 2.2.11	POWHEG +PYTHIA 8, SHERPA 2.2.1	μ_R, μ_F, PDF electroweak corrections
$t\bar{t}$ and single-top	POWHEG +PYTHIA 8	POWHEG +HERWIG 7, MADGRAPH 5_aMC@NLO+PYTHIA 8	Additional ISR/FSR DS/DR (single-top Wt)
V+jets	SHERPA 2.2.11	MADGRAPH FxFx, SHERPA 2.2.1	$\mu_R, \mu_F, \text{PDF,}$ electroweak corrections

Table 4-20: Summary of samples in the analysis, their nominal and alternative generators and systematic effects used to assess signal and background modelling uncertainties.

Table 4-20 summarizes the nominal samples, alternative samples and scale variations used for all the samples in this analysis.

Signal Modelling

A full set of systematic uncertainties are derived for the $VH(\rightarrow b\bar{b}, c\bar{c})$ signal. The sources of the systematic uncertainties includes QCD scale, PDF+ α_S variations, electroweak corrections, branching ratio, parton shower and underlying events. The details of the signal uncertainties will be discussed below.

STXS signal parameterization One of the main goal of the analysis is to measure the fiducial cross-section for $VH(\rightarrow b\bar{b})$ process based on STXS Stage 1.2 Scheme^[136-137] as illustrated in Figure 4-30. The scheme split the cross-section in terms of p_T^V and the jet multiplicity (n_{jet}) as well as the production mode. The p_T^V is the approximation of the momentum of Higgs and n_{jet} reflects the number of ISR jets in the event. There are in total of 45 bins in the STXS 1.2 scheme, and it is very challenging to constrain all the bins in the fit due to the statistic limitation. As a result, the reduced STXS split is used in the fit which merge some STXS bins to obtain enough number of events for a reasonable constraint, the details of the split will be discussed in Section 4.8.2. It should be noticed that the $VH(\rightarrow b\bar{b})$ and $VH(\rightarrow c\bar{c})$ signals are produced in full STXS 1.2 split as well as the signal systematic uncertainties, and merged to the scheme used in the fit in a later stage.

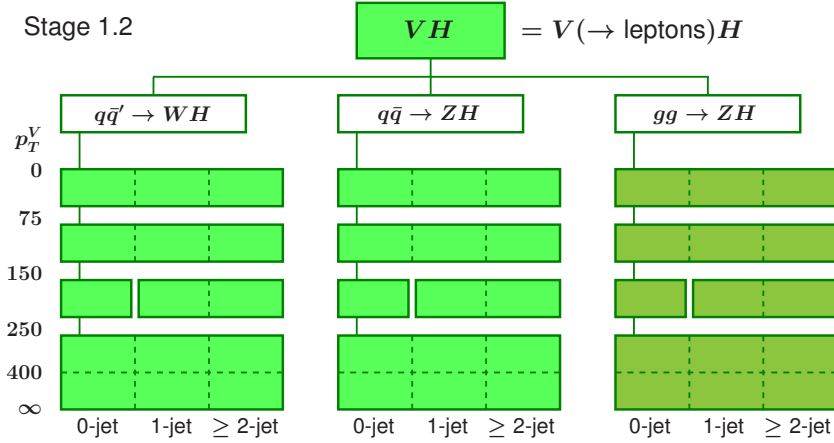


Figure 4-30: Illustration of full STXS 1.2 scheme used in the analysis.

For ZH process, 5 p_T^V bins are covered: [75,150], [150,250], [250,400], [400,600] and >600 GeV. The first three p_T^V bins are further split into two based on n_{jet} : one for 0-jet and one for ≥ 1 -jets. For WH process, similar split as ZH are used with the only exception that the [75,150] GeV bin is not further split in n_{jet} . In the final fit results, some bins are merged to have a better constraint.

All the systematic uncertainties are derived with the STXS split (which is much finer than the STXS scheme used for fit) and partially merged into the scheme used. The $VH(\rightarrow c\bar{c})$ process also applied the STXS scheme in order to correlate the uncertainties with $VH(\rightarrow b\bar{b})$. However, only an inclusive signal strength is used in the analysis due to the limited statistics

in each bin, which means that all the STXS bins are merged. The acceptance uncertainties of signal process are derived using the Steward-Tackmann (ST) method^[138] for the consideration of signal migration among the STXS bins.

QCD scale uncertainties The most important uncertainties in the theoretical prediction of VH production cross-section come from the variations of the renormalization and factorization scale, μ_r and μ_f , which will affect ISR and FSR. They are considered as normalization and shape uncertainties.

PDF+ α_S uncertainties The PDF+ α_S uncertainties consider the variations of PDF setup and the strong coupling strength. The nominal PDF set PDF4LHC15NLO^[115] defines 30 sets of alternative PDFs and two α_S variations. They are considered as normalization uncertainties.

Electroweak corrections Uncertainties on the NLO electroweak corrections modify the p_T^V shape and the cross-section. The uncertainties are considered as shape and normalization uncertainties.

Branching ratios The theoretical uncertainties on the $H \rightarrow b\bar{b}$ is 1.61%^[19], which is dominated by uncertainties on the b -quark mass and $\alpha_S(m_Z)$. For $H \rightarrow c\bar{c}$, the uncertainties is 5.53% for up variation and -1.99% for down variation.

Parton Shower and underlying event The parton shower and underlying event uncertainties are considered by the alternative sample using a different PS model (HERWIG 7) than the nominal one (PYTHIA 8). The MVA distribution from the alternative sample is directly used as shape and normalization variations, meanwhile the acceptance uncertainties are included to take into accounts the effects on STXS normalization.

Background Modelling

Most of the background process are modelled by Monte Carlo simulation, as mentioned in Section 4.2. A full set of systematic uncertainties are included for these processes. The treat-

ment of systematic is coherent between resolved regime and boosted regime unless specified. Table 4-21 gives the summary of all the systematic uncertainties included in the analysis.

W +jets The production of W +jets is a main background in the 1-lepton channel. In the 0-lepton channel, the events with hadronically decay τ leptons or unidentified electron/muons also contribute to the background. According to the flavor composition of the jets that used to reconstruct the H_{cand} , the W +jets process is divided to three different components: $W + hf$ (including $W + bb$ and $W + cc$), $W + mf$ (including $W + bc$, $W + bl$, $W + cl$) and $W + lf$. The normalization factor of these three kind of background are allowed to free float in the fit. The floating normalizations are all decorrelated in p_T^V and n_{jets} . Two sets of alternative samples are used for W +jets process as listed in Table 4-20. Deriving from these alternative samples, several kinds of acceptance are considered, including extrapolation uncertainties from 1-lepton to 0-lepton channel and between SRs and CRs, several ratios between different flavor composition and the acceptance uncertainties between different jet multiplicities regions.

Several kinds of shape uncertainties are considered for W +jets. The alternative samples are used for the derivation of ME and PS shape uncertainties using CARL. As the SHERPA 2.2.11 is found to disagree with the data more than SHERPA 2.2.1 in some certain p_T^V regions, additional shape uncertainty is derived from the SHERPA 2.2.1 distribution. The shape uncertainties originated from QCD scale and electroweak corrections are also considered.

Z +jets is the main background in 0-lepton channel and 2-lepton channel. The treatment of Z +jets uncertainties is consistent with the W +jets. It is also categorized into three components: $Z + hf$, $Z + mf$ and $Z + lf$, with corresponding normalization factors applied to them. The normalization factors are decorrelated in p_T^V and n_{jets} , with some slight adjustment of correlation scheme for better constraint. Similar acceptance uncertainties and shape uncertainties as W +jets are considered for Z +jets process, with the exception that the acceptance uncertainties between different jet multiplicity regions are removed since it is covered in floating normalizations.

Top The top background contains the $t\bar{t}$ production and single-top production. The top background in $VH(\rightarrow b\bar{b})$ 2-lepton is estimated from data-driven method and an extrapolation uncertainty of 0.8% is applied to it. In $VH(\rightarrow c\bar{c})$ 2-lepton channel, the top background is estimated

using the MC simulation and the floating normalization are applied to simultaneously control the $t\bar{t}$ and single-top process. An additional 4.6% cross-section uncertainties are applied to single-top s -channel.

In the 0-lepton and 1-lepton channel, $t\bar{t}$ has much more contamination and thus the following systematic uncertainties are applied, including floating normalizations, relative acceptance uncertainties and shape uncertainties. The floating normalizations take care of the main processes related to top quark ($t\bar{t}$ and Wt) and leave them float freely, and the dedicated topCR and High ΔR CR can provide constraints to the normalizations¹. The relative acceptance uncertainties are derived for the ME and PS contributions as well as for the ISR and FSR contributions. The shape uncertainties in top related backgrounds come from two types of sources. For the ME and PS contributions, CARL framework is used to compare the nominal POWHEG +PYTHIA 8 samples with POWHEG +HERWIG 7 and MADGRAPH 5_aMC@NLO+PYTHIA 8 samples to derive the shape uncertainties. For ISR and FSR contributions, the shape uncertainties are extracted with nominal sample using internal weight. To estimate the effect of different treatments of the Wt - $t\bar{t}$ interference, an additional DS-DR uncertainty is applied to single-top Wt events, derived directly use the difference between the two samples. The DS scheme is used as nominal and DR is used as alternative.

Diboson The diboson background consists of WW , WZ and ZZ processes, which constitute a small background in all regions. However, the $VZ(\rightarrow b\bar{b})$ and $VZ(\rightarrow c\bar{c})$ process are used as the cross-check signals to test the analysis strategy. Four normalization uncertainties for ZZ , WW , WZ and $ggVV$ are calculated for each process and harmonized for $VH(\rightarrow b\bar{b})$ and $VH(\rightarrow c\bar{c})$. For the acceptance uncertainties of the VZ signal process, the ST method is used same as VH signals. The acceptance uncertainties can be divided into the following categories: acceptance uncertainties among STXS bins, lepton channels, jet multiplicities, p_T^V regions and between SRs and CRs. For the sources of the acceptance uncertainties, they are mainly coming from: PS+ME difference evaluated by generator difference, QCD scale variations, electroweak corrections and PDF+ α_S variations. The shape uncertainties come from four sources. The ME+PS one is derived with CARL framework. The ones from QCD scale, PDF and electroweak

¹ For single top s - and t -channel events, no floating normalization is applied, and instead an overall normalization uncertainty is derived

are derived by direct comparison.

4.8.4 V +jets p_T^V shape uncertainties study

The modelling of V +jets, one of the major background of the analysis, has significant impact on the signal extraction. It is simulated with two versions of SHERPA, 2.2.1 and 2.2.11, and the later version is used as the nominal sample. However, it has been observed that the p_T^V modelling is different between SHERPA 2.2.1 and SHERPA 2.2.11, likely due to an updated scale choice in SHERPA 2.2.11. As can be seen in Figure 4-31, SHERPA 2.2.1 overshoots the data at very high p_T^V , while the SHERPA 2.2.11 prediction is lower than the data, with the discrepancy increasing with p_T^V . As shown in Figure 4-32 for 2-lepton $VH(\rightarrow c\bar{c})$, SHERPA2.2.1 seems to agree better with data in the parameter space that this analysis targets.

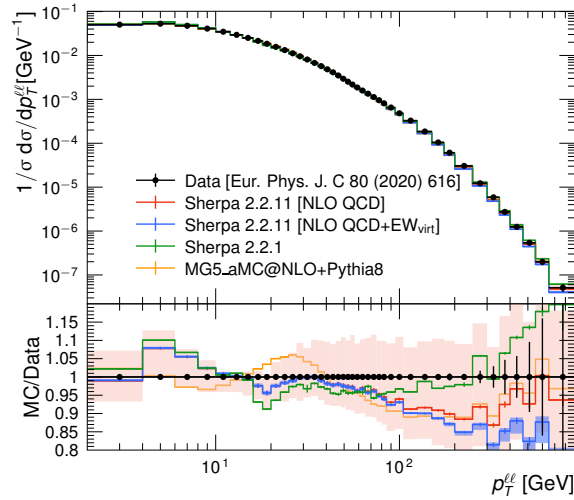


Figure 4-31: PMG SHERPA 2.2.1 (green), SHERPA 2.2.11 (blue), and data (black) agreement for Z boson dilepton decays .

Since the observed differences cannot be covered by the QCD scale uncertainties, dedicated p_T^V shape uncertainties were derived from comparisons of SHERPA 2.2.11 to SHERPA 2.2.1. As shown in Figure 4-33, a polynomial function is fitted to the ratio between SHERPA 2.2.1 over SHERPA 2.2.11 over p_T^V , which is then propagated to the other distributions in the analysis regions, and used as a shape uncertainty. The shape uncertainties are derived inclusively in tag regions and jet multiplicity, but separately for W +jets and Z +jets, and split in the V +hf, V +mf and V +light components. The reweighting polynomials are derived in $VH(\rightarrow c\bar{c})$ and applied to all $VH(\rightarrow b\bar{b}, c\bar{c})$ V +jets.

Uncertainties	resolved $VH(\rightarrow b\bar{b}, c\bar{c})$	boosted $VH(\rightarrow b\bar{b})$
VH $WH/qqZH/ggZH$ normalisation/acceptance $H \rightarrow b\bar{b}$ BR $H \rightarrow c\bar{c}$ BR	to be updated (using values from previous analyses) 1.61% +5.53% -1.99%	
Diboson $WW/ZZ/WZ$ normalisation $ggVV$ normalisation Lepton channel acceptance N_{jet} acceptance p_{T}^V acceptance SR-CR acceptance STXS like binning acceptance	16%/17%/19% 2-23% 10%-42% 3%-16% 6%-50% -37.4-32.0%	16%/17%/27% 7-10% - 7%-40% - -22-10.6%
Z+jets $Z + hf$ normalisation $Z + mf$ normalisation $Z + lf$ normalisation $Z + hf$ flavour composition acceptance $Z + mf$ flavour composition acceptance Flavour composition acceptance between Zhf and Zmf High- ΔR -CR-SR acceptance topCR-SR acceptance 2- to 0-lepton acceptance p_{T}^V acceptance	Floating Floating 8%-12% 4%-10% - 5%-30% - 2%-10% -	Floating Floating together with Zhf 35% 6% 6% 5% - 15%-25% 3% 15%
W+jets $W + hf$ normalisation $W + mf$ normalisation $W + lf$ normalisation $W + hf$ flavour composition acceptance $W + mf$ flavour composition acceptance $W + lf$ flavour composition acceptance Flavour composition acceptance between Whf and Wmf High/Low- ΔR -CR-SR acceptance topCR-SR acceptance 1- to 0-lepton acceptance p_{T}^V acceptance N_{jet} extrapolation	Floating Floating 4%-25% 8-29% 9% - 2-50% - 3%-30% - 12-20%	Floating Floating together with Whf 38% 11% 9%-15% - 5% - 16%-27% 20% 3% -
Top (0- and 1-lepton, excluding single top s/t) Top(bb) normalisation Top(others) normalisation Flavour composition acceptance 1- to 0-lepton acceptance High/Low- ΔR -CR-SR acceptance topCR-SR acceptance $Wt / t\bar{t}$ ratio	Floating Floating 5% - 10% 2% - 8% 2% - 10% - 12-48%	Floating (together with Top(others)) Floating (together with Top(bb)) - 6-17% - 14-19% 22-36%
Top (2-lepton) Normalisation	Floating ($VH(\rightarrow c\bar{c})$), 0.08% ($VH(\rightarrow b\bar{b})$ *)	
Single-top s-/t-channel (0- and 1-lepton) Normalisation High/Low- ΔR -CR-SR acceptance p_{T}^V extrapolation ratios N_{jet} acceptance 1- to 0-lepton acceptance ratio	4.6% (s -channel), 17% (t -channel) 3% - 17% 7% - 15% 15% 6%	4.6% (s -channel), 10% (t -channel) - - - -
Multi-jet (1-lepton)* Normalisation	20%-100%	

Table 4-21: Summary of the background modelling systematic uncertainties considered. The values given refer to the size of the uncertainty affecting the yield of each background.

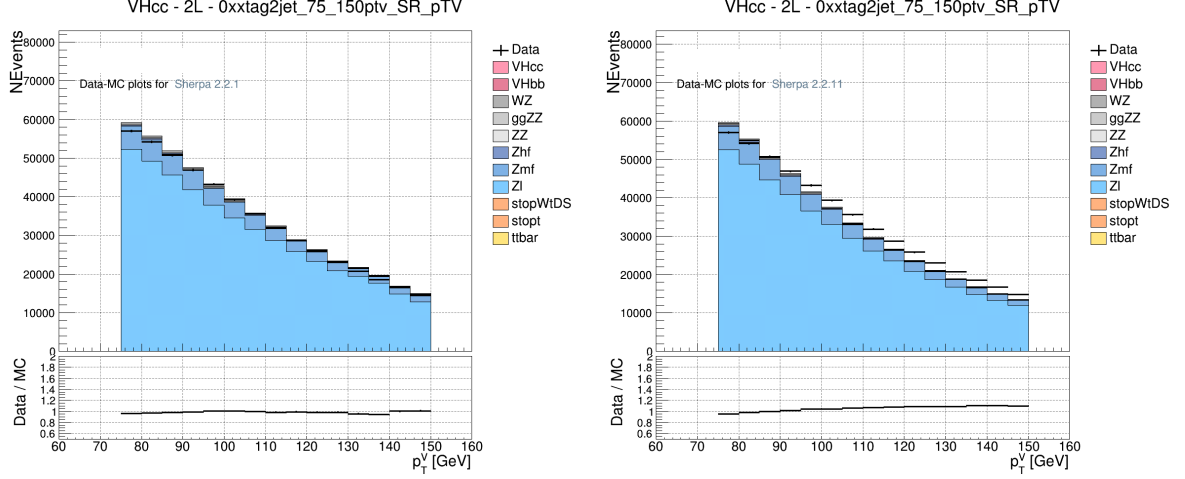


Figure 4-32: SHERPA 2.2.1 (left), SHERPA 2.2.11 (right), and data (black) agreement in 2-lepton $VH(\rightarrow c\bar{c})$.

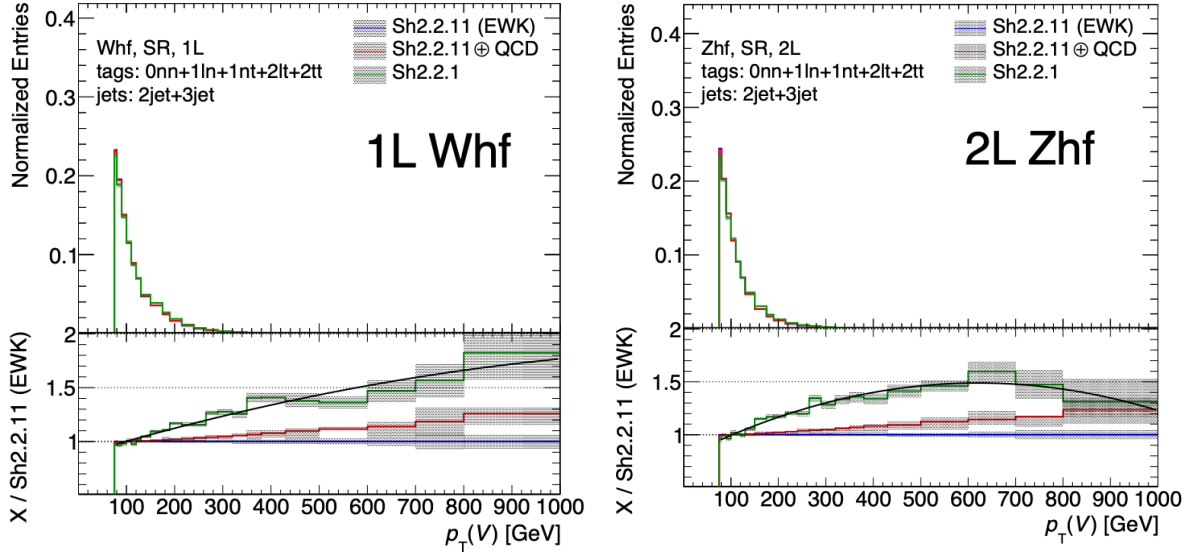


Figure 4-33: W+jets (left) and Z+jets (right) distribution of SHERPA 2.2.11 .

The SHERPA 2.2.1 p_T^V uncertainties are used as a shape-only uncertainty and introduce around a 10% shape effect in all analysis phase space. Detailed fit studies were performed to understand the behaviour of this uncertainty and use the control regions to constrain it well. It was found that the shape uncertainties behave similarly for $V+hf$ and $V+mf$, and differently for $V+l$, hence the uncertainties are treated as correlated for $V+hf/mf$, and kept separate for $V+l$. The fit variables in the high ΔR control regions were explicitly chosen to ensure the p_T^V shape uncertainties are well-constrained for all flavour components. To constrain the $V+l$ component, p_T^V is chosen as the fit variable in the 1-lepton and 2-lepton LN-tag V +light control regions. To constrain the $V+hf/mf$ components, p_T^V is chosen as the fit variable in the 1-lepton and 2-lepton

TN-tag high ΔR control regions. Additionally, the p_T^V distribution is also fitted in the BB-tag high ΔR control region in the 2-lepton channel to add additional constraints for the $V+hf/mf$ component.

As shown in Figure 4-34, the Z+l and Z+hfmf pulls are well-constrained in the resolved regions. There is no sensitivity to the shape uncertainty in the boosted region.

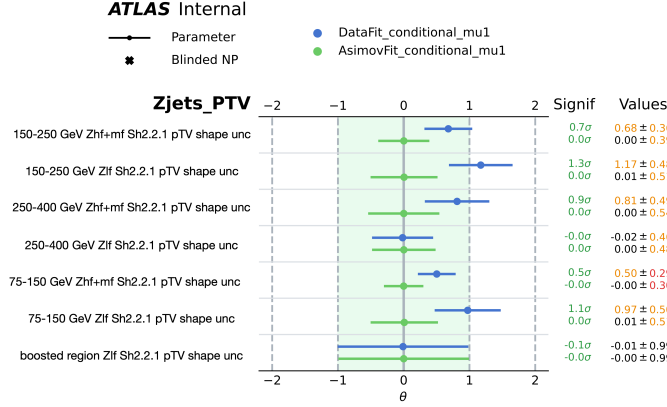


Figure 4-34: SHERPA 2.2.1 $p_T^{V,t}$ pulls in 2-lepton $VH(\rightarrow b\bar{b}, c\bar{c})$.

Pseudo-data fit

Though the p_T^V mismodelling is not visible in the post-fit p_T^V distribution of control regions and signal regions, as the numerous number of nuisance parameters, there is doubt that whether these shape uncertainties can capture the shape discrepancies. Especially, since the high BDT score bins in signal region is less populated, there is concern that the p_T^V mismodelling brings bias on signal extraction. Thus, a Pseudo dataset is built with all the p_T^V shape uncertainties are pulled to 1σ , while other nuisance parameters are fixed to their expected value, which represents the situation that there is a mismodelling that is exactly like the SHERPA 2.2.1. Figure 4-35 shows the p_T^V distribution with the Pseudo dataset in some regions that is sensitive to the mismodelling. Compared with a real data fit, the fit to Pseudo Data could rule out the possibility that the nuisance parameters and signal strengths are pulled by the statistical fluctuation of the data as well as the mismodelling of other background components.

An unconditional fit is then applied to this Pseudo dataset, to see if the shape nuisance parameters are correctly pulled and other nuisance parameters are not affected. As shown in Figure 4-36, the p_T^V shape divergency is corrected after the fit. Figure 4-37 and 4-38 show the

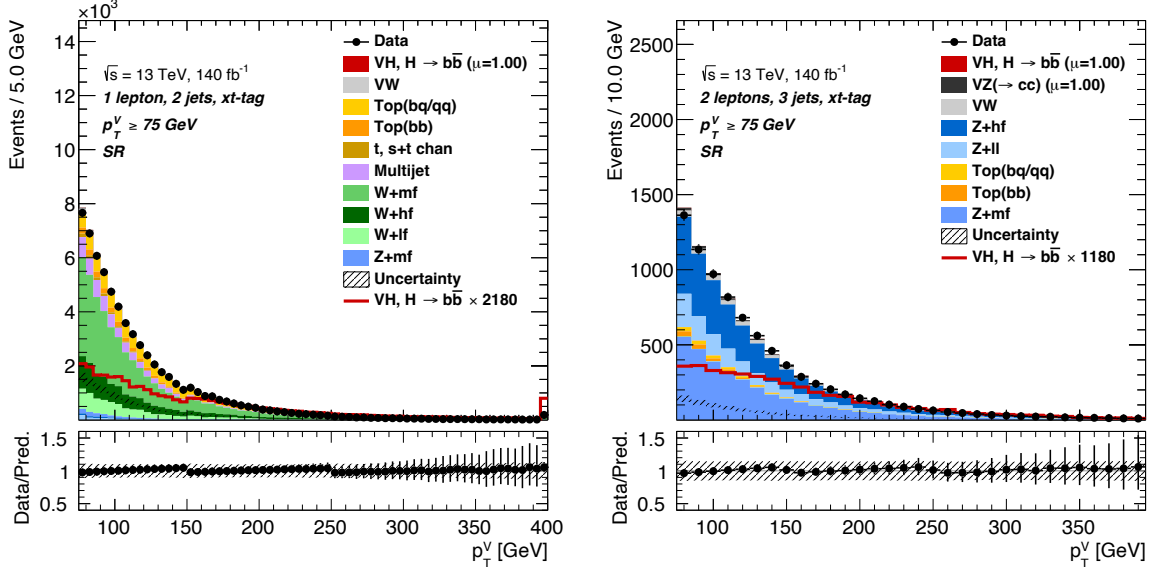


Figure 4-35: Prefit distribution with the Pseudo dataset in 1-lepton 2c-tag 2-jets SR (left) and 2-lepton 2c-tag 3-jets SR (right).

pulls of these p_T^V shape nuisance parameters. Except for the ones related to boosted region, where the p_T^V control regions are not used, and the one related to Whf component which the shape cannot be well constrained in CRLow, all the other nuisance parameters are sufficiently pulled to the value close to 1. In the meantime, the other nuisance parameters are mildly pulled from the expected value. This test indicates that the p_T^V shape uncertainties can indeed capture the p_T^V mismodelling, and the discrepancies will not be captured by other nuisance parameters.

The corresponding signal strength in the Pseudo dataset fit is:

	bb	cc
μ_{VH}	1.00 ± 0.13	1.15 ± 5.10
μ_{VZ}	1.00 ± 0.13	1.00 ± 0.23

The final fitted signal strength is consistent with the expected value, the $VH(\rightarrow b\bar{b})$ signal strength is consistent with 1 and $VH(\rightarrow c\bar{c})$ signal strength is slightly pulled compared to its error, which means that the impact of the p_T^V mismodelling on the signal strength is negligible.

In order to further test whether these p_T^V shape NPs can handle larger discrepancy, a 2σ Pseudo dataset is built by fixing the p_T^V NPs to 2σ and other NPs fixed to expected values. The fit results show consistent results with the 1σ case, the p_T^V shape NPs are pulled to the values close to 2, as shown in Figure 4-39 and Figure 4-40. The bias on $VH(\rightarrow b\bar{b})$ signal strength ($\mu_{VH(\rightarrow b\bar{b})} = 1.00 \pm 0.13$) is negligible and the bias on $VH(\rightarrow c\bar{c})$ signal strength

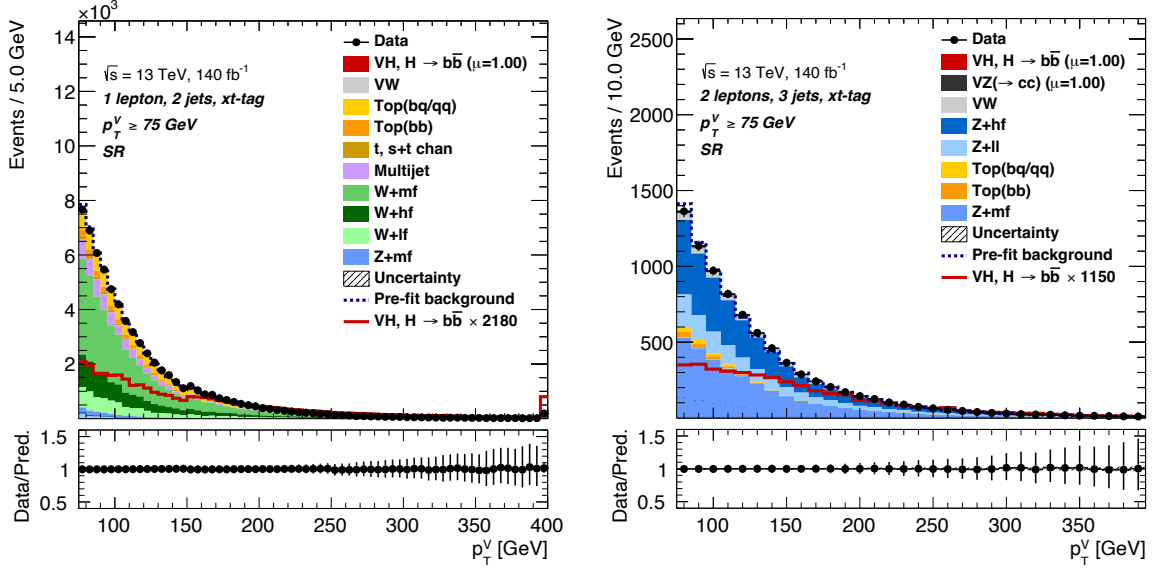
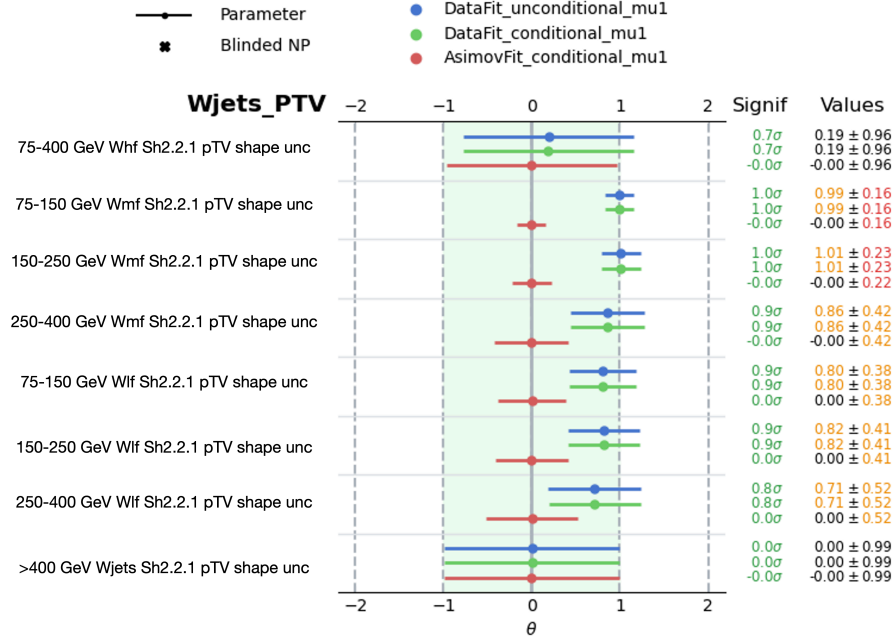
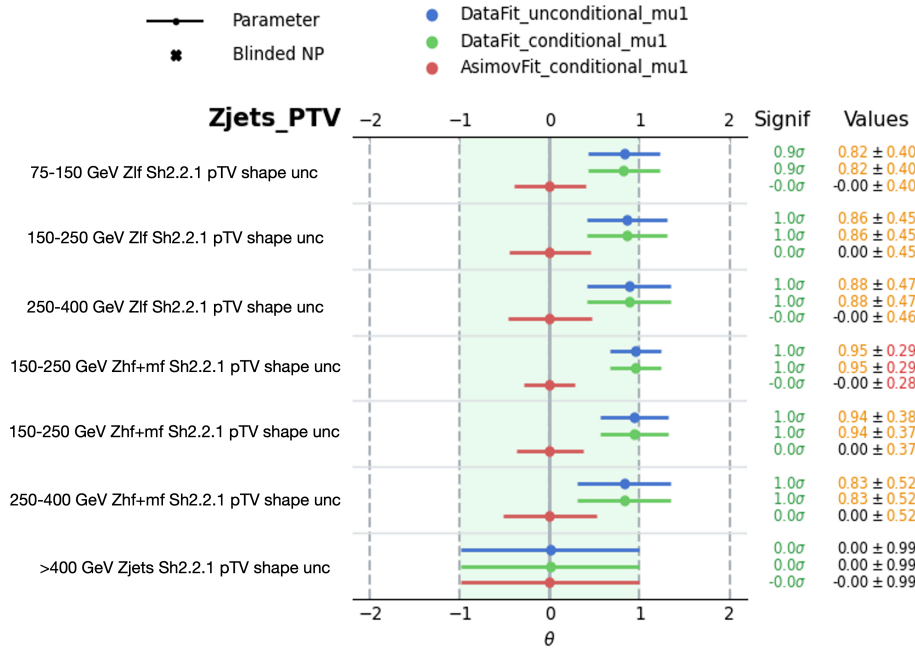


Figure 4-36: Postfit distribution with the Pseudo dataset in 1-lepton 2c-tag 2-jets SR (left) and 2-lepton 2c-tag 3-jets SR (right).

($\mu_{VH(\rightarrow c\bar{c})} = 1.29 \pm 4.81$) is two times the 1σ case, which is still negligible compared to its error.

A similar test is done with the STXS fit to the 1σ pull Pseudo dataset, to see if the STXS signal extraction will be biased by the p_T^V mismodelling. The results show that the bias on the STXS signals are still negligible, all of the STXS signal strengths are close to 1, with maximum deviation smaller than 0.05σ . The other NPs related to the signal modelling are not pulled. The rest of the nuisance parameters are consistent with their performance in the inclusive mu fit.

Figure 4-37: W +jets p_T^V shape pulls in fit to Pseudo dataset.Figure 4-38: Z +jets p_T^V shape pulls in fit to Pseudo dataset.

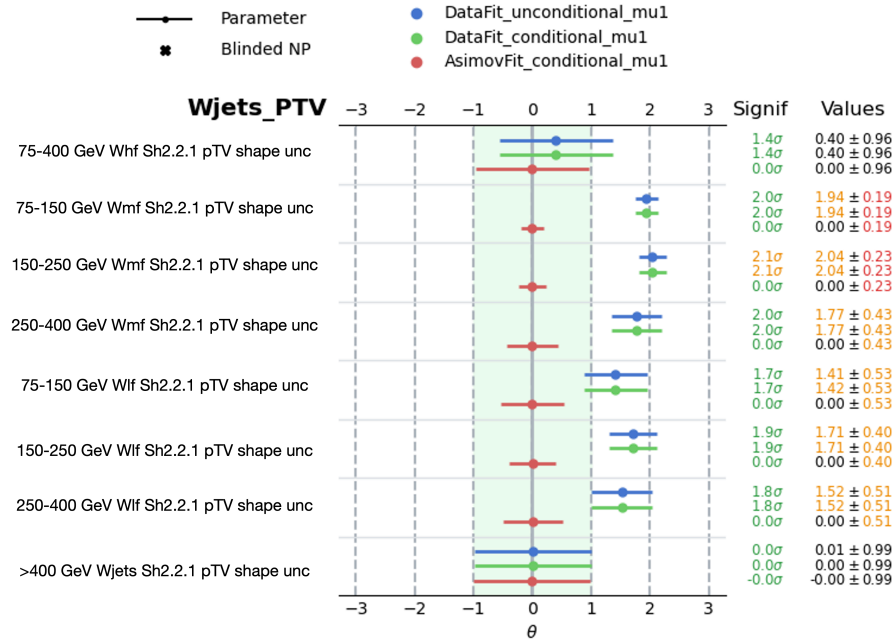


Figure 4-39: W +jets p_T^V shape pulls in fit to Pseudo dataset that pull V +jets p_T^V shape NPs to 2σ .

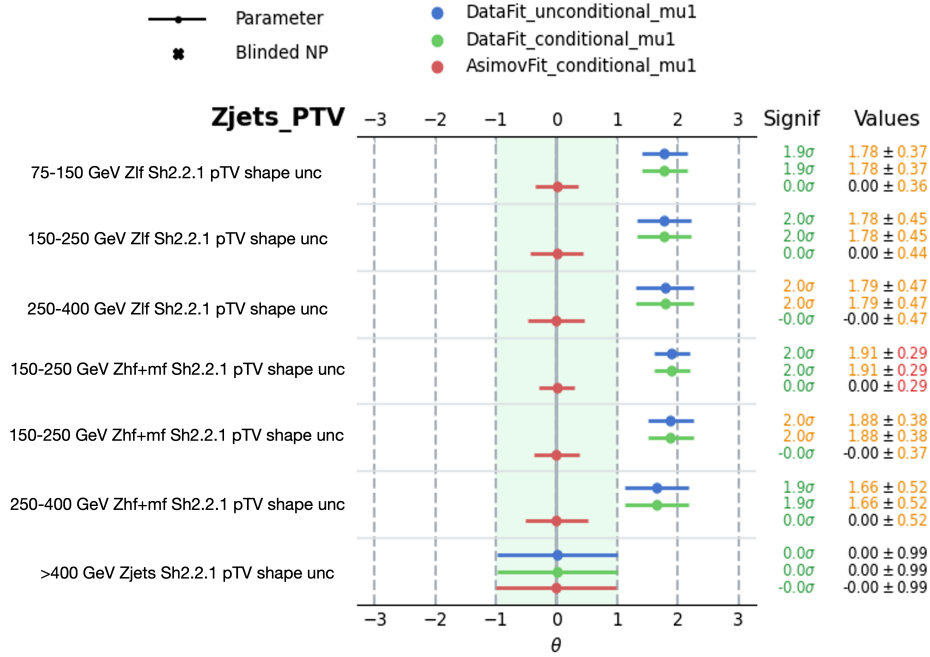


Figure 4-40: Z +jets p_T^V shape pulls in fit to Pseudo dataset that pull V +jets p_T^V shape NPs to 2σ .

4.9 Results

After the fit model is established, the fit can be performed to extract the signal strength as well as other statistical results, e.g. significance and upper limit, of the signal process. This Section will present the fit results from $VH(\rightarrow b\bar{b}, c\bar{c})$ fit and Diboson cross-check fit.

4.9.1 $VH(\rightarrow b\bar{b}, c\bar{c})$ Combined Fit Results

The best fit signal strength and uncertainties for $VH(\rightarrow b\bar{b})$ process are:

$$\mu_{VH}^{bb} = 0.91_{-0.14}^{+0.16} = 0.91_{-0.10}^{+0.10} \text{ (stat.) }_{-0.11}^{+0.12} \text{ (syst.)} \quad (4-21)$$

and for $VH(\rightarrow c\bar{c})$ process:

$$\mu_{VH}^{cc} = 1.0_{-5.2}^{+5.4} = 1.0_{-3.9}^{+4.0} \text{ (stat.) }_{-3.5}^{+3.6} \text{ (syst.)} \quad (4-22)$$

The expected significance for $VH(\rightarrow b\bar{b})$ signal is 8.0σ , while the observed significance is 7.4σ . The upper limit at 95% confidence level (CL) on the $VH(\rightarrow c\bar{c})$ signal strength at $11.3\times$ SM prediction, with the expected value being $10.4_{-3.0}^{+4.2}\times$ SM prediction. This is the best observed limit on $VH(\rightarrow c\bar{c})$ process up to now. Compared with previous ATLAS results, the upper limit on $VH(\rightarrow c\bar{c})$ improves by more than 100%. It mainly profits from the improved c -jet tagging efficiency with the new tagger and much better signal-background separation with the MVA. Additional reasons for the improvement includes the application of kinematic fit in $VH(\rightarrow c\bar{c})$ 2-lepton channel, improved MC statistics and better control of top and V +jets process with new CRs.

Figure 4-41 shows the fit results and 68% and 95% CL contours. The results have good consistency with the SM with the compatibility of 85.6%. The correlation between 2 POI is 5%.

The postfit distribution of the BDT score in some selected sensitive SRs are shown in Figure 4-42~4-44. The distribution of all regions in the fit are shown in Appendix 6. The normalization of the major background, W +jets, Z +jets and $t\bar{t}$, are shown in Table 4-22, 4-23 and 4-24 respectively. In general, the W +jets and Z +jets normalization factors exhibit similar behaviors,

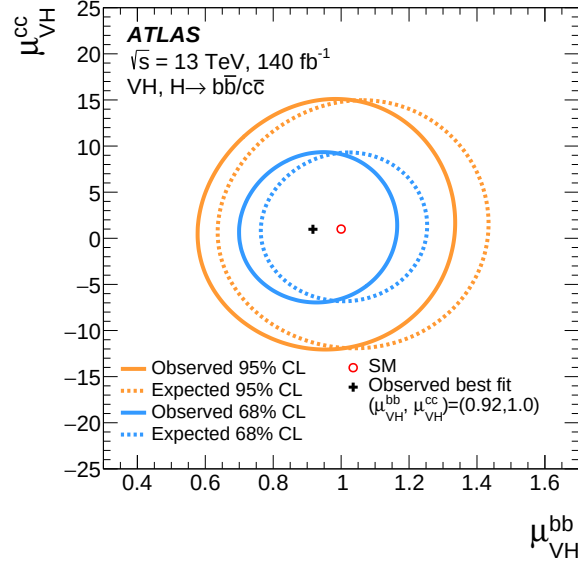


Figure 4-41: The observed (solid lines) and expected (dashed lines) 68% and 95% CL contours of the $VH(\rightarrow b\bar{b})$ and $VH(\rightarrow c\bar{c})$ signal strengths, along with their best fit values.

increasing with the number of additional jets and with p_T^V . The normalization factors for $t\bar{t}$ process are more close to unity and have a different trend, decreasing with p_T^V .

p_T^V region	num. jet	$W + hf$	$W + mf$	$W + lf$
[75,150] GeV	2	1.09 ± 0.06	1.20 ± 0.03	1.03 ± 0.04
	≥ 3	1.30 ± 0.07	1.16 ± 0.04	1.07 ± 0.05
[150,250] GeV	2	1.00 ± 0.05	1.31 ± 0.03	1.08 ± 0.03
	≥ 3	1.28 ± 0.07	1.31 ± 0.04	1.07 ± 0.04
[250,400] GeV	2	0.97 ± 0.08	1.35 ± 0.07	1.05 ± 0.03
	≥ 3	1.46 ± 0.12	1.32 ± 0.07	1.10 ± 0.04
[400,600] GeV	-	1.49 ± 0.25		-
>600 GeV	-	2.03 ± 0.25		-

Table 4-22: Normalization factors applied to the W +jets backgrounds processes in the analysis as obtained from the VH fit to the 13TeV data.

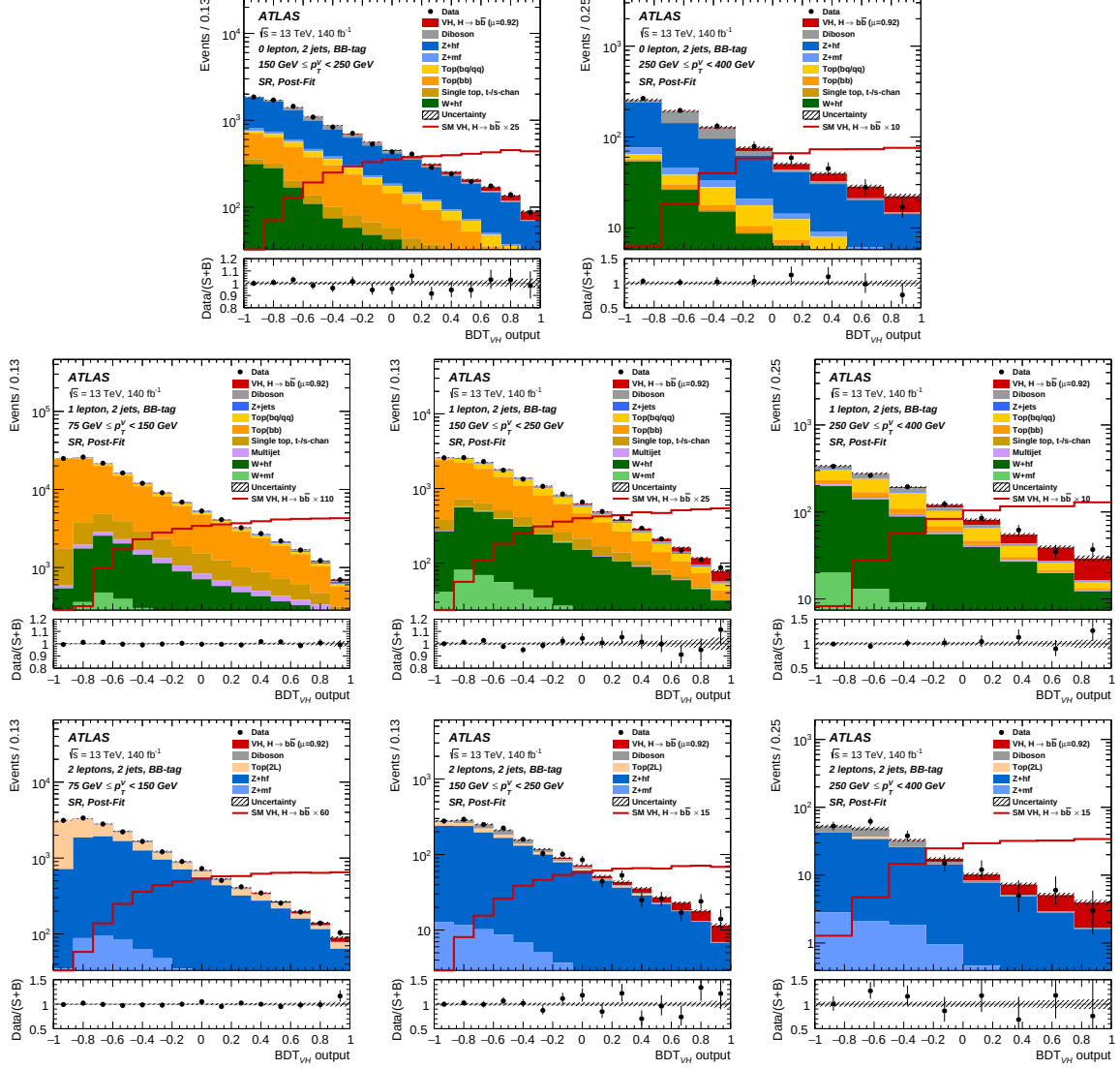


Figure 4-42: The BDT_{VH} post-fit distributions in the $75\text{GeV} < p_T^V < 150\text{GeV}$ (left), $150\text{GeV} < p_T^V < 250\text{GeV}$ (middle) and $250\text{GeV} < p_T^V < 400\text{GeV}$ (right) signal regions of the 2 b -tagged category in the 0-lepton (top), 1-lepton (middle) and 2-lepton (bottom) channel for events with 2 jets. The background contributions after the VH fit are shown as filled histograms. The Higgs boson signal $VH(\rightarrow b\bar{b})$ is shown as a filled histogram on top of the fitted backgrounds normalized to the signal yield extracted from data ($\mu = 0.91$), and unstacked as an unfilled histogram, scaled by a value reported in the legend for better visualization. The hatched band represents the combination of statistical and systematic uncertainties for the sum of the fitted signal and background. The lower panel displays the ratio between the data and the sum of postfit signal and background.

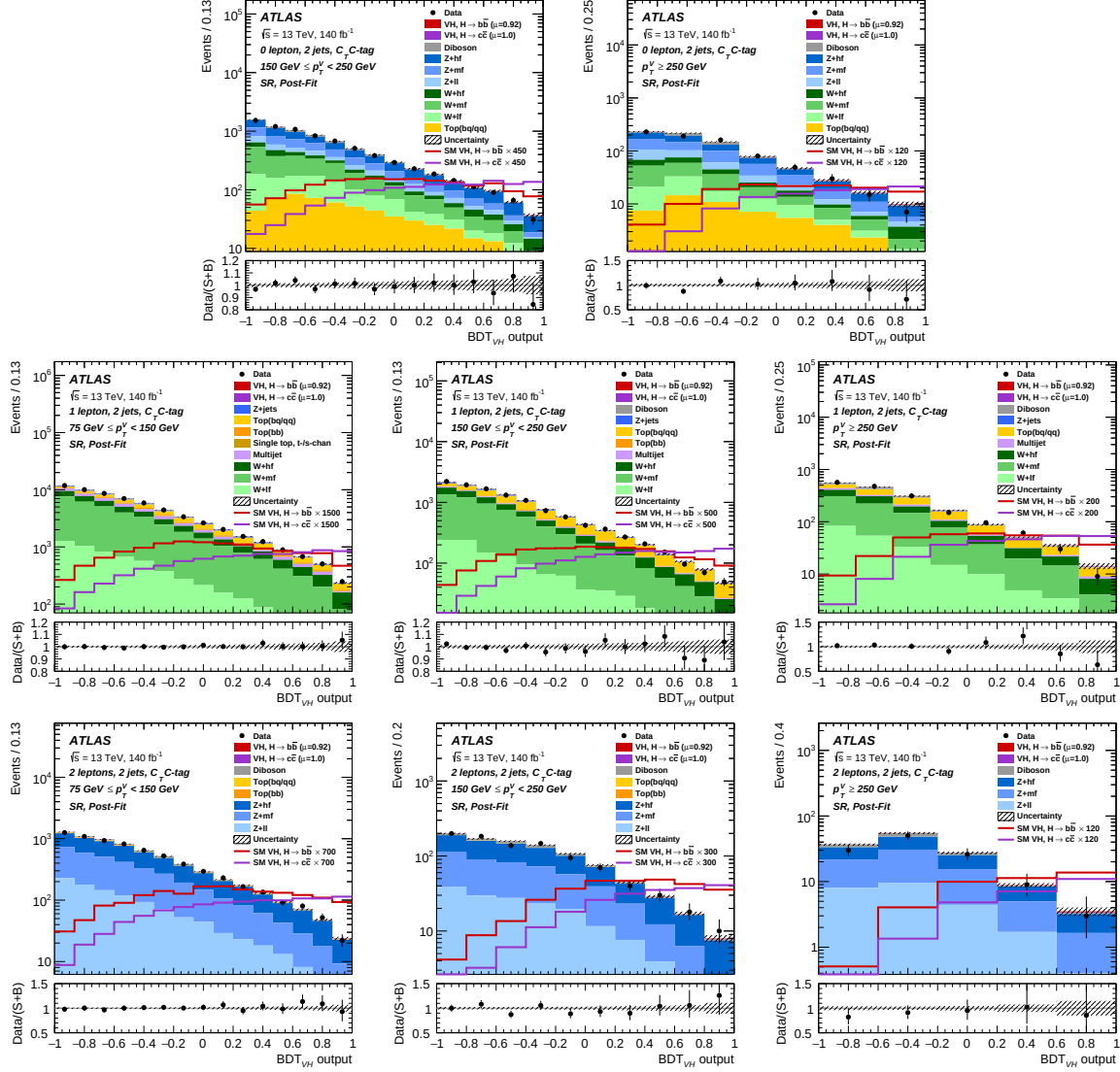


Figure 4-43: The BDT_{VH} post-fit distributions in the $75\text{GeV} < p_T^V < 150\text{GeV}$ (left), $150\text{GeV} < p_T^V < 250\text{GeV}$ (middle) and $p_T^V > 600\text{GeV}$ (right) signal regions of the H_{cc} 2 c -tagged category in the 0-lepton (top), 1-lepton (middle) and 2-lepton (bottom) channel for events with 2 jets. The background contributions after the VH fit are shown as filled histograms. The $VH(\rightarrow c\bar{c})$ signal and the contribution from $VH(\rightarrow b\bar{b})$ are shown unstacked as unfilled histograms, scaled by the factor indicated in the legend. The hatched band represents the combination of statistical and systematic uncertainties for the sum of the fitted signal and background. The lower panel displays the ratio between the data and the sum of postfit signal and background.

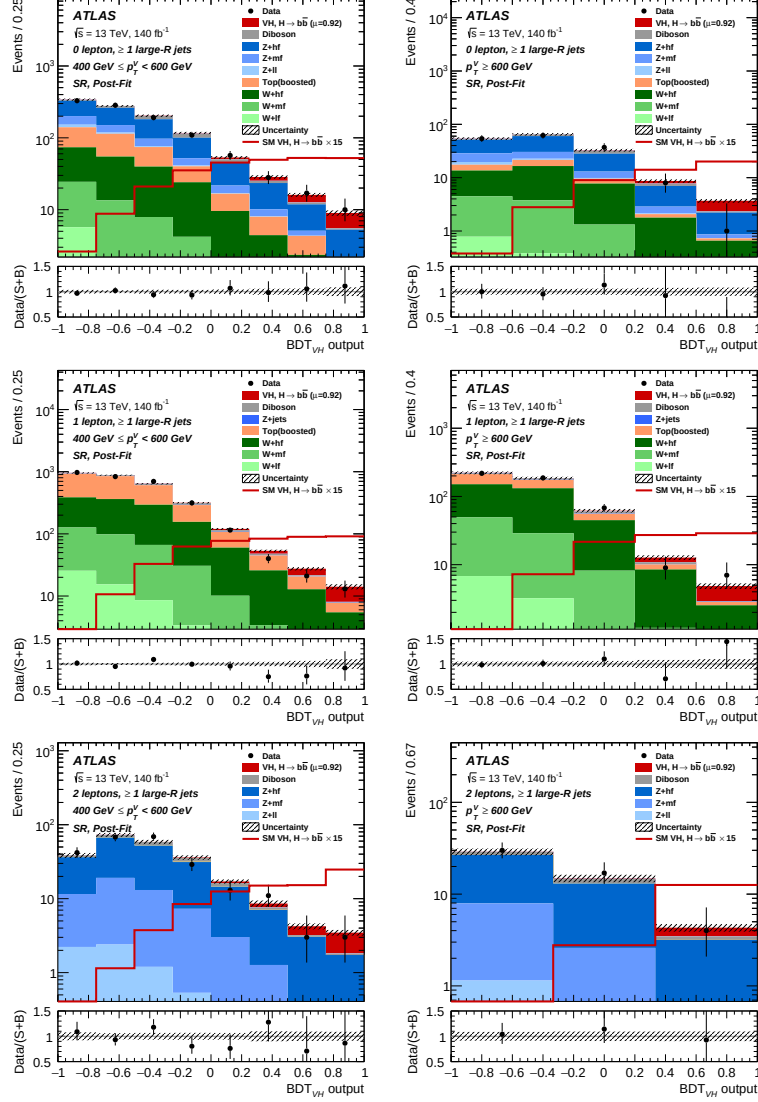


Figure 4-44: The BDT_{VH} post-fit distributions in the $400\text{GeV} < p_T^V < 600\text{GeV}$ (left) and $p_T^V > 600\text{GeV}$ (right) signal regions of the boosted regime in the 0-lepton (top), 1-lepton (middle) and 2-lepton (bottom) channels. The background contributions after the VH fit are shown as filled histograms. The Higgs boson signal $VH(\rightarrow b\bar{b})$ is shown as a filled histogram on top of the fitted backgrounds normalized to the signal yield extracted from data ($\mu = 0.91$), and unstacked as an unfilled histogram, scaled by a value reported in the legend for better visualization. The hatched band represents the combination of statistical and systematic uncertainties for the sum of the fitted signal and background. The lower panel displays the ratio between the data and the sum of postfit signal and background.

p_T^V region	num. jet	$Z + hf$	$Z + mf$	$Z + lf$
[75,150] GeV	2	1.20 ± 0.04	1.04 ± 0.04	1.12 ± 0.03
	≥ 3	1.49 ± 0.06	1.11 ± 0.05	1.12 ± 0.05
	$3/\geq 3$	0.77 ± 0.03	—	—
[150,250] GeV	2	1.30 ± 0.04	1.08 ± 0.04	1.17 ± 0.02
	≥ 3	1.59 ± 0.07	1.14 ± 0.05	1.17 ± 0.04
	$3/\geq 3$	0.80 ± 0.04	—	—
[250,400] GeV	2	1.40 ± 0.07	1.31 ± 0.08	1.16 ± 0.03
	≥ 3	1.78 ± 0.09	1.32 ± 0.07	1.20 ± 0.04
	$3/\geq 3$	0.74 ± 0.04	—	—
>400 GeV	—	1.63 ± 0.13		—

Table 4-23: Normalization factors applied to the Z +jets backgrounds processes in the analysis as obtained from the VH fit to the 13TeV data. The $3/\geq 3$ value is an additional correction factor applied to $Z + hf$ in categories with exactly three jets on top of the ≥ 3 normalization factors.

p_T^V region	num. jet	Top(bb)	Top(bq,qq)	Top 2L
[75,150] GeV	2	1.02 ± 0.04	0.98 ± 0.05	1.05 ± 0.05
	3	0.97 ± 0.03	0.98 ± 0.03	0.98 ± 0.05
[150,250] GeV	2	0.89 ± 0.05	0.83 ± 0.04	1.07 ± 0.16
	3	0.91 ± 0.03	0.86 ± 0.03	0.95 ± 0.14
	4	0.97 ± 0.02	0.95 ± 0.03	
[250,400] GeV	2	0.78 ± 0.08	0.82 ± 0.05	1.10 ± 0.50
	3	0.83 ± 0.04	0.80 ± 0.03	
	4	0.93 ± 0.05	0.86 ± 0.04	
[400,600] GeV	—	0.83 ± 0.05		—
>600 GeV	—	0.69 ± 0.07		—

Table 4-24: Normalization factors applied to the top quark background processes in the analysis as obtained from the VH fit to the 13TeV data.

WH/ZH Decorrelation Fit

A simultaneous fit with $VH(\rightarrow b\bar{b})$ and $VH(\rightarrow c\bar{c})$ signal strength decorrelated to 4POI: $WH(\rightarrow b\bar{b})$, $ZH(\rightarrow b\bar{b})$, $WH(\rightarrow c\bar{c})$ and $ZH(\rightarrow c\bar{c})$ is also performed. The WH production mode signal strengths are mostly constrained by 1-lepton channel while ZH production mode is mostly constrained by 0-lepton and 2-lepton channel. Figure 4-45 shows the fitted signal strength. The significance and limits are shown in Table 4-25 and 4-26. For $WH(\rightarrow b\bar{b})$, the significance is 5.3 standard deviation for observed data. This indicates the first observation of $WH(\rightarrow b\bar{b})$ process.

With respect to the previous $VH(\rightarrow b\bar{b})$ results from ATLAS^[103], the WH signal strength uncertainties improves by 23% and ZH signal strength uncertainties improves by 10%. The improvement in WH is mostly credit to the c -jet rejection of the new PCFT tagger and the

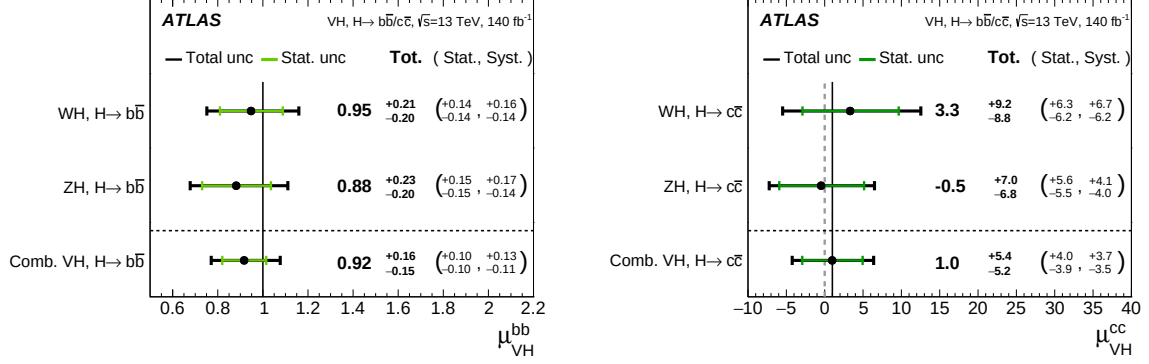


Figure 4-45: Observed signal strength of $WH(\rightarrow b\bar{b})$, $ZH(\rightarrow b\bar{b})$ (left) and $WH(\rightarrow c\bar{c})$, $ZH(\rightarrow c\bar{c})$ (right) process from a simultaneous fit.

Production mode	Expected sig. (cond. data)	Observed sig.
$WH(\rightarrow b\bar{b})$	5.5	5.3
$ZH(\rightarrow b\bar{b})$	5.7	4.9
$VH(\rightarrow b\bar{b})$	8.0	7.4

Table 4-25: Expected and observed significance for $WH(\rightarrow b\bar{b})$ and $ZH(\rightarrow b\bar{b})$ process, with $VH(\rightarrow b\bar{b})$ inclusive results in comparison.

dedicated CRs to constrain Top background.

Lepton Channel Decorrelation Fit

The lepton channel decorrelation fit have six POIs with $VH(\rightarrow b\bar{b})$ and $VH(\rightarrow c\bar{c})$ signal strength decorrelated in lepton channels (0-lepton, 1-lepton and 2-lepton). Figure 4-46 shows the fitted signal strength. Table 4-27 shows the $VH(\rightarrow b\bar{b})$ significance and Figure 4-47 shows the $VH(\rightarrow c\bar{c})$ upper limit in each lepton channels. Considering only the statistical uncertainties, the three channels give the upper limit of 14 (0-lepton), 13 (1-lepton) and 15 (2-lepton) times SM prediction, respectively. The three lepton channels now have comparable sensitivity for the $VH(\rightarrow c\bar{c})$ search.

Breakdown of Uncertainties

The breakdown of uncertainties shows the impact of different kinds of nuisance parameters have on the total uncertainties of the POI. The impact of a group of NPs is obtained from a fit that fix the NP belonging to that particular group to the post-fit values and floating the rest of the NPs. This fit will result in a new best-fit value μ' and uncertainties $\sigma_{\mu'}$. The impact of the

Production mode	Expected limit (cond. data)	Observed limit
$WH(\rightarrow c\bar{c})$	17.2	20.3
$ZH(\rightarrow c\bar{c})$	14.0	13.7
$VH(\rightarrow c\bar{c})$	10.4	11.3

Table 4-26: Expected and observed limit on $WH(\rightarrow c\bar{c})$ and $ZH(\rightarrow c\bar{c})$ process, with $VH(\rightarrow c\bar{c})$ inclusive results in comparison.

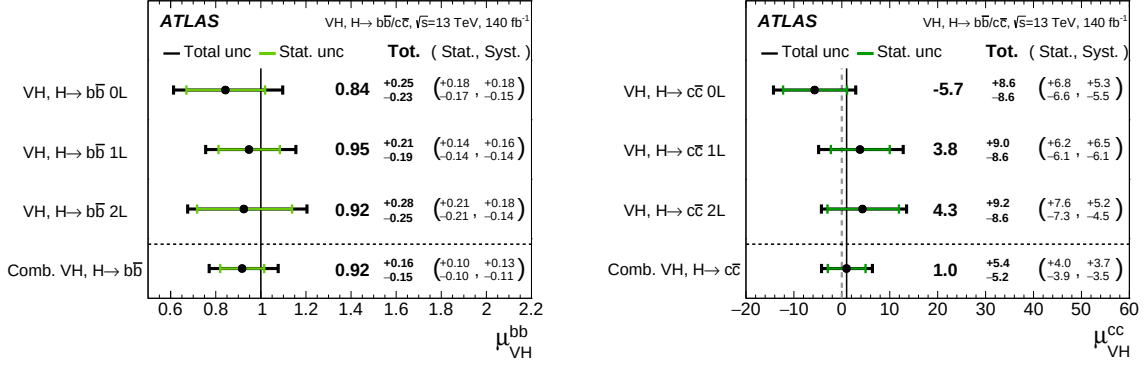


Figure 4-46: Observed signal strength of $VH(\rightarrow b\bar{b})$ (left) and $VH(\rightarrow c\bar{c})$ (right) process in each lepton channel from a simultaneous fit.

NP group is thus obtained by comparing $\sigma_{\mu'}$ with the one from nominal fit σ_{μ} :

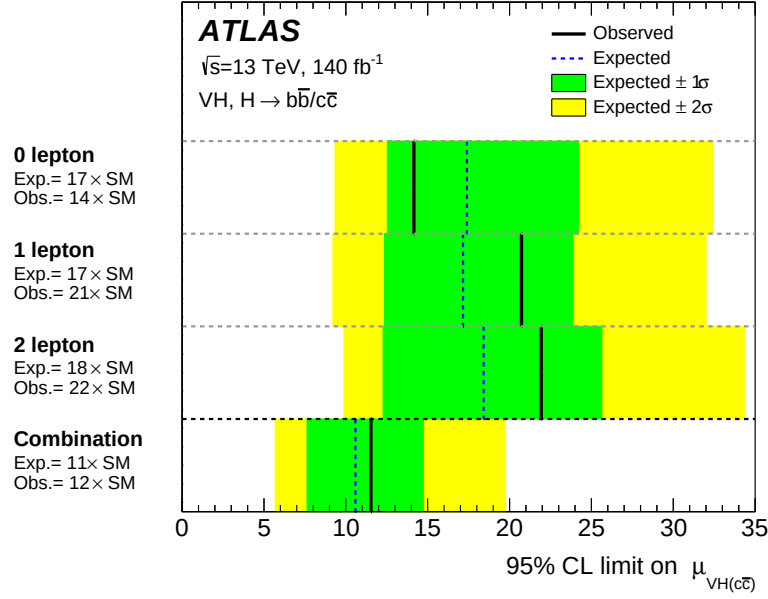
$$\text{impact} = \sqrt{\sigma_{\mu}^2 - \sigma_{\mu'}^2}, \quad (4-23)$$

For the statistical uncertainties, it is defined as the uncertainty of a fit that fix all the systematic NPs except the floating normalizations to post-fit values. The total systematic uncertainty is obtained by the quadratic difference between total uncertainty and statistical uncertainty.

Table 4-28 shows the breakdown table of $VH(\rightarrow b\bar{b})$ signal strength and $VH(\rightarrow c\bar{c})$ signal strength. The breakdown of $WH(\rightarrow b\bar{b})$ and $ZH(\rightarrow b\bar{b})$ signal strength are also shown for comparison.

For $VH(\rightarrow b\bar{b})$, the statistical and systematic uncertainties are at same order, with systematic uncertainty being a bit larger. The systematic uncertainty mainly comes from the modelling uncertainties, including the modelling for the signal and V +jets. For $VH(\rightarrow c\bar{c})$, the statistical and systematic uncertainties are also in the same level with statistical uncertainties being a bit larger. The systematic uncertainty is dominated by the modelling uncertainties, especially the top, V +jets backgrounds modelling as well as the limited MC statistics.

Channel	Expected sig. (cond. data)	Observed sig.
MVA $VH(\rightarrow b\bar{b})$		
0L	4.7	4.0
1L	5.6	5.4
2L	4.5	4.1
0L+1L+2L	8.0	7.4

Table 4-27: Expected and observed significances of $VH(\rightarrow b\bar{b})$ in each lepton channels.Figure 4-47: Observed and expected upper limit of $VH(\rightarrow c\bar{c})$ in each lepton channel and combined results.

Nuisance Parameter Ranking

The ranking of nuisance parameters are based on the impact of the NP on signal strength. The NP is fixed to the up and down variation of their post-fit values of nominal fit and then a new fit is performed, resulting in the fitted signal strength μ' . The impact of the NP is calculated as the difference between μ' and the nominal fit result μ .

The ranking of the $VH(\rightarrow b\bar{b})$ signal strength from a simultaneous fit are shown in Figure 4-48. For $VH(\rightarrow b\bar{b})$, the NPs that have leading impact on the signal strength are the ones for signal and V +jets modelling uncertainties. The top NP is the $W + hf$ extrapolation uncertainty from Low ΔR CR to SR, which have the normalization effect on the $W + hf$ process in 1-lepton $150 < p_T^V < 250$ GeV region, which is one of the most sensitive regions in $VH(\rightarrow b\bar{b})$ regime. The variation of the major background will greatly affect the extraction of signal strength.

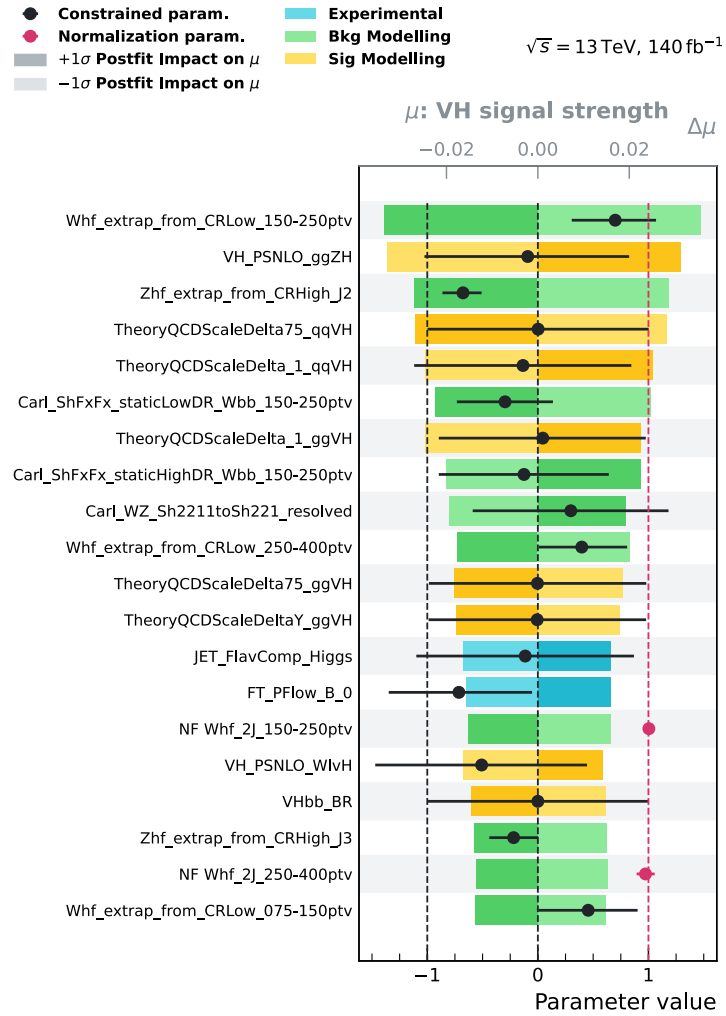


Figure 4-48: Nuisance parameter ranking of $VH(\rightarrow b\bar{b})$ signal strength from a simultaneous fit.

Source of uncertainty	σ_μ			
	$VH(\rightarrow b\bar{b})$	$WH(\rightarrow b\bar{b})$	$ZH(\rightarrow b\bar{b})$	$VH(\rightarrow c\bar{c})$
Total	0.151	0.200	0.220	5.29
Statistical	0.097	0.139	0.151	3.94
Systematic	0.116	0.144	0.160	3.53
Statistical uncertainties				
Data statistical	0.089	0.129	0.137	3.70
$t\bar{t} e\mu$ control region	0.009	0.004	0.020	0.06
Background floating normalisations	0.034	0.049	0.040	1.23
Other VH floating normalisation	0.007	0.013	0.007	0.24
Simulation samples size	0.023	0.034	0.030	1.61
Experimental uncertainties				
Jets	0.028	0.035	0.030	1.00
E_T^{miss}	0.009	0.004	0.018	0.24
Leptons	0.004	0.002	0.008	0.23
b -tagging	b -jets	0.020	0.018	0.30
	c -jets	0.013	0.017	0.73
	light-flavour jets	0.006	0.009	0.67
Pile-up	0.009	0.017	0.003	0.24
Luminosity	0.006	0.007	0.006	0.08
Theoretical and modelling uncertainties				
Signal	0.073	0.066	0.112	0.56
Z + jets	0.039	0.017	0.079	1.76
W + jets	0.055	0.087	0.027	1.41
$t\bar{t}$ and Wt	0.018	0.032	0.018	1.03
Single top quark (s -, t -ch.)	0.010	0.018	0.003	0.15
Diboson	0.032	0.040	0.048	0.51
Multi-jet	0.006	0.010	0.005	0.57

Table 4-28: Breakdown of contributions to the uncertainty in the fitted value of the signal strengths for $VH(\rightarrow b\bar{b})$, $WH(\rightarrow b\bar{b})$, $ZH(\rightarrow b\bar{b})$ and $VH(\rightarrow c\bar{c})$.

For $VH(\rightarrow c\bar{c})$, the NP ranking is shown in Figure 4-49. The leading NPs are the ones for V +jets normalization factor and the V +jets modelling uncertainties. It is consistent with the results shown in breakdown tables. The top NP is the shape uncertainty of $Z + cc$ process extracted with alternative MADGRAPH sample using CARL in $150 < p_T^V < 250$ GeV region of all three lepton channels. It has a large impact on the high BDT bins where the signal are most sensitive.

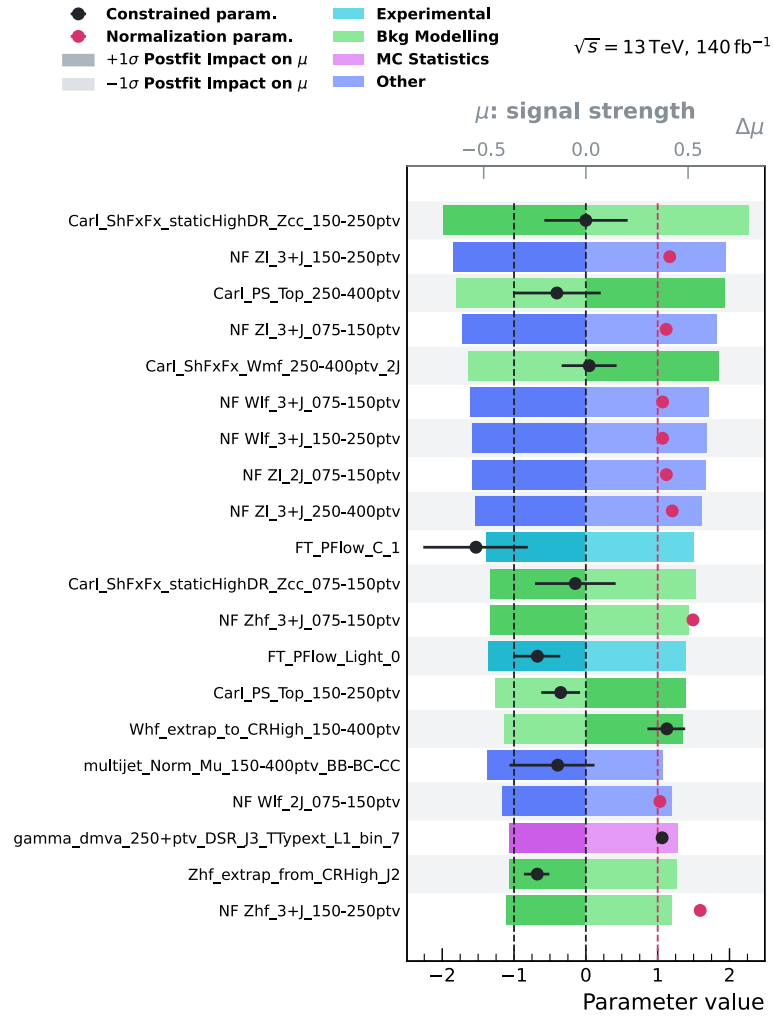


Figure 4-49: Nuisance parameter ranking of $VH(\rightarrow c\bar{c})$ signal strength from a simultaneous fit.

4.9.2 Diboson cross-check Fit Results

The diboson cross-check fit uses the $VZ(\rightarrow b\bar{b})$ and $VZ(\rightarrow c\bar{c})$ signal strength as POIs, with exact same fit setup. A dedicated BDT model is trained for the SRs with $VZ(\rightarrow b\bar{b}, c\bar{c})$ process as signal. The best-fit signal strength and uncertainties for $VZ(\rightarrow b\bar{b})$ and $VZ(\rightarrow c\bar{c})$ process are:

$$\begin{aligned}\mu_{VZ}^{bb} &= 0.91^{+0.13}_{-0.11} = 0.91^{+0.05}_{-0.05} \text{ (stat.)}^{+0.12}_{-0.10} \text{ (syst.)} \\ \mu_{VZ}^{cc} &= 0.97^{+0.25}_{-0.22} = 0.97^{+0.13}_{-0.13} \text{ (stat.)}^{+0.22}_{-0.18} \text{ (syst.)}\end{aligned}\tag{4-24}$$

The results show good consistency with the SM. For $VZ(\rightarrow b\bar{b})$, the expected and observed significance over the background only hypothesis are over 10σ . For $VZ(\rightarrow c\bar{c})$, the observed significance is 5.3σ , while the expected significance is 5.2σ . This is the first observation of $VZ(\rightarrow c\bar{c})$ process at ATLAS. The correlation between the two POI is 46%, which is mainly coming from the common signal modelling uncertainties.

The fit with decorrelated WZ and ZZ process is also performed, the signal strength for $WZ(\rightarrow b\bar{b})$, $ZZ(\rightarrow b\bar{b})$, $WZ(\rightarrow c\bar{c})$ and $ZZ(\rightarrow c\bar{c})$ are shown in Figure 4-50.

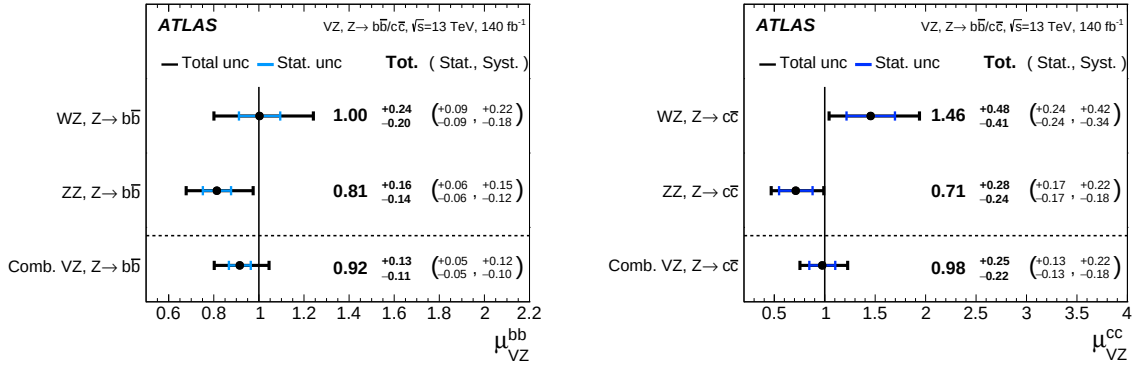


Figure 4-50: Observed signal strength of $WZ(\rightarrow b\bar{b})$, $ZZ(\rightarrow b\bar{b})$ (left) and $WZ(\rightarrow c\bar{c})$, $ZZ(\rightarrow c\bar{c})$ (right) process from a simultaneous fit.

The $WZ(\rightarrow b\bar{b})$ process is observed at significance of 6.4σ . The significance of the $ZZ(\rightarrow b\bar{b})$ process is observed to be larger than 10σ . Evidence for both $WZ(\rightarrow c\bar{c})$ and $ZZ(\rightarrow c\bar{c})$ is found with an observed (expected) significance of 3.9σ (2.7σ) and 3.1σ (4.2σ) respectively.

Since the fit setup and dataset used in VH and VZ fit are same, the nuisance parameters, especially the ones related to the background, should be consistent between the two fits. If the MVA is well-trained and have consistent performance with data and MC, the divergence between data and MC should be the same in two fits. Figure 4-51 shows the comparison of

the normalization factors in two fits, and it shows good consistency. More NP pull comparison can be found in the Appendix 6 and share the same conclusion. It means that the MVA has consistency performance in VH and VZ , and does not bring bias to the modelling.

An alternative parameterization is studied for measuring the ratio between $BR(Z \rightarrow cc)$ and $BR(Z \rightarrow bb)$ as it is an important observable in the electroweak measurement. It reveals the coupling universality of b - and c - quarks coupling to the Z boson. The signal strength of $VZ(\rightarrow b\bar{b})$ and $VZ(\rightarrow c\bar{c})$ are re-parameterized to the signal strength of $VZ(\rightarrow bb+cc)$ process and the ratio, by the following relations, with $r = \frac{BR(Z \rightarrow cc)}{BR(Z \rightarrow bb)}$:

$$\begin{aligned}\mu_{VZ}^{bb} &= \mu_{VZ}^{bb+cc} \cdot \frac{1}{(1+r) \cdot 0.5569} \\ \mu_{VZ}^{cc} &= \mu_{VZ}^{bb+cc} \cdot \frac{r}{(1+r) \cdot 0.4431}\end{aligned}\tag{4-25}$$

The numerical values are derived with the standard model prediction from *GFitter* group^[139], which stands for the relative fraction of the $BR(Z \rightarrow bb/cc)$ in $BR(Z \rightarrow bb+cc)$. The fit gives:

$$\begin{aligned}\mu_{VZ}^{bb+cc} &= 0.94_{-0.14}^{+0.16} = 0.94_{-0.06}^{+0.06} \text{ (stat.) }_{-0.12}^{+0.15} \text{ (syst.)} \\ \frac{BR(Z \rightarrow cc)}{BR(Z \rightarrow bb)} &= 0.85_{-0.18}^{+0.19} = 0.85_{-0.12}^{+0.12} \text{ (stat.) }_{-0.15}^{+0.14} \text{ (syst.)}\end{aligned}\tag{4-26}$$

In comparison, the PDG group gives the measured value of $BR(Z \rightarrow bb) = 15.12 \pm 0.05\%$ and $BR(Z \rightarrow cc) = 12.03 \pm 0.21\%$ from combined fit of LEP and SLC results^[9].

4.9.3 STXS Fit Results

Two STXS schemes are used in the final fit, STXS13 and STXS10 as illustrated in Figure 4-28. STXS10 do not have the jet multiplicity split and only split in p_T^V for WH and ZH . STXS13 has in addition, the jet multiplicity split in the $p_T^V < 400$ GeV regions. Figure 4-52 shows the cross-section times BR and the signal strength of STXS13 scheme and Figure 4-53 shows the STXS10 scheme. Note that in the STXS fit, the $VH(\rightarrow c\bar{c})$ regime is also included, and the $VH(\rightarrow c\bar{c})$ inclusive signal strength is also one POI in the fit.

The results are consistent with SM expectations within one standard deviation, except for the WH , $400 < p_T^V < 600$ GeV bin and ZH , $p_T^V > 400$ GeV bin, which are the regions that have

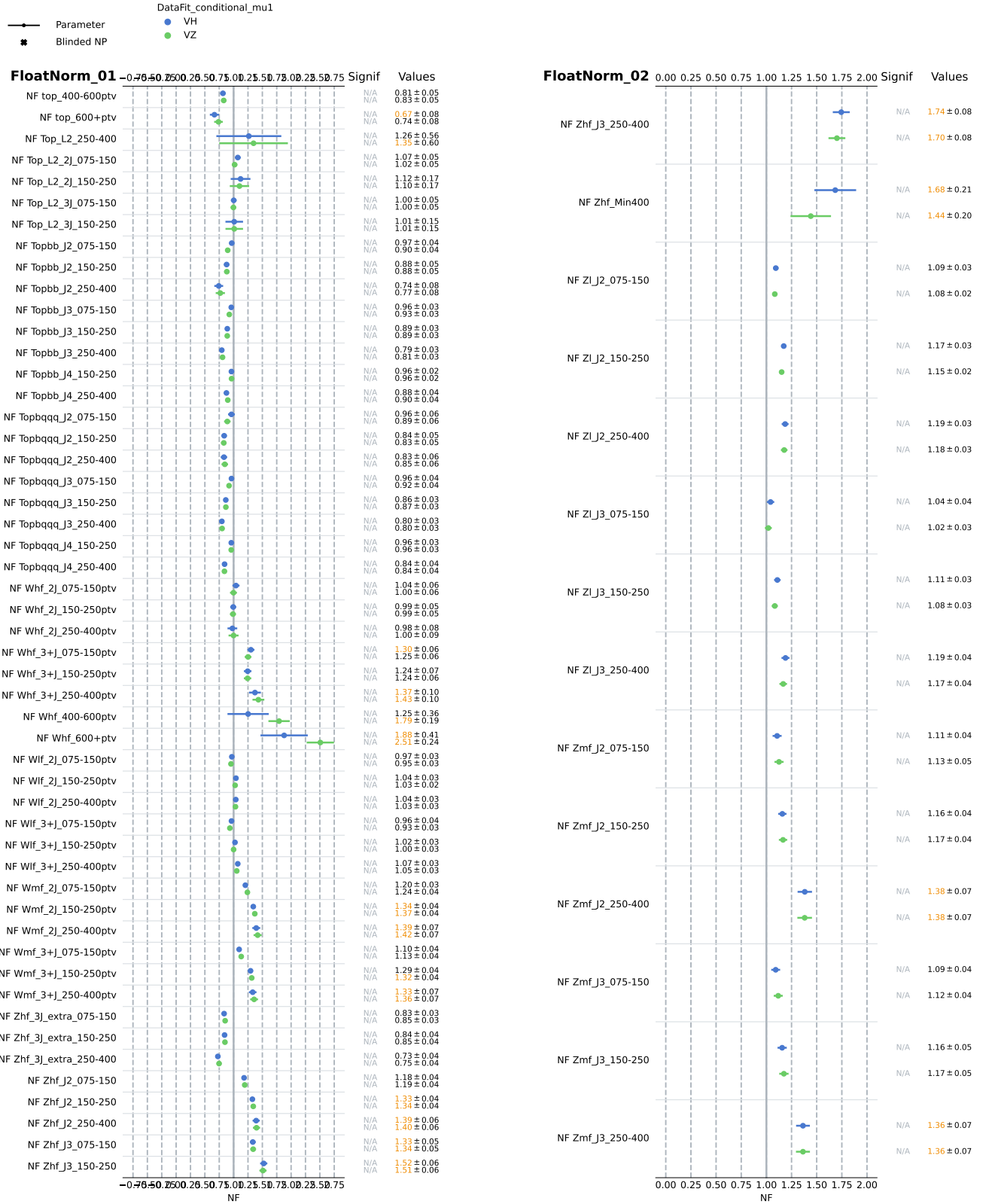


Figure 4-51: Comparison of floating normalization nuisance parameters in nominal VH fit and VZ cross-check fit.

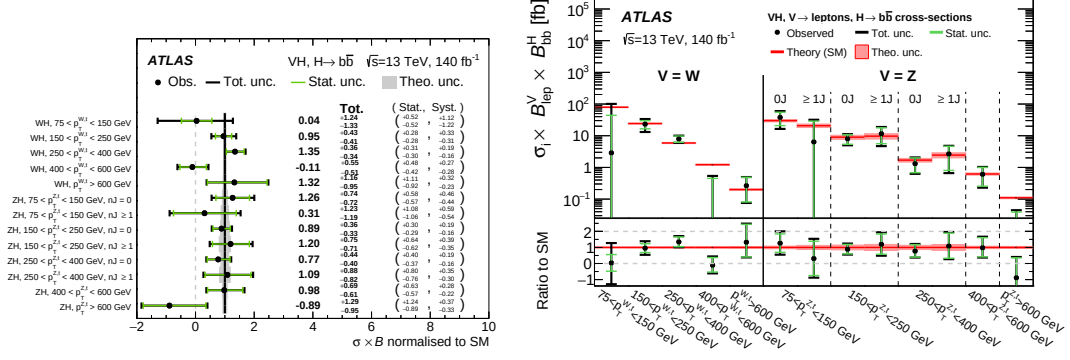


Figure 4-52: Signal Strength (left) and cross-section times BR (right) in the STXS13 scheme.

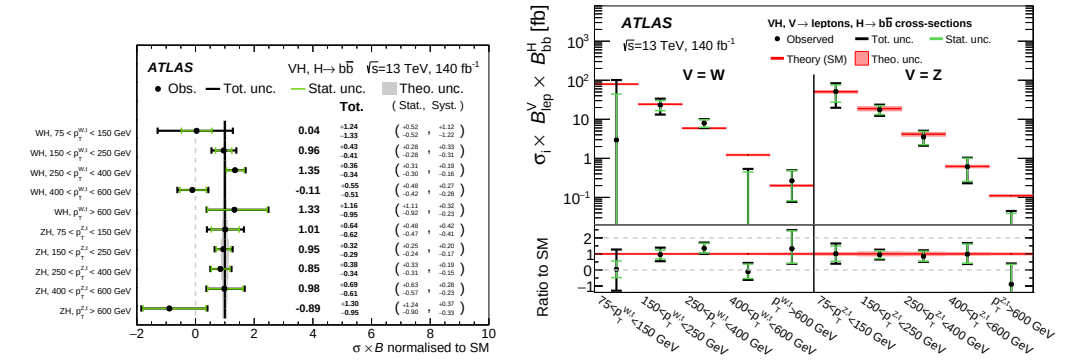


Figure 4-53: Signal Strength (left) and cross-section times BR (right) in the STXS10 scheme.

the small number of events. As a result, the relative low measured cross-sections may due to the statistical fluctuation. Overall, the compatibility with SM is 90%.

The correlation between the STXS POIs are shown in Figure 4-54. In both scheme, the correlation between STXS POIs are small overall, with WH POIs have a slightly higher correlation with each other for about 10%.

4.9.4 Kappa Interpretation

The fit results of VH signal strengths are interpreted with the κ framework^[19]. The signal strengths are re-parameterized with the coupling modifiers κ that is defined as the multiplying factor applied on the SM coupling strength. In this study, the Higgs-bottom coupling modifier κ_b and Higgs-charm coupling modifier κ_c are considered, all the other coupling modifiers are set to the SM prediction - unity. Considering only the effects of these coupling modifiers on branching ratios, the signal strength of $VH(\rightarrow b\bar{b})$ and $VH(\rightarrow c\bar{c})$ can be written as:

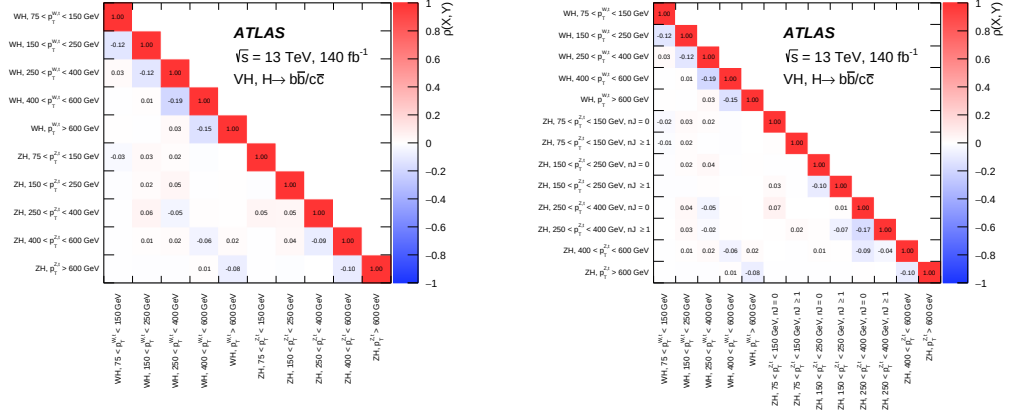


Figure 4-54: Correlation between STXS bins with STXS10 scheme (left) and STXS13 (right).

$$\mu_{VH(\rightarrow b\bar{b})} = \frac{\kappa_b^2}{1 + BR_{h \rightarrow bb}^{SM} \cdot (\kappa_b^2 - 1) + BR_{h \rightarrow cc}^{SM} \cdot (\kappa_c^2 - 1)} \quad (4-27)$$

$$\mu_{VH(\rightarrow c\bar{c})} = \frac{\kappa_c^2}{1 + BR_{h \rightarrow bb}^{SM} \cdot (\kappa_b^2 - 1) + BR_{h \rightarrow cc}^{SM} \cdot (\kappa_c^2 - 1)} \quad (4-28)$$

Different parameterization schemes are considered, and the results are shown in the following:

κ_c Only scheme

In this scheme, only the parameterization for $VH(\rightarrow c\bar{c})$, shown in Equation 4-28, is considered, with κ_b set to 1, resulting the final parameterization for $VH(\rightarrow c\bar{c})$ is:

$$\mu_{VH(\rightarrow c\bar{c})} = \frac{\kappa_c^2}{1 + BR_{h \rightarrow cc}^{SM} \cdot (\kappa_c^2 - 1)} \quad (4-29)$$

The signal strength of $VH(\rightarrow b\bar{b})$ process is not parameterized, and is used as a floating parameter in the fit. For the measurement of κ_c , profile Likelihood ratio test statistic is used, the log likelihood ratio value with different κ_c is shown in Figure 4-55. The observed (expected) constraint on κ_c at 95% CL is $|\kappa_c| < 4.1(4.2)$.

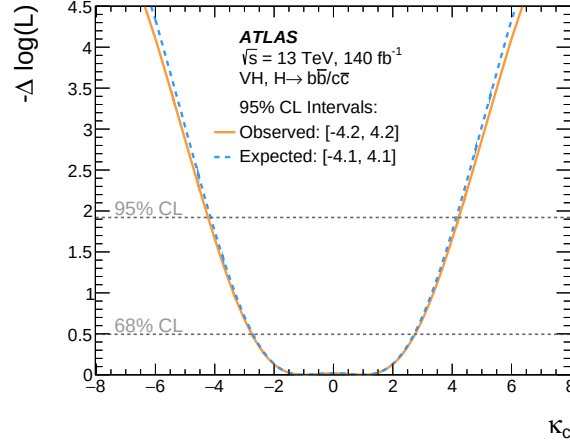


Figure 4-55: Observed (solid) and expected (dashed) values of the negative profile log-likelihood ratio as a function of κ_c , is obtained in a fit with κ_b fixed to unity. The signal strength $\mu_{VH(\rightarrow b\bar{b})}$ is not parameterized but taken as a free-floating parameter in the fit. The 68% and 95% CL intervals are indicated by the vertical lines.

κ_b and κ_c scheme

In this scheme, the coupling modifiers on Higgs-bottom and Higgs-charm are considered as free parameters in the fit. The $qqVH$ signal strength for bb or cc final state is parameterized using the Equation 4-27 and 4-28. The $ggZH$ signal strength is parameterized differently, since the box diagram of $ggZH$ process has the Higgs-bottom coupling vertex. The parameterization of $ggZH$ production cross-section in the κ framework is:

$$\mu_{ggZH} = 2.456\kappa_Z^2 + 0.456\kappa_t^2 - 1.903\kappa_Z \cdot \kappa_t - 0.011\kappa_Z\kappa_b + 0.003\kappa_t\kappa_b \quad (4-30)$$

Assuming κ_Z and κ_t is unity, the signal strength of $ggZH(\rightarrow b\bar{b}c\bar{c})$ is:

$$\mu_{ggZH}^{bb} = (1.008 - 0.008 \cdot \kappa_b) \cdot \frac{\kappa_b^2}{1 + BR_{h \rightarrow bb}^{SM} \cdot (\kappa_b^2 - 1) + BR_{h \rightarrow cc}^{SM} \cdot (\kappa_c^2 - 1)} \quad (4-31)$$

$$\mu_{ggZH}^{cc} = (1.008 - 0.008 \cdot \kappa_b) \cdot \frac{\kappa_c^2}{1 + BR_{h \rightarrow bb}^{SM} \cdot (\kappa_b^2 - 1) + BR_{h \rightarrow cc}^{SM} \cdot (\kappa_c^2 - 1)} \quad (4-32)$$

Figure 4-56 shows the observed and expected constraint on the κ_b and κ_c at 68% and 95% CL. The profile likelihood ratio with different κ_b and κ_c values are shown in Figure 4-57.

Note that in the 1-dimensional case, the 95% confidence intervals can be set while in the 2-dimensional case cannot, which is due to the difference of χ^2 values with different degree of freedom.

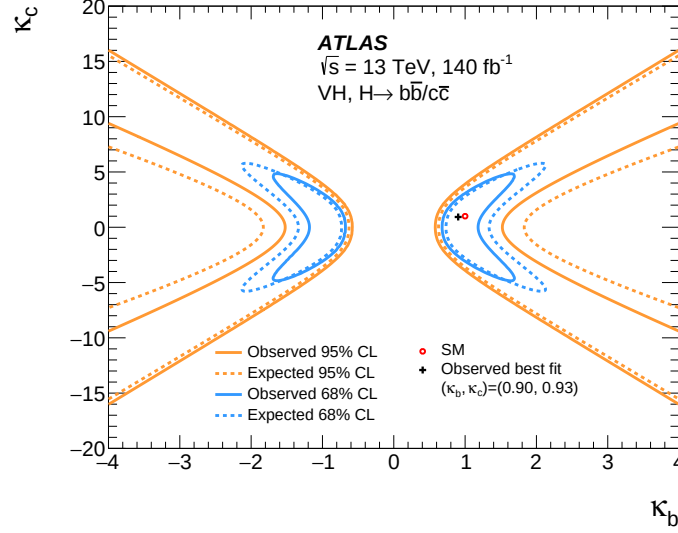


Figure 4-56: Observed (solid) and expected (dashed) constraint on the κ_b and κ_c at 68% (blue) and 95% (orange) CL.

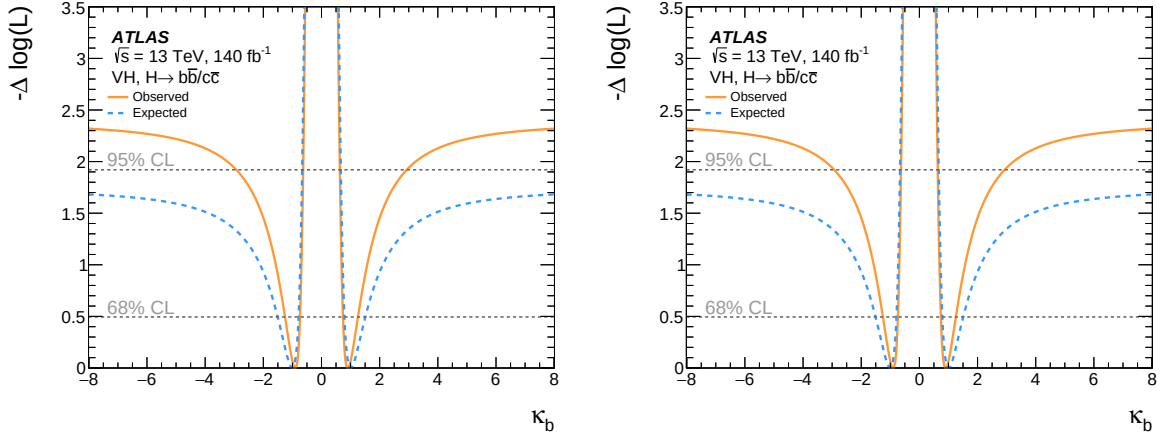


Figure 4-57: Observed (solid) and expected (dashed) values of the negative profile log-likelihood ratio as a function of κ_b (left) and κ_c (right), is obtained in a fit with another κ floating in the fit. The $ggZH$ production mode is parameterized as a function of κ_b .

κ Ratio scheme

In this scheme, the ratio of κ_c to κ_b is measured. In the SM prediction, the Yukawa coupling strength of Higgs to fermions is proportional to the mass of the fermions, so the cou-

pling strength of Higgs to bottom is 4.578 ± 0.008 times of the coupling strength of Higgs to charm^[140]. The signal strengths are parameterized as following:

$$\mu_{VH(\rightarrow b\bar{b})} = \left(\frac{\kappa_b}{\kappa_H}\right)^2 \quad (4-33)$$

$$\mu_{VH(\rightarrow c\bar{c})} = \left(\frac{\kappa_c}{\kappa_b}\right)^2 \cdot \left(\frac{\kappa_b}{\kappa_H}\right)^2 \quad (4-34)$$

where κ_H is the modifier of total Higgs width. $\frac{\kappa_b}{\kappa_H}$ is a free float parameter in the fit, which means there is no assumption made for the total Higgs width. Figure4-58 shows the profile log likelihood ratio as a function of $\frac{\kappa_c}{\kappa_b}$. The observed (expected) constraint on the ratio at 95% CL is 3.6 (3.5). The ratio equals to 4.578 is excluded in 99.7% CL, further confirming the Higgs-charm coupling strength is smaller than Higgs-bottom coupling strength.

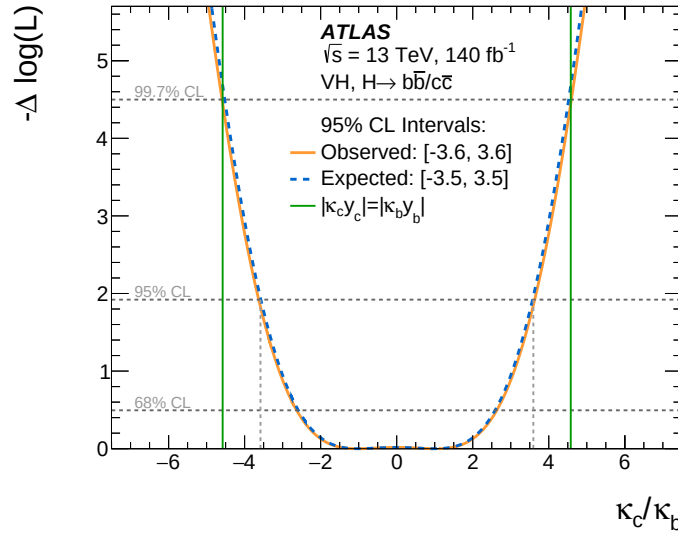


Figure 4-58: Observed (solid) and expected (dashed) values of the negative profile log-likelihood ratio as a function of $\frac{\kappa_c}{\kappa_b}$. The signal strength $\mu_{VH(\rightarrow b\bar{b})}$ is taken as a free-floating parameter in the fit. The 68% and 95% CL intervals are indicated by the vertical lines. The green vertical line correspond to the $\frac{\kappa_c}{\kappa_b}$ equals to 4.578, which is the ratio of bottom mass to charm mass, indicating the case the coupling strength of Higgs-charm is same as coupling strength of Higgs-bottom.

4.10 Conclusion

This chapter presented the results of combined analysis of search for $H \rightarrow c\bar{c}$ and measurement of $H \rightarrow b\bar{b}$ in VH production mode with vector boson decay leptonically, using the full Run-2

dataset collected by ATLAS detector. Three channels are considered based on the number of charged leptons from the vector boson decay. A custom flavor tagger is designed to coherently identify the b - and c - jets. The events are categorized based on the flavor tagging information. For $VH(\rightarrow c\bar{c})$, only resolved topology is considered and for $VH(\rightarrow b\bar{b})$, resolved and boosted topology is considered.

Multi-variate analysis technique is used to separate signal and backgrounds. Dedicated Control regions are defined and shared between resolved $VH(\rightarrow b\bar{b})$ and $VH(\rightarrow c\bar{c})$ regimes to better control the main backgrounds: V +jets and top process. To validate the BDT model and fit robustness, the $VZ(\rightarrow b\bar{b})$ and $VZ(\rightarrow c\bar{c})$ process are used as cross-check by measuring their signal strength with a dedicated fit. The fit results show good consistency with SM, and the $VZ(\rightarrow c\bar{c})$ process is observed in the first time at ATLAS with a significance of 5.3σ .

The signal strength of $VH(\rightarrow c\bar{c})$ and $VH(\rightarrow b\bar{b})$ are in good agreement with SM prediction. An observed(expected) upper limit of 11(10) times SM cross-section times branching ratio at 95% CL for the $VH(\rightarrow c\bar{c})$ process is set. The results significantly improved by more than 100% compared with last iteration thanks to the application of MVA, better tagging performance and better background control. The results are interpreted in kappa framework. The observed (expected) constraint on $|\kappa_c|$ is $|\kappa_c| < 4.1(4.2)$ at 95% CL. The ratio between κ_b and κ_c is constrained to be $|\kappa_c/\kappa_b| < 3.6(3.5)$ with observed (expected) data. The $|\kappa_c/\kappa_b|$ value corresponding to the universality of Higgs coupling to charm and bottom quarks is excluded by a significance of 3σ . The cross-section of $VH(\rightarrow b\bar{b})$ process in STXS is measured, the uncertainties improved by up to 100% compared with the previous analysis.

Compared with the previous results, the results presented in this chapter have significant improvements. It is mostly coming from the optimization of flavor tagging scheme that has a better flavor tagging efficiency, and the introduction of boosted decision tree for the signal and background classification. Other minor improvements comes from various analysis techniques, including the increased statistics and better modelling of Monte Carlo sample, coherent constraint on the background across $VH(\rightarrow b\bar{b})$ and $VH(\rightarrow c\bar{c})$ regimes, improved Higgs invariant mass corrections and so on. The results show good agreement with the SM prediction, providing strong evidence for the mass generation via Yukawa coupling in the BEH mechanism. The charm quark Yukawa coupling is confirmed to be smaller than the bottom quark Yukawa

coupling at around 3σ , which is crucial for the understanding of the fermion mass hierarchy puzzle.

Chapter 5

Searches for BSM with Combined Measurements

5.1 Introduction

Since the SM is widely believed not to be the ultimate theory, the searches for the new physics have been carried out extensively. The searches for BSM can be divided into two approaches: direct search and indirect search. The direct searches target the new particles or the processes that is not present in the SM, and the indirect searches target the small deviation on the SM process brought by the new physics. Given that there is no obvious deviation from SM and direct observation of new physics yet, it indicates that the effect of new physics at the energy reach of current colliders may be tiny. Thus, it is beneficial to combine all the studies available to acquire more power for the search.

The *combination* refers to the analysis that statistically combine individual analysis (input) without drastically modifying the analysis strategy of each input. There are two compelling reason to carry out the combination. Firstly, by combining different analyses that sensitive to the same process or coupling, the increased statistic as well as the correlated uncertainties can improve the precision of the measurements. For example, the non-resonant Di-Higgs production in several final states, including $b\bar{b}b\bar{b}$, $b\bar{b}\tau\tau$ and $b\bar{b}\gamma\gamma$, that have comparable sensitivity on the Higgs self-coupling. By combining these three analyses (or named as channels in the combined analysis), a better constraint on the self-coupling than any individual channels can be derived. Secondly, the combined measurement provides more comprehensive understanding of

the theoretical model, relieving the model dependence of interpretation. For better optimization of analysis strategy, the specific final state(s) is targeted in the single channel, providing constraint on the specific process and corresponding couplings. Nevertheless, in some circumstance, the interpretation in single channel is limited to certain assumptions. For instance, in the $VH(\rightarrow b\bar{b}, c\bar{c})$ kappa interpretation results, the hidden assumption is that the Higgs couplings to vector bosons is not modified, i.e. the VH production cross-section remain the SM prediction, which is usually not the case in the beyond SM Higgs sector. Meanwhile, if combining the $VH(\rightarrow b\bar{b}, c\bar{c})$ measurement with other $H \rightarrow VV$ measurements, the HVV and Hbb/cc couplings can be floated and measured at the same time. This will also be beneficial in the search for the BSM model that enhance these couplings at the same time.

As a result, the combined measurement provides a coherent and more precise picture, making it a perfect portal to search for the new physics which is not sensitive in single analysis due to the limitation of statistic. In this chapter, in total of three sets of combination of different measurements are performed, and their results are used for the interpretation of new physics models:

1. The combined SM Higgs coupling measurements. It makes use of an unprecedented number of SM Higgs production and decay process to scrutinize its interaction with elementary particles. The combined coupling strength results are published in Ref^[1] for the 10th anniversary of the Higgs boson discovery, providing the most stringent and comprehensive measurements on the Higgs properties, making it an ultimate test for the SM.
2. The combined resonant Di-Higgs production searches. In many BSM models that extend the Higgs sector, there typically exist one additional neutral scalar boson (denoted as X) with sizeable couplings to the SM-like Higgs boson. If $m_X > 2m_H$, the existence of X could be detected through its decays to Higgs boson pairs. Several final states are targeted in the searches carried out by ATLAS. In this thesis, three final states: $b\bar{b}b\bar{b}$, $b\bar{b}\tau\tau$ and $b\bar{b}\gamma\gamma$ are used in the combination.
3. The combined electroweak precision measurements. The electroweak process, namely the process dominated by electroweak interactions, as well as the fundamental parameters in electroweak sector such as the Z and W boson mass, has deep connection with the BEH mechanism. These processes and parameters are measured in electron collider

such as the Large Electron-Positron Collider (LEP) and several low energy deep inelastic scattering experiments like CHARM in high precision. A collection of these electroweak measurements are combined in this thesis.

These combined measurements are interpreted in two kinds of BSM theoretical frameworks: The BSM UV models and the Standard Model effective field theory (SMEFT). The UV model refers to the ultraviolet complete models, while "ultraviolet" stands for the model that is well-defined at much higher energy than the reach of current experiment, e.g. the electroweak scale. The ultraviolet complete models are required to be renormalizable. Several popular BSM UV models have been introduced in Section 2.3, including the 2HDM and MSSM that will be used for interpretation in this thesis. These models can be searched via either direct approach or the indirect approach. Since these models usually predict the new particle presents at very high mass, its impact at low energy hardly relies on the details of the new physics (e.g. the mass of new particles and coupling strength). In this case, the SMEFT can be used for the approximation of the BSM behaviors at low energy, acting as a perturbation theory. The SMEFT builds the interactions using the SM particles and fields, which can have the canonical mass dimension larger than 4, making it non-renormalizable. Compared with BSM UV models, SMEFT drastically simplify calculations by only focusing on relevant degrees of freedom. Additionally, SMEFT contains a systematic parametrization of the neglected physics in a model independent manner. By comparing the effect of BSM UV model and of SMEFT operators, it is also possible to translate the effect from SMEFT to the one from UV model, which is referred as "matching". With all these advantages, the SMEFT is a popular theoretical framework for the indirect search of new physics. In this thesis, the BSM UV model interpretation is carried out for the combined SM Higgs coupling measurements and the combined resonant Di-Higgs production searches. The SMEFT interpretation is performed for the combined SM Higgs coupling measurements and the combined electroweak precision measurements.

This chapter is organized to present these three studies separately: The EFT and BSM UV model interpretation of combined Higgs measurements, the BSM UV model interpretation of combined Di-Higgs resonant searches and the Top quark EFT study using electroweak precision measurements. In each section, the details of input analyses, statistic description and the interpretation results will be shown.

5.2 Interpretation of Higgs Combination

The Higgs boson sits at the heart of SM, which is also the focus of many BSM theories. In several BSM models, the properties of Higgs boson is predicted to be different from SM, such as the coupling strength of Higgs boson with other particles, making it a perfect portal to search for the new physics. Thus, to characterize experimental deviations from the SM predictions pointing towards the structure of BSM physics, the combined Higgs boson measurements presented in the Ref^[1] for the 10th anniversary of the Higgs boson discovery are interpreted in the context of different theoretical models.

Two sets of interpretations of the combined Higgs boson measurements are presented in exclusive kinematic regions of the production phase-space, defined within the Simplified Template Cross-Section (STXS) framework. The first one is based on the Standard Model Effective Field Theory (SMEFT) which provides a consistent approach to probe BSM physics in a model independent way. The second set based on the BSM UV models such as Two Higgs Doublet Models (2HDMs) as well as dedicated benchmark scenarios of the Minimal Supersymmetric Standard Model (MSSM). This section will mostly focus on the interpretation of specific UV models, the results of EFT interpretation will be mentioned briefly. Additionally, the matching from EFT constraints to the UV models is presented, which tests whether EFT could be a good approximation of high energy scale theory at low energy.

5.2.1 Input Measurements

The results of this analysis are based on proton-proton collision data collected by the ATLAS experiment in 2015–2018 at a centre-of-mass energy of 13 TeV. Input analyses for both the SMEFT and BSM interpretations are summarized along with the targeted Higgs decay channels, production modes, their integrated luminosities and the STXS binning in Table 5-1. The differential combination is based on the $H \rightarrow \gamma\gamma$ and the $H \rightarrow ZZ^* \rightarrow 4\ell$ fiducial differential analyses. Further details on the different analyses can be found in the references provided in the table.

Decay channel	Analysis Production mode	$\mathcal{L}$ [fb ⁻¹]	Reference	Binning	SMEFT	2HDM and (h)MSSM
$H \rightarrow \gamma\gamma$	(ggF, VBF, WH , ZH , $t\bar{t}H$, tH)	139	[141]	STXS-1.2	✓	✓
$H \rightarrow ZZ^*$	($ZZ^* \rightarrow 4\ell$: ggF, VBF, $WH + ZH$, $t\bar{t}H + tH$)	139	[142]	STXS-1.2	✓	✓
	($ZZ^* \rightarrow \ell\ell\nu\bar{\nu}/\ell\ell q\bar{q}$: $t\bar{t}H$ multileptons)	36.1	[143]	STXS-0*		✓
$H \rightarrow \tau\tau$	(ggF, VBF, $WH + ZH$, $t\bar{t}H + tH$)	139	[144]	STXS-1.2	✓	✓
	($t\bar{t}H$ multileptons)	36.1	[143]	STXS-0*		✓
$H \rightarrow WW^*$	(ggF, VBF)	139	[145]	STXS-1.2	✓	✓
	(WH , ZH)	36.1	[146]	STXS-0*		✓
	($t\bar{t}H$ multileptons)	36.1	[143]	STXS-0*		✓
$H \rightarrow b\bar{b}$	(WH , ZH)	139	[147-148]	STXS-1.2	✓	✓
	(VBF)	126	[149]	STXS-1.2	✓	✓
	($t\bar{t}H + tH$)	139	[150]	STXS-1.2	✓	✓
	(boosted Higgs bosons: inclusive production)	139	[151]	STXS-1.2	✓	✓
$H \rightarrow Z\gamma$	(inclusive production)	139	[152]	STXS-0*	✓	✓
$H \rightarrow \mu\mu$	(ggF + $t\bar{t}H + tH$, VBF + $WH + ZH$)	139	[153]	STXS-0*	✓	✓

Table 5-1: Input analysis of the combined Higgs boson measurement, the decay channels, targeted production modes, integrated luminosity, the phase-space binning, and the models used for interpretation are reported. The differential cross-section measurements are independent and target a subset of all considered operators. All the inputs used for the STXS SMEFT interpretation are also used for the mapping SMEFT to 2HDM .

5.2.2 EFT Interpretation

As introduced in Section 2.3.3, Effective field theories (EFTs) provide a consistent approach to probe the presence of BSM physics in a model-independent way at the LHC, even if the energy scale, Λ , of the new physics phenomena, is not directly accessible at the LHC. If this scale fulfills $\Lambda \gg v$, where v is the vacuum expectation value of the Higgs field, the new physics decouples from the SM, which can be approximated as no new on-shell intermediate state is produced. In this case, an expansion of the Lagrangian in canonical dimensions $\frac{v}{\Lambda}$ can be performed. The precision of the theory is chosen by the cut-off scale of the expansion, which is set to be $\Lambda = 1 \text{ TeV}$. In this analysis the “Warsaw” basis^[154] is used, which forms a complete, non-redundant set of dimension-5 and -6 operators allowed by the SM gauge symmetries. Furthermore, the top-flavour symmetry scheme is employed, which assumes a $U(2)^3$ symmetry in the quark sector, while in the lepton sector, a $U(1)_{l+e}^3$ symmetry is assumed. The lone dimension-5 operator is neglected assuming lepton number conservation, leaving dimension-6 operators as the leading-order terms in the expansion.

Operators directly relevant to Higgs processes are shown in Figure 5-1. A detailed description of the procedure can be found in Ref^[155].

Under SMEFT, the scattering amplitude of a process with dimension-6 operators included is given by¹:

$$|\mathcal{M}_{\text{SMEFT}}|^2 = |\mathcal{M}_{\text{SM}}|^2 + 2 \sum_i \frac{c_i}{\Lambda^2} \text{Re}(\mathcal{M}_{\text{SM}}^* \mathcal{O}_i) + \sum_{i,j} \frac{c_i c_j}{\Lambda^4} (\mathcal{O}_i^* \mathcal{O}_j), \quad (5-1)$$

where σ_{SM} is the SM amplitude, σ_{int} describes the interference between the BSM physics and the SM, and σ_{BSM} is a pure-BSM part that does not depend on the SM amplitude. Due to their dependence on the associated Wilson coefficients, the interference terms are referred to as the “linear” terms and pure-BSM as “quadratic”. The linear terms, suppressed by Λ^{-2} , are the leading-order modifications to cross-sections and decay widths. The quadratic terms are suppressed by Λ^{-4} , and thus expected to be sub-leading for measurements within the accuracy of Higgs measurements at the LHC. However, they can become important in certain regions of the phase space as well as prevent negative cross-sections when only considering linear terms. The interference between SM and dimension-8 operators is also suppressed by the same factor. Since no calculations based on a complete basis are currently available, these (and higher-order terms) operators are neglected in this analysis.

As a result of Equation 5-1, the cross-section of a specific process as predicted by SMEFT receives three contributions,

$$\sigma_{\text{SMEFT}} = \sigma_{\text{SM}} + \sigma_{\text{int}} + \sigma_{\text{BSM}}, \quad (5-2)$$

corresponding to those from the SM, linear, and quadratic terms as described above. An analogous form applies to the decay widths.

Some eigen directions in the EFT basis are not constrained by the data and are the so-called “flat directions” of the likelihood. These can be single operators or combinations of them. The most straightforward way to find the sensitive parameters would be to evaluate the fit for all possible combinations of Wilson coefficients. However, this is computationally not manageable

¹ EFT effects on PDFs, parton showers, detector interactions, etc. are not taken into account.

Wilson coefficient	Operator	Wilson coefficient	Operator
c_H	$(H^\dagger H)^3$	$c_{Qq}^{(1,1)}$	$(\bar{Q}\gamma_\mu Q)(\bar{q}\gamma^\mu q)$
$c_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	$c_{Qq}^{(1,8)}$	$(\bar{Q}T^a\gamma_\mu Q)(\bar{q}T^a\gamma^\mu q)$
c_G	$f^{abc}G_\mu^{a\nu}G_\nu^{b\rho}G_\rho^{c\mu}$	$c_{Qq}^{(3,1)}$	$(\bar{Q}\sigma^i\gamma_\mu Q)(\bar{q}\sigma^i\gamma^\mu q)$
c_W	$\epsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$c_{Qq}^{(3,8)}$	$(\bar{Q}\sigma^iT^a\gamma_\mu Q)(\bar{q}\sigma^iT^a\gamma^\mu q)$
c_{HDD}	$(H^\dagger D^\mu H)^*(H^\dagger D_\mu H)$	$c_{qq}^{(3,1)}$	$(\bar{q}\sigma^i\gamma_\mu q)(\bar{q}\sigma^i\gamma^\mu q)$
c_{HG}	$H^\dagger H G_{\mu\nu}^A G^{A\mu\nu}$	$c_{tu}^{(1)}$	$(\bar{t}\gamma_\mu t)(\bar{u}\gamma^\mu u)$
c_{HB}	$H^\dagger H B_{\mu\nu} B^{\mu\nu}$	$c_{tu}^{(8)}$	$(\bar{t}T^a\gamma_\mu t)(\bar{u}T^a\gamma^\mu u)$
c_{HW}	$H^\dagger H W_{\mu\nu}^I W^{I\mu\nu}$	$c_{td}^{(1)}$	$(\bar{t}\gamma_\mu t)(\bar{d}\gamma^\mu d)$
c_{HWB}	$H^\dagger \tau^I H W_{\mu\nu}^I B^{\mu\nu}$	$c_{td}^{(8)}$	$(\bar{t}T^a\gamma_\mu t)(\bar{d}T^a\gamma^\mu d)$
$c_{Hl,11}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_1\gamma^\mu l_1)$	$c_{Qu}^{(1)}$	$(\bar{Q}\gamma_\mu Q)(\bar{u}\gamma^\mu u)$
$c_{Hl,22}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_2\gamma^\mu l_2)$	$c_{Qu}^{(8)}$	$(\bar{Q}T^a\gamma_\mu Q)(\bar{u}T^a\gamma^\mu u)$
$c_{Hl,33}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_3\gamma^\mu l_3)$	$c_{Qd}^{(1)}$	$(\bar{Q}\gamma_\mu Q)(\bar{d}\gamma^\mu d)$
$c_{Hl,11}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{l}_1\tau^I\gamma^\mu l_1)$	$c_{Qd}^{(8)}$	$(\bar{Q}T^a\gamma_\mu Q)(\bar{d}T^a\gamma^\mu d)$
$c_{Hl,22}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{l}_2\tau^I\gamma^\mu l_2)$	$c_{tq}^{(1)}$	$(\bar{q}\gamma_\mu q)(\bar{t}\gamma^\mu t)$
$c_{Hl,33}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{l}_3\tau^I\gamma^\mu l_3)$	$c_{tq}^{(8)}$	$(\bar{q}T^a\gamma_\mu q)(\bar{t}T^a\gamma^\mu t)$
$c_{He,11}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_1\gamma^\mu e_1)$	$c_{eH,22}$	$(H^\dagger H)(\bar{l}_2 e_2 H)$
$c_{He,22}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_2\gamma^\mu e_2)$	$c_{eH,33}$	$(H^\dagger H)(\bar{l}_3 e_3 H)$
$c_{He,33}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_3\gamma^\mu e_3)$	c_{uH}	$(H^\dagger H)(\bar{q}Y_u^\dagger u \tilde{H})$
$c_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q)$	c_{tH}	$(H^\dagger H)(\bar{Q}\tilde{H}t)$
$c_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{q}\tau^I\gamma^\mu q)$	c_{bH}	$(H^\dagger H)(\bar{Q}Hb)$
c_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p\gamma^\mu u_r)$	c_{tG}	$(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{H}G_{\mu\nu}^A$
c_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p\gamma^\mu d_r)$	c_{tW}	$(\bar{Q}\sigma^{\mu\nu}t)\tau^I\tilde{H}W_{\mu\nu}^I$
$c_{HQ}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{Q}\gamma^\mu Q)$	c_{tB}	$(\bar{Q}\sigma^{\mu\nu}t)\tilde{H}B_{\mu\nu}$
$c_{HQ}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{Q}\tau^I\gamma^\mu Q)$	$c_{ll,1221}$	$(\bar{l}_1\gamma_\mu l_2)(\bar{l}_2\gamma^\mu l_1)$
c_{Ht}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{t}\gamma^\mu t)$		

Figure 5-1: Definition of the relevant EFT operators impacting the Higgs boson production and decay. The operators are given in the Warsaw basis, follows the convention of Ref^[156].

due to the large number of combinations. The sensitivity of the measurement to different Wilson coefficients is therefore evaluated using the covariance matrix, by the Principle Component Analysis (PCA). Due to the fit can hardly converge when fitting all the wilson coefficient at the same time, the PCA is applied separately to several groups of operators, which is grouped based on the similar physics impact on the observables.

Figure 5-2 shows the impact of operators in the rotated basis c' on the STXS regions.

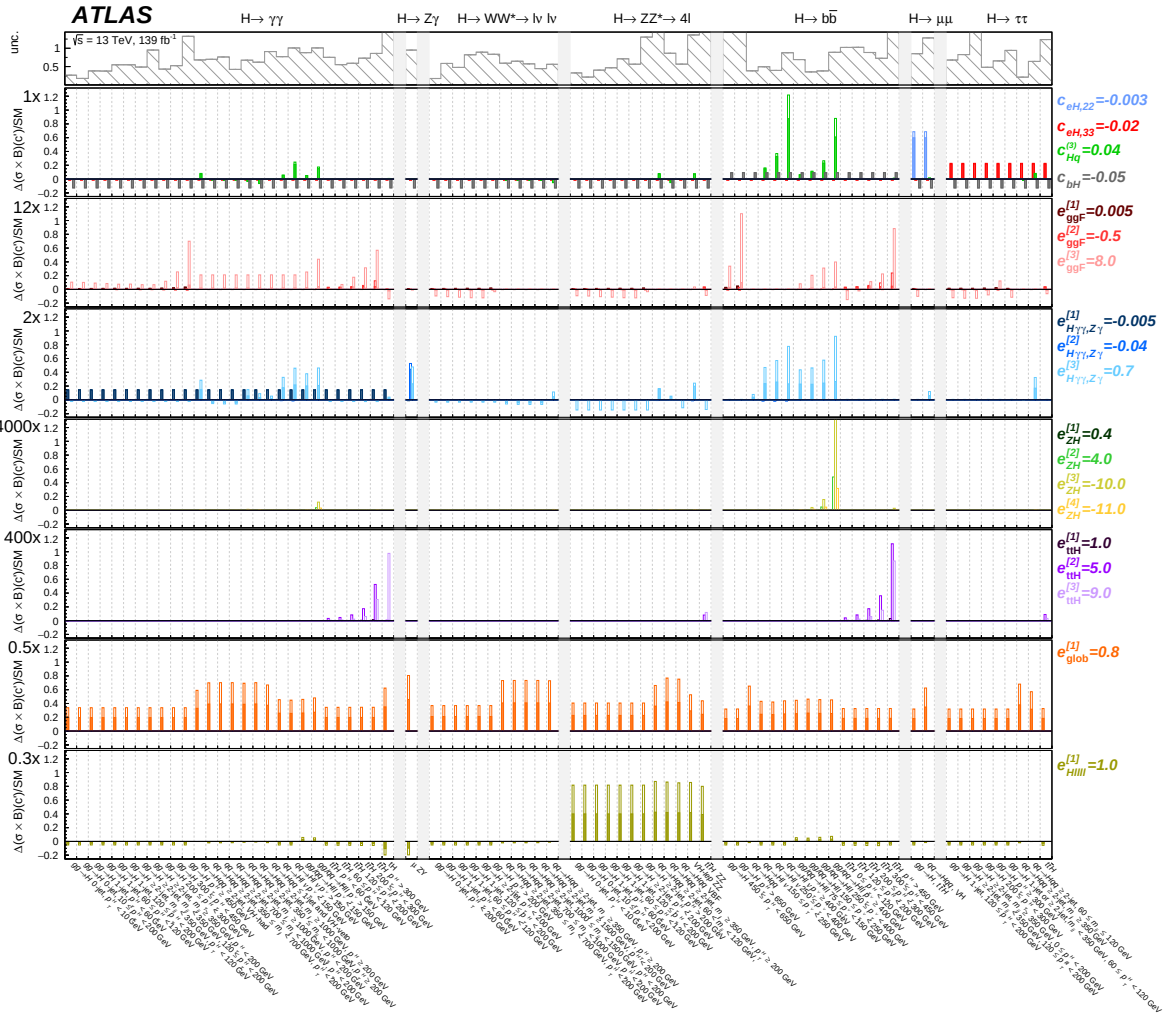


Figure 5-2: Impact of coefficients of the rotated basis c' on the STXS regions, relative to the SM cross-section, under the assumption of the linearised SMEFT model (shaded histogram) and the SMEFT model including quadratic terms (open histogram). For all coefficients, a variation equal to the expected uncertainty when using the linearised model is shown. .

A standard likelihood is built for the derivation of best-fit and constraint on the Wilson

coefficient

$$L(\mathbf{N}_k | \boldsymbol{\mu}, \boldsymbol{\theta}) = \prod_r \text{Poisson} \left(N_{k,r} | s_k(\boldsymbol{\mu}, \boldsymbol{\theta}) \cdot f_s^{k,r}(\boldsymbol{\theta}) + b_{k,r}(\boldsymbol{\theta}) \right), \quad (5-3)$$

where $N_{k,r}$ is the observed event count of bin r in region k , s_k is the expected signal count in region k , $f_s^{k,r}$ is the expected fraction of the signal in region k that is contained in bin r , and $b_{k,r}$ represents the expected event count from background processes. The ensemble of *parameters of interest* $\boldsymbol{\mu}$ describes the Higgs boson signal normalisation, while $\boldsymbol{\theta}$ represents the set of *nuisance parameters* taking into account the systematic uncertainties that originate from theoretical and experimental sources, as well as additional degrees of freedom without prior constraints such as background yields or normalisations in some of the input channels. The full likelihood function is then the product of the likelihood functions for each signal region k and of Gaussian or log-normal probability density functions that constrain the nuisance parameters.

Figure 5-3 and Figure 5-4 show the expected and observed results using linear and quadratic model respectively.

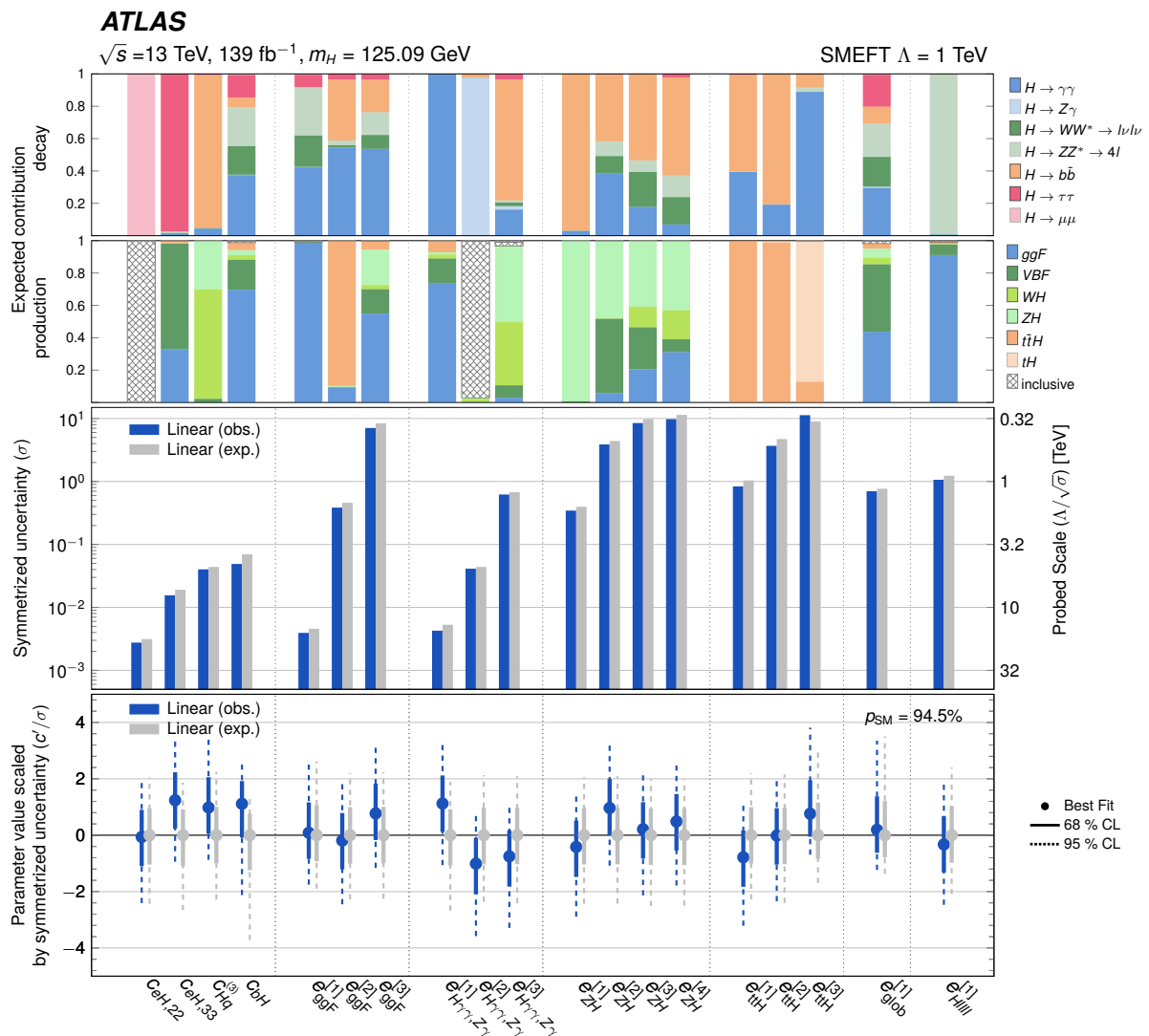


Figure 5-3: Comparison of the expected (gray) and observed (blue) parameters of the rotated basis $\mathbf{c}'$ with the SMEFT linearised model, where all other coefficients and nuisance parameters are profiled. The middle panel shows the symmetrized 68% CL uncertainty σ of each parameter measurement (left vertical axis) and the corresponding energy scale $\Lambda/\sqrt{\sigma}$ that is probed (right vertical axis). The bottom panel shows the measured parameter value (dot) and 68% (solid line) and 95% (dashed line) CL intervals, divided by the symmetrised uncertainty shown in the middle panel. The p -value for the compatibility of the data with the Standard Model expectation (all coefficients vanishing) is 94.5%. The top panel shows the expected breakdown of contributions to the sensitivity of each measurement from the various measured Higgs boson decay and production modes. Green shades represent production and decay modes with Higgs boson couplings to vector bosons, red shades represent modes with Higgs boson couplings to fermions, and blue shades represent modes with loop couplings. .

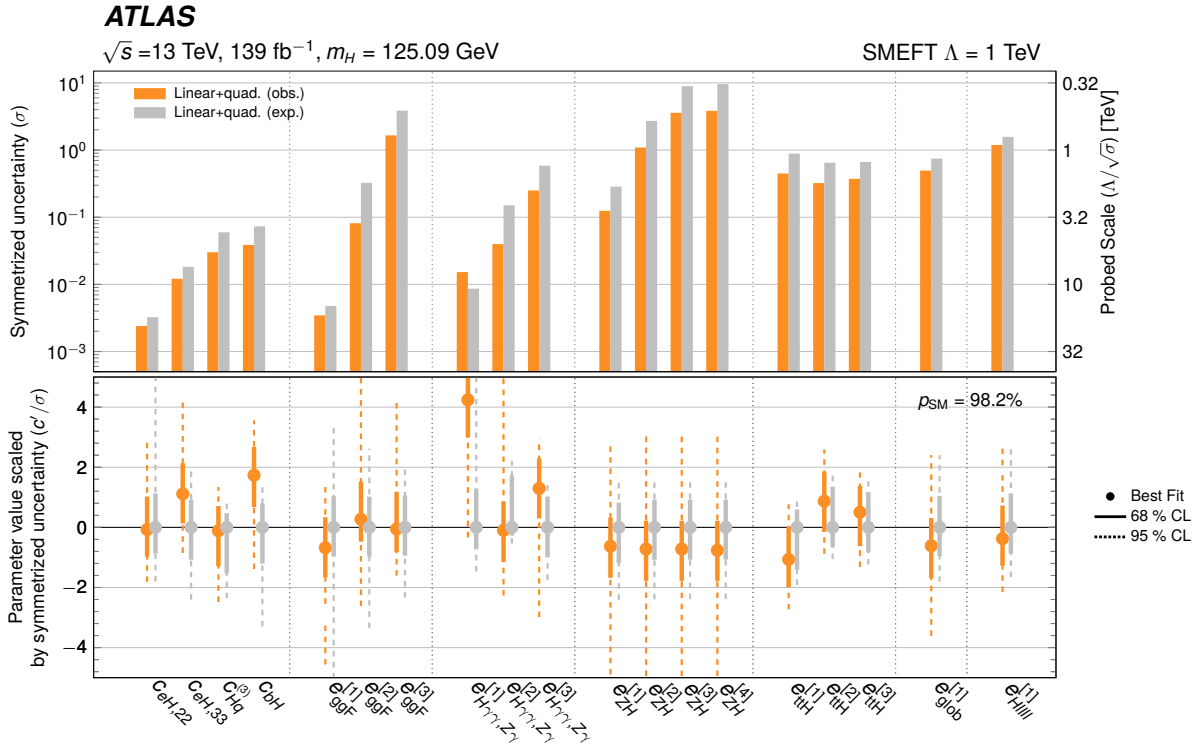


Figure 5-4: Comparison of the expected (gray) and observed (orange) parameters of the rotated basis c' with the SMEFT model with quadratic terms, where all other coefficients and nuisance parameters are profiled. The top panel shows the symmetrised 68% uncertainty σ of each parameter measurement (left vertical axis) and the corresponding energy scale $\Lambda/\sqrt{\sigma}$ that is probed (right vertical axis). The bottom panel shows the measured parameter value and 68% (solid) and 95% (dashed) CL intervals, divided by the symmetrised uncertainty shown in the top panel. Some of the observed intervals shown are clipped off. .

5.2.3 BSM Interpretation

One of the important question about the Higgs observed now is whether it is the only Higgs boson as predicted by the SM, or is part of an extended scalar sector, such as the ones with an additional doublet as predicted by many BSM UV models. Being complementary to the direct searches of the particles predicted in those BSM models, the coupling measurements of the SM Higgs boson can indirectly impose stringent constraints on their parameter space.

The input analyses used in BSM UV model interpretation is mentioned in Table 5-1. Since the prediction of BSM models are given inclusively, the combined workspace is parameterized into the inclusive signal strength (μ) of separate production and decay processes. In this μ -workspace, the POIs are the ratio of the observed results of total Higgs width, decay width and cross-section to their Standard Model values. So for a given production mode j and decay mode i , the expected number of events when the POIs are set to specific values could be written as:

$$N_{exp} = \mathcal{L} \cdot (r_j \cdot \sigma_j^{SM}(m_h = 125 \text{ GeV})) \cdot \frac{r_i \cdot \Gamma_i^{SM}(m_h = 125 \text{ GeV})}{r_\Gamma^{-1} \cdot \Gamma_h^{SM}(m_h = 125 \text{ GeV})} \quad (5-4)$$

where the POIs is derived from:

$$r_\Gamma = \frac{\Gamma_h^{SM}}{\Gamma_h}, r_i = \frac{\Gamma_i}{\Gamma_i^{SM}}, r_j = \frac{\sigma_j}{\sigma_j^{SM}} \quad (5-5)$$

The SM prediction, denoted by the label “SM”, by definition corresponds to POIs equal to 1. For the 2HDM, these ratios are derived using the kappa framework, where the coupling strength modifier are related to the free parameters of 2HDM. For MSSM, the loop effect makes the analytical form of coupling strength modifiers difficult to derive. Thus, theorists provide several kinds of information based on the simulation in the format of a ROOT file, which can be used to compute the corresponding values of POIs when the two parameters are set to a specific value. Table 5-2 lists all the POIs included in this study as well as the MSSM prediction and SM prediction that is used to get the value of POI. Note that the cross-section or decay width for both MSSM prediction and SM prediction is related to the Higgs mass. In the MSSM benchmark scenarios, the mass of the light scalar h (m'_h) is allowed to be in the range of 125 ± 3 GeV considering the effect of missing high order loops^[157-158]. The missing high order loops can

be used to compensate the mass difference between the predicted Higgs mass and the observed value (125.09 GeV) that up to 3 GeV. As a result, the Higgs mass in the input workspace is still taken as the observed value and thus the uncertainty of the Higgs mass prediction is also neglected. However, the prediction of MSSM models are given with the shifted Higgs scalar mass (m'_h), so the SM prediction of cross-sections and Branch Ratios for calculating the ratios are also taken with this shifted mass. A more detailed discussion of the POI computation strategy will be stated in the following part.

Production	POI	Expression	Decay	POI	Expression
VBF	r_{VBF}	$0.73r_W + 0.27r_Z$	$h \rightarrow WW$	r_W	$\Gamma'_h \cdot BR'_{h \rightarrow WW} / \Gamma^{SM'}_{h \rightarrow WW}$
ggF	r_{ggF}	$\sigma'_{ggF} / \sigma^{SM'}_{ggF}$	$h \rightarrow ZZ$	r_Z	$\Gamma'_h \cdot BR'_{h \rightarrow ZZ} / \Gamma^{SM'}_{h \rightarrow ZZ}$
ttH	r_{ttH}	$\sigma'_{ttH} / \sigma^{SM'}_{ttH}$	$h \rightarrow bb$	r_b	$\Gamma'_h \cdot BR'_{h \rightarrow bb} / \Gamma^{SM'}_{h \rightarrow bb}$
tHW	r_{tHW}	$2.909\kappa_t'^2 + 2.310r_W - 4.220\kappa_t' \sqrt{r_W}$	$h \rightarrow \tau\tau$	r_τ	$\Gamma'_h \cdot BR'_{h \rightarrow \tau\tau} / \Gamma^{SM'}_{h \rightarrow \tau\tau}$
tHq	r_{tHq}	$2.633\kappa_t'^2 + 3.578r_W - 5.211\kappa_t' \sqrt{r_W}$	$h \rightarrow \mu\mu$	r_μ	$\Gamma'_h \cdot BR'_{h \rightarrow \mu\mu} / \Gamma^{SM'}_{h \rightarrow \mu\mu}$
$qqZH$	r_Z	$\Gamma'_h \cdot BR'_{h \rightarrow ZZ} / \Gamma^{SM'}_{h \rightarrow ZZ}$	$h \rightarrow \gamma\gamma$	r_γ	$\Gamma'_h \cdot BR'_{h \rightarrow \gamma\gamma} / \Gamma^{SM'}_{h \rightarrow \gamma\gamma}$
$qqWH$	r_W	$\Gamma'_h \cdot BR'_{h \rightarrow WW} / \Gamma^{SM'}_{h \rightarrow WW}$	$h \rightarrow gg$	r_g	$\Gamma'_h \cdot BR'_{h \rightarrow gg} / \Gamma^{SM'}_{h \rightarrow gg}$
bbH	r_{bbH}	$\sigma'_{bbH} / \sigma^{SM'}_{bbH}$	$h \rightarrow Z\gamma$	$r_{Z\gamma}$	$\Gamma'_h \cdot BR'_{h \rightarrow Z\gamma} / \Gamma^{SM'}_{h \rightarrow Z\gamma}$
$ggZH$	r_{ggZH}	$2.456r_Z + 0.456\kappa_t'^2 - 1.903\sqrt{r_Z}\kappa_t' - 0.011\sqrt{r_Z r_b} + 0.003\kappa_t' \sqrt{r_b}$	Γ_h	r_Γ	$\Gamma'_h / \Gamma^{SM'}_h$

Table 5-2: List of POIs involved in the current analysis; they are defined as the branching ratios or decay widths divided by their SM prediction. The MSSM input predictions are provided in the ROOT file, noted with an apostrophe, with the Higgs mass equals to the MSSM predicted value (m'_h) instead of 125.09 GeV. The SM value can be found in^[159], with the assumption that the Higgs mass equals to the predicted value (m'_h).

For the total Higgs width, the MSSM prediction is available directly, so the μ can be computed accordingly. For all the decay width, what contains in the ROOT file is the MSSM prediction for Branch Ratio (BR), and the MSSM decay width is then calculated by multiplying total Higgs width and the BR.

$$r_\Gamma = \frac{\Gamma'_h}{\Gamma^{SM}_h(m'_h)}, \quad r_i = \frac{\Gamma'_h \cdot BR'_i}{\Gamma^{SM}_i(m'_h)} \quad (5-6)$$

where the term with apostrophe stands for the MSSM input provided in the ROOT file with the Higgs mass equals to the MSSM predicted value. The meaning of the apostrophe is the same in the following part.

ggF , bbH and ttH production For ggF , bbH and ttH production, MSSM prediction of cross-section is available. Note that the SM predictions provided by the LHCHXSWG are calculated to the 'state-of-the-art', while the MSSM predictions are calculated to a lower order. In the ROOT file, the SM predictions which are calculated to the same 'lower' order are provided. So, the rescaling factors of these production modes, that only consider the MSSM effect on the couplings, are given by dividing the MSSM prediction with the SM prediction that shares the same Higgs mass (m'_h).

VBF and $qqVH$ production For $qqVH$ production, where the V could be Z or W boson, it shares the same modifier r with decay width of corresponding $h \rightarrow VV$ as they all have hVV vertex in the diagrams. It is believed that the MSSM has the same effect on the $h \rightarrow VV$ and these two production modes. For VBF production, the modifier uses the SM κ framework parameterization. Actually, in MSSM models, the rescaling factor for $h \rightarrow ZZ$ and $h \rightarrow WW$ should be the same. However, due to the precision of calculation and numerical numbers, they are not totally equal but very close to each other. Validation has been conducted to confirm that there are negligible changes between using the SM κ framework parameterization and using the same rescale factor for $h \rightarrow ZZ$ or $h \rightarrow WW$.

tH and $ggZH$ productions In the absence of better information about them, the tH and $ggZH$ production modes are parameterized as functions of the Higgs couplings as in the κ -framework. This typically assumes that the MSSM does not affect significantly the loops, but only the vertices. In any case, the effect is expected to be small as these production modes have a subdominant impact on the results.

Two-Higgs-doublet models

In 2HDM, the Higgs sector is extended by introducing one additional doublet of the complex field^[19,24-25,160]. The model considered here assumes CP conservation and a $\mathbb{Z}_2$ symmetric potential, which result in 5 Higgs bosons after electroweak symmetry breaking: two neutral CP-even Higgs bosons H and S , one neutral CP-odd Higgs boson A , and two charged Higgs bosons $H^\pm$. The masses of S , A and $H^\pm$ are assumed to be heavier than the one of the SM Higgs

boson H , so that there is no new decay channel of the SM Higgs boson H opened and its total width is not modified.

The Z_2 symmetry of the potential constraints flavour changing neutral currents at tree-level (see Glashow-Weinberg condition^[161-162]), which are strongly constrained by existing data, and implies that all right-handed quarks of a given charge must couple to a single Higgs multiplet. Accordingly, 4 types of 2HDM are defined:

- Type I: one Higgs doublet couples to vector bosons, while the other couples to fermions. The first doublet is “fermiophobic” in the limit that the two Higgs doublets do not mix.
- Type II: this is an “MSSM-like” model, in which one Higgs doublet couples to up-type quarks and the other to down-type quarks and charged leptons. This model is realised in the Minimal Supersymmetric Standard Model (MSSM).
- Lepton-specific: the Higgs bosons have the same couplings to quarks as in the Type I model and to charged leptons as in Type II.
- Flipped: the Higgs bosons have the same couplings to quarks as in the Type II model and to charged leptons as in Type I.

The Higgs sector of the 2HDM models discussed here can be described by 7 parameters: 4 Higgs boson masses (m_H , m_S , m_A and $m_{H^\pm}$), $\tan \beta$, $\cos(\beta - \alpha)$ and m_{12} , where $\tan \beta$ stands for the ratio of the vacuum expectation values of the two Higgs doublets ($\tan \beta = v_2/v_1$ with $v_1^2 + v_2^2 = v^2 \approx (246 \text{ GeV})^2$), α for the mixing angle of the 2 neutral CP-even Higgs states, and the Higgs potential parameter m_{12}^2 .

Coupling scale factor	Type I	Type II	Lepton-specific	Flipped
κ_V			$s_{\beta-\alpha}$	
κ_u	$s_{\beta-\alpha} + c_{\beta-\alpha}/\tan \beta$	$s_{\beta-\alpha} + c_{\beta-\alpha}/\tan \beta$	$s_{\beta-\alpha} + c_{\beta-\alpha}/\tan \beta$	$s_{\beta-\alpha} + c_{\beta-\alpha}/\tan \beta$
κ_d	$s_{\beta-\alpha} + c_{\beta-\alpha}/\tan \beta$	$s_{\beta-\alpha} - \tan \beta c_{\beta-\alpha}$	$s_{\beta-\alpha} + c_{\beta-\alpha}/\tan \beta$	$s_{\beta-\alpha} - \tan \beta c_{\beta-\alpha}$
κ_l	$s_{\beta-\alpha} + c_{\beta-\alpha}/\tan \beta$	$s_{\beta-\alpha} - \tan \beta c_{\beta-\alpha}$	$s_{\beta-\alpha} - \tan \beta c_{\beta-\alpha}$	$s_{\beta-\alpha} + c_{\beta-\alpha}/\tan \beta$

Table 5-3: The scale factors (coupling modifications with respect to SM) at lowest order for the SM Higgs boson H couplings to vector bosons κ_V , up-type quarks κ_u , down-type quarks κ_d , and charged leptons κ_l , parameterized by $\tan \beta$ and $\cos(\beta - \alpha)$ in 2HDMs 4 different types. $c_{\beta-\alpha}$ stands for $\cos(\beta - \alpha)$ and $s_{\beta-\alpha}$ for $\sin(\beta - \alpha)$.

The interpretation of 2HDM applies to the case near decoupling limit where the heavy fields decouple from the light fields. The decoupling limit in 2HDM is given by Ref^[24]. In the

decoupling, the masses of the heavy Higgs bosons relate to the scale of New Physics (Λ)

$$m_A^2 \sim m_{H_0}^2 \sim m_{H^\pm}^2 \equiv M^2 \gg v^2, m_h^2 \sim v^2 \quad (5-7)$$

Near the decoupling limit, the light Higgs in 2HDM can be considered as the SM Higgs, the heavy Higgs is heavy enough to have negligible loop contribution to the SM Higgs process. There is another *alignment* limit which is also crucial in 2HDM, where the $\cos(\beta - \alpha) = 0$. In the alignment limit, the heavy Higgs sector completely decouple with the light Higgs one, and the light Higgs sector falls back to the SM.

With the assumptions described above, the scale factors for the SM Higgs boson H couplings ($\kappa_V, \kappa_u, \kappa_d, \kappa_l$) to vector bosons, up-type quarks, down-type quarks and leptons, respectively, are parameterized with $\tan \beta$ and $\cos(\beta - \alpha)$ in 2HDM, as shown in Table 5-3 for all the 4 types^[163]. The measurements of the SM Higgs boson H in different production and decay modes are used to constrain the 2HDM parameters $\tan \beta$ and $\cos(\beta - \alpha)$ via the κ parameters.

At $\cos(\beta - \alpha) = 0$, the SM alignment limit is defined^[25], in which all the Higgs boson H couplings acquire their SM values respectively. At $\cos(\beta + \alpha) = 0$, the wrong-sign Yukawa limit is defined^[164-165], in which at least one of the Higgs boson H couplings to down-type quarks and leptons are opposite in sign to the corresponding SM values. For example, the Type II model has an opposite sign on the Higgs boson H couplings to both down-type quarks and leptons, the Flipped model has it only on the ones to down-type quarks, and the Lepton-specific model has it only on the ones to leptons which is also called symmetric limit.

The self-coupling dependence in the 2HDM model is derived from the tri-linear hhh coupling given in^[166] as,

$$\kappa_\lambda = \sin^3(\beta - \alpha) + (3 - 2\frac{\bar{m}^2}{m_h^2}) \cos^2(\beta - \alpha) \sin(\beta - \alpha) + 2 \cot 2\beta (1 - \frac{\bar{m}^2}{m_h^2}) \cos^3(\beta - \alpha) \quad (5-8)$$

where $\bar{m}$ is an additional free parameter which can be written in terms of the Higgs potential parameter as m_{12}^2 as,

$$\bar{m}^2 = \frac{m_{12}^2}{\sin \beta \cos \beta} \quad (5-9)$$

The parameter relates to the heavy Higgs boson mass, m_A , as follows,

$$\bar{m}_{12}^2 = \frac{M_A^2 \tan \beta}{1 + \tan^2 \beta} \quad (5-10)$$

Therefore, the new mass parameter, $\bar{m}$, can be re-written as,

$$\begin{aligned} \bar{m}^2 &= \frac{M_A^2 \cdot \tan \beta}{(\sin \beta \cos \beta)(1 + \tan^2 \beta)} \\ &= \frac{M_A^2}{\cos^2 \beta (1 + \tan^2 \beta)} \\ &= M_A^2 \end{aligned} \quad (5-11)$$

The self-coupling dependence in the κ framework is parameterized by κ_λ . The parameterization of κ_λ is based on the NLO-EW correction to single-Higgs production and decay is taken from^[167]. Introducing the dependence on κ_λ brings an additional dependence on the mass of the heavy Higgs boson. In this study, since it does not directly probe the production of the heavy Higgs boson, it is chosen that $M_A = 1$ TeV. This choice is also consistent with the new physics energy scale Λ used in EFT, and their further relationship in self-coupling will be discussed later.

The regions of the $(\tan \beta, \cos(\beta - \alpha))$ plane expected to be excluded at 95% CL for the 4 types of 2HDM models are shown in Figure 5-5. The parameters α and β are required to satisfy $0 \leq \beta \leq \pi/2$ and $0 \leq \beta - \alpha \leq \pi$ without loss of generality.

There is a physical boundary $\kappa_V \leq 1$ ($V = W, Z$) in all four 2HDM types, to which the profile likelihood ratio is restricted. The data are expected to be consistent with the SM alignment limit. In the upper right plane of Type II, Lepton-specific, and Flipped models, there is a narrow curved petal region of allowed parameter space that is not expected to be excluded. These correspond to regions with $\cos(\beta - \alpha) \approx 0$, for which some fermion couplings have the same magnitude as in the SM, but the opposite sign. These couplings are measured with insufficient precision to be excluded. There is no upper petal in the Type I mode given all the Yukawa couplings are identical.

Similar petal regions without exclusion could happen to the low right plane. This corresponds to an opposite sign on the Higgs H boson couplings to all fermions in Type I, up-type

quarks in Type II, all quarks in the Lepton-specific, and lastly up-type quarks and leptons in the Flipped. However, they do not appear thanks to the top quark coupling that is well constrained in the production: both directly with $t\bar{t}H$ and in the loop with ggF and in decay in the loop decay to diphotons.

For the Type-I model, the observed and expected regions excluded at 95% CL when the κ_λ constraint is considered are also shown in Figure 5-5. By considering the loop effect of κ_λ , the expected constraint at high $\tan\beta$ region is improved by nearly 100%.

EFT-matching Constraints

As the behaviors of high energy scale UV model at low energy can be described using EFT framework, it is possible to translate the constraint on EFT coefficients to the constraint on BSM parameters, which is named as *matching*. This matching can validate whether the EFT is the low energy approximation of UV models. Theorists have provided the matching rule for various models. In this analysis, the 2HDM is used to perform such matching since it only modify the Higgs sector thus the Higgs operators in EFT is most sensitive in the measurements considered in this analysis.

The SMEFT matching of the 2HDM model applies in the decoupling limit of the 2HDM. In the exact alignment limit, $\cos(\beta - \alpha) \rightarrow 0$, SMEFT operators are not generated at tree-level but appear at 1-loop. Away from the alignment limit, tree-level contributions to the Higgs Yukawa couplings are generated, along with a correction to the Higgs trilinear coupling. The relevant Wilson coefficients ($c_{eH,22}, c_{eH,33}, c_{tH}, c_{bH}, c_H$) are expressed in terms of $\cos(\beta - \alpha)$ and $\tan\beta$ through a parameterization given in Table 5-4^[168]. It should be noted that all the Yukawa coupling modifier parameterization are given in linear expansion as it is the leading order effect. The coupling of Higgs to vector boson is not considered in the mapping since it only presents at $D = 8$ operators. This can be understood by expanding the vector boson coupling modifier in 2HDM:

$$\sin(\beta - \alpha) = \sqrt{1 - \cos(\beta - \alpha)^2} = 1 - \frac{1}{2} \cos(\beta - \alpha)^2 - \frac{1}{8} (\cos(\beta - \alpha)^4) + O(\cos(\beta - \alpha)^6) \quad (5-12)$$

, where the $\cos(\beta - \alpha)$ only presents at $O(\cos(\beta - \alpha))^2$. All other Wilson coefficients not

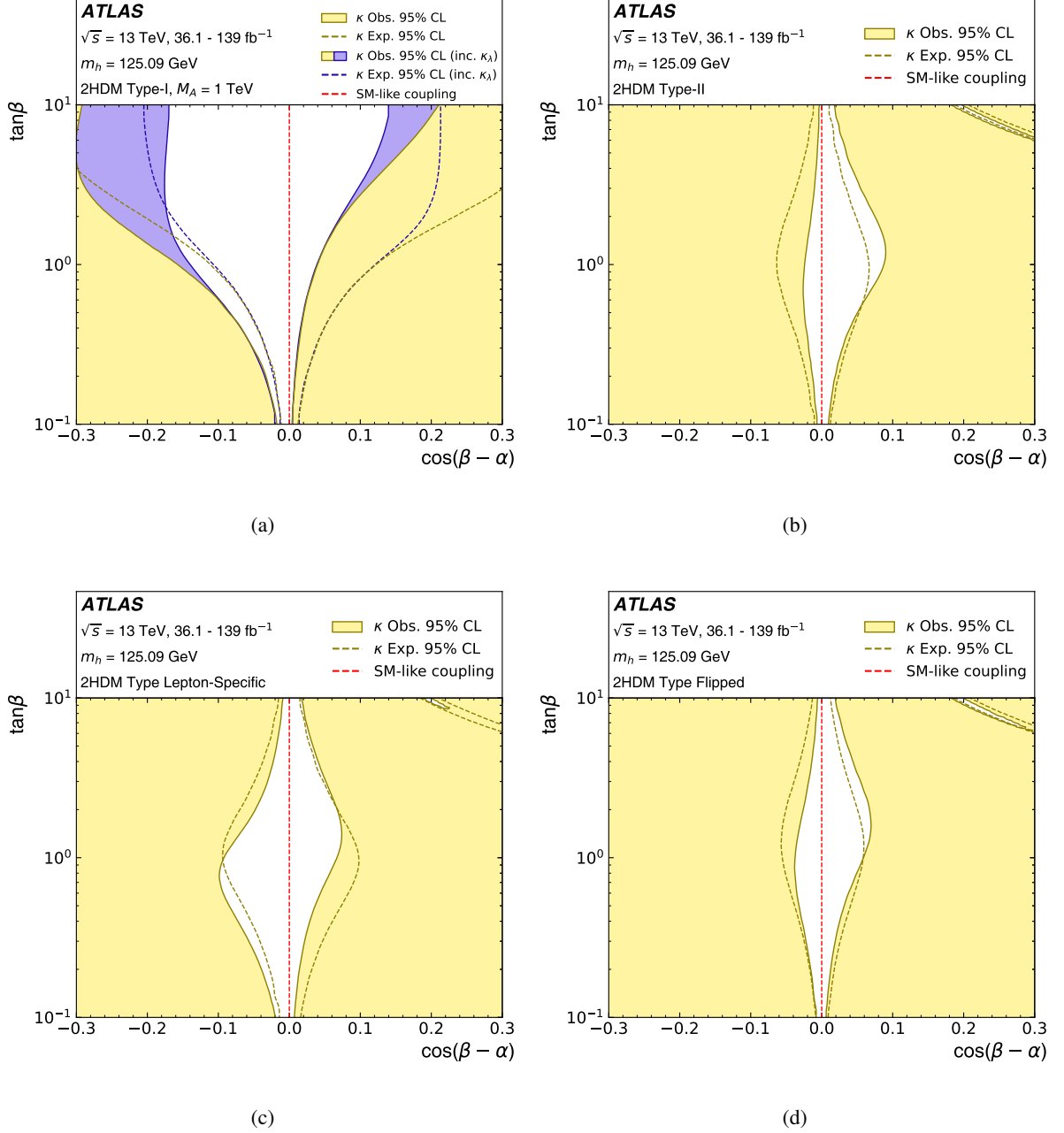


Figure 5-5: Regions of the $(\tan\beta, \cos(\beta-\alpha))$ plane in 2HDM excluded by fits to the measured rates of Higgs boson production and decays: (a) Type I, (b) Type II, (c) Lepton-specific and (d) Flipped. The likelihood contours correspond approximately to the 95% CL (i.e. 2 std. dev. at $-2\ln\Lambda = 5.99$) are indicated for expectation for the SM Higgs sector. For the Type-I model, the observed and expected regions excluded at 95% CL when the κ_λ constraint is considered are also shown (solid and dashed blue lines).

mentioned are fixed to zero as they are not considered to be modified in the 2HDM model.

SMEFT parameters	Type I	Type II	Lepton-specific	Flipped
$\frac{v^2 c_{tH}}{\Lambda^2}$	$-Y_t c_{\beta-\alpha} / \tan \beta$	$-Y_t c_{\beta-\alpha} / \tan \beta$	$-Y_t c_{\beta-\alpha} / \tan \beta$	$-Y_t c_{\beta-\alpha} / \tan \beta$
$\frac{v^2 c_{bH}}{\Lambda^2}$	$-Y_b c_{\beta-\alpha} / \tan \beta$	$Y_b c_{\beta-\alpha} \tan \beta$	$-Y_b c_{\beta-\alpha} / \tan \beta$	$Y_b c_{\beta-\alpha} \tan \beta$
$\frac{v^2 c_{eH,22}}{\Lambda^2}$	$-Y_\mu c_{\beta-\alpha} / \tan \beta$	$Y_\mu c_{\beta-\alpha} \tan \beta$	$Y_\mu c_{\beta-\alpha} \tan \beta$	$-Y_\mu c_{\beta-\alpha} / \tan \beta$
$\frac{v^2 c_{eH,33}}{\Lambda^2}$	$-Y_\tau c_{\beta-\alpha} / \tan \beta$	$-Y_\tau c_{\beta-\alpha} \tan \beta$	$Y_\tau c_{\beta-\alpha} \tan \beta$	$-Y_\tau c_{\beta-\alpha} / \tan \beta$
$\frac{v^2 c_H}{\Lambda^2}$	$c_{\beta-\alpha}^2 M_A^2 / v^2$	$c_{\beta-\alpha}^2 M_A^2 / v^2$	$c_{\beta-\alpha}^2 M_A^2 / v^2$	$c_{\beta-\alpha}^2 M_A^2 / v^2$

Table 5-4: The Wilson coefficients at lowest order for SMEFT, modifying the Yukawa couplings c_{tH} , c_{bH} , $c_{eH,33}$, and $c_{eH,22}$ for the top quark, bottom quark, τ , and μ parameterised by $\tan \beta$ and $\cos(\beta - \alpha)$ in 2HDMs 4 different types where $c_{\beta-\alpha}$ stands for $\cos(\beta - \alpha)$. c_H corresponds to modification to the self-coupling of the Higgs and M corresponds to the mass of the Heavy Higgs bosons in 2HDM. Y_i corresponds to $\sqrt{(2)m_i}/v$. For the purposes of this analysis, $M_A = \Lambda = 1$ TeV is considered. The parameterization is taken from Ref^[168].

The self-coupling modifier κ_λ can be mapped to the SMEFT equivalent as follows^[156,169]:

$$\kappa_\lambda = 1 + \frac{v^2 c_{H\Box}}{\Lambda^2} - \frac{v^2 c_{HDD}}{4\Lambda^2} - \frac{c_{HI(3),11}}{2\Lambda^2} - \frac{c_{HI(3),22}}{2\Lambda^2} + \frac{v^2 c_{ll,1221}}{2\Lambda^2} - \frac{v^2 c_H}{\lambda \Lambda^2} \quad (5-13)$$

, where the parameter λ is given by $\lambda = (G_f * m_h^2)/\sqrt{2}$. The $c_{H\Box}$ and c_{HDD} provides the extra kinematic structures, which is not considered in this analysis. As a result, only c_H is considered in the matching to 2HDM.

$$\kappa_\lambda = 1 - \frac{v^2 c_H}{\lambda \Lambda^2} \quad (5-14)$$

To better understand the relationship of Λ in SMEFT and M_A in the 2HDM, it is instructive to re-write the Equation 5-8. The $\sin(\beta - \alpha)$, $\cos(\beta - \alpha)^2$ term and the $\cos(\beta - \alpha)^3$ terms can be neglected as they are of $O(\frac{v^d}{\Lambda^d})$, $d \geq 4$. The remaining terms can be written as:

$$\kappa_\lambda = 1 - 2 \frac{\bar{m}^2}{m_h^2} \cos^2(\beta - \alpha) = 1 - \frac{c_{\beta-\alpha}^2 M_A^2}{\lambda v^2} \quad (5-15)$$

By comparing with Equation 5-14, it can be obtained that

$$\frac{v^2 c_H}{\Lambda^2} = c_{\beta-\alpha}^2 M_A^2 / v^2 \quad (5-16)$$

This relationship reveals the connection between SMEFT energy scale and the new particles in UV models. The higher M_A is, the larger impact of 2HDM modification on the self-coupling

becomes. By absorbing this impact into the EFT operators, the constraint on the corresponding coefficients will be tighter, which indicates a higher energy scale probed. Thus, it is natural to choose the same value for M_A and Λ .

Figure 5-6 shows the comparison of direct interpretation (based on κ framework, so named κ approach) and EFT matching approach in four scenarios of 2HDM. For Type II, Lepton-specific and Flipped scenarios, the results are very similar, which proves that EFT can be a very good approximation of the UV models. The petal regions, however, is not present in the EFT matching approach, since the parameterization of Yukawa coupling is given in linear expansion. For the Type-I 2HDM, the constraint obtained from EFT matching approach is looser than the κ approach. This is due to the absence of HVV coupling in the EFT matching approach.

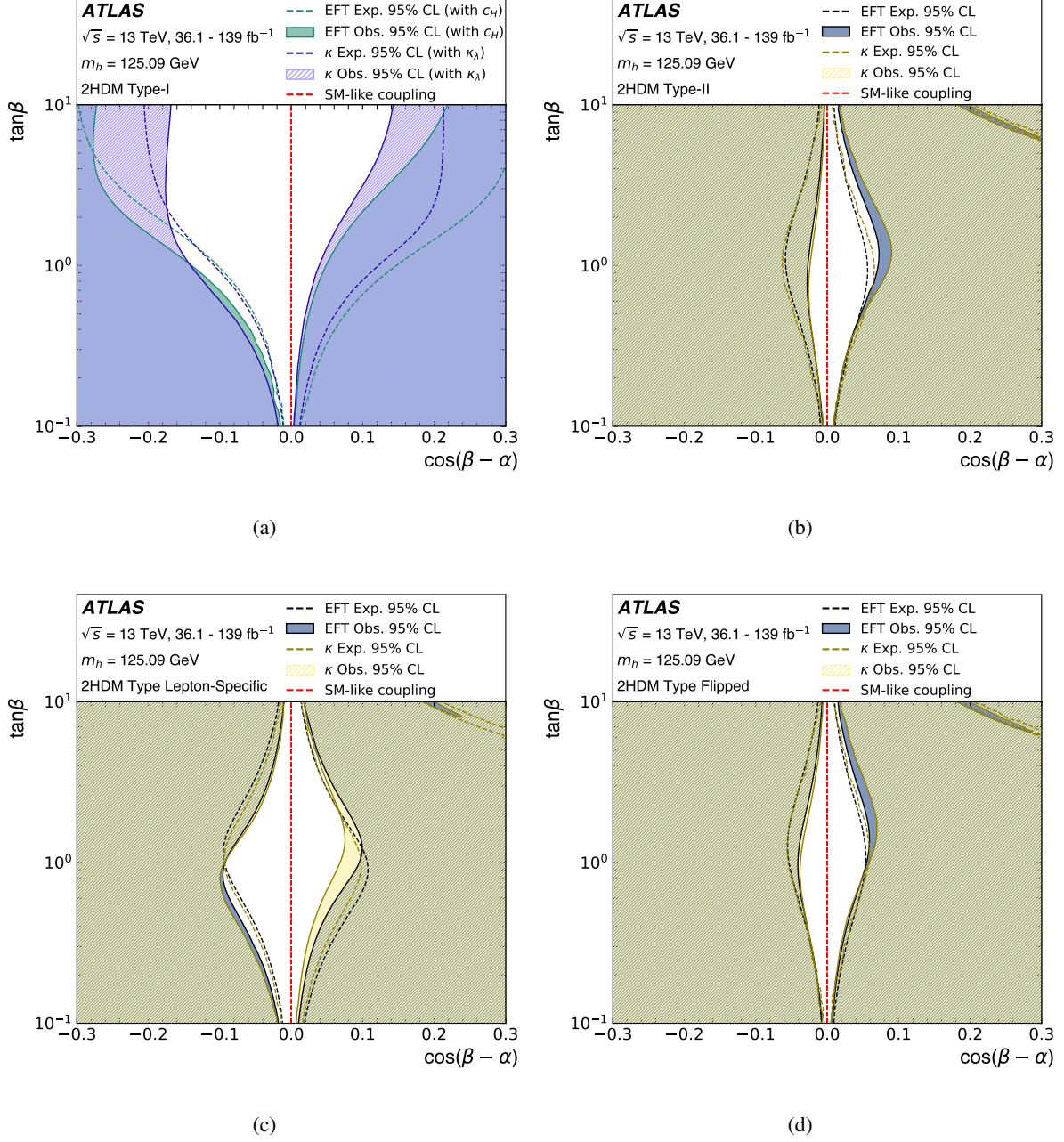


Figure 5-6: Comparison of the constraints from the approaches based on the direct interpretation and EFT matching approach in the $(\tan\beta, \cos(\beta - \alpha))$ plane in 2HDM by fits to the measured rates of Higgs boson production and decays: (a) Type I, (b) Type II, (c) Lepton-specific and (d) Flipped. The likelihood contours correspond approximately to the 95% CL (i.e. 2 std. dev. at $-2\ln\Lambda = 5.99$) are indicated for expectation for the SM Higgs sector. .

MSSM benchmark scenarios

Supersymmetry^[170-178] provides a mean to solve the hierarchy problem by introducing superpartners whose radiative corrections to the Higgs boson mass cancel those of the corresponding SM particles. Many supersymmetric models also provide a candidate for a dark matter particle.

Minimal Supersymmetric Standard Model (MSSM)^[179-183] is one of the most popular extension of SM. Its Higgs sector consists of two SU(2) doublets, H_1 and H_2 . The spectrum of physical Higgs bosons consists of two neutral CP-even scalars, of which we denote the lighter as h and the heavier as H , one CP-odd scalar, A , and a charged-scalar pair, $H^\pm$.

In the Minimal Supersymmetric Standard Model, the mass mixing matrix for the neutral, CP-even Higgs bosons is:

$$\mathcal{M}_S^2 = (m_Z^2 + \delta_1) \begin{bmatrix} \cos^2(\beta) & -\cos(\beta)\sin(\beta) \\ -\cos(\beta)\sin(\beta) & \sin^2(\beta) \end{bmatrix} + m_A^2 \begin{bmatrix} \sin^2(\beta) & -\cos(\beta)\sin(\beta) \\ -\cos(\beta)\sin(\beta) & \cos^2(\beta) \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & \frac{\delta}{\sin^2(\beta)} \end{bmatrix} \quad (5-17)$$

where δ_1 and δ are radiative corrections involving primarily top quarks and stops.

In MSSM, there are numerous free parameters, which makes the complete scan of these parameters impractical. As a result, several benchmark scenarios have been proposed over the years. They can reduce the number of free parameters by making some assumptions. In this study, seven scenarios are selected and in these scenarios, two parameters in Higgs sector are varied. For the CP-conserving cases analysed here, the two parameters are usually M_A and $\tan\beta$ (where A is the pseudoscalar CP-odd Higgs boson).

Detailed information on the benchmarks and their specific parameter settings can be found in^[184-185]. For all the scenarios used in this study, the role of SM-like Higgs is played by the light CP-even scalar, h . And in most of the scenarios except $M_h^{125}(\text{alignment})$, the mass splitting between the h and other scalars is so big that the interference between them is negligible. In the allowed region of $M_h^{125}(\text{alignment})$ scenario, the interference effect is also very small as the tree-level mixing cancels with the radiative correction.

M_h^{125} scenario In this benchmark scenario, all superparticles are chosen to be so heavy that production and decays of the MSSM Higgs bosons are only mildly affected by their presence. The loop-induced SUSY contribution to the couplings of the light CP-even scalar is small, and the heavy Higgs bosons with masses up to 2 TeV decay only to SM particles.

$M_h^{125}(\text{CPV})$ **scenario** This scenario is characterized by CP violation in the Higgs sector and provides an illustration of the interference effects in Higgs production and decay.

$M_h^{125}(\tilde{\chi})$ **scenario** This scenario is characterized by all charginos and neutralinos being relatively light, with significant higgsino-gaugino mixing. This affects the decays of the heavier Higgs bosons, weakening the exclusion bounds from $H/A \rightarrow \tau\tau$ searches, as well as the decay of the SM-like Higgs boson to photons. On the other hand, the possibility to look for additional Higgs bosons through their decays to charginos and neutralinos opens up.

$M_h^{125}(\tilde{\tau})$ **scenario** This scenario is characterized by light staus (the superpartner of τ) and light gaugino-like charginos and neutralinos. The effect of the light staus on the decays of the heavier Higgs bosons, as well as on the decay of the SM-like Higgs boson to photons, is most relevant at large $\tan\beta$. Compared with the previous scenario, a larger mass for the higgsinos implies that the decays of the heavier Higgs bosons to charginos and neutralinos become relevant at larger values of M_A .

$M_h^{125}(\text{alignment})$ **scenario** This scenario is characterized by the phenomenon of “alignment without decoupling”, in which, for a given value of $\tan\beta$, one of the two neutral CP-even scalars has SM-like couplings independently of the mass spectrum of the remaining Higgs bosons. In particular, for $\tan\beta$ around 7, the properties of the lighter scalar h are in agreement with those of the observed Higgs boson also for relatively low values of M_A .

$M_{h,\text{EFT}}^{125}$ **scenario** This scenario is characterized by a flexible M_{SUSY} that is raised to very high values ($6\text{--}10^{13}$ TeV) to reach $M_h \sim 125$ GeV. In all the original benchmark scenarios presented above, the supersymmetric partners of the SM fermions (sfermions) are tied to the TeV scale. In this case, the parameter region $\tan\beta < 5$ is ruled out because the mass of the SM-like Higgs boson is predicted to be lower than the measured value. To re-open the parameter region of low $\tan\beta$ values, the sfermion mass scale, M_{SUSY} is adjusted dynamically from 6 TeV to 10^{16} TeV to achieve a 125 GeV Higgs. Higher M_{SUSY} is impractical as it is larger than the GUT limit. The SUSY contribution to the Higgs properties is calculated with the effective field theory (EFT). Like the M_h^{125} scenario, all superparticles are chosen to be so heavy that production and decays

of the MSSM Higgs bosons are only mildly affected by their presence.

$M_{h,\text{EFT}}^{125}(\tilde{\chi})$ scenario In contrast to the $M_{h,\text{EFT}}^{125}$ scenario, this scenario features light neutralinos and charginos whose presence significantly alters the Higgs phenomenology. The SUSY scale is again adjusted at every parameter point to obtain a light Higgs mass of $M_h \approx 125$ GeV.

$h\text{MSSM}$ scenario $h\text{MSSM}^{[186-187]}$, which assumes that the superpartners are heavy (apart from the Higgs sector particles) and the lowest order relations hold. The scenario is a convenient approximation, which allows a simple parametrization of the couplings. The $h\text{MSSM}$ is not valid for low $\tan \beta$ values ($\mathcal{O}(1)$ or lower). Missing radiative corrections also lowers the precision of the approximation at high $\tan \beta$ values ($\mathcal{O}(10)$ or larger). Due to the lowest order mass relation among the MSSM Higgs bosons the approximation breaks completely for low m_A and low $\tan \beta$. Detailed discussion of its validity and prediction can be found in Ref^[188]

The trace of the mass mixing matrix is taken and evaluated at the light Higgs boson mass of 125.09 GeV, allowing the δ_1 and δ corrections to be determined as a function of m_A and $\tan \beta$. Neglecting the sub-leading correction δ_1 , then by substituting for δ the mass mixing matrix is fully determined by m_A and $\tan \beta$. This matrix is diagonalized to find the eigenvectors, and in particular those components of the eigenvector corresponding to the light Higgs boson, s_u and s_d . This allows the Higgs boson couplings to vector bosons (κ_V), up-type fermions (κ_u), and down-type fermions (κ_d), as ratios to the corresponding SM expectations, to be determined as functions of m_A and $\tan \beta$ only:

$$\begin{aligned}\kappa_V &= \frac{s_d(m_A, \tan \beta) + \tan \beta s_u(m_A, \tan \beta)}{\sqrt{1 + \tan^2 \beta}} \\ \kappa_u &= s_u(m_A, \tan \beta) \frac{\sqrt{1 + \tan^2 \beta}}{\tan \beta} \\ \kappa_d &= s_d(m_A, \tan \beta) \sqrt{1 + \tan^2 \beta},\end{aligned}\tag{5-18}$$

where the functions s_u and s_d are given by:

$$s_u = \frac{1}{\sqrt{1 + \frac{(m_A^2 + m_Z^2)^2 \tan^2 \beta}{(m_Z^2 + m_A^2 \tan^2 \beta - m_h^2 (1 + \tan^2 \beta))^2}}}$$

$$s_d = \frac{(m_A^2 + m_Z^2) \tan \beta}{m_Z^2 + m_A^2 \tan^2 \beta - m_h^2 (1 + \tan^2 \beta)} s_u. \quad (5-19)$$

The behaviour of MSSM benchmark scenarios is provided by the LHCHXSWG in the format of ROOT file. In the file, the information about Higgs mass, total width of Higgs decay, branch ratio of different decay channel and the cross-section about some production modes are provided in the form of a histogram in terms of two free parameters in the model. As stated in the previous part, the definition of the scenarios and the setup for these MSSM benchmark calculation can be found in^[184-185]. For all scenarios in this study, Higgs masses and mixing (and effective Yukawa couplings) have been calculated with the code Feynhiggs^[158,189-194]. The Branch Ratio results combine the most precise results of FeynHiggs, HDECAY^[195-196] and PROPHECY4f^[197-198]. For the gluon-fusion process inclusive cross sections are obtained with SusHi^[199-200], which includes NLO QCD corrections^[201], NNLO QCD corrections for the top-quark contribution in the effective theory of a heavy top quark^[202-206] and electroweak effects by light quarks^[207-208]. For the SM-like Higgs boson SusHi adds N3LO corrections in the effective theory of a heavy top quark in a threshold expansion^[209-211]. Cross sections for bottom-quark initiated Higgs production rely on matched predictions^[212-215], which are based on the five flavour NNLO QCD calculation^[216] and the four flavour NLO QCD calculation^[217-218]. The details of the MSSM prediction of Higgs behaviour contained in the ROOT file and used in this analysis can be found in table 5-2.

The results for the different benchmark scenarios are shown in Figures 5-7 and 5-8. Figure 5-7 shows the observed and expected 95% CL exclusion limits of the MSSM in the two-dimensional plane $(m_A, \tan \beta)$ for the M_h^{125} , $M_h^{125}(\tilde{\chi})$, $M_h^{125}(\tilde{\tau})$, and $M_h^{125}(\text{alignment})$ benchmark scenarios. For all four scenarios, the regions excluded by the Higgs boson mass requirement ($|m_h - 125.09 \text{ GeV}| < 3 \text{ GeV}$) are separately indicated with gray shaded areas. For completeness, the constraints from previous searches for $H/A \rightarrow \tau\tau$ ^[219] and $H^+ \rightarrow t\bar{b}$ ^[220] are also overlaid.

In the M_h^{125} and $M_h^{125}(\tilde{\chi})$ scenarios, the low m_A region, in which an enhancement of the $h \rightarrow b\bar{b}$ branching ratio and a suppression of the branching ratios of the other decay modes such as $h \rightarrow \gamma\gamma$ are predicted, is disfavored. Since the data marginally prefer $B(h \rightarrow b\bar{b})/B_{\text{SM}}(h \rightarrow b\bar{b}) < 1$ and $B(h \rightarrow \gamma\gamma)/B_{\text{SM}}(h \rightarrow \gamma\gamma) > 1$, the observed constraints are tighter than those expected under the SM hypothesis. In the $M_h^{125}(\tilde{\tau})$ scenario, the region at low m_A and $\tan\beta < 53$ is excluded for the same reason. The region $\tan\beta > 53$, in which the $\tilde{\tau}$ loop reduces the hbb coupling, leading to an enhanced prediction of $B(h \rightarrow \gamma\gamma)$, is also largely excluded. In the $M_h^{125}(\text{alignment})$ scenario, the limit of alignment without decoupling is only realised for $\tan\beta \approx 7$ and $m_A \approx 200$ GeV. For larger values of m_A , MSSM couplings are more similar to SM couplings, causing the allowed $\tan\beta$ region to broaden.

In all four benchmark scenarios, the MSSM analysis generally excludes the low m_A regime for most of the scanned $\tan\beta$ range, while the requirement $|m_h - 125.09 \text{ GeV}| < 3 \text{ GeV}$ excludes the low $\tan\beta$ range for all scanned values of m_A , a range not fully covered by the direct searches for $H/A \rightarrow \tau\tau$ and $H^\pm \rightarrow t\bar{b}$ decays. The exclusion range due to the m_h requirement is qualitatively different in the $M_h^{125}(\text{alignment})$ scenario, as this scenario can only be realized for a value of $\tan(\beta) \approx 7$.

Figure 5-8 shows the observed and expected 95% CL exclusion limits on the MSSM in the two-dimensional plane of $m_{H^\pm}$ versus $\tan\beta$ for the $M_{h_1}^{125}(\text{CPV})$ scenario and of m_A versus $\tan\beta$ for the $M_{h,\text{EFT}}^{125}$, $M_{h,\text{EFT}}^{125}(\tilde{\chi})$ and hMSSM scenarios. The condition $|m_h - 125.09 \text{ GeV}| < 3 \text{ GeV}$ excludes values of $\tan\beta \lesssim 6$ for all values of $m_{H^\pm}$ in the $M_{h_1}^{125}(\text{CPV})$ scenario, while no part of the parameter space is excluded in the $M_{h,\text{EFT}}^{125}$ and $M_{h,\text{EFT}}^{125}(\tilde{\chi})$ benchmark scenarios, in which $m_h = 125.09 \text{ GeV}$ can be achieved through the flexible m_{SUSY} scale. In these four models, the low m_A region, where an enhancement of the hbb coupling is predicted, is excluded, and the excluded region is larger than expected in the SM hypothesis for the same reason as for the previous four models.

5.3 Interpretation of Di-Higgs Combination

The Higgs pair production, as introduced in Section 2.2.3, is quite rare at LHC due to its small cross-section. However, the Di-Higgs production is a good portal to the search for new physics.

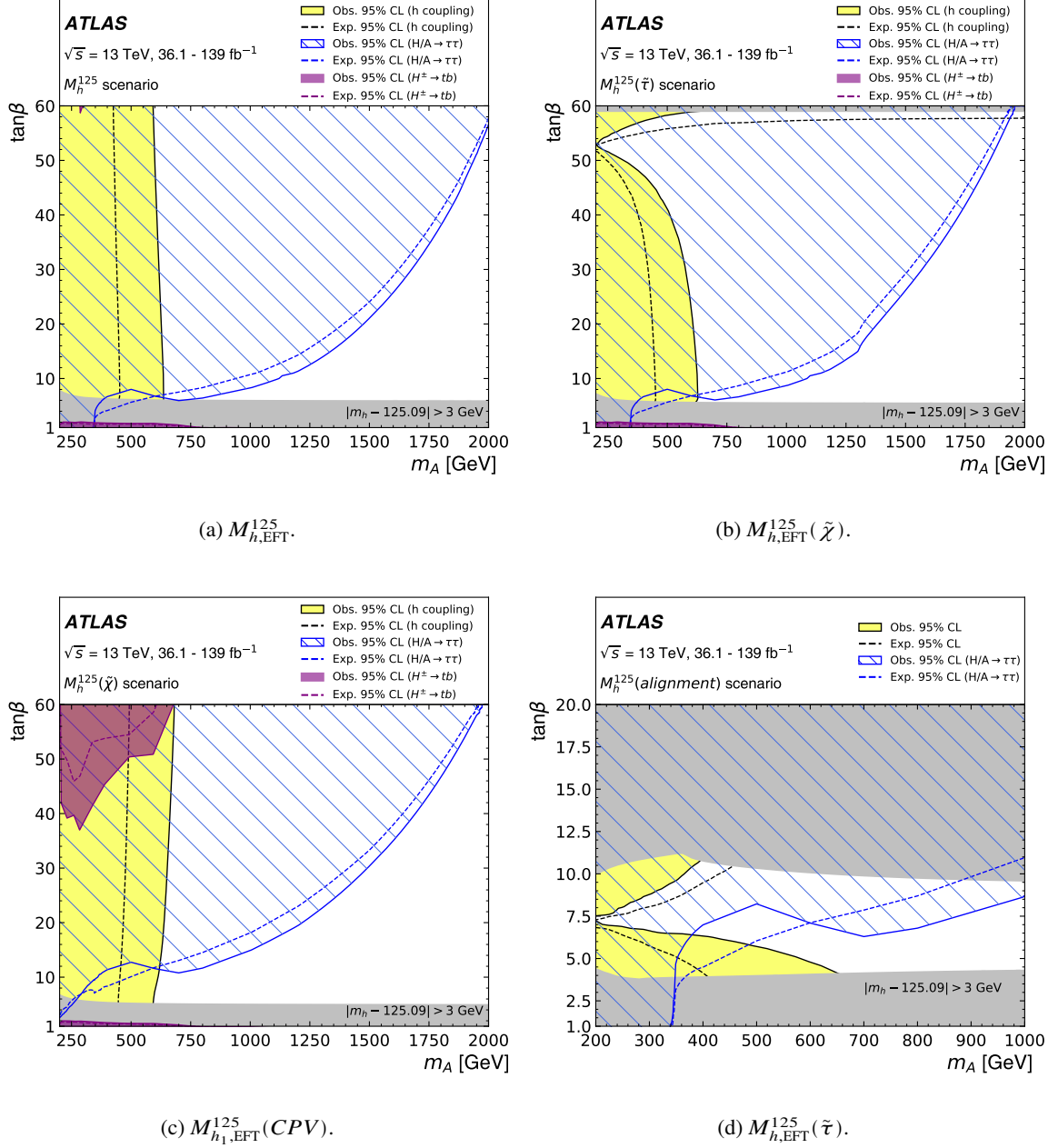


Figure 5-7: Observed (solid yellow area) and expected (dashed line) exclusion contours at 95% CL in the $(m_A, \tan \beta)$ plane for the (a) M_h^{125} , (b) $M_h^{125}(\tilde{\tau})$, (c) $M_h^{125}(\tilde{\chi})$ and (d) $M_h^{125}(\text{alignment})$ scenarios. The parameter space excluded by the condition $|m_h - 125.09 \text{ GeV}| < 3 \text{ GeV}$ is marked in gray. For comparison, the parameter space excluded by the searches for $H/A \rightarrow \tau\tau$ ^[219] and for $H^\pm \rightarrow t\bar{b}$ ^[220] are overlaid in blue and purple, respectively. For the $M_h^{125}(\text{alignment})$ scenario, no constraints from the search for $H^\pm \rightarrow t\bar{b}$ are available.

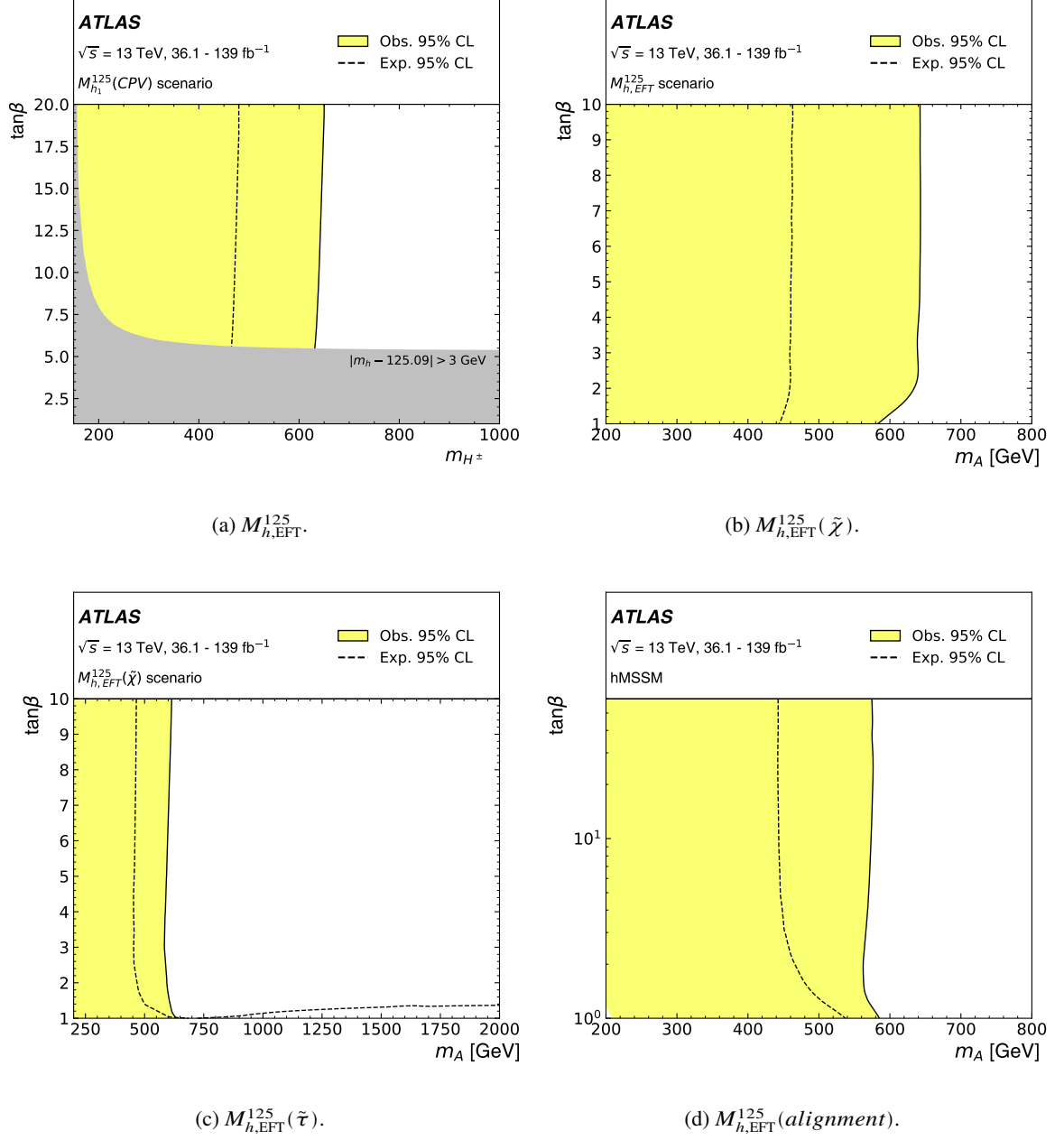


Figure 5-8: Observed (solid yellow area) and expected (dashed line) exclusion contours at 95% CL in (a) the $(m_{H^\pm}, \tan\beta)$ plane for the $M_{h_1}^{125}$ (CPV) scenario and in the $(m_A, \tan\beta)$ plane for the (b) $M_{h,EFT}^{125}$, (c) $M_{h,EFT}^{125}(\tilde{\chi})$ and (d) hMSSM scenarios. In (a), the parameter space excluded by the condition $|m_h - 125.09| < 3$ GeV is marked in gray..

Not only its SM production is very sensitive to the deviation of self-coupling, but also it can be enhanced through the decay from new resonant. In many BSM models that feature an extension of the Higgs sector, there typically exist at least one additional neutral scalar boson (denoted as X) with sizeable couplings to the SM-like Higgs boson. If $m_X > 2m_H$, the existence of X could be detected through its decays to Higgs boson pairs. The Feynman diagram of this resonant production is shown in Figure 5-9.

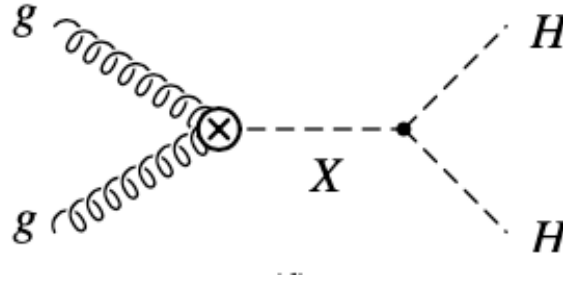


Figure 5-9: Feynman diagram of Higgs pair production through an intermediate resonance X , the cross indicates the effective coupling between X and gluons.

Examples of the theories that predict the resonant production of Higgs bosons pairs are the 2HDM, MSSM and its realisation as the hMSSM, EWK-singlet model^[221-222]. All these models predict a second heavier CP-even scalar in addition to the SM-like Higgs bosons.

A series of search for the resonant production in different final states has been carried out by ATLAS using the LHC Run-2 dataset. The decay of the Higgs pair is the combination of the decays of each single Higgs. The branch ratios of the main decay channels are shown in Figure 5-10.

The $H \rightarrow b\bar{b}$ decay has the largest branch ratios, but also with large multijet background. While the $H \rightarrow \tau\tau$ and $H \rightarrow \gamma\gamma$ have small branch ratios but a relative clean background. As a result, the $b\bar{b}b\bar{b}$, $b\bar{b}\tau\tau$ and $b\bar{b}\gamma\gamma$ final states are the most sensitive channels used for DiHiggs searches at ATLAS for now, and they are used in this combined analysis.

5.3.1 Input Measurements

This analysis combine the results from the search for resonant Higgs pair production utilizing the full Run2 dataset corresponding to an integrated luminosity of up to 139 fb^{-1} , including $b\bar{b}b\bar{b}$, $b\bar{b}\tau\tau$ and $b\bar{b}\gamma\gamma$ final states. A summary of the input analyses is shown in Table 5-5

	bb	WW	$\tau\tau$	ZZ	$\gamma\gamma$
bb	34%				
WW	25%	4.6%			
$\tau\tau$	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
$\gamma\gamma$	0.26%	0.10%	0.028%	0.012%	0.0005%

Figure 5-10: Branch ratios of Higgs pair decay modes in SM.

	$b\bar{b}b\bar{b}^{[223]}$	$b\bar{b}\tau\tau^{[224]}$	$b\bar{b}\gamma\gamma^{[225]}$
$\mathcal{B}(HH \rightarrow x\bar{x}y\bar{y})$	0.3392	0.073	$2.6 \cdot 10^{-3}$
$\mathcal{L}_{\text{int}}[\text{fb}^{-1}]$	126 139	139	139
Discriminant	m_{HH}	NN/BDT	$m_{\gamma\gamma}$
$m_X [\text{GeV}]$	251–1500 900–5000	251–1600	251–1000

Table 5-5: Summary of the main characteristics of input analyses: branching fraction, integrated luminosity analyses, final discriminant used in the statistical analysis and mass range (lower-upper limits) .

The difference in the range of resonant mass m_X is driven by analysis sensitivity. The $bbbb$ channel is divided into two regimes according to the topology: the resolved regime and boosted regime. The resolved regime targets the low resonance mass while the boosted regime target the high resonance mass. In the resolved regime, the b -jets are reconstructed as small- R jets, resulting in a four-jet topology. The boosted regime targets the Higgs with large p_T . The b -jets from one Higgs are highly boosted and merged into a large- R jet, leading to a two large- R jets topology. The boosted regime allows the $b\bar{b}b\bar{b}$ channel to have the best sensitivity at high resonance mass region. The final discriminant used in $b\bar{b}b\bar{b}$ is the binned distribution of m_{HH} .

The $b\bar{b}\gamma\gamma$ channel only considers the resolved topology. Especially for $\gamma\gamma$, the two photons will be merged into one at high p_T , which brings difficulty to separate them. As a result, $b\bar{b}\gamma\gamma$ channel has the lowest reach for the resonance mass, only up to 1 TeV. However, the requirement of photons greatly reduce the multijet background which is the major background at low mass for $b\bar{b}b\bar{b}$ and $b\bar{b}\tau\tau$, making it the most sensitive channel at low mass region. An unbinned maximum likelihood fit of the $m_{\gamma\gamma}$ distribution is used for the final results.

The $b\bar{b}\tau\tau$ only consider the resolved topology as well. It is divided into two categories according to the decay mode of tau leptons: The lephad channel where one tau decays leptonically and another decays hadronically; the hadhad channel where both of tau decay hadronically. The presence of tau brings a relative clean background compared to $b\bar{b}b\bar{b}$ and the larger branch ratio brings a larger statistics compared to $b\bar{b}\gamma\gamma$, so the $b\bar{b}\tau\tau$ channel is the most sensitive channel at intermediate mass region. Parametric Neural Networks (PNN) are used for the extraction of the signal and the distribution is used as fit variable.

The combination of various channels is realized by constructing a combined likelihood function that takes into account data, models and correlated (when applicable) systematic uncertainties from all channels. The general formula of the likelihood function $\mathcal{L}$ reads

$$\mathcal{L}(\mathcal{D}|\mu, \alpha) = \left[\prod_{c \in bbyy} \text{Pois}(n_c | \nu_c(\mu, \alpha)) \prod_{e=1}^{n_c} f_c(x_{ce} | \mu, \alpha) \right] \cdot \left[\prod_{c \in bbyy} \prod_{b \in \text{bins}} \text{Pois}(n_{cb} | \nu_{cb}(\mu, \alpha)) \right] \times \prod_{p \in \mathbb{S}} f_p(\alpha_p | \alpha_p) \quad (5-20)$$

with the following definitions:

- $\mathcal{D}$, the set of (observed or Asimov) data.
- μ , the parameter of interest (POI) to measure in the analysis. It is usually the absolute or relative signal strength of the model to test, and can also be a (coupling) parameter that

varies the signal prediction in certain scenarios.

- α , the parameters of "no" interest with respect to μ , i.e. the nuisance parameters (NPs) that stand for the experimental or theoretical or statistical parameters in expectation from a certain model.
- Index $c \in \mathbb{C}$, indicating one category in the whole set ($\mathbb{C}$) of channels considered in the combination.
- Index e , indicating one event in n_c number of events in data $\mathcal{D}$ of the category c .
- Index $p \in \mathbb{S}$, numbering the constrained NPs in the set named $\mathbb{S}$.
- Index b , indicating the one bin in the category c that belongs to the $b\bar{b}b\bar{b}$ and $b\bar{b}\tau\tau$ channels.
- Pois , the probability function of a Poisson distribution to model the total number of events.
- $n_c(b)$, the total number of events found in data $\mathcal{D}$ of (the bin b of) the category c that belongs to $b\bar{b}\gamma\gamma$ channel.
- $\nu_{c(b)}(\mu, \alpha)$, the expected total number of events as a function of μ and α .
- $f_c(x_{ce}|\mu, \alpha)$, the probability function of a variable x_{ce} in the category c that belongs to the $b\bar{b}\gamma\gamma$ channel, as a function of μ and α .
- x_{ce} , the value of the variable x of an event e , used for the fit in the search of signals from the category c that belongs to $b\bar{b}\gamma\gamma$.
- $f_p(a_p|\alpha_p)$, the constraint function for a certain NP with the prediction α_p and the measurement a_p .
- a_p (roman letter), one global observable, i.e. the measurement of a parameter corresponding to α_p (greek letter).

The data present as a set of events (in $b\bar{b}\gamma\gamma$) or a set of histograms (in $b\bar{b}b\bar{b}$ and $b\bar{b}\tau\tau$), and the likelihood function is a combination of the unbinned likelihood and binned likelihood. f_c will be a probability function in $b\bar{b}\gamma\gamma$. The constraint function adopts a Gaussian function for the experimental and theoretical uncertainties, while presents as a Poisson function for the MC statistical uncertainty per bin when using histograms.

The frequentist exclusion limits based on profile likelihood ratio tests are performed using the asymptotic formulas^[133]. The profile likelihood ratio is constructed as follows:

$$\tilde{\lambda}(\mu) = \begin{cases} \frac{\mathcal{L}(\mu, \hat{\boldsymbol{\theta}}(\mu))}{\mathcal{L}(0, \hat{\boldsymbol{\theta}}(0))} & \hat{\mu} < 0, \\ \frac{\mathcal{L}(\mu, \hat{\boldsymbol{\theta}}(\mu))}{\mathcal{L}(\hat{\mu}, \hat{\boldsymbol{\theta}})} & \hat{\mu} \geq 0. \end{cases} \quad (5-21)$$

The test statistic $\tilde{q}_\mu$ considered for limit setting is

$$\tilde{q}_\mu = \begin{cases} -2 \ln \tilde{\lambda}(\mu) & \hat{\mu} \leq \mu \\ 0 & \hat{\mu} > \mu \end{cases} = \begin{cases} -2 \ln \frac{\mathcal{L}(\mu, \hat{\boldsymbol{\theta}}(\mu))}{\mathcal{L}(0, \hat{\boldsymbol{\theta}}(0))} & \hat{\mu} < 0, \\ -2 \ln \frac{\mathcal{L}(\mu, \hat{\boldsymbol{\theta}}(\mu))}{\mathcal{L}(\hat{\mu}, \hat{\boldsymbol{\theta}})} & 0 \leq \hat{\mu} \leq \mu, \\ 0 & \hat{\mu} > \mu. \end{cases} \quad (5-22)$$

The combination can only be done for the analyses that search for the same mass point. For the mass points that do not have all three analyses, only the available ones will be combined.

5.3.2 BSM Interpretation

Two BSM UV-complete models are considered: the 2HDM and MSSM. Both of them have the extended Higgs sector with additional doublet, resulting in an additional CP-even scalar H . This scalar can be resonance searched in this analysis. The details of these models have been introduced in Section 5.2.3

The basic idea of the interpretation is to find out the parameter points that can be ruled out by the combined analysis. It is done by comparing the upper limit with the BSM predicted cross-section at given parameter point. If the 95% CL upper-limit is smaller than the predicted cross-section, the parameter point is excluded at 95% confidence level. A scan in a dense grid of the parameter spaces of the BSM model can thus create a region of exclusion. The BSM predictions are provided by the LHCHSWG. In the BSM models considered, the coupling strength of the SM Higgs with the fermions are also altered. It will subsequently change branch ratios of Higgs decay to bottom quark pair, tau leptons pair and photons pair, and these branch ratios are dependent with the parameters in the BSM models. With different BRs, the three channels should be combined with different weight. As a result, the following two kinds of interpretation machinery are used.

In the traditional machinery, the combined workspace is created for every scan point with

the BSM predicted branching ratios. The workspace is a combination of histograms and the statistical model which can be used for fit and the calculation of upper limit. In total of three dimension of freedom need to be considered in the interpretation: the resonance mass plus two ratios between $\text{BR}(H \rightarrow b\bar{b})$, $\text{BR}(H \rightarrow \tau^+\tau^-)$ and $\text{BR}(H \rightarrow \gamma\gamma)$. The calculation of upper limit costs a lot of computing resources due to the complexity of the analysis. A typical number of the scan grid in one BSM model is at the order of one thousand. As a result, the traditional interpretation method will need a huge amount of computing resources in total.

An alternative interpretation machinery is used in this analysis, which makes use of one feature in these BSM models. The ratios between $\text{BR}(H \rightarrow b\bar{b})$ and $\text{BR}(H \rightarrow \tau\tau)$ remains the SM value in almost all parameter spaces. Figure 5-11 shows the comparison of this ratio with the SM value in the $M_{h,\text{EFT}}^{125}$ model, similar case can be found in other models considered in this analysis.

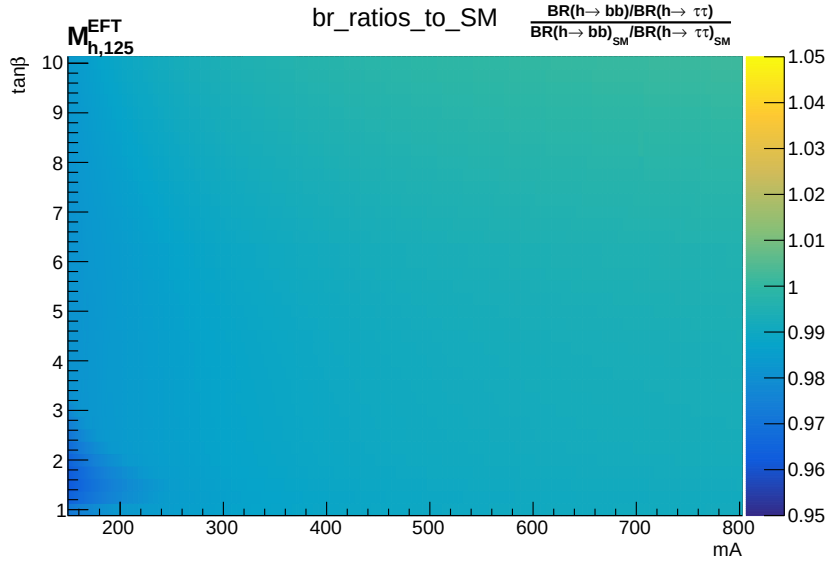


Figure 5-11: Distribution of ratio between $\text{BR}(H \rightarrow b\bar{b})$ and $\text{BR}(H \rightarrow \tau\tau)$ over the SM value in $M_{h,\text{EFT}}^{125}$ scenario, which is close to unity in almost all area.

By using this feature, the dimension of the freedom considered in this machinery is reduced to only two: the resonance mass and the ratio between $\text{BR}(\gamma\gamma)$ and $\text{BR}(H \rightarrow b\bar{b})$. The workspaces from each of the channels are re-parameterized by three parameters of interest: $\sigma \cdot \text{BR}^2(h \rightarrow b\bar{b})$, $\frac{\text{BR}(h \rightarrow \gamma\gamma)}{\text{BR}(h \rightarrow b\bar{b})}$, $\frac{\text{BR}(h \rightarrow \tau\tau)}{\text{BR}(h \rightarrow b\bar{b})}$ and combined. So the dependence of upper limit of $\sigma \cdot \text{BR}^2(h \rightarrow b\bar{b})$ between $\frac{\text{BR}(h \rightarrow \gamma\gamma)}{\text{BR}(h \rightarrow b\bar{b})}$ is scanned and the combined upper limit at a given parameter point of BSM model can be calculated using this dependence. The scanning grid of

$\frac{BR(h \rightarrow \gamma\gamma)}{BR(h \rightarrow b\bar{b})}$ is 69 points in the range $[0, 0.05]$ for every mass point, which is scattered more dense in low values and sparse in high values. Linear interpolation is used to get the dependence of upper limits on the BR-ratios and heavy Higgs mass. It has been testified that in the hMSSM, this methods give consistent results with the one used in previous analysis, with difference of upper limit around 1% as shown in Figure 5-12. This method does not work for scenarios like lepton-specific 2HDM, or flipped 2HDM, in which the ratio of the branching ratios to $\tau\tau$ over $b\bar{b}$ depends on other model parameters.

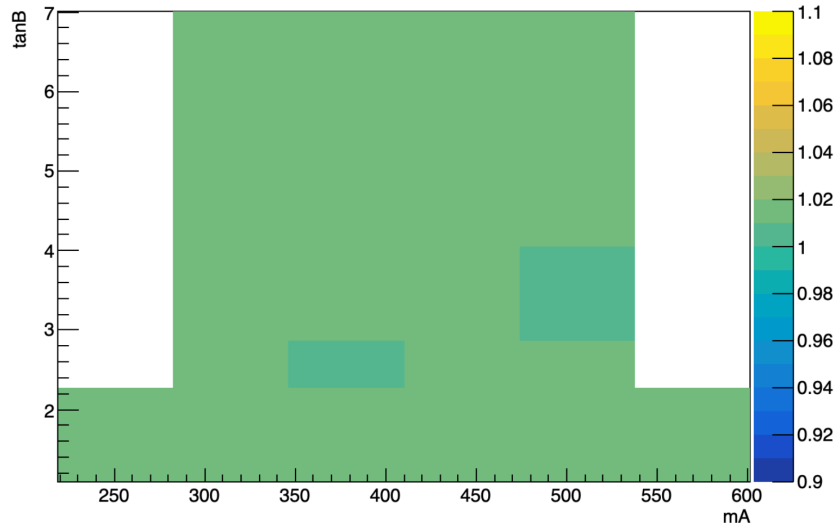


Figure 5-12: Distribution of ratio between the upper limits derived with two machinery, which is close to unity in almost all area.

In all three analyses considered, the resonance signal is assumed to have a narrow width about few MeV. However, the width of CP-even Higgs in 2HDM and MSSM can be large. The large width will have significant effect on the distribution of the invariant mass, which is the fit variable for $b\bar{b}b\bar{b}$ and $b\bar{b}\gamma\gamma$, and important inputs of the PNN. The $b\bar{b}\gamma\gamma$ channel is especially sensitive to the resonance width as a narrow invariant mass cut is applied to select the signal events. As a result, a 2% width upper limit is set for the $b\bar{b}\gamma\gamma$ channel. For the region where the CP-even Higgs has a width larger than 2%, the $b\bar{b}\gamma\gamma$ channel is not included in the combination, only $b\bar{b}b\bar{b}$ and $b\bar{b}\tau\tau$ will be combined. The 2% value is decided to keep at least 90% of signal events for all mass of heavy Higgs. An overall 5% upper limit is also applied, over which all the three analyses will be considered invalid and no exclusion can be made in this region.

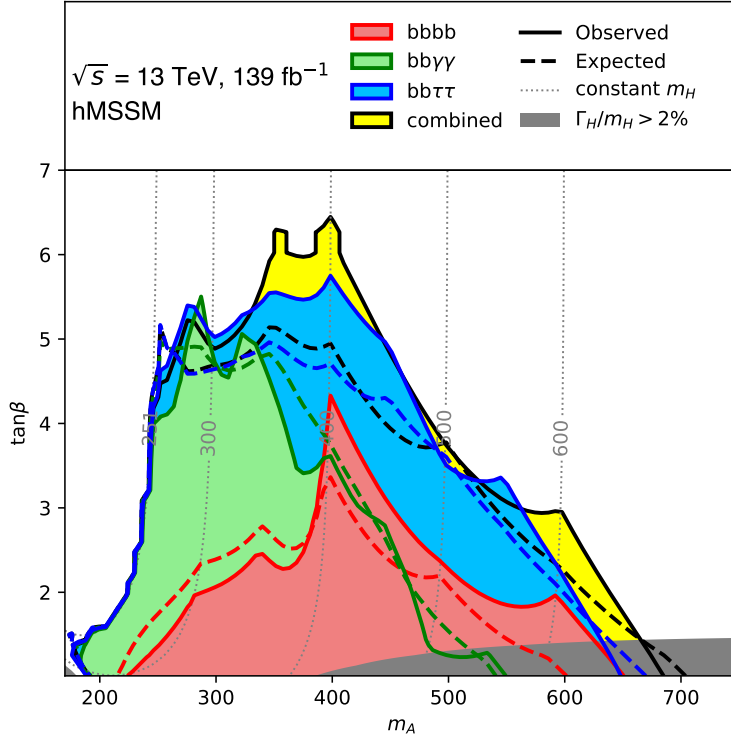


Figure 5-13: 95% CL observed and expected contours of the $b\bar{b}b\bar{b}$ (red), $b\bar{b}\gamma\gamma$ (blue) and $b\bar{b}\tau\tau$ (green) channels and their combined results (orange) on hMSSM parameter space. The region where the width of heavy Higgs larger than 2% is marked in gray, the contours does not apply this 2% upper limit.

MSSM scenarios

In this study, two kinds of MSSM scenarios are discussed, hMSSM and two MSSM scenarios especially designed for low $\tan\beta$ region. They have been briefly introduced in Section 5.2.3.

In the hMSSM, the SM Higgs is assumed to have a mass of 125 GeV, which is consistent with the current measurements. The 95% CL observed and expected contours of three single channels and their combined results are shown in Figure 5-13. The final combined results considering the 2% upper limit in $b\bar{b}\gamma\gamma$ channel is shown in Figure 5-14. There is no region where the width is larger than 5% is present in the phase space that this analysis is sensitive.

For the MSSM benchmarks, the $M_{h,\text{EFT}}^{125}$ and $M_{h,\text{EFT}}^{125}(\tilde{\chi})$ scenarios are considered. In these benchmarks, the mass of supersymmetric particles are adjustable and can be very heavy up to the GUT scale, to achieve a light CP-even Higgs boson is compatible with 125 GeV in most low $\tan\beta$ region. However, there is still some regions where the SM Higgs mass can not achieve 125

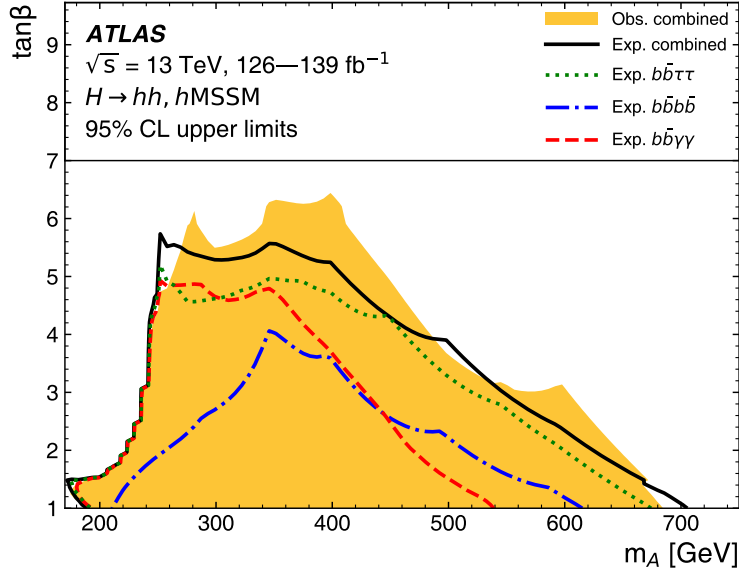


Figure 5-14: 95% CL observed and expected contours of the combined results on hMSSM parameter space. For region where the heavy Higgs width is larger than 2%, only the $b\bar{b}b\bar{b}$ and $b\bar{b}\tau\tau$ channel are combined.

GeV since the scale of supersymmetric M_{SUSY} needs to be raised to be larger than 100 TeV to achieve that. Therefore, the region that $m_h < 122.09$ GeV is excluded given the theoretical uncertainty of the Higgs mass calculation is estimated to be 3 GeV.

The constraints on the MSSM parameter space from each single channel and their combination are shown in Figure 5-15 and the final exclusion regions are presented in Fig. 5-16. As expected, the constraints on the $M_{h,EFT}^{125}$ benchmark are similar to those obtained in hMSSM since it is a concrete realization of the hMSSM approximations. The $M_{h,EFT}^{125}(\tilde{\chi})$ benchmark that assumes some light degrees of freedom that couple to the Higgs bosons (thus open up more decay channels of Higgs) lead to smaller branching ratios and hence smaller exclusions.

Singlet model

The Singlet model is the simplest extension of the Standard Model Higgs sector by adding a real singlet scalar, which gives an additional singlet Higgs, denoted as S . As the v.e.v. of doublet $v_d = 246$ GeV and Standard Model Higgs mass $m_H = 125.09$ GeV are known, the independent variables of the models are:

1. m_S , heavy Higgs mass

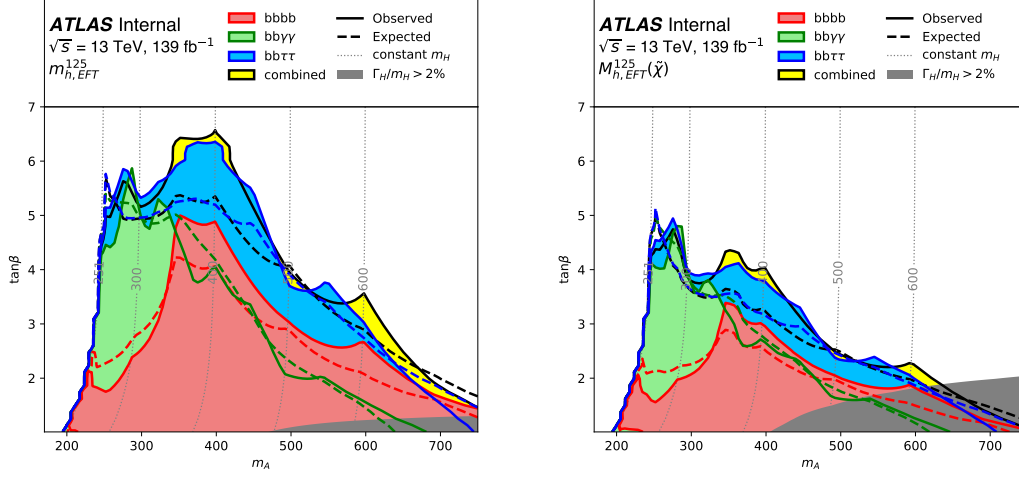


Figure 5-15: 95% CL observed and expected contours of the $b\bar{b}b\bar{b}$ (red), $b\bar{b}\gamma\gamma$ (blue) and $b\bar{b}\tau\tau$ (green) channels and their combined results (orange) on MSSM parameter space for $M_{h,EFT}^{125}$ (left) and $M_{h,EFT}^{125}(\tilde{\chi})$ (right). The region where the width of heavy Higgs larger than 2% is marked in gray, the contours does not apply this 2% upper limit.

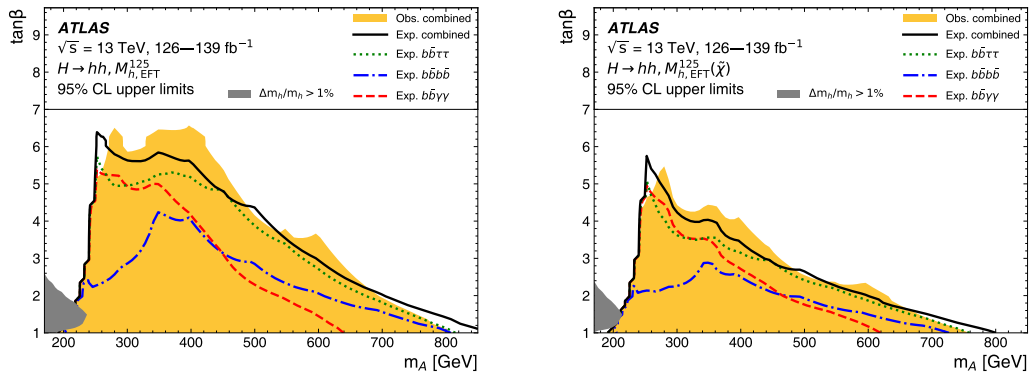


Figure 5-16: 95% CL observed and expected contours of the combined results on MSSM parameter space for $M_{h,EFT}^{125}$ (left) and $M_{h,EFT}^{125}(\tilde{\chi})$ (right). For region where the heavy Higgs width is larger than 2%, only the $b\bar{b}b\bar{b}$ and $b\bar{b}\tau\tau$ channel are combined.

2. $\sin \alpha$, mixing angle
3. $\tan \beta$, ratio of the vevs

In this analysis, only $m_S > 250\text{GeV}$ is considered to generate the $S \rightarrow HH$ decay. Two m_S values are considered in this analysis, $m_S = 275\text{ GeV}$ and $m_S = 500\text{ GeV}$. For higher m_S values, most of the parameter spaces will have large width, and the $H \rightarrow hh$ search lose its sensitivity compared to the SM Higgs coupling measurements, so they are not considered. The production cross-section and decay of the scalars follows the recommendation of LHCHWG. The ggF production cross-section of heavy Higgs scales with $\sin^2 \alpha$ the general heavy Higgs production calculated at NNLO+NNLL QCD accuracy^[19,226]. The branching ratios are calculated with the code **sDECAY** with electroweak corrections turned off. For the SM Higgs, its couplings to SM particles are scaled by $\cos^2 \alpha$, which means the BRs do not change and the measurement of SM Higgs signal strength will impose $|\sin \alpha| < 0.26(0.34)$ observed (expected) limits derived from Ref^[227].

The constraint on Singlet model are shown in Figure 5-17. Note that the coupling Hhh has a non-trivial dependence on $\sin \alpha$ and it is not symmetric with its sign.

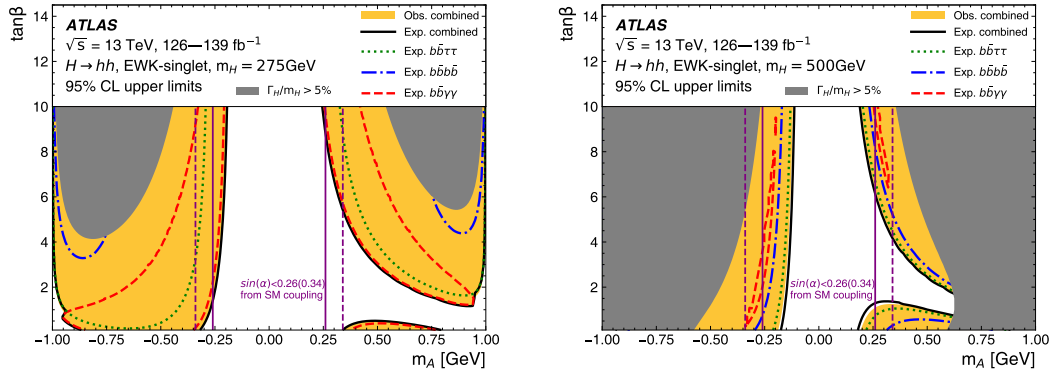


Figure 5-17: 95% CL observed and expected contours of the combined results on the Singlet model parameter space for $m_S = 275\text{ GeV}$ (left) and $m_S = 500\text{ GeV}$ (right).

2HDM

The results are also interpreted in the context of type-I 2HDM^[25]. It has seven free parameters: m_A , m_H , $m_{H^\pm}$, m_h , $\tan \beta$, $\cos(\beta - \alpha)$ and m_{12}^2 . In the benchmark scenario considered in this work, the following assumptions are made: $m_H = m_A = m_{H^\pm}$, $m_h = 125\text{ GeV}$,

$m_{12}^2 = m_A^2 \sin \beta \cos \beta$. This leaves three free parameters: m_H , $\tan \beta$ and $\cos(\beta - \alpha)$. The search interpretations are shown for two different planes:

- m_H – $\tan \beta$ plane for different values of $\cos(\beta - \alpha)$;
- m_H – $\cos(\beta - \alpha)$ plane for different values of $\tan \beta$.

The exclusion plots for the m_H – $\tan \beta$ plane are shown for two values of $\cos(\beta - \alpha)$ ($\cos(\beta - \alpha) = \pm 0.1$) in Figure 5-18. The plots for the m_H – $\cos(\beta - \alpha)$ plane are shown for two values of $\tan \beta$ (1 and 10) in Figure 5-19.

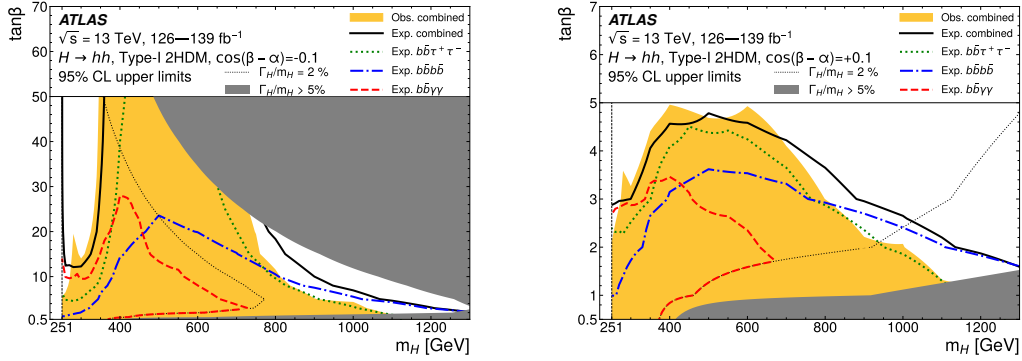


Figure 5-18: 95% CL observed and expected contours of the combined results on the type-I 2HDM model parameter space in m_H – $\tan \beta$ plane with for $\cos(\beta - \alpha) = -0.1$ (left) and $\cos(\beta - \alpha) = +0.1$ (right).

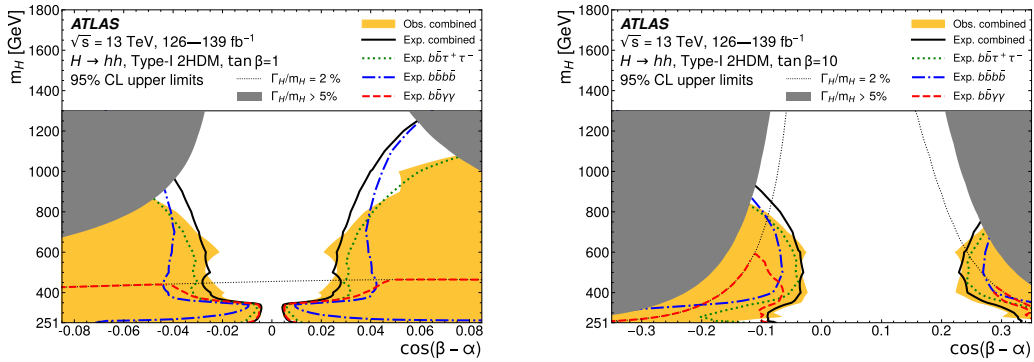


Figure 5-19: 95% CL observed and expected contours of the combined results on the type-I 2HDM model parameter space in m_H – $\cos(\beta - \alpha)$ plane with for $\tan \beta = 1$ (left) and $\tan \beta = 10$ (right).

5.4 Top-quark EFT Study using Electroweak Precision Measurements

The Effective Field Theory is a powerful tool to simplify and probe the effect of high energy UV models to the low energy process. The EFT operators have effect on many processes, not only limited to the Higgs production, which some results have been shown in Section 5.2.2, and top production, but also includes electroweak process. By using the experimental results of precision measurement of the Z and W bosons at lepton colliders, the related dim-6 operators have been extensively probed and stringently constrained. A lot of studies have been performed to constrain these operators at both current and future colliders^[228-230]. Similar studies have also been performed in Higgs and top sector, but some operators are not so well constrained due to the smallness of their tree-level contribution. One of the famous example is the $(H^\dagger H)^3$ operator which modifies the trilinear Higgs coupling, which can be probed at tree-level with DiHiggs production. However, even with HL-LHC, its coefficient is expected to be constrained at order of 1 through DiHiggs production^[159]. Interestingly, the measurements of single-Higgs processes, where the $(H^\dagger H)^3$ operator contributes at the one-loop order, offer competitive reaches on it due to their much better measurement precision^[231-234]. Similarly, operators that generate anomalous gauge couplings of the top quark are generally less-well constrained at the tree level, and contribute to many Higgs and electroweak processes at the one-loop order^[235-237]. These loop contributions are enhanced by the large top mass. In the meantime, these top-quark operators are sensitive to the new physics. In many BSM models, these operators are greatly enhanced due to the interplay between the top quark with the BSM sector.

Therefore, it is beneficial to study the one-loop effects from the top-quark operators on the electroweak process. A total of eight operators that generate anomalous couplings between the electroweak gauge bosons and the third-generation quarks are considered in this study. In this study, the loop effect are calculated to see if they are sizable enough for the electroweak measurements to have a sensitivity that is comparable, or even better than, the ones from LHC, which probes them directly. In addition, it is important to understand if these operators can be constrained in a global framework, which indicates whether the loop operators are degenerate enough to separate from the tree-level operators in electroweak measurements. A global fit is performed including the eight top-quark operators plus the tree-level operators. The elec-

electroweak measurements includes the Z-pole measurements at LEP and SLD, the measurements of the $e^+e^- \rightarrow WW$ process at LEP2, as well as measurements of several low energy scattering processes.

This chapter is organized as follows: the Section 5.4.1 gives a brief theoretical description about the operators and their effect. In Section 5.4.2, a summary of the experimental inputs used in this study is shown, including the study about the acceptance impact of the operators. The fit results are shown in Section 5.4.3 and the projection for future colliders are shown in Section 5.4.4.

5.4.1 Theoretical Setup

The global SMEFT framework is employed and the Warsaw basis is used. Since the study especially considers the loop contribution from the third generation quarks, a $U(2)_u \otimes U(2)_d \otimes U(2)_q \otimes U(3)_l \otimes U(3)_e$ flavor symmetry is imposed. All the operators that contribute to the electroweak measurements (listed in Section 5.4.2) are considered, as listed in Table 5-6.

$\psi^2 \phi^3$	X^3	$\phi^4 D^2$
$Q_{u\phi}^{ij} = (\phi^\dagger \phi)(\bar{q}_i u_j \tilde{\phi})$ $Q_{d\phi}^{ij} = (\phi^\dagger \phi)(\bar{q}_i d_j \phi)$	$Q_W = \epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\phi D} = (\phi^\dagger D^\mu \phi)^* (\phi^\dagger D_\mu \phi)$
$\psi^2 \phi^2 D$	$\psi^2 X \phi$	$X^2 \phi^2$
$Q_{\phi l}^{ij(1)} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi) (\bar{l}_i \gamma^\mu l_j)$ $Q_{\phi l}^{ij(3)} = (\phi^\dagger i \overleftrightarrow{D}_\mu^I \phi) (\bar{l}_i \tau^I \gamma^\mu l_j)$ $Q_{\phi e}^{ij} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi) (\bar{e}_i \gamma^\mu e_j)$ $Q_{\phi q}^{ij(1)} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi) (\bar{q}_i \gamma^\mu q_j)$ $Q_{\phi q}^{ij(3)} = (\phi^\dagger i \overleftrightarrow{D}_\mu^I \phi) (\bar{q}_i \tau^I \gamma^\mu q_j)$ $Q_{\phi u}^{ij} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi) (\bar{u}_i \gamma^\mu u_j)$ $Q_{\phi d}^{ij} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi) (\bar{d}_i \gamma^\mu d_j)$ $Q_{\phi ud}^{ij} = i(\tilde{\phi}^\dagger D_\mu \phi)(\bar{u}_i \gamma^\mu d_j)$	$Q_{uW}^{ij} = (\bar{q}_i \sigma^{\mu\nu} u_j) \tau^I \tilde{\phi} W_{\mu\nu}^I$ $Q_{uB}^{ij} = (\bar{q}_i \sigma^{\mu\nu} u_j) \tilde{\phi} B_{\mu\nu}$ $Q_{dW}^{ij} = (\bar{q}_i \sigma^{\mu\nu} d_j) \tau^I \phi W_{\mu\nu}^I$ $Q_{dB}^{ij} = (\bar{q}_i \sigma^{\mu\nu} d_j) \phi B_{\mu\nu}$	$Q_{\phi WB} = \phi^\dagger \tau^I \phi W_{\mu\nu}^I B^{\mu\nu}$
$(\bar{L}L)(\bar{L}L)$ $Q_{ll}^{prst} = (\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$ $Q_{lq}^{prst(1)} = (\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$ $Q_{lq}^{prst(3)} = (\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	$(\bar{R}R)(\bar{R}R)$ $Q_{ee}^{prst} = (\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$ $Q_{eu}^{prst} = (\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$ $Q_{ed}^{prst} = (\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$	$(\bar{L}L)(\bar{R}R)$ $Q_{le}^{prst} = (\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$ $Q_{lu}^{prst} = (\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$ $Q_{ld}^{prst} = (\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$ $Q_{qe}^{prst} = (\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$

Table 5-6: The operators in the Warsaw basis^[27] that are used in our study. The indices i, j and p, r, s, t label the fermion generation.

The operators can be divided into two categories. One category involves the third generation

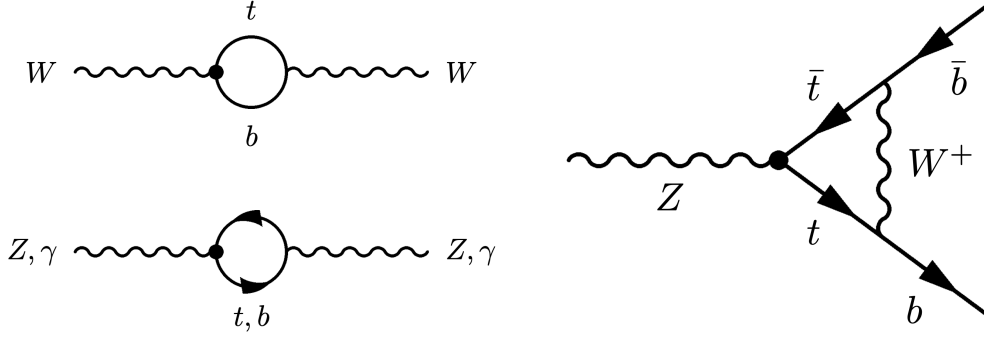


Figure 5-20: Feynman diagram of the loop contribution from the operators on gauge boson self-energy (left) and Zbb vertex (right).

quarks, which are

$$Q_{\varphi Q}^{(1)}, \quad Q_{\varphi Q}^{(3)}, \quad Q_{\varphi t}, \quad Q_{\varphi b}, \quad Q_{tW}, \quad Q_{tB}, \quad Q_{bW}, \quad Q_{bB} \quad (5-23)$$

The four operators $Q_{\varphi Q}^{(1)}$, $Q_{\varphi Q}^{(3)}$, $Q_{\varphi t}$ and $Q_{\varphi b}$ modify the SM gauge couplings between the 3rd generation quarks and the W , Z bosons. The rest four operators, Q_{tW} , Q_{tB} , Q_{bW} and Q_{bB} , generate dipole interactions between the 3rd generation quarks and the gauge bosons. For these operators, they will sometimes also have tree-level contribution, such as bottom-quark operators to $e^+e^- \rightarrow b\bar{b}$. In this case, only the tree-level contribution is considered as it is the leading order one. Figure 5-20 shows the example Feynman diagrams of the loop contribution of the operators on electroweak process.

The second category contain all other operators that contribute to the electroweak processes at the tree level, including the ones that modify the propagators of Z and W bosons, their couplings to fermions (excluding the 3rd generation quarks) and the triple gauge couplings, as well as the 4-fermion operators that directly contribute to the $e^+e^- \rightarrow f\bar{f}$ processes and several low energy scattering processes. For convenience, the following combinations of operators instead of the original ones for the 3rd generation quarks are used:

$$\begin{aligned} Q_{\varphi Q}^{(+)} &\equiv Q_{\varphi Q}^{(1)} + Q_{\varphi Q}^{(3)}, & Q_{lQ}^{(+)} &\equiv Q_{lQ}^{(1)} + Q_{lQ}^{(3)}, \\ Q_{\varphi Q}^{(-)} &\equiv Q_{\varphi Q}^{(1)} - Q_{\varphi Q}^{(3)}, & Q_{lQ}^{(-)} &\equiv Q_{lQ}^{(1)} - Q_{lQ}^{(3)}, \end{aligned} \quad (5-24)$$

and their Wilson coefficients follow the same labels. $Q_{lQ}^{(-)}$ contributes only to a contact $e^+e^-t\bar{t}$

interaction and is not considered. In total, 33 Wilson coefficients are included in this analysis.

Due to the fact that in Warsaw basis, the operators contribute to the Z -pole observables at tree level exhibit flat direction. These flat directions can be lifted by the measurement of $e^+e^- \rightarrow WW$ process^[228]. However, since the precision of W measurement is not as good as Z -pole, there still remains large correlation between the operators. In order to solve this problem, the following conversions are used by replacing operators $Q_{\phi D}$, $Q_{\phi WB}$ with

$$Q_{D\phi W} = iD_\mu \phi^\dagger \sigma_a D_\nu \phi W^{a\mu\nu}, \quad Q_{D\phi B} = iD_\mu \phi^\dagger D_\nu \phi B^{\mu\nu}, \quad (5-25)$$

which do not contribute to the Z -pole observables. The following input parameters are used in the calculation:

$$\alpha = \frac{1}{127.9}, \quad m_Z = 91.1876 \text{ GeV}, \quad G_F = 1.166379 \times 10^{-5} \text{ GeV}, \\ m_b = 4.7 \text{ GeV}, \quad m_t = 172.5 \text{ GeV}. \quad (5-26)$$

The theoretical calculation of the operators' impact is not a focus of this thesis, the details can be found in Ref^[4]. The loop contributions are derived from Monte Carlo Simulation due to the complexity of the calculation. The MadGraph5_aMC@NLO^[118] is used and the reweighting method^[238] is employed to reduce the computing consumption. The size of Monte Carlo sample is chosen to ensure the statistical uncertainties of the sample is lower than 10%. For inclusive cross-sections, the MC statistic uncertainties are usually smaller 1%.

5.4.2 Input Measurements

The input measurements used in this analysis is mainly from the LEP experiment. Some low energy experiments are also considered, including CHARM^[239], CDHS^[240], CCFR^[241], NuTeV^[242], APV^[243], QWEAK^[244] and PVDIS^[245]. The measurements can be divided into the following categories and the:

- Precision Electroweak Measurement: the Z -pole measurement from LEP experiment, W mass measurement taken from combined results of PDG Group and branching ratios (BR) information from LEP.

- $e^+e^- \rightarrow f\bar{f}$: the measurements of electron collision to quark pair and lepton pair from the LEP experiment are collected. Some observables measured by TRISTAN at 58 GeV are also included.
- $e^+e^- \rightarrow W^+W^- \rightarrow 4f$: the total cross-section and differential cross-section measurements of $e^+e^- \rightarrow W^+W^- \rightarrow 4f$ from the LEP experiment.
- Low Energy Measurement: the neutral-current parameters for ν -hadron and $\nu - e$ processes measured by deep inelastic scattering (DIS) experiments including CDHS and CHARM in CERN, CCFR and NuTeV in FermiLab. The parameters for electron scattering is measured by the Cs atomic parity violation (APV) experiment, electron-deuteron DIS (eDIS) experiment PVDIS and Qweak that measure the weak charge of proton. Additionally, the measurement of the cross-section of trident production ($\nu_\mu \gamma^* \rightarrow \nu_\mu \mu^+ \mu^-$) over its SM prediction by CHARM and CDHS is included.

Table 5-7 shows the details of the observables. The center values and the uncertainties as well as the correlations (if provided) are taken from the input analyses. The correlations between different categories and experiments are taken as zero. For those measurements that do not provide the correlation between the observables, it is assumed that they are not correlated with each other.

Table 5-8 list the operators that have impact on the above-mentioned observables. Five operators ($Q_{\phi WB}, Q_{ll}^{ijji}, Q_{\phi D}, Q_{\phi l}^{11(3)}, Q_{\phi l}^{22(3)}$) have impact on all the observables as they will affect the electroweak parameters: g, g', v , and thus not included in the table. Additional information of some observables will be discussed in the following, including the theory and experimental uncertainties and details of the MC simulation.

Z, W pole observables and low energy couplings

The theoretical prediction of Z pole observables and W pole observables are taken from the Table 10.5 of Ref^[246] and the Table 2 of Ref^[229]. The theoretical errors of Z, W pole observables are ignored and low energy couplings, except for m_W , which is taken as 0.004GeV^[139,246].

	Experiment	Observables	Reference
Low Energy	CHARM/CDHS/ CCFR/NuTeV/ APV/QWEAK/ PVDIS	Effective Couplings	[246], [247]
Z-pole	LEP/SLC	$\frac{\text{Total decay width } \Gamma_Z}{\text{Hadronic cross-section } \sigma_{had}}$ $\frac{\text{Ratio of decay width } R_f}{\text{Forward-Backward Asymmetry } A_{FB}^f}$ $\frac{\text{Polarized Asymmetry } A_f}{\text{Forward-Backward Asymmetry } A_{FB}^f}$	[248]
W-pole	LHC/Tevatron/ LEP/SLC	$\frac{\text{Total decay width } \Gamma_W}{\text{W branching ratios } Br(W \rightarrow l\nu_l)}$ $\frac{\text{Mass of W Boson } M_W}{\text{Forward-Backward Asymmetry for } b/c A_{FB}^f}$	[248], [246]
$ee \rightarrow qq$	LEP/TRISTAN	$\frac{\text{Hadronic cross-section } \sigma_{had}}{\text{Ratio of cross-section } R_f}$ $\frac{\text{Forward-Backward Asymmetry for } b/c A_{FB}^f}{\text{Forward-Backward Asymmetry for } b/c A_{FB}^f}$	[249], [250], [251]
$ee \rightarrow ll$	LEP	$\frac{\text{cross-section } \sigma_f}{\text{Forward-Backward Asymmetry } A_{FB}^f}$ $\frac{\text{Differential cross-section } \frac{d\sigma_f}{d\cos\theta}}{\text{Forward-Backward Asymmetry } A_{FB}^f}$	[249]
$ee \rightarrow WW$	LEP	$\frac{\text{cross-section } \sigma_{WW}}{\text{Differential cross-section } \frac{d\sigma_{WW}}{d\cos\theta}}$	[249]

Table 5-7: Observables used in Top EFT study.

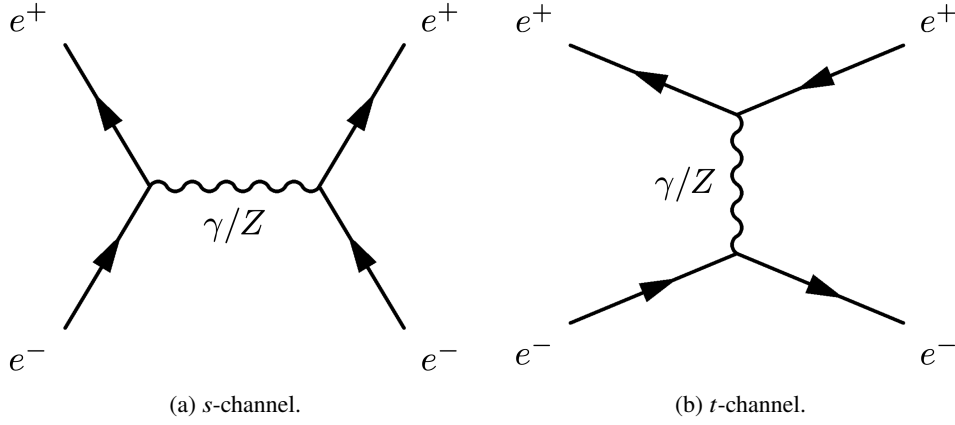
Fermion-Pair Production

The LO Feynman diagram of $e^+e^- \rightarrow f\bar{f}$ process is the s-channel photon and Z annihilation (Figure 5-21a). However, there are additional t-channel photon and Z exchange in $e^+e^- \rightarrow e^+e^-$ process (Figure 5-21b), which have a quite small contribution at Z-pole. The electron and muon are assumed to be massless in this study. As a result, there would be only a negligible difference between the contribution of new operators to observables of $e^+e^- \rightarrow e^+e^-$ and $e^+e^- \rightarrow \mu^+\mu^-$ process. Thus, the results of $e^+e^- \rightarrow \mu^+\mu^-$ is used for $e^+e^- \rightarrow e^+e^-$ at Z-pole. At other energies, both the t-channel and s-channel production of $e^+e^- \rightarrow e^+e^-$ are considered and computed separately.

For the fermion-pair production, especially at the energies above Z resonance, the QED radiative corrections are very large. This is caused by initial-state radiation of photons, which will lower the center-of-mass energy, $\sqrt{s}$, to the value $\sqrt{s'}$. In the LEP experiment, the measurement is done using events which have small amount of initial state radiation, *i.e.*, large $\sqrt{s/s'}$. So initial-state radiation is not considered in the MC simulation. The experimental and theoretical uncertainties of various processes are shown below:

Processes	Observables	Wilson Coefficient
Neutrino DIS and APV	$g_{LV}^{\nu e}, g_{LA}^{\nu e}$	$c_{\phi l}^{(1)}, c_{\phi e}, c_{ll}, c_{le}$
	$g_{AV}^{eu} + 2g_{AV}^{ed}$ $2g_{AV}^{eu} - g_{AV}^{ed}$ $2g_{VA}^{eu} - g_{VA}^{ed}$	$c_{\phi q}^{(1)}, c_{\phi q}^{(3)}, c_{\phi u}, c_{\phi d}, c_{\phi l}^{(1)}$ $c_{\phi e}, c_{lq}^{(1)}, c_{lq}^{(3)}, c_{lu}, c_{ld}, c_{qe}, c_{eu}, c_{ed}$
	g_{VA}^{ee}	$c_{\phi l}^{(1)}, c_{\phi e}, c_{ee}, c_{ll}$
	$2 \frac{g_{LV}^{\nu \mu, SM} \delta g_{LV}^{\nu \mu} + g_{LA}^{\nu \mu, SM} \delta g_{LA}^{\nu \mu}}{(g_{LV}^{\nu \mu, SM})^2 + (g_{LA}^{\nu \mu, SM})^2}$	$c_{\phi l}^{(1)}, c_{\phi e}, c_{le}, c_{ll}$
Z-pole	Γ_Z	$c_{\phi l}^{(1)}, c_{\phi e}, c_{\phi q}^{(3)}, c_{\phi q}^{(1)}, c_{\phi u}, c_{\phi d}, c_{\phi Q}^{(+)}, c_{\phi b}, c_{bB}, c_{bW}$
	σ_{had}	$c_{\phi l}^{(1)}, c_{\phi e}, c_{\phi q}^{(3)}, c_{\phi q}^{(1)}, c_{\phi u}, c_{\phi d}, c_{\phi Q}^{(+)}, c_{\phi b}, c_{bB}, c_{bW}$
	R_e	$c_{\phi l}^{(1)}, c_{\phi e}, c_{\phi q}^{(3)}, c_{\phi q}^{(1)}, c_{\phi u}, c_{\phi d}, c_{\phi Q}^{(+)}, c_{\phi b}, c_{bB}, c_{bW}$
	R_μ	$c_{\phi l}^{(1)}, c_{\phi e}, c_{\phi q}^{(3)}, c_{\phi q}^{(1)}, c_{\phi u}, c_{\phi d}, c_{\phi Q}^{(+)}, c_{\phi b}, c_{bB}, c_{bW}$
	R_τ	$c_{\phi l}^{(1)}, c_{\phi e}, c_{\phi q}^{(3)}, c_{\phi q}^{(1)}, c_{\phi u}, c_{\phi d}, c_{\phi Q}^{(+)}, c_{\phi b}, c_{bB}, c_{bW}$
	$A_{FB}^{\sigma, e}$	$c_{\phi l}^{(1)}, c_{\phi e}$
	$A_{FB}^{\sigma, \mu}$	$c_{\phi l}^{(1)}, c_{\phi e}$
	$A_{FB}^{\sigma, \tau}$	$c_{\phi l}^{(1)}, c_{\phi e}$
	R_b	$c_{\phi q}^{(3)}, c_{\phi q}^{(1)}, c_{\phi u}, c_{\phi d}, c_{\phi Q}^{(+)}, c_{\phi b}, c_{bB}, c_{bW}$
	R_c	$c_{\phi q}^{(3)}, c_{\phi q}^{(1)}, c_{\phi u}, c_{\phi d}, c_{\phi Q}^{(+)}, c_{\phi b}, c_{bB}, c_{bW}$
	A_{FB}^b	$c_{\phi l}^{(1)}, c_{\phi e}, c_{\phi Q}^{(+)}, c_{\phi b}, c_{bB}, c_{bW}$
	A_{FB}^c	$c_{\phi l}^{(1)}, c_{\phi e}, c_{\phi q}^{(1)}, c_{\phi q}^{(3)}, c_{\phi u},$
	A_e	$c_{\phi l}^{(1)}, c_{\phi e}$
	A_μ	$c_{\phi l}^{(1)}, c_{\phi e}$
	A_τ	$c_{\phi l}^{(1)}, c_{\phi e}$
	A_b	$c_{\phi Q}^{(+)}, c_{\phi b}, c_{bB}, c_{bW}$
	A_c	$c_{\phi q}^{(1)}, c_{\phi q}^{(3)}, c_{\phi u}$
	A_s	$c_{\phi q}^{(1)}, c_{\phi q}^{(3)}, c_{\phi d}$
W-pole	M_W	
	$Br(W \rightarrow e \nu_e) Br(W \rightarrow \mu \nu_\mu)$ $Br(W \rightarrow \tau \nu_\tau) \Gamma_W$	$c_{\phi q}^{(3)}$
$ee \rightarrow q \bar{q}$	σ_{eeqq}	$c_{\phi l}^{(1)}, c_{\phi e}, c_{\phi q}^{(3)}, c_{\phi q}^{(1)}, c_{\phi u}, c_{\phi d}, c_{\phi Q}^{(+)}, c_{\phi b}, c_{lq}^{(1)}, c_{lq}^{(3)},$ $c_{lu}, c_{ld}, c_{lQ}^{(+)}, c_{lb}, c_{qe}, c_{eu}, c_{ed}, c_{eQ}, c_{eb}, c_{bB}, c_{bW}$
$ee \rightarrow b \bar{b}$	σ_{eebb}	$c_{\phi l}^{(1)}, c_{\phi e}, c_{\phi Q}^{(+)}, c_{\phi b}, c_{lQ}^{(+)}, c_{lb}, c_{eQ}, c_{eb}, c_{bB}, c_{bW}$
$ee \rightarrow c \bar{c}$	σ_{eccc}	$c_{\phi l}^{(1)}, c_{\phi e}, c_{\phi q}^{(1)}, c_{\phi q}^{(3)}, c_{\phi u}, c_{lq}^{(1)}, c_{lq}^{(3)}, c_{lu}, c_{qe}, c_{eu}$
$ee \rightarrow \mu^+ \mu^-$	$\sigma_{ee\mu\mu}$	$c_{\phi l}^{(1)}, c_{\phi e}, c_{ll}, c_{le}, c_{ee}$
$ee \rightarrow \tau^+ \tau^-$	$\sigma_{ee\tau\tau}$	$c_{\phi l}^{(1)}, c_{\phi e}, c_{ll}, c_{le}, c_{ee}$
$ee \rightarrow e^+ e^-$	σ_{eeee}	$c_{\phi l}^{(1)}, c_{\phi e}, c_{ll}, c_{le}, c_{ee}$
$ee \rightarrow W^+ W^-$	σ_{eeWW}	$c_{\phi l}^{(1)}, c_{\phi e}, c_W$

Table 5-8: The list of corresponding coefficients of the operators that have contribution to different observables. Besides these coefficients, there are also four operators that will contribute to all observables (represented by their coefficient here): $c_{\phi l}^{(3)}, c_{ll}', c_{\phi D}, c_{\phi WB}$.

Figure 5-21: Feynman diagrams for $e^+e^- \rightarrow f\bar{f}$ process.

- For $e^+e^- \rightarrow f\bar{f}$ ($f = \mu, \tau, q$) process, the experimental values of cross-sections (in pb) and forward-backward asymmetries are reported in Table 3.4 of^[249]. The theoretical prediction uncertainties of $\sigma(q\bar{q})$, $\sigma(\mu^+\mu^-)$, $\sigma(\tau^+\tau^-)$ and leptonic forward-backward asymmetries are 0.26%, 0.4%, 0.4% and 0.4% respectively^[249,252]. Their theoretical prediction uncertainties can be neglected since the experimental uncertainties are at least four times larger.
- The experimental and theoretical value of the $e^+e^- \rightarrow \mu^+\mu^-$, $e^+e^- \rightarrow \tau^+\tau^-$ differential cross-section are reported in Table 3.8 and 3.9 of^[249]. In the processes of $e^+e^- \rightarrow \mu^+\mu^-$, $e^+e^- \rightarrow \tau^+\tau^-$, it is assumed that theoretical uncertainties of differential distribution are 0.4%, which can be neglected compared with experimental ones.
- The experimental and theoretical value of the $e^+e^- \rightarrow e^+e^-$ differential cross-section are reported in Table 3.11 and 3.12 of^[249]. The theoretical uncertainties of the large-angle Bhabha scattering for $\sqrt{s}$ ranging from 189 GeV to 207 GeV are around 0.5%^[252-253]. Theoretical uncertainties of differential distribution are taken as 0.5% as well.
- In the process of $e^+e^- \rightarrow q\bar{q}$ at $\sqrt{s} = 58$ GeV, the Table 8 in^[254] shows the measured results for R_b and R_c , which are the bottom and charm quark pair production cross-section ratio to the total hadronic cross-section. In^[255], their theoretical uncertainties are estimated as 1% and can be ignored.
- For $e^+e^- \rightarrow q\bar{q}$ process at $\sqrt{s}$ ranging from 189 GeV to 207 GeV, the Table 8.9, 8.10 in^[250] show the measured results for R_b and R_c without the theoretical uncertainties. The theoretical uncertainties are assumed to be negligible.

Boson-Pair Production

The boson-pair production is also one of the crucial process in LEP experiment. In our study, $e^+e^- \rightarrow W^+W^-$ process is included. There are three leading Feynman diagrams of this process, shown in Figure 5-22, which are named as CC03 (Charged Current).

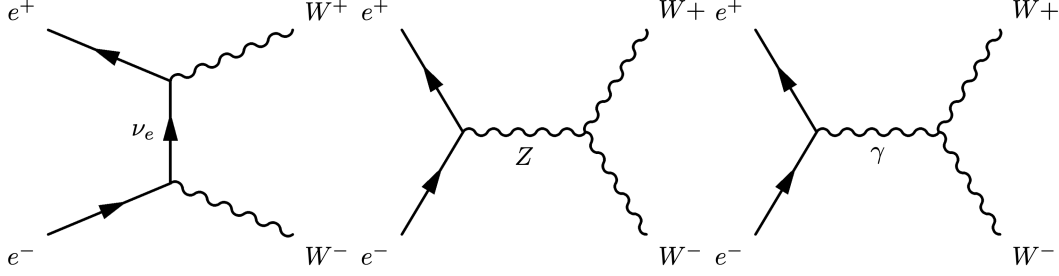


Figure 5-22: Leading Feynman diagrams for $e^+e^- \rightarrow W^+W^-$ process.

The W boson will decay to a quark-antiquark pair or a lepton-neutrino pair. The branch ratio of hadronic decay is about 67% and that of leptonic decay is around 33%. The WW events are classified into three categories depending on the decay of W boson: fully hadronic, semi-leptonic and fully leptonic. In the Monte Carlo simulation of the total cross-section of WW production, we ignore the decay of W boson and only produce the events that take W pair as the final state for convenience.

The angular distribution of WW events ($d\sigma_{WW}/dcos\theta_{W^-}$) is also included in this study, where θ_{W^-} is the polar angle between W^- and the e^- beam direction. In the differential cross-section measurement, the decay of WW is selected as $q\bar{q}e\nu$ and $q\bar{q}\mu\nu$ for the reason that these two kinds of leptonic decay provides the charge tag and a clean background compared to τ channel. In the experiment, it is required that the charged lepton should be 20° away from the beam, $|\theta_l| > 20^\circ$. This angular cut brings about a 93% cut efficiency in the experiment^[249], which is further validated with the SM MC simulation by this study. This angular requirement corresponds to the experimental acceptance of the four LEP experiments and greatly reduces the difference between the full $4f$ cross-section and the CC03 cross-section by reducing the contribution of t-channel diagrams in the $q\bar{q}e\nu$ final state. As stated in the LEP result, the difference of $4f$ and CC03 cross-section reduced from 24.0% to about 3.5% with the angular cut. However, since the angular distribution from the dim-6 operators does not follow the SM, the angular cut will bring a different acceptance effect for these operators. Thus, this cut is also

considered in the MC simulation. The decay of W boson is simulated with MadSpin^[256], and it is required to be on-shell decay to guarantee the gauge invariance. The angular cut efficiency of some operators is shown in the Figure 5-23.

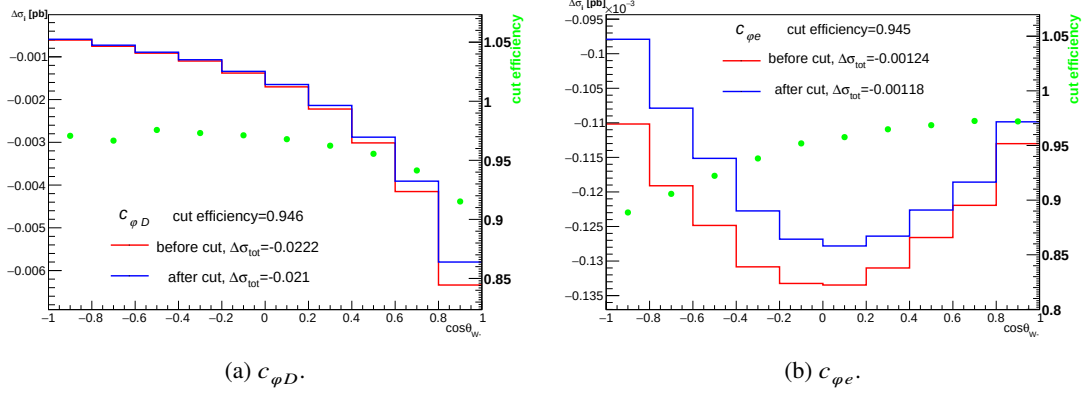


Figure 5-23: The impact of angular cut of the operator $c_{\varphi D}$ and $c_{\varphi e}$ on $ee \rightarrow WW$ differential distribution at 183 GeV. The red lines show the differential cross-section of the operators before the angular cut and the blue line show the differential cross-section after the cut. The overall cut efficiency is given by the total cross-section after the cut divided by the one before cut..

According to Ref^[257-258], the theoretical uncertainties of W^- angular distribution are around 0.5% when $\sqrt{s}$ ranges from 180 GeV to 210 GeV. Since the experimental precision of W^- differential angular cross-section are seven times larger than theoretical ones at least, the theoretical prediction uncertainties of W^- differential angular cross-section can be neglected. For the inclusive cross-section, the theoretical uncertainty is non-negligible.

5.4.3 EFT Interpretation

Statistical Description

The central value of the Wilson coefficient and the constraint is extracted from maximizing the χ^2 function. The χ^2 function is constructed as:

$$\chi^2 = (\mathbf{y} - A\mathbf{c})^T V^{-1} (\mathbf{y} - A\mathbf{c}), \quad (5-27)$$

where $\mathbf{y}$ is the vector of the difference between the experimental result and SM prediction of observables, A is the contribution matrix (A_{ij} is the i -th operator's contribution to j -th observables),

$\mathbf{c}$ is the vector of the Wilson coefficient and V is the covariance matrix of observables.

the Least Square Estimator $\hat{\mathbf{c}}$ that minimize χ^2 and its covariance matrix U is derived by letting $\nabla \chi^2 = 0$:

$$\hat{\mathbf{c}} = (A^T V^{-1} A)^{-1} A^T V^{-1} \mathbf{y} = B \mathbf{y} \quad (5-28)$$

$$U = B V B^T = (A^T V^{-1} A)^{-1} \quad (5-29)$$

The element of covariance matrix, U_{ij} , stands for the covariance of the estimator $\hat{c}_i$ and $\hat{c}_j$. The one-sigma bound of c_i can be obtained from the diagonal element of this matrix.

Since there is no obvious deviation from SM of the electroweak measurements are found, the central values of the coefficients are not so attractive which is usually close to zero. The constraint (or named as bounds) on the coefficients are more of importance as it indicates the energy scale of potential new physics happens. Two kinds of bounds are derived, the marginalized bounds and individual bounds. The marginalized bounds of the operators are derived with free floating all the coefficients. The individual bounds are derived with only one coefficient is float and all the others are fixed to zero. Several fit scenarios are also used, by allowing different number of Wilson coefficients to float in the fit. The energy scale Λ is chosen to be 1 GeV in the following context. All the results are given in 68% CL.

Individual and Marginalized Results

Figure 5-24 shows the individual and marginalized bounds of the 33 operators' coefficients considered in this analysis. The general results include the top and bottom loop effect. Two additional scenarios are considered in comparison with the general results to better understand the effect of the 3rd generation quark operators. The first considers only the tree-level contributions of the operators and the second only consider the bottom quark loop contribution. Both scenarios are only used in the marginalized fit.

It can be found from the fit results that for the four top quark EFT operators, $Q_{\varphi Q}^{(-)}$, $Q_{\varphi t}$, Q_{tW} , Q_{tB} , they are constrained to be in the range of 0.1 to 1 in the individual fit, which corresponds to a new physics scale of a few TeVs. Though they only contribute to the electroweak process through loops, the electroweak measurements are still powerful enough to constrain them. Comparing with other results that constrain these operators using LHC data^[259], it can

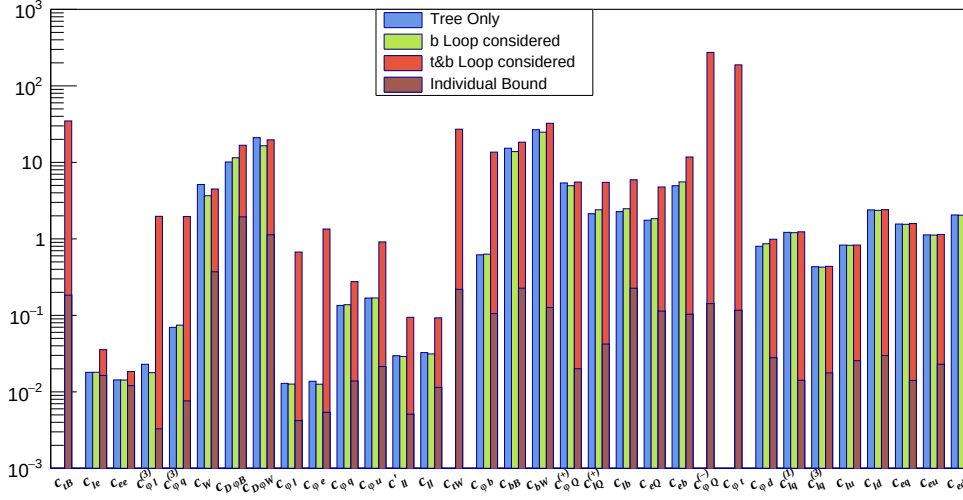


Figure 5-24: The 68%CL bounds of the coefficients of operators in modified Warsaw basis for three different scenarios. Blue: tree-level contribution only. Green: tree-level contribution and the loop contributions from the bottom-quark operators. Red: tree-level contribution and the loop contributions of all third-generation-quark operators, the dark red bar is the individual bound in this scenario. The value of Λ is set to 1 TeV for all coefficients.

be found that the electroweak data have greater constraining power on $Q_{\phi Q}^{(-)}$ and $Q_{\phi t}$, whose advantage is estimated to be order of 10. While for Q_{tW} and Q_{tB} , the LHC data is more powerful. The comparison of 95% CL individual bounds are listed in Table 5-9 for comparison.

	$c_{\phi t}$	$c_{\phi Q}^{(-)}$	c_{tW}	c_{tB}
Electroweak	0.286	0.336	0.822	0.592
LHC data	2.275	1.22	0.06	0.145

Table 5-9: 95% CL individual bounds of top quark EFT operators' coefficients using different sets of observables. The electroweak results are the ones in this study while the LHC refers to the results in^[259].

In a global fit that float all the coefficients, the marginalized bounds of the top-quark operator coefficients become much looser, and some of them have possibly exceeded the range of EFT validity. As the introduction of additional degrees of freedom tends to bring additional flat directions, making the fit difficult to converge. Figure 5-25 and Figure 5-26 show the correlations between the operators considering only tree-level contribution and include loop contributions respectively. It can be found that after considering the loop contributions, the correlations between operators are much larger. The inclusion of top operators also significantly degrade the reaches of some other operator coefficients. Among them, the most notable ones are the

leptonic operators: c_{le} , c_{ee} , $c_{\phi l}^{(3)}$, $c_{\phi l}$, $c_{\phi e}$ (as well as $c_{\phi q}^{(3)}$), which were previously very well constrained and are thus most sensitive to additional degrees of freedom. On the other hand, when only consider the bottom quark operator loop contribution, the overall reach of global fit is not significantly degraded compared with the tree-level fit, and the constraints on some operators coefficients are even improved.



Figure 5-25: Correlation matrix between operators' Wilson coefficients in modified Warsaw basis. Only the tree-level contribution of these operators are considered.

Table 5-10 gives the numerical fit results. Figure 5-27 shows the Fisher information matrix, which indicates the impact from each set of measurement on every Wilson coefficients. The Fisher information of set i have on coefficient c_j is calculated by:

$$f_i = \frac{\frac{\partial^2 \chi_i^2}{\partial c_f^2}}{\frac{\partial^2 \chi_{all}^2}{\partial c_f^2}}, \quad (5-30)$$

where χ_i^2 indicated the chi-square calculated with only the data of set i and χ_{all}^2 indicates the chi-square with all sets of measurements.

Operators	Marginalized, tree-only	Marginalized, b loop considered	Marginalized, t/b loop considered	Individual, t/b loop considered
c_{tB}	-	-	30 ± 35	-0.13 ± 0.18
c_{te}	0.0019 ± 0.018	0.0014 ± 0.018	0.036 ± 0.036	-0.0015 ± 0.016
c_{ee}	-0.019 ± 0.014	-0.019 ± 0.014	-0.0082 ± 0.018	-0.012 ± 0.012
$c_{\phi l}^{(3)}$	-0.023 ± 0.023	-0.027 ± 0.018	-0.42 ± 2	-0.0036 ± 0.0033
$c_{\phi q}^{(3)}$	-0.079 ± 0.07	-0.11 ± 0.074	-0.47 ± 2	0.0025 ± 0.0076
c_W	-7.9 ± 5.1	-1.8 ± 3.7	-4.5 ± 4.5	0.41 ± 0.37
$c_{D\phi B}$	-13 ± 10	-7.9 ± 11	-12 ± 17	-0.2 ± 1.9
$c_{D\phi W}$	35 ± 21	12 ± 17	23 ± 20	0.82 ± 1.1
$c_{\phi l}$	0.024 ± 0.013	0.021 ± 0.013	-0.26 ± 0.67	0.0014 ± 0.0042
$c_{\phi e}$	0.0051 ± 0.014	$-2.5e-05 \pm 0.013$	-0.57 ± 1.3	-0.0018 ± 0.0054
$c_{\phi q}$	-0.042 ± 0.13	-0.053 ± 0.14	0.085 ± 0.28	-0.015 ± 0.014
$c_{\phi u}$	0.086 ± 0.17	0.11 ± 0.17	0.49 ± 0.91	-0.011 ± 0.021
c'_{ll}	-0.043 ± 0.03	-0.055 ± 0.029	-0.069 ± 0.094	0.0035 ± 0.0051
c_{ll}	0.054 ± 0.033	0.066 ± 0.031	0.1 ± 0.093	0.0037 ± 0.011
c_{tW}	-	-	4.2 ± 27	-0.3 ± 0.22
$c_{\phi b}$	-0.34 ± 0.62	-0.27 ± 0.63	-12 ± 14	-0.17 ± 0.11
c_{bB}	10 ± 15	9.2 ± 14	12 ± 18	0.25 ± 0.23
c_{bW}	16 ± 27	9.7 ± 25	17 ± 32	0.1 ± 0.13
$c_{\phi Q}^{(+)}$	-3.5 ± 5.4	-2.3 ± 5	-6.1 ± 5.5	0.017 ± 0.02
$c_{lQ}^{(+)}$	-1.5 ± 2.1	-2 ± 2.4	-4.7 ± 5.5	-0.048 ± 0.042
c_{lb}	1.2 ± 2.3	1.4 ± 2.5	-1.2 ± 5.9	0.0074 ± 0.23
c_{eQ}	0.64 ± 1.8	0.56 ± 1.8	-1.5 ± 4.8	0.035 ± 0.11
c_{eb}	3.6 ± 5	5.1 ± 5.6	11 ± 12	-0.1 ± 0.1
$c_{\phi Q}^{(-)}$	-	-	$31 \pm 2.7e+02$	-0.043 ± 0.14
$c_{\phi t}$	-	-	$3.8 \pm 1.9e+02$	0.011 ± 0.12
$c_{\phi d}$	-0.7 ± 0.8	-0.92 ± 0.86	-0.69 ± 0.99	-0.038 ± 0.028
$c_{lq}^{(1)}$	2.3 ± 1.2	2.7 ± 1.2	2.6 ± 1.2	0.014 ± 0.014
$c_{lq}^{(3)}$	0.74 ± 0.43	0.88 ± 0.43	0.84 ± 0.44	0.029 ± 0.018
c_{lu}	-1.1 ± 0.83	-1.3 ± 0.82	-1.3 ± 0.83	0.017 ± 0.026
c_{ld}	-4.8 ± 2.4	-5.8 ± 2.4	-5.2 ± 2.4	0.042 ± 0.03
c_{eq}	2.6 ± 1.6	3 ± 1.6	2.8 ± 1.6	-0.019 ± 0.014
c_{eu}	-2.2 ± 1.1	-2.6 ± 1.1	-2.4 ± 1.1	-0.039 ± 0.023
c_{ed}	-3.6 ± 2.1	-4.2 ± 2	-4.1 ± 2.1	-0.022 ± 0.029

Table 5-10: Numerical fit result of the coefficients of operators in modified Warsaw basis for three different scenarios. The error bound is given in 68%CL.

$STtb$ scenario

In addition to the general global-fitting framework, we also consider a special case denoted here as the “ $STtb$ ” scenario, where it is assumed that all new physics effects apart from the third generation quark operators in Eq. 5-23 can be parameterized by the two oblique parameters, S and T ^[260]. This scenario is motivated by a large class of models with top/bottom partners, which generally mixes with 3rd generation quarks and could also contribute to oblique parameters at the one-loop order. For convenience, the modified oblique parameters $\hat{S}$ and $\hat{T}$ ^{Barbieri:2004qk} are used, which are related to the original ones by:

$$\hat{S} = \frac{\alpha}{4s_w^2} S, \quad \hat{T} = \alpha T. \quad (5-31)$$

$\hat{S}, \hat{T}$ are defined from^[261]. The fit that float only the $\hat{S}$ and $\hat{T}$ gives:

$$\begin{aligned} \hat{S} &= (-2.8 \pm 2.5) \times 10^{-4} \\ \hat{T} &= (2.7 \pm 1.9) \times 10^{-4} \end{aligned} \quad (\text{individual bound}), \quad (5-32)$$

and

$$\begin{aligned} \hat{S} &= (4.0 \pm 6.9) \times 10^{-4} \\ \hat{T} &= (5.5 \pm 5.1) \times 10^{-4} \end{aligned} \quad (\text{marginalized bound}). \quad (5-33)$$

, with 93% correlation between the two parameters. The results are consistent with the one from Ref^[262] that use similar measurements.

With the inclusion of the 3rd-generation quark operators, a 10-parameter fit is performed, and the results are presented in Figure 5-28. It should be noted that, part of the loop contributions of 3rd-generation quark operators are universal and can be absorbed in the original definition of the S and T parameters. Here the $\hat{S}, \hat{T}$ only denote the contributions of the corresponding tree-level operators. A significantly better reach on the top quark EFT operators compared with the general case can be found. On the other hand, the constraining power to the $\hat{S}$ and $\hat{T}$ parameters with the electroweak data is significantly reduced from the 2-parameter case, as expected.

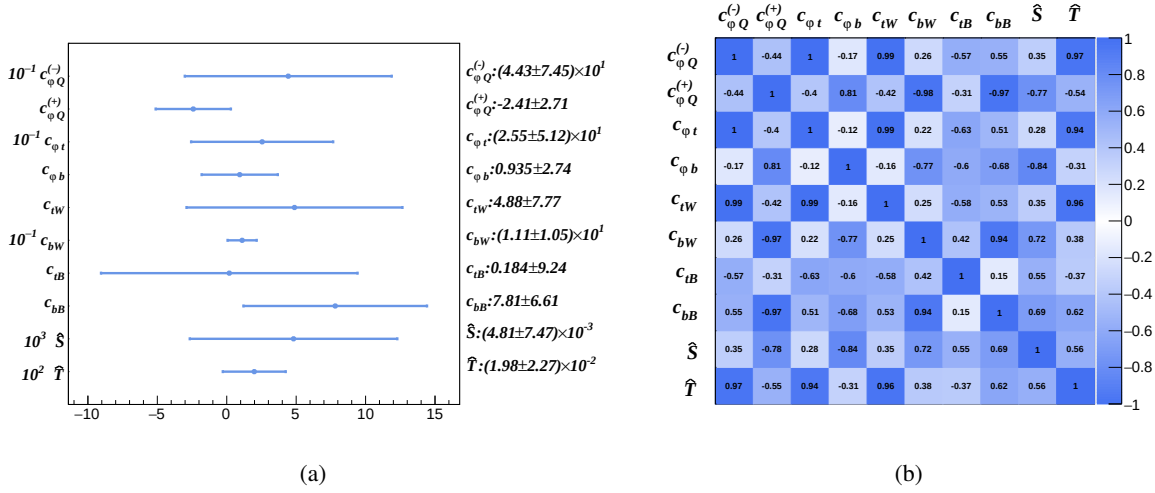


Figure 5-28: Fit results (Left: 68% CL Marginalized bound, Right: correlation matrix) of the $\hat{S}$, $\hat{T}$ parameters plus 8 top/bottom quark EFT operator coefficients.

5.4.4 Future Collider Projection

There have been several proposals of constructing future colliders which can reach higher luminosity and energies than LHC. A lot of the proposals are aim for an electron-positron collider, which is perfect for the electroweak measurements. Thus, it is interesting to see how the improvement in measurements will affect the constraints of these EFT operators. Two future colliders are considered, the FCC-ee^[263] and CEPC^[264].

Table 5-11 shows the projection of the two colliders on electroweak observables and the comparison with current precision. The projections of CEPC are taken from Ref.^[264] while for FCC-ee are taken from Ref.^[265]. The projections of the observables are not complete from the reference, thus some uncertainties are estimated from the expected luminosity such as WW process. And since both two experiments are designed to be a tera-Z factory, the projections of observables at Z-pole are taken as a common value.

Figure 5-29 shows the constraint on the EFT operators using the projection of the electroweak observables. There is no obvious difference on the constraining power between CEPC and FCC-ee. In general, the future collider will greatly improve the constraint on these EFT operators, most of the coefficients will get at least 10 times better constraints, both on individual and marginalized bound. Though the 3rd-generation quark operators can only be probed at loop level in current projections, their improvements with future colliders are still in the same level with tree-level operators. For few operators, like Q_W and Q_{eq} , as their constraints are mainly

Observables	SM	Current Precision	CEPC	FCC-ee
Γ_Z	2.4942GeV	2.3MeV	0.1MeV	0.1MeV
σ_{had}	41.481nb	0.037nb	0.004nb	0.004nb
R_e	20.737	0.05	0.001	0.001
R_μ	20.737	0.033	0.001	0.001
R_τ	20.782	0.045	0.001	0.001
R_b	0.21582	0.00066	0.00006	0.00006
R_c	0.17221	0.003	0.00026	0.00026
A_{FB}^b	0.103	0.0003	0.0003	0.0003
A_τ	0.1472	0.00216	0.0002	0.0002
M_W	80.379GeV	12MeV	1MeV	0.5MeV
Γ_W	2.085GeV	42MeV	2.8MeV	1.2MeV
$\sigma_{ee \rightarrow ff}^{160GeV}$	-	-	$\sqrt{\frac{\sigma_{SM}}{2.6ab^{-1}}}$	$\sqrt{\frac{\sigma_{SM}}{12ab^{-1}}}$
$\sigma_{ee \rightarrow ff}^{240GeV}$	-	-	$\sqrt{\frac{\sigma_{SM}}{5.6ab^{-1}}}$	$\sqrt{\frac{\sigma_{SM}}{5ab^{-1}}}$
$\sigma_{ee \rightarrow \mu\mu/\tau\tau, differential}^{240GeV}$	-	-	$\sqrt{\frac{\sigma_{SM}}{5.6ab^{-1}}}$	$\sqrt{\frac{\sigma_{SM}}{5ab^{-1}}}$

Table 5-11: Comparison of the projections of electroweak observables for CEPC^[264] and FCC-ee^[265]..

from $e^+e^- \rightarrow W^+W^-$ process or low energy coupling measurements, which lack the projection of their precision on future collider, their constraints have a relatively small improvement. However, it is believed that they can also benefit from the high precision measurements on future collider. Finally, a high-energy lepton collider running at and above the top threshold will be able to measure the $e^+e^- \rightarrow t\bar{t}$ process to an unprecedented precision, providing the ultimate probe of the 3rd-generation quark operators^[237,266-267] at tree-level.

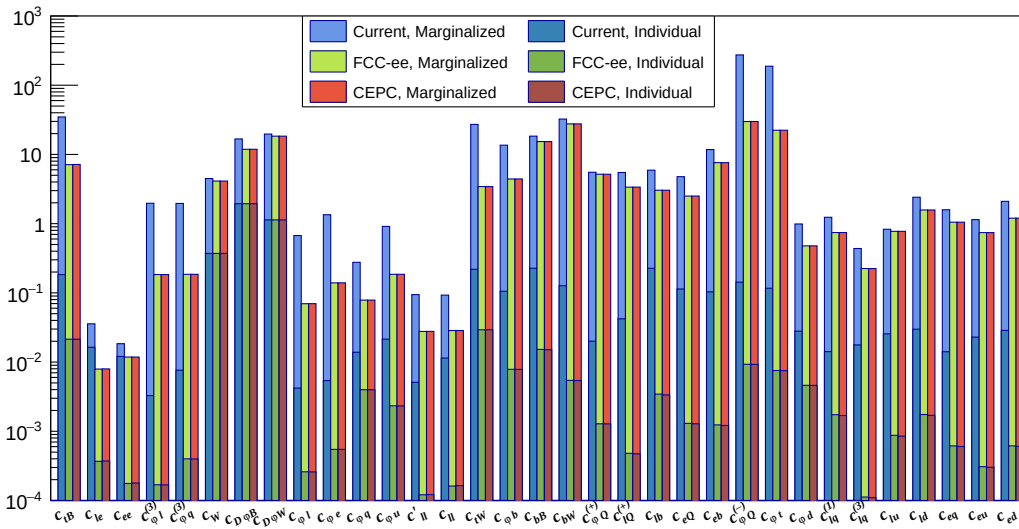


Figure 5-29: Comparison of the current precision of EW observables and the projections for CEPC and FCC-ee..

5.5 Conclusion

In this chapter, the studies that search for the new physics beyond SM via direct and indirect approaches are presented, including: indirect search using combined Higgs production and decay mode measurements, direct search using combined searches for a resonance decaying into a pair of Higgs bosons and indirect search using combined electroweak precision measurements. The searches are interpreted in several BSM UV models and EFT framework. In all searches, no obvious deviation from SM is observed, and stringent constraints are obtained on these BSM theories.

The combined Higgs measurements are interpreted in EFT and BSM UV models. For the SMEFT, the constraint on the Wilson coefficients corresponding to a rotated basis of Warsaw basis are shown. Two scenarios are considered, one only includes the linear effect of the operators and the other includes both linear and quadratic effect. In general, a good constraint are observed. Some coefficients are constrained to the level of $O(10^{-3})$ with only linear effect, which corresponds to the new physics scale of few hundreds TeV. The least constrained coefficients also reach the level of $O(1)$, which shows the outstanding sensitivity of Higgs measurements at LHC on Higgs operators. By considering the quadratic effect, the constraints are tightened even further. For the UV models, four scenarios in 2HDM and in total of eight benchmarks of MSSM are shown. These results are complementary to direct searches for the BSM Higgs. The self-coupling loop effect on the SM Higgs process are considered for the first time in Higgs interpretation. By comparing the constraint obtained in 2HDM Type-I, It can be found that the self-coupling plays an important role in specific models and its sizeable effect can help constrain the parameter spaces in the model. While in other 2HDM scenarios, its impact is much smaller as they are already well constrained by the Yukawa coupling measurements. In addition, a matching of EFT constraint to the UV models are conducted for 2HDM. It is found that the results are consistent with the results obtained from direct interpretation, proving that EFT is the valid low energy approximation of high energy UV models.

The combined direct search for a resonance decaying to a pair of Higgs bosons is interpreted in BSM UV models, including h MSSM, several benchmarks of MSSM, Singlet model and 2HDM. Three dominant final states are considered: $b\bar{b}b\bar{b}$, $b\bar{b}\tau\tau$ and $b\bar{b}\gamma\gamma$. A new inter-

pretation scheme is introduced in this study, which relies on the feature in the BSM models considered that the ratio between branching ratio of $b\bar{b}b\bar{b}$ and $b\bar{b}\tau\tau$ remains the same as SM. The new interpretation scheme greatly improve the consumption of fit, producing the interpretation of a variety of models in a relative short time. The interpretation results show good sensitivity of the resonant Higgs pair production in the searching for heavy Higgs.

The combined electroweak precision measurements are interpreted in EFT framework, with an emphasis on the effect of Top quark EFT operators. These top quark EFT operators enter the electroweak process via loop contribution, which is previously neglected in the tree-level treatment. In this study, the tree-level framework is extended by adding the one-loop contributions of the operators that involve the third generation quarks. This is motivated by the many new physics where the third generation quarks play a special role as a portal to the BSM effect. It is found that these third generation quark operators, especially the top quark ones, have significant contributions to the electroweak processes. In an individual fit that only consider the impact of single one operator at one time, these operators are constrained to a competitive level as the tree-level operators. However, in a global fit that consider all the operators at the same time, the reaches on the operator coefficients become significantly worse, as it is difficult to separate the loop effects of the 3rd-generation quark operators from other tree-level effects. However, in the UV models, the parameter spaces are usually much smaller. The less degree of freedom will make it much easier for degenerate the effect of loop operators with tree-level effect. As a demonstration, a fit is performed in a more constrained scenario where the only tree level contributions are parameterized by the two oblique parameters S and T . In this case, much better constraints on the third generation quark operators are obtained. Finally, this study makes the prediction of future colliders' performance on constraining these third generation quark operators with their better precision on electroweak process. It is found that in the current projection, the constraint on these operators will be much improved. And if the running energy of these colliders can reach the top pair production threshold, the top operators can be probed at tree-level. These results further validate the advantage of building an electron-positron collider with higher energy and luminosity.

In conclusion, the three studies presented in this chapter search for the new physics via direct or indirect approaches using different processes, showing comparable and complementary

sensitivity in the BSM theories. These studies demonstrate the deep connection between the Higgs, electroweak and top sectors. Thus, the precise measurements of these processes are of vital importance for the ultimate test of SM and searches for BSM. It also proves the necessity of building the future colliders that will bring us to a new uncharted territory of particle physics.

Chapter 6

Conclusion and Outlook

The ATLAS experiment at LHC has gained enormous success in discovering and measuring the properties of Higgs boson, and there is no obvious deviation from the Standard Model prediction so far. However, the Standard Model is believed not to be the ultimate theory due to its lack of explanation in many phenomena, and numerous beyond Standard Model theory has been raised. Many of them has modification to the Higgs sector and predict a different behavior of Higgs boson than the SM prediction. As a result, measuring the Higgs boson in more detail and searching for the undiscovered decay modes as well as the BSM signatures are the focus of ATLAS experiments.

This thesis presents the study of a search for Higgs decay to charm quarks in VH production mode, using the pp collision at centre-of mass $\sqrt{s} = 13$ TeV data collected by ATLAS detector during the LHC Run-2. Due to the similar topology, the measurement of $VH(\rightarrow b\bar{b})$ is carried out simultaneously. Three channels are considered based on the number of charged leptons from the vector boson decay. A custom flavor tagger is designed to coherently identify the b - and c - jets. The events are categorized based on the flavor tagging information. For $VH(\rightarrow c\bar{c})$, only resolved topology is considered and for $VH(\rightarrow b\bar{b})$, resolved and boosted topology is considered. Multi-variate analysis technique is used to separate signal and backgrounds. Dedicated Control regions are defined and shared between resolved $VH(\rightarrow b\bar{b})$ and $VH(\rightarrow c\bar{c})$ regimes to better control the main backgrounds: V +jets and top process. The signal strength of $VH(\rightarrow c\bar{c})$ and $VH(\rightarrow b\bar{b})$ are in good agreement with SM prediction. An observed(expected) upper limit of 11(10) times SM cross-section times branching ratio at 95% CL for the $VH(\rightarrow c\bar{c})$ process is set. The results significantly improved by more than 100% compared with last

iteration thanks to the application of MVA, better tagging performance and better background control. The results are interpreted in kappa framework. The observed (expected) constraint on $|\kappa_c|$ is $|\kappa_c| < 4.1(4.2)$ at 95% CL. The ratio between κ_b and κ_c is constrained to be $|\kappa_c/\kappa_b| < 3.6(3.5)$ with observed (expected) data. The $|\kappa_c/\kappa_b|$ value corresponding to the universality of Higgs coupling to charm and bottom quarks is excluded by a significance of 3σ . The cross-section of $VH(\rightarrow b\bar{b})$ process in STXS is measured, the uncertainties improved by up to 100% compared with the previous study. To validate the BDT model and fit robustness, the $VZ(\rightarrow b\bar{b})$ and $VZ(\rightarrow c\bar{c})$ process are used as cross-check. A dedicated BDT model is trained for them and the analysis strategy remains the exact same as $VH(\rightarrow b\bar{b}, c\bar{c})$ analysis. The fit results agree with SM, and the $VZ(\rightarrow c\bar{c})$ process is observed in the first time at ATLAS with a significance of 5.3σ . All the results in this study show good consistency with the SM prediction, which provides strong evidence for the BEH mechanism where the fermion masses are generated via Yukawa coupling.

The thesis also presents the search for new physics beyond SM with the three sets of combined measurements: combined Higgs production and decay mode measurements, combined resonant Di-Higgs production and combined electroweak precision measurements.

The combined Higgs production and decay mode measurements are interpreted with EFT and several BSM models: 2HDM and MSSM benchmark scenarios. The result is found to be consistent with the SM and no indication for the new physics is found yet. Comparing with the previous study, much larger phase spaces in the BSM models are excluded, mainly due to the larger size of data collected and the effect of self-coupling is considered. A matching of EFT constraint to the BSM UV model parameters are shown, which shows good consistency with the direct interpretation results of BSM models. It validates that the EFT is the low energy approximation of high energy UV models in Higgs process. In complementary to the searches for deviation of SM process, the direct searches for the BSM particles is another approach to exploit the physics beyond SM. A combined search for the BSM resonance decay to a pair of Higgs bosons is also presented in this thesis. The results are interpreted in several BSM models: h MSSM, 2HDM, Singlet model and MSSM benchmarks. No direct evidence of heavy resonance is found and specific phase spaces in these models are excluded, which shows that resonant Higgs pair production is one of the most sensitive channels in the searches for heavy

Higgs. Finally, the study that probes the Top EFT operators with electroweak precision measurement is shown. These operators are found to generate sizeable loop effect to the electroweak process, which is neglected before in tree-level treatment. After considering these loop effect, these top operators can be well constrained individually, but degenerate with other tree level operators when considered simultaneously. By taking the projections from the future colliders, these operators are expected to be much well constrained and can be separated from other operators with measurements above the top pair threshold, which indicates of advantages of future colliders. All three searches did not observe obvious deviation from the SM. Meanwhile, these studies demonstrate the effect of new physics at the electroweak energy scale, as well as the interplay between the Higgs, electroweak and top sectors, which provides useful hints for the construction and operation of future colliders.

The LHC has begun its Run-3 since 2022, with the aim of collecting a dataset twice large as the one collected in Run-2. A lot of upgrades in the detector are also developed to ensure the smooth operation of its run. A new flavor tagging scheme that utilize advance machine learning techniques has been developed which significantly improve the ability to identify the charm jets and lower the mis-tag rate. Furthermore, it provides the ability to tag the large- R jet initiated from charm quark pairs that can be used to search $VH(\rightarrow c\bar{c})$ process with high p_T Higgs, which is very sensitive to BSM effect. Similar improvements can be expected for other objects identification and calibration. With the new dataset and all these improvements in combined performance, in addition to the developments of more advanced analysis techniques, the Higgs properties can be measured in more details.

As indicated in Figure 2-8, which shows the exclusion region in h MSSM phase spaces by different channels, ATLAS has made huge effort in searching for the sign of physics beyond Standard Model in various models and signatures, and lots of parameter spaces have been excluded so far. Yet there still remains huge parameter spaces to be tested, and there is the possibility that the new physics lies in there.

After the Run-3, the LHC will be upgraded to the High-Luminosity LHC (HL-LHC) which will collect at least 3000 fb^{-1} dataset at $\sqrt{s} = 14 \text{ TeV}$. It is expected to have evidence of Higgs self coupling, which will be another milestone for the understanding of Higgs potential. The Yukawa coupling of Higgs boson will also be measured with higher precision, which allows

us to probe potential deviation from the Standard Model that can indicate the existence of new physics. It is also possible to have direct observation of new physics which could bring the particle physics to a new era.

Finally, with the future colliders that is now in the designing stage, the precision of electroweak, Higgs and top process measurements will be improved to an exceptional high level. The hidden sector of new physics can probably be revealed as well under the powerful inspection. At that time, these energy-frontier facilities will bring us to a completely uncharted territory of physics.

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Publications

Collaboration publications

- Journal of High Energy Physics, Measurements of WH and ZH production with Higgs boson decays into bottom quarks and direct constraints on the charm Yukawa coupling in 13 TeV pp collisions with the ATLAS detector, under review
- Journal of High Energy Physics, Interpretations of the ATLAS measurements of Higgs boson production and decay rates and differential cross-sections in pp collisions at $\sqrt{s} = 13\text{TeV}$, 2024
- Physics Review Letter, Combination of searches for resonant Higgs boson pair production using pp collisions at $\sqrt{s} = 13\text{ TeV}$ with the ATLAS detector, 2024
- Nature, A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery, 2022

Second author publication

- Chinese Physics C, Probing top-quark operators with precision electroweak measurements, 2022

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High voltage connections optimization for HGTD modules

Introduction

High Granularity Timing Detector

The large increase of pile-up interactions is one of the main experimental challenges for the HL-LHC physics program. Therefore, a High Granularity Timing Detector (HGTD)^[268], based on low gain avalanche detector (LGAD), has been proposed for the ATLAS Phase-II Upgrade. Taking into account the typical number of hits per track in the detector, the target average time resolution per track for a minimum-ionising particale is 30 ps at the start of lifetime, increasing to 50 ps at the end of HL-LHC operation. The active detector element is made of LGADs read-out by dedicated front-end electronics ASICs (ALTIROC). In the design, a bare module is made of two parts: an LGAD sensor and two ASICs. The sensor and the ASICs are connected through a flip-chip bump bonding process called hybridization. The ASICs are then connected to the peripheral electronics through the module flex cable. The size of the bare modules is around $2 \times 4 \text{ cm}^2$ with 450 pads, and the nominal numbers of bare modules is 7984, all of them are identical. The size of the pad is $1.3 \times 1.3 \text{ mm}^2$ and each of the ASIC reads a matrix of 225 pads. The size of the ASIC is about $19 \times 22 \text{ mm}^2$.

Front End ASIC

The global architecture of the ASIC, called ALTIROC, is similar to the ASICs developed for pixel detectors but with a significantly reduced number of channels, as shown in figure 1. The ASIC will transform the analog signal from sensor to the digital information of hit, Time Of

Arrival (TOA), Time Over Threshold (TOT). The sensor signal is amplified using a voltage preamplifier with about 1 GHz bandwidth. Currently, there are two alternative kind of preamplifier: Transimpedance preamplifier (TZ) and Voltage preamplifier (VPA). The preamplifier is followed by a fast discriminator. There are two Time to Digital Converter (TDC), one for TOA and one for TOT measurement. For TOA measurement, architecture of TOA TDC is vernier delay line, the leading edge of the discriminator's output works as the start pulse and initializes the TDC operation. The stop is given by the clock. This structure will minimize the power dissipation when hits are absent. The TOA measurements are restricted to a 2.5ns windows centered on the bunch crossing and the quantisation step is 20ps. The falling edge of discriminator output provides the stop of the TOT TDC, which also use the leading edge as start, with 40ps quantisation step. The TOT information is used offline to correct the TOA for timewalk effect. After correction, the residual variations are well within 10ps.

In order to test and qualify the production and connection of the sensors and ASICs, some prototypes are made. Currently, a 5×5 channels sensor and ALTIROC1 is made and under test. ALTIROC1 is the second ALTIROC ASIC prototype with 25 channels to readout 5×5 sensor cells of $1.3\text{ mm} \times 1.3\text{ mm}$ with phase shifter. Figure 2 shows a typical mini-module which is wire bonded to the test board and high voltage.

There are several versions of ALTIROC1 chips: ALTIROC1_V1, ALTIROC1_V2, ALTIROC1_V3 and the chips that tested in this task are ALTIROC1_V2 and ALTIROC1_V3. For both of them, all pads are accessible when the sensor is bump bonded on the ASIC. Figure 3 shows the layout of ALTIROC1_V2. The mandatory pads are for clocks, slow controls (SC), probe signals, command and data transmission. The debug pads are for debug and characterize the ASIC, as well as check the power supplies. In the ALTIROC1_V2, two kinds of preamplifier are used, 15 pads use VPA while the rest 10 pads use TZ preamplifier. For the last pixel of each column, its additional capacitance can be adjusted from 0 to 3.5pF using SC parameters. The additional capacitance on other channels is 0. For ALTIROC1_V3, all the preamplifier is VPA. Similar to V2, the additional capacitance of all the channels in the first 4 columns can be adjusted from 0 to 7 pF. The pixels located in a same column share the same capacitance set. In the last column, only the capacitance of last pixel can be adjusted.

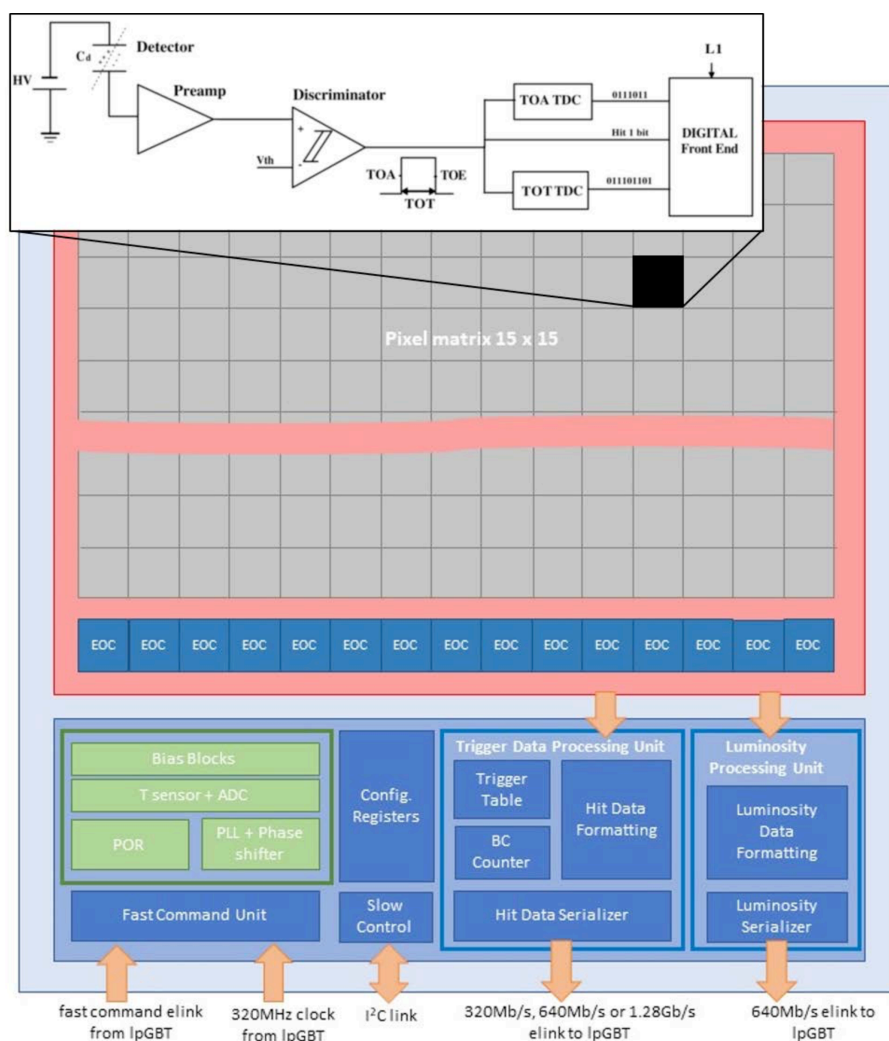


Figure 1: Global architecture of the ALTIROC ASIC.

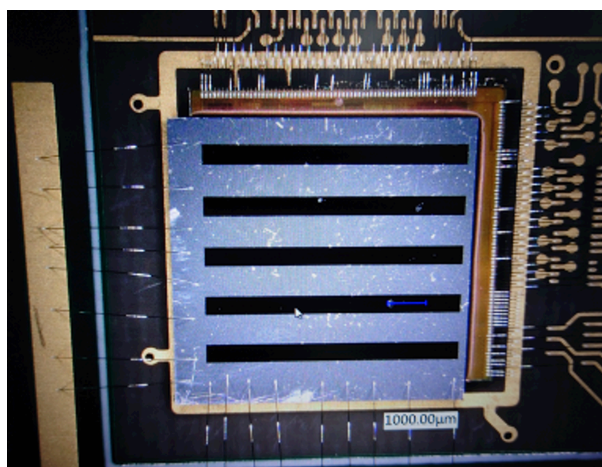


Figure 2: A typical mini-module.

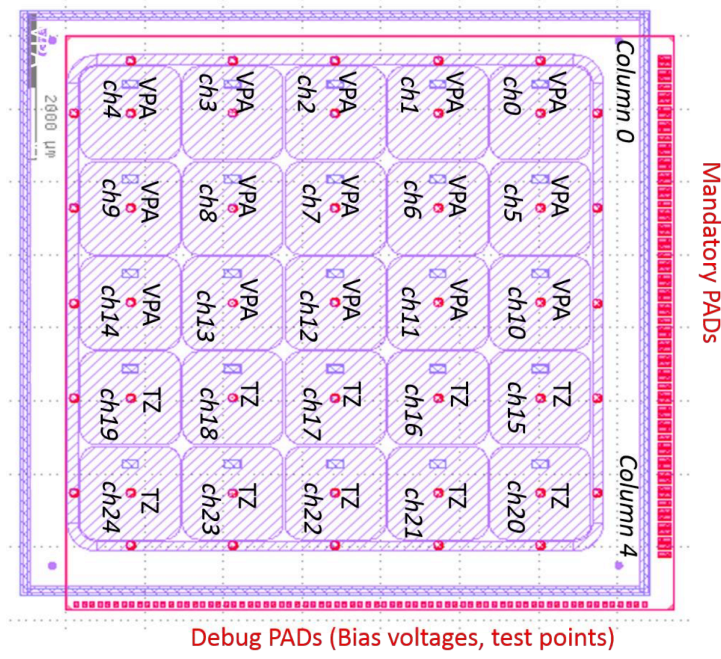


Figure 3: Layout of ALTIROC1_V2 ASIC.

Timewalk Correction and High Voltage effect

The timewalk effect is brought by different rising time of different quantities of charge^[269]. The large charge will have a signal that rises faster than the slow one, which means the measured TOA will be earlier than the slow one, as is shown in Figure 4. In order to correct this effect, TOT information, which reflects the size of charge, will be used. As shown in Figure 5, as long as the relationship between the TOT (given different quantities of electric) and the TOA value ($t_1 - t_0$ in the figure) is measured, the timewalk effect can be corrected. This correction will require an additional FPGA to apply during the operation of HGTD.

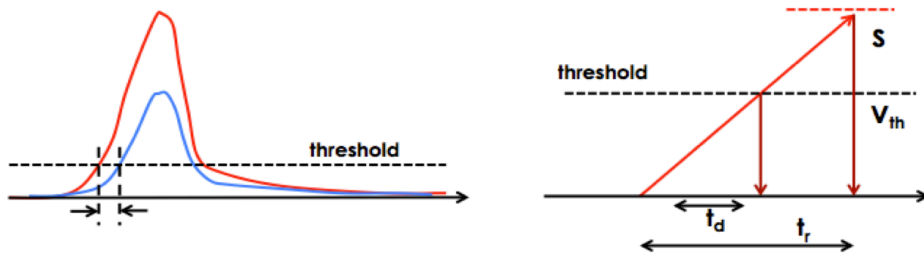


Figure 4: Left side: signals of different amplitude cross a fix threshold at different times, generating a delay t_d on the on the firing of the discriminator that depends upon the signal amplitude. Right side: a linear signal, with amplitude S and rise time t_r , crosses the threshold V_{th} with a delay t_d .

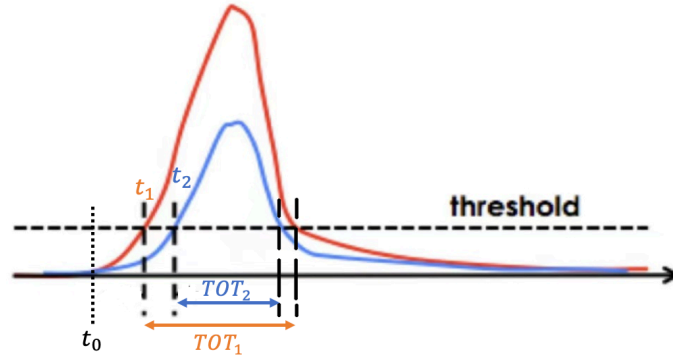


Figure 5: Illustration of using TOT information to correct the TOA error brought by the time-walk effect. t_0 is the actual TOA of the two signal with different size, t_1 and t_2 is the measured TOA respectively. TOT_1 and TOT_2 is the measured TOT of two signals.

As a result, it is important to study the formula of TOT and TOA with the amplitude of the signals, in another word, the timing calibration. A smooth and stable relationship is expected so that the uncertainty of the timewalk correction would be small. Some test have already been done to study this relationship. As the sensor needs a bias voltage to drive the charge, a wire is needed to connect the module with the high voltage (HV). In the TDR, one single HV wire goes through a ring on the PEB board that holds module and connected to the HV source. In the current test PEB board, the HV wires are wire-bonded to a L-shape HV pad. However, these wires were found to make timing calibration unpredictable. Figure 6 shows preliminary test results presented by OMEGA. The test is about the TOT measurement results of pixels with two types of preamplifier when injecting different values of charge. The left plot is the results when only have ASIC without sensor bonded, there are some small kinks, but the curve is continuous overall. The right plot is the results when ASIC bump-bonded to sensor and bias voltage wire-bonded. The VPA preamplifier results shows that there are discontinuities when the injected charge around 8fC while the channels with TZ preamplifier shows better behavior. The discontinuities will bring difficulties for the calibration of TOT measurement as well as the timewalk correction. It is believed that this circumstance is due to the inductance brought by the bias voltage wire-bonding and the VPA preamplifier is thus been affected. This study aims to quantify this impact and optimize the best way of bias voltage connection.

As it is believed that the discontinuities is brought by the inductance of HV wires, this study try to find if the timing calibration have some dependence on the number of HV wires. Few test boards which have good performance are selected (reasonable TOA delay test, TOT

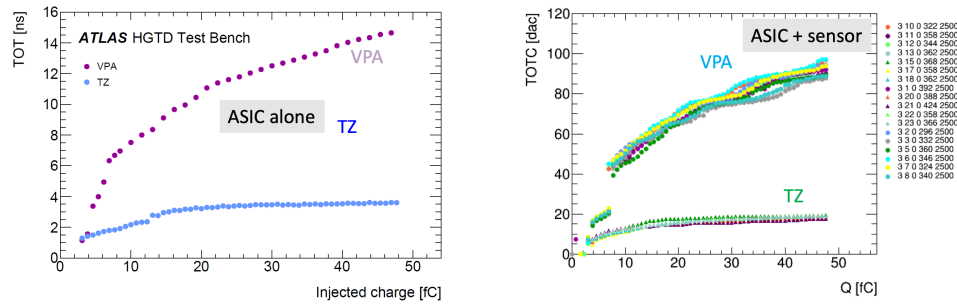


Figure 6: Test result of TOT behaviour done by OMEGA. The left plot is results with ASIC alone, the right plot is results with ASIC bump bonded to sensor and bias voltage wire-bonded .

width test, threshold results and timewalk results) and initially they have tens of HV wires. The module is wire-bonded to one specific test board, so the ID of the board is used to distinguish different module. The wires are then gradually removed and timewalk test is done with different number of wires for comparison. As it has been confirmed that different preamplifiers have different response to the HV wires, the results are divided into two categories based on the type of preamplifier.

Test Procedures

Test System

In the past one year, several sensors and ALTIROC1 ASICs are manufactured, assembled and then delivered to IHEP. A test system is built to verify the function of the modules, including the study of timewalk effect. All the tests done in this study are based on this system. Figure 7 is a schematic diagram of the test system and Figure 8 is a photo of the test system. The PC is connected to the FPGA board (the black one) by Ethernet to setup the firmware and software of FPGA and receive the output from FPGA. The FPGA board is designed by SLAC, in order to control the ALTIROC1 test board and readout the data. The FPGA then connected to the ALTIROC1 test board through PCI-E connection. The ASIC test board is designed by OMEGA, whose major functionality includes controlling ASIC, power supply and voltage measurement. The ASIC's pad is connected to the pins on test board by wire bonding and the sensor is also connected to HV pads in the same way. The HV is supplied by external voltage source. There is an additional interface board which can be added between FPGA and ASIC boards, which is

used to filter digital signals provided by FPGA. It can also translate the TOA busy CLPS signal into CMOS signal, and this function is disabled in this test as it is designed for testbeam only.

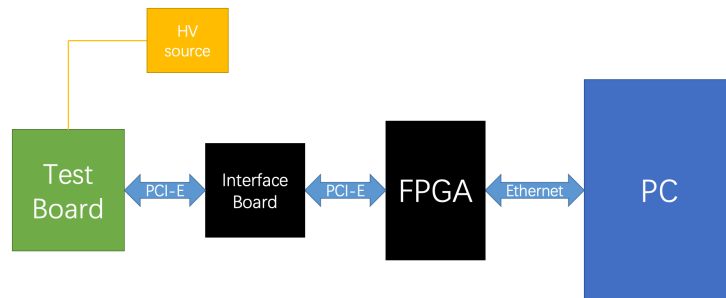


Figure 7: Schematic diagram of the test system.

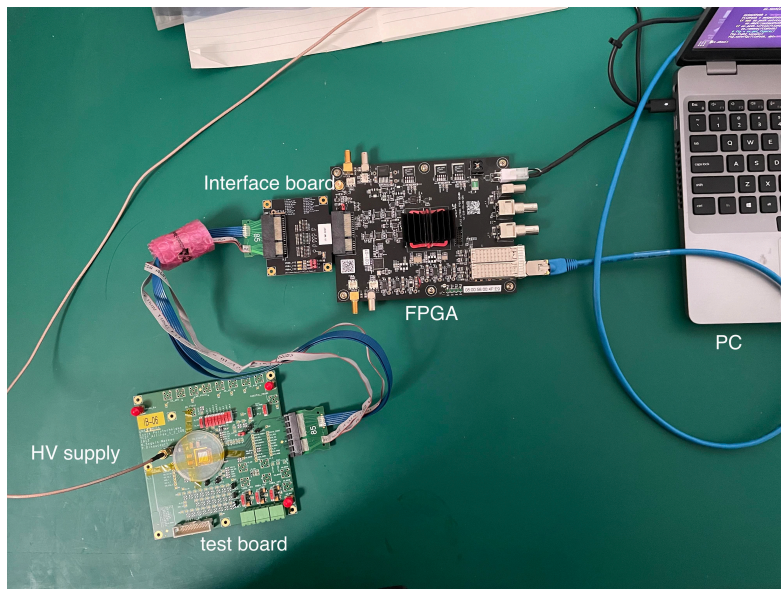


Figure 8: Photo of the test system.

All the different kinds of test need a signal that is controllable, so the signals are generated by ASIC to mimic the signals from sensor. The signals are controlled by the *cmd_pulse* input which is generated by the FPGA and synchronous to 40 MHz . There is also an external trigger that can characterize the TOT TDC or TOA TDC, which is sometimes enabled when doing measurement of signals with different delay and width.

Timewalk test

As have been mentioned above, the timewalk test is for testing the TOA and TOT measured results given different size of signals starting at the same time. It is desired that the TOT v.s. the

signal amplitude would be in a good shape, in the other words, would be smooth, continuous and distinguishable. Figure 9 shows example timewalk test results. Note that larger TOA readout values indicate earlier time of arrival. This example is measured with a pixel using VPA of one ASIC+sensor module, but no HV wires bonded. In this case, the timewalk effect can be corrected with small error due to the smooth and continuous relationship between TOT and TOA. It is hoped that after HV wire-bonding, the relationship of TOT-Q and TOT-TOA could be similar to these results instead of the shape in Figure 6.

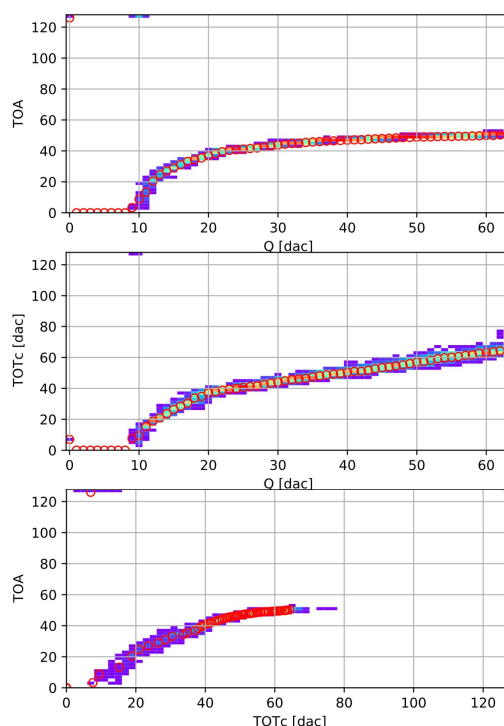


Figure 9: Example results of timewalk test. From up to down is: TOA readout value v.s. injected charge (top), TOTc readout value v.s. injected charge (middle) and TOA readout value v.s. TOTc readout value (bottom).

Besides from the timewalk test, there are some other tests need to be done to ensure the module is working properly, which is listed in the following.

TOA measurement

The TOA test is for testing the relationship of 7 bit TOA output between the actual arrival time, in another word, the quantisation step. The designed value of the step is 20 ps. The FPGA will send commands to generate signals with programmed delay and receive the TOA output of the

ASIC, and estimate the step using the least square estimation. Figure 10 shows typical results of TOA results. The upper left panel shows the plot of TOA readout value v.s. delay value of the signal. One unit of the delay value is 9.5582 ps, which is measured in July 2019. The slope of the non-zero part can be translated to the quantisation step. The other panels show the jitter and distribution of the TOA measurement.

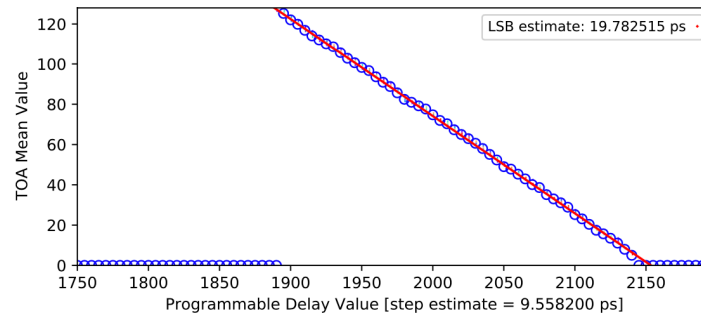


Figure 10: An example results of TOA test.

coarse TOT measurement

Similar to TOA test, coarse TOT (TOTc) test aims to measure the relationship between the 7-bit TOTc output with the width of signal. The FPGA will generate signals with different values of width, also in the unit of 9.5582 ps and get the output of TOTc measurement. An example of test results is shown in Figure 11. One unit of TOTc readout is designed to correspond to 160 ps width.

Threshold scan

The threshold scan will measure the threshold voltage with a given quantity of electric charge and this test reflects the noise of the signals. The program will gradually change the threshold voltage and measure the number of hit. The low threshold voltage that passes all signals and noises will be removed by a saturated TOA measured value. Figure 12 shows example test results of threshold scan with an injected quantity of charge equals to 5 fC. The slope of the falling edge of number of hits indicate the voltage noise. The more dramatically of the edge falls, the smaller is the noise.

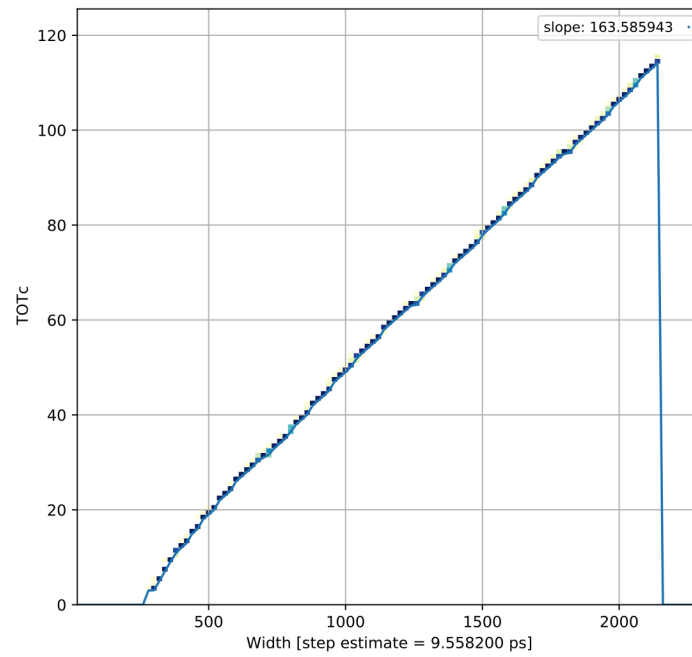


Figure 11: An example results of TOTc test.

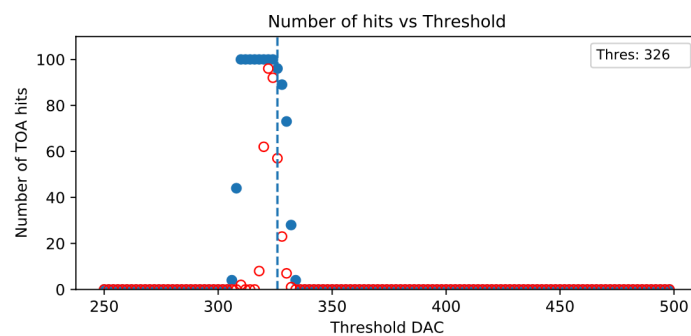


Figure 12: An example results of threshold scan. The blue dot for the number of TOA hit, no matter the value of it. The red dot for the number of TOA hit that TOA readout value smaller then 127, where 127 means the TOA readout is saturated.

High Voltage wires removal

After doing the above-mentioned test and confirming that some channels in the module is working properly, the HV wires that are bonded to the HV pad are gradually removed using tweezers. For Board 32 (B32), when the remaining number of wires is larger than 5 before removal, two wires will be removed, one on the upper side and one on the left side. When there will be less than 5 wires left, 1 wire will be removed each time. The numbers of wires on the left and upper side are controlled to be close to each other. The other boards follow the similar strategy. Figure 13 is a photo of B32 that is taken when there is only one line left on the left side of the module. Each time wires are removed, the timewalk test is done to study the relationship of TOT, TOA and injected electric quantities. At some points, the TOA delay test and TOT width test is done again to ensure the module is working as expected throughout the whole test. After all HV wires are removed, the HV can no longer imposed on the module and thus the module works like a bare ASIC.

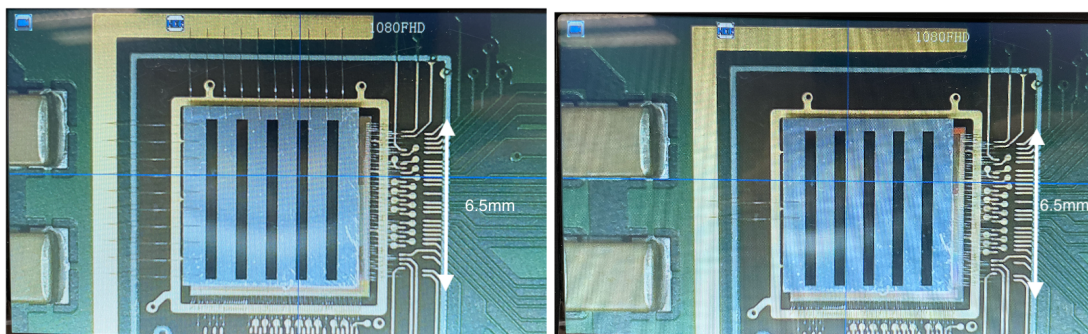


Figure 13: Photo of IB06 with different number of HV wire. Left: with all 20 initially bonded HV wires. Right: only two HV wires left.

Test Results

As it has been confirmed that channels with different preamplifiers have different reaction to the HV wires, the test results are divided into two parts, based on the preamplifier used in the pixel. There are in total three boards used in this study: B32, IB03 and IB06. The 'I' prefix stands for the boards manufactured by IHEP. Dedicated tests have been done to ensure that they have the same performance with the original boards. For simplicity, in the following part, the channels using voltage preamplifiers will be named as VPA channels and the ones using TZ

preamplifiers will be called TZ channels.

Voltage Preamplifier

Two boards are used for the performance of VPA: B32 and IB03. All the channels in them uses VPA so in the following part, there will not be specific statement of what preamplifier does the channel use.

Board 32

Board 32 (B32) is one selected test board with ALTIROC1_v3 module on it. It initially have 31 HV wires, bonded to the up and left side of the sensor evenly (in the direction same as Figure 3). The TOA using both external trigger and internal trigger, TOT width test and threshold scan shows that this board have a relatively good performance, except for a few channels. Some selected test results are shown in Figure 14. For the TOA test, most quantisation step is measured to be around 20 *ps*. For TOT test, most quantisation step is measured to be around 160 *ps*. After imposing a bias voltage of 70V, the TOA and TOT results hardly changes. The timewalk test is also done with and without the bias voltage, as is shown in Figure 15, which indicates that the amplitude of the high voltage doesn't matter much.

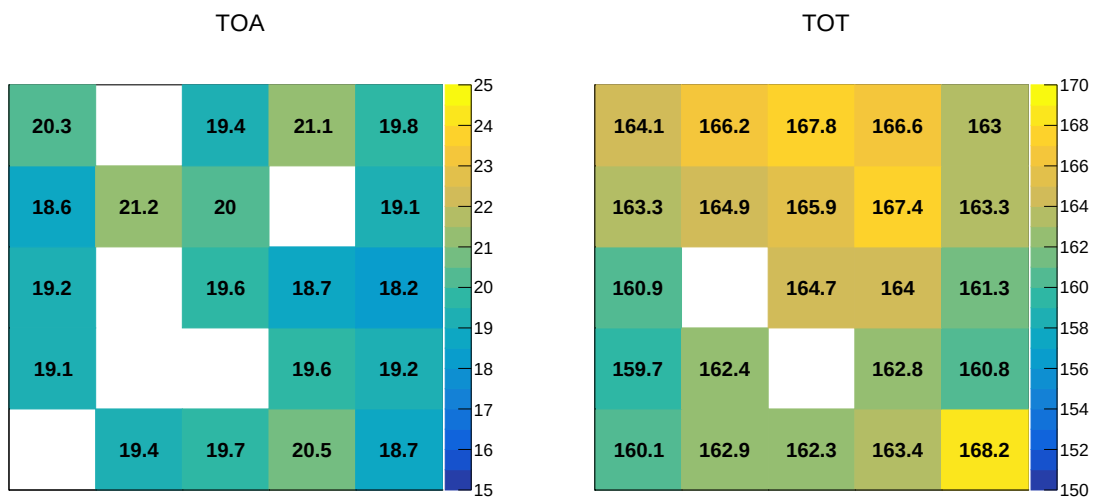


Figure 14: B32 TOA test (left) and TOTc test (right) results using external trigger. The numbers in the grid is the measured quantisation step of the corresponding channel, in *ps*. Order of the channels is same as Figure 3. The blank block indicates that channel didn't give reasonable test results.

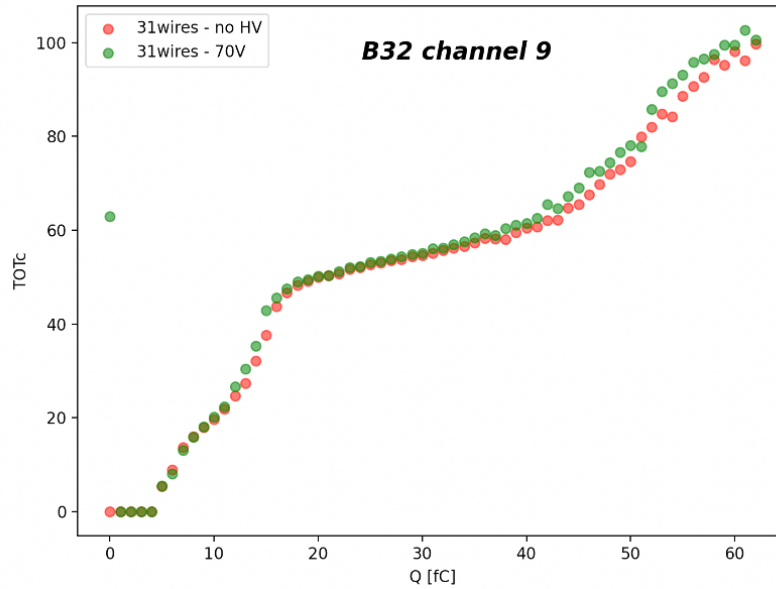


Figure 15: TOTc v.s. injected electric quantities relationship of channel 9 in B32, the green dot is results with 70V bias voltage imposed and the orange one is without bias voltage.

The left plot of Figure 16 shows the results of TOTc v.s. injected electric quantities (TOTc-Q curve) with different number of wires. 70V high voltage is imposed in the case there are wires connected. For 0 wire, as no voltage can be imposed, the results is marked with triangle. From this plot, it can be found that when there is no wire connected, the performance is quite stable, the TOTc-Q curve is smooth and continuous. As long as there is HV wire connected to the module, there appear a platform, ranging from around 20fC to 40fC, where the TOTc remains almost flat with the value around 60. The right plot of Figure 16 shows the results of TOA v.s. TOTc with different number of wires. Due to the above-mentioned platform at TOT readout value around 60 in the case there have HV wires connected, the slopes of TOA-TOT curves also change dramatically at this point. In comparison, the 0 wire case gives a smooth curve. It means that using this module, when the signal amplitude ranges from 20fC to 40fC, the timewalk correction have large error as little deviation in TOTc readout value will translate to large deviation of TOA readout value. Though from these plot, it can be found that increasing the number of HV wires can help make these curves smooth and more like the case that there is no HV wires, but the improvement is quite limited.

Same tests are done with wires connected but without high voltage imposed, which are shown in Figure 17. The results indicate that even without high voltage imposed, the VPA will still be affected and the timewalk correction will have large error. These results mean that the

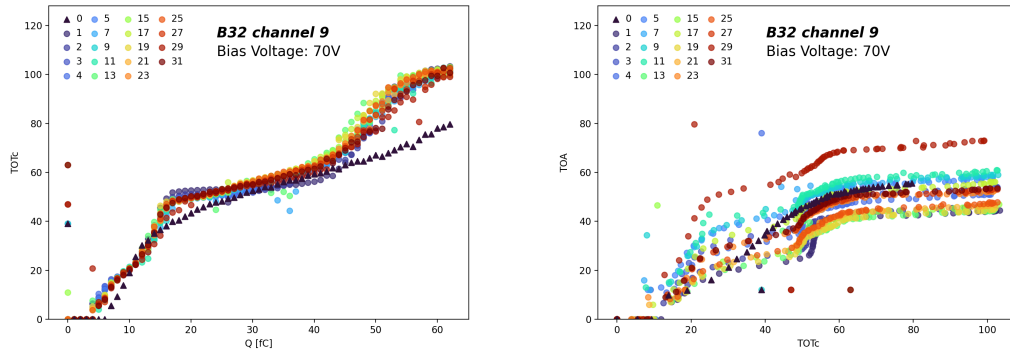


Figure 16: B32 channel 9 test result of TOTc v.s. Q (left) and TOA v.s. TOTc (right) with different number of wires, 70V bias voltage imposed (except for 0 wire that have no voltage). Different colors stand for results of different number of wires connected.

main reason for the discontinuities of VPA is not the electric fields generated by the HV wires. Additionally, in some channels, imposing high voltage will give a more stable TOT readout value at large Q, but not a common case for all channels, so it is considered as a coincidence.

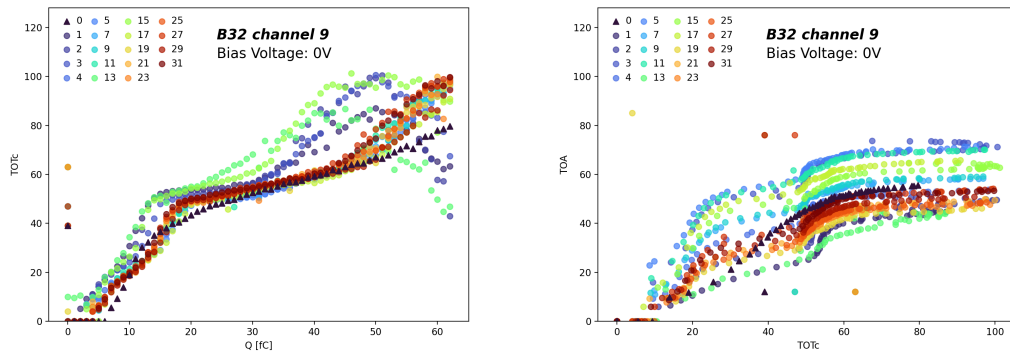


Figure 17: B32 channel 9 test result of TOT v.s. Q (left) and TOA v.s. TOT (right) with different number of wires, no bias voltage imposed. Different colors stand for results of different number of wires connected.

Other channels of B32 shows the similar results. Figure 18 shows the results of channel 10. The y-axis is the TOTc readout value of different number of wires divided by the TOTc readout value of 0 wire. It also shows that the amplifier is affected mostly when the injected electric charges are around 30fC.

Figure 19 shows the derivatives of TOA-TOTc curve. The left plot is B32 channel 10 test result of TOA v.s. TOTc, the measured values are in dot and the solid line is the fitted curve using B-Spline function. The right plot is the derivatives of the fitted curve, which can be considered as the reflection of timewalk correction uncertainty with the assumption that the TOTc

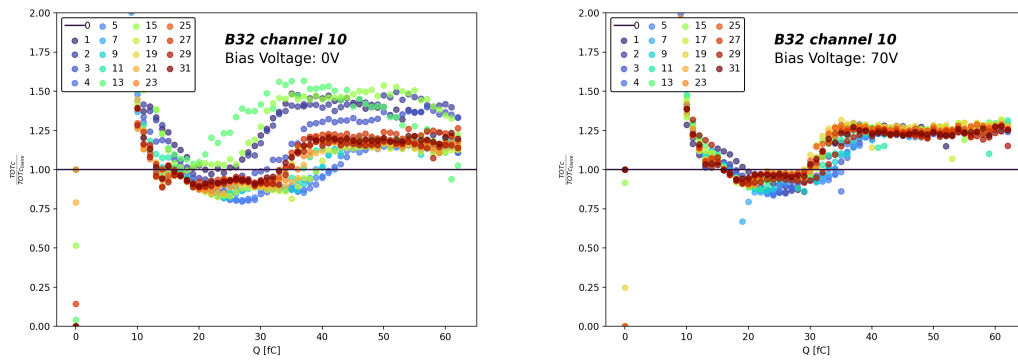


Figure 18: B32 channel 10 test result of TOT divided by TOT value of 0 wires. The left plot is without high voltage imposed and the right one is with 70V. Different colors stand for results of different number of wires connected.

measurement have a consistent uncertainty. Figure 20 are the results of channel 10 but without bias voltage imposed on the module. As the plots show, as long as the wires are connected even without bias voltage imposed, the performance of time calibration will suffer. From these plots, it can be concluded that the HV wire itself will bring the time calibration unstable and large uncertainty.

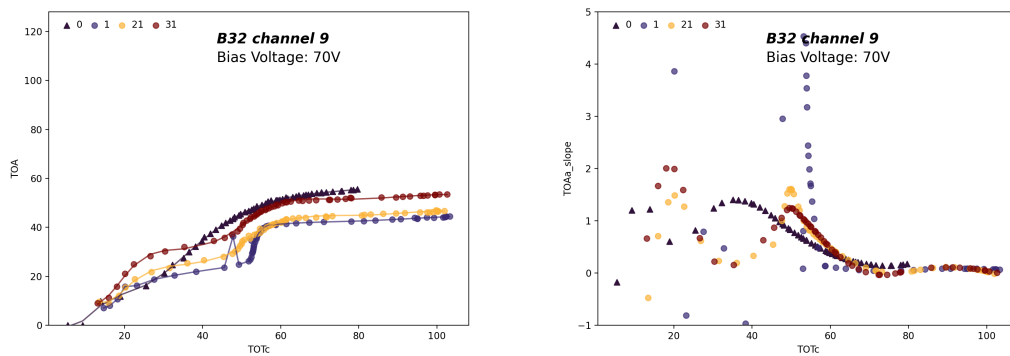


Figure 19: Left: B32 channel 9 test result of TOA v.s. TOTc, the measured values are in dot and the solid line is the fitted curve using B-Spline. The left plot the derivatives calculated with the fitted curve. These tests are done with 70V bias voltage imposed (except for 0 wire that have no voltage). Different colors stand for results of different number of wires connected.

IB03

The IB03 is another selected boards for testing the VPA channels. It also have an ALTIROC1_v3 module on it and initially have 20 HV wires bonded, evenly connected to the HV pad. TOA

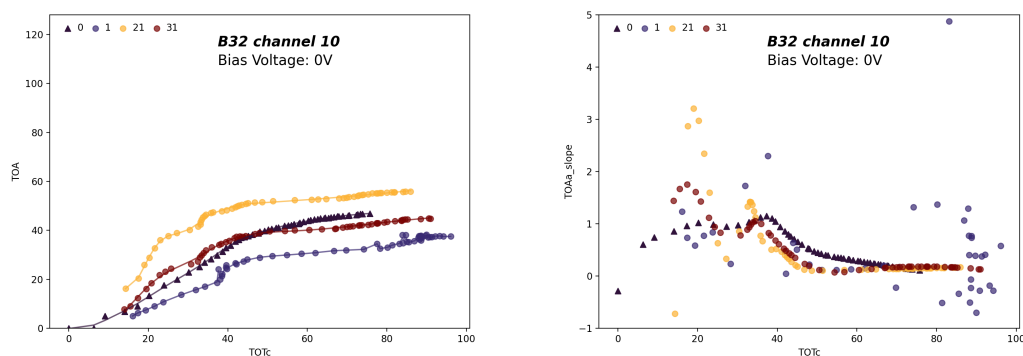


Figure 20: Left: B32 channel 10 test result of TOA v.s. TOTc, the measured values are in dot and the solid line is the fitted curve using B-Spline. The left plot the derivatives calculated with the fitted curve. These tests are done without bias voltage imposed. Different colors stand for results of different number of wires connected.

delay test and TOT width test using internal pulser and external pulser are done to ensure the function of this test board. Unluckily, only the last column of the module is working properly due to the poor bump-bonding.

Figure 21 shows the test results of channel 22. The left plot is the TOTc-Q curve with 70V high voltage imposed and the right plot is the TOA-TOTc curve. The results are similar to those of B32, there is a flat platform at Q around 20fC and the TOA-TOTc curve have some discontinuities when TOTc readout value is around 40.

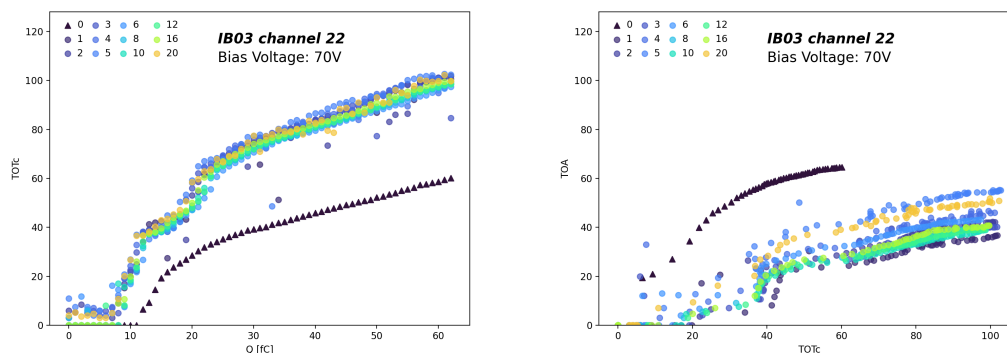


Figure 21: IB03 channel 22 test result of TOTc v.s. Q (left) and TOA v.s. TOTc (right) with different number of wires, 70V bias voltage imposed (except for 0 wire that have no voltage). Different colors stand for results of different number of wires connected.

Figure 22 shows the results of TOA v.s. TOT with B-Spline fit and the derivatives of the fitted curve, which are similar to the B32 test results. Having HV wires will bring larger fluctuation to the derivatives, which means larger error for timewalk correction.

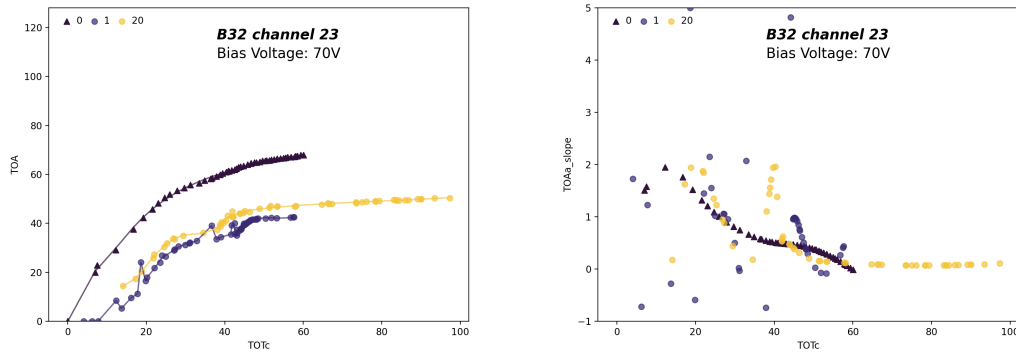


Figure 22: IB03 channel 23 test result of TOA v.s. TOT (left) with B-Spline fit and the derivatives of the fitted curve (right) with different number of wires, 70V bias voltage imposed (except for 0 wire that have no voltage). Different colors stand for results of different number of wires connected.

From these results and the results of B32, it can be concluded that the HV wires will have a significant impact on the performance of channels that uses VPA, regardless the number of the HV wires and whether the bias voltage is imposed. The number of HV wires has some minor effect, the performance of timing calibration will be slightly better when increasing the number of HV wires. However, the improvement is small and there will always be large difference with the case when there is no HV wires connected. The amplitude of high voltage also has a minor effect. Discontinuities in time calibration exists in both 70V bias voltage and 0 bias voltage, as long as the HV wires are connected. It indicates that the effect may not due to the electric field brought by the wires.

TZ Preamplifier

From the previously results, it can be seen that the TZ preamplifier seem to be hardly affected by the HV wires. However, the drawback of using TZ preamplifier is that the TOTc readout is insensitive to the injected electric quantities. When the Q is increased to larger than 20 fC, the TOTc readout will almost remain same.

One test board is selected to test the channels using TZ preamplifier: IB06. This board have ALTIROC1_v3b on it, which have 15 TZ channels and 10 VPA channels. There are 20 HV wires connected initially. The regular tests show that the VPA channels are not working properly, so only the TZ channels are used for further test. Additionally, the TOA TDC of this

module is broken so only the TOTc-Q curve can be used.

The selected timewalk test results are shown in Figure 23. The left plot is channel 11 test results with 20 HV wires and imposing different amplitude of bias voltage, which indicate that the performance of TOT measurement is hardly affected by the amplitude of bias voltage for TZ channels. The right plot is channel 4 test results with different number of HV wires, 70V bias voltage imposed. This plot shows that the number of HV wires have mild effect on the TOT measurements of TZ channels. In general, the TZ channels work consistently with or without HV wires.

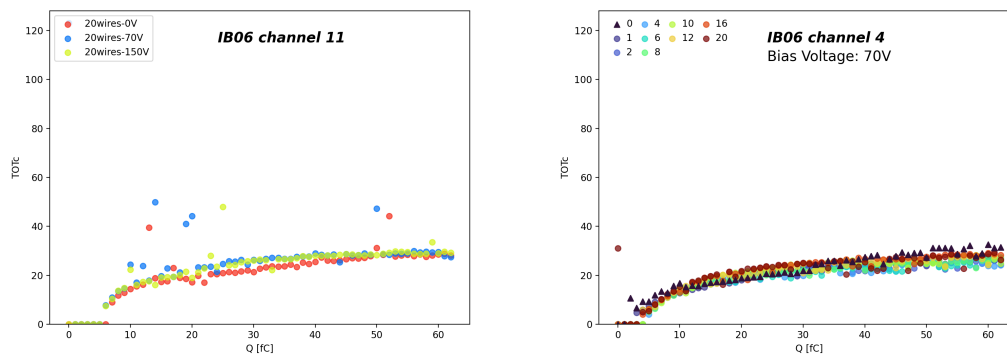


Figure 23: IB03 test result of TOTc v.s. Q. Left: channel 11 test results with 20 HV wires and imposing different amplitude of bias voltage. Different colors stand for different voltage amplitude. Right: channel 4 test results with different number of HV wires, 70V bias voltage imposed. Different colors stand for results of different number of wires connected.

Conclusion

Given all the test results shown above in this study, it can be confirmed that the HV wires have different degrees of effect on two kinds of preamplifiers. For channels using VPA, the HV wires will have a significant effect on the performance of timing calibration, which makes the error of timewalk correction large. Moreover, changing number of HV wires would relieve this effect, but only with limited improvement. Having a dense number of HV wires has a slightly better performance of timing calibration than having only one HV wire. As a result, the inductance between the HV wires could be a really minor reason for this effect. Because this effect exists as long as the wire connected, even without bias voltage imposed, the electric field generated by the HV wires may also not be the reason for the effect. Changing the method of

high voltage (e.g. using conductive glue) would also hardly help and difficult to conduct in the final module assembly. By contrast, the channels using TZ preamplifier are hardly affected by the HV wires. Thus using TZ preamplifiers seems to be the best solution to this high voltage connection problem. However, TZ preamplifier makes TOT measurement insensitive to the size of injected charge, which will also bring some error to the timewalk correction. Given the results from this study, the later prototypes of ALTIROC manufactured (ALTIROC3) are using the TZ preamplifiers.

$VH(\rightarrow b\bar{b}, c\bar{c})$ Analysis Detail

Kinematic Fit Transfer function

The distribution of $p_T(OneMu)/p_T(TruthWZ)$ (solid) and fitted transfer function (dashed) of C_T , C_L and N_{jets} in $VH(\rightarrow c\bar{c})$ 2-lepton 2+3 jets events are shown in Figure 24 and 25.

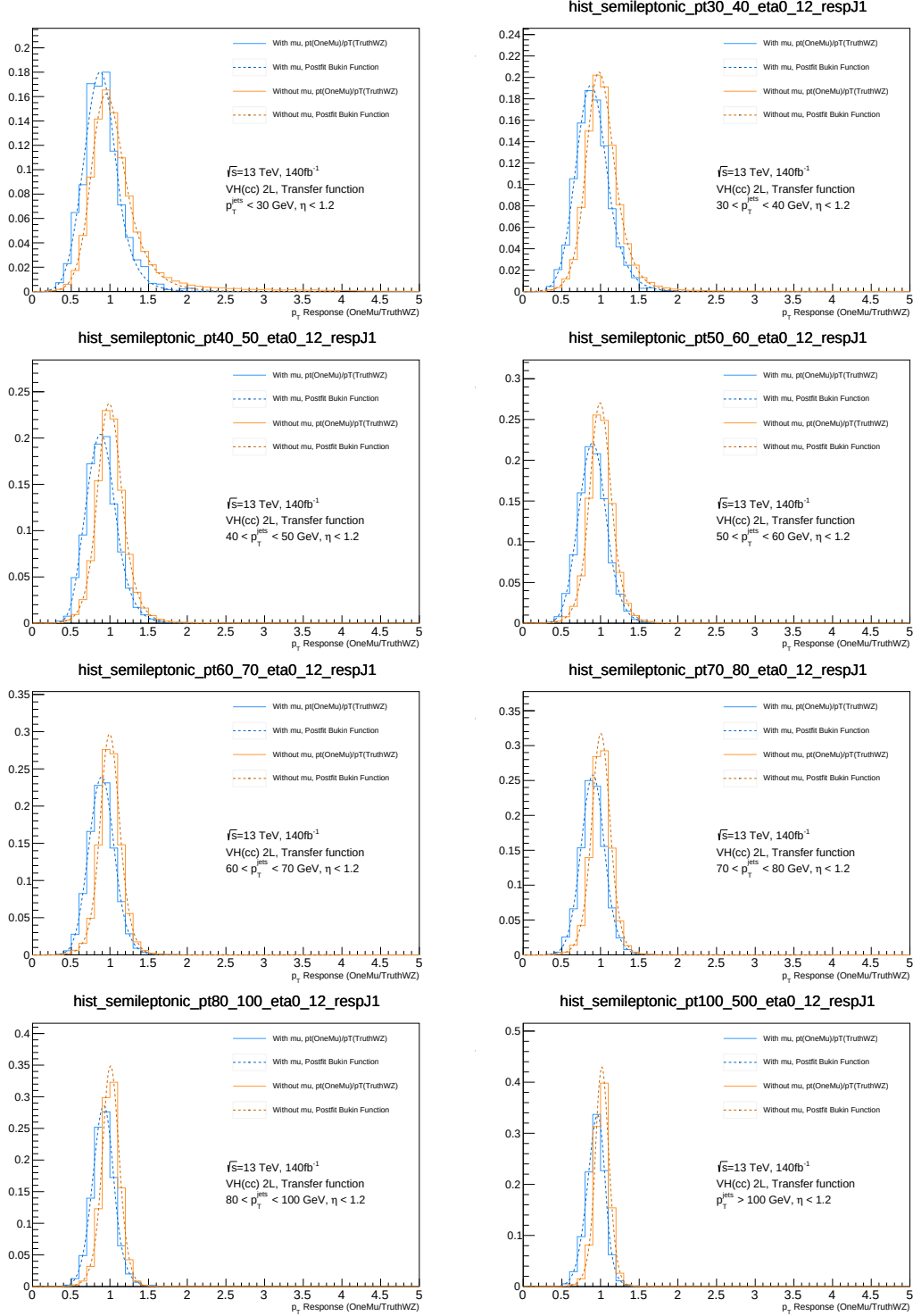


Figure 24: The distribution of $p_T(\text{OneMu})/p_T(\text{TruthWZ})$ (solid) and fitted transfer function (dashed) of C_T , C_L and N jets in $VH(\rightarrow c\bar{c})$ 2-lepton 2+3 jets events. Blue indicates the jets has a muon in its decay and orange indicates the jets without the muon. The jets are required to have $\eta < 1.2$.

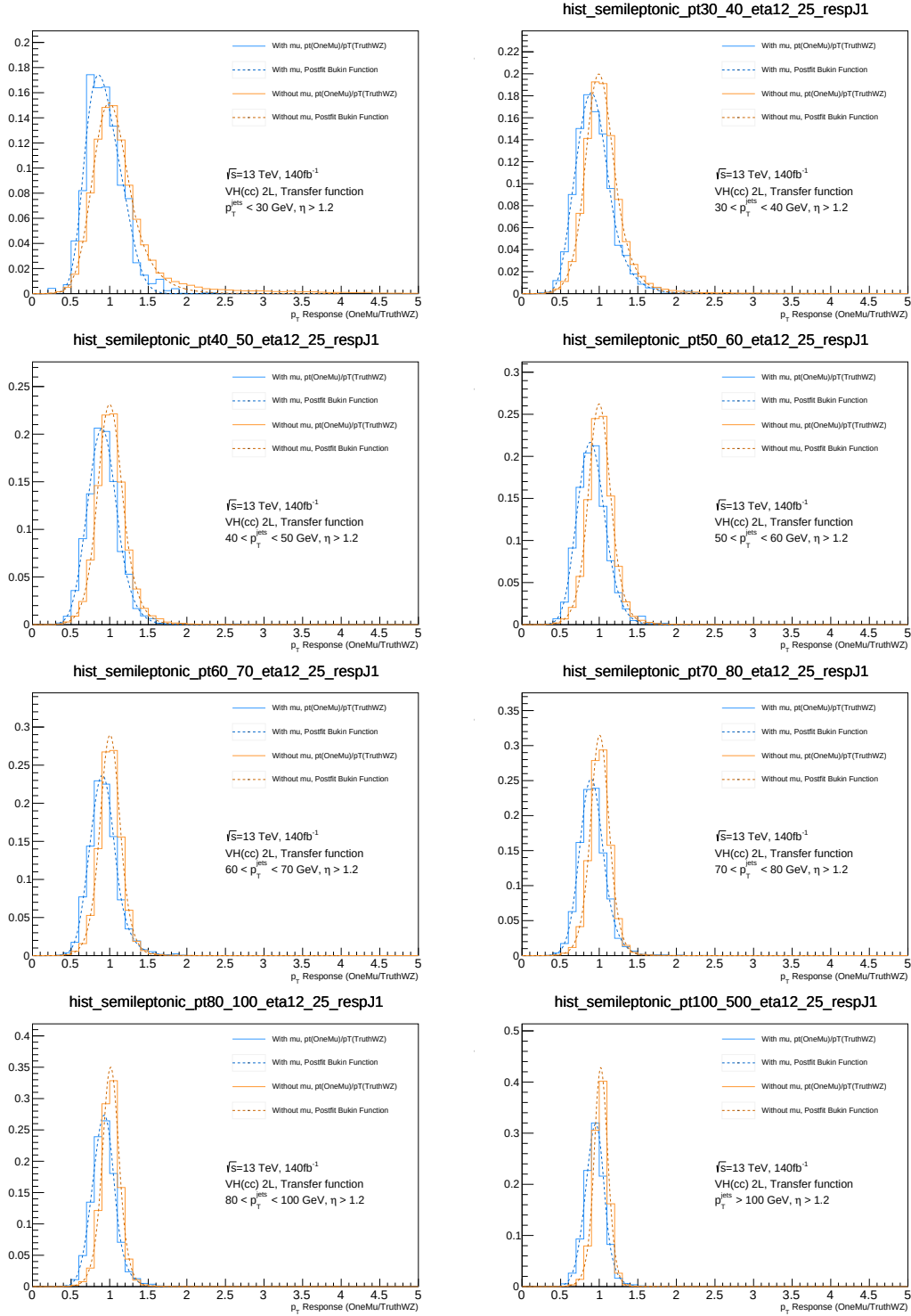


Figure 25: The distribution of $p_T(\text{OneMu})/p_T(\text{TruthWZ})$ (solid) and fitted transfer function (dashed) of C_T , C_L and N jets in $VH(\rightarrow c\bar{c})$ 2-lepton 2+3 jets events. Blue indicates the jets has a muon in its decay and orange indicates the jets without the muon. The jets are required to have $\eta > 1.2$.

$VH(\rightarrow b\bar{b}, c\bar{c})$ Post-fit Distribution

Resolved 0-lepton channel

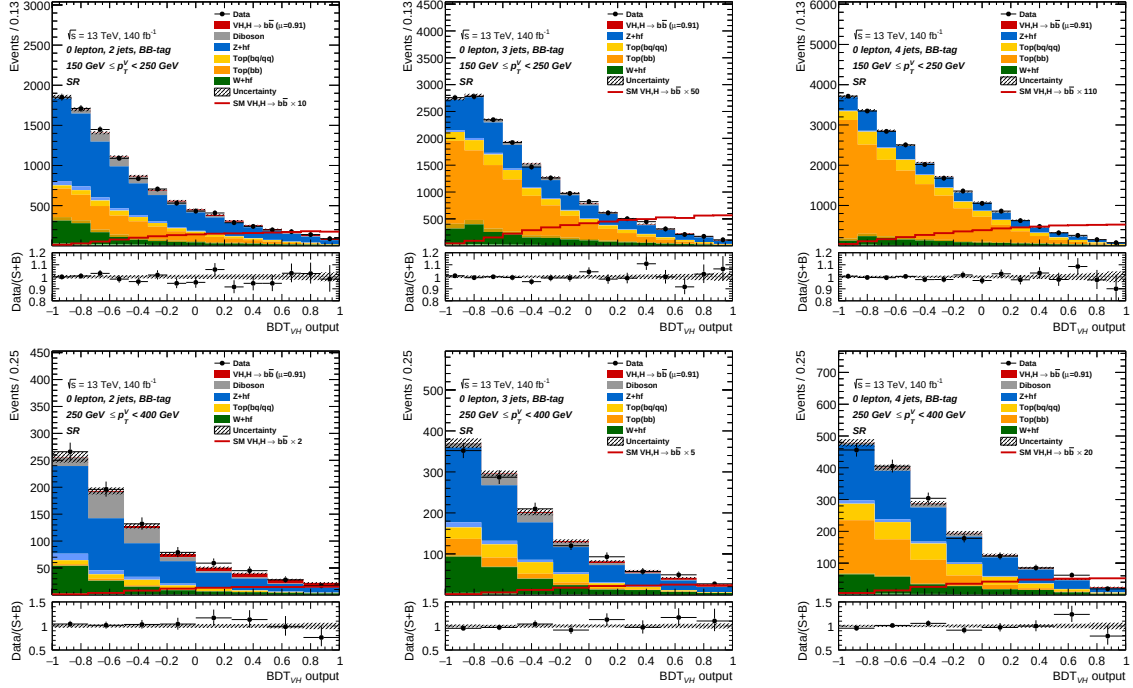


Figure 26: MVA in resolved $VH(\rightarrow b\bar{b})$ 0-lepton SR.

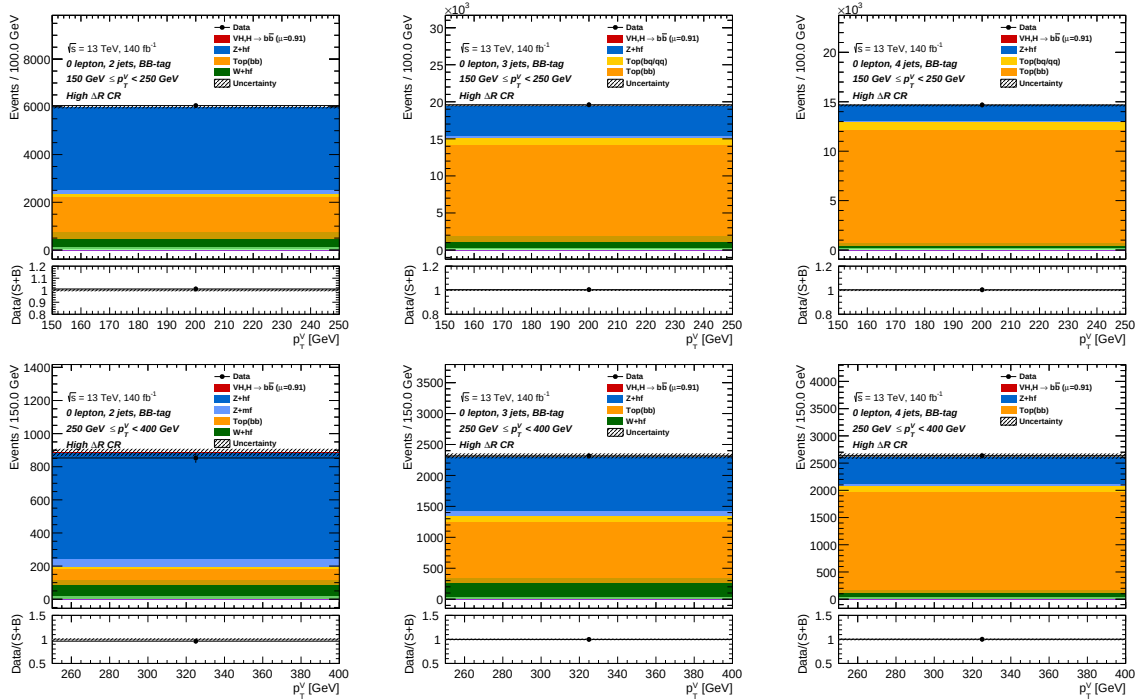


Figure 27: p_T^V in resolved $VH(\rightarrow b\bar{b})$ 0-lepton High- ΔR -CR.

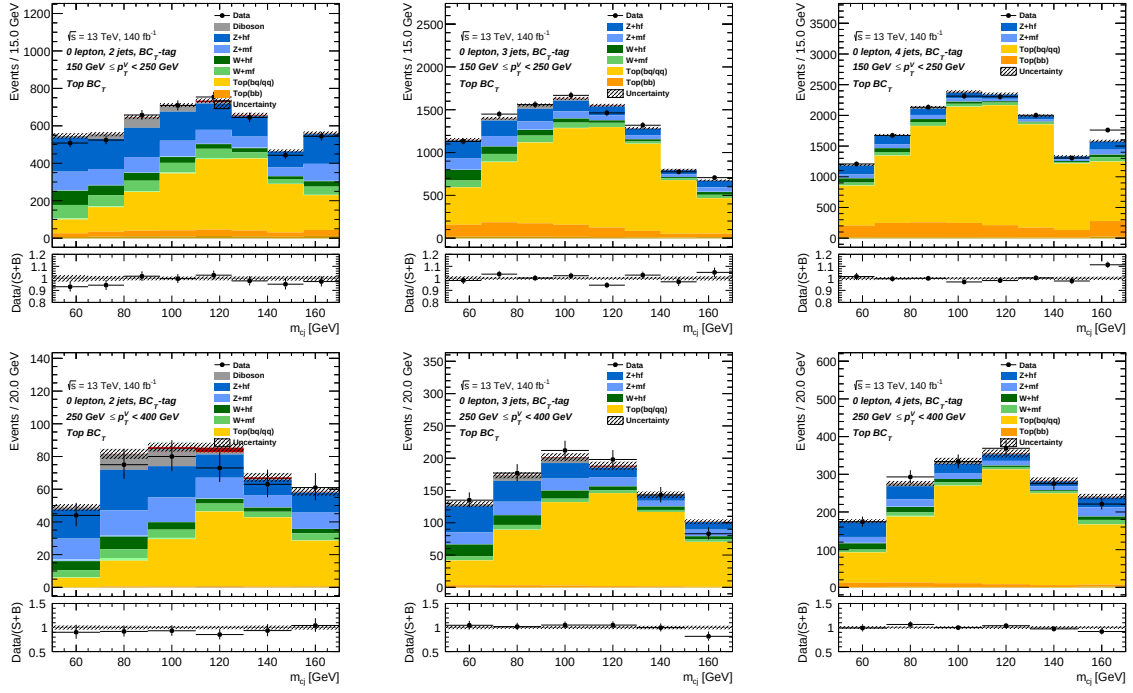


Figure 28: $m_{c\bar{j}}$ in 0-lepton topCR.

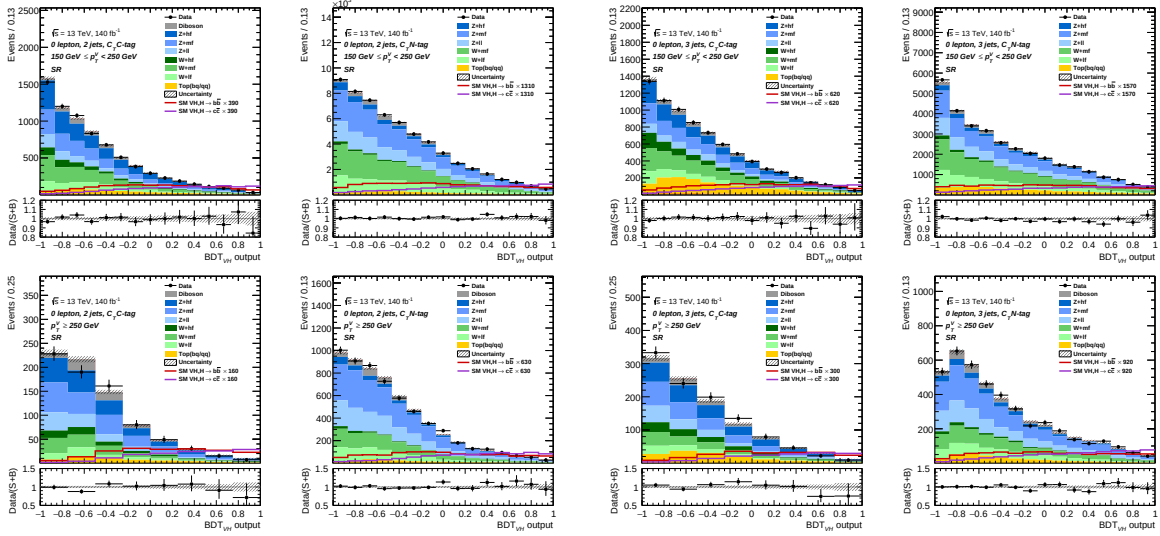


Figure 29: MVA in $VH(\rightarrow c\bar{c})$ 0-lepton SR.

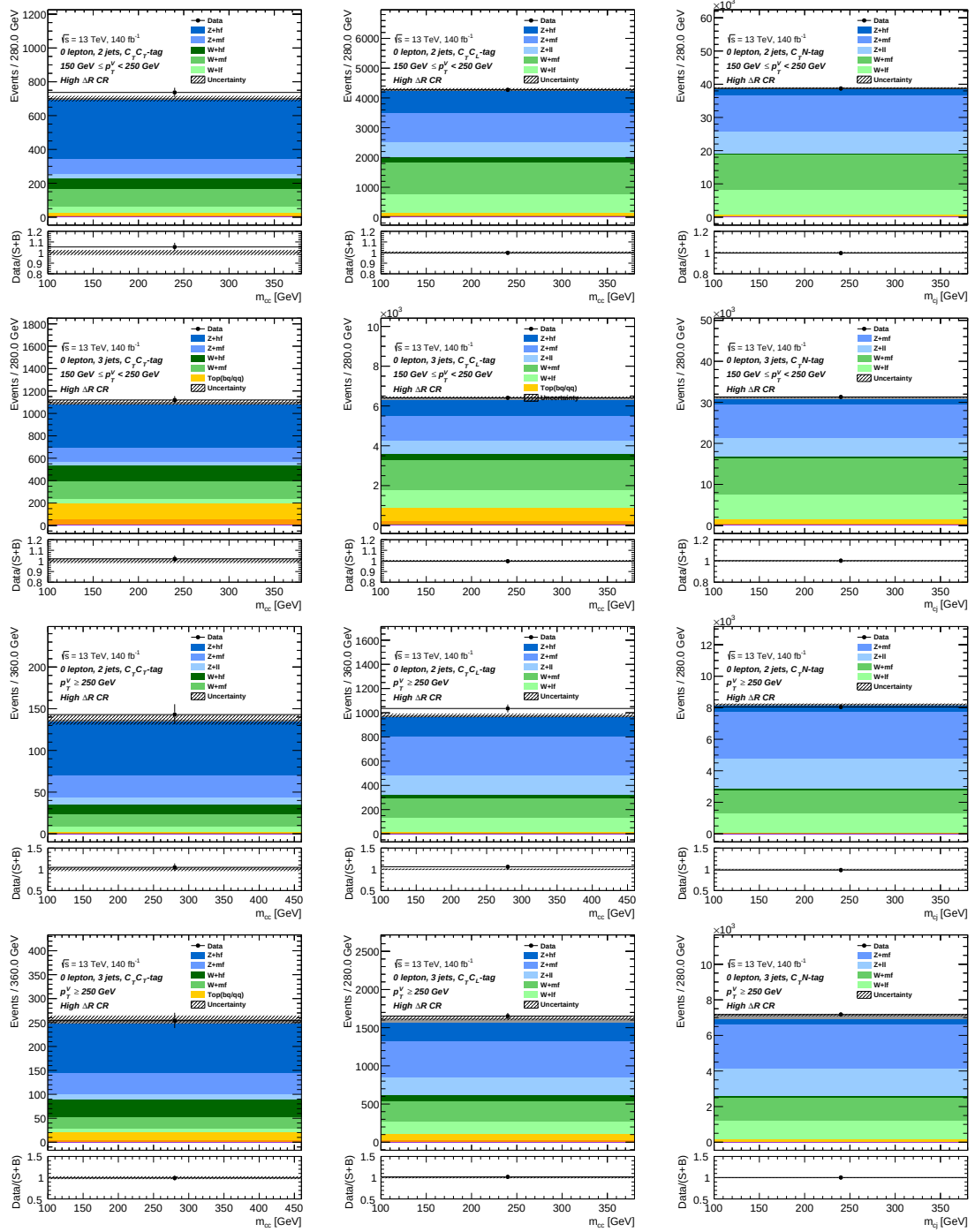


Figure 30: m_{cc} in $VH(\rightarrow c\bar{c})$ 0-lepton CRHigh.

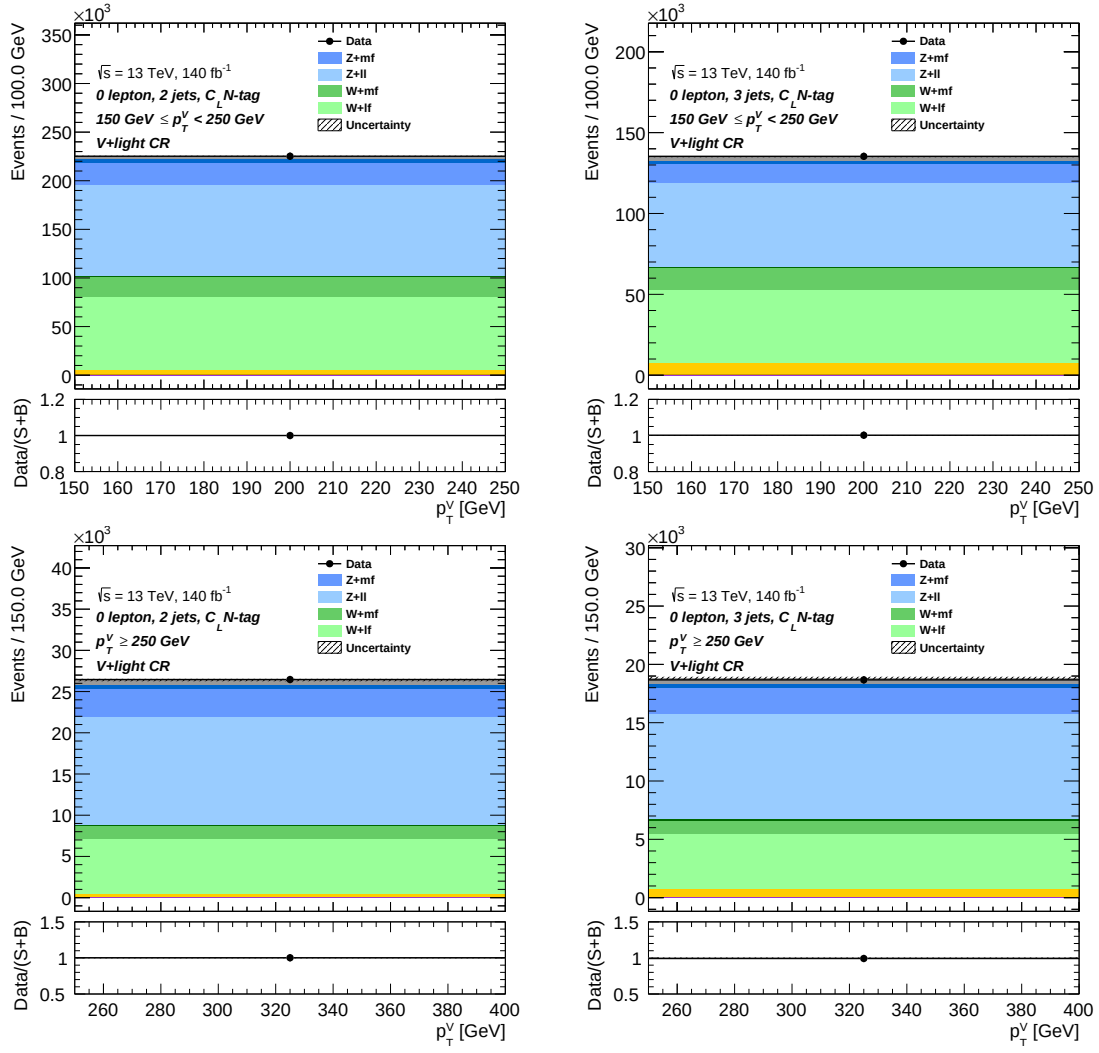


Figure 31: p_T^V in $VH(\rightarrow c\bar{c})$ 0-lepton V+l CR.

Resolved 1-lepton channel

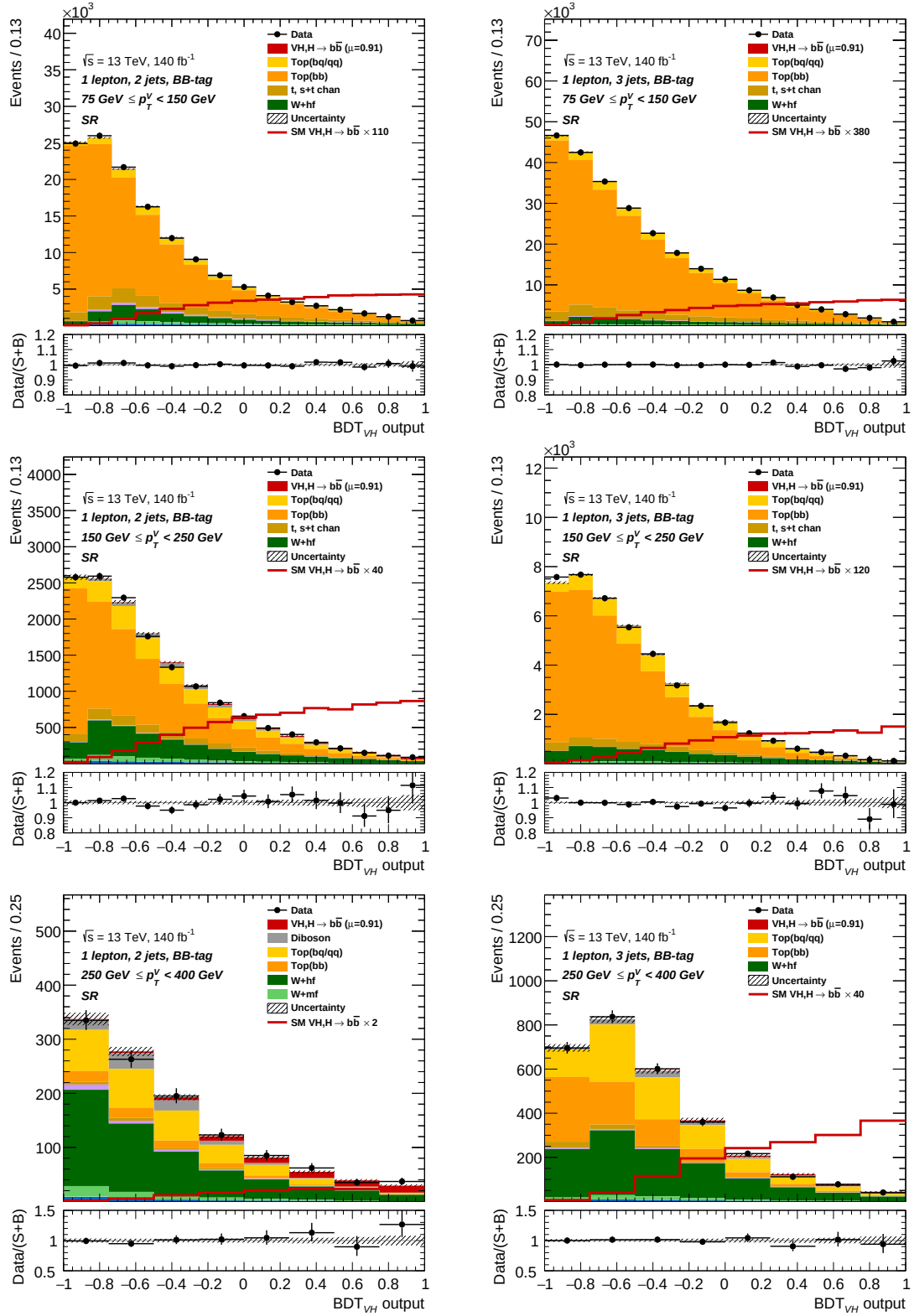


Figure 32: MVA in resolved $VH(\rightarrow b\bar{b})$ 1-lepton SR.

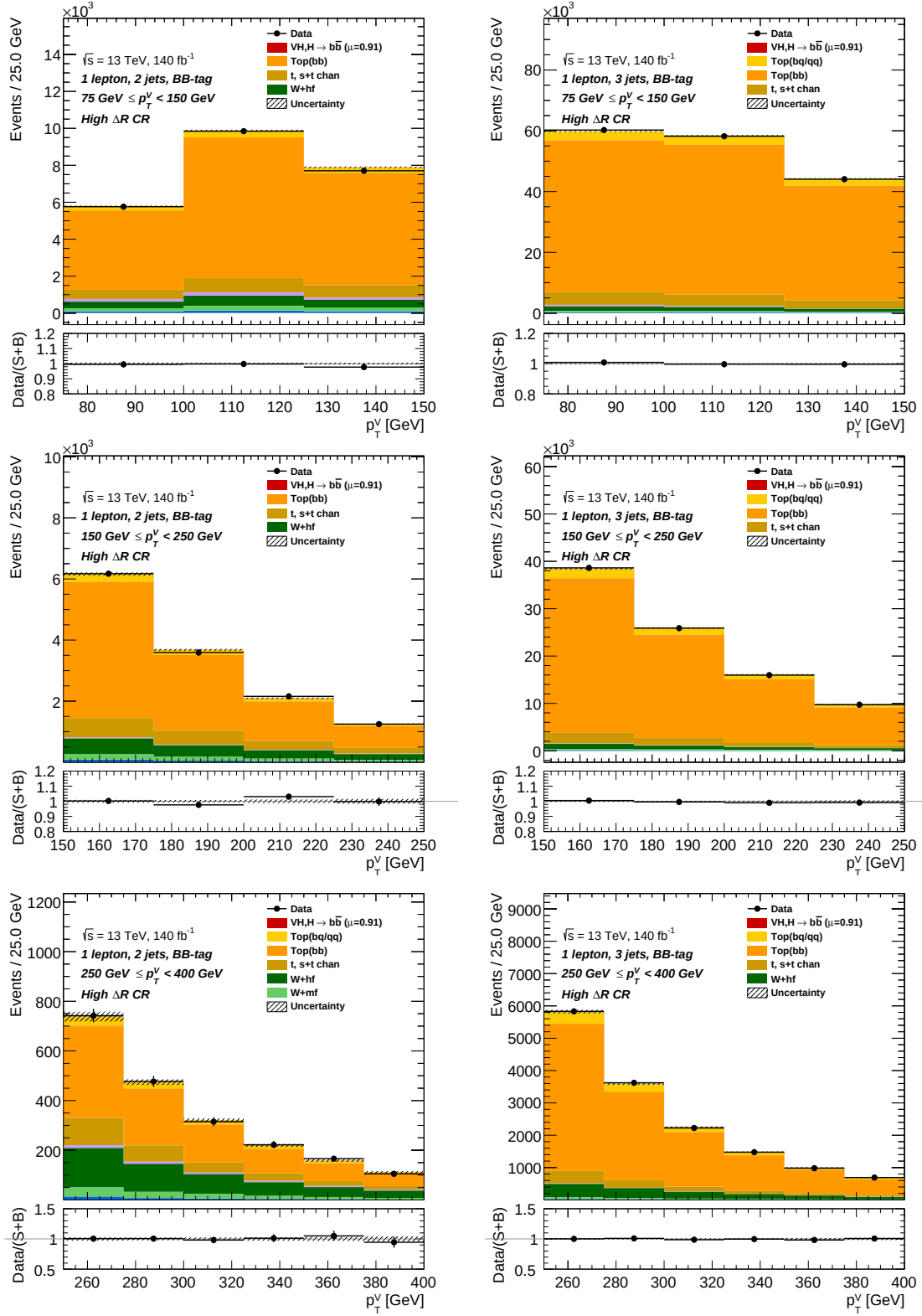


Figure 33: p_T^V in resolved $VH(\rightarrow b\bar{b})$ 1-lepton High- ΔR -CR.

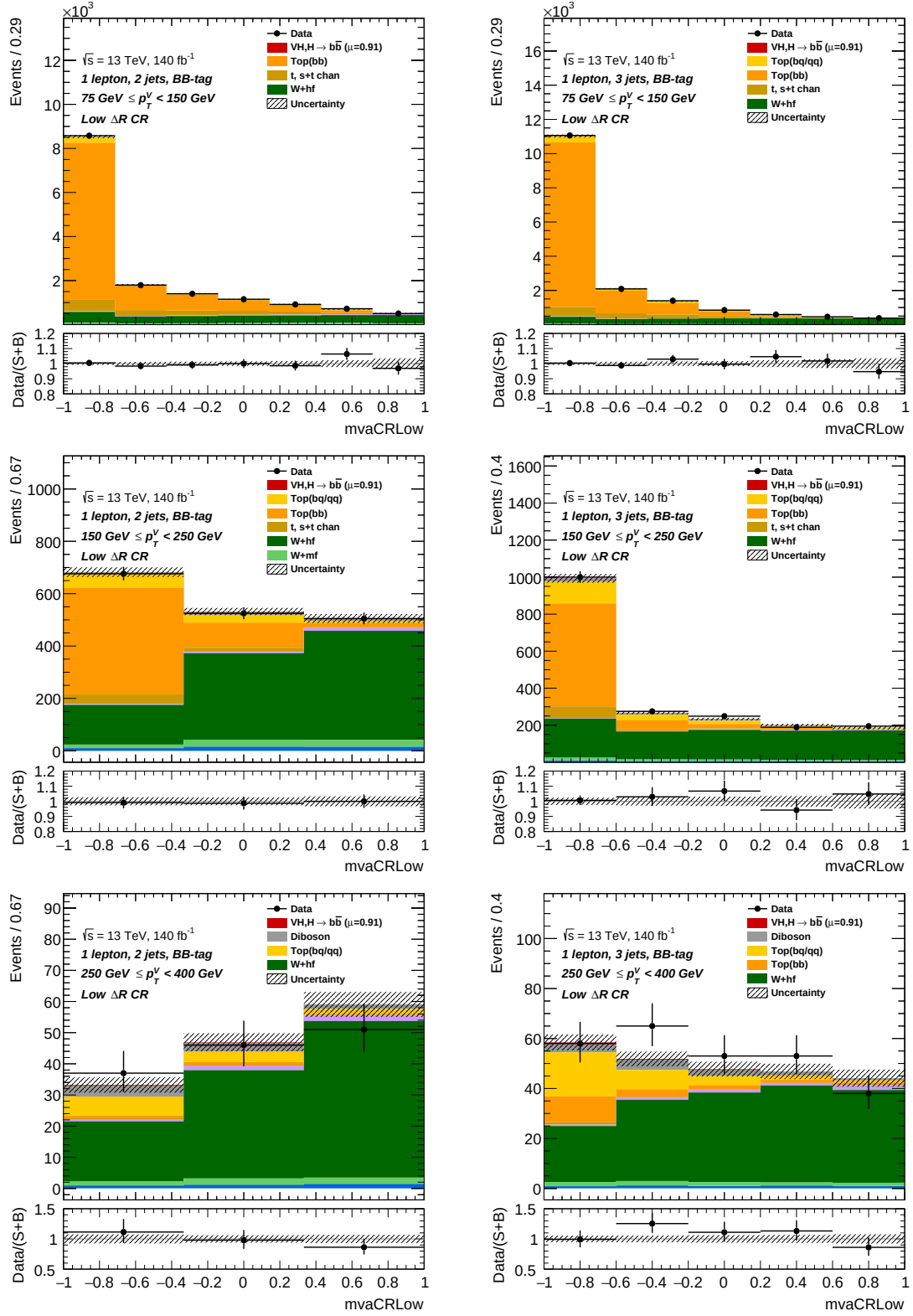


Figure 34: $m_{b\bar{b}}$ in resolved $VH(\rightarrow b\bar{b})$ 1-lepton High- ΔR -CR.

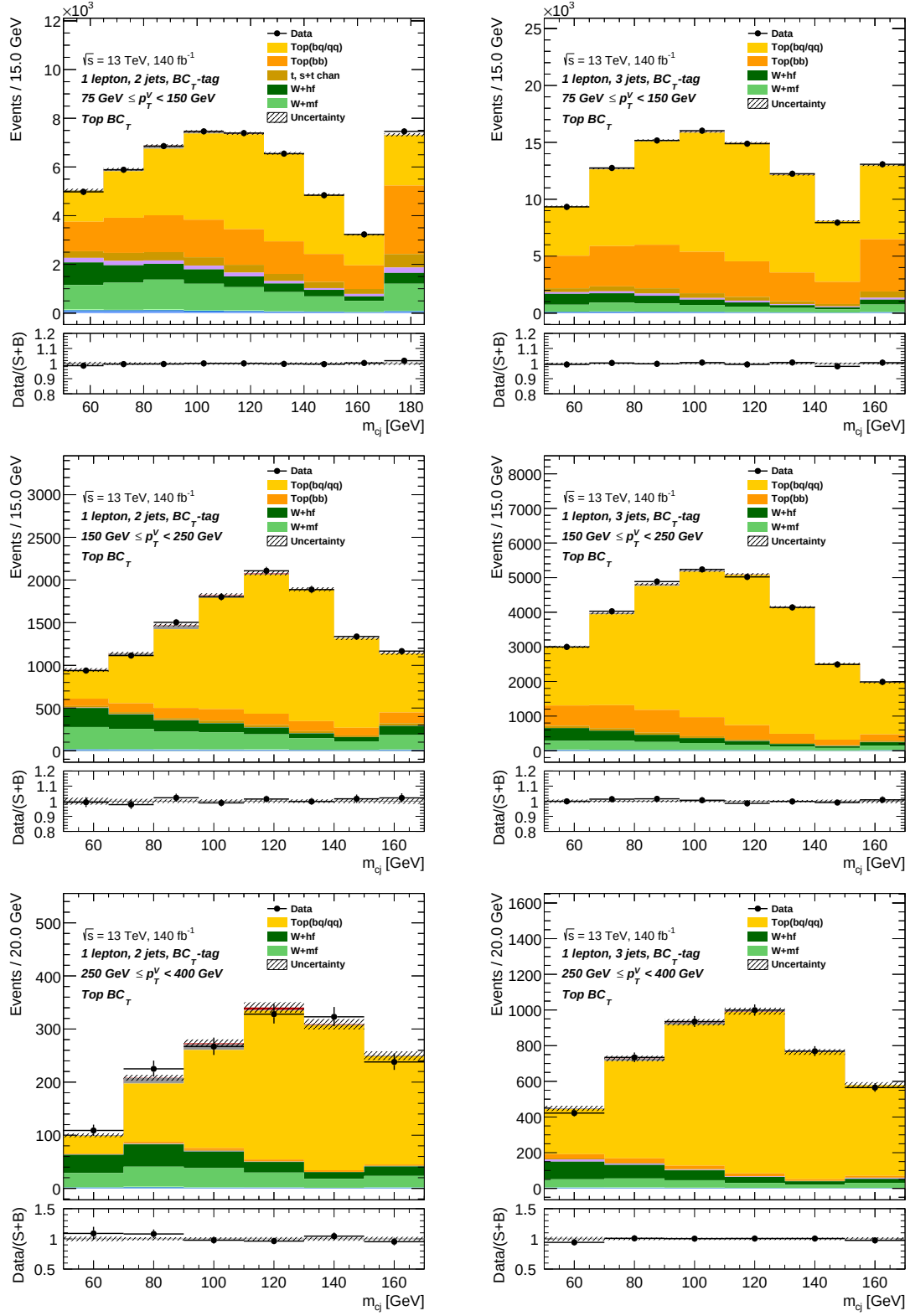


Figure 35: m_{cj} in 0-lepton topCR.

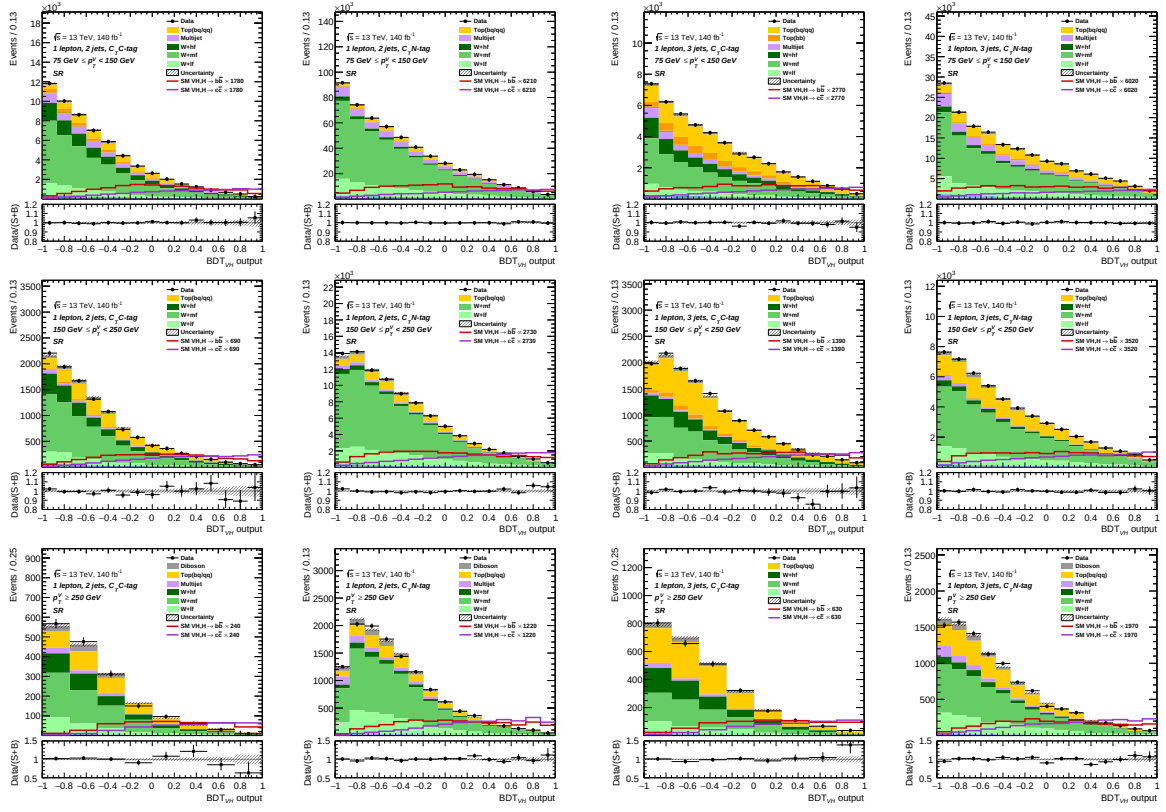


Figure 36: MVA in $VH(\rightarrow c\bar{c})$ 1-lepton SR..

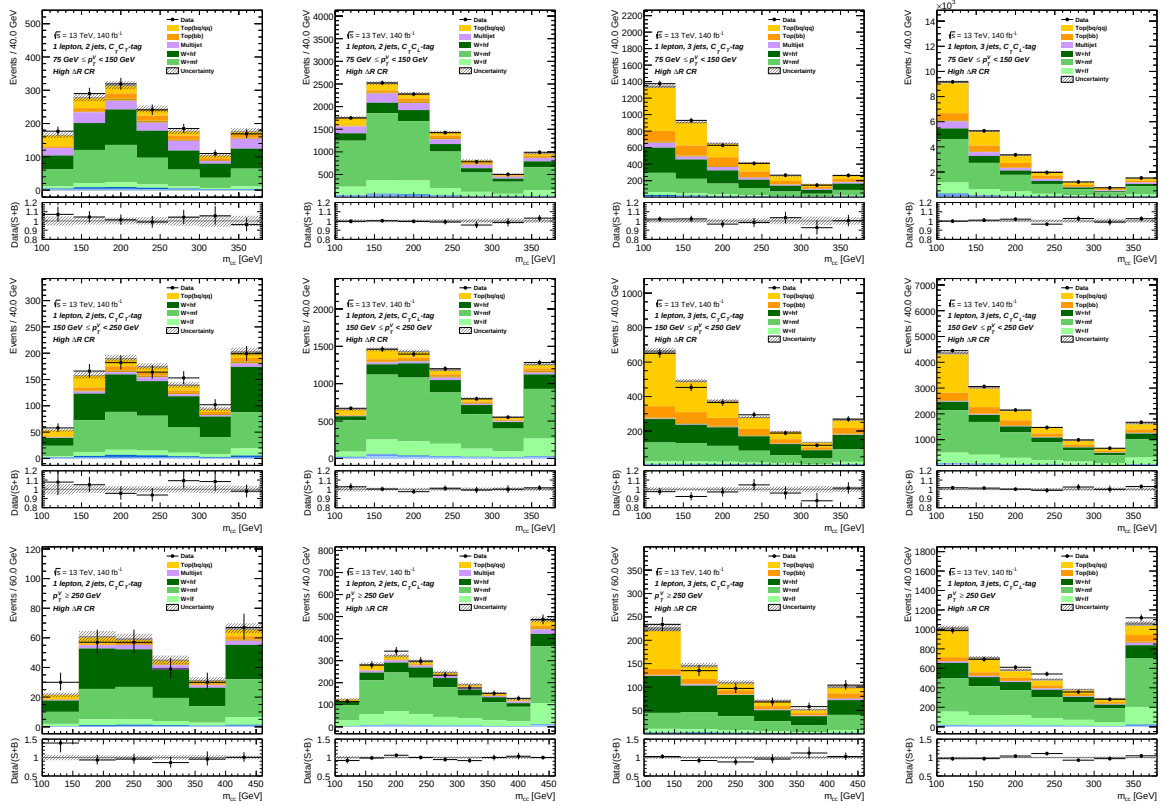


Figure 37: m_{cc} in $VHcc$ 1-lepton CRHigh, 2 c -tag regions..

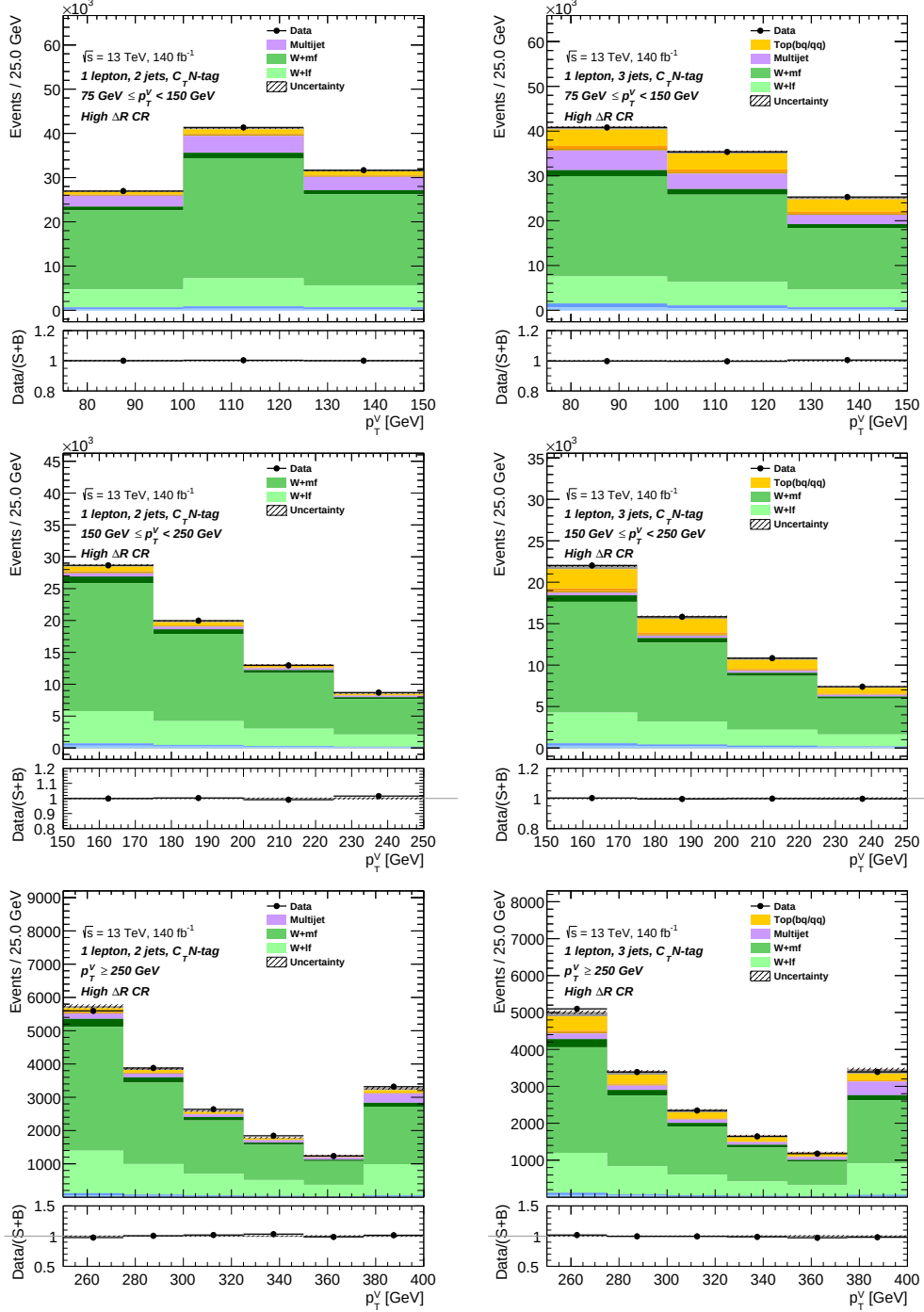


Figure 38: p_T^V in VHcc 1-lepton CRHigh, 1 c -tag regions.

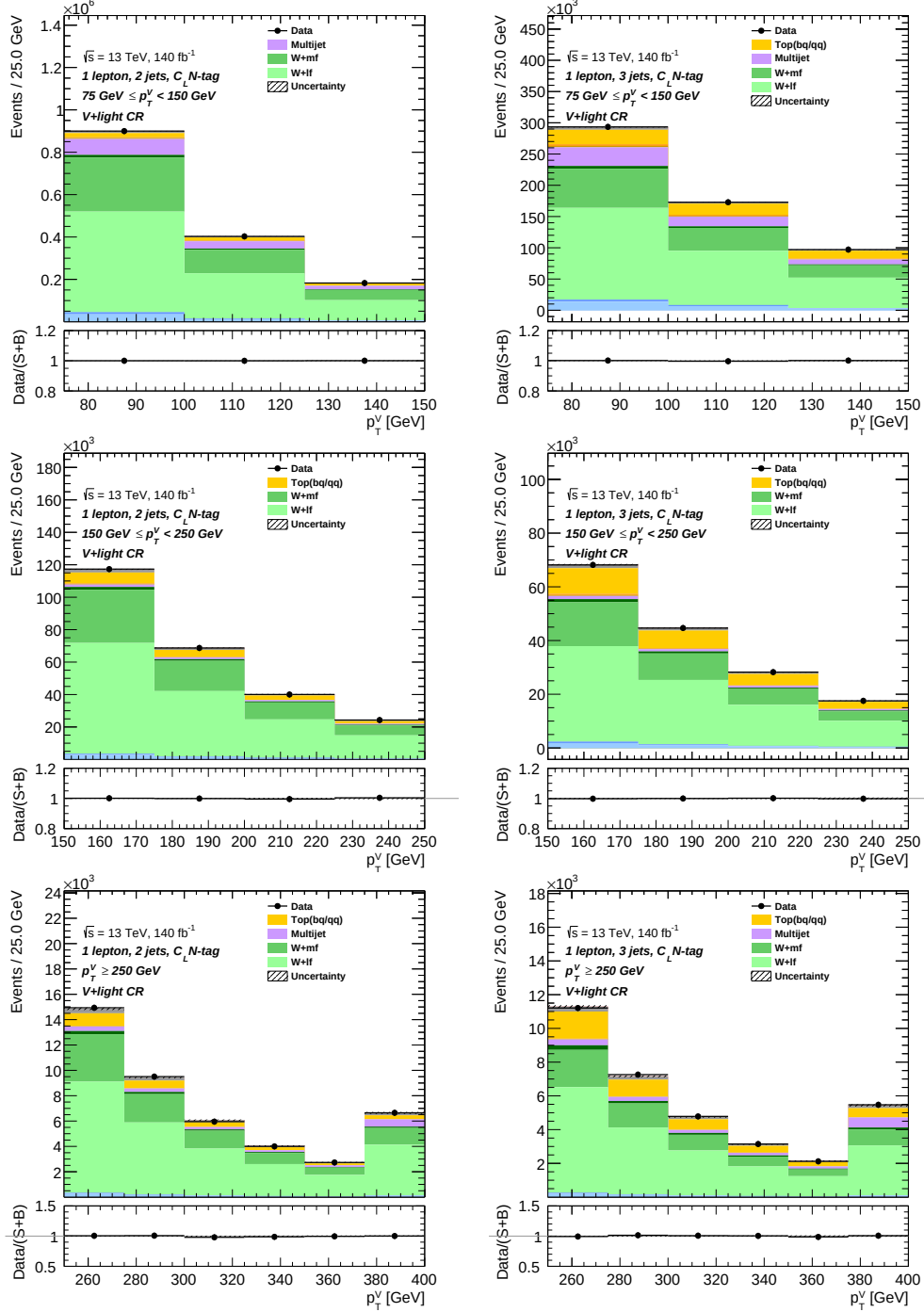


Figure 39: p_T^V in VHcc 1-lepton V+l CR.

Resolved 2-lepton channel

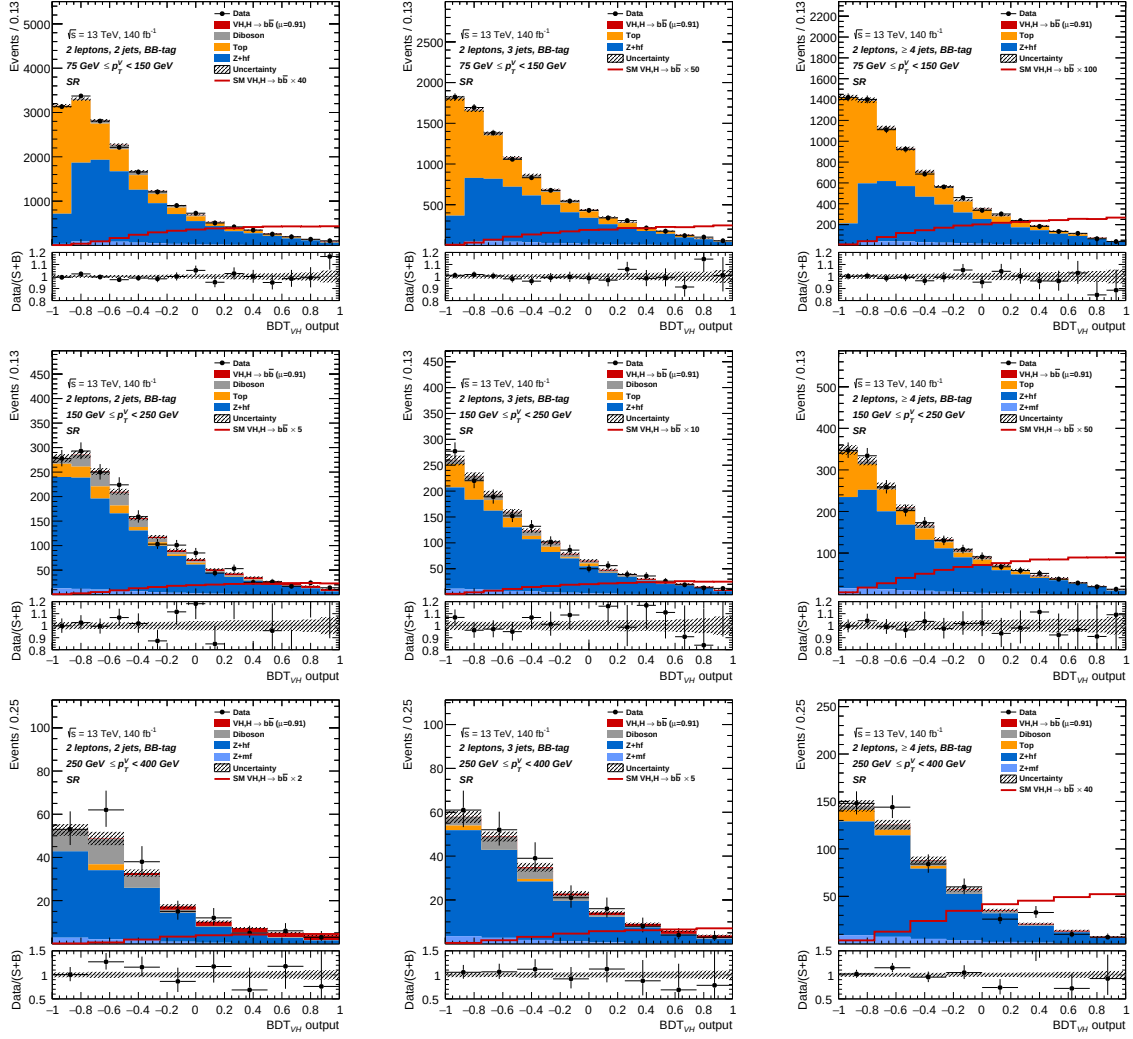


Figure 40: MVA in resolved $VHbb$ 2-lepton SR.

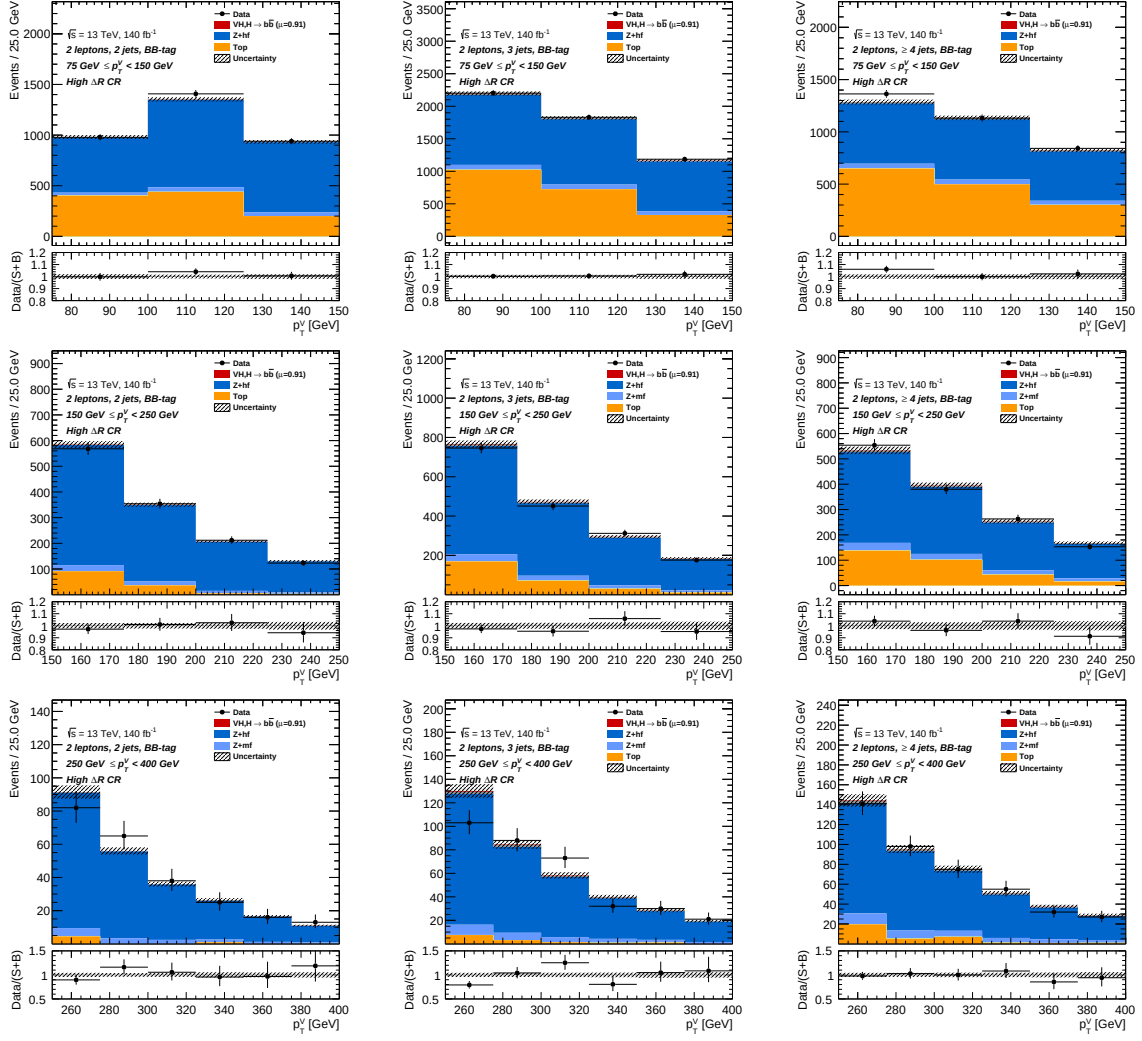


Figure 41: p_T^V in resolved $VHbb$ 2-lepton High- ΔR -CR.

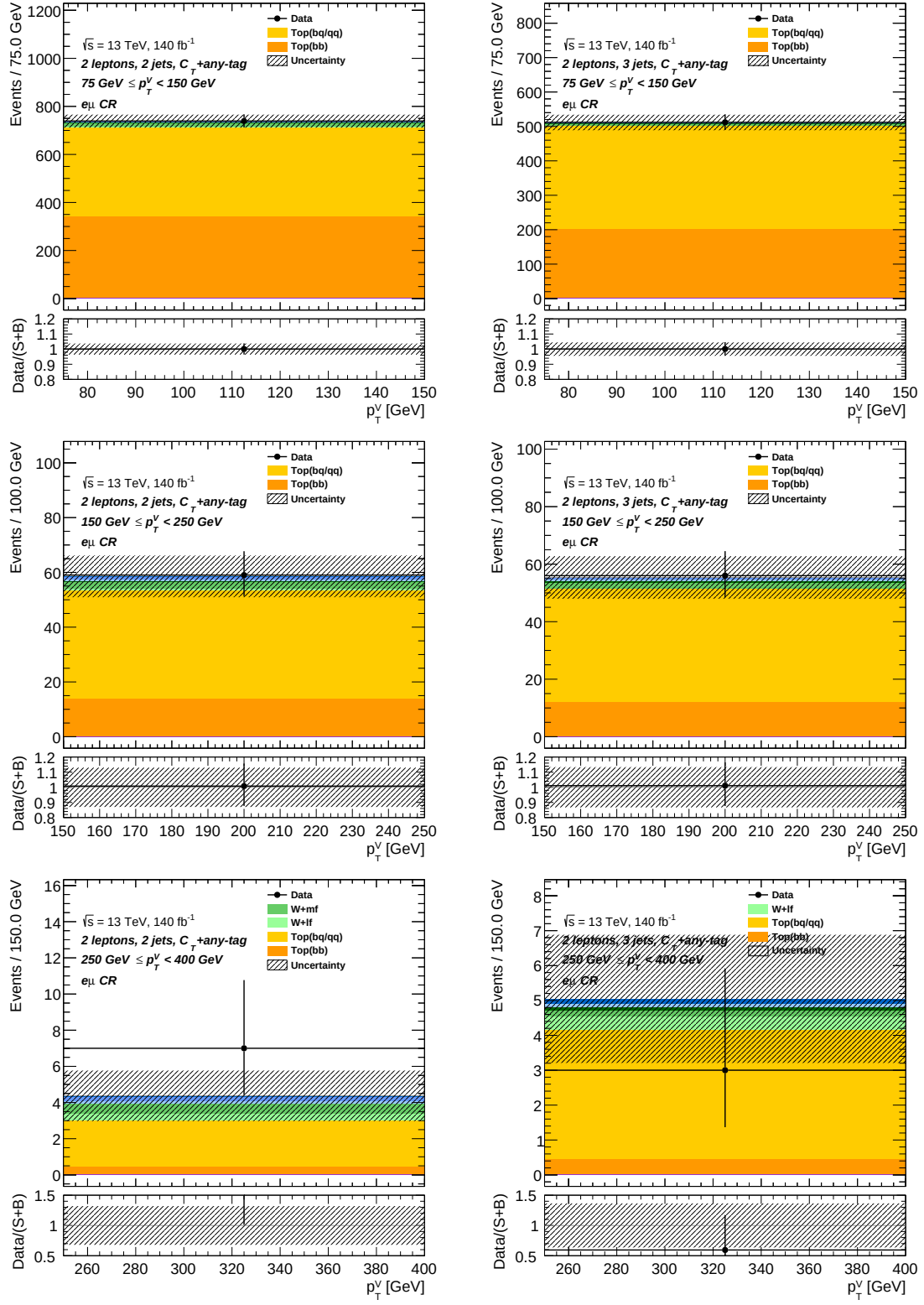


Figure 42: p_T^V in 2-lepton top $e\mu$ CR.

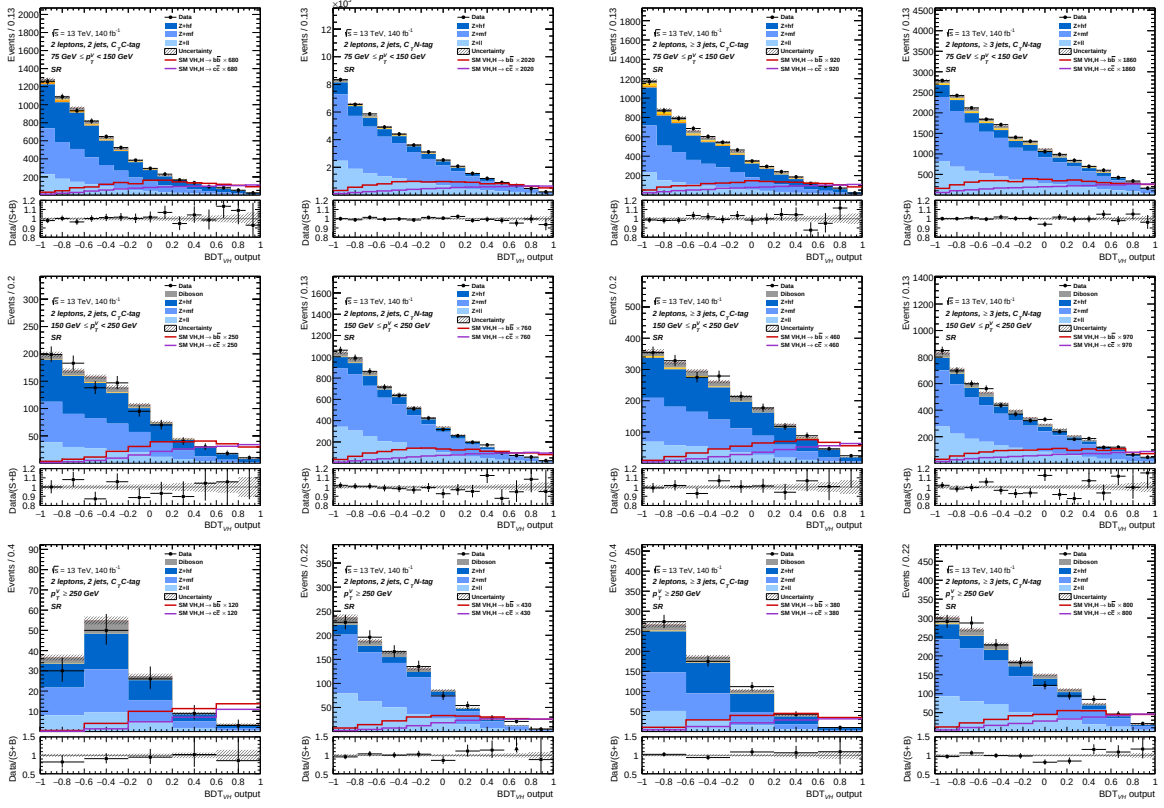


Figure 43: MVA in VHcc 12-lepton SR.

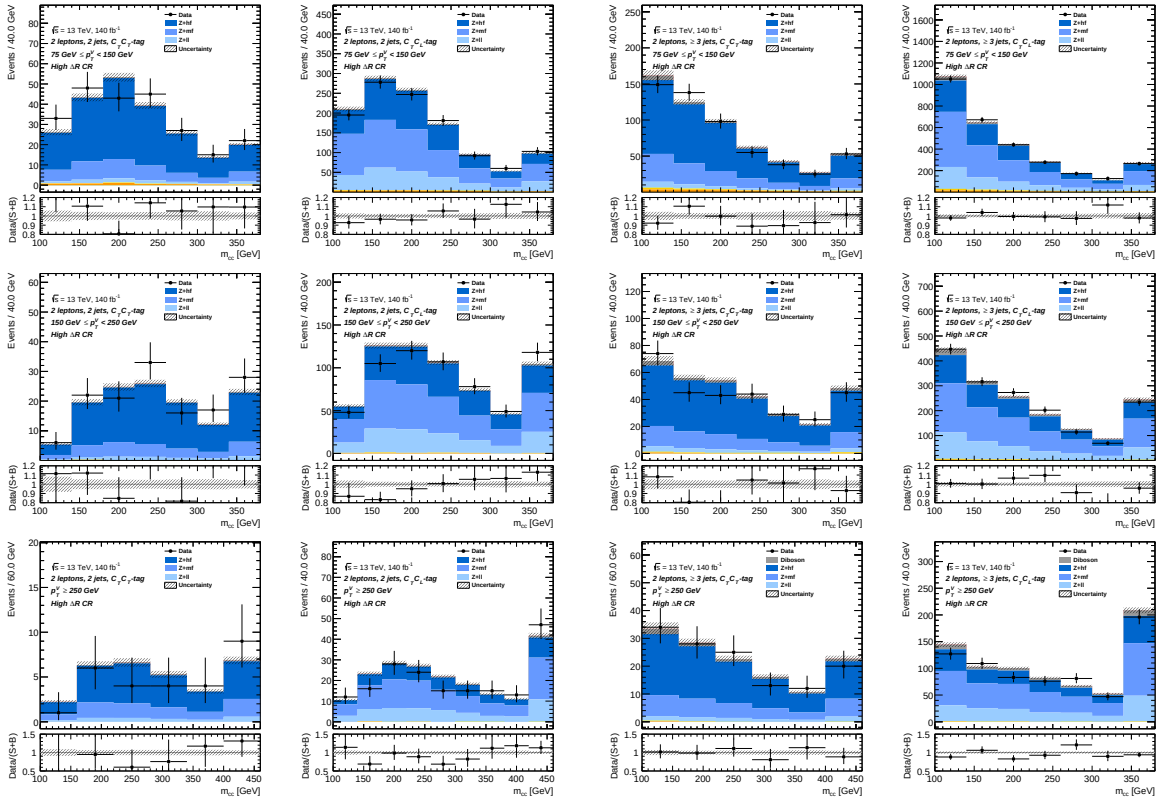


Figure 44: m_{cc} in VHcc 2-lepton CRHigh.

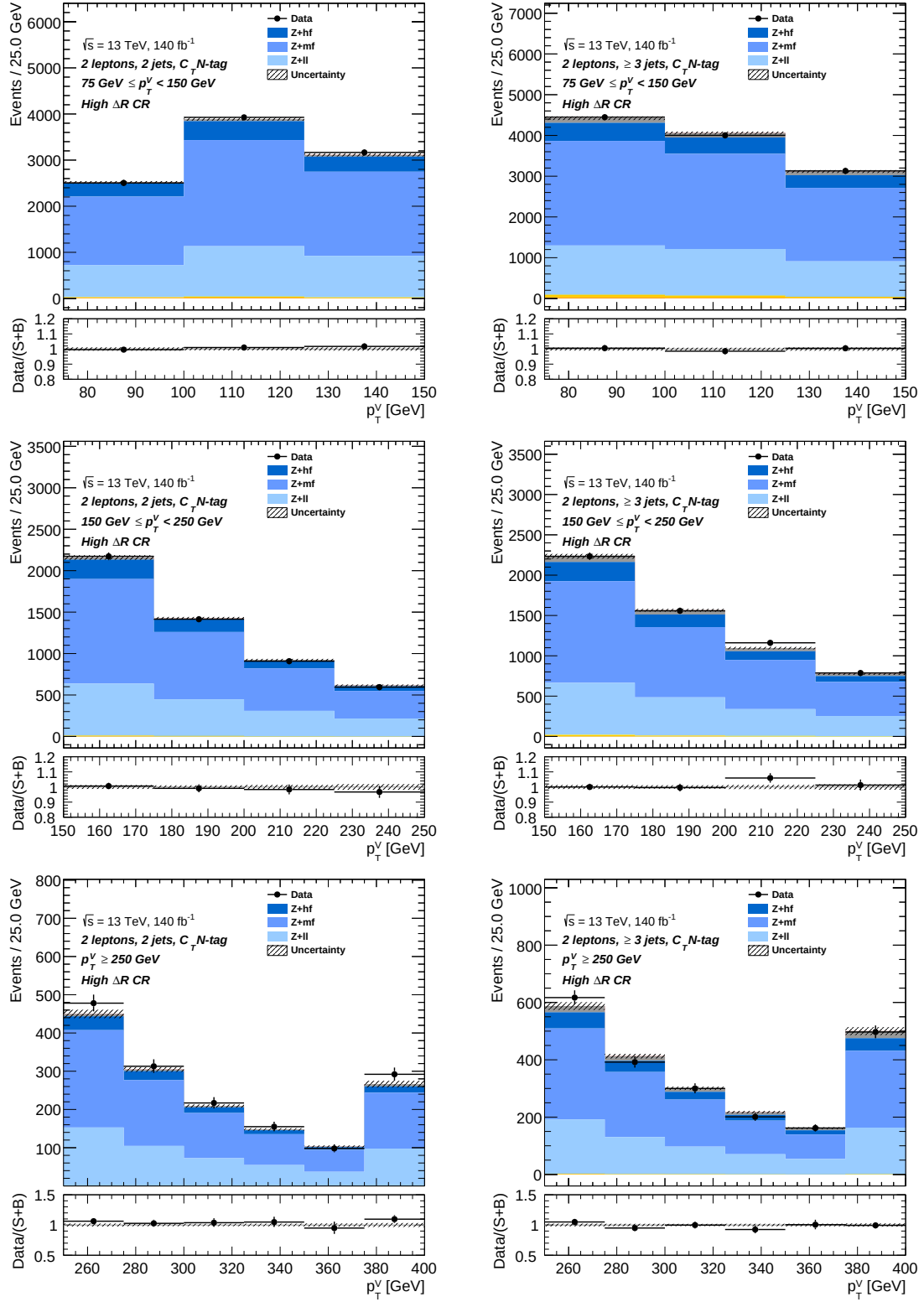


Figure 45: p_T^V in $VHcc$ 2-lepton CRHigh.

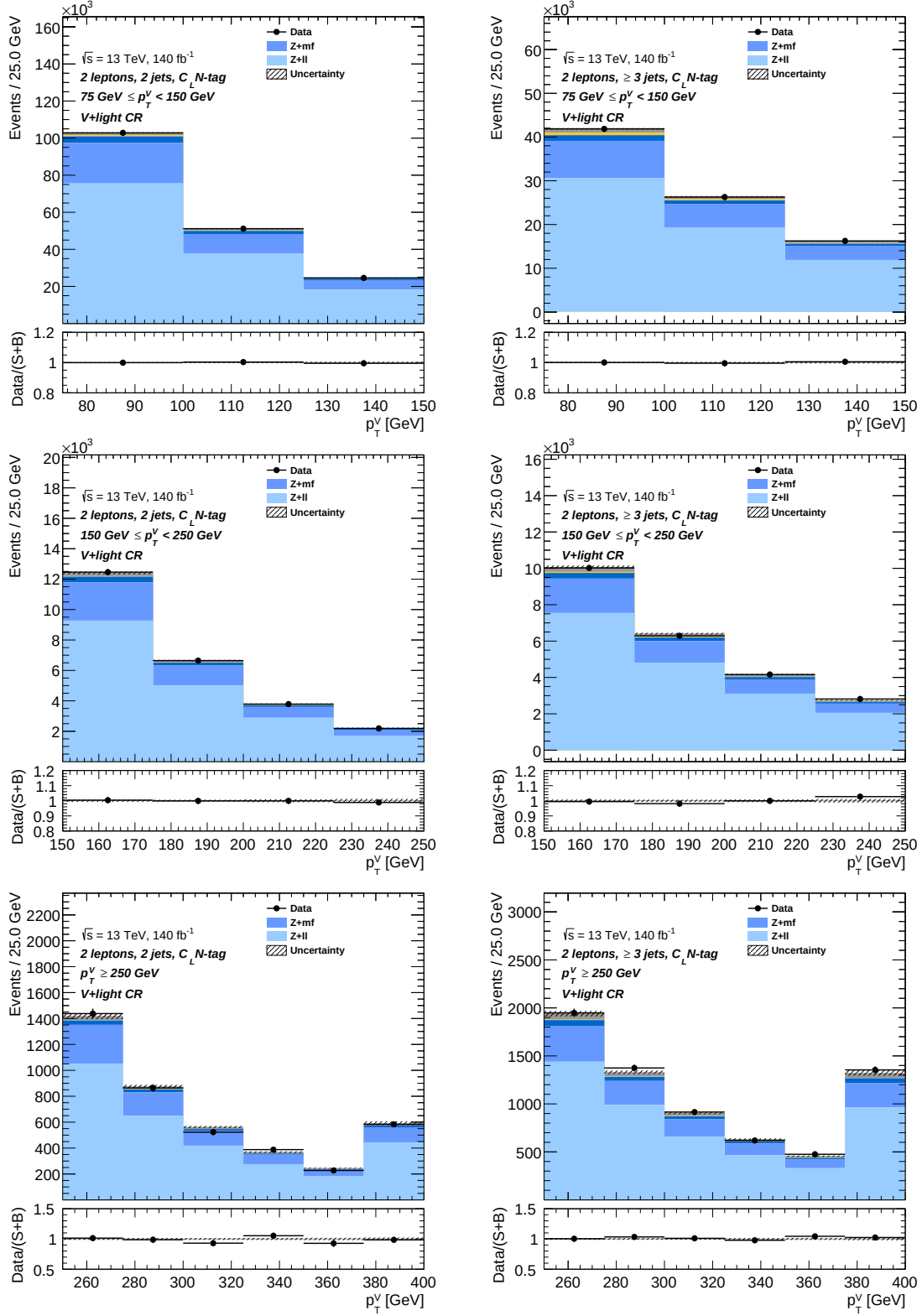


Figure 46: p_T^V in $VHcc$ 2-lepton $V+l$ CR.

Boosted $VH(\rightarrow b\bar{b})$

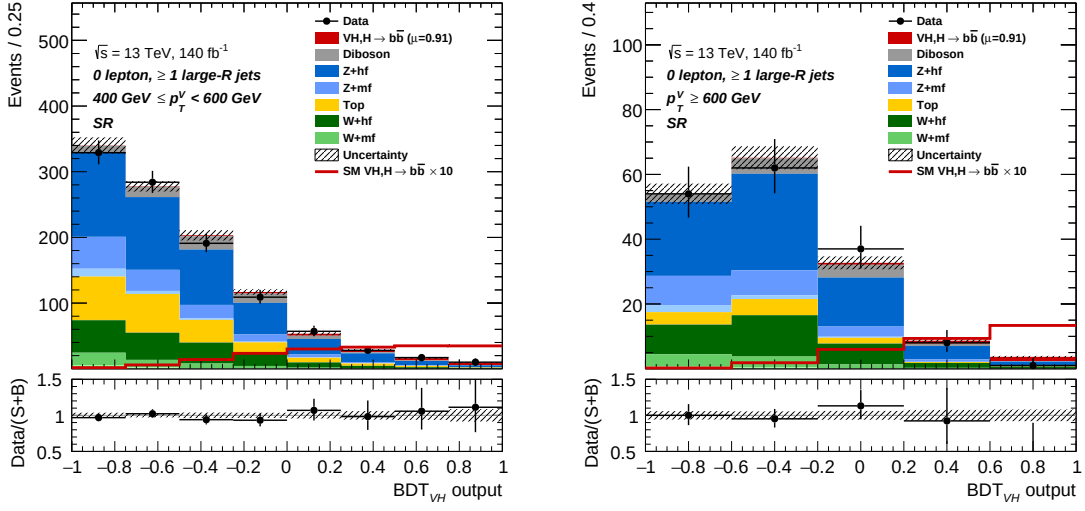


Figure 47: MVA in boosted $VHbb$ 0-lepton SR.

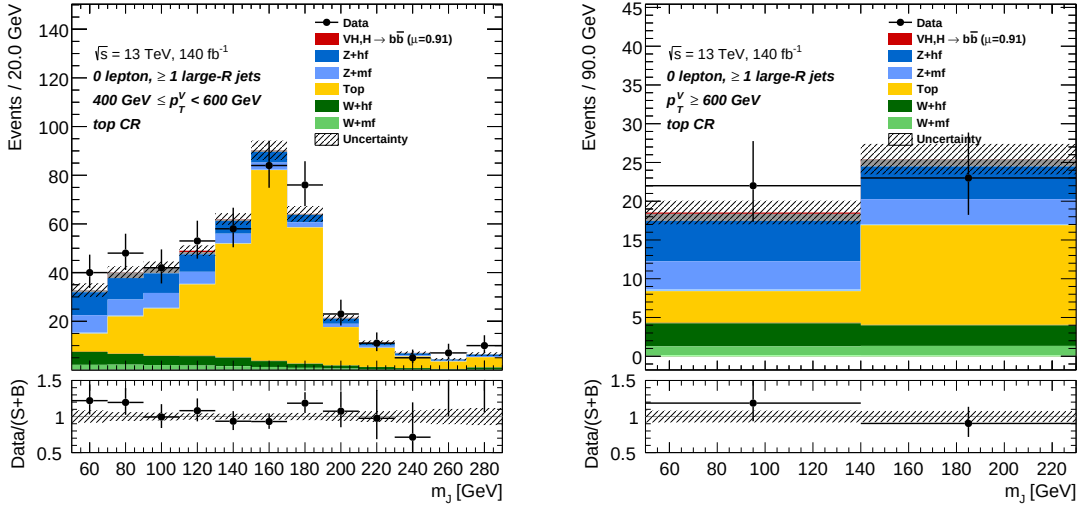


Figure 48: m_{bb} in boosted $VHbb$ 0-lepton CR.

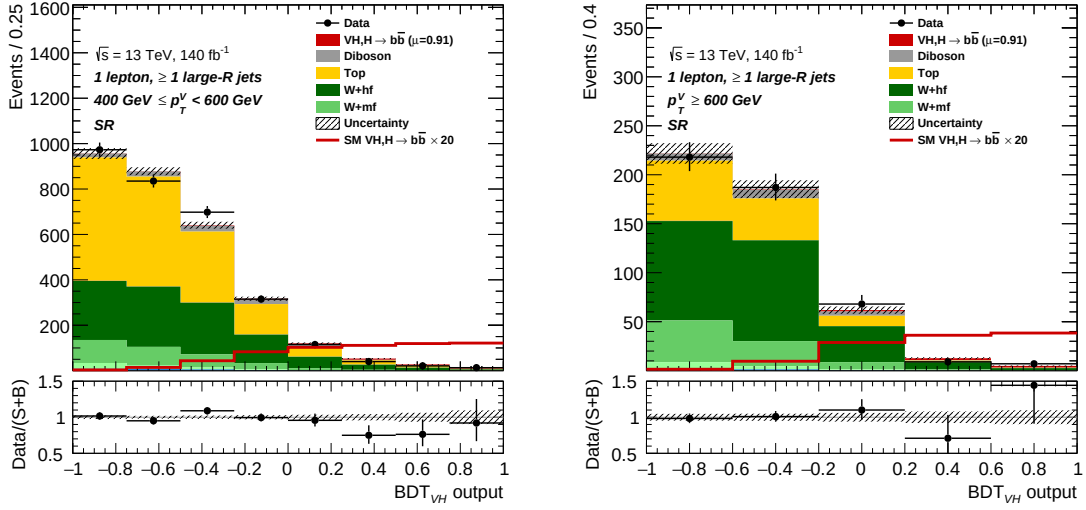


Figure 49: MVA in boosted VHbb 1-lepton SR.

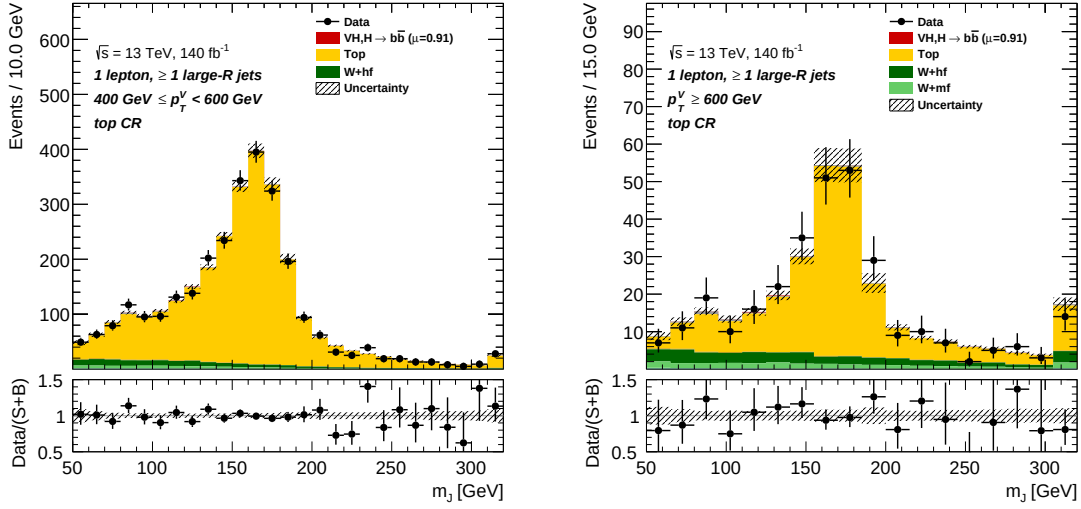


Figure 50: $m_{b\bar{b}}$ in boosted VHbb 1-lepton CR.

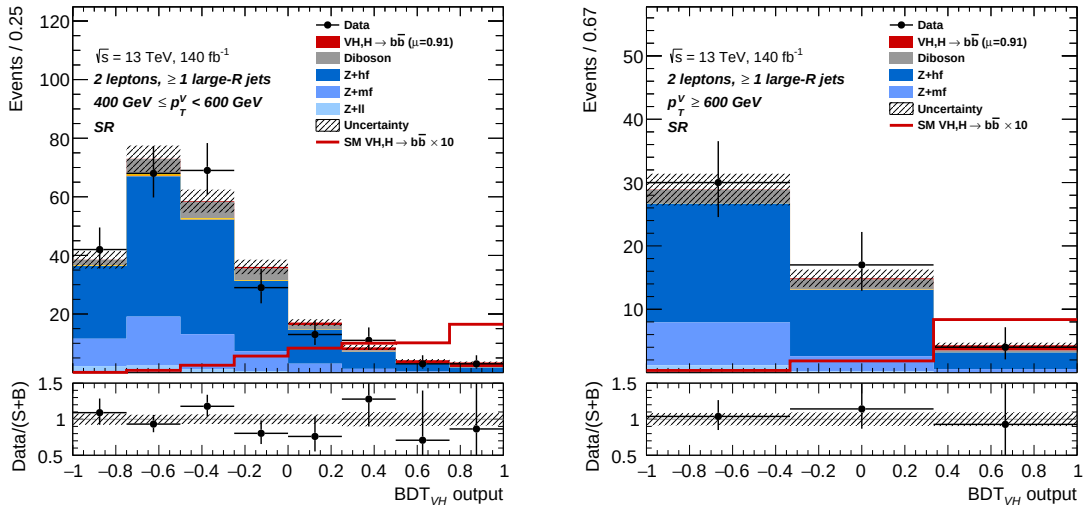


Figure 51: MVA in boosted VHbb 2-lepton category.

Experimental Uncertainties

Systematic uncertainty name	Description	Categories
Luminosity & Pile-up		
LUMI_2015_2018	Uncertainty on total integrated luminosity	all
PRW_DATASF	Uncertainty on pile-up modelling	all
Electrons		
EL_EFF_Trigger_TOTAL	Trigger efficiency uncertainty	all
EL_EFF_Reco_TOTAL	Reconstruction (reco.) efficiency uncertainty	all
EL_EFF_ID_TOTAL	Identification (id.) efficiency uncertainty	all
EL_EFF_Iso_TOTAL	Isolation efficiency uncertainty	all
EG_SCALE_ALL	Energy scale uncertainty	all
EG_RESOLUTION_ALL	Energy resolution uncertainty	all
Muons		
MUON_EFF_RECO_STAT(SYS)	Reconstruction and ID efficiency uncertainty for muons with $p_T > 15$ GeV	all
MUON_EFF_RECO_STAT(SYS)_LOWPT	Reco. and ID efficiency uncertainty for muons with $p_T \leq 15$ GeV	all
MUON_EFF_ISO_STAT(SYS)	Isolation efficiency uncertainty	all
MUON_EFF_TTVA_STAT	Track-to-vertex association efficiency uncertainty	all
MUON_SCALE	Momentum scale uncertainty	all
MUON_SAGITTA_DATASTAT(RESBIAS)	Momentum scale uncertainty to cover charge-dependent local misalignment effects	all
MUON_CB	Combined momentum resolution uncertainty of the inner detector (muon spectrometer)	all
MUON_EFF_TrigStat(Syst)Uncertainty	Trigger efficiency uncertainty	all
Taus		
TAUS_TRUEHADTAU_EFF_RECO_TOTAL	Reconstruction efficiency	all
TAUS_TRUEHADTAU_EFF_ELEOLR_TOTAL	Electron veto efficiency for taus that truth matched to an electron	all
TAUS_TRUEHADTAU_EFF_RNNID_*	RNN ID efficiency	all
TAUS_TRUEHADTAU_SME_TES_*	In-Situ Tau Energy Scale correction	all
TAUS_TRUEELECTRON_EFF_ELEBDT_*	Electron Veto efficiency SF	all
E_T^{miss} and $E_{T,\text{trk}}^{\text{miss}}$		
MET_SoftTrk_ResoPara(Perp)	'Soft term'-related longitudinal(transverse) resolution uncertainty	all
MET_SoftTrk_Scale	'Soft term'-related scale uncertainty	all
MET_JetTrk_Scale	$E_{T,\text{trk}}^{\text{miss}}$ scale uncertainty	all
METTrig(Stat,W,Z,Sumpt)	trigger efficiency uncertainty	resolved

Table 1: Summary of experimental systematic uncertainties on luminosity, pile-up, lepton and E_T^{miss} reconstruction.

Systematic uncertainty name	Description	Categories
Small-R jets		
JET_BJES_Response	Energy scale uncertainties for b -jets	all
JET_EffectiveNP_Detector{1-2}	Energy scale uncertainties due to in-situ calibration	resolved
JET_EffectiveNP_Mixed{1-3}	Energy scale uncertainties due to in-situ calibration	resolved
JET_EffectiveNP_Modelling{1-4}	Energy scale uncertainties due to in-situ calibration	resolved
JET_EffectiveNP_Statistical{1-6}	Energy scale uncertainties due to in-situ calibration	resolved
JET_EtaIntercal_Modelling(TotalStat)	Energy scale uncertainties to cover η -intercalibration non-closure	resolved
JET_EtaIntercal_NonClosure_2018data	Energy scale uncertainties to cover non-closure with 2018 data	resolved
JET_Flav_Comp(Flavor_Response)	Energy scale uncertainty related to flavour composition (response)	resolved
JET_PU_{OffsetMu(NPV),PtTerm,RhoTopology}	Energy scale uncertainties due to pile-up effects	resolved
JET_PunchTroughMC16	Energy scale uncertainty for 'punch-through'	resolved
JET_SingleParticle_HighPt	Energy scale uncertainty for the behavior of high- p_T jets	resolved
JET_JvtEfficiency	JVT efficiency uncertainty	resolved
JET_fJvtEfficiency	fJVT efficiency uncertainty	resolved
JET_JER_DataVsMC_MC16	Energy resolution uncertainty	resolved
JET_JER_EffectiveNP_{1-11,12restTerm}	Energy resolution uncertainty	resolved
Large-R jets		
FJ_CR_JET_EffectiveNP_R10_Detector{1-2}	Energy and mass scale uncertainty due to in-situ calibration	boosted
FJ_CR_JET_EffectiveNP_R10_Mixed{1-4}	Energy and mass scale uncertainty due to in-situ calibration	boosted
FJ_CR_JET_EffectiveNP_R10_Modelling{1-4}	Energy and mass scale uncertainty due to in-situ calibration	boosted
FJ_CR_JET_EffectiveNP_R10_Statistical{1-6}	Energy and mass scale uncertainty due to in-situ calibration	boosted
FJ_CR_JET_EtaIntercal_Modelling	Energy and mass scale uncertainties to cover η -intercalibration non-closure	boosted
FJ_CR_JET_EtaIntercal_NonClosure_2018data	Energy and mass scale uncertainties to cover non-closure with 2018 data	boosted
FJ_CR_JET_R10_TotalStat	Energy and mass scale uncertainties to cover non-closure	boosted
FJ_CR_JET_Flav_Comp(Flavor_Response)	Energy and mass scale uncertainty related to flavour composition (response)	boosted
FJ_CR_JET_SingleParticle_HighPt	Energy and mass scale uncertainty for the behavior of high- p_T jets	boosted
FJ_CR_JET_LargeR_TopologyUncertainty_top (V)	Energy and mass scale uncertainty on topology	boosted
FJ_CR_JET_JMS_FF_*	Mass scale uncertainty due to basic data-simulation differences	boosted
FJ_CR_JET_JMS_Rtrk_*	Mass scale uncertainty on reference tracks	boosted
FJ_CR_JET_JMS_Topology_QCD	Mass scale uncertainty due to modelling	boosted
FJ_JER_DataVsMC_R10_MC16	Energy resolution uncertainty	boosted
FJ_JER_dijet_R10_*	Energy resolution uncertainty	boosted
FJ_JER_AllOthers	Energy resolution uncertainty	boosted
FJ_JMR_COMB_*	Mass resolution uncertainty	boosted

Table 2: Summary of jets experimental systematic uncertainties.

Systematic uncertainty name	Description	Categories
b -tagging: VR track jets		
FT_EFF_VR_Eigen_B_{0-44}	b -tagging efficiency uncertainties for b -jets	boosted
FT_EFF_VR_Eigen_C_{0-19}	b -tagging efficiency uncertainties for c -jets	boosted
FT_EFF_VR_Eigen_Light_{0-35}	b -tagging efficiency uncertainties for light jets	boosted
FT_EFF_VR_Eigen_T_{0-19}	b -tagging efficiency uncertainties for τ -jets ¹	boosted
FT_EFF_VR_extrapolation_pt	b -tagging efficiency uncertainty for high- p_T jets	boosted
Flavour tagging: PFlow jets		
FT_EFF_PFlow_Eigen_B_{0-44}	b -tagging efficiency uncertainties for b -jets	resolved
FT_EFF_PFlow_Eigen_C_{0-19}	b -tagging efficiency uncertainties for c -jets	resolved
FT_EFF_PFlow_Eigen_Light_{0-35}	b -tagging efficiency uncertainties for light jets	resolved
FT_EFF_PFlow_Eigen_T_{0-19}	b -tagging efficiency uncertainties for τ -jets ²	resolved
FT_EFF_PFlow_extrapolation_pt	b -tagging efficiency uncertainty for high- p_T jets	resolved

Table 3: Summary of flavor tagging experimental systematic uncertainties.

Modelling Nuisance Parameters

The following tables summarize the nuisance parameters concerning the modelling of the physics process used in the $VH(\rightarrow b\bar{b}, c\bar{c})$ analysis.

Syst Name	Description	Samples/Categories	Value	Effect
VHbb_BR	$VH(\rightarrow b\bar{b})$ BR unc	VHbb, 0,1,2 lep	1.61%	Norm
VHcc_BR	$VH(\rightarrow c\bar{c})$ BR unc	VHcc, 0,1,2 lep	+5.5%	Norm
VHcc_ZHXsec	ZH production cross-section	ZHcc, 0,1,2 lep	+2.0%	Norm
VHcc_WHXsec	WH production cross-section	WHcc, 0,1,2 lep	+4.1%	Norm
			-3.5%	Norm
			+2.0%	Norm
			-2.1%	Norm
VH_PwPy8toPwHwg7	VH Parton shower uncertainty	VH(bb/cc), 0,1,2 lep	-	Shape + Norm
VHNLOEWK	VH NLO EW uncertainty	VH(bb/cc), 0,1,2 lep	-	Shape + Norm
SysMURMUUFUP_Higgs_[075-150,150-250,250-400,400-600,600+]ptv	renormalisation scale shape	VH(bb/cc), 0,1,2 lep	-	Shape
TheoryPDF_[01-28]	PDF uncertainty from STXS templates	VH(bb/cc), 0,1,2 lep	-	Shape + Norm
TheoryQCDscaleDelta[75,150,250,400,Y]_[qq,gg]VH	QCD scale variations among p_T^Y bins	VH(bb/cc), 0,1,2 lep	-	Shape + Norm

Table 4: Signal nuisance parameters.

Syst Name	Description	Samples/Categories applied to	Value	Effect
WWNorm_[boosted, resolved]	WW normalisation uncertainty	WW, VH(bb/cc)	16%	norm
WZNorm	WZ normalisation uncertainty	WZ, resolved VH(bb/cc)	19%	norm
WZNorm_boosted	WZ normalisation uncertainty	WZ, boosted VH(bb)	27%	norm
ZZNorm	ZZ normalisation uncertainty	ZZ, resolved VH(bb/cc)	17%	norm
ZZNorm_boosted	ZZ normalisation uncertainty	ZZ, boosted VH(bb)	17%	norm
ggVVNorm_[boosted, resolved]	ggVV normalisation uncertainty	ggVV, VH(bb/cc)	30%	norm
WZ_nLepAcc_L0	WZbb and WZcc 1lep/0lep acceptance	WZhf, Resolved 0lep	4%-10%	Norm
WZ_nLepAcc_boosted_L0	WZbb and WZcc 1lep/0lep acceptance	WZhf, Boosted VH(bb) 0lep	7%	Norm
ZZ_nLepAcc_L0	ZZbb and ZZcc 2lep/0lep acceptance	ZZhf, Resolved 0lep	2%-23%	Norm
ZZ_nLepAcc_boosted_L0	ZZbb and ZZcc 2lep/0lep acceptance	ZZhf, Boosted VH(bb) 0lep	7%	Norm
WW_nLepAcc_L0	WW 1lep/0lp acceptance	WW, Resolved 0L	6%	Norm
WW_nLepAcc_boosted_L0	WW 1lep/0lp acceptance	WW, Boosted 0L	10%	Norm
WZhadlep_nLepAcc_L0	WZhadlep 2lep/0lep acceptance	WZhadlep, Resolved 0L	10%	Norm
WZhadlep_nLepAcc_boosted_L0	WZhadlep 2lep/0lep acceptance	WZhadlep, boosted 0L	10%	Norm
WZlephadbkg_nLepAcc_L0	WZlephad 1lep/0lep acceptance	WZlephadbkg, Resolved 0L	4%	Norm
WZlephadbkg_nLepAcc_boosted_L0	WZlephad 1lep/0lep acceptance	WZlephadbkg, Resolved 0L	10%	Norm
ZZbkg_nLepAcc_L0	ZZ 2lep/0lep acceptance	ZZbkg, Resolved 0L	13%	Norm
ZZbkg_nLepAcc_boosted_L0	ZZ 2lep/0lep acceptance	ZZbkg, Resolved 0L	10%	Norm
ZZ_extrap_to_CRHigh	ZZbb and ZZcc SR/CRHigh acceptance	ZZhf, Resolved 0 and 2L	12%-20%	Norm
WZ_extrap_to_CRHigh	WZ SR/CRHigh acceptance	WZhf, Resolved 0 and 1L	12%-20%	Norm
WZ_extrap_to_CRLow_L1	WZ SR/CRHigh acceptance	WZhf, Resolved 1L	18%-50%	Norm
WW_extrap_to_CRHigh	WW SR/CRHigh acceptance	WW, Resolved 0 and 1L	10%-16%	Norm
WZhadlep_extrap_to_CRHigh	WZhadlep SR/CRHigh acceptance	WZhadlep, Resolved VH(bb/cc)	12%-16%	Norm
WZlephadbkg_extrap_to_CRHigh	WZlephadbkg SR/CRHigh acceptance	WZlephadbkg, Resolved 0 and 1L	10%-11%	Norm
ZZbkg_extrap_to_CRHigh	ZZbkg SR/CRHigh acceptance uncertainties	ZZbkg, Resolved 0 and 2L	6%-7%	Norm
ZZ_nJAcc_[3,4]J	ZZbb and ZZcc 2jets/3jets, 3jets/4jets acceptance	ZZhf, Resolved 0 and 2L	10%-30%	Norm
WZ_nJAcc_[3,4]J	WZbb and WZcc 2jets/3jets, 3jets/4jets acceptance	WZhf, Resolved 0 and 1L	16%-22%	Norm
WW_nJAcc_[3,4]J	WW 2J to 3J and 3J to 4J acceptance	WW, Resolved 0L 3 and 4jets and 1L 3jets	12%	Norm
WZhadlep_nJAcc_[3,4]J	WZhadlep 2J to 3J and 3J to 4J acceptance	WZhadlep, Resolved 0L and 2L 3 and 4(+)jets and 1L 3jets	10%-37%	Norm
WZlephadbkg_nJAcc_[3,4]J	WZlephadbkg 2J to 3J and 3J to 4J acceptance	WZlephadbkg, Resolved 0L 3 and 4(+)jets and 1L 3jets	11%-14%	Norm
ZZbkg_nJAcc_[3,4]J	ZZbkg 2J to 3J and 3J to 4J acceptance	ZZbkg, Resolved 0L and 2L 3 and 4(+)jets	10%-42%	Norm
ZZ_pTVAcc_[075-150,250-400]ptv	ZZbb and ZZcc p_T^V med-low and med-high acceptance	ZZhf, Resolved 0 and 2L	3%-9%	Norm
ZZ_pTVAcc_600ptv	ZZbb and ZZcc p_T^V 400-600 to >600 acceptance	ZZhf, 0 and 2L Boosted, $p_T^V > 600$ GeV	8%	Norm
WZ_pTVAcc_[75-150,250-400]ptv	WZbb and WZcc p_T^V med-low and med-high acceptance	WZhf, Resolved 0 and 1L	2%-16%	Norm
WZ_pTVAcc_600ptv	WZbb and WZcc p_T^V 400-600 to >600 acceptance	WZhf, 0 and 1L Boosted, $p_T^V > 600$ GeV	7%-40%	Norm
WW_pTVAcc_[75-150,250-400]ptv	WW med-low and med-high p_T^V acceptance	WW, Resolved 0,1L	7%	Norm
WW_pTVAcc_600ptv	WW med-low and med-high p_T^V acceptance	WW, Boosted 0,1L	10%	Norm
WZhadlep_pTVAcc_[75-150,250-400]ptv	WZhadlep med-low and med-high p_T^V acceptance	WZhadlep, Resolved 0,1,2L	4%-10%	Norm
WZhadlep_pTVAcc_600ptv	WZhadlep med-low and med-high p_T^V acceptance	WZhadlep, Boosted 0,2L	30%	Norm
WZlephadbkg_pTVAcc_[75-150,250-400]ptv	WZlephadbkg med-low and med-high p_T^V acceptance	WZlephadbkg, Resolved 0,1L	5%-9%	Norm
WZlephadbkg_pTVAcc_600ptv	WZlephadbkg med-low and med-high p_T^V acceptance	WZlephadbkg, Boosted 0,1L	30%	Norm
ZZbkg_pTVAcc_[75-150,250-400]ptv	ZZbkg med-low and med-high p_T^V acceptance	ZZbkg, Resolved 0,2L	4%-8%	Norm
ZZbkg_pTVAcc_600ptv	ZZbkg med-low and med-high p_T^V acceptance	ZZbkg, Boosted 0,2L	10%	Norm
Sys[WZ,ZZ]QCDscale_d[3J,4J,150,250,600]	WZ, ZZ signal components $p_T^V \times nJ$ acceptance uncertainties	WZhf, ZZhf, Resolved and Boosted VH(bb/cc)	-42.2%-32%	Norm

Table 5: Diboson norm nuisance parameters shapes.

Syst Name	Description	Samples/Categories applied to	Effect
Carl_WW_Sh2211toPwPy8_[resolved,boosted]	WW Sherpa2211 vs. PwPy8	WW 0 and 1L	shape
Carl_WW_Sh2211toSh221_[resolved,boosted]	WW Sherpa2211 vs. Sh221	WW 0 and 1L	shape
Carl_ZZ_Sh2211toPwPy8_[resolved,boosted]	ZZ Sherpa2211 vs. PwPy8	ZZ 0 and 2L	shape
Carl_ZZ_Sh2211toSh221_[resolved,boosted]	ZZ Sherpa2211 vs. Sh221	ZZ 0 and 2L	shape
Carl_WZ_Sh2211toPwPy8_[resolved,boosted]	WZ Sherpa2211 vs. PwPy8	WZ 0, 1 and 2L	shape
Carl_WZ_Sh2211toSh221_[resolved,boosted]	WZ Sherpa2211 vs. Sh221	WZ 0, 1 and 1L	shape
Diboson_ME_ONLY_MUR2_MUF2_PDF303200_PSMUR2_PSMUF2_[resolved,boosted]	Diboson, Sh2.2.11 QCD variation	Diboson, all channel	shape
Diboson_MUR1_MUF1_PDF303200_MULTIASSEW	Diboson, EWK shape	Diboson, all channel	shape

Table 6: Diboson shape nuisance parameters shapes.

Syst Name	Description	Samples/Categories applied to	Value	Effect
norm_Zhf_J[2,3+]_[075-150, 150-250, 250-400]	Zhf norm	Zhf, 0 and 2L, VH(bb/cc)	Floating	Norm
norm_Zhf_J3_[075-150, 150-250, 250-400]	Zhf norm	Zhf, VH(bb) 0 and 2L, VH(cc) 0L	Floating	Norm
norm_Zhfmf_Min400	Zhf norm	Zhf and Zmf, 0 and 2L, $p_T^V > 400$ GeV, VH(bb)	Floating	Norm
norm_Zmf_J[2,3+]_[075-150, 150-250, 250-400]	Zmf norm	Zmf, 0, 1 and 2L, VH(bb/cc)	Floating	Norm
norm_Zl_J[2,3+]_[075-150, 150-250, 250-400]	Zlf norm	Zlf, 0, 1 and 2L, VH(bb/cc)	Floating	Norm
ZbbZccRatio_resolved	Zcc/Zbb ratio	Zcc, resolved	8-12%	Norm
ZblZclRatio_resolved	Zbl/Zcl ratio	Zbl, resolved	4%	Norm
ZbcZclRatio_resolved	Zbc/Zcl ratio	Zcl, resolved	10%	Norm
ZbbZccRatio_boosted	Zcc/Zbb ratio	Zcc, 0 and 2L, boosted	6%	Norm
ZbcZblRatio_boosted	Zbc/Zbl ratio	Zbc, 0 and 2L, boosted	6%	Norm
ZbcZclRatio_boosted	Zcl/Zbc ratio	Zcl, 0 and 2L, boosted	6%	Norm
ZhfmfRatio_boosted	Zhf/Zmf ratio	Zmf, 0 and 2L, boosted	5%	Norm
Zhf_extrap_from_CRHigh_BMin_J[2,3,4]	Zhf SRCR ratio	Zhf, 0 and 2L, SR	7-30%	Norm
Zmf_extrap_from_CRHigh	Zmf SRCR ratio	Zmf, 0 and 2L, SR	5-7%	Norm
Zl_extrap_to_CRHigh	Zl SRCR ratio	Zmf, 0 and 2L, CRHigh	5-7%	Norm
ZlNorm_boosted	Zl norm	Zl, 0 and 2L, boosted	35%	Norm
Zjets_extrap_from_SR_boosted	Zjets SR to top CR extrap.	Zhf and Zmf, 0L, boosted Top CR	15%	Norm
Zhf_nLepAcc_L0_resolved	Zhf 2L to 0L channel acceptance	Zhf, 0L, Resolved	4-8%	Norm
Zmf_nLepAcc_L0_resolved_[2,3]J	Zmf channel acceptance	Zmf, 0L, Resolved	3-8%	Norm
Zl_nLepAcc_L0_resolved_[2,3]J	Zl channel acceptance	Zl, 0L, Resolved	4-10%	Norm
Zjets_nLepAcc_boosted	Zhf and Zmf channel acceptance boosted	Zhf and Zmf, 0L	3%	Norm
RatioPTV_Zjets_boosted_Zhf	Zhf boosted p_T^V acceptance ratio	Zhf, $p_T^V > 600$ GeV	15%	Norm
RatioPTV_Zjets_boosted_Zmf	Zmf boosted p_T^V acceptance ratio	Zmf, $p_T^V > 600$ GeV	15%	Norm

Table 7: Z+jets normalisation nuisance parameters.

Syst Name	Description	Samples/Categories applied to	Effect
Carl_Z_Sh2211toFxFx_staticHighDR_[Zbb,Zcc]_[075-150ptv, 150-250ptv]	Zbb and Zcc Sherpa 2.2.11 vs. FxFx	Zbb and Zcc, $dR > 1$, 0 and 2L	Shape
Carl_Z_Sh2211toFxFx_staticLowDR_[Zbb,Zcc]_[075-150ptv, 150-250ptv]	Zbb and Zcc Sherpa 2.2.11 vs. FxFx	Zbb and Zcc, $dR < 1$, 0 and 2L	Shape
Carl_Z_Sh2211toFxFx_staticHighDR_[Zmf,Zl]_[075-150ptv, 150-250ptv]_[2,3+J]	Zmf and Zlf Sherpa 2.2.11 vs. FxFx	Zmf and Zlf, $dR > 1$, 0 and 2L	Shape
Carl_Z_Sh2211toFxFx_staticLowDR_[Zmf,Zl]_[075-150ptv, 150-250ptv]	Zmf and Zlf Sherpa 2.2.11 vs. FxFx	Zmf and Zlf, $dR < 1$, 0 and 2L	Shape
Carl_Z_Sh2211toFxFx_Zbb_250-400ptv	Zbb Sherpa 2.2.11 vs. FxFx	Zbb, 0 and 2L	Shape
Carl_Z_Sh2211toFxFx_Zcc_250-400ptv	Zcc Sherpa 2.2.11 vs. FxFx	Zcc, 0 and 2L	Shape
Carl_Z_Sh2211toFxFx_Zmf_250-400ptv_[2,3+J]	Zmf Sherpa 2.2.11 vs. FxFx	Zmf, 0 and 2L	Shape
Carl_Z_Sh2211toFxFx_Zl_250-400ptv_[2,3+J]	Zl Sherpa 2.2.11 vs. FxFx	Zl, 0 and 2L	Shape
Carl_Z_Sh2211toFxFx_Z_400+ptv	Z+jets Sherpa 2.2.11 vs. FxFx	Zl, 0 and 2L, $p_T^V > 400$ GeV	Shape
Z_shape_Sh221_pTV_ZmfZhf_[075-150, 150-250, 250-400]ptv	Z+hf/mf Sherpa 2.2.11 vs. Sherpa 2.2.1	Z+hf/mf, 0 and 2L	Shape
Z_shape_Sh221_pTV_Zl_[075-150, 150-250, 250-400]ptv	Z+l Sherpa 2.2.11 vs. Sherpa 2.2.1	Z+l, 0 and 2L	Shape
Z_shape_Sh221_pTV_Z_400+ptv	Z+jets Sherpa 2.2.11 vs. Sherpa 2.2.1	Z+jets, 0 and 2L	Shape
ME_ONLY_MUR2_MUF2_PDF303200_PSMUR2_PSMUF2_075-150ptv_[Zhf,Zmf,Zl]	Z+jets Sherpa 2.2.11 QCD variation	Z+jets, 0 and 2L, resolved VH(bb/cc), 75-150 GeV	Shape
ME_ONLY_MUR2_MUF2_PDF303200_PSMUR2_PSMUF2_150-400ptv_[Zhf,Zmf,Zl]	Z+jets Sherpa 2.2.11 QCD variation	Zhf, 0 and 2L, resolved VH(bb/cc), 150-400 GeV	Shape
ME_ONLY_MUR2_MUF2_PDF303200_PSMUR2_PSMUF2_400+ptv_[Zhf,Zmf,Zl]	Z+jets Sherpa 2.2.11 QCD variation	Zhf, 0 and 2L, boosted VH(bb)	Shape
MUR1_MUF1_PDF303200_MULTIASSEW_[Zhf, Zmf, Zl]	Zhf Sherpa 2.2.11 ewk correction	Zhf, 0 and 2L, $150 \leq p_T^V < 250$ GeV	Shape

Table 8: Z+jets shape nuisance parameters shapes.

Syst Name	Description	Samples/Categories applied to	Value	Effect
norm_Whf_J[2,3+][075-150, 150-250, 250-400]ptv	Whf norm	Whf, 0 and 1L, VH(bb/cc)	Floating	Norm
norm_Whfmf_[400-600, 600+]	Whf+Wmf norm	Whf and Wmf, 0 and 1L, $p_T^V > 400$ GeV, VH(bb)	Floating	Norm
norm_Wmf_J[2,3+][075-150, 150-250, 250-400]ptv	Wmf norm	Wmf, 0 and 1L, VH(bb/cc)	Floating	Norm
norm_Wlf_J[2,3+][150-250, 250-400]ptv	Wlf norm	Wlf, 0 and 1L, VH(bb/cc)	Floating	Norm
WccWbbRatio_[75-150,150-250,250-400]ptv	Wcc/Wbb ratio	Wcc, resolved	4-25%	Norm
WbcWclRatio_[75-400]ptv	Wbc/Wcl ratio	Wbc, resolved	14-24%	Norm
WblWclRatio_[75-400]ptv	Wbl/Wcl ratio	Wbl, resolved	29%	Norm
WqtauWclRatio_[75-400]ptv	Wctau+Wbtau/Wcl ratio	Wctau + Wbtau, resolved	20%	Norm
WltauWlRatio_[75-400]ptv	Wltau+Wtautau/Wl ratio	Wltau + Wtautau, resolved	9%	Norm
WccWbbRatio_400+ptv	Wcc/Wbb ratio	Wcc, boosted	11%	Norm
WclWbcRatio_400+ptv	Wbc/Wbl ratio	Wbc, boosted	15%	Norm
WblWbcRatio_400+ptv	Wbc/Wbl ratio	Wbl, boosted	9%	Norm
WhfmfRatio_400+ptv	Whf/Wmf ratio	Wmf, boosted	5%	Norm
Whf_extrap_from_CRLow_[75-150, 150-250, 250-400]ptv	Whf CRLow to SR ratio	Whf, 0 and 1L, SR	20%	Norm
Whf_extrap_to_CRHigh_[75-150, 150-400]ptv	Whf CRLow+SR to CRHigh ratio	Whf, 0 and 1L, CRHigh	3-50%	Norm
Wmf_extrap_from_CRHigh_[75-150, 150-400]ptv	Wmf SRCR ratio	Wmf, 0 and 1L, SR	2-16%	Norm
Wlf_extrap_to_CRHigh_75-400ptv	Wlf SRCR ratio	Wlf, 0 and 1L, CRHigh	5-17%	Norm
WlNorm_400+ptv	Wl norm	Wl, 0 and 1L, boosted	38%	Norm
RatioSRTopCR_Wjets_400+ptv	Wjets SR to top CR extrap.	Wjets, 0 and 1L, boosted Top CR	16%-27%	Norm
Whf_nLepAcc_[150-250,250-400]ptv_L0	Whf channel acceptance	Whf, 0L, resolved	13-30%	Norm
Wmf_nLepAcc_[150-250,250-400]ptv_L0	Wmf channel acceptance	Wmf, 0L, resolved	3-10%	Norm
Wl_nLepAcc_[075-400]ptv_L0	Wlf channel acceptance	Wlf, 0L, resolved	4%	Norm
Whfmf_nLepAcc_400+ptv_L0	Whf+Wmf channel acceptance	Whf and Wmf, 0L, boosted	20%	Norm
Wlf_nLepAcc_400+ptv_L0	Wlf channel acceptance	Wlf, 0L, boosted	20%	Norm
RatioPTV_Wmf_600+ptv	Wmf boosted p_T^V acceptance ratio	Wmf, $p_T^V > 600$ GeV	3%	Norm
RatioPTV_Wlf_600+ptv	Wlf boosted p_T^V acceptance ratio	Wlf, $p_T^V > 600$ GeV	3%	Norm

Table 9: W+jets normalisation nuisance parameters.

Syst Name	Description	Samples/Categories applied to	Effect
Carl_W_Sh2211toFxFx_staticHighDR_[Wbb,Wcc][075-150, 150-250]ptv	Wbb and Wcc Sherpa 2.2.11 vs. FxFx	Wbb and Wcc, $dR > 1$, 0 and 1L, 75-150 and 150-250GeV	Shape
Carl_W_Sh2211toFxFx_staticLowDR_[Wbb,Wcc][075-150, 150-250]ptv	Wbb and Wcc Sherpa 2.2.11 vs. FxFx	Wbb and Wcc, $dR < 1$, 0 and 1L, 75-150 and 150-250GeV	Shape
Carl_W_Sh2211toFxFx_staticHighDR_[Wmf,Wlf][075-150, 150-250]ptv_[2,3+J]	Wmf and Wlf Sherpa 2.2.11 vs. FxFx	Wmf and Wlf, $dR > 1$, 0 and 1L, 75-150 and 150-250GeV	Shape
Carl_W_Sh2211toFxFx_staticLowDR_[Wmf,Wlf][075-150, 150-250]ptv_[2,3+J]	Wmf and Wlf Sherpa 2.2.11 vs. FxFx	Wmf and Wlf, $dR < 1$, 0 and 1L, 75-150 and 150-250GeV	Shape
Carl_W_Sh2211toFxFx_[Wbb,Wcc][250-400]ptv	Wbb and Wcc Sherpa 2.2.11 vs. FxFx	Wbb and Wcc, 0 and 1L, 250-400GeV	Shape
Carl_W_Sh2211toFxFx_[Wmf,Wlf][250-400]ptv_[2,3+J]	Wmf and Wlf Sherpa 2.2.11 vs. FxFx	Wmf and Wlf, 0 and 1L, 250-400GeV	Shape
Carl_W_Sh2211toFxFx_W_400+ptv	W+jets Sherpa 2.2.11 vs. FxFx,	W+jets, 0 and 1L, $p_T^V > 400$ GeV	Shape
W_shape_Sh2211_pTV_Whf_[075-400]ptv	W+hf Sherpa 2.2.11 vs. Sherpa 2.2.1	W+hf, 0 and 1L	Shape
W_shape_Sh2211_pTV_Wmf_[075-150,150-250, 250-400]ptv	W+mf Sherpa 2.2.11 vs. Sherpa 2.2.1	W+mf, 0 and 1L	Shape
W_shape_Sh2211_pTV_Wlf_[075-150,150-250, 250-400]ptv	W+lf Sherpa 2.2.11 vs. Sherpa 2.2.1	W+lf, 0 and 1L	Shape
W_shape_Sh2211_pTV_W_400+ptv	Z+jets Sherpa 2.2.11 vs. Sherpa 2.2.1	W+jets, 0 and 1L	Shape
ME_ONLY_MUR2_MUF2_PDF303200_PSMUR2_PSMUF2_[75-150,150-400]ptv_[Whf,Wmf,Wl]	W+jets Sherpa 2.2.11 QCD variation	Whf, 0 and 1L, resolved VH(bb/cc), 75-150 and 150-400 GeV	Shape
ME_ONLY_MUR2_MUF2_PDF303200_PSMUR2_PSMUF2_400+ptv_[Whf,Wmf,Wl]	W+jets Sherpa 2.2.11 QCD variation	W+jets, 0 and 1L, boosted VH(bb)	Shape
MUR1_MUF1_PDF303200_MULTIASSEW_[Whf, Wmf, Wl]	W+jets Sherpa 2.2.11 ewk correction	W+jets, 0 and 2L	Shape

Table 10: W+jets shape nuisance parameters shapes.

Syst Name	Description	Samples/Categories applied to	Value	Effect
norm_Top_[2J, 3+J]_[075-150, 150-250]ptv	Top norm	Top, 2L, Resolved VH(bb/cc)	Floating	Norm
norm_[Topbb, Topbqqq]_[2J, 3J, 4J]_[075-150, 150-250, 250-400]	Top norm	Topbb/bqqq, 0/1L, Resolved VH(bb/cc) (4J norm without 75-150ptv bin)	Floating	Norm
norm_Top_250-400ptv_2L	Top norm	Top, 2L, Resolved VH(bb/cc)	Floating	Norm
norm_Top_[400-600, 600+]ptv	Top norm	Top, 0/1L, Boosted VH(bb)	Floating	Norm
TopNorm_400+ptv_2L	Top norm	Top, 2L, Boosted VH(bb)	20%	Norm
Top_Extrapolation_From_Topemu_[bb,cc]	Top emu extrap	emuCRdata, 2L, VH(bb/cc)	0.8%	Norm
Top_extrap_from_CRHigh_[075-150,150-400]ptv_Topbb	Top CRHigh to SR extrap	Topbb, 1L VH(bb/cc)	2% - 8%	Norm
Top_extrap_to_CRHigh_[075-250, 250-400]ptv_Topbqqq	Top SR to CRHigh extrap	Topbqqq, 0,1L VH(bb/cc)	4% - 10%	Norm
Top_extrap_to_CRLow_[075-150, 150-400]ptv_Topbb	Top SR to CRLow extrap	Topbb, 1L VH(bb)	2.5% - 9%	Norm
Top_extrap_to_CRLow_Topbqqq	Top SR to CRLow extrap	Topbqqq, 1L VH(bb), 75-400 GeV	2.5% - 4%	Norm
RatioSRTopCR_400+ptv_DSReoadbjetsr_Top	Top SR/topCR ratio	Top, 0/1L, boosted VH(bb)	14-19%	Norm
Top_nLepAcc_[150-250, 250-400]ptv_0L_[Topbb, Topbqqq]	Top 1L to 0L acceptance	Top, 0L Resolved VH(bb/cc)	2% - 8%	Norm
Top_nLepAcc_400+ptv_0L	Top 1L to 0L acceptance	Top, 0L Boosted VH(bb/cc)	6% - 17%	Norm
TopblbcRatio	Topbl/bc ratio	Topbl, 0,1L, Resolved VH(bb/cc)	5%	Norm
TopqgbcRatio	Topqg/bc ratio	Topqg, 0,1L, Resolved VH(bb/cc)	10%	Norm
WtTtbarRatio_[075-400, 400+]ptv	Wt/ttbar ratio	single-top Wt , 0 and 1L resolved and boosted	12-48%	Norm

Table 11: Top normalisation nuisance parameters.

Syst Name	Description	Samples/Categories applied to	Effect
Carl_PwPy8toPwHwg7_Top_[075-150, 150-250, 250-400, 400+]ptv	ttbar/Wt PwPy8 vs PwHwg7	Top, 0,1L	shape
Carl_PwPy8toaMCatNLOPy8_Top_[075-150, 150-250, 250-400, 400+]ptv	ttbar/Wt PwPy8 vs aMCatNLOPy8	Top, 0,1L	shape
ISR_Top_[075-400, 400+]ptv	Top ISR shape	Top, 0/1L	Shape
FSR_Top_[075-400, 400+]ptv	Top FSR shape	Top, 0/1L	Shape
WtDR_[075-150, 150-400, 400+]ptv	Wt DS-DR shape	single-top Wt , 0/1L	Shape

Table 12: Top shape nuisance parameters shapes.

Syst Name	Description	Samples/Categories	Value	Effect
stopsNorm	single-top s -channel cross-section	s -channel, 0,1,2L	4.6%	Norm
stoptNorm_075-400ptv	single-top t -channel normalisation	t -channel, 0,1L resolved	17%	Norm
stoptNorm_400+ptv	single-top t -channel normalisation	t -channel, 0,1L boosted	10%	Norm
stopt_extrap_to_CRs_075-150ptv	single-top t -channel SRCR ratio	t -channel, 1L resolved, CRHigh and CRLow	3%	Norm
stopt_extrap_to_CRLow_[075-150, 150-400]ptv	single-top t -channel SRCR ratio	t -channel, 1L resolved, CRLow	6-17%	Norm
stopt_extrap_from_CRHigh_[075-150, 150-400]ptv	single-top t -channel SRCR ratio	t -channel, 0,1L resolved, SR, topCR, CRLow	6%	Norm
stopt_nJet_to_[2,4J]	single-top t -channel jet multiplicity ratio	t -channel, 0,1L resolved, 2- and 4-jet events	15%	Norm
stopt_nLepAcc_075-400ptv	single-top t -channel lepton channel ratio	t -channel, 0L resolved	6%	Norm
stopt_pTV_from_LowPTV_150-400ptv	single-top t -channel p_T^V bin ratio	t -channel, 0,1,2L resolved	7%	Norm
stopt_pTV_to_HighPTV_250-400ptv	single-top t -channel p_T^V bin ratio	t -channel, 0,1L resolved	15%	Norm
ISR_stopT_075-400ptv	single-top t -channel ISR shape uncertainties	t -channel, 0,1L resolved		Shape
FSR_stopT_075-400ptv	single-top t -channel FSR shape uncertainties	t -channel, 0,1L resolved		Shape
Carl_PwPy8toPwHwg7_stopT_075-400ptv	single-top t -channel PS Carl uncertainty	t -channel, 0,1L resolved		Shape
Carl_PwPy8toaMCatNLOPy8_stopT_075-400ptv	single-top t -channel ME Carl uncertainty	t -channel, 0,1L resolved		Shape

Table 13: single-top s -channel and t -channel nuisance parameters.

Syst Name	Description	Samples/Categories	Value	Derived in	Effect
MJNorm_El_075-150ptv_BB-BC-CC	MJ el norm	MJ el, 1 lep, BB-BC-CC-tag 75_150GeV,	-100% +339%	BB-BC-CC-tag region	Norm
MJNorm_El_075-150ptv_CN	MJ el norm	MJ el, 1 lep, CN-tag 75_150GeV,	5%	CN-tag region	Norm
MJNorm_Mu_075-150ptv_BB-BC-CC	MJ el norm	MJ mu, 1 lep, BB-BC-CC-tag 75_150GeV,	-100% +22%	BB-BC-CC-tag region	Norm
MJNorm_mu_075-150ptv_CN	MJ mu norm	MJ mu, 1 lep, CN-tag 75_150GeV,	5%	CN-tag region	Norm
MJNorm_El_150-400ptv_BB-BC-CC	MJ el norm	MJ el, 1 lep, BB-BC-CC-tag 150-250GeV,	-92% +66%	BB-BC-CC-tag region	Norm
MJNorm_El_150-400ptv_CN	MJ el norm	MJ el, 1 lep, CN-tag 150-250GeV,	15%-25%	CN-tag region	Norm
MJNorm_Mu_150-400ptv_BB-BC-CC	MJ el norm	MJ mu, 1 lep, BB-BC-CC-tag 150-250GeV,	-100% +412%	BB-BC-CC-tag region	Norm
MJNorm_mu_150-400ptv_CN	MJ mu norm	MJ mu, 1 lep, CN-tag 150-250GeV,	40%-90%	CN-tag region	Norm
SysMJReduced_El_[075-150,150-400]ptv_[BB-BC-CC,CN]	MJ shape	MJ el, 1 lep	shape	1 lep	Shape
SysMJReduced_Mu_[075-150,150-400]ptv_[2,3+]J_[BB-BC-CC,CN]	MJ shape	MJ mu, 1 lep	shape	1 lep	Shape
SysMJSFsCR_El_[075-150,150-400]ptv_[BB-BC-CC,CN]	MJ shape	MJ el, 1 lep	shape	1 lep	Shape
SysMJSFsCR_Mu_[075-150,150-400]ptv_[BB-BC-CC,CN]	MJ shape	MJ mu, 1 lep	shape	1 lep	Shape

Table 14: Multi-jet nuisance parameters.

VH and VZ Fit Pull Comparison

This section presents the pull and constraint of the NPs in $VH(\rightarrow b\bar{b}, c\bar{c})$ analysis. Two fit are compared: The nominal VH 2POI fit (shown in blue), which use $VH(\rightarrow b\bar{b})$ and $VH(\rightarrow c\bar{c})$ signal strength as POI, and cross-check VZ 2POI fit (shown in green), which use $VZ(\rightarrow b\bar{b})$ and $VZ(\rightarrow c\bar{c})$ signal strength as POI. Both fits are the unconditional fit to the Run-2 Data combining the resolved and boosted regimes.

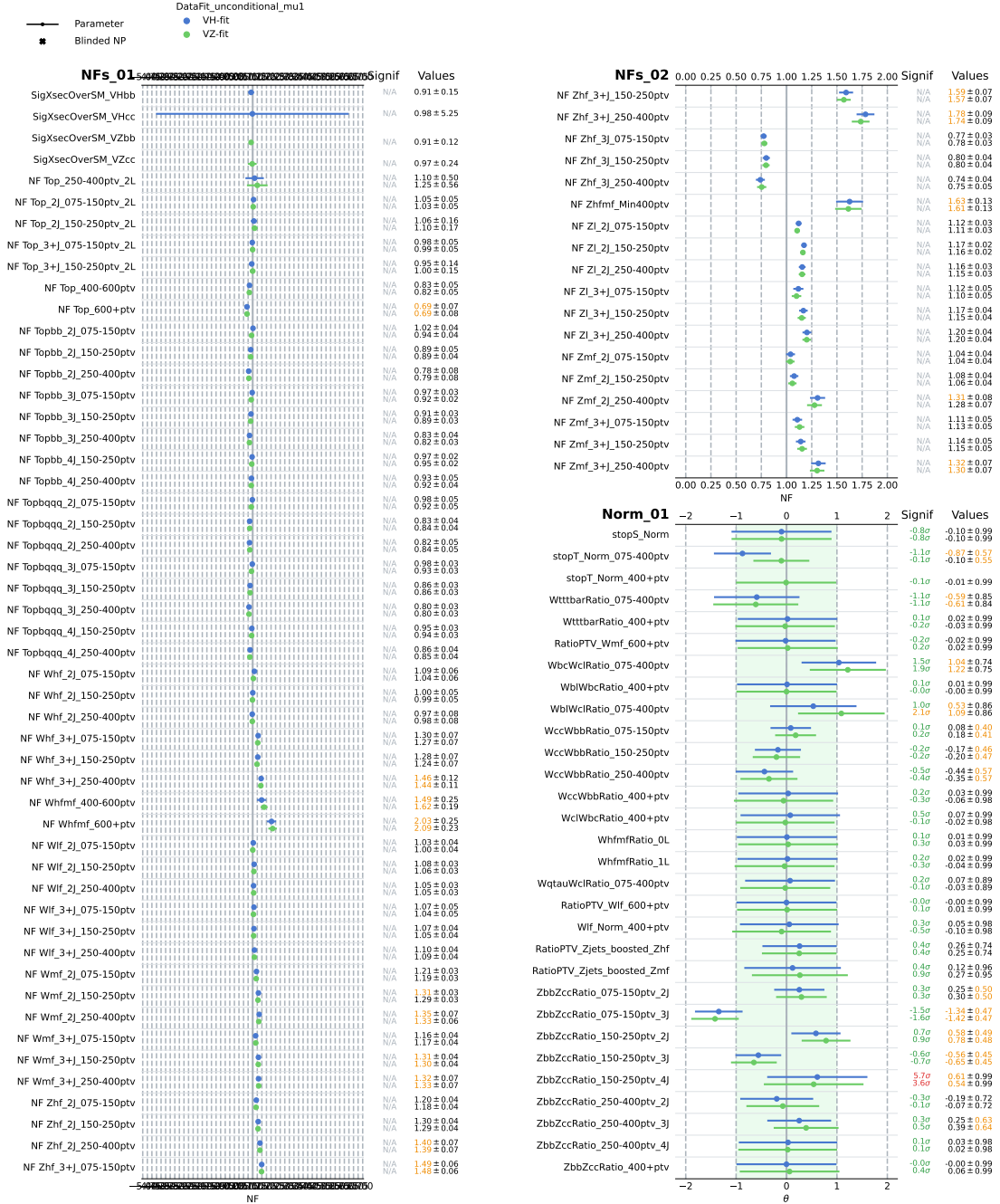


Figure 52: MC modelling nuisance parameter pulls and the free parameter scale factors comparing VH (blue) or VZ (green) fit.

$VH(\rightarrow b\bar{b}, c\bar{c})$ Analysis Detail

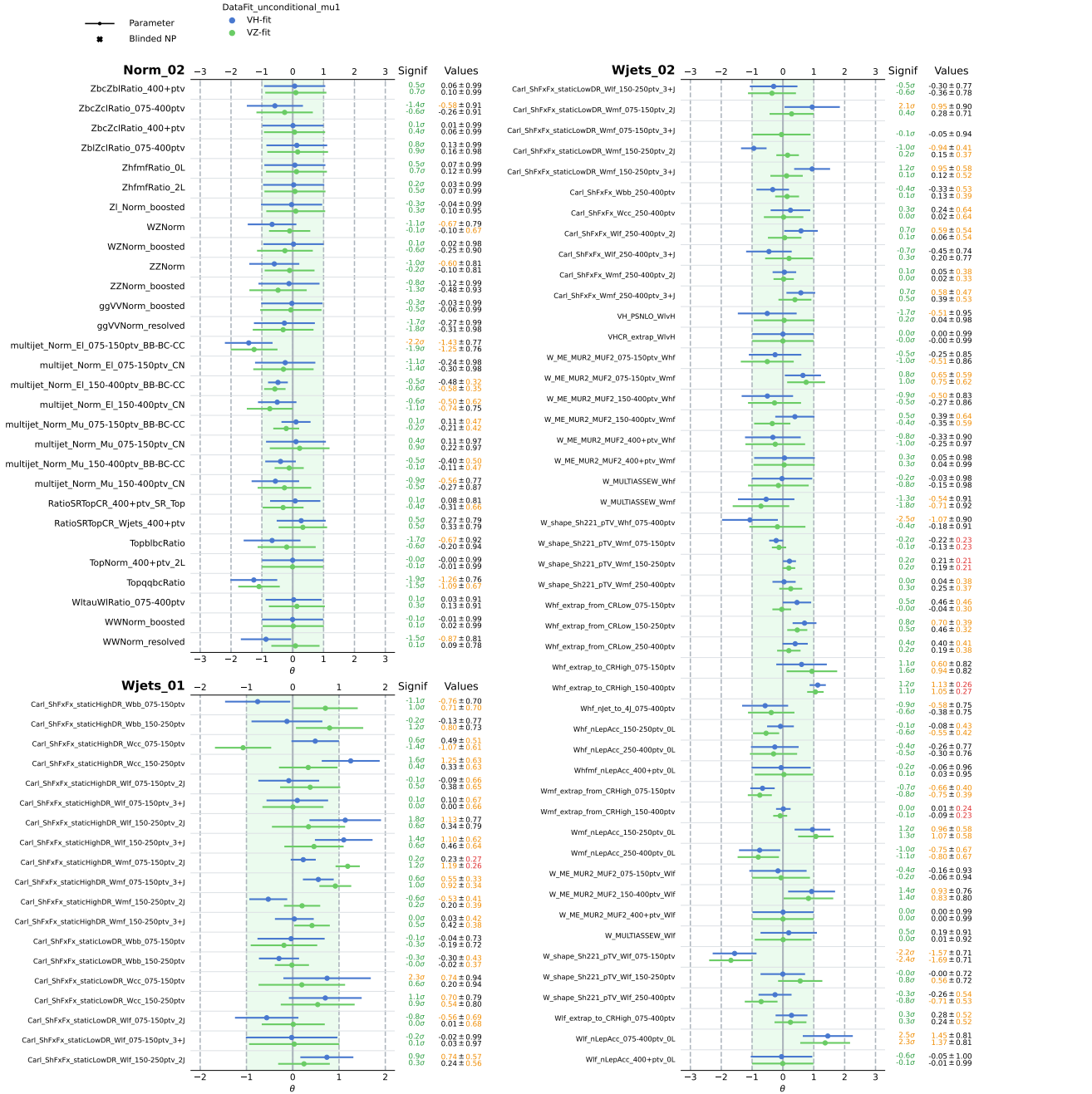


Figure 53: MC modelling nuisance parameter pulls and the free parameter scale factors comparing VH (blue) or VZ (green) fit.



Figure 54: MC modelling nuisance parameter pulls and the free parameter scale factors comparing VH (blue) or VZ (green) fit.

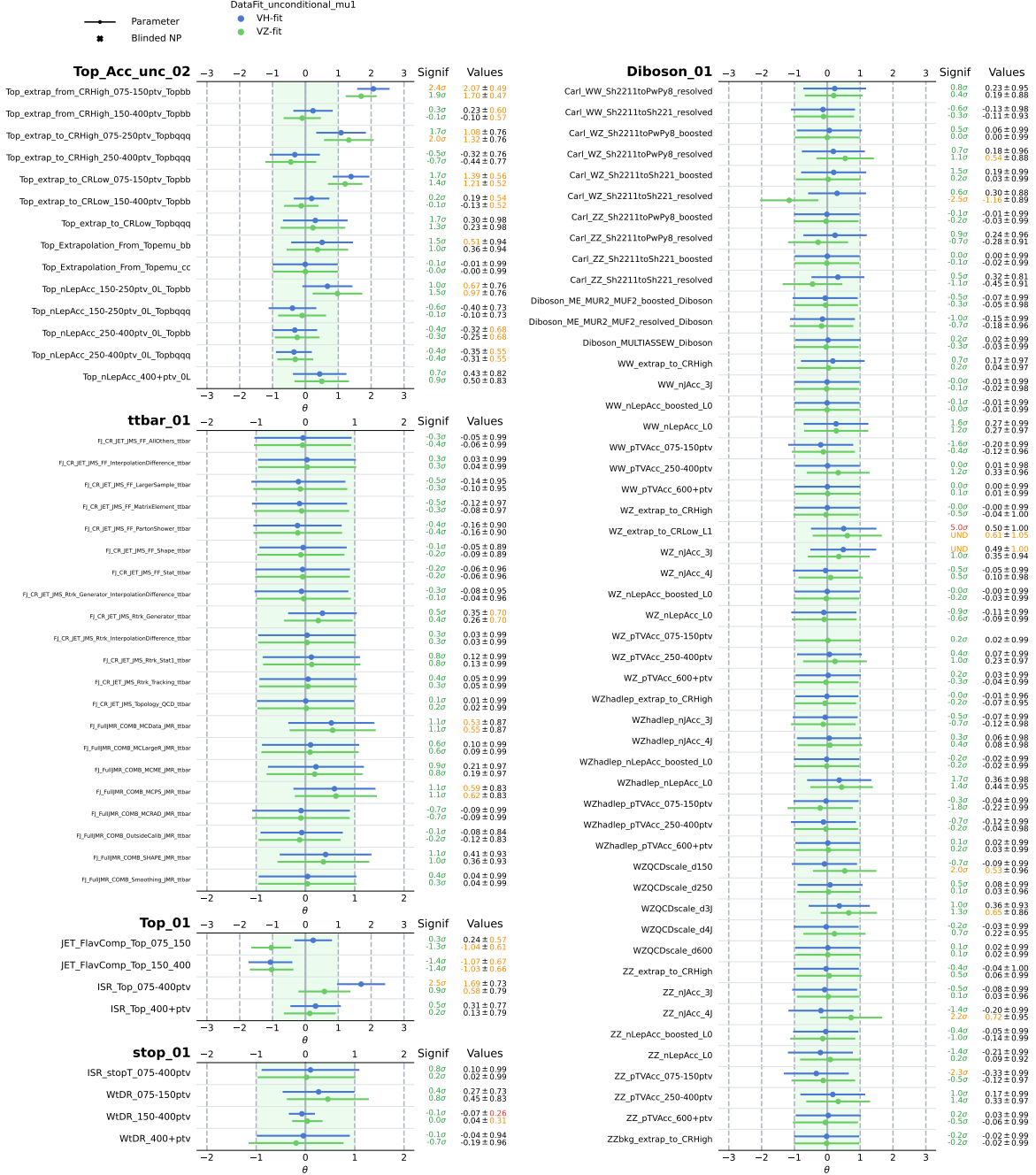


Figure 55: MC modelling nuisance parameter pulls and the free parameter scale factors comparing VH (blue) or VZ (green) fit.

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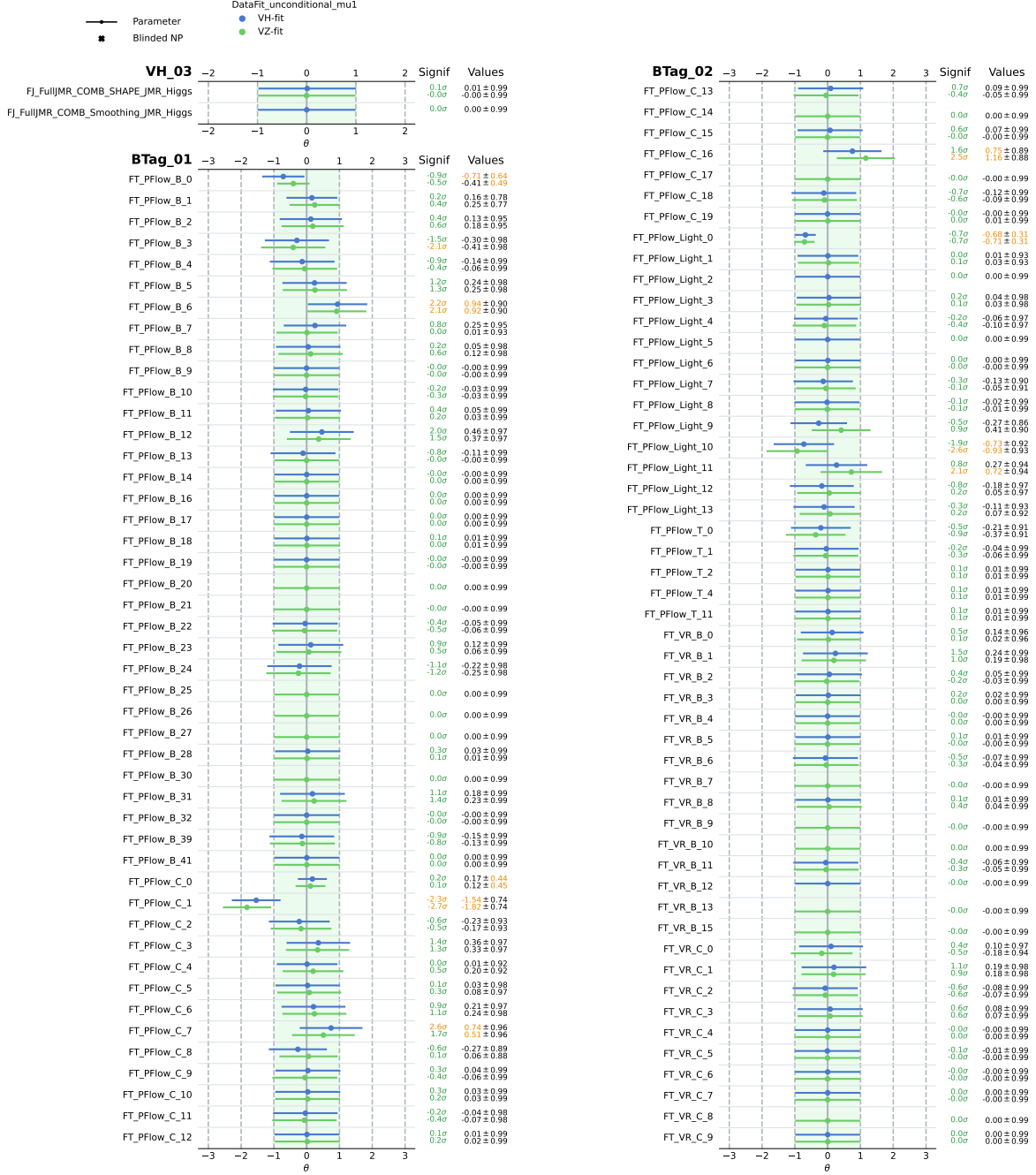


Figure 57: MC modelling nuisance parameter pulls and the free parameter scale factors comparing VH (blue) or VZ (green) fit.

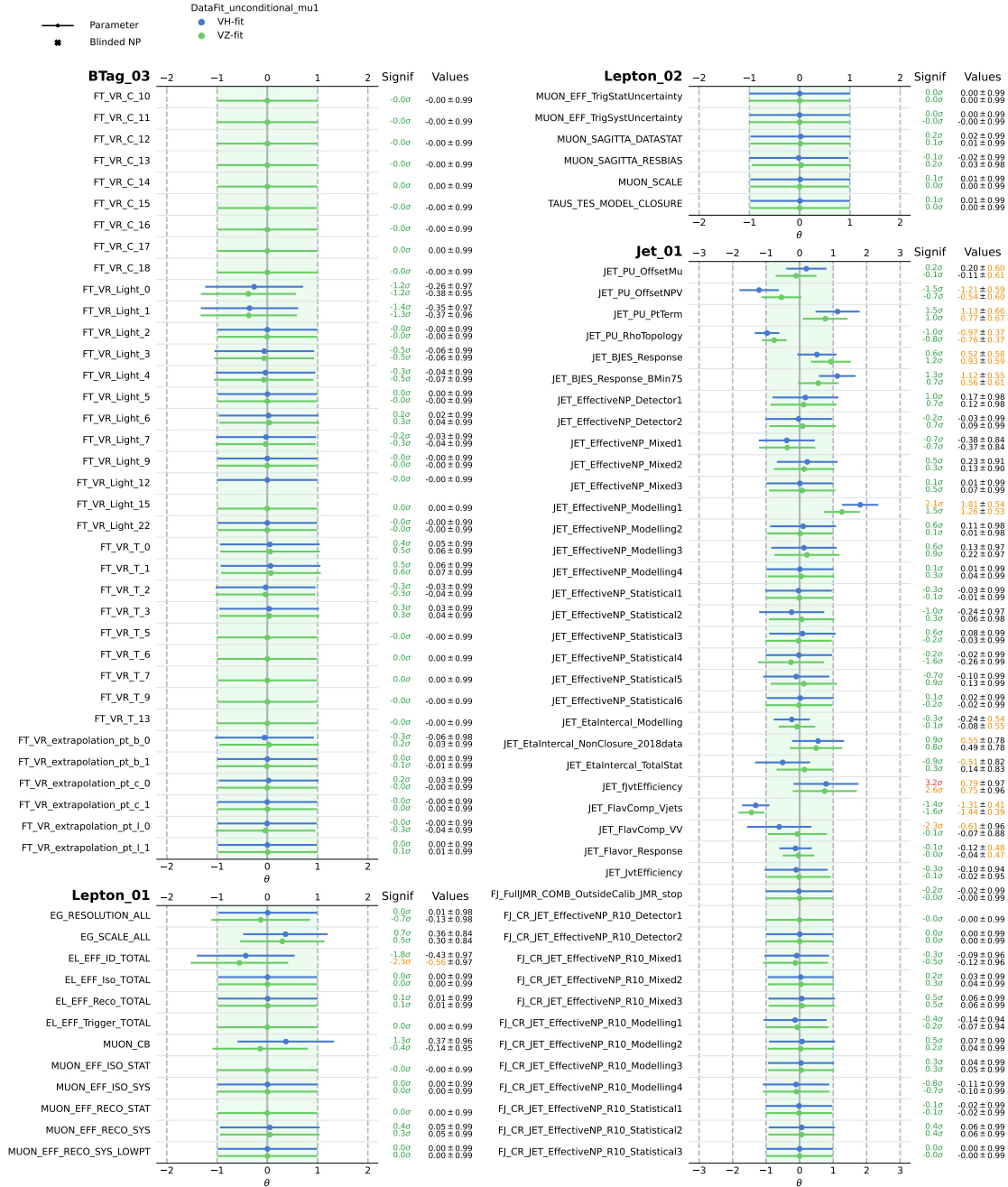


Figure 58: MC modelling nuisance parameter pulls and the free parameter scale factors comparing VH (blue) or VZ (green) fit.

$VH(\rightarrow b\bar{b}, c\bar{c})$ Analysis Detail

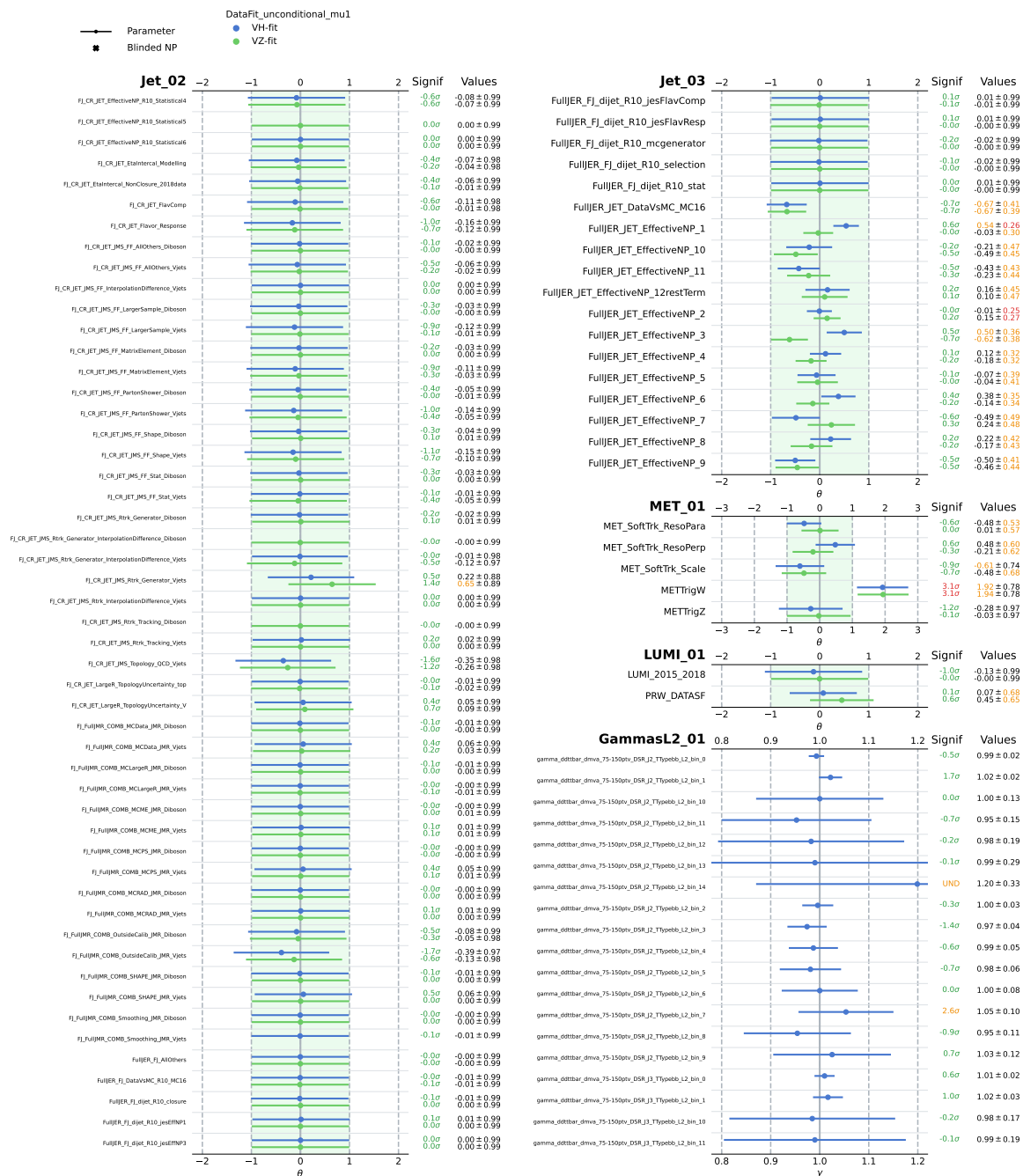


Figure 59: MC modelling nuisance parameter pulls and the free parameter scale factors comparing VH (blue) or VZ (green) fit.

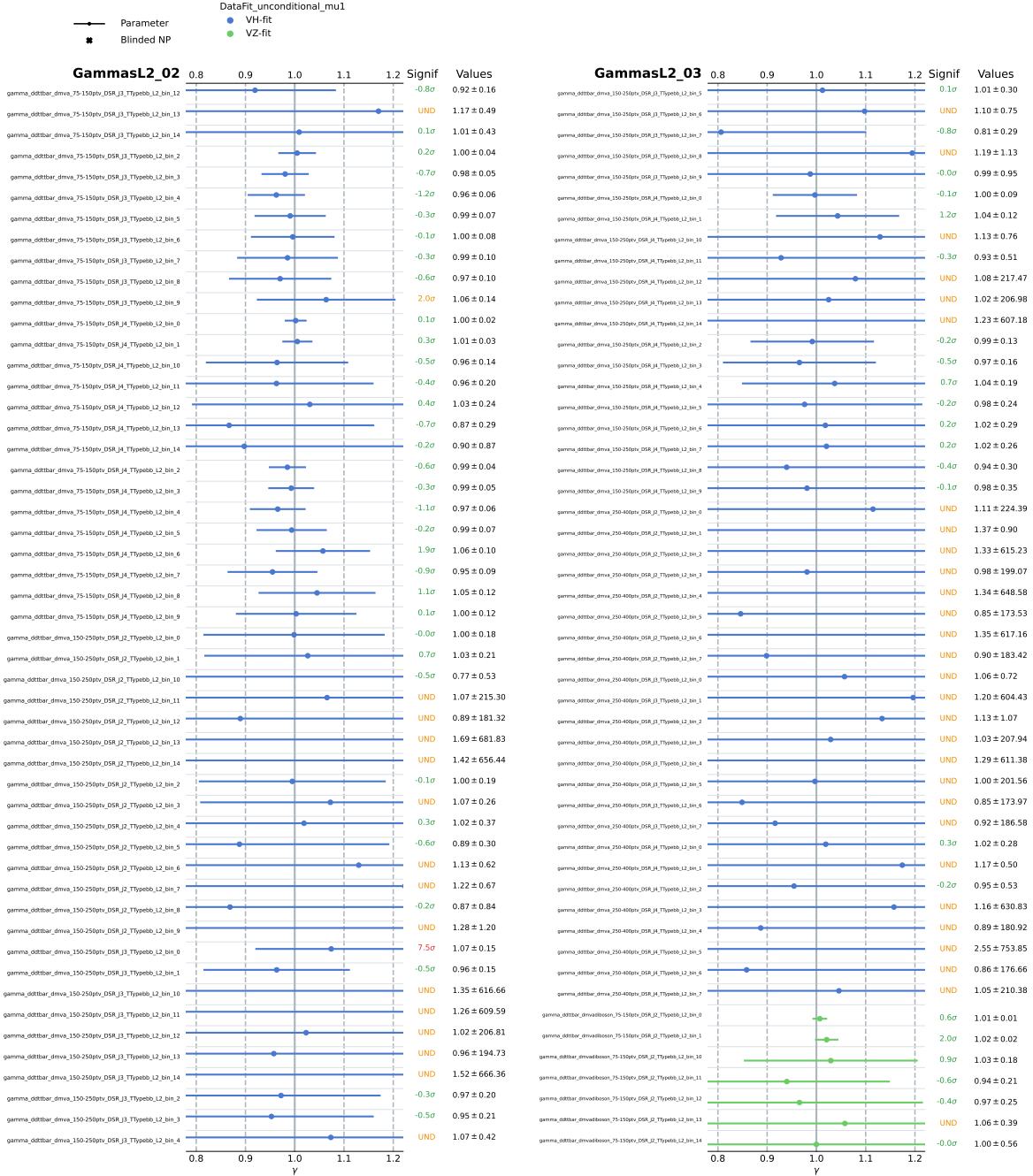


Figure 60: MC modelling nuisance parameter pulls and the free parameter scale factors comparing VH (blue) or VZ (green) fit.

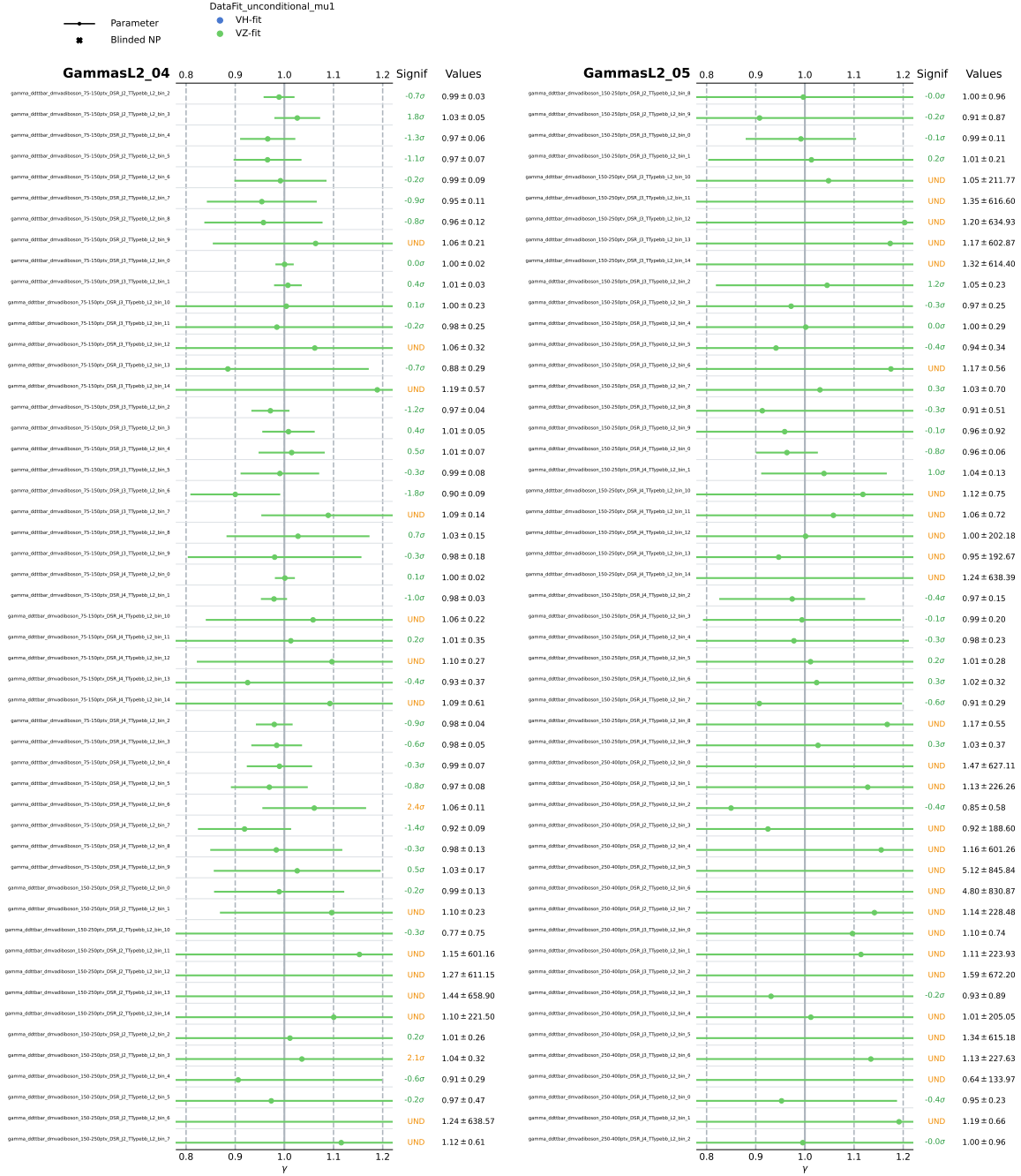


Figure 61: MC modelling nuisance parameter pulls and the free parameter scale factors comparing VH (blue) or VZ (green) fit.

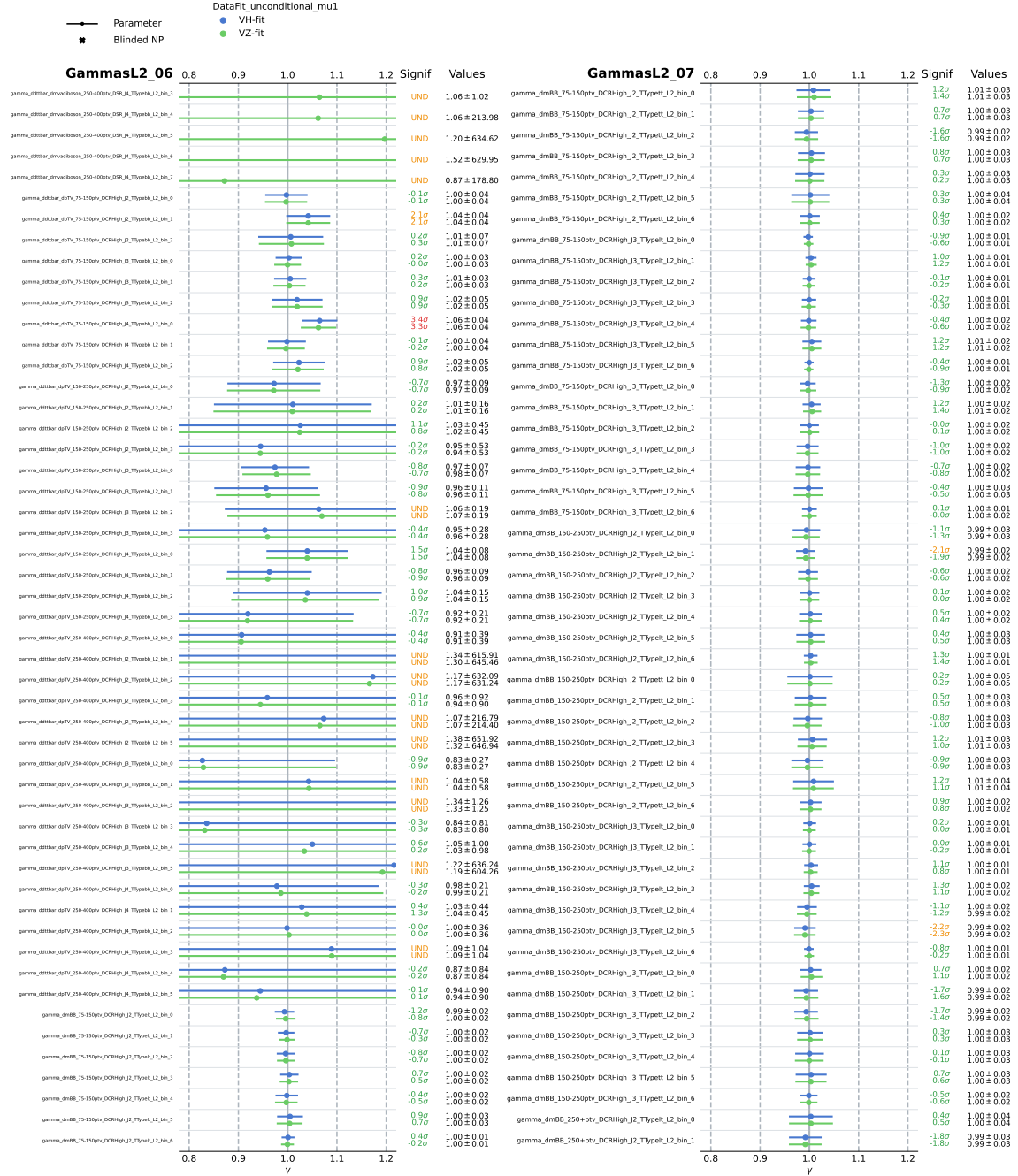


Figure 62: MC modelling nuisance parameter pulls and the free parameter scale factors comparing VH (blue) or VZ (green) fit.

$VH(\rightarrow b\bar{b}, c\bar{c})$ Analysis Detail

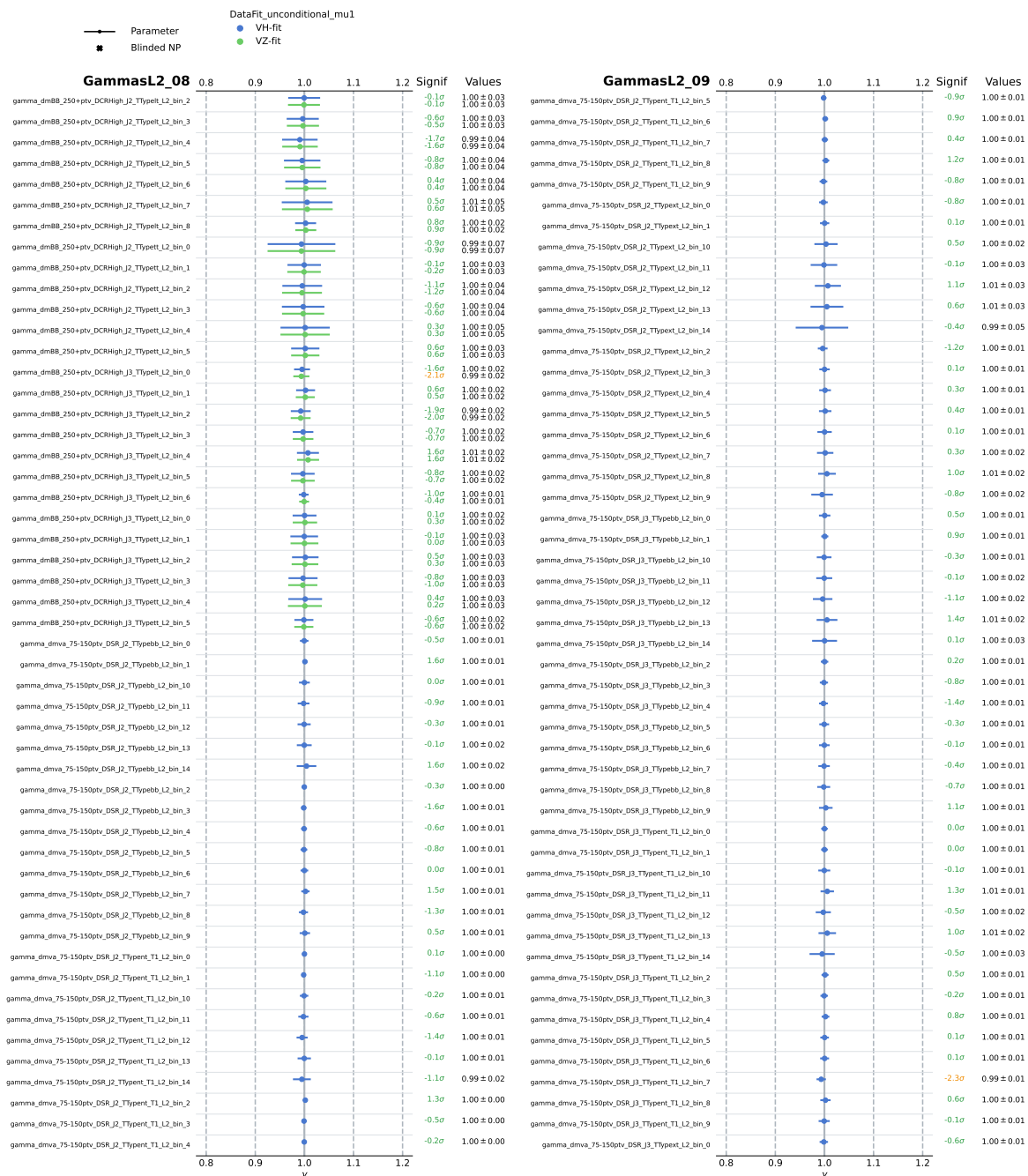


Figure 63: MC modelling nuisance parameter pulls and the free parameter scale factors comparing VH (blue) or VZ (green) fit.

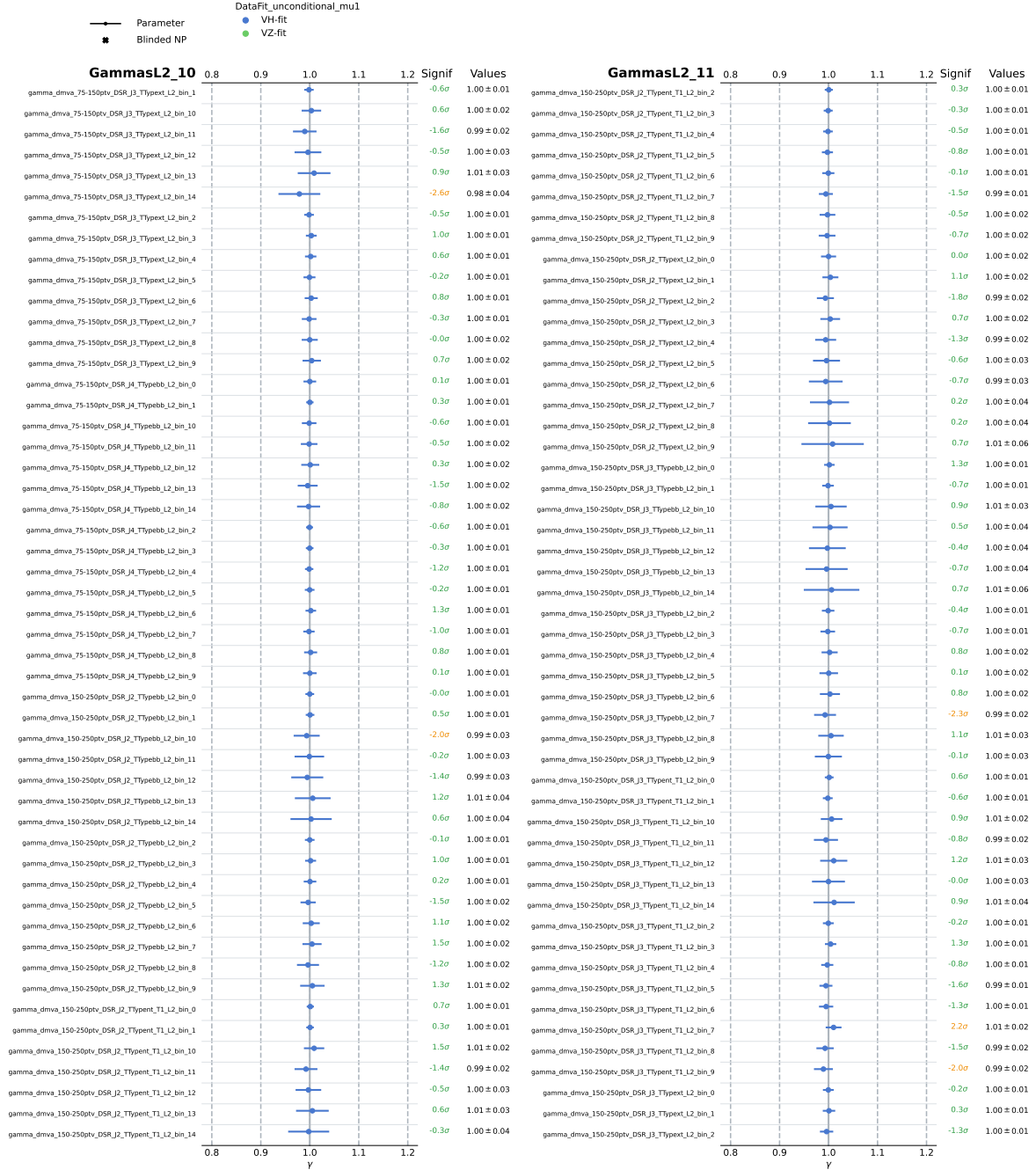


Figure 64: MC modelling nuisance parameter pulls and the free parameter scale factors comparing VH (blue) or VZ (green) fit.

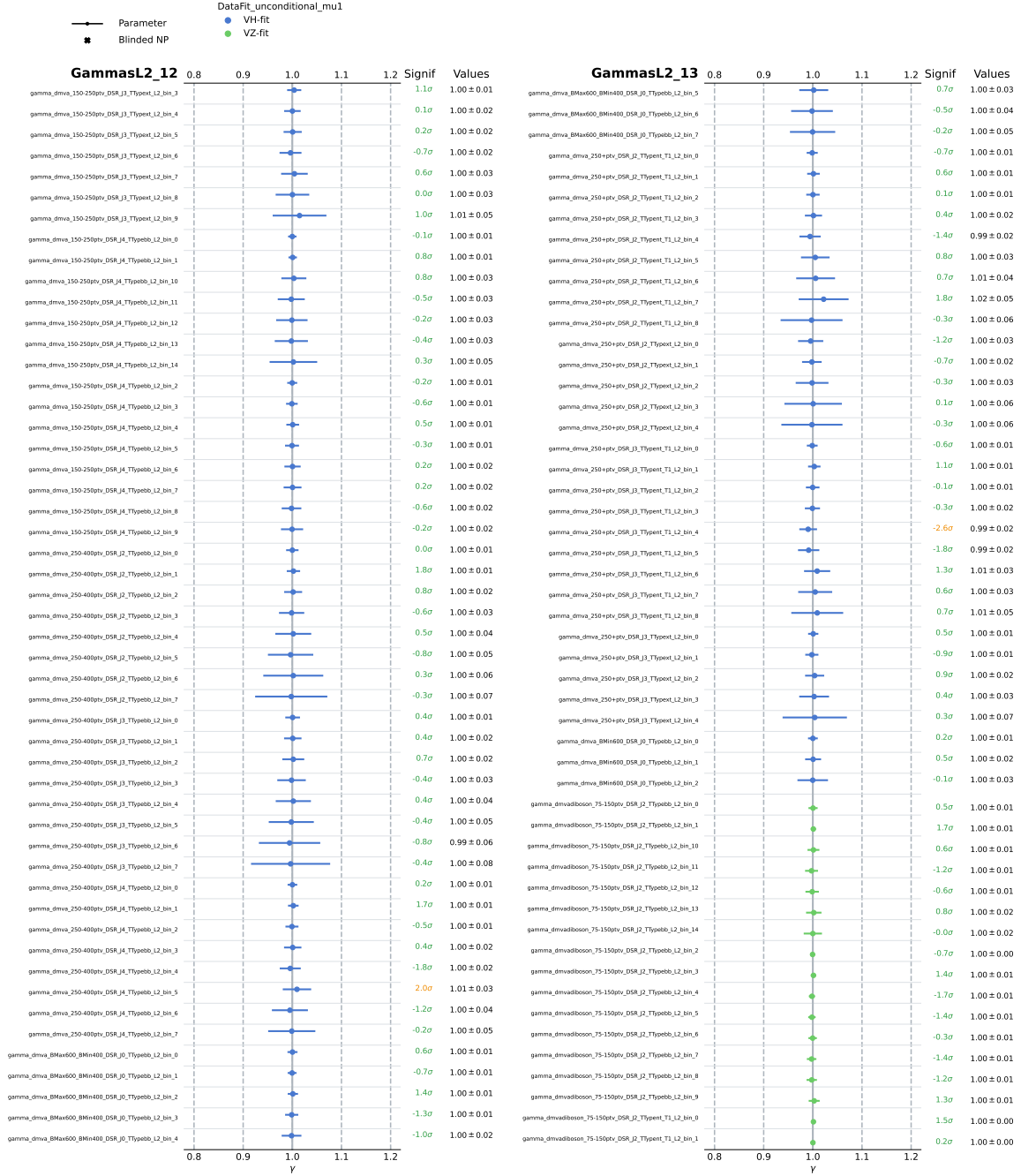


Figure 65: MC modelling nuisance parameter pulls and the free parameter scale factors comparing VH (blue) or VZ (green) fit.

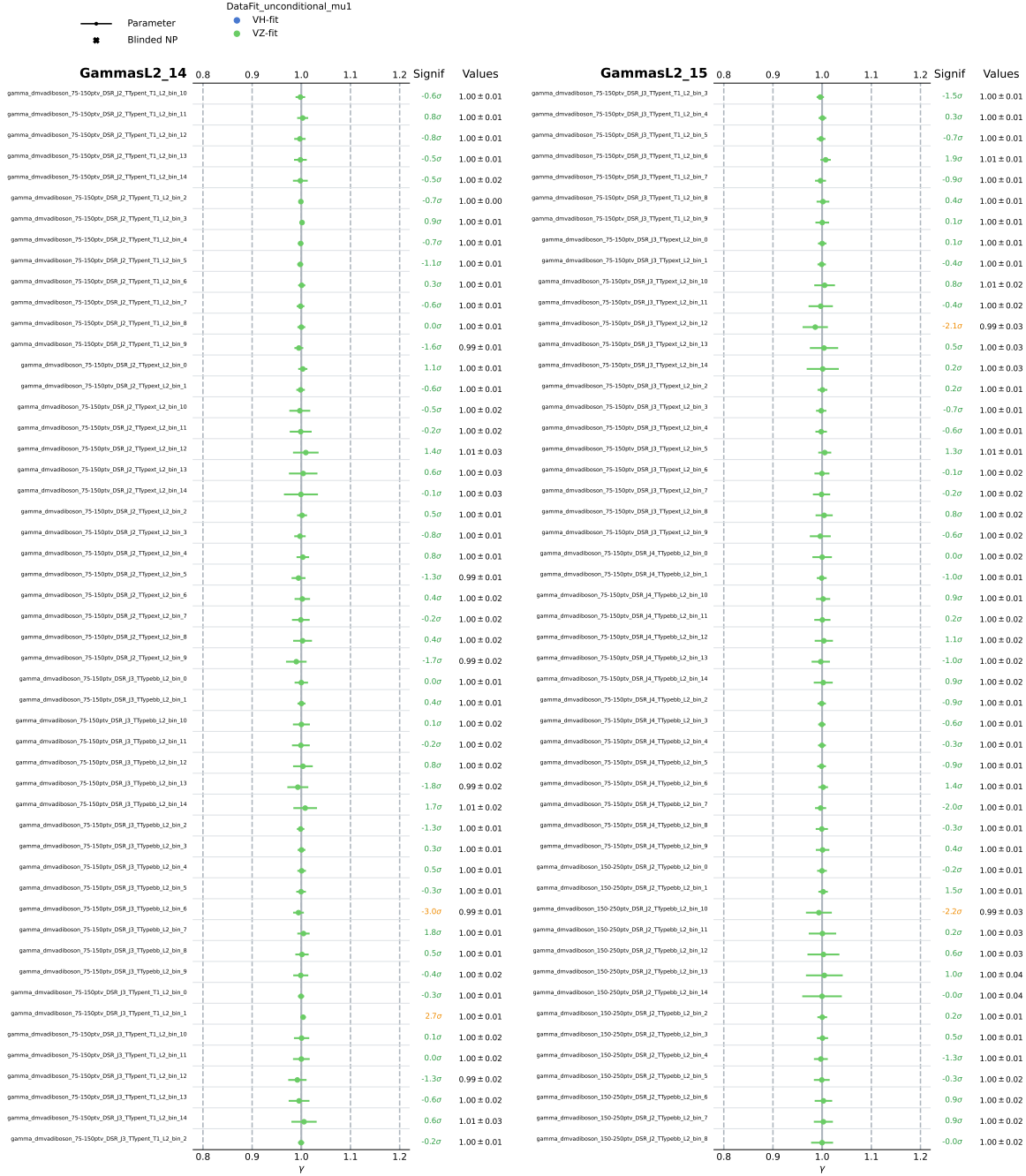


Figure 66: MC modelling nuisance parameter pulls and the free parameter scale factors comparing VH (blue) or VZ (green) fit.

$VH(\rightarrow b\bar{b}, c\bar{c})$ Analysis Detail

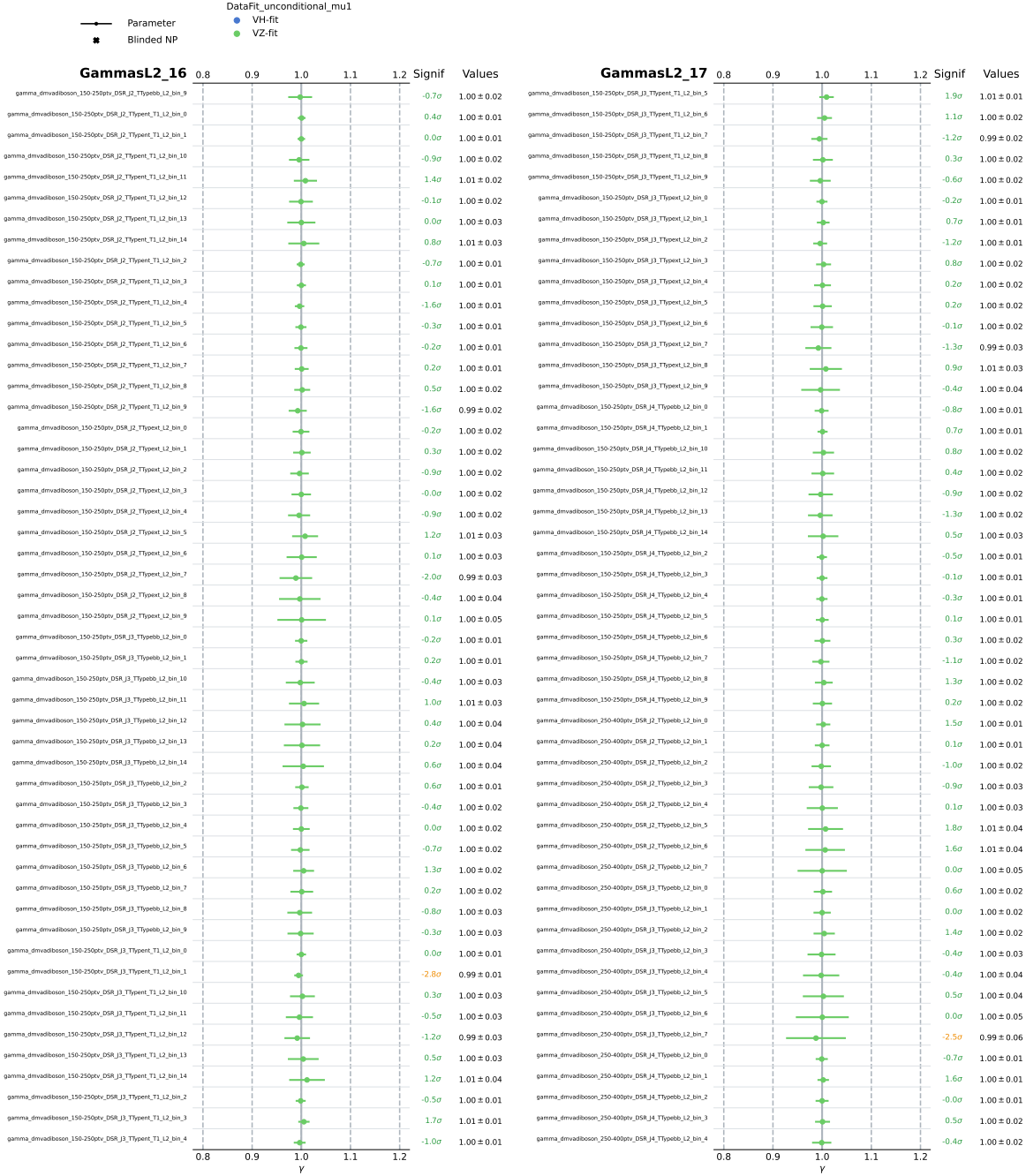
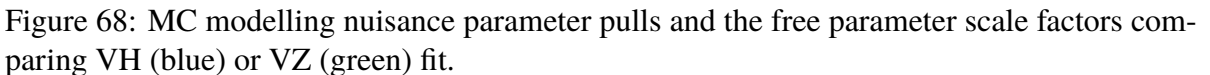


Figure 67: MC modelling nuisance parameter pulls and the free parameter scale factors comparing VH (blue) or VZ (green) fit.



$VH(\rightarrow b\bar{b}, c\bar{c})$ Analysis Detail

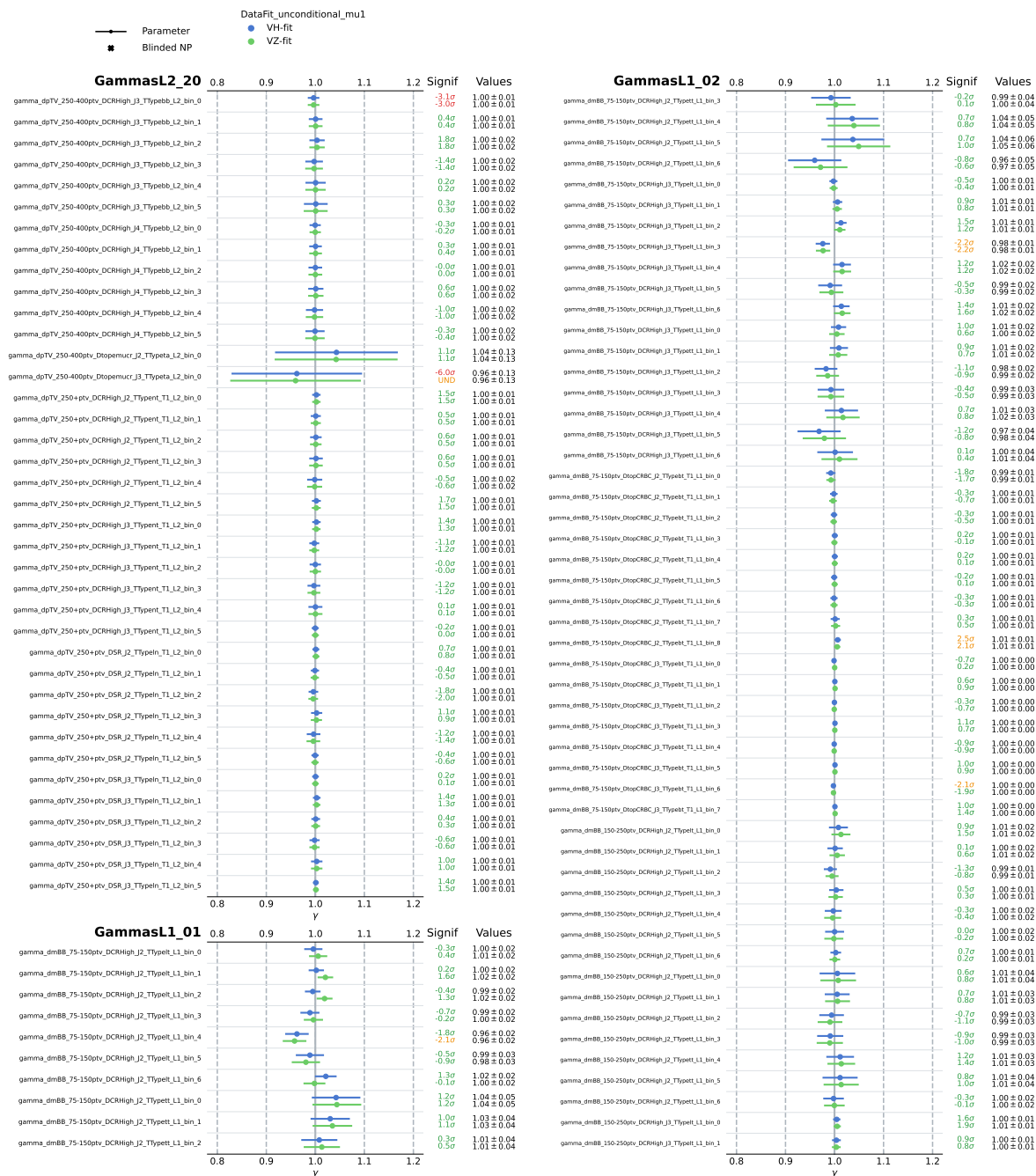


Figure 69: MC modelling nuisance parameter pulls and the free parameter scale factors comparing VH (blue) or VZ (green) fit.

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$VH(\rightarrow b\bar{b}, c\bar{c})$ Analysis Detail

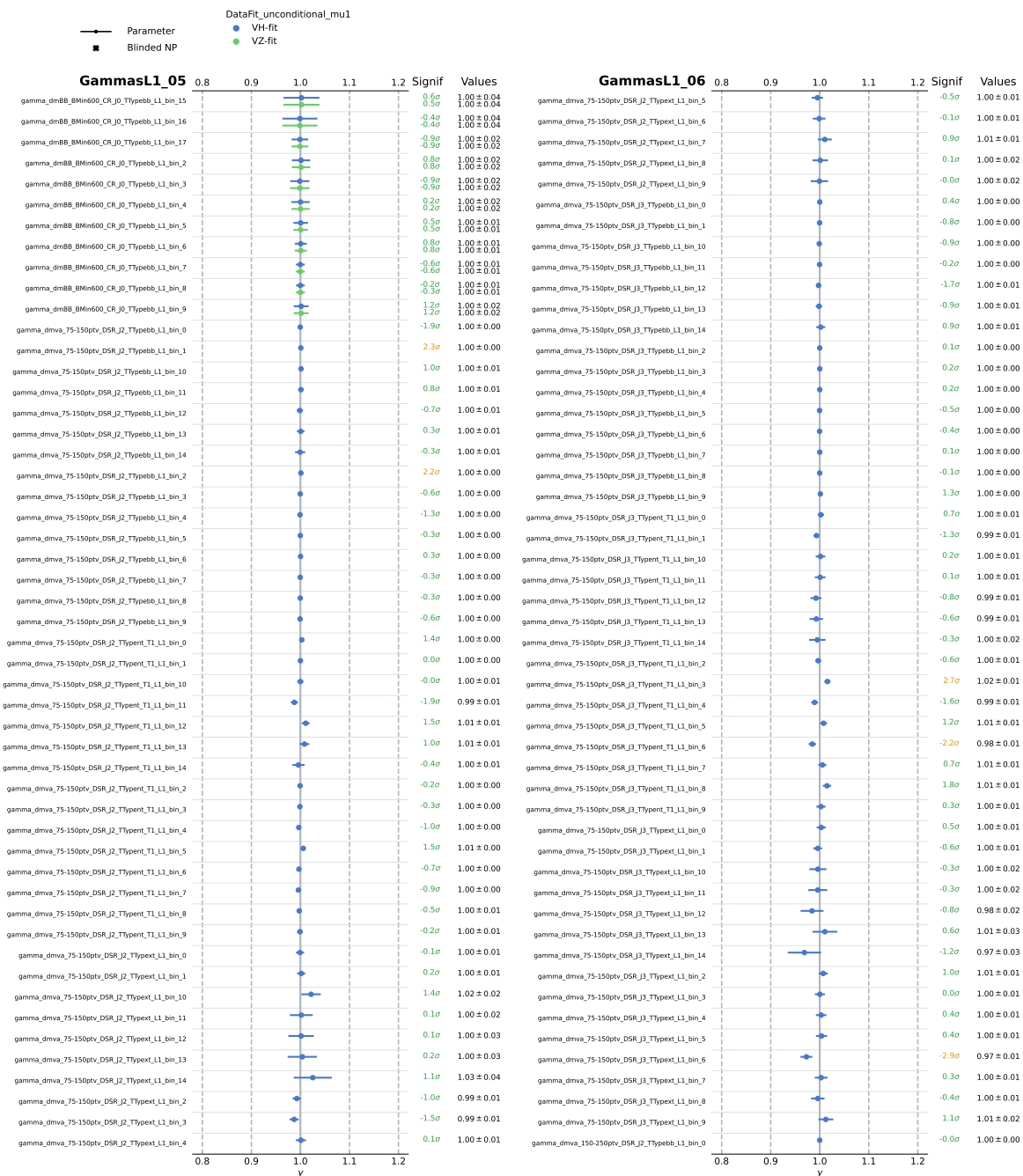


Figure 71: MC modelling nuisance parameter pulls and the free parameter scale factors comparing VH (blue) or VZ (green) fit.

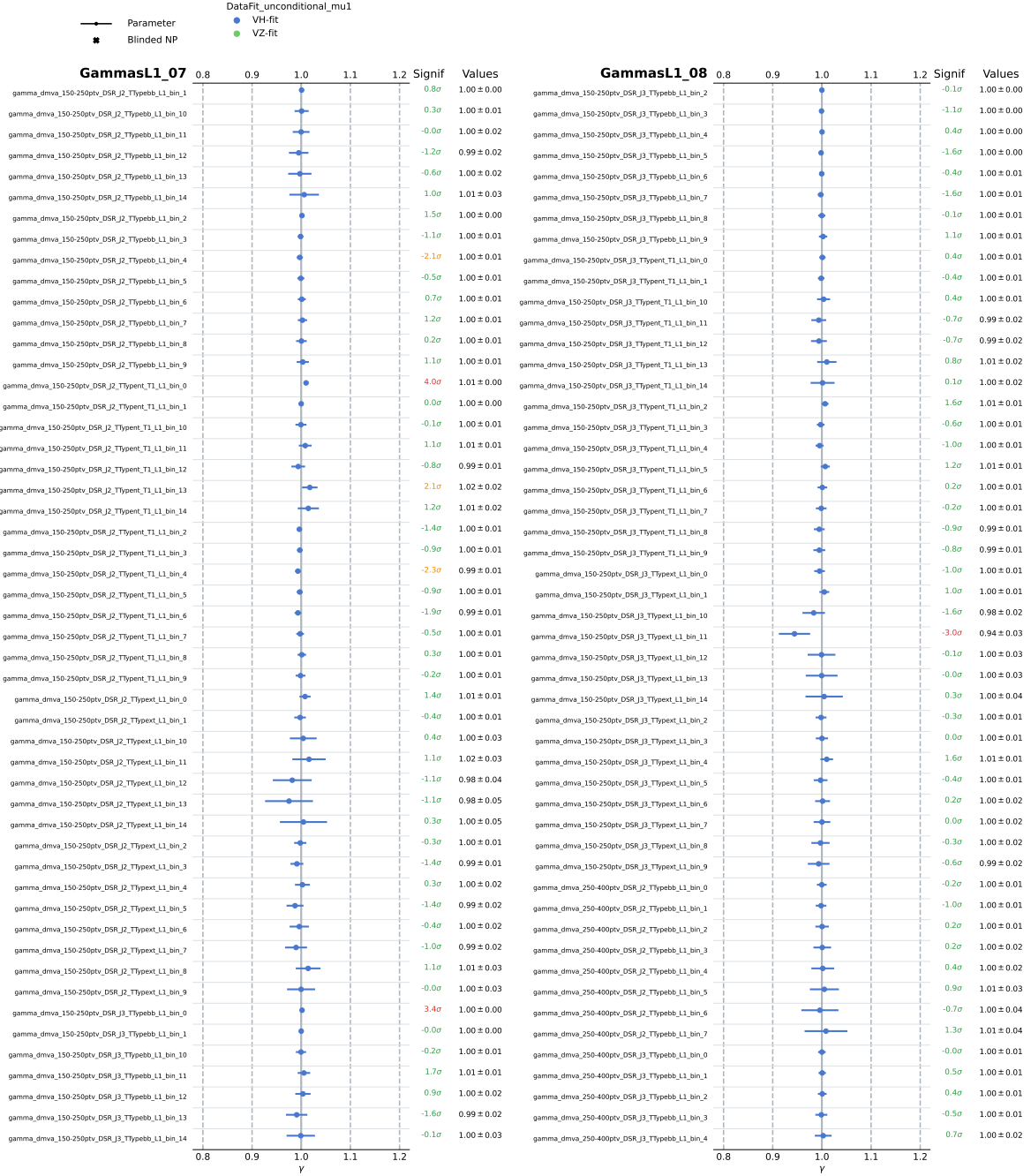


Figure 72: MC modelling nuisance parameter pulls and the free parameter scale factors comparing VH (blue) or VZ (green) fit.

$VH(\rightarrow b\bar{b}, c\bar{c})$ Analysis Detail

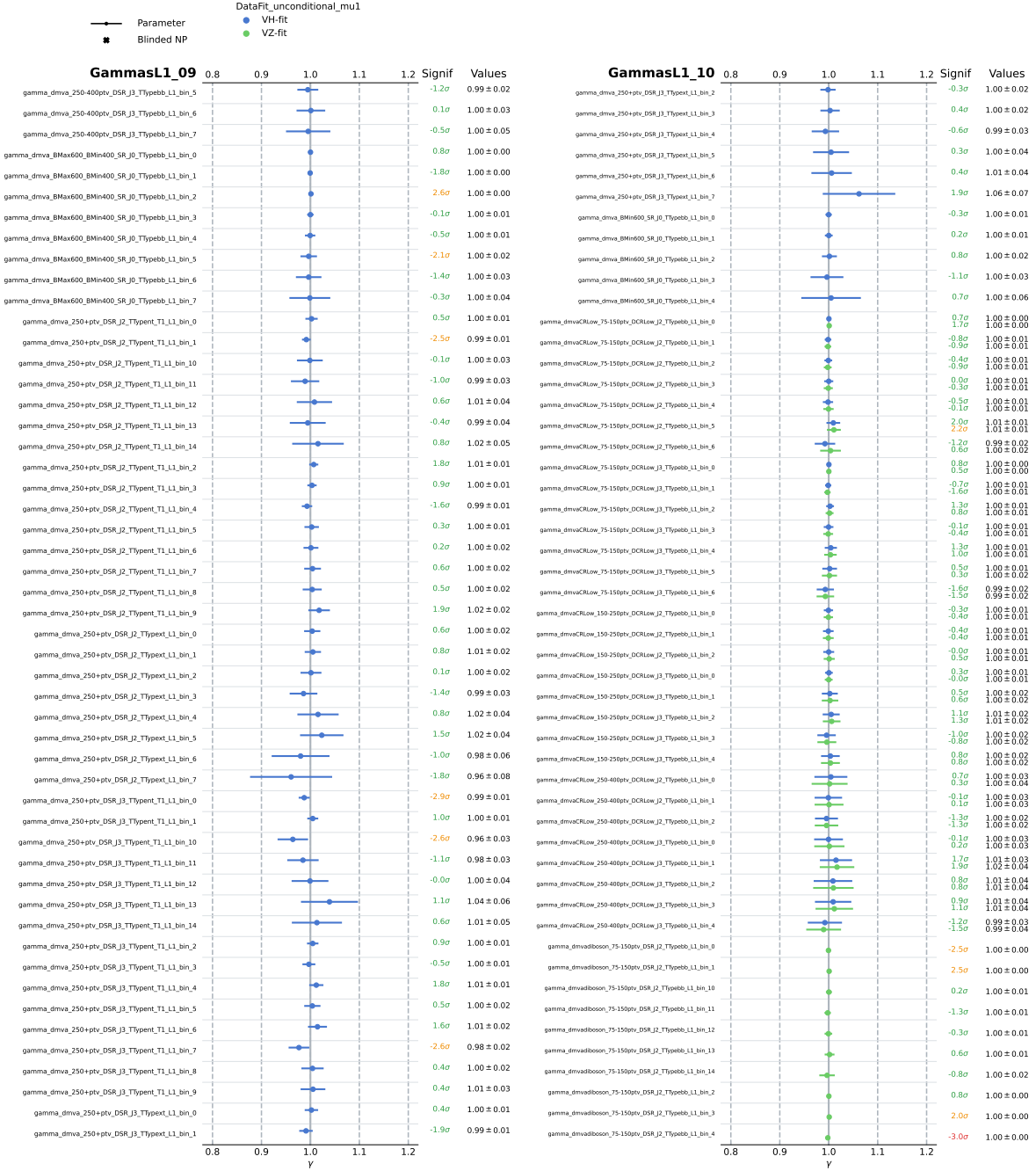


Figure 73: MC modelling nuisance parameter pulls and the free parameter scale factors comparing VH (blue) or VZ (green) fit.

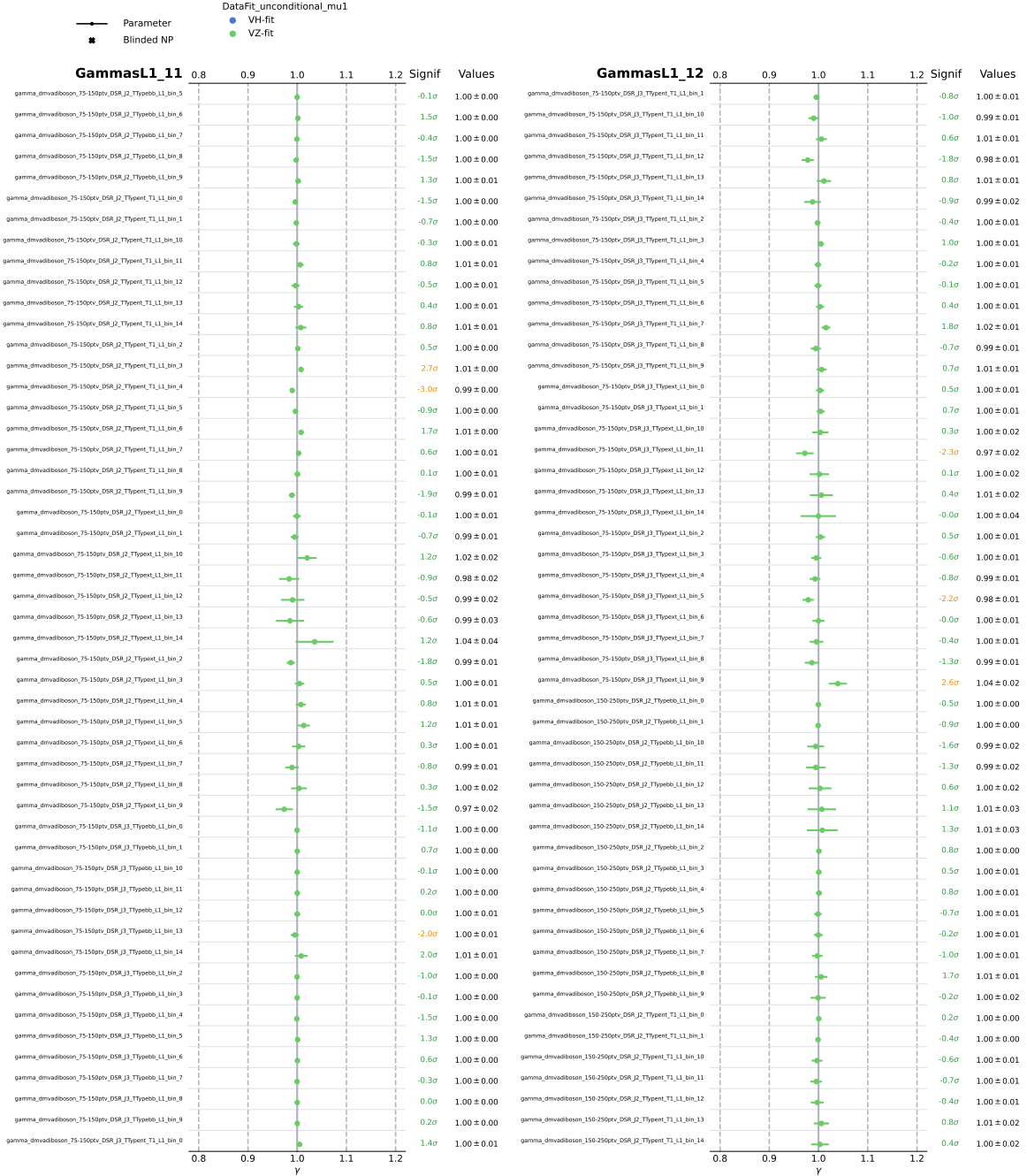
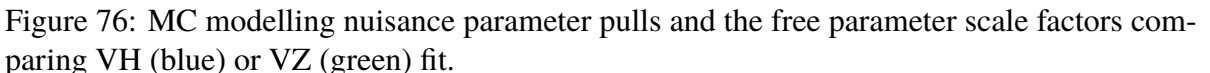


Figure 74: MC modelling nuisance parameter pulls and the free parameter scale factors comparing VH (blue) or VZ (green) fit.

$VH(\rightarrow b\bar{b}, c\bar{c})$ Analysis Detail



Figure 75: MC modelling nuisance parameter pulls and the free parameter scale factors comparing VH (blue) or VZ (green) fit.



$VH(\rightarrow b\bar{b}, c\bar{c})$ Analysis Detail

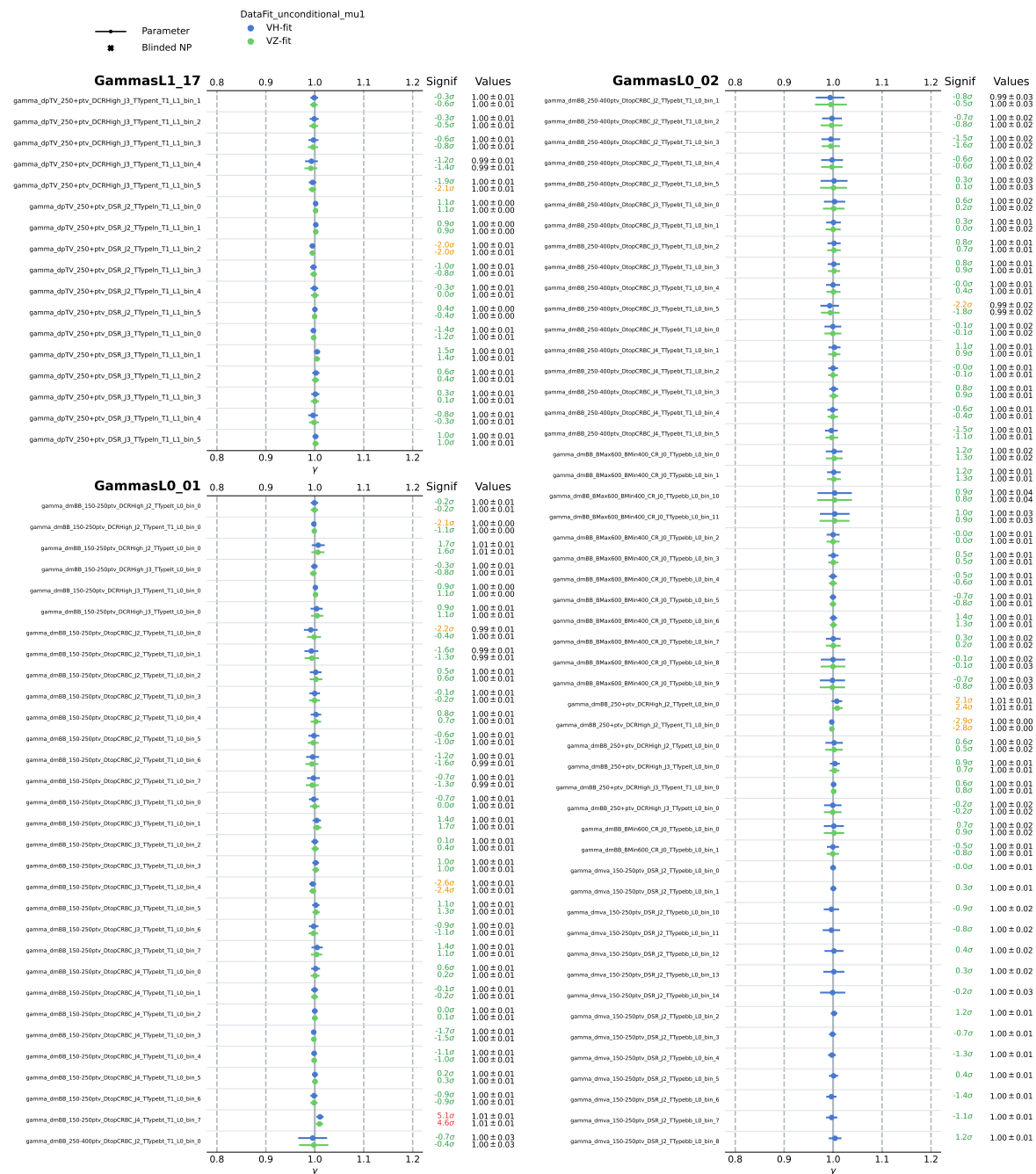


Figure 77: MC modelling nuisance parameter pulls and the free parameter scale factors comparing VH (blue) or VZ (green) fit.



Figure 78: MC modelling nuisance parameter pulls and the free parameter scale factors comparing VH (blue) or VZ (green) fit.

$VH(\rightarrow b\bar{b}, c\bar{c})$ Analysis Detail



Figure 79: MC modelling nuisance parameter pulls and the free parameter scale factors comparing VH (blue) or VZ (green) fit.

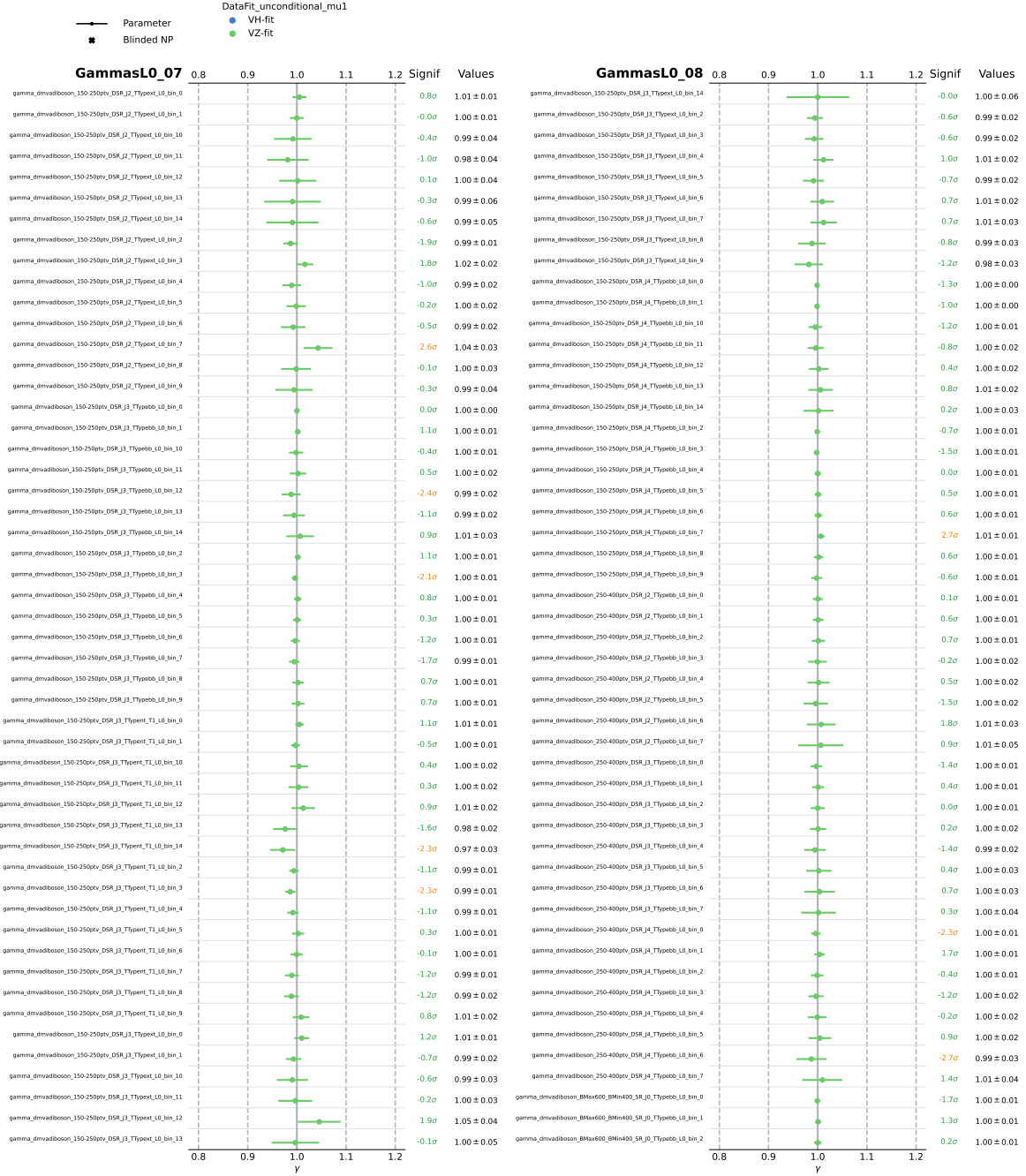


Figure 80: MC modelling nuisance parameter pulls and the free parameter scale factors comparing VH (blue) or VZ (green) fit.

$VH(\rightarrow b\bar{b}, c\bar{c})$ Analysis Detail

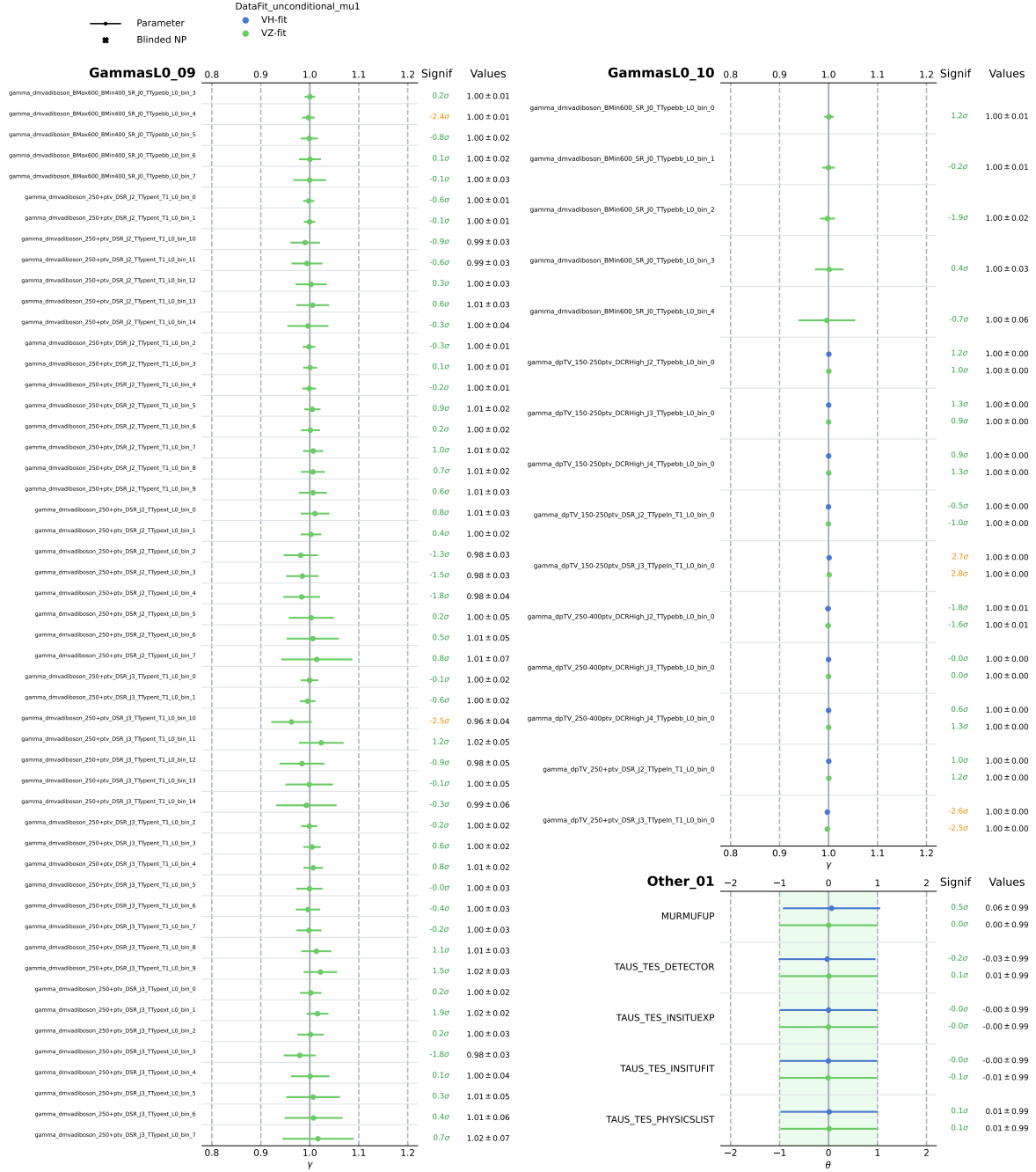


Figure 81: MC modelling nuisance parameter pulls and the free parameter scale factors comparing VH (blue) or VZ (green) fit.