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Measurement of Vector Boson Scattering in semileptonic final
states with the ATLAS detector using LHC Run-2 data

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Abstract

The discovery of the Higgs boson in 2012 confirmed the existence of all particles in the Standard Model (SM). Although the SM can predict precisely various phenomena up to around the electroweak scale, it is still an incomplete theoretical model. It is necessary to explore the possibilities of physics beyond the SM through measurements of the SM processes and searches for new particles. Vector Boson Scattering (VBS) is an important process to probe the electroweak symmetry breaking in the SM, and its' cross section can be easily modified by the anomalous gauge couplings at high transverse momenta of the vector bosons. Therefore the measurement of the VBS is one of the most essential topics in the physics program at the LHC experiment. This thesis reports the measurement of the electroweak production of a pair of weak vector bosons in association with two forward jets (EW VV+jj), including the VBS, with the semi-leptonic final states. The analysis has been done with data collected by the ATLAS detector during the whole Run 2 of the LHC, corresponding integrated luminosity of 139 fb^{-1} . The signal strength and the significance of the EW VV+jj process are reported. The measured results with all three decay channels are interpreted in terms of the anomalous quartic gauge coupling appearing in the dimension-8 effective field theory.

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Chapter 1

Introduction

The Standard Model (SM) of particle physics describes the fundamental particles composing matters in nature and the interactions among them. The discovery of a Higgs boson in 2012 by the ATLAS and the CMS experiments confirmed the existence of all particles in the SM [14, 54]. Although the SM can predict precisely phenomena up to around the electroweak scale, it is still an incomplete theory model, as there are several phenomena that cannot be explained by the SM such as the existence of dark matter and the hierarchy problem. It is necessary to explore the physics beyond the SM (BSM) through both precise measurements of the SM processes and direct searches of the new particles.

One of the most important topics of the research program is to reveal the underlying mechanism behind the electroweak symmetry breaking, and the precise understanding of the electroweak sector of the SM. The electroweak symmetry breaking can be tested in detail by investigating the properties of the VBS since it is sensitive to interactions between the longitudinal components of the gauge bosons.

In addition, in case the origin of the electroweak symmetry breaking is not unity or there is a new resonant state at the energy scale that cannot be explored directly at the LHC, the VBS cross section is expected to be modified by the interactions involving the new particle.

Experimentally, the VBS signature is characterized by the presence of a pair of vector bosons (W , Z , or γ) and two forward jets with a large separation in rapidity and a large dijet invariant mass. Both ATLAS and CMS discovered the VBS process [42, 57] with 5 standard deviations from the null hypothesis in the full-leptonic final state, but due to the small branching ratio, the measurement can reach the energy scale of new physics only up to around 500 GeV. To cover a wider mass range up to TeV, the VBS measurement including the semi-leptonic final states are needed.

This thesis reports the measurement of the electroweak production of the pair of vector bosons in association with two hadron jets, including VBS, in the semi-leptonic final states.

The main challenge of the semi-leptonic channel ($V(qq')Z(\nu\nu)$, $V(qq')W(l\nu)$ and $V(qq')Z(l\bar{l})$ ($V = W, Z$)) is the presence of large backgrounds from W +jets, Z +jets and $t\bar{t}$ events. These backgrounds make a VBS measurement in this channel challenging, but despite that, the semi-leptonic channel has some advantages compared to the full-leptonic channel. The hadronically

decaying branching fractions are much larger than the leptonically decaying branching fractions which benefit especially in high- p_T region and the use of jet substructure techniques allows good background rejection despite its high branching ratio.

Another advantage of the semi-leptonic channel is a suitable channel not only for the SM cross-section measurement but also for its interpretation into the BSM physics with more statistics compared to the full-leptonic channel in the phase space with high transverse momentum (p_T) of the vector bosons and at a high invariant mass of the diboson system. A common way of parameterizing BSM physics in VBS is through an effective field theory (EFT) [77], which is a model-independent approach to avoid focussing on a specific BSM theory. In the EFT framework, VBS can be modified.

This thesis consists of the following chapters. Chapter 2 describes briefly the theoretical overview of the SM and VBS analysis, and its interpretation in the EFT framework. Chapter 3 describes the experimental setup of the LHC collider and the ATLAS detectors. The definition of the physics objects and how they are reconstructed is described in chapter 4. The definition of the signal and the background process definition are listed in chapter 5. Chapter 6 shows the event selection applied to the whole analysis. The background modeling validation and its estimation method are summarized in chapter 7, and the multi-variate techniques used for extracting the signals are explained in chapter 7. The details of systematic uncertainties are described in chapter 8, and the statistical analysis is shown in chapter 9. Finally, the results of the measurement are shown in chapter 10. Chapter 11 describes the interpretation of the results with the EFT. The conclusion of this thesis is summarized in chapter 12.

Chapter 2

Theoretical overview

2.1 The Standard Model

The Standard Model (SM) represents a description of the elementary particles and their interactions. It is a successful theory model to explain the experimental results observed until today, and it has predicted a lot of parameters. All particles predicted by the SM have been confirmed. Most recently, the Higgs boson was discovered by ATLAS and CMS experiments in 2012. The SM predicts the existence of elementary particles which form the matter; leptons and quarks. The interactions among them are described by gauge fields mediated by the exchange of the corresponding gauge bosons. There are four types of known interactions in nature, namely electromagnetic, weak and strong force, and gravitational interactions. The first three of them are described by the SM.

The theoretical description is given with the Quantum Field Theory (QFT) framework. The invariance under the local gauge transformation is the key of the framework. The underlying symmetry is described by the Lie groups. It is written by $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge group and some more details are discussed in the following subsections.

2.1.1 Particle content

Figure 2.1 shows 17 fundamental particles, consisting of the SM. They are classified into two types following Fermi-Dirac or Bose-Einstein statistics.

- Fermions

Fermions are elementary particles with a spin of $1/2$. There are three generations also known as flavors. The particle mass increases from the first to third generations. The other parameters are exactly the same for those in the same category. They are two types of fermions; quarks and leptons, each has 6 particles. Quark has up-type and down-type quark, and lepton has charged and neutral lepton, classified by its charge. Leptons do not interact through the strong force, unlike the quarks.

- Bosons

Bosons are integer-spin particles and mediate the interaction of the fermions. The photon (γ) is the mediator of the electromagnetic force. The photon is massless and stable, hence

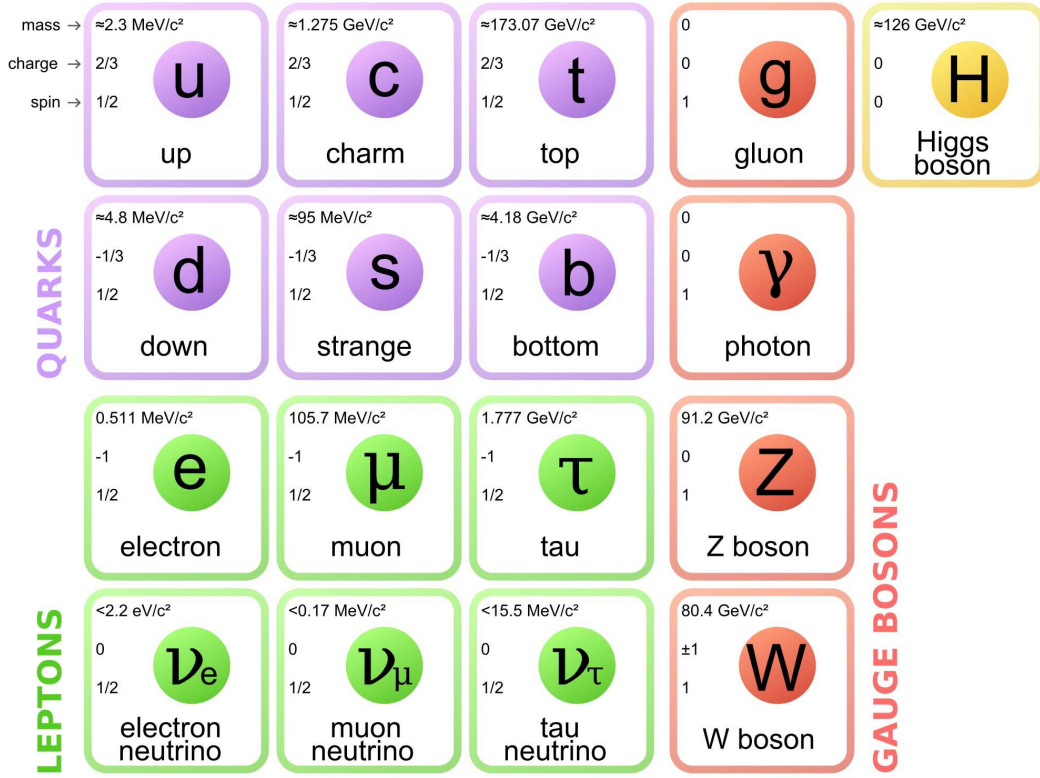


Figure 2.1: All particles exist in the SM

the electromagnetic force can reach infinite ranges. The photons interact with every particle with electric charges. The gluon (g) is the intermediate particle of the strong force. The gluon is also massless, and interacts with particles with the color charge, i.e. quarks. In addition, due to the non-Abelian nature of the $SU(3)$ gauge group, gluons have a self coupling and they can interact with each other. The $W^\pm$ and the Z bosons carry the weak force. They are massive particles and interact with all particles carrying the weak hypercharges. The $W^\pm$ can change the flavor of the quarks.

2.1.2 SM Lagrangian

The SM Lagrangian and its origin are shown in this subsection. They are mathematically described as the Lagrangian density, $\mathcal{L}$, and hereafter it is denoted as Lagrangian.

Quantum Electro Dynamics (QED)

The QED describes the dynamics of fermions and their electromagnetic interactions.

The free fermion with the spin $1/2$ is described by the Lagrangian

$$\mathcal{L} = i\bar{\psi}\gamma^\mu\partial_\mu\psi - m\bar{\psi}\psi \quad (2.1)$$

The ψ here is the spinor of the fermion field, γ^μ ($\mu = 0,1,2,3$) is the Dirac gamma 4×4 matrix. $\partial_\mu = \frac{\delta}{\delta x_\mu}$ are the partial derivatives, and the $\bar{\psi} = \psi^\dagger\gamma^0$. Solving the Lagrangian equation for this

yields, the Dirac equation of motion for ψ :

$$(i\gamma^\mu \partial_\mu - m) \psi = 0 \quad (2.2)$$

The Lagrangian is required to be invariant under the "local" gauge transformation, i.e. the gauge transformation parameter depends on x :

$$\psi(x) \rightarrow \psi'(x) = e^{i\alpha(x)} \psi(x) \quad (2.3)$$

where the local phase is given by $\alpha(x)$, depending on space and time. This transformation forms the Abelian unitary group $U(1)$ with $e^{i\alpha(x)}$ written as the 1×1 matrix with $U^\dagger U = 1$. The first term of the Lagrangian (2.1) is not invariant under this transformation:

$$\partial_\mu \psi \rightarrow \partial_\mu \psi' = e^{i\alpha(x)} \partial_\mu \psi + ie^{i\alpha(x)} \psi \partial_\mu \alpha(x) \quad (2.4)$$

The requirement of the invariance leads to introduce an additional field A_μ , transforming as:

$$A_\mu \rightarrow A'_\mu = A_\mu + \frac{1}{e} \partial_\mu \alpha(x) \quad (2.5)$$

where e is a coupling constant, which is the elementary electric charge and ∂_μ is replaced with the covariant derivative D_μ :

$$D_\mu = \partial_\mu - ieA_\mu \quad (2.6)$$

Then the derivative part can be replaced with:

$$D_\mu \psi \rightarrow D'_\mu \psi' = e^{i\alpha(x)} D_\mu \psi \quad (2.7)$$

which leads the Lagrangian as:

$$\begin{aligned} \mathcal{L} &= i\bar{\psi}\gamma^\mu D_\mu \psi - m\bar{\psi}\psi \\ &= \bar{\psi} (i\gamma^\mu \partial_\mu - m) \psi + e\bar{\psi}\gamma^\mu \psi A_\mu \end{aligned} \quad (2.8)$$

The Lagrangian now restores the invariance with the gauge field A_μ . By using the strength tensor $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$, the Lagrangian of QED is defined as:

$$\mathcal{L}_{\text{QED}} = i\bar{\psi}\gamma^\mu \partial_\mu \psi - m\bar{\psi}\psi + e\bar{\psi}\gamma^\mu \psi A_\mu - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} \quad (2.9)$$

The Lagrangian is invariant under the $U(1)_{\text{EM}}$ local gauge transformations of fields. The field A_μ is identified as photon, and the invariance forbids the introduction of a mass term of the A_μ , of the form of $\frac{1}{2}m^2 A_\mu A^\mu$. The photon is required to be massless, which agrees with all experiment results.

Quantum Chromo Dynamis (QCD)

The QCD describes the strong force interactions between quarks and gluons. The concept of the required invariance is similar to the QED, while an additional degree of freedom is introduced: the charge is denoted as color, red (r), green(g), and blue(b). The Dirac spinor is replaced with a vector of three spinors for quarks:

$$\psi = \begin{pmatrix} \psi_r \\ \psi_g \\ \psi_b \end{pmatrix} \quad (2.10)$$

The Lagrangian of QCD is described as:

$$\mathcal{L}_{\text{QCD}} = i\bar{\psi}\gamma^\mu\partial_\mu\psi - m\bar{\psi}\psi - g_s\left(\bar{\psi}\gamma^\mu\frac{\lambda_a}{2}\psi\right)G_\mu^a - \frac{1}{4}G_{\mu\nu}^aG_a^{\mu\nu} \quad (2.11)$$

with the gauge fields G_μ^a ($a = 1, 2, \dots, 8$) represents the gluons. While QED is an Abelian gauge theory, for QCD, the underlying group is the non-Abelian group $\text{SU}(3)_C$, whose generators $T_a = \lambda_a/2$. λ_a are called Gell-Mann matrices. They satisfy the commutation relation:

$$\left[\frac{\lambda_a}{2}, \frac{\lambda_b}{2}\right] = if_{abc}\frac{\lambda_c}{2} \quad (2.12)$$

g_s denotes the strong coupling constant, and $G_a^{\mu\nu}$ is the field strength tensor, written as:

$$G_{\mu\nu}^a = \partial_\mu G_\nu^a - \partial_\nu G_\mu^a - g_s f_{abc} G_\mu^b G_\nu^c \quad (2.13)$$

The non-Abelian group structure produces the last term of the field strength, which enables the gluons to interact among themselves in contrast to the QED. Gluons are also required to be massless from the gauge invariance of the fields.

ElectroWeak Model

It is shown by experiments that the weak interaction only acts on left-handed fermions. In the electroweak model, the $\text{SU}(2)_L \times \text{U}(1)_Y$ symmetry is conserved. Here the left-handed fermions are assigned to $\text{SU}(2)_L$ doublets with weak isospin $I = 1/2$, and gauge field W_μ^a . The right-handed fermions are assigned to $\text{SU}(2)_L$ singlets with weak isospin $I = 0$, and gauge field B_μ . The left-handed doublets and right-handed singlets are denoted as χ_L and ψ_R , respectively. Specifically χ_L is written as $\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$ for the leptons of the first generation, and ψ_R is written as (e_R) . For the quarks of the first generation, χ_L is $\begin{pmatrix} u_L \\ d_L \end{pmatrix}$ and ψ_R is (u_R) and (d_R) .

These behave under the local gauge transformations as:

$$\begin{aligned} \chi_L(x) &\rightarrow \chi'_L(x) = e^{i\alpha_a(x)\tau_a/2} e^{i\beta(x)Y} \chi_L \\ \psi_R(x) &\rightarrow \psi'_R(x) = e^{i\beta(x)Y/2} \psi_R \end{aligned} \quad (2.14)$$

where $\alpha_a(x)$ and $\beta(x)$ are the local phases, τ_a are the generators of $\text{SU}(2)_L$ with $a = 1, 2, 3$, and Y is the weak hypercharge operator of $\text{U}(1)_Y$. The covariant derivative is:

$$D_\mu = \partial_\mu + igW_\mu^a\frac{\tau_a}{2} + ig'B_\mu\frac{Y}{2} \quad (2.15)$$

g here is the coupling constant of the $\text{SU}(2)_L$ gauge field written as W_μ^a . g' is the coupling constant of the $\text{U}(1)_Y$ gauge field B_μ . The electroweak Lagrangian results in:

$$\mathcal{L}_{\text{EW}} = i\bar{\chi}_L^i\gamma^\mu D_\mu\chi_L^i + i\bar{\psi}_R^i\gamma^\mu D_\mu\psi_R^i - \frac{1}{4}W_{\mu\nu}^aW_a^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} \quad (2.16)$$

The field strength tensors are:

$$\begin{aligned} W_{\mu\nu}^a &= \partial_\mu W_\nu^a - \partial_\nu W_\mu^a - g\epsilon_{abc}W_\mu^bW_\nu^c \\ B_{\mu\nu} &= \partial_\mu B_\nu - \partial_\nu B_\mu \end{aligned} \quad (2.17)$$

where ε_{abc} is an antisymmetric tensor, which is the structure constant of $SU(2)_L$. This term enables the $W_a^{\mu\nu}$ field to interact with themselves, while B_μ cannot self-interact. The physical fields represent the $W^\pm$, Z bosons and photons are formed by a linear combination of $W_{\mu\nu}^a$ and $B_{\mu\nu}$.

$$\begin{aligned} W_\mu^\pm &= \frac{1}{\sqrt{2}} (W_\mu^1 \mp iW_\mu^2) \\ Z_\mu &= \cos \theta_W W_\mu^3 - \sin \theta_W B_\mu \\ A_\mu &= \sin \theta_W W_\mu^3 + \cos \theta_W B_\mu \end{aligned} \quad (2.18)$$

where the $\theta_W = \arctan (g'/g)$ represents the weak mixing angle, so called Weinberg angle. By rewriting the Lagrangian with physical fields and comparing the A_μ components with the QED Lagrangian (2.9), the relations between e and g , g' is obtained:

$$\begin{aligned} e &= g \sin \theta_W = g' \cos \theta_W \\ Q &= I_3 + \frac{Y}{2} \end{aligned} \quad (2.19)$$

The local gauge invariance forbids the introduction of the mass term of the bosons like $m_W^2 W_\mu W^\mu$, since it is not invariant under $SU(2)_L \times U(1)_Y$ local transformations. This statement that the local phase invariance in the electroweak model requests the fermions and bosons to be massless particles, is conflicted against the experimental results, where $W^\pm$, Z bosons and fermions are found to be massive.

Spontaneous Symmetry Breaking

The disagreement of the electroweak model forbidding the masses of the fermions and bosons with the experimental results can be solved by introducing a spontaneous symmetry breaking. It is known as Brout-Englert-Higgs (BEH) mechanism or ‘‘Higgs mechanism’’ for short.

A complex scalar field, ϕ , which is a weak isospin doublet, with four degrees of freedom is introduced as the Higgs field:

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} \quad (2.20)$$

The corresponding Lagrangian is written as:

$$\mathcal{L}_{\text{Higgs}} = (D_\mu \phi)^\dagger (D^\mu \phi) - \mu^2 \phi^\dagger \phi - \lambda (\phi^\dagger \phi)^2 \quad (2.21)$$

This is invariant under $SU(2)_I \times U(1)_Y$ phase transformation. The potential of ϕ can be parametrize as:

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2 \quad (2.22)$$

where $\lambda > 0$. The value of the ϕ at the vacuum is chosen by minimizing $V(\Phi)$. In case $-\mu^2 > 0$, the $V(\phi)$ has its minimum value at

$$\phi_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \quad (2.23)$$

where $v = \sqrt{-\mu^2/\lambda}$, while in case $-\mu^2 < 0, \phi_0 = 0$ gives the minimum of $V(\phi)$. The v is called the vacuum expectation value. In the former case, by assigning the ground state of the equation 2.23 the local $SU(2)_L \times U(1)_Y$ symmetry of the vacuum is broken spontaneously. Three of the four degrees of freedom of the gauge field (2.20) are absorbed by the $W^\pm$ and Z bosons, and the fourth generates the Higgs boson.

The field is parameterized as:

$$\phi(x) = \frac{e^{i\tau_a\theta_a(x)/v}}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix} \quad (2.24)$$

where $\theta_a(x)$ ($a = 1, 2, 3$) and $h(x)$ are the real field, and $h(x)$ represents the Higgs boson which is associated with the Higgs fields. The exponential term including $\theta_a(x)$ is defined to be specific since local gauge transformation needs to be invariant;

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix} \quad (2.25)$$

The specific gauge has been chosen by defining the vacuum expectation value. That is why we call spontaneous symmetry breaking.

The Lagrangian of Higgs (2.21) can be substituted and the terms represent the mass terms and their relations are written as:

$$\begin{aligned} \left| \left(ig \frac{\tau_a}{2} W_\mu^a + ig' \frac{Y}{2} B_\mu \right) \phi_0 \right|^2 &= \left(\frac{1}{2} v g \right)^2 W_\mu^+ W^{\mu-} \\ &+ \left(\frac{1}{2} v g \right)^2 \frac{1}{2 \cos^2 \theta_W} Z_\mu Z^\mu \\ &+ 0 \cdot A_\mu A^\mu \end{aligned} \quad (2.26)$$

The mass terms for the $W_\pm$ and Z bosons are naturally obtained through the symmetry breaking of $SU(2)_L$. :

$$\begin{aligned} m_\gamma &= m_A = 0 \\ m_Z &= \frac{v}{2} \sqrt{g^2 + g'^2} \\ m_W &= \frac{v}{2} g \end{aligned} \quad (2.27)$$

Yukawa Coupling

The fermion mass term is also not invariant under the local phase transformations of $SU(2)_L$. It is also generated with the Higgs mechanism, using their coupling to the Higgs boson. The newly introduced coupling g_f is called Yukawa coupling.

For the down type fermions, the same Higgs field ϕ is used, while for the up type fermions, the charge conjugate of the Higgs field ϕ^C is employed instead:

$$\phi^C = i\tau_2 \phi^* = \begin{pmatrix} \phi^{0*} \\ -\phi^{+*} \end{pmatrix} \quad (2.28)$$

For the quarks, the additional Lagrangian can be described as follows:

$$\mathcal{L}_q = \left[-g_d (\bar{\psi}_L^d \phi \psi_R^d) + \text{h.c.} \right] + \left[-g_u (\bar{\psi}_L^u \phi^C \psi_R^u) + \text{h.c.} \right] + \text{h.c.} \quad (2.29)$$

These are local gauge invariant before the symmetry breaking. After the symmetry breaking, ϕ^C can be written as:

$$\phi^c = \frac{1}{\sqrt{2}} \begin{pmatrix} v+h \\ 0 \end{pmatrix} \quad (2.30)$$

Then the additional Lagrangian substituted into:

$$\mathcal{L}_q = -\frac{1}{\sqrt{2}}g_d v \bar{d}_L d_R \left(1 + \frac{h}{v}\right) - \frac{1}{\sqrt{2}}g_u v \bar{u}_L u_R \left(1 + \frac{h}{v}\right) + \text{h.c.} \quad (2.31)$$

In the case of leptons, the additional Lagrangian is:

$$\mathcal{L}_e = [-g_e (\bar{\psi}_L^e \phi \psi_R^e) + \text{h.c.}] \quad (2.32)$$

then after the symmetry breaking:

$$\mathcal{L}_e = -\frac{1}{\sqrt{2}}g_e v \bar{e}_L e_R \left(1 + \frac{h}{v}\right) + \text{h.c.} \quad (2.33)$$

The mass of the fermions is to be obtained as:

$$m_f = \frac{1}{\sqrt{2}}g_f v \quad (2.34)$$

When summarizing the quarks and leptons, Lagrangian of the Yukawa couplings can be written as:

$$\mathcal{L}_{\text{Yukawa}} = -g_l^{ij} \bar{\Psi}_L^i \phi l_R^j - g_d^{ij} \bar{\Psi}_L^i \phi d_R^j - g_u^{ij} \bar{\Psi}_L^i \phi^c u_R^j + \text{h.c.} \quad (2.35)$$

Finally, the total Standard Model Lagrangian is described as

$$\mathcal{L}_{\text{SM}} = \mathcal{L}_{\text{QCD}} + \mathcal{L}_{\text{EW}} + \mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{Yukawa}} \quad (2.36)$$

This Lagrangian is invariant under local transformations of $\text{SU}(3) \times \text{SU}(2)_L \times \text{U}(1)_Y$, while the vacuum is breaking the symmetry and not invariant.

The coupling constants appearing in the Lagrangian are determined by the experimental measurement. The measured values are summarized in Table 2.1.

2.2 Phenomenology of proton-proton collision

The standard model physics can be tested with the scattering experiments like pp collisions at LHC. The physics related to the proton-proton interaction is described in this section. Since there is a substructure inside the proton, the proton-proton collision cross section needs to be modeled through the introduction of the parton distribution function (PDF).

Coupling constants	Measured Value
Yukawa Couplings	$g_u = 10^{-5}, g_c = 7 \times 10^{-5}, g_t = 1,$ $g_d = 3 \times 10^{-5}, g_s = 5 \times 10^{-4}, g_b = 0.03,$ $g_e = 3 \times 10^{-6}, g_\mu = 6 \times 10^{-4}, g_\tau = 0.01$
Fine Structure Constant	$\alpha = e^2/4\pi\epsilon_0\hbar c = 1/137$
Strong Coupling Constant	$\alpha_s = 0.11$
Weinberg Angle	$\sin^2 \theta_W = 0.231$
Higgs Self Coupling Constant	$\lambda = 0.1$

Table 2.1: coupling constants [87]

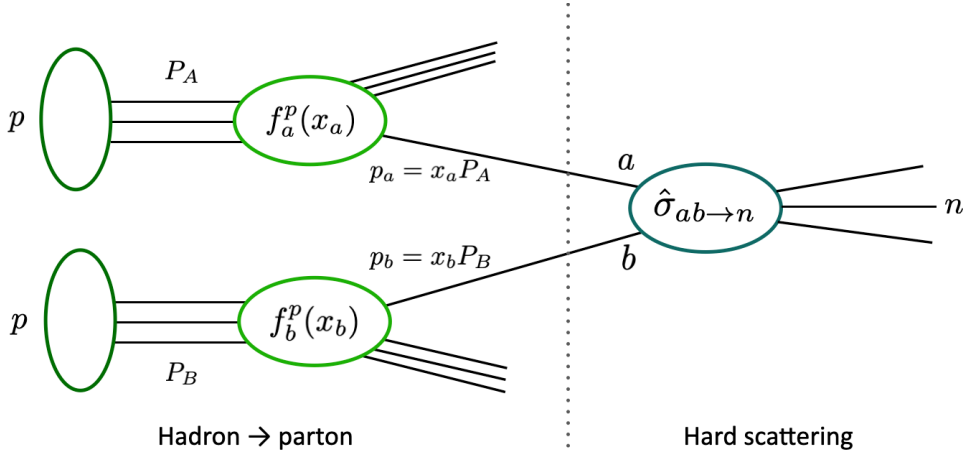


Figure 2.2: factorization theorem

2.2.1 Factorization

The scattering cross section among quarks and gluons can be calculated with perturbative QCD. However, the size of the coupling constant, α_s even at the rather large momentum, q^2 , the perturbative expansion converges really slowly. The factorization theorem [60] allows us to calculate the total cross section approximately with two parts; (1) the probability of obtaining the initial partons that contribute to the hard scattering from the original protons, (2) the partonic cross section calculation as illustrated in Figure 2.2. In the scattering process $ab \rightarrow n$ at a hadron collider can be written as:

$$\sigma_{ab \rightarrow n} = \sum_{a,b} \int_0^1 dx_a dx_b \int d\Phi_n f_a^{h_1}(x_a, \mu_F) f_b^{h_2}(x_b, \mu_F) \times \frac{1}{2\hat{s}} |\mathcal{M}_{ab \rightarrow n}|^2(\Phi_n; \mu_F, \mu_R) \quad (2.37)$$

where a and b are summed over all partonic constituents of the colliding hadrons, h_1 and h_2 , respectively. ($\hat{s} = (p_a + p_b)^2$.) $f_a^{h_1}(x_a, \mu_F)$ and $f_b^{h_2}(x_b, \mu_F)$ are the PDF, obtaining the partons from the original colliding hadrons, at a given momentum fraction x . The factorization depends on the arbitrary cutoff scale, referred to as the factorization scale, μ_F . Then the partonic cross section of the hard scattering, $\hat{\sigma}_{ab \rightarrow n}(\mu_F, \mu_R)$ can be calculated perturbatively with Feynman-diagrams technique by considering the process $ab \rightarrow n$ with free partons in the initial state. This calculation

is done with the Matrix element $|\mathcal{M}_{ab \rightarrow n}|$ for the phase-space Φ_n . When calculating the matrix element of the hard-scattering process, the divergent terms are absorbed into the redefinition of fields or parameters via subtractions. This procedure is usually referred to as renormalization, and the subtraction scale is called the renormalization scale, μ_R . The PDF is estimated by the collision data from previous and current experiments and extrapolated to the appropriate energy using the so-called DGLAP evolution equations. [79]. Since the matrix element is calculated at a fixed order, the final states of parton-level events calculated so far is neglecting higher-order corrections, which have a sizable effect on the particle kinematics. In order to account for the effects of higher order QCD correction and hadronization, parton showering and hadronization algorithm are employed.

2.2.2 Parton shower

The parton shower manages the parton emissions from the outgoing colored partons based on the QCD splitting functions. The Monte Carlo (MC) simulations are based on the Markov chain, in which the components of the hard subprocess are evolved by adding branchings of one parton into two partons, in the limit of the infrared cutoff scale, t_{cutoff} , typically $t_{\text{cutoff}} = t_0 \approx 1 \text{ GeV}$. Typical generators: Pythia [86] and Herwig [69] use different choices of t_{cutoff} . Pythia uses a p_T ordered shower [83], whereas Herwig uses angular ordering [63].

2.2.3 Hadronization

The partons generated after the parton shower are combined to form hadrons. Hadronization is performed in a completely non-perturbative way, based on several models. Pythia and Herwig adopt different phenomenological models: String Model [8], based on the linear confinement of partons, and the Cluster Model [78], based on the preconfinement of parton showers, respectively.

2.3 Vector Boson Scattering

The scattering of two electroweak vector gauge bosons can probe the structure of the electroweak symmetry breaking (EWSB) mechanism directly. The Vector Boson Scattering (VBS) is therefore one of the key processes to be investigated in the LHC experiment. The Vector Boson indicates W, Z, γ here, which are fundamental electroweak bosons. Though the massive vector bosons, W and Z are only sensitive to the mechanism of the EWSM, γ is also included since it is impossible to fully separate the γ and Z contributions experimentally. As described in section 2.1.2, the spontaneous symmetry breaking of the local gauge invariance with the Higgs field introduces the masses of the longitudinal, massive weak gauge bosons. Measuring the VBS processes provides the information related to that mechanism. The typical Feynman diagram of VBS is shown in Figure 2.3.

Here, the amplitude of the longitudinal WW scattering is discussed further to see the effect of the existence of the Higgs boson for example. The combination of other weak massive bosons like WZ, as well as ZZ can be considered similarly.

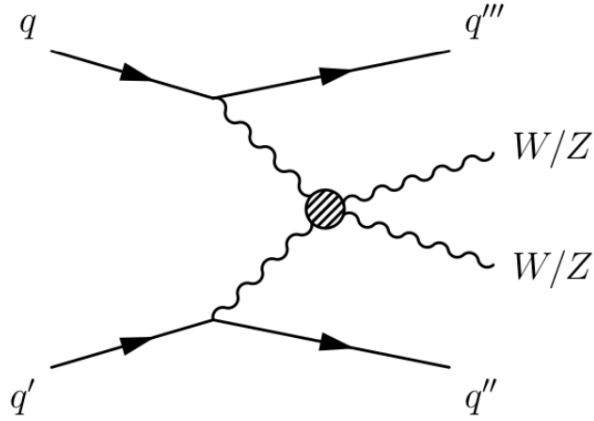


Figure 2.3: The Feynman diagram of the VBS. The circle includes any connected diagrams with the external lines at leading order.

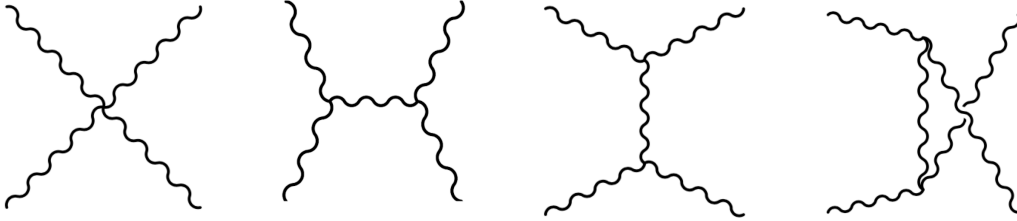


Figure 2.4: The VV to VV interaction Feynman diagram at tree-level. Contributions from EW gauge boson interactions.

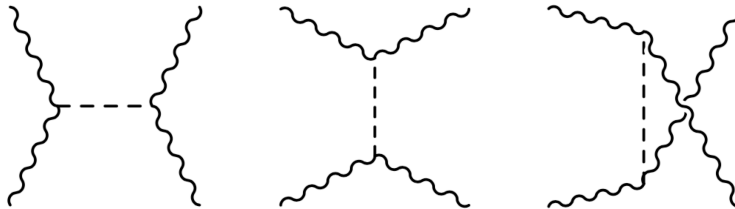


Figure 2.5: The VV to VV interaction Feynman diagram at tree-level. Contributions include Higgs boson interactions.

Since the polarization vector of the longitudinal weak vector boson can be written in the form:

$$\varepsilon_L^\mu = \frac{1}{m_V} \left(|\vec{p}|, \frac{\vec{p}}{|\vec{p}|} E \right) = \frac{p^\mu}{m_V} + \mathcal{O}\left(\frac{m_V}{E}\right) \quad (2.38)$$

as the p_T grows, the yields with massive vector particles in the initial and final states will be longitudinal-dominant [80]. At high-energy limit, the amplitude for $W_L^+ W_L^-$ without the existence of the Higgs boson (Figure 2.4) can be describes in the form of:

$$\mathcal{M}^{\text{gauge}} = -\frac{g^2}{4m_W^2} u + \mathcal{O}\left(\left[\frac{E}{m_W}\right]^0\right) \quad (2.39)$$

The remaining amplitude from the second term will rise with energy and eventually violates the unitarity at the unitarity bound. The amplitude including the Higgs contributions (Figure 2.5) is:

$$\begin{aligned} \mathcal{M}^{\text{Higgs}} &= -\frac{g^2}{4m_W^2} \left[\frac{(s - m_W^2)^2}{s - m_H^2} + \frac{(t - m_W^2)^2}{t - m_H^2} \right] \\ &\approx \frac{g^2}{4m_W^2} u, \end{aligned} \quad (2.40)$$

in the high-energy limit $s \gg m_H^2, m_W^2$, where s, t, u are the Mandelstam variables. Therefore the terms affected by the rising energy cancel and leave the constant term, which is not violating the unitarity.

This effect is also described in the Figure 2.6 [62]. The figure shows that if diagrams with Higgs contribution are missing, the electroweak couplings become strong around $\sqrt{s}$ is around 1 TeV, and the unitarity of the $W_L W_L \rightarrow W_L W_L$ process is violated, which means the SM without the Higgs boson is no longer valid above TeV-scale.

2.4 Several decay channels in VBS analysis

The VBS analysis is performed in several decay channels with respect to the boson type and its decay products. The latest significance obtained by ATLAS and CMS in each channel is summarized in the table 2.2.

		ATLAS	CMS
Full-leptonic	ssWW → lνlν	6.5 (4.4 ^{Sherpa}) σ (36.1 fb ⁻¹) [35]	5.5 (5.7) σ (35.9 fb ⁻¹) [59]
	osWW	—	—
	WZ → lνll	5.3 (3.2) σ (36.1 fb ⁻¹) [36]	2.2 (2.5) σ (35.9 fb ⁻¹) [56]
	ZZ → ll ll/llνν	5.5 (4.3) σ (139 fb ⁻¹) [42]	2.7 (1.6) σ (35.9 fb ⁻¹) (llll) [55]
Semi-leptonic		2.7 (2.5) σ (36.1 fb ⁻¹) [37]	4.4 (5.1) σ (138 fb ⁻¹) [58]
Full-hadronic		—	—

Table 2.2: Significance obtained by the VBS analyses in several decay channels

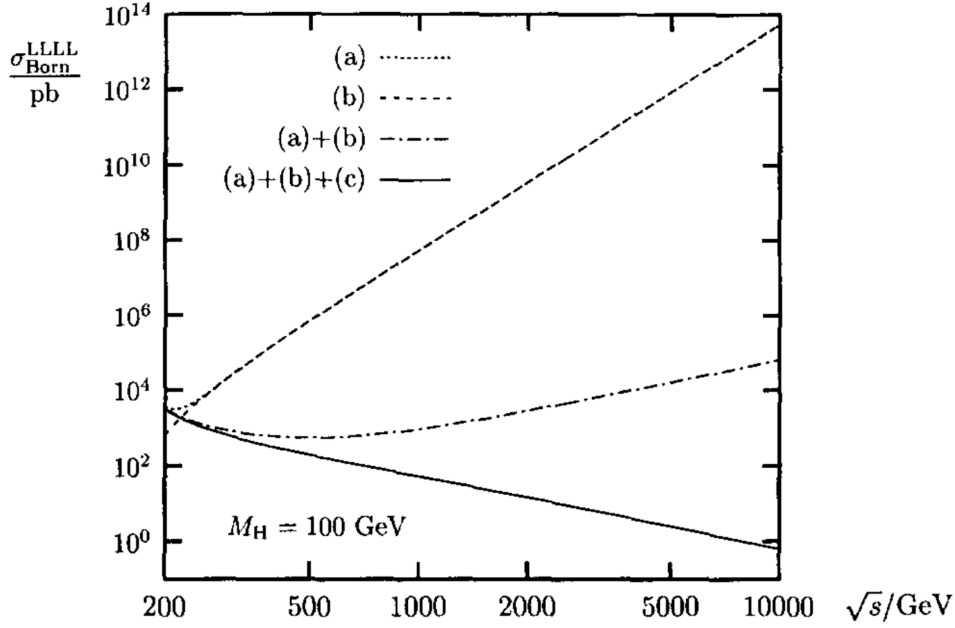


Figure 2.6: Cross section at tree-level [62] for various cases in (a) Triple Gauge Coupling, (b) Quartic Gauge Coupling, and (c) Higgs exchanges are shown. The solid, dashed, dash-dotted lines represent the SM, SM without QGC nor Higgs changes, and SM without Higgs exchanges, respectively.

The VBS process has already been observed in the full-leptonic channel at LHC. In this thesis, semi-leptonic channel is studied where one weak vector boson (W or Z) decays into leptons (electrons or muons or neutrino) and the other decays into hadrons. The first measurement of this channel in ATLAS using 35.5 fb^{-1} of the Run 2 dataset with a significance of 2.7σ [37]. CMS has recently published a measurement of 4.4σ using only the 1-lepton channel [58] using 138 fb^{-1} dataset.

The advantage of semileptonic final states, with respect to fully leptonic channel, is the higher branching ratio as well as the exploitation of substructure techniques, for the W/Z identification, which allows high reconstruction efficiency in the high- p_T regions where we are sensitive to anomalous quartic gauge couplings (aQGC). On the other hand, the large background contributions coming from V+jets and $t\bar{t}$ events are the largest disadvantages.

2.5 Anomalous Quartic Gauge Coupling and Effective Field Theory

The divergence of the VBS process amplitude at the high mass region is miraculously canceled by the Higgs boson contribution, but an additional source of EWSB would easily modify it. The existence of an additional source of EWSB would contribute in the form of its corresponding mediator that affects the amplitudes of the VBS process. The additional couplings are referred to as anomalous gauge couplings (aGC). The considerable models of new physics for aGC consist of the SM coupled to additional resonances to the diboson system. In these models any enhancement in the high-energy tails of VBS observable can be understood as the onset of a new resonance that

is just at or near the kinematic reach of the LHC. Typical examples of these models in which such resonances can appear are extended scalar sectors [68], like two (or multi) Higgs doublet models (2HDM [49]), Higgs singlet extensions, Higgs triplet extensions (e.g. the GM model [72]), Little Higgs models [74], super-symmetric models, composite Higgs models, Randall-Sundrum and other extra-dimensional models [65].

Since the aGC can claim many different models, the Effective Field Theory (EFT) is considered. The concept of the EFT is explained in the following sections.

2.5.1 EFT

New physics contribution is generally described by the EFT as a model-independent way of interpretation. The EFT models the effects of new physics at an energy scale much higher than the currently accessible range by the experiments. They are based on the following expansion of the EFT Lagrangian;

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_{d>4} \sum_i \frac{f_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)} \quad (2.41)$$

where Λ is the typical scale of new physics, called cutoff scale. $f_i^{(d)}$ are the Wilson coefficients, the dimensionless coupling-strength coefficients of the new operators, $\mathcal{O}_i^{(d)}$. Any new physics can be modeled in this framework by certain additional operators, where their coefficients are also fixed as long as the new physics scale is above Λ . The SM is a low-energy theory in this framework, i.e. if $\Lambda \rightarrow \infty$, the SM is reproduced.

The operators are constructed from the following fields;

- Higgs double field Φ ,
- covariant derivative D^μ ,
- field strength tensors $W^{\mu\nu}$, $B^{\mu\nu}$,
- fermion fields ψ

In general, all operators with an odd number of dimensions involve fermion fields and lead to lepton or baryon number violation [88]. Therefore we need to consider even dimension only, starting from $d = 6$. Equation (2.41) is then written like;

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{f_i^{(d)}}{\Lambda^2} \mathcal{O}_i^{(d)} + \sum_j \frac{f_j^{(d)}}{\Lambda^4} \mathcal{O}_j^{(d)} + \dots \quad (2.42)$$

where the second term represents the dimension-6 operators which affect triple gauge couplings (TGC) and quartic gauge couplings (QGC), and the third term represents the dimension-8 operators, which affect only QGCs. To model possible anomalous QGC (aQGC) effect in the VBS process, the Eboli model [64], introduces new dimension-8 operators which satisfy the SM $SU(2) \times U(1)_Y$ symmetry is used. TGC is already strongly constrained through the study using dimension-6 operators via the pair production of electroweak gauge bosons. To focus more on the effect of QGC, only dimension-8 operators are considered here, as the operators that generate QGC but do not have any TGC associated with them. These operators are with weak boson field either

from the covariant derivative of Higgs doublet Φ or from the field strength tensor. All the corresponding operators are shown hereafter. $\hat{W}_{\mu\nu} \equiv \Sigma W_{\mu\nu}^j \frac{\sigma^j}{2}$, where $W_{\mu\nu}^i$ is the $SU(2)_L$ field strength and $B_{\mu\nu}$ is the $U(1)_Y$ one. The covariant derivative is given by $D_\mu \Phi = \left(\partial_\mu - ig W_\mu^j \frac{\sigma^j}{2} - ig' B_\mu \frac{1}{2} \right) \Phi$. The analysis usually focuses on these operators on a one-by-one basis.

- Operators containing just $D_\mu \Phi$: (Scalar type)

$$\begin{aligned}\mathcal{O}_{S,0} &= \left[(D_\mu \Phi)^\dagger D_\nu \Phi \right] \times \left[(D^\mu \Phi)^\dagger D^\nu \Phi \right] \\ \mathcal{O}_{S,1} &= \left[(D_\mu \Phi)^\dagger D^\mu \Phi \right] \times \left[(D_\nu \Phi)^\dagger D^\nu \Phi \right] \\ \mathcal{O}_{S,2} &= \left[(D_\mu \Phi)^\dagger D_\nu \Phi \right] \times \left[(D^\nu \Phi)^\dagger D^\mu \Phi \right]\end{aligned}\tag{2.43}$$

- Operators containing $D_\mu \Phi$ and field strength : (Mixed type)

$$\begin{aligned}\mathcal{O}_{M,0} &= \text{Tr} \left[\hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \right] \times \left[(D_\beta \Phi)^\dagger D^\beta \Phi \right] \\ \mathcal{O}_{M,1} &= \text{Tr} \left[\hat{W}_{\mu\nu} \hat{W}^{\nu\beta} \right] \times \left[(D_\beta \Phi)^\dagger D^\mu \Phi \right] \\ \mathcal{O}_{M,2} &= \left[B_{\mu\nu} B^{\mu\nu} \right] \times \left[(D_\beta \Phi)^\dagger D^\beta \Phi \right] \\ \mathcal{O}_{M,3} &= \left[B_{\mu\nu} B^{\nu\beta} \right] \times \left[(D_\beta \Phi)^\dagger D^\mu \Phi \right] \\ \mathcal{O}_{M,4} &= \left[(D_\mu \Phi)^\dagger \hat{W}_{\beta\nu} D^\mu \Phi \right] \times B^{\beta\nu} \\ \mathcal{O}_{M,5} &= \left[(D_\mu \Phi)^\dagger \hat{W}_{\beta\nu} D^\nu \Phi \right] \times B^{\beta\mu} \\ \mathcal{O}_{M,6} &= \left[(D_\mu \Phi)^\dagger \hat{W}_{\beta\nu} \hat{W}^{\beta\nu} D^\mu \Phi \right] \\ \mathcal{O}_{M,7} &= \left[(D_\mu \Phi)^\dagger \hat{W}_{\beta\nu} \hat{W}^{\beta\mu} D^\nu \Phi \right]\end{aligned}\tag{2.44}$$

- Operators containing just the field strength tensor : (Tensor type)

$$\begin{aligned}\mathcal{O}_{T,0} &= \text{Tr} \left[\hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \right] \times \text{Tr} \left[\hat{W}_{\alpha\beta} \hat{W}^{\alpha\beta} \right] \\ \mathcal{O}_{T,1} &= \text{Tr} \left[\hat{W}_{\alpha\nu} \hat{W}^{\mu\beta} \right] \times \text{Tr} \left[\hat{W}_{\mu\beta} \hat{W}^{\alpha\nu} \right] \\ \mathcal{O}_{T,2} &= \text{Tr} \left[\hat{W}_{\alpha\mu} \hat{W}^{\mu\beta} \right] \times \text{Tr} \left[\hat{W}_{\beta\nu} \hat{W}^{\nu\alpha} \right] \\ \mathcal{O}_{T,3} &= \text{Tr} \left[\hat{W}_{\alpha\mu} \hat{W}^{\mu\beta} \hat{W}^{\nu\alpha} \right] \times B_{\beta\nu} \\ \mathcal{O}_{T,4} &= \text{Tr} \left[\hat{W}_{\alpha\mu} \hat{W}^{\alpha\mu} \hat{W}^{\beta\nu} \right] \times B_{\beta\nu} \\ \mathcal{O}_{T,5} &= \text{Tr} \left[\hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \right] \times B_{\alpha\beta} B^{\alpha\beta} \\ \mathcal{O}_{T,6} &= \text{Tr} \left[\hat{W}_{\alpha\nu} \hat{W}^{\mu\beta} \right] \times B_{\mu\beta} B^{\alpha\nu} \\ \mathcal{O}_{T,7} &= \text{Tr} \left[\hat{W}_{\alpha\mu} \hat{W}^{\mu\beta} \right] \times B_{\beta\nu} B^{\nu\alpha} \\ \mathcal{O}_{T,8} &= B_{\mu\nu} B^{\mu\nu} B_{\alpha\beta} B^{\alpha\beta} \\ \mathcal{O}_{T,9} &= B_{\alpha\mu} B^{\mu\beta} B_{\beta\nu} B^{\nu\alpha}\end{aligned}\tag{2.45}$$

It is found via simulations that the tensor type operators produce purely transversely polarized W/Z bosons, while the scalar type operators longitudinal bosons. The summary of correspondences

operators	WWWW	WWZZ	ZZZZ	WW γ Z	WW $\gamma\gamma$	ZZZ γ	ZZ $\gamma\gamma$	Z $\gamma\gamma\gamma$	$\gamma\gamma\gamma\gamma$
$\mathcal{O}_{S02}, \mathcal{O}_{S1}$	✓	✓	✓						
$\mathcal{O}_{M0}, \mathcal{O}_{M1}, \mathcal{O}_{M7}$	✓	✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{M2}, \mathcal{O}_{M3}, \mathcal{O}_{M4}, \mathcal{O}_{M5}$		✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{T0}, \mathcal{O}_{T1}, \mathcal{O}_{T2}$		✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{T5}, \mathcal{O}_{T6}, \mathcal{O}_{T7}$	✓	✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T8}, \mathcal{O}_{T9}$			✓			✓	✓	✓	✓

Table 2.3: operators and the vertices

of the operators and the vertices are summarized in the table 2.3. Since the operator $\mathcal{O}_{S,2}$ is the Hermite conjugate of the $\mathcal{O}_{S,0}$, those 2 operators are treated as single operator denoted as $\mathcal{O}_{S02}$, with the coefficient f_{S02} . The operator $\mathcal{O}_{T,3}$ and $\mathcal{O}_{T,4}$ vanish identically. For $\mathcal{O}_{T,3}$, the trace is symmetric under permutation of indices β and ν , while the field-strength tensor $B_{\beta\nu}$ is anti-symmetric, and for $\mathcal{O}_{T,4}$, the trace itself vanishes. The operator $\mathcal{O}_{M,6}$ is equivalent to $\mathcal{O}_{M,0}$. The VBS semi-leptonic channel has both WZ and ZZ for the weak vector bosons, therefore can get the limits for all these 17 operators.

2.5.2 Unitarity bound

The departures of the TGC and QGC from the SM predictions lead to the growth of scattering amplitude eventually leads to unitarity violation. When probing aQGC, we must verify whether unitarity is satisfied to guarantee the consistency of the analyses. This unitarity bound can be calculated from the partial wave function of the process of two-to-two scattering of electroweak gauge bosons [6]. These are used as the theoretical unitarity bound in this analysis.

In the experiment side, how to treat and deal with the unitarity problem depends on each analysis. There are basically two mainstreams currently;

- Disregard unitarity limits

This is what is done in most of the CMS analyses. It is technically the simplest way to implement, and it's fair to quantify the relative precision of different measurements and their agreement/disagreement with the SM. However, the unitarity violation usually occurs well within the measured range.

- Clipping method

Define some cut-off scale Λ as "Clipping energy", and only take SM contribution above that clipping energy. This method can offer the most conservative signal estimate that gives limits guaranteed to be true, when compared to the theoretical unitarity bound. The limits on f can only be determined for an assumed value of Λ .

In this analysis clipping method is used as well as the unitarity-disregarding limits. More detailed description will be shown in chapter 11.

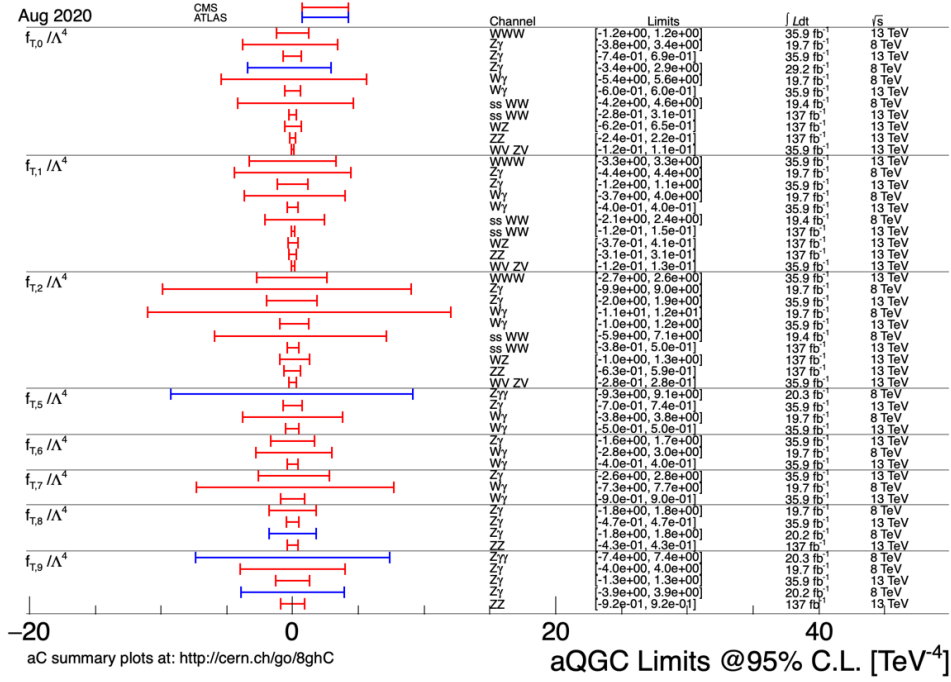


Figure 2.7: CMS and ATLAS limits on FT operators [66]

2.5.3 Latest limit for the dimension-8 operators

The latest limits on the Wilson coefficients of the 8-dimension operators obtained by the CMS and ATLAS are shown in figure 2.7,2.8,2.9. All of these limits are disregarding the unitarity.

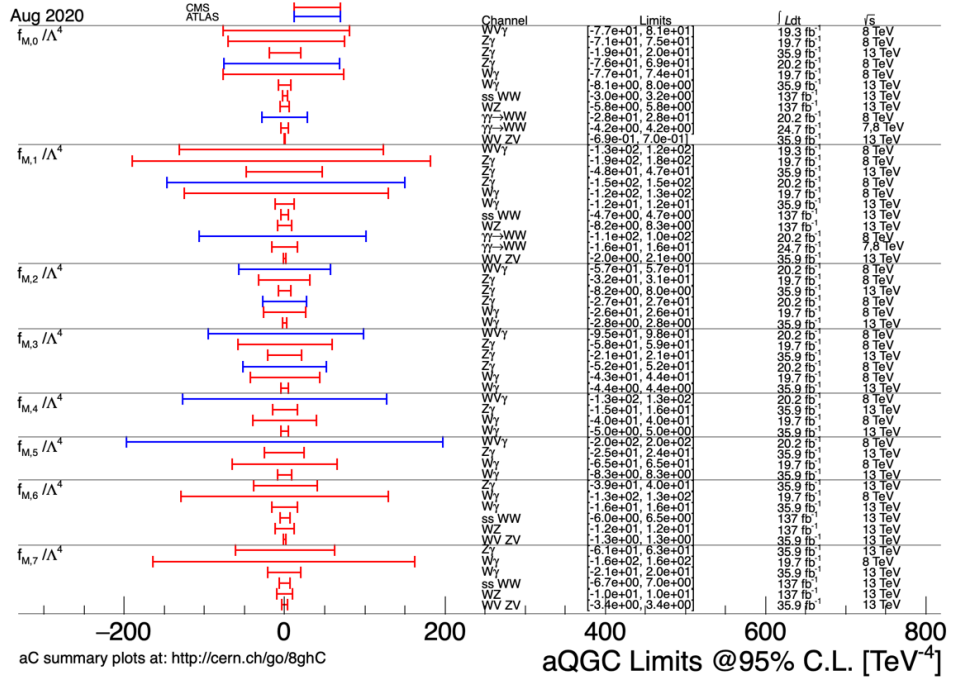


Figure 2.8: CMS and ATLAS limits on FM operators [66]

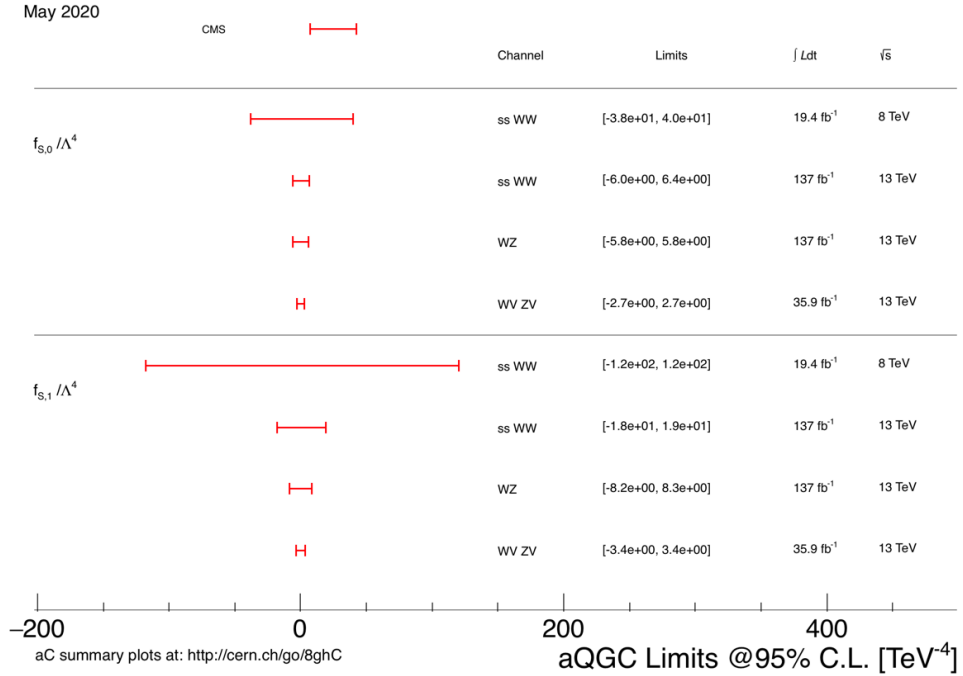


Figure 2.9: CMS and ATLAS limits on FS operators [66]

Chapter 3

The LHC-ATLAS Experiment

3.1 Large Hadron Collider

The Large Hadron Collider (LHC) is a circular collider which is located at CERN, Geneva. It was built inside the existing 27 km tunnel, previously housing the Large Electron-Positron Collider (LEP). The LHC project was planned in the 1990s and its construction started in 2000.

The LHC accelerates mainly protons and also heavy ions such as lead (Pb) in two beams running in opposite directions and collides them. The machine has been operated since 2008 and the first physics run, referred to as Run 1, was completed in 2012 with the center-of-mass energy of $\sqrt{s} = 7$ and 8 TeV. The Higgs boson was discovered by the ATLAS and CMS experiments in 2012 [14] [54], which was one of the most important accomplishments of this period. The energy was increased to $\sqrt{s} = 13$ TeV for the second phase of the LHC between 2015 and 2018 referred to as Run 2. The large amount of data provided by the LHC and its increasing in energy allowed to push the limit of our understanding of the particle physics.

3.1.1 Accelerator complex

The particles are gradually accelerated by a chain of linear and circular accelerator complex, shown in Figure 3.1. At first protons are in the form of hydrogen atoms. After being ionized, they are fed into the linear accelerator (LINAC 2), where they reach to the energy of 50 MeV and formed into bunches. Then they are guided to the Proton Synchrotron Booster (PSB). The PSB consists of four synchrotrons of 25 m which bring protons' energy to 1.4 GeV. The protons enter the Proton Synchrotron (PS) after that. This PS is a 638 m synchrotron and it increases the energy of the protons to 25 GeV. The final injector for the LHC is Super Proton Synchrotron (SPS), increasing the protons' energy up to 450 GeV with 7 km radius synchrotron. The SPS also provides particles for some CERN-based experiments such as AWAKE, as well as the CERN testbeam areas.

The SPS injects protons to the LHC with the energy of 450 GeV in the form of bunches, separated by 25 ns, each of which contains 1.15×10^{11} protons. They are circulated in the two separated beam pipes. They are accelerated by an electric field while being kept curved by a magnetic field. The acceleration is performed by the eight superconducting radio frequency cavities. They switch the direction of the electric field at 400 MHz frequency. They are operated at a temperature of

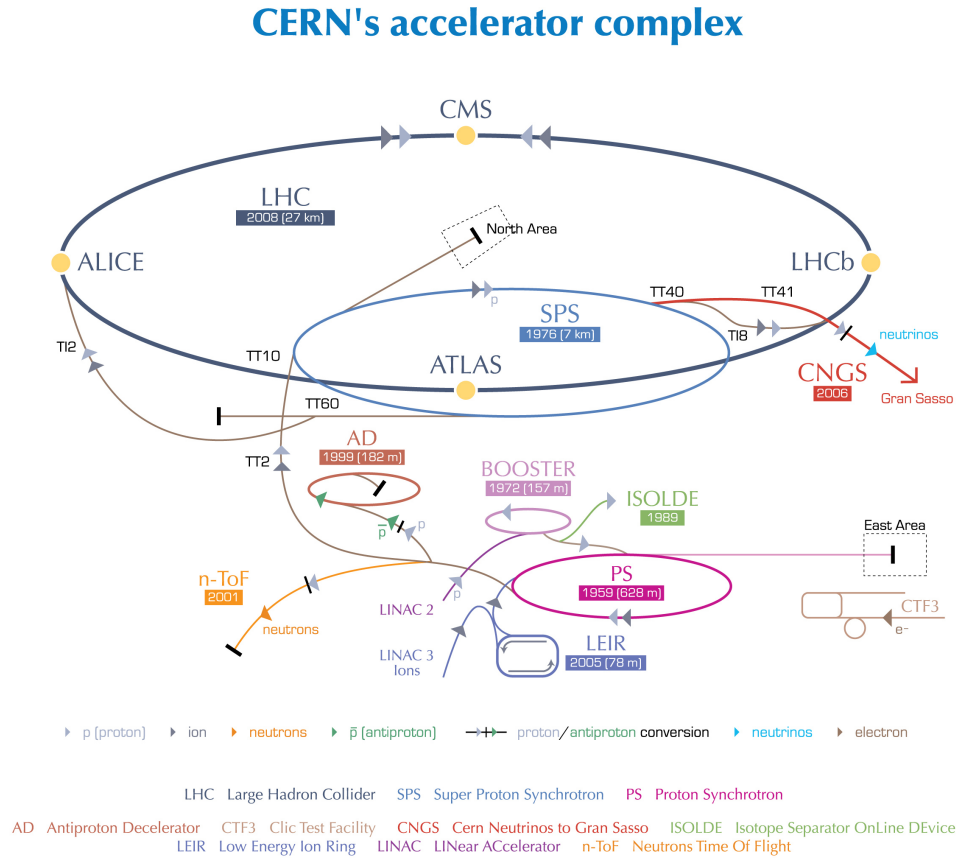


Figure 3.1: The whole picture of the CERN accelerator complex [1] is shown. The protons are accelerated by LINAC 2, PSB, PS and SPS. The ATLAS detector as well as the CMS, ALICE, and LHCb detectors are placed on the collision of the LHC.

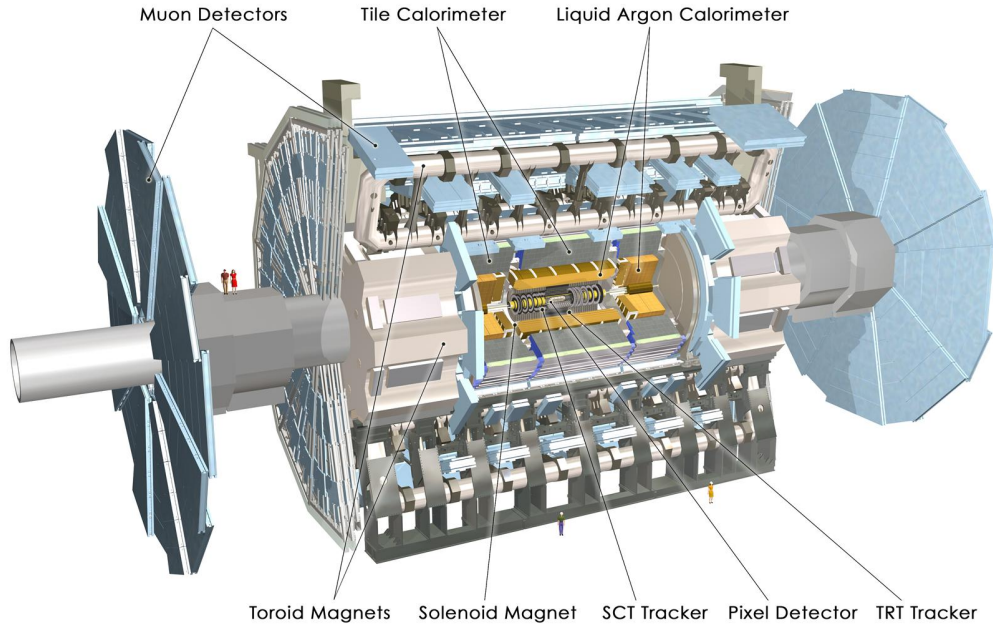


Figure 3.2: The whole picture of the ATLAS detector

4.5 K. The beams are bent by the 1232 super-conducting dipole magnets to be kept in the circle trajectory. The magnetic field strength is 8.3 T, and they are operated at a temperature of 1.9 K. In addition, 392 quadrupole magnets are used to focus the beams.

When the protons reach the desired energy, they are collided in the experiments, at the four interaction points (IP). The experiments are ATLAS [11], CMS [53], ALICE and LHCb. ATLAS and CMS are the general purpose experiments, for both the precise measurement of the SM processes and the discovery of the physics beyond the SM, ALICE is a detector dedicated to the heavy-ion collisions, which studies quark-gluon plasma, and LHCb is a forward experiment that is optimized for the heavy-flavour physics.

This thesis is based on the data taken by the ATLAS experiment in the Run 2 data-taking period at $\sqrt{s}=13$ TeV corresponding to an integrated luminosity of 139 fb^{-1} .

3.2 ATLAS Detector

The ATLAS detector is a multi purpose detector, and designed to measure all standard model particles produced at the LHC. An overview of the whole ATLAS detector is shown in Figure 3.2. The ATLAS is a cylindrical detector, which is 44 m in length and 25 m in height. It consists of two areas; one is the central region, referred to as barrel region, and the other is the forward region, referred to as end-caps.

3.2.1 The ATLAS coordinate system

ATLAS adopts a right-handed coordinate system with its origin at the interaction point. The z -axis is defined along the beam pipe, the y -axis points upwards and the x -axis points toward the center of the LHC. The azimuthal angle ϕ is the angle around the beam pipe, measured in the x - y plane with respect to the x -axis. The polar angle θ is the angle to z -axis. A commonly used variable is the pseudorapidity η , which is defined as:

$$\eta = -\ln \tan(\theta/2)$$

The low η corresponds to the central part of the detector, while the high η region points the beam axis. At the massless limit, the difference in η between two particles, $\Delta\eta$ is invariant under the Lorentz transformation along the z -axis. The other variable used often is the distance in the cylindrical coordinate system; $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$. Both $\Delta\eta$ and $\Delta\phi$ are lorentz invariant, hence ΔR is also a lorentz invariant variable along z -axis.

3.2.2 Magnet

The ATLAS magnet system consists of four large superconducting magnets with a dimension of 22 m in diameter and 26 m in length with a stored energy of 1.6 GJ. A solenoid aligned on the beam axis generates 2 T axial magnetic field for the inner detector, which is placed inside the calorimeter system. Toroidal magnets are installed in the barrel and end-cap regions and provide 0.5 and 1 T magnetic fields for muon detectors, respectively.

There are different subsystems of the detector, the Inner Detector with the coverage of $|\eta| < 2.5$, the calorimeters with $|\eta| < 4.9$, and the muon spectrometer with $|\eta| < 2.7$ from the inside to outside as shown in Figure 3.2. More details are described below.

3.2.3 Inner Detector

The inner detector (ID) is a tracking detector with a radius of 1.2 m and 6.2 m in length along the beam pipe. The ID is used for the reconstruction of the trajectory of charged particles.

The designed track momentum resolution is

$$\frac{\sigma_{p_T}}{p_T} = 0.05 \% p_T [\text{GeV}] \oplus 1 \ \%.$$

The ID consists of three subsystems, Pixel, SCT, and TRT, introduced below. The overview of the ID is shown in Figure 3.3.

3.2.3.1 Pixel Detector

The Pixel Detector covers the most inner layers of the ID system in a radius of 3 cm to 12 cm, and $|\eta| < 2.5$. It consists of four cylindrical layers of silicon (Si) pixel modules. The innermost layer is called Insertable B-Layer (IBL), which is newly installed before the 2015 run [3]. The IBL was inserted for ensuring a better quality of the track and vertex reconstruction, including the improvement of reconstructing the secondary vertex. The IBL uses specifically radiation hard

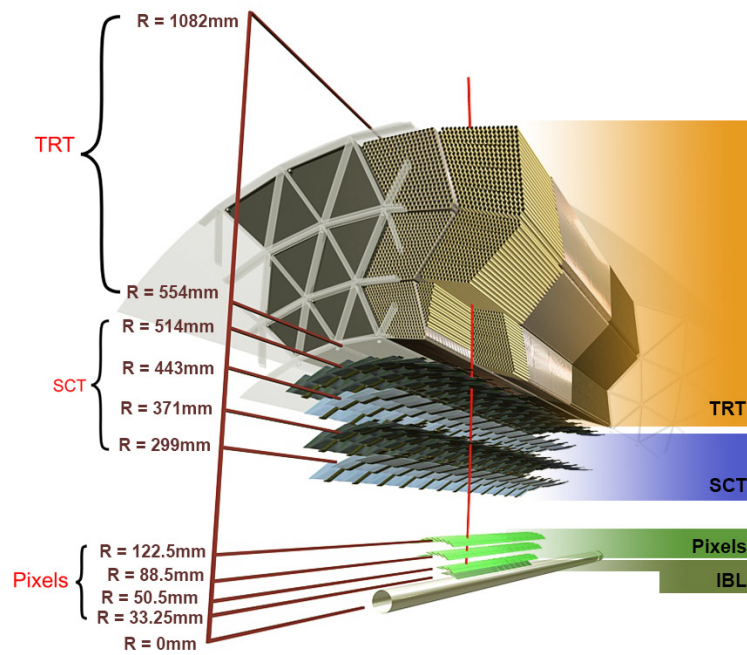
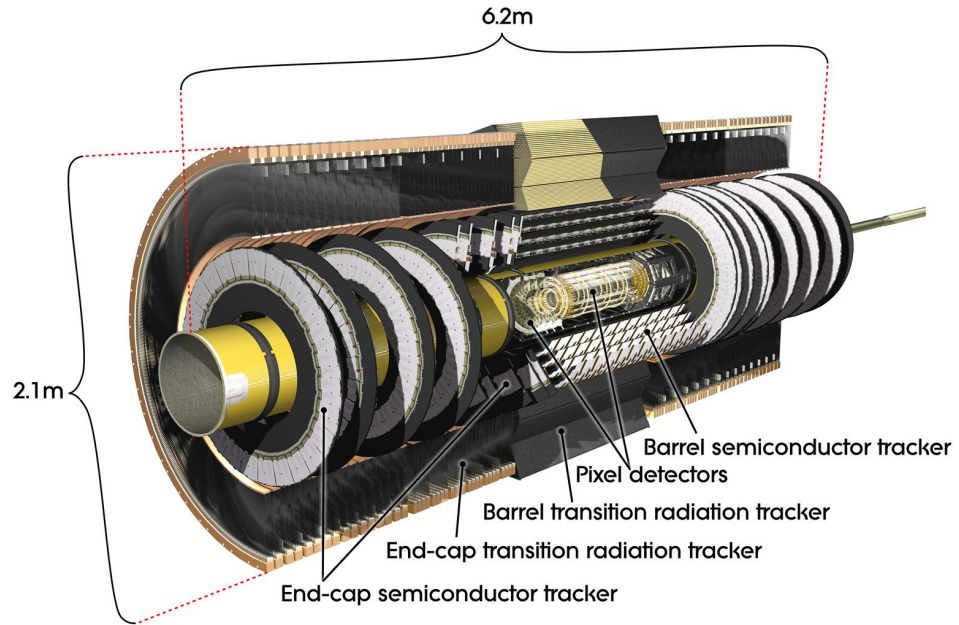


Figure 3.3: The whole picture of the ID in section.

pixel sensors with a size of $50\ \mu\text{m} \times 250\ \mu\text{m}$ to deal with the increasing luminosity and the radiation damage of the existing systems. Surrounding the IBL there are three layers with 1744 pixel sensors with a size of $50\ \mu\text{m} \times 400\ \mu\text{m}$. The layer next to the IBL is located at $R = 50.5\ \text{mm}$. In total there are roughly 80 million readout channels, and the high granularity provides a track reconstruction with a resolution of $14\ \mu\text{m} \times 115\ \mu\text{m}$.

3.2.3.2 SCT

The Semiconductor Tracker (SCT) surrounds the Pixel Detector and is located at about 30 to 50 cm from the beamline. It consists of silicon microstrip modules in 4 barrel layers and 9 end-cap disks. The modules in the barrel have two layers that are slightly rotated each other. This layout allows the 2-dimensional measurement, which is the determination of the position along the strips. There are 2112 modules on the barrel and 1976 modules in the end-cap regions and the tracking resolution is about $17\ \mu\text{m} \times 580\ \mu\text{m}$.

3.2.3.3 TRT

Outside of the SCT, there is the Transition Radiation Tracker (TRT), which is located 50 to 100 cm from the beamline, covering $|\eta| < 2.0$. It consists of drift tubes filled with gas. The tubes have a diameter of 4 mm and length of 144 m along the beam. Gas is the mixture of Xenon (70%), CO₂ (27%), and Oxygen (3%). In addition to the measurement of the track momentum, it is used for particle identifications. The amount of transition radiation, which is emitted by particles crossing the interface of two materials, heavily depends on the mass of the crossing particles. Since electrons are the lightest stable charged particles and emit the most transition radiation, the TRT can be used for the separation between electrons and pions.

3.2.4 Calorimeters

The calorimeters measure the deposited energy of particles. The coverage of the calorimeter extends up to $|\eta| = 4.9$. A schematic view of the system with the various components can be seen in Figure 3.4. It consists of an electromagnetic calorimeter (ECal) ($|\eta| < 3.2$) and a hadronic calorimeter (HCal) ($|\eta| < 4.9$), covering full ϕ -range. ECal is specifically designed for the measurement of photons and electrons, and the HCal for the decays of hadronic particles. The details of each subcomponent are shown below.

3.2.4.1 ElectroMagnetic Calorimeter

ECal measures the electromagnetic showers, initiated by electrons or photons. It is a sampling calorimeter using liquid Argon (LAr) with the lead (Pb) absorbers. They are arranged in an accordion geometry, which enables to cover the full ϕ -range without azimuthal gaps. It is divided into barrel region ($|\eta| < 1.4$) and end-caps ($1.4 < |\eta| < 3.2$). The end-caps are divided into a central region ($1.375 < |\eta| < 2.5$) with finer granularity and a forward region ($2.5 < |\eta| < 3.2$) with a coarser granularity. The designed energy resolution is $\delta E/E = 10\% \sqrt{E/\text{GeV}} \oplus 0.7\%$.

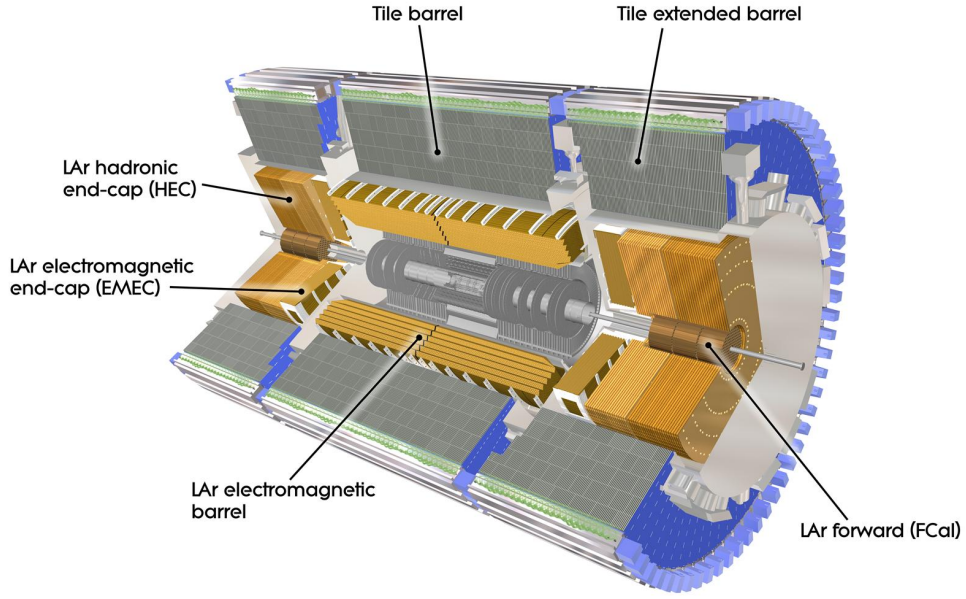


Figure 3.4: The whole picture of the Calorimeter with electromagnetic and hadronic subcomponents

3.2.4.2 Hadron Calorimeter

The HCal is placed outside of the ECal to detect the hadronic shower made by hadrons. It is divided into the barrel ($|\eta| < 1.7$), and end-caps ($1.5 < |\eta| < 3.2$) regions. The barrel region is called the tile calorimeter and uses scintillating tiles with the steel absorber. The end-caps use LAr as detector material with copper absorber. The designed resolution of the hadronic in the coverage of HCal is $\delta E/E = 50\% \sqrt{E/\text{GeV}} \oplus 3\%$.

3.2.4.3 Forward Calorimeter

The Forward Calorimeter (FCAL) measure the energy of both electromagnetic and hadronic particles in the forward region ($3.1 < |\eta| < 4.9$) It has three layers of absorber material. The first one is copper, optimized for electromagnetic measurements and the other two are made of tungsten for hadronic measurements. The design resolution of the forward calorimeter for jets is $\delta E/E = 100\% \sqrt{E/\text{GeV}} \oplus 10\%$.

3.2.5 Muon Spectrometer

The Muon Spectrometer (MS) is placed on the most outside of the ATLAS detector to identify muons and to make a precise estimation of their transverse momentum. The coverage of the MS extends up to $|\eta| < 2.7$. A schematic view of the whole MS is shown in Figure 3.5. It is divided into barrel ($|\eta| < 1.4$), end caps ($1.6 < |\eta| < 2.7$) and transition region ($1.4 < |\eta| < 1.6$).

The MS is an ionization detector using gas. When a charged particle crosses the active area, it ionizes the gas, and the applied electric field guides the electrons and ions to be collected. It

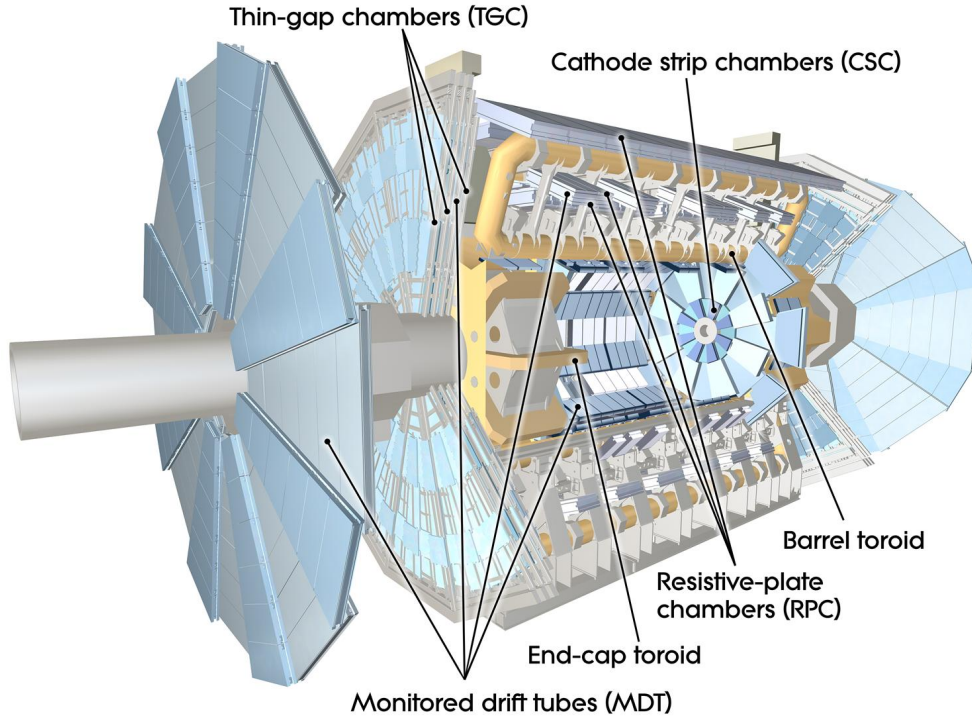


Figure 3.5: The whole picture of the Muon Spectrometer

consists of 4 sub-detectors, described below.

3.2.5.1 Monitored Drift Tubes and Cathode Strip Chambers

The Monitored Drift Tubes (MDTs) perform the precision position measurement of muons in $|\eta| < 2.7$. It consists of the 30 mm diameter drift tubes filled with gas of Ar and CO₂ and wires operated at high voltage to collect the electrons. The tubes are organized in layers and form chambers.

The Cathode Strip Chambers (CSCs) are multi-wire proportional chambers also filled with gas. They perform the same task as the MDTs in the forward region ($2 < |\eta| < 2.7$), where the counting rate is rather high.

3.2.5.2 Resistive Plate Chambers and Thin Gap Chambers

The Resistive Plate Chambers (RPCs) are installed in the barrel in $|\eta| < 1.05$. Single RPC consists of two resistive plates separated by a thin gas gap. They are mainly used to provide the muon triggers for the Data Acquisition (DAQ) system.

The Thin Gap Chambers (TGCs) are also multi-wire proportional chambers similar to the CSCs. They serve the same purpose as the RPCs, but in the forward region.

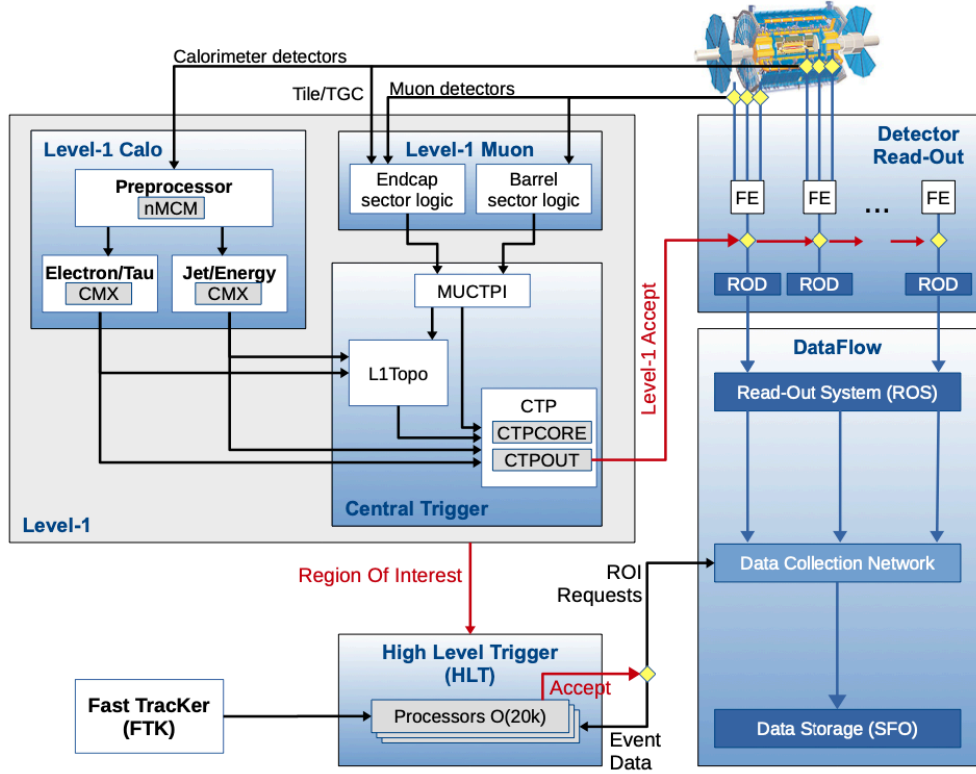


Figure 3.6: The layout of the ATLAS trigger system in Run 2

3.2.6 Triggers

The event rate provided by the LHC is around 40 MHz. It is impossible to record all the information from the detectors at such a high rate, hence the selection of the event of interest to have high- p_T e , μ , τ , and jets is performed with a trigger system. The layout of the ATLAS trigger system is shown in Figure 3.6.

The ATLAS trigger system [43] consists of hardware based Level-1 (L1) trigger, and software based High Level Trigger (HLT). The L1 trigger is implemented with custom electronics and roughly reconstructs high- p_T , e/γ , μ , j , and so on to determine the Regions-of-Interest (RoIs) in the HLT algorithms, from coarse granularity calorimeter and the muon spectrometer information. These data are treated by sub-systems, the L1Calo and L1Muon, respectively. L1 electron is reconstructed by L1Calo. 2×2 core towers and 12 surrounded towers of ECal are used for capturing the electron energy and calculating isolation requirement, respectively. The sketch of these calorimeter towers is shown in Figure 3.7. The L1 Muon makes use of RPC and TGC hits and fires if there is a coincidence between different chambers based on the predefined look-up-tables. The schematic of the muon barrel trigger is shown in figure 3.8. The reconstructed L1 objects by the L1Calo and the L1Muon are sent to the L1Topo, and the selections based on kinematical information can be performed. Then all information from L1Calo, L1Muon, and the L1Topo are sent to the Central Trigger Processor (CTP). The L1 trigger reduces the event rate from approximately 40 MHz to 100 kHz, and the decision time of the L1 is $2.5 \mu\text{s}$. The RoIs decided at L1

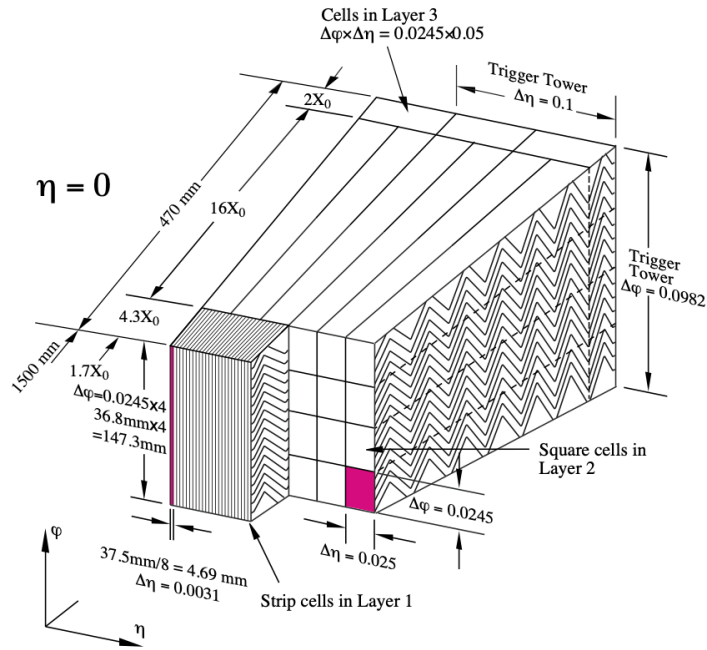


Figure 3.7: The sketch of the barrel module of the ECAL [11].

are then sent to the HLT, which is a farm of large CPU cores. The HLT reconstructs objects with the full detector information around the RoIs. It reduces the rate of the L1 output of 100 kHz to approximately 1 kHz on average, within a processing time of about 200 ms. Events that pass the trigger selections are recorded on disk, where data can be used for further analysis off-line.

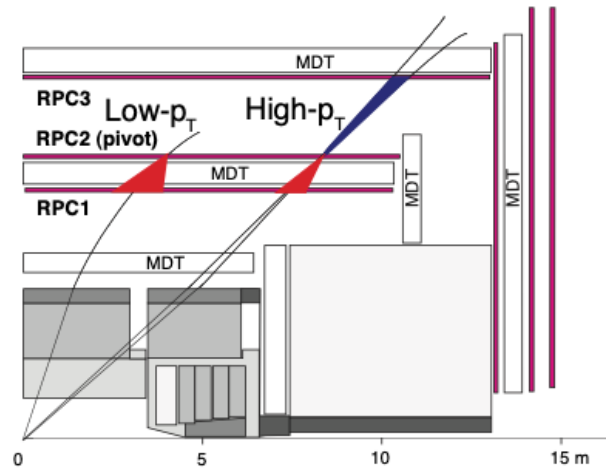


Figure 3.8: The schematic of the muon barrel trigger. [11]. RPC hits are used for triggers.

Chapter 4

Reconstruction

The physics objects are detected as signals in each detector described in Section 3.2. Figure 4.1 shows the schematic diagram of the particle reconstructions with the ATLAS detector. To reconstruct the VBS process in this analysis, electrons, muons, jets, and missing transverse energy (MET) are used. Electrons leave trajectories in the inner detector and develop an electromagnetic shower in the ECal. Most of the energy is absorbed in the ECal and very little energy deposit is expected in the HCal. Muons also leave trajectories in the inner detector. As muons interact weakly with material, they are not absorbed in the calorimeters and leave tracks in the muon spectrometers. Jets are spray of bundles of particles produced by the hadronization of the final-state partons, collimated towards a certain direction, which are detected as hadron shower at the ECal and HCal. While most of the particles in a jet are hadrons, they may contain leptons and photons coming from the decay products of some hadrons. Charged particles in a jet leave tracks in the inner detector and ID tracks are used to correct the observations at the calorimeter. Neutral particles like neutrinos, are not detected at any subdetectors, but can be reconstructed as a MET in the event. All of these physics objects need to be calibrated, in order to correct the translation from signals to original partons to take into account detector effects. These reconstruction, identification and calibration processes performed are described in this chapter.

4.1 Tracks and Vertices

The inner detector (ID) tracks are used for the reconstructions of the primary vertex and charged-particles kinematics. The reconstruction of tracks [24] starts with the formation of clusters of the hits in each ID component. Three-dimensional space points are reconstructed from these clusters. The track candidate is then selected with a set of space points by using combinatorial Kalman filter [67]. The best track is selected using a scoring function, then finally the track is fitted and decided. The primary vertex, which represents the interaction point of the proton-proton collision, is reconstructed by fitting a common point to all reconstructed tracks [25]. It is used to distinguish particles coming from the collision of interest from the ones produced by pileups.

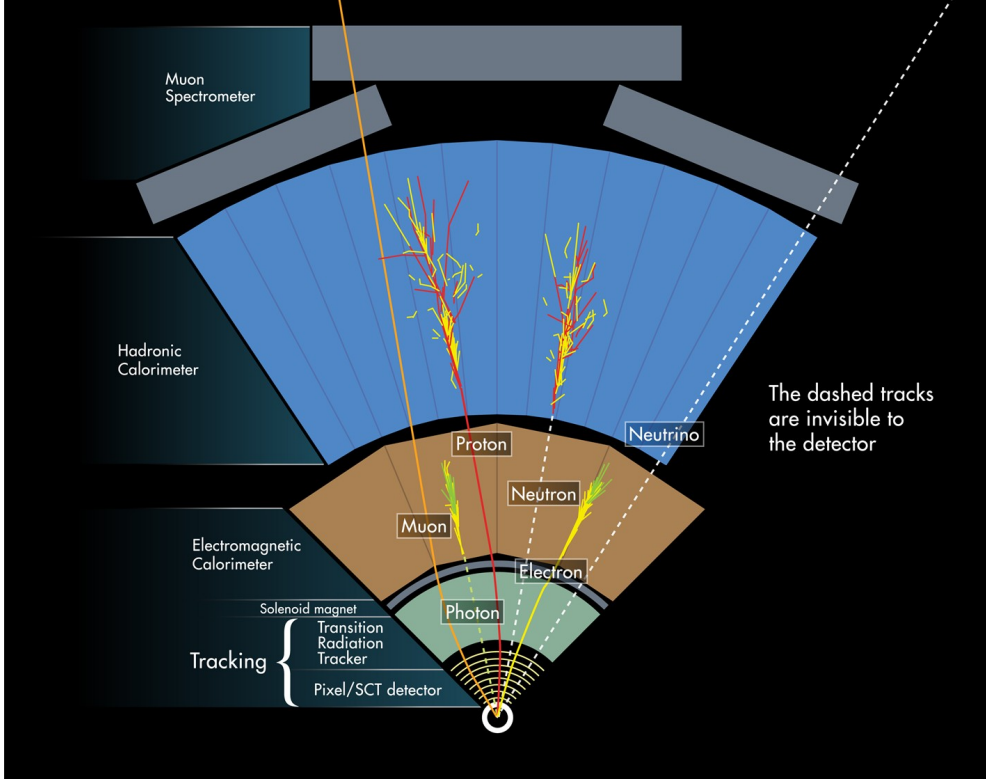


Figure 4.1: Schematics of the particle path

4.2 Calorimeter clusters

The topological cluster (topo-cluster) is used for reconstruction of each physics object. It is a four-momentum formed by cell signals of both the ECal and the HCal. The cluster is reconstructed following cell signal-significance patterns generated by electromagnetic and hadronic showers [27]. The clustering algorithm implicitly performs topological noise suppression by removing cells with insignificant signals which are not in close proximity to cells with significant signals.

4.3 Electrons

Electron candidates are reconstructed from topo-clusters in the ECal matched to a track identified by the ID [19]. The reconstructed electron candidates are required to have $|\eta| < 2.47$, excluding the transition region between barrel and endcap ($1.37 < |\eta| < 1.52$). A likelihood-based identification is required to reduce the backgrounds from photon conversion or hadrons, e.g. charged pion and $\pi^0 \rightarrow \gamma\gamma$. This identification algorithm combines various identification variables, like shower shape of the ECal, the track conditions, and the matching of the tracks and the clusters. The ratio of the energy deposit in the HCal to that of the whole ECal cluster can be used to separate the electrons from the hadrons. The track requirement is useful to distinguish electrons from photons. Electron candidates are categorized into three categories: LooseLH, MediumLH, and TightLH corresponding to 96%, 94%, 88% of identification efficiencies to signal electrons at

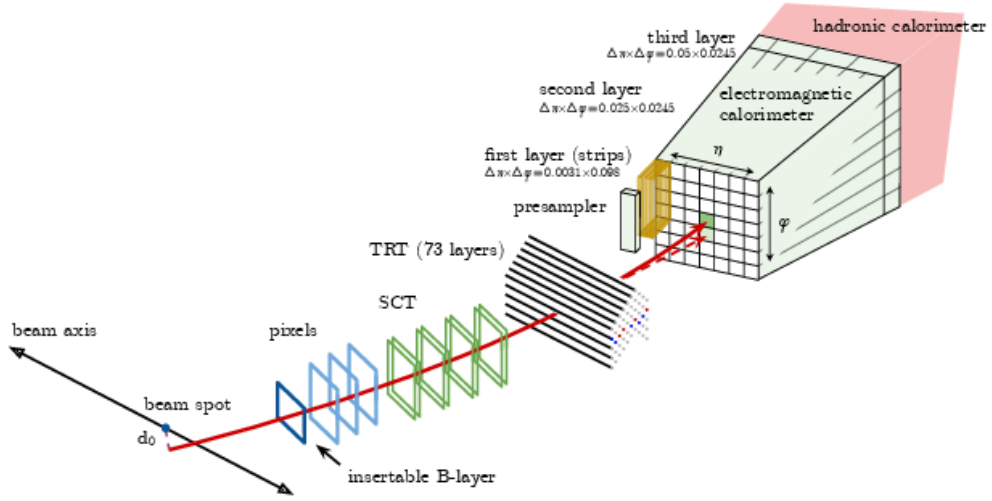
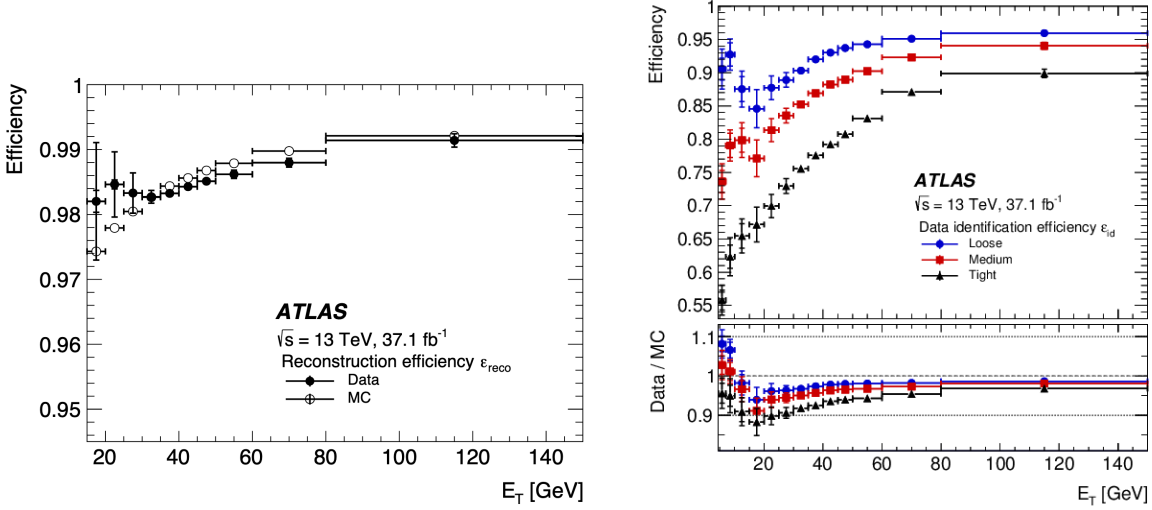


Figure 4.2: Schematics of the electron going through the detectors

$E_T = 100$ GeV respectively, for the rejections of the backgrounds from misidentified hadrons, electrons from photon conversions, and non-isolated electrons originating from heavy-flavour decays. In this analysis, TightLH and LooseLH working points are employed. The reconstruction and identification efficiencies are measured using $J/\Psi \rightarrow ee$ and $Z \rightarrow ee$, $Z \rightarrow ee\gamma$ events [33]. The efficiencies are shown in Figure 4.3. The discrepancy between the data and the MC is corrected by using event-weight scale factors, parametrized with E_T and η . Additional requirements are applied for isolation, to reduce the contamination of jets. The two isolation working points used in this analysis, which are determined by the track and ECal information. The selections applied in this analysis are shown in the table 4.1. Furthermore, track-to-vertex association requirements are applied. d_0 is the minimum distance between the primary vertex (PV) and the track, and σ_{d_0} is its uncertainty. z_0 is the longitudinal impact parameter relative to the beamline.

	Loose	Tight
p_T	7 GeV	30 GeV
$ \eta $	$ \eta < 2.47 \notin [1.37, 1.52]$	
Identification	LooseLH	TightLH
Isolation	FCLoose ($p_T < 100$ GeV) no isolation requirement (> 100 GeV)	FixedCutHighPtCaloOnly
$ d_0/\sigma_{d_0} $	< 5	
$ z_0 \sin \theta $	< 0.5 mm	

Table 4.1: Summary of electron selection used in this analysis

Figure 4.3: electron reconstructing and identification efficiency with respect to the E_T

4.4 Muons

Muons are reconstructed by the combination of the tracks in the ID and Muon Spectrometer (MS) [17]. The reconstruction is performed by a simultaneous fit to the ID and MS information, taking also into account energy losses in the calorimeter. Muon identification is performed by applying quality requirements that suppress backgrounds, mainly from pion and kaon decays. Similarly to electrons, they are classified in three categories; Loose, Medium, and Tight which correspond to an efficiency of 98.1%, 96.1% and 91.8% for muons with $p_T = [20, 100]$ GeV. The identification used in this analysis is shown in Table 4.2. The muon reconstruction efficiencies are measured with samples of $J/\Psi \rightarrow \mu\mu$ and $Z \rightarrow \mu\mu$, as well as the momentum scale and resolution [41]. The reconstruction efficiency is found to be close to 99% over most of the covered phase space ($|\eta| < 2.5$ and $5 < p_T < 100$ GeV). The isolation efficiency varies between 93 and 100 % depending on the selection applied and on the momentum of the muon. Both efficiencies are checked to be well reproduced in MC simulation. Similar to the electron, the isolation requirement

	Loose	Tight
p_T	7 GeV	30 GeV
$ \eta $	$ \eta < 2.5$	
Identification	Loose	Medium
Isolation	FCLoose ($p_T < 100$ GeV) no isolation requirement (> 100 GeV)	FixedCutHighPtCaloOnly
$ d_0/\sigma_{d_0} $	< 3	
$ z_0 \sin \theta $	< 0.5 mm	

Table 4.2: Summary of muon selection used in this analysis

is also applied to the muons, as shown in the Table 4.2.

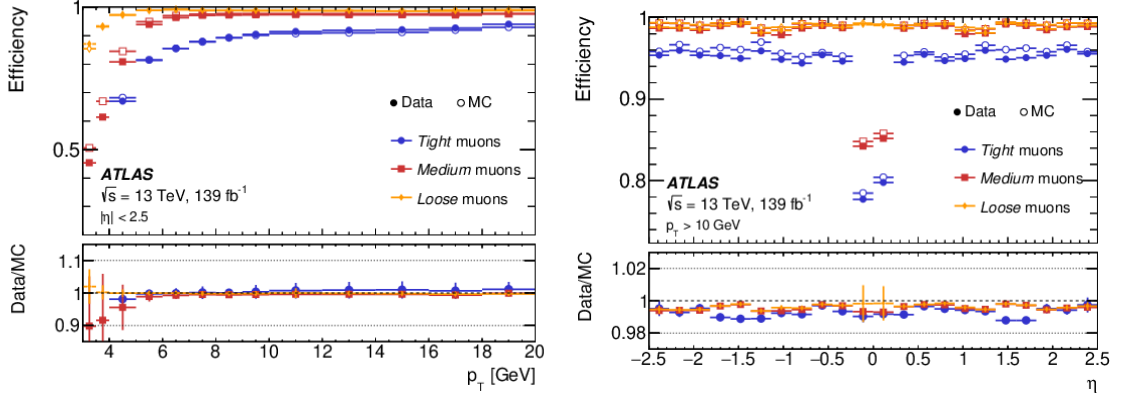


Figure 4.4: muon reconstructing and identification efficiency with respect to p_T (left) and η (right) [41]

4.5 Jets

Jets are basically reconstructed by grouping topo-clusters by the anti- k_t algorithm [50], with a radius of $R = 0.4$ (small- R jets) or $R = 1.0$ (large- R jets). The small- R jet contains most of the radiation from the quark or gluon jets. The large- R jets represent the hadronic decays of the heavy, boosted objects where two jets from the quarks overlap.

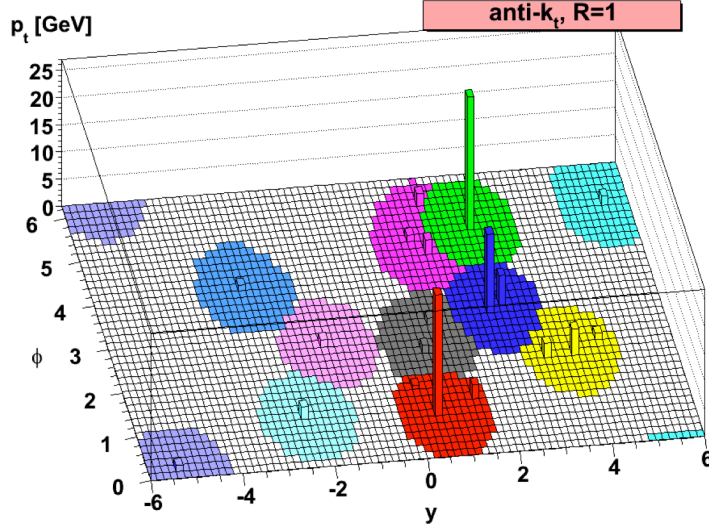
The anti- k_t algorithm defines a measure of distance d_{ij} between the clusters in the calorimeter,

$$d_{ij} = \min \left\{ \frac{1}{k_{T,i}^2}, \frac{1}{k_{T,j}^2} \right\} \times \frac{(\Delta R_{ij})^2}{R^2} \quad (4.1)$$

where $k_{T,i}$ is the transverse momentum of the cluster i and $\Delta R_{ij} = \sqrt{(\Delta y_{ij})^2 + (\Delta \phi_{ij})^2}$ is the distance between the clusters i and j where y is the rapidity. The algorithm searches for the minimum $d_{ij}(k)$ combinations and merges them. It iterates that procedure until $d_{ij}(k) = d_{iB}(k)$, where $d_{iB}(k) = \frac{1}{k_{T,i}^2}$, where cluster i is regarded as a jet. This procedure is repeated until all clusters are grouped into jets. Figure 4.5 shows how the clustering performed for example.

4.5.1 Small- R Jets

The small- R jets are reconstructed using anti- k_T algorithm with a radius of $R = 0.4$. The particle flow (PFlow) algorithm [22] is used in order to prepare the inputs for the jet reconstruction. The PFlow algorithm uses an ensemble of signals from the calorimeter and the ID to remove overlaps between the energy and the momentum measurements made in the calorimeter and the ID. In the PFlow algorithm, firstly tracks from the ID are selected, then the tracks to corresponding topo-clusters are matched to them. The expected energy in the calorimeter, deposited by the particle that also created the track, is computed based on the topo-cluster position and the track momentum. For each track/topo-cluster system, the algorithm evaluates the probability that the particle energy was deposited in more than one topo-cluster. If this is found to be high, the algorithm adds more topo-clusters to the system, to recover the entire shower energy. Finally, the expected energy deposited in the calorimeter by the particle is subtracted cell by cell from the

Figure 4.5: anti- k_T algorithm [50]

topo-clusters assigned to the track. If the energy left-overs in the calorimeter are found and if the remnants are compatible with the expected shower fluctuation of a single particle, they are removed. In the case they are significant, they are kept, assuming they were created by another neutral particle and are referred to as modified clusters. From the collection of tracks, those associated to the vertex of interest, as well as, modified or unmodified topo-clusters are used as inputs to the jet reconstruction. The ID tracker information has better resolution for low- p_T particles, and better angular resolution and can trace the particles to hard-scatter interaction or pile-up. On the other hand, calorimeters have better resolutions for high p_T and can get neutral particles. Therefore the combined information can improve energy and angular resolution, as well as reduce the pile-up contributions.

The calibration for the PFlow jets are done with several steps in order to do the correction for all detector effects.

- pileup-substruction

The per-event pileup contributions to the p_T of each jet are removed based on each area. It is subtracted based residual N_{PV} and μ (average interaction per crossing) [39]. The corrected jet p_T is described as:

$$p_T^{\text{corr}} = p_T^{\text{reco}} (-\rho \times A) - \alpha (N_{PV} - 1) - \beta \langle \mu \rangle \quad (4.2)$$

where ρ is the median pile-up momentum density, A is the jet area, respectively. This correction with respect to η is shown in Figure 4.6.

- MC-based JES, η , calibration

The ratio of the reconstructed jet p_T with the truth jet p_T strongly depends on the detector position. Truth jets are built from stable particles in the MC generator event record. Some corrections are applied as a function of E and η , by comparing the reconstructed jets to truth jets (energy response, $E^{\text{reco}}/E^{\text{truth}}$) [39]. Figure 4.7 shows the jet energy response as

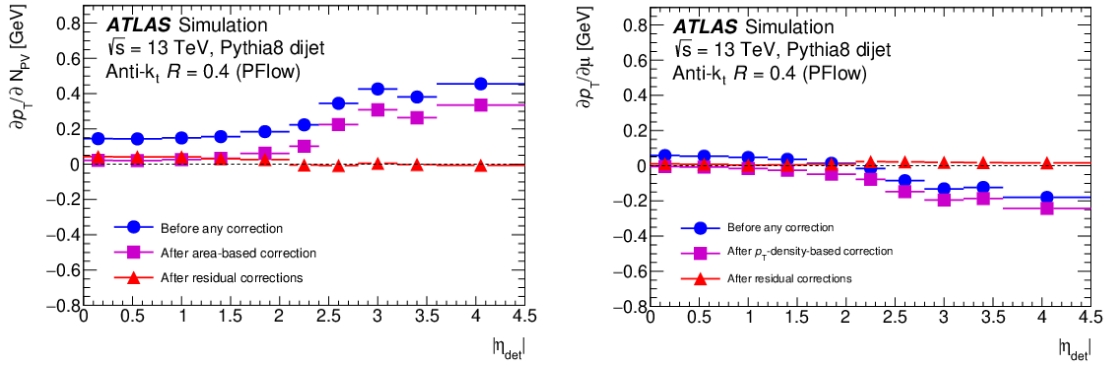


Figure 4.6: pile-up subtraction [39]

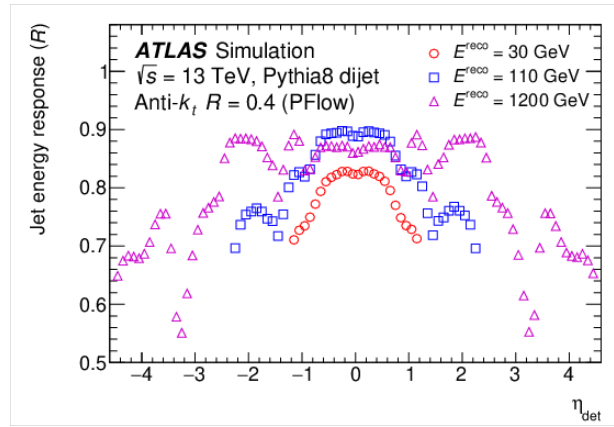


Figure 4.7: Jet energy response [39]

a function of η .

- Global sequential calibration

The Global Sequential Calibration (GSC) is applied, mainly to account for the different responses to quark and gluon-initiated jets. This calibration procedure reduces flavour dependence and energy leakage effects using calorimeter, track, and muon-segment variables. It also includes the correction for the punch-through, which happens for jets with large p_T whose energy is not fully contained in calorimeter [39]. The dependence of the n_{trk} on p_T response is shown in figure 4.8.

- In-situ calibration

The last calibration step is a correction with respect to the data. This is an adjustment for the potential differences between data and MC, and this is only applied to the data. The jet response is estimated by balancing the jet p_T to a well-measured recoil object. The first procedure denotes intercalibration, corrects the JES of forward jets to agree with that of central jets, by exploiting the p_T balance in dijet events. In the second procedure corrections are derived by balancing the jet p_T against a calibrated Z boson or photon (Z+jet and γ +jet analyses). Finally in the procedure called the multijet balance, a system of well-calibrated

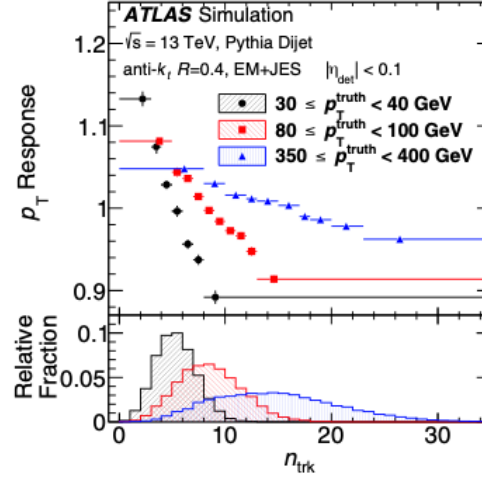
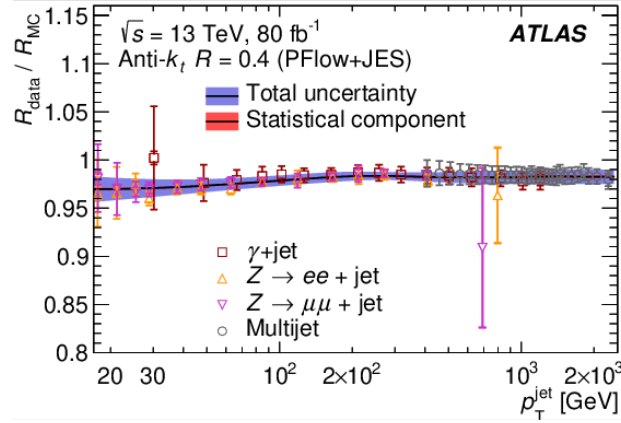
Figure 4.8: p_T response with respect to the number of tracks [39]

Figure 4.9: in-situ calibration [39]

low p_T jets is used to calibrate a single high p_T jet. Sets of the measurements are combined to give a continuous calibration curves of the ratio of the jet response as a function of jet p_T , shown in Figure 4.10. The jet energy resolution (JER) is also measured in-situ. The JER is usually derived in dijet events by exploiting momentum conservation.

The jet vertex tagger (JVT) is applied to identify the jets only from the hard interaction. Furthermore, in the context of the pile-up suppression, forward jet vertex tagger (fJVT) has been introduced, motivated by the forward-like topology in this analysis. The b-tagging is used for rejecting the jets tagging including the b-hadrons, to suppress the top contributions.

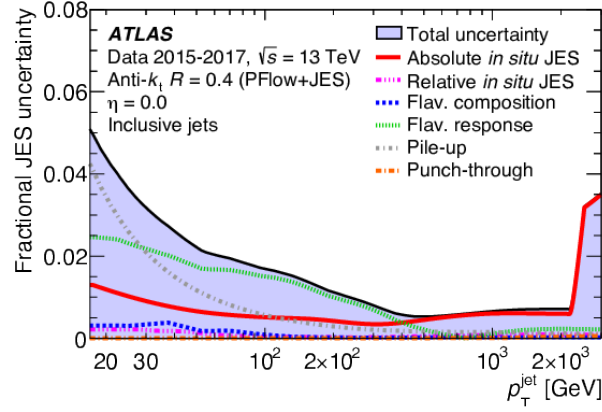
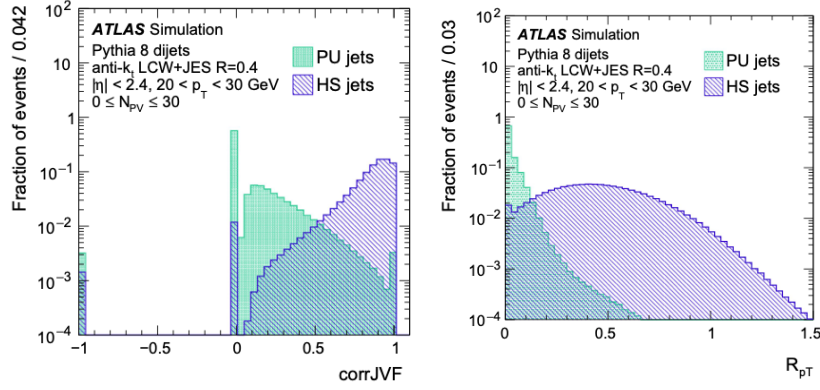


Figure 4.10: All JES-related uncertainties is shown in black line. [39]

Figure 4.11: Distributions of corrJVF (left) and R_{p_T} (right) for PileUp jets and Hard Scattering jets. [18]

4.5.1.1 Jet Vertex Tagger

The Jet Vertex Tagger (JVT) [18] is constructed using a two-dimensional likelihood derived from the combination of two jet variables, corrJVF and $R_{p_T}^0$;

$$\text{corrJVF} = \frac{\sum p_T^{\text{track}}(\text{PV}_0)}{\sum p_T^{\text{track}}(\text{PV}_0) + \frac{\sum_{i \geq 1} \sum p_T^{\text{track}}(\text{PV}_i)}{k \cdot n_{\text{trk}}^{\text{PU}}}} \quad (4.3)$$

and

$$R_{p_T}^0 = \sum_{\text{trk}} \frac{p_T^{\text{trk}}(\text{PV}_0)}{p_T^{\text{jet}}} \quad (4.4)$$

where PV_i is the reconstructed vertex i of the event. $i = 0$ represents the primary vertex. The $\sum p_T^{\text{track}}(\text{PV}_0)$ is the scalar sum of the p_T of the tracks that are associated with the jet and originate from the primary vertex (PV_0), and $\sum_{i \geq 1} \sum p_T^{\text{track}}(\text{PV}_i)$ represents the scalar p_T sum of the tracks that are associated with the jet and originate from pile-up vertices. k is a constant ($k = 0.01$), in order to suppress the pileup dependence, and $n_{\text{trk}}^{\text{PU}}$ denotes the total number of pileup tracks in an event. The distributions of two variables are shown in figure 4.11.

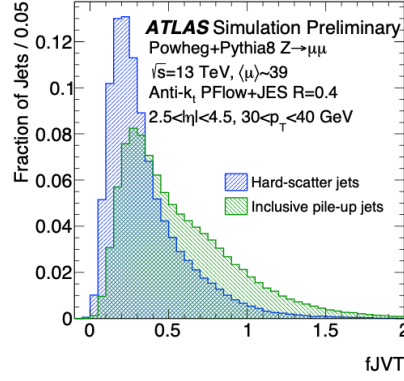


Figure 4.12: Distributions of fJVT for PileUp jets and Hard Scattering forward jets in $30 < p_T < 40$ GeV. [20]

4.5.1.2 forward Jet Vertex Tagger

The forward jet vertex tagger (fJVT) [20] employs momentum conservation in order to tag a forward PFlow jet. First central jets (jets with $|\eta| < 2.5$.) are reconstructed per every vertex, and the relevant calibration is applied. The QCD pile-up jets are identified by using JVT and the $R_{p_T}^i$ discriminant:

$$R_{p_T}^i = \sum_{\text{trk}} \frac{p_T^{\text{trk}}(\text{PV}_i)}{p_T^{\text{jet}}} \quad (4.5)$$

defined as the scalar p_T sum of the tracks that are associated with the jet and originate from the pile-up vertex i divided by the fully calibrated jet p_T . The missing transverse momentum per vertex i ($p_{T,i}^{\text{miss}}$) is then calculated as

$$\mathbf{p}_{T,i}^{\text{miss}} = - \left(\sum_{\text{jets}, p_T^{\text{jet}} > 20 \text{ GeV}} \mathbf{p}_T^{\text{jet}} + \sum_{\text{tracks}, p_T^{\text{jet}} < 20 \text{ GeV}} \mathbf{p}_T^{\text{track}} + \sum_{\text{tracks, jets fail } R_{p_T}^i \text{ cut}} \mathbf{p}_T^{\text{track}} \right) \quad (4.6)$$

For every forward jet fj, (jet in $2.5 < |\eta| < 4.5$.), the normalized projection of $p_{T,i}^{\text{miss}}$ on the direction of the forward jet,

$$\text{fJVT}_i = \frac{\mathbf{p}_{T,i}^{\text{miss}} \cdot \mathbf{p}_T^{\text{fj}}}{|\mathbf{p}_T^{\text{fj}}|^2} \quad (4.7)$$

is computed. The final forward JVT (fJVT) discriminant is defined as

$$\text{fJVT} = \max(\text{fJVT}_i) \quad (4.8)$$

The distributions of fJVT variable is shown in figure 4.12.

4.5.1.3 B-tagging

The small- R jets containing a b-hadron are called b-jets and identified by performing b-tagging. The algorithm makes use of the characteristics of the b-hadron whose lifetime is long enough to travel several mm from the primary interaction point before decaying, and create secondary vertices. These can be reconstructed using the tracks from the inner detector. Additional kinematic

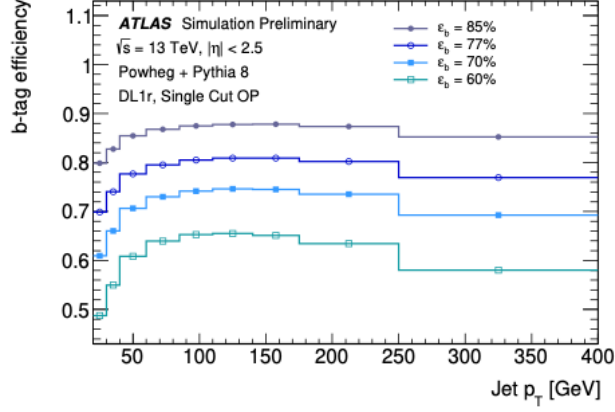


Figure 4.13: Distributions of btag efficiency with respect to the jet p_T [40]

properties of b-jets such as the mass and the momentum are also used in order to enhance separation with c-jets or light-jets originating from u-, d-, s- quarks or gluons. The DL1r algorithm [40], using a deep-learning neural network, is adopted in this analysis. The DL1r combines four low-level taggers, IP3D [23], SV1 [26], JetFitter [31], and RNNIP [21]. The IP3D uses signed impact parameter significance. The impact parameter, d_0 denotes the distance between tracks and the primary vertex. The SV1 reconstructs the secondary vertex in a jet. The JetFitter reconstructs the topology of b/c-hadron decay chains using Kalman filter [67]. Additionally, the RNNIP uses the track features including the track quality information. Finally the DL1r combines the outcomes all of these four low-level taggers by deep-learning neural network algorithm. Figure 4.13 shows the efficiency of b-tagging with respect to jet p_T . In this analysis the b-tagging working point is fixed at 70% efficiency.

4.5.2 Large-R Jets

The hadronic decaying objects from high- p_T W/Z boson cannot be separated as two small-R jets with large Lorentz boosts [44] and the angle between quarks is small, hence they are reconstructed as one large-R jet. Large-R jets are reconstructed with topo-cluster using anti- k_T algorithm with $R = 1.0$. The calibration applied for the large-R jets is mainly the same as the procedure with the small-R jets, described in subsection 4.5.1, though there are some specific calibrations for large-R jets. What is specific to the large-R jet is that the reconstructed topo-clusters are highly contaminated by the calorimeter noises, particles from pile-up, soft radiations. Therefore it is first applied grooming and then applied MC and in-situ calibrations.

- Grooming

Grooming techniques reduce contributions from pile-up and soft and wide angle emissions. Trimming algorithm [75] is used for this analysis. The original $R = 1.0$ jet is reclustered into the subjet with $R = 0.2$ using k_T algorithm, then only subjets with $p_T > 5\%$ of the original jet p_T are remained. The detailed calibration is provided for these trimmed jets.

- MC-based JES, η , mass calibration

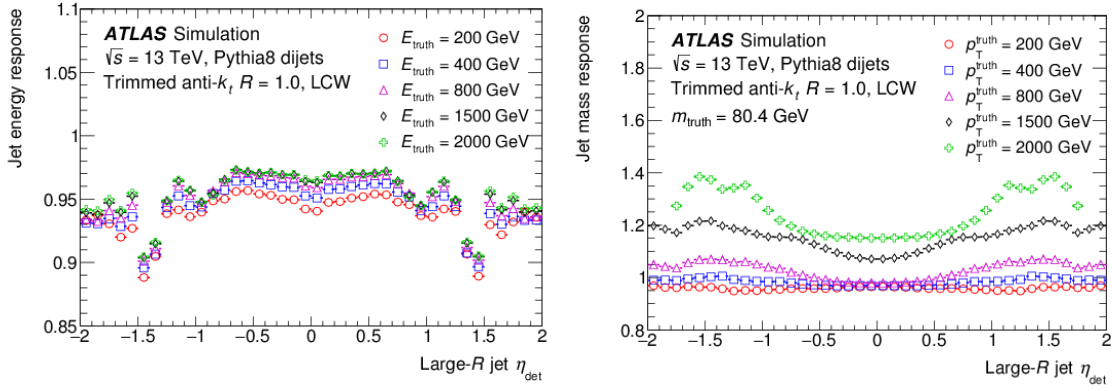


Figure 4.14: jet energy response of large-R jets [34]

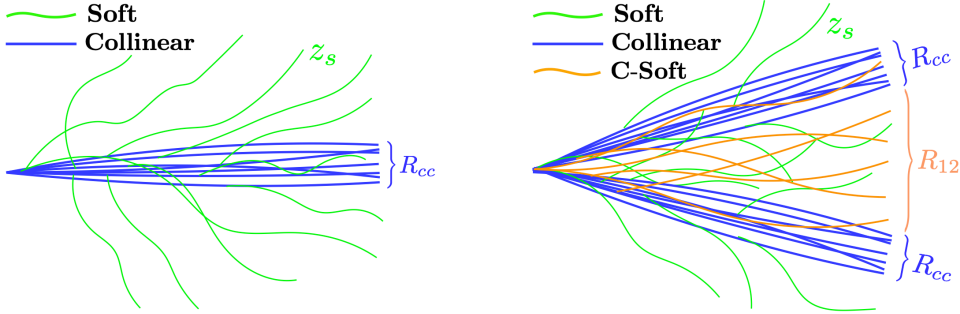


Figure 4.15: jet substructure [76]

The JES is evaluated as a ratio of their energy to the truth jets as the function of jet energy and η . The jet mass scale (JMS) calibration using the jet mass response of reconstructed jets to the truth is also applied. Figure 4.14 shows the jet energy and mass response.

- In-situ jet energy scale (JES) and jet mass scale (JMS) calibration

In-situ calibration is applied for the remaining difference in the jet energy between the data and MC. It is performed with a similar procedure with small-R jets. The JES is calibrated in events where the jet recoils against a reference object, which are calibrated photon, reconstructed Z boson, or a system of well-measured small-R jets. The in-situ JMS calibration is performed after the application of the in-situ JES corrections. The jet mass response is measured from fits to the jet mass peaks formed from by high p_T W bosons and top quark decaying hadronically. It is done by the R_{trk} method using the independent measurements by the calorimeter and the inner tracker [34].

4.5.3 Jet substructure

The large-R jet from boson has 2-prong structure, since it was originally collimated two quarks. This substructure can be the key to distinguish the boson jets to quark or gluon jets, which have 1-prong structure. Figure 4.15 shows the schematic view of the substructure. The jet substructure

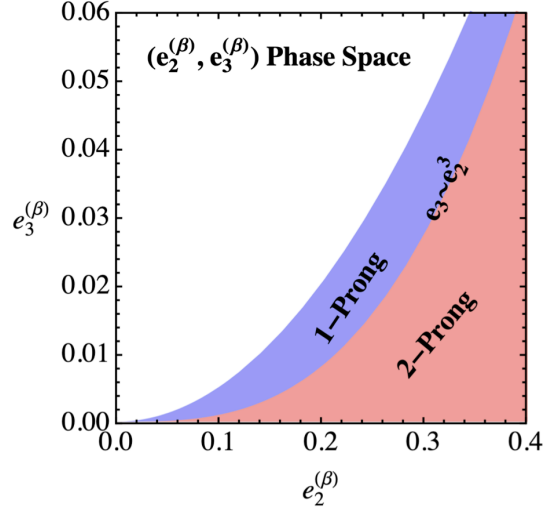


Figure 4.16: boundaries of energy correlation function [76]

variable, D_2 is used to characterize the structure. D_2 is defined as:

$$D_2^{(\beta)} = \frac{e_3^{(\beta)}}{\left(e_2^{(\beta)}\right)^3} \quad (4.9)$$

where the 2 and 3-point energy correlation function $e_n^{(\beta)}$ is defined as:

$$\begin{aligned} e_2^{(\beta)} &= \frac{1}{p_{TJ}^2} \sum_{1 \leq i < j \leq n_J} p_{Ti} p_{Tj} R_{ij}^\beta \\ e_3^{(\beta)} &= \frac{1}{p_{TJ}^3} \sum_{1 \leq i < j < k \leq n_J} p_{Ti} p_{Tj} p_{Tk} R_{ij}^\beta R_{ik}^\beta R_{jk}^\beta \end{aligned} \quad (4.10)$$

where p_{TJ} is the transverse momentum of the jet with respect to the beam, p_{Ti} is the transverse momentum of particle i , and n_J is the number of particles in the jet. The boost-invariant angle $R_{ij}^2 = (\phi_i - \phi_j)^2 + (y_i - y_j)^2$ is the distance in the azimuthrapidity plane and for infrared and collinear (IRC) safety, the angular exponent $\beta > 0$. These energy correlation depends on how the soft and the collinear jet contributions are. The 1-prong and the 2-prong jets can be distinguished at the boundary of $e_3^{\beta=1} \sim \left(e_2^{\beta=1}\right)^3$ as shown in Figure 4.16 [76]. The D_2 variable tends to get the lower value for 2-prong jet, boson jet while it tends to get the higher value for 1-prong jet, which is q/g jet.

4.5.4 Boosted Boson Tagger

The 3-variable cut-based tagger, that relies on D_2 , jet mass, and the number of the tracks is used for identifying the large- R jet from W/Z boson and to reject the other SM background processes [38]. The combined mass, reconstructed as the weighted sum of masses from calorimeter information and from mixed calorimeter and tracking information, is exploit since the W/Z decaying jet mass peaks around 80/91 GeV. The 2-prong energy structure inside jet which is characterized by D_2

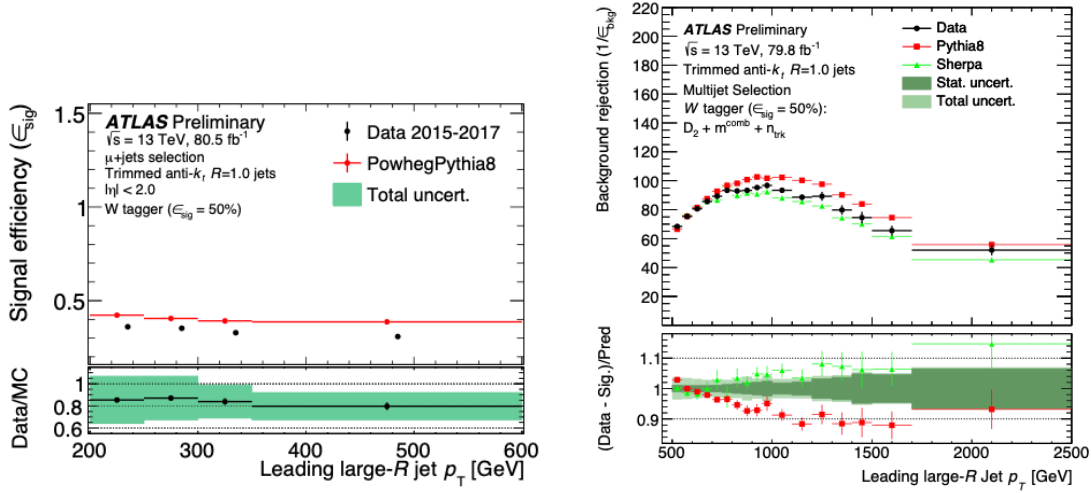


Figure 4.17: Measured signal efficiency (left) and background rejection (right) for 50 % W tagger [38]

is used. The number of track has been found to improve background rejection for a fixed signal efficiency [16] due to the rejection of jets seeded by gluons. Unlike jets from massive boson decays in which the hadron multiplicity is essentially independent of the jet p_T , energetic gluon jets are typically composed of more hadrons, so the number of charged-particle tracks associated with the original, ungroomed jet is required to be small. The tagger provides two fixed working points defined at 50% and 80 % signal efficiency. Figure 4.17 shows the measured signal efficiency plot of the boson tagger and the measured background rejection plot for 50 % efficiency working point.

4.6 Missing Transverse Momentum

The particle such as neutrinos traverses the whole detector and cannot be detected in the detector, as the Figure 4.1 shows. Those invisible particles are reconstructed by using the imbalance of the transverse momenta. It is calculated by the following formula:

$$\mathbf{E}_T^{\text{miss}} = - \sum_{i \in \{\text{hard objects}\}} \mathbf{p}_{T,i} - \sum_{j \in \{\text{soft objects}\}} \mathbf{p}_{T,j} \quad (4.11)$$

by taking the negative sum of the momenta of detected objects, electrons, muons, and jets and additionally, so called soft terms, which are charged-particle tracks not matched to the reconstructed objects [28].

Chapter 5

Experimental signature of the processes

In the following chapters, the measurement of an electroweak (EW) diboson (VV) production in association with a high-mass dijet system (jj) in the semileptonic final states is studied. This EW VV+jj process includes the VBS process described in section 2.3. In this analysis the fiducial volume is defined as a volume which is sensitive to the VBS process by applying the event selection

5.1 Feature of the process

EW VV+jj process is experimentally identified with the existence of two bosons ($VV = WW, ZZ$, or WZ) associated with two jets in opposite hemisphere with a large dijet invariant mass. The typical EW VV+jj processes are shown in figure 5.1. The VBS diagram, which is physically the most interesting one is shown in the left of the figure 5.1. The figure in the middle and the right represent non-VBS EW and QCD VV+jj production. EW non-VBS diagrams are also included in the signal process since they cannot be distinguished from VBS process for the gauge invariant conservation.

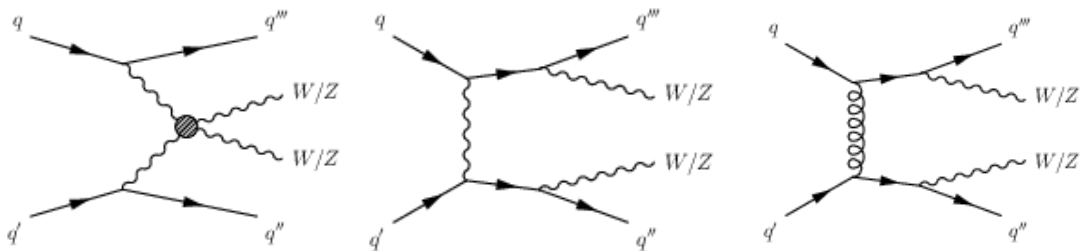


Figure 5.1: Feynman diagrams for EW VV+jj signals. Each diagram shows VBS process (left), EW non-VBS process (middle), and QCD non-VBS process (right).

This analysis focuses on the semileptonic final states, where one of the bosons decays leptonically, and the other hadronically. The schematic of the process is shown in Figure 5.2.

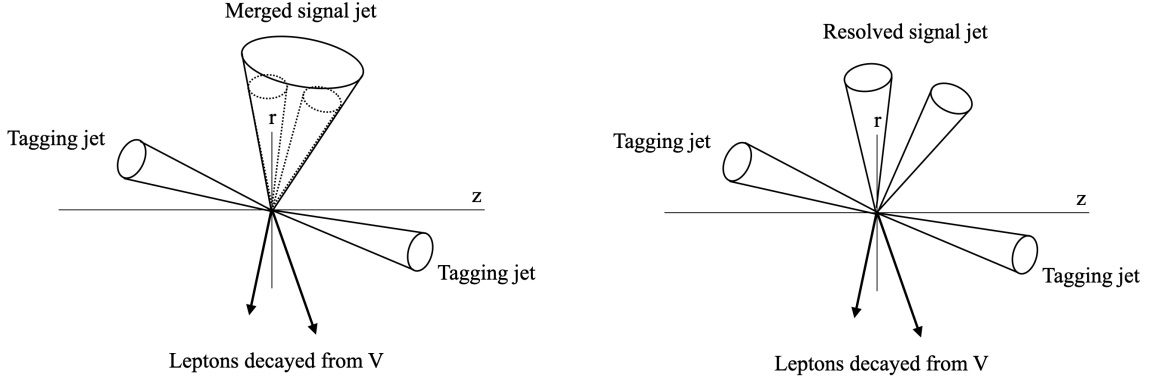


Figure 5.2: The schematic representation of a EW $VV+jj$ event. The hadronic decay of the V is reconstructed as one large- R jet in the merged selection (left), or two small- R jets in resolved selection (right).

The analysis is split into three channels, classified by the numbers of charged leptons decaying from one of the bosons: 0-lepton, 1-lepton, 2-lepton. In the 0-lepton channel, $Z \rightarrow \nu\nu$ is considered, experimentally reconstructed as the missing transverse energy (MET). In 1-lepton channel one of the bosons decays as $W \rightarrow \nu l$ where we can find exactly the lepton, $l = e, \mu$ with MET. In 2-lepton channel $Z \rightarrow ll$ is required with $l = e, \mu$. In all three channels, the process requires a hadronically decaying boson candidate, and two additional jets. These additional two jets are initially from the quarks from VBS production, referred to as tagging jets. The hadronic decaying objects are reconstructed as a pair of small- R jets or as a single large- R jet. The former case is called as the resolved selection, and the latter the merged selection. More details about the objects in each category is shown in section 6.1.

The relevant background processes include $W/Z + \text{jets}$, single top (t) and top quark pair production ($t\bar{t}$) process, QCD diboson process, and QCD multijet process. In 0-lepton channel, all of the background processes contribute significantly. In 1-lepton channel $W + \text{jets}$ and the $t\bar{t}$ process dominate, and in 2-lepton channel $Z + \text{jets}$ process is the dominant process.

5.2 Data and Monte Carlo Simulation

5.2.1 Data

The data used in the analysis is collected by the ATLAS detector with pp collisions at a center of mass energy of 13 TeV during the full Run 2 data taking period during the years 2015 to 2018. The total integrated luminosity in this period is 139 fb^{-1} with the uncertainty of 1.7 % [13]. Along with the higher luminosity, the number of collisions per bunch crossing increases. This phenomenon is usually referred to as pile-up. The pile-up effects introduce contamination for the physics process of interest in LHC. Figure 5.3 shows the cumulative luminosity versus time during the Run 2, and the distribution of the interactions per bunch crossing.

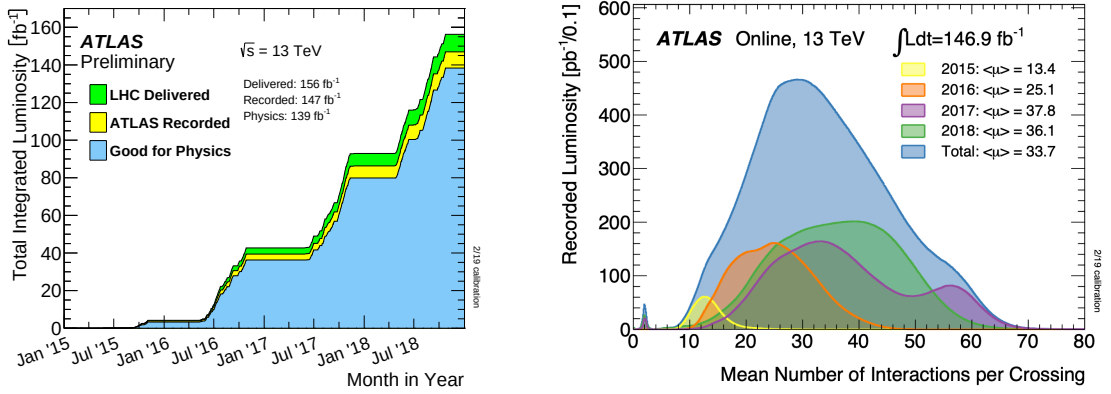


Figure 5.3: Cumulative luminosity delivered to ATLAS (green), recorded by ATLAS (yellow), and good quality data (blue) during full Run 2 period (left), and the mean number of interactions per bunch crossing $\langle \mu \rangle$ for the Run 2 period collision data (right). [13]

5.2.2 Signal and Background Monte Carlo simulation

The details of the signal and the background production in the Monte-Carlo simulation are discussed in this subsection. The Monte Carlo (MC) samples are used for the production of the background process, optimization of the event selection and the multivariate techniques to enhance the signal sensitivities, and the estimation of the systematic uncertainties.

Signal EW VV+jj process

The EWK VV+jj production signal is modeled using MadGraph5_aMC@NLO v2.3.3 [7] event generator, with PYTHIA8 [85] for the parton shower modeling and hadronization. The NNPDF30LO PDF set [47] is used. The EWK VV+jj samples are generated at LO with two on-shell V bosons, with one of which decays leptonically ($Z \rightarrow \ell\ell$ with $\ell = e, \mu$, $Z \rightarrow \nu\nu$, $W \rightarrow \ell\nu$ with $\ell = e, \mu, \tau$), and the other decays hadronically. For the W boson, both W^+ and W^- are considered. For each sample, all purely-electroweak tree-level diagrams (i.e. $\mathcal{O}(\alpha_{EW}^6)$ diagrams) that contribute to the final state are considered.

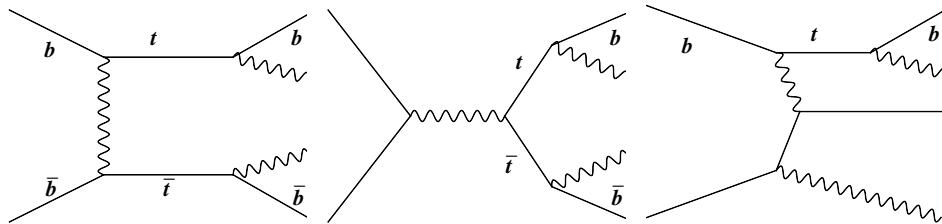


Figure 5.4: non-VBS diagrams contribute to the signal, include top.

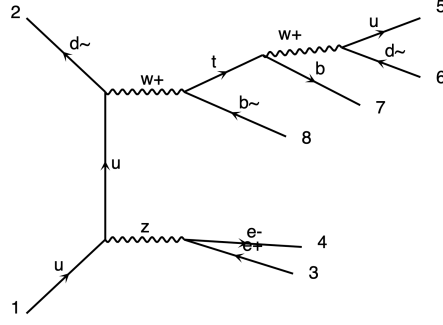


Figure 5.5: The example of the tZb diagram, which included in non-VBS diagrams.

Especially the contribution from electroweak $t\bar{t}b$ process shown in figure 5.4 is included about 50 % of the whole EW $VV+jj$ signal samples, which can be suppressed by applying b-veto (not requiring the b-tagged jets). After applying b-veto in the event selection, there is still non-negligible contributions from tZb process, shown in figure 5.5. This contribution is reduced by applying additional cut described in section 6.2. The production cross section calculated by MadGraph is shown in the table 5.1.

Process	cross section (pb)
$W(l\nu)W(qq')jj, b - veto$	1.99
$W(l\nu)W(qq')jj, b - filter$	1.97
$W(l\nu)W(qq')jj$	3.96
$W(l\nu)Z(qq')jj$	0.25
$W(\nu\nu)W(qq')jj$	0.15
$Z(ll)W(qq')jj$	0.045
$Z(\nu\nu)Z(qq')jj$	0.032
$Z(ll)Z(qq')jj$	0.0096

Table 5.1: List of production cross sections of the signal samples. b-veto/b-filter correspond to samples without/with decays containing b -quarks.

Background processes

The $W/Z + jets$ background is modeled by using Sherpa 2.2.1 [70] generator. The $W/Z + jets$ process includes only $V \rightarrow ll$ process, and $V \rightarrow qq$ process is not considered, since it is estimated directly from data in the 1-lepton channel, and almost negligible in the 2-lepton channel. Matrix element is calculated for up to 2 partons at next-to-leading order (NLO), and 4 partons at leading order (LO) with Comix [71] and OpenLoops[51] matrix element generators, with the Sherpa parton shower [81] using the ME+PS@NLO prescription [73]. The NNPDF3.0NNLO PDF set is used in association with authors' tuning. The resulting events are normalized to the NNLO cross sections.

The QCD diboson background is also generated with Sherpa 2.2.1 generator. The diboson process includes only semi-leptonic process. The full-leptonic process has fairly small contribution.

Single-top and $t\bar{t}$ backgrounds are generated with the Powheg-Box [5] generator with the NNPDF3.0NLO PDF[48] sets in the matrix element calculation. The top mass is set to 172.5 GeV. The parton shower and the hadronization is simulated using Pythia 8.230.

Considered $t\bar{t}$ process is not all-hadronic process, since other processes are negligible.

All simulated events are processed with the same trigger and reconstruction algorithms as the data. Additional pp collisions generated with Pythia 8.186[84] are overlaid to model the effect of the pileup, the particles coming from secondary collisions in the same data-taking timing, for all MC events. In order to take into account the detector geometry and the reconstruction efficiency, samples are processed through the full ATLAS detector simulation[12] based on GEANT4[4].

5.2.3 aQGC signal process Monte Carlo simulation

To model possible aQGC effect in the VBS process, the Eboli model [64] which introduces 21 new dim-8 operators is used as described in section 2.5.1. Of these operators, 19 can affect the semileptonic VBS final state.

In generality, the matrix-element of a SM process with the addition of new EFT contributions can be written as:

$$|A_{SM} + c_i A_i|^2 = |A_{SM}|^2 + \sum_i c_i^2 |A_i|^2 + \sum_i 2c_i \text{Re}(A_{SM}^* A_i) + \sum_{i \neq j} c_i c_j \text{Re}(A_i^* A_j) \quad (5.1)$$

where $|A_{SM}|^2$ is the SM matrix element, $|A_i|^2$ represents the pure-EFT matrix element, $2\text{Re}(A_{SM}^* A_i)$ is their corresponding interference term, and $\text{Re}(A_i^* A_j)$ is the possible interference between EFT amplitudes. This structure can be exploited in recent MadGraph5_aMC@NLO versions which allows the specific generation of each of these terms individually, known as the matrix-element decomposition method.

Typically one would need to generate a series of samples for each operator A_i at different c_i values, to derive a series of template functions for $|A_{SM} + c_i A_i|$ which would need to be interpolated between for arbitrary c_i . Generating samples with the decomposition method greatly simplifies this procedure as one only now needs to generate for each operator A_i the corresponding pure-EFT and interference terms (as well as cross-interference terms if needed). These templates can then be scaled either quadratically or linear with the corresponding c_i values to generate the required full template $|A_{SM} + c_i A_i|$.

The Eboli dim-8 EFT processes are modeled using MadGraph5_aMC@NLO v2.7.2 [7] at LO with the NNPDF30LO PDF set [47] plus 8.244 [85] for fragmentation. The matrix-element calculation produces two on-shell W/Z bosons, which are subsequently decayed with Madspin [9] to simulate the leptonic and hadronic decays of the bosons. The use of Madspin is required for use of the matrix-element weighting and requires separate generation for each weak isospin state of the boson (i.e the following processes are simulated separately: W^+W^- , W^+W^+ , W^-W^- , W^+Z , W^-Z , ZZ).

Chapter 6

Event selection

The event selection has been optimized for the EW VV+jj signals against the background processes. First the object definition is shown in section 6.1, then the detail of the whole event selection is presented in section 6.2.

6.1 Object definition

In this section object definition employed in the analysis is shown.

6.1.1 Triggers

Trigger selection is firstly applied in order to select events in interest. The triggers applied depend on the channel and on the data taking period. The trigger selection is done using single-electron or single-muon triggers. The list of the trigger names applied in this analysis is summarized in table 6.1.

Data-taking period	$evqq$ and $eeqq$ channels	$\mu\nu qq$ ($(\mu\nu) < 150\text{GeV}$) and $\mu\mu qq$ channels	$\mu\nu qq$ ($(\mu\nu) > 150\text{GeV}$) and $\nu\nu qq$ channels
2015	HLT_e24_lhmedium_L1EM20 OR HLT_e60_lhmedium OR HLT_e120_lhloose	HLT_mu20_loose_L1MU15 OR HLT_mu50	HLT_xe70
2016a (run < 302919) ($L < 1.0 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$)	HLT_e26_lhtight_nod0_ivarloose OR HLT_e60_lhmedium_nod0 OR HLT_e140_lhloose_nod0 HLT_e300_etcut	HLT_mu26_ivarmedium OR HLT_mu50	HLT_xe90_mht_L1XE50
2016b (run ≥ 302919) ($L < 1.7 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$)	same as above	same as above	HLT_xe110_mht_L1XE50
2017	same as above	same as above	HLT_xe110_pufit_L1XE55
2018	same as above	same as above	HLT_xe110_pufit_xe70_L1XE50

Table 6.1: The list of triggers used in the analysis.

6.1.2 Leptons

Electrons are required to have: $p_T > 30 \text{ GeV}$ in 1-lepton channel and $p_T > 7 \text{ GeV}$ in the 2-lepton channel, and pseudorapidity $|\eta| < 2.47$ while muons should satisfy: $p_T > 30 \text{ GeV}$ in the 1-lepton

channel and $p_T > 7$ GeV in 2-lepton channel, and $|\eta| < 2.5$. “Tight” identified electron and muon described in chapter 4, is used for the 1-lepton channel, while “Loose” electron and muon candidate is used for the 2-lepton channel. Electrons and muons are required to have a transverse impact parameter significance relative to the beamline ($|d_0|/\sigma_{d_0}$) smaller than 5 and 3, respectively, and a longitudinal impact parameter $|z_0 \times \sin\theta| < 0.5$ mm relative to the primary vertex.

6.1.3 Jets

Small-R jets

Small-R jets are reconstructed using the anti- k_T algorithm from the PFlow objects, described in chapter 4. Small-R jets in $|\eta| < 2.5$ (central jets) are required to have a $p_T > 20$ GeV while jets with $|\eta| > 2.5$ (forward jets) requires $p_T > 30$ GeV. In order to reassure that the selected jets are coming from the hard-scatter vertex, the “tight” working point JVT cut, introduced in chapter 4, is applied for jets with $p_T < 60$ GeV and $|\eta| < 2.4$. The “loose” working point fJVT cut is also applied to the jets outside the tracking coverage ($2.5 < |\eta| < 4.5$).

Large-R jets

Large-R jets are required to have $p_T > 200$ GeV, $|\eta| < 2.0$ and $m > 50$ GeV. In order to identify a large-R jet coming from a W/Z boson decay, a 3-variable W/Z tagger described in chapter 4 is employed.

6.2 Event selection

Common preselection cuts are applied including event cleaning and the trigger requirements, followed by a specific event selection to each of the 0,1,2-lepton channels. For the main event selection, first the W/Z boson decaying leptonically is selected, then pair of forward jets to enhance the VBS topology is selected, and finally the signal region (SR) and the control region (CR) are defined by the hadronically decaying W/Z boson reconstruction. Several CRs dedicated to main background processes (V+jets, $t\bar{t}$) are defined separately, and they are used to estimate the normalization of the simulated background events from the data.

6.2.1 Selection of the leptonically decaying boson

The selection to reconstruct the leptonically decaying W/Z boson is applied separately in each lepton channel.

0-lepton

In the 0-lepton channel, a high missing transvers momentum E_T^{miss} is expected to originate from two neutrinos in the final state. Cuts on $E_T^{miss} (> 200$ GeV) and $E_T^{miss, track} (> 50$ GeV) is applied. The QCD-induced multijet background with fake E_T^{miss} due to the mis-reconstruction and momentum resolution of the jets is significant in the 0-lepton channel. To suppress its contribution, several cuts are applied related to the direction of E_T^{miss} and the jet: $\Delta\phi(E_T^{miss}, p_T^{miss}) < \pi/2$,

$\min(\Delta\phi(E_T^{\text{miss}}, j)) > \pi/6$ and, $\Delta\phi(E_T^{\text{miss}}, V_{\text{had}}) > \pi/9$. The fake E_T^{miss} contribution can be ignored after this selection.

1-lepton

One tight-lepton with $p_T > 30$ GeV and $E_T^{\text{miss}} > 80$ GeV is required. In 1-lepton channel there are significant contribution from $t\bar{t}$ background hence b-veto is applied to all small-R jets to reduce its contribution.

2-lepton

Two same flavor loose-leptons satisfying $p_T > 28$ GeV ($p_T > 20$ GeV) for the leading (sub leading) one and an invariant mass of the lepton system (m_{ll}) close to the Z boson mass are requested. Figure 6.1 shows a peak of the invariant mass reconstructed by two selected leptons around the Z boson mass. Depending on the lepton pair (ee , $\mu\mu$) different mass window requirements are applied; for electrons, $83 < m_{ee} < 99$ GeV is applied, for muons $p_{T, ll}$ -dependent mass window is required in order to recover the dimuon mass resolution degradation at high- $p_{T, ll}$ [30]:

$$(85.6 - 0.0117p_{T, \ell\ell}) < m_{\mu\mu} < (94.0 + 0.0185p_{T, \ell\ell}) \text{ GeV}$$

In addition, muons are required to have opposite charges. The opposite charge requirement is not requested for electrons which are more susceptible to charge mis-identification due to the conversions of photons from bremsstrahlung. After this selection most of the background process exist is Z+jets.

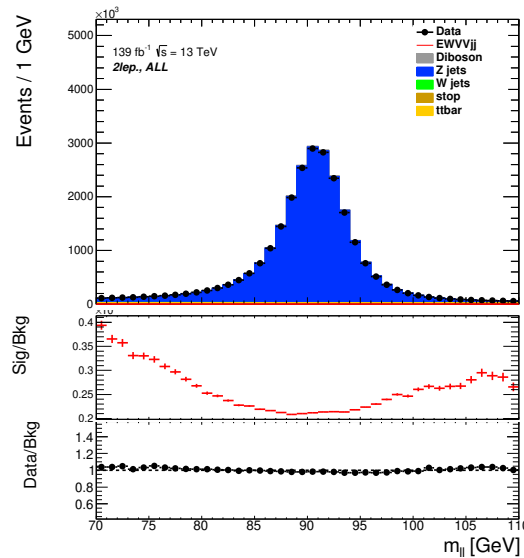


Figure 6.1: Lepton distributions in 2-lepton channel. The events before any selections are shown. Z mass peak can be seen in M_{ll} distribution.

6.2.2 Selection of the tagging jet

It is expected for VBS process to have a pair of small-R jets in the forward-backward directions, referred to as tagging jets, in addition to the jets induced from hadronically-decaying quarks.

Requiring the tagging jets is a particular feature of the VBS process, and it helps separating signal process efficiently from the main backgrounds. The fJVT selection is applied to suppress the pileup jets contributions. Tagging jet candidates are selected from the pairs of jets in opposite hemispheres, $\eta_{\text{tag } j_1} \cdot \eta_{\text{tag } j_2} < 0$, each of which have $p_T > 30$ GeV and $|\eta| < 4.5$, and the one with the highest dijet invariant mass is chosen. Selected tagging jets are required to have the dijet invariant mass, $m_{jj}^{\text{tag}} > 400$ GeV. The tagging jets are selected prior to the signal jets. This order of the jet selection is optimized to maximize the signal sensitivity. Figure 6.2 shows the m_{jj}^{tag} distribution before selecting the analysis regions in 2-lepton channel. As shown in the figure 6.2, m_{jj}^{tag} in the simulated events does not agree with data well. The m_{jj}^{tag} reweighting, which is described in Chapter 7, is applied before defining the analysis regions to correct the shape of the Z+jet modeling.

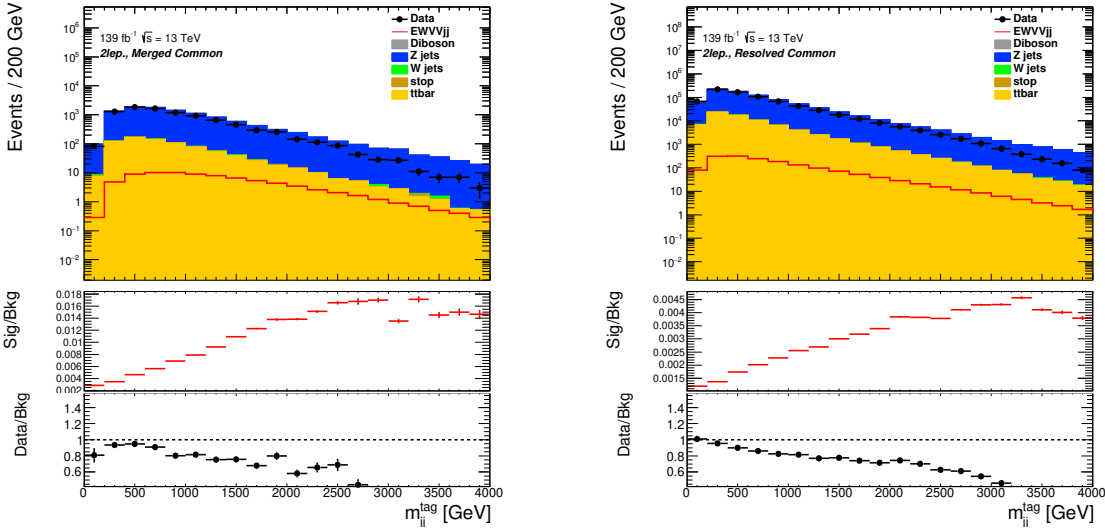


Figure 6.2: m_{jj}^{tag} distribution before defining the SRs in merged selection (left) and in resolved selection (right). The known slope due to the Z+jets modeling issue can be seen. Details are described in Chapter 7. $m_{jj}^{\text{tag}} > 400$ GeV cut is applied to these distribution to enhance the signal sensitivity.

6.2.3 Selection of hadronically decaying boson

Hadronically decaying boson (V_{had}) is reconstructed as a single large-R jet and a pair of small-R jets in merged selection and resolved selection, respectively.

Merged selection

The leading large-R jet not overlapping with any of the tagging jets by $|\Delta R| > 1.4$, to avoid the double counting of the energy deposits, is selected as the signal jet candidate (sigJ). The sigJ is required to have a $p_T \geq 200$ GeV, $|\eta| < 2.0$, and not overlapping with leptons by $|\Delta R| > 1.0$. Figure 6.3 shows the mass of these sigJ distribution.

In order to select events including sigJ coming from the W/Z hadronically decay, the boson-tagger is applied. Events are further divided into subcategories depending on the result of the boson-tagger. The events passing the boson-tagger 50 % efficiency working point is categorized in

the so-called high-purity (HP) signal region (SRVBS_HP), while those failing 50 % working point but passing 80 % working point are considered in the low-purity (LP) signal region (SRVBS_LP) as shown in figure 6.6.

Resolved selection

For the bosons with the lower p_T ranges, the boson decays into the two well-separated jets. The two leading- p_T small-R jets are selected as the signal jet candidates, from the rest of the jets after tagging jets selection. The leading jet is required to have $p_T > 40$ GeV and the subleading, $p_T > 20$ GeV. Their invariant mass (m_{jj}^{sig}) should be inside the mass window of $64 < m_{jj}^{sig} < 106$ GeV, near the W/Z mass. Figure 6.3 shows that the reconstructed boson peak before requiring the mass window.

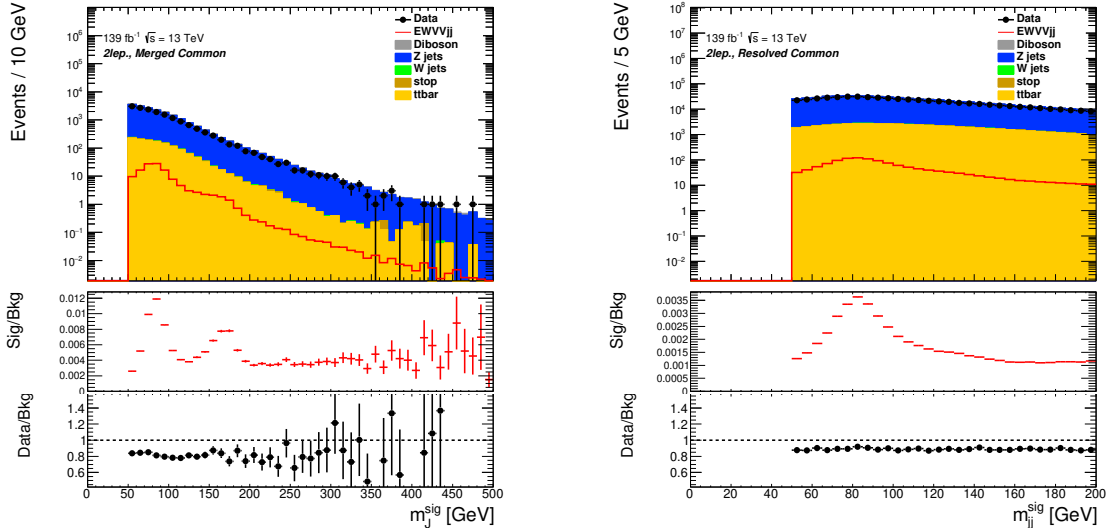


Figure 6.3: Invariant mass of the two signal jets before requiring the boson tagger in merged region (left) and before requiring the mass window in the resolved region (right), in 2-lepton channel. The second peak shown in the signal sample in merged region comes from the top contribution, for example from the process including the Wtb vertex.

An additional cut is applied to suppress the top contributions discussed in section 5.2.2. A cut to the reconstructed top mass, $m_{jjj} > 220$ GeV is applied in the resolved selection. The m_{jjj} is derived with the two signal jets and the third jet which forms the three-jet mass, the closest to the Top mass (172.76 GeV). The third jet is selected from the small-R jets without the signal jets, hence can include the forward jets. The m_{jjj} for events including truth particle of top, triboson, and the others is shown in figure 6.4. The reconstructed top mass peak can be seen.

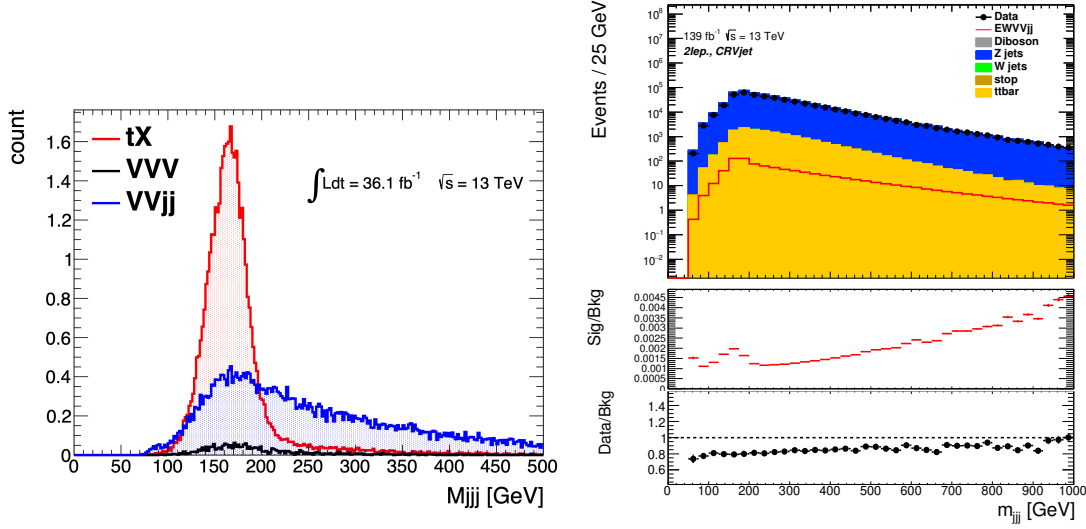


Figure 6.4: Mass of 3 jets in the 2-lepton channel resolved signal region with events including top (tX, in red), 3 bosons (VV, in black), and others, which is VBS-like events (VVjj, in blue). (left) The modeling plot in resolved control region is also shown. (right)

This top-mass cut can reduce the top contributions, as shown in Table 6.5 in resolved selection, therefore the resolved signal region (denoted as SRVBS_Tight) is defined with this additional cut to get more VBS-like phase space. In merged selection top-mass can be defined in the similar manner, m_{Jj} , by the invariant mass of the large-R signal jet and the additional jet which make the closest invariant mass to the top mass. However, top contribution is already small without the top mass cut, after the event selections above, hence this cut is not added to the merged selection.

	SRVBS (resolved)	VBS enhanced (resolved)	SRVBS (merged)	VBS enhanced (merged)
Truth Top	0.48	0.14	0.14	0.10
Truth VVV	0.03	0.03	0.08	0.08
Truth VBS	0.49	0.83	0.78	0.82

Figure 6.5: Fraction of event yields for 2lepton channel. The truth information is used to know if the event includes each contributions. Only EWWZjj events are checked here since there are no Top contributions in EWZZjj events.

6.2.4 Control region definitions

The control region (CR) is defined to estimate the normalization of the main backgrounds and apply it in the signal region. CRs should be defined in a similar way as the SRs so that the uncertainty on the extrapolation from CRs to SRs is minimized. It is defined by inverting one of the cuts to define merged and resolved categories, with keeping the other cuts to be the same as the SRs. The dedicated CRs to the V+jets and $t\bar{t}$ background events are defined in this analysis.

V+jets CR

There are separate CRs for V+jet in merged and resolved categories (V is Z/W for 0-lepton, W for 1-lepton, Z for 2-lepton channel) since they have the different phase spaces and possible mismodeling of the cross section depending on the mass. Merged V+jets CR is defined by requiring events to fail boson tagger 80 % efficiency working point. Merged CR and SR definition is shown in the Figure 6.6.

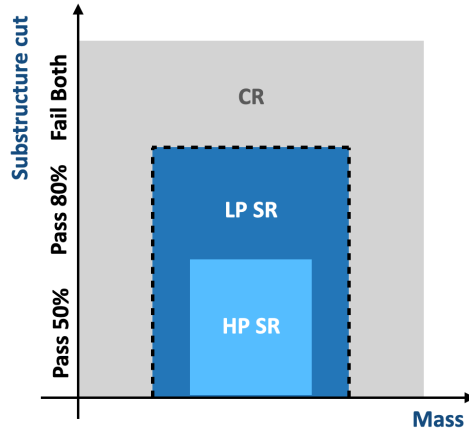


Figure 6.6: The selection of the merged SR and CR are shown. The CR definition is what was changed from the previous round of the analysis, in order to fulfill the requirement to derive the scale factors.

The normalization of the V+jets background is estimated in merged CR, and is propagated to the SR by assuming the efficiency of the boson tagger is well modeled by the simulation. The possible data-to-MC disagreement of the efficiency and its uncertainty is estimated using dedicated data samples independent of this study.

In the resolved V+jets CR, events are selected by reverting the mass window cut, which should satisfy $50 < m_{ii} < 64$ GeV, or $m_{ii} > 106$ GeV. Figure 6.7 shows the mass of the reconstructed boson in CRs. The Z+jets background has continuous mass distributions in CR and SR hence its normalization can be estimated from mass-sideband in CR, while signal has a significant peak in SR as can be seen in figure 6.3.

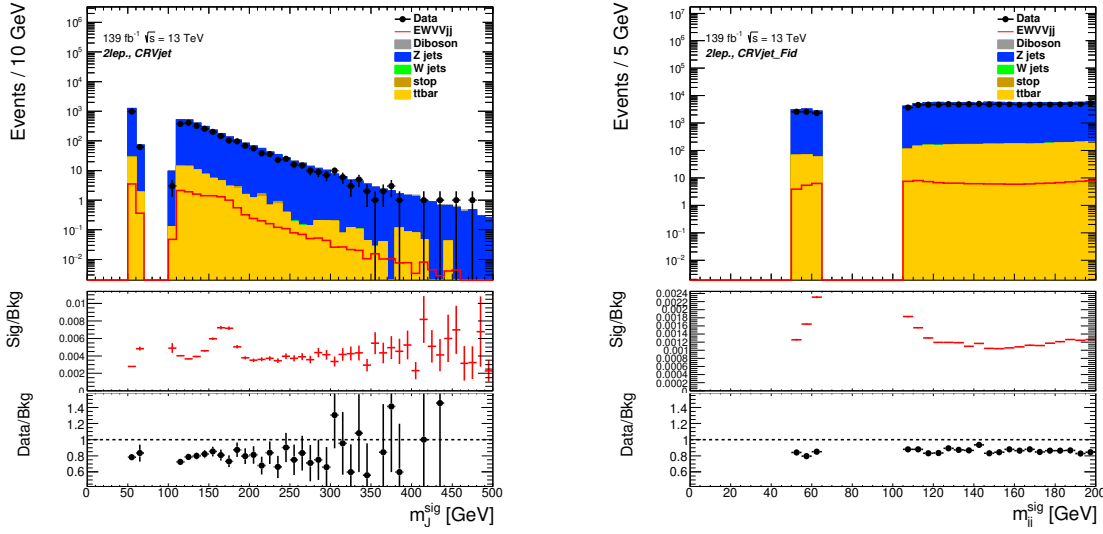


Figure 6.7: Mass of reconstructed boson in the resolved CR

In the intermediate p_T range, hadronically decaying boson can be reconstructed by both merged and resolved selections. The order of the event selection is optimized to increase the sensitivity after the combination of merged and resolved analyses. Event is first analyzed in the merged selection, and if it does not satisfy the selection cut for that, it is reanalyzed in the resolved category. The event selection is performed subsequently in the order shown in the diagram in figure 6.8.

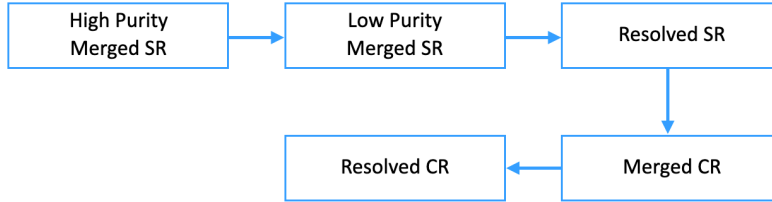


Figure 6.8: The order of defining the SR and the CR. The merged SR are defined at first, and the events failed the merged SR selections goes to the selection of the resolved SR, therefore there are no overlapped events within several SR and CRs.

Top CR

Top CR is used to constraint the normalization of the $t\bar{t}$ background. It exists only in 1-lepton channel, where selected events contain plenty of $t\bar{t}$ background. It is defined by requiring at least one b-tagged jet instead of b-veto. Requiring of the b-tagging is applied after the hadronically decaying boson selection, therefore there is three Top CRs according to the SRs: Resolved Top CR, Merged HP CR, Merged LP CR.

6.3 Summary of the event selections

The summary of the whole event selection applied in each channel is shown here in the Table 6.2-6.3 (0-lepton), 6.4-6.5 (1-lepton), 6.6-6.7 (2-lepton).

Selection		SR		V CR
		HP	LP	
$Z \rightarrow \nu\nu$	Number of Loose leptons	0		
	E_T^{miss}	$> 200 \text{ GeV}$		
	p_T^{miss}	$> 50 \text{ GeV}$		
anti-QCD	$\min(\Delta\Phi(E_T^{\text{miss}}, \text{small} - R\text{jets}))$	$> \pi/6$		
	$\Delta\Phi(E_T^{\text{miss}}, p_T^{\text{miss}})$	$< \pi/2$		
	$\Delta\phi(E_T^{\text{miss}}, \text{Sig} - J)$	$> \pi/9$		
VBS jets candidates	Leading Tag jet	$> 30 \text{ GeV}$		
	Subleading Tag jet	$> 30 \text{ GeV}$		
	m_{jj}	$> 400 \text{ GeV}$		
$W/Z \rightarrow J$	Num of large-R jets	≥ 1		
	3-Var Tagger	pass50WP	pass80WP && !pass50WP	fail80WP

Table 6.2: A summary of regions event selection for 0-leptonchannel in the merged regime.

Selection		SR	V CR
$Z \rightarrow \nu\nu$	Number of Loose leptons	0	
	E_T^{miss}	$> 200 \text{ GeV}$	
	p_T^{miss}	$> 50 \text{ GeV}$	
anti-QCD	$\min(\Delta\Phi(E_T^{\text{miss}}, \text{small} - R\text{jets}))$	$> \pi/6$	
	$\Delta\Phi(E_T^{\text{miss}}, p_T^{\text{miss}})$	$< \pi/2$	
	$\Delta\phi(E_T^{\text{miss}}, \text{Sig} - J)$	$> \pi/9$	
VBS jets candidates	Leading Tag jet	$> 30 \text{ GeV}$	
	Subleading Tag jet	$> 30 \text{ GeV}$	
	m_{jj}	$> 400 \text{ GeV}$	
$W/Z \rightarrow jj$	Number of small-R jets	≥ 4	
	Leading signal jet	$> 40 \text{ GeV}$	
	Subleading signal jet	$> 20 \text{ GeV}$	
	$Z \rightarrow q\bar{q}$ and $W \rightarrow q\bar{q}$	$64 < m_{jj} < 106$	$50 < m_{jj} < 64 \text{ GeV}$ or $m_{jj} > 106$
VBS enhancing	m_{jjj}	$> 220 \text{ GeV}$	

Table 6.3: A summary of regions event selection for 0-leptonchannel in the resolved regime.

Selection		SR		W CR (WR)	$t\bar{t}$ CR (TR)	
		HP	LP	incl	HP	LP
$W \rightarrow \ell\nu$	Num of Tight leptons	1				
	Num of Loose (!Tight) leptons	0				
	E_T^{miss}	$> 80 \text{ GeV}$				
	(ℓ)	$> 30 \text{ GeV}$				
VBS jets candidates	Leading Tag jet	$> 30 \text{ GeV}$				
	Subleading Tag jet	$> 30 \text{ GeV}$				
	m_{jj}	$> 400 \text{ GeV}$				
$W/Z \rightarrow J$	Num of large-R jets	≥ 1				
	3-Var Tagger	pass50WP	pass80WP && !pass50WP	fail80WP	pass50WP	pass80WP && !pass50WP
Top veto	Num of b -tagged jets outside of large-R jet	0			≥ 1	

Table 6.4: A summary of regions event selection for 1-leptonchannel in the merged regime.

Selection		SR	W CR (WR)	tCR (TR)
$W \rightarrow \ell \nu$	Number of Tight leptons	1		
	Number of Loose (!Tight) leptons	0		
	E_T^{miss}	$> 80 \text{ GeV}$		
	(ℓ)	$> 30 \text{ GeV}$		
VBS jets candidates	Leading Tag jet	$> 30 \text{ GeV}$		
	Subleading Tag jet	$> 30 \text{ GeV}$		
	m_{jj}	$> 400 \text{ GeV}$		
$W/Z \rightarrow jj$	Number of small-R jets	≥ 4		
	Leading jet	$> 40 \text{ GeV}$		
	Subleading jet	$> 20 \text{ GeV}$		
	$Z \rightarrow q\bar{q}$ and $W \rightarrow q\bar{q}$	$64 < m_{jj} < 106$	$50 < m_{jj} < 64 \text{ GeV}$ or $m_{jj} > 106$	$64 < m_{jj} < 106$
Top veto	Number of additional b -tagged jets	0		
VBS enhancing	m_{jjj}	$> 220 \text{ GeV}$		

Table 6.5: A summary of regions event selection for 1-lepton channel in the resolved regime.

Selection		SR		Z CR
		HP	LP	incl
$Z \rightarrow \ell\ell$	Number of Loose leptons	2		
	Same flavor	yes		
	Leading lepton	$> 27 \text{ GeV}$		
	Subleading lepton	$> 27 \text{ GeV}$		
	dilepton invariant mass	$83 < m_{ee} < 99$ $-0.01170 p_{T,\ell\ell} + 85.63 < m_{\mu\mu} < 0.01850 p_{T,\ell\ell} + 94.00$		
	Opposite sign	For $\mu\mu$ channel only		
VBS jets candidates	Leading Tag jet	$> 30 \text{ GeV}$		
	Subleading Tag jet	$> 30 \text{ GeV}$		
	m_{jj}	$> 400 \text{ GeV}$		
$W/Z \rightarrow J$	Num of large-R jets	≥ 1		
	3-Var Tagger	pass50WP	pass80WP && !pass50WP	fail80WP

Table 6.6: A summary of regions event selection for 2-lepton channel in the merged selection.

Selection		SR	Z CR
$Z \rightarrow \ell\ell$	Number of Loose leptons	2	
	Same flavor	yes	
	Leading lepton	$> 27 \text{ GeV}$	
	Subleading lepton	$> 27 \text{ GeV}$	
	dilepton invariant mass	$83 < m_{ee} < 99$ $-0.01170 p_{T,\ell\ell} + 85.63 < m_{\mu\mu} < 0.01850 p_{T,\ell\ell} + 94.00$	
	Opposite sign	For $\mu\mu$ channel only	
VBS jets candidates	Leading Tag jet	$> 30 \text{ GeV}$	
	Subleading Tag jet	$> 30 \text{ GeV}$	
	m_{jj}	$> 400 \text{ GeV}$	
$W/Z \rightarrow jj$	Num of signal small-R jets	2	
	Leading signal jet	$> 40 \text{ GeV}$	
	Subleading signal jet	$> 20 \text{ GeV}$	
	$Z \rightarrow q\bar{q}$ and $W \rightarrow q\bar{q}$	$64 < m_{jj} < 106$	$50 < m_{jj} < 64 \text{ GeV}$ or $m_{jj} > 106$
VBS enhancing	m_{jjj}	$> 220 \text{ GeV}$	

Table 6.7: A summary of regions event selection for 2-lepton channel in the resolved selection.

The signal selection efficiencies after applying all the selections in those tables are shown in the table 6.9.

	Resolved SR	Merged HP SR	Merged LP SR
0-lepton	1.4 %	0.6 %	0.5 %
1-lepton	1.3 %	0.4 %	0.6 %
2-lepton	2.1 %	0.4 %	0.3 %

Figure 6.9: Signal selection efficiencies in each signal region.

The signal/background ratios after applying all the selections in those tables are shown in the table 6.10.

	Resolved SR	Merged HP SR	Merged LP SR
0-lepton	1.0 %	2.6 %	1.0 %
1-lepton	0.9 %	1.9 %	1.1 %
2-lepton	0.5 %	2.7 %	0.8 %

Figure 6.10: Signal over background ratio in each signal region.

6.4 Multivariate Analysis

The difficulty of the VBS semi-leptonic channel is its low signal background ratio. Even after applying the event selection described in section 6.2, they are still many backgrounds left. In order to improve the sensitivity of the EW VV+jj signals with respect to the other backgrounds, a machine learning approach is used for this analysis. The idea is to use several features that have differences between signal and background and make new phase space optimized to get better separation. The produced distributions in the SRs are used as a final discriminant in the final fitting to extract the signal strength.

6.4.1 Architecture of the multivariate analysis

The architecture used for this analysis is a Recurrent Neural Network (RNN) - based DeepLearning technique. RNN [82] is a class of the neural network architecture, recently used for the flavor tagging [21] or VV semi-leptonic resonant search [45] that has the similar final states with diboson with extra jets in ATLAS experiment. One of the general features of the RNN is using the output in each layer recurrently; unlike conventional deep learning techniques, the output of the middle layers is used as an input hence it learns the relation of the previous sequence input as visualized in figure 6.11.

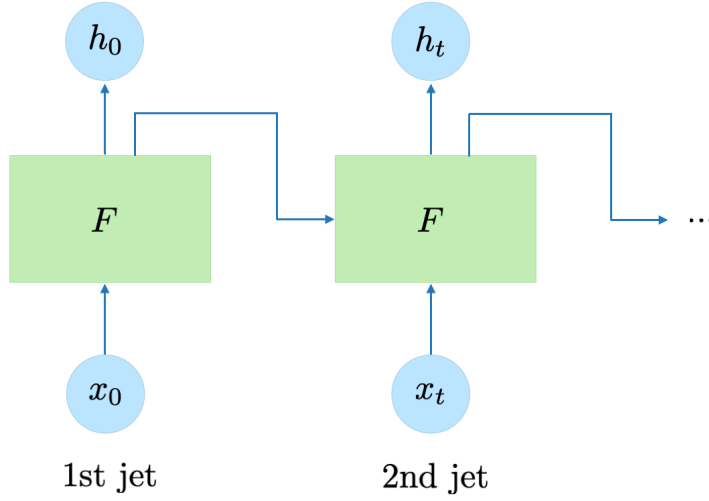


Figure 6.11: The simple visualization of the RNN. x is an input layer and F is an intermediate layer, and h is an output layer. The inputs are used recurrently by repeating the process of assigning the result of an operation performed in the intermediate layer to itself (intermediate layer) again for the next jet.

The good point of using RNN is we do not need to fix the number of inputs when using it. The jet multiplicity can be used with RNN since it is a variable feature event by event and cannot be fixed as the input value. The RNN is built with the Keras [52]. Tensorflow package [2] is used as a backend for mathematical computation. The RNN has 2 hidden layers with 25 recurrent cells to exploit the hidden correlation of the input sequence. Further details on the technical setups are summarized in Appendix .1.

6.4.2 Input variables and setups

The p_T, η, ϕ, E , of the small-R jets as well as the track multiplicity (n_{Tracks}) are used as inputs in a recurrent way. Figure 6.12 shows the signal and the background distributions of input variables of the leading jet. Only jet information is used without labeling signal jets or forward jets. Lepton information is not included as input variables to use the similar architecture among three lepton channels.

As actual input information, only these low-level information of p_T ordered small-R jets are used regardless they are signal and forward jets or other jets. The maximum variable length given by the jets multiplicity, is fixed to be 5 in this analysis. The values are filled with a masking value if the jet is not reconstructed in the event, and the tool knows to consider only the actual jets during the training phase according to the Keras RNN implementation. The maximum length (i.e. jet multiplicity) is fixed to get the significance to some extent and a rather small modeling uncertainty because of the poor modeling of the higher jet multiplicity. The RNN model is trained to separate the signal from the background in each SR of each lepton channel separately, due to the different background compositions. In merged SR, large-R jet candidate information (p_T, η, ϕ, E) is additionally used to further enhance the separation. The output scores (RNN score) as a result of training are not used as a categorization variable by applying cut on it but used as a final

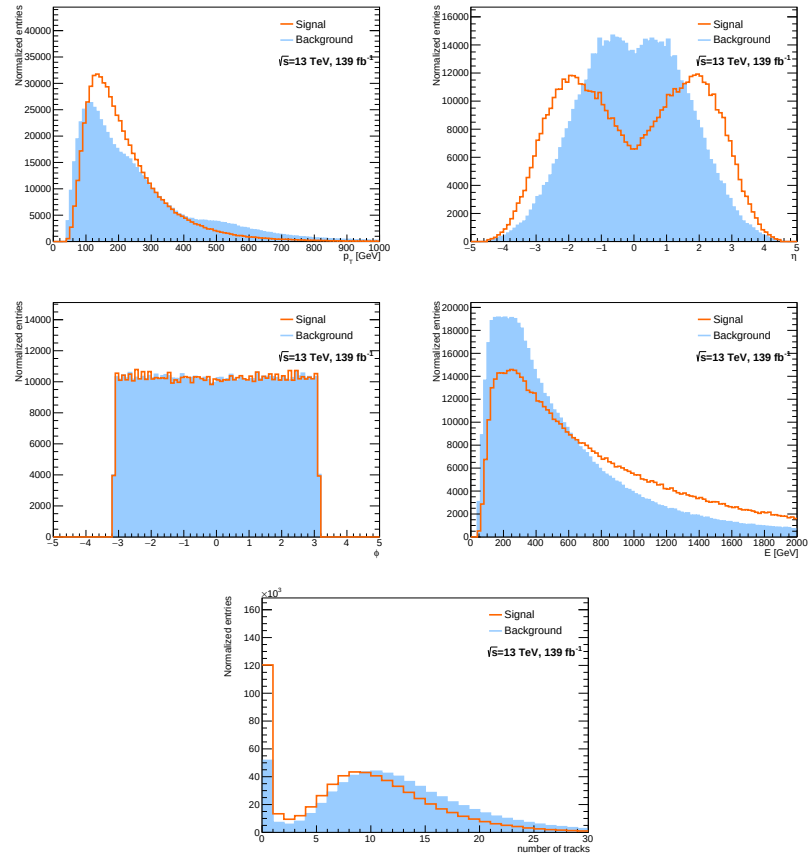


Figure 6.12: The input distributions of the leading jet.

discriminant for the final fitting in SRs.

6.4.3 Output variable

The output distribution as the result of the machine learning is shown in figure 6.13 as RNN scores in each signal region of the 2-lepton channel. The distribution shows a nice separation between the signal and the background. These distributions are used as final discriminants in the SRs.

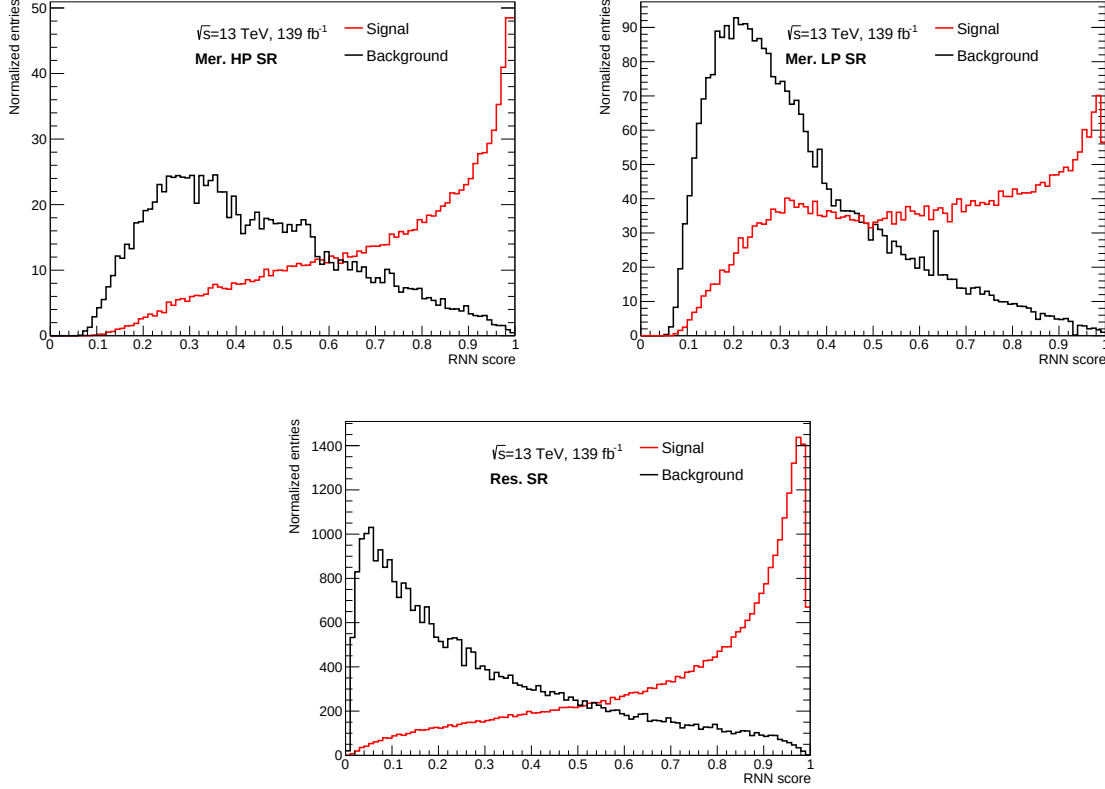


Figure 6.13: The output RNN score distributions of signal and background samples in merged SRs (top) and in resolved SR (bottom), in the 2-lepton channel. Signal distribution is normalized to the background distribution to compare the shape.

The output RNN score learns high-level information for example the m_{jj}^{tag} . Figure 6.14 shows the 2-dimension plots in the resolved signal region with signal and background. The correlation between RNN score and m_{jj}^{tag} can be seen.

6.4.4 Optimization of the binning

The optimization of the binning is needed to get the optimal performance of the RNN, in order to get better significance. The transformation of the RNN output [32] is implemented to optimize the number of bins and get the best sensitivity. The binning of the RNN score starts from 100 bins and is summed up from the right side of the distribution until getting the best sensitivity. MC statistical uncertainty in each bin is required to be $< 20\%$ to minimize the bias on fitted signal strength, μ [32]. For the current analysis, binning is required to have 15 bins.

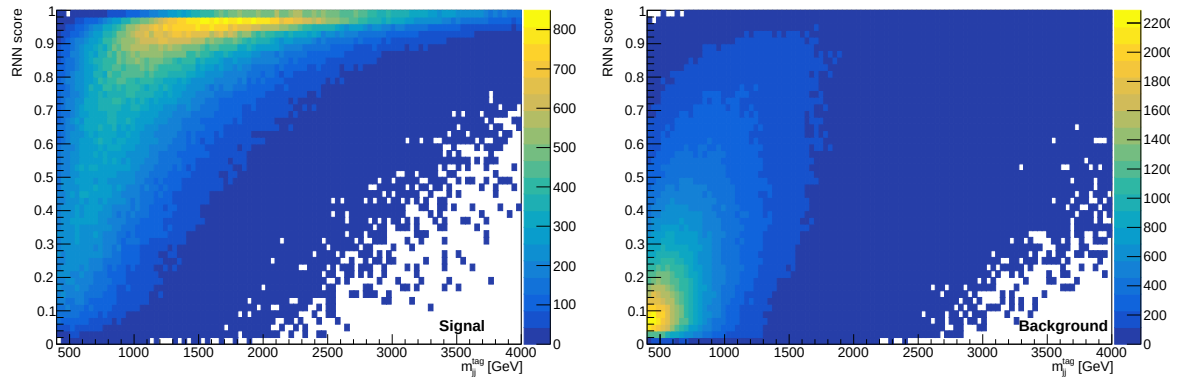


Figure 6.14: The 2D plots of output RNN score (y-axis) versus m_{jj}^{tag} (x-axis) in the resolved signal region with signal (left) and background (right) in the 2-lepton channel.

Chapter 7

Background Modeling

The study dedicated to the modeling of the major background is shown in this chapter. The V+jets, which is the dominant background in all three lepton channels, has a known issue of mismodeling. The reweighting is applied to the V+jet background sample, as described in the following sections. Details are shown in the 2-lepton channel for Z+jets sample. In the 1-lepton channel, a similar procedure is applied to the W+jets sample, and in the 0-lepton channel reweighting is applied for the sum of Z+jets sample and W+jets sample.

7.1 m_{jj}^{tag} reweighting

Figure 7.1 shows the m_{jj}^{tag} distributions in CR of merged and resolved selection in the 2-lepton channel.

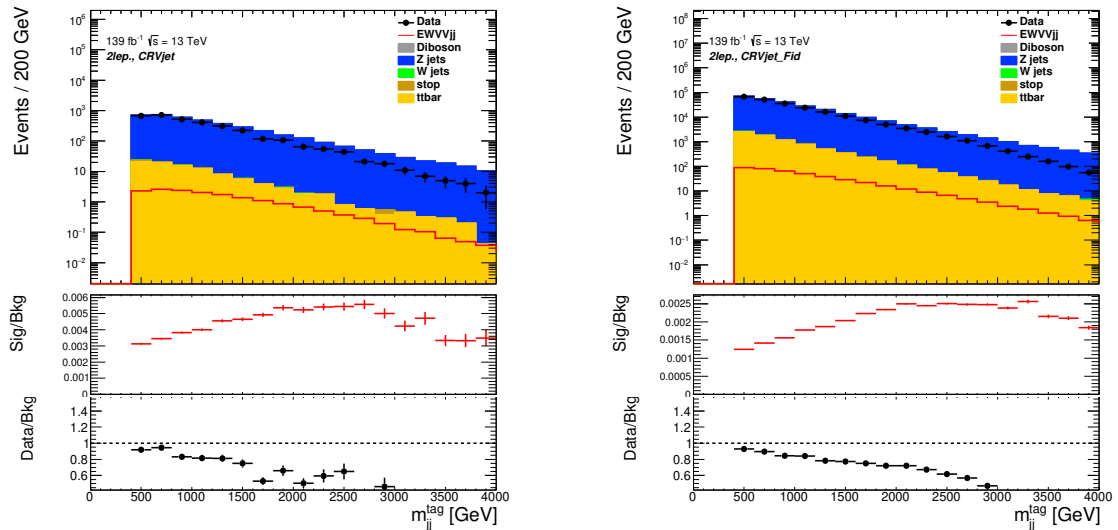


Figure 7.1: m_{jj}^{tag} distributions before applying reweighting for the merged (left) and resolved (right) control regions in the 2-lepton channel.

The mismodelling is observed as a slope in the ratio of data/MC in both regions. These discrepancies have been known in the previous analysis round [37], as well as in other ATLAS

analyses. This effect is believed to be due to the tuning of the QCD parameters, related to the combination of the shower activity and the scale choice for NLO real emissions in Sherpa 2.2.1. The discrepancies are also seen with other kinematics mainly related to the jets other than signal jets. The distribution of the number of small-R jets and the RNN score are shown in figure 7.2, showing discrepancies as slopes between data and MC.

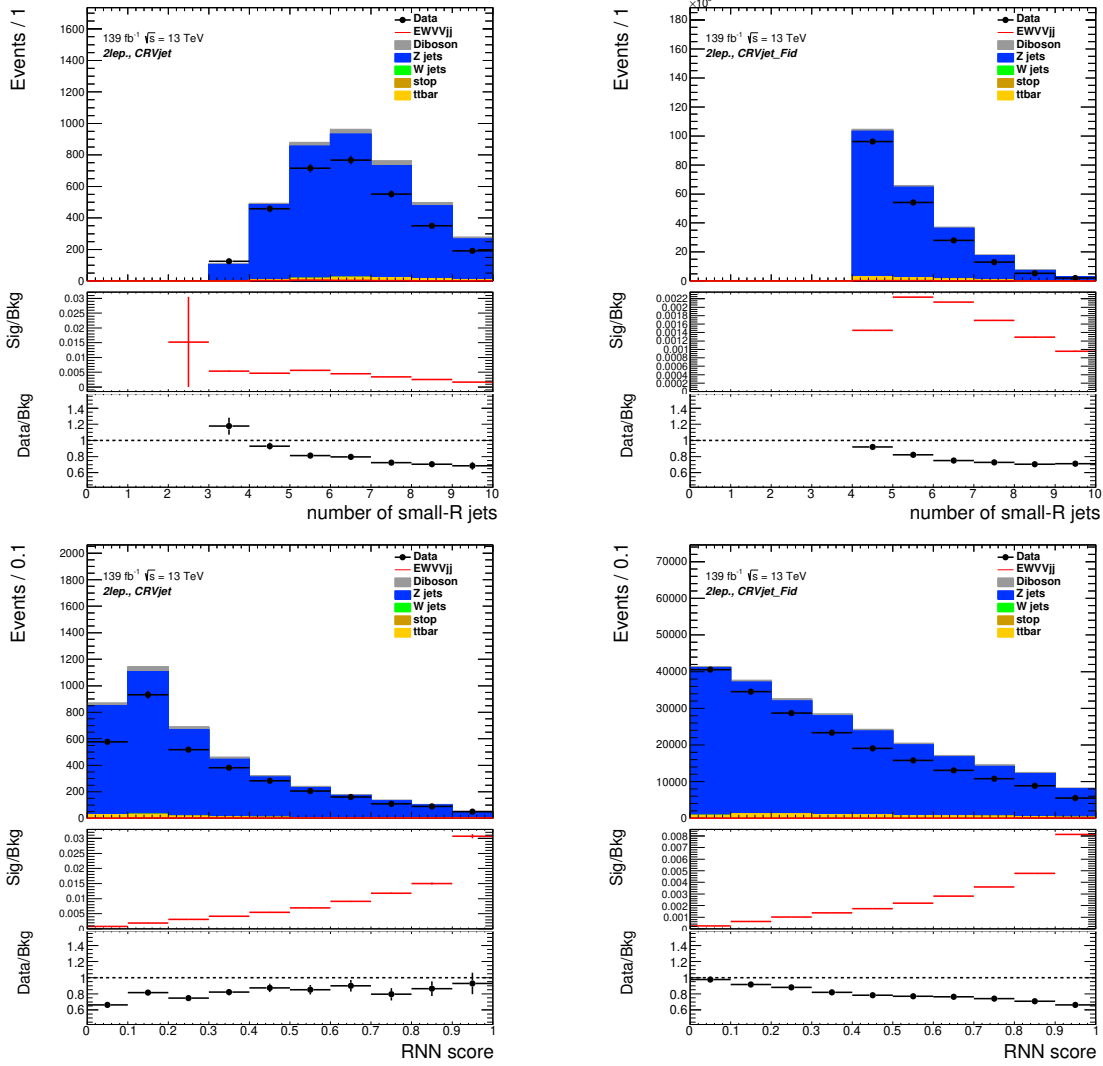


Figure 7.2: Distributions of number of jets and RNN score before applying reweighting for the merged (left) and resolved (right) control regions in the 2-lepton channel.

The reweighting is applied to the V+jets background sample to partly compensate for this mismodeling before defining the SRs and CRs. The data/MC ratio is parameterized by the simple linear function and the estimated reweighting factor is applied by the event-by-event weight. The fit function is defined as:

$$R = p_0 * m_{jj}^{tag} + p_1 \quad (7.1)$$

where the R is defined as the ratio of data over V+jets MC in each bin. The fitting and the correction is performed only for the V+jets samples, therefore contributions of other MC samples are subtracted from data at first. Inclusive MC samples corresponding to the full Run-2 dataset

are used for deriving the reweighting function, since the fitted value did not depend on the pile-ups. In figure 7.3, the fitted line as a function of m_{jj}^{tag} is shown.

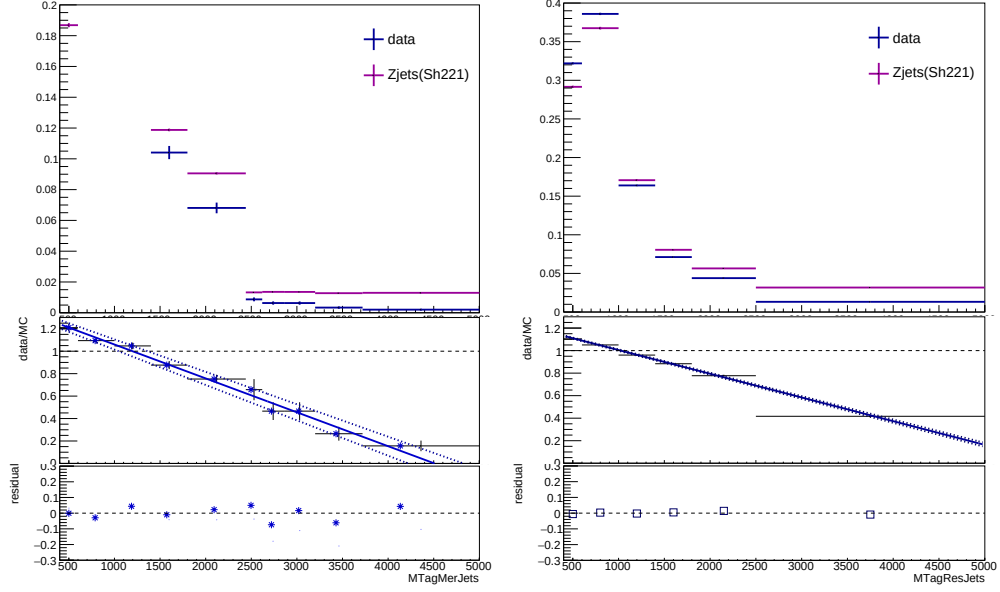


Figure 7.3: Fitted slope in data/MC ratio of m_{jj}^{tag} distributions, in merged CR (left) and resolved CR (right). The dotted line shows the 1σ error of the fitting result of the linear function.

Both distributions of the V+jets MC are first normalized to the data then the correction function (7.1) is derived. The binning is done in such a way that each bin contains at least 100 Z+jets events in order to have less than 10 % statistical uncertainty. In merged control region, due to the large statistic difference between the low-mass region and the high-mass region, the barycenter of each bin is used as a fitting point, while in resolved control region the bin center is used. The estimated reweighting factor is applied as an event-by-event weight, also in the signal region. The fitted parameter is summarized in the table 7.1. The reweighted distributions are

Parameter	Merged CRVjet	Resolved CRVjet
p_0 (slope) [GeV^{-1}]	$(30.2 \pm 3.1) e^{-5}$	$(-17.5 \pm 0.5) e^{-5}$
p_1 (constant)	1.362 ± 0.032	1.187 ± 0.005

Table 7.1: Fitted re-weighting parameters for the merged and resolved regions of the 2-lepton channel. The errors written here are the uncertainties of the fitted parameters.

shown in Figure 7.4. The data/MC ratios are more flat compared to the figure 7.1, indicating successful reweighting. Only the difference of the shape is corrected by this reweighting procedure as seen in the data/MC ratio around 0.8. The difference in the normalization is accounted for in the final fitting. In the resolved CR, there is still a discrepancy above 2500 GeV since it seems the linear function is not enough to model the mismodelling in this CR. The uncertainty on the reweighting factor is conservatively assigned in the final fitting setup, which is going to be explained in chapter 8.

The comparison of distributions of data and MC for the number of small-R jets and the RNN

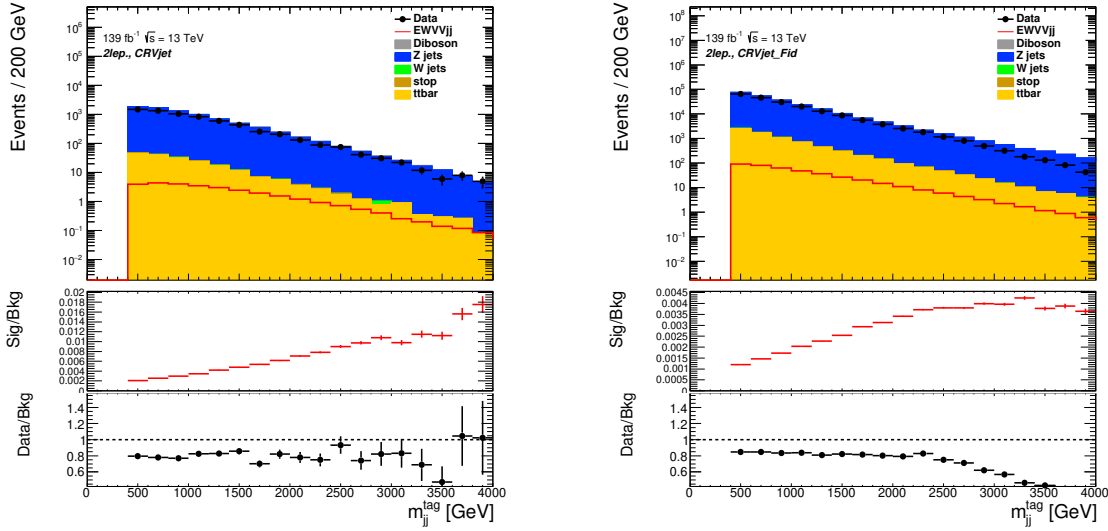


Figure 7.4: m_{jj}^{tag} distributions after applying reweighting for the merged (left) and resolved (right) control regions in the 2-lepton channel. The slope seen before reweighting is corrected in the Z+jet CR.

score after reweighting are shown in Figure 7.5 respectively. The discrepancy is relaxed by the reweighting procedure. The RNN score distribution is also corrected since it learns high-level information like m_{jj}^{tag} . The RNN score still has a discrepancy in the normalization as well as its shape, which can be seen as a slope, especially in the merged CR. That discrepancy will be corrected by the final fitting described in chapter 9.

There is alternative samples using MadGraph instead of Sherpa 2.2.1 as a generator. The modeling of the MadGraph in 2-lepton Z+jets CRs is shown in figure 7.6. No reweighting is applied in figure 7.6 for comparison. Backgrounds are normalized to the data to see the shapes of the MC. MadGraph has better modeling in our phase space including the high m_{jj}^{tag} region. However, Sherpa is used as the baseline sample since the sample with larger statistics was available. This difference between the two generators is included in the final fitting as a theoretical uncertainty, described in detail in chapter 8.

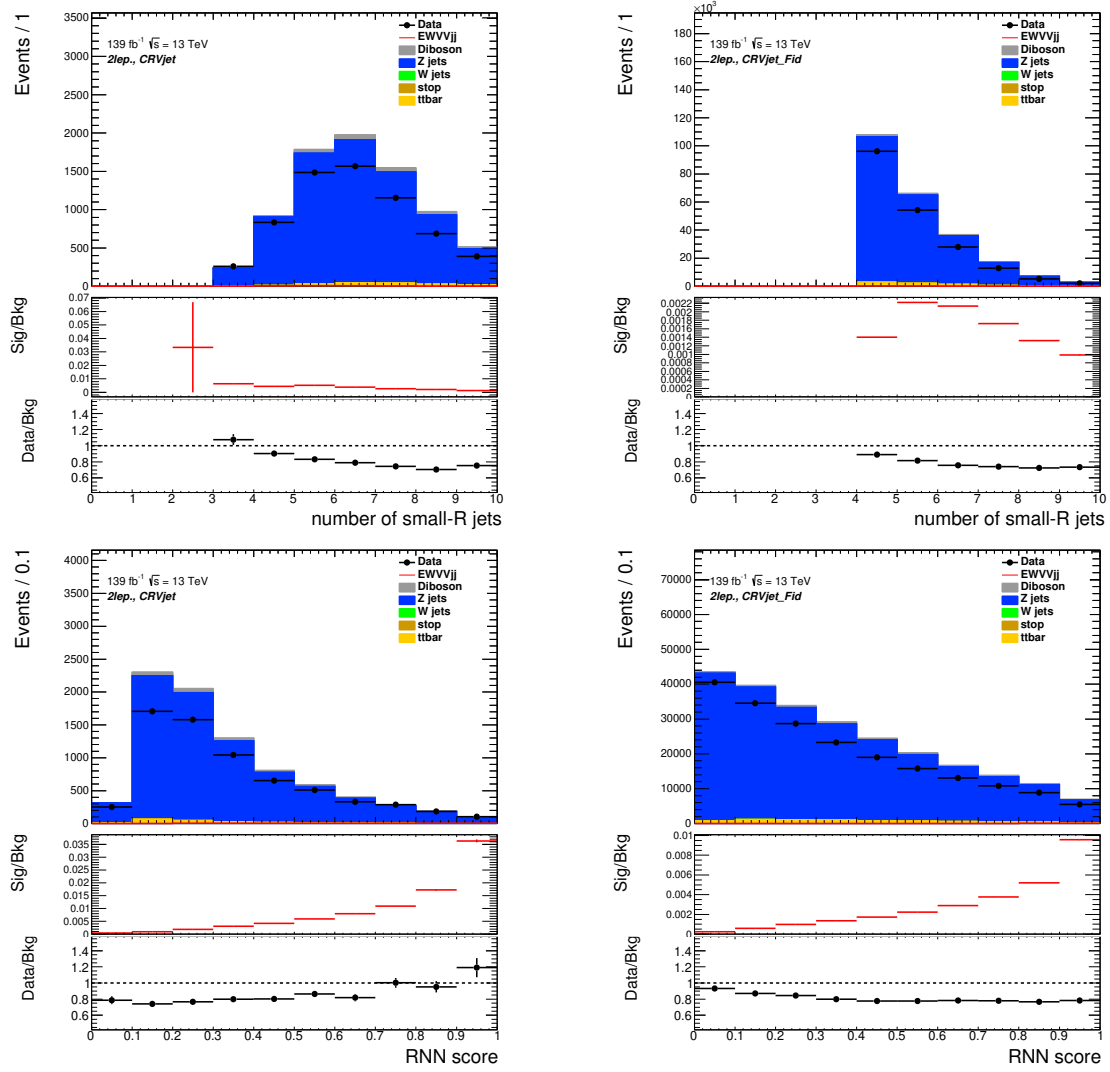


Figure 7.5: Distributions of the number of jets and the RNN score after applying reweighting for the merged (left) and resolved (right) control regions in the 2-lepton channel.

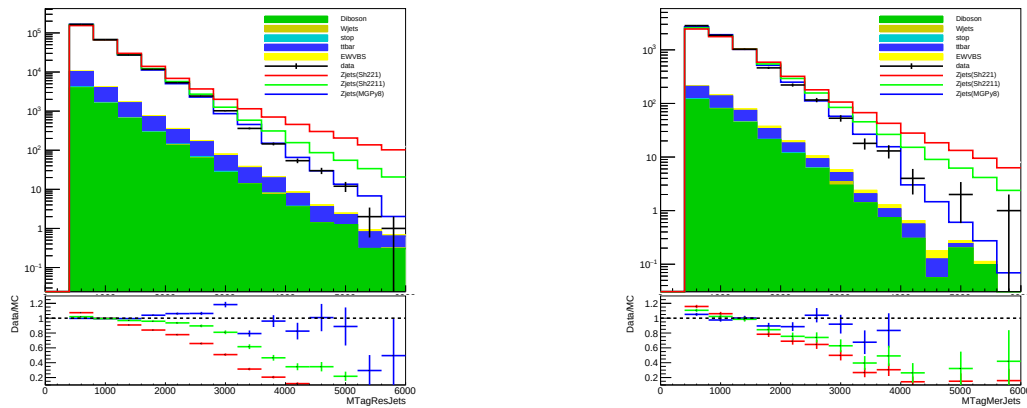


Figure 7.6: m_{jj}^{tag} distributions in resolved (left) and merged (right) control region, before applying reweighting for Sherpa 2.2.1 (red) and MadGraph (blue). Sherpa 2.2.11 (green), the newly modified version is also compared, showing that there is little improvement in slope compared to MadGraph.

Chapter 8

Systematic uncertainties

In this section, all systematic uncertainties considered in the analysis are described. Systematic uncertainty is treated as nuisance parameter in the statistical analysis, and is estimated with respect to the final discriminants. Each systematic uncertainty is considered to be the combination of two elements, normalization uncertainty and the shape uncertainty. Normalization uncertainty is the uncertainty of the yields compared to the nominal yields in each region, while shape uncertainty is the variation of the shape of the discriminant, when the yields are normalized. The source of the uncertainties are classified into two categories; the experimental uncertainties, mainly come from the reconstruction and calibration of the physics objects, and the theory uncertainties, come from the modeling or the theoretical calculation of the signal and background MC samples. Each uncertainty in two categories considered in the analysis is discussed in the following sections. The amount of uncertainties quoted here are the impacts of the variations with respect to the yield of total backgrounds.

8.1 Experimental uncertainties

Luminosity

The uncertainty on the integrated luminosity, obtained using the LUCID-2 detector for the primary luminosity measurements for the 2015+2016 dataset is 2.1%, and 2.4% for the 2017 dataset. The uncertainty for the 2018 data alone is 2.0%, and the uncertainty for the combined run-2 dataset (2015-2018) is 1.7%. The combined uncertainty is applied to all MC samples. [10].

Pileup reweighting

The MC events are weighted in order to match μ of the MC, the average number of interactions per bunch crossing, to that of data. The pileup reweighting uncertainty is estimated by changing its scaling.

Leptons

The uncertainties related to the lepton triggers are negligible, since their efficiencies are almost 100 %. The uncertainties from the reconstruction and identification, and the calibration of the

energy scale and resolution described in chapter 4 is considered. The variations are order of 1 %.

Small-R jets

Uncertainties on the jet energy scale (JES) and the jet energy resolution (JER) are considered. The JES and JER are measured in situ by calculating the response between MC and data, as detailed in chapter 4. The uncertainties on the efficiency of the pile-up jets and the forward vertex tagger, and the tracking reconstruction uncertainties are also considered, as well as b-tagging tool uncertainties. The impacts from these uncertainties are expected to be low, as they are less than 5 % in the high RNN bins of the signal regions.

Large-R jets

JES and JER uncertainties are also considered with large-R jet. Uncertainty related to the boson tagger efficiency scale factors (SFs) [15] are considered. The scale factors that correct the tagger efficiency in simulation to match that in data are derived from data using $t\bar{t}$ events for signal-like labelled jets, while extracted from γ +jet and multijet events for background jets. There are several sources of uncertainties, including the theoretical uncertainty in the MC samples used for deriving the SFs, as well as, reconstruction of calibration of the physics objects. This uncertainty is designed to change the ratio of the normalization between CR and the SR.

8.2 Theory uncertainties

For the main sources of the background samples, only shapes of these theoretical uncertainties are considered in the final fitting. The normalization is not included in the fitting, since it is determined by the free normalization factor in the fit from the data in CRs.

8.2.1 Reweighting uncertainties

As described in chapter 7, the m_{jj}^{tag} reweighting is applied to the V+jet background, and the distribution is corrected. The dedicated uncertainty is assigned conservatively, considering a 100 % uncertainty on the linear fit parameter; the distribution without the correction is used as a pre-fit -1σ variation; and the uncertainty is symmetrized to define $+1 \sigma$ variation. The pre-fit variation of the Z+jets sample in the 2-lepton channel is shown in figure 8.1. The reweighting uncertainty is estimated in the CRs and propagated to the SRs with an event-by-event weight. To cover the possible remaining mis-modeling with the RNN score considering that the modeling is different between m_{jj}^{tag} and the RNN score, this uncertainty is designed to be large and enough conservatively.

8.2.2 Generator difference uncertainities

The difference of the distribution after the reweighting and the distribution using the alternative sample (MadGraph + Pythia 8) is assigned as a modeling uncertainty for V+jets background. There is a large difference in the modeling of the different generators, Sherpa and MadGraph, and

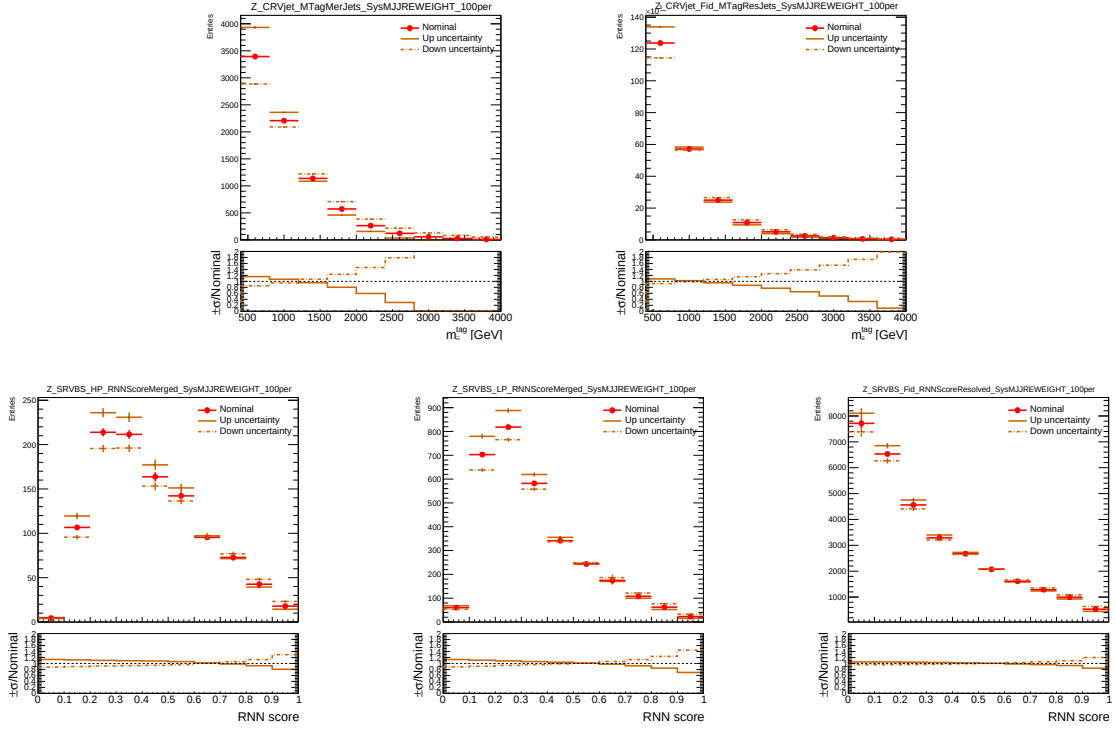


Figure 8.1: Pre-fit variation of the reweighting uncertainty of Z+jets sample in the 2-lepton channel.

we cannot know exactly which models the data correctly or not, hence the difference by using different generators is taken into account as an uncertainty. The MadGraph distribution used to evaluate this uncertainty is not reweighted since it is well matched to the data in the control region as figure 7.6 shows. For the $t\bar{t}$ and the QCD diboson sample, the difference of the nominal sample and the alternative sample is also assigned as the uncertainty. The nominal and the alternative sample used for $t\bar{t}$ is Powheg + Pythia and Powheg + Herwig respectively. For diboson sample, nominal sample is Sherpa 2.2.1 and the alternative is Powheg + Pythia. The pre-fit variation of Z+jets samples in the 2-lepton channel is shown in figure 8.2.

8.2.3 QCD scale and PDF uncertainties

QCD scale uncertainties

QCD scale uncertainties are determined by varying the renormalization (μ_R) and factorization (μ_F) scale factor (2.2.1) sets. They are estimated by taking the envelope of the 6 set of the combination of the μ_R and μ_F , which are fixed to be 1, 0.5, or 2.0. This uncertainties are implemented to the background samples as well as signal EW VV+jj sample.

The estimated QCD scale uncertainties with Z+jets background and the EW VV+jj signal in the 2-lepton channels are shown in figure 8.3 and 8.4, respectively.

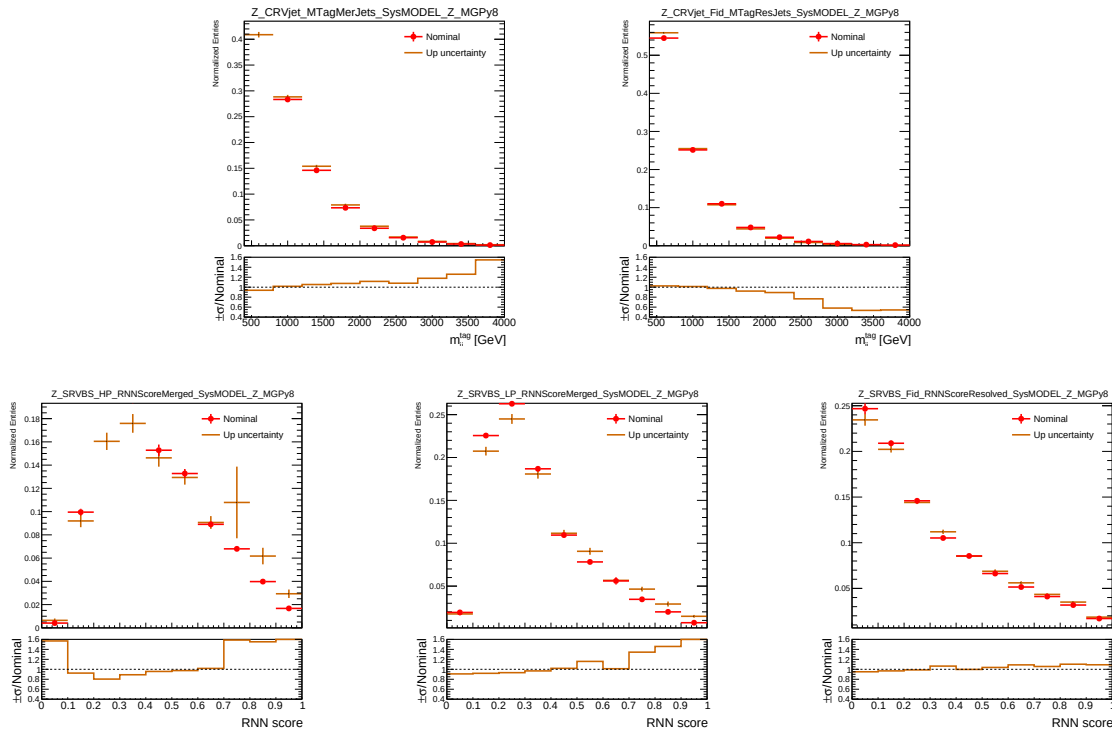


Figure 8.2: Pre-fit variation of the modeling uncertainty of Z+jets sample in the 2-lepton channel. Variation distributions are normalized to the nominal one to see the shapes.

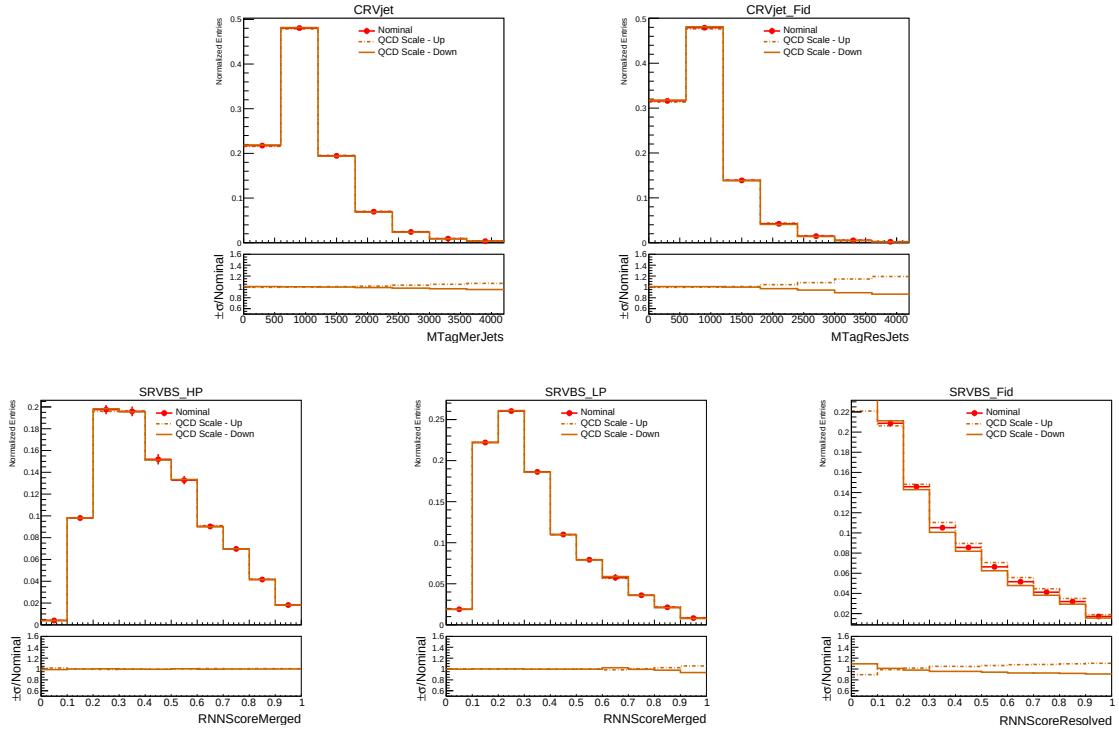


Figure 8.3: Pre-fit variation of the QCD scale uncertainty of Z+jets sample in the 2-lepton channel. Variation distributions are normalized to the nominal one to see the shapes.

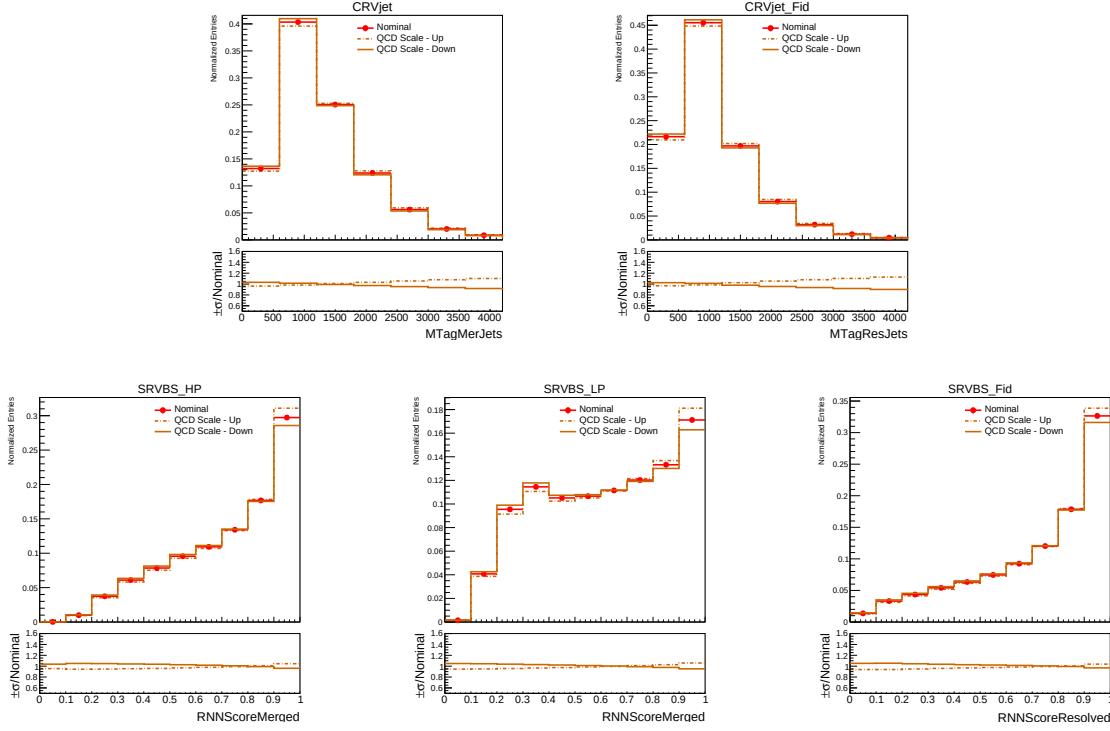


Figure 8.4: Pre-fit variation of the QCD scale uncertainty of EW VV+jj signal sample in the 2-lepton channel. Variation distributions are normalized to the nominal one to see the shapes.

PDF + α_s uncertainties

Parton Distribution Function (PDF) sets are obtained by the fit to experimental datasets. There are uncertainties originated from the experimental uncertainties from the datasets and from the choice of the functional form adapted in the PDF fits. The uncertainty from the PDF set choice can be assessed by two approaches.

One is to calculate the difference of a single PDF set by varying its internal parameters, which is called internal PDF uncertainties. For this study the 100 MC replicas of the NNPDF [48] sets are used. The standard deviation of the mean value of the 100 MC replicas for each bin of the final discriminant is taken as the uncertainty. An uncertainty on the strong coupling constant value, α_s is also considered. It is defined from the experimental uncertainties, and included to the estimation of the internal PDF uncertainties. The internal PDF uncertainty is considered both in V+jets background and the signal EW VV+jj samples. The other is from the difference between the different PDF sets, which is called external PDF uncertainties. This uncertainty is estimated by comparing the nominal distributions with the alternative PDF sets. The uncertainties are combined by taking the envelope of all uncertainties, which means the most varied uncertainty is taken as the final uncertainty. External PDF uncertainty is considered only in V+jets background sample due to the missing of the alternative sample in signal.

Chapter 9

Statistical treatment

9.1 Fiducial cross-section extraction

In addition to the observation of the EW VV+ jj production, the fiducial cross-section measurement is performed at the same time. The fiducial cross-section, which is the cross-section that takes the detector acceptance into account is exploited and it allows easier comparisons with other theoretical predictions. The fiducial selection is done at MC samples using the stable final state particle, and these cuts are chosen to be as similar as possible to those at reconstruction level selection, described in Chapter 6. These selections are summarized in the table 9.1.

Object selection			
Leptons	$> 27 \text{ GeV}, \eta < 2.5$		
Small-R jets	$> 20 \text{ GeV}$ if $ \eta < 2.5$ and $> 30 \text{ GeV}$ if $2.5 < \eta < 4.5$		
Large-R jets	$> 200 \text{ GeV}, \eta < 2.0$		
Event selection			
Leptonic V selection	0-lep $E_{\text{T}}^{\text{miss}} > 200 \text{ GeV}$	1-lep One lepton $E_{\text{T}}^{\text{miss}} > 80 \text{ GeV}$	2-lep Two leptons
	$\eta_{\text{tag } j_1} \cdot \eta_{\text{tag } j_2} < 0$, highest M_{jj} $p_T^{\text{tag } jet_{1,2}} > 30 \text{ GeV}, M_{jj} > 400 \text{ GeV}$		
Tagging jets	Merged	Leading large-R jet $64 < M_J < 106 \text{ GeV}$	
	Resolved	Two leading small-R jets $p_T^{j_1} > 40 \text{ GeV}, p_T^{j_2} > 20 \text{ GeV}$ $64 < M_{jj} < 106 \text{ GeV}$	
Hadronic V selection			
Extra b-jets Veto selection	$N_{\text{ExtraBJets}} = 0$ (only for 1-lepton channel)		
Additional (EW)Top Veto selection	$M_{jjj} > 220 \text{ GeV}$ (only resolved)		

Table 9.1: Summary of the event selection performed at the particle level to define the fiducial regions.

The expected cross-section from the standard model prediction, $\sigma_{EWVVjj, \text{SM}}$ can be exploited by using the truth event yields, which are the yields after applying the fiducial selections, and the luminosity. Fiducial cross-section is evaluated by scaling the measured signal strength μ , defined

as;

$$\mu = \frac{\sigma_{EWVVjj, \text{ obs}}}{\sigma_{EWVVjj, \text{ SM}}} \quad (9.1)$$

where $\sigma_{EWVVjj, \text{ obs}}$ is the cross-section of the EW VV+jj process observed with data, the exact fiducial cross-section we finally want to measure. How to obtain μ is described in section 9.2.

9.2 Likelihood function definition

This section describes how to extract the signal strength μ and the significance. Binned maximum likelihood fit is performed to get the signal strength μ . The likelihood function is written as:

$$\mathcal{L}(\mu, \theta) = P(N_i | \mu s_i + b_i) \cdot G(\theta) \quad (9.2)$$

where the P is the Poisson probability terms:

$$P(N_i | \mu s_i + b_i) = \prod_{i \in \text{bins}} \frac{(\mu s_i + b_i)^{N_i}}{N_i!} e^{-(\mu s_i + b_i)} \quad (9.3)$$

s_i and b_i are the expected number of the signal and the background events yield in bin i , and N_i is the number of the observed events from data in the bin. The μ is also called as the parameter of interest (POI). θ is a set of nuisance parameters (NPs) associated with each systematic uncertainty. θ affects the signal and background yields so it can be written like $s_i = s_i(\theta)$ and $b_i = b_i(\theta)$. The second term in equation 9.2, $G(\theta)$ is often called penalty term, to represent the supplementary information of the systematic uncertainty effect, and to constrain each uncertainty. It is a product from all single uncertainty θ_j ; $G(\theta) = \prod_j G_j(\theta_j)$. In this analysis, this term is given by the Gaussian distribution with a standard deviation of $\sigma = 1$. It is designed so that $\theta_j = 0$ corresponds to the nominal value, and $\theta_j = \pm 1$ corresponds to the $\pm 1\sigma$ variations of the systematic source. Some parameters for example Z+jets background normalization factors do not have these penalty terms and are determined completely from the data, called floating parameters. The statistical uncertainties of the total background are also included in the likelihood function as γ parameter. The additional nuisance parameter called gamma parameter is also added to the initial $\mathcal{L}$ as γ_i for each bin, where γ_i is the total statistical uncertainty of a specific histogram bin i . The Poisson distribution is expected for the gamma parameters, conventionally they are parametrized so that the nominal expectation is 1 and its variation corresponds to $\pm 1\sigma$, where the σ is the MC statistical uncertainty of the bin i . An estimate on μ is obtained by maximizing the likelihood function 9.2 with respect to all the parameters.

In order to test a hypothesized value of μ , the profile likelihood is given:

$$\lambda(\mu) = \frac{\mathcal{L}(\mu, \hat{\theta})}{\mathcal{L}(\hat{\mu}, \hat{\theta})} \quad (9.4)$$

where $\hat{\mu}$ and $\hat{\theta}$ are the parameters that maximize $\mathcal{L}$, and $\hat{\theta}$ is the best fit value that maximize $\mathcal{L}$ for a certain signal strength μ .

A test statistic to test μ is constructed with:

$$t_\mu = -2 \log \lambda(\mu) \quad (9.5)$$

The higher t_μ values correspond to increasing incompatibility between a specific hypothesis μ and the observed data. The level of the incompatibility is quantified by the p-value:

$$p_\mu = \int_{t_{\mu,\text{obs}}}^{\infty} f(t_\mu | \mu) dt_\mu \quad (9.6)$$

where the $t_{\mu,\text{obs}}$ is the value of the test statistic t_μ observed from the data, and $f(t_\mu | \mu)$ denotes the probability density function (pdf) of t_μ under the assumption of the signal strength μ . The p-value is often converted into an equivalent significance, Z :

$$Z = \Phi^{-1}(1 - p) \quad (9.7)$$

where Φ^{-1} is the inverse of the cumulative standard Gaussian. A given hypothesis is excluded if the p-value is sufficiently small, that is, Z is sufficiently large.

To reject the background-only hypothesis and claim the discovery of a new phenomenon, the significance is estimated for the background-only hypothesis, corresponding to $\mu = 0$. This background-only hypothesis in the case of p_0 is regarded as a null hypothesis. This is to be tested against the alternative hypothesis, which includes both background and the EW VV+jj signal. Typically significance of $Z = 5 \sigma$ is used as an appropriate level to constitute a discovery ($p_0 = 2.87 \times 10^{-7}$).

9.3 Fitting setups

A simultaneous likelihood fit to all 18 merged and resolved signal and control regions is performed. The final discriminant in each region is summarized in table 9.2. In the signal regions, the RNN

	0-lepton	1-lepton	2-lepton
Merged HP SR	RNN score	RNN score	RNN score
Merged LP SR	RNN score	RNN score	RNN score
Resolved SR	RNN score	RNN score	RNN score
V+jet Merged CR	m_{jj}^{tag}	m_{jj}^{tag}	m_{jj}^{tag}
V+jet Resolved CR	m_{jj}^{tag}	m_{jj}^{tag}	m_{jj}^{tag}
Top Merged HP CR		yields	
Top Merged LP CR		yields	
Top Resolved CR		m_{jj}^{tag}	

Table 9.2: Final discriminant in each region used in the fitting.

score is used to get maximized sensitivity, while in the CRs the m_{jj}^{tag} is employed in order to give better constraints to the m_{jj}^{tag} reweighting uncertainty. In the Top merged CRs single bin setting is adapted since these CRs are for constraining $t\bar{t}$ background normalization and there is no need to use the shape.

The background is estimated using the MC for the RNN shape in SRs, while the normalization is estimated using the data in CRs. The normalization in the SR is designed to be extrapolated from the CR with the ratio of SR/CR obtained by the nominal MC modeling. As the NPs which

change the ratio of the normalization of SR/CR, theoretical variation and the boson tagging scale factor uncertainty are taken into account. All systematic uncertainties are included in the fit as NPs with penalty terms or floating parameters as described in section 9.2. Since the definition of the CR is basically same as SR but inverted the mass window or the boson tagging, it is designed that most of the NPs are expected to be canceled each other out.

The normalization of the dominant background (Z+jets, W+jets, $t\bar{t}$) is assigned as the floating parameter, while the background with a small contribution which has a small impact on the signal extraction is assigned as the NP with a penalty term of a certain amount of the error. The normalization of the floated backgrounds is designed to be obtained separately in the merged region and the resolved region, in order to absorb the effect of the possible mismodeling in the high center-of-mass energy region and/or in merged regions. The diboson contribution has anti-correlation with the EW signal. Normally it should be constrained with data, but it is assigned with a penalty term currently, due to the lack of a dedicated control region. The treatment of each background normalization is summarized in table 9.3. The amount of the error of the penalty term is estimated by comparing the nominal MC yields to that of the alternative sample in each analysis region. An extrapolation uncertainty in the combined fit is also added to take into account differences in the background composition coming from the different lepton channels. The error is obtained from the double ratio between the channel with the largest yield and another channel.

Normalization name	treatment	error of the penalty term	
		Merged	Resolved
Z norm.	Float		
W norm.	Float		
$t\bar{t}$ norm.	Float		
Diboson norm.		0.5	0.3
Single top norm		0.3	
Z norm 2lep to 0lep		0.234	0.293
Z norm 2lep to 1lep		0.454	0.410
W norm 1lep to 0lep		0.127	0.094
$t\bar{t}$ norm 1lep to 0lep		0.304	0.601
Diboson norm 1lep to 0lep		0.061	0.078
Diboson norm 1lep to 2lep		0.152	0.098

Table 9.3: The treatment of the background normalization. The main background sources (Z+jets, W+jets, $t\bar{t}$) are floated in the fitting setup, while the other backgrounds are treated as NPs with penalty terms. The amounts of errors of the penalty terms are shown in the table.

9.4 Smoothing and pruning

The smoothing algorithm is applied to the variation of the systematic uncertainties enter into the likelihood fit to alleviate statistical fluctuations, that might create suspicious effects in the fit. During this procedure, bins are migrated from left to right until the statistical uncertainty per bin is less than 5%. The nominal and smoothed variation histograms are then compared to derive the

up and down uncertainties. The resulting uncertainties are associated to the initial finer binned distribution.

Systematic variations that have a very small effect and are negligible for the measurement are neglected for speeding up the fitting, this procedure is called pruning. The uncertainties removed are:

- Normalization uncertainties with a less than 1 % relative variation effects or same sign effects (relative variation being positive (or negative) for both the up and down uncertainty)
- Shape uncertainties with less than 1 % effect for all bins of the distribution or missing one of the up or down variations.

Chapter 10

Results of the SM EW VV+ jj measurement

This chapter shows the results of the likelihood fit described in section 9.2. First, whether the machine learning discriminant is modeled well is checked in section 10.1. The expected event yields are compared with the observed data yields in section 10.2. In section 10.3 distributions after the fit are shown, and the impact of nuisance parameters over signal strength is discussed in section 10.4. Finally the signal strength μ is extracted and the observed significance is estimated in section 10.5.

10.1 Validation of the background modeling of the RNN score

The validity of the fitting setup is confirmed by checking the information after fitting using the CRs. In this section validation was performed by not looking at the observed data in the signal-sensitive regions, for the purpose of not being biased by looking at the signals and just checking the background modeling. The following “left-side” bins of the SR discriminant distribution are introduced which refer to as the bins in the SR without the right-side bins that contains 75 % of the signal sample. It is the background-dominant region in the SR. The post-fit RNN distributions in the CRs are checked to make sure that the machine learning discriminant models the data well. The fitting result using m_{jj}^{tag} in CRs and the left-side bins of the RNN score in SRs as summarized in table 9.2 are applied to the RNN score distributions in CRs. Obtained distributions are shown in figure 10.1. Overall the post-fit RNN distributions in the CRs show good background modeling except for the right-most bin of the 1-lepton channel, which indicates that the RNN score discriminant is modeled well with all NPs. For the 2-lepton channel, it is shown that the discrepancy seen in figure 7.5 as a slope is well corrected. As seen in the pre/post-fit plots of the 2-lepton merged CR in figure 10.1, the shape of the RNN score is corrected by the fitting. A similar correction is also expected with the RNN distributions in the SRs. The NPs assigned to modify the shape of the RNN score are the m_{jj}^{tag} reweighting uncertainty and the modeling uncertainties. As shown in figure 8.1 and 8.2 in chapter 8, these variations are rather large in the rightmost bins in SRs and CRs, which can correct the shape of high-RNN bins in the fitting.

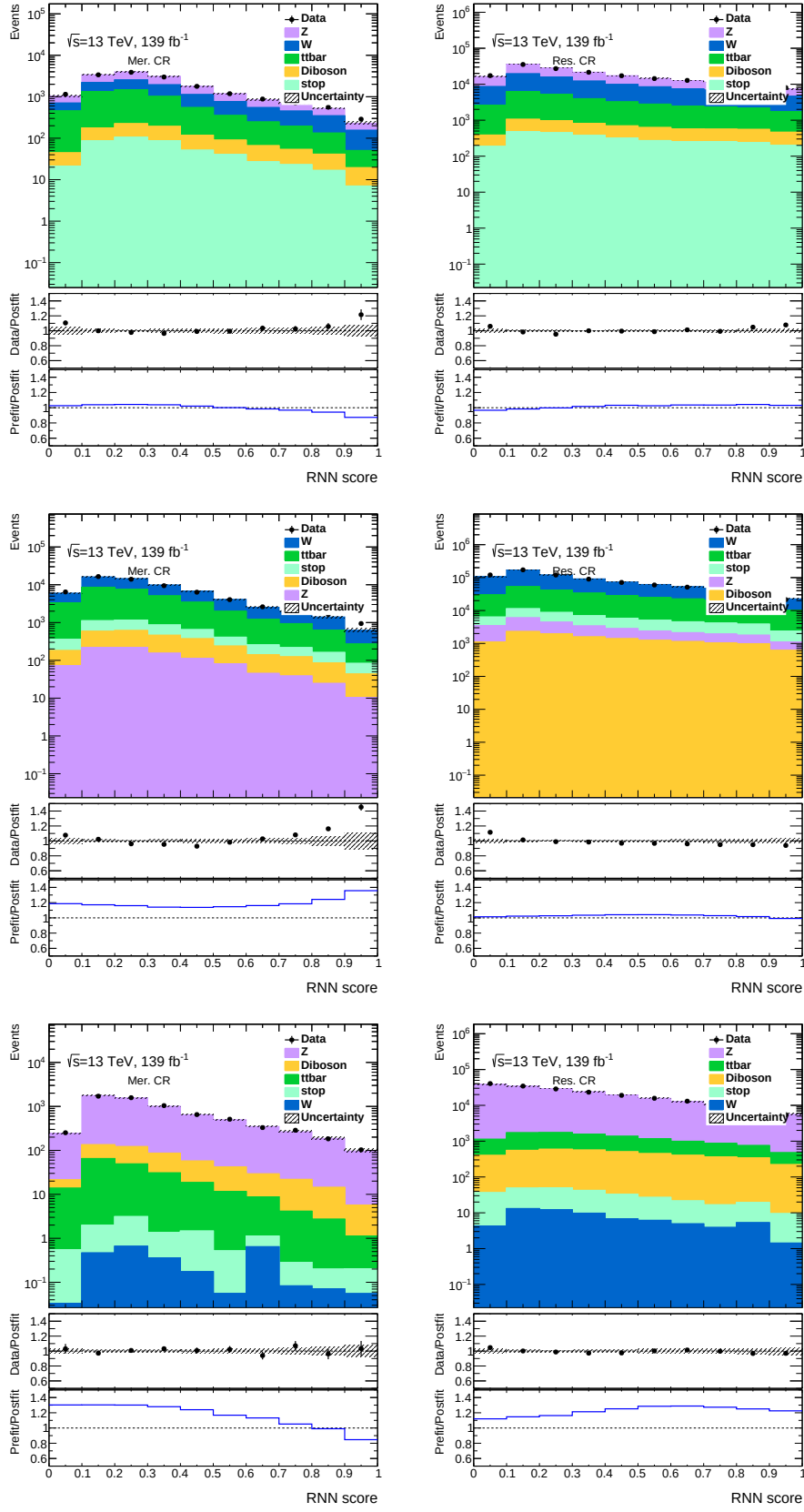


Figure 10.1: Post-fit RNN score distributions in merged CR (left) and in resolved CR (right) in the 0-lepton channel (top), the 1-lepton channel (middle), and the 2-lepton channel (bottom). The comparison of the data and the post-fit expected MC is shown in the middle panel, and the ratio of the pre-fit and the post-fit MC is shown in the bottom panel.

10.2 Event yields after fitting

From this section all the bins from CRs and SRs are used in the fitting. The observed and the estimated event yields after fitting is shown in table 10.1. The dominant background component is V+jets among all three channels. The second dominant background is $t\bar{t}$ process. The fit constrains the background towards the observed data and reduces the total background uncertainty by correlating them from the individual backgrounds. The correlations between the normalizations and the NPs are shown in figure 10.2. The observed event yields are compatible with the SM expectations in each region.

Channel	Sample	Number of events		
0-lepton		Merged HP	Merged LP	Resolved
	Z + jets	628.7 ± 90.2	2022.3 ± 257.7	10176.2 ± 835.2
	W + jets	584.8 ± 79.1	1718.5 ± 212.9	8705.0 ± 762.6
	$t\bar{t}$	1548.0 ± 126.2	2078.7 ± 172.0	1764.0 ± 225.5
	Single t	158.3 ± 43.9	204.5 ± 58.5	272.5 ± 76.2
	Diboson	344.3 ± 97.7	494.0 ± 141.0	576.3 ± 173.6
	Total background	3264.1 ± 57.3	6518.1 ± 79.0	21493.9 ± 149.4
	Signal	91.2 ± 16.6	80.0 ± 15.8	216.7 ± 39.5
	Data	3349	6585	21789
1-lepton		Merged HP	Merged LP	Resolved
	Z + jets	97.8 ± 45.0	299.70 ± 136.6	1507.2 ± 629.9
	W + jets	3038.8 ± 231.6	9385.32 ± 485.6	58369.4 ± 933.3
	$t\bar{t}$	7101.7 ± 257.7	9913.70 ± 396.9	7654.4 ± 362.6
	Single t	613.0 ± 172.7	861.01 ± 246.5	1427.8 ± 398.7
	Diboson	1011.0 ± 272.0	1540.2 ± 420.0	1709.4 ± 481.9
	Total background	11862.3 ± 111.8	22000.0 ± 150.0	70668.2 ± 324.8
	Signal	222.6 ± 40.4	203.7 ± 42.6	643.2 ± 117.3
	Data	12178	22158	71272
2-lepton		Merged HP	Merged LP	Resolved
	Z + jets	696.2 ± 47.6	2152.8 ± 94.1	25819.3 ± 243.6
	W + jets	0.5 ± 0.0	1.4 ± 0.1	17.7 ± 2.2
	$t\bar{t}$	27.2 ± 1.6	64.5 ± 4.1	873.7 ± 44.7
	Single t	2.0 ± 0.6	3.2 ± 0.9	27.3 ± 7.7
	Diboson	188.5 ± 51.07	281.5 ± 77.6	572.9 ± 165.8
	Total background	914.2 ± 26.1	2503.4 ± 43.0	27310.9 ± 172.0
	Signal	36.1 ± 6.7	33.2 ± 7.0	172.8 ± 32.3
	Data	960	2516	27463

Table 10.1: Number of observed and predicted events in each signal region, obtained from the log-likelihood fitting. The uncertainties combine statistical and systematic contributions.

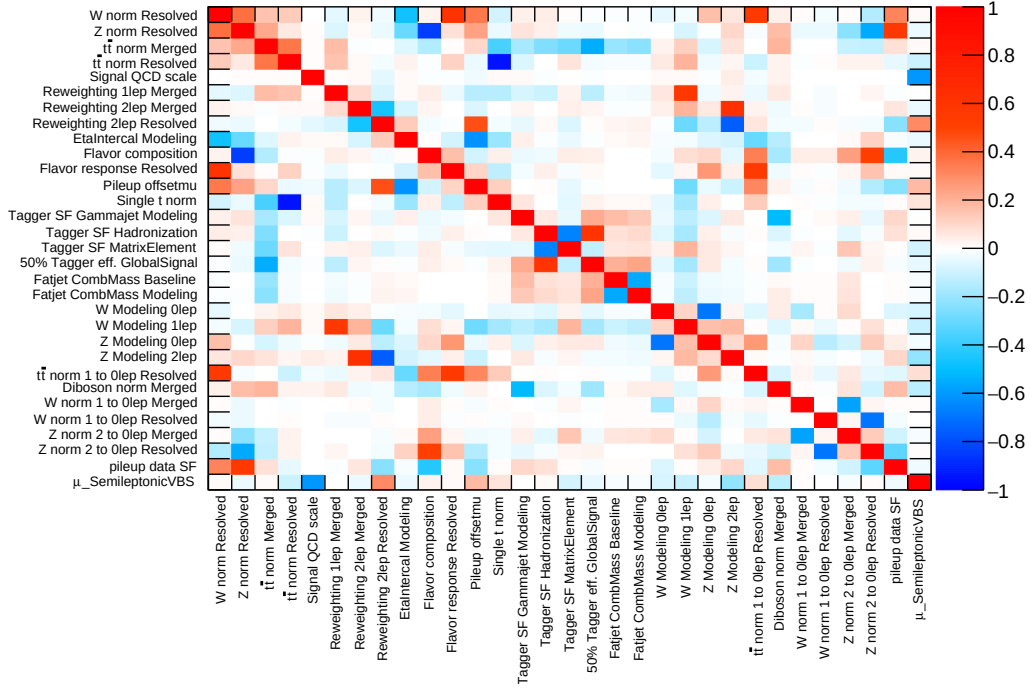


Figure 10.2: The correlation matrix of nuisance parameters from the fit is shown. Only the NPs which have correlations with other NPs of more than 50 % are shown.

The summary of the normalization factor for each background component extracted from the fitting is shown in table 10.2. The lower normalization value is reported especially for V+jets merged regions. For V+jets samples, overestimating the cross-section in the high center-of-mass region is known as mentioned in section 9.2. This tendency is also reported in other analyses [29]. Different normalization factor in merged and resolved regions shows different normalization value as designed, considered to be due to the mismodeling of the samples.

normalization	post fit value (in σ unit)
W+jets Merged	$0.80^{+0.044}_{-0.044}$
W+jets Resolved	$1.04^{+0.045}_{-0.045}$
Z+jets Merged	$0.708^{+0.036}_{-0.036}$
Z+jets Resolved	$0.85^{+0.047}_{-0.047}$
$t\bar{t}$ Merged	$0.89^{+0.058}_{-0.058}$
$t\bar{t}$ Resolved	$1.07^{+0.048}_{-0.048}$

Table 10.2: A summary of floated normalization factors obtained from the fit to the observed data.

10.3 Post fit plots

The distributions obtained after the final fitting are shown to check if it performed well, and to ensure the validity of the finally obtained μ value.

10.3.1 m_{jj}^{tag} distributions at CRs after fitting

The m_{jj}^{tag} distributions in each CRs after fitting are shown in figure 10.3 and 10.4. All the distributions of the V+jets CRs after fitting show nice agreement with the observed data, which implies the V+jets background is well corrected and controlled by the fit. Assigned uncertainties seem to work well to fix the discrepancy. The uncertainty are much reduced by the fit, as it is designed to be constrained a lot in these CRs.

10.3.2 RNN score distributions at SRs after fitting

The RNN score distributions in each SR after fitting are shown in figure 10.5, 10.6, 10.7. Confirming the modeling of these distributions are important to justify the obtained value of μ , since they are most sensitive distributions to the signal strength. In the low-RNN score bins, where the events are dominated by the background samples, the predicted MCs nicely reproduce the observed data in each region and channel. In the right-most bins which include signal contribution, a little overshoot can be seen, especially for the 0-lepton Merged HP region and Resolved region, although overall the MC fits the data within the uncertainty of 1σ . In most regions, the background yields are decreased in low-RNN bins after fitting, while increased in high-RNN bins, which can be the effect of the NPs that change RNN score shapes, mainly the modeling uncertainty of the V+jets sample.

10.3.3 Several distributions at SRs after fitting

Several distributions other than those used in the fitting is checked to see how the fitting setup works within our SRs and CRs.

The m_{jj}^{tag} distributions in each SRs after fitting are shown in figure 10.8, 10.9, 10.10. In the 0-lepton channel they show that the expected MC is fairly compatible with the data, while in the 1-lepton channel there is a slope in the ratio of the data and MC. In the 2-lepton channel there is a discrepancy in the highest bin in merged regions. It seems the difference of the modeling of the m_{jj}^{tag} after reweighting between the CR and SR appears here. With the RNN score in the same region this tendency is not reflected a lot, and it seems the NPs like the modeling uncertainty works to correct the RNN shape.

The diboson invariant mass (m_{VV}) distributions in each SRs after fitting are shown in figure 10.11, 10.12, 10.13. The statistical fluctuation is large in the high- m_{VV} bins, and overall it shows an agreement between data and MC within the statistical fluctuations. After the confirmation of the fine modeling of these distributions with our fitting setup, they can be used in the EFT/aQGC interpretation described in chapter 11.

10.4 Impact of nuisance parameters on signal strength

To check the impact of the given NP, θ , to the signal strength, the fit is redone by fixing θ to be $\hat{\theta} \pm 1\sigma$ and treating all other parameter floated. The difference of the obtained μ and $\hat{\mu}$ in the nominal fit is quoted in the ranking plot shown in figure 10.14.

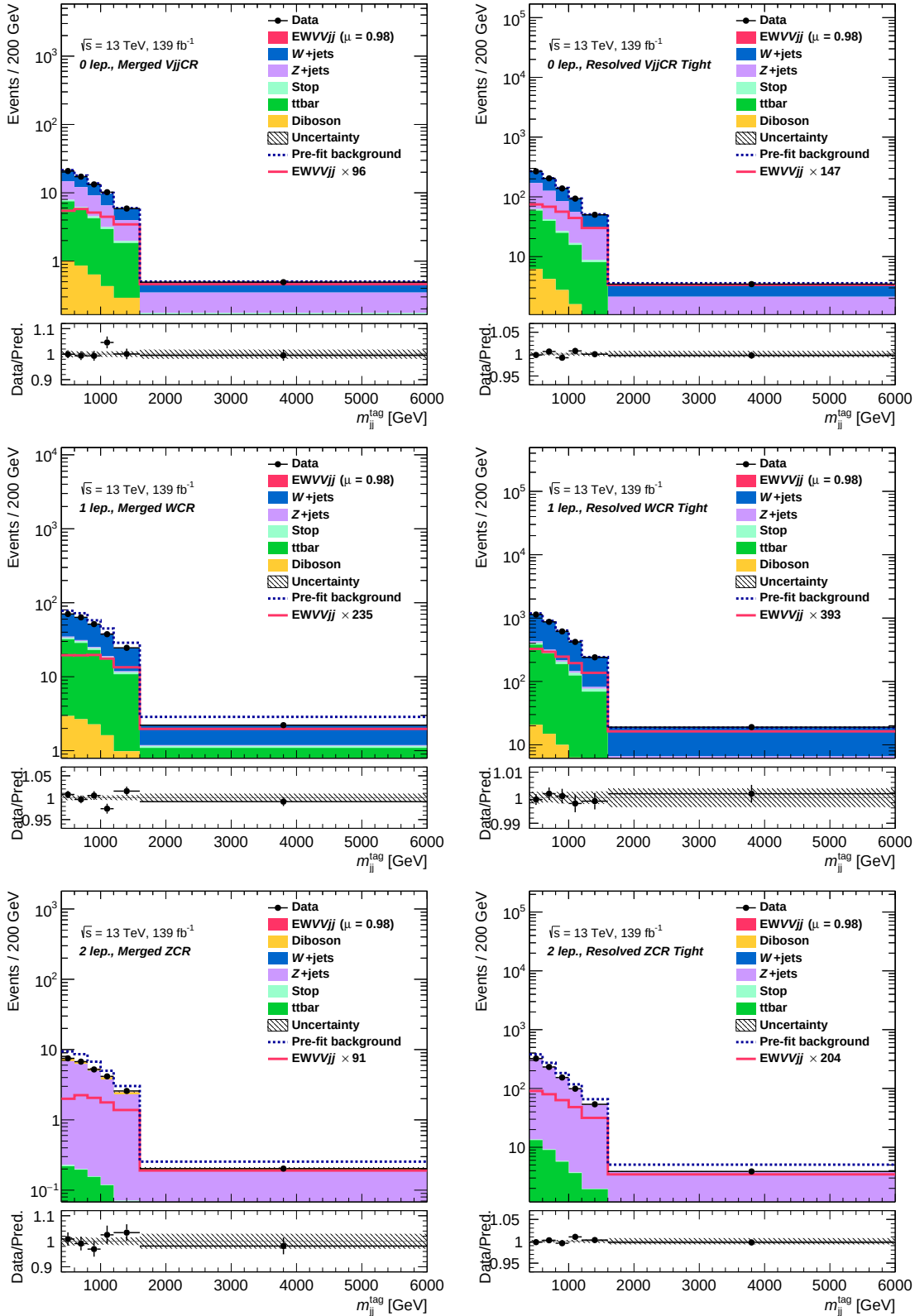


Figure 10.3: Comparisons of the observed data and expected background distributions of m_{jj}^{tag} in V+jets CRs in the 0-lepton channel (1st line), the 1-lepton channel (2nd line), and the 2-lepton channel (3rd line). The EW VV+jj signal is filled on top of the fitted backgrounds, normalized to the signal yield extracted from the observed data ($\mu = 0.98$). The bottom panel show the ratio of the observed data to the post fit signal and background predictions.

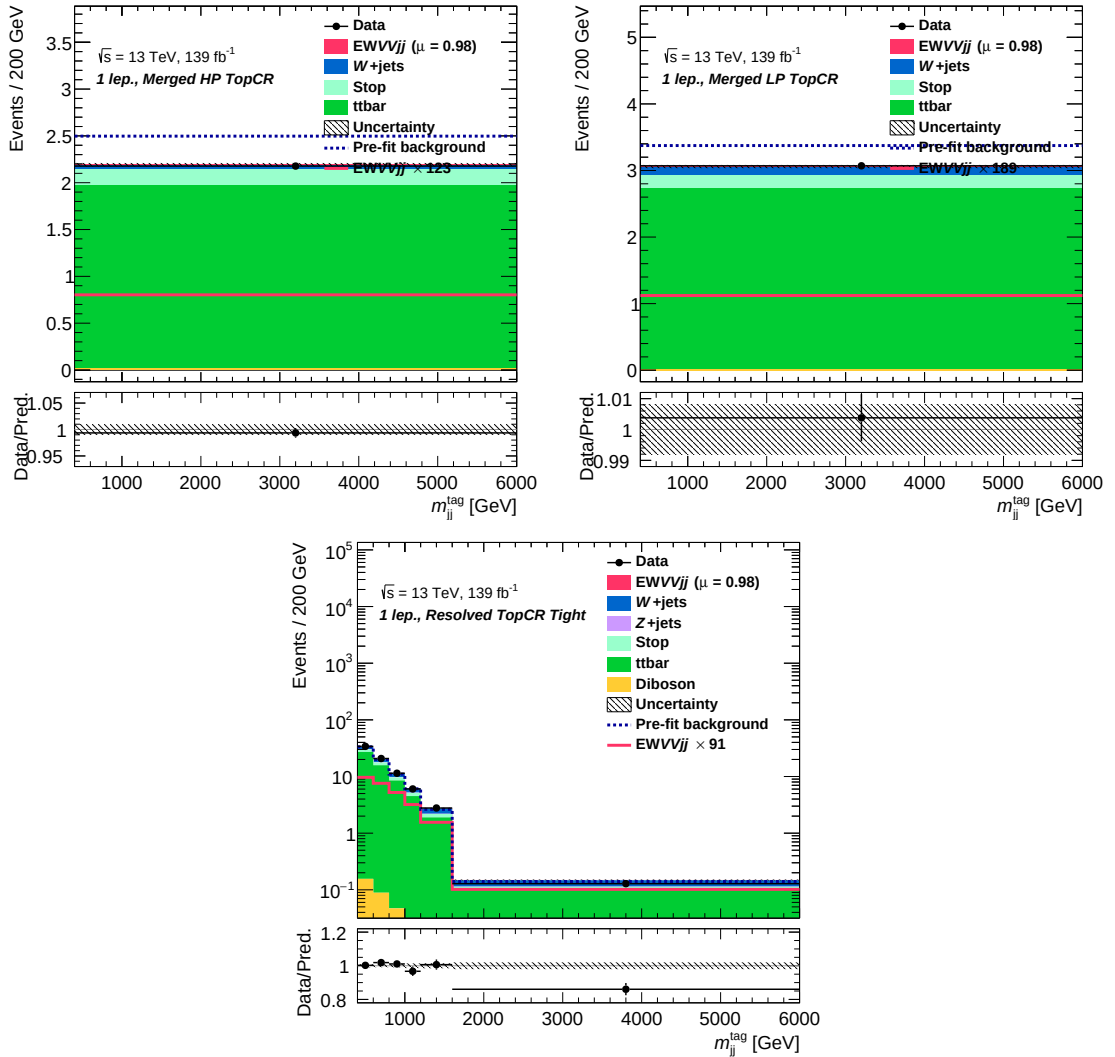


Figure 10.4: Comparisons of the observed data and expected background distributions of m_{jj}^{tag} in Top CRs in the 1-lepton channel. The EW VV+ jj signal is filled on top of the fitted backgrounds, normalized to the signal yield extracted from the observed data ($\mu = 0.98$). The bottom panel shows the ratio of the observed data to the post fit signal and background predictions.

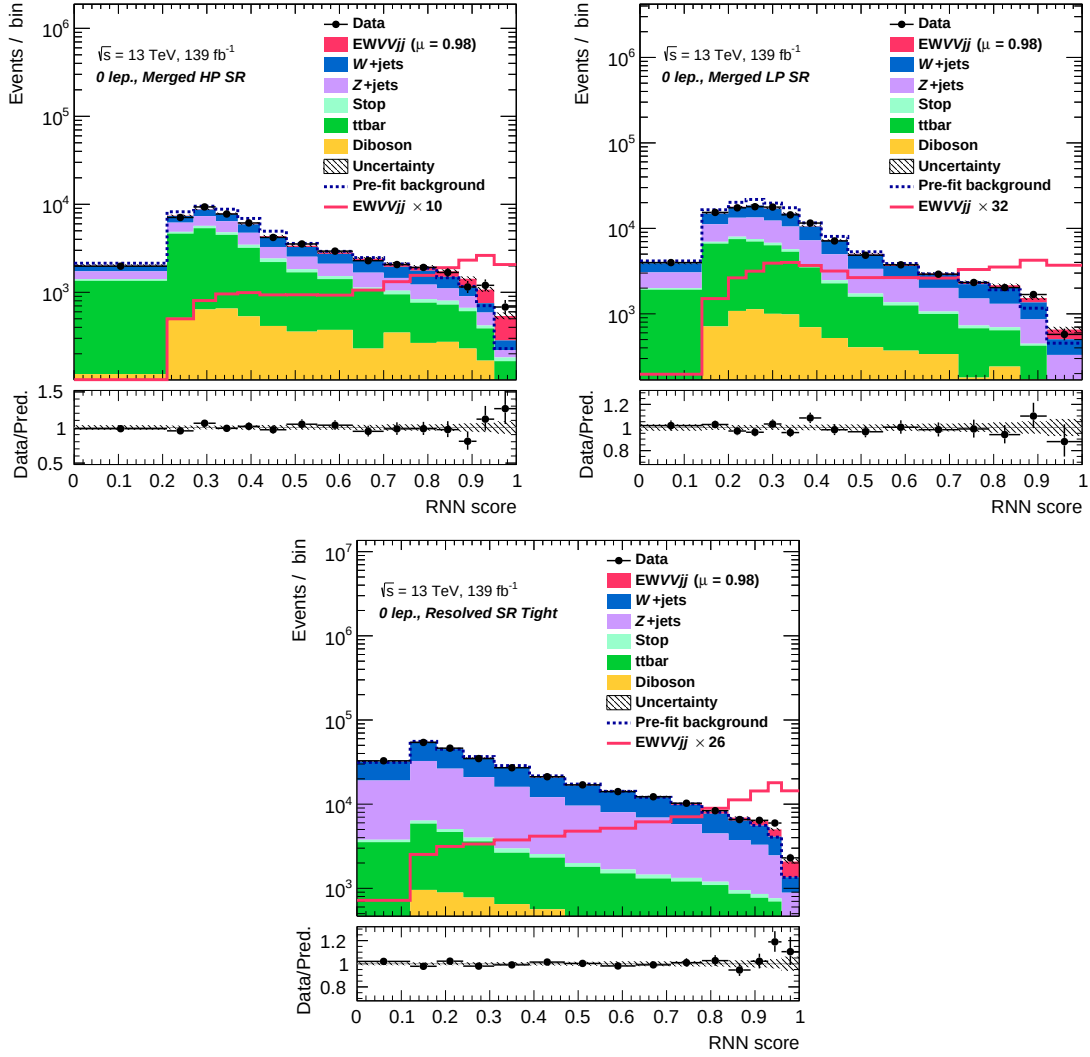


Figure 10.5: Comparisons of the observed data and expected background distributions of RNN score in the 0-lepton channel signal regions. The EW VV+jj signal is filled on top of the fitted backgrounds, normalized to the signal yield extracted from the observed data ($\mu = 0.98$). The bottom panel shows the ratio of the observed data to the post fit signal and background predictions.

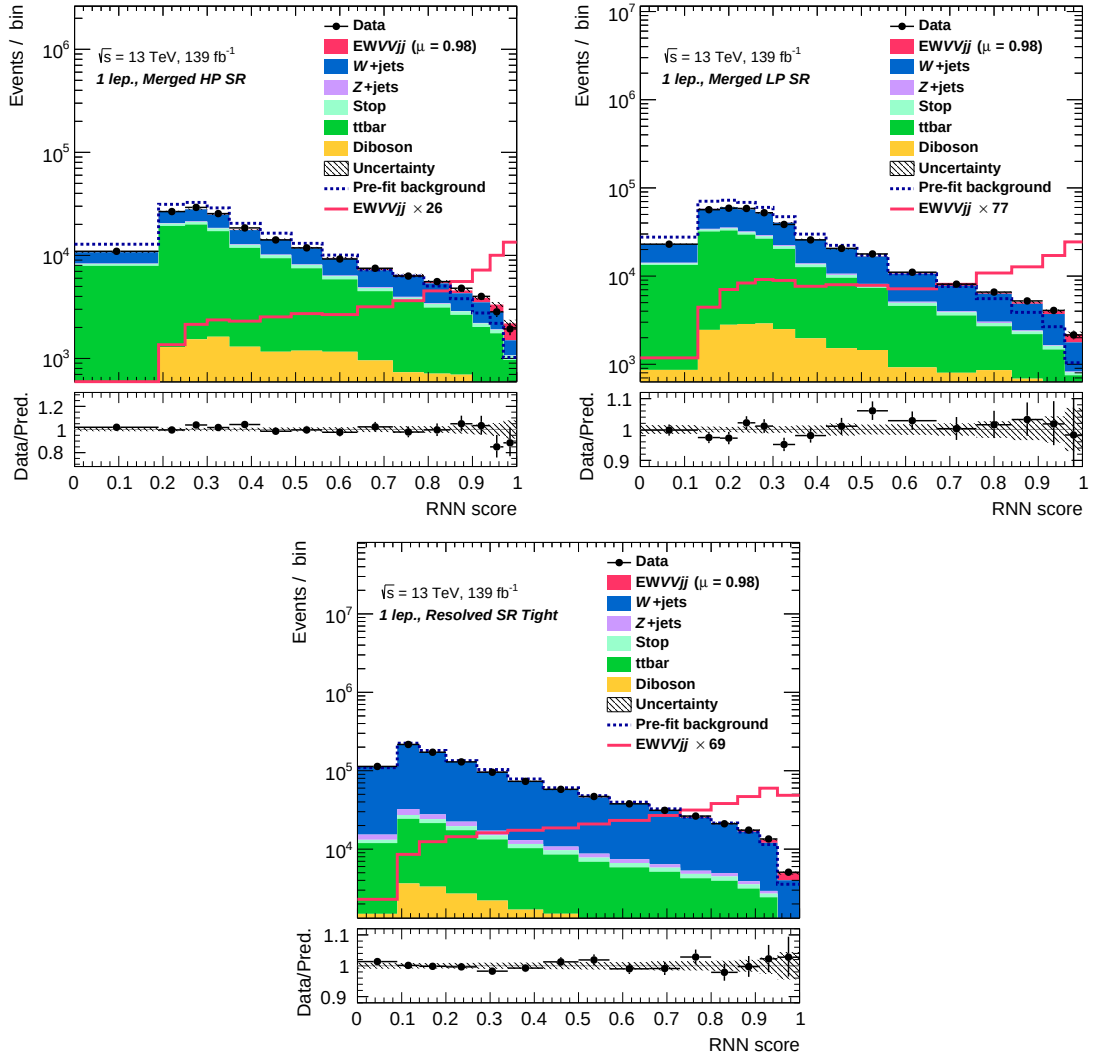


Figure 10.6: Comparisons of the observed data and expected background distributions of RNN score in the 1-lepton channel signal regions. The EW VV+ jj signal is filled on top of the fitted backgrounds, normalized to the signal yield extracted from the observed data ($\mu = 0.98$). The bottom panel shows the ratio of the observed data to the post fit signal and background predictions.

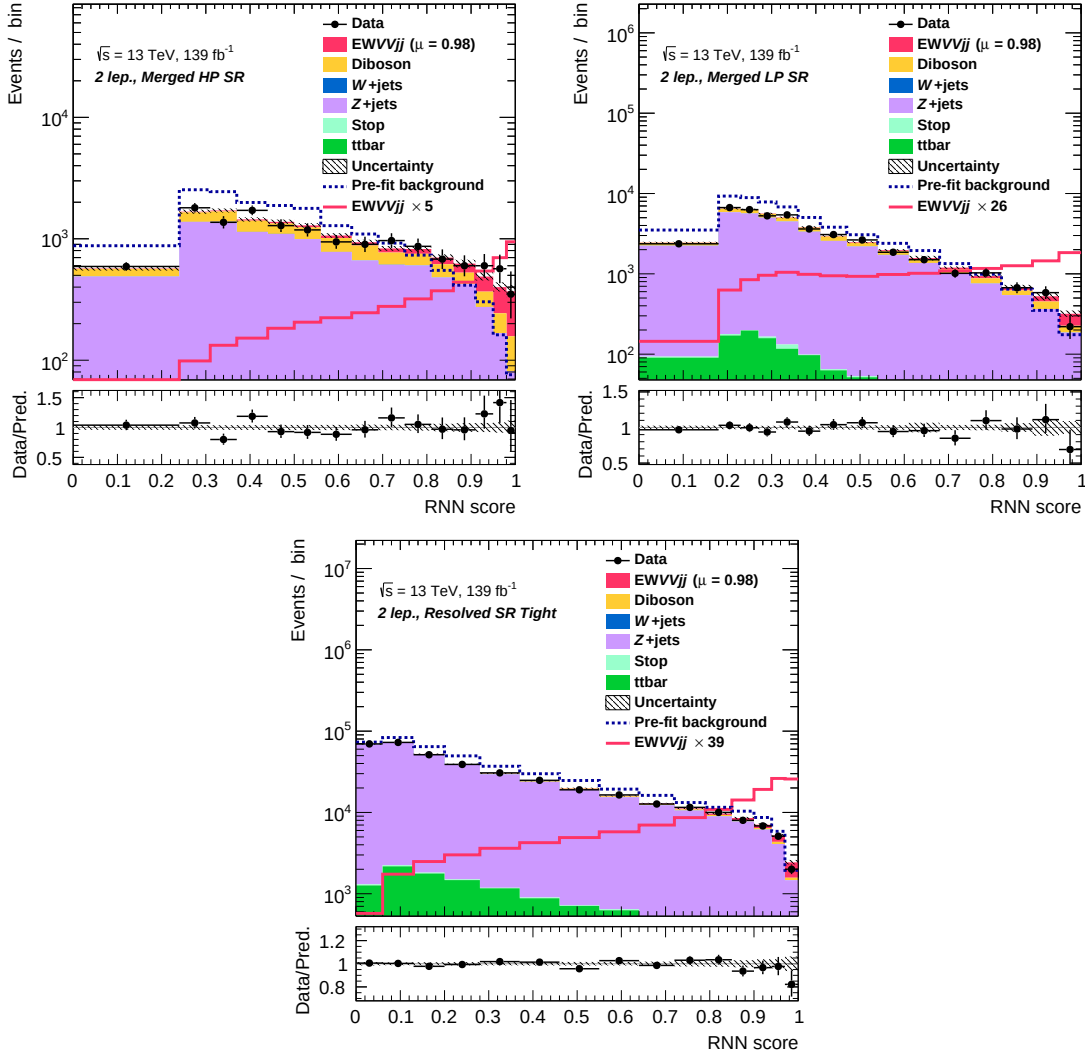


Figure 10.7: Comparisons of the observed data and expected background distributions of RNN score in the 2-lepton channel signal regions. The EW VV+jj signal is filled on top of the fitted backgrounds, normalized to the signal yield extracted from the observed data ($\mu = 0.98$). The bottom panel shows the ratio of the observed data to the post fit signal and background predictions.

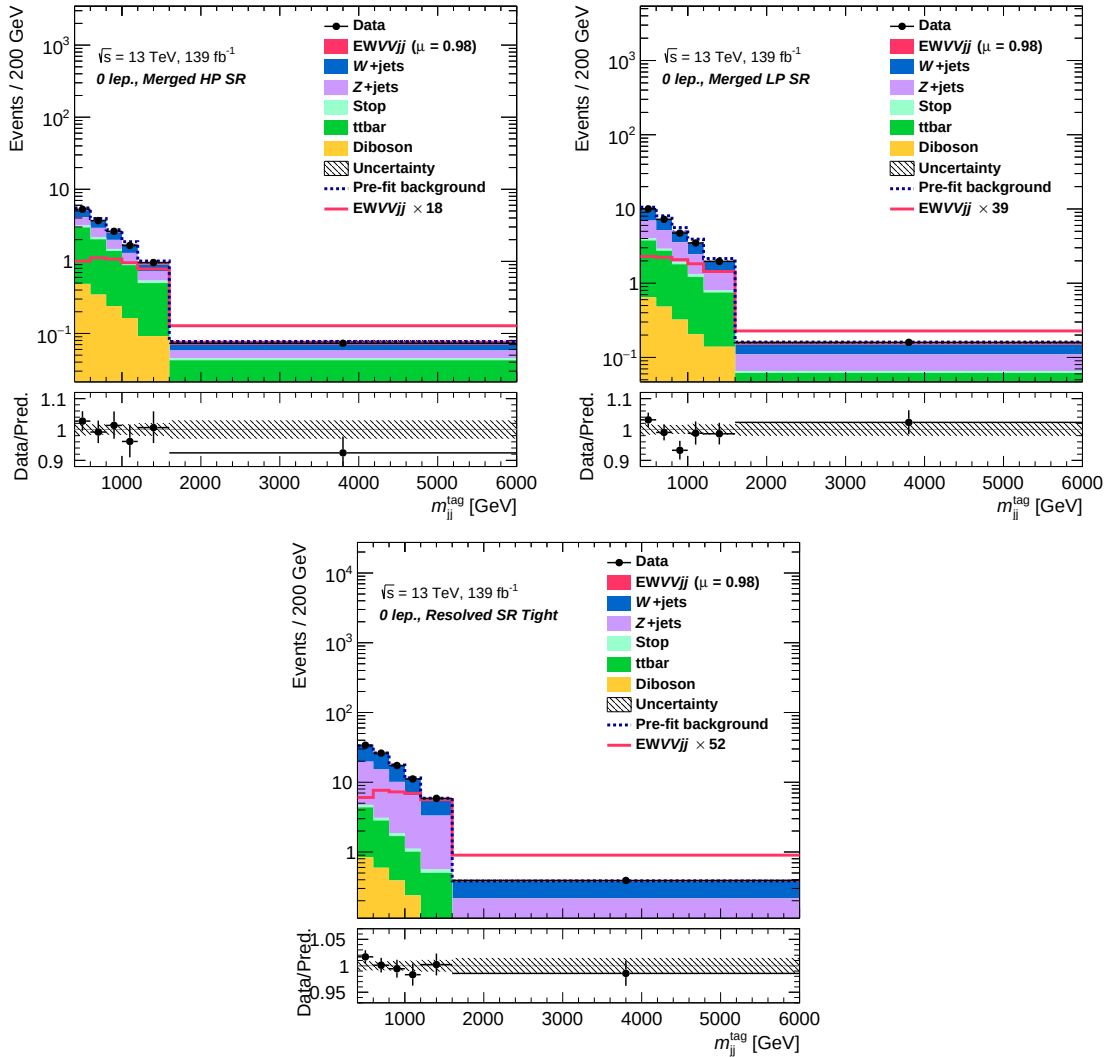


Figure 10.8: Comparisons of the observed data and expected background distributions of m_{jj}^{tag} in the 0-lepton channel signal regions. The EW VV+ jj signal is filled on top of the fitted backgrounds, normalized to the signal yield extracted from the observed data ($\mu = 0.98$). The bottom panel shows the ratio of the observed data to the post fit signal and background predictions.

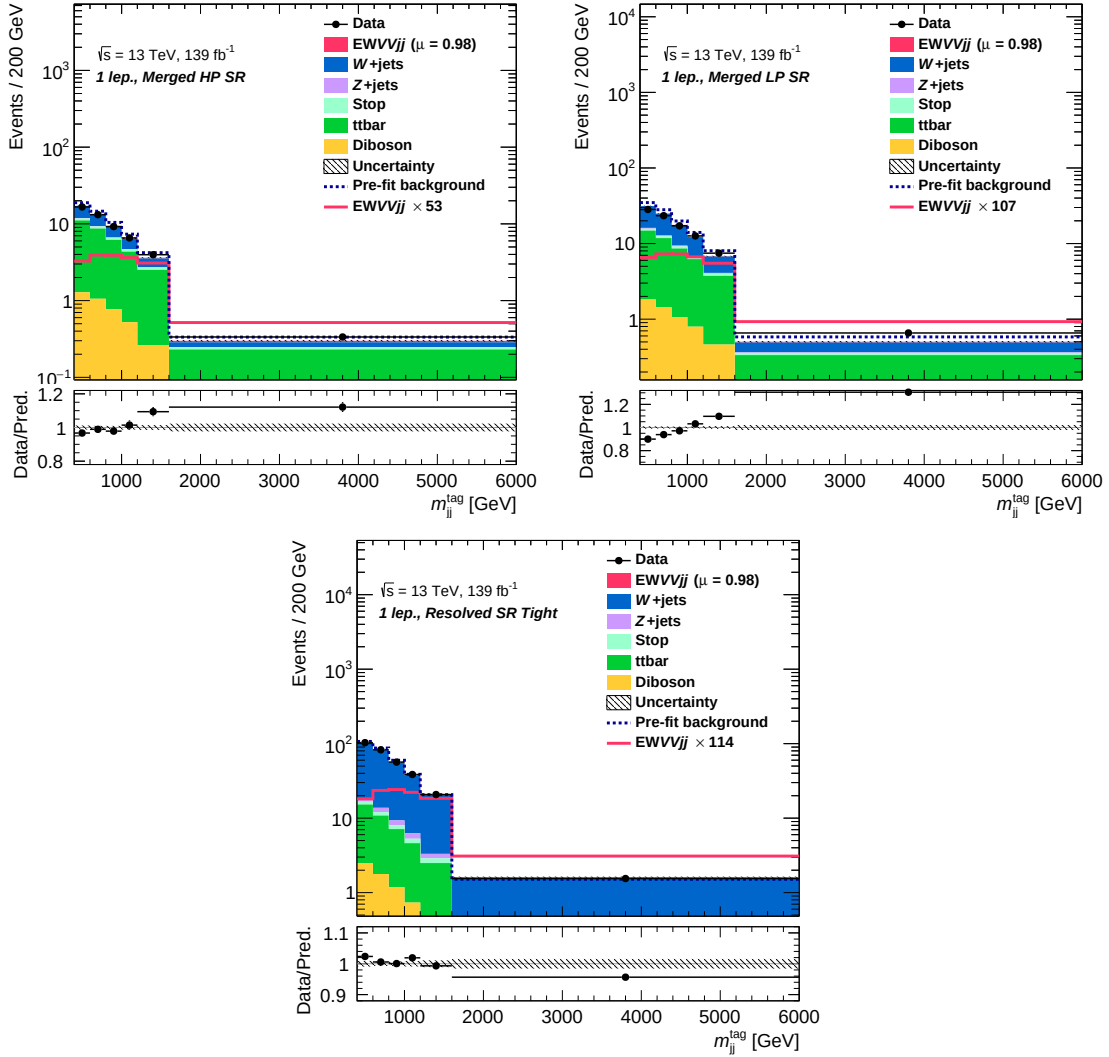


Figure 10.9: Comparisons of the observed data and expected background distributions of m_{jj}^{tag} in the 1-lepton channel signal regions. The EW VV+ jj signal is filled on top of the fitted backgrounds, normalized to the signal yield extracted from the observed data ($\mu = 0.98$). The bottom panel shows the ratio of the observed data to the post fit signal and background predictions.

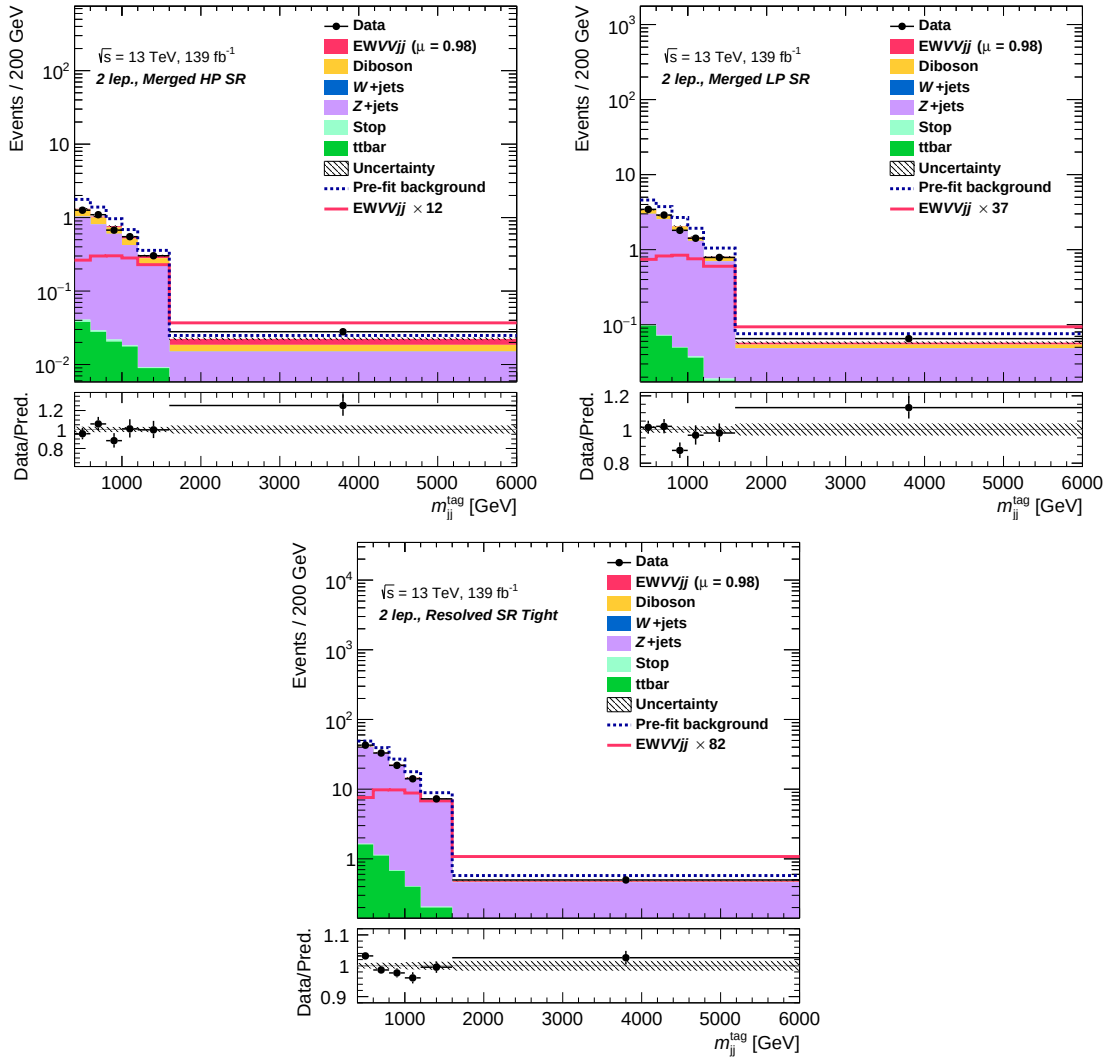


Figure 10.10: Comparisons of the observed data and expected background distributions of m_{jj}^{tag} in the 2-lepton channel signal regions. The EW VV+ jj signal is filled on top of the fitted backgrounds, normalized to the signal yield extracted from the observed data ($\mu = 0.98$). The bottom panel shows the ratio of the observed data to the post fit signal and background predictions.

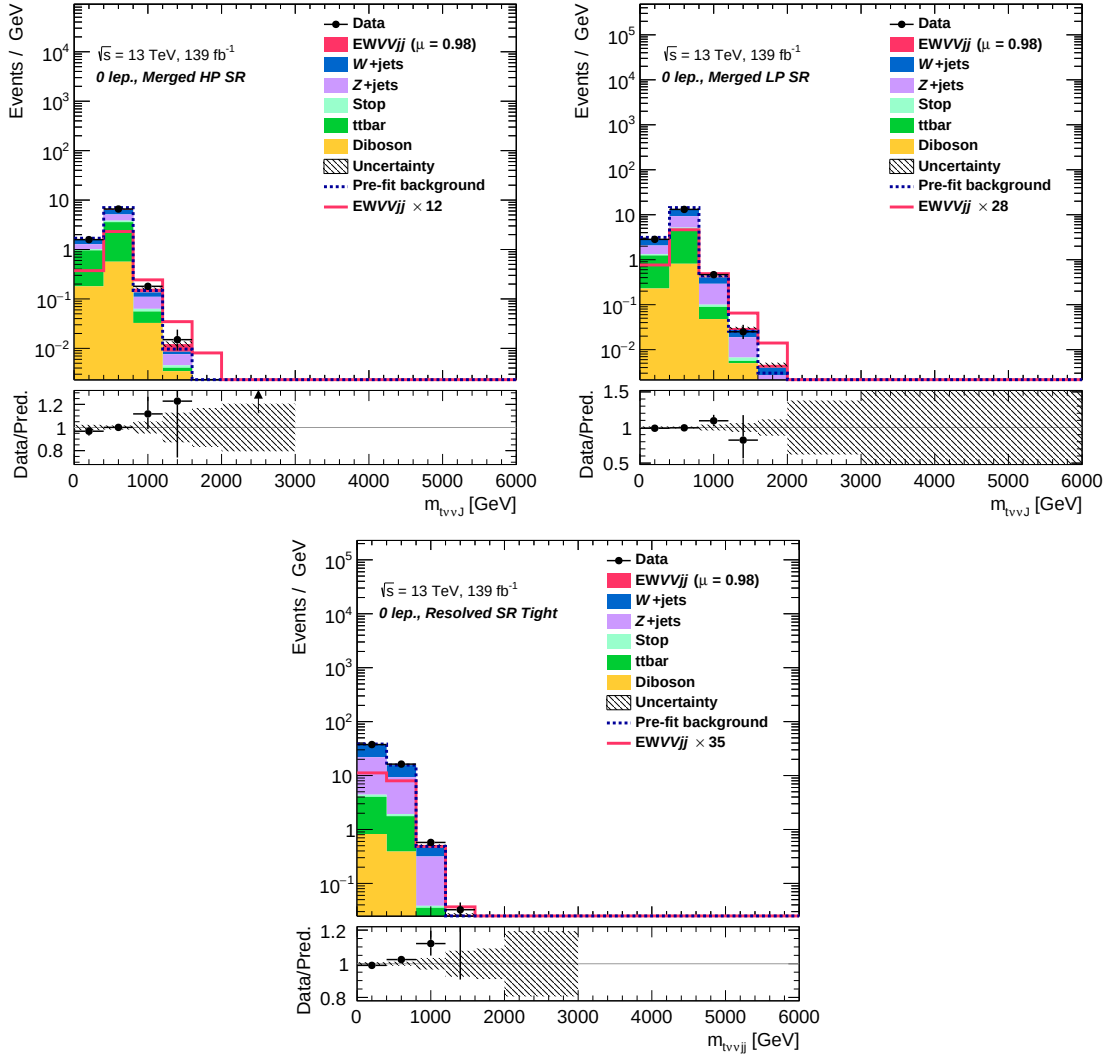


Figure 10.11: Comparisons of the observed data and expected background distributions of diboson invariant mass (m_{VV}) in the 0-lepton channel signal regions. The EW VV+jj signal is filled on top of the fitted backgrounds, normalized to the signal yield extracted from the observed data ($\mu = 0.98$). The bottom panel shows the ratio of the observed data to the post fit signal and background predictions.

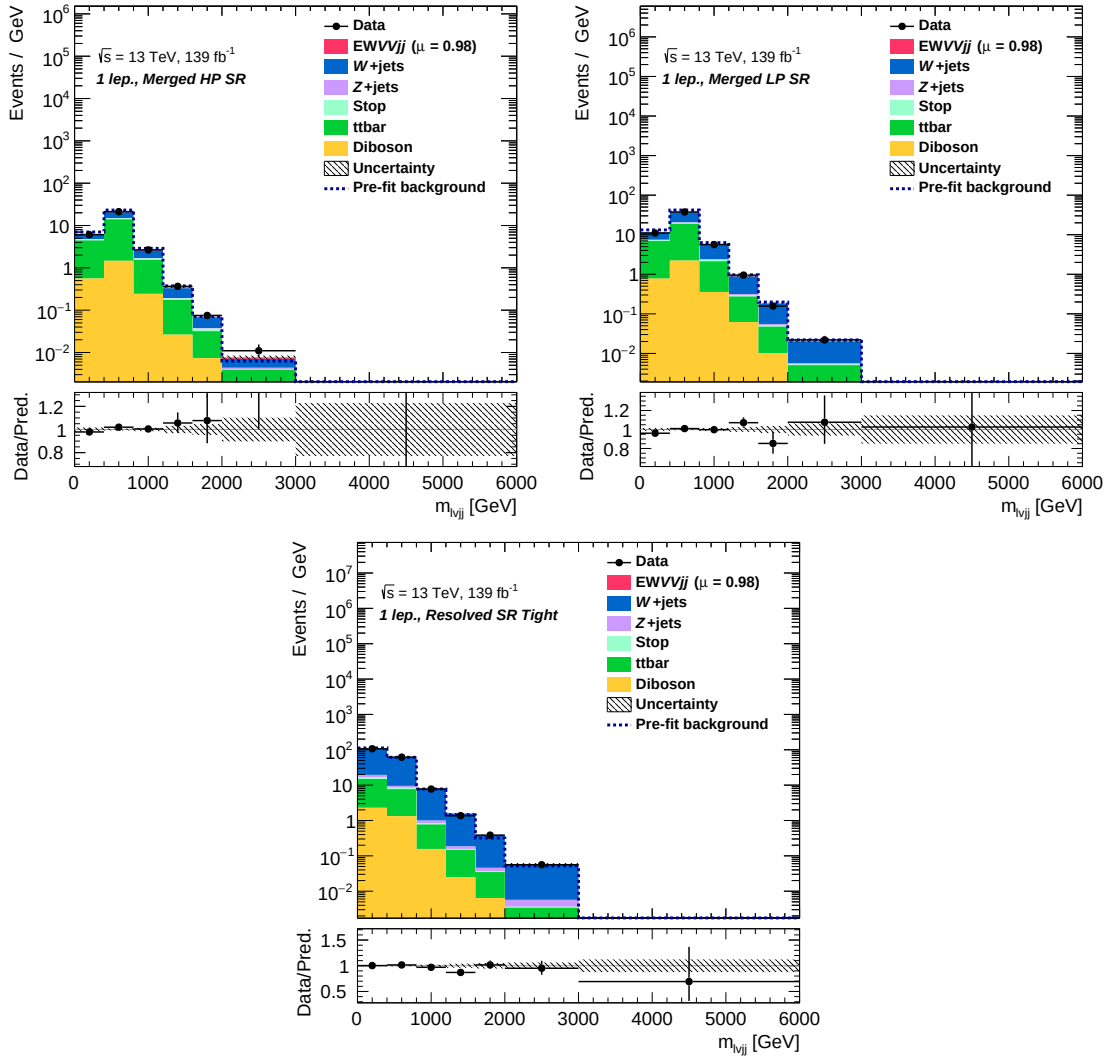


Figure 10.12: Comparisons of the observed data and expected background distributions of diboson invariant mass (m_{VV}) in the 1-lepton channel signal regions. The EW VV+ jj signal is filled on top of the fitted backgrounds, normalized to the signal yield extracted from the observed data ($\mu = 0.98$). The bottom panel shows the ratio of the observed data to the post fit signal and background predictions.

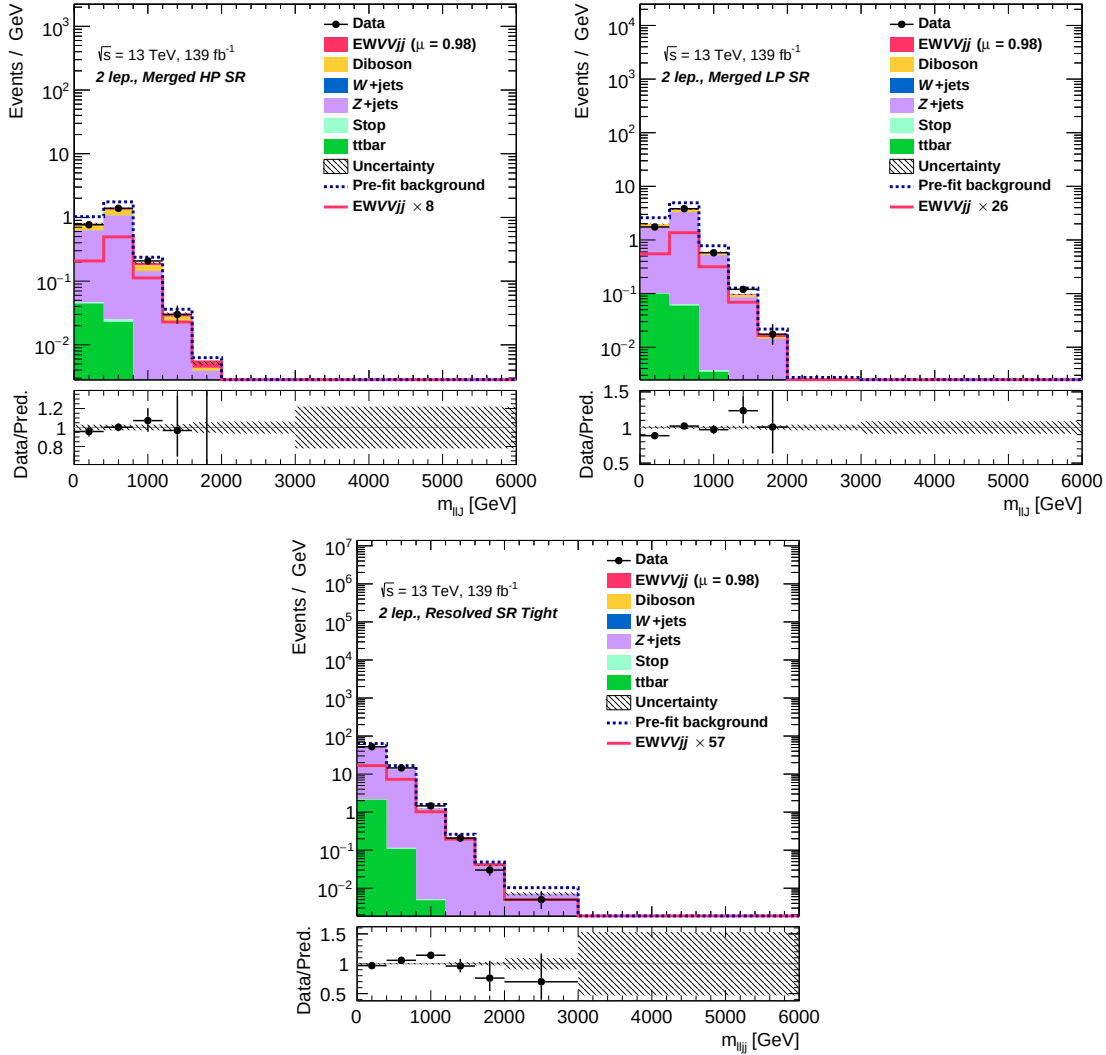


Figure 10.13: Comparisons of the observed data and expected background distributions of diboson invariant mass (m_{VV}) in the 2-lepton channel signal regions. The EW VV+jj signal is filled on top of the fitted backgrounds, normalized to the signal yield extracted from the observed data ($\mu = 0.98$). The bottom panel shows the ratio of the observed data to the post fit signal and background predictions.

The NP which has the largest impact is the QCD scale systematic uncertainty on EW VV+ jj signal sample. Varying this QCD scale parameter by 1σ changes the signal strength by $\Delta\mu \simeq 0.11$. The second and third-ranked parameters are from the 2-lepton channel, and both are related to the modeling of the Z+jets background sample discussed in chapter 7. These uncertainties are ranked high because of its large variations. The diboson-related uncertainties are also ranked high because the lack of the dedicated CRs and they have correlations with the EW VV+ jj signal since their shape is rather similar to the signal samples. The pulls and constraints for these high-impact

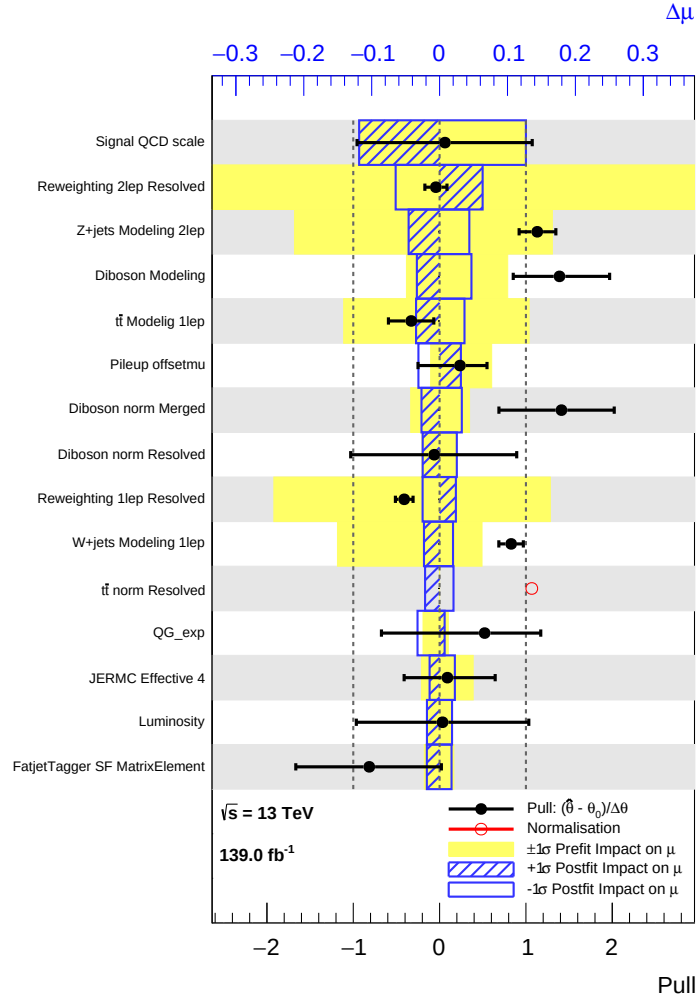


Figure 10.14: Pre-fit (yellow) and post-fit (blue) nuisance parameter impacts on the signal strength, for all three combined channels. The black and red dots denote pulls (defined as $(\hat{\theta} - \theta)/\Delta\theta$, where $\Delta\theta$ represents the magnitude of prior uncertainty, and θ and $\hat{\theta}$ denote pre- and post-fit nuisance parameters) and normalization factors, respectively.

parameters are also shown in figure 10.14 in black dots. The definition of the pull is $(\hat{\theta} - \theta)/\Delta\theta$, where $\Delta\theta$ represents the magnitude of uncertainty, and θ and $\hat{\theta}$ denote pre- and post-fit nuisance parameters. The pull, which can be seen as the deviation of the certain NP from zero, represents how the expectation of that NP does not describe the observed data. The size of the error bar of each uncertainty is the constraints, represent its reduction from its initial uncertainty value and

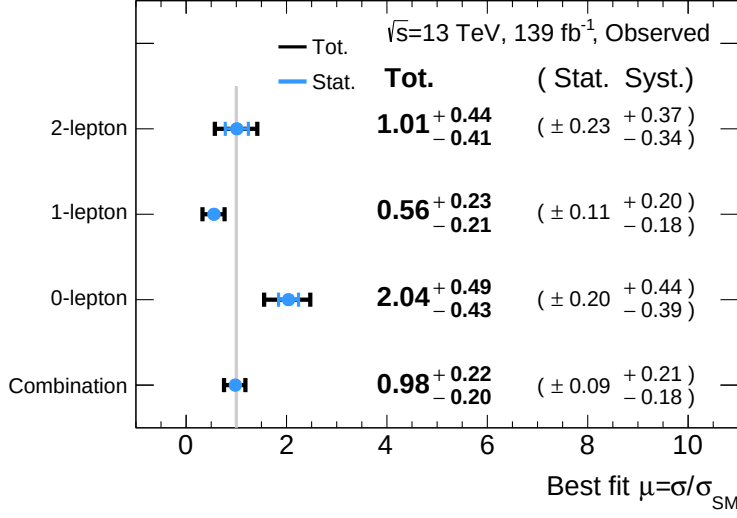


Figure 10.15: Fitted signal strength μ_{obs} from each 2-lepton, 1-lepton, 0-lepton channel and their combination. The signal strength of each channel is obtained from the individual fit using only each channel.

show how much that uncertainty is constrained by the observed data after fitting. Ideally, the pull and the constraints of specific NP are zero and 1σ when the uncertainty is perfectly applied.

The reweighting systematic uncertainty is highly constrained in figure 10.14 as it was set conservatively, as well as modeling Z uncertainty. The modeling Z uncertainty is pulled about 1σ , which adjusts the Z+jets background to the observed data in the fitting. The modeling W uncertainty is also pulled and works similarly with modeling Z uncertainty. The diboson modeling uncertainty and the normalization of the Diboson is also pulled, which can be caused from the mis-modeling of the diboson samples. All of these highly-ranked NPs are not unexpectedly pulled or constrained, which indicates the likelihood fit performed in this analysis is valid enough.

10.5 The observed signal strength

The estimated signal strength in the fit is:

$$\mu = 0.98^{+0.22}_{-0.20} = 0.98^{+0.09}_{-0.09}(\text{Stat})^{+0.21}_{-0.18}(\text{Syst}) \quad (10.1)$$

The corresponding observed (expected) significance is 5.90 (6.47) σ , which claims the observation of the EW VV+jj signal in the semileptonic final state for the first time. The expected significance is estimated by prefit Asimov dataset (an artificial dataset with MC simulations). The 1 sigma of the total uncertainty covers $\mu = 1$, this measurement is consistent with the SM prediction, and there is no significant excess against it.

The signal strength from the combined fit and from each channel fit is shown in figure 10.15. The signal strength from the 0-lepton channel is greater than 2, while in the 1-lepton channel it is around 0.5, hence after combining three channels the signal strength is 0.98. The 1-lepton channel contributes to the combined signal strength most because of its dominance in the signal yields.

10.6 Fiducial cross section

The fiducial cross section, $\sigma_{EWVVjj, \text{ obs}}$, defined in section 9.1, is derived using the observed μ value. The expected cross-section, $\sigma_{EWVVjj, \text{ SM}}$, obtained by truth event selection using the stable final state particle is shown in table 10.3. The expected cross-section is the sum of the cross-section of each lepton channel. The merged HP SR and LP SR are combined into a single merged signal region.

$\sigma_{EWVVjj, \text{ SM}} [\text{ fb }]$	0-lepton	1-lepton	2-lepton	Combined
Merged	1.76	3.05	0.74	5.55
Resolved	1.98	4.50	1.55	8.03
Combined	3.74	7.55	2.29	13.58

Table 10.3: A summary of predicted fiducial cross section.

The observed fiducial cross section obtained is listed in table 10.4. The fiducial cross-section is observed to be $13.3^{+2.99}_{-2.72}$ fb.

$\sigma_{EWVVjj, \text{ obs}} [\text{ fb }]$	0-lepton	1-lepton	2-lepton	Combined
Merged	$1.72^{+0.39}_{-0.35}$	$2.99^{+0.76}_{-0.61}$	$0.73^{+0.16}_{-0.15}$	$5.4^{+1.22}_{-1.11}$
Resolved	$1.94^{+0.44}_{-0.40}$	$4.41^{+0.99}_{-0.90}$	$1.52^{+0.34}_{-0.31}$	$7.9^{+1.77}_{-1.61}$
Combined	$3.67^{+0.82}_{-0.75}$	$7.40^{+1.66}_{-1.51}$	$2.24^{+0.50}_{-0.46}$	$13.3^{+2.99}_{-2.72}$

Table 10.4: A summary of observed fiducial cross section. Uncertainties are propagated from the systematic and statistical uncertainties estimated when deriving observed μ .

Chapter 11

Interpretation with Effective Field Theory

Given the results in chapter 10 that there is no significant excess against the SM expectations, the limits on new physics contributions are evaluated in this chapter.

As mentioned in Section 2.5.1, aQGC interpretation is done via EFT Lagrangian. The SM+EFT matrix element can be written as

$$|A_{SM} + \frac{f_i}{\Lambda^4} A_i|^2 = |A_{SM}|^2 + \sum_i \frac{f_i^2}{\Lambda^8} |A_i|^2 + \sum_i 2 \frac{f_i}{\Lambda^4} \text{Re}(A_{SM}^* A_i) + \sum_{i \neq j} \frac{f_i}{\Lambda^4} \frac{f_j}{\Lambda^4} \text{Re}(A_i^* A_j) \quad (11.1)$$

where $|A_{SM}|^2$ is the SM matrix element, $|A_i|^2$ represents the pure-EFT matrix elements for the O_i operator listed in eq 2.43-2.45, $2\text{Re}(A_{SM}^* A_i)$ is its corresponding interference term with the SM, and $\text{Re}(A_i^* A_j)$ is possible interference term between EFT operators O_i and O_j . Theoretically, it cannot separate the effects of Wilson coefficients f_i and the scale Λ^4 , so the parameter of interest in this analysis is the ratio $\frac{f_i}{\Lambda^4}$. The pure-EFT term is scaled by the quadrature of $\frac{f_i}{\Lambda^4}$ and the interference term by $\frac{f_i}{\Lambda^4}$. They are also called as the quadratic term and the interference (linear) term, respectively. In this analysis, the term with $\text{Re}(A_i^* A_j)$ is ignored for simplicity and for consistency to other previous results on aQGC search, and evaluate the contributions from each operator on a one-by-one basis.

11.1 Statistical interpretation

The aQGC signal is extracted with a profile-likelihood fit as described in section 9.2, but replacing the signal to the aQGC sample, and the standard model EW VV+jj signal is included as background with other standard model background samples. The POI is set as $\mu_{\text{aQGC}} = \frac{f_i}{\Lambda^4}$, where signal template is defined as μ_{aQGC}^2 * quadratic signal + μ_{aQGC} * interference signal. Figure 11.2 shows the quadratic and interference signal distributions of di-boson invariant mass (m_{VV}) in HP SR. All m_{VV} distributions for other Wilson coefficients are shown in appendix .3. The contribution of quadratic term and the linear term depends on the magnitude of μ_{aQGC} . As figure 11.1 shows, the contribution of the quadratic term is dominant where the μ_{aQGC} is large, and the number of signal becomes more symmetrical. Where the μ_{aQGC} is small, the interference term contribution is dominant, the number of signal becomes more asymmetrical and can take negative values. For the purpose of excluding a signal hypothesis, confidence intervals are derived to set limits.

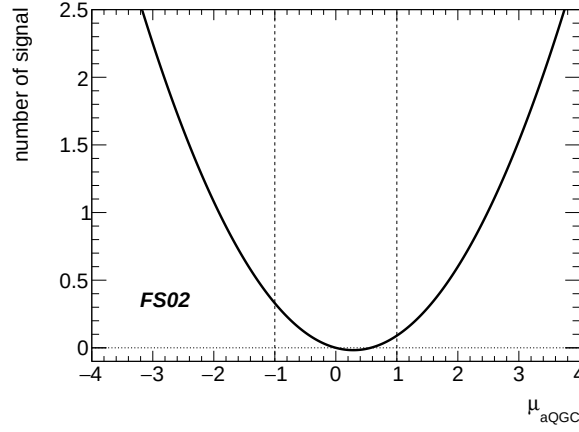


Figure 11.1: Number of the FS02 signals with respect to the μ_{aQGC} value. The signal is produced at $\frac{f_i}{\Lambda^4} = 1 \text{ [TeV}^{-4}\text{]}$.

Confidence intervals are calculated with asymptotic formulae using Wilks' theorem [89], assuming that the profile likelihood test statistic follows χ^2 distribution [61].

11.2 Clipping method

As the EFT may violate unitarity at a large energy scale, the clipping method, mentioned in section 2.5.1, is used to study the range of cut-off scale that the experimental result can give limits on perturbatively calculable models. The EFT signal is set to zero at truth $m_{VV} > E_{\text{clip}}$, where the E_{clip} is [1.5, 2, 3, 5, ∞] TeV. The background samples, which are all standard model predictions, are not clipped. The expected and observed limits are obtained with all 3 channels at each of the clipping points and compared with the theoretical unitarity bound.

11.3 Study of final discriminant in aQGC search

The aQGC terms can modify the amplitude of the VBS process at the higher effective center-of-mass energy, m_{VV} , as shown in Figure 11.3. It is found that the reconstructed m_{VV} (or m_T in 0-lepton channel) is the best variable to separate the aQGC signals from the all SM processes, while it cannot separate the SM EW $VV+jj$ process from the SM background as shown in figure 11.3. The RNN score distributions for the aQGC samples are similar to the one for the SM electroweak signal and still useful to suppress the non-VBS background as shown in Fig. 11.4. Finally we would like to separate aQGC signals from both SM electroweak signal and the SM non-VBS background. So that the final discriminant can make use of the both separation power of m_{VV} and the RNN score, ideally 2-dimensional likelihood fit using m_{VV} and RNN score is the best option, but considering that number of bins deteriorates the stability of the fit, we briefly optimized the binning strategy. We found a fit to RNN score distributions after SRs are further separated into 2 bin m_{VV} categories is usable enough. Its sensitivity is comparable with a fit to m_{VV} distribution. The optimal threshold to separate the SRs may depends on the clipping energy. The threshold

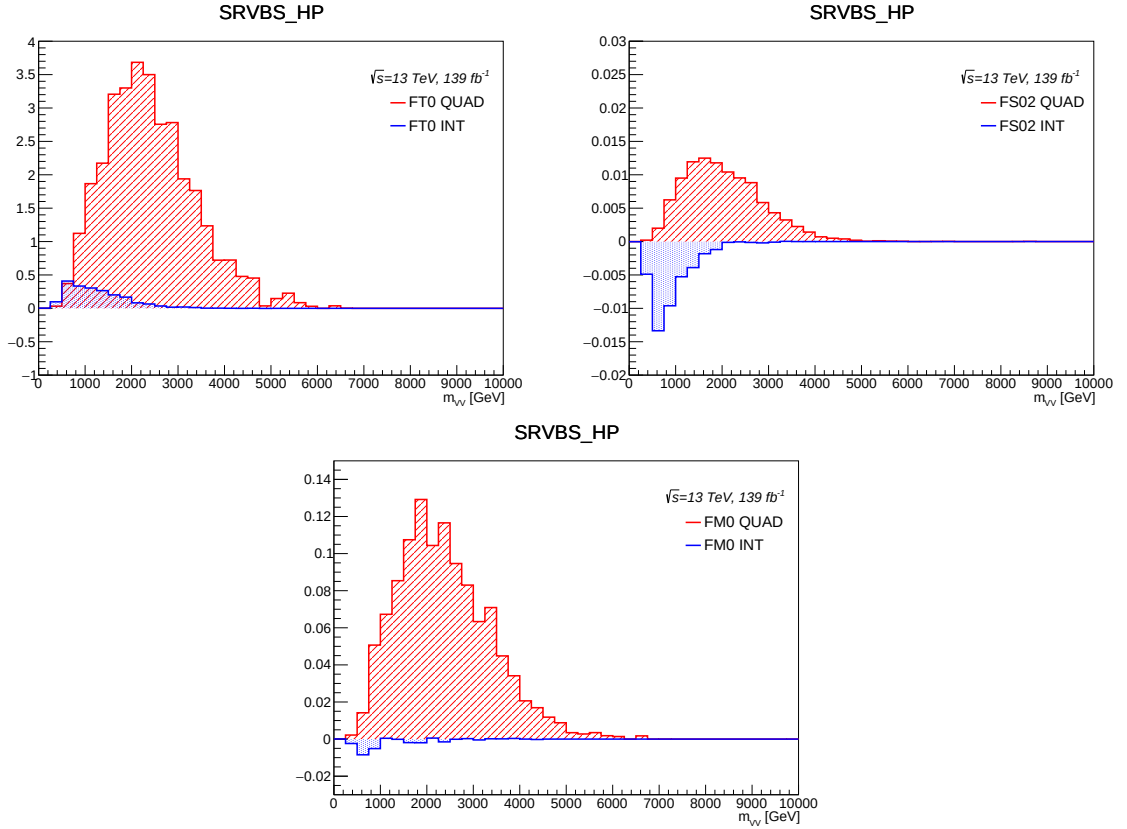


Figure 11.2: The comparison of the quadratic term and the interference term with FT0 (top left), FS02 (top right), and FM0 (bottom middle) in 2-lepton channel HP SR. The contribution of the interference term can be negative, and it is larger in FS terms. The signal sample is produced at $\frac{f_i}{\Lambda^4} = 1$ [TeV⁻⁴].

value at each clipping value is scanned and checked the sensitivity in figure 11.5.

As expected, a higher m_{VV} threshold is preferred at the higher clipping point, while a lower m_{VV} threshold is favored at the lower clipping point. 1500 GeV is chosen as the best compromise to separate SRs into low- and high- m_{VV} bins for the 2-lepton channel.

Since the meaning of the actual m_{VV} distributions used in each lepton channel are different, (fully reconstructed system in the 2-lepton and in the 1-lepton and transverse mass in the 0-lepton solving neutrino ambiguity) the optimal thresholds to separate SRs into low- and high- m_{VV} bins in 1-lepton and 0-lepton channels are also studied and determined in table 11.1.

Threshold values (GeV)	SRVBS_HP	SRVBS_LP	SRVBS_Fid
0-lepton	1050	1200	1200
1-lepton	1500	1500	1500
2-lepton	1500	1500	1500

Table 11.1: Threshold value to separate the m_{VV} distribution for the 1-lepton and the 2-lepton and m_{TV} distribution for the 0-lepton channel.

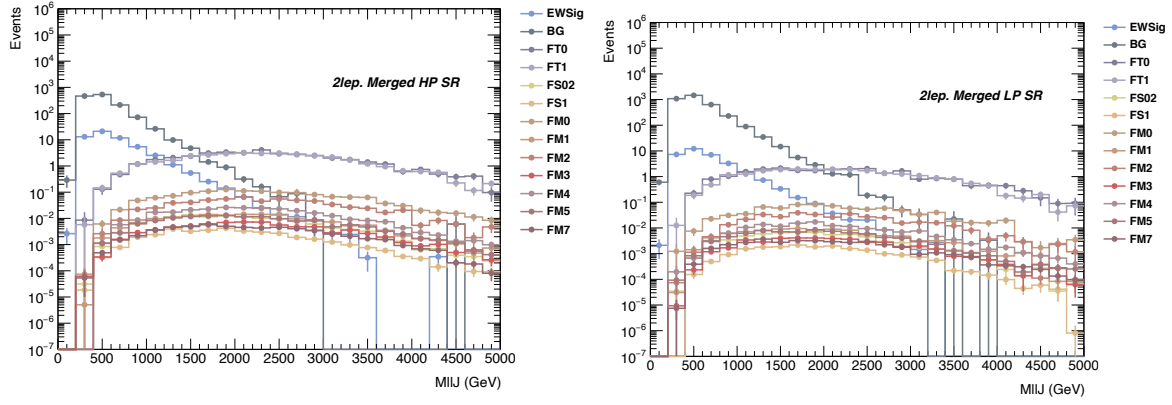


Figure 11.3: m_{VV} shape distribution of each Wilson coefficient in Merged Signal regions. Only quadratic terms are shown.

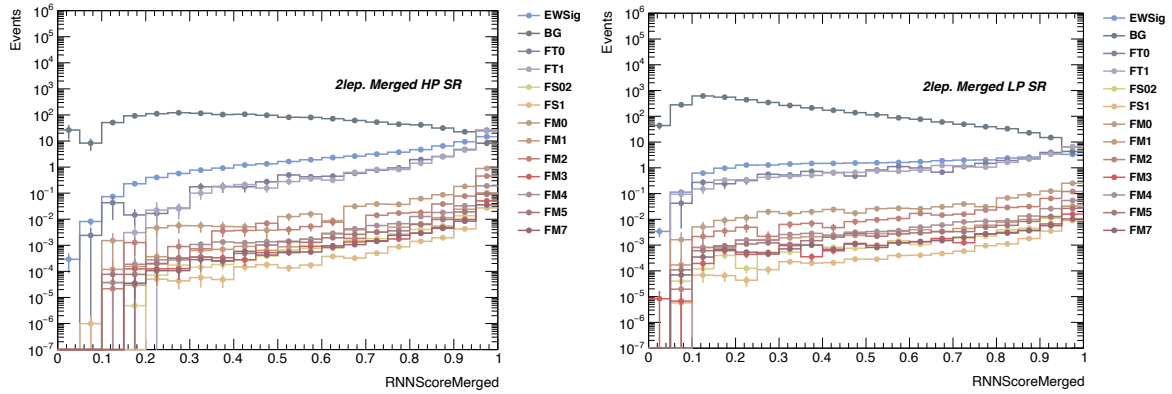


Figure 11.4: RNN score shape distribution of each Wilson coefficient in Merged Signal regions. Only quadratic terms are shown.

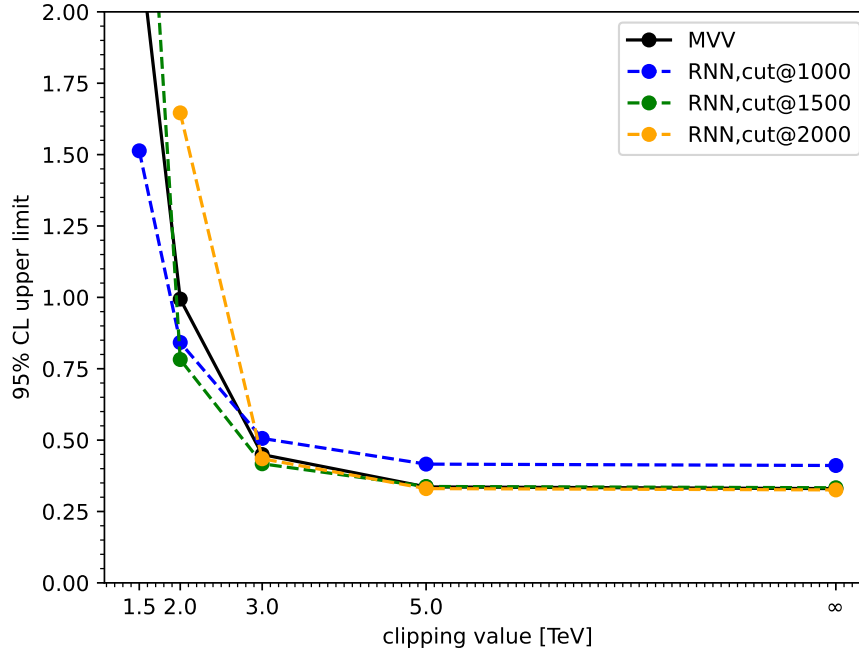


Figure 11.5: Expected limits for 5 clipping points with each threshold for dividing m_{VV} into 2 bins.

11.4 Limits setting

Finally, by using both quadratic and interference terms as a combined signal template, the expected 95% CL upper and lower limits are obtained by the fit to the Asimov dataset constructed from the background plus SM EW VV+ jj samples, as well as observed limits with data. All SRs in 0-lepton, 1-lepton and 2-lepton channels are separated into low- and high- m_{VV} bins as discussed in Section 11.3 and combined statistically. All systematic uncertainties discussed for Standard Model measurement are included in the fitting. The SM EW VV+ jj signal samples are added to the background as a free floated normalization factor, and all the analysis regions are correlated with EW VV+ jj signal samples. Due to the small statistics in high- m_{VV} regions compared with the low- m_{VV} regions, the overall behaviors of the post-fit nuisance parameters are almost the same as the SM measurement. The postfit plots for FT0 parameter in signal regions are shown in figure 11.6, 11.7, 11.8. Overall the expected background reproduces the data well within the uncertainty except for the several right-most bins of the high- m_{VV} region. In the right-most bins of the high- m_{VV} region, some data excess can be seen in the 0-lepton resolved signal region and in the 1-lepton merged LP signal region.

The expected and observed limits are shown at 5 clipping energy points of [1.5, 2.0, 3.0, 5.0, ∞] TeV in Figure 11.12. The unitarity bound from the theoretical calculation [6] is overlaid. The log-likelihood ($-2 \ln \lambda$; λ is a likelihood ratio) distributions with respect to the μ_{aQGC} , is shown in figure 11.9, 11.10, 11.11 for FT0, FS02, FM0 operator, for each clipping energy of 1500 GeV, 2000 GeV, ∞ . Due to the large contribution of the quadratic term in the parametrization of the μ_{aQGC} , the log-likelihood curve has two local minimums where there is an excess in data. At the

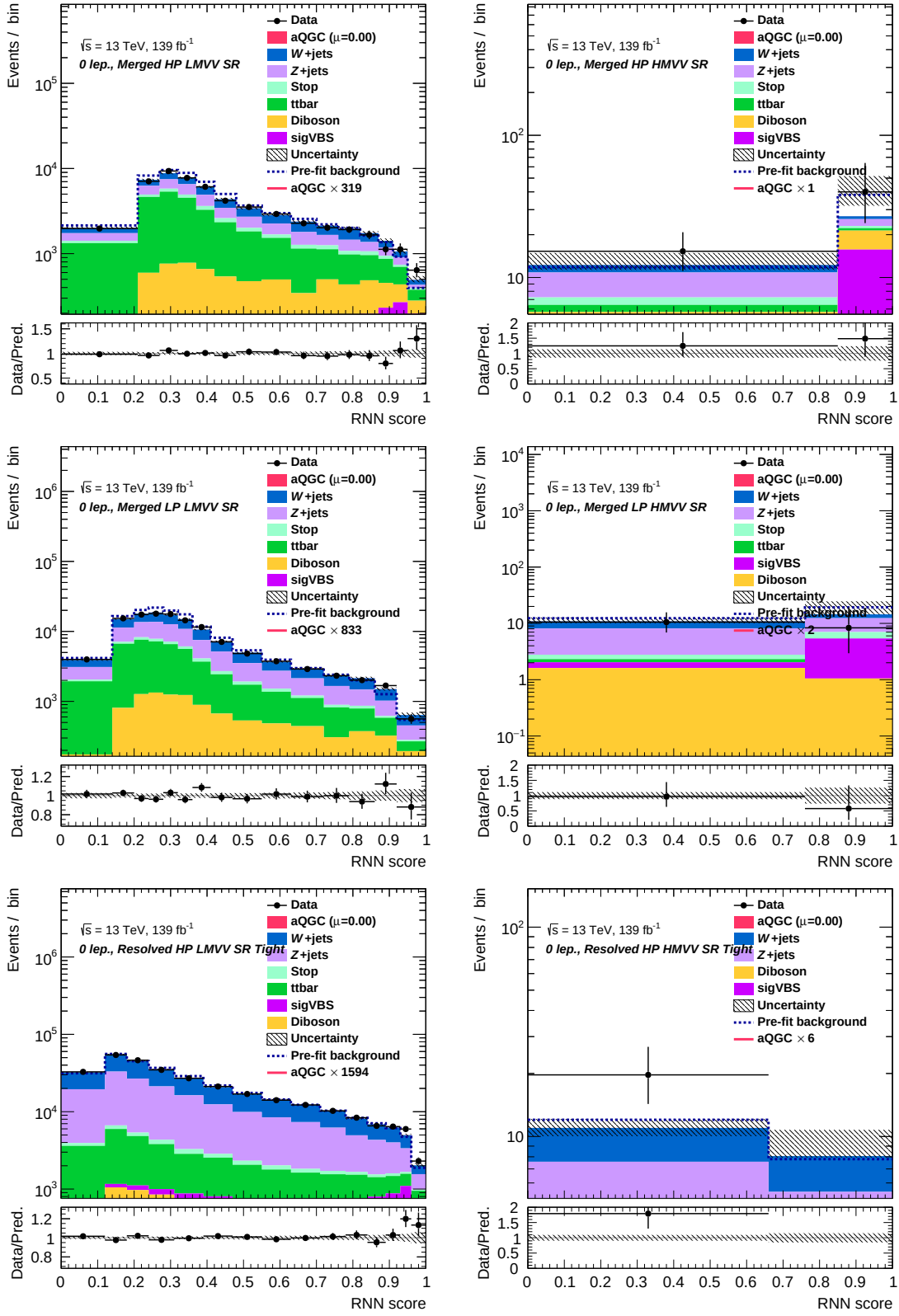


Figure 11.6: Comparisons of the observed data and expected background distributions of RNN score in 0-lepton channel signal regions. Low- m_{VV} region (left) and the high- m_{VV} region (right) are shown.

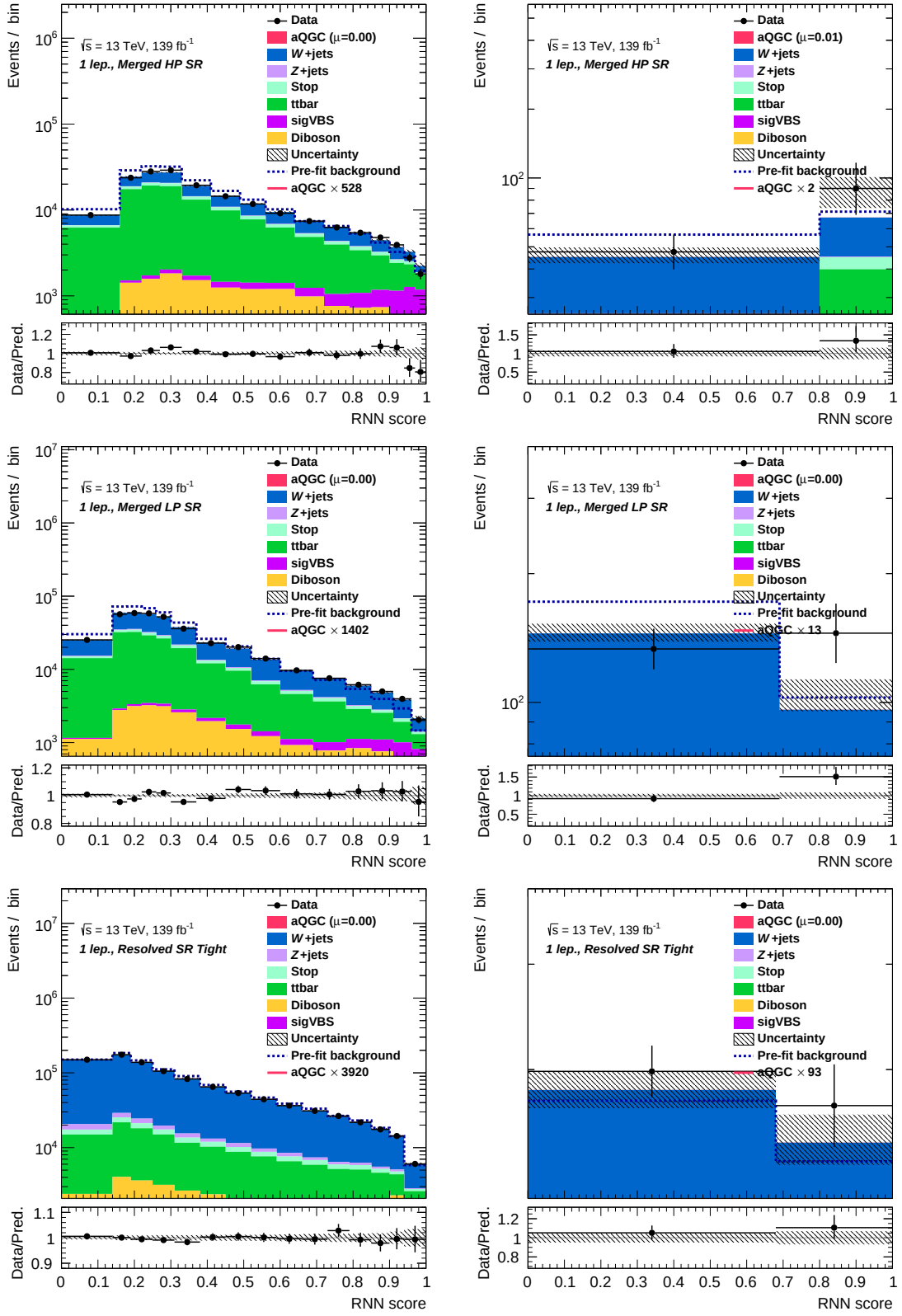


Figure 11.7: Comparisons of the observed data and expected background distributions of RNN score in 1-lepton channel signal regions. Low- m_{VV} region (left) and the high- m_{VV} region (right) are shown.

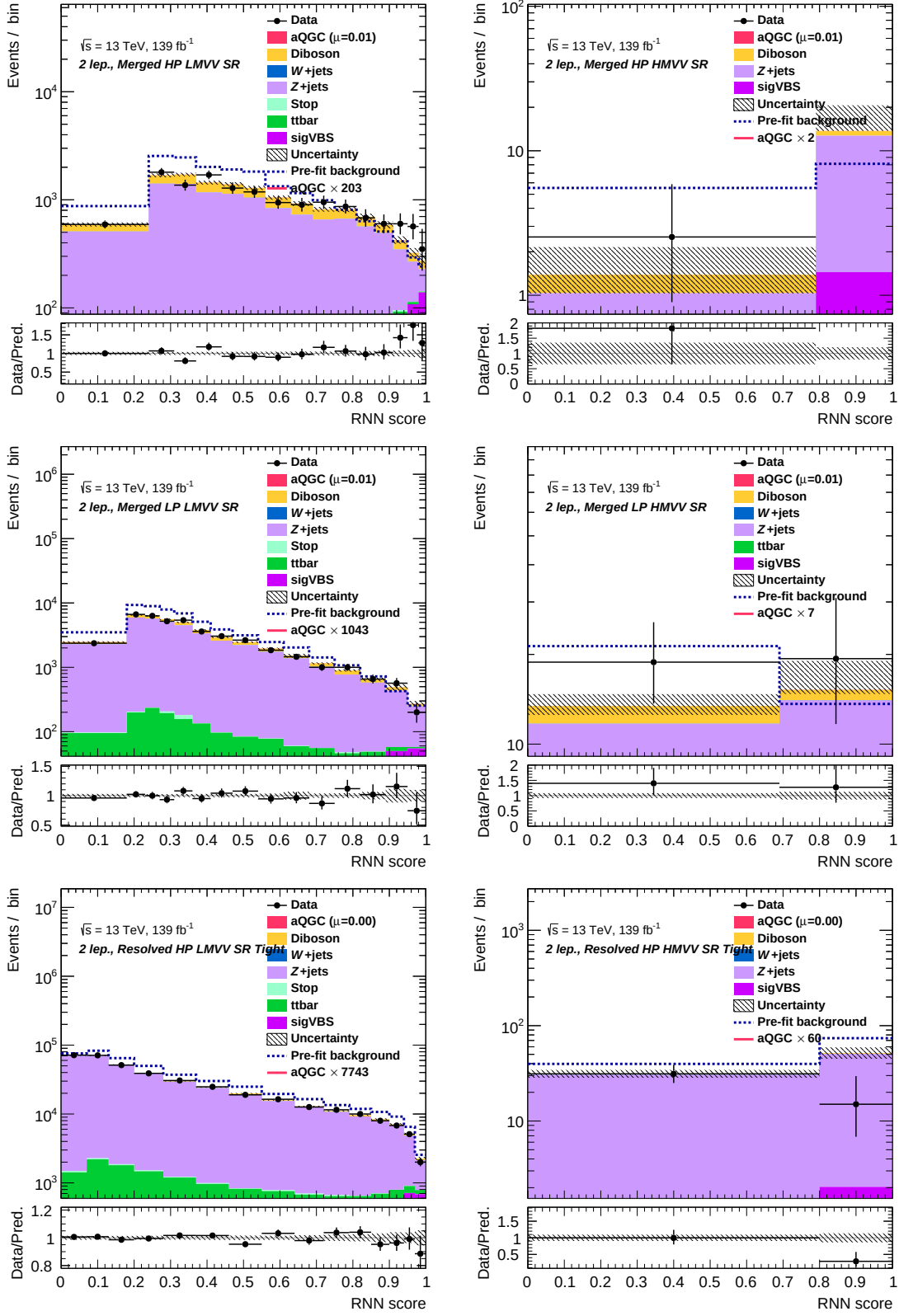


Figure 11.8: Comparisons of the observed data and expected background distributions of RNN score in 2-lepton channel signal regions. Low- m_{VV} region (left) and the high- m_{VV} region (right) are shown.

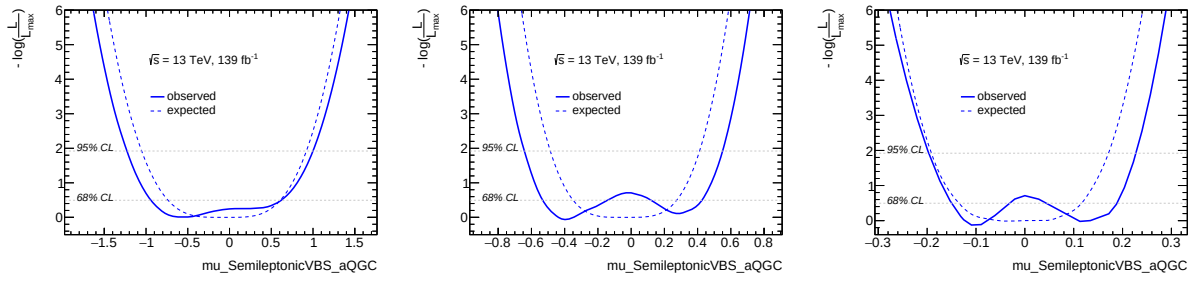


Figure 11.9: The observed log-likelihood curves of FT0 Wilson coefficient where the clipping energy is 1.5 TeV (left), 2.0 TeV (middle), ∞ (right).

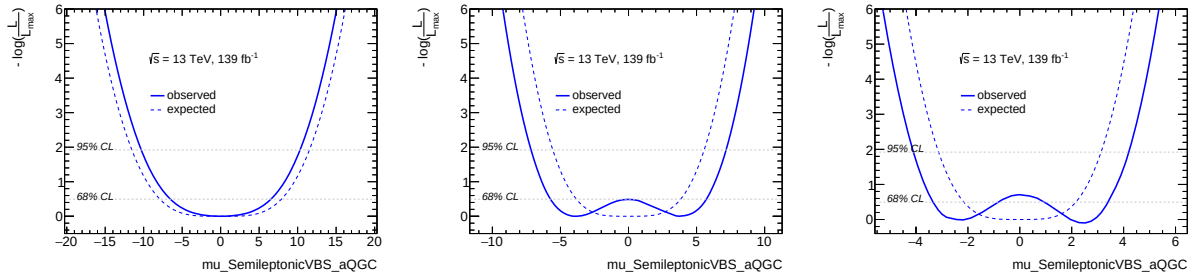


Figure 11.10: The observed log-likelihood curves of FS02 Wilson coefficient where the clipping energy is 1.5 TeV (left), 2.0 TeV (middle), ∞ (right).

low clipping value at 1.5 TeV the feature of having the two local minimums gets mild since there is no signal contribution by clipping in the high-mass bins with data excess. Similar plots for other Wilson coefficients are shown in appendix .3. A μ_{aQGC} value at crossing the 95% confidence interval line and the likelihood curve is used to calculate upper and lower limits on the coefficients. For high clipping values, the observed limit is weaker than the theoretical prediction to conserve the unitarity of the model. Table 11.2 shows the uniterized and ununiterized expected and observed limits from figure 11.12, where uniterized limit is the intersection point of the theoretical unitality bound and experimental limit line, while ununiterized limit is the limit with no clipping energy. Distributions of the obtained limit in each clipping value for other Wilson coefficients are shown in appendix .3.

The ununiterized limits can be compared with the results of other analyses. Compared to the figure 2.7,2.8, 2.9, these results give similar or a little weaker limits compared to the CMS results, which seems due to the difference of the fiducial volume definition. In the ATLAS experiment limits for the same operators are recently derived in $Z(\nu\bar{\nu})\gamma jj$ channel [46] with the luminosity of 139 fb^{-1} . The comparison with their results in observed limits is shown in table 11.3. For the tensor type operators $Z(\nu\bar{\nu})\gamma jj$ channel can get more stringent limits because of its fewer backgrounds. For the mixed type operators, our channel can get similar or better limits due to its larger production cross section despite the larger backgrounds. It is desirable to combine the results of several channels in the future since operators which are sensitive are different between each channel.

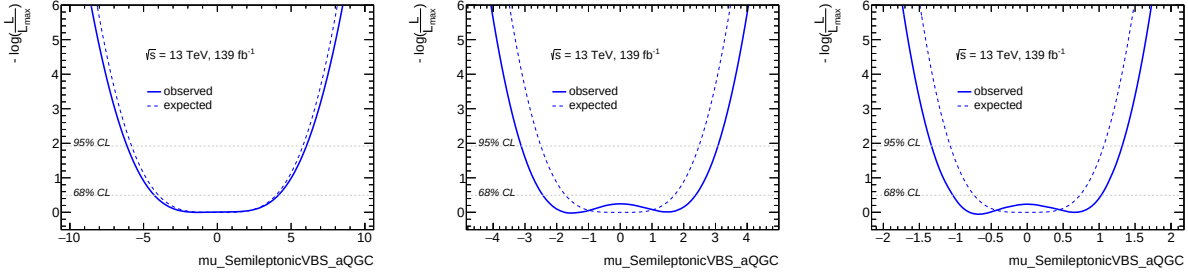


Figure 11.11: The observed log-likelihood curves of FM0 Wilson coefficient where the clipping energy is 1.5 TeV (left), 2.0 TeV (middle), ∞ (right).

	expected limit		observed limit	
Coefficient	uniterized	ununiterized	uniterized	ununiterized
f_{T0}/Λ^4	$[-0.48, 0.39]$ at $[1.99, 2.09]$ TeV	$[-0.16, 0.16]$	$[-1.04, 0.74]$ at $[1.64, 1.78]$ TeV	$[-0.25, 0.23]$
f_{T1}/Λ^4	$[-0.31, 0.31]$ at $[2.65, 2.63]$ TeV	$[-0.19, 0.19]$	$[-0.44, 0.51]$ at $[2.42, 2.33]$ TeV	$[-0.25, 0.25]$
f_{T2}/Λ^4	$[-0.88, 0.90]$ at $[2.26, 2.25]$ TeV	$[-0.41, 0.41]$	$[-1.35, 1.36]$ at $[2.04, 2.03]$ TeV	$[-0.42, 0.52]$
f_{T5}/Λ^4	$[-2.87, 2.36]$ at $[1.50, 1.57]$ TeV	$[-0.53, 0.51]$	$[-3.04, 2.93]$ at $[1.50, 1.50]$ TeV	$[-0.46, 0.62]$
f_{T6}/Λ^4	$[-2.16, 2.19]$ at $[1.69, 1.77]$ TeV	$[-0.71, 0.68]$	$[-3.13, 2.87]$ at $[1.62, 1.66]$ TeV	$[-0.71, 0.68]$
f_{T7}/Λ^4	$[-7.07, 4.05]$ at $[1.69, 1.91]$ TeV	$[-1.67, 1.50]$	$[-8.39, 6.37]$ at $[1.62, 1.73]$ TeV	$[-1.67, 1.50]$
f_{T8}/Λ^4	—	$[-0.56, 0.56]$	—	$[-0.44, 0.47]$
f_{T9}/Λ^4	—	$[-1.16, 1.18]$	—	$[-1.02, 0.94]$
f_{S02}/Λ^4	$[-5.46, 5.61]$ at $[2.05, 2.07]$ TeV	$[-3.27, 3.32]$	$[-7.53, 7.80]$ at $[1.91, 1.90]$ TeV	$[-3.45, 4.19]$
f_{S1}/Λ^4	—	$[-6.70, 6.74]$	—	$[-8.57, 8.57]$
f_{M0}/Λ^4	$[-3.03, 3.03]$ at $[1.92, 1.92]$ TeV	$[-1.06, 1.07]$	$[-1.63, 1.63]$ at $[2.24, 2.24]$ TeV	$[-1.32, 1.31]$
f_{M1}/Λ^4	$[-5.79, 5.80]$ at $[2.31, 2.31]$ TeV	$[-3.04, 3.05]$	$[-8.66, 8.68]$ at $[2.09, 2.09]$ TeV	$[-4.01, 4.07]$
f_{M2}/Λ^4	—	$[-1.57, 1.57]$	—	$[-1.94, 1.94]$
f_{M3}/Λ^4	$[-22.11, 21.80]$ at $[1.59, 1.60]$ TeV	$[-5.02, 5.01]$	$[-22.50, 23.54]$ at $[1.59, 1.57]$ TeV	$[-5.93, 6.00]$
f_{M4}/Λ^4	$[-4.92, 4.90]$ at $[2.13, 2.13]$ TeV	$[-2.36, 2.45]$	$[-6.27, 6.25]$ at $[2.0, 2.0]$ TeV	$[-3.10, 3.10]$
f_{M5}/Λ^4	$[-6.39, 6.39]$ at $[2.37, 2.37]$ TeV	$[-3.62, 3.62]$	$[-8.72, 8.74]$ at $[2.19, 2.19]$ TeV	$[-4.60, 4.61]$
f_{M7}/Λ^4	$[-8.74, 8.41]$ at $[2.48, 2.50]$ TeV	$[-4.99, 4.88]$	$[-13.62, 13.13]$ at $[2.22, 2.24]$ TeV	$[-6.75, 6.62]$

Table 11.2: Uniterized and ununiterized expected limits and observed limits. Uniterized limit is the intersection point of the theoretical unitarity bound and experimental limit line. Ununiterized limit is the limit with no clipping energy, labeled as ∞ in figure 11.12. Operator FT8, FT9, FS1, FM2 don't have the uniterized limits, since the theoretical unitarity bounds still have more stringent limits.

Coefficient	Observed limit $[\text{TeV}^{-4}]$ ($Z(\nu\bar{\nu})\gamma jj$)	Observed limit $[\text{TeV}^{-4}]$ (EW VV+ jj semi-lep)
f_{T0}/Λ^4	$[-9.4, 8.4] \times 10^{-2}$	$[-25, 23] \times 10^{-2}$
f_{T5}/Λ^4	$[-8.8, 9.9] \times 10^{-2}$	$[-46, 62] \times 10^{-2}$
f_{T8}/Λ^4	$[-5.9, 5.9] \times 10^{-2}$	$[-44, 47] \times 10^{-2}$
f_{T9}/Λ^4	$[-1.3, 1.3] \times 10^{-1}$	$[-10.2, 9.4] \times 10^{-1}$
f_{M0}/Λ^4	$[-4.6, 4.6]$	$[-1.3, 1.3]$
f_{M1}/Λ^4	$[-7.7, 7.7]$	$[-4.0, 4.0]$
f_{M2}/Λ^4	$[-1.9, 1.9]$	$[-1.9, 1.9]$

Table 11.3: Comparison of the observed limits derived in $Z(\nu\bar{\nu})\gamma jj$ channel and the EW VV+ jj semi-leptonic channel. Uniterization is not preserved.

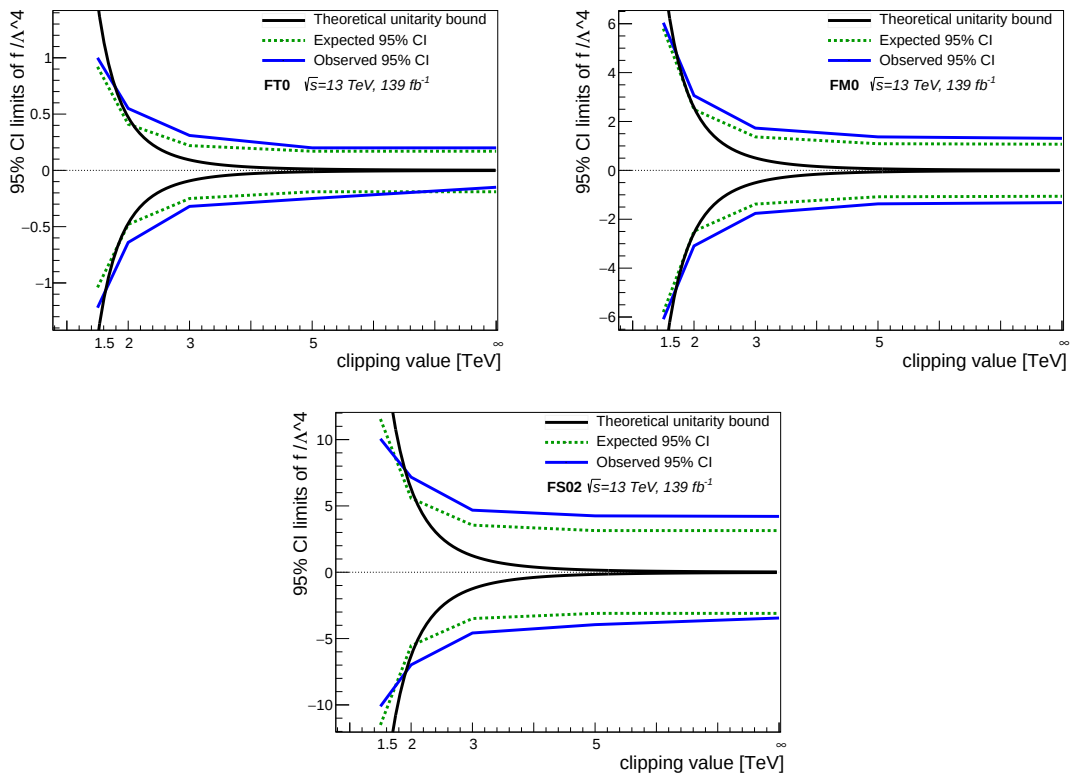


Figure 11.12: Expected limits (green) and observed limits (blue) for 5 clipping points are shown for each Wilson coefficient FT0 (left), FM0 (right), FS02 (middle). The black line is the theoretical unitarity bound.

Chapter 12

Conclusions

In this thesis, the vector boson scattering (VBS) in semileptonic final states is studied as the production of a pair of vector bosons associated with a pair of forward jets (EW VV+ jj).

The study is performed using the full Run-2 dataset collected by the ATLAS detector during 2015 to 2018, corresponding to an integrated luminosity of 139 fb^{-1} . The analysis resulted in a measured signal strength of $\mu_{obs} = 0.98_{-0.09}^{+0.09}(\text{Stat})_{-0.18}^{+0.21}(\text{Syst})$. The background-only hypothesis is rejected with an observed (expected) significance of 5.9 (6.5) σ , therefore claiming the observation of the EW VV+ jj signal in semileptonic final state. Compared to the previous analysis with an integrated luminosity of 35.5 fb^{-1} [37], the significance is improved from 2.7 (2.5) to 5.9 (6.5). Extrapolating the luminosity from 35.5 fb^{-1} to 139 fb^{-1} gives a naive estimation of the significance of about 4 σ . The significant improvements to push for more than 5 σ can be attributed to several reasons; the updated jet reconstruction using PFlow algorithm, and the updated W/Z boson tagger using 3-variables instead of 2-variables (mass and D2 requirements) previously. The multivariate analysis based on the RNN also took a role to have the improvement over the previous round of analysis. These updates related to the jet reconstruction and selection are validated well in terms of the background modeling and the fitting in this thesis. The signal strength is used to obtain the fiducial cross section. The fiducial cross section is observed to be $13.3_{-2.72}^{+2.99} \text{ fb}$. The measurement of EW VV+ jj processes is consistent with the SM prediction, hence the results are interpreted as limits on coefficients of the dimension-8 EFT operators.

The LHC-ATLAS experiment has started acquiring data again after a hiatus of about three years for upgrades. Further data to be acquired, together with data from the planned high-luminosity LHC experiment, will enable a more detailed study and this process will continue to be studied. The research methods of this study will serve as a springboard for future research. The main limitations in the current analysis lie in the large systematic uncertainty related to the V+jets sample mismodeling. This mismodeling is expected to be corrected in the future hence the improvement of the significance by reducing the dedicated uncertainties is expected.

For the SM measurement, now that this process is measured with a significance more than 5 σ , future directions of analysis could include boson polarization study since longitudinally polarized bosons give more detailed information about the EWSB. In addition, for the aQGC search, the limits in the EFT signal presented in this study are going to be updated with more statistics in the

future. Obtained limits should be interpreted in conjunction with the results of other processes, which will be discussed and developed in future studies. Now the limits are obtained one-by-one basis, it is important to study the correlation between the two parameters to get information about what kind of models we need to investigate theoretically, taking the results of the EFT studies.

Appendices

.1 RNN training setups

A scheme of the architecture is reported in figure 1 and some technical details are in table 1.

Epochs	200 but EarlyStopping Callback after 10 unchanged iterations
Dropout	0.3
LSTM Layer Activation	<i>tanh</i>
Output Layer activation	Sigmoid
LSTM layers	2
Optimiser	Adam
Train:Test:Validation set	56 : 30 : 14%

Table 1: Technical setup of the RNN architecture. “LSTM” stands for long short-term memory, an RNN architecture for deep learning.

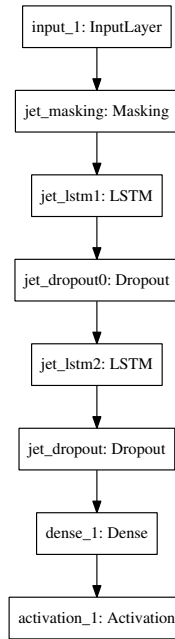


Figure 1: RNN architecture scheme.

In addition to the small-R jets information we decided to add large-R jet candidate information to further enhance the separation in the merged category; this addition is related only to the hadronically decaying boson part ($W/Z \rightarrow qq$) of the signal event topology, it is not adding anything more about the forward jets of the VBS signature. The extra large-R information is, indeed, just completing the set of information related to the VBS jets and the V-hadronic decay; in this way, the combined RNN-DNN network is able to exploit the correlation across the VBS jets and the V-hadronic of the signal topology. The resulting architecture is schematically shown in Figure 2.

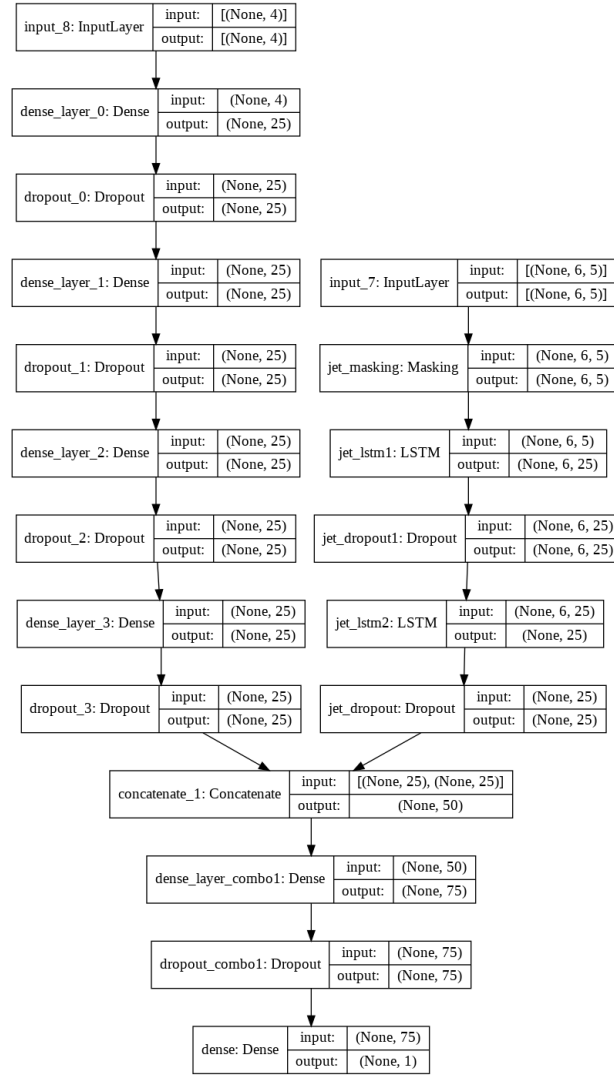


Figure 2: Model architecture for the combined DNN + RNN based model used for the merged category.

.2 All systematics

All experimental systematics used for the analysis is listed.

Source	Description	Analysis Name
Small-R Jets	the scale of forward jets w.r.t. central jets	JET_CR_JET_BJES_Response
Small-R Jets		JET_CR_JET_EffectiveNP_Detector1
Small-R Jets		JET_CR_JET_EffectiveNP_Detector2
Small-R Jets		JET_CR_JET_EffectiveNP_Mixed1
Small-R Jets		JET_CR_JET_EffectiveNP_Mixed2
Small-R Jets		JET_CR_JET_EffectiveNP_Mixed3
Small-R Jets		JET_CR_JET_EffectiveNP_Modelling1
Small-R Jets		JET_CR_JET_EffectiveNP_Modelling2
Small-R Jets		JET_CR_JET_EffectiveNP_Modelling3
Small-R Jets		JET_CR_JET_EffectiveNP_Modelling4
Small-R Jets		JET_CR_JET_EffectiveNP_Statistical1
Small-R Jets		JET_CR_JET_EffectiveNP_Statistical2
Small-R Jets		JET_CR_JET_EffectiveNP_Statistical3
Small-R Jets		JET_CR_JET_EffectiveNP_Statistical4
Small-R Jets		JET_CR_JET_EffectiveNP_Statistical5
Small-R Jets		JET_CR_JET_EffectiveNP_Statistical6
Small-R Jets		JET_CR_JET_Flavor_Composition
Small-R Jets		JET_CR_JET_Flavor_Response
Small-R Jets		JET_CR_JET_Pileup_OffsetMu
Small-R Jets		JET_CR_JET_Pileup_OffsetNPV
Small-R Jets		JET_CR_JET_Pileup_PtTerm
Small-R Jets		JET_CR_JET_Pileup_RhoTopology
Small-R Jets		JET_CR_JET_PunchThrough_MC16
Small-R Jets		JET_CR_JET_SingleParticle_HighPt
Small-R Jets		JET_CR_JET_EtaIntercalibration_TotalStat
Small-R Jets		JET_CR_JET_EtaIntercalibration_Modelling
Small-R Jets		JET_CR_JET_EtaIntercalibration_NonClosure_highE
Small-R Jets		JET_CR_JET_EtaIntercalibration_NonClosure_negEta
Small-R Jets		JET_CR_JET_EtaIntercalibration_NonClosure_posEta
Small-R Jets	JER	JET_CR_JET_JER_DataVsMC
Small-R Jets	JER	JET_CR_JET_JER_EffectiveNP_1
Small-R Jets	JER	JET_CR_JET_JER_EffectiveNP_2
Small-R Jets	JER	JET_CR_JET_JER_EffectiveNP_3
Small-R Jets	JER	JET_CR_JET_JER_EffectiveNP_4
Small-R Jets	JER	JET_CR_JET_JER_EffectiveNP_5
Small-R Jets	JER	JET_CR_JET_JER_EffectiveNP_6
Small-R Jets	JER	JET_CR_JET_JER_EffectiveNP_7restTerm

Source	Description	Analysis Name
Large-R Jets	scale	FATJET_Medium_JET_Rtrk_Baseline_pT
Large-R Jets	scale	FATJET_Medium_JET_Rtrk_Modelling_pT
Large-R Jets	scale	FATJET_Medium_JET_Rtrk_TotalStat_pT
Large-R Jets	scale	FATJET_Medium_JET_Rtrk_Tracking_pT
Large-R Jets	scale	FATJET_BJT_JET_EtaIntercalibration_Modelling
Large-R Jets	scale	FATJET_BJT_JET_Flavor_Composition
Large-R Jets	scale	FATJET_BJT_JET_Flavor_Response
Large-R Jets	Mass resolution	FATJET_JMR
Large-R Jets	JER	FATJET_JER

Table 2: Qualitative summary of the systematic uncertainties included in this analysis.

Source	Description	Analysis Name
Luminosity	LumiNP	ATLAS_LUMI_2015_2018
Pileup reweighting	PRW_DATASF	PRW_DATASF

Source	Description	Analysis Name
Electrons	Energy scale	EG_SCALE_ALL
Electrons	Energy resolution	EG_RESOLUTION_ALL
Electrons	Trigger	EL_EFF_Trigger_TOTAL_1NPCOR_PLUS_UNCOR
Electrons	ID efficiency SF	EL_EFF_ID_TOTAL_1NPCOR_PLUS_UNCOR
Electrons	Isolation efficiency SF	EL_EFF_Iso_TOTAL_1NPCOR_PLUS_UNCOR
Electrons	Reconstruction efficiency SF	EL_EFF_Reco_TOTAL_1NPCOR_PLUS_UNCOR
Muons	scale	MUONS_SCALE
Muons	scale (charge dependent)	MUON_SAGITTA_RHO
Muons	scale (charge dependent)	MUON_SAGITTA_RESBIAS
Muons	resolution MS	MUONS_MS
Muons	resolution ID	MUONS_ID
Muons	Isolation efficiency SF	MUON_ISO_SYS
Muons	Isolation efficiency SF	MUON_ISO_STAT
Muons	Muon reco & ID efficiency SF	MUONS_EFF_STAT
Muons	Muon reco & ID efficiency SF	MUONS_EFF_STAT_LOWPT
Muons	Muon reco & ID efficiency SF	MUONS_EFF_SYST
Muons	Muon reco & ID efficiency SF	MUONS_EFF_SYST_LOWPT
Muons	Track-to-vertex association efficiency SF	MUON_TTVA_SYS
Muons	Track-to-vertex association efficiency SF	MUON_TTVA_STAT
MET	Soft term	MET_SoftTrk_ResoPerp
MET	Soft term	MET_SoftTrk_ResoPara
MET	Soft term	MET_SoftTrk_Scale

Table 3: Qualitative summary of the systematic uncertainties included in this analysis.

Source	Description	Analysis Name
B-tagging	Flavor tagging scale factors	FT_EFF_Eigen_B_0_AntiKt4PFlowJets
B-tagging	Flavor tagging scale factors	FT_EFF_Eigen_B_1_AntiKt4PFlowJets
B-tagging	Flavor tagging scale factors	FT_EFF_Eigen_B_2_AntiKt4PFlowJets
B-tagging	Flavor tagging scale factors	FT_EFF_Eigen_C_0_AntiKt4PFlowJets
B-tagging	Flavor tagging scale factors	FT_EFF_Eigen_C_1_AntiKt4PFlowJets
B-tagging	Flavor tagging scale factors	FT_EFF_Eigen_C_2_AntiKt4PFlowJets
B-tagging	Flavor tagging scale factors	FT_EFF_Eigen_C_3_AntiKt4PFlowJets
B-tagging	Flavor tagging scale factors	FT_EFF_Eigen_Light_0_AntiKt4PFlowJets
B-tagging	Flavor tagging scale factors	FT_EFF_Eigen_Light_1_AntiKt4PFlowJets
B-tagging	Flavor tagging scale factors	FT_EFF_Eigen_Light_2_AntiKt4PFlowJets
B-tagging	Flavor tagging scale factors	FT_EFF_Eigen_Light_3_AntiKt4PFlowJets
B-tagging	Flavor tagging scale factors	FT_EFF_extrapolation_AntiKt4PFlowJets
B-tagging	Flavor tagging scale factors	FT_EFF_extrapolation_from_charm_AntiKt4PFlowJets

Table 4: Qualitative summary of the systematic uncertainties included in this analysis.

.3 aQGC fitting results for all Wilson coefficient

The detailed plots for all the Wilson coefficients are shown here. All diboson invariant mass (m_{VV}) distributions in HP SR for quadratic term and interference term are shown in figure 3 to figure 5.

All log-likelihood distributions are shown in figure 6 to figure 22.

All expected and observed limits are shown in figure 23, 24, 25.

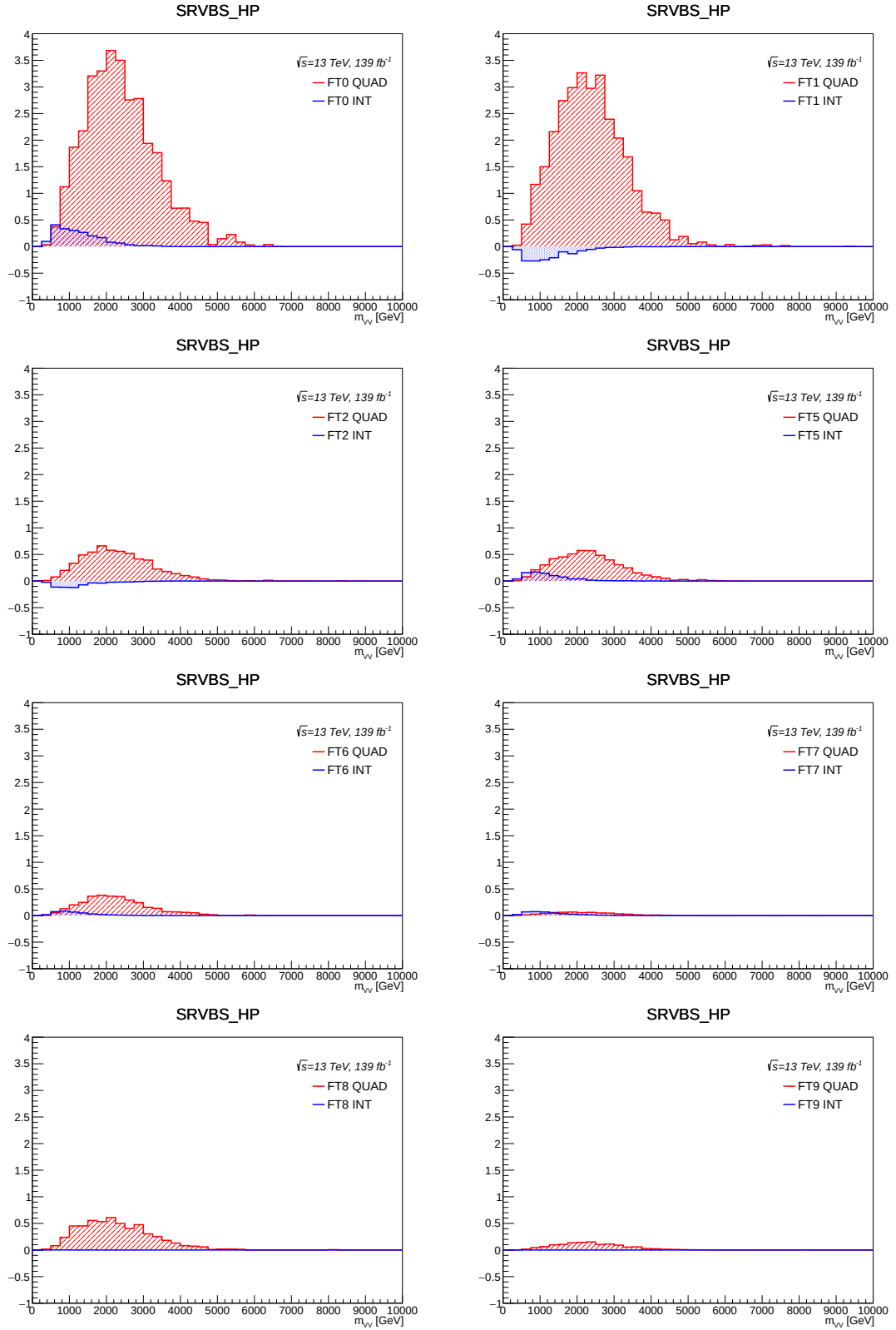


Figure 3: The comparison of the quadratic term and the interference term with FT0 (top left), FS02 (top right), and FM0 (bottom middle) in 2-lepton channel HP SR. The contribution of the interference term can be negative, and it is larger in FS terms.

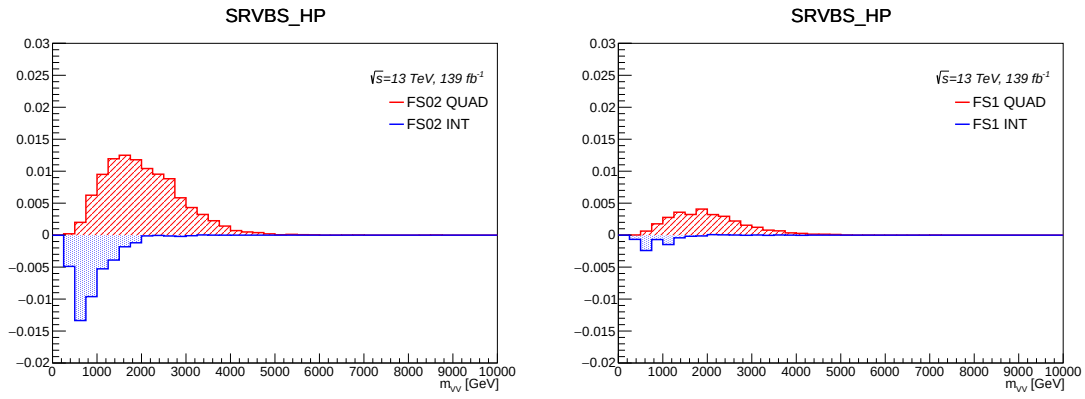


Figure 4: The comparison of the quadratic term and the interference term with FT0 (top left), FS02 (top right), and FM0 (bottom middle) in 2-lepton channel HP SR. The contribution of the interference term can be negative, and it is larger in FS terms.

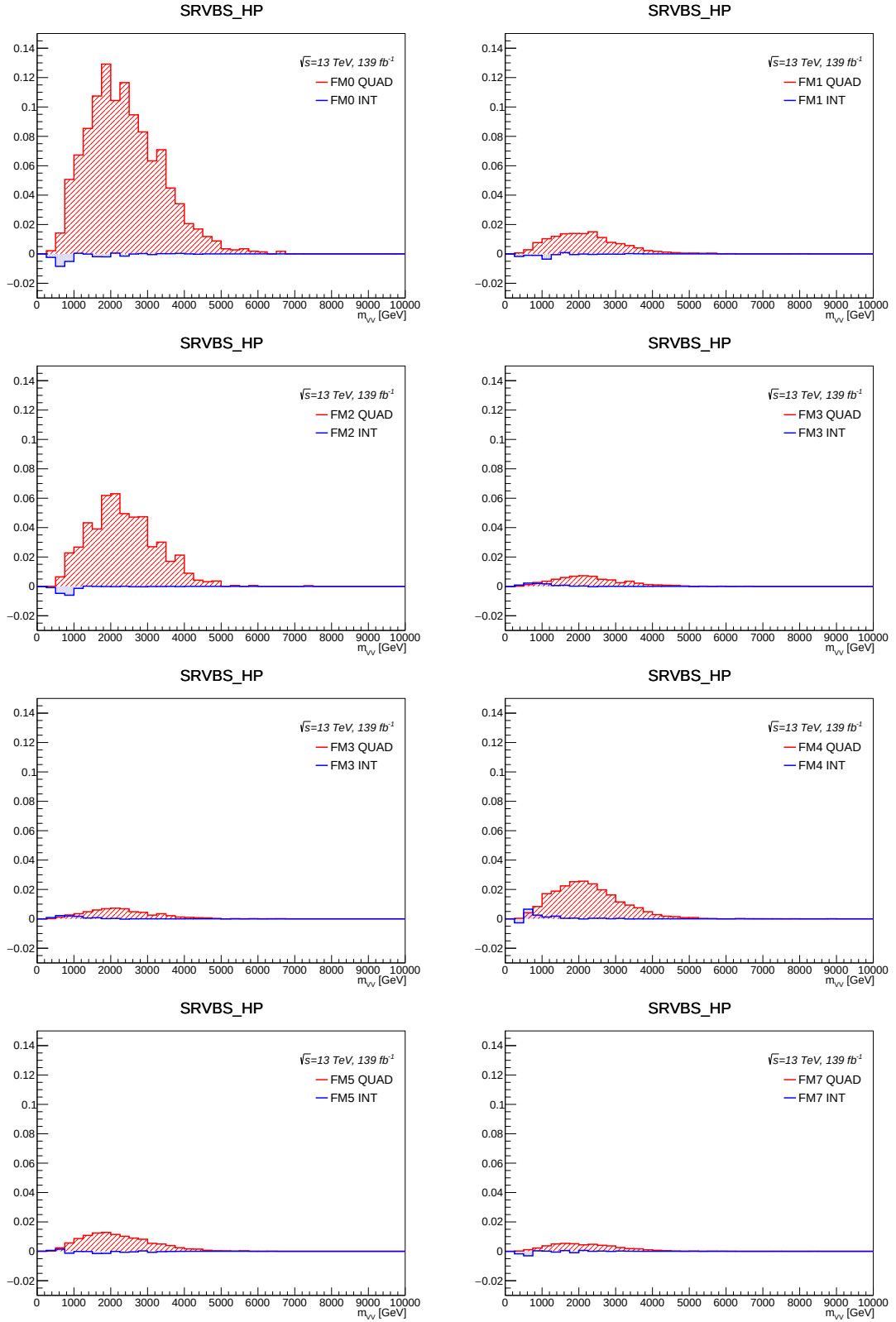


Figure 5: The comparison of the quadratic term and the interference term with FT0 (top left), FS02 (top right), and FM0 (bottom middle) in 2-lepton channel HP SR. The contribution of the interference term can be negative, and it is larger in FS terms.

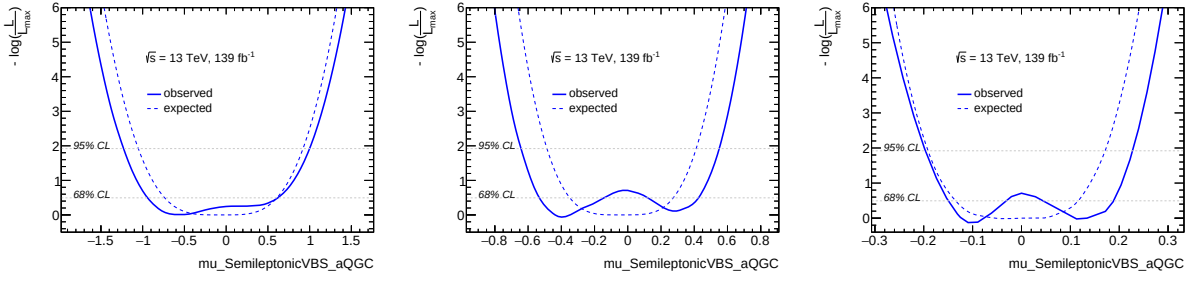


Figure 6: The observed log-likelihood curves of FT0 Wilson coefficient where the clipping energy is 1.5 TeV (left), 2.0 TeV (middle), ∞ (right).

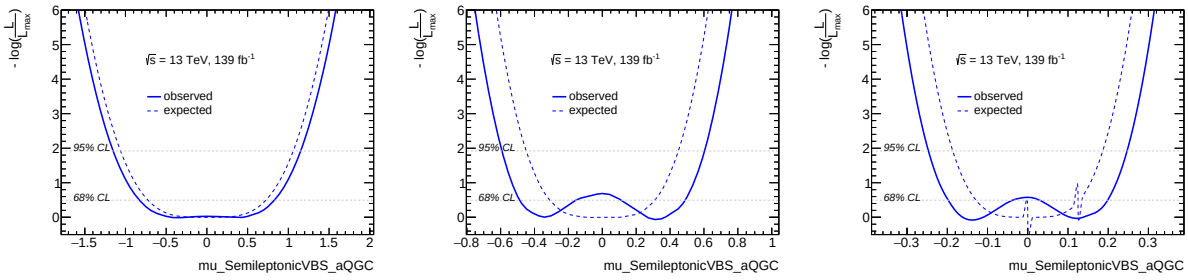


Figure 7: The observed log-likelihood curves of FT1 Wilson coefficient where the clipping energy is 1.5 TeV (left), 2.0 TeV (middle), ∞ (right).

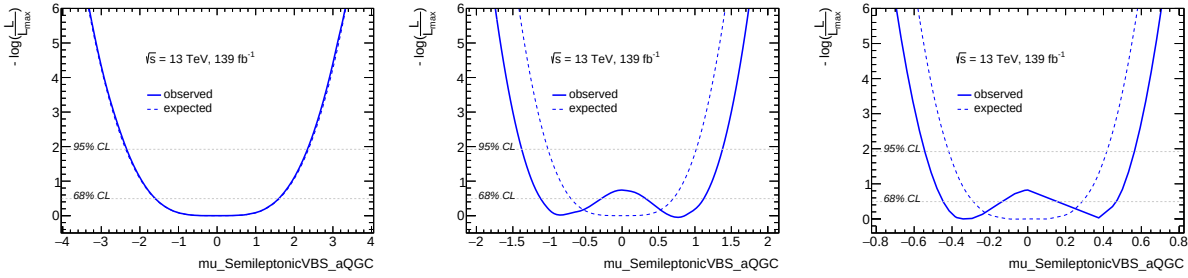


Figure 8: The observed log-likelihood curves of FT2 Wilson coefficient where the clipping energy is 1.5 TeV (left), 2.0 TeV (middle), ∞ (right).

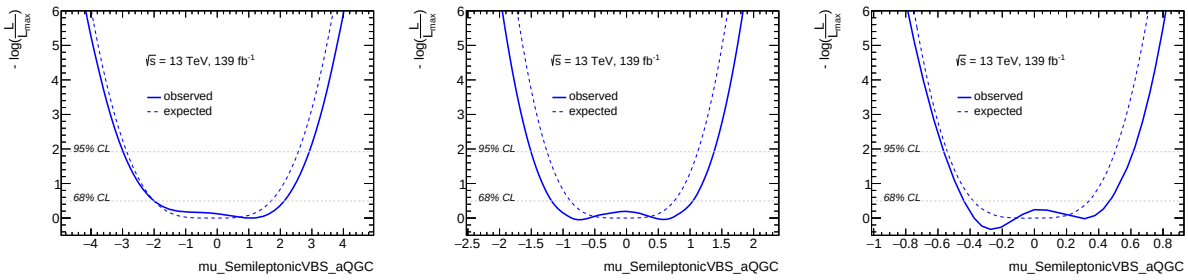


Figure 9: The observed log-likelihood curves of FT5 Wilson coefficient where the clipping energy is 1.5 TeV (left), 2.0 TeV (middle), ∞ (right).

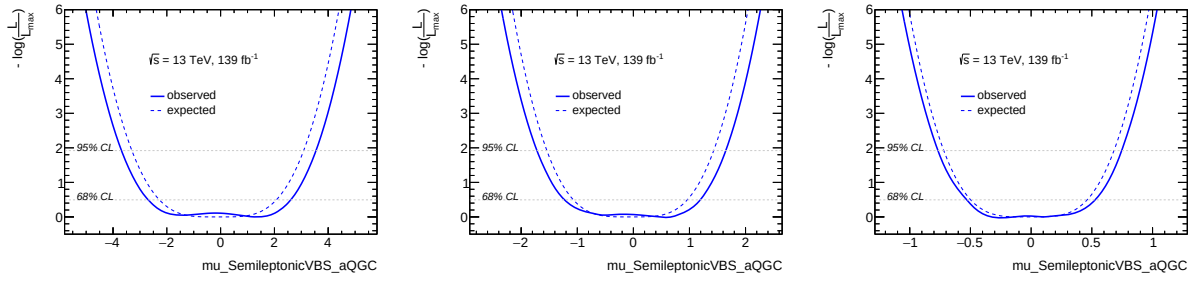


Figure 10: The observed log-likelihood curves of FT6 Wilson coefficient where the clipping energy is 1.5 TeV (left), 2.0 TeV (middle), ∞ (right).

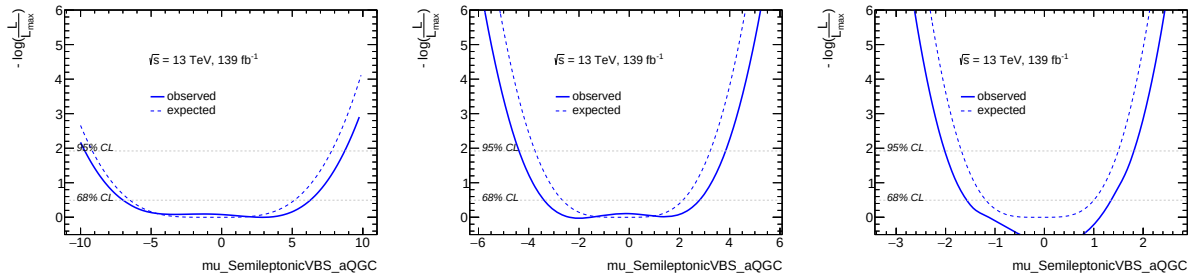


Figure 11: The observed log-likelihood curves of FT7 Wilson coefficient where the clipping energy is 1.5 TeV (left), 2.0 TeV (middle), ∞ (right).

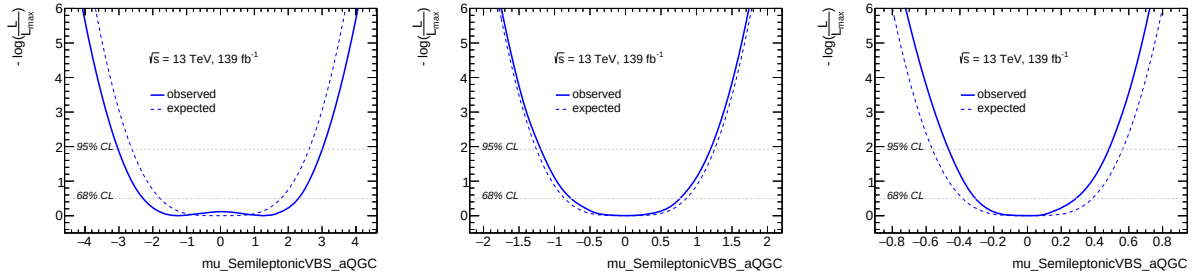


Figure 12: The observed log-likelihood curves of FT8 Wilson coefficient where the clipping energy is 1.5 TeV (left), 2.0 TeV (middle), ∞ (right).

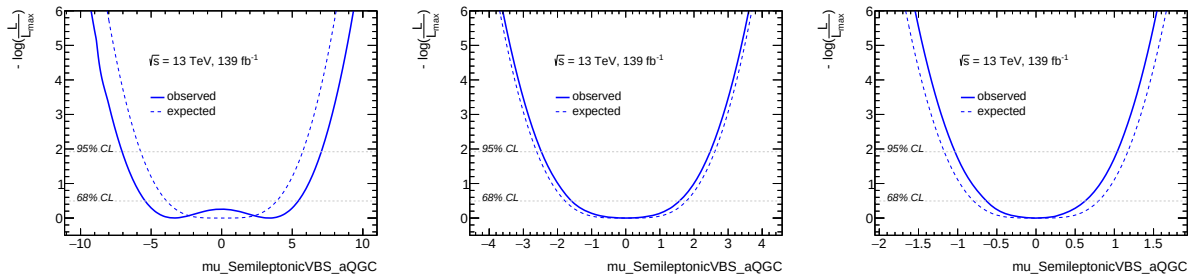


Figure 13: The observed log-likelihood curves of FT9 Wilson coefficient where the clipping energy is 1.5 TeV (left), 2.0 TeV (middle), ∞ (right).

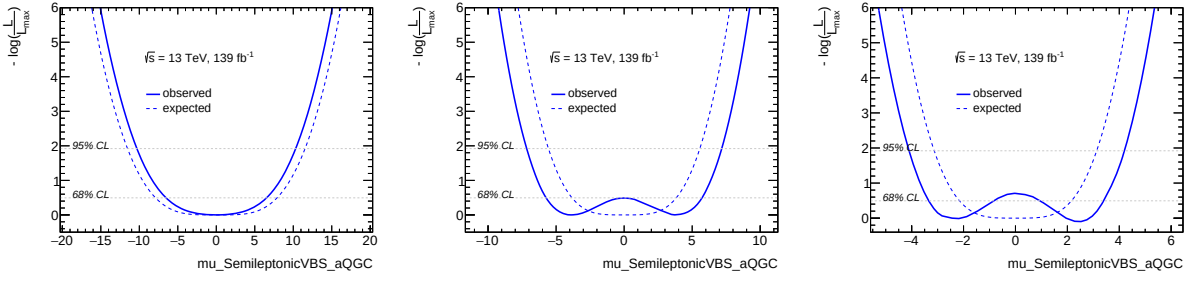


Figure 14: The observed log-likelihood curves of FS02 Wilson coefficient where the clipping energy is 1.5 TeV (left), 2.0 TeV (middle), ∞ (right).

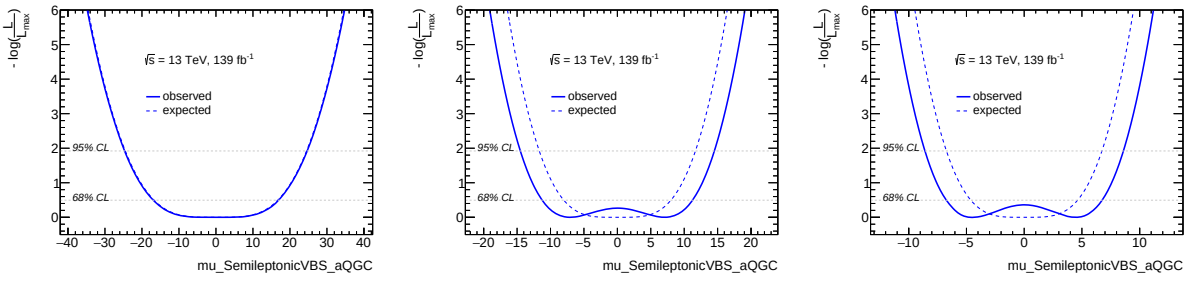


Figure 15: The observed log-likelihood curves of FS1 Wilson coefficient where the clipping energy is 1.5 TeV (left), 2.0 TeV (middle), ∞ (right).

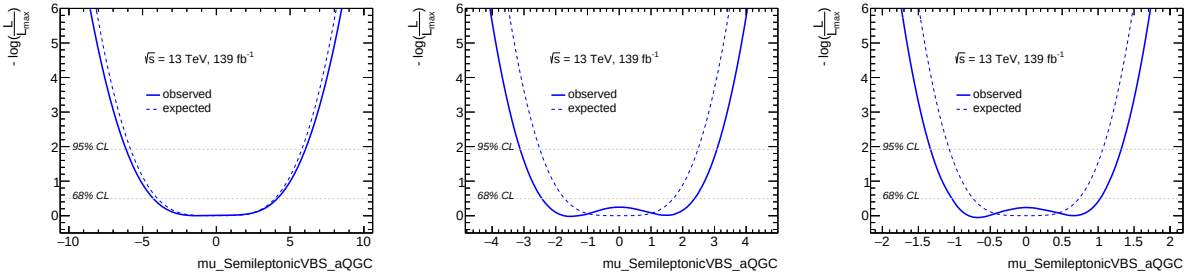


Figure 16: The observed log-likelihood curves of FM0 Wilson coefficient where the clipping energy is 1.5 TeV (left), 2.0 TeV (middle), ∞ (right).

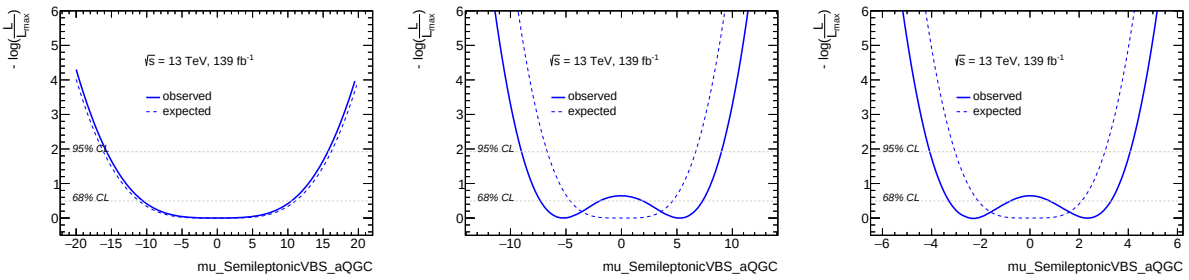


Figure 17: The observed log-likelihood curves of FM1 Wilson coefficient where the clipping energy is 1.5 TeV (left), 2.0 TeV (middle), ∞ (right).

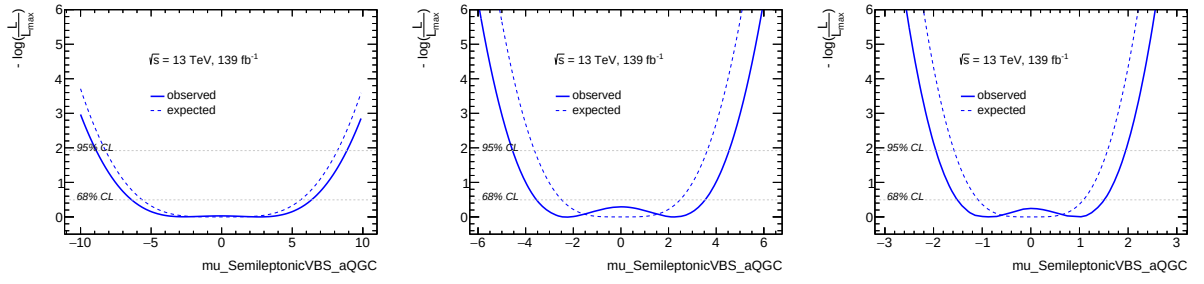


Figure 18: The observed log-likelihood curves of FM2 Wilson coefficient where the clipping energy is 1.5 TeV (left), 2.0 TeV (middle), ∞ (right).

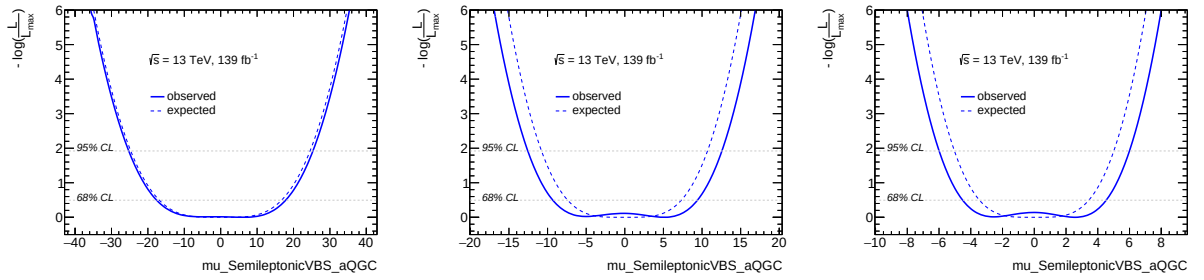


Figure 19: The observed log-likelihood curves of FM3 Wilson coefficient where the clipping energy is 1.5 TeV (left), 2.0 TeV (middle), ∞ (right).

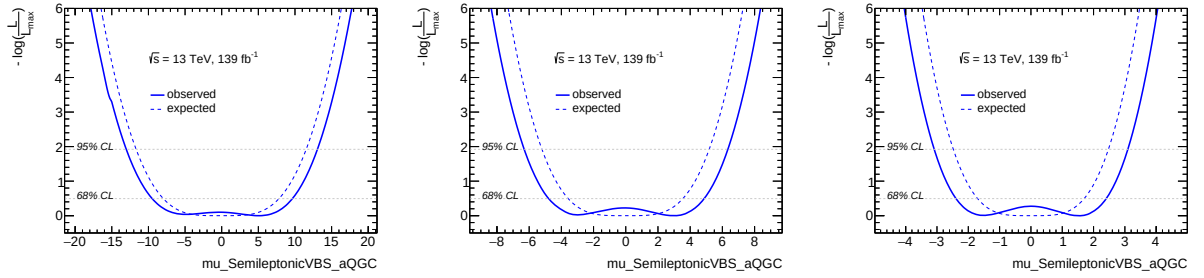


Figure 20: The observed log-likelihood curves of FM4 Wilson coefficient where the clipping energy is 1.5 TeV (left), 2.0 TeV (middle), ∞ (right).

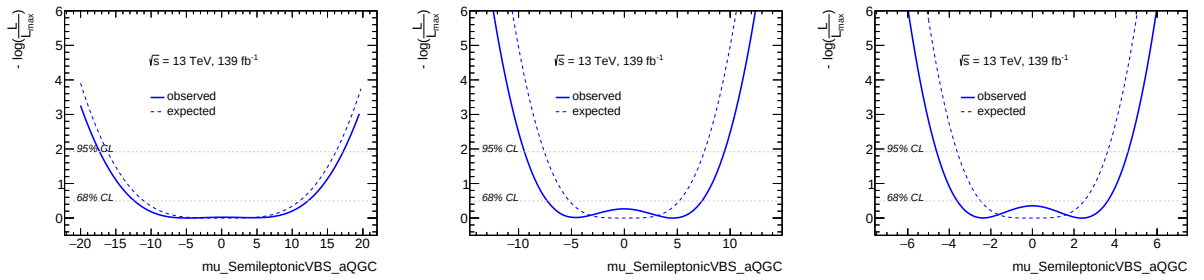


Figure 21: The observed log-likelihood curves of FM5 Wilson coefficient where the clipping energy is 1.5 TeV (left), 2.0 TeV (middle), ∞ (right).

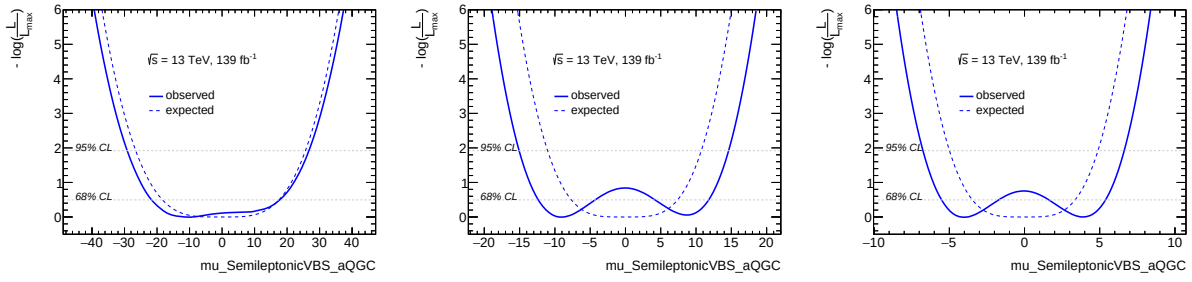


Figure 22: The observed log-likelihood curves of FM7 Wilson coefficient where the clipping energy is 1.5 TeV (left), 2.0 TeV (middle), ∞ (right).

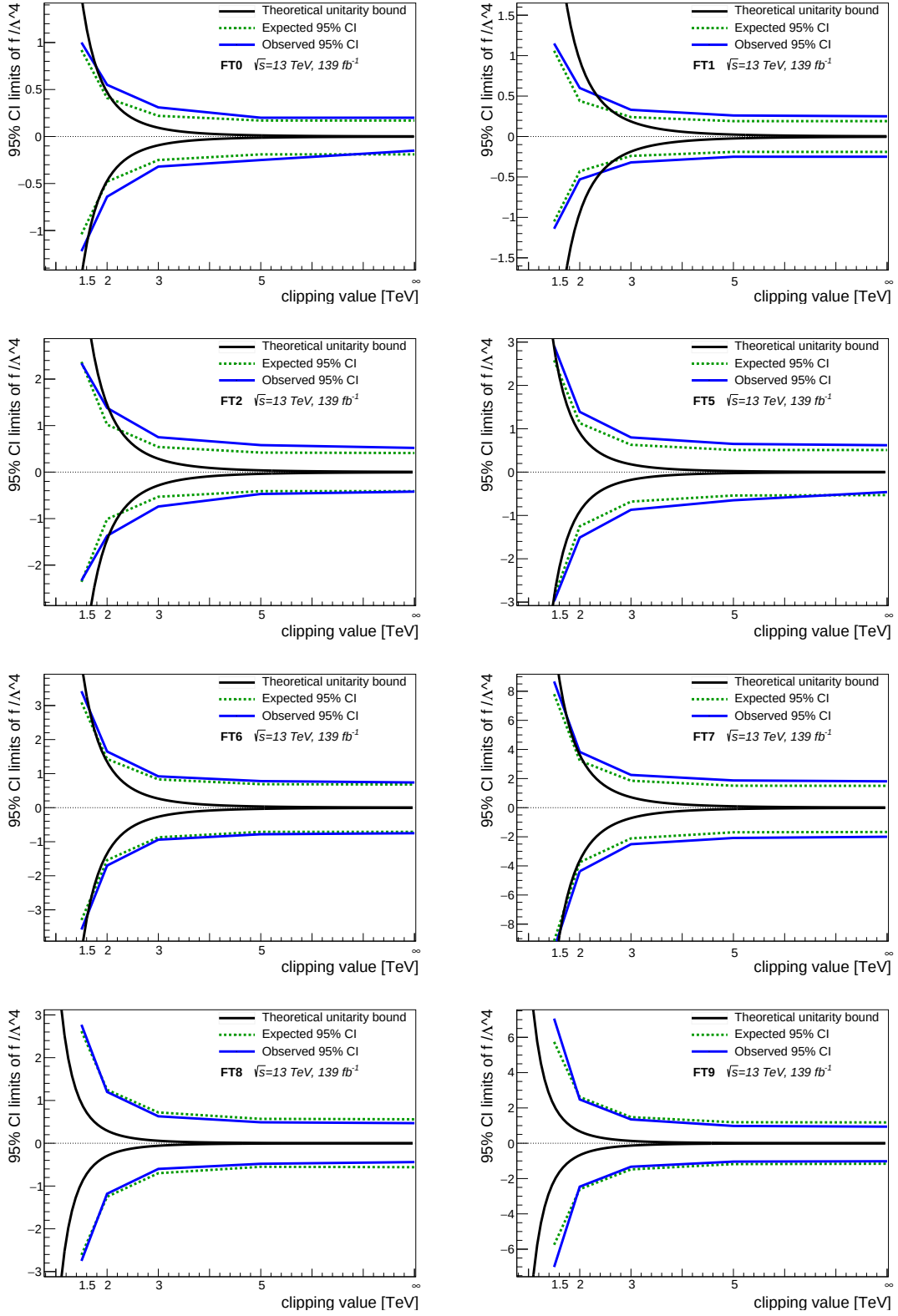


Figure 23: Expected limits (green) and observed limits (blue) for 5 clipping points are shown for each Wilson coefficient of FT-type. The black line is the theoretical unitarity bound.

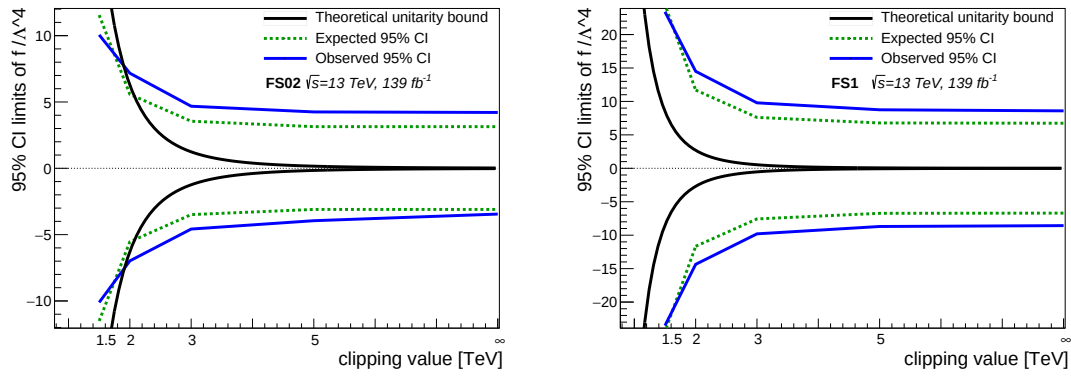


Figure 24: Expected limits (green) and observed limits (blue) for 5 clipping points are shown for each Wilson coefficient of FS-type. The black line is the theoretical unitarity bound.

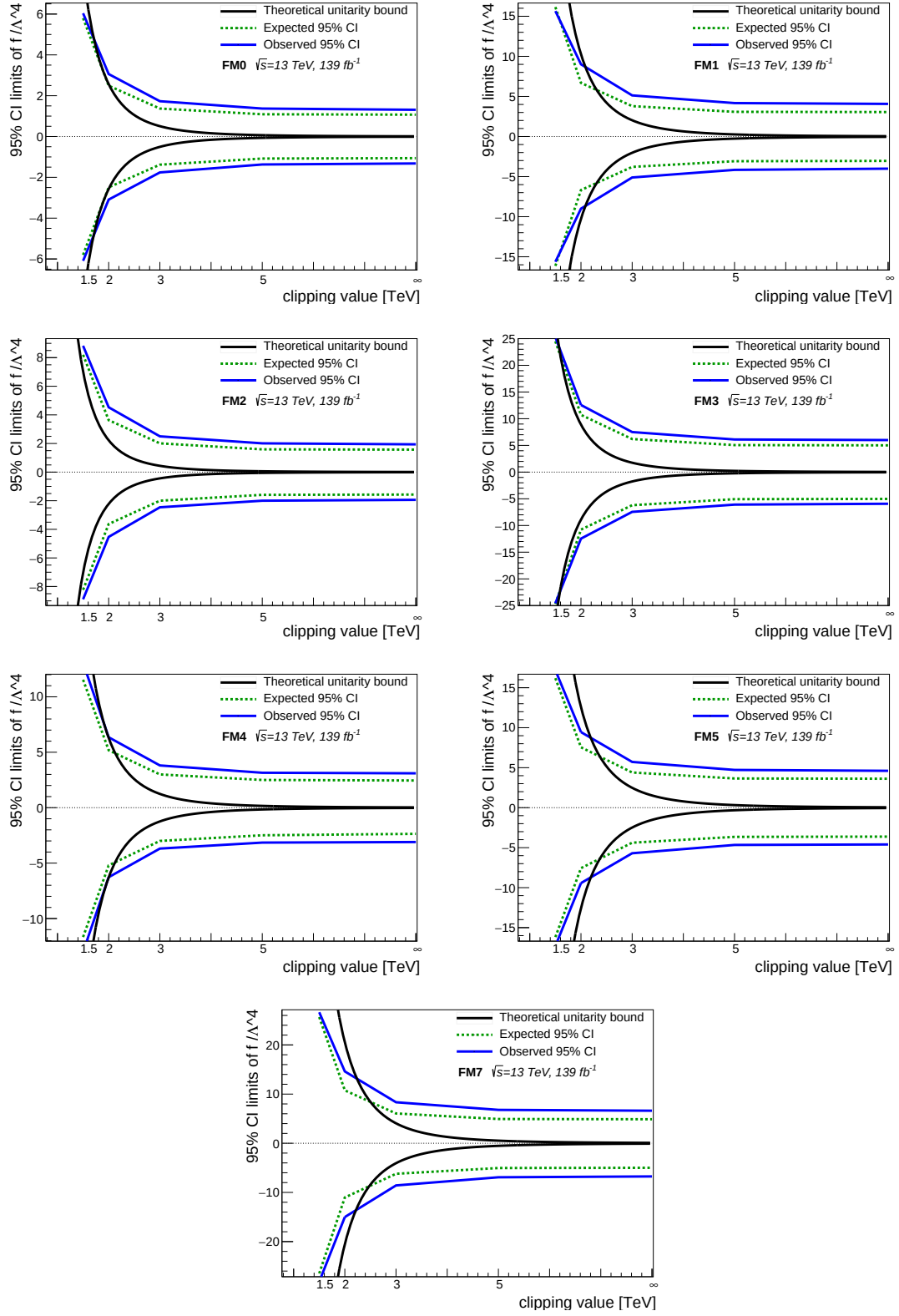


Figure 25: Expected limits (green) and observed limits (blue) for 5 clipping points are shown for each Wilson coefficient of FM-type. The black line is the theoretical unitarity bound.

.4 Fix on the cross-checking plots and its impact

There were some significant discrepancies in the background modeling in the validation plot in the 1-lepton V+jet merged CR in figure 26 and in 1-lepton merged LP SR in figure 33. Though both plots are not used as inputs for the final fitting, some exercises have been done to fix these validation plots and see their impact on the final results.

Several changes are applied to fix these discrepancies;

- Fixed the reweighting in the 1-lepton channel (It was not applied in the CRs before)
- $t\bar{t}$ modeling systematics has fixed
- De-correlated modelling W/Z + jets systematics across merged/resolved categories
- De-correlated QCD theory systematics across merged/resolved categories and lepton channels
- Finer binning in the V+jets CRs in the all control regions

The similar plots in the chapter 10 with these changes are shown. The large discrepancy that existed in the 1-lepton V+jet merged CR disappeared, mainly due to the de-correlation of the modelling systematics uncertainty across the merged/resolved regions, as shown in figure 26. The discrepancy that existed in the 1-lepton merged LP SR disappeared, due to the fixing of the reweighting in the 1-lepton channel, as shown in figure 33.

As shown in figure 35, the observed value of combined μ_{obs} matches within the uncertainty with the one in the body of this thesis, shown in figure 10.15. The 2-lepton results have changed within uncertainty from 1.01 to 1.50, which seems to be due to decorrelating the QCD theory systematics across the lepton channels. However the result of this thesis is the combined value of μ_{obs} , and it is confirmed that by these changes to fix the discrepancy in the validation plots don't change the final result. Observed significance is 5.88 with these fixes, which didn't change a lot.

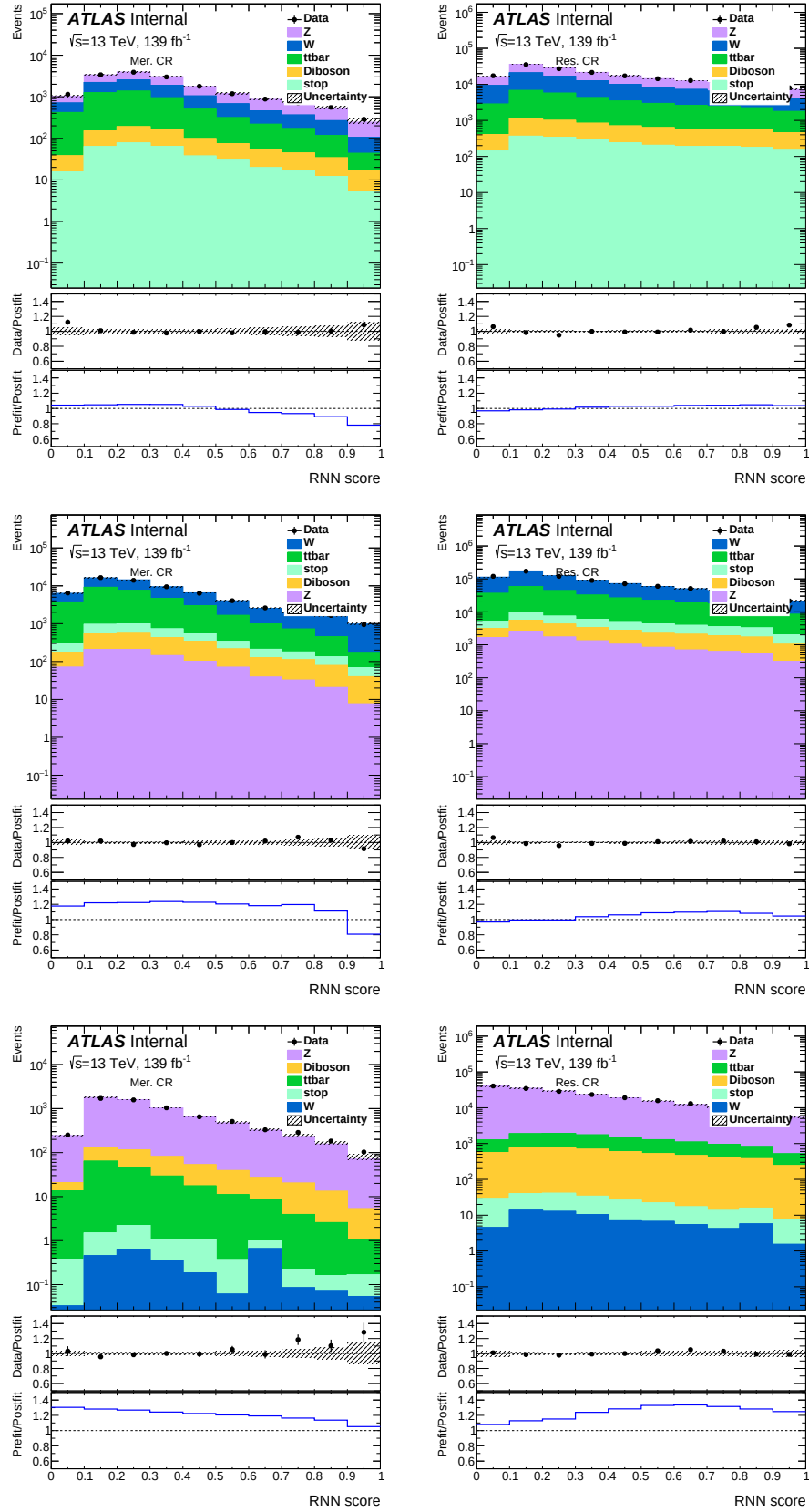


Figure 26: Post-fit RNN score distributions in merged CR (left) and in resolved CR (right) in the 0-lepton channel (top), the 1-lepton channel (middle), and the 2-lepton channel (bottom). The comparison of the data and the post-fit expected MC is shown in the middle panel, and the ratio of the pre-fit and the post-fit MC is shown in the bottom panel.

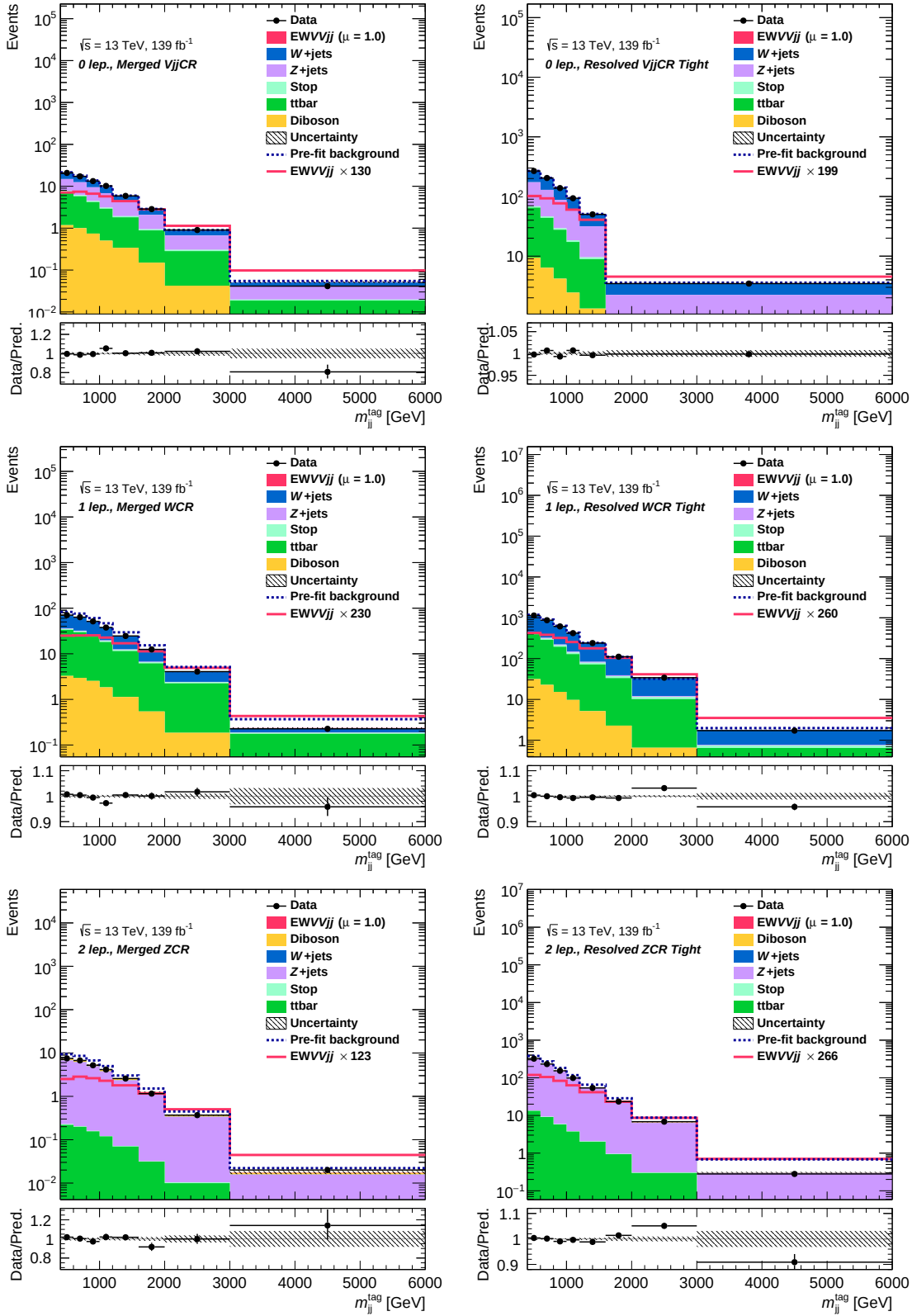


Figure 27: Comparisons of the observed data and expected background distributions of m_{jj}^{tag} in V+jets CRs in the 0-lepton channel (1st line), the 1-lepton channel (2nd line), and the 2-lepton channel (3rd line). The EW VV+ jj signal is filled on top of the fitted backgrounds, normalized to the signal yield extracted from the observed data ($\mu = 1.00$). The bottom panel show the ratio of the observed data to the post fit signal and background predictions.

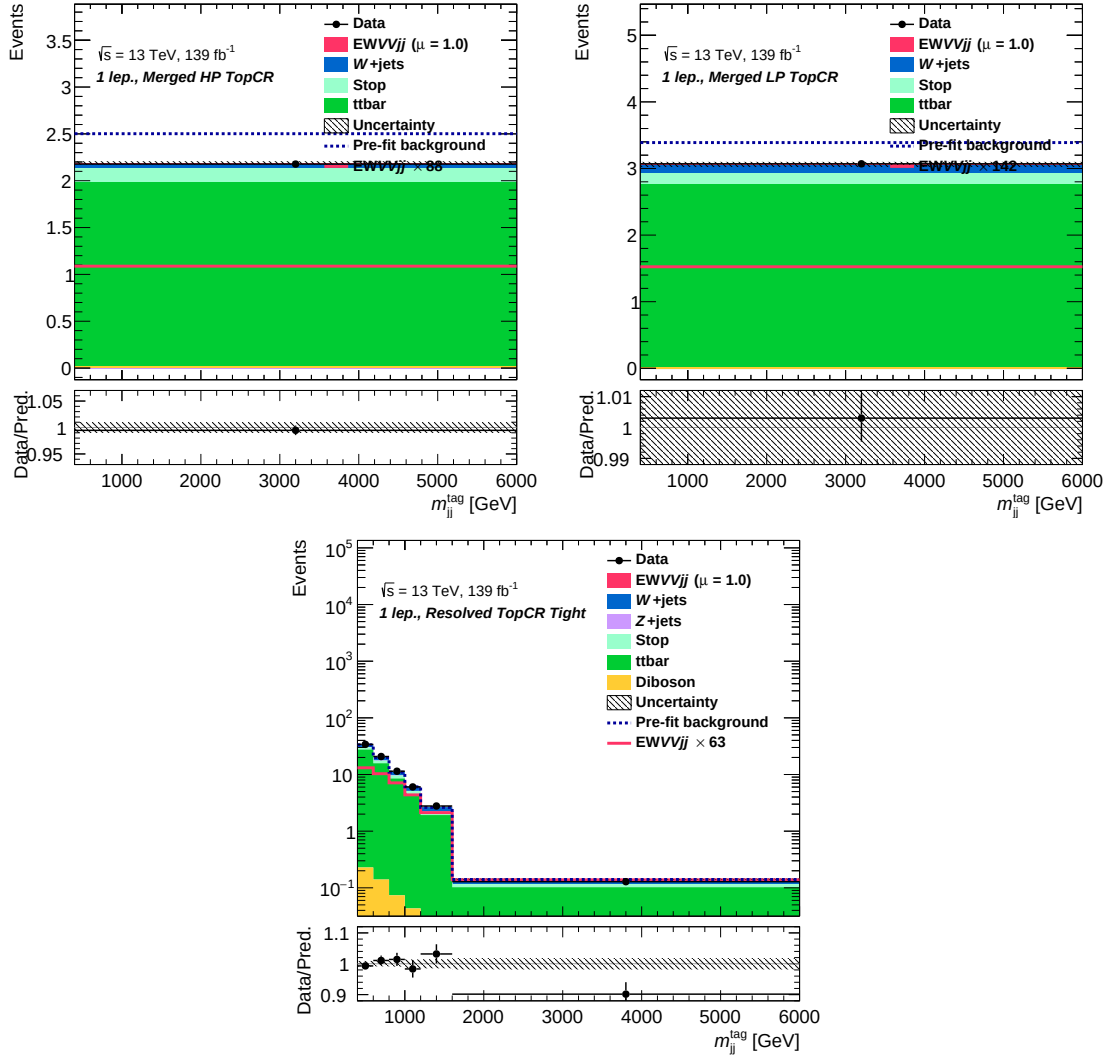


Figure 28: Comparisons of the observed data and expected background distributions of m_{jj}^{tag} in Top CRs in the 1-lepton channel. The EW VV+ jj signal is filled on top of the fitted backgrounds, normalized to the signal yield extracted from the observed data ($\mu = 1.00$). The bottom panel shows the ratio of the observed data to the post fit signal and background predictions.

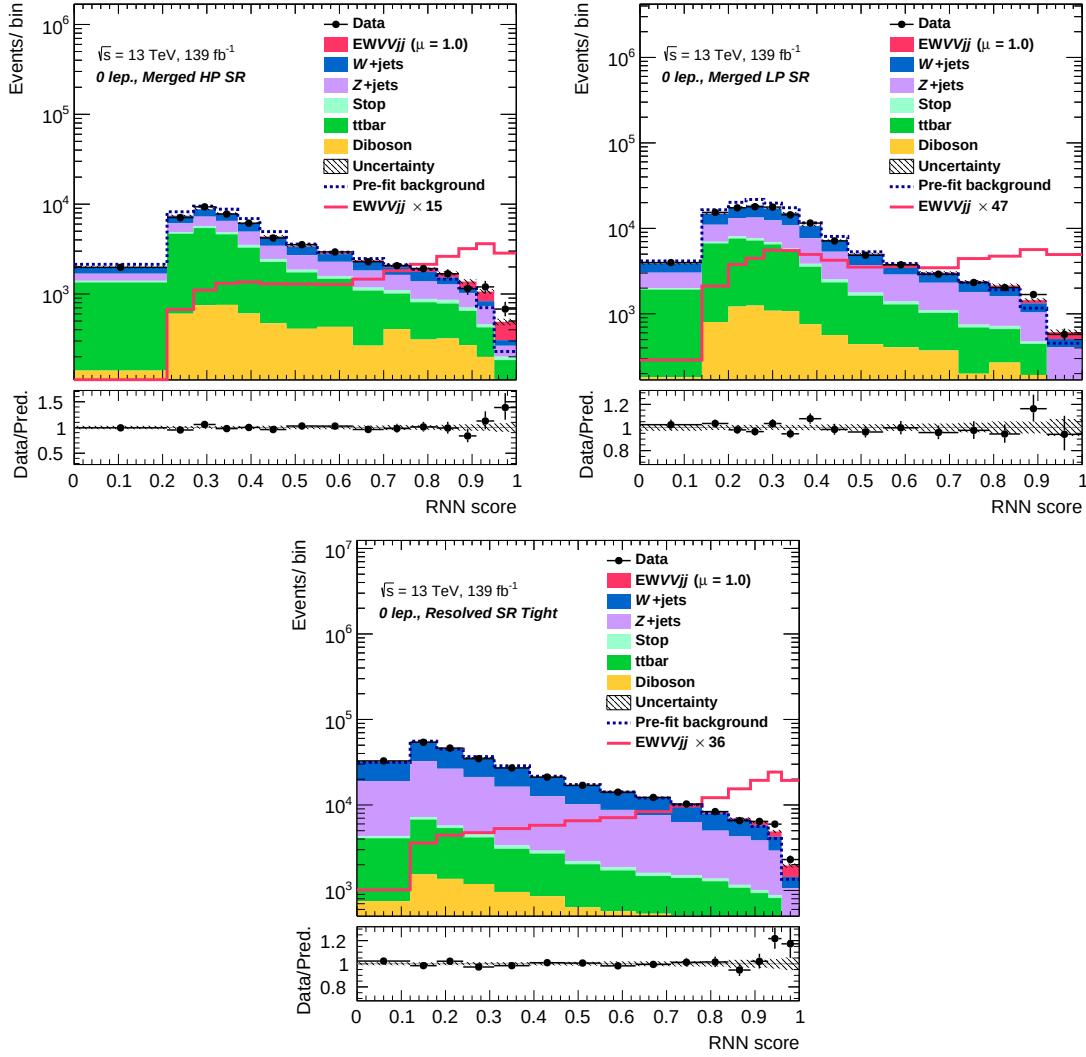


Figure 29: Comparisons of the observed data and expected background distributions of RNN score in the 0-lepton channel signal regions. The EW VV+ jj signal is filled on top of the fitted backgrounds, normalized to the signal yield extracted from the observed data ($\mu = 1.00$). The bottom panel shows the ratio of the observed data to the post fit signal and background predictions.

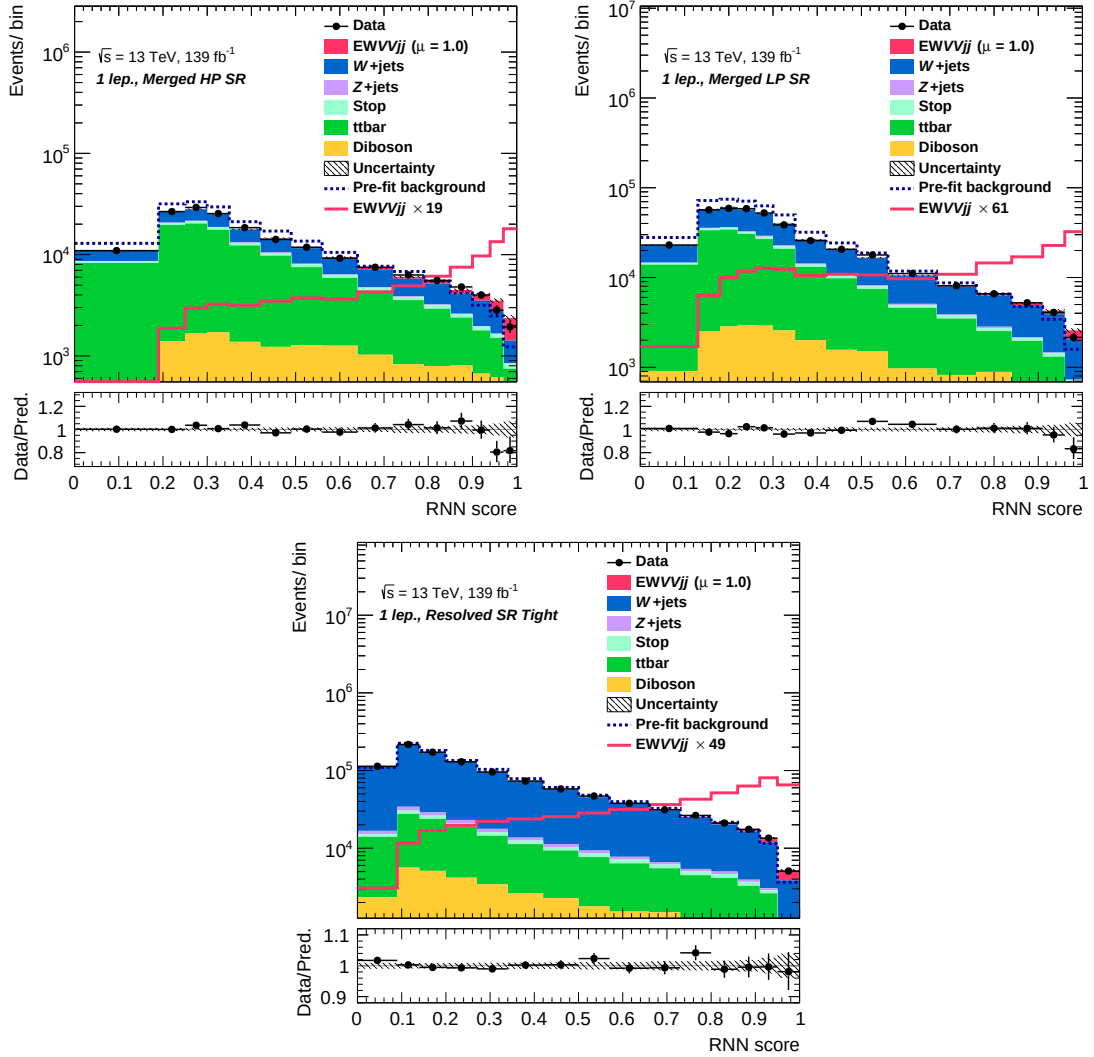


Figure 30: Comparisons of the observed data and expected background distributions of RNN score in the 1-lepton channel signal regions. The EW VV+ jj signal is filled on top of the fitted backgrounds, normalized to the signal yield extracted from the observed data ($\mu = 1.00$). The bottom panel shows the ratio of the observed data to the post fit signal and background predictions.

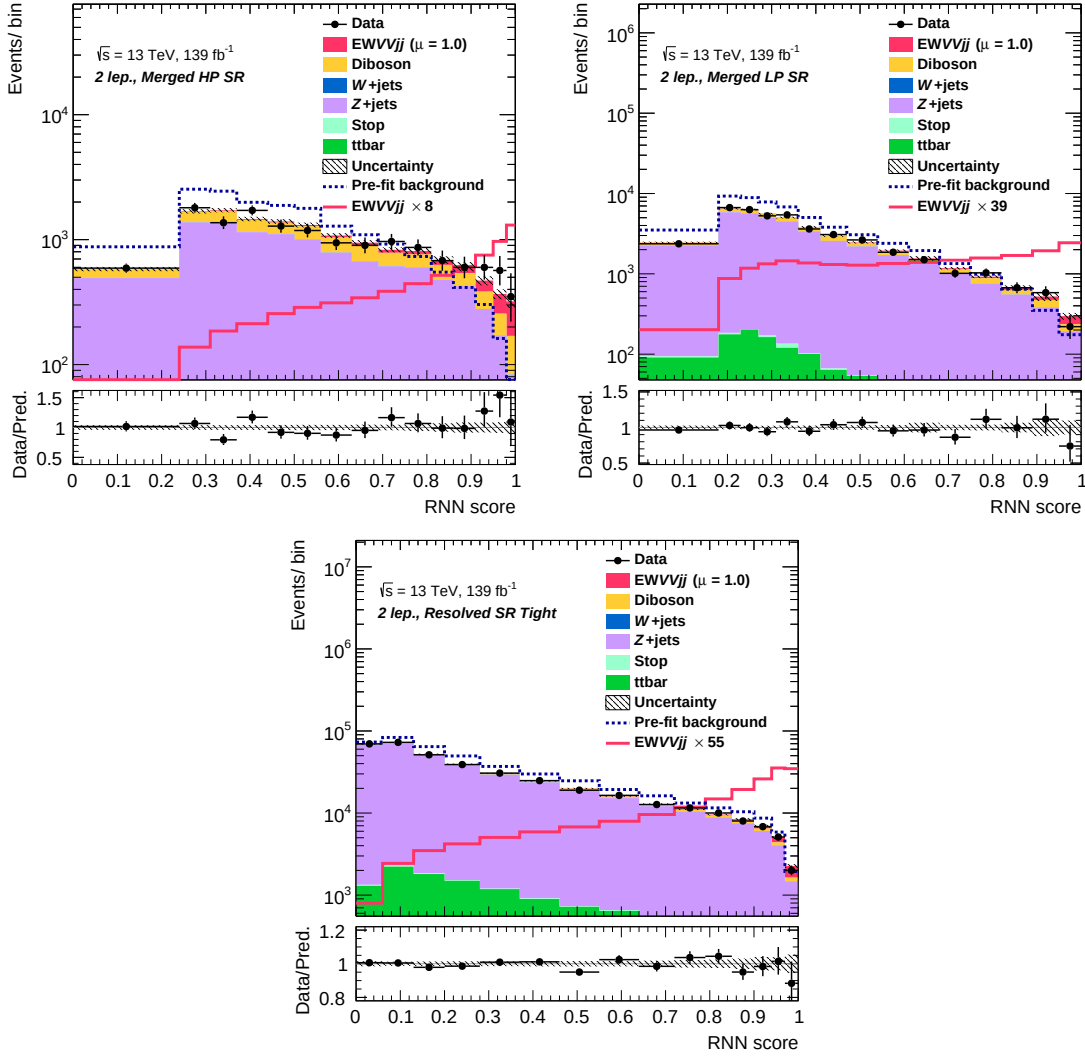


Figure 31: Comparisons of the observed data and expected background distributions of RNN score in the 2-lepton channel signal regions. The EW VV+ jj signal is filled on top of the fitted backgrounds, normalized to the signal yield extracted from the observed data ($\mu = 1.00$). The bottom panel shows the ratio of the observed data to the post fit signal and background predictions.

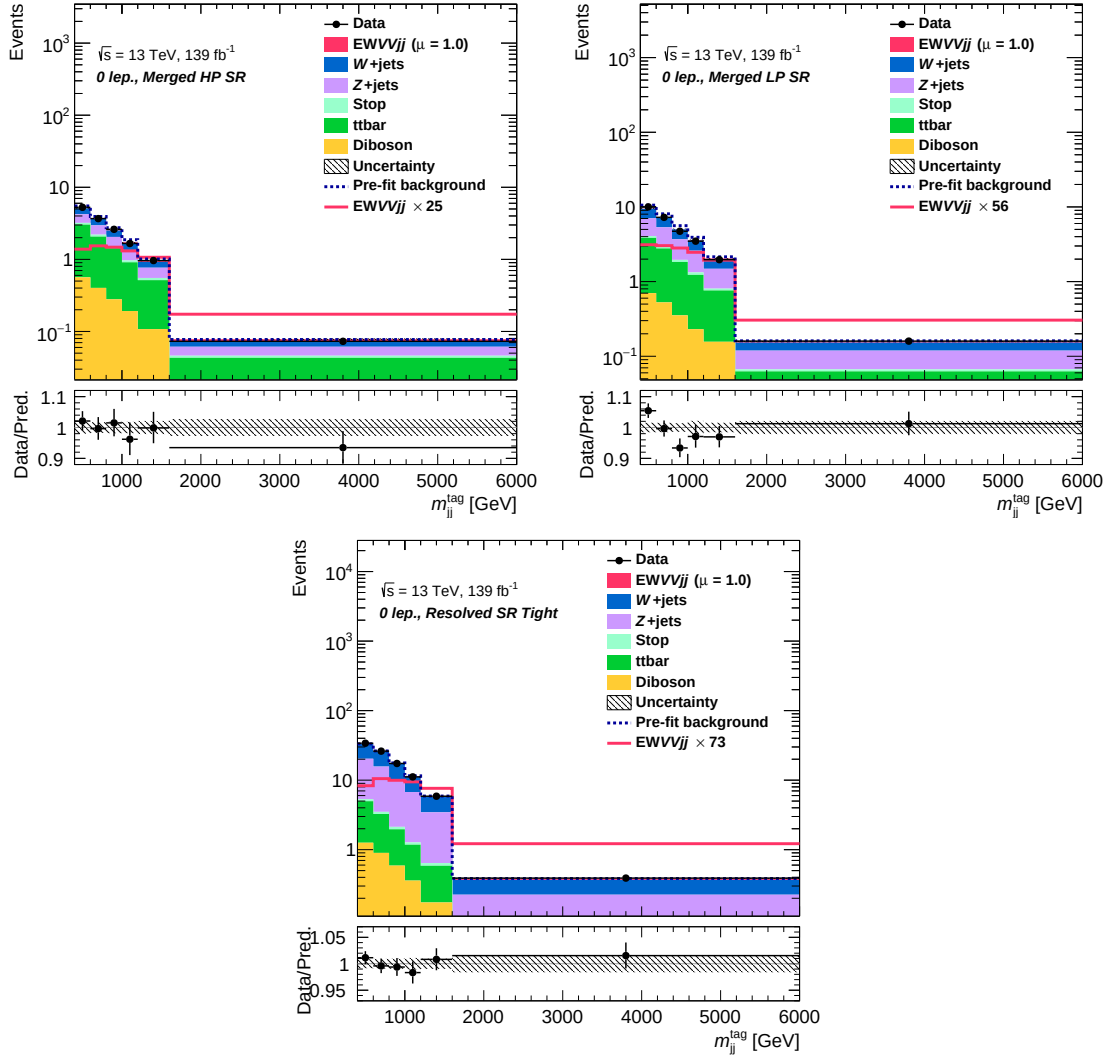


Figure 32: Comparisons of the observed data and expected background distributions of m_{jj}^{tag} in the 0-lepton channel signal regions. The EW VV+ jj signal is filled on top of the fitted backgrounds, normalized to the signal yield extracted from the observed data ($\mu = 1.00$). The bottom panel shows the ratio of the observed data to the post fit signal and background predictions.

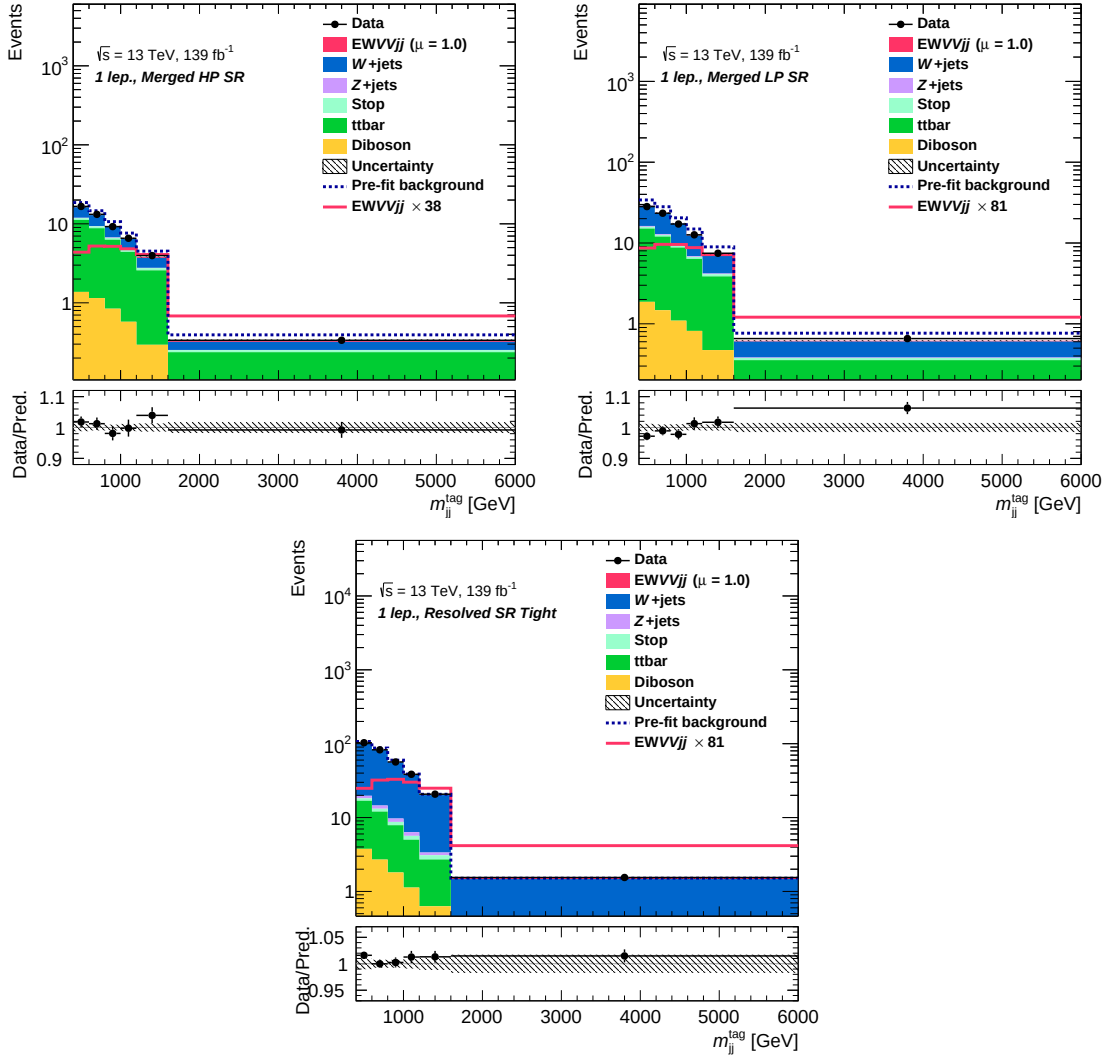


Figure 33: Comparisons of the observed data and expected background distributions of m_{jj}^{tag} in the 1-lepton channel signal regions. The EW VV+ jj signal is filled on top of the fitted backgrounds, normalized to the signal yield extracted from the observed data ($\mu = 1.00$). The bottom panel shows the ratio of the observed data to the post fit signal and background predictions.

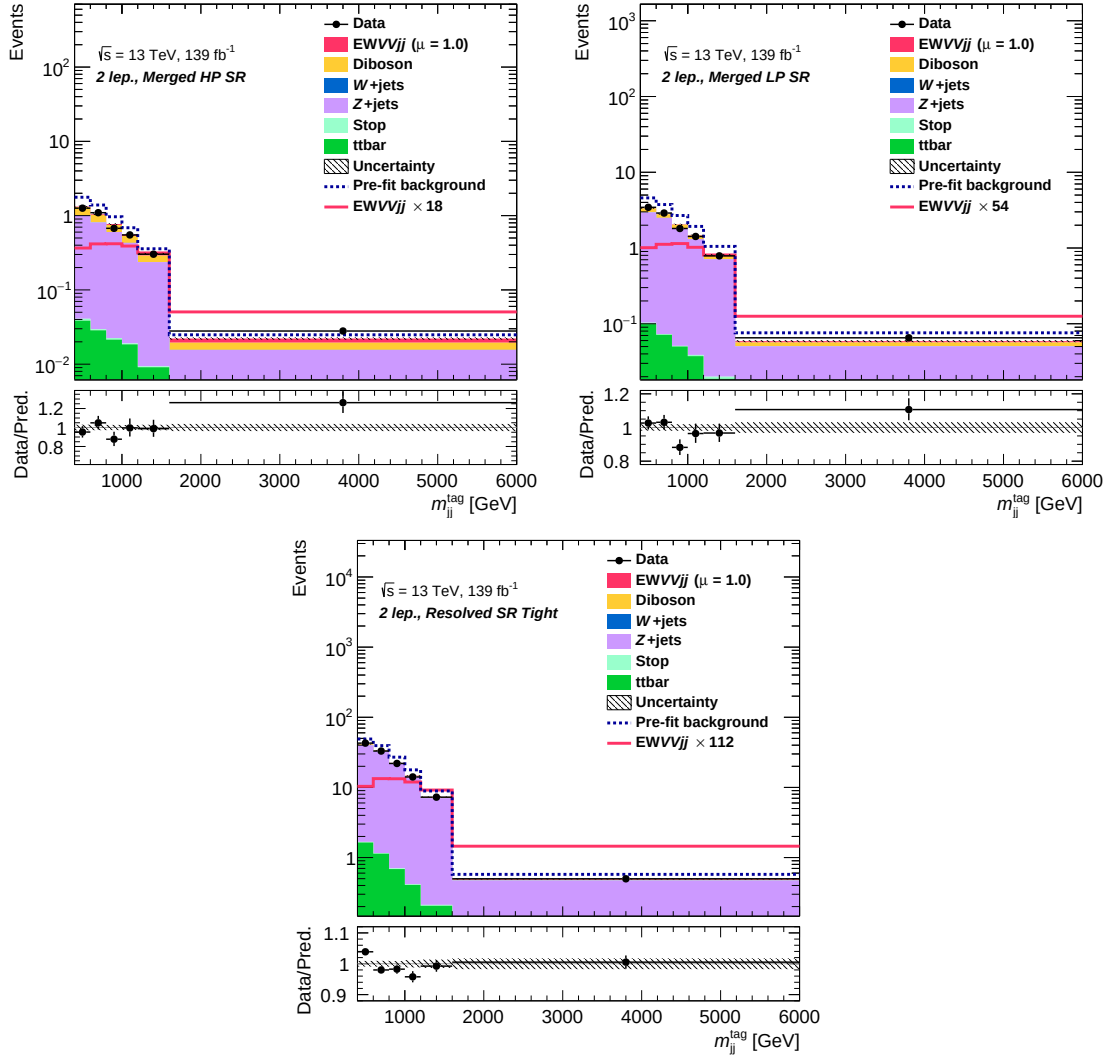


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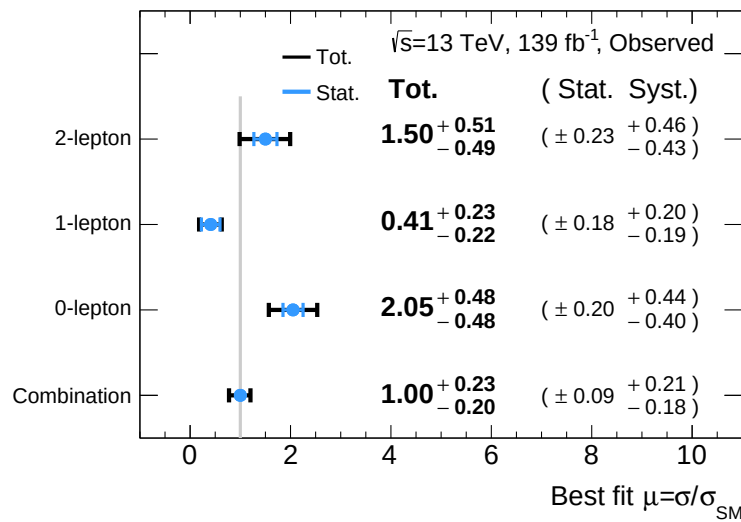


Figure 35: Fitted signal strength μ_{obs} from each 2-lepton, 1-lepton, 0-lepton channel and their combination. The signal strength of each channel is obtained from the individual fit using only each channel.

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