



DOCTORAL DISSERTATION

---

# Searches for the Standard Model Higgs Boson Decaying into $\mu^+\mu^-$ and New Phenomena at TeV Mass Scale with the ATLAS Detector

---

*Author:*

Yanlin Liu

*Supervisor:*

Prof. Bing Zhou

Prof. Zhengguo Zhao

*A dissertation submitted in partial fulfillment of the requirements  
for the degree of Doctor of Philosophy*

*in the*

Department of Modern Physics  
University of Science and Technology of China

July 2018

# Abstract

The greatest triumph of the Standard Model (SM) of particle physics over the past half century is the discovery of the Higgs boson by the ATLAS and CMS experiments at the Large Hadron Collider (LHC) in 2012 during the Run 1 program. The Higgs boson, predicted in the early 1960s, is the cornerstone of the SM. All the massive elementary particles acquire masses through the interactions with it. Different from the gauge field couplings, the Higgs couplings to different particles are dependent on their masses. After the discovery of the Higgs boson, one of the highest priorities of the LHC experiments is to measure its properties, particularly its non-uniform couplings. The Higgs signal strength together with its couplings measured in the bosonic decay channels ( $WW$  and  $ZZ$ ) have already achieved precision better than 15%. Observation of the Higgs decaying into fermion pairs is much harder due to larger background or smaller branching ratio (Br). During the Run 2 program (started in 2015) at the LHC operated with center-of-mass energy  $\sqrt{s}=13$  TeV, the Higgs decaying into the third generation of fermion pairs,  $\tau\bar{\tau}$  and  $b\bar{b}$ , has been observed. But the Higgs boson decaying into the second generation of lighter fermions has not shown any evidence in the experiments at the LHC.

This dissertation will present a search for the SM Higgs boson decaying into the dimuon final state.  $H \rightarrow \mu\mu$  is a rare decay process but also a unique and relatively clean channel to study the Yukawa coupling between the Higgs boson and the second generation of fermions. However, the Br of  $H \rightarrow \mu\mu$  is only  $\sim 0.02\%$ , and the irreducible dimuon event rate from the Drell-Yan process is three orders of magnitude higher. To improve the detection sensitivity, the multivariate analysis (MVA) method is incorporated for the first time in the  $H \rightarrow \mu\mu$  search program. The output of the MVA, the *Boosted Decision Trees* (BDT) score, is used as the discriminant for event categorization to tag the  $H \rightarrow \mu\mu$  event produced in the Vector-Boson Fusion (VBF) process. Using data collected by the ATLAS experiment in 2015 and 2016, corresponding to an integrated luminosity of  $36.1 \text{ fb}^{-1}$ , a much more sensitive upper limit on the Higgs boson production cross section times  $\text{Br}(H \rightarrow \mu\mu)$  is set to be 3.0 times the SM prediction at 95% confidence level (CL) for the Higgs mass of 125 GeV. This result has been improved by a factor of more than two comparing with the previous Run 1 result.

Despite its great success in providing experimental predictions for the particles and describing their interactions, the SM is not considered as the ultimate theory. Since many mysteries observed in the universe, such as dark matter and dark energy, cannot be explained by the SM. Therefore, searching for new physics beyond the SM (BSM) becomes

---

a strong scientific driver for the LHC experiments. The second part of this dissertation will present studies of searching for new phenomena in high-mass scale with the dilepton final states,  $\mu^+\mu^-$  and  $e^+e^-$ . The dilepton final states provide clean and robust signatures with relatively better-understood background to explore the new phenomena in the high-mass regime. The invariant mass spectra of the dilepton final states are used as the discriminants to search for resonance or broad excess as new physics signature. No deviation from the SM prediction is observed with  $36.1 \text{ fb}^{-1}$  data. Much more stringent limits have been set on the parameters of interest for various models comparing with the Run 1 results. For new gauge bosons,  $Z'_{SM}$ ,  $Z'_\chi$  and  $Z'_\psi$  predicted in extended gauge theory models, the observed lower limits on mass have been set to be 4.5 TeV, 4.1 TeV and 3.8 TeV at 95% CL, respectively. While for the Contact Interactions, the observed lower limits on the corresponding energy scale  $\Lambda$  are set between 24 TeV and 40 TeV depending on the different scenarios.

# *Acknowledgements*

First, I want to express my great gratitude to my two supervisors Prof. Bing Zhou and Prof. Zhengguo Zhao, who have led me to frontier of particle physics field. For the past few years, I have benefited a lot from their broad vision of physics and life, and tremendous support on my thesis work as well. They can always give me valuable guidance on my working status as well as the presentations. Whenever I was running into difficulty or confused about the future, they always would like to listen to me and give me suggestions, and more importantly they could always re-build my hope and confidence. I will not be able to proceed in this field without their enormous help.

Then I would like to give my gratitude to many colleagues from the ATLAS groups of the University of Science and Technology of China (USTC) and University of Michigan (UM) which I have been working closely with during my PhD career. I want to thank Prof. Yusheng Wu, who has been supervising me for the past few years on many aspects of my work and always in a patient manner. I have gained a lot on the understanding of physics, techniques and even everyday life from him. I will always remember those long but rather valuable discussions with him, as well as those encouraging chats which help me overcome the frustration. I want to give thanks to Prof. Jianbei Liu, who has taught me much knowledge on particle physics and coding at the beginning of my PhD. I am also grateful to Dr. Cong Geng, who has developed the flexible and efficient analysis framework, and shared many valuable ideas during numerous discussions. Also I would like to thank Dr. Bing Li, Dr. Nan Lu and Dr. Lailin Xu for their much help on techniques learning and experience sharing as well. Thanks to Dr. Tiesheng Dai who has provided much help on samples generating, and Dr. Edward Diehl with whom I worked on a small project on the Monitored Drift Tubes (MDT) during my early stay in Michigan. I also would like to thank Prof. Minghui Liu, Prof. Yanwen Liu, Prof. Haiping Peng and Prof. Junjie Zhu for their much help.

I want to give special thanks to many colleagues from the ATLAS community, with whom I have been working and collaborating for the past few years. Thanks to Dr. Daniel Hayden, Prof. Haifeng Li and Dr. Markus Zinser who have led the very successful analysis groups, which I have been involved with since the end of 2014. Thanks to Antony Fray, Sebastien Rettie, Prof. Dmitri Tsybychev, Christopher Willis and many other members from the analysis groups, who have shared many useful insights and help. I also want to thank Prof. Melissa Franklin, Tony Tong and other colleagues from the muon data quality group for their support and help on my qualification task. Thanks to Dr. Stefano



---

Rosati and Dr .Federico Sforza for their discussions and insights on the inner detector and muon spectrometer alignment study I have been working on.

I want to thank many friends I have met inside and outside the ATLAS community over the past several years: Jing Chen, Jue Chen, Dr. Tom Cheng, Dr. Wen Guo, Yicheng Guo, Changqiao Li, Heng Li, Quanyin Li, Prof. Shu Li, Hao Liu, Mingyi Liu, Jingyu Luo, Dr. Xiangting Meng, Xinmei Niu, Lingling Peng, Rongkun Wang, Wenxiao Wang, Zirui Wang, Aaron White, Dr. Zhaoxu Xi, Lei Xia, Xiangyu Xie, Wenhao Xu, Guoduo Zhang, Liqing Zhang, Yateng Zhang, Prof. Wanxiang Zhao, Zhi Zheng and so on. I will never forget those wonderful moments of traveling, exercising, dining, hot pot party, and card games together with you guys.

I also want to give thanks to Jane Zhang, Jay Chou, JJ Lin, Leehom Wang, Ellie Goulding, Katy Perry, Maroon 5, The Chainsmokers and Zedd for performing such wonderful pop and EDM, which accompany me through those long coding and debugging times:)

Finally I want to express my sincere gratitude to my parents Meiliang Liu and Xiuying Wang, who have given me endless love and care since I was born. During this long journey to PhD, you always raise me up from the disappointing situations and cheer me up from the depressed mood. I will never have made it without your endless support. This thesis is dedicated to you, my beloved parents!



# Contents

|                                                                   |             |
|-------------------------------------------------------------------|-------------|
| <b>Abstract</b>                                                   | <b>ii</b>   |
| <b>Acknowledgements</b>                                           | <b>iv</b>   |
| <b>Contents</b>                                                   | <b>vi</b>   |
| <b>List of Figures</b>                                            | <b>xi</b>   |
| <b>List of Tables</b>                                             | <b>xvii</b> |
| <br>                                                              |             |
| <b>1 Introduction</b>                                             | <b>1</b>    |
| <b>2 Theory</b>                                                   | <b>5</b>    |
| 2.1 The Standard Model of particle physics . . . . .              | 5           |
| 2.1.1 Elementary particles in the Standard Model . . . . .        | 5           |
| 2.1.2 Theoretical formalism of the Standard Model . . . . .       | 7           |
| 2.1.3 The Higgs mechanism . . . . .                               | 10          |
| 2.2 The Related Theories Beyond the Standard Model . . . . .      | 14          |
| 2.2.1 Sequential Standard Model . . . . .                         | 14          |
| 2.2.2 $E_6$ –motivated $Z'$ models . . . . .                      | 15          |
| 2.2.3 Contact interactions . . . . .                              | 16          |
| 2.3 Physics at the Large Hadron Collider . . . . .                | 17          |
| 2.3.1 Phenomenology of hadronic collision . . . . .               | 17          |
| 2.3.2 Higgs boson production at the LHC . . . . .                 | 19          |
| <br>                                                              |             |
| <b>3 The Large Hadron Collider and the ATLAS Detector</b>         | <b>23</b>   |
| 3.1 The Large Hadron Collider . . . . .                           | 23          |
| 3.1.1 General introduction of the Large Hadron Collider . . . . . | 23          |
| 3.1.2 Luminosity and pile-up . . . . .                            | 26          |
| 3.2 The ATLAS Detector . . . . .                                  | 28          |
| 3.2.1 Physics requirements and detector overview . . . . .        | 28          |
| 3.2.2 Magnet system . . . . .                                     | 32          |
| 3.2.3 Inner Detector . . . . .                                    | 32          |

---

|          |                                                                          |           |
|----------|--------------------------------------------------------------------------|-----------|
| 3.2.3.1  | Pixel detector . . . . .                                                 | 34        |
| 3.2.3.2  | The semiconductor tracker . . . . .                                      | 34        |
| 3.2.3.3  | Transition radiation tracker . . . . .                                   | 35        |
| 3.2.4    | Calorimeters . . . . .                                                   | 35        |
| 3.2.4.1  | LAr electromagnetic calorimeter . . . . .                                | 37        |
| 3.2.4.2  | Hadronic calorimeters . . . . .                                          | 37        |
| 3.2.5    | Muon Spectrometer . . . . .                                              | 38        |
| 3.2.5.1  | Monitored drift tube chambers . . . . .                                  | 41        |
| 3.2.5.2  | Cathode strip chambers . . . . .                                         | 43        |
| 3.2.5.3  | Resistive plate chambers . . . . .                                       | 43        |
| 3.2.5.4  | Thin gap chambers . . . . .                                              | 43        |
| 3.2.6    | Forward detectors . . . . .                                              | 44        |
| 3.2.7    | Trigger system . . . . .                                                 | 45        |
| 3.2.7.1  | Level-1 Trigger . . . . .                                                | 46        |
| 3.2.7.2  | High-level trigger . . . . .                                             | 48        |
| <b>4</b> | <b>Simulation and Object Reconstruction for the ATLAS Experiment</b>     | <b>51</b> |
| 4.1      | Detector Simulation . . . . .                                            | 52        |
| 4.1.1    | Event generation . . . . .                                               | 53        |
| 4.1.2    | Detector simulation . . . . .                                            | 54        |
| 4.1.3    | Digitization . . . . .                                                   | 55        |
| 4.2      | Object Reconstruction . . . . .                                          | 55        |
| 4.2.1    | Track . . . . .                                                          | 56        |
| 4.2.1.1  | Inner detector track . . . . .                                           | 56        |
| 4.2.1.2  | Muon spectrometer track . . . . .                                        | 57        |
| 4.2.2    | Primary vertex . . . . .                                                 | 58        |
| 4.2.3    | Electron . . . . .                                                       | 60        |
| 4.2.3.1  | Electron reconstruction . . . . .                                        | 60        |
| 4.2.3.2  | Electron identification . . . . .                                        | 61        |
| 4.2.3.3  | Electron isolation . . . . .                                             | 62        |
| 4.2.4    | Muon . . . . .                                                           | 63        |
| 4.2.4.1  | Muon reconstruction . . . . .                                            | 63        |
| 4.2.4.2  | Muon identification . . . . .                                            | 64        |
| 4.2.4.3  | Muon isolation . . . . .                                                 | 66        |
| 4.2.4.4  | Muon momentum scale and resolution . . . . .                             | 67        |
| 4.2.4.5  | Impact of ID–MS alignment on high $p_T$ muon resolution . . . . .        | 68        |
| 4.2.5    | Jet . . . . .                                                            | 70        |
| 4.2.5.1  | Jet reconstruction . . . . .                                             | 72        |
| 4.2.5.2  | Jet energy scale calibration . . . . .                                   | 73        |
| 4.2.5.3  | $b$ -jet tagging . . . . .                                               | 74        |
| 4.2.6    | Missing transverse energy . . . . .                                      | 76        |
| <b>5</b> | <b>Search for Standard Model Higgs Boson with the Dimuon Final State</b> | <b>77</b> |
| 5.1      | Introduction . . . . .                                                   | 77        |

---

|          |                                                                                   |            |
|----------|-----------------------------------------------------------------------------------|------------|
| 5.2      | Data and MC samples . . . . .                                                     | 78         |
| 5.3      | Object and Event Selection . . . . .                                              | 81         |
| 5.3.1    | Object level selection . . . . .                                                  | 81         |
| 5.3.1.1  | Muons . . . . .                                                                   | 81         |
| 5.3.1.2  | Jets . . . . .                                                                    | 82         |
| 5.3.1.3  | Electrons . . . . .                                                               | 83         |
| 5.3.1.4  | $E_T^{miss}$ . . . . .                                                            | 84         |
| 5.3.1.5  | Overlap removal between objects . . . . .                                         | 85         |
| 5.3.2    | Event level selection . . . . .                                                   | 85         |
| 5.3.2.1  | $Z$ control region . . . . .                                                      | 88         |
| 5.3.2.2  | $Z$ plus two jets control region . . . . .                                        | 88         |
| 5.3.2.3  | Data/MC comparisons for the kinematic variables in the<br>signal region . . . . . | 90         |
| 5.4      | Categorization for the Signal Region . . . . .                                    | 93         |
| 5.4.1    | Selection for the VBF enriched categories . . . . .                               | 94         |
| 5.4.2    | Selection for the ggF enriched categories . . . . .                               | 97         |
| 5.4.3    | Event yields in eight signal categories . . . . .                                 | 99         |
| 5.5      | Signal and Background Modeling . . . . .                                          | 100        |
| 5.5.1    | Signal modeling . . . . .                                                         | 100        |
| 5.5.2    | Background modeling . . . . .                                                     | 101        |
| 5.6      | Systematic Uncertainties . . . . .                                                | 103        |
| 5.6.1    | Theoretical uncertainties on the signal . . . . .                                 | 103        |
| 5.6.2    | Experimental uncertainties on the signal . . . . .                                | 103        |
| 5.6.3    | Spurious signal uncertainty from the background modeling . . . . .                | 105        |
| 5.7      | Statistical Analysis . . . . .                                                    | 110        |
| 5.8      | Results . . . . .                                                                 | 112        |
| <b>6</b> | <b>Search for New Phenomena with the Dilepton Final State</b>                     | <b>115</b> |
| 6.1      | Introduction . . . . .                                                            | 115        |
| 6.2      | Monte Carlo Samples . . . . .                                                     | 116        |
| 6.2.1    | Background samples . . . . .                                                      | 116        |
| 6.2.2    | Signal samples . . . . .                                                          | 116        |
| 6.3      | Event Selection . . . . .                                                         | 117        |
| 6.3.1    | Electron channel . . . . .                                                        | 118        |
| 6.3.2    | Muon channel . . . . .                                                            | 118        |
| 6.4      | Background Estimation and Kinematic Distributions . . . . .                       | 120        |
| 6.4.1    | Background estimation . . . . .                                                   | 120        |
| 6.4.2    | Kinematic distributions . . . . .                                                 | 123        |
| 6.5      | Systematic Uncertainties . . . . .                                                | 125        |
| 6.6      | Statistical Analysis . . . . .                                                    | 128        |
| 6.6.1    | Log-likelihood ratio test . . . . .                                               | 129        |
| 6.6.2    | Exclusion limits with Bayesian approach . . . . .                                 | 130        |
| 6.7      | Results . . . . .                                                                 | 131        |

---

|                       |     |
|-----------------------|-----|
| 7 Summary and Outlook | 135 |
|-----------------------|-----|

|              |     |
|--------------|-----|
| Bibliography | 139 |
|--------------|-----|

# List of Figures

|      |                                                                                                                                                                                                                                                                                |    |
|------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| 2.1  | The elementary particles of the Standard Model (Wikipedia). . . . .                                                                                                                                                                                                            | 6  |
| 2.2  | The SM interactions mediated by gauge bosons (Wikipedia). The solid straight lines represent the fermions (e.g. $u$ , $d$ , $e$ , $\mu$ ...), while the wave lines denote electroweak bosons (i.e. $W$ , $Z$ and $\gamma$ ), and the loops lines stand for the gluons. . . . . | 7  |
| 2.3  | The Higgs potential $V(\phi)$ for $\mu^2 > 0$ (left) and $\mu^2 < 0$ (right). . . . .                                                                                                                                                                                          | 11 |
| 2.4  | Higgs interaction vertices in the SM. The wave line represents the $W$ or $Z$ boson; the dashed line represents the Higgs boson; while the solid line represents the fermion. . . . .                                                                                          | 13 |
| 2.5  | Leading-order cross-section times branching ratio to a single dilepton flavour for various $Z'$ models as a function of polemass for $pp$ collisions at $\sqrt{s} = 13$ TeV . . . . .                                                                                          | 15 |
| 2.6  | Feynman diagram of LO DY process with additional CI process with energy scale $\Lambda$ in the $\mu^+\mu^-$ final state. . . . .                                                                                                                                               | 16 |
| 2.7  | Schematic view of a hadron-hadron collision. . . . .                                                                                                                                                                                                                           | 18 |
| 2.8  | NNPDF3.0 NNLO PDF set for $Q^2 = 10 \text{ GeV}^2$ and $Q^2 = 10^4 \text{ GeV}^2$ . . . .                                                                                                                                                                                      | 18 |
| 2.9  | Representative Feynman diagrams of the Higgs production mechanisms: (a) gluon-gluon fusion (VH), (b) vector boson fusion (VBF), (c) associated production with a vector boson (VH) and (d) associated production with top quarks (ttH). . . . .                                | 20 |
| 2.10 | The SM Higgs boson decay branching ratios as a function of the Higgs pole mass. . . . .                                                                                                                                                                                        | 21 |
| 3.1  | The peak luminosity of the LHC for different operation runs [53]. . . . .                                                                                                                                                                                                      | 24 |
| 3.2  | Schematic layout of the LHC complex . . . . .                                                                                                                                                                                                                                  | 25 |
| 3.3  | Delivered luminosity ( $pp$ collisions) vs time for 2011–2017 (left); luminosity-weighted distribution of the mean number of interactions per crossing at 13 TeV from 2015–2017 (right). . . . .                                                                               | 28 |
| 3.4  | Cut-away view of the ATLAS detector. The dimensions of the detector are 25 m in height and 44 m in length. The overall weight of the detector is approximately 7000 tonnes. . . . .                                                                                            | 30 |
| 3.5  | Cut-away view of the ATLAS inner detector. . . . .                                                                                                                                                                                                                             | 33 |
| 3.6  | Plan view of a quarter-section of the ATLAS inner detector showing each of the major detector elements with its active dimensions and envelopes. . . . .                                                                                                                       | 33 |
| 3.7  | Cut-away view of the ATLAS calorimeter. . . . .                                                                                                                                                                                                                                | 36 |
| 3.8  | Cut-away view of the ATLAS muon spectrometer. . . . .                                                                                                                                                                                                                          | 39 |

---

|      |                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |    |
|------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| 3.9  | Cross-section view of the muon spectrometer system in the non-bending plane (top) and bending plane (bottom) . . . . .                                                                                                                                                                                                                                                                                                                                          | 40 |
| 3.10 | Cross-section view of a MDT tube (a) and an example of drift time spectrum for a MDT tube (b). . . . .                                                                                                                                                                                                                                                                                                                                                          | 42 |
| 3.11 | A quarter-section view of the muon trigger system . . . . .                                                                                                                                                                                                                                                                                                                                                                                                     | 44 |
| 3.12 | Placement of the ATLAS forward detectors along the beam line . . . . .                                                                                                                                                                                                                                                                                                                                                                                          | 45 |
| 3.13 | Schematic view of the ATLAS TDAQ system for Run 2 . . . . .                                                                                                                                                                                                                                                                                                                                                                                                     | 46 |
| 3.14 | Schematic view of the input trigger towers for the L1Calo trigger algorithms. . . . .                                                                                                                                                                                                                                                                                                                                                                           | 47 |
| 3.15 | Schematic view of the MS with lines indicating various $\eta$ regions. The curved arrow (in red color) shows an example of a trajectory from slow particles generated at the beam pipe around $z \sim 10$ m. Triggers due to events of this type are mitigated by requiring an additional coincidence with the TGC-FI chambers in the region $1.3 <  \eta  < 1.9$ . . . . .                                                                                     | 48 |
| 4.1  | Schematic description of the particle identification of the ATLAS detector . . . . .                                                                                                                                                                                                                                                                                                                                                                            | 52 |
| 4.2  | The schematic flow of the ATLAS simulation software, from event generators (top left) to reconstruction (top right). . . . .                                                                                                                                                                                                                                                                                                                                    | 53 |
| 4.3  | Sketch of a hadron-hadron collision event simulated by Sherpa generator. The red blob in the center stands for the hard collision, which is surrounded by a tree-like structure representing Bremsstrahlung simulated by parton showers. The purple blob represents a secondary hard scattering event. Light green blobs indicate hadronization process. Dark green blobs represent hadron decays. Yellow lines stand for signal soft photon radiation. . . . . | 54 |
| 4.4  | The sketch of the data flow for the ATLAS experiment. . . . .                                                                                                                                                                                                                                                                                                                                                                                                   | 56 |
| 4.5  | Schematic view of the ATLAS inner detector showing all the corresponding components, including the new new insertable B-layer (IBL). . . . .                                                                                                                                                                                                                                                                                                                    | 57 |
| 4.6  | The identification efficiencies of different working points for $Z \rightarrow ee$ (left) and dijet (right) samples. . . . .                                                                                                                                                                                                                                                                                                                                    | 62 |
| 4.7  | Distributions of $E_T^{cone0.2}$ (left) and $p_T^{varcone0.2}$ (right) for selected electrons of MC $Z \rightarrow ee$ and data samples. . . . .                                                                                                                                                                                                                                                                                                                | 63 |
| 4.8  | Muon reconstruction efficiency as function of $\eta$ for Medium (left) and High- $p_T$ (right) derived from $Z \rightarrow \mu\mu$ events for muons with $p_T > 10$ GeV. The left plot also shows the efficiency of Loose in the region $ \eta  < 0.1$ . . . . .                                                                                                                                                                                                | 66 |
| 4.9  | Mean value of $\Delta z_0$ distribution in each sector versus muon ID track $\eta$ and $\phi$ with Medium WP applied for MC alines 0.1 (top left), 0.3 (top right), 1.0 (middle left), 3.0 mm (middle right) and data (bottom) samples. . . . .                                                                                                                                                                                                                 | 70 |
| 4.10 | Mean value of $\Delta\theta$ distribution in each sector versus muon ID track $\eta$ and $\phi$ with Medium WP applied for MC alines 0.1 (top left), 0.3 (top right), 1.0 (middle left), 3.0 mm (middle right) and data (bottom) samples. . . . .                                                                                                                                                                                                               | 71 |
| 4.11 | Mean value distributions in each $\eta - \phi$ sector for $\Delta z_0$ (left) and $\Delta\theta$ (right). . . . .                                                                                                                                                                                                                                                                                                                                               | 71 |
| 4.12 | Comparisons of $p_T$ resolution for four MC alines smearing samples with Medium WP (left) and High- $p_T$ WP (right) applied. . . . .                                                                                                                                                                                                                                                                                                                           | 72 |
| 4.13 | Comparisons of $p_T$ resolution for MC alines 1.0 mm sample w/o ID-MS alignment correction with Medium WP (left) and High- $p_T$ WP (right) applied. . . . .                                                                                                                                                                                                                                                                                                    | 72 |



---

|      |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |    |
|------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| 4.14 | Schematic workflow of the calibration stages for EM-scale jets. Each stage of the calibration is applied to the four-momentum of the jet except for the origin correction. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | 74 |
| 4.15 | Diagram showing the $b$ -hadron decay. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | 75 |
| 5.1  | Total integrated luminosity recorded online at the ATLAS experiment in 2015 (left) and 2016 (middle), and the mean number of interactions per crossing for these two years (right). . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | 79 |
| 5.2  | Isolation efficiency versus leading muon $p_T$ (left) and subleading muon $p_T$ (right) for various isolation working points. The efficiency is defined with regarding to muons selected with all the other criteria defined in Table 5.3 except the isolation cut. The “LooseTrackOnly” working point is used in this analysis. Plotted efficiencies are calculated from MC Drell-Yan events. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | 82 |
| 5.3  | $\eta - \phi$ monitoring maps for muons associated with $J/\psi$ (left) and $Z$ (right) for Run 284420 in 2015. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | 86 |
| 5.4  | Comparison between data and MC predictions for $E_T^{miss}$ before cut on 80 GeV in the signal region (defined below). The Drell-Yan events are generated with MadGraph and normalized using the NNLO cross section to $36.1 \text{ fb}^{-1}$ corresponding to the data collected in 2015 and 2016. MC statistical and experimental systematic (muon, jet and MET) uncertainties are shown in the error band. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | 87 |
| 5.5  | Comparison between data and MC predictions for leading muon $p_T$ (top left), subleading muon $p_T$ (top right), dimuon invariant mass (middle left), $p_T^Z$ (middle right), total $H_t$ (bottom left) and jet multiplicity (bottom right) in the $Z$ control region. The Drell-Yan events are generated with MadGraph and normalized using the NNLO cross section to $36.1 \text{ fb}^{-1}$ corresponding to the data collected in 2015 and 2016. MC statistical and experimental systematic (muon, jet and MET) uncertainties are shown in the error band. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                       | 89 |
| 5.6  | Comparison between data and MC predictions for $m_{\mu\mu}$ (top), $m_{jj}$ (middle left), $\Delta\eta_{jj}$ (middle right), $\Delta R_{jj}$ (bottom left) and centrality (bottom right). MC statistical uncertainty, $m_{jj}$ modeling related systematic uncertainty and experimental systematic (muon, jet and MET) uncertainties are shown in the error band. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | 91 |
| 5.7  | Comparison between data and MC predictions for $p_T$ of the dijet system ( $p_T^{jj}$ , top left), $p_T$ of the dimuon plus leading jet system ( $p_T^{lj1}$ , top middle), $p_T$ of the dimuon plus subleading jet system ( $p_T^{lj2}$ , top right), $p_T$ of the dimuon plus dijet system ( $p_T^{ljj}$ , middle left), $\Delta\eta$ between dimuon system with dijet system ( $\Delta\eta_{ljj}$ , middle middle), leading jet ( $\Delta\eta_{lj1}$ , middle right), subleading jet ( $\Delta\eta_{lj2}$ , bottom left), and scalar sum of lepton and jet $p_T$ ( $H_t$ , bottom right) in the final state in the dijet validation region. The Drell-Yan events are generated with MadGraph and normalized using the NNLO cross section to $36.1 \text{ fb}^{-1}$ corresponding to the data collected in 2015 and 2016. MC statistical uncertainty, $m_{jj}$ modeling related systematic uncertainty and experimental systematic (muon, jet and MET) uncertainties are shown in the error band. . . . . | 92 |

---

|      |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |     |
|------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 5.8  | Comparison between data and MC predictions for $m_{\mu\mu}$ (top left), $p_T^{\mu\mu}$ (top middle), $Ht$ (top right), $n_{jet}$ (bottom left) and $E_T^{miss}$ (bottom right, before $E_T^{miss} < 80$ GeV cut) in the inclusive signal region. MC statistical uncertainty and experimental systematic (muon, jet and MET) uncertainties are shown in the error band. . . . .                                                                                                                                                  | 93  |
| 5.9  | Comparison between data and MC predictions for $m_{jj}$ (top left), $\Delta\eta_{jj}$ (top right), $p_T$ for leading (bottom left) and subleading (bottom right) jets in the VBF-like signal region. MC statistical uncertainty, $m_{jj}$ modeling related systematic uncertainty and experimental systematic (muon, jet and MET) uncertainties are shown in the error band. . . . .                                                                                                                                            | 94  |
| 5.10 | BDT response comparison between training and testing (left) and ROC curve namely background rejection efficiency <i>vs</i> signal selection efficiency (right). . . . .                                                                                                                                                                                                                                                                                                                                                         | 96  |
| 5.11 | Comparisons between data and MC predictions for BDT score in control region (left) and signal region (right). The Drell-Yan events are generated with MadGraph and normalized using the NNLO cross section to $36.1 \text{ fb}^{-1}$ corresponding to the data collected in 2015 and 2016. MC statistical uncertainty, $m_{jj}$ modeling related systematic uncertainty and experimental systematic (muon, jet and MET) uncertainties are shown in the error band. . . . .                                                      | 96  |
| 5.12 | $m_{\mu\mu}$ distributions for background and signal for VBF Loose (left) and Tight (right) categories Shapes are normalized to $36.1 \text{ fb}^{-1}$ . VBF filtered samples are used for $m_{\mu\mu}$ shape and normalized to the yields of spectrum from Madgraph $Ht$ sliced samples. MC statistical uncertainty, $m_{jj}$ modeling related systematic uncertainty and experimental systematic (muon, jet and MET) uncertainties are shown in the error band. . . . .                                                       | 97  |
| 5.13 | $m_{\mu\mu}$ distributions for background and signal for low (top), medium (middle) and high (bottom) $p_T^{\mu\mu}$ categories in central (left) and non-central (right) regions. Shapes are normalized to $36.1 \text{ fb}^{-1}$ . Powheg Drell-Yan samples (high statistics) are used for $m_{\mu\mu}$ shape and normalized to the yields of the corresponding spectrum from Madgraph $Ht$ sliced samples. MC statistical and experimental systematic (muon, jet and MET) uncertainties are shown in the error band. . . . . | 98  |
| 5.14 | Signal model fits to the $m_{\mu\mu}$ distributions of simulated ggF signal events in the central (left) and non-central (right) medium $p_T^{\mu\mu}$ categories. . . . .                                                                                                                                                                                                                                                                                                                                                      | 101 |
| 5.15 | Signal model fits to the $m_{\mu\mu}$ distributions of simulated VBF signal events in the VBF loose (left) and VBF tight (right) categories . . . . .                                                                                                                                                                                                                                                                                                                                                                           | 101 |
| 5.16 | Background-only fit to the observed $m_{\mu\mu}$ distribution in the central high $p_T^{\mu\mu}$ (left) and VBF tight (right) categories. Only the statistical uncertainties are shown for the data points. The expected signal shape is scaled up by a factor of 20. . . . .                                                                                                                                                                                                                                                   | 102 |
| 5.17 | Comparison of reconstruction-level $m_{\mu\mu}$ distributions between the fully-simulated MC events and the corrected truth events after requirement at least two selected muons in the events and the leading muon with $p_T > 27$ GeV, in low (top), medium (middle) and high (bottom) $p_T^{\mu\mu}$ categories in central (left) and non-central (right) regions. Distributions are normalized to $36.1 \text{ fb}^{-1}$ , and only MC statistical uncertainty is shown. . . . .                                            | 106 |

---

|      |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |     |
|------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 5.18 | Comparison of reconstruction-level $m_{\mu\mu}$ distributions between the fully-simulated MC events and the corrected truth events after requirement at least two selected muons in the events and the leading muon with $p_T > 27$ GeV, in VBF loose (left) and VBF tight (right) categories. Distributions are normalized to $36.1 \text{ fb}^{-1}$ , and only MC statistical uncertainty is shown.                                                                                                                                                                                                                                                                                                                                                                    | 107 |
| 5.19 | The combined signal (125 GeV) plus background fits to $m_{\mu\mu}$ distributions form the corrected truth events after requirement at least two selected muons in the events and the leading muon with $p_T > 27$ GeV, in central low- $p_T$ category (top left), non-central low- $p_T$ category (top middle), central medium- $p_T$ category (top right), non-central medium- $p_T$ category (middle left), central high- $p_T$ category (middle middle), non-central high- $p_T$ category (middle right), VBF loose category (bottom left) and VBF tight category (bottom right). Distributions are normalized to the MC equivalent luminosity so that the fitting errors reflects that of MC statistical fluctuations, and only MC statistical uncertainty is shown. | 108 |
| 5.20 | The fitted spurious signal event yields corresponding to $36.1 \text{ fb}^{-1}$ as a function of signal pole mass in central low- $p_T$ category (top left), non-central low- $p_T$ category (top middle), central medium- $p_T$ category (top right), non-central medium- $p_T$ category (middle left), central high- $p_T$ category (middle middle), non-central high- $p_T$ category (middle right), VBF loose category (bottom left) and VBF tight category (bottom right). Only MC statistical uncertainty coming out of the fit is shown.                                                                                                                                                                                                                          | 109 |
| 5.21 | Observed and expected upper limits on $\mu$ at 95% CL for data recorded in 2015 and 2016 at $\sqrt{s} = 13 \text{ TeV}$ corresponding to $36.1 \text{ fb}^{-1}$ .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | 112 |
| 6.1  | Electron identification efficiency of various WPs as a function of leading $E_T$ for Drell-Yan (left) and Dijet samples (right).                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         | 118 |
| 6.2  | Resolution comparisons for two-station and three-station muons in the central region ( $ \eta  < 1.05$ ) (left); High- $p_T$ WP efficiency versus truth muon $\eta$ and $\phi$ for muons with $p_T > 500 \text{ GeV}$ (right).                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | 119 |
| 6.3  | Distribution of fake background estimation (derived using matrix method) together with its systematic uncertainties.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | 122 |
| 6.4  | Distributions of $p_T$ (top), $\eta$ (middle) and $\phi$ (bottom) for the electrons (left) and muons (right) after applying signal selection criteria with additional $m_{ll} > 120 \text{ GeV}$ requirement. The shaded band in the lower panel illustrates the total systematic uncertainty.                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | 124 |
| 6.5  | Distributions of dielectron (left) and dimuon (right) invariant mass after applying signal selection criteria. The bin width of the spectra is constant in $\log(m_{ll})$ while the total systematic uncertainty is shown in the shaded band.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | 125 |

---

|      |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |     |
|------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 6.6  | Event displays for the highest $m_{ll}$ events in $ee$ (left) and $\mu\mu$ (right) channels. Green and red towers represent energy deposition in the cells of the EM and tile calorimeter respectively. Red lines illustrate the reconstructed ID tracks associated with the selected electron candidates. Cyan lines represent the other tracks with $E_T > 2$ GeV, including the tracks coming from pile-up effect. For the dielectron event, the leading electron has an $E_T$ of 841 GeV, an $\eta$ of -1.26 and a $\phi$ of -1.15, while the subleading one has an $E_T$ of 655 GeV, an $\eta$ of 1.32 and a $\phi$ of 1.83. For the dimuon event, the leading muon has a $p_T$ of 636 GeV, an $\eta$ of -0.43 and a $\phi$ of -2.16 while the subleading muon has a $p_T$ of 545 GeV, an $\eta$ of 1.81 and a $\phi$ of 0.90. The additional muon has a $p_T$ of 145 GeV and the missing transverse energy of this event is 109 GeV. . . . . | 126 |
| 6.7  | Asymmetric uncertainty on the Drell-Yan cross section as a function of $m_{ll}$ due to the PDF eigenvector variations shown in two solid grey lines, with other possible PDF choices overlayed. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | 127 |
| 6.8  | Local and global $p$ -value as a function of $Z'$ polemass in $ee$ (top left), $\mu\mu$ (top right) and combined channels (bottom). . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | 132 |
| 6.9  | Observed and expected 95% CL upper limits on $Z'$ cross section times branching ratio ( $\sigma B$ ) as a function of $Z'$ polemass in $ee$ (top left), $\mu\mu$ (top right) and combined channels (bottom). . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | 133 |
| 6.10 | Observed and expected 95% CL lower limits on the CI energy scale scale $\Lambda$ for various models with constructive (const) and destructive (dest) interference in $ee$ (top left), $\mu\mu$ (top right) and combined channels (bottom). . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | 134 |
| 7.1  | Rough estimation of signal significance <i>vs</i> integrated luminosity for different spurious signal (SS) uncertainty scenarios. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | 136 |
| 7.2  | Ratio of the observed limit for the $Z'$ search to the $Z'_{SSM}$ cross section for current searches together with previous results at $\sqrt{s} = 7, 8$ and 13 TeV. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | 137 |

# List of Tables

|      |                                                                                                                                                                                                                                                                                                                                                       |     |
|------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 2.1  | Standard Model Higgs boson production cross sections at $m_H = 125.09$ GeV at center-of-mass energy $\sqrt{s} = 7, 8$ and 13 TeV at the LHC. The uncertainties on the cross sections are the quadratic sum of the uncertainties from variations of QCD scales, parton distribution functions and the strong interaction coupling $\alpha_s$ . . . . . | 20  |
| 2.2  | Standard Model Higgs boson decay branching ratios at $m_H = 125.09$ GeV. . . . .                                                                                                                                                                                                                                                                      | 21  |
| 3.1  | The LHC main parameters required to reach the peak luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ for $pp$ collisions at $\sqrt{s}=14$ TeV [52]. . . . .                                                                                                                                                                                        | 24  |
| 3.2  | General performance goals of the ATLAS detector. The units for $E$ and $p_T$ are in GeV. . . . .                                                                                                                                                                                                                                                      | 31  |
| 3.3  | Main parameters of the four components of the muon spectrometer . . . .                                                                                                                                                                                                                                                                               | 41  |
| 5.1  | Summary of the MC simulated background samples adopted, including Drell-Yan, $t\bar{t}$ , single-top and diboson processes. . . . .                                                                                                                                                                                                                   | 80  |
| 5.2  | Signal samples (ggF, VBF and VH) for $m_H = 125$ GeV. . . . .                                                                                                                                                                                                                                                                                         | 80  |
| 5.3  | Summary of the muon object selection criteria used in this analysis. . . .                                                                                                                                                                                                                                                                            | 83  |
| 5.4  | Summary of the jet selection criteria used in this analysis. . . . .                                                                                                                                                                                                                                                                                  | 84  |
| 5.5  | Summary of the electron selection criteria used in this analysis. Please note electrons are not explicitly used, instead they are mainly taken into account in the electron-jet overlap removal. . . . .                                                                                                                                              | 84  |
| 5.6  | Ranking of the input variables contributing to the BDT (top variable is best ranked) . . . . .                                                                                                                                                                                                                                                        | 95  |
| 5.7  | Categorization criteria for ggF enriched categories. . . . .                                                                                                                                                                                                                                                                                          | 99  |
| 5.8  | Expected event yields (for different signal and background processes) and observed data yields in eight signal categories. The yields are corresponding to $36.1 \text{ fb}^{-1}$ and calculated within a $m_{\mu\mu}$ interval which centers at the simulated signal peak and contains 90% of the total signal events. . . . .                       | 99  |
| 5.9  | Expected signal event yields (normalized to $36.1 \text{ fb}^{-1}$ ; $m_{\mu\mu}$ within an interval, which centers at the simulated signal peak and contains 90% of the total signal events) from different production modes in eight signal categories. . . . .                                                                                     | 99  |
| 5.10 | Summary of the $\sigma_{\text{GS}}^{\text{B}}$ values adopted for each signal category. . . . .                                                                                                                                                                                                                                                       | 102 |
| 5.11 | Higgs $p_T$ systematic uncertainties for different ggF related categories. . .                                                                                                                                                                                                                                                                        | 103 |
| 5.12 | Systematic variation amplitudes for ggF and VBF 125 GeV signal between [110 GeV, 160 GeV] mass region in different signal categories. . . . .                                                                                                                                                                                                         | 104 |
| 5.13 | Spurious signal event yields corresponding to $36.1 \text{ fb}^{-1}$ for various mass points in different ggF and VBF categories. . . . .                                                                                                                                                                                                             | 107 |

---

|      |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |     |
|------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 5.14 | Final adopted spurious signal systematic uncertainties for each category, corresponding to $36.1 \text{ fb}^{-1}$ . . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | 109 |
| 6.1  | Summary of the simulated signal and background processes used for this analysis. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | 117 |
| 6.2  | Summary of the detailed criteria for the High- $p_T$ WP. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | 120 |
| 6.3  | Event yields for the background and data calculated in different $m_{ll}$ intervals beyond 400 GeV for electron channel. The errors quoted represent the total uncertainties including statistical, theoretical and experimental systematic uncertainties. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | 123 |
| 6.4  | Event yields for the background and data calculated in different $m_{ll}$ intervals beyond 400 GeV for muon channel. The errors quoted represent the total uncertainties including statistical, theoretical and experimental systematic uncertainties. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | 123 |
| 6.5  | Summary of the relative systematic uncertainties in the expected number of events at $m_{ll}$ of 2 TeV and 4 TeV. The values quoted in parenthesis correspond to $m_{ll} = 4 \text{ TeV}$ . The values shown for the background represent the relative variations in the total expected number of events in the corresponding $m_{ll}$ histogram bin containing the reconstructed $m_{ll}$ mass of 2 TeV (4 TeV). For the signal uncertainties the values are derived using the $Z'_\chi$ signal model with a pole mass of 2 TeV (4 TeV) by comparing yields around the mass peak (within the full width at half maximum) between the spectrum varied due to a given uncertainty and the nominal spectrum. “N/A” represents cases where the uncertainty is not applicable. . . . . | 128 |
| 6.6  | Observed and expected 95% CL lower mass limits for various $Z'$ theory models. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | 133 |
| 6.7  | Summary of observed and expected 95% CL lower limit numbers on $\Lambda$ for the LL, LR, RL, and RR chiral coupling scenarios, for both the constructive (const) and destructive (dest) interference cases using a uniform positive prior in $1/\Lambda^2$ or $1/\Lambda^4$ . . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | 134 |

*Dedicated to my parents!*





# Chapter 1

## Introduction

This dissertation presents the research work in the field of particle physics at the energy frontier, the Large Hadron Collider (LHC), with the ATLAS detector. Particle physics is pursuing the mysteries of the basic construction of matter and the fundamental forces at the smallest scale accessible. Based on modern quantum mechanics, the wave length of the particle is inversely proportional to the particle momentum. Therefore, a smaller distance is corresponding to a higher energy.

What's the fundamental building blocks of matter? This is an old and classical question that human beings tried to answer since a long time ago. The Chinese ancestors believed that matter is built from the combination of five basic elements: wood, fire, earth, metal and water. While the ancient Greek philosophers Leucippus, Democritus, and Epicurus brought up a philosophical idea around the 6th century BC that everything is composed of “uncuttable” elementary particles. These early ideas were all originating from the philosophical reasoning rather than based on the experimentation as the modern physics science.

Until the 19th century, John Dalton, an English chemist and physicist proposed that elements were composed of a fundamental particle based on his research on stoichiometry. Dalton named this particle “atom” after the Greek word atomos, with the meaning of “indivisible” [1]. However this Dalton's atom theory was strongly challenged later. In 1897, J.J. Thomson discovered an even smaller subatomic particle: electron [2], and after that in 1909 its charge was precisely measured through the famous “oil drop experiment” [3]. As a result, electron becomes the first elementary building block ever discovered. Then by the early 20th century, physicists found out that each atom contains a nucleus with positive charge and majority of its mass concentrated, which was

deducted from the remarkable Rutherford gold foil experiment [4]. Then in 1913 Niels Bohr proposed the Bohr model [5, 6, 7], stating that electrons in atoms can only move in nucleus certain orbits without electromagnetic radiation, and energy change can only happen for the cases when electrons jump from one allowed orbit to another. In 1918, the hydrogen nucleus was confirmed as a particle with a positive charge and named as proton by Rutherford [8]. Later in 1932, James Chadwick discovered another constituent of nucleus, neutron, a neutrally-charged twin to proton [9]. Up to then, people were finally convinced that nucleus are composed of protons and neutrons. In 1936, another elementary particle “muon” was discovered by Carl D. Anderson [10].

Throughout the 1950s and 1960s, particle accelerators were invented for the particle physics researches. With the beam collision or beam-target experiments, a large variety of particles (“hadrons”) were discovered, which were referred to as the “particle zoo”. To classify these particles, in 1964 Murray Gell-Mann and George Zweig independently proposed the quark model [11, 12]. Later in the 1970s, a gauge theory was developed to describe the strong interactions, known as quantum chromodynamics (QCD) [13, 14, 15]. The theory on the electromagnetic and weak interactions were developed prior to the birth of QCD. In 1961, Sheldon Glashow brought up the unified electroweak (EW) theory to combine these two interactions [16]. Later in 1964, Robert Brout, Francois Englert and Peter Higgs from three independent groups proposed the Higgs mechanism [17, 18, 19, 20] to explain the generation of masses of the vector bosons  $W$  and  $Z$ , which are the weak interaction force carriers, through electroweak symmetry breaking (EWSB). Then in 1967, this Higgs mechanism was incorporated into the Glashow’s theory by Steven Weinberg and Abdus Salam [21, 22], which gave the final formulation of the EW theory. Together with QCD, they formed the foundation of the well-known Standard Model (SM) theory, which describes three of the four fundamental forces existing in our universe: strong, electromagnetic, and weak interactions. The gravity is not included in the SM since it is too weak and irrelevant to sub-atomic physics.

Since developed in the 1970s, the SM has been well tested by various experiments. In addition to the known electromagnetic force carrier  $\gamma$ , all the other predicted force carriers have been discovered: in 1979, through three-jet events the strong interaction carrier gluon was observed indirectly at DESY [23]; and in 1983 weak gauge bosons  $W$  and  $Z$  were discovered at CERN by Carlo Rubbia and Simon van der Meer [24, 25]. The last matter particle, the heaviest quark “top”, was discovered at Fermilab in 1995 [26]. By the end of the 20th century, the only missing particle in the SM was the Higgs boson.

Moving into the 21th century, physicists have successfully carried out a magnificent project: the LHC at CERN, which becomes the largest and most powerful collider ever built. The LHC opens a new era for the particle physics and provides plenty of opportunities for people to explore the less-known or un-known fields. On July 4th 2012, the discovery of Higgs boson was announced by the ATLAS and CMS collaborations at CERN [27, 28]. This landmark discovery solved the last missing piece of the SM. The Nobel Prize in Physics 2013 was awarded jointly to Peter Higgs and Francois Englert “for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particles, by the ATLAS and CMS experiments at CERN’s Large Hadron Collider”.

After the Higgs discovery during the LHC Run 1 program, one of the major missions of the experiments for the LHC Run 2 is to deeply explore the SM Higgs sector by measuring the Higgs couplings with high precision and searching for its rare decay modes. Dimuon decays from the SM Higgs boson can provide clean signature to measure a new type of Yukawa coupling to the second generation of fermions, which is crucial for the Higgs property study. In the SM, the predicted branching fraction for the Higgs boson decaying into dimuon is  $2.18 \times 10^{-4}$  for  $m_H = 125$  GeV. And any deviations observed in experiments from this prediction could be a sign of new physics. A search for the SM  $H \rightarrow \mu\mu$  process was carried out by the ATLAS collaboration using the data collected at the LHC Run 1, corresponding to a total integrated luminosity of  $24.8 \text{ fb}^{-1}$  [29]. For  $m_H = 125$  GeV, the observed (expected) upper limit on signal strength was set to be 7.1 (7.2) times the SM prediction at 95% confidence level (CL). The CMS collaboration performed this search as well at the Run 1, and set similar limit results [30]. After two years’ long shutdown, the LHC re-started the Run 2 collisions at a center-of-mass energy  $\sqrt{s} = 13$  TeV in June 2015. The data collected by the ATLAS detector in 2015 and 2016 is corresponding to a total integrated luminosity of  $36.1 \text{ fb}^{-1}$ , which is used to search for the SM  $H \rightarrow \mu\mu$  process as one major aspect of this dissertation. The corresponding results have already been published in the journal [31].

Another major mission of the LHC experiments is to search for new physics beyond the SM (BSM) at the highest energies. It is commonly believed that the SM is not an ultimate theory for the particle physics since there are important physics questions that cannot be answered by the SM. Such as it cannot explain the baryon asymmetry, dark matter, and dark energy observed in the universe. Also, the SM does not incorporate the gravity in its framework, and it cannot explain the different mass scales of three

generations of quarks and leptons. Therefore various BSM theoretical models have been developed to address the unanswered questions of the SM, such as super-symmetry models, the Sequential Standard Model (SSM), and Grand Unified theory (GUT). All these models predict a new neutral gauge boson  $Z'$  which can manifest as a narrow resonance via decaying into dileptons. In addition to the new resonance predictions, some BSM models describe a new interaction which can be explored at a lower energy scale. Such kind of interaction can represent a Contact Interaction (CI) between the initial quarks and final-state leptons. During the Run 1, the searches for  $Z'$  and CI were carried out by the ATLAS collaboration using  $20.3 \text{ fb}^{-1}$  of data [32, 33]. The lower limit on the  $Z'_{SSM}$  mass was set to be 2.90 TeV at 95% CL. And the most stringent lower limits on the CI energy scale,  $\Lambda$ , were set at 21.6 TeV and 17.2 TeV for constructive and destructive interference respectively. The CMS collaboration reported similar results based on the Run 1 data as well [34]. Another major research work that will be presented in this dissertation is searching for new phenomena with the dilepton final state using the data ( $36.1 \text{ fb}^{-1}$ ) recorded during the first two years of Run 2. The corresponding results from this work have also been published in the journal [35].

This dissertation's contents are organized in the following ways. Chapter 2 briefly introduces the SM, BSM models related to this dissertation, and the LHC phenomenology. Chapter 3 gives an overview of the LHC and the ATLAS detector. The detector simulation and object reconstruction at the ATLAS experiment are described in Chapter 4. Chapter 5 presents the search for the SM Higgs boson decaying into dimuon. And the search for new high-mass phenomena with the dilepton final state is presented in Chapter 6. In the end, the summary and outlook are given in Chapter 7.

# Chapter 2

## Theory

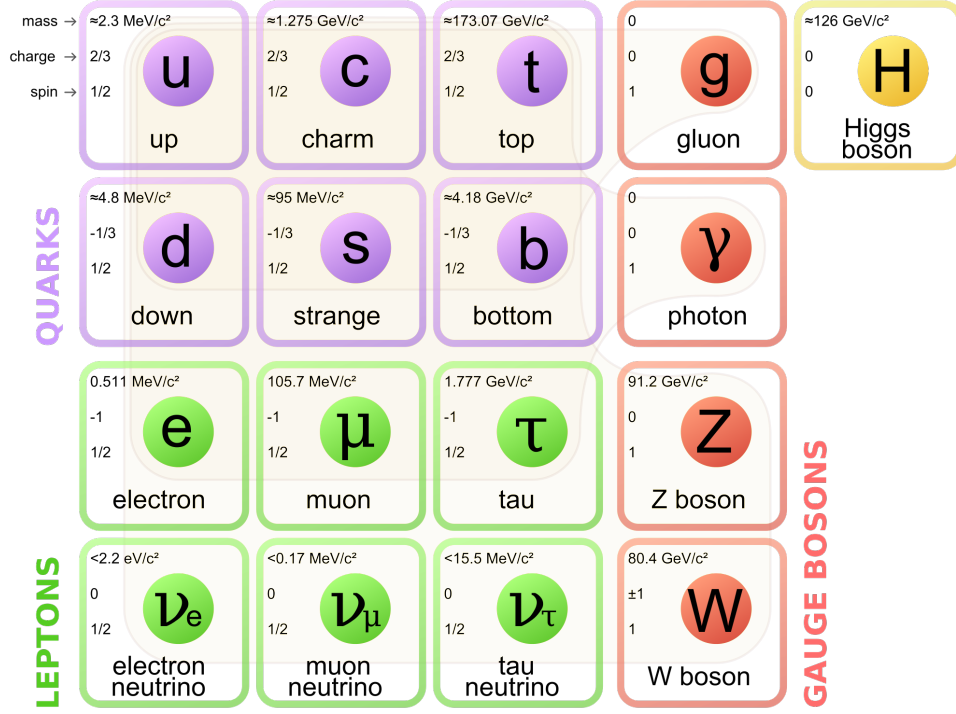
### 2.1 The Standard Model of particle physics

The SM represents our current understanding of particle physics in describing the elementary particles and their interactions. It is a quantum field theory, developed since the 1960s based on gauge invariance which naturally introduces interactions, as well as the Higgs mechanism, which breaks the gauge symmetry to generate masses to the weak force carriers ( $W$  and  $Z$ ). The SM provides an elegant theoretical framework constructed with symmetry groups  $SU(3)_C \times SU(2)_L \times U(1)_Y$ , where the  $SU(3)_C$  group represents the strong interactions with subscript  $C$  denoting the color charge, while the  $SU(2)_L \times U(1)_Y$  groups describe the electroweak interactions with  $L$  and  $Y$  denoting the left-handed fermions and weak hypercharge, respectively. Over the past four decades, the SM predictions have been successfully examined through various experiments with high degrees of precision.

#### 2.1.1 Elementary particles in the Standard Model

The elementary particles in the SM are classified into three generations of fermions (spin- $\frac{1}{2}$ ), vector bosons (spin-1 force carriers), and a scalar (spin-0 Higgs boson), as shown in Figure [2.1](#).

The fermions include three generations of left-handed lepton doublets: electron ( $e$ ) and electron neutrino ( $\nu_e$ ); muon ( $\mu$ ) and muon neutrino ( $\nu_\mu$ ); tau ( $\tau$ ) and tau neutrino ( $\nu_\tau$ ). Besides there are three generations of left-handed quark doublets: up ( $u$ ) and


 FIGURE 2.1: The elementary particles of the Standard Model ([Wikipedia](#)).

down ( $d$ ); charm ( $c$ ) and strange ( $s$ ); top ( $t$ ) and bottom ( $b$ ). The leptons  $e$ ,  $\mu$  and  $\tau$  carry electric charge of  $-1$  (in the unit of elementary charge  $e$ ), while the neutrinos  $\nu_e$ ,  $\nu_\mu$  and  $\nu_\tau$  are electrically neutral. All these leptons can participate in electroweak interactions. For the quarks,  $u$ ,  $c$  and  $t$  carry electric charge of  $2/3$ , while  $d$ ,  $s$  and  $b$  carry electric charge of  $-1/3$ . Besides the electric charge, quarks also carry color charges, thus they can interact via the strong interaction as well. As a result, quarks can participate in all the three types of interactions described in the SM. The quarks can be strongly bound together to form color-neutral composite particles: hadrons, which either contain a quark and an antiquark (mesons) or three quarks (baryons).

For the boson category of the SM, there are three types of gauge bosons with the spin of 1, among which there are 8 massless gluons ( $g$ ) as the strong force carriers, and a massless photon ( $\gamma$ ) as the electromagnetic force carrier, while the  $Z$  and the  $W^\pm$  bosons are massive ( $91.2 \text{ GeV}$  and  $80.4 \text{ GeV}$  respectively) as the weak force carriers. In the SM, electromagnetic and weak interactions are unified as the electroweak interactions. Figure 2.2 depicts the corresponding forces mediated by these gauge bosons in the SM.

Besides the gauge bosons, there is another massive elementary scalar particle: the Higgs boson which is crucial for explaining the origin of masses of massive gauge bosons

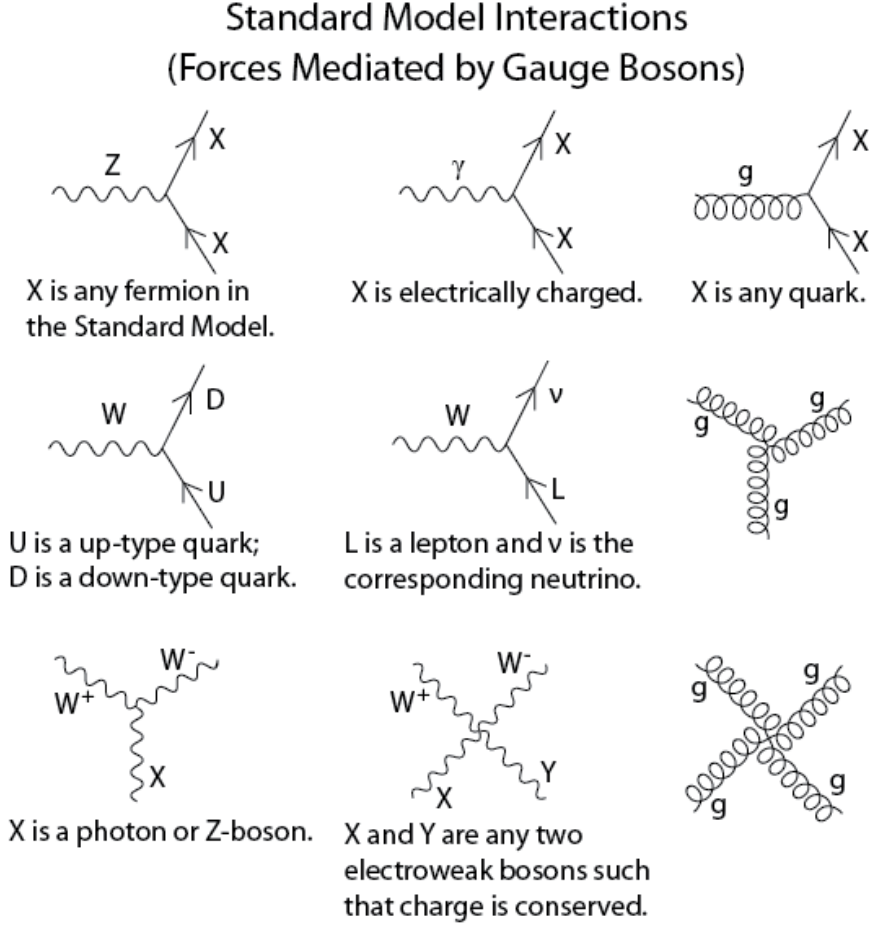


FIGURE 2.2: The SM interactions mediated by gauge bosons ([Wikipedia](#)). The solid straight lines represent the fermions (e.g.  $u$ ,  $d$ ,  $e$ ,  $\mu$ ...), while the wave lines denote electroweak bosons (i.e.  $W$ ,  $Z$  and  $\gamma$ ), and the loops lines stand for the gluons.

and fermions. According to the most precise ATLAS and CMS combined measurement using the LHC Run 1 dataset, the mass of the Higgs boson is  $125.09 \pm 0.24$  GeV [36].

### 2.1.2 Theoretical formalism of the Standard Model

The Lagrangian of the SM, which describes the interactions of the elementary particles, can be written as

$$\mathcal{L}_{SM} = \mathcal{L}_{EW} + \mathcal{L}_{QCD} \quad (2.1)$$

where  $\mathcal{L}_{EW}$  is the term from unified electroweak theory and  $\mathcal{L}_{QCD}$  represents the quantum chromodynamics (QCD) term. Further deductions of  $\mathcal{L}_{EW}$  and  $\mathcal{L}_{QCD}$  are described in the following contents.

The QCD term  $\mathcal{L}_{QCD}$  [37] can be written as:

$$\mathcal{L}_{QCD} = \bar{\psi}_q^i (i\gamma^\mu) (D_\mu)_{ij} \psi_q^j - m_q \bar{\psi}_q^i \psi_{qi} - \frac{1}{4} F_{\mu\nu}^a F^{a\mu\nu}. \quad (2.2)$$

For this equation,  $\psi_q^i$  represents a quark field with  $i$  denoting color index,  $\psi_q = (\psi_{qR}, \psi_{qG}, \psi_{qB})^T$ , and  $\gamma^\mu$  is a Dirac matrix which depicts the vector nature of the strong interaction with  $\mu$  representing a Lorentz vector index. The term  $m_q$  accounts for the possibility of non-zero quark mass, which is induced by the Higgs mechanism (more details in the next Subsection 2.1.3).  $F_{\mu\nu}^a$  denotes the gluon field strength tensor for a gluon with color index  $a$  (in the adjoint representation,  $a \in [1, 2, \dots, 8]$ ). And  $D_\mu$ , which is the covariant derivative in QCD, can be written into the formula below

$$(D_\mu)_{ij} = \delta_{ij} \partial_\mu - i g_s t_{ij}^a A_\mu^a, \quad (2.3)$$

with  $g_s$  denoting the strong coupling parameter which can be expressed in the relation with  $\alpha_s$ :  $g_s^2 = 4\pi\alpha_s$ .  $t_{ij}^a$  term is proportional to the hermitian and traceless Gell-Mann matrices of  $SU(3)_C$ , while  $A_\mu^a$  is the gluon field with color index  $a$ .

The  $\mathcal{L}_{EW}$  term of Equation 2.1 is based on  $SU(2)_L \times U(1)_Y$  gauge symmetry group, which can be further written into a combination of four terms as below [38]

$$\mathcal{L}_{EW} = \mathcal{L}_{gauge} + \mathcal{L}_{fermion} + \mathcal{L}_{Higgs} + \mathcal{L}_{Yukawa}. \quad (2.4)$$

For Equation 2.4,  $\mathcal{L}_{gauge}$  is the gauge part, which can be expressed as

$$\mathcal{L}_{gauge} = -\frac{1}{4} W_{\mu\nu}^i W^{\mu\nu i} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}, \quad (2.5)$$

where  $W_\mu^i$  ( $i = 1, 2, 3$ ) and  $B_\mu$  represent  $SU(2)_L$  and  $U(1)_Y$  gauge fields respectively, with the corresponding field strength tensors given by

$$\begin{aligned} B_{\mu\nu} &= \partial_\mu B_\nu - \partial_\nu B_\mu \\ W_{\mu\nu}^i &= \partial_\mu W_\nu^i - \partial_\nu W_\mu^i - g \epsilon_{ijk} W_\mu^j W_\nu^k, \end{aligned} \quad (2.6)$$

and here  $g$  is the coupling strength to the  $SU(2)_L$  gauge coupling and  $\epsilon_{ijk}$  is defined as the total antisymmetric tensor. The gauge Lagrangian has three and four-point self interaction of the  $W^i$  fields, from which the triple and quartic gauge boson couplings arise.



The gauge covariant derivative  $D_\mu$  is defined as:

$$D_\mu = \partial_\mu + ig \frac{\tau^i}{2} W_\mu^i + ig' \frac{Y}{2} B_\mu, \quad (2.7)$$

where  $Y$  represents the  $U(1)$  charge and  $\tau^i$  are the Pauli matrices.  $g'$  is the  $U(1)$  gauge coupling. The square of the covariant derivative leads to three and four-point interactions between the gauge and scalar fields. Then we can write the fermion term of Equation 2.4 as:

$$L_{fermion} = \sum_{m=1}^F (\bar{q}_{mL}^0 i \gamma_\mu D_\mu q_{mL}^0 + \bar{l}_{mL}^0 i \gamma_\mu D_\mu l_{mL}^0 + \bar{u}_{mR}^0 i \gamma_\mu D_\mu u_{mR}^0 + \bar{d}_{mR}^0 i \gamma_\mu D_\mu d_{mR}^0 + \bar{e}_{mR}^0 i \gamma_\mu D_\mu e_{mR}^0), \quad (2.8)$$

where  $m$  is the family index, and  $F$  is the number of families for fermions. The subscripts  $L$  ( $R$ ) stand for the left (right) chiral projections of the fermion field  $\psi$ :  $\psi_{L(R)} \equiv (1 \mp \gamma_5)\psi/2$ . The left-handed quarks ( $q_{mL}^0$ ) and leptons ( $l_{mL}^0$ ) transform as  $SU(2)$  doublets, which can be expressed as the following terms in Equation 2.9 and Equation 2.10. The other right-handed fields  $u_{mR}^0$ ,  $d_{mR}^0$  and  $e_{mR}^0$  are  $SU(2)$  singlets, representing the right-handed  $u$ ,  $d$  and  $e$  respectively. The superscripts 0 in the terms denotes weak eigenstates (i.e. fields transforming according to definite  $SU(2)$  representations).

$$q_{mL}^0 = \begin{pmatrix} u_m^0 \\ d_m^0 \end{pmatrix}_L \quad (2.9)$$

$$l_{mL}^0 = \begin{pmatrix} \nu_m^0 \\ e_m^0 \end{pmatrix}_L \quad (2.10)$$

Then for the Higgs term of  $\mathcal{L}_{EW}$ , it can be written into:

$$\mathcal{L}_{Higgs} = (D^\mu \phi)^\dagger D_\mu \phi - V(\phi), \quad (2.11)$$

and here  $\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$  is a complex Higgs scalar, which is a doublet under  $SU(2)$  with  $U(1)$  charge  $y_\phi = +\frac{1}{2}$ .  $V(\phi)$  term is the Higgs potential. The combination of  $SU(2)_L \times U(1)_Y$  invariance and renormalizability restricts  $V$  into the form as below:

$$V(\phi) = +\mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2. \quad (2.12)$$

When  $\mu^2$  is less than 0, the spontaneous symmetry breaking (more details in Subsection 2.1.3) happens.  $\lambda$  term represents a quartic self-interaction between the scalar fields and  $\lambda > 0$  is the necessary condition of vacuum stability.

The last piece of  $\mathcal{L}_{EW}$  is the Yukawa term, which is shown as below

$$\begin{aligned} \mathcal{L}_{Yukawa} = & - \sum_{m,n=1}^F [\Gamma_{mn}^u \bar{q}_{mL}^0 \tilde{\phi} u_{nR}^0 + \Gamma_{mn}^d \bar{q}_{mL}^0 \phi d_{nR}^0 \\ & + \Gamma_{mn}^e \bar{l}_{mn}^0 \phi e_{nR}^0] + h.c.. \end{aligned} \quad (2.13)$$

and here the  $\Gamma_{mn}$  matrices are used to describe the Yukawa couplings between the single Higgs doublet ( $\phi$ ) and the various flavors of quarks and leptons ( $m$  and  $n$ ). The  $\mathcal{L}_{Yukawa}$  is associated with the Higgs mechanism, which will be discussed in the next subsection.

### 2.1.3 The Higgs mechanism

Initially in the SM, the gauge invariance does not allow mass terms for the gauge bosons and fermions, which are not consistent with the experimental observations. Thus, the Higgs field as described in the previous subsection is introduced to trigger the electroweak symmetry breaking (EWSB) in vacuum, and as a result the  $W$ ,  $Z$  bosons and fermions interact with the Higgs field to acquire masses. In the SM, this specific process for the generation of gauge bosons' masses through EWSB is named ‘‘Higgs Mechanism’’.

The Higgs field  $\phi$  is a doublet in the  $SU(2)$  space and can be written in a Hermitian basis as

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 - i\phi_2 \\ \phi_3 - i\phi_4 \end{pmatrix}, \quad (2.14)$$

where  $\phi_i = \phi_i^\dagger$  denotes four Hermitian fields. In this new basis, the Higgs potential term of Equation 2.11 can be expressed as

$$V(\phi) = +\mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2 = \frac{1}{2} \mu^2 \left( \sum_{i=1}^4 \phi_i^2 \right) + \frac{1}{4} \lambda \left( \sum_{i=1}^4 \phi_i^2 \right)^2, \quad (2.15)$$

where  $\mu$  is a mass-dependent parameter and  $\lambda$  term represents the quartic Higgs scalar coupling. This Higgs potential  $V(\phi)$  is minimized for any  $\phi_i$  that satisfies  $\langle 0 | \phi_i | 0 \rangle = (-\mu^2/\lambda)^{1/2}$ . To simplify the situation but without losing generality, the axis in this four-dimensional space is chosen to make  $\langle 0 | \phi_i | 0 \rangle = 0$ ,  $i = 1, 2, 4$  and  $\langle 0 | \phi_3 | 0 \rangle = \nu$ . As a result,

Equation 2.15 can be re-written into

$$V(\phi) \rightarrow V(v) = \frac{1}{2}\mu^2\nu^2 + \frac{1}{4}\lambda\nu^4. \quad (2.16)$$

Then the minimization of this potential is dependent on the sign of  $\mu^2$ . As depicted in Figure 2.3, for  $\mu^2 > 0$  case (left plot in Figure 2.3), the minimization can be acquired at  $\nu = 0$ , which means that the vacuum is empty space and  $SU(2)_L \times U(1)_Y$  is not broken through this minimization. A more exciting scenario happens for  $\mu^2 < 0$  (right plot in Figure 2.3). Under this situation the minimum occurs when  $\nu$  equals  $\sqrt{\frac{-\mu^2}{\lambda}}$ , and the  $SU(2)_L \times U(1)_Y$  symmetry is broken spontaneously. Therefore, the vacuum  $\phi_0$  of Higgs

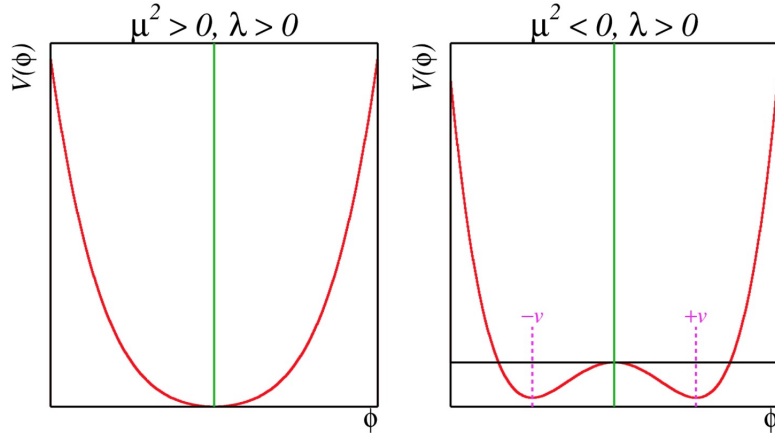


FIGURE 2.3: The Higgs potential  $V(\phi)$  for  $\mu^2 > 0$  (left) and  $\mu^2 < 0$  (right).

field can be expressed as

$$\phi_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \nu \end{pmatrix}. \quad (2.17)$$

Furthermore, the Higgs field can be expanded around the vacuum as

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \nu + H \end{pmatrix}, \quad (2.18)$$

where  $H$  is a Hermitian field, representing the physical Higgs scalar. Then the scalar covariant kinetic energy term of Equation 2.11 can be re-written into

$$(D^\mu \phi)^\dagger D_\mu \phi = \frac{1}{2} \begin{pmatrix} 0 & \nu \end{pmatrix} \left[ \frac{g}{2} \tau^i W_\mu^i + \frac{g'}{2} B_\mu \right]^2 \begin{pmatrix} 0 \\ \nu \end{pmatrix} + H \text{ terms}. \quad (2.19)$$

By using  $\tau^i = \sigma^i/2$ , we can evaluate the matrix product and further express Equation 2.19 into

$$(D^\mu \phi)^\dagger D_\mu \phi = \frac{1}{2} \frac{\nu^2}{4} [g^2 (W_\mu^1)^2 + g^2 (W_\mu^2)^2 + (-gW_\mu^3 + g'B_\mu)^2] \quad (2.20)$$

Then the three massive vector bosons can be notated as the following equations

$$\begin{aligned} W_\mu^\pm &= \frac{1}{\sqrt{2}} (W_\mu^1 \mp iW_\mu^2), \\ Z_\mu &= \frac{1}{\sqrt{g^2 + g'^2}} (gW_\mu^3 - g'B_\mu), \end{aligned} \quad (2.21)$$

which correspond to the  $W^\pm$  and  $Z$  gauge bosons. The fourth vector field, which is orthogonal to  $Z_\mu$  and corresponding to the photon:

$$A_\mu = \frac{1}{\sqrt{g^2 + g'^2}} (g'W_\mu^3 + gB_\mu). \quad (2.22)$$

After substitution by using Equation 2.21 and 2.22, we can re-write the  $\mathcal{L}_{Higgs}$  into:

$$\begin{aligned} \mathcal{L}_{Higgs} &= (D^\mu \phi)^\dagger D_\mu \phi - V(\phi) \\ &= m_W^2 W^{\mu+} W_\mu^- \left(1 + \frac{H}{\nu}\right)^2 + \frac{1}{2} m_Z^2 Z^\mu Z_\mu \left(1 + \frac{H}{\nu}\right)^2 \\ &\quad + \frac{1}{2} (\partial_\mu H)^2 - V(\phi). \end{aligned} \quad (2.23)$$

Here  $m_W$  and  $m_Z$  denote the  $W$  and  $Z$  boson masses after the EWSB, which are expressed in Equation 2.24, while the photon remains massless. It also describes the triple ( $W^+W^-H$  and  $ZZH$ ) and quartic ( $W^+W^-H^2$  and  $ZZH^2$ ) interactions between the  $W/Z$  boson and Higgs boson, which are shown in the left and middle plots of the first two rows in Figure 2.4. And such kind of gauge coupling is proportional to the mass of the gauge boson squared.

$$\begin{aligned} m_W &= g \frac{\nu}{2}, \\ m_Z &= \sqrt{g^2 + g'^2} \cdot \frac{\nu}{2}, \end{aligned} \quad (2.24)$$

Further a weak mixing angle  $\theta_W$  can be defined by

$$\cos\theta_W = \frac{g}{\sqrt{g^2 + g'^2}}, \quad \sin\theta_W = \frac{g'}{\sqrt{g^2 + g'^2}}, \quad \tan\theta_W = \frac{g'}{g}. \quad (2.25)$$

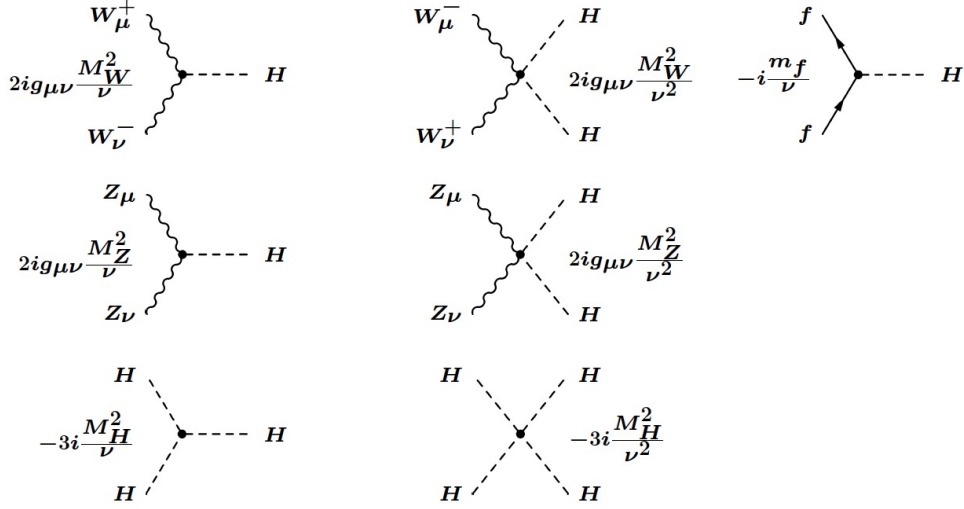


FIGURE 2.4: Higgs interaction vertices in the SM. The wave line represents the  $W$  or  $Z$  boson; the dashed line represents the Higgs boson; while the solid line represents the fermion.

Then the  $m_W$  and  $m_Z$  can be written into a relation with  $\theta_W$  as

$$m_W = \cos\theta_W \cdot m_Z \quad (2.26)$$

After the symmetry breaking, the Higgs potential term in the unitary gauge can be written into

$$V(\phi) = -\frac{\mu^4}{4\lambda} - \mu^2 H^2 + \lambda \nu H^3 + \frac{\lambda}{4} H^4. \quad (2.27)$$

Here the first term is a constant while the second term denotes the mass of the Higgs boson (tree-level):

$$m_H = \sqrt{-2\mu^2} = \sqrt{2\lambda} \cdot \nu. \quad (2.28)$$

The third and fourth terms denote the triple and quartic interactions of the Higgs scalar, as shown in the bottom two plots in Figure 2.4.  $\lambda$  specifies the quartic Higgs coupling which is not predicted in the SM.

Similarly, through the Higgs mechanism, the fermions can acquire their own masses. The Yukawa interaction term  $\mathcal{L}_{Yukawa}$  in the unitary gauge can be written into:

$$\begin{aligned} \mathcal{L}_{Yukawa} &= -\left( \sum_{m,n=1}^F \bar{u}_{mL}^0 \Gamma_{mn}^u \left( \frac{\nu + H}{\sqrt{2}} \right) u_{mR}^0 + (d, e) \text{ terms} \right) + h.c. \\ &= -(\bar{u}_L^0 (M^u + h^u H) u_R^0 + (d, e) \text{ terms}) + h.c., \end{aligned} \quad (2.29)$$

where  $u_L^0 = (u_{1L}^0 u_{2L}^0 \dots u_{FL}^0)^T$  denotes an  $F$ -component column vector and  $u_R^0$  has a similar definition.  $M^\mu = \Gamma_{mn}^u \nu / \sqrt{2}$ , which is an  $F \times F$  fermion mass matrix induced by the EWSB.  $h^u = M^u / \nu = g M^u / 2m_W$  is the Yukawa coupling matrix. Then in terms of the mass eigenstate fermions, the Yukawa term can be further written as:

$$\mathcal{L}_{Yukawa} = - \sum_i m_i \bar{\psi}_i \psi_i (1 + \frac{g}{2m_W} H) = - \sum_i m_i \bar{\psi}_i \psi_i (1 + \frac{H}{\nu}), \quad (2.30)$$

where  $\psi_i$  and  $m_i$  represent the field and mass for the  $i^{th}$  fermion respectively. Then we can define a parameter  $g_i^Y$ , denoting the Yukawa coupling between the Higgs boson and the  $i^{th}$  fermion, as:

$$g_i^Y = \frac{gm_i}{2m_W}, \quad (2.31)$$

which shows that this Yukawa coupling is proportional to the mass of the corresponding fermion.

## 2.2 The Related Theories Beyond the Standard Model

As described in Section 1, although the SM can successfully explain most of the current particles and phenomena, it's still not a perfect theoretical framework. Various theories Beyond the SM (BSM) have been predicted. Using the dilepton final states is one of the methodologies to explore the new BSM phenomena, since its experimental signature is rather simple, which can be fully reconstructed with relatively high acceptance efficiencies. This subsection briefly introduces several BSM theories related to the new phenomena decaying into dilepton final states.

### 2.2.1 Sequential Standard Model

Several BSM theories predict the existence of a neutral heavy gauge boson:  $Z'$ . As the benchmark, the Sequential Standard Model (SSM) [39] predicts that  $Z'$  boson has the same couplings to fermions as the SM  $Z$  boson. The  $Z'_{SSM}$  has a width of approximately 3% of its mass. In the context of gauge theories, the  $Z'_{SSM}$  is not existing. It is only expected when  $Z'_{SSM}$  has different couplings to the exotic fermions, or its existence is an excited state of the  $Z$  boson in models with extra dimensions at the weak scale. Nevertheless, the  $Z'_{SSM}$  plays an important role as a useful reference case when comparing constraints from various sources.

### 2.2.2 $E_6$ –motivated $Z'$ models

Besides the SSM theory, a more theoretically-motivated (by the Grand Unification Theories) is the  $E_6$  based model [40]. In this model,  $E_6$  gauge group is first broken into  $SO(10) \times U(1)_\psi$ , and  $SO(10)$  is further broken into  $SU(5) \times U(1)_\chi$ . The existences of  $U(1)_\psi$  and  $U(1)_\chi$  symmetries predict two additional gauge bosons  $Z'_\psi$  and  $Z'_\chi$  which can mix as well, with  $\theta_{E_6}$  as the corresponding mixing angle. As a result, the corresponding  $Z'$  bosons can be expressed as

$$Z'(\theta_{E_6}) = Z'_\psi \cos\theta_{E_6} + Z'_\chi \sin\theta_{E_6} \quad (2.32)$$

For this equation,  $\theta_{E_6}$  determines the  $Z'$  boson's coupling strength to SM fermions and also its intrinsic width. And six different values of  $\theta_{E_6}$  result in six  $Z'$  states:  $Z'_\psi$ ,  $Z'_N$ ,  $Z'_\eta$ ,  $Z'_I$ ,  $Z'_S$  and  $Z'_\chi$ . Their corresponding widths range between 0.5% and 1.2% of their individual masses. For  $E_6$  model, the  $Z'$  couplings to the SM  $W_\pm$  and  $Z$  bosons are zero. Figure 2.5 shows the Leading-Order (LO) cross-section times the branching ratio of decaying into dilepton final states for various  $E_6$   $Z'$  models as a function of pole mass at  $\sqrt{s} = 13$  TeV with  $Z'_{SSM}$  curve overlaid as well.

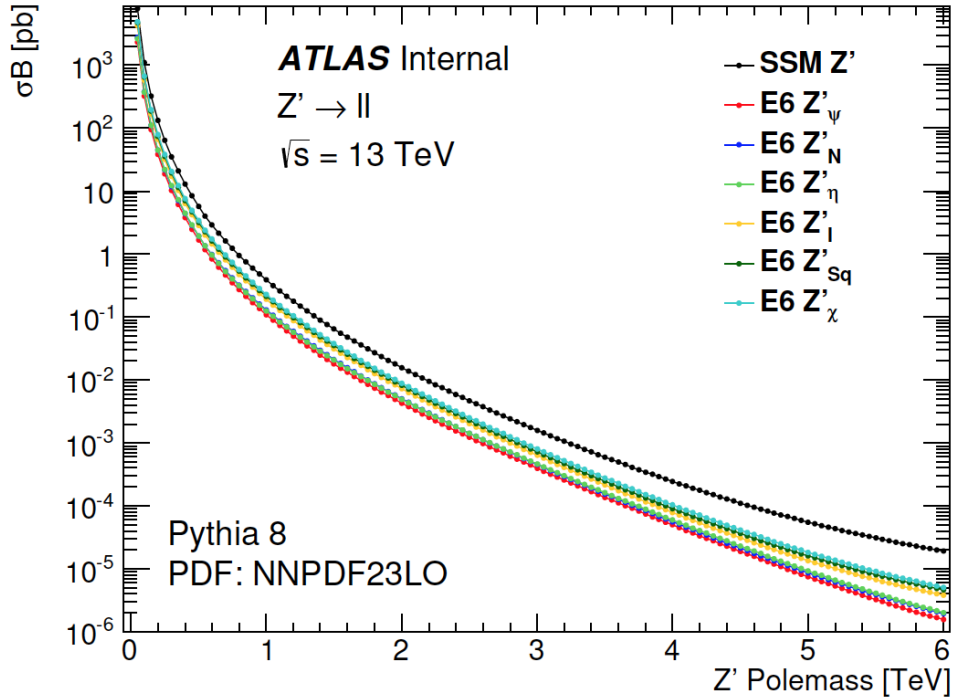


FIGURE 2.5: Leading-order cross-section times branching ratio to a single dilepton flavour for various  $Z'$  models as a function of polemass for  $pp$  collisions at  $\sqrt{s} = 13$  TeV

### 2.2.3 Contact interactions

With dilepton final state, we can also try to search for the non-resonant phenomena “Contact Interactions (CI)” [41, 42] at a relatively lower energy scale. The CI accommodates deviations from the SM prediction in proton–proton scattering originating from quark and lepton compositeness with a characteristic energy scale  $\Lambda$ , which is corresponding to the binding energy between fermion constituents. The Lagrangian of this process can be written as below

$$\begin{aligned} \mathcal{L} = & \frac{g^2}{\Lambda^2} [\eta_{LL}(\bar{q}_L \gamma_\mu q_L)(\bar{l}_L \gamma^\mu l_L) + \eta_{RR}(\bar{q}_R \gamma_\mu q_R)(\bar{l}_R \gamma^\mu l_R) \\ & + \eta_{LR}(\bar{q}_L \gamma_\mu q_L)(\bar{l}_R \gamma^\mu l_R) + \eta_{RL}(\bar{q}_R \gamma_\mu q_R)(\bar{l}_L \gamma^\mu l_L)]. \end{aligned} \quad (2.33)$$

Here  $g$  is a coupling constant, which is set to satisfy  $g^2/4\pi=1$  by convention. And  $q_{L,R}$  and  $l_{L,R}$  represent left-handed and right-handed quark and lepton fields. The parameters  $\eta_{ij}$  ( $i$  and  $j$  represent L (left) or R (right)) determine the chiral structure of CI. Furthermore, the sign of  $\eta_{ij}$  reflects whether the interference between the CI process and Drell–Yan (DY) process is constructive ( $\eta_{ij} = -1$ ) or destructive ( $\eta_{ij} = +1$ ). The cross section of  $q\bar{q} \rightarrow l^+l^-$ , with the CI process taken into account, can be written as

$$\sigma_{tot}(m_{ll}) = \sigma_{DY}(m_{ll}) - \eta_{ij} \frac{F_I}{\Lambda^2} + \frac{F_C}{\Lambda^4}, \quad (2.34)$$

where the term  $\sigma_{DY}(m_{ll})$  accounts for the DY process, and the second term denotes the interference between the CI and DY processes, while the last term represent the pure CI process. Figure 2.6 depicts the Feynman diagram of the LO DY process with additional CI process in the  $\mu^+\mu^-$  final state. A similar diagram can be applied to the  $e^+e^-$  final state as well.

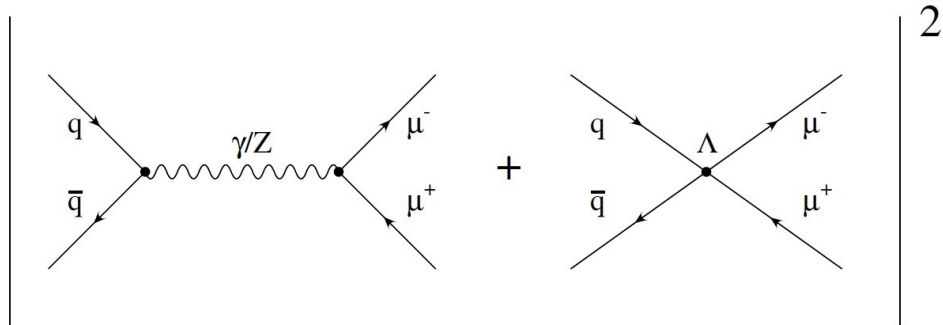


FIGURE 2.6: Feynman diagram of LO DY process with additional CI process with energy scale  $\Lambda$  in the  $\mu^+\mu^-$  final state.



## 2.3 Physics at the Large Hadron Collider

The development of hadron colliders is one of the major driving forces for particle physics research to move forward. From 2009, the operation of the Large Hadron Collider (LHC) has opened a new chapter for probing the nature of the particles. This subsection briefly introduces the phenomenology of the hadron collider and also the Higgs boson production at the LHC.

### 2.3.1 Phenomenology of hadronic collision

As we know, protons are composed of quarks and gluons. Therefore, for the proton-proton ( $pp$ ) collisions at the LHC, the interactions actually take place at the partons (quark and gluon) level instead of the protons level. The parton interaction can be classified into either hard or soft scattering process, which depends on the momentum transfer during the interaction. QCD is the underlying theory for hard and soft processes, however the approach and level of understanding quite differ between these two cases. For hard processes, like Higgs boson or high  $p_T$  jet production, the rates and event properties can be precisely predicted using the perturbation theory. While on the other hand, for soft processes (e.g. the total cross section, the underlying event and so on), their rates and properties are dominated by non-perturbative QCD effects, which are less understood. For many hard processes, soft interactions are occurring along with the hard interactions. Figure 2.7 depicts a typical event from the hadronic collisions [43] and its main features are summarized below:

- Parton Distribution Function (PDF)  $f_i(x, Q^2)$  represents the probability of finding a parton with flavor  $i$  (quark or gluon) carrying a momentum fraction of  $x$  at an energy scale of  $Q$ . Figure 2.8 illustrates the measured PDFs from NNPDF3.0 which is accurate in perturbative QCD at NNLO [44].
- Fragmentation and hadronization are the processes of producing final state particles (jets) from the partons produced in the hard scattering.
- Initial/Final state radiation results from QCD or QED radiation of incoming or outgoing partons that carry color charge as well as the QED final state radiation from outgoing leptons.
- Underlying events are composed of all the soft processes which accompany with the hard scattering, including proton remnants, multiple parton interactions and so on.

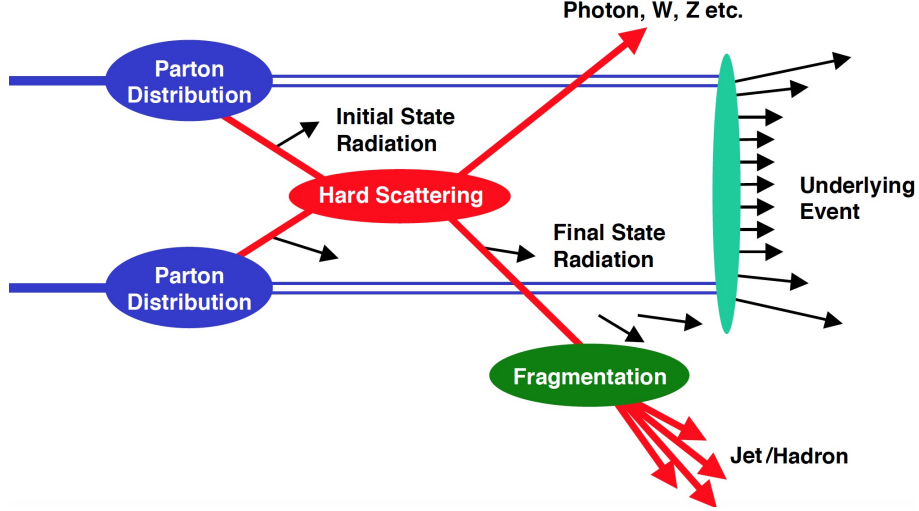
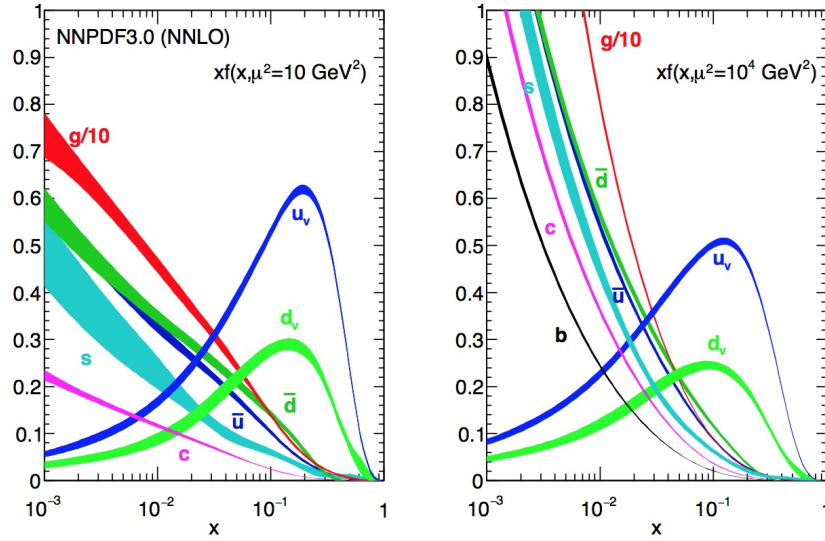


FIGURE 2.7: Schematic view of a hadron-hadron collision.


 FIGURE 2.8: NNPDF3.0 NNLO PDF set for  $Q^2 = 10 \text{ GeV}^2$  and  $Q^2 = 10^4 \text{ GeV}^2$ .

- Minimum bias events are inelastic events selected with very loose triggers with as little bias as possible.

The QCD factorization theorem [45] can be used to calculate the cross sections for a wide variety of hard scattering processes in the hadronic collisions. Considering a process with scattering of two hadrons  $A$  and  $B$  to produce a final state  $X$ , the cross section can be

factorized into the following formula [46]:

$$\sigma_{AB} = \int dx_a dx_b f_{a/A}(x_a) f_{b/B}(x_b) \hat{\sigma}_{ab \rightarrow X} . \quad (2.35)$$

Taking into account the leading logarithm corrections, Equation 2.35 becomes:

$$\sigma_{AB} = \int dx_a dx_b f_{a/A}(x_a, Q^2) f_{b/B}(x_b, Q^2) \hat{\sigma}_{ab \rightarrow X} . \quad (2.36)$$

Here the  $Q^2$  is a large momentum scale which characterizes the hard scattering, e.g.  $m_\ell^2$ ,  $p_T^2$ , ... . Any changes to the  $Q^2$  scale of  $\mathcal{O}(1)$  (like  $Q^2 = 2m_\ell^2$ ,  $m_\ell^2/2$ ) are equivalent in the leading logarithm approximation.

Furthermore, by applying the perturbative  $\mathcal{O}(\alpha_S^n)$  corrections to the leading logarithm cross section for Equation 2.36, we can get:

$$\sigma_{AB} = \int dx_a dx_b f_{a/A}(x_a, \mu_F^2) f_{b/B}(x_b, \mu_F^2) \times [\hat{\sigma}_0 + \alpha_S(\mu_R^2) \hat{\sigma}_1 + \dots]_{ab \rightarrow X} . \quad (2.37)$$

Here  $\mu_F$  is the factorization scale, which can be regarded as the scale separating the long-distance and short-distance physics. While  $\mu_R$  is the renormalization scale for the QCD running coupling. Formally, the cross section calculated to all orders in perturbation theory is invariant under changes in these parameters, the  $\mu_F^2$  and  $\mu_R^2$  dependence of the coefficients, e.g.  $\hat{\sigma}_1$  exactly compensating the explicit scale dependence of the parton distributions and the coupling constant. To make cross section predictions, special values for the two scales need to be chosen. And different choices can lead to different results, which are taken as the uncertainties for the prediction due to unknown higher-order corrections. To avoid unnaturally large logarithms reappearing in the perturbation series, it is sensible to choose  $\mu_F$  and  $\mu_R$  values of the order of the typical momentum scales of the hard scattering process, and  $\mu_F = \mu_R$  is also often assumed. Taking the Drell-Yan process as an example, the standard choice is  $\mu_F = \mu_R = m_{\ell\ell}$ , the invariant mass of the lepton pair.

### 2.3.2 Higgs boson production at the LHC

The main Higgs boson production mechanisms at the LHC are gluon-gluon fusion (ggF), vector boson fusion (VBF), associated production with a vector boson (VH) and also associated production with a pair of top/antitop quarks (ttH). Figure 2.9 shows the representative Feynman diagrams for these corresponding production modes.

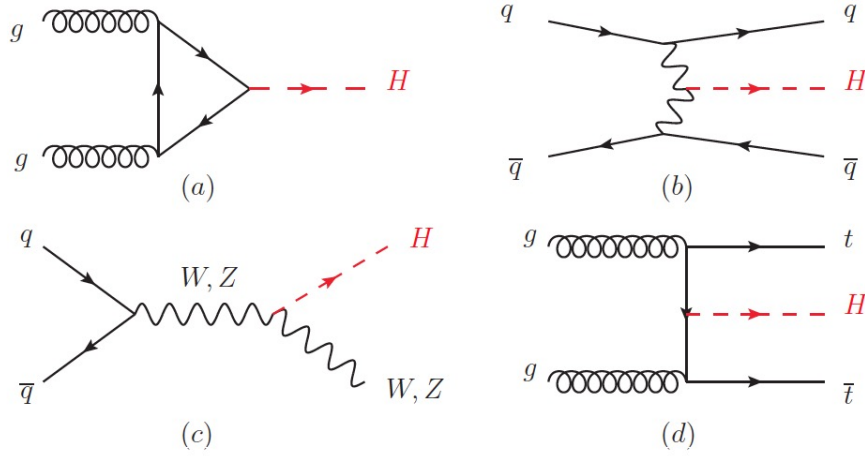


FIGURE 2.9: Representative Feynman diagrams of the Higgs production mechanisms: (a) gluon-gluon fusion (VH), (b) vector boson fusion (VBF), (c) associated production with a vector boson (VH) and (d) associated production with top quarks (ttH).

The cross sections for various Higgs production mechanisms are dependent on the center-of-mass energy  $\sqrt{s}$ . Table 2.1 summarizes the cross section values for different production processes at the mass of 125.09 GeV, which are calculated from the official LHC Higgs cross section working group [47].

| Production mechanism | Cross section (pb) |                    |                     |                      |
|----------------------|--------------------|--------------------|---------------------|----------------------|
|                      | $\sqrt{s} = 7$ TeV | $\sqrt{s} = 8$ TeV | $\sqrt{s} = 13$ TeV | Order of calculation |
| $ggF$                | $16.8 \pm 0.9$     | $21.4 \pm 1.1$     | $48.5 \pm 2.4$      | N <sup>3</sup> LO    |
| $VBF$                | $1.24 \pm 0.06$    | $1.60 \pm 0.04$    | $3.78 \pm 0.08$     | NLO                  |
| $WH$                 | $0.576 \pm 0.012$  | $0.70 \pm 0.015$   | $1.37 \pm 0.03$     | NLO                  |
| $ZH$                 | $0.338 \pm 0.011$  | $0.420 \pm 0.014$  | $0.882 \pm 0.04$    | NLO                  |
| $bbH$                | $0.155 \pm 0.035$  | $0.202 \pm 0.045$  | $0.486 \pm 0.12$    | NLO                  |
| $ttH$                | $0.089 \pm 0.009$  | $0.133 \pm 0.013$  | $0.507 \pm 0.05$    | NLO                  |
| Total                | $17.7 \pm 0.7$     | $24.5 \pm 1.1$     | $55.5 \pm 2.4$      |                      |

TABLE 2.1: Standard Model Higgs boson production cross sections at  $m_H = 125.09$  GeV at center-of-mass energy  $\sqrt{s} = 7, 8$  and 13 TeV at the LHC. The uncertainties on the cross sections are the quadratic sum of the uncertainties from variations of QCD scales, parton distribution functions and the strong interaction coupling  $\alpha_s$ .

Figure 2.10 depicts the branching ratios of the Higgs boson decaying into different final states as a function of  $m_H$ . And Table 2.2 summarizes the corresponding values for  $m_H = 125.09$  GeV specifically. For the decay channel relevant to this thesis work:  $H \rightarrow \mu\mu$ , its corresponding branching ratio is  $2.171 \times 10^{-4}$ . This value is much smaller comparing with the branching ratio of  $\tau$  lepton and  $b$  quark due to the fact that Higgs boson's coupling to fermion is proportional to the fermion's mass.

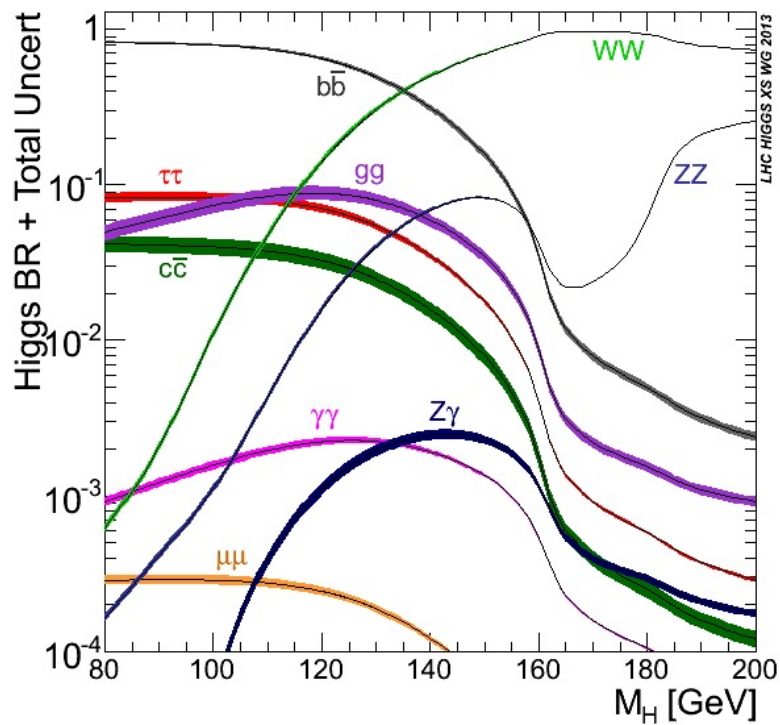


FIGURE 2.10: The SM Higgs boson decay branching ratios as a function of the Higgs pole mass.

| Decay channel                | Branching ratio (%) |
|------------------------------|---------------------|
| $H \rightarrow b\bar{b}$     | 58.09               |
| $H \rightarrow WW^*$         | 21.52               |
| $H \rightarrow gg$           | 8.18                |
| $H \rightarrow t\bar{t}$     | 6.256               |
| $H \rightarrow c\bar{c}$     | 2.884               |
| $H \rightarrow ZZ^*$         | 2.641               |
| $H \rightarrow \gamma\gamma$ | 0.227               |
| $H \rightarrow Z\gamma$      | 0.154               |
| $H \rightarrow \mu\mu$       | 0.0217              |

TABLE 2.2: Standard Model Higgs boson decay branching ratios at  $m_H = 125.09$  GeV.



# Chapter 3

## The Large Hadron Collider and the ATLAS Detector

### 3.1 The Large Hadron Collider

#### 3.1.1 General introduction of the Large Hadron Collider

The Large Hadron Collider (LHC) [48, 49, 50, 51] is the world’s largest facility used for particle physics, located at European Organization for Nuclear Research (CERN), near Geneva, Switzerland. It is a two-ring-superconducting-hadron accelerator and collider, residing in a 26.7 km tunnel which is  $\sim 100$  m beneath the ground. The LHC was constructed from 1998 to 2008 and aimed to explore the unprecedented energy frontier. It is designed to operate proton-proton ( $pp$ ) collisions eventually at a center-of-mass energy ( $\sqrt{s}$ ) up to 14 TeV with a designed luminosity of  $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ . And Table 3.1 summarizes the corresponding design parameters for the LHC  $pp$  collisions. Besides, the LHC can also accommodate heavy ion (lead) collisions with a beam energy of 2.76 TeV/nucleon and a designed luminosity of  $10^{27} \text{ cm}^{-2}\text{s}^{-1}$ .

The LHC first started to operate in 2008 but then run into an incident. It resumed the operation in late 2009 at a lower energy. From March 2010 to early 2013, physics runs took place at a center-of-mass energy of 7 and 8 TeV, and this period is called “Run 1”. After Run 1, the LHC was shut down for two years mainly aiming for collider and detector maintenance together with certain upgrade. In 2015, the second operation period “Run 2” started with the  $\sqrt{s}$  increased to 13 TeV. Currently Run 2 is still ongoing,

|                             |                                        |
|-----------------------------|----------------------------------------|
| Circumference               | 26.7 km                                |
| Beam energy at collision    | 7 TeV                                  |
| Beam energy at injection    | 0.45 TeV                               |
| Dipole field at 7 TeV       | 8.33 T                                 |
| Luminosity                  | $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ |
| Beam current                | 0.56 A                                 |
| Protons per bunch           | $1.1 \times 10^{11}$                   |
| Number of bunches           | 2808                                   |
| Nominal bunch spacing       | 24.95 ns                               |
| Normalized emittance        | $3.75 \mu\text{m}$                     |
| Total crossing angle        | $300 \mu\text{rad}$                    |
| Energy loss per turn        | 6.7 keV                                |
| Critical synchrotron energy | 44.1 eV                                |
| Radiated power per beam     | 3.8 kW                                 |
| Stored energy per beam      | 350 MJ                                 |
| Stored energy in magnets    | 11 GJ                                  |
| Operating temperature       | 1.9 K                                  |

TABLE 3.1: The LHC main parameters required to reach the peak luminosity of  $10^{34} \text{ cm}^{-2}\text{s}^{-1}$  for  $pp$  collisions at  $\sqrt{s}=14 \text{ TeV}$  [52].

which will continue until the end of 2018. The peak luminosity achieved in 2017 is  $2.05 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ , which is already twice the designed luminosity. Until the end of 2017, the total integrated luminosity produced since the start of the LHC is  $\sim 120 \text{ fb}^{-1}$ . Figure 3.1 shows the peak luminosity of the LHC as a function of the different operation runs.

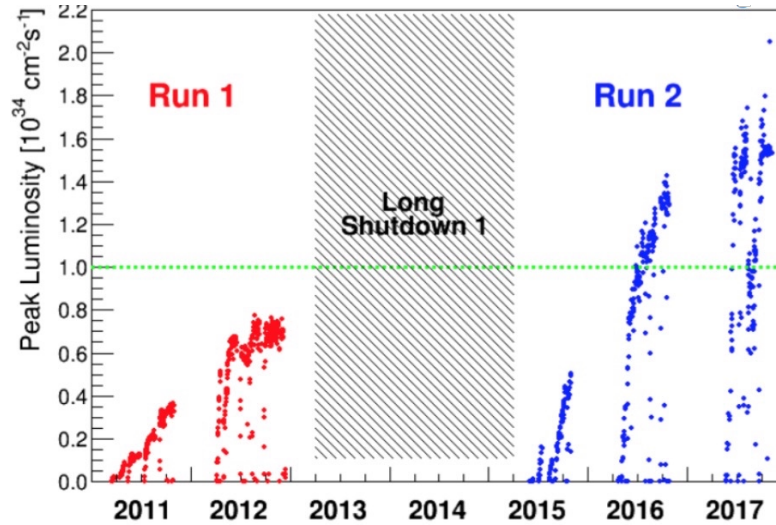


FIGURE 3.1: The peak luminosity of the LHC for different operation runs [53].

Figure 3.2 depicts the layout of the LHC complex system, which is a succession



of machines accelerating particles to the increasingly higher energies. The protons are required to pass through a series of accelerators to boost their energies before injected into the main cavity. The proton source is simply coming from a bottle of hydrogen gas, and an electric field is adopted to strip hydrogen atoms of their electrons in order to yield protons. Then protons are accelerated in Linac 2, which is the first accelerator in this chain, to the energy of 50 MeV. After this the proton beam is injected into the Proton Synchrotron Booster (PSB), which can further accelerate the beam to 1.4 GeV. Then the protons pass through the Proton Synchrotron (PS), with the beam energy increased to 25 GeV. Following this, protons are sent to the Super Proton Synchrotron (SPS) and their energies are further boosted to 450 GeV. Finally, the protons are transferred to the two beam pipes of the LHC. The beam in one of the pipes is accelerated clockwise while the other one is accelerated anticlockwise. In about 20 minutes, the protons reach the goal energy of 6.5 TeV since for this time being the LHC operates at a center-of-mass energy of 13 TeV.

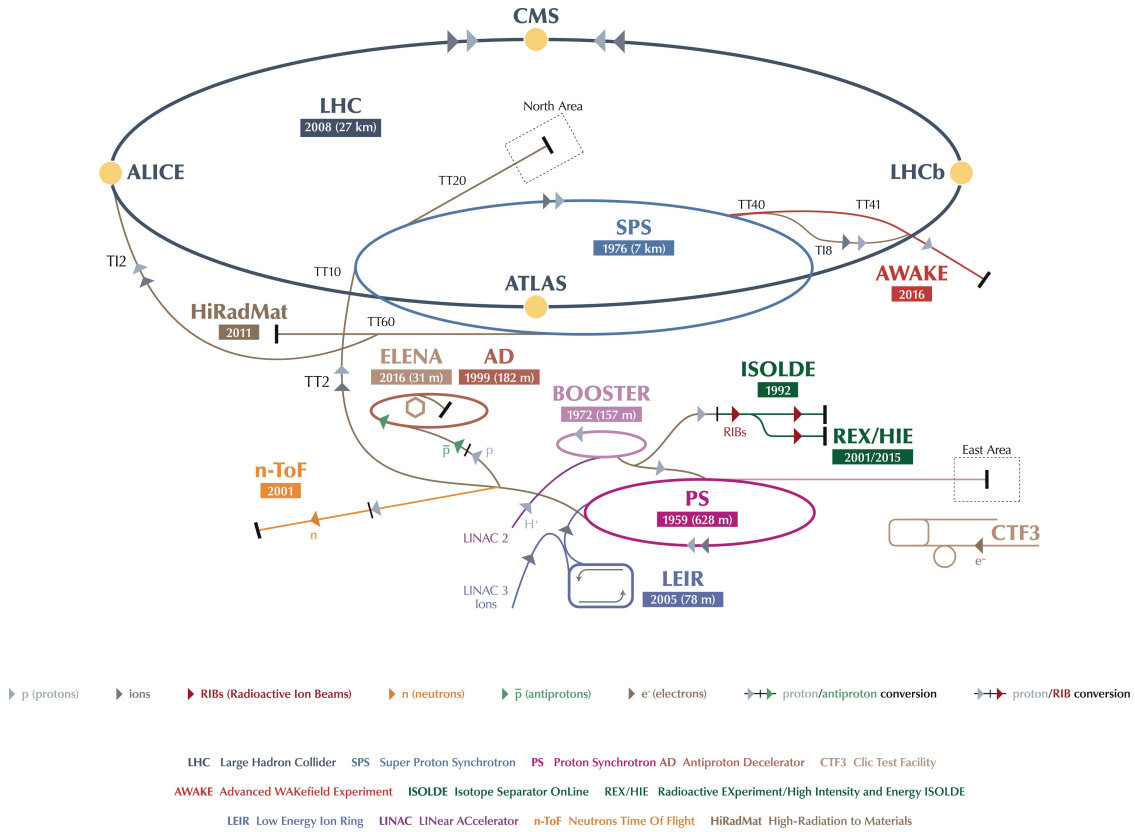


FIGURE 3.2: Schematic layout of the LHC complex

There are four colliding points at the LHC, which accommodate four different detectors with multipurpose to record the collision events. These four detectors together

with their major physics goals are briefly described as below:

- **ATLAS** (A Toroidal LHC Apparatus): one of two general-purpose detectors to search for the Higgs boson and new physics beyond the SM, which can also make precise test and measurement of the SM.
- **CMS** (Compact Muon solenoid): the other general-purpose detector like ATLAS with basically the same physics goals.
- **ALICE** (A Large Ion Collider Experiment): a heavy-ion detector designed to study the physics of quark-gluon plasma that existed shortly after the Big Bang.
- **LHCb** (Large Hadron Collider beauty): a specialized  $b$ -physics detector to measure the parameters of CP violation in the interactions of  $b$ -hadrons and other related physics in the  $b$ -sector.

### 3.1.2 Luminosity and pile-up

Luminosity ( $L$ ) is one important characteristic of the LHC performance, which reflects the number of particles per area per time during the collisions. As a result, it can be expressed in the unit of  $\text{cm}^{-2}\text{s}^{-1}$ . The LHC luminosity purely depends on the beam parameters and based on the assumption of a Gaussian beam distribution we can write the luminosity formula as:

$$L = \frac{N_b^2 n_b f_{rev} \gamma_r}{4\pi \epsilon_n \beta^*} F, \quad (3.1)$$

where  $N_b$  is the number of particles per bunch.  $n_b$  denotes the number of bunches per beam, and  $f_{rev}$  denotes the revolution frequency.  $\gamma_r$  represents the relativistic gamma factor, while  $\epsilon_n$  represents the normalized transverse beam emittance.  $\beta^*$  is the beta function at the collision point, and  $F$  is the geometric luminosity reduction factor due to the crossing angle at the interaction point (IP), which can be expressed as below:

$$F = 1 / \sqrt{1 + \left(\frac{\theta_c \sigma_z}{2\sigma^*}\right)^2}, \quad (3.2)$$

where  $\theta_c$  is the full crossing angle at the IP, while  $\sigma_z$  is the root mean square (RMS) of bunch length and  $\sigma^*$  is the transverse RMS of beam size at the IP. One thing needed to emphasize is that the Equation 3.2 above is based on the assumption of equal beam parameters for both circulating beams.

The luminosity definition shown in Equation 3.1 is normally referred to as the instantaneous luminosity. In reality the running conditions usually change with time, and as a result the luminosity can have a time dependence. To take into account such time dependence, we have imported another definition called integrated luminosity, which is calculated as the integral over time:  $L = \int \mathcal{L}(t)dt$ , and in units of  $b^{-1}$  ( $1b^{-1} = 10^{24}cm^{-2}$ ). Furthermore, we can define another two related variables: one is called delivered integrated luminosity referring to the integrated luminosity that the LHC has delivered to a certain detector; the other one is called recorded integrated luminosity, which represents the actual amount of data that has been stored to disk by the detector.

For the LHC collisions, multiple interactions can happen for one single bunch crossing, which is the so-called “pile-up” effect. To describe this, we define a variable  $\mu$  as the average number of interactions per bunch crossing. The pile-up effect is dependent on the bunch spacing and luminosity as well. Normally it becomes more and more significant with the decreasing bunch spacing and increasing luminosity. More explicitly, the  $\mu$  value can be expressed into the formula as below:

$$\langle \mu \rangle = \frac{L_{bunch}\sigma_{inel}}{f_r n_{bunch}} \quad (3.3)$$

where  $L_{bunch}$  is the instantaneous luminosity for each bunch, and  $\sigma_{inel}$  is the inelastic cross section (at center-of-mass energy of 13 TeV, its value is 78 mb).  $n_{bunch}$  denotes the number of colliding bunches and  $f_r$  represents the LHC revolution frequency.

The left plot of Figure 3.3 describes the delivered luminosity as a function of the months during the years between 2011 and 2017. In total, around  $90 \text{ fb}^{-1}$  integrated luminosity has been already delivered during Run 2. The work of this thesis is based on a integrated luminosity of  $36.1 \text{ fb}^{-1}$ , which was recored in 2015 and 2016. The plot on the right in Figure 3.3 depicts the luminosity-weighted distribution for the mean number of interactions per crossing ( $\langle \mu \rangle$ ) from 2015 to 2017. As can be seen from the plot, with the significantly increasing luminosity in 2017, the  $\langle \mu \rangle$  shows much larger values comparing with the first two years of the Run 2.

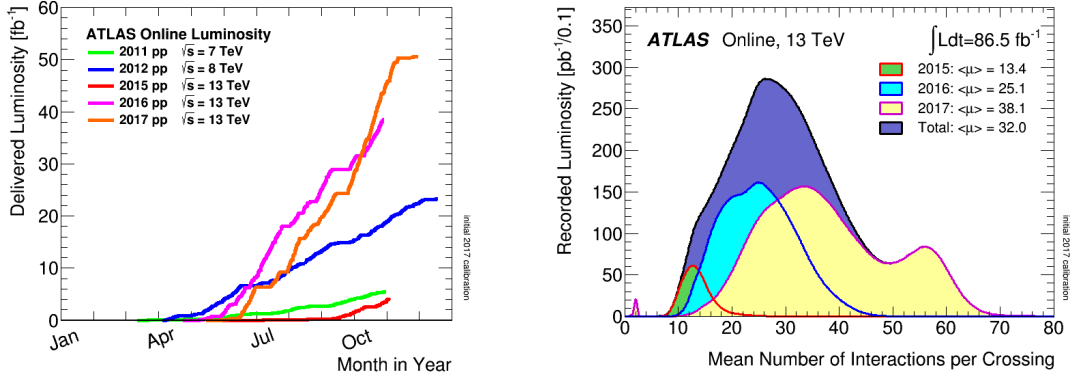


FIGURE 3.3: Delivered luminosity ( $pp$  collisions) vs time for 2011–2017 (left); luminosity-weighted distribution of the mean number of interactions per crossing at 13 TeV from 2015–2017 (right).

## 3.2 The ATLAS Detector

### 3.2.1 Physics requirements and detector overview

ATLAS (A Toroidal LHC ApparatuS) [54] is the largest particle detector ever built, which is located at one of the collision points of the LHC, CERN. It is 46 metres long, and 25 metres in diameter. ATLAS detector contains around 3000 km of cables and its total weight is about 7,000 tonnes. Around 3000 physicists from over 182 institutions of 38 countries are working at the ATLAS experiment currently, forming the largest particle physics collaboration all over the world.

This paragraph briefly introduces the coordinate system and jargons used to describe the ATLAS detector, which will be also used throughout this thesis. The nominal interaction point (IP) is used to define the origin of the coordinate system, while  $z$ -axis is determined by the beam direction and the  $x - y$  plane is defined as the plane transverse to the beam direction. Moreover, the positive  $x$ -axis is defined as the direction pointing from the IP to the centre of the LHC ring, while the positive  $y$ -axis is defined as pointing upwards. Then the side-A/C of the detector is defined as that with positive/negative  $z$  coordinate. The azimuthal angle  $\phi$  is measured around the beam axis, while the polar angle  $\theta$  is the angle from the beam axis. In reality we often use the pseudorapidity instead of  $\theta$ , which is defined as  $\eta = -\ln \tan(\theta/2)$  (the variable named rapidity:  $y = \frac{1}{2} \ln[(E + p_z)/(E - p_z)]$  is used for massive objects). The transverse momentum  $p_T$ , the transverse energy  $E_T$ , and the missing transverse energy  $E_T^{miss}$  are defined in the

$x - y$  plane. The distance  $\Delta R$  in the pseudorapidity-azimuthal angle space is defined as  $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ .

As already mentioned in Subsection 3.1.1, ATLAS (A Toroidal LHC ApparatuS) is one of two detectors designed with general-purpose including searching for the SM Higgs boson as one benchmark, and also searching for heavy BSM gauge bosons like  $Z'$  and  $W'$ . Besides, the detector is also designed to detect possible decays of supersymmetric particles (like squarks and gluinos). It can also explore the possibility of extra dimensions proposed by several models, which can lead to a characteristic energy scale of quantum gravity in the TeV region. Nevertheless, the ATLAS detector is not just dedicated for exploring the un-known world, and it can accommodate the abilities of making precise test and measurement of the SM as well. To fulfill such diverse physics targets, the ATLAS detector is designed to satisfy the following general requirements

- Firstly fast, radiation-hard electronics and sensor elements are necessary for the detector. And high detector granularity is also needed to handle the particle fluxes and to reduce the influence of overlapping events as well.
- The detector is required to have large acceptance in pseudorapidity together with nearly full  $\phi$  coverage.
- It is essential for the detector to keep good charged-particle momentum resolution and reconstruction efficiency in the inner tracker. For offline tagging of  $\tau$ -leptons and  $b$ -jets, vertex detectors close to the interaction region are required to have the capability to observe secondary vertices.
- Also as the basis of achieving the physics goals described above, the detector needs to have decent electromagnetic (EM) calorimetry for electron and photon identification and measurements, complemented by full-coverage hadronic calorimetry for accurate jet and  $E_T^{miss}$  measurements.
- Other necessary requirements include decent muon identification and momentum resolution over a wide range of muon momenta and also the ability to determine the charge of high  $p_T$  muons.
- Besides, in order to keep an acceptable trigger rate for the most relevant physics of interest, it is prerequisite for the detector to have highly efficient triggering on low  $p_T$  objects but also with sufficient background rejection.

Figure 3.4 shows the overall ATLAS detector layout, which is generally forward-backward symmetric with respect to the IP. The magnet configuration comprises a thin superconducting solenoid surrounding the inner-detector cavity, and three large superconducting toroids (one barrel and two end-caps) arranged with an eight-fold azimuthal symmetry around the calorimeters.

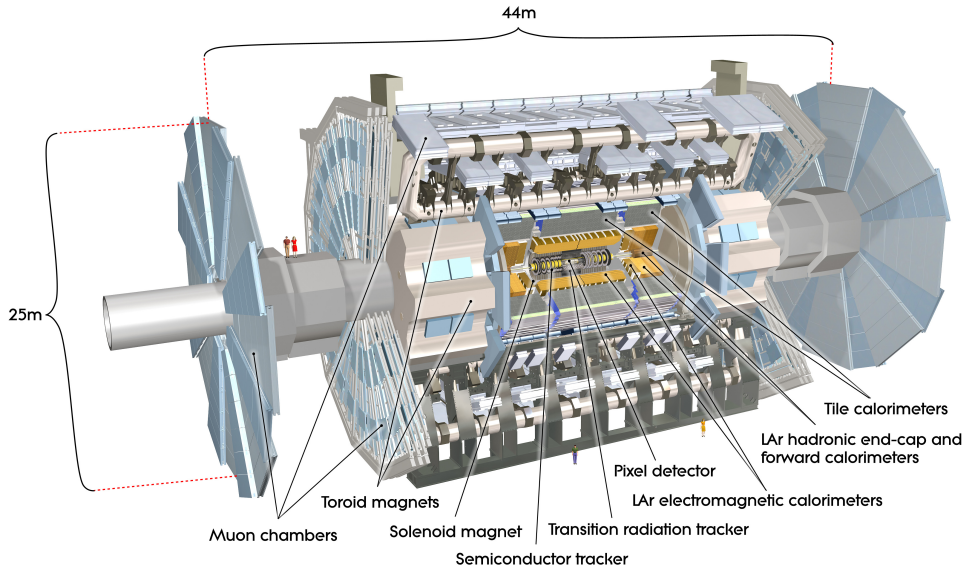


FIGURE 3.4: Cut-away view of the ATLAS detector. The dimensions of the detector are 25 m in height and 44 m in length. The overall weight of the detector is approximately 7000 tonnes.

The inner detector (ID) is the innermost part of the ATLAS detector and immersed in a 2 T solenoidal magnetic field. It can fulfill pattern recognition, momentum/vertex measurements, and electron identification through a combination of different components of the tracking system, with the  $\eta$  coverage up to 2.5.

Calorimetry system resides outside the ID and solenoid, which is crucial for the energy and position measurements. High granularity liquid-argon (LAr) electromagnetic sampling calorimeters, mainly used for energy deposition of electrons and photons, can cover the  $\eta$  range up to 3.2. While the hadronic calorimetry in the range  $|\eta| < 1.7$  is provided by a scintillator-tile calorimeter, which is separated into a large barrel and two small extended barrel cylinders. And in the end-caps ( $|\eta| > 1.5$ ), LAr technology is also adopted for the hadronic calorimeters, matching the outer  $|\eta|$  limits of end-cap electromagnetic calorimeters. The LAr forward calorimeters provide both electromagnetic and hadronic energy measurements, and the corresponding  $\eta$  coverage is extended up to 4.9.

The outermost part of the ATLAS detector is the muon spectrometer (MS), which surrounds the calorimeter. The air-core toroid system, including a long barrel and two inserted end-cap magnets, generates strong bending power in a large volume within a light and open structure. It can minimize the multiple-scattering effects as well. Besides, the three layers of high precision tracking chambers can guarantee decent muon momentum resolution. The muon instrumentation also includes another key component: trigger chambers with timing resolution in the order of 1.5–4 ns. In the end, the MS defines the overall dimensions of the ATLAS detector.

As already mentioned in the previous contents, the interaction rate of the LHC  $pp$  collisions at the design luminosity of  $10^{34} \text{ cm}^{-2}\text{s}^{-1}$  is approximately 1 GHz, and during Run 2, the peak luminosity has already reached twice as the designed luminosity. Thus, the trigger system for the ATLAS detector is quite crucial for rejecting against minimum-bias processes and also maintaining a maximum efficiency for the physics of interest, especially given the limitations of technology and resource for event recording. During the first long shutdown (LS1) of the LHC, the trigger system has been improved and almost every component has been tuned, in order to meet the requirements coming from the high luminosity and also increased pile-up for Run 2. Currently, the relevant constraints include the maximum L1 rate of 100 kHz (75 kHz in Run 1) which is determined by the ATLAS detector readout capability, and an average HLT physics output rate of 1 kHz (400 Hz in Run 1) which is determined by the offline computing model.

Table 3.2 summarizes the main performance goals for the different components of the ATLAS detector, and more detailed descriptions about each component are given in the following subsections.

| Detector component          | Required resolution                            | $\eta$ coverage  |                  |
|-----------------------------|------------------------------------------------|------------------|------------------|
|                             |                                                | Measurement      | Trigger          |
| Tracking                    | $\sigma_{p_T}/p_T=0.05\%p_T\oplus1\%$          | $\pm2.5$         |                  |
| EM calorimetry              | $\sigma_E/E=10\%\sqrt{E}\oplus0.7\%$           | $\pm3.2$         | $\pm2.5$         |
| Hadronic calorimetry (jets) |                                                |                  |                  |
| barrel and end-cap          | $\sigma_E/E=50\%\sqrt{E}\oplus3\%$             | $\pm3.2$         | $\pm3.2$         |
| forward                     | $\sigma_E/E=100\%\sqrt{E}\oplus10\%$           | $3.1< \eta <4.9$ | $3.1< \eta <4.9$ |
| Muon spectrometer           | $\sigma_{p_T}/p_T=10\%$ at $p_T=1 \text{ TeV}$ | $\pm2.7$         | $\pm2.4$         |

TABLE 3.2: General performance goals of the ATLAS detector. The units for  $E$  and  $p_T$  are in GeV.



### 3.2.2 Magnet system

The magnet system of the ATLAS detector is 22 m in diameter and 26 m in length. It is composed of four large superconducting magnets: one solenoid which is aligned along the beam axis; one barrel toroid and two end-cap toroids that produce a toroidal magnetic field of approximately 0.5 T and 1 T for the MS in the central and end-cap regions respectively.

The central solenoid is designed to generate a 2 T axial field for the ID. Besides, in order to meet the desired calorimeter performance, the solenoid's layout needed careful optimization to keep the material in front of the calorimeter as thin as possible. And this also requires that the solenoid windings and LAr calorimeter share a common vacuum vessel, resulting in eliminating two vacuum walls.

The barrel toroid consists of eight coils encased in individual racetrack-shaped, stainless-steel vacuum vessels and provides the magnetic field in the cylindrical volume surrounding the calorimeters. Overall, the size of the barrel toroid is 25.3 m in length, with inner and outer diameters of 9.4 m and 20.1 m respectively. And the coil assembly of the system is supported by eight inner together with eight outer rings of struts.

The two end-cap toroids are responsible for providing the magnetic field used to optimise the bending power in the end-cap regions of the MS system. Each end-cap toroid is composed of a single cold mass built up from eight flat, square coil units and eight keystone wedges, which are bolted and glued together into a rigid structure to withstand the Lorentz forces.

### 3.2.3 Inner Detector

As the tracking system of the ATLAS experiment, the Inner Detector (ID) is designed to provide hermetic and robust pattern recognition, together with good momentum resolution within the pseudorapidity range  $|\eta| < 2.5$ . It can also measure the primary and secondary vertex for charged tracks with  $p_T$  above the give threshold (normally it is 0.5 GeV). Besides it accommodates the ability for electron identification for  $|\eta| < 2.0$  with a wide range of energies (between 0.5 and 150 GeV) as well. Figure 3.5 illustrates the corresponding cut-away view of ID, which consists of three independent but also complementary sub-detectors and is contained within a cylindrical envelope of length  $\pm 3512$  mm and of radius 1150 mm.



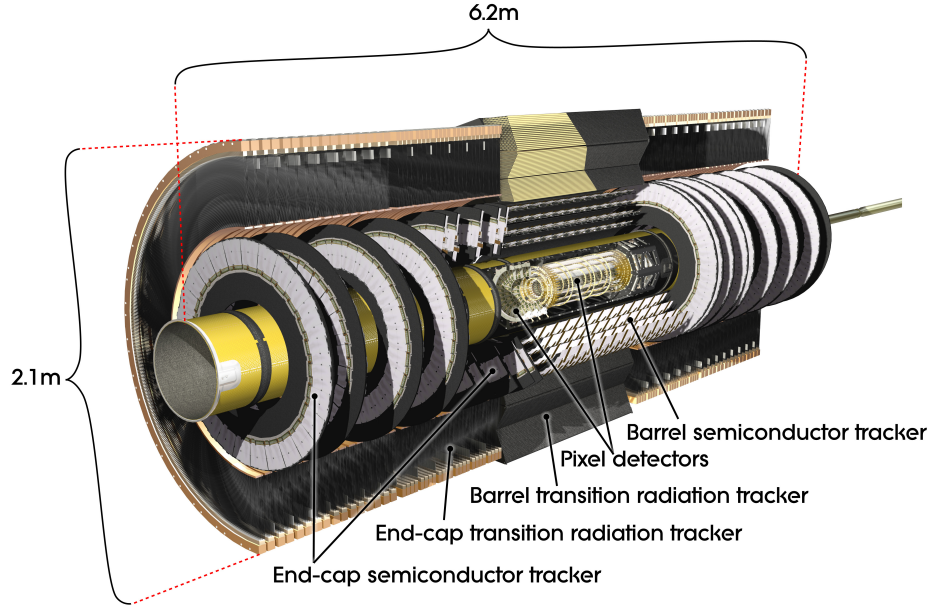


FIGURE 3.5: Cut-away view of the ATLAS inner detector.

A detailed layout of the ID is shown in Figure 3.6. As depicted in this figure, at inner radii, silicon pixel layers and stereo pairs of silicon microstrip (SCT) layers can provide high-resolution pattern recognition through discrete space-points. While at larger radii, the transition radiation tracker (TRT) comprises many layers of gaseous straw tube elements interleaved with transition radiation material.

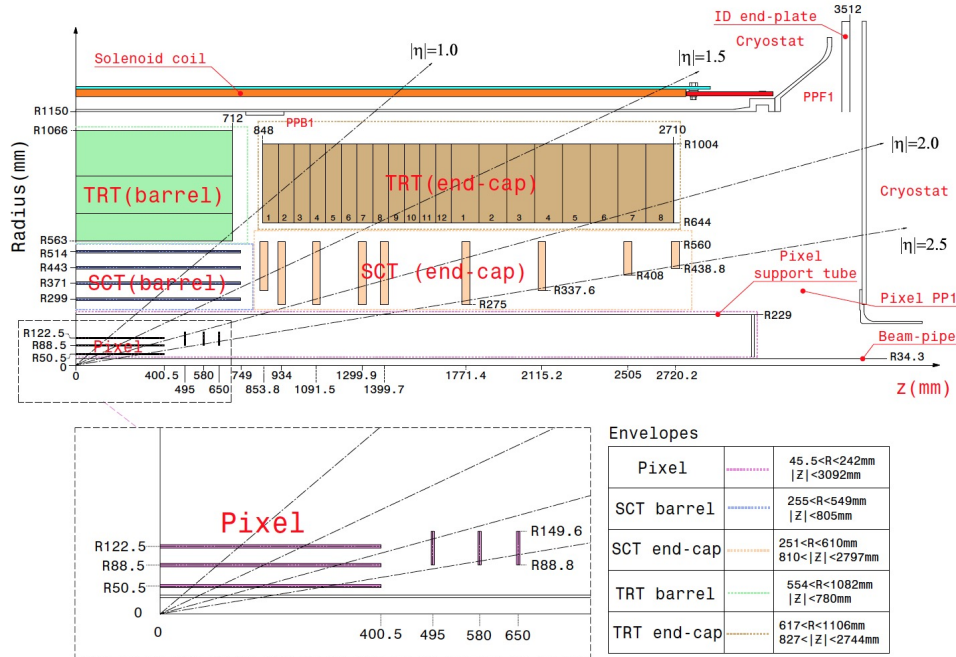


FIGURE 3.6: Plan view of a quarter-section of the ATLAS inner detector showing each of the major detector elements with its active dimensions and envelopes.

### 3.2.3.1 Pixel detector

The pixel detector system [55] is the innermost part of the ID. Originally at Run 1, it was composed of three barrel layers placed at the radius of 50.5 mm, 88.5 mm and 122.5 mm centered around the beam axis and two end-caps with three disk layers on each side. The pixel contains approximately 80 million channels, which is used in the identification and reconstruction of secondary vertices from the decay of particles like hadrons containing  $b$ -quarks or  $\tau$  leptons. Additionally, it also provides excellent spatial resolution for reconstructing primary vertices coming from the  $pp$  interaction region.

The basic building block of the active part of the pixel detector is a module composed of silicon sensors, front-end electronics and flex-hybrids with control circuits. Generally all the modules are functionally identical at the sensor/integrated circuit level, but still differ somewhat in the interconnection schemes between barrel modules and end-cap disk modules. The nominal pixel size is 50 microns in the  $\phi$  direction and 400 microns in  $z$  (barrel region, along the beam axis) or  $r$  (disk region), but a few special pixels in the region between integrated circuits on a module have larger dimensions. For each module, there are 46,080 pixel electronics channels in total.

As already described, for Run 2, pile-up effect is significantly increased. In order to guarantee the excellent vertex reconstruction performance and also provide redundancy in case of failures or radiation damage for the existing three layers, therefore a fourth layer named the Insertable B-Layer (IBL) was added between the existing pixel detector and a new smaller beam pipe at a radius of 33 mm during the LS1. As a result, the new pixel detector contains four layers now, which helps to improve the impact parameter resolution by nearly a factor of two for low  $p_T$  tracks and also make the pattern recognition even more robust because of adding an additional space point. Besides, the new Service Quarter Panels (nSQP) were also installed during the LS1 to provide a relocation of the Optoboards, making it more accessible. The nSQP helps to increase the bandwidth of Layer-1 to become the same as Layer-0 (160 Mbits/s), which can adjust to the much higher luminosity at the Run 2.

### 3.2.3.2 The semiconductor tracker

The semiconductor tracker (SCT) [56] is a precision silicon microstrip detector forming an integral part of this corresponding tracking system, covering radial regions between 30 and 52 cm and  $\eta$  up to 2.5. For the barrel, there are four cylindrical layers, while for

the end-caps, there are nine annular disks on each side. The design of such corresponding layout can realize that each charged particle crosses at least four layers, which leaves four space points anywhere in SCT's acceptance region. For the barrel, the SCT uses small-angle (40 mrad) stereo strips to measure both coordinates, with one set of strips in each layer parallel to the beam direction, measuring  $r - \phi$ . They are composed of two 6.4 cm long daisy-chained sensors with a strip pitch of  $80 \mu m$ . While for the end-cap, the SCT has a set of strips aligned radially and also a set of stereo strips at an angle of 40 mrad. The mean pitch of the strips is around  $80 \mu m$ . In the barrel, the intrinsic accuracies for each module are  $17 \mu m$  ( $r - \phi$ ) and  $580 \mu m$  ( $z$ ), while for the end-cap disks, the accuracies are  $17 \mu m$  ( $r - \phi$ ) and  $580 \mu m$  ( $R$ ). There are around 6.3 million readout channels in total for the SCT.

### 3.2.3.3 Transition radiation tracker

The transition radiation tracker (TRT) [57], located in the outermost region of the ID, is composed of thin-walled proportional drift tubes named straw tube or just straws. The TRT can be separated into three parts: a barrel and two end-caps, with the  $\eta$  coverage up to 2.0. For the barrel part, it consists of 52544 straws with 144 cm in length oriented parallel to the beam direction; while for the two end-cap regions, each side is comprised of 122880 straws with 37 cm in length aligned radially with respect to the beam direction. There are approximately 351,000 readout channels in total for the TRT.

The straw tubes of the TRT can provide a large number of hits normally 36 hits for each track. The TRT can only provide  $R - \phi$  information, for which it achieves an intrinsic accuracy of  $130 \mu m$  for each straw. The joint system of the precision trackers at small radii and the TRT at a larger radius provides robust pattern recognition and also high precision in both  $R - \phi$  and  $z$  coordinates. The straw hits at the larger radius make significant contributions to the momentum measurement, due to the fact that the lower precision per point compared to the silicon can be compensated by the large number of measurements and longer measured track length.

### 3.2.4 Calorimeters

Calorimeters in the particle physics experiments are designed to measure the energy of incoming particles, which could be either charged or neutral ones. Figure 3.7 depicts the layout of the ATLAS calorimeter system, which consists of a number of sampling

detectors with full  $\phi$ -symmetry and coverage around the beam axis. The calorimeters are designed to cover the  $\eta$  range up to 4.9, by using different techniques to adjust to the widely varying requirements from the physics processes of interest and also the radiation environment. For example, for the  $\eta$  region overlapped with the ID, the fine granularity of the EM calorimeter is ideally designed for precision measurements for electrons and photons; while the rest parts of the calorimeter use the relatively coarser granularity but sufficient enough to satisfy the physics requirements for jet reconstruction and  $E_T^{miss}$  measurements.

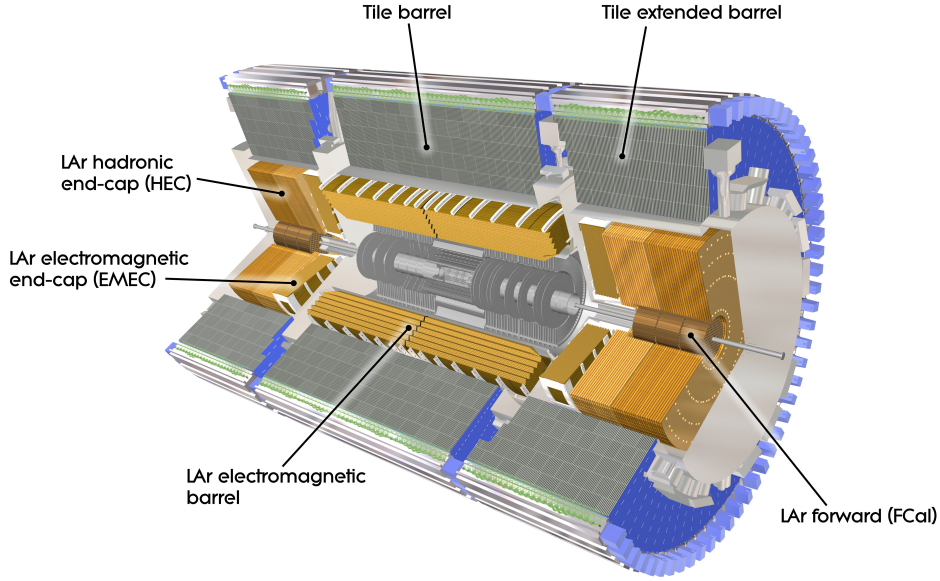


FIGURE 3.7: Cut-away view of the ATLAS calorimeter.

The major functionalities of the calorimeters include providing good containment and absorption for electromagnetic and hadronic showers and limiting the corresponding punch-through into the muon system. Therefore the calorimeter depth is a really crucial parameter for the design. The total thickness of the EM calorimeter is more than 22 radiation lengths ( $X_0$ ) for the barrel region and more than 24  $X_0$  for the end-caps. The approximate 9.7 interaction lengths ( $\lambda$ ) of active calorimeter for the barrel region (10  $\lambda$  for the end-cap regions) are sufficient enough to keep good resolution for high energy jets. For  $\eta=0$  region, a total thickness of 11  $\lambda$  (including 1.3  $\lambda$  from the outer support) is adopted, and based on both measurements and simulations, it shows good performance of reducing the punch-through effect below the irreducible level of prompt or decay muons.

The EM calorimeters are purely based on liquid argon technology, while for the hadronic calorimeters the scintillating tiles technology is also adopted. More details for these two types of calorimeters are described in the following subsections.

#### 3.2.4.1 LAr electromagnetic calorimeter

The EM calorimeter (EMC) is divided into a barrel part ( $|\eta| < 1.475$ ) and two end-cap components ( $1.375 < |\eta| < 3.2$ ), each housed in their own cryostat. For the barrel part, it consists of two identical half-barrels, which are separated by a small gap (4 mm) at  $z = 0$ . While for the end-caps, each calorimeter is mechanically divided into two coaxial wheels: an outer wheel covering the region of  $1.375 < |\eta| < 2.5$ , and an inner wheel covering the region of  $2.5 < |\eta| < 3.2$ . The EM calorimeters are lead-liquid argon detectors [58] with accordion-shaped absorbers and electrodes. Such geometry allows the calorimeters to be segmented into several active layers in depth: three in the precision-measurement region ( $0 < |\eta| < 2.5$ ) and two in the higher- $\eta$  region ( $2.5 < |\eta| < 3.2$ ) and in the overlap region between the barrel and the electromagnetic end-cap calorimeter (EMEC). For the region of  $0 < |\eta| < 2.5$ , the accurate position measurement can be guaranteed by finely segmenting the first layer along  $\eta$ . Besides, the  $\eta$ -direction of photons can be determined by the position of the photon cluster in the first and second layers. For the region of  $|\eta| < 1.8$ , the presamples are used to complement the EM calorimeters, which can correct for the energy loss of the electrons and photons upstream of the calorimeters. The presampler is composed of an active LAr layer with thickness of 1.1 cm (0.5 cm) for the barrel (end-cap) part.

#### 3.2.4.2 Hadronic calorimeters

This subsection describes the ATLAS hadronic calorimeters including the tile calorimeter, the liquid-argon hadronic end-cap calorimeter (HEC) and the liquid-argon forward calorimeter (FCal).

The tile calorimeter [59] is a sampling calorimeter using steel as the absorber and scintillator as the active medium, which covers the  $|\eta|$  range to 1.7 and is located right outside the EM calorimeter envelope. It can be separated into a central barrel ( $|\eta| < 1.0$ ), and two extended barrels ( $0.8 < |\eta| < 1.7$ ). The tile calorimeter is segmented into three layers in depth, approximately 1.5, 4.1 and 1.8 interaction lengths ( $\lambda$ ) thick for the barrel

and 1.5, 2.6, and 3.3  $\lambda$  for the extended barrel. And two sides of the scintillating tiles are read out by wavelength shifting fibers into two separate photomultiplier tubes.

The HEC consists of two independent wheels for each end-cap, residing just behind the EMEC and sharing the same LAr cryostats. It is a copper/LAr sampling calorimeter with a flat-plate design, covering region of  $1.5 < |\eta| < 3.2$ . Such coverage choice is the consideration of reducing the drop in material density at the transition between the end-cap and the forward calorimeter (around  $|\eta| = 3.1$ ) by making the HEC overlapped with the forward calorimeter a little bit. Based on the similar reason, the HEC's lower boundary of  $\eta$  (1.5) is also chosen to slightly overlap with the tile calorimeter ( $|\eta| < 1.7$ ). Each wheel of the HEC is divided into two segments in depth, with a total of four layers for each end-cap.

The FCals are located in the same cryostats as the end-cap calorimeters and provide coverage of  $3.1 < |\eta| < 4.9$ . Such design provides significant benefits regarding the uniformity of the calorimetric coverage together with reduced radiation background levels in the muon spectrometer. The FCal has an interaction length of approximately 10  $\lambda$  deep. And it consists of three modules for each end-cap: the first one is made of copper and optimized for EM measurements, while the other two are made of tungsten, which can measure predominantly the energy of hadronic interactions. Each module consists of a metal matrix, with regularly spaced longitudinal channels filled with the electrode structure consisting of concentric rods and tubes parallel to the beam axis. The LAr in the gap between the rod and the tube is the sensitive medium, which allows for the design with very small gaps. This consideration is based on the fact that the FCal modules are in the very high  $\eta$  regions, and exposed to high particle fluxes.

### 3.2.5 Muon Spectrometer

The muon spectrometer (MS) [60] forms the outermost part of the ATLAS detector and its conceptual layout is shown in Figure 3.8. The MS is designed to detect the charged particles for the region of  $|\eta| < 2.7$ , which exit the calorimeter system. And it can also measure their corresponding momenta based on the magnetic deflection of the charged tracks in the large superconducting air-core toroid magnets. For  $|\eta| < 1.4$ , magnetic bending power is provided by the barrel toroid, and for  $1.6 < |\eta| < 2.7$ , charged tracks are bent by two smaller end-cap toroid magnets inserted into both ends of the barrel toroid. While for  $1.4 < |\eta| < 1.6$ , which is referred to as the transition region, magnetic deflection is provided by the combination of barrel and end-cap fields. Such kind of magnet



configuration can provide a field that is mostly orthogonal to the muon trajectories, but also accommodate the capability of minimising the degradation of resolution caused by multiple scattering. The performance goal of the MS is to achieve approximately 10%  $p_T$  resolution for 1 TeV tracks, which translates into a sagitta along the beam direction  $z$  of about  $500\text{ }\mu\text{m}$  required to be measured with a resolution of  $\leq 50\text{ }\mu\text{m}$ . Momenta down to a few GeV (around 3 GeV, due to the energy loss in the calorimeter system) can be measured by the MS alone. And the stand-alone measurements can still keep adequate  $p_T$  resolution and decent charge identification even for very high  $p_T$  cases (like 3 TeV).

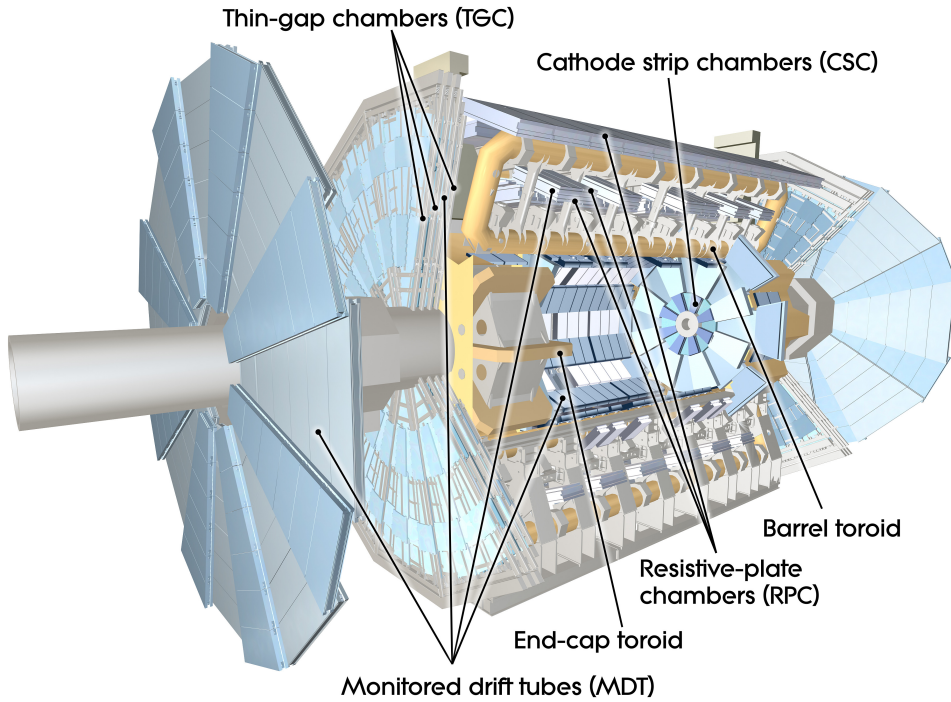


FIGURE 3.8: Cut-away view of the ATLAS muon spectrometer.

Figure 3.9 depicts the cross-section view of the MS in the planes transverse to, and containing, the beam axis  $z$ . As shown in the figures, for the barrel part, muon chambers are arranged in three concentric cylindrical shells around the  $z$  axis at radii of around 5 m, 7.5 m and 10 m. While for the two end-cap regions, the chambers form large wheels, which are perpendicular to the  $z$ -axis and placed at distances of  $|z| \approx 7.4\text{ m}$ ,  $10.8\text{ m}$ ,  $14\text{ m}$  and  $21.5\text{ m}$  with respect to the IP.

For the MS, there are four types of chambers: Monitored Drift Tubes (MDT) and Cathode Strip Chambers (CSC) used for precision measurement of the track coordinates, together with Resistive Plate Chambers (RPC) and Thin Gap Chambers (TGC) employed

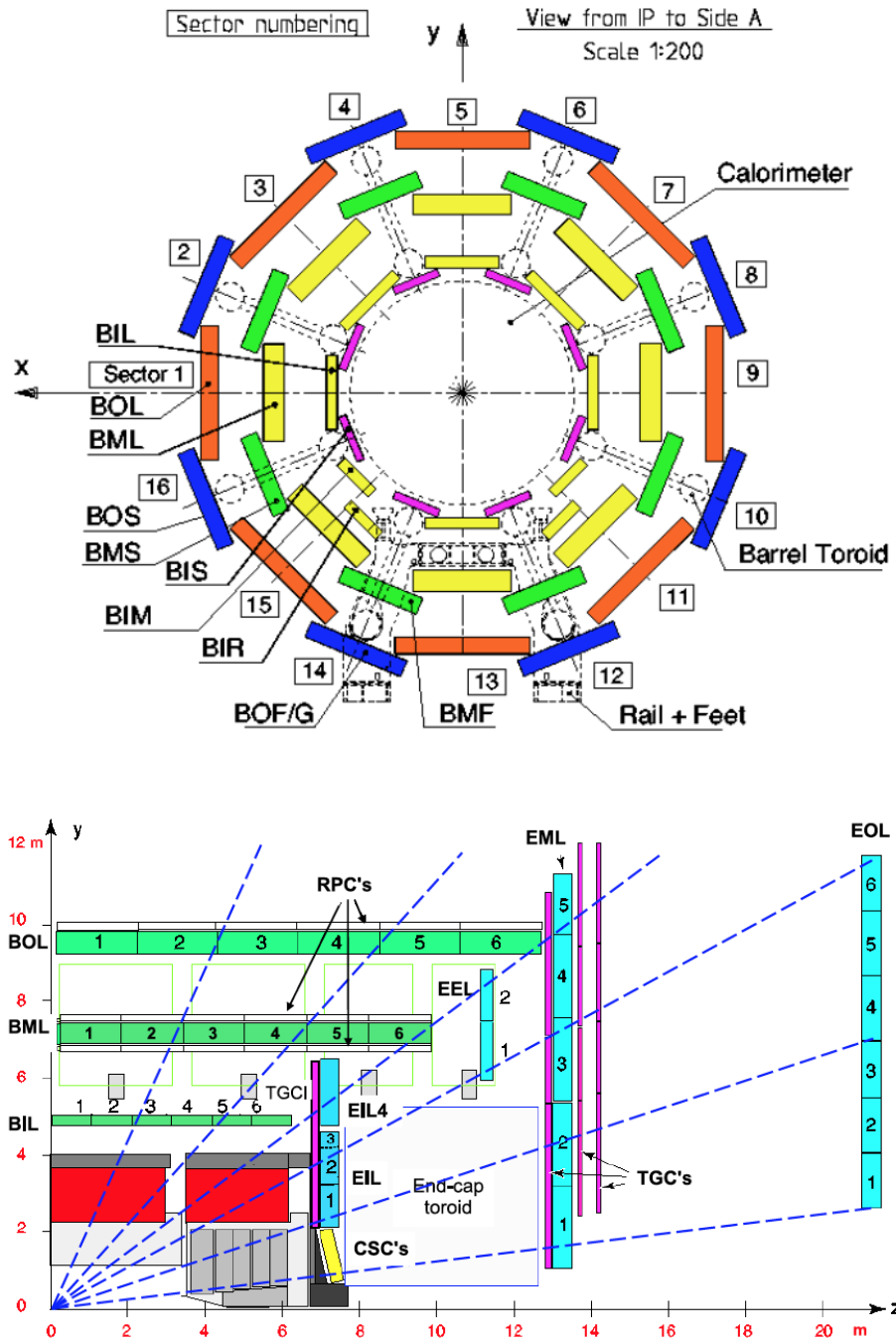


FIGURE 3.9: Cross-section view of the muon spectrometer system in the non-bending plane (top) and bending plane (bottom)



as the trigger system. Table 3.3 describes the main parameters for the design of these four types of chambers.

| <b>Monitored Drift Tubes</b>    | <b>MDT</b>                                        |
|---------------------------------|---------------------------------------------------|
| -Coverage                       | $ \eta  < 2.7$ (innermost layer: $ \eta  < 2.0$ ) |
| -Number of chambers             | 1150                                              |
| -Number of channels             | 354 000                                           |
| -Function                       | Precision tracking                                |
| <b>Cathode strip chambers</b>   | <b>CSC</b>                                        |
| -Coverage                       | $2.0 <  \eta  < 2.7$                              |
| -Number of chambers             | 32                                                |
| -Number of channels             | 31 000                                            |
| -Function                       | Precision tracking                                |
| <b>Resistive plate chambers</b> | <b>RPC</b>                                        |
| -Coverage                       | $ \eta  < 1.05$                                   |
| -Number of chambers             | 606                                               |
| -Number of channels             | 373 000                                           |
| -Function                       | Triggering, second coordinate                     |
| <b>Thin gap chambers</b>        | <b>TGC</b>                                        |
| -Coverage                       | $1.05 <  \eta  < 2.7$ (2.4 for triggering)        |
| -Number of chambers             | 3588                                              |
| -Number of channels             | 318 000                                           |
| -Function                       | Triggering, second coordinate                     |

TABLE 3.3: Main parameters of the four components of the muon spectrometer

### 3.2.5.1 Monitored drift tube chambers

As the major precision-tracking chambers, the MDT can cover the  $\eta$  range up to 2.7 except for the innermost end-cap layer where the coverage is limited to 2.0. The MDT chambers are comprised of three to eight layers of drift tubes, with a diameter of 29.970 mm, operated at an absolute pressure of 3 bar with Ar/CO<sub>2</sub> gas (93/7), which can achieve an average resolution of 80  $\mu\text{m}$  per tube, or about 35  $\mu\text{m}$  per chamber. Figure 3.10(a) shows the cross section of a MDT tube, for which the wall thickness is 0.4 mm and the inner radius is 14.58 mm ( $r_{max}$ ). When a charged track passes through a MDT tube, it causes the gas ionization and the primary electrons are produced through this process. These electrons drift towards the anode wire and when they get closer to the wire, they can gain more energy due to the increasing of electric field. After achieving enough energy, they can further produce the secondary electrons, eventually leading to the avalanche effect. The amplified signals propagate through the anode wire to the

tube ends and finally reach the readout system. The coordinate of this charged track is determined by the radius of the circle ( $r_{min}$ ) around the wire to which the track is tangential. Figure 3.10(b) [61] depicts one example for the drift time spectrum of the electrons propagating to the anode wire of a MDT tube. The spectrum shows the feature of a steeply rising edge at  $t_0$  representing the muons which pass very close to the wire, and a broad distribution of hits extending to a less well defined  $t_{max}$  representing those muons near the tube walls.

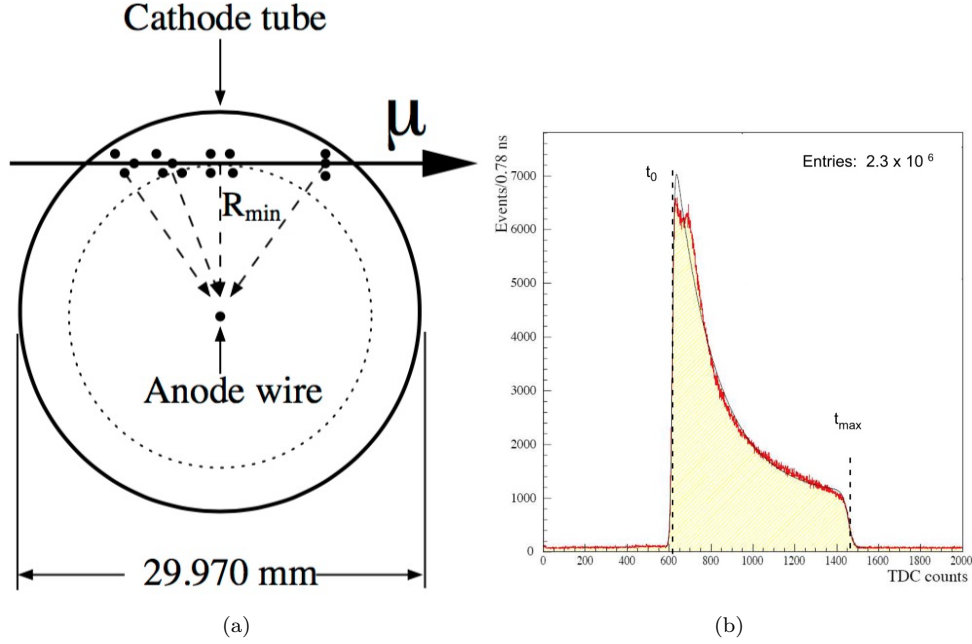


FIGURE 3.10: Cross-section view of a MDT tube (a) and an example of drift time spectrum for a MDT tube (b).

The naming of the MDT chambers is based on their location either in the barrel (B) or end-cap (E), also their assignment to inner (I), middle (M) or outer (O) chamber layer and their belonging to a large (L) or a small (S) sector. Besides these, the sector number (1–16) and the sequence number of the chamber in a row of chambers of a sector are added for a complete MDT chamber naming.

Each MDT chamber consists of two groups of tube layers, which are multi-layers and separated by a mechanical spacer. For the innermost layer of the MS, each multi-layer is comprised of four tube layers in order to enhance the pattern-recognition performance, while for the middle and outer layer, each multi-layer only contains three layers.

### 3.2.5.2 Cathode strip chambers

Cathode strip chambers (CSC) are used for the forward region ( $2 < |\eta| < 2.7$ ) in the innermost tracking layer because of their high spatial, time and double track resolution with high rate capability. They can keep low neutron sensitivity as well. The CSC are multi-wire proportional chambers (MWPC) with the wires oriented in the radial direction and the cathode planes segmented into strips in orthogonal directions (one perpendicular to the wires to provide precision coordinate, while the other one parallel to the wires to provide transverse coordinate). The resolution of a chamber is  $40\ \mu\text{m}$  for the bending plane and around  $5\ \text{mm}$  for the transverse plane. Such difference of the resolution is due to the different readout pitch and to the fact that the azimuthal readout runs parallel to the anode wires.

### 3.2.5.3 Resistive plate chambers

Resistive plate chambers (RPC) serve as the fast trigger system in the barrel region ( $|\eta| < 1.05$ ) to deliver the track information within a few  $ns$  after the passage of a charged track. There are three concentric cylindrical layers around the beam axis, known as the three trigger stations. The RPC is a gaseous parallel electrode-plate detector, which has no wires. As shown in Figure 3.11, two RPC layers (RPC1 and RPC2) are below and above the MDT's middle chamber, while the third layer (RPC3) is located above (below) the MDT's outer chamber for the large (small) sectors. There is a large lever arm between inner and outer RPC, which allows the trigger to select the tracks with high  $p_T$  ranging between 9 and 35 GeV, known as the high- $p_T$  trigger. And the two inner stations provide the low- $p_T$  trigger for the  $p_T$  range between 6 and 9 GeV. Each station of the RPC consists of two independent layers and both of them are used for measuring transverse coordinates namely  $\eta$  and  $\phi$ .

### 3.2.5.4 Thin gap chambers

For the end-cap region ( $1.05 < |\eta| < 2.4$ ), TGC are adopted for triggering, which are operated based on the same principle as MWPC. TGC can provide two functionalities for end-cap: one is the muon trigger capability and the other one is the determination of the second azimuthal coordinate to complement the MDT's measurement in the bending direction. As depicted in Figure 3.11, there are three layers located in front of (TGC1) and behind (TGC2 and TGC3) the middle MDT wheel (EM). And the fourth layer is

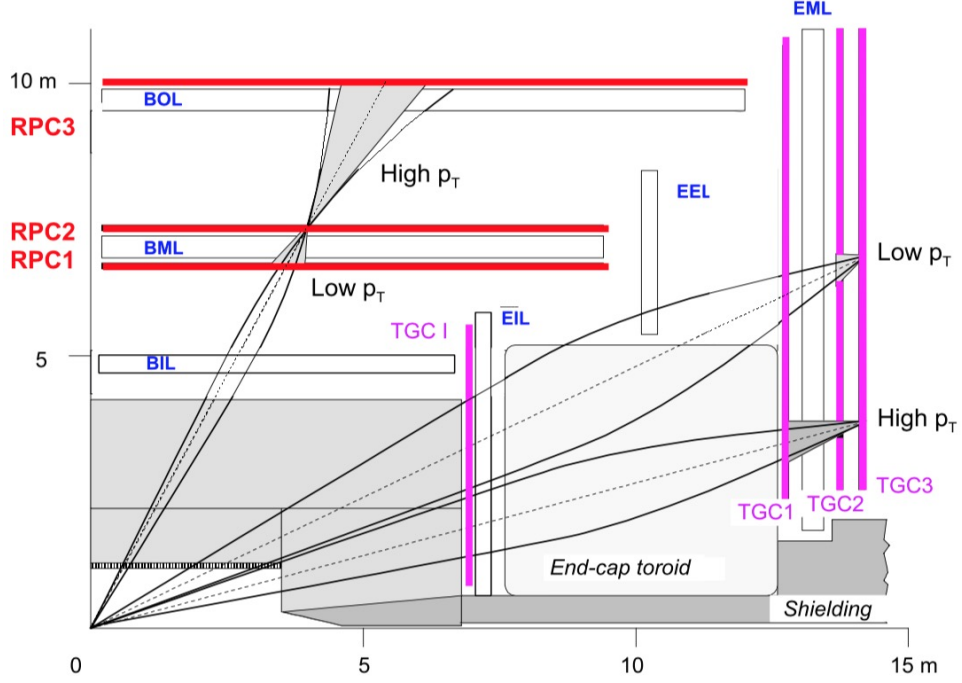


FIGURE 3.11: A quarter-section view of the muon trigger system

in front of the innermost MDT layer, which is segmented radially into two parts: end-cap (EI) and forward (FI, also known as the small wheel). The azimuthal coordinate in the outer MDT wheel (EO) can be obtained by the extrapolation of the track from the middle layer accurately because of no magnetic field existing between the EM and EO.

### 3.2.6 Forward detectors

Originally there are three smaller types of detectors covering the ATLAS forward region as shown in Figure 3.12. Ordered with respect to the corresponding distance from the IP, the first part is Luminosity measurement using Cherenkov Integrating Detector (LUCID), which is located at  $\pm 17$  m from the IP. LUCID is the major relative luminosity monitor for the ATLAS and the only detector primarily dedicated to online luminosity monitoring. Its major purpose is to detect inelastic  $p - p$  scattering in the forward region aiming to both measure the integrated luminosity and also to provide online monitoring for the instantaneous luminosity and beam conditions. While the second part is the Zero-Degree Calorimeter (ZDC), residing at a distance of  $\pm 140$  m from the IP, where the LHC beam pipe is separated into two pipes. And its major goal is to detect the forward neutrons ( $|\eta| > 8.3$ ) for the heavy-ion collisions. The third detector, which

is also the most remote ( $\pm 240$  m) one from the IP, is the Absolute Luminosity detector For ATLAS (ALFA).

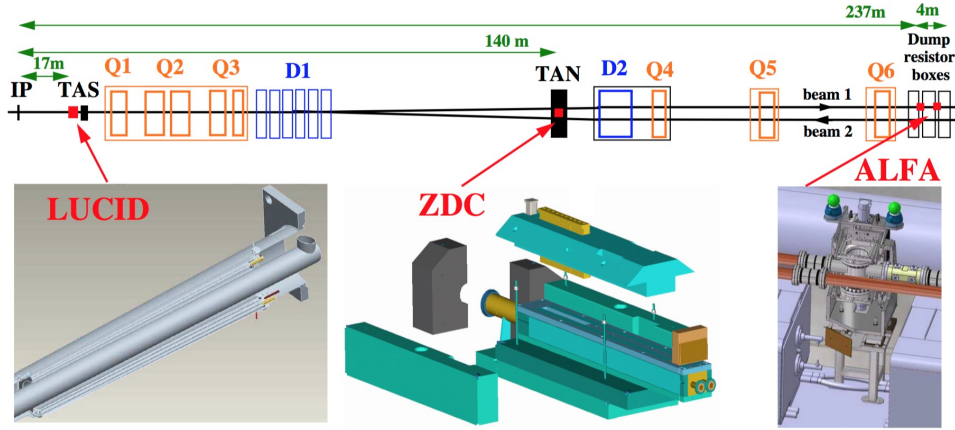


FIGURE 3.12: Placement of the ATLAS forward detectors along the beam line

During the shutdown in the end of 2016, a new component was added to complement the ALFA, which is the ATLAS Forward Proton (AFP) detector [62]. The AFP is located  $\sim 210$  m from the IP, which is mainly composed of two components: the tracking detectors and the high-resolution time-of-flight (ToF) detector. For the Run 2, the goal with the AFP is to carry out measurements of the soft and hard diffractive processes in dedicated low pile-up runs, which is crucial for the detailed understanding of the QCD.

### 3.2.7 Trigger system

As described in the previous paragraph, the trigger system is a very crucial component for the ATLAS experiment. During the LS1, many upgrade operations have been carried out for the trigger system in order to satisfy the challenging requirements with the much higher luminosity and pile-up in Run 2. Figure 3.13 [63] depicts the upgraded Trigger and Data Acquisition (TDAQ) system, which is comprised of a hardware-based first level trigger (L1) and a software-based high-level trigger (HLT). As shown in the figure, the inputs from the L1 calorimeter (L1Calo) and L1 muon (L1Muon) triggers together with some other subsystems like the Minimum Bias Trigger Scintillators (MBTS), the LUCID Cherenkov counter and ZDC are sent to the Central Trigger Processor (CTP), which then generates the L1 Trigger decision. After this, the events are buffered in the Read-Out System (ROS) and processed by the HLT. The HLT receives Region-of-Interest (RoI) information from the L1, which is used for regional reconstruction in the trigger algorithms. And after accepted by the HLT, the events are transferred to local

storage at the experimental site and exported to the Tier-0 facility at CERN's computing center for offline reconstruction. More details about the L1 and HLT are described in the following subsections.

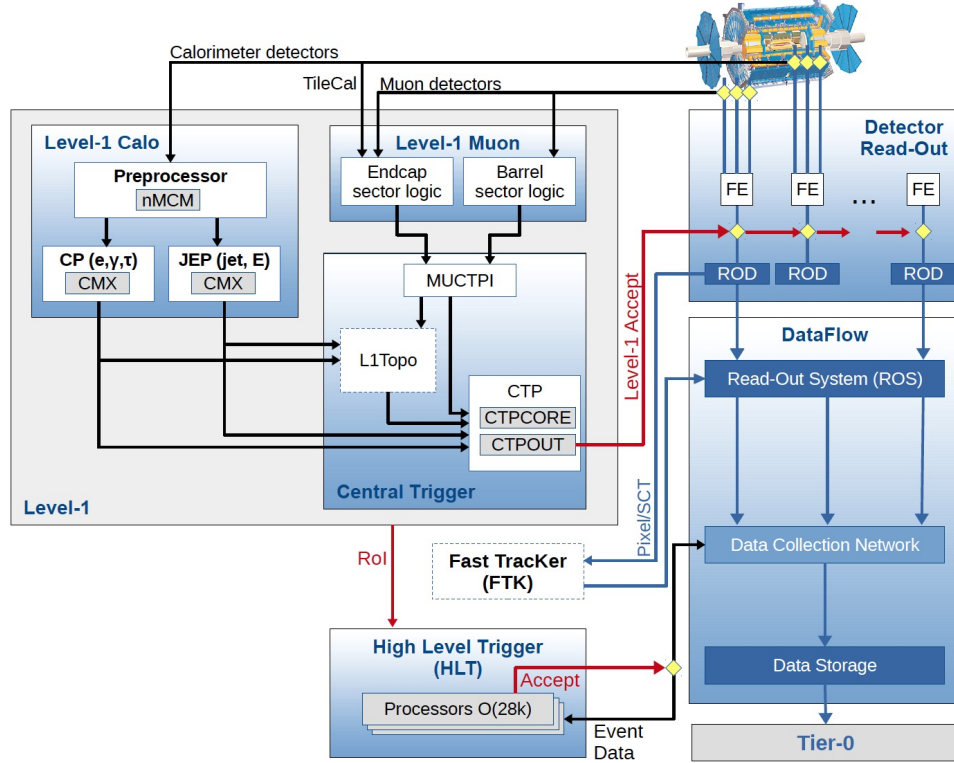


FIGURE 3.13: Schematic view of the ATLAS TDAQ system for Run 2

### 3.2.7.1 Level-1 Trigger

Substantial upgrades have been performed for the L1 trigger system, leading to the maximum L1 trigger rate increasing from 70 kHz (Run 1) to 100 kHz (Run 2). The Level-1 calorimeter (L1calo) trigger and Level-1 muon trigger are briefly introduced in the following paragraphs.

Figure 3.14 illustrates an example of the electron/photon and tau trigger algorithm. It can identify an Region-of-Interest (RoI) as a  $2 \times 2$  trigger tower cluster in the EM calorimeter, for which the sum of the transverse energy ( $E_T$ ) from at least one of the four possible pairs of nearest neighbour towers ( $1 \times 2$  or  $2 \times 1$ ) exceeds a predefined threshold. Jet RoIs are defined as  $4 \times 4$  or  $8 \times 8$  trigger tower windows, with the corresponding sum of the electromagnetic and hadronic  $E_T$  exceeding the predefined thresholds. The  $2 \times 2$  trigger tower core surrounded is the local maximum, which is used to determine

the coordinates of this jet RoI. The new FPGA-based multi-chip module (nMCM) is adopted as the preprocessor system, which accommodates more flexibility and functionality comparing with the old system and eventually leads to a significant rate reduction of the L1 jet and L1  $E_T^{miss}$  triggers. Then the outputs from this preprocessor are sent to the Cluster Processor (CP) together with Jet/Energy-sum Processor (JEP) subsystems in parallel. The CP subsystem can identify electron/photon and tau candidates if the  $E_T$  threshold and certain isolation criteria are satisfied. While the JEP subsystem can receive jet trigger elements ( $0.2 \times 0.2$  sums in  $\eta \times \phi$ ) and use these information to identify jets and also to produce global sums of scalar and missing transverse momentum. Then after this, the new developed cluster merger modules (CMX) are used to transmit both the location and energy of the identified trigger objects to the new L1Topo modules. The speed of such transmission is with a bandwidth of 6.4 Gbps per channel, and the total output bandwidth of above 2 Tbps. Besides, the processed trigger selections and isolation thresholds are doubled for most L1 triggers by using the new CMX modules comparing with the Run 1.

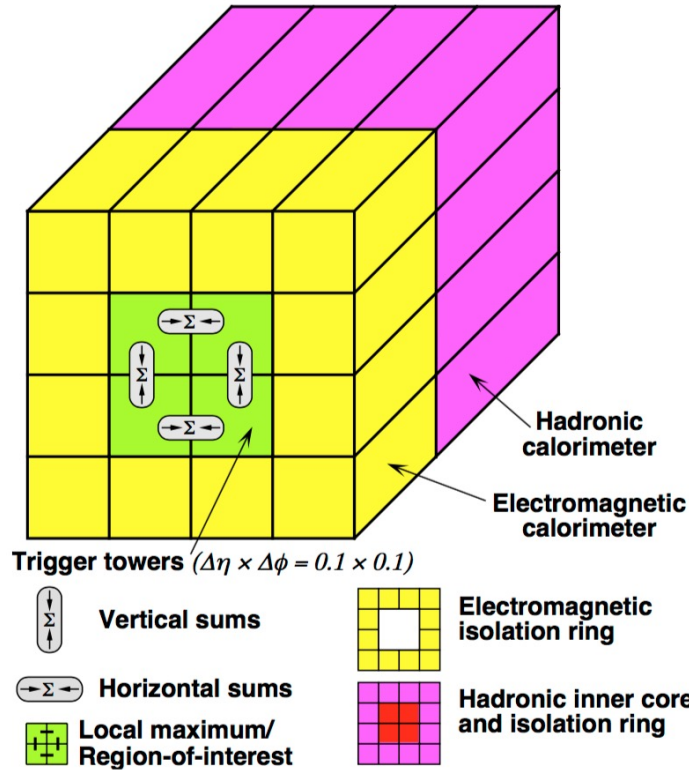


FIGURE 3.14: Schematic view of the input trigger towers for the L1Calo trigger algorithms.

The Level-1 muon trigger system relies on RPC (barrel) and TGC (end-cap) chambers, for which the details have been described in previous sections 3.2.5.3 and 3.2.5.4.



In the Run 1, for the end-cap region, a large amount of the trigger rates were found to be induced by the particles not really originating from the IP, as depicted in Figure 3.15. Then during the LS1, an additional TGC coincidence technique has been developed and adopted for the region  $1.3 < |\eta| < 1.9$  (TGC-FI) in order to reject these background particles. Besides, further coincidence logic for the region  $1.0 < |\eta| < 1.3$  is also introduced requiring the coincidence with the inner TGC chambers (EIL4) or the Tile hadronic calorimeter. After adopting these coincidence, the trigger rate is reduced by up to 60% with only around 2% of offline reconstructed muons lost in the corresponding region.

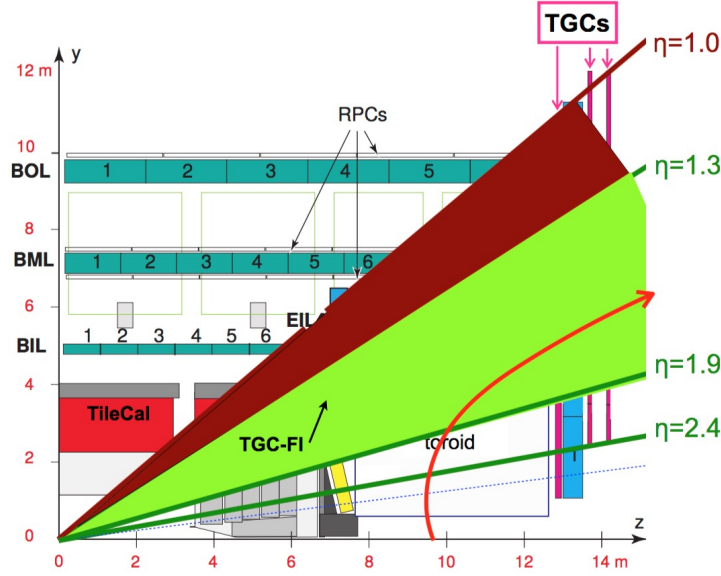


FIGURE 3.15: Schematic view of the MS with lines indicating various  $\eta$  regions. The curved arrow (in red color) shows an example of a trajectory from slow particles generated at the beam pipe around  $z = 10$  m. Triggers due to events of this type are mitigated by requiring an additional coincidence with the TGC-FI chambers in the region  $1.3 < |\eta| < 1.9$ .

### 3.2.7.2 High-level trigger

During the Run 1, the HLT is comprised of separated Level-2 (L2) and Event Filter (EF) farms. While in the Run 2, the L2 and EF farms are merged into a single homogeneous farm, which can realize better resource sharing and also an overall simplification for both hardware and software. After the L1 trigger stage, the events are processed by the HLT with the inputs from the ID, calorimeter and also MS, which are not available at the L1.



The tracking trigger can be divided into two stages: fast tracking and precision tracking. The fast tracking contains the trigger-specific pattern recognition algorithms while the latter one mainly relies on offline tracking algorithms. In 2018, the full Fast TracKer (FTK) system is expected to be adopted, which will provide global ID information and the corresponding HLT tracking algorithms have been already developed.

For the calorimeter algorithms, it firstly unpacks the data either within the RoIs identified at the L1 or from the full calorimeter. The former approach is applied for the well-separated objects (like electron, photon, muon and tau), while the latter one is adopted for jets and global event quantities (like  $E_T^{miss}$ ). After this stage, the raw unpacked data is converted into a collection of cells. And there are two different clustering algorithms used to reconstruct the clusters of energy deposited in the calorimeter: the sliding-window and the topo-clustering.

For muons, they are identified at the L1 trigger using the spatial and temporal coincidence of hits in the RPC or TGC. The HLT receives the L1 information with the RoI position and also makes use of the MDT and CSC to further refine the L1 muon candidates. For the HLT muon, the reconstruction contains two stages: fast (trigger specific) and precision (close to offline). For the fast stage, a track fit is performed by using the MDT drift time and positions and a  $p_T$  measurement is assigned, which can create the MS-only muon candidate. Then this MS-only track can be back-extrapolated to the IP and combined with the ID track, resulting in a combined muon candidate with refined track parameter resolution. While for the precision stage, based on the refined RoIs from the previous fast stage, the segments and tracks are reconstructed by using the information from the MS. And similar as the fast stage, combined muon candidates are formed by taking into account the ID track information. Additionally, an inside-out approach, which forms the combined muon candidate by extrapolating the ID track to the MS, is adopted as well when no matching ID track is found.



# Chapter 4

## Simulation and Object Reconstruction for the ATLAS Experiment

For the  $pp$  collisions at the LHC, currently the bunch spacing is 25 ns and the peak luminosity already exceeds the designed one as mentioned in the previous sections. For each bunch crossing, the average number of interactions is more than 30 and a large amount of particles can be produced accordingly, with the majority coming from the QCD processes. Therefore, certain selection requirements are needed to distinguish the process of interest, which is treated as the signal, from the other remaining processes regarded as the background. To predict and model the signal and background, Monte-Carlo (MC) simulation is adopted. The simulation software chain of the ATLAS experiment [64] can be divided into three stages: event generation including the hard scattering process, underlying events as well as the immediate decays, simulation of the detector and physics interactions, and digitization of the energy deposited in the detector's sensitive area into mimic readout signal (voltages and currents). Through such simulation process, the simulated output is already equivalent to that of the recorded data, and can be further sent into the reconstruction phase. As depicted in the Section 3, the ATLAS detector is designed with quite general purpose, and different particles can interact with certain sensitive area of the detector and give different responses. Figure 4.1 shows the graphic mechanism of the particle identification for the ATLAS detector. Based on these interaction responses, we are able to reconstruct the corresponding objects (e.g. track, vertex, electron, muon, jet,  $E_T^{miss}$ ...), which can be used for the latter physics analysis.

The following sections 4.1 and 4.2 will describe the detector simulation and analysis object reconstruction respectively.

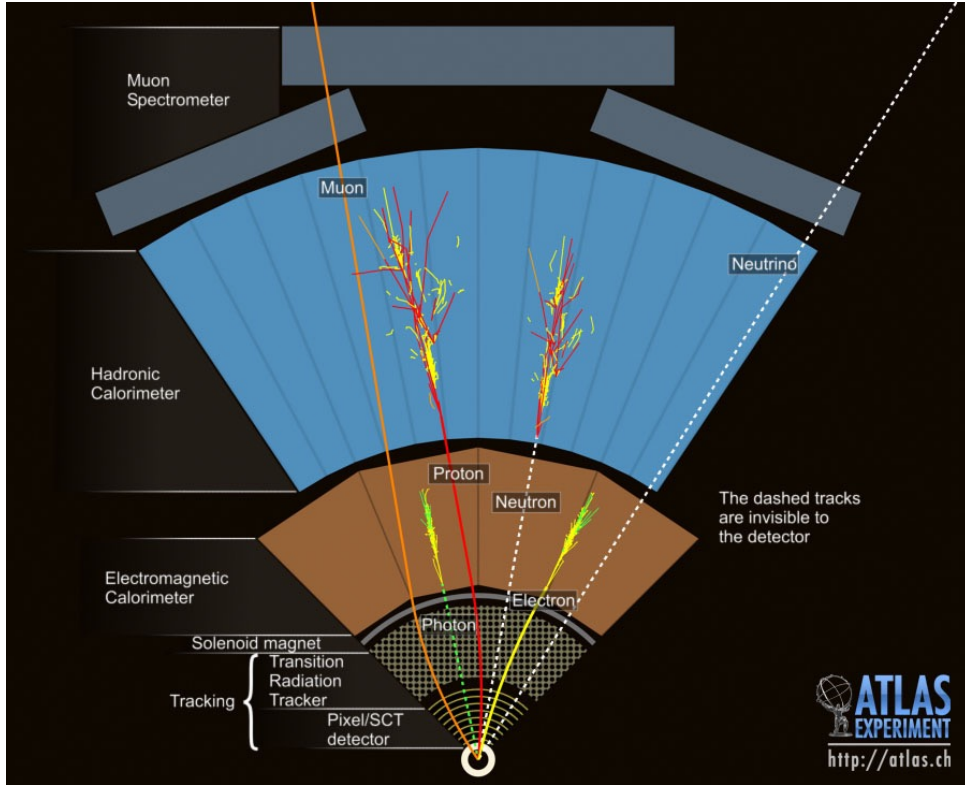


FIGURE 4.1: Schematic description of the particle identification of the ATLAS detector

## 4.1 Detector Simulation

The simulation program used for the ATLAS experiment is integrated into the so-called Athena software framework [65], which adopts PYTHON as the object-oriented scripting and interpreter language to configure and load C++ algorithms and objects. Figure 4.2 shows the overview of the ATLAS simulation work flow. Firstly, certain MC generators are used to produce events in the standard HepMC format. Afterwards, these events are loaded into simulation, for which GEANT4 is used for the complete ATLAS detector configuration. During the simulation process, the energies deposited in the detector's sensitive regions are recorded as hits (including information on the total energy deposition, position, and time) and written into a simulation hit file. Then this hit file is sent for digitization, which can construct digits and send inputs to the read out drivers (RODs) of the detector electronics with the emulated functionality. After this,



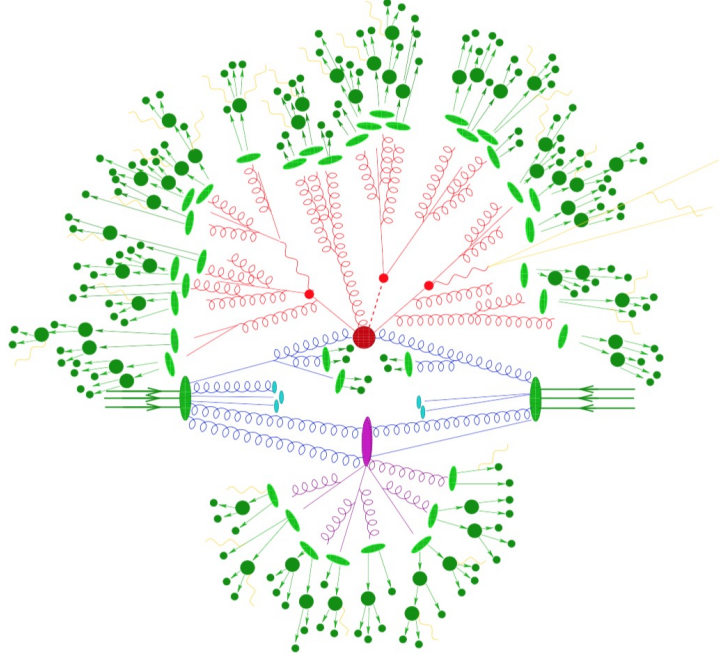


FIGURE 4.3: Sketch of a hadron-hadron collision event simulated by Sherpa generator. The red blob in the center stands for the hard collision, which is surrounded by a tree-like structure representing Bremsstrahlung simulated by parton showers. The purple blob represents a secondary hard scattering event. Light green blobs indicate hadronization process. Dark green blobs represent hadron decays. Yellow lines stand for signal soft photon radiation.

### 4.1.2 Detector simulation

GEANT4 [71, 72] is adopted as the standard simulation for the ATLAS experiment, which provides models for physics and infrastructure of the particle transportation through the detector's geometry. The events produced by the MC generators are taken as the inputs for the GEANT4 simulation, and cuts and transformations can be made to these events. The GEANT4 simulated information is added to the MC truth record, which is defined from the generation step. Since many secondary tracks can be produced during this simulation stage, therefore only those information from the interactions of interest are stored, including the incoming particles, step sequence, vertex and also outgoing particles. The output format of the GEANT4 simulation is a hit file, which contains the metadata depicting the configuration of the simulation during the run, all truth information needed and also a set of hits for each subdetector. The full GEANT4 simulation can be quite time consuming because of the complicated detector geometry. Instead several fast simulation methods have been developed to meet the needs for large statistics simulation, including Fast G4 Simulation [73], ATLFAST-I [74] and ATLFAST-II [75].

### 4.1.3 Digitization

The hit file produced by GEANT4 simulation includes hard scattering signal, minimum bias, beam halo, beam gas and cavern background events. They are then sent as inputs to the corresponding ATLAS software for digitization, which can convert hits into detector response digits. Normally the digits can be produced if the voltage or current for a specific readout channel surpasses a pre-defined threshold during a specific time window. The pile-up effect is also mimicked from a soft-QCD process generated by PYTHIA8 [67] during the digitization phase so as to save the simulation time. The output of the digitization is written into RDOs as mentioned above. Besides, the digitization can also produce Simulated Data Objects (SDOs), containing the information of all the particles and noise contributing to the signal produced in a given sensor and the amount of energy contributing to the signal by each. SDOs are mainly adopted to determine the tracking efficiency and fake track rates. The output for this digitization stage can be further used for object reconstruction which will be introduced in the following section.

## 4.2 Object Reconstruction

Figure 4.4 sketches the data flow for the ATLAS experiment [76]. After passing the L1 and HLT triggers, the data are sent to Tier 0 for initial processing. A small amount of express stream is processed for the purpose of online data quality monitoring. Besides, a dedicated amount of data stream is sent out at the trigger level for the use of detector alignment and calibration, which is normally performed within 24 hours after the data taking. Through this step, the time-dependent calibrations and alignments together with the beamspot position can be determined. These information are used for the further bulk reconstruction that takes up the majority of the Tier 0 resources. For the end of the reconstruction chain, the data are distributed to the Tier 1 and Tier 2 centers which are used for the analysis and production of simulated data. Besides, the Tier 1 is also used for the data reprocessing by re-running reconstruction with improved calibration and alignment constants and with improved algorithms for reconstruction as well. This section will describe the reconstruction of the physics objects for the ATLAS experiment, including track, vertex, electron, muon, jet, b-jet and  $E_T^{miss}$  as well.

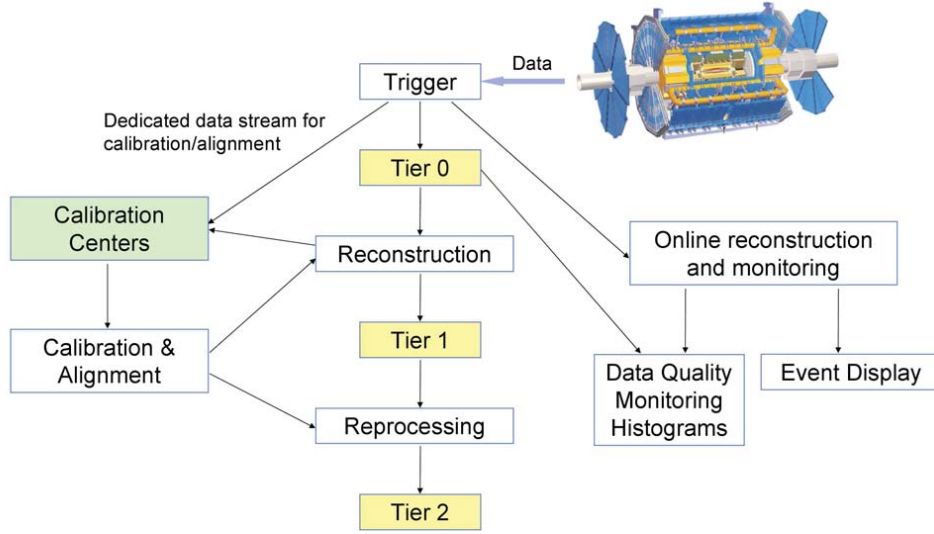


FIGURE 4.4: The sketch of the data flow for the ATLAS experiment.

### 4.2.1 Track

There are two sets of independent track devices for the ATLAS experiment, one of which is the inner detector (ID) close to the IP, while the other one is the muon spectrometer (MS). The reconstructed charged-particle trajectories in the ID and MS are referred to as ID tracks and MS tracks respectively. The ID track reconstruction needs to cope with the high track density which imposes a large amount of combinatorial track candidates, and the MS reconstruction is largely limited by the huge part of inert material, the cavern background and also the highly inhomogeneous magnetic field.

#### 4.2.1.1 Inner detector track

Figure 4.5 depicts the ID system with the new insertable B-layer (IBL) included. The ID track reconstruction [77] contains two sequences: the inside-out as the primary method and also a consecutive outside-in strategy.

For the inside-out, it makes use of the high granularity of the pixel and SCT to get prompt tracks originating from the IP. As the first step, the spacepoint objects (three-dimensional representations of the detector measurements) are created. And then the



track seeds are formed by combining the spacepoints in the three pixel layers and the first SCT layer. After this, these generated seeds are extended throughout the SCT to form track candidates. Then these candidates are further fitted, and quality cuts are applied as well to remove outlier clusters, reject fake tracks and resolve ambiguities in the cluster-to-track association. In the end the selected tracks are extended into the TRT, which are refitted with the full information of pixel, SCT and TRT detectors.

The outside-in, which is a complementary approach, starts track searching from segments in the TRT and extends inwards to add silicon hits. This can help to improve the tracking efficiency for secondary particles from conversions or decays of long-lived particles.

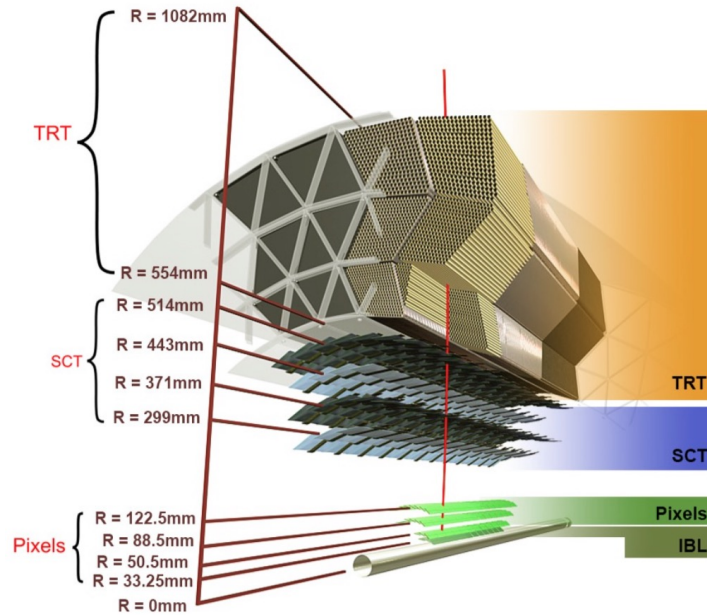


FIGURE 4.5: Schematic view of the ATLAS inner detector showing all the corresponding components, including the new new insertable B-layer (IBL).

#### 4.2.1.2 Muon spectrometer track

The MS track reconstruction [78] starts with a search for hit patterns inside each muon chamber to form segments. For each MDT chamber and neighbouring trigger chamber, a Hough transform [79] is adopted to search for hits on a certain trajectory in the bending plane. The MDT segments are reconstructed by performing a straight-line fit to the hits in each layer, while the RPC or TGC hits can measure the coordinates which are orthogonal to the bending plane. The CSC segments are built by using a separate combinatorial search in the  $\eta$  and  $\phi$  planes.

Then the muon track candidates are built by fitting the hits from the reconstructed segments in different layers. The algorithm adopted here carries out a segment-seeded combinatorial searching which starts by using as seeds the segments generated in the middle layers of the detector where more trigger hits are available. Then the searching is extended to use the segments from the outer and inner layers as seeds. The segments are selected by utilizing the criteria based on hit multiplicity and fit quality, and are matched with their relative positions and angles. At least two matching segments are needed to build a track, except for the barrel–endcap transition region where one single segment in high-quality with  $\eta$  and  $\phi$  information can be used to build a track. Initially one segment can be used to build several track candidates. But later an overlap removal procedure is performed to select the best assignment to a single track or allow for the segment to be shared between two tracks. Besides, in order to guarantee the high efficiencies for close-by muons, all tracks with segments in three different MS layers are kept if they are identical in two out of three layers but share no overlapped hits in the outermost layer.

The associated hits for each track candidate are fitted with a global  $\chi^2$  fit. And the track is selected as candidate if the  $\chi^2$  value of this fit passes the certain criteria. Otherwise, those hits inducing large  $\chi^2$  values are removed and then the fit is repeated. Besides a hit recovery method is adopted to look for any additional hits which are consistent with the trajectory of a track candidate, and the track refit is performed by adding these additional hits.

### 4.2.2 Primary vertex

This subsection briefly introduces the reconstruction of the primary vertex (PV) [80] by using a collection of reconstructed tracks as the inputs. For the tracks to be considered as inputs, they need to pass a set of selection criteria as described below [81]:

- $p_T > 400$  MeV
- $|\eta| < 2.5$
- Number of silicon hits  $\geq \begin{cases} 9 & \text{if } |\eta| \leq 1.65 \\ 11 & \text{if } |\eta| \geq 1.65 \end{cases}$
- IBL hits+B-layer hits  $\geq 1$
- A maximum of 1 shared module (1 shared pixel hit or 2 shared SCT hits)

- Pixel holes = 0
- SCT holes  $\leq 1$

The PV reconstruction is divided into two steps: vertex finding and vertex fitting. The vertex finding represents the pattern recognition process, namely the association of reconstructed tracks to the vertex candidates. While the latter one mainly copes with reconstruction of the actual vertex position together with its covariance matrix.

The first step of the procedures is selecting a set of tracks passing the criteria described above and then selecting a seed position for the first vertex. This seed position is determined based on the beam spot in the transverse plane. And the transverse coordinates ( $x$  and  $y$ ) of the starting point are directly taken from the center of the beam spot, while the  $z$ -coordinate is calculated as the mode of the  $z$ -coordinates of the tracks located at their respective points with closest approach to the center of the beam spot.

After fixing the seed position, we can determine the vertex position by using an adaptive vertex fitting algorithm. This algorithm performs an iterative  $\chi^2$  minimisation to find the optimal vertex position by using the seed position as the starting point and parameters of reconstructed tracks as input measurements. For this fitting process, each input track is assigned a weight, which reflects its compatibility with the vertex estimation. The vertex position is re-calculated with the weighted tracks, and then the iterative procedure is repeated by re-calculating track weight with respect to the new vertex position. Eventually after the last iteration, the final weight of each track adopted for the vertex fit is estimated. And those tracks incompatible with the vertex by  $\geq 7 \sigma$  are removed from the vertex candidate and sent back to the category of unused tracks.

Once a vertex candidate is found, the rejected tracks are treated as the inputs for a new vertex finding iteration. And the iterative procedures depicted above are repeated by calculating a new starting position from remaining tracks until no un-associated tracks are left in this corresponding event or no additional vertex is found in the remaining tracks.

In the end, all the vertices with at least two associated tracks are treated as the valid PV candidates. And generally for the physics analysis, the PV adopted is the reconstructed vertex with the largest value of  $\Sigma p_T^2$ .

### 4.2.3 Electron

At the ATLAS experiment, quite many physics processes of interest involve one or multiple electrons or positrons, which hereafter are referred to as electrons collectively. Electrons leave tracks in the ID and energy deposits in the EM calorimeter. The signatures in the calorimeter are adopted in the L1 trigger system, and then combined with the ID tracks to reconstruct the electron candidates, which are used for the HLT decision algorithms. The candidates can be further distinguished from background (e.g. hadrons and non-prompt electrons mainly coming from photon conversions and heavy flavor ( $b$ ) hadron decays) by using several sets of electron identification criteria depending on the levels of signal acceptance versus background rejection efficiency. Such identification requirements are determined based on the shapes of EM showers in the calorimeter together with tracking and track-to-cluster matching quantities [82]. Besides, further criteria are made to require electron candidates to be isolated from other activities in the calorimeter or ID so as to enhance the background rejection capacity. This subsection gives brief descriptions of the electron reconstruction, identification, and isolation.

#### 4.2.3.1 Electron reconstruction

Electrons are reconstructed in the region of  $|\eta| < 2.47$  for the ATLAS detector and can be separated into the following steps [83]:

As a first step, a sliding window with a size of  $3 \times 5$  in units of  $0.025 \times 0.025$  in  $\eta \times \phi$  is utilized to search for cluster seeds as longitudinal towers with total cluster transverse energy beyond 2.5 GeV. Then the clusters are formed surrounding the seeds by adopting a clustering algorithm [84] which can allow for the duplications to be removed.

Then we need to deal with the electron track reconstruction which can be divided into two steps namely pattern recognition and track fit. The standard way for pattern recognition is to use the pion hypothesis for the energy loss caused by the interactions with the detector material. If a track seed with a  $p_T > 1$  GeV can not be extended successfully to a full track with at least seven hits by using this pion hypothesis and it falls into one of the EM cluster RoI, then another electron hypothesis which allows for larger energy loss is adopted to re-perform the pattern recognition. After this, track fit is performed by using either of the hypotheses described above with the ATLAS Global  $\chi^2$  Track Fitter [85]. And if the track candidate fails the pion hypothesis track fit, it is then refitted using the electron hypothesis. Once the tracks are obtained, they are loosely

matched to the EM clusters by using the distance in  $\eta$  and  $\phi$  between the position of the track after extrapolation in the calorimeter middle layer and the cluster barycenter. And the energy loss caused by the bremsstrahlung, together with the number of precision hits in the SCT are taken into account for the matching conditions.

The next step is to reconstruct the electron candidate by matching the track candidate to the cluster seed. If several tracks satisfy the matching condition, a primary track is chosen based on an algorithm [86] utilizing the cluster-track distance  $R$  with different momentum hypotheses, the number of pixel hits together with the presence of a hit in the first silicon layer. For those electron candidates without any associated tracks, they are treated as photons and removed.

For the Run 2, additional requirements related to the impact parameters like  $d_0/\sigma_{d_0} < 5$  and  $\Delta z_0 \sin\theta < 0.5$  mm are applied to ensure the track associated with the electron to be compatible with the PV, which can help to further reject background from conversions and secondary particles. The  $d_0$  is the impact parameter representing the distance of closest approach for the track calculated with respect to the beam line and  $\sigma_{d_0}$  is the estimated uncertainty of  $d_0$ . While  $z_0$  is calculated along the beam line direction, which is the distance between the beam spot position and the point where  $d_0$  is measured.  $\theta$  is the polar angle of the track.

#### 4.2.3.2 Electron identification

Electron identification algorithms are developed using the quantities related to the electron cluster and track measurements, which include calorimeter shower shapes, the information from TRT, track properties, track-cluster matching related variables and also quantities that measure bremsstrahlung effects for separating signal from background. For the Run 2, with the new IBL, the number of hits in the innermost pixel layer is adopted for distinguishing between the electrons and converted photons. Besides, a likelihood method based on the TRT high-threshold hits is developed to complement the lower transition radiation absorption probability of the argon.

The baseline identification algorithm adopted for the Run 2 is the likelihood-based (LH) method, which uses the multivariate analysis (MVA) technique to simultaneously evaluate several properties of the electron candidates for the selection decision. There are three levels of identification working points (WPs) for the LH algorithm provided: Loose, Medium and Tight, in the order of increasing background rejection. These three WPs are

defined in such a way that the samples selected by them are subsets of one another, which means that the electrons passing Medium can also be selected by Loose, while electrons selected by Tight are also Medium electrons. Figure 4.6 depicts the performance of these three LH WPs, and the signal (background) acceptance efficiencies for electron candidates with  $E_T = 25$  GeV are in the range from 78 to 90% (0.3 to 0.8%) and increase (decrease) with  $E_T$ .

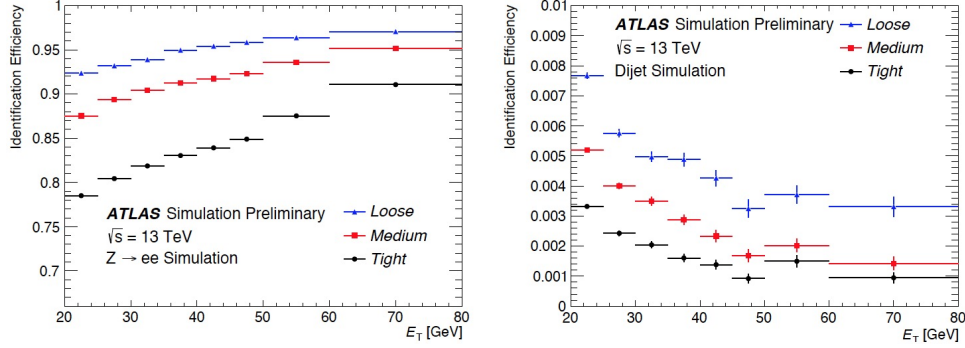


FIGURE 4.6: The identification efficiencies of different working points for  $Z \rightarrow ee$  (left) and dijet (right) samples.

#### 4.2.3.3 Electron isolation

Electron isolation related variables are developed to help further separate signal from background. In general these variables can quantify the energy of the particles produced surrounding the electron candidate, which allows to distinguish the prompt electrons from non-isolated candidates (e.g. electrons from converted photons, electrons originating from heavy flavor hadron decays, and also light hadrons mis-identified as electrons). There are two isolation variables developed:

- Calorimeter-based variable  $E_T^{cone0.2}$ , which is defined as the sum of transverse energies of the topological clusters [87] calibrated at the EM scale within a cone size of  $\Delta R=0.2$  around the electron candidate cluster. For the sum calculation, only those clusters with positive reconstructed energies are taken into account.
- Track-based variable  $p_T^{varcone0.2}$  is defined as the sum of the  $p_T$  of all the tracks originating from the PV, which pass quality requirements ( $E_T > 1$  GeV,  $|\Delta z_0 \sin \theta| < 3$  mm and also ID hits criteria) within a cone size of  $\Delta R = \min(0.2, 10 \text{ GeV}/E_T)$  around the electron candidate track. When calculating this sum, the electron candidate itself

associated tracks (including the electron track and additional tracks from converted bremsstrahlung photons) are not considered.

Figure 4.7 shows the distributions of these two isolation variables for the selected electrons ( $E_T > 27$  GeV and Tight requirement) from data and  $Z \rightarrow ee$  samples. Based on the quantities  $E_T^{cone0.2}/E_T$  and  $p_T^{varcone0.2}/E_T$ , a set of working points for the electron isolation are developed and used for the physics analysis.

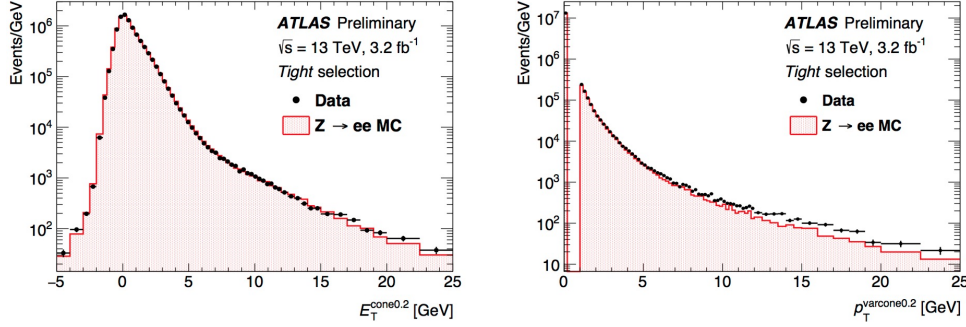


FIGURE 4.7: Distributions of  $E_T^{cone0.2}$  (left) and  $p_T^{varcone0.2}$  (right) for selected electrons of MC  $Z \rightarrow ee$  and data samples.

## 4.2.4 Muon

Muons are quite common signatures in the final states of many physics analyses, including the Higgs boson study, SM measurements, BSM physics searches and so on. This subsection will describe muon reconstruction, identification, isolation, and momentum scale and resolution [78].

### 4.2.4.1 Muon reconstruction

For the muon reconstruction, firstly the ID and MS tracks are formed independently as described in Subsection 4.2.1. Then the combined ID-MS reconstruction is carried out with several algorithm based on the information received from the ID, MS and calorimeters. We can define four types of muons based on the subdetectors used in the reconstruction.

- Combined (CB) muons: based on the reconstructed ID and MS tracks, a combined track is formed with a global refit, which make use of the hits from the ID and MS

subsystems. For this global fit, certain MS hits can be added to or removed from the track in order to improve the fit quality. The outside-in pattern recognition (muons are first reconstructed in the MS and then extrapolated inward to match an ID track) is the primary strategy for reconstruction, while the inside-out approach (ID track is extrapolated outward to match a MS track) is utilized as a complementary method.

- Segment-tagged (ST) muons: an ID track is categorized as a muon if it is associated with at least one local segment in the MDT or CSC when extrapolated to the MS. Generally ST muons are adopted for those cases when muons cross only one layer of the MS chambers, either due to their low  $p_T$  or due to that they fall into the regions with less MC acceptance.
- Calorimeter-tagged (CT) muons: if an ID track can be matched to an energy deposit in the calorimeter which is consistent with a minimum-ionizing particle, then it is classified as a CT muon. For the region  $|\eta| < 0.1$  and  $p_T$  ranging between 15 and 100 GeV, the identification criteria for CT muons are optimal.
- Extrapolated (ME) muons: ME muons are reconstructed only based on the MS track and a loose requirement on compatibility with originating from the IP. ME muons generally need to pass through at least two layers of the MS chambers in order to provide a track measurement, but for the forward region they are required to pass through three layers. ME muons are basically designed for extending the acceptance of muon reconstruction for the region  $2.5 < |\eta| < 2.7$ , since there is no associated ID track in that area.

The overlaps between these four different types are already dealt with before generating the collection of muons used for physics analyses. For example, when two muon types share the same ID track, priority first goes to CB muons, then to ST muons and finally to CT muons. And the overlaps with ME muons are settled by analyzing the track hit contents and also selecting the track with a better fit quality and a larger number of hits.

#### 4.2.4.2 Muon identification

To suppress the background mostly from light hadron (e.g. pion or kaon) decays and also keep a high selection efficiency for the prompt signal muons, the muon identification is



carried out by using quality requirements (such as quality of the track fit). The variables adopted in the muon identification for CB tracks include:

- $q/p$  significance which is defined as the absolute value of the difference between the  $q/p$  values measured in the ID and MS, divided by the sum in quadrature of their corresponding uncertainties;
- $\rho'$  which is defined as the absolute value of the  $p_T$  difference between the ID and MS measurements divided by the  $p_T$  of the CB track;
- Normalized  $\chi^2$  value of the CB track fit;
- The number of hits in the ID and MS.

There are four working points developed for the muon identification to fulfill the specific needs for different physics goals: Loose, Medium, Tight and High- $p_T$ . The Loose, Medium and Tight are inclusive categories, which means that muons sorted into tighter categories can also pass the looser requirements.

- Loose: this identification WP is developed to maximize the reconstruction efficiency while providing the muon tracks in good quality. All the muon types described in [4.2.4.1](#) are adopted for Loose WP. For CB and ME muons, they are sorted into Loose category if they satisfy the Medium WP (described below). And CT and ST muons are required to reside in the  $|\eta| < 0.1$  region.
- Medium: this one is the default identification WP used for muon selection, which minimises the systematic uncertainties associated with muon reconstruction and calibration. Only CB and ME muons are considered for Medium WP. The CB muons are required to have  $\geq 3$  hits in at least two MDT layers, except for the  $|\eta| < 0.1$  region, where tracks are required to have one MDT layer and  $\leq 1$  MDT hole layer. For the ME muons, they are required to have at least three MDT/CSC layers, residing in the region  $2.5 < |\eta| < 2.7$ . Besides,  $q/p$  significance is required to be  $< 7$ , which can help to reduce the contamination from hadrons misidentified as muons.
- Tight: this WP is designed to enhance the purity of muons with the cost of some certain efficiencies. The candidates only come from the CB muons which pass the Medium WP and have hits in at least two stations of the MS. In order to remove pathological tracks, it is required that the normalized  $\chi^2$  of the combined track fit is less than 8.

- High- $p_T$ : this WP is developed to guarantee the optimal momentum resolution for muons with  $p_T > 100$  GeV, which is mainly used for high-mass resonances searches (adopted for the dilepton search of this thesis work). The CB muons that satisfy the Medium WP and have at least three hits in three stations of the MS are tagged as High- $p_T$  ones. And certain MS regions with suboptimal alignment situation are removed for this WP identification.

Figure 4.8 shows the muon reconstruction efficiency as a function of  $\eta$  for Medium and High- $p_T$  WPs, which is measured by using  $Z \rightarrow \mu\mu$  events for muons with  $p_T > 10$  GeV.

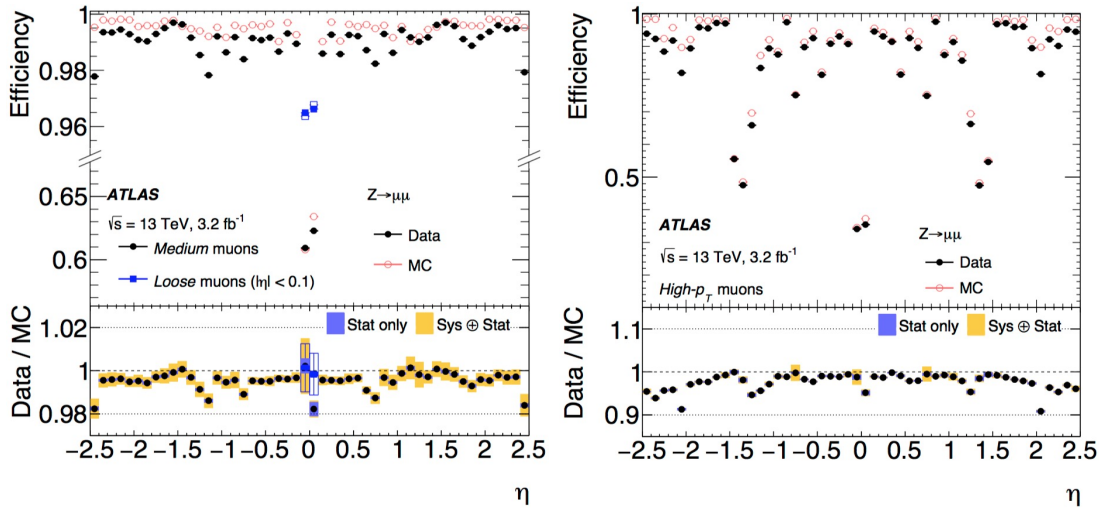


FIGURE 4.8: Muon reconstruction efficiency as function of  $\eta$  for Medium (left) and High- $p_T$  (right) derived from  $Z \rightarrow \mu\mu$  events for muons with  $p_T > 10$  GeV. The left plot also shows the efficiency of Loose in the region  $|\eta| < 0.1$ .

#### 4.2.4.3 Muon isolation

Similar to the electron case, muon isolation is adopted as well to help to distinguish the prompt muons from non-prompt ones, and two isolation related variables are developed. One is the track-based variable  $p_T^{varcone30}$ , which is defined as the scalar sum of the  $p_T$  of the tracks with  $p_T > 1$  GeV within a cone size of  $\Delta R = \min(10\text{GeV}/p_T^\mu, 0.3)$  around the muon candidate with  $p_T^\mu$ , and the candidate track itself is excluded. Another one is the calorimeter-based variable  $E_T^{topocone20}$ , which is defined as the sum of the  $E_T$  of topological clusters within a cone size of  $\Delta R = 0.2$  around the muon candidate, after subtracting the contribution from the energy deposit of the muon itself and correcting

for the pile-up effects. Based on these two variables, a set of isolation WPs are designed and adopted for various analyses.

#### 4.2.4.4 Muon momentum scale and resolution

Despite that the GEANT4 simulation covers a relatively accurate description for the detector, the level of detail is not sufficient enough to precisely depict the muon momentum scale to the 0.1% level and the muon momentum resolution to the 1% level. Therefore the related corrections are derived and applied to the simulated muon  $p_T$ . Muon momentum calibration is referred to as the procedure to identify the corrections to the simulated  $p_T$  reconstructed in the ID and MS in order to accurately describe the same quantities measured in data. The symbols  $p_T^{ID}$  and  $p_T^{MS}$  are used to represent the  $p_T$  of the ID and MS components for a CB track. And the corrected transverse momentum  $p_T^{Cor,Det}$  (Det=ID,MS) can be expressed into the equation below:

$$p_T^{Cor,Det} = \frac{p_T^{MC,Det} + \sum_{n=0}^1 s_n^{Det}(\eta, \phi)(p_T^{MC,Det})^n}{1 + \sum_{m=0}^2 \Delta r_m^{Det}(\eta, \phi)(p_T^{MC,Det})^{m-1} g_m}. \quad (4.1)$$

Here  $p_T^{MC,Det}$  is the uncorrected transverse momentum from simulation,  $s_n^{Det}(\eta, \phi)$  and  $\Delta r_m^{Det}(\eta, \phi)$  represent the momentum scale and resolution smearing corrections in a certain  $(\eta, \phi)$  region respectively, and  $g_m$  are normally distributed random variables with mean value of zero and unit width. The corresponding numerator depicts the momentum scales part. The  $s_1^{Det}$  term accounts for the correction of inaccuracy in the description of the magnetic field integral and also the dimension of the detector in the direction perpendicular to the magnetic field. And the  $s_0^{MS}(\eta, \phi)$  is used to model the effect on the MS momentum coming from the inaccuracy of the simulation for the energy loss in the calorimeter and materials between the IP and MS. While  $s_0^{ID}(\eta)$  is set to be zero since the energy loss between the IP and ID is negligible. The denominator of the Equation 4.1 represents the momentum smearing term which broadens the relative  $p_T$  resolution  $\sigma(p_T)/p_T$  from simulation, in order to describe the data more precisely. Based on assumption, we can parameterize the  $\sigma(p_T)/p_T$  term into the following equation:

$$\frac{\sigma(p_T)}{p_T} = r_0/p_T \oplus r_1 \oplus r_2 \cdot p_T, \quad (4.2)$$

with  $\oplus$  representing the sum in quadrature. The first term of Equation 4.2 mainly accounts for the fluctuations of the energy loss in the traversed material, and the second term mainly accounts for multiple scattering, local magnetic field inhomogeneities and local radial displacements of the hits, while the third term is mainly used to represent intrinsic resolution effects due to the spatial resolution of the hit measurements and also due to residual misalignment of the MS. The terms  $\Delta r_0^{ID}$  and  $\Delta r_0^{MS}$  are set to be zero given the fact that the energy loss is negligible in both the ID and MS measurements.

By combining the corrected  $p_T$  of the ID and MS components derived from Equation 4.1 with a weighted average, we can express the final corrected momentum for the combined muons,  $p_T^{Cor,CB}$ , into the formula:

$$p_T^{Cor,CB} = f \cdot p_T^{Cor,ID} + (1 - f) \cdot p_T^{Cor,MS}. \quad (4.3)$$

Here,  $f$  represents the weight, which is derived from the linear equation below:

$$p_T^{MC,CB} = f \cdot p_T^{MC,ID} + (1 - f) \cdot p_T^{MC,MS}, \quad (4.4)$$

which is based on the assumption that the relative contribution of the ID and MS to the CB muons stays unchanged before and after the momentum corrections applied.

#### 4.2.4.5 Impact of ID–MS alignment on high $p_T$ muon resolution

As we know the precision of muon detector alignment plays a crucial role for the high  $p_T$  muon resolution. This small subsection will describe the study of ID–MS alignment impact on resolution, which my colleague and I have performed within the muon performance group. The goal for this study is to validate the alignment simulation in MC samples by comparing to data, and also demonstrate whether there is potentially improved space for high  $p_T$  muon resolution with a better alignment scenario.

Four slices of MC samples corresponding to different alines smearing situations are adopted, which are 0.1, 0.3, 1.0 and 3.0 mm representing the errors on ID–MS misalignment. The smearing is also applied to the parameters affecting MS internal alignment like sagitta and hits positions, however this is not so relevant for this study here. In the meanwhile, around  $30 \text{ fb}^{-1}$  data samples are processed for the comparisons with MC.

Two variables sensitive to the ID–MS alignment are used:  $\Delta z_0 = (z_0^{ID} - z_0^{MEMS}) \times \sin\theta_{ID}$  and  $\Delta\theta = \theta_{MEMS} - \theta_{ID}$ . Here ID represents the inner detector track, while MEMS

represents the MS track which is extrapolated back with energy correction but without constrained to the PV.  $z_0^{ID}$  and  $z_0^{MEMS}$  denotes the longitudinal impact parameter calculated with respect to the beam line for ID and MEMS tracks. And  $\theta_{ID}$  and  $\theta_{MEMS}$  are the polar angles of these two tracks. For this study, only muons with  $p_T$  surpassing 300 GeV are selected. And two sets of muon identification WPs are tested: Medium and High- $p_T$ .

The  $\Delta z_0$  and  $\Delta\theta$  distributions are checked in each  $\eta - \phi$  sector using the MC and data samples and the mean value of the corresponding distributions are plotted into  $\eta - \phi$  2D maps as shown in Figure 4.9 and Figure 4.10 with Medium WP applied. While Figure 4.11 depicts the mean value distributions in each sector for these two variables. The 2D maps and 1D distributions for High- $p_T$  WP show similar patterns, which is also expected since the relative alignment between the ID and MS is an intrinsic feature for the detector. As shown in these figures, through the comparisons, the actual ID–MS mis-alignment situation in the data is more close to alines 1 mm scenario.

The combined muon  $p_T$  resolution is compared for the four slices of MC samples, which is shown in Figure 4.12. It can be seen that the resolution is strongly dependent on alignment, and such impact is enlarged with the muon  $p_T$  increasing.

Furthermore, in order to quantitatively assess the impact on  $p_T$  resolution with an improved alignment situation, attempts are made to correct  $z_0^{MEMS}$  and  $\theta_{MEMS}$  with respect to the ID track based on the mean value in each  $\eta - \phi$  sector as shown in Figure 4.9 and Figure 4.10. After the correction, a statistical combination between the ID and MEME tracks is performed to demonstrate the improvement on the combined muon  $p_T$  resolution. Figure 4.13 depicts the corresponding comparisons with and without correcting the relative mis-alignment between the ID and MS detectors for alines 1.0 mm sample. And clear improvement can be observed with the correction, and especially for the very high  $p_T$  end around 1 TeV, the relative improvement is about 5%.

For the next steps, more efforts will be carried out by using the official reconstruction method (combined fit for the hits in the ID and MEMS tracks), expecting to more precisely quantify the gain on muon  $p_T$  resolution with ID–MS mis-alignment corrected. Ideally, this can be potentially adopted for the samples reprocessing during the summer.

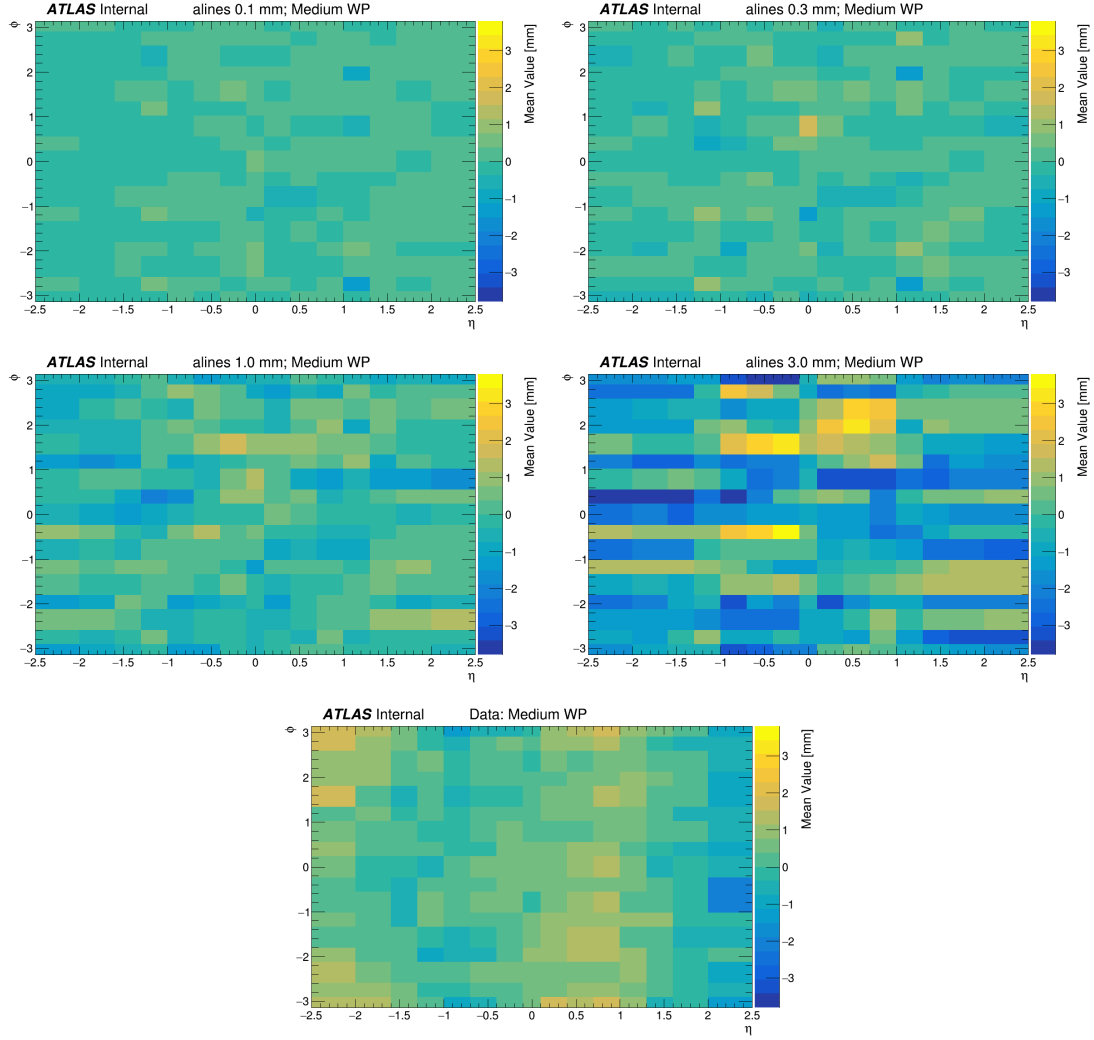


FIGURE 4.9: Mean value of  $\Delta z_0$  distribution in each sector versus muon ID track  $\eta$  and  $\phi$  with Medium WP applied for MC alines 0.1 (top left), 0.3 (top right), 1.0 (middle left), 3.0 mm (middle right) and data (bottom) samples.

#### 4.2.5 Jet

Jets, composed of collimated showers of hadrons, are prevalent final states for many physics analyses at the LHC (including SM measurements, Higgs related topics and also BSM new phenomena searches). Besides, they are also sensitive to the topology of vector boson fusion/scattering (VBF/VBS) related processes. The jets are reconstructed by using the clustering algorithm based on a collection of input four-vectors, which are generally acquired from topologically associated energy deposits, charged tracks or simulated particles. This subsection will describe the jet reconstruction and jet energy scale (JES) calibration [88] and following that the  $b$ -tagging technique [89] will be briefly introduced as well.

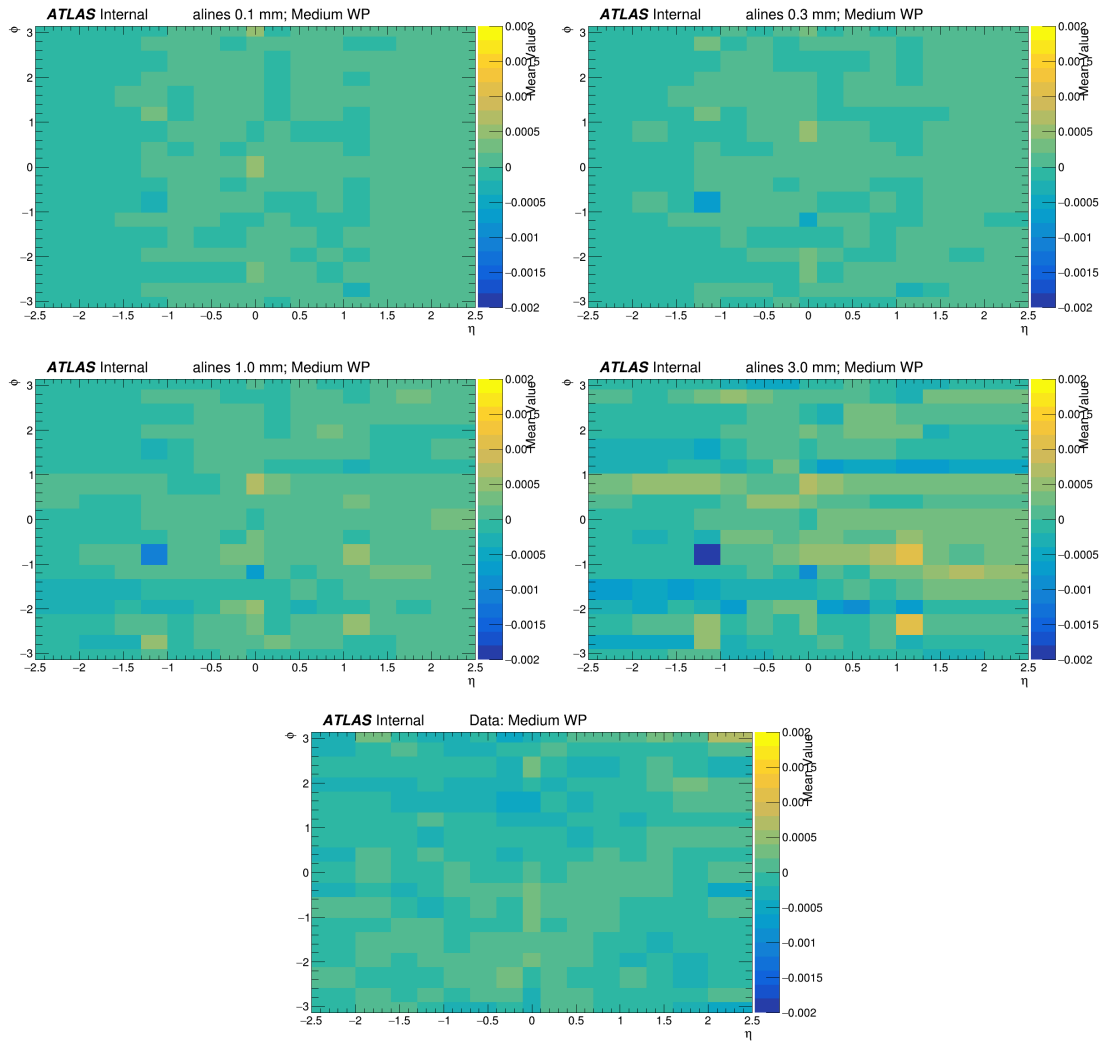


FIGURE 4.10: Mean value of  $\Delta\theta$  distribution in each sector versus muon ID track  $\eta$  and  $\phi$  with Medium WP applied for MC alines 0.1 (top left), 0.3 (top right), 1.0 (middle left), 3.0 mm (middle right) and data (bottom) samples.

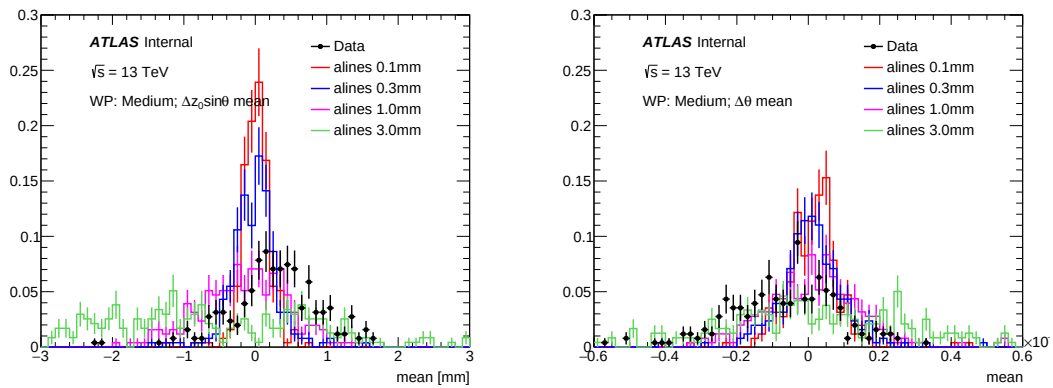
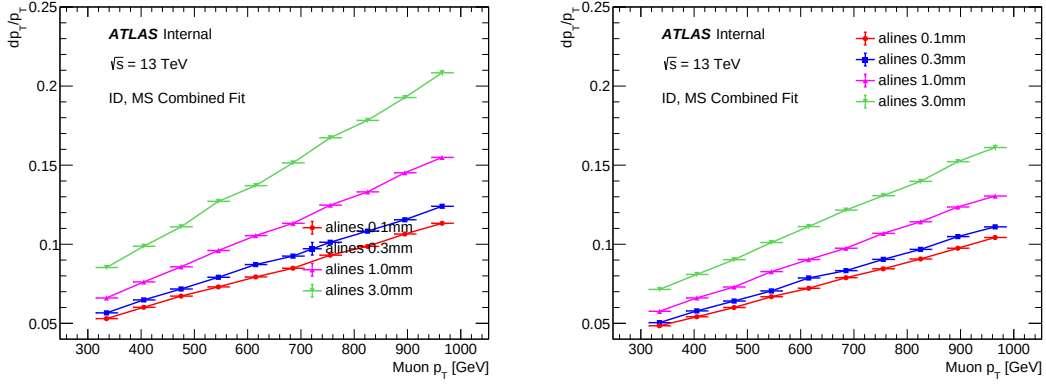
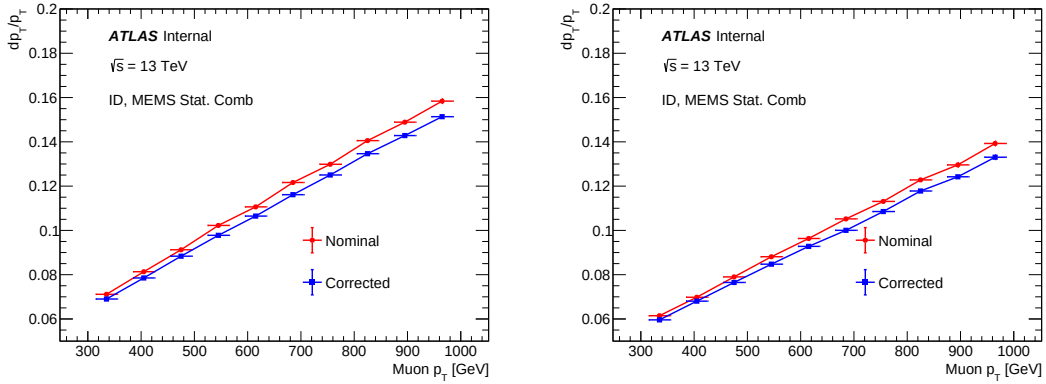


FIGURE 4.11: Mean value distributions in each  $\eta$ - $\phi$  sector for  $\Delta z_0$  (left) and  $\Delta\theta$  (right).


 FIGURE 4.12: Comparisons of  $p_T$  resolution for four MC alines smearing samples with Medium WP (left) and High- $p_T$  WP (right) applied.

 FIGURE 4.13: Comparisons of  $p_T$  resolution for MC alines 1.0 mm sample w/o ID-MS alignment correction with Medium WP (left) and High- $p_T$  WP (right) applied.

#### 4.2.5.1 Jet reconstruction

Jets are reconstructed from the calorimeter clusters at the EM energy scale using the anti- $k_t$  algorithm [90] and radius parameter  $R = 0.4$ . The FASTJET 2.4.3 software package [91] for the jet reconstruction, with a set of three-dimensional, massless, positive energy topological clusters (topo-clusters) comprised of calorimeter cell energies as the inputs. The topo-clusters are built from nearby calorimeter cells, which contain a significant energy beyond a certain noise threshold estimated from the measurements of the calorimeter electronic noise and simulated pile-up noise. The so-called truth jets are reconstructed with the anti- $k_t$  algorithm and  $R = 0.4$  as well, with the stable final-state particles from MC generators treated as the inputs. And the truth jets with  $p_T > 7$  GeV and  $|\eta| < 4.5$  are adopted for the studies of jet calibration with MC simulation.



The charged tracks used for the jet calibration are reconstructed in the ID acceptance range  $|\eta| < 2.5$  as described in the previous contents, which are required to pass the normal requirement for track selection. And then the selected tracks are assigned to jets using the ghost association [92], a procedure which treats the tracks as four-vectors of infinitesimal magnitude for the jet reconstruction and assigns them to the jet which they are clustered with. Muon segments used for the jet calibration are treated as a proxy for the un-captured jet energy carried by those particles which pass through the calorimeters but without being completely absorbed. Similar to the ID track, muon segments are also assigned to the jets reconstruction with ghost association and treated as input four-vectors with infinitesimal magnitude.

#### 4.2.5.2 Jet energy scale calibration

Figure 4.14 depicts an overview of the calibration workflow for the EM-scale jets. Through this process, the jet energy scale can be restored to that of the truth jets which are reconstructed at the particle-level energy scale.

As the first step, the origin correction is performed by recalculating the four-momentum of jets to point to the hard-scatter PV instead of the center of the detector, while the jet energy is kept unchanged for this step. This correction step can improve the  $\eta$  resolution for the jets, which is the measured difference between reconstructed jets and truth jets for MC. Then for the next step, the pile-up effect is corrected to remove the excess energy caused by in-time and out-of-time pile-up. This correction step contains two parts: an area-based  $p_T$  density subtraction which is applied on top of each event, and a residual correction which is derived from the simulation. After this, the absolute JES calibration is performed to correct the jet four-momentum to the particle-level energy scale, which is derived with the truth jets in the dijet MC sample. Then after this, by making use of the calorimeter, MS and also track-based variables for the global sequential calibration, we can further improve the reconstructed energy and corresponding uncertainties as well. In the end, as shown in the figure, a residual *insitu* calibration is adopted for the jet correction in data with the well-measured reference objects, like photons,  $Z$  bosons and also calibrated jets.

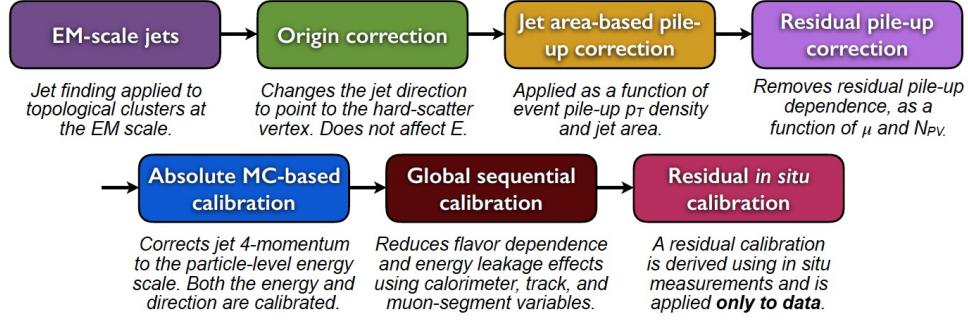
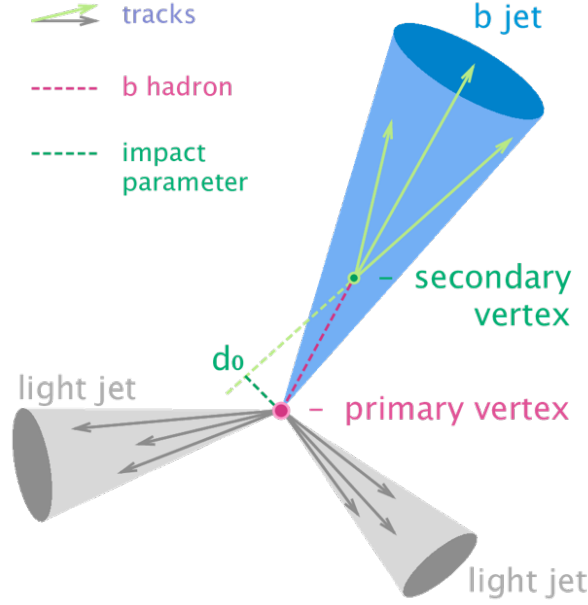


FIGURE 4.14: Schematic workflow of the calibration stages for EM-scale jets. Each stage of the calibration is applied to the four-momentum of the jet except for the origin correction.

#### 4.2.5.3 $b$ -jet tagging

The identification of jets containing  $b$ -hadrons ( $b$ -tagging) is important for the physics processes involving the  $b$  or  $t$  quark. Besides for quite some analyses (including the search for SM Higgs decaying into dimuon which will be described in the latter section), usually we apply a  $b$ -tagging jet veto to suppress the top-antitop process. There are three basic  $b$ -tagging algorithms [93] for the identification of  $b$ -quark jets for the ATLAS experiment: impact parameter based algorithms (IP2D and IP3D), secondary vertex finding algorithm (SV) and decay chain multi-vertex algorithm (JetFitter). Then the output of these three  $b$ -tagging algorithms are combined together in a multivariate discriminant (MV2), which is algorithm adopted by default for the ATLAS experiment.

Since the  $b$ -hadrons generally have a long lifetime ( $\sim 1.5$  ps,  $c\tau \sim 450$   $\mu\text{m}$ ), we can develop the lifetime-based tagging algorithms by exploiting this property. Figure 4.15 depicts the typical topology of the  $b$ -hadron decay: a secondary vertex (SV) displaced from the PV. As a result, the tracks produced from  $b$ -hadron decay generally have larger impact parameters ( $d_0$  and  $z_0 \sin\theta$ ). And we can further assign a sign to these corresponding impact parameters depending on whether the PV is in front of the SV or behind it with respect to the jet direction. For the latter case when the SV is behind the PV, normally this is due to the light quark background. The impact parameter taggers IP2D and IP3D are developed based on this sign convention. The IP2D tagger uses  $d_0/\sigma_{d_0}$  as discriminant while IP3D makes use of both  $d_0/\sigma_{d_0}$  and  $z_0 \sin\theta/\sigma_{z_0 \sin\theta}$  in a two-dimensional template by taking into account their correlation as well. The SV finding algorithm is designed to reconstruct an inclusive displaced SV within the jet. Basically, all the track pairs within a jet are tested with a two-track vertex hypothesis. And the two-track vertices found are removed if they are more likely originating from the decay of the long-lived particle (e.g.

FIGURE 4.15: Diagram showing the  $b$ -hadron decay.

$K_s$  or  $\Lambda$ ), photon conversions or hadronic interactions with the detector material. For the remaining two-track vertices, a new vertex is fitted with all the tracks associated with these accepted vertices, where outliers are removed iteratively from this set of tracks. The tracks used to form the possible two-track vertices are required to pass the track quality criteria. And the formed candidates for two-track vertices need to be displaced significantly from the PV.

Another algorithm, JetFitter [94], is based on the decay chain multi-vertex reconstruction, which makes use of the topological structure of weak  $b$ - and  $c$ -hadron decays inside the jet and attempts to reconstruct the full  $b$ -hadron decay chain. A Kalman filter is adopted to search for a common line that the PV and the  $b$  and  $c$  vertices lie on, approximating the  $b$ -hadron flight path together with their positions.

The final identification algorithm used for physics analyses is MV2, which is a Boosted Decisions Tree (BDT) [95] based algorithm, by combining the output of the basic taggers as described above. The MV2 can achieve a much better discriminating power comparing with the basic algorithms individually. The BDT training is performed using the jets from  $t\bar{t}$  sample:  $b$ -jets treated as signal, while  $c$  and light-flavor jets treated as background. In the end there are three MV2 variants provided: MV2c00, MV2c10 and MV2c20, depending on the varying  $c$ -jet fraction in the training. For example, the  $c$ -jet fraction used for MV2c20 is 15%, which means that the training is performed with  $b$ -jets regarded as signal and a mixture of 85% light-flavor jets and 15%  $c$ -jets regarded

as background. For the training of MV2c10, the  $c$ -jet fraction adopted is 7%. And for MV2c00, no  $c$ -jet is used for the training.

### 4.2.6 Missing transverse energy

For many physics processes, neutrinos are involved in the final states and they do not interact with any materials of the detector. Based on the conservation of momentum in the plane transverse to the beam axis  $z$ , the neutrinos can result in imbalance which is known as the missing transverse momentum denoted as  $E_T^{miss}$ . The  $E_T^{miss}$  adopted for this thesis work is reconstructed with the so-called track-based soft term (TST  $E_T^{miss}$ ) [96], which comprises contributions from the hard term (reconstructed and fully calibrated physics objects that are selected) and soft term (reconstructed tracks associated with the hard scatter vertex which are not associated to the hard term).

For each event,  $E_{x(y)}^{miss}$ , the two components of  $E_T^{miss}$ , can be calculated as [97]:

$$E_{x(y)}^{miss} = E_{x(y)}^{miss,e} + E_{x(y)}^{miss,\gamma} + E_{x(y)}^{miss,\tau} + E_{x(y)}^{miss,jets} + E_{x(y)}^{miss,\mu} + E_{x(y)}^{miss,soft}. \quad (4.5)$$

Here each object term represents the negative vectorial sum of the momenta for the corresponding calibrated objects. The calorimeter signals are associated with the reconstructed objects of Equation 4.5 in the following order:  $e$ ,  $\gamma$ , hadronically decaying  $\tau$ , jets and  $\mu$ . Further we can write the azimuthal angle  $\phi^{miss}$  and the magnitude of  $E_T^{miss}$  into the formulas as below:

$$E_T^{miss} = \sqrt{(E_x^{miss})^2 + (E_y^{miss})^2}, \quad (4.6)$$

$$\phi^{miss} = \arctan(E_y^{miss} / E_x^{miss}). \quad (4.7)$$

The physics objects (e.g. track,  $e$ ,  $\gamma$ ,  $\mu$ ,  $\tau$  and jet) are required to pass certain criteria and calibrated before taken as inputs for the  $E_T^{miss}$  reconstruction. The TST is built from the tracks passing the standard track quality requirements but not matched to any hard objects. And only the tracks associated with the PV, satisfying the requirements related to the longitudinal and transverse impact parameters, are considered. As a result, the TST  $E_T^{miss}$  can mitigate the pile-up effect, but it does not consider the contributions originating from the soft neutral particles.

# Chapter 5

## Search for Standard Model Higgs Boson with the Dimuon Final State

### 5.1 Introduction

As described in the theory section, the Higgs mechanism was introduced to explain the origin of gauge bosons' mass and it predicted the existence of the Higgs boson ( $H$ ), a neutral scalar particle. In 2012, the ATLAS and CMS collaborations announced the discovery of a new particle with a mass of around 125 GeV [27, 28], which has the properties consistent with those of the predicted SM Higgs boson.

Study on the Higgs boson decaying into fermions is very crucial for understanding the properties of the Higgs boson and also assessing whether the related SM prediction can be well examined. For the ATLAS experiment, searches have been carried out for these three fermion channels:  $H \rightarrow b\bar{b}$ ,  $H \rightarrow \tau^+\tau^-$  and  $H \rightarrow \mu\mu$ . The branching ratios for their decays are proportional to their corresponding masses respectively. As a result,  $H \rightarrow \mu\mu$  is the one with the smallest branching ratio among the three channels, which is  $2.18 \times 10^{-4}$  for  $m_H = 125$  GeV. Nevertheless, the  $H \rightarrow \mu\mu$  is a sensitive channel to study the Higgs boson's couplings to the second generation of fermions with a relatively clean final-state signature. The dominant and irreducible background as well for this channel is coming from  $Z/\gamma^* \rightarrow \mu^+\mu^-$  process, which has a very large production rate.

A search for the  $H \rightarrow \mu\mu$  process was performed by the ATLAS collaboration using data recorded in 2011 and 2012 (LHC Run 1) [29] corresponding to a total integrated luminosity of  $24.8 \text{ fb}^{-1}$  ( $4.5 \text{ fb}^{-1}$  at  $\sqrt{s}=7$  TeV and  $20.3 \text{ fb}^{-1}$  at  $\sqrt{s}=8$  TeV). For a

Higgs boson with  $m_H = 125$  GeV, the observed (expected) upper limit on the signal strength (the measured production rate divided by the SM predicted one:  $\sigma_{\text{measure}}/\sigma_{\text{SM}}$ ) was set to be 7.1 (7.2) at the 95% confidence level (CL). The CMS collaboration also carried out this search using the data collected during the Run 1 [30]. And the observed (expected) upper limit on the signal strength from the CMS was 7.4 (6.5) at the 95% CL for  $m_H = 125$  GeV.

This chapter will describe the search for  $H \rightarrow \mu\mu$  process based on the data collected in 2015 and 2016 corresponding to a total integrated luminosity of  $36.1 \text{ fb}^{-1}$  at the LHC Run 2 with the center-of-mass energy increased to 13 TeV. The signal signature is two isolated muons with opposite charge sign. And to enhance the signal sensitivity, categorization method is adopted to exploit the characteristic topology for the two dominant Higgs production modes: gluon-gluon fusion (ggF) and vector-boson fusion (VBF). For VBF process, signal events tend to have two high- $p_T$  jets in the two opposite detector hemispheres. And the multivariate technique (BDT) [95] is introduced to this analysis for the first time and used to define two VBF related categories, which helps to improve the final signal sensitivity by more than 10% comparing with the purely cut-based method from the Run 1. For ggF process, due to the gluon initial state radiation, signal events tend to have larger jet multiplicity comparing with the dominant Drell-Yan background, and therefore the ggF signal tends to have a relatively harder distribution for the transverse momentum of the dimuon system ( $p_T^{\mu\mu}$ ). Besides, the muon momentum resolution in the central region ( $|\eta| < 1$ ) is better than that in the end-cap region ( $|\eta| > 1$ ). Thus another six categories are defined for ggF process based on  $p_T^{\mu\mu}$  and  $\eta$  of the two muons. After the categorization, a simultaneous fit to the observed data distributions for the dimuon invariant mass  $m_{\mu\mu}$  across all the categories is performed to derive the final signal strength.

## 5.2 Data and MC samples

The data samples used for this analysis are equivalent to an integrated luminosity of  $36.1 \text{ fb}^{-1}$ , which were collected at  $\sqrt{s}=13$  TeV during 2015 and 2016. And the physics main stream is adopted and data quality checks are performed before they are used for analyzing. Figure 5.1 depicts the ATLAS online luminosity recorded and also the mean number of interactions per crossing in 2015 and 2016.

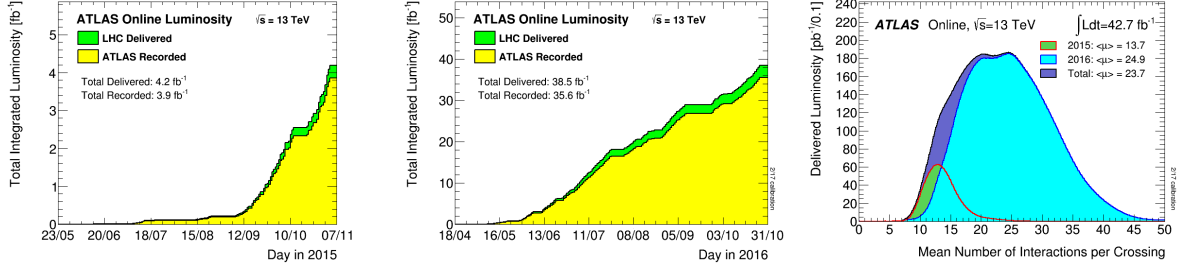


FIGURE 5.1: Total integrated luminosity recorded online at the ATLAS experiment in 2015 (left) and 2016 (middle), and the mean number of interactions per crossing for these two years (right).

Despite the fact that this analysis is based on a data-driven approach, MC simulated samples are still adopted for validating the background fitting function, selection optimization and categorization development. Dominant background contribution is coming from the Drell-Yan (DY) process, for which the nominal samples adopted are sliced in  $H_t$  (scalar sum of  $p_T$  of all the partons) and generated with MADGRAPH5 [98] interfaced to PYTHIA8 [67] with NNPDF23LO [99] parton distribution function (PDF) set. Besides, alternative Drell-Yan samples are used for estimating the systematic uncertainty coming from background modeling function, which are generated with POWHEG-BOX v2 [100] at next-to-leading order (NLO) in QCD using the CT10 [101] parton distribution PDF set and PYTHIA8 for parton showering and hadronization. Electroweak  $Zjj$  process through VBF production is simulated with SHERPA [69]. Other sub-dominant background like the  $t\bar{t}$  and single-top processes are simulated with POWHEG-BOX v2 using CT10 PDF interfaced to PYTHIA6 [66] for parton shower, using the PERUGIA2012 [102] tune with CTEQ6L1 [103] PDF for the underlying event descriptions. While EVTGEN v1.2.0 [104] is used for properties of the bottom and charm hadron decays and the mass of the top quark is set as  $m_t = 172.5$  GeV. For signal-top samples, each process ( $t$ -channel,  $s$ -channel and  $Wt$ -channel) is separately generated. The other background coming from diboson processes ( $WW$ ,  $WZ$  and  $ZZ$ ) are simulated with SHERPA with the CT10 PDF set. Table 5.1 summarizes the simulated background processes adopted for this analysis.

Signal samples through the ggF and VBF production modes are generated with POWHEG-BOX v2 at next-to-leading order (NLO) in QCD with the CT10 PDF set and PYTHIA8 used for parton showering and hadronization. And the signal events through the production associated with a  $W$  or  $Z$  boson (VH) are simulated with PYTHIA8 at LO with the NNPDF23LO PDF set and the ATLAS A14 set of tuned parameters [105] used for the event generation, parton showering and hadronization. For the VH samples, the



| DCID   | Processes                                             | Cross section (pb)    | Sum of MC event weights |
|--------|-------------------------------------------------------|-----------------------|-------------------------|
| 361107 | PowhegPythia8EvtGen_AZNLOCTEQ6L1_Zmumu                | 1950.63               | 147334693300            |
| 363123 | MGPY8EG_N30NLO_Zmumu_Ht0_70_CVetoBVeto                | 1626.75               | 1967220                 |
| 363124 | MGPY8EG_N30NLO_Zmumu_Ht0_70_CFilterBVeto              | 212.08                | 576685                  |
| 363125 | MGPY8EG_N30NLO_Zmumu_Ht0_70_BFilter                   | 115.82                | 511660                  |
| 363126 | MGPY8EG_N30NLO_Zmumu_Ht70_140_CVetoBVeto              | 69.29                 | 675161                  |
| 363127 | MGPY8EG_N30NLO_Zmumu_Ht70_140_CFilterBVeto            | 16.80                 | 198836                  |
| 363128 | MGPY8EG_N30NLO_Zmumu_Ht70_140_BFilter                 | 10.45                 | 118075                  |
| 363129 | MGPY8EG_N30NLO_Zmumu_Ht140_280_CVetoBVeto             | 27.61                 | 106655                  |
| 363130 | MGPY8EG_N30NLO_Zmumu_Ht140_280_CFilterBVeto           | 8.17                  | 38255.8                 |
| 363131 | MGPY8EG_N30NLO_Zmumu_Ht140_280_BFilter                | 5.16                  | 13249.1                 |
| 363132 | MGPY8EG_N30NLO_Zmumu_Ht280_500_CVetoBVeto             | 5.87                  | 161673                  |
| 363133 | MGPY8EG_N30NLO_Zmumu_Ht280_500_CFilterBVeto           | 2.13                  | 75370.6                 |
| 363134 | MGPY8EG_N30NLO_Zmumu_Ht280_500_BFilter                | 1.33                  | 50458.4                 |
| 363135 | MGPY8EG_N30NLO_Zmumu_Ht500_700_CVetoBVeto             | 0.87                  | 16554.5                 |
| 363136 | MGPY8EG_N30NLO_Zmumu_Ht500_700_CFilterBVeto           | 0.36                  | 15240.5                 |
| 363137 | MGPY8EG_N30NLO_Zmumu_Ht500_700_BFilter                | 0.22                  | 17186.1                 |
| 363138 | MGPY8EG_N30NLO_Zmumu_Ht700_1000_CVetoBVeto            | 0.28                  | 8331.76                 |
| 363139 | MGPY8EG_N30NLO_Zmumu_Ht700_1000_CFilterBVeto          | 0.13                  | 8347.54                 |
| 363140 | MGPY8EG_N30NLO_Zmumu_Ht700_1000_BFilter               | $8.12 \times 10^{-2}$ | 7753.34                 |
| 363141 | MGPY8EG_N30NLO_Zmumu_Ht1000_2000_CVetoBVeto           | $9.33 \times 10^{-2}$ | 7563.37                 |
| 363142 | MGPY8EG_N30NLO_Zmumu_Ht1000_2000_CFilterBVeto         | $4.53 \times 10^{-2}$ | 1642.3                  |
| 363143 | MGPY8EG_N30NLO_Zmumu_Ht1000_2000_BFilter              | $2.90 \times 10^{-2}$ | 1668.07                 |
| 363144 | MGPY8EG_N30NLO_Zmumu_Ht2000_E_CMS_CVetoBVeto          | $3.56 \times 10^{-3}$ | 1617.16                 |
| 363145 | MGPY8EG_N30NLO_Zmumu_Ht2000_E_CMS_CFilterBVeto        | $1.85 \times 10^{-3}$ | 1544.97                 |
| 363146 | MGPY8EG_N30NLO_Zmumu_Ht2000_E_CMS_BFilter             | $1.05 \times 10^{-3}$ | 1553.63                 |
| 410009 | PowhegPythiaEvtGen_P2012_ttbar_hdamp172p5_dil         | 87.63                 | 39598300                |
| 410011 | PowhegPythiaEvtGen_P2012_singletop_tchan_lept_top     | 44.15                 | 0.22                    |
| 410012 | PowhegPythiaEvtGen_P2012_singletop_tchan_lept_antitop | 26.23                 | 0.13                    |
| 410015 | PowhegPythiaEvtGen_P2012_Wt_dilepton_top              | 3.78                  | 993200                  |
| 410016 | PowhegPythiaEvtGen_P2012_Wt_dilepton_antitop          | 3.77                  | 991600                  |
| 361063 | Sherpa_CT10_llll                                      | 11.69                 | 2131120                 |
| 361064 | Sherpa_CT10_lllvSFMinus                               | 1.68                  | 439585                  |
| 361065 | Sherpa_CT10_lllvOFMinus                               | 3.30                  | 878139                  |
| 361066 | Sherpa_CT10_lllvSFPlus                                | 2.12                  | 588399                  |
| 361067 | Sherpa_CT10_lllvOFPlus                                | 4.57                  | 1180790                 |
| 361068 | Sherpa_CT10_llvv                                      | 12.74                 | 4040330                 |
| 361094 | Sherpa_CT10_WqqZll                                    | 3.12                  | 302171                  |
| 361096 | Sherpa_CT10_ZqqZll                                    | 2.14                  | 2656620                 |

TABLE 5.1: Summary of the MC simulated background samples adopted, including Drell-Yan,  $t\bar{t}$ , single-top and diboson processes.

hadronic and leptonic decays of the  $W$  or  $Z$  boson are generated separately. The signal samples are generated at multiple mass points for  $m_H$  from 100 GeV to 150 GeV with an interval of 5 GeV. Table 5.2 summarizes the signal samples for  $m_H = 125$  GeV used for this analysis.

| DCID   | Processes                                          | Cross section (pb)    | Sum of MC event weights |
|--------|----------------------------------------------------|-----------------------|-------------------------|
| 341195 | PowhegPythia8EvtGen_CT10_AZNLOCTEQ6L1_ggH125_mumu  | $1.06 \times 10^{-2}$ | 28894697                |
| 341206 | PowhegPythia8EvtGen_CT10_AZNLOCTEQ6L1_VBFH125_mumu | $8.23 \times 10^{-4}$ | 3890370                 |
| 343345 | Pythia8EvtGen_A14NNPDF23LO_WqqH125_mumu            | $2.01 \times 10^{-4}$ | 43000                   |
| 343356 | Pythia8EvtGen_A14NNPDF23LO_ZqqH125_mumu            | $1.34 \times 10^{-4}$ | 30000                   |
| 343964 | Pythia8EvtGen_A14NNPDF23LO_WlvH125_mumu            | $9.74 \times 10^{-5}$ | 25000                   |
| 343975 | Pythia8EvtGen_A14NNPDF23LO_ZllH125_mumu            | $1.94 \times 10^{-5}$ | 15000                   |

TABLE 5.2: Signal samples (ggF, VBF and VH) for  $m_H = 125$  GeV.



To take into account the pile-up effect, additional  $pp$  collisions generated with PYTHIA8 are overlaid for all simulated events. And all the MC samples need to go through the full ATLAS detector simulation based on GEANT4 [71] and are further processed with the same reconstruction algorithm as used for data.

## 5.3 Object and Event Selection

### 5.3.1 Object level selection

The object reconstruction has been described in Section 4.2. For this analysis, muons are the main signal signatures. Additionally, jets are used for VBF categories selection and  $E_T^{miss}$  is used for rejecting top quarks and diboson related background processes. Besides, electrons are also required to be identified in order to remove overlaps with jets. This subsection depicts the criteria used for object level selection together with the overlap removal requirement between the objects.

#### 5.3.1.1 Muons

For the signal selection, only the combined (CB) muons satisfying the medium WP are taken into account. And muon's  $p_T$  is required to surpass 15 GeV and its  $|\eta|$  is within ID acceptance ( $|\eta| < 2.5$ ) to suppress the QCD background and guarantee the reconstruction quality of the CB muons as well. The  $p_T$  requirement has minimal impact on the signal muons, since muons from the Higgs and high mass Drell-Yan decays have genuinely large  $p_T$ . Furthermore, muons are required to pass the “LooseTrackOnly” isolation WP which is based on the  $p_T^{varcone30}$  variable as described in 4.2.4.3, which can provide a flat  $\sim 99\%$  efficiency for all the phase spaces of the signal muons. Figure 5.2 depicts the isolation efficiencies from Drell-Yan MC events, for various isolation WPs as a function of muon  $p_T$ , showing that the adopted “LooseTrackOnly” WP gives the highest selection efficiency. Then in order to reduce the non-collision muons either originating from pile-up vertices or cosmic rays, the muons are further required to satisfy certain requirements on the impact parameters. The impact parameter on the transverse plane is defined with respect to the beam line ( $d_0^{BL}$ ), and its significance is required to be less than three,  $|d_0^{BL}significance| < 3$ . The major consideration of using  $d_0^{BL}$  instead of  $d_0$  which is calculated with respect to the PV (adopted during the Run 1) is for the simplicity of implementation as well as the fact that beam spot is expected to be much narrower

than the resolution of the PV in the transverse plane. Besides, the longitudinal impact parameter is defined against the PV and required to be less than 0.5 mm:  $|z_0^{PV} \times \sin(\theta)| < 0.5$  mm. All the muon related selection criteria are summarized in Table 5.3.

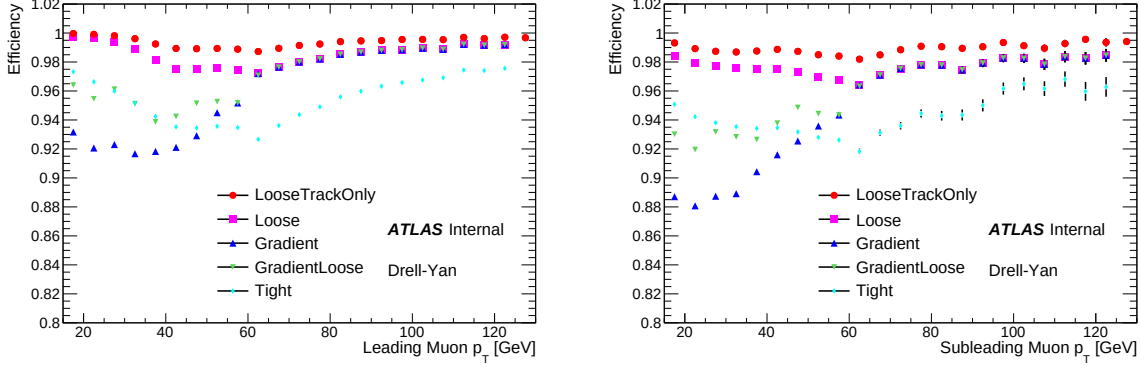


FIGURE 5.2: Isolation efficiency versus leading muon  $p_T$  (left) and subleading muon  $p_T$  (right) for various isolation working points. The efficiency is defined with regarding to muons selected with all the other criteria defined in Table 5.3 except the isolation cut. The “LooseTrackOnly” working point is used in this analysis. Plotted efficiencies are calculated from MC Drell-Yan events.

The MC efficiencies for identification and isolation selections, together with the muon momentum scale and resolution are corrected to match the data based on the Tag-and-Probe studies with  $Z$  and  $J/\psi$  events. The relevant analysis packages (based on analysis release 2.4.22) for implementing the muon selections or making corrections to the MC are summarized below:

- MuonEfficiencyCorrections-04-00-02
- MuonSelectorTools-00-05-33
- MuonMomentumCorrections-01-00-37

### 5.3.1.2 Jets

The calibrated jets adopted for this analysis are the so-called “Antikt4TopoEM” jets. They are required to satisfy  $p_T > 25$  GeV in the central region ( $|\eta| < 2.4$ ) while  $p_T > 30$  GeV in the forward region ( $2.4 < |\eta| < 4.5$ ). The increased threshold in the high  $\eta$  region is the consideration of mitigating the pile-up effect.

|                   |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |
|-------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Muon Selection    |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |
| Identification    | <i>Medium</i> and Combined muons<br>ID hits: $n_{hits}^{pixel} > 0$ , $n_{hits}^{SCT} > 4$ , $n_{holes}^{pixel+SCT} < 3$<br>$n_{hits+outliers}^{TRT} > 5$ and $n_{hits}^{TRT} > 0.1 \times n_{hits+outliers}^{TRT}$ for $0.1 <  \eta  < 1.9$<br>MDT/CSC hits: $n_{layers} > 1$ for $ \eta  > 0.1$ , $n_{layers} \geq 1$ and $n_{layerholes} < 2$ for $ \eta  < 0.1$<br>where hit layers are defined for layers in MDT or CSC with at least three hits<br>Track Quality: $q/p$ significance $< 7$ |
| $p_T$             | $> 15$ GeV                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |
| $ \eta $          | $< 2.5$                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |
| Isolation         | pass “LooseTrackOnly”                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |
| Impact Parameters | $ d_0^{BL} significance  < 3$ , $ z_0^{PV} \times \sin(\theta)  < 0.5$ mm                                                                                                                                                                                                                                                                                                                                                                                                                        |

TABLE 5.3: Summary of the muon object selection criteria used in this analysis.

In order to reject the fake jets induced by the significant coherent or sporadic noise in the LAr calorimeters, the jets tagged as “BadLoose” [106] are removed from the event. The “BadLoose” selection is implemented by cutting on the quantities which can discriminate between the good and fake jets, such as pulse shape of the LAr calorimeter cells, total energy of cells that have negative energy, maximum ratio of energy deposited in one single calorimeter layer over total energy of a jet, and fraction of sum  $p_T$  of associated tracks over the jet  $p_T$  as well.

Then to further reduce pile-up jets, a requirement on the Jet Vertex Tagger (JVT) [107] is applied. The JVT is constructed as a 2D likelihood using two discriminating variables based on tracks associated with a jet: ratio of scalar  $p_T$  sum of tracks originating from the PV over scalar  $p_T$  sum of all tracks or the jet  $p_T$ . Jets with  $p_T < 60$  GeV and  $|\eta| < 2.4$  are required to have  $JVT > 0.59$ .

Besides, in order to suppress the  $t\bar{t}$  background, b-jets are identified using the MV2c10 tagger [89] and vetoed. For this analysis, jets with  $|\eta| < 2.5$  and  $p_T > 20$  GeV, which satisfy MV2c10 weight  $> 0.9349$ , are identified as b-jets. And the selection of MV2c10 tagger has an efficiency of around 60% for b-jets and a strict rejection for light-flavour and charm jets (more than 95.5% rejection).

All the jet selection criteria are summarized in Table 5.4.

### 5.3.1.3 Electrons

Electrons are not explicitly selected in this analysis, instead they are only used for electron-jet overlap removal. The candidates are required to pass the medium WP [83],

| Jet Selection |                                                                                                                      |
|---------------|----------------------------------------------------------------------------------------------------------------------|
| Algorithm     | “Antikt4TopoEM”                                                                                                      |
| $ \eta $      | $< 4.5$                                                                                                              |
| $p_T$         | $> 25$ GeV for $ \eta  < 2.4$ , $> 30$ GeV for $2.4 <  \eta  < 4.5$                                                  |
| Cleaning      | Not “LoosBad” jet                                                                                                    |
| JVT           | $> 0.59$ for $p_T < 60$ GeV and $ \eta  < 2.4$                                                                       |
| b-jet         | Pass MV2c10 60% working point for $ \eta  < 2.5$<br>Only used for the purpose of b-veto<br>$p_T > 20$ GeV for b-jets |

TABLE 5.4: Summary of the jet selection criteria used in this analysis.

with  $E_T > 7$  GeV and  $|\eta| < 2.47$  but excluding the region for  $1.37 < |\eta| < 1.52$ . Electrons are rejected if their clusters are found to be “BADCLUSELECTRON” so as to remove the bad electrons with presence of a dead FEB in the first or second sampling, a dead HV region affecting the three samplings or a masked cell in the core. Then the electrons are required to satisfy the criteria related to the impact parameters:  $|d_0^{BL} \text{significance}| < 5$  and  $|z_0^{PV} \times \sin(\theta)| < 0.5$  mm. Additionally, electrons need to pass the “loose” isolation WP (based on *topoetcone20* and *ptvarcone30* variables) to further remove background electrons induced by pile-up or hadron decays.

The entire electron selection criteria for this analysis are summarized in Table 5.5.

| Electron Selection |                                                                                    |
|--------------------|------------------------------------------------------------------------------------|
| Identification     | “medium” likelihood                                                                |
| $p_T$              | $> 7$ GeV                                                                          |
| $ \eta $           | $< 2.47$ excluding crack region ( $1.37 <  \eta  < 1.52$ )                         |
| Quality            | Not “BADCLUSELECTRON”                                                              |
| Isolation          | “loose” working point                                                              |
| Impact Parameters  | $ d_0^{BL} \text{significance}  < 5$ and $ z_0^{PV} \times \sin(\theta)  < 0.5$ mm |

TABLE 5.5: Summary of the electron selection criteria used in this analysis. Please note electrons are not explicitly used, instead they are mainly taken into account in the electron-jet overlap removal.

#### 5.3.1.4 $E_T^{miss}$

The  $E_T^{miss}$  used for this analysis is calculated based on the reconstructed and calibrated physics objects (including  $\mu$  and  $e$  passing the object selection defined in 5.3.1.1

and 5.3.1.3 as well as all the jets), together with the track-based soft term built from the detector signals not associated with the physics objects. The “METMaker” package is used for rebuilding  $E_T^{miss}$ .

### 5.3.1.5 Overlap removal between objects

Despite that different physics objects are reconstructed based on their individual algorithms with different detector signatures, there are still overlaps between them due to common detector inputs used for the reconstruction (e.g. electrons and jets built using common tracks and clusters) or physics connection between two objects (e.g.  $e$  from muon bremsstrahlung or muons from hadron decays inside the jets). For these cases, it is essential to carefully remove the overlaps and avoid the double counting any detector signatures in the final state.

The following strategy of overlap removal, as recommended by the performance groups and implemented in the “AssociationUtils” tool, is performed sequentially:

- Any selected electrons sharing an ID track with a selected muon candidate are ignored.
- Jets found within  $\Delta R < 0.2$  of a selected electron are discarded, and jets with less than three tracks and close to a selected muon within  $\Delta R < 0.4$  are further removed.
- Electron candidates that overlap with the selected jets within  $\Delta R < 0.4$  are rejected.
- Finally, selected muons that overlap with a selected jet which has more than three associated ID tracks are removed.

## 5.3.2 Event level selection

For the event level selection, first the data events are required to pass the Good-Run-List (GRL), which can guarantee that the data are recorded under the good condition of the detector. The GRLs adopted are “data15\_13TeV.periodAllYear\_DetStatus-v79-repro20-02\_DQDefects-00-02-02\_PHYS\_StandardGRL\_All\_Good\_25ns.xml” for 2015 data (corresponding to  $3.2 \text{ fb}^{-1}$ ) and “data16\_13TeV.periodAllYear\_DetStatus-v83-pro20-15\_DQDefects-00-02-04\_PHYS\_StandardGRL\_All\_Good\_25ns.xml” for 2016 data (corresponding to  $32.9 \text{ fb}^{-1}$ ).

The GRLs are provided by the Data Quality (DQ) group of the ATLAS collaboration. And as my qualification task, I have participated in the muon offline DQ monitoring efforts. Collaborating with other colleagues, we have maintained and developed the primary packages adopted for the offline monitoring at the Run 2. The original “MuonDetectors” package used for the Run 1 has been re-structured as well as substantial updates being made, which now is mainly responsible for scrutinizing the working status of the four sub-systems of the muon detector. Another package “MuonTracking” has been re-written, which mainly accommodate the functionalities of monitoring the muon performance by making use of the muon segments and tracks together with the “standard candles”  $Z$  and  $J/\psi$  related plots. Figure 5.3 shows examples of the monitoring plots for the muons associated with  $Z$  and  $J/\psi$  for Run 284420 during the 2015 data taking. Besides, monitoring plots with normalization to the instantaneous luminosity are also added. All these new updates and developments help the offline shifters monitor the muon DQ more efficiently, which is quite crucial for the final GRL generating.

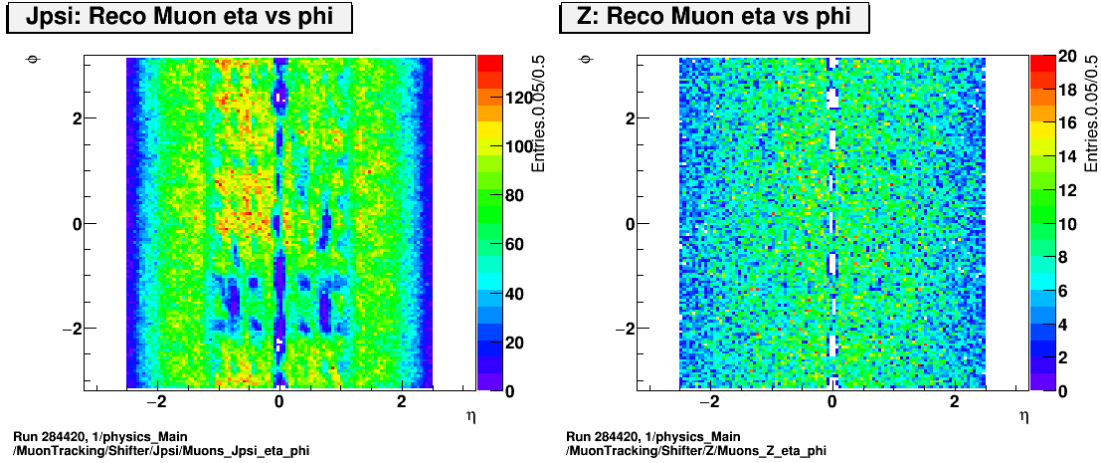


FIGURE 5.3:  $\eta-\phi$  monitoring maps for muons associated with  $J/\psi$  (left) and  $Z$  (right) for Run 284420 in 2015.

In addition to the GRL requirement, the LAr, Tile and SCT corrupted events, and the incomplete events are rejected in the data. Besides cleaning cut concerning the bad jets is imposed on the both data and MC samples, and events are rejected if they contain at least one jet classified as “BadLoose” as described in 5.3.1.2. Events are further required to have a PV with at least two associated tracks, where the ID tracks are selected with  $p_T > 400$  MeV and  $|\eta| < 2.5$ .

For 2015 data, events are required to pass logic “OR” of two single muon triggers, “HLT\_mu24\_imedium” or “HLT\_mu50”; and for 2016 data, events are required to pass logic “OR” of the following two single muon triggers: “HLT\_mu26\_ivarmedium” or

“HLT\_mu50”. The single muon trigger “HLT\_mu24\_Imedium” requires a trigger muon with  $p_T > 24$  GeV and imposes the “medium” isolation cut (fixed cone size) on trigger-level muon at the HLT; while the single muon trigger “HLT\_mu26\_ivarmedium” requires a trigger muon with  $p_T > 26$  GeV and imposes the “medium” isolation cut (varying cone size depending on muon  $p_T$  value) as well at the HLT. The higher  $p_T$  muon trigger requires a trigger muon with  $p_T > 50$  GeV but without explicit requirement on isolation. Such trigger configuration is applied consistently to both 2015 and 2016 data as well as the MC samples. And the trigger requirement is very efficient (about 95%) for signal and Drell-Yan events that pass all the other kinematic selections, and the difference between the trigger-level isolation cut and the offline selection is found to be very minor. Trigger matching is applied to both the data and MC, by requiring at least one of the selected two muons to be close to the corresponding trigger muon within  $\Delta R < 0.1$ .

Then selected events are required to have exactly two muons with opposite charge sign. And the leading muon needs to have  $p_T > 27$  GeV so as to surpass the trigger threshold. To reduce the contributions from the top and diboson backgrounds, events are vetoed if a large  $E_T^{miss}$  is present ( $E_T^{miss} < 80$  GeV). Figure 5.4 shows the data/MC comparison for  $E_T^{miss}$  before this requirement. And top related backgrounds are further reduced by requiring no b-jets in the final state.

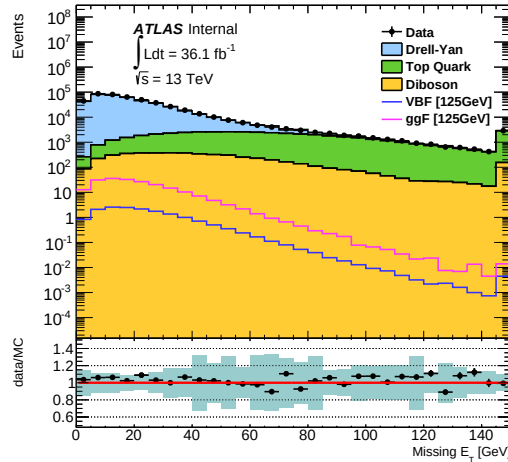


FIGURE 5.4: Comparison between data and MC predictions for  $E_T^{miss}$  before cut on 80 GeV in the signal region (defined below). The Drell-Yan events are generated with MadGraph and normalized using the NNLO cross section to  $36.1 \text{ fb}^{-1}$  corresponding to the data collected in 2015 and 2016. MC statistical and experimental systematic (muon, jet and MET) uncertainties are shown in the error band.

### 5.3.2.1 $Z$ control region

After the general event level selections, an on-shell  $Z$  dominant control region can be defined by requiring dimuon invariant mass around the  $Z$  pole within 15 GeV mass window ( $76 < m_{\mu\mu} < 106$  GeV). This control region is served to examine data and MC predictions under the dimuon selection deployed in this analysis.

To improve the agreement between data/MC for muon  $p_T$  related variables, a  $p_T^Z$  ( $p_T$  of the dimuon system) reweighting method is adopted to force the  $p_T^Z$  distribution from the Drell-Yan process to match the data with the top and diboson contributions subtracted. All the other kinematic distributions are adjusted accordingly after the reweighting. And this method has negligible impact on  $m_{\mu\mu}$  distribution.

Figure 5.5 depicts the  $p_T$  of leading and subleading muons dimuon invariant mass ( $m_{\mu\mu}$ ),  $p_T^Z$ , Ht (scalar sum of muons and jets  $p_T$ ) and jet multiplicity ( $n_{jet}$ ) for the data and MC comparisons in the  $Z$  control region, corresponding to  $36.1 \text{ fb}^{-1}$  recorded in 2015 and 2016. The MC predictions are generally in reasonable agreement with data. And the mis-modeling of jet multiplicity for the  $n_{jet} \geq 4$  bins connects to imprecision of MC calculation in the case of radiation of multiple partons. Besides large theoretical and jet-related experimental uncertainties are expected in this phase space. Since for this analysis, the concerned signature are mostly in  $n_{jet} \leq 3$  bins (VBF topology), thus this  $n_{jet}$  mis-modelling is not a major issue.

### 5.3.2.2 $Z$ plus two jets control region

Another  $Z$  plus two jets control region is defined by requiring events to contain at least two selected jets on top of the on-shell  $Z$  mass window criteria. Selection of two jets is motivated to enhance the sensitivity to the VBF signature. Events produced in the VBF channel are usually characterized by two forward jets which have large rapidity gap and dijet invariant mass ( $m_{jj}$ ), as well as some topological features such as the electroweak production contained within the rapidity gap. Therefore the jet-related kinematic variables are useful to discriminate between the VBF signal process and more dominating QCD production of dimuon plus two jets. This  $Z$  plus two jets control region can be used to examine the modeling of the jet related kinematics.

To improve the agreement between data/MC for the jets related variables, a  $m_{jj}$  reweighting method is adopted to force the  $m_{jj}$  distribution from the Drell-Yan process



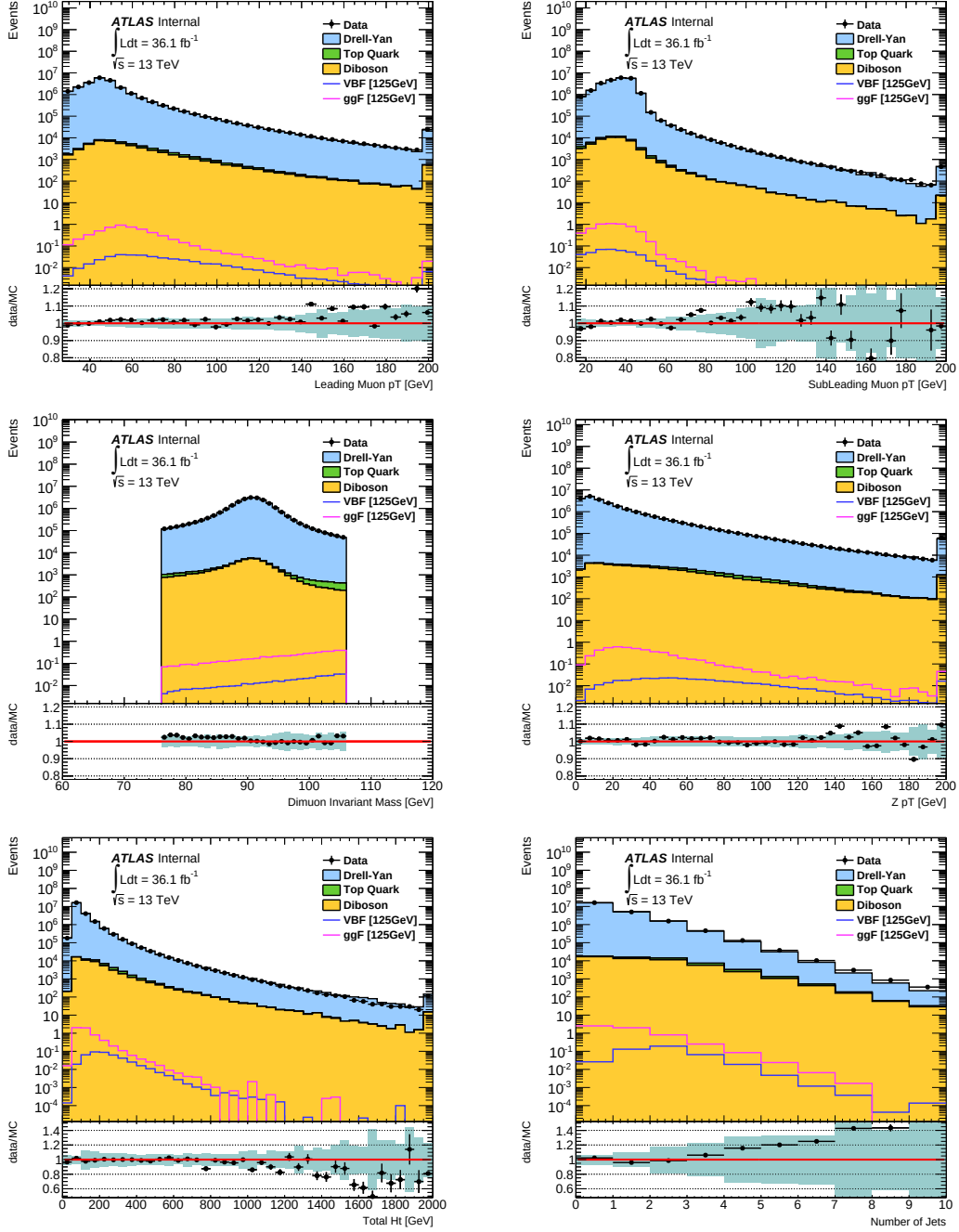


FIGURE 5.5: Comparison between data and MC predictions for leading muon  $p_T$  (top left), subleading muon  $p_T$  (top right), dimuon invariant mass (middle left),  $p_T^Z$  (middle right), total  $H_T$  (bottom left) and jet multiplicity (bottom right) in the Z control region. The Drell-Yan events are generated with MadGraph and normalized using the NNLO cross section to 36.1 fb<sup>-1</sup> corresponding to the data collected in 2015 and 2016. MC statistical and experimental systematic (muon, jet and MET) uncertainties are shown in the error band.

to match the data with the top and diboson contributions subtracted. All the other kinematic distributions are adjusted accordingly after the reweighting. The difference between the original and reweighted distributions are considered as the uncertainty related to mis-modeling of  $m_{jj}$ , which are then included in the uncertainty bands for the corresponding figures.

Figure 5.6 shows  $m_{\mu\mu}$ ,  $m_{jj}$ ,  $\Delta\eta_{jj}$ ,  $\Delta R_{jj}$  and centrality distributions in the  $Z$  plus two jets control region for data collected in 2015 and 2016 and MC predictions. The centrality here is defined as

$$centrality = \frac{y_{\mu\mu} - \frac{y_{j_1} + y_{j_2}}{2}}{|y_{j_1} - y_{j_2}|}. \quad (5.1)$$

Further kinematic variables, such as  $p_T$  of the dijet system ( $p_T^{jj}$ ),  $p_T$  of the dimuon plus leading jet system ( $p_T^{llj1}$ ),  $p_T$  of the dimuon plus subleading jet system ( $p_T^{llj2}$ ),  $p_T$  of the dimuon plus dijet system ( $p_T^{lljj}$ ),  $\Delta y$  of the dimuon system plus dijet system ( $\Delta y_{lljj}$ ), leading jet ( $\Delta y_{llj1}$ ), subleading jet ( $\Delta y_{llj2}$ ), and scalar sum of lepton and jet  $p_T$  ( $Ht$ ) are shown in Figure 5.7.

Reasonable agreement are observed between the MC modeling and data. There is some level (around 20%) of mis-modeling in certain phase spaces for jet-related variables, for instance, the discrepancies seen outside the current uncertainty bands for  $\Delta y_{lljj}$ ,  $\Delta y_{llj1}$ , and  $\Delta y_{llj2}$ . However, since these phase spaces are not sensitive to the signal events, so such kind of mis-modeling is not a major problem for this analysis.

### 5.3.2.3 Data/MC comparisons for the kinematic variables in the signal region

The inclusive signal region is defined by making the requirement  $110 < m_{\mu\mu} < 160$  GeV on top of the general event selection as described in the previous paragraph. And similar as 5.3.2.2, to examine the modeling of the jet related kinematics, the VBF-like signal region is defined by requiring  $110 < m_{\mu\mu} < 160$  GeV plus two selected jets.

Data and MC predictions are then compared under these two regions. The  $p_T^Z$  and  $m_{jj}$  reweighting methods derived from the  $Z$  control region (5.3.2.1) and  $Z$  plus two jets control region (5.3.2.2) are adopted to improve the agreement between data/MC. And they have negligible impacts on  $m_{\mu\mu}$  distributions.

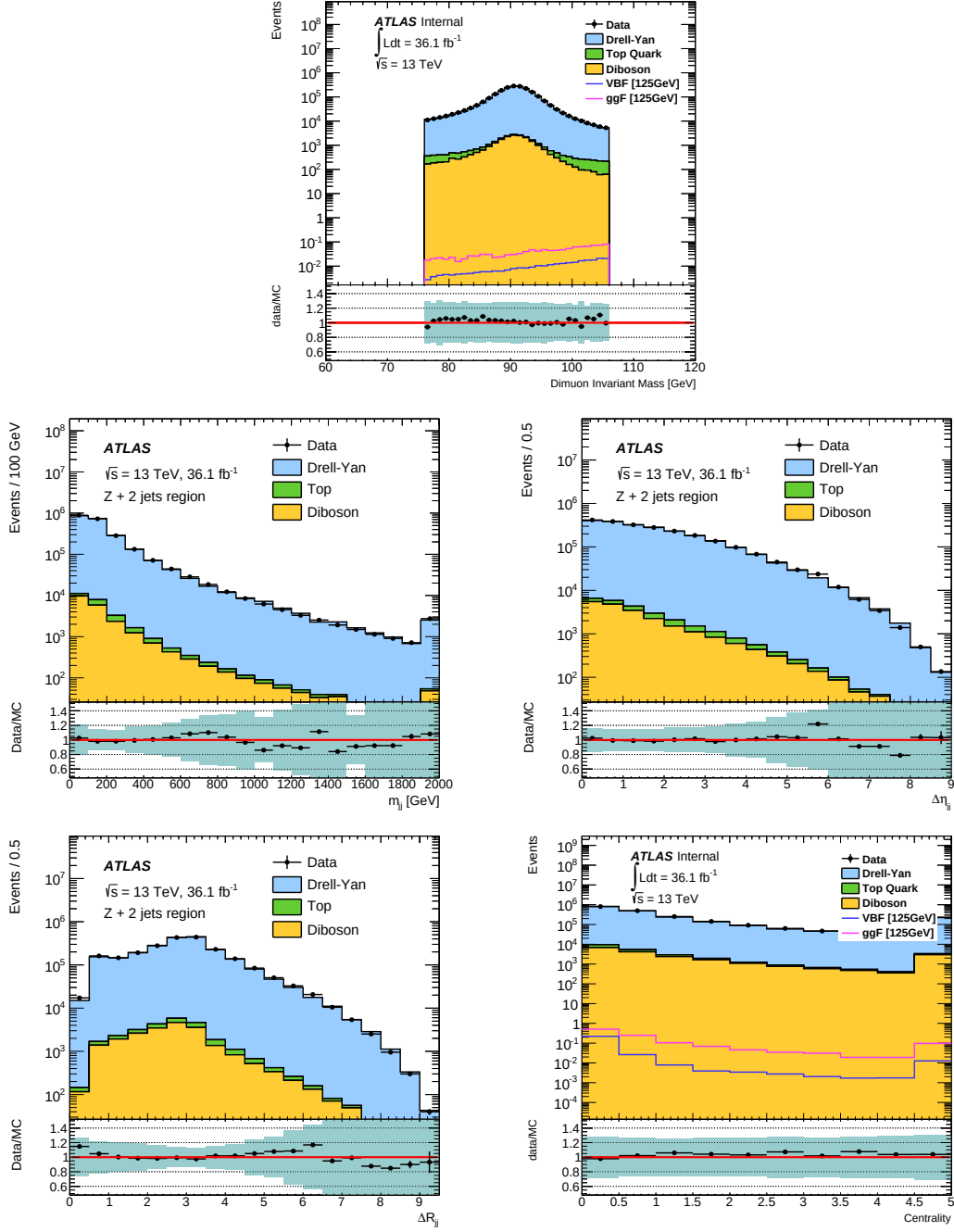


FIGURE 5.6: Comparison between data and MC predictions for  $m_{\mu\mu}$  (top),  $m_{jj}$  (middle left),  $\Delta\eta_{jj}$  (middle right),  $\Delta R_{jj}$  (bottom left) and centrality (bottom right). MC statistical uncertainty,  $m_{jj}$  modeling related systematic uncertainty and experimental systematic (muon, jet and MET) uncertainties are shown in the error band.

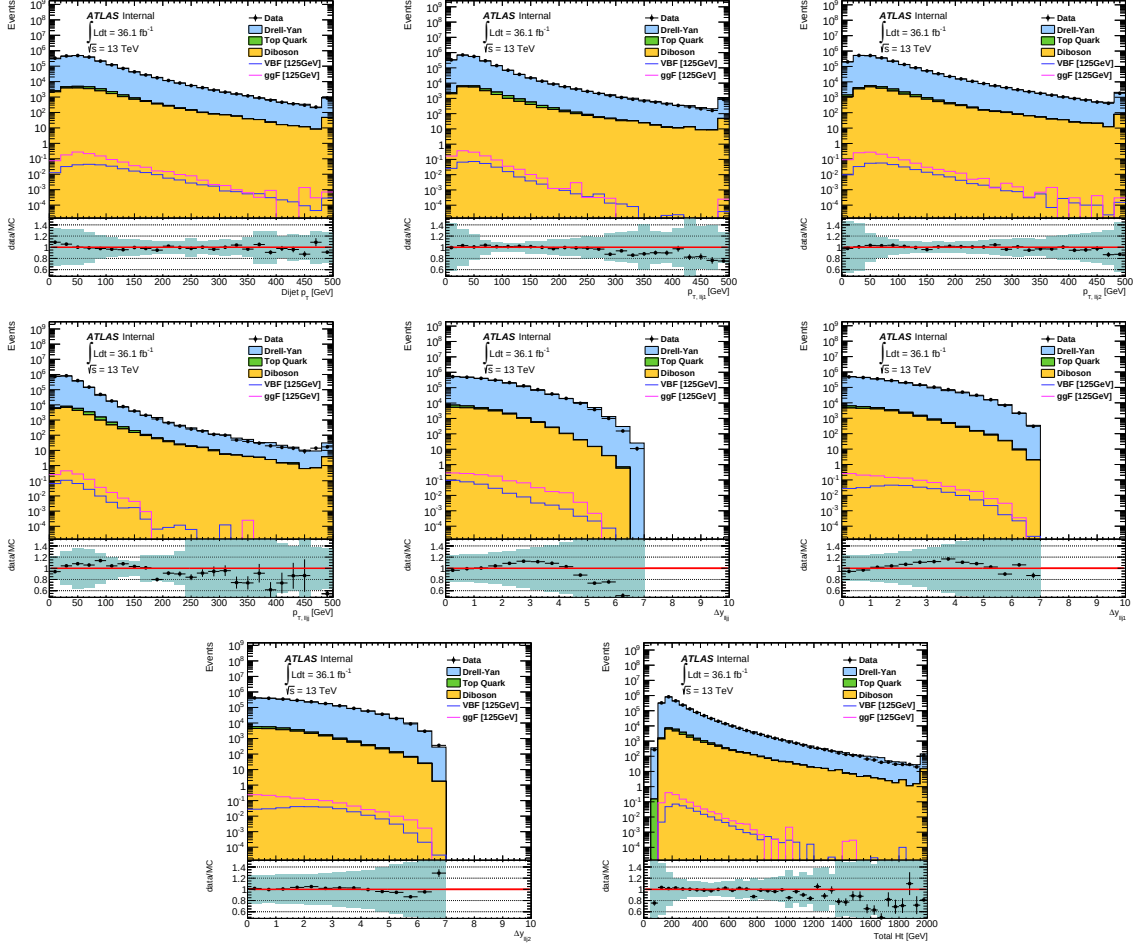


FIGURE 5.7: Comparison between data and MC predictions for  $p_T$  of the dijet system ( $p_T^{jj}$ , top left),  $p_T$  of the dimuon plus leading jet system ( $p_T^{lj1}$ , top middle),  $p_T$  of the dimuon plus subleading jet system ( $p_T^{lj2}$ , top right),  $p_T$  of the dimuon plus dijet system ( $p_T^{ljj}$ , middle left),  $\Delta\eta$  between dimuon system with dijet system ( $\Delta\eta_{ljj}$ , middle middle), leading jet ( $\Delta\eta_{lj1}$ , middle right), subleading jet ( $\Delta\eta_{lj2}$ , bottom left), and scalar sum of lepton and jet  $p_T$  ( $Ht$ , bottom right) in the final state in the dijet validation region. The Drell-Yan events are generated with MadGraph and normalized using the NNLO cross section to  $36.1 \text{ fb}^{-1}$  corresponding to the data collected in 2015 and 2016. MC statistical uncertainty,  $m_{jj}$  modeling related systematic uncertainty and experimental systematic (muon, jet and MET) uncertainties are shown in the error band.

Figure 5.8 depicts the  $m_{\mu\mu}$ ,  $p_T^{\mu\mu}$ ,  $Ht$ ,  $n_{jet}$  and  $E_T^{miss}$  (before  $E_T^{miss}$  cut) distributions in the inclusive signal region corresponding to  $36.1 \text{ fb}^{-1}$  recorded in 2015 and 2016. While Figure 5.9 shows  $m_{jj}$ ,  $\Delta\eta_{jj}$ , leading and subleading jet  $p_T$  comparisons in the VBF-like signal region. In general, reasonable agreement between the data and MC modeling can be observed, with some discrepancies that can be covered by the systematic uncertainties.

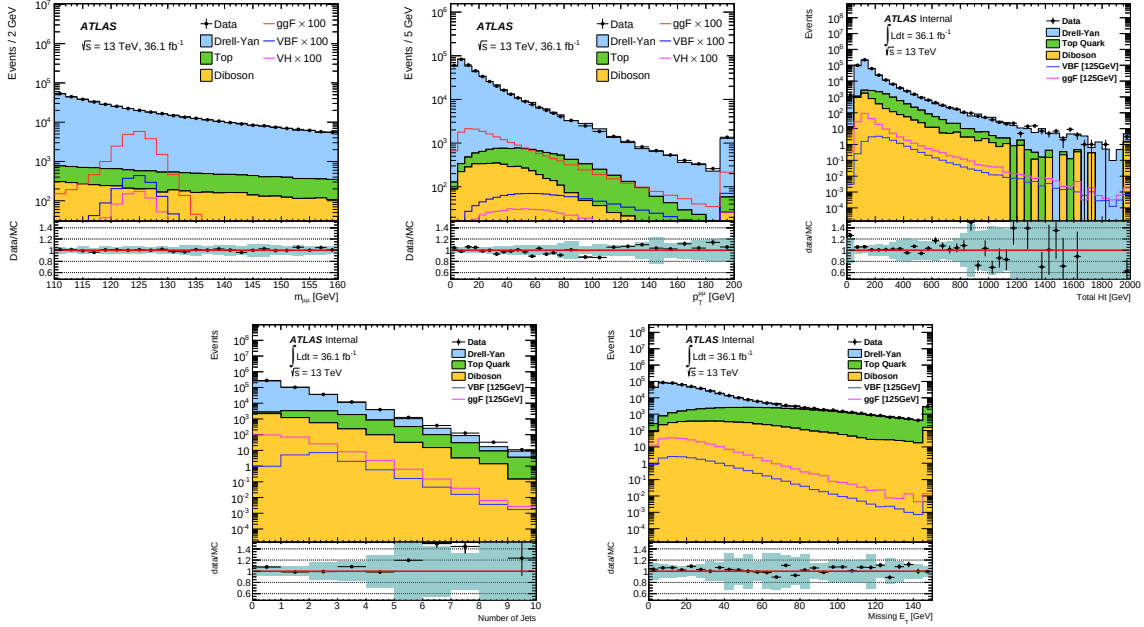


FIGURE 5.8: Comparison between data and MC predictions for  $m_{\mu\mu}$  (top left),  $p_T^{\mu\mu}$  (top middle),  $Ht$  (top right),  $n_{jet}$  (bottom left) and  $E_T^{miss}$  (bottom right, before  $E_T^{miss} < 80 \text{ GeV}$  cut) in the inclusive signal region. MC statistical uncertainty and experimental systematic (muon, jet and MET) uncertainties are shown in the error band.

## 5.4 Categorization for the Signal Region

As described in 5.3.2.3, the inclusive signal region is defined by requiring  $m_{\mu\mu}$  within 110 and 160 GeV. To enhance the signal sensitivity, this inclusive signal region is divided into eight orthogonal categories, either sensitive to VBF or ggF Higgs production mode.

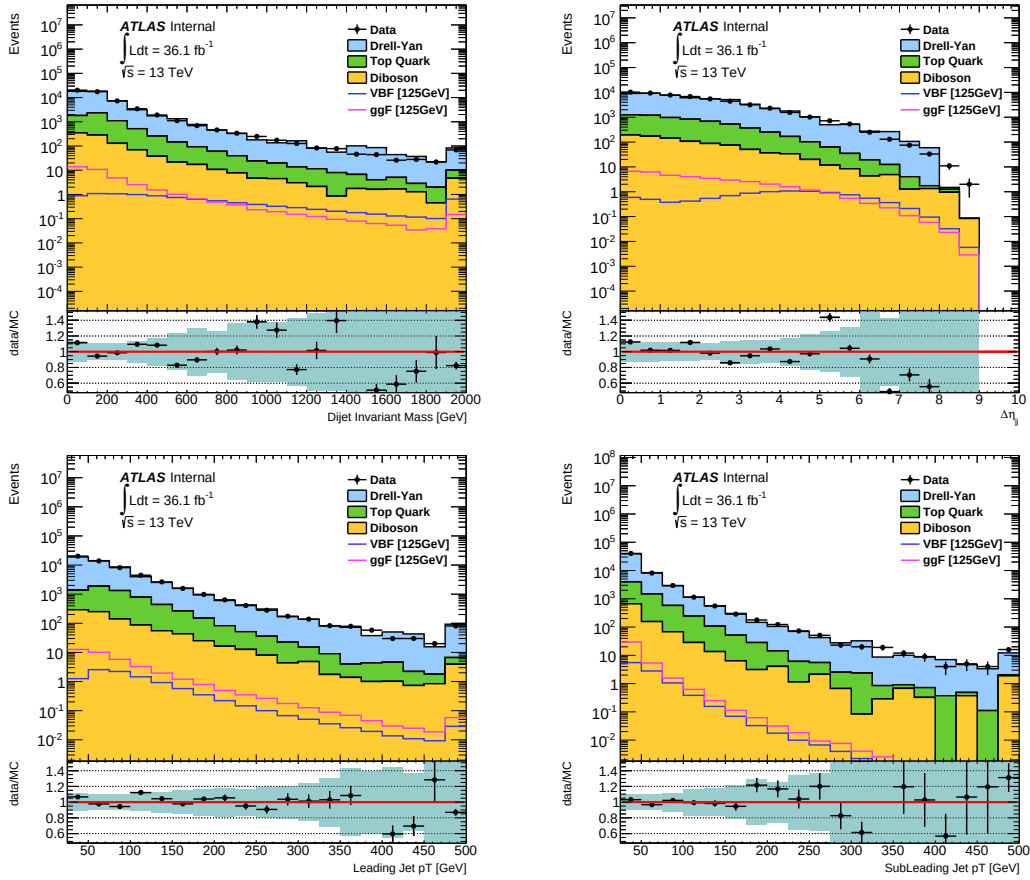


FIGURE 5.9: Comparison between data and MC predictions for  $m_{jj}$  (top left),  $\Delta\eta_{jj}$  (top right),  $p_T$  for leading (bottom left) and subleading (bottom right) jets in the VBF-like signal region. MC statistical uncertainty,  $m_{jj}$  modeling related systematic uncertainty and experimental systematic (muon, jet and MET) uncertainties are shown in the error band.

#### 5.4.1 Selection for the VBF enriched categories

VBF related categories are selected with a higher priority by adopting the multivariate analysis (MVA) method. The selection is based on the typical topology of the VBF associated jets, like the forwardness and  $\eta$  separation between the two jets. The MVA method used in this search is Boosted Decision Tree (BDT) implemented in TMVA package [95].

Background (including Drell-Yan, Top and Diboson) and VBF Higgs signal samples are used as the inputs for the BDT training. And pre-selections are applied for both the background and signal samples before the training. Most of these criteria are the same as described in Subsection 5.3.2 except that the invariant mass is required to be between 110 GeV and 140 GeV. Around 30 k background MC events and 300 k VBF signal MC

events are used in the training, and they are split into two, with the first half for training, while the second half for testing.

Fourteen input variables are used for the training, including the angular variables between two selected jets:  $\Delta\eta_{jj}$  and  $\Delta R_{jj}$ , centrality (defined in Equation 5.1),  $m_{jj}$ ,  $p_T^{jj}$ ,  $p_T^{\mu\mu}$ ,  $E_T^{miss}$ ,  $Ht$ , rapidity and  $p_T$  between the selected dimuon system plus leading/sub-leading/both jet(s):  $y_{\mu\mu j1}$ ,  $y_{\mu\mu j2}$ ,  $y_{\mu\mu jj}$  and  $p_T^{\mu\mu j1}$ ,  $p_T^{\mu\mu j2}$ ,  $p_T^{\mu\mu jj}$ . These kinematic variables have been checked in the control regions as shown in Figure 5.6 and 5.7. And reasonable agreement between data and MC predictions can be observed.

For the BDT training process, 200 trees are used and the Gradient boosting type is adopted. While the Max depth of the decision tree allowed is 4 and nCuts (number of grid points in variable range used in finding optimal cut in node splitting) is 20.

Table 5.6 summarizes the individual input variable's contribution to the BDT discrimination (namely BDT ranking). The ranking of the input variables is derived by counting how often the variables are used to split decision tree nodes, and by weighting each split occurrence by the separation gain-squared it has achieved and by the number of events in the node. The outcome shown in the table is actually expected: major sensitivity comes from  $\Delta\eta_{jj}$ ,  $m_{jj}$ , centrality, and  $p_T^{\mu\mu}$ , which are the variables most sensitive to the VBF-like topology; additional variables contribute and help to bring up the overall signal and background separation.

| Rank | Variable          | Variable Importance |
|------|-------------------|---------------------|
| 1    | $\Delta\eta_{jj}$ | 2.440e-01           |
| 2    | $m_{jj}$          | 1.731e-01           |
| 3    | $p_T^{\mu\mu}$    | 1.338e-01           |
| 4    | $\Delta R_{jj}$   | 9.217e-02           |
| 5    | $p_T^{jj}$        | 5.416e-02           |
| 6    | $y_{\mu\mu j1}$   | 5.209e-02           |
| 7    | centrality        | 4.729e-02           |
| 8    | $Ht$              | 4.381e-02           |
| 9    | $p_T^{\mu\mu jj}$ | 4.040e-02           |
| 10   | $E_T^{miss}$      | 3.308e-02           |
| 11   | $y_{\mu\mu jj}$   | 2.719e-02           |
| 12   | $p_T^{\mu\mu j1}$ | 2.361e-02           |
| 13   | $p_T^{\mu\mu j2}$ | 1.923e-02           |
| 14   | $y_{\mu\mu j2}$   | 1.602e-02           |

TABLE 5.6: Ranking of the input variables contributing to the BDT (top variable is best ranked)

Figure 5.10 shows the BDT training response distribution (comparison between the training and testing) as well as the ROC curve (background rejection efficiency *vs* signal selection efficiency). And to further validate the BDT training performance, the BDT score is examined in the control region and signal region as shown in Figure 5.11 and decent agreement can be observed between the data and MC predictions.

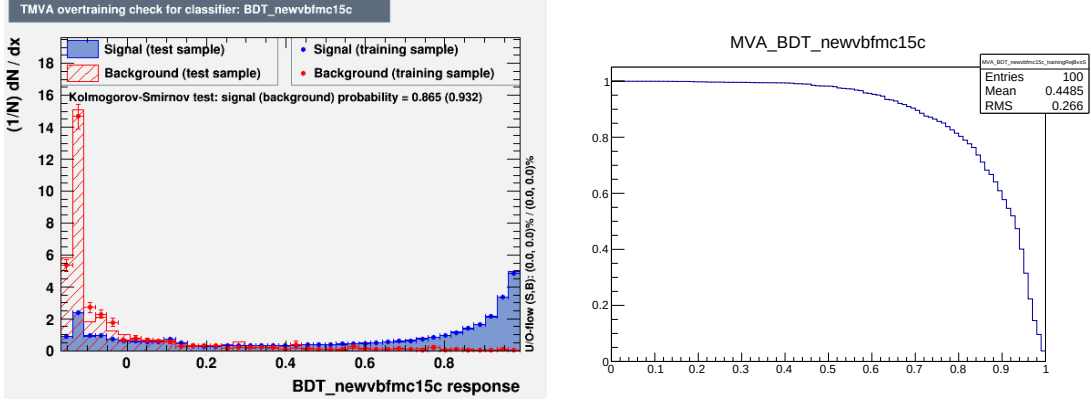


FIGURE 5.10: BDT response comparison between training and testing (left) and ROC curve namely background rejection efficiency *vs* signal selection efficiency (right).

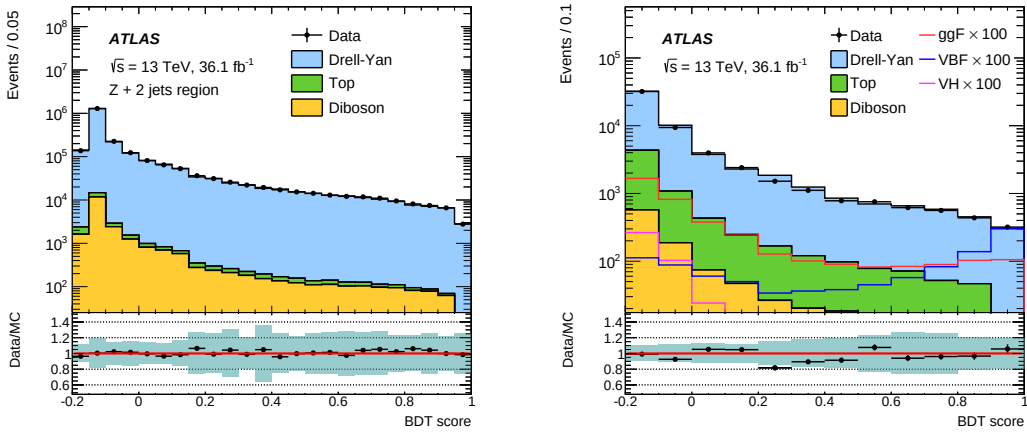


FIGURE 5.11: Comparisons between data and MC predictions for BDT score in control region (left) and signal region (right). The Drell-Yan events are generated with Mad-Graph and normalized using the NNLO cross section to  $36.1 \text{ fb}^{-1}$  corresponding to the data collected in 2015 and 2016. MC statistical uncertainty,  $m_{jj}$  modeling related systematic uncertainty and experimental systematic (muon, jet and MET) uncertainties are shown in the error band.

In order to select a sample with good signal over background ratio while keep a reasonable amount of background events for the dimuon mass fit as well, a cut  $>0.7$  is picked up on this BDT score to select VBF-like events. The relative efficiency of this cut on VBF signal and total background is 53.0% and 2.5% respectively. Two VBF categories



are defined in the corresponding phase space: “VBF Loose” ( $0.7 < \text{BDT score} < 0.9$ ) and “VBF Tight” ( $\text{BDT score} > 0.9$ ). And Figure 5.12 depicts the  $m_{\mu\mu}$  spectra for the data and MC predictions in these two categories.

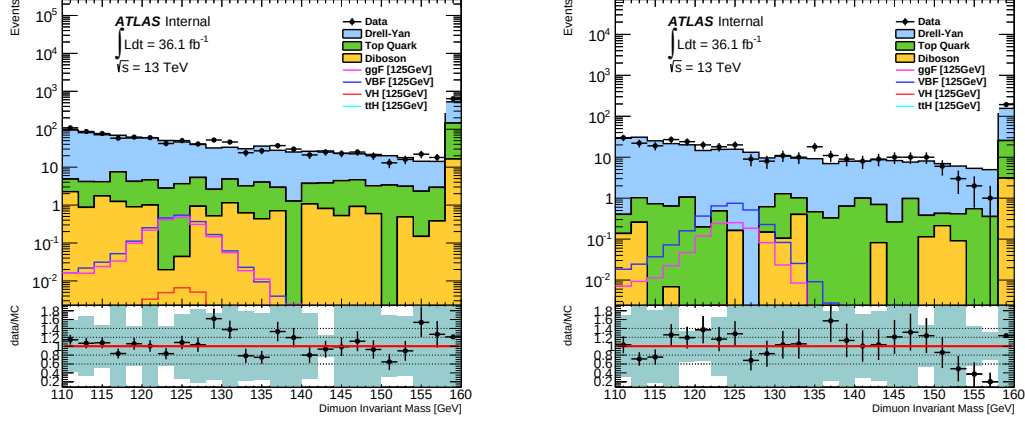


FIGURE 5.12:  $m_{\mu\mu}$  distributions for background and signal for VBF Loose (left) and Tight (right) categories. Shapes are normalized to  $36.1 \text{ fb}^{-1}$ . VBF filtered samples are used for  $m_{\mu\mu}$  shape and normalized to the yields of spectrum from Madgraph Ht sliced samples. MC statistical uncertainty,  $m_{jj}$  modeling related systematic uncertainty and experimental systematic (muon, jet and MET) uncertainties are shown in the error band.

#### 5.4.2 Selection for the ggF enriched categories

After the selection for VBF categories by using the BDT method, the remaining events failing the VBF selection are categorized into ggF enriched categories with the cut-based method. Since the ggF signal events tend to have averagely larger values of  $p_T^{\mu\mu}$  than the Drell-Yan background events, thus the events are separated into three  $p_T^{\mu\mu}$  categories: low ( $< 15 \text{ GeV}$ ), medium ( $15\text{--}50 \text{ GeV}$ ) and high ( $> 50 \text{ GeV}$ ). To further improve the signal sensitivity, each of these three categories is subdivided into a central category with  $|\eta_{\mu 1}| < 1$  and  $|\eta_{\mu 2}| < 1$  and a non-central category containing all the other events. Table 5.7 summarizes the detailed criteria for selecting the ggF enriched categories.

Figure 5.13 depicts the  $m_{\mu\mu}$  comparisons between the data and MC predictions in the selected six ggF categories, and the shapes are corresponding to  $36.1 \text{ fb}^{-1}$ .

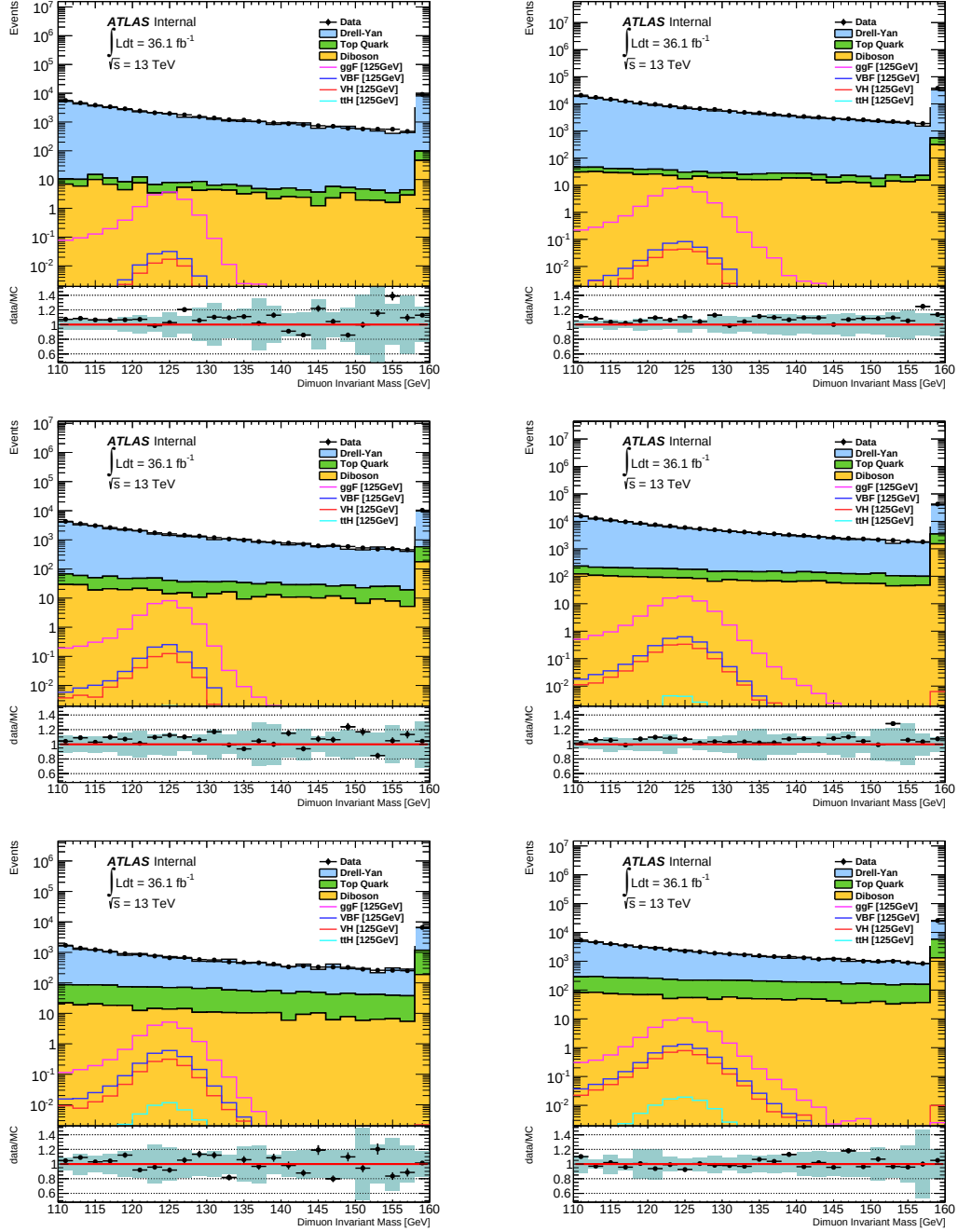


FIGURE 5.13:  $m_{\mu\mu}$  distributions for background and signal for low (top), medium (middle) and high (bottom)  $p_T^{\mu\mu}$  categories in central (left) and non-central (right) regions. Shapes are normalized to  $36.1 \text{ fb}^{-1}$ . Powheg Drell-Yan samples (high statistics) are used for  $m_{\mu\mu}$  shape and normalized to the yields of the corresponding spectrum from Madgraph Ht sliced samples. MC statistical and experimental systematic (muon, jet and MET) uncertainties are shown in the error band.

|                                    |                                                                                                           |
|------------------------------------|-----------------------------------------------------------------------------------------------------------|
| Non-central, low $p_T^{\mu\mu}$    | $p_T^{\mu\mu} < 15 \text{ GeV AND } ( \eta_{\mu 1}  > 1 \text{ OR }  \eta_{\mu 2}  > 1)$                  |
| Central, low $p_T^{\mu\mu}$        | $p_T^{\mu\mu} < 15 \text{ GeV AND }  \eta_{\mu 1}  < 1 \text{ AND }  \eta_{\mu 2}  < 1$                   |
| Non-central, medium $p_T^{\mu\mu}$ | $15 \text{ GeV} < p_T^{\mu\mu} < 50 \text{ GeV AND } ( \eta_{\mu 1}  > 1 \text{ OR }  \eta_{\mu 2}  > 1)$ |
| Central, medium $p_T^{\mu\mu}$     | $15 \text{ GeV} < p_T^{\mu\mu} < 50 \text{ GeV AND }  \eta_{\mu 1}  < 1 \text{ AND }  \eta_{\mu 2}  < 1$  |
| Non-central, high $p_T^{\mu\mu}$   | $p_T^{\mu\mu} > 50 \text{ GeV AND } ( \eta_{\mu 1}  > 1 \text{ OR }  \eta_{\mu 2}  > 1)$                  |
| Central, high $p_T^{\mu\mu}$       | $p_T^{\mu\mu} > 50 \text{ GeV AND }  \eta_{\mu 1}  < 1 \text{ AND }  \eta_{\mu 2}  < 1$                   |

TABLE 5.7: Categorization criteria for ggF enriched categories.

### 5.4.3 Event yields in eight signal categories

Table 5.8 summarizes the expected signal and background event yields as well as the observed number of data events within a  $m_{\mu\mu}$  interval for each signal category. The interval in each category is chosen to be centered at the simulated signal peak and contain 90% of the expected signal events. While Table 5.9 shows the expected signal event yields for different Higgs production modes. And the yields are calculated in the same  $m_{\mu\mu}$  intervals as described above.

|                                    | Signal[125]    | Z+jets          | Top          | Di-boson     | Total background | $S/\sqrt{B}$ | Data            |
|------------------------------------|----------------|-----------------|--------------|--------------|------------------|--------------|-----------------|
| Central, low $p_T^{\mu\mu}$        | $10.9 \pm 0.1$ | $7989 \pm 205$  | $15 \pm 2$   | $21 \pm 2$   | $8025 \pm 205$   | 0.12         | $7885 \pm 89$   |
| Non-central, low $p_T^{\mu\mu}$    | $31.6 \pm 0.1$ | $38189 \pm 454$ | $65 \pm 4$   | $108 \pm 5$  | $38361 \pm 454$  | 0.16         | $38777 \pm 197$ |
| Central, medium $p_T^{\mu\mu}$     | $23.4 \pm 0.1$ | $6244 \pm 179$  | $107 \pm 4$  | $68 \pm 4$   | $6419 \pm 179$   | 0.29         | $6585 \pm 81$   |
| Non-central, medium $p_T^{\mu\mu}$ | $66.5 \pm 0.2$ | $29683 \pm 402$ | $488 \pm 10$ | $441 \pm 11$ | $30612 \pm 402$  | 0.38         | $31291 \pm 177$ |
| Central, high $p_T^{\mu\mu}$       | $15.5 \pm 0.1$ | $3008 \pm 135$  | $255 \pm 7$  | $58 \pm 3$   | $3321 \pm 135$   | 0.27         | $3160 \pm 56$   |
| Non-central, high $p_T^{\mu\mu}$   | $39.7 \pm 0.1$ | $12047 \pm 263$ | $962 \pm 14$ | $309 \pm 9$  | $13318 \pm 264$  | 0.34         | $12829 \pm 113$ |
| VBF Loose                          | $3.4 \pm 0.0$  | $236 \pm 8$     | $18 \pm 2$   | $3 \pm 1$    | $257 \pm 8$      | 0.21         | $274 \pm 17$    |
| VBF Tight                          | $3.4 \pm 0.0$  | $76 \pm 5$      | $2 \pm 1$    | $0 \pm 1$    | $78 \pm 5$       | 0.39         | $79 \pm 9$      |

TABLE 5.8: Expected event yields (for different signal and background processes) and observed data yields in eight signal categories. The yields are corresponding to  $36.1 \text{ fb}^{-1}$  and calculated within a  $m_{\mu\mu}$  interval which centers at the simulated signal peak and contains 90% of the total signal events.

|                                    | ggF              | VBF             | WH (hadronic)   | WH (leptonic)   | ZH (hadronic)   | ZH (leptonic)   | ttH             |
|------------------------------------|------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Central, low $p_T^{\mu\mu}$        | $10.82 \pm 0.08$ | $0.09 \pm 0.00$ | $0.02 \pm 0.00$ | $0.01 \pm 0.00$ | $0.01 \pm 0.00$ | $0.00 \pm 0.00$ | $0.00 \pm 0.00$ |
| Non-central, low $p_T^{\mu\mu}$    | $31.19 \pm 0.13$ | $0.27 \pm 0.00$ | $0.07 \pm 0.00$ | $0.03 \pm 0.00$ | $0.05 \pm 0.00$ | $0.00 \pm 0.00$ | $0.00 \pm 0.00$ |
| Central, medium $p_T^{\mu\mu}$     | $22.39 \pm 0.11$ | $0.69 \pm 0.01$ | $0.16 \pm 0.01$ | $0.06 \pm 0.00$ | $0.09 \pm 0.00$ | $0.01 \pm 0.00$ | $0.01 \pm 0.00$ |
| Non-central, medium $p_T^{\mu\mu}$ | $63.32 \pm 0.18$ | $2.05 \pm 0.01$ | $0.57 \pm 0.01$ | $0.21 \pm 0.01$ | $0.34 \pm 0.01$ | $0.04 \pm 0.00$ | $0.01 \pm 0.00$ |
| Central, high $p_T^{\mu\mu}$       | $12.76 \pm 0.07$ | $1.78 \pm 0.01$ | $0.50 \pm 0.01$ | $0.11 \pm 0.00$ | $0.29 \pm 0.01$ | $0.03 \pm 0.00$ | $0.03 \pm 0.00$ |
| Non-central, high $p_T^{\mu\mu}$   | $32.19 \pm 0.12$ | $4.66 \pm 0.01$ | $1.52 \pm 0.02$ | $0.37 \pm 0.01$ | $0.87 \pm 0.01$ | $0.09 \pm 0.00$ | $0.07 \pm 0.00$ |
| VBF Loose                          | $1.54 \pm 0.03$  | $1.83 \pm 0.01$ | $0.01 \pm 0.00$ | $0.00 \pm 0.00$ | $0.00 \pm 0.00$ | $0.00 \pm 0.00$ | $0.00 \pm 0.00$ |
| VBF Tight                          | $0.86 \pm 0.02$  | $2.55 \pm 0.01$ | $0.00 \pm 0.00$ | $0.00 \pm 0.00$ | $0.00 \pm 0.00$ | $0.00 \pm 0.00$ | $0.00 \pm 0.00$ |

TABLE 5.9: Expected signal event yields (normalized to  $36.1 \text{ fb}^{-1}$ ;  $m_{\mu\mu}$  within an interval, which centers at the simulated signal peak and contains 90% of the total signal events) from different production modes in eight signal categories.

## 5.5 Signal and Background Modeling

This analysis is based on a data-driven method and analytical functions are adopted to depict the  $m_{\mu\mu}$  distributions for signal and background processes. This section will introduce the corresponding modeling functions.

### 5.5.1 Signal modeling

The signal model is developed for the purpose of describing the Higgs boson peak together with the lower-mass tail due to the photon radiation from final state. And in order to guarantee the fitting stability, some certain parameters for the modeling function are fixed with the empirical values. Equation 5.2 represents the analytic function used for signal, which is the sum of a Crystal Ball function (CB) and a Gaussian function (GS):

$$P_S(m_{\mu\mu}) = f_{CB} \times CB(m_{\mu\mu}, m_{CB}, \sigma_{CB}, \alpha, n) + (1 - f_{CB}) \times GS(m_{\mu\mu}, m_{GS}, \sigma_{GS}^S), \quad (5.2)$$

where  $x$  denotes the dimuon invariant mass, and  $f_{CB}$  (floating between 0.6 and 1) is the fraction of the CB contribution when each component (CB or GS) is normalized to unity. While the parameters  $\alpha$  (floating between 1 and 2) and  $n$  (fixed at 1) determine the power-law tail of the CB distribution. The other parameters  $m_{CB}$ ,  $\sigma_{CB}$ ,  $m_{GS}$  and  $\sigma_{GS}^S$  represent the CB mean value, CB width, GS mean value and GS width respectively, which are all floating. These floating parameters are determined for each signal category by fitting the signal model to the simulated  $m_{\mu\mu}$  spectra. And for each category, the ggF, VBF, and VH signal shapes are obtained separately and then combined into a total signal shape according to their individual SM predictions.

Figure 5.14 shows the signal fitting for the  $m_{\mu\mu}$  distributions from simulated ggF signal events in the central and non-central medium  $p_T^{\mu\mu}$  categories. And clearly we can see the mass resolution from the central category is much better comparing with the non-central one.

Figure 5.15 depicts the fitting results for the simulated VBF signal events in the VBF loose and VBF tight categories. And the much larger resolution values in VBF categories are expected due to the fact that the muons in VBF categories tend to have harder  $p_T$  distributions caused by much more enriched jet activities comparing with the ggF categories.

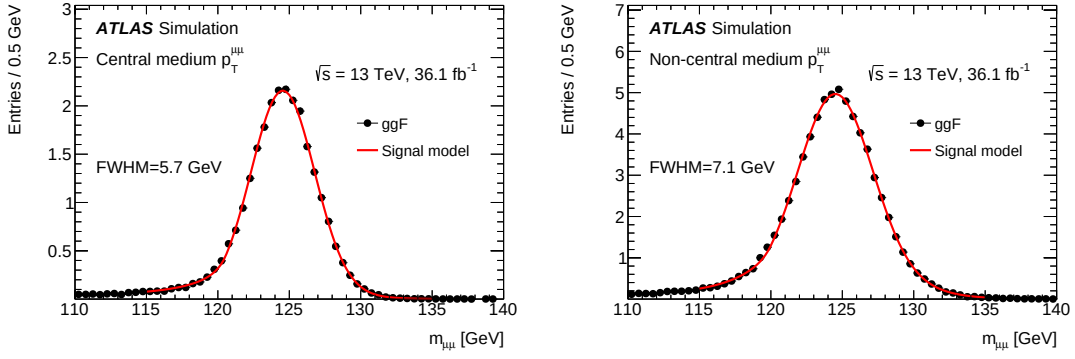


FIGURE 5.14: Signal model fits to the  $m_{\mu\mu}$  distributions of simulated ggF signal events in the central (left) and non-central (right) medium  $p_T^{\mu\mu}$  categories.

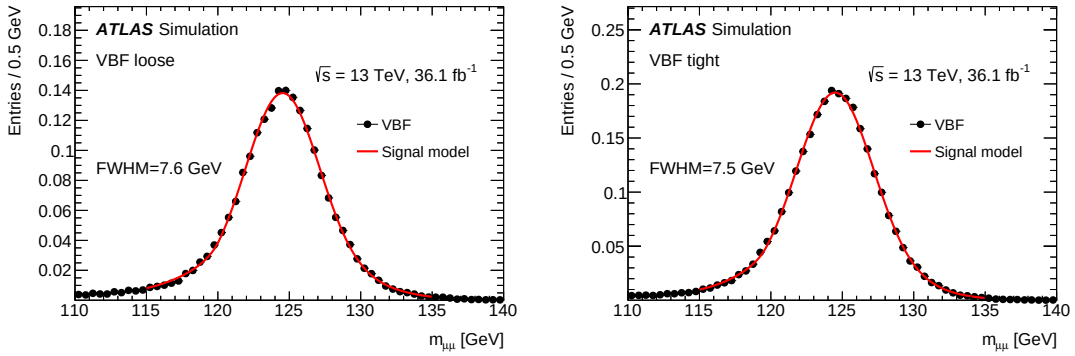


FIGURE 5.15: Signal model fits to the  $m_{\mu\mu}$  distributions of simulated VBF signal events in the VBF loose (left) and VBF tight (right) categories

### 5.5.2 Background modeling

The background model is developed aiming to describe the steeply falling  $m_{\mu\mu}$  distributions of the dominant Drell-Yan process. In the meantime, it also needs to accommodate enough flexibility to take into account potential differences between data and MC simulation, and allow variations in the  $m_{\mu\mu}$  spectra caused by the different selections and additional contributions from sub-dominant background processes as well. In the end, the adopted background model is the sum of a Breit-Wigner function (BW) convolved with a GS, and an exponential function divided by a cubic function, which is shown in Equation 5.3:

$$P_B(m_{\mu\mu}) = f \times [\text{BW}(m_{\text{BW}}, \Gamma_{\text{BW}}) \otimes \text{GS}(\sigma_{\text{GS}}^{\text{B}})](m_{\mu\mu}) + (1 - f) \times e^{A \cdot m_{\mu\mu}} / m_{\mu\mu}^3, \quad (5.3)$$

where  $f$  (floating between 0 and 1) denotes the fraction of the BW component when each component is normalized to unity. The BW parameters  $m_{\text{BW}}$  and  $\Gamma_{\text{BW}}$  are fixed to be 91.2 GeV and 2.49 GeV [108] respectively across all the categories. And  $\sigma_{\text{GS}}^{\text{B}}$  in

each category is obtained by using a simple Gaussian function to fit the difference between  $m_{reco}$  (reconstructed  $m_{\mu\mu}$ ) and  $m_{truth}$  ( $m_{\mu\mu}$  at truth level) from Drell-Yan samples. Table 5.10 summarizes the  $\sigma_{GS}^B$  values adopted for each category. The parameter  $A$  is floating between -1 and 1.

| Signal category      | $\sigma_{GS}^B$ [GeV] |
|----------------------|-----------------------|
| LowPtll central      | 2.24                  |
| LowPtll non-central  | 2.76                  |
| MidPtll central      | 2.33                  |
| MidPtll non-central  | 2.82                  |
| HighPtll central     | 2.53                  |
| HighPtll non-central | 3.07                  |
| VBF Loose            | 3.07                  |
| VBF Tight            | 3.07                  |

TABLE 5.10: Summary of the  $\sigma_{GS}^B$  values adopted for each signal category.

Figure 5.16 depicts the background-only fit to the observed  $m_{\mu\mu}$  spectra in the selected central high  $p_T^{\mu\mu}$  and VBF tight categories. The expected signal shapes in the figures are scaled up by a factor of 20 for visibility. In general, the background model shows good performance when fitted to the corresponding  $m_{\mu\mu}$  spectra. The systematic uncertainty originating from the potential bias of the particular background model is evaluated by using the so-called spurious signal technique, which will be introduced in the next section.

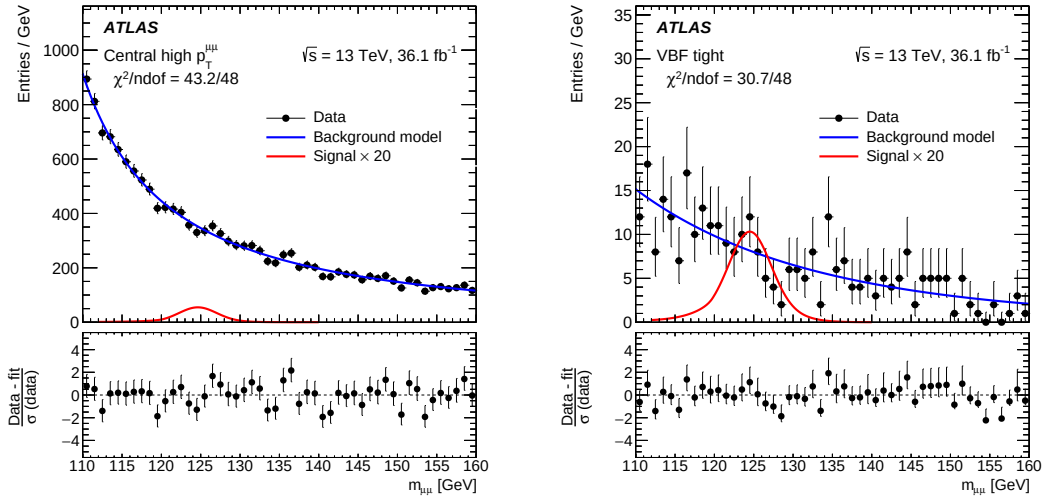


FIGURE 5.16: Background-only fit to the observed  $m_{\mu\mu}$  distribution in the central high  $p_T^{\mu\mu}$  (left) and VBF tight (right) categories. Only the statistical uncertainties are shown for the data points. The expected signal shape is scaled up by a factor of 20.

## 5.6 Systematic Uncertainties

Systematic uncertainties are treated as nuisance parameters for the final statistical analysis when deriving the signal strength, which include the theoretical and experimental uncertainties on the signal and also spurious signal uncertainty due to the bias in the background model.

### 5.6.1 Theoretical uncertainties on the signal

The systematic uncertainties on the Higgs production cross section originate from QCD scales and PDF set variations, and the uncertainty of branching ratio for  $H \rightarrow \mu\mu$  is 1.23% [109, 110]. The theoretical uncertainty in the signal acceptance for the ggF categories due to the modeling of the Higgs boson  $p_T$  spectrum arising from missing high-order corrections, is estimated by varying the QCD renormalization, factorisation and resummation scales used in the HRES program [111, 112]. Table 5.11 summarizes the corresponding uncertainty values. And the acceptance uncertainty for the ggF signal in the VBF categories is  $\sim 17\%$ . The theoretical uncertainties associated with the modeling of multiparton interactions are estimated via turning them off during the event generation [113]. Overall, the theoretical uncertainty value for the ggF signal prediction varies from 15% to 25%, which is dominated by the uncertainties caused by missing high-order effects. While for VBF signal, the total uncertainty is generally  $\sim 5\%$ .

| Higgs $p_T$ range [GeV] | 0-15 (Low) | 15-50 (Medium) | >50 (High) |
|-------------------------|------------|----------------|------------|
| Syst. Up                | -20%       | +11.8%         | 0          |
| Syst. Down              | 0          | -13.6%         | 15.3%      |

TABLE 5.11: Higgs  $p_T$  systematic uncertainties for different ggF related categories.

### 5.6.2 Experimental uncertainties on the signal

The uncertainty on the integrated luminosity recorded in 2015 and 2016 is 3.2%, which is derived following a similar methodology as described in Ref. [114], through a preliminary calibration of the luminosity scale using  $x - y$  beam-separation scans carried out in August 2015 and May 2016. The other experimental uncertainties mainly come from the physics objects adopted for this analysis, which are listed as below:

- Muon:
  - Trigger, isolation, identification, and reconstruction efficiency
  - Muon energy/momentum scale and resolution
- Missing transverse energy: MET soft term track scale and resolution
- Jet:
  - Jet energy scale and resolution
  - JVT efficiency
  - $b$ -tagging efficiency

The sources of systematic uncertainty are assessed as a function of  $m_{\mu\mu}$ . For each systematic type, the variation value is calculated as the event yield with this systematic uncertainty applied divided by the yield for nominal case within a  $m_{\mu\mu}$  interval between 110 GeV and 160 GeV. Table 5.12 shows the total object related systematic variation amplitudes for ggF and VBF 125 GeV signal in the eight signal categories.

| Signal category                    | Up (ggF) | Down (ggF) | Up (VBF) | Down (VBF) |
|------------------------------------|----------|------------|----------|------------|
| Central, low $p_T^{\mu\mu}$        | 1.36%    | 1.35%      | 4.26%    | 2.67%      |
| Non-central, low $p_T^{\mu\mu}$    | 1.49%    | 1.54%      | 2.20%    | 2.17%      |
| Central, medium $p_T^{\mu\mu}$     | 1.77%    | 1.64%      | 2.60%    | 2.51%      |
| Non-central, medium $p_T^{\mu\mu}$ | 1.72%    | 1.65%      | 2.57%    | 2.46%      |
| Central, high $p_T^{\mu\mu}$       | 2.52%    | 2.48%      | 4.28%    | 4.30%      |
| Non-central, high $p_T^{\mu\mu}$   | 2.47%    | 2.41%      | 3.90%    | 3.99%      |
| VBF Loose                          | 13.48%   | 14.13%     | 7.44%    | 6.01%      |
| VBF Tight                          | 9.80%    | 12.01%     | 6.90%    | 7.85%      |

TABLE 5.12: Systematic variation amplitudes for ggF and VBF 125 GeV signal between [110 GeV, 160 GeV] mass region in different signal categories.

Overall, the total experimental uncertainty on the predicted signal yield for each ggF category is between 4% and 6%, which is dominated by the luminosity, muon, jet, and pileup contributions. For VBF categories, the experimental uncertainty goes up to 15%, mainly due to larger contributions from the jet energy scale and resolution uncertainties. The effects of the experimental uncertainties on the predicted signal  $m_{\mu\mu}$  shapes are found to be minor, which are therefore neglected for this analysis.



### 5.6.3 Spurious signal uncertainty from the background modeling

Since this data-driven analysis purely relies on a simultaneous fit to the observed data  $m_{\mu\mu}$  spectrum to extract the final result on signal strength, therefore it is crucial to estimate the spurious signal uncertainty originating from potential bias of background modeling with the methodology described in Ref. [115]. The first step is to produce a smooth enough MC background  $m_{\mu\mu}$  spectrum at the reconstruction level, and then the signal plus background template (describe in Section 5.5) is used to fit this spectrum to examine whether there are any spurious signal events. As the dominant background comes from the Drell-Yan production, thus we focus on this process for the spurious signal study.

It is not really realistic to generate a large amount of fully simulated MC events to fulfill the requirement for spurious signal estimation. The actual procedure adopted is to produce high-statistics truth Drell-Yan samples and then apply the efficiency correction and momentum smearing (derived from the official Powheg Drell-Yan sample) on top of the truth events to mimic a smooth spectrum at the reconstruction level. To carry out this, we generate  $\sim 870$  M truth Drell-Yan events with born mass between 95 and 200 GeV (corresponding to an equivalent integrated luminosity of  $\sim 5 \text{ ab}^{-1}$  which is about 140 times larger than the data luminosity recorded in 2015 and 2016) using the official PowHeg+Pythia8 for ggF categories. While for the two VBF categories, we use the Madgraph5 (Np2) generator to produce about 15 M truth Drell-Yan events also with born mass between 95 and 200 GeV. After we get the mimic “reconstructed” spectra, a closure test is performed by comparing the mimic spectra with the real reconstructed spectra from official fully simulated samples, as shown in Figure 5.17 and Figure 5.18. Reasonable agreement in the signal region can be observed for this test, and the statistical errors in the lower panel are due to the relatively low statistics of the official Drell-Yan samples.

Finally, the signal plus background analytic function is fitted to these mimic  $m_{\mu\mu}$  distributions in each of the signal category to determine the spurious signal contribution. The spurious signal strength is defined as the spurious signal events divided by the predicted signal events ( $\mu_{spur} = N_{spur}/N_{predicted}$ ), which is allowed to be either positive or negative. Figure 5.19 shows the spurious signal fits to each of the signal category for the 125 GeV signal mass point. As can be seen, the fitted  $\mu_{spur}$  is either small (comparing to

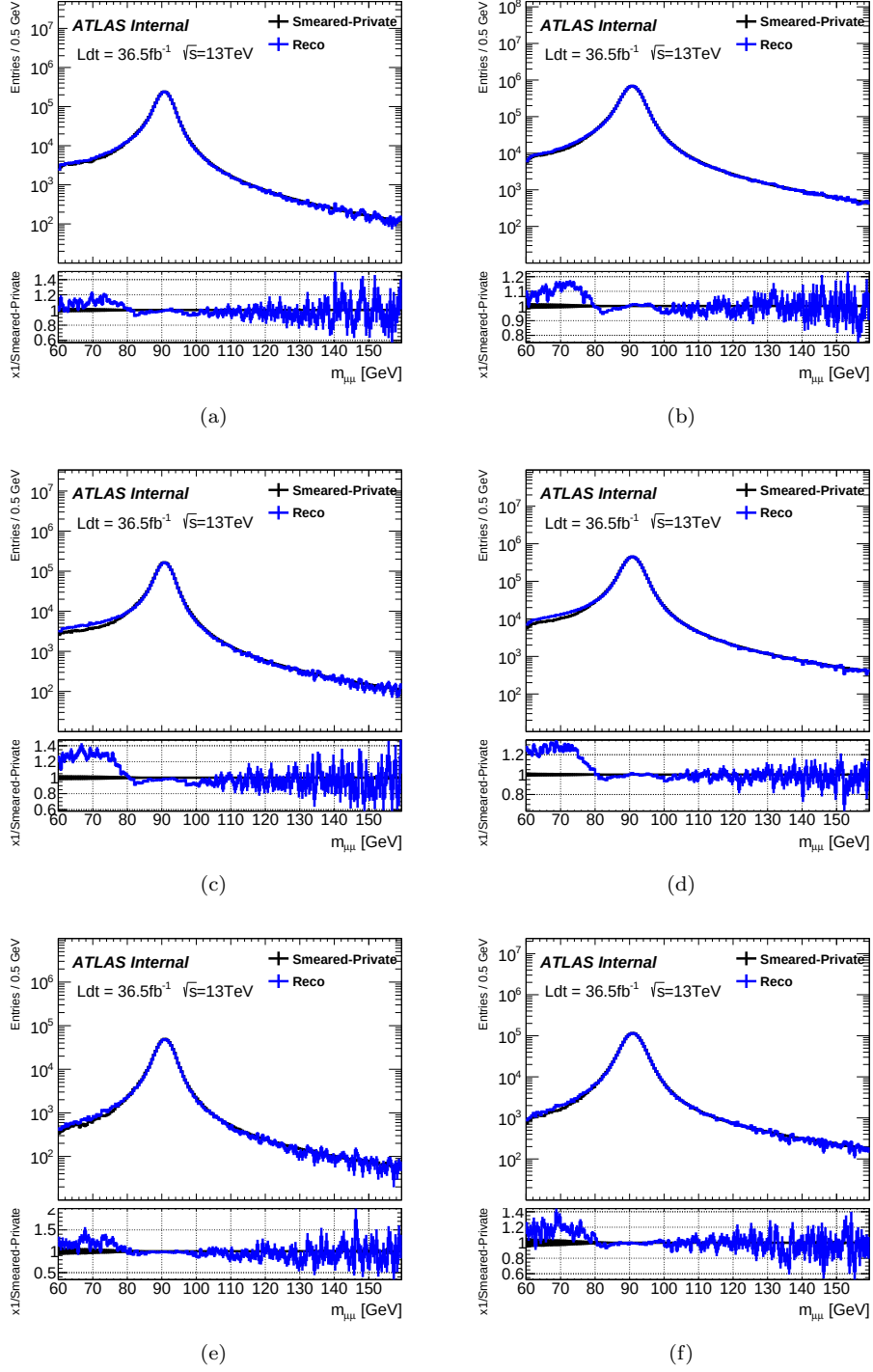


FIGURE 5.17: Comparison of reconstruction-level  $m_{\mu\mu}$  distributions between the fully-simulated MC events and the corrected truth events after requirement at least two selected muons in the events and the leading muon with  $p_T > 27$  GeV, in low (top), medium (middle) and high (bottom)  $p_T^{\mu\mu}$  categories in central (left) and non-central (right) regions. Distributions are normalized to  $36.1 \text{ fb}^{-1}$ , and only MC statistical uncertainty is shown.

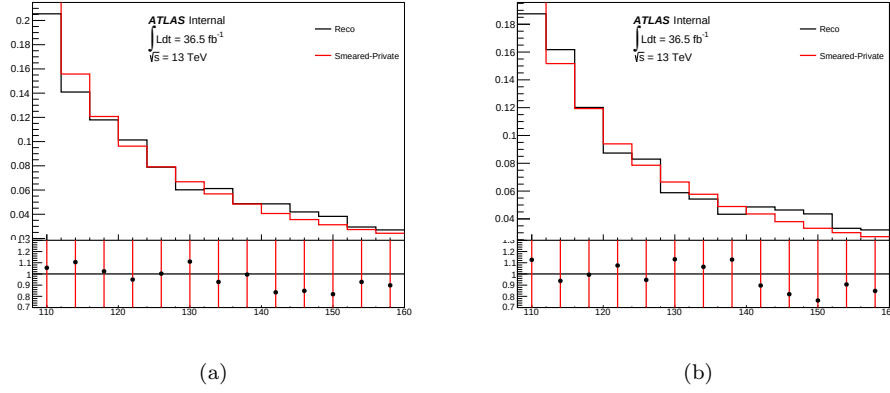


FIGURE 5.18: Comparison of reconstruction-level  $m_{\mu\mu}$  distributions between the fully-simulated MC events and the corrected truth events after requirement at least two selected muons in the events and the leading muon with  $p_T > 27$  GeV, in VBF loose (left) and VBF tight (right) categories. Distributions are normalized to  $36.1 \text{ fb}^{-1}$ , and only MC statistical uncertainty is shown.

the current sensitivity) or negative, and this fluctuation demonstrates that the spurious signal contribution is not significant in this analysis.

The fitted spurious signal event yields corresponding to  $36.1 \text{ fb}^{-1}$  as a function of signal pole masses are shown in Figure 5.20 for each of the signal regions. Table 5.13 summarizes the spurious signal event yields corresponding to  $36.1 \text{ fb}^{-1}$  for various mass points in different categories. Since for the final statistical interpretation, we only want to show the upper limit result for 125 GeV mass point, thus we take the largest magnitude of the central value and the error of  $\mu_{spur}$  among 120, 125 and 130 GeV mass points as the spurious signal contribution for each category.

|         | Central, low $p_T^{\mu\mu}$ | Non-central, low $p_T^{\mu\mu}$ | Central, medium $p_T^{\mu\mu}$ | Non-central, medium $p_T^{\mu\mu}$ | Central, high $p_T^{\mu\mu}$ | Non-central, high $p_T^{\mu\mu}$ | VBF Loose        | VBF Tight        |
|---------|-----------------------------|---------------------------------|--------------------------------|------------------------------------|------------------------------|----------------------------------|------------------|------------------|
| 115 GeV | $43.44 \pm 17.20$           | $163.61 \pm 41.25$              | $46.37 \pm 15.67$              | $275.65 \pm 36.01$                 | $31.37 \pm 10.61$            | $93.72 \pm 22.56$                | $-4.44 \pm 2.07$ | $-0.31 \pm 0.74$ |
| 120 GeV | $-29.95 \pm 12.68$          | $-35.74 \pm 30.29$              | $10.59 \pm 12.18$              | $63.09 \pm 26.38$                  | $-7.33 \pm 8.02$             | $19.56 \pm 16.41$                | $-2.44 \pm 1.46$ | $0.13 \pm 0.56$  |
| 125 GeV | $-42.75 \pm 11.39$          | $-113.43 \pm 26.88$             | $-1.39 \pm 10.64$              | $-64.58 \pm 24.32$                 | $1.71 \pm 7.48$              | $6.92 \pm 15.68$                 | $-1.99 \pm 1.38$ | $-0.75 \pm 0.52$ |
| 130 GeV | $0.01 \pm 9.34$             | $-91.39 \pm 22.77$              | $-13.48 \pm 9.36$              | $-96.93 \pm 21.34$                 | $-7.01 \pm 6.67$             | $-4.75 \pm 14.00$                | $3.45 \pm 1.24$  | $0.15 \pm 0.46$  |
| 135 GeV | $13.36 \pm 8.27$            | $-32.84 \pm 18.97$              | $-17.75 \pm 8.04$              | $-52.81 \pm 18.08$                 | $-3.96 \pm 6.03$             | $-35.74 \pm 12.12$               | $3.72 \pm 1.03$  | $0.50 \pm 0.40$  |
| 140 GeV | $2.71 \pm 7.60$             | $50.93 \pm 17.40$               | $-8.66 \pm 7.22$               | $-17.49 \pm 15.98$                 | $-2.98 \pm 5.32$             | $-36.36 \pm 10.76$               | $0.19 \pm 0.92$  | $0.14 \pm 0.38$  |
| 145 GeV | $17.63 \pm 7.32$            | $73.22 \pm 16.72$               | $-3.44 \pm 6.95$               | $-15.59 \pm 15.60$                 | $0.13 \pm 5.19$              | $-20.21 \pm 10.62$               | $-2.10 \pm 0.92$ | $-0.01 \pm 0.35$ |

TABLE 5.13: Spurious signal event yields corresponding to  $36.1 \text{ fb}^{-1}$  for various mass points in different ggF and VBF categories.

The final adopted spurious signal uncertainties, calculated as  $\mu_{spur} \times \text{SM predicted signal yields}$ , for the 125 GeV signal point is shown in Table 5.14. For the final simultaneous fit to derive the signal strength of  $H \rightarrow \mu\mu$  production, this spurious signal

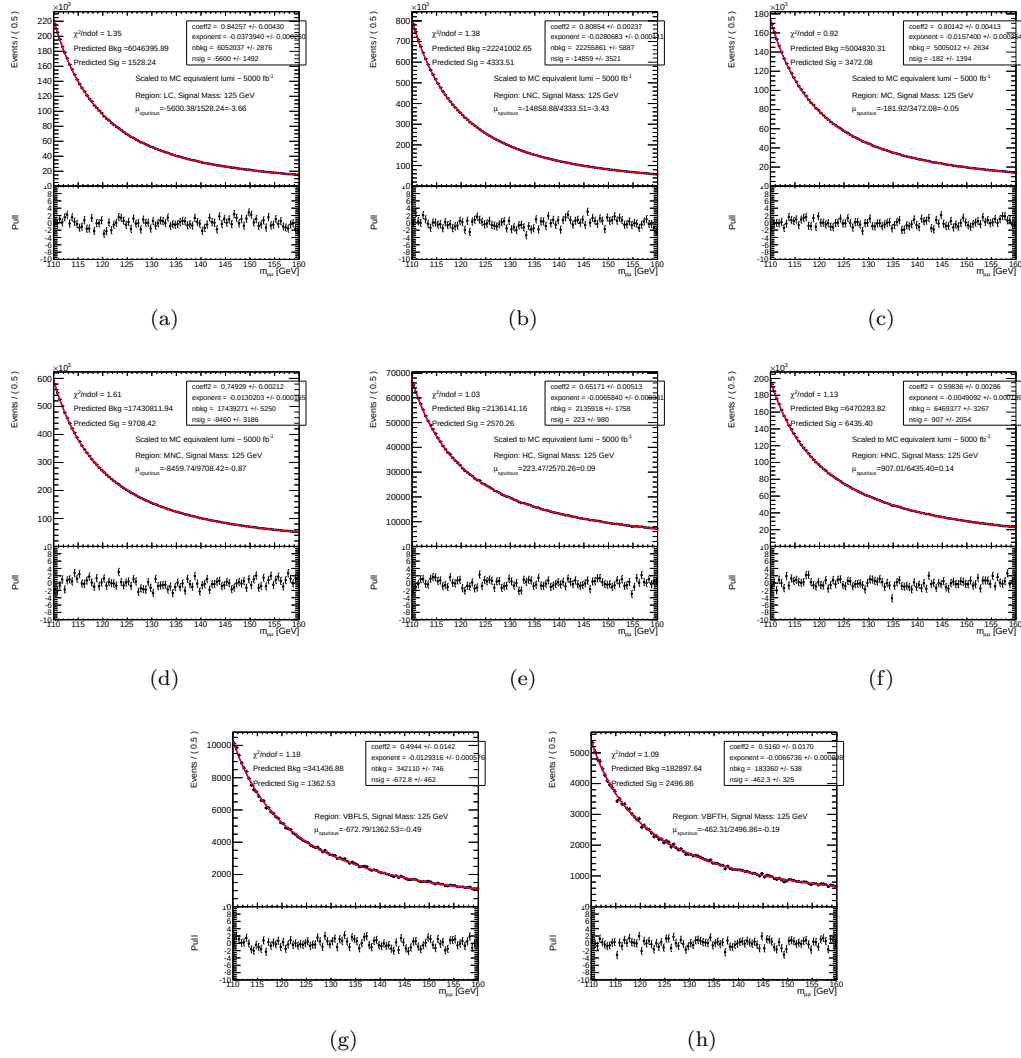


FIGURE 5.19: The combined signal (125 GeV) plus background fits to  $m_{\mu\mu}$  distributions form the corrected truth events after requirement at least two selected muons in the events and the leading muon with  $p_T > 27$  GeV, in central low- $p_T$  category (top left), non-central low- $p_T$  category (top middle), central medium- $p_T$  category (top right), non-central medium- $p_T$  category (middle left), central high- $p_T$  category (middle middle), non-central high- $p_T$  category (middle right), VBF loose category (bottom left) and VBF tight category (bottom right). Distributions are normalized to the MC equivalent luminosity so that the fitting errors reflects that of MC statistical fluctuations, and only MC statistical uncertainty is shown.

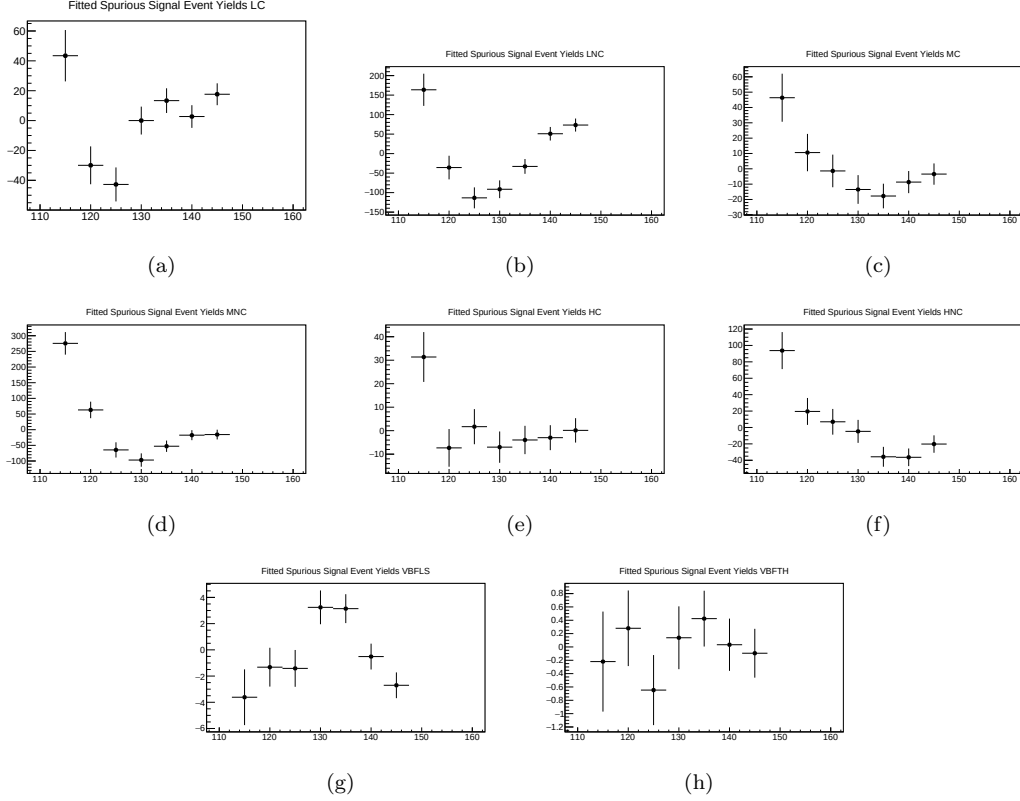


FIGURE 5.20: The fitted spurious signal event yields corresponding to  $36.1 \text{ fb}^{-1}$  as a function of signal pole mass in central low- $p_T$  category (top left), non-central low- $p_T$  category (top middle), central medium- $p_T$  category (top right), non-central medium- $p_T$  category (middle left), central high- $p_T$  category (middle middle), non-central high- $p_T$  category (middle right), VBF loose category (bottom left) and VBF tight category (bottom right). Only MC statistical uncertainty coming out of the fit is shown.

contribution is added to the  $N_{sig}$  term and constrained by Gaussian nuisance parameters, treated uncorrelated across all the categories. The impact of this spurious signal uncertainty on the upper limits is found to be  $\sim 2\%$ .

| Categories                         | Uncertainty [Number of events] |
|------------------------------------|--------------------------------|
| Central, low $p_T^{\mu\mu}$        | 42.75                          |
| Non-central, low $p_T^{\mu\mu}$    | 113.43                         |
| Central, medium $p_T^{\mu\mu}$     | 13.48                          |
| Non-central, medium $p_T^{\mu\mu}$ | 96.93                          |
| Central, high $p_T^{\mu\mu}$       | 8.02                           |
| Non-central, high $p_T^{\mu\mu}$   | 19.56                          |
| VBF Loose                          | 3.45                           |
| VBF Tight                          | 0.75                           |

TABLE 5.14: Final adopted spurious signal systematic uncertainties for each category, corresponding to  $36.1 \text{ fb}^{-1}$ .

## 5.7 Statistical Analysis

After the selected events sorted into eight different signal categories, a binned maximum-likelihood fit (bin size is 125 MeV) is performed to the observed  $m_{\mu\mu}$  spectra across all the categories simultaneously with the sum of signal and background models as described in Section 5.5. The signal normalization (signal strength  $\mu$  times expected signal yield) and background normalization are treated as free parameters for the fitting procedure. And  $\mu$ , which is the single parameter of interest (POI), can be derived and presented as the result after the fitting.

As a first step, the full likelihood can be constructed as below:

$$L\left(\mu, \boldsymbol{\theta} = \bigcup_{c=1}^8 \boldsymbol{\theta}_c\right) = \prod_{c=1}^8 L_c(\mu, \boldsymbol{\theta}_c) \quad (5.4)$$

where  $c$  is the index for looping over the 8 categories, and  $\boldsymbol{\theta}_c$  are the nuisance parameters taken into account for category  $c$ .  $L_c$  is the likelihood for category  $c$ , which can be further written into

$$L_c(\mu, \boldsymbol{\theta}_c) = \prod_{k=1}^{N_c} \mathcal{L}_c(m_{\mu\mu}(k); \mu, \boldsymbol{\theta}_c) \quad (5.5)$$

where  $N_c$  is the the number of bins in category  $c$ , with the index  $k$  running over the bins. And  $m_{\mu\mu}(k)$  is the value of the content for bin  $k$ .  $\mathcal{L}_c$  is the per-bin likelihood, which can be written into the form of signal and background probability density functions as:

$$\begin{aligned} \mathcal{L}_c(m_{\mu\mu}; \mu, \boldsymbol{\theta}_c) = & \mu_S \cdot N_{\text{ggF},c}(\boldsymbol{\theta}_c^{\text{norm}}) f_{\text{ggF},c}(m_{\mu\mu}) \\ & + \mu_S \cdot N_{\text{VBF},c}(\boldsymbol{\theta}_c^{\text{norm}}) f_{\text{VBF},c}(m_{\mu\mu}) \\ & + \mu_S \cdot N_{\text{VH},c}(\boldsymbol{\theta}_c^{\text{norm}}) f_{\text{VH},c}(m_{\mu\mu}) \\ & + N_{\text{spur}}(\theta) f_{\text{ggF},c}(m_{\mu\mu}) \\ & + N_{\text{spur}}(\theta) f_{\text{VBF},c}(m_{\mu\mu}) \\ & + N_{\text{spur}}(\theta) f_{\text{VH},c}(m_{\mu\mu}) \\ & + N_{\text{bkg},c} f_{\text{bkg},c}(m_{\mu\mu}; \boldsymbol{\theta}_c^{\text{bkg}}) \end{aligned} \quad (5.6)$$

where  $N_{\text{ggF},c}$ ,  $N_{\text{VBF},c}$ ,  $N_{\text{VH},c}$  and  $N_{\text{bkg},c}$  are the numbers of ggF signal, VBF signal, VH signal and background events in category  $c$  while  $f_{\text{ggF},c}$ ,  $f_{\text{VBF},c}$ ,  $f_{\text{VH},c}$  and  $f_{\text{bkg},c}$  are the corresponding signal and background probability density functions (PDFs).  $\boldsymbol{\theta}_c^{\text{norm}}$  and  $\boldsymbol{\theta}_c^{\text{bkg}}$  are the nuisance parameters used for the description of signal normalization and the

background parametrization respectively.  $N_{spur}$  denotes the spurious signal systematic uncertainty.

To derive the POI  $\mu$ , the test statistics is adopted, which is computed as the profile likelihood ratio [116]:

$$\tilde{q}_\mu = \begin{cases} -2 \ln \tilde{\lambda}(\mu) & \hat{\mu} \leq \mu \\ 0 & \hat{\mu} > \mu \end{cases} = \begin{cases} -2 \ln \frac{L(\mu, \hat{\hat{\theta}}(\mu))}{L(0, \hat{\hat{\theta}}(0))} & \hat{\mu} < 0 \\ -2 \ln \frac{L(\mu, \hat{\hat{\theta}}(\mu))}{L(\hat{\mu}, \hat{\hat{\theta}})} & 0 \leq \hat{\mu} \leq \mu \\ 0 & \hat{\mu} > \mu \end{cases} \quad (5.7)$$

where  $L$  is the likelihood function constructed in Equation 5.4.  $\hat{\mu}$  and  $\hat{\theta}$  are the values for  $\mu$  and  $\theta$  when maximizing the  $L$  with all parameters floating, which are named as the unconditional maximum-likelihood (ML) estimators.  $\hat{\hat{\theta}}(\mu)$  is the conditional ML estimator of  $\theta$  for a fixed value of  $\mu$ . The test statistic estimates the compatibility of the data with the  $\mu$  hypothesis using the ratio of likelihood for the case of a floating  $\mu$  (denominator for Equation 5.7), and the case where it is fixed at the hypothesis value (numerator for Equation 5.7).

The final upper limits on the  $\mu$  are set using a modified frequentist method [117] as:

$$CL_s = \frac{CL_{s+b}}{CL_b}, \quad (5.8)$$

where  $CL_{s+b}$  and  $CL_b$  denote the confidence intervals corresponding to signal+background ( $s+b$ ) and background-only ( $b$  – only) hypotheses. The  $CL_s$  exclusion can be further calculated as:

$$CL_s(\mu) = \frac{p_\mu}{1 - p_b} \quad (5.9)$$

where  $p_\mu$  is the  $p$ -value with  $s+b$  hypothesis,  $p_b$  is the  $p$ -value of  $b$  – only hypothesis.  $p_\mu$  and  $p_b$  can be computed as:

$$p_\mu = \int_{\tilde{q}_\mu^{obs}}^{\infty} f(\tilde{q}_\mu | \mu, \hat{\theta}_\mu^{obs}) d\tilde{q}_\mu, \quad (5.10)$$

$$p_b = 1 - \int_{q_0^{obs}}^{\infty} f(\tilde{q}_\mu | 0, \hat{\theta}_0^{obs}) d\tilde{q}_\mu, \quad (5.11)$$

where  $\hat{\theta}_0^{obs}$  and  $\hat{\theta}_\mu^{obs}$  are the nuisance parameters after fitting with data, while  $f(\tilde{q}_\mu | \mu, \hat{\theta}_\mu^{obs})$  and  $f(\tilde{q}_\mu | 0, \hat{\theta}_0^{obs})$  are sampling functions. For this analysis, asymptotic formula [116] is used to derive the  $p$ -values.

Limits at the 95% CL on  $\mu$  are then computed by scanning values of the  $\mu$  hypothesis, computing the  $CL_s$  exclusions and identifying the  $\mu_{up}$  for which this corresponding value equals 0.05.

## 5.8 Results

Based on the simultaneous fit described in Section 5.7, the observed and expected upper limits on  $\mu$  can be derived at the 95% CL. Figure 5.21 depicts these corresponding results for the  $m_{\mu\mu}$  ranging between 115 and 145 GeV. For  $m_H = 125$  GeV, the observed (expected) upper limit on  $\mu$  at the 95% CL is 3.0 (3.1) with  $36.1 \text{ fb}^{-1}$  of data collected in 2015 and 2016 at  $\sqrt{s}=13$  TeV. The measured signal strength is  $\mu = -0.11^{+1.49}_{-1.51}$ , with the expected best fit value  $\mu = 0.97^{+1.49}_{-1.56}$ .

The statistical combination is performed by using the LHC Run 1 and Run 2 data, and the observed (expected) upper limits is  $\sim 2.7$  (2.8) for  $m_H = 125$  GeV. The measured signal strength is  $\mu = -0.15^{+1.38}_{-1.45}$ .

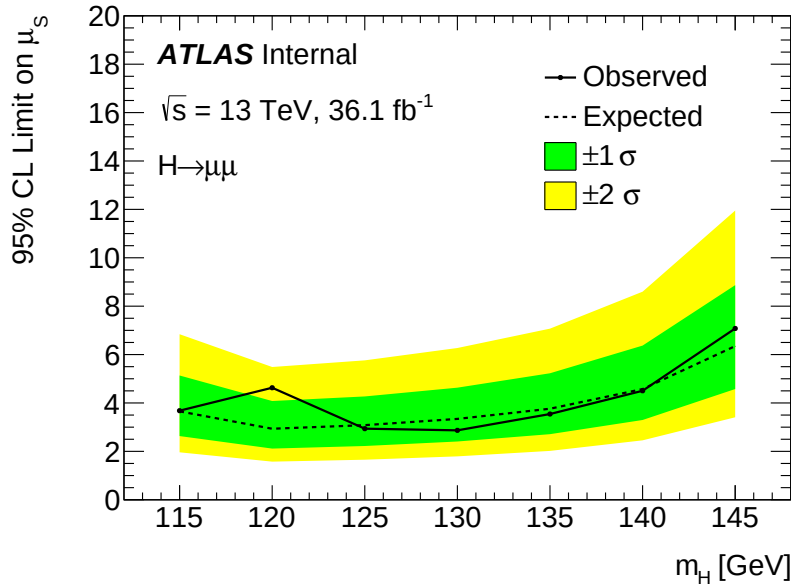


FIGURE 5.21: Observed and expected upper limits on  $\mu$  at 95% CL for data recorded in 2015 and 2016 at  $\sqrt{s} = 13$  TeV corresponding to  $36.1 \text{ fb}^{-1}$ .

As mentioned in Section 5.1, with the data collected during the Run 1, the ATLAS experiment has set an upper limit on  $\mu$  to be 7.1 [29]. As can be seen, our results with the Run 2 data is much significantly improved. A search for the SM  $H \rightarrow \mu\mu$  is



also performed by CMS experiment with a similar amount of dataset and they have set observed (expected) upper limit on  $\mu$  to be 2.64 (2.08) [118]. The relatively better result from the CMS experiment is mainly due to the fact that the CMS detector has much better muon  $p_T$  resolution comparing with the ATLAS detector. And the reason behind this is that the Inner Detector of the CMS has much larger bending power from magnet system.



# Chapter 6

## Search for New Phenomena with the Dilepton Final State

### 6.1 Introduction

As we know, there are enough reasons to believe that the current SM is not a complete story, and theories beyond the SM (BSM) have predicted various new physics. The motivation of the work described in this chapter is to search for new TeV phenomena e.g.  $Z'$  or contact interaction (CI) as described in Section 2.2. Dilepton final states ( $ee$  and  $\mu\mu$ ) provide relatively simple and clean signatures, and good sensitivity for detecting these BSM phenomena. The advantages of adopting such experimental signatures include high selection efficiency for signal, with relatively small and well-understood background processes as well.

During the Run 1 at the LHC, searches for  $Z'$  and CI with dilepton final states were performed by both the ATLAS and CMS experiments using  $20 \text{ fb}^{-1}$  data at  $\sqrt{s} = 8 \text{ TeV}$  [32, 33, 34]. The ATLAS collaboration set a lower mass limit on the  $Z'_{SSM}$  of 2.90 TeV at the 95% CL combining two channels. While for the CI, lower limit on the scale  $\Lambda$  were set ranging between 15.4 TeV and 26.3 TeV. The CMS collaboration set similar results for the corresponding models.

This chapter will describe the searches for  $Z'$  and CI based on  $36.1 \text{ fb}^{-1}$  data recorded at  $\sqrt{s} = 13 \text{ TeV}$ , which is the same amount of data sample as described in Section 5.2. The analysis strategy is to look for deviations (resonance or broad excess) from the reconstructed dilepton invariant mass ( $m_{ll}$ ) spectra in  $ee$  and  $\mu\mu$  channels. These

two channels are treated separately for physics analyzing and then combined together for statistical interpretation. The signal and background processes are mainly coming from simulation, except for the fake background in  $ee$  channel which is estimated using a data-driven approach. In the end, the exclusion limits are set on  $m_{Z'}$  ( $Z'$  mass) and  $\Lambda$  (CI scale) under the specific theory models for the occasion of no significant excess observed.

## 6.2 Monte Carlo Samples

### 6.2.1 Background samples

For this analysis, the dominant irreducible background is Drell-Yan process which is simulated with Powheg (NLO) [100] generator with PYTHIA8 [67] for event showering. In order to guarantee a smooth spectrum with enough statistics to the very high-mass phase space, the mass-binned samples are generated for truth  $m_{ll}$  between 120 GeV and  $>5$  TeV. While for region below 120 GeV, the inclusive Powheg Drell-Yan sample (as described in Table 5.1 with DCID of 361107) is adopted and merged together with the mass-binned ones by removing events with  $m_{ll} > 120$  GeV at the truth level. Higher order corrections (NNLO) are performed by applying the mass-dependent  $K$ -factors, which are calculated using VRAP 0.9 [119] and the CT14NNLO PDF set [120].

The other background like the  $t\bar{t}$  and single-top processes are modeled with the same samples adopted for  $H \rightarrow \mu\mu$  analysis, and the detailed information for the samples are already described in Section 5.2. The diboson processes ( $WW$ ,  $WZ$  and  $ZZ$ ) are simulated with SHERPA [69] with the CT10 PDF set [101] for a series of mass thresholds, so as to ensure a smooth spectrum for the entire mass region. For multi-jet and  $W$ +jets background, they are estimated using matrix element method for  $ee$  channel which will be described in Section 6.4. And for  $\mu\mu$  channel, their contributions are found to be negligible.

### 6.2.2 Signal samples

For the final statistical analysis,  $Z'$  signal templates for multiple mass points are needed. Therefore, a reweighting method is used for generating the templates with LO Drell-Yan samples. These LO Drell-Yan samples are simulated using PYTHIA8 [67] with the NNPDF23LO PDF set [99] and the ATLAS A14 set of tuned parameters [105] used

for event generation, parton showering and hadronization. The reweighting procedure is carried out on an event-by-event basis, and the desired  $Z'$  polemass or  $\Lambda$  value for CI, as well as the event born mass and the incoming quark flavour are taken as the inputs. Then for each event, the LO Feynman diagrams for Drell-Yan and BSM  $Z'$  (or CI) of choice are calculated respectively. And the ratio of these two are used as an event weight to transform Drell-Yan spectrum into the desired  $Z'$  (or CI) for a given polemass (or  $\Lambda$ ).

For validation of this reweighting method, dedicated  $Z'_\chi$  and CI signal samples are generated with the same generator and setup as LO Drell-Yan samples. Four mass points are produced for  $Z'_\chi$  signal: 2, 3, 4, and 5 TeV. While for CI, five benchmark values of  $\Lambda$  (10-30 TeV in 5 TeV steps) are generated for both the constructive and destructive interference scenarios.

Table 6.2.2 summarizes the information of the signal and background samples used for this analysis. After the generation, all these MC samples will pass through the GEANT4 [71] detector simulation and then will be reconstructed with the same software release as for processing data.

| Process                                                    | Generator     | Original Order | Corrected Order | Parton Shower | PDF       |
|------------------------------------------------------------|---------------|----------------|-----------------|---------------|-----------|
| $q\bar{q} \rightarrow Z/\gamma^* \rightarrow \ell^+\ell^-$ | POWHEG-BOX v2 | NLO            | NNLO            | PYTHIA8       | CT10      |
| $t\bar{t} \rightarrow \ell X, Wt \rightarrow X$            | POWHEG-BOX v2 | NLO            | NNLO            | PYTHIA6       | CT10      |
| $WW, WZ, ZZ \rightarrow \ell X/\ell\nu/\ell\ell$           | SHERPA 2.1.1  | NLO            | NLO             | SHERPA 2.1.1  | CT10      |
| $q\bar{q} \rightarrow Z/\gamma^* \rightarrow \ell^+\ell^-$ | PYTHIA8       | LO             | NNLO            | PYTHIA8       | NNPDF23LO |
| $q\bar{q} \rightarrow Z' \rightarrow \ell^+\ell^-$         | PYTHIA8       | LO             | NNLO            | PYTHIA8       | NNPDF23LO |
| CI: $q\bar{q} \rightarrow \ell^+\ell^-$                    | PYTHIA8       | LO             | NNLO            | PYTHIA8       | NNPDF23LO |

TABLE 6.1: Summary of the simulated signal and background processes used for this analysis.

### 6.3 Event Selection

Signal candidates are selected by requiring at least one pair of reconstructed same-flavour leptons ( $ee$  or  $\mu\mu$ ) with high  $p_T$  and at least one reconstructed  $pp$  interaction vertex, with the PV defined as the one with the largest value of  $\Sigma p_T^2$  for the associated tracks. Data samples are required to pass the GRL and also event cleaning as already described in Subsection 5.3.2. Afterwards, specific selection criteria are applied for the electron and muon channels respectively.

### 6.3.1 Electron channel

The trigger used for electron channel is dielectron trigger: 2e17\_lhloose. Electron candidate is required to pass  $E_T > 30$  GeV, and also satisfy  $|\eta| < 2.47$  (excluding crack region  $1.37 < |\eta| < 1.52$ ). And the electrons reconstructed from the bad calorimeters are removed. Besides, the candidate needs to fulfill the impact parameter related requirements:  $|d_0^{BL}/\sigma| < 5$  and  $|\Delta z_0 \sin \theta| < 0.5$  mm, with respect to the beam line. Furthermore, to reject background electrons originating from pile-up or hadron decays, “Loose” isolation WP is applied. While for electron identification, “Likelihood Medium” WP is adopted. Figure 6.1 depicts the electron identification efficiency of various WPs as a function of leading  $E_T$  for Drell-Yan (treated as signal) and Dijet (treated as background) samples respectively. “Likelihood Loose” and “Likelihood Medium” have shown similar signal selection efficiency, but “Likelihood Medium” shows more robust performance for rejecting fake electron.

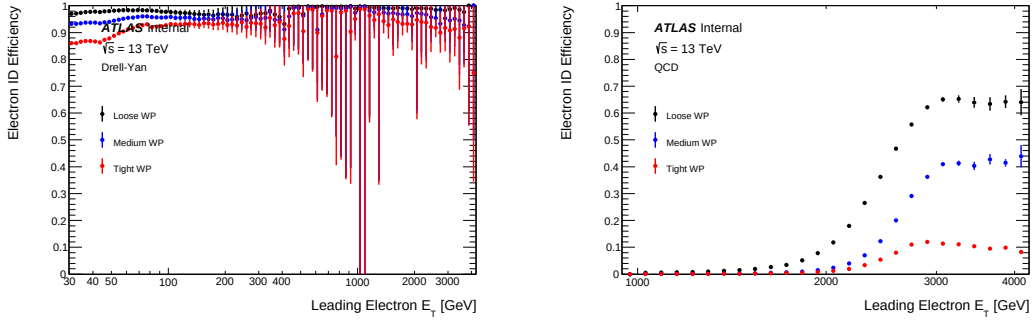


FIGURE 6.1: Electron identification efficiency of various WPs as a function of leading  $E_T$  for Drell-Yan (left) and Dijet samples (right).

After the electron level selection, a pair of electrons with the highest  $E_T$  is selected. In the end, we require the invariant mass of this pair  $m_{ee} > 80$  GeV. Overall, the selection efficiency for  $Z'_\chi$  (3 TeV) signal in  $ee$  channel is  $\sim 71\%$ .

### 6.3.2 Muon channel

Two single muon triggers are adopted for muon channel: mu26\_imedium OR mu50 for 2015 data while mu26\_ivarmedium OR mu50 for 2016 data. Muon candidate is required to be combined muon with  $p_T$  surpassing 30 GeV. Criteria related to impact

parameter are also applied:  $|d_0/\sigma| < 3$  and  $|\Delta z_0 \sin \theta| < 0.5$  mm, both calculated with respect to the beam line. Similar as the SM  $H \rightarrow \mu\mu$  analysis, “LooseTrackOnly” isolation WP is used for rejecting background muons.

Since this analysis is aimed to detect the very high-mass region, and in such extreme phase space much more stringent requirements for muon identification is needed to guarantee a relatively decent resolution for high  $p_T$  regime. Therefore, High- $p_T$  WP, described in Subsection 4.2.4 which is a dedicated design for high-mass resonance search from performance group, is used for muon candidate selection in this analysis. For this WP, a primary criterion is three stations in the MS. And by doing this, it can effectively increase the number of hits available to calculate the track’s curvature which is the dominant resource for resolution at the very high  $p_T$  region. The  $p_T$  resolution by applying the three stations requirements is improved by a factor of two comparing with the two-station muons as depicted in the left plot in Figure 6.2. The three-station criterion certainly causes additional loss of selection efficiency, which is  $\sim 20\%$  comparing with the two-station requirement. Nevertheless, it is still worth adopted considering the significant improvement for resolution. In addition, those MS chambers in poor alignment condition (BIS 7–8 and barrel-endcap transition region) are vetoed to make the  $Z'$  candidate selection more reliable. The right plot in Figure 6.2 shows the efficiency versus truth  $\eta$ - $\phi$  for muons with  $p_T > 500$  GeV and passing High- $p_T$  WP. And clearly we can see a geometry-dependent pattern for efficiency loss. The more detailed criteria for High- $p_T$  WP are summarized in Table 6.2.

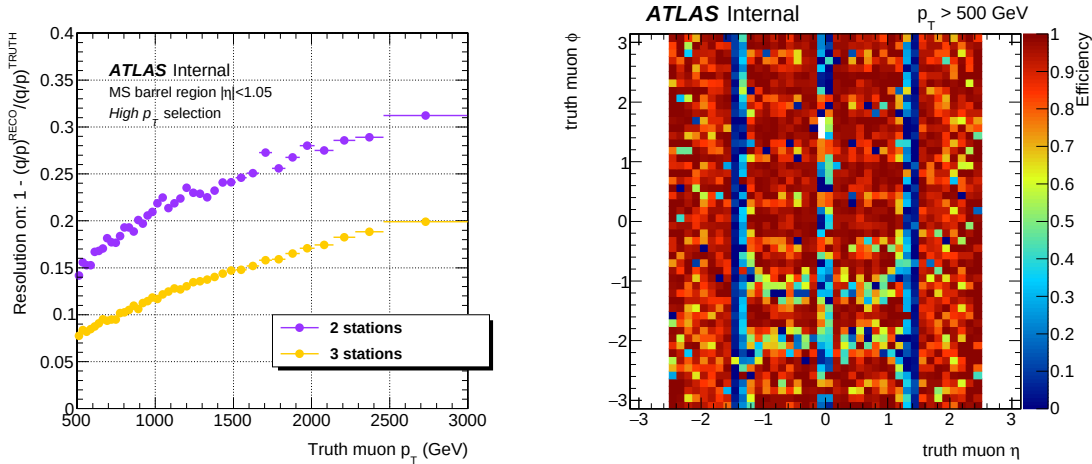


FIGURE 6.2: Resolution comparisons for two-station and three-station muons in the central region ( $|\eta| < 1.05$ ) (left); High- $p_T$  WP efficiency versus truth muon  $\eta$  and  $\phi$  for muons with  $p_T > 500$  GeV (right).

| Criterion                                                                                                                                                                                                                   |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 3 stations requirement: MS tracks has at least three hits in at least three precision layers of the MS                                                                                                                      |
| MS chamber vetoes: BIS 7-8 ( $1.3 <  \eta  < 1.5$ && ( $0.21 <  \phi  < 0.57$    $1.00 <  \phi  < 1.33$    $1.78 <  \phi  < 2.14$    $2.57 <  \phi  < 2.93$ );<br>barrel/endcap transition region ( $1.01 <  \eta  < 1.1$ ) |

 TABLE 6.2: Summary of the detailed criteria for the High- $p_T$  WP.

On top of the selection criteria above, a pair of muons with the highest  $p_T$  is selected, which need to have opposite charges as well. Afterwards, the invariant mass of this dimuon pair ( $m_{\mu\mu}$ ) needs to surpass 80 GeV. In the end, the selection efficiency for  $Z'_\chi$  (3 TeV) signal in muon channel is around 40%, much lower than that of the electron channel, which is mainly due to the High- $p_T$  WP requirement.

## 6.4 Background Estimation and Kinematic Distributions

### 6.4.1 Background estimation

For this analysis, the background contributions containing two real and prompt leptons in the final state are mainly coming from the Drell-Yan, top and diboson processes, which are modeled using the simulation samples as already described in Section 6.2.

This section is dedicated for estimation on the background resulting from the  $W$ +jets and multi-jets processes, for which one or more jets are reconstructed as “fake” leptons. For  $\mu\mu$  channel, such kind of contributions are negligible. While for  $ee$  channel, a data driven approach named “matrix method” is adopted, and this methodology is based on two sets of selection criteria: *tight* ( $T$ ) and *loose* ( $L$ ). Here *tight* selection is exactly the same as nominal selection described in Subsection 6.3.1 and *loose* selection differs from the *tight* one by using Loose identification WP and without isolation requirement.  $N_{tight}$  and  $N_{loose}$  denote the number of events passing these two sets of criteria respectively. Then two probabilities  $r$  (a real electron passing the *loose* selection fulfills the tight selection) and  $f$  (a jet passing the *loose* selection fulfills the tight selection) are estimated based on the equations below:

$$f = \frac{N_{tight}^{fake}}{N_{loose}^{fake}} \quad r = \frac{N_{tight}^{real}}{N_{loose}^{real}} \quad (6.1)$$



Here  $N_{tight}^{fake}$  ( $N_{loose}^{fake}$ ) denotes the number of jets passing the *tight* (*loose*) selection and  $N_{tight}^{real}$  ( $N_{loose}^{real}$ ) represents the corresponding numbers for real electrons.  $r$  is estimated by using the simulated Drell-Yan samples while  $f$  is estimated with the data samples triggered on the presence of a VeryLoose or Loose electron candidate and with suppressing criteria for  $W$  and  $Z$  bosons. And both  $r$  and  $f$  are determined in several slices of  $E_T$  and  $|\eta|$ . The selected pair of electrons can be sorted based on the identification criteria passed by the electrons, with  $N_{ab}$  ( $E_T^a > E_T^b$ ) used to represent this paired electrons. Equation 6.2 shows the relation between the measurable quantities ( $N_{TT}, N_{TL}, N_{LT}, N_{LL}$ ) and the “true” ones ( $N_{RR}, N_{RF}, N_{FR}, N_{FF}$ ) which can not be measured directly. The subscripts  $R$  and  $F$  here represent real electrons and fakes (jets) respectively.

$$\begin{pmatrix} N_{TT} \\ N_{TL} \\ N_{LT} \\ N_{LL} \end{pmatrix} = \begin{pmatrix} r^2 & rf & fr & f^2 \\ r(1-r) & r(1-f) & f(1-r) & f(1-f) \\ (1-r)r & (1-r)f & (1-f)r & (1-f)f \\ (1-r)^2 & (1-r)(1-f) & (1-f)(1-r) & (1-f)^2 \end{pmatrix} \begin{pmatrix} N_{RR} \\ N_{RF} \\ N_{FR} \\ N_{FF} \end{pmatrix} \quad (6.2)$$

For fakes estimation, the quantity of interest is  $N_{TT}$  which originates from a pair of objects containing at least one fake electron. And according to the relation depicted above, we can derive the corresponding contributions from the  $W$ +jets and Multi-jets individually as below:

$$\begin{aligned} N_{TT}^{W+jets} &= rf(N_{RF} + N_{FR}) \\ N_{TT}^{Multi-jets} &= f^2 N_{FF} \end{aligned} \quad (6.3)$$

To sum them together, we can get the final fake electron contributions:

$$N_{TT}^{W+jets\&Multi-jets} = rf(N_{RF} + N_{FR}) + f^2 N_{FF} \quad (6.4)$$

For this formula, the true quantities on the right hand side can be determined by inverting the matrix in Equation 6.2, which is shown as below:

$$\begin{pmatrix} N_{RR} \\ N_{RF} \\ N_{FR} \\ N_{FF} \end{pmatrix} = \frac{1}{(r-f)^2} \begin{pmatrix} (f-1)^2 & (f-1)f & f(f-1) & f^2 \\ (f-1)(1-r) & (1-f)r & f(1-r) & fr \\ (r-1)(1-f) & (1-r)f & r(1-f) & fr \\ (1-r)^2 & (r-1)r & r(r-1) & r^2 \end{pmatrix} \begin{pmatrix} N_{TT} \\ N_{TL} \\ N_{LT} \\ N_{LL} \end{pmatrix} \quad (6.5)$$

Then after the substitution, the estimation on the fakes can be written into the formula as below which purely relies on the measurable quantities.

$$\begin{aligned}
 N_{TT}^{W+jets\&Multi-jets} = & \alpha[2rf(f-1)(1-r) + f^2(1-r)^2]N_{TT} \\
 & + \alpha fr^2(1-f)(N_{TL} + N_{LT}) \\
 & + \alpha f^2 r^2 N_{LL}
 \end{aligned} \tag{6.6}$$

where

$$\alpha = \frac{1}{(r-f)^2}. \tag{6.7}$$

Due to the limited statistics in the high-mass region and also instable performance of matrix method in the  $Z$  peak region, the estimation on the fakes is extrapolated for the full mass range by using an analytic function to fit the  $m_{ee}$  spectrum above  $\sim 125$  GeV. Various fits are performed, and the weighted mean of all the fits is used as the central value for estimation while the envelope is taken as the related uncertainty. Other uncertainties are evaluated by taking into account the differences between the estimation for events with same-charge and opposite-charge electrons as well as by varying the probability value  $r$ . All these uncertainties are treated uncorrelated and added in quadrature to get the final uncertainty. In the end, Figure 6.3 depicts the  $m_{ee}$  distribution of the fake background estimated with the matrix method, with the corresponding systematic uncertainties shown as well.

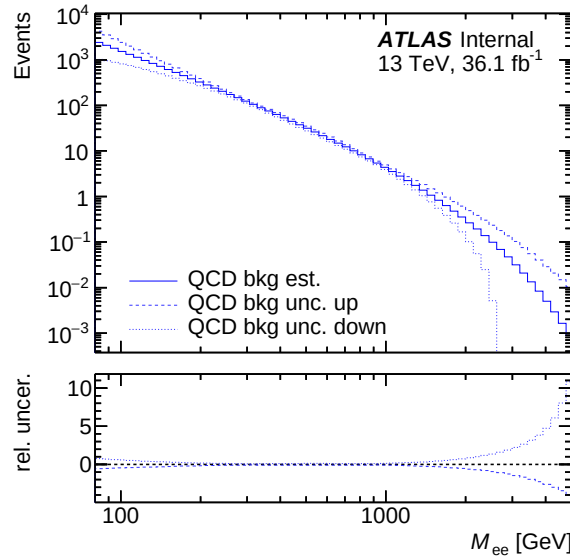


FIGURE 6.3: Distribution of fake background estimation (derived using matrix method) together with its systematic uncertainties.

### 6.4.2 Kinematic distributions

In this subsection, selected kinematic variables are checked to compare the data and SM predictions in the phase space with the complete event selection criteria applied. Figure 6.4 depicts the  $p_T$ ,  $\eta$  and  $\phi$  distributions for electrons and muons after further requiring  $m_{ll} > 120$  GeV on top of the signal selection criteria. The reason of applying an additional  $m_{ll}$  threshold is due to the  $p_T$  mismodeling issue of Powheg Drell-Yan samples in the on-shell  $Z$  region. Generally decent agreement is observed for the data and predictions. And the features in muon  $\eta$  and  $\phi$  distributions reflect the cut effect of High- $p_T$  WP described in Subsection 6.3.2.

Figure 6.5 shows the dilepton invariant mass distributions for electron and muon channel after the general signal selection requirements. There is no significant data excess observed over the background spectra in two channels.

The event yields for the predicted background and data are calculated in different  $m_{ll}$  intervals beyond 400 GeV for both electron and muon channels, as shown in Table 6.3 and Table 6.4 respectively. The total background generally shows consistent numbers with the observed data in two channels.

| $m_{ee}$ [GeV]         | 400–500        | 500–700        | 700–900      | 900–1200       | 1200–1800     | 1800–3000       | 3000–6000         |
|------------------------|----------------|----------------|--------------|----------------|---------------|-----------------|-------------------|
| Drell–Yan              | $2640 \pm 180$ | $1620 \pm 120$ | $421 \pm 34$ | $176 \pm 17$   | $62 \pm 7$    | $8.7 \pm 1.3$   | $0.34 \pm 0.07$   |
| Top quarks             | $1130 \pm 80$  | $560 \pm 40$   | $94 \pm 8$   | $27.9 \pm 2.8$ | $5.1 \pm 0.7$ | $< 0.001$       | $< 0.001$         |
| Dibosons               | $228 \pm 25$   | $146 \pm 16$   | $39 \pm 4$   | $16.9 \pm 2.1$ | $5.8 \pm 0.8$ | $0.74 \pm 0.11$ | $0.028 \pm 0.004$ |
| $W$ +jets & Multi-jets | $151 \pm 21$   | $113 \pm 17$   | $39 \pm 6$   | $16.1 \pm 2.0$ | $7.9 \pm 2.3$ | $1.6 \pm 1.2$   | $0.08 \pm 0.27$   |
| Total background       | $4150 \pm 200$ | $2440 \pm 130$ | $590 \pm 40$ | $237 \pm 17$   | $81 \pm 7$    | $11.0 \pm 1.8$  | $0.45 \pm 0.28$   |
| Data                   | 4140           | 2390           | 589          | 209            | 61            | 10              | 0                 |

TABLE 6.3: Event yields for the background and data calculated in different  $m_{ll}$  intervals beyond 400 GeV for electron channel. The errors quoted represent the total uncertainties including statistical, theoretical and experimental systematic uncertainties.

| $m_{\mu\mu}$ [GeV] | 400–500        | 500–700       | 700–900        | 900–1200       | 1200–1800     | 1800–3000       | 3000–6000           |
|--------------------|----------------|---------------|----------------|----------------|---------------|-----------------|---------------------|
| Drell–Yan          | $1770 \pm 120$ | $1060 \pm 80$ | $263 \pm 23$   | $110 \pm 11$   | $37 \pm 4$    | $5.4 \pm 0.8$   | $0.30 \pm 0.07$     |
| Top quarks         | $830 \pm 70$   | $401 \pm 33$  | $68 \pm 6$     | $24.5 \pm 3.0$ | $5.3 \pm 0.9$ | $0.11 \pm 0.08$ | $< 0.001$           |
| Dibosons           | $155 \pm 17$   | $93 \pm 11$   | $24.3 \pm 2.9$ | $9.8 \pm 1.2$  | $3.2 \pm 0.4$ | $0.45 \pm 0.07$ | $0.0184 \pm 0.0035$ |
| Total background   | $2760 \pm 140$ | $1550 \pm 90$ | $355 \pm 24$   | $144 \pm 11$   | $45 \pm 4$    | $6.0 \pm 0.8$   | $0.32 \pm 0.07$     |
| Data               | 2766           | 1532          | 322            | 141            | 48            | 4               | 0                   |

TABLE 6.4: Event yields for the background and data calculated in different  $m_{ll}$  intervals beyond 400 GeV for muon channel. The errors quoted represent the total uncertainties including statistical, theoretical and experimental systematic uncertainties.

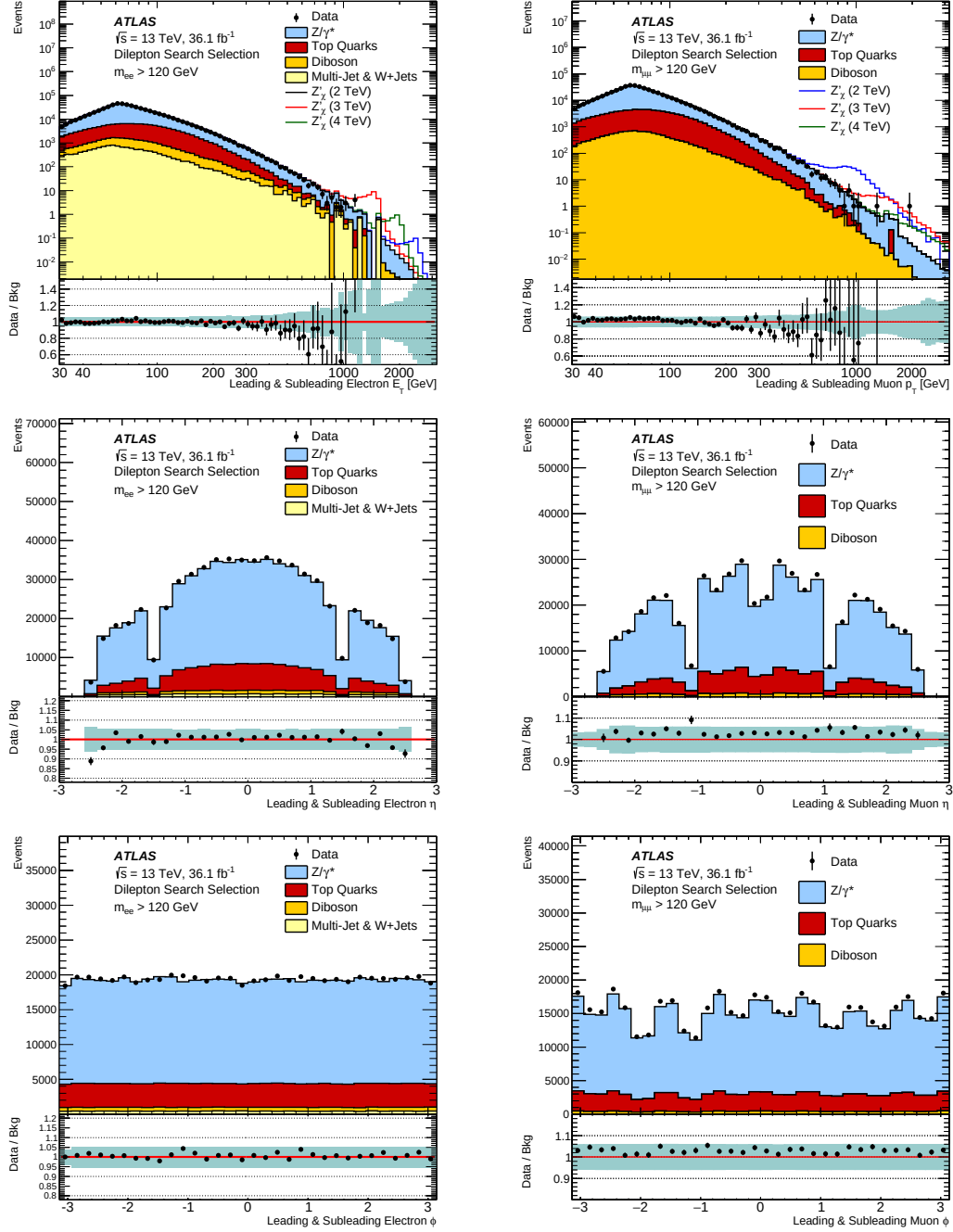


FIGURE 6.4: Distributions of  $p_T$  (top),  $\eta$  (middle) and  $\phi$  (bottom) for the electrons (left) and muons (right) after applying signal selection criteria with additional  $m_{\ell\ell} > 120$  GeV requirement. The shaded band in the lower panel illustrates the total systematic uncertainty.

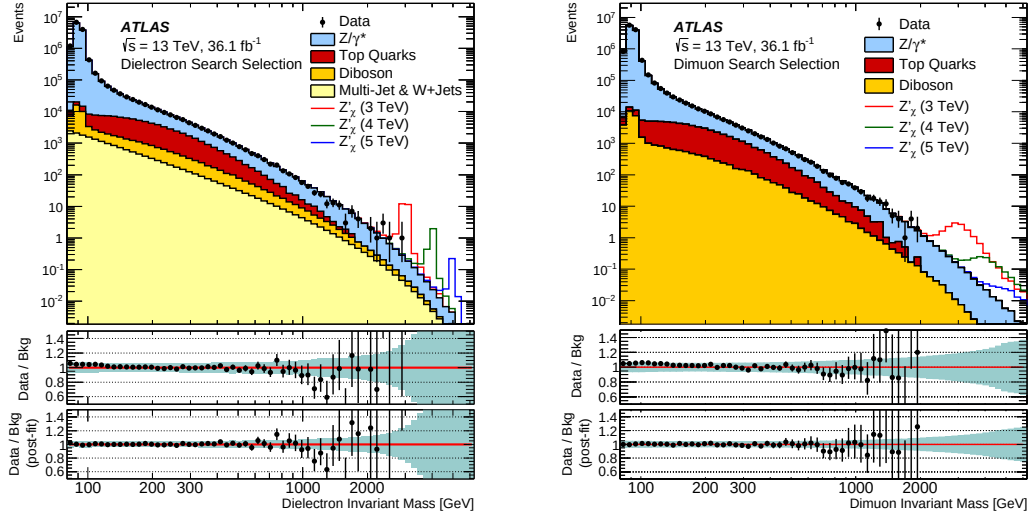


FIGURE 6.5: Distributions of dielectron (left) and dimuon (right) invariant mass after applying signal selection criteria. The bin width of the spectra is constant in  $\log(m_{ll})$  while the total systematic uncertainty is shown in the shaded band.

The highest  $m_{ll}$  event for electron channel is 2.90 TeV while for muon channel it is 1.99 TeV. Figure 6.6 shows the event displays for these two selected events. For the dielectron event, there are two additional jets besides the two selected electron candidates. While for the dimuon event, a third muon is found to be existing as well as a relatively large  $E_T^{miss}$ . Therefore neither of these two high-mass events is a good candidate for  $Z'$  signal.

## 6.5 Systematic Uncertainties

For this analysis, systematic uncertainties play non-trivial roles, which are treated as nuisance parameters for the final statistical interpretation (described in Section 6.6). The systematic uncertainties considered contain both theoretical and experimental uncertainties on the total background as well as the experimental uncertainties on the signal. All these corresponding uncertainties are estimated as a function of  $m_{ll}$ . For each source of systematic uncertainty, the larger value between the up and down variations is adopted, and in the end we can get a symmetric and  $m_{ll}$ -dependent variation shape which is used for the statistical analysis later.

Theoretical uncertainties on the background prediction originate from the eigenvector variations of PDF, together with variations of PDF scale, the strong coupling ( $\alpha_s$ ),

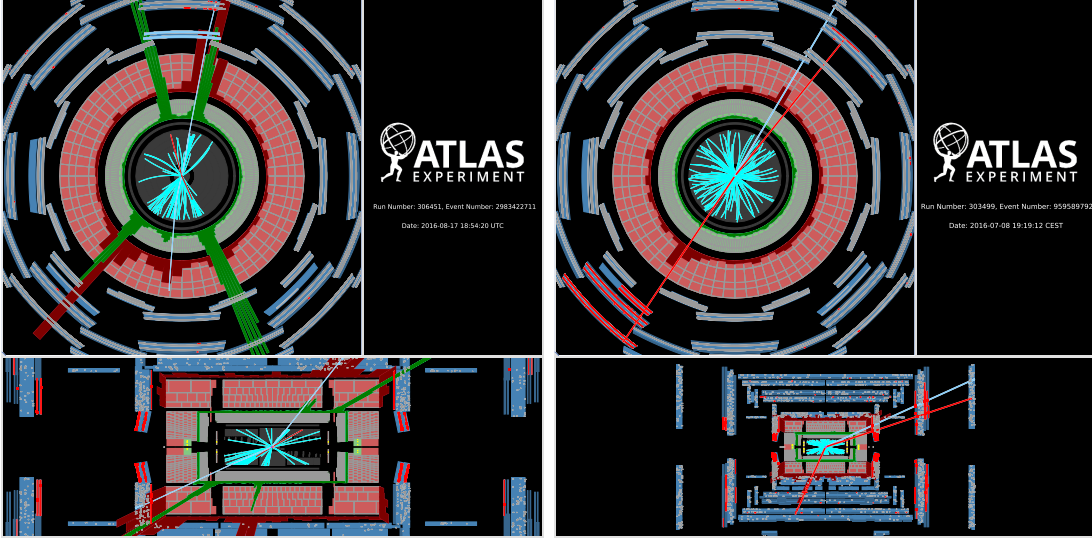


FIGURE 6.6: Event displays for the highest  $m_{ll}$  events in  $ee$  (left) and  $\mu\mu$  (right) channels. Green and red towers represent energy deposition in the cells of the EM and tile calorimeter respectively. Red lines illustrate the reconstructed ID tracks associated with the selected electron candidates. Cyan lines represent the other tracks with  $E_T > 2$  GeV, including the tracks coming from pile-up effect. For the dielectron event, the leading electron has an  $E_T$  of 841 GeV, an  $\eta$  of -1.26 and a  $\phi$  of -1.15, while the subleading one has an  $E_T$  of 655 GeV, an  $\eta$  of 1.32 and a  $\phi$  of 1.83. For the dimuon event, the leading muon has a  $p_T$  of 636 GeV, an  $\eta$  of -0.43 and a  $\phi$  of -2.16 while the subleading muon has a  $p_T$  of 545 GeV, an  $\eta$  of 1.81 and a  $\phi$  of 0.90. The additional muon has a  $p_T$  of 145 GeV and the missing transverse energy of this event is 109 GeV.

EW corrections, photon-induced (PI) corrections as well as PDF choices. The PDF variation uncertainty is estimated using a re-diagonalised set of 7 PDF eigenvectors [120] which are orthogonal between the  $W$  and  $Z$  bosons and treated as separate nuisance parameters. In the end, PDF variation is one of the largest theoretical uncertainty sources for this analysis. Figure 6.7 depicts the PDF variation related uncertainty as shown in solid grey lines, which is quite large in the very high-mass region. And this might be potentially a limitation factor for the future sensitivity improvement.

The VRAP [119] is used to estimate PDF scales and  $\alpha_S$  variation uncertainties. For scale uncertainty, it is assessed by varying the nominal CT14NNLO PDF [120] renormalization and factorization scales by a factor of two. While  $\alpha_S$  uncertainty is estimated by using the nominal value of 0.118 with a variation of  $\pm 0.003$ . The EW correction related uncertainty is calculated by comparing the nominal additive  $(1 + \delta_{EW} + \delta_{QCD})$  treatment with the multiplicative approximation  $((1 + \delta_{EW})(1 + \delta_{QCD}))$  treatment of the EW correction in the combination of the higher-order EW and QCD effects. The PI correction uncertainty is computed based on the quark masses and the photon PDF related uncertainties. Besides, the uncertainty arising from the PDF choice is estimated with

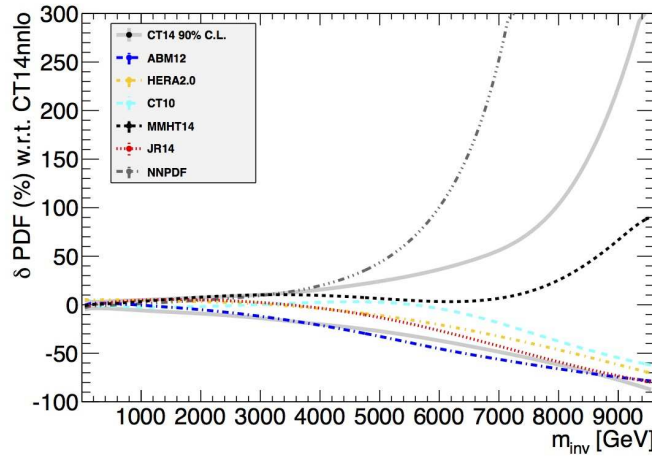


FIGURE 6.7: Asymmetric uncertainty on the Drell-Yan cross section as a function of  $m_{ll}$  due to the PDF eigenvector variations shown in two solid grey lines, with other possible PDF choices overlayed.

the recommendations from Ref. [121], by comparing the central values of CT14NNLO, MMHT14 [122] and NNPDF3.0 [123], and the maximum absolute deviation from the envelope of their comparisons is taken into account as the uncertainty on PDF choice.

The experimental uncertainties considered include lepton trigger, isolation, identification and reconstruction efficiency, together with the lepton energy and momentum scale and resolution. These related uncertainties are provided by the official recommendations of performance groups. For the  $ee$  channel, the identification uncertainty effect is 2.0%, which is independent of  $E_T$  when it goes beyond 150 GeV. And a relatively large uncertainty arising from the isolation is due to the calorimeter-based isolation variable adopted for electrons. Also as described in Subsection 6.4.1, the uncertainty on the fakes estimation for electron channel is considered by varying the extrapolation method as well as the probability value.

While for the  $\mu\mu$  channel, the largest uncertainty comes from the muon reconstruction efficiency, which includes the uncertainty obtained from  $Z \rightarrow \mu\mu$  data studies and a high- $p_T$  extrapolation uncertainty. And muon momentum resolution uncertainty is estimated in certain data-taking periods with no magnetic field applied in the MS system. Besides the lepton related uncertainties above, the uncertainty due to the pile-up effect is derived by applying a variation in the reweighting of MC events, which can cover the uncertainty on the ratio of the predicted and measured inelastic cross-section within the fiducial volume of  $m_X > 13$  GeV ( $m_X$  is the mass of the non-diffractive hadronic system) [124]. The uncertainty on the total integrated luminosity in 2015 and 2016 is 3.2%

| Source                           | Dielectron channel [%] |             | Dimuon channel [%] |             |
|----------------------------------|------------------------|-------------|--------------------|-------------|
|                                  | Signal                 | Background  | Signal             | Background  |
| Luminosity                       | 3.2 (3.2)              | 3.2 (3.2)   | 3.2 (3.2)          | 3.2 (3.2)   |
| MC statistical                   | <1.0 (<1.0)            | <1.0 (<1.0) | <1.0 (<1.0)        | <1.0 (<1.0) |
| Beam energy                      | 2.0 (4.1)              | 2.0 (4.1)   | 1.9 (3.1)          | 1.9 (3.1)   |
| Pile-up effects                  | <1.0 (<1.0)            | <1.0 (<1.0) | <1.0 (<1.0)        | <1.0 (<1.0) |
| DY PDF choice                    | N/A                    | <1.0 (8.4)  | N/A                | <1.0 (1.9)  |
| DY PDF variation                 | N/A                    | 8.7 (19)    | N/A                | 7.7 (13)    |
| DY PDF scales                    | N/A                    | 1.0 (2.0)   | N/A                | <1.0 (1.5)  |
| DY $\alpha_s$                    | N/A                    | 1.6 (2.7)   | N/A                | 1.4 (2.2)   |
| DY EW corrections                | N/A                    | 2.4 (5.5)   | N/A                | 2.1 (3.9)   |
| DY $\gamma$ -induced corrections | N/A                    | 3.4 (7.6)   | N/A                | 3.0 (5.4)   |
| Top quarks theoretical           | N/A                    | <1.0 (<1.0) | N/A                | <1.0 (<1.0) |
| Dibosons theoretical             | N/A                    | <1.0 (<1.0) | N/A                | <1.0 (<1.0) |
| Reconstruction efficiency        | <1.0 (<1.0)            | <1.0 (<1.0) | 10 (17)            | 10 (17)     |
| Isolation efficiency             | 9.1 (9.7)              | 9.1 (9.7)   | 1.8 (2.0)          | 1.8 (2.0)   |
| Trigger efficiency               | <1.0 (<1.0)            | <1.0 (<1.0) | <1.0 (<1.0)        | <1.0 (<1.0) |
| Identification efficiency        | 2.6 (2.4)              | 2.6 (2.4)   | N/A                | N/A         |
| Lepton energy scale              | <1.0 (<1.0)            | 4.1 (6.1)   | <1.0 (<1.0)        | <1.0 (<1.0) |
| Lepton energy resolution         | <1.0 (<1.0)            | <1.0 (<1.0) | 2.7 (2.7)          | <1.0 (6.7)  |
| Multi-jet & $W$ +jets            | N/A                    | 10 (129)    | N/A                | N/A         |
| Total                            | 10 (11)                | 18 (132)    | 11 (18)            | 14 (24)     |

TABLE 6.5: Summary of the relative systematic uncertainties in the expected number of events at  $m_{ll}$  of 2 TeV and 4 TeV. The values quoted in parenthesis correspond to  $m_{ll} = 4$  TeV. The values shown for the background represent the relative variations in the total expected number of events in the corresponding  $m_{ll}$  histogram bin containing the reconstructed  $m_{ll}$  mass of 2 TeV (4 TeV). For the signal uncertainties the values are derived using the  $Z'_\chi$  signal model with a pole mass of 2 TeV (4 TeV) by comparing yields around the mass peak (within the full width at half maximum) between the spectrum varied due to a given uncertainty and the nominal spectrum. “N/A” represents cases where the uncertainty is not applicable.

while the beam energy uncertainty is 0.65%.

Table 6.5 summarizes the systematic uncertainties quantitatively at  $m_{ll}$  of 2 and 4 TeV.

## 6.6 Statistical Analysis

This section will describe the statistical interpretation for this search. A frequentist-based method (log-likelihood ratio test) is used to search for any data excess in the  $m_{ll}$



spectra. And in the absence of any significant bumps, a Bayesian approach is adopted to set the exclusion limits on related POI for the corresponding theory models.

### 6.6.1 Log-likelihood ratio test

The log-likelihood ratio (LLR) test [116] is utilized to search for data excess and provide the corresponding local and global significance. Similarly as described in Section 5.7, the likelihood function is defined by taking the product of per-bin likelihood across the  $m_{ll}$  distribution. To quantify the importance of an excess,  $p$ -value ( $p_0$ ) is adopted, which represents the probability that the background fluctuation creates an equal or larger excess as observed. For simplicity, the  $p_0$  values can be transformed into an equivalent significance  $Z$ , which is defined in a way that a Gaussian distributed variable with  $Z$  standard deviations above its mean value has an upper-tail probability equal to  $p_0$ . The relation between  $p_0$  and  $Z$  can be described as below:

$$Z = \Phi^{-1}(1 - p_0), \quad (6.8)$$

where  $\Phi^{-1}$  is the inverse of the cumulative function for the standard Gaussian. Hence, for the background-only hypothesis, the probability to have an excess with  $5\sigma$  significance ( $Z = 5$ ) is  $p_0 = 2.87 \times 10^{-7}$ . And by convention,  $5\sigma$  is the desired significance value for claiming a discovery in the particle physics.

To calculate  $p_0$ , the corresponding test statistic is constructed as below:

$$q_0 = \begin{cases} +2 \ln \frac{\mathcal{L}(\text{data}|0, \hat{\theta}_0)}{\mathcal{L}(\text{data}|\hat{\mu}, \hat{\theta})} & \text{for } \hat{\mu} < 0. \\ -2 \ln \frac{\mathcal{L}(\text{data}|0, \hat{\theta}_0)}{\mathcal{L}(\text{data}|\hat{\mu}, \hat{\theta})} & \text{for } \hat{\mu} \geq 0. \end{cases} \quad (6.9)$$

Based on frequentist, the background-only toys can be generated using the nuisance parameter  $\hat{\theta}_0^{obs}$  and events following the Poisson distribution. And then a PDF  $f(q_0|0, \hat{\theta}_0^{obs})$  is built from the generated toys. Afterwards, we can evaluate the probability  $p_0$  for a certain observation value  $q_0^{obs}$  as the equation below:

$$p_0 = P(q_0 \geq q_0^{obs} | \text{background-only}) = \int_{q_0^{obs}}^{\infty} f(q_0|0, \hat{\theta}_0^{obs}) dq_0 \quad (6.10)$$

To save the computing time and resource, we adopt the asymptotic approximation method and simply calculate  $p_0$  from  $q_0$  following the expression below:

$$p_0 = 1 - \Phi(\sqrt{q_0}) \quad (6.11)$$

And the significance can be calculated accordingly:

$$Z = \sqrt{q_0}. \quad (6.12)$$

In general, we need to take into account the “look elsewhere effect” [125] when quantifying a data excess and calculate the so-called global  $p$ -value. This is the probability of finding a fluctuation with a local  $p$ -value equal or lower than the minimum local  $p$ -value observed anywhere in the explored  $m_{ll}$  range. Based on asymptotic relations, we can calculate the global  $p$ -value following the equation below:

$$p_{\text{global}} = P(q(\hat{\theta}) \geq c) \leq P(\chi^2 > c) + \langle N(c_0) \rangle e^{-(c-c_0)/2}, \quad (6.13)$$

where  $c$  is the observed value of the test statistic  $q_0$  while  $c_0$  is a certain reference value. For the right hand side of Equation 6.13, the first term denotes the local  $p$ -value from an expression of Wilks’ theorem [126] for one degree of freedom, and the second term quantifies the look elsewhere effect by introducing the  $\langle N(c_0) \rangle$  which is defined as the average number of upcrossings of  $q_0$  for the level  $c_0$ . Due to the look elsewhere effect, to claim an evidence with  $3\sigma$  global significance, generally we need a data excess with a local significance surpassing  $4.4\sigma$ .

### 6.6.2 Exclusion limits with Bayesian approach

With the LLR test as described above, if there is no significant excess observed, exclusion limits on the POIs ( $\Theta$ ) are set for specific theory models by adopting the Bayesian approach for this analysis. We can write the number of total expected events  $\mu$  (passing signal selection criteria) into the formula below:

$$\mu = n_s(\Theta, \bar{\Omega}) + n_b(\bar{\Omega}) \quad (6.14)$$

Here  $n_s(\Theta, \bar{\Omega})$  denotes the number of signal events predicted by the PYTHIA8 [67]  $Z'$  or CI MC for a certain choice of model parameter  $\Theta$ . And  $\Theta$  represents the choice of  $Z'$  polemass for the resonance case, or the energy scale  $\Lambda$  and interference parameter

$\eta_{LL}$  for the CI case.  $n_b(\bar{\Omega})$  is the number of total background events.  $\bar{\Omega}$  in the signal and background terms depict the set of Gaussian nuisance parameters that account for the systematic uncertainties on the number of expected signal and background events respectively.

Then similarly as described in the previous section, the likelihood can be constructed by taking the product of the Poisson probabilities for each  $m_{ll}$  bin  $k$  in each channel  $l$ , which is shown below:

$$\mathcal{L}(n | \Theta, \bar{\Omega}) = \prod_{l=1}^{N_{channel}} \prod_{k=1}^{N_{bin}} \frac{\mu_{lk}^{n_{lk}} e^{-\mu_{lk}}}{n_{lk}!}, \quad (6.15)$$

here  $n_{lk}$  and  $\mu_{lk}$  represent the corresponding number of events for observation (data) and prediction (expressed in Equation 6.14) respectively.

Furthermore based on Bayes' theorem and likelihood Equation 6.15, the posterior probability can be written as:

$$\mathcal{P}(\Theta | n) = \frac{1}{\mathcal{Z}} \mathcal{L}_{\mathcal{M}}(n | \Theta) P(\Theta) \quad (6.16)$$

For this equation,  $\mathcal{Z}$  corresponds to a normalization constant while the marginalized likelihood  $\mathcal{L}_{\mathcal{M}}$  is the likelihood after all nuisance parameters integrated out based on the assumption that they are correlated across all the bins.  $P(\Theta)$  denotes the prior probability which is chosen to be uniform and positive in the cross-section for the  $Z'$  search. Then the 95% CL limit can be obtained by searching for a value  $\Theta_{lim}$  satisfying  $\int_0^{\Theta_{lim}} \mathcal{P}(\Theta | n) d\Theta = 0.95$ . And  $\Theta_{lim}$  can be transformed into either lower limit on  $Z'$  mass or lower limit on CI scale  $\Lambda$  for the corresponding models. The Bayesian Analysis Toolkit (BAT) [127] is adopted for the limits calculation, with a Markov Chain Monte Carlo technique utilised for the nuisance parameters integration.

## 6.7 Results

As described in Section 6.6, first the LLR tests are performed to search for any significant deviations in the data comparing with the predictions. Figure 6.8 shows the local and global  $p$ -value as function of the  $Z'$  polemass for individual channel as well as the results by combining two channels. The largest deviation observed is around 2.37 TeV

in  $ee$  channel with a local significance value of  $2.5\sigma$ . But after taking into account the look elsewhere effect, this excess is not really significant.

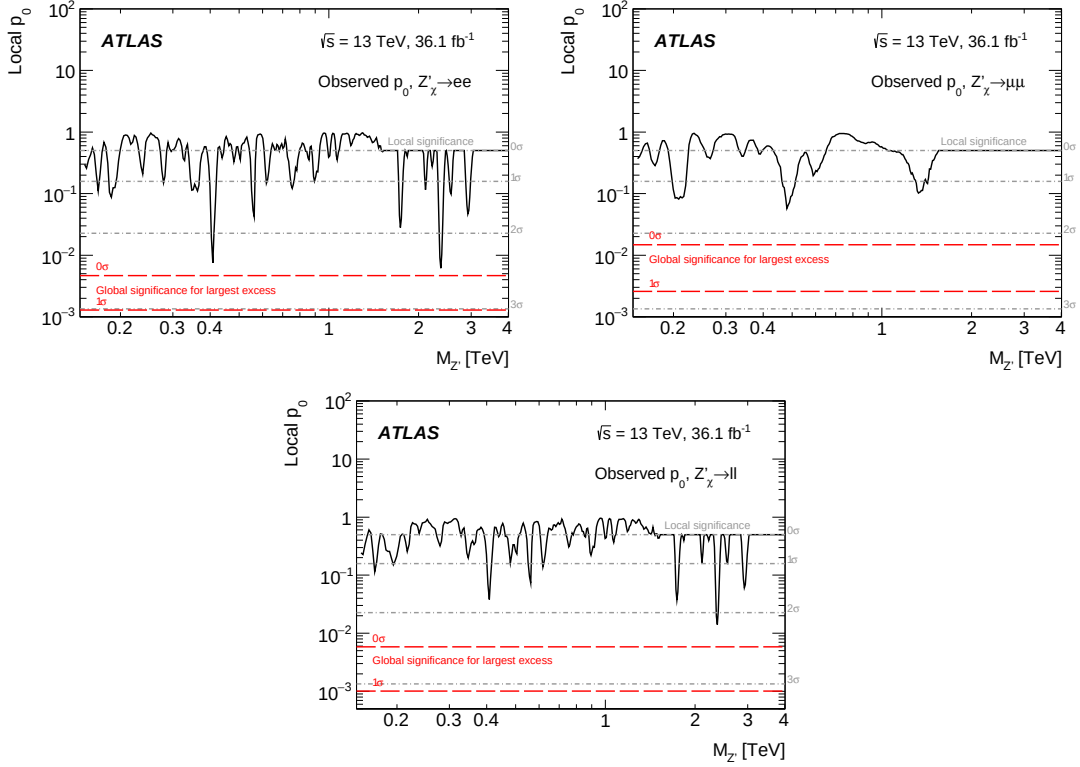


FIGURE 6.8: Local and global  $p$ -value as a function of  $Z'$  polemass in  $ee$  (top left),  $\mu\mu$  (top right) and combined channels (bottom).

Since there is no clear evidence for the observation of any new physics, the exclusion limits are set for the specific models at the 95% CL. Figure 6.9 depicts the upper limits on the  $Z'$  cross section times branching ratio ( $\sigma B$ ) as a function of  $Z'$  polemass in  $ee$ ,  $\mu\mu$  and combined channels. Then the lower limits on  $Z'$  mass can be derived for different theory models, which are summarized in Table 6.6. Specifically, by combining two channels, the mass below 4.5 TeV is excluded at the 95% CL for  $Z'_{SSM}$ , 4.1 TeV for  $Z'_\chi$ , and 3.8 TeV for  $Z'_\psi$  [35]. Comparing with the Run 1 results [32], which is 2.90 TeV for  $Z'_{SSM}$ , the sensitivity gained at the Run 2 is significantly improved. The CMS collaboration has also performed a search of narrow resonances with the dilepton final states and set the lower mass limits on  $Z'_{SSM}$  and  $Z'_\psi$  to be 4.50 TeV and 3.90 TeV [128], which are consistent with our results.

Then for the CI, Figure 6.10 shows lower limits on the energy scale  $\Lambda$  for the LL, LR, RL and RR CI models in the constructive and destructive interference scenarios at

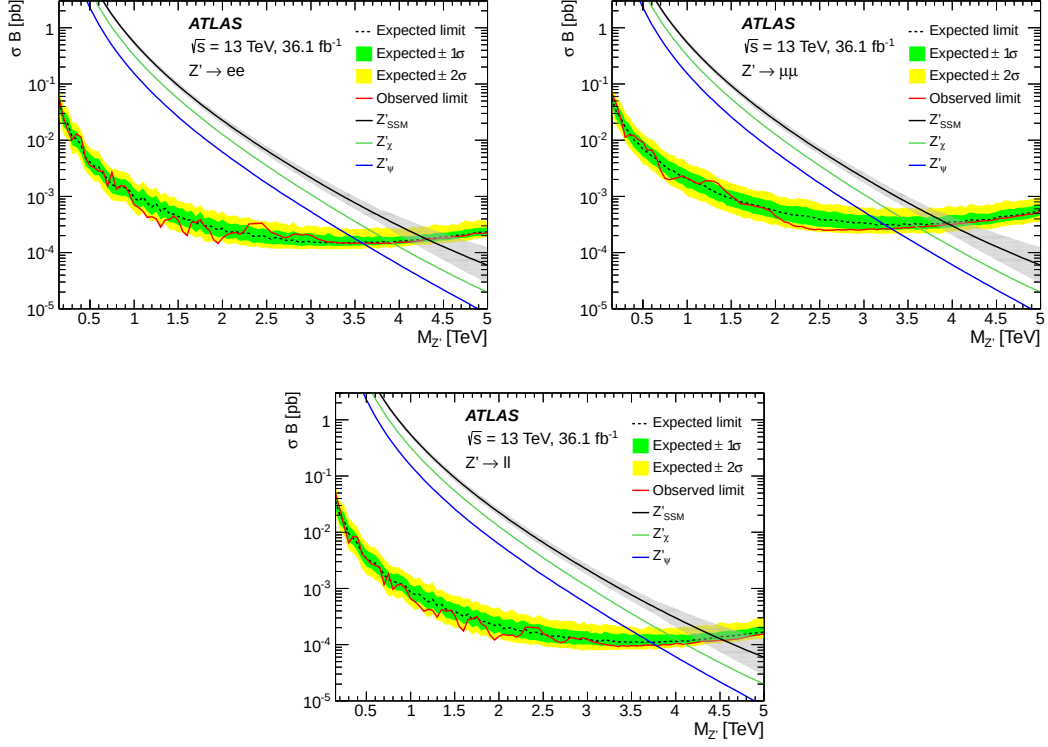


FIGURE 6.9: Observed and expected 95% CL upper limits on  $Z'$  cross section times branching ratio ( $\sigma B$ ) as a function of  $Z'$  polemass in  $ee$  (top left),  $\mu\mu$  (top right) and combined channels (bottom).

| Model             | Width [%] | $\theta_{E_6}$ [rad] | Lower limits on $m_{Z'}$ [TeV] |     |          |     |            |     |
|-------------------|-----------|----------------------|--------------------------------|-----|----------|-----|------------|-----|
|                   |           |                      | $ee$                           |     | $\mu\mu$ |     | $\ell\ell$ |     |
|                   |           |                      | Obs                            | Exp | Obs      | Exp | Obs        | Exp |
| $Z'_{\text{SSM}}$ | 3.0       | -                    | 4.3                            | 4.3 | 4.0      | 3.9 | 4.5        | 4.5 |
| $Z'_{\chi}$       | 1.2       | $0.50 \pi$           | 3.9                            | 3.9 | 3.6      | 3.6 | 4.1        | 4.0 |
| $Z'_S$            | 1.2       | $0.63 \pi$           | 3.9                            | 3.8 | 3.6      | 3.5 | 4.0        | 4.0 |
| $Z'_I$            | 1.1       | $0.71 \pi$           | 3.8                            | 3.8 | 3.5      | 3.4 | 4.0        | 3.9 |
| $Z'_\eta$         | 0.6       | $0.21 \pi$           | 3.7                            | 3.7 | 3.4      | 3.3 | 3.9        | 3.8 |
| $Z'_N$            | 0.6       | $-0.08 \pi$          | 3.6                            | 3.6 | 3.4      | 3.3 | 3.8        | 3.8 |
| $Z'_\psi$         | 0.5       | $0 \pi$              | 3.6                            | 3.6 | 3.3      | 3.2 | 3.8        | 3.7 |

TABLE 6.6: Observed and expected 95% CL lower mass limits for various  $Z'$  theory models.

the 95% CL. Table 6.7 summarizes the quantitative limit numbers for various models, ranging between 24 TeV and 40 TeV [35].

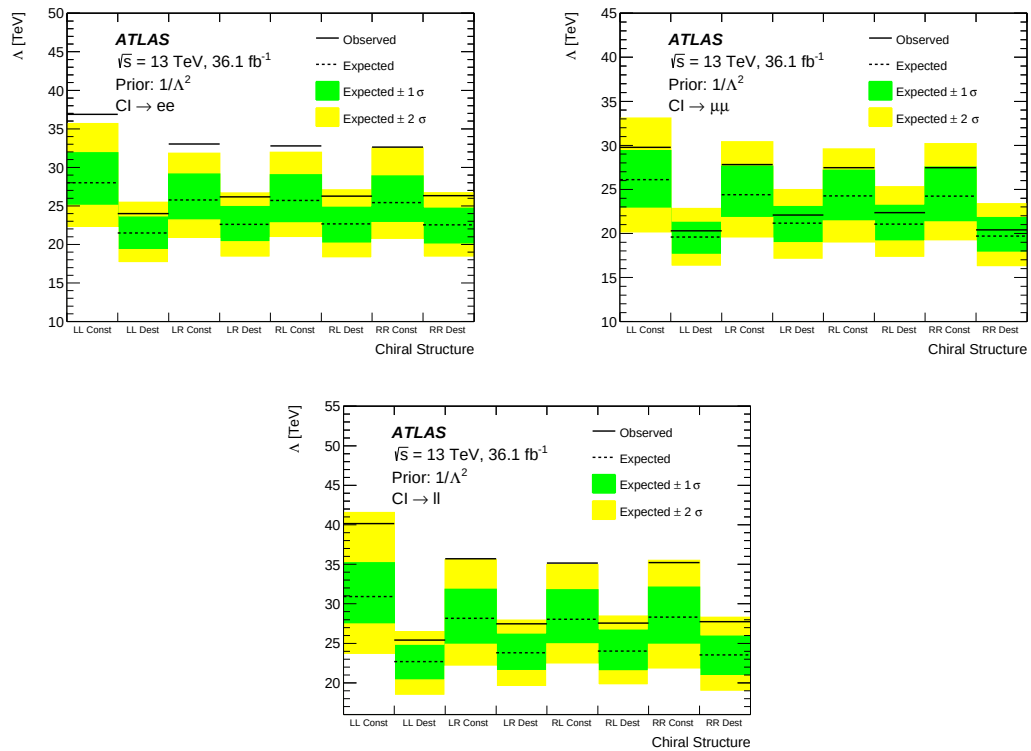


FIGURE 6.10: Observed and expected 95% CL lower limits on the CI energy scale  $\Lambda$  for various models with constructive (const) and destructive (dest) interference in  $ee$  (top left),  $\mu\mu$  (top right) and combined channels (bottom).

| Channel                            | Prior         | Lower limits on $\Lambda$ [TeV] |              |              |              |              |              |              |              |
|------------------------------------|---------------|---------------------------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
|                                    |               | Left–Left                       |              | Left–Right   |              | Right–Left   |              | Right–Right  |              |
|                                    |               | Const                           | Dest         | Const        | Dest         | Const        | Dest         | Const        | Dest         |
| Obs: $ee$<br>Exp: $ee$             | $1/\Lambda^2$ | 36.9<br>28.0                    | 24.0<br>21.5 | 33.0<br>25.8 | 26.1<br>22.6 | 32.8<br>25.7 | 26.3<br>22.7 | 32.6<br>25.4 | 26.3<br>22.5 |
| Obs: $ee$<br>Exp: $ee$             | $1/\Lambda^4$ | 31.7<br>25.7                    | 22.3<br>19.9 | 28.9<br>23.9 | 24.0<br>21.2 | 28.6<br>23.8 | 24.1<br>21.2 | 28.7<br>23.6 | 24.1<br>21.0 |
| Obs: $\mu\mu$<br>Exp: $\mu\mu$     | $1/\Lambda^2$ | 29.8<br>26.1                    | 20.3<br>19.6 | 27.8<br>24.4 | 22.0<br>21.2 | 27.5<br>24.3 | 22.4<br>21.0 | 27.5<br>24.2 | 20.4<br>19.7 |
| Obs: $\mu\mu$<br>Exp: $\mu\mu$     | $1/\Lambda^4$ | 26.7<br>23.8                    | 18.9<br>18.4 | 25.1<br>22.5 | 20.7<br>19.7 | 25.0<br>22.4 | 20.9<br>19.8 | 24.9<br>22.2 | 19.0<br>18.4 |
| Obs: $\ell\ell$<br>Exp: $\ell\ell$ | $1/\Lambda^2$ | 40.1<br>30.9                    | 25.4<br>22.7 | 35.7<br>28.2 | 27.5<br>23.8 | 35.1<br>28.0 | 27.5<br>24.0 | 35.2<br>28.3 | 27.7<br>23.5 |
| Obs: $\ell\ell$<br>Exp: $\ell\ell$ | $1/\Lambda^4$ | 35.2<br>28.4                    | 23.5<br>21.1 | 31.8<br>26.3 | 25.1<br>22.4 | 31.5<br>26.2 | 25.3<br>22.5 | 31.4<br>26.0 | 25.2<br>22.0 |

TABLE 6.7: Summary of observed and expected 95% CL lower limit numbers on  $\Lambda$  for the LL, LR, RL, and RR chiral coupling scenarios, for both the constructive (const) and destructive (dest) interference cases using a uniform positive prior in  $1/\Lambda^2$  or  $1/\Lambda^4$ .





# Chapter 7

## Summary and Outlook

This thesis presents two physics analysis topics: the first one is searching for the SM  $H \rightarrow \mu\mu$ ; and the second one is searching for the new physics phenomena at TeV mass scale with the dilepton final state. Data used in these analyses are collected by the ATLAS experiment during 2015 and 2016 from the LHC proton-proton collisions at the center-of-mass energy of 13 TeV, corresponding to a total integrated luminosity of  $36.1 \text{ fb}^{-1}$ .

For the SM  $H \rightarrow \mu\mu$  search, the BDT technique has been implemented in this analysis for the first time, which is used for the VBF-sensitive categories selection and helps to improve the overall sensitivity by more than 10%. This analysis produced the most sensitive search result on the SM  $H \rightarrow \mu\mu$  at the time when it was published in 2017. Our observed (expected) upper limit on the signal strength  $\mu$  is set to be 3.0 (3.1) at 95% CL, which has been improved by more than a factor of two, comparing with the Run 1 result based on  $24.8 \text{ fb}^{-1}$  data from the LHC proton-proton collisions at 7 and 8 TeV. Evidently, by applying the advanced data analysis technique in this thesis work, the  $H \rightarrow \mu\mu$  detection sensitive improvement has largely exceeded originally expected improvement based on statistical increase with the new Run 2 dataset. With a statistical combination of the Run 1 and Run 2 results, the corresponding observed (expected) upper limit on the  $H \rightarrow \mu\mu$  signal strength is 2.8 (2.9). A rough sensitivity projection for this analysis is performed based on the current categorization method by varying the spurious signal (SS) uncertainty (the dominant systematic uncertainty for this analysis) impact on the signal strength ( $\mu$ ) measurement. Figure 7.1 shows the estimated signal significance as a function of the integrated luminosity for different SS uncertainty scenarios. The red curve in Figure 7.1 represents the current SS uncertainty impact on  $\mu$ , which is  $\sim 0.3$ .

As shown in the projection plot, in order to further improve the sensitivity in the future analysis, further optimization on the selection and categorization criteria are needed in order to enhance the *Signal/Background* ratio, while on the other hand the methodology on the SS uncertainty estimating or background modeling function can be improved to further reduce the SS uncertainty impact.

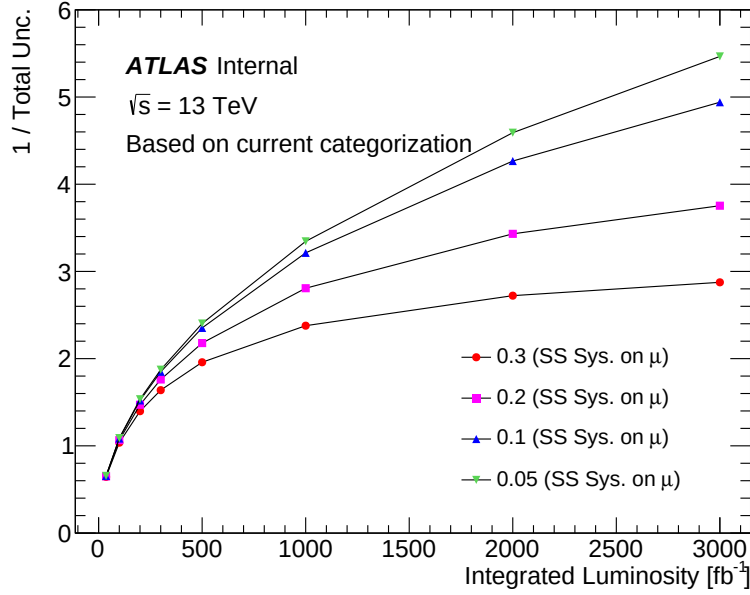


FIGURE 7.1: Rough estimation of signal significance *vs* integrated luminosity for different spurious signal (SS) uncertainty scenarios.

The increasing of the center-of-mass energy at the LHC run 2 provides unique opportunity for the physicists to search for the new physics beyond the SM at TeV mass scale. Moreover, the clean dilepton final state with high mass resolution provides the most sensitive experiment approach to look for new physics signature with broad range of the dilepton invariant mass spectrum. In the ATLAS Run 2 program, a dedicated High- $p_T$  working-point has been developed by the muon performance group, particularly for the new physics searches at high-mass scale, which helps to improve the resolution for muons with very high  $p_T$ . With 36.1 fb<sup>-1</sup> Run 2 data, no significant data excess is observed over the background predicted by the SM. Therefore much more stringent limits have been set on the POIs for the corresponding  $Z'$  and CI models comparing with the Run 1 results. For the  $Z'_{SSM}$ ,  $Z'_\chi$  and  $Z'_\psi$  models, masses below 4.5 TeV, 4.1 TeV and 3.8 TeV have been excluded at 95% CL. Figure 7.2 shows the observed limits for  $\mu_{SSM}$  ( $\sigma_{limit}/\sigma_{SSM}$ ) from different searching phases at  $\sqrt{s} = 7, 8$  and 13 TeV. The black curve represents the current search, which shows around 50% improvement for the mass

limit comparing with the one obtained in the Run 1 analysis (blue curve). While for the CI, the observed lower limits on energy scale  $\Lambda$  for fermion internal structure have been set ranging between 24 TeV and 40 TeV.

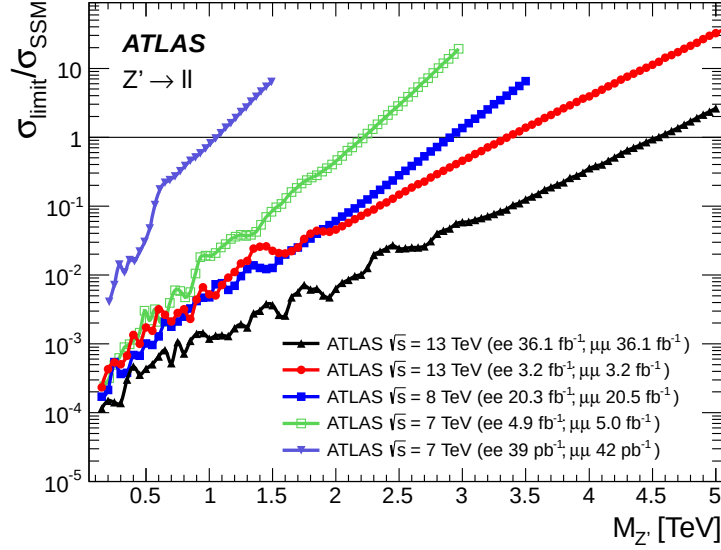


FIGURE 7.2: Ratio of the observed limit for the  $Z'$  search to the  $Z'_{SSM}$  cross section for current searches together with previous results at  $\sqrt{s} = 7, 8$  and 13 TeV.

Besides the two analyses described above, the studies on the muon offline DQ task (as my qualification task for the ATLAS experiment), and on the impact of ID–MS alignment on high  $p_T$  muon resolution have also been briefly described in Subsection 5.3.2 and Sub-subsection 4.2.4.5, respectively.

The software packages for muon offline DQ monitoring have been re-written with substantial updates and more functionality added. Comparing with the previous packages used in the Run 1, the new packages are more user-friendly and adopted since the start of the Run 2, which help the offline shifters scrutinize the data quality more efficiently. The effort on this task is very crucial for generating the final Good-Run-List of the dataset to be used for various physics analyses including searches for the SM Higgs decaying into dimuon and new phenomena searches with the dilepton final state presented in this dissertation.

The other study on the ID–MS alignment is quite important for the muons with very high  $p_T$  (above 300 GeV), which could potentially help to improve the detection sensitivities for new phenomena (e.g.  $Z'$ , CI,  $W'$ ...) searches at high-mass regime. The preliminary results have shown that with a simplified statistical combination between the

ID and MEMS tracks, we can gain  $\sim 5\%$  improvement on the resolution for muons with  $p_T$  of  $\sim 1$  TeV after correcting the mis-alignment between the ID and MS detectors. More efforts are underway to further demonstrate and quantify the improvement on muon  $p_T$  resolution with the official reconstruction program.

By the end of 2018 (the end of the Run 2), a total integrated luminosity of  $>120 \text{ fb}^{-1}$  data will be collected. With this amount of dataset, searches for both the SM  $H \rightarrow \mu\mu$  and high-mass phenomena will be re-performed. Currently, efforts are ongoing for developing the methodology and strategy for these two analyses in the next round, as well as improving the related object reconstruction and performance. Therefore, we expect to further gain much better sensitivities for these two analyses with the full dataset collected in the Run 2. After the Run 2, the LHC will be upgraded to 14 TeV and continue running for decades. Eventually a total amount of data corresponding to  $\sim 3000 \text{ fb}^{-1}$  integrated luminosity will be recorded by the experiments at the LHC. We expect to discover the  $H \rightarrow \mu\mu$  decay channel in the coming years at the LHC. With  $3000 \text{ fb}^{-1}$  data, we expect to detect  $H \rightarrow \mu\mu$  with  $\sim 9 \sigma$  significance which would allow to measure the Higgs boson to dimuon coupling with an accuracy better than 10%. In the meanwhile, there will be much more enlarged phase space for new physics searches at the LHC.

# Bibliography

- [1] J. Dalton, *A New System of Chemical Philosophy*. Manchester, London: S. Russell for R. Bickerstaff, 1808.
- [2] J. Thomson, *Cathode Rays*, *Philosophical Magazine* **44** (1897) 293–316.
- [3] R. Millikan, *On the Elementary Electrical Charge and the Avogadro Constant*, *Phys.Rev.* **2** **2** (1913) 109.
- [4] E. Rutherford, *The scattering of alpha and beta particles by matter and the structure of the atom*, *Phil.Mag.Ser.6* **21** (1911) 669–688.
- [5] N. Bohr, *On the Constitution of Atoms and Molecules, Part I*, *Philosophical Magazine* **26** (1913) 1–24.
- [6] N. Bohr, *On the Constitution of Atoms and Molecules, Part II Systems Containing Only a Single Nucleus*, *Philosophical Magazine* **26** (1913) 476–502.
- [7] N. Bohr, *On the Constitution of Atoms and Molecules, Part III Systems containing several nuclei*, *Philosophical Magazine* **26** (1913) 857–875.
- [8] E. Rutherford, *Collision of alpha particles with light atoms. IV. An anomalous effect in nitrogen*, *Philosophical Magazine* **44** (1919) 581–587.
- [9] J. Chadwick, *Possible Existence of a Neutron*, *Nature* **129** (1932) 312.
- [10] J. Chadwick, *New Evidence for the Existence of a Particle of Mass Intermediate Between the Proton and Electron*, *Phys.Rev.* **52** (1937) 1003–1004.
- [11] M. Gell-Mann, *A schematic model of baryons and mesons*, *Physics Letters* **8** (1964) 214–215. <https://www.sciencedirect.com/science/article/pii/S0031916364920013?via%3Dihub>.

- [12] G. Zweig, *An  $SU_3$  model for strong interaction symmetry and its breaking*, CERN Report No.8419/TH.412 (1964).  
<http://inspirehep.net/record/4674/files/cern-th-412.pdf>.
- [13] H. Fritzsch and M. Gell-Mann, *Advantages of the Color Octet Gluon Picture*, *Physics Letters* **47B** no. 4, (1973) 365–368. <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.453.4712&rep=rep1&type=pdf>.
- [14] D. J. Gross and F. Wilczek, *Ultraviolet Behavior of Non-Abelian Gauge Theories*, *Phys. Rev. Lett.* **30** (1973) 1343–1346.  
<https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.30.1343>.
- [15] H. David Politzer, *Reliable Perturbative Results for Strong Interactions?*, *Phys. Rev. Lett.* **30** (1973) 1346–1349.  
<https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.30.1346>.
- [16] S. L. Glashow, *Partial-symmetries of weak interactions*, *Nuclear Physics* **22** no. 4, (1961) 579 – 588.  
<http://www.sciencedirect.com/science/article/pii/0029558261904692>.
- [17] F. Englert and R. Brout, *Broken Symmetry and the Mass of Gauge Vector Mesons*, *Phys. Rev. Lett.* **13** (1964) 321–323.  
<http://link.aps.org/doi/10.1103/PhysRevLett.13.321>.
- [18] P. Higgs, *Broken symmetries, massless particles and gauge fields*, *Physics Letters* **12** no. 2, (1964) 132 – 133.  
<http://www.sciencedirect.com/science/article/pii/0031916364911369>.
- [19] P. Higgs, *Broken Symmetries and the Masses of Gauge Bosons*, *Phys. Rev. Lett.* **13** (1964) 508–509. <http://link.aps.org/doi/10.1103/PhysRevLett.13.508>.
- [20] P. Higgs, *Spontaneous Symmetry Breakdown without Massless Bosons*, *Phys. Rev.* **145** (1966) 1156–1163. <http://link.aps.org/doi/10.1103/PhysRev.145.1156>.
- [21] S. Weinberg, *A Model of Leptons*, *Phys. Rev. Lett.* **19** (1967) 1264–1266.  
<http://link.aps.org/doi/10.1103/PhysRevLett.19.1264>.
- [22] A. Salam, *Elementary Particle Physics: Relativistic Groups and Analyticity*, Tech. Rep. Eighth Nobel Symposium, Stockholm: Almquist and Wiksell, 1968.

- [23] PETRA Collaboration , *Discovery of Three-Jet Events and a Test of Quantum Chromodynamics at PETRA*, *Phys. Rev. Lett.* **43** (1979) 830.  
<https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.43.830>.
- [24] UA1 Collaboration , *Experimental observation of isolated large transverse energy electrons with associated missing energy at  $\sqrt{s}=540$  GeV*, *Phys.Lett.* **B122** (1983) 103–116.
- [25] UA1 Collaboration , *Experimental observation of lepton pairs of invariant mass around 95 GeV/c<sup>2</sup> at the CERN SPS collider*, *Phys.Lett.* **B126** (1983) 398–410.
- [26] CDF Collaboration , *Observation of top quark production in  $\bar{p}p$  collisions*, *Phys. Rev. Lett.* **74** (1995) 2626–2631.  
<https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.74.2626>.
- [27] ATLAS Collaboration, *Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC*, *Physics Letters B* **716** no. 1, (2012) 1 – 29, [arXiv:1207.7214 \[hep-ex\]](#).
- [28] CMS Collaboration, *Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC*, *Physics Letters B* **716** no. 1, (2012) 30 – 61, [arXiv:1207.7235 \[hep-ex\]](#).
- [29] ATLAS Collaboration , *Search for the Standard Model Higgs boson decay to  $\mu^+\mu^-$  with the ATLAS detector*, *Phys. Lett. B* **738** (2014) 68, [arXiv:1406.7663 \[hep-ex\]](#).
- [30] CMS Collaboration , *Search for a standard model-like Higgs boson in the  $\mu^+\mu^-$  and  $e^+e^-$  decay channels at the LHC*, *Phys. Lett. B* **744** (2015) 184, [arXiv:1410.6679 \[hep-ex\]](#).
- [31] ATLAS Collaboration , *Search for the Dimuon Decay of the Higgs boson in pp Collisions at  $\sqrt{s} = 13$  TeV with the ATLAS Detector*, *Phys. Rev. Lett.* **119** (2017) 051802, [arXiv:1705.04582 \[hep-ex\]](#).
- [32] ATLAS Collaboration , *Search for high-mass dilepton resonances in pp collisions at  $\sqrt{s} = 8$  TeV with the ATLAS detector*, *Phys. Rev. D* **90** (2014) 052005, [arXiv:1405.4123 \[hep-ex\]](#).
- [33] ATLAS Collaboration , *Search for contact interactions and large extra dimensions in the dilepton channel using proton–proton collisions at  $\sqrt{s} = 8$  TeV with the ATLAS detector*, *Eur. Phys. J. C* **74** (2014) 3134, [arXiv:1407.2410 \[hep-ex\]](#).

- [34] CMS Collaboration , *Search for physics beyond the standard model in dilepton mass spectra in proton-proton collisions at  $\sqrt{s} = 8$  TeV*, [JHEP \*\*04\*\* \(2015\) 025](#), [arXiv:1412.6302 \[hep-ex\]](#).
- [35] ATLAS Collaboration , *Search for new high-mass phenomena in the dilepton final state using  $36\text{ fb}^{-1}$  of proton-proton collisions data at  $\sqrt{s} = 13$  TeV with the ATLAS detector*, [JHEP \*\*10\*\* \(2017\) 182](#), [arXiv:1707.02424 \[hep-ex\]](#).
- [36] ATLAS Collaboration, CMS Collaboration , *Combined Measurement of the Higgs Boson Mass in pp collisions at  $\sqrt{s}=7$  and 8 TeV with the ATLAS and CMS Experiments*, [Phys. Rev. Lett. \*\*114\*\* \(2015\) 191803](#), [arXiv:1503.07589 \[hep-ex\]](#).
- [37] P. Skands, *QCD for collider physics*, [arXiv:1104.2863 \[hep-ph\]](#).
- [38] P. Langacker, *Introduction to the Standard Model and Electroweak Physics*, [arXiv:0901.0241 \[hep-ph\]](#).
- [39] P. Langacker, *The Physics of Heavy  $Z'$  Gauge Bosons*, [Rev. Mod. Phys. \*\*81\*\* \(2009\) 1199–1228](#), [arXiv:0801.1345 \[hep-ph\]](#).
- [40] D. London and J. L. Rosner, *Extra Gauge Bosons in  $E(6)$* , [Phys. Rev. D \*\*34\*\* \(1986\) 1530](#).
- [41] E. Eichten, K. D. Lane, and M. E. Peskin, *New Tests for Quark and Lepton Substructure*, [Phys. Rev. Lett. \*\*50\*\* \(1983\) 811–814](#).
- [42] E. Eichten, I. Hinchliffe, K. D. Lane, and C. Quigg, *Super Collider Physics*, [Rev. Mod. Phys. \*\*56\*\* \(1984\) 579–707](#).
- [43] J. Womersley, *QCD at the Tevatron: Status and prospects*, [arXiv:hep-ex/0012061 \[hep-ex\]](#).
- [44] NNPDF Collaboration , *Parton distributions and lattice QCD calculations: a community white paper*, [Progress in Particle and Nuclear Physics \*\*100\*\* \(2018\) 107–160](#), [arXiv:1711.07916](#).
- [45] J. C. Collins, D. E. Soper, and G. F. Sterman, *Factorization of Hard Processes in QCD*, [Adv.Ser.Direct.High Energy Phys. \*\*5\*\* \(1988\) 1–91](#), [arXiv:hep-ph/0409313 \[hep-ph\]](#).
- [46] W. Stirling, *Perturbative QCD*, Tech. Rep. CERN-OPEN-2000-296, 2000. <https://cds.cern.ch/record/1194745/>.



- [47] “LHC Higgs Cross Section Working Group.”  
<https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG>.
- [48] O. S. Bruning, P. Collier, P. Lebrun, S. Myers, R. Ostojic, et al., *LHC Design Report. 1. The LHC Main Ring*,.
- [49] O. Buning, P. Collier, P. Lebrun, S. Myers, R. Ostojic, et al., *LHC Design Report. 2. The LHC infrastructure and general services*,.
- [50] M. Benedikt, P. Collier, V. Mertens, J. Poole, and K. Schindl, *LHC Design Report. 3. The LHC injector chain*,.
- [51] L. Evans and P. Bryant, *LHC Machine*, [JINST 3 \(2008\) S08001](#).
- [52] L. Evans, *The Large Hadron Collider*, [New J.Phys. 9 \(2007\) 335](#).
- [53] R. B. on behalf of the LHC team, “LHC machine status report.”  
[https://indico.cern.ch/event/679087/contributions/2781751/attachments/1567494/2471324/2017.11.30\\_LHCC\\_LHC\\_machine\\_status.pdf](https://indico.cern.ch/event/679087/contributions/2781751/attachments/1567494/2471324/2017.11.30_LHCC_LHC_machine_status.pdf).
- [54] ATLAS Collaboration , *The ATLAS Experiment at the CERN Large Hadron Collider*, [JINST 3 \(2008\) S08003](#).
- [55] G. Aad, M. Ackers, F. Alberti, M. Aleppo, G. Alimonti, et al., *ATLAS pixel detector electronics and sensors*, [JINST 3 \(2008\) P07007](#).
- [56] A. Ahmad, Z. Albrechtskirchinger, P. Allport, J. Alonso, L. Andricek, et al., *The Silicon microstrip sensors of the ATLAS semiconductor tracker*,  
[Nucl.Instrum.Meth. A578 \(2007\) 98–118](#).
- [57] ATLAS TRT Collaboration , E. Abat et al., *The ATLAS Transition Radiation Tracker (TRT) proportional drift tube: Design and performance*, [JINST 3 \(2008\) P02013](#).
- [58] ATLAS Collaboration , *ATLAS liquid-argon calorimeter: Technical Design Report*. Technical Design Report ATLAS. CERN, Geneva, 1996.
- [59] ATLAS Collaboration , *ATLAS tile calorimeter: Technical Design Report*. Technical Design Report ATLAS. CERN, Geneva, 1996.
- [60] ATLAS Collaboration , *ATLAS muon spectrometer: Technical design report*. Technical Design Report ATLAS. CERN, Geneva, 1997.

- [61] Y.Arai et al., *ATLAS muon drift tube electronics*, [JINST \*\*3\*\* \(2008\) P09001](#).
- [62] ATLAS Collaboration , L. Adamczyk and others, “Technical Design Report for the ATLAS Forward Proton Detector.” CERN-LHCC-2015-009, 2015.  
<https://cds.cern.ch/record/2017378/>.
- [63] ATLAS Collaboration , *Performance of the ATLAS Trigger System in 2015*, [Eur.Phys.J. \*\*C77\*\* no. 5, \(2017\) 317](#), [arXiv:1611.09661 \[hep-ex\]](#).
- [64] ATLAS Collaboration , G. Aad et al., *The ATLAS Simulation Infrastructure*, [Eur.Phys.J. \*\*C70\*\* \(2010\) 823–874](#), [arXiv:1005.4568 \[physics.ins-det\]](#).
- [65] ATLAS Collaboration , G. Duckeck et al., *ATLAS computing: Technical design report*,.
- [66] T. Sjostrand, S. Mrenna, and P. Z. Skands, *PYTHIA 6.4 Physics and Manual*, [JHEP \*\*0605\*\* \(2006\) 026](#), [arXiv:hep-ph/0603175 \[hep-ph\]](#).
- [67] T. Sjostrand, S. Mrenna, and P. Z. Skands, *A Brief Introduction to PYTHIA 8.1*, [Comput.Phys.Comm. \*\*178\*\* \(2008\) 852–867](#), [arXiv:0710.3820 \[hep-ph\]](#).
- [68] M. Bahr, S. Gieseke, M. Gigg, D. Grellscheid, K. Hamilton, et al., *Herwig++ Physics and Manual*, [Eur.Phys.J. \*\*C58\*\* \(2008\) 639–707](#), [arXiv:0803.0883 \[hep-ph\]](#).
- [69] T. Gleisberg, S. Hoeche, F. Krauss, M. Schonherr, S. Schumann, et al., *Event generation with SHERPA 1.1*, [JHEP \*\*0902\*\* \(2009\) 007](#), [arXiv:0811.4622 \[hep-ph\]](#).
- [70] S. Höche, *Introduction to parton-shower event generators*, [arXiv:1411.4085 \[hep-ex\]](#).
- [71] GEANT4 , S. Agostinelli et al., *GEANT4: A Simulation toolkit*, [Nucl.Instrum.Meth. \*\*A506\*\* \(2003\) 250–303](#).
- [72] J. Allison, K. Amako, J. Apostolakis, H. Araujo, P. Dubois, et al., *Geant4 developments and applications*, [IEEE Trans.Nucl.Sci. \*\*53\*\* \(2006\) 270](#).
- [73] E. Barberio, J. Boudreau, B. Butler, S. Cheung, A. DellaAcqua, et al., *The Geant4-Based ATLAS Fast Electromagnetic Shower Simulation*, Tech. Rep. ATL-SOFT-CONF-2007-002, 2007.

- [74] E. Richter-Was, D. Froidevaux, and L. Poggioli, *ATLFAST 2.0 a fast simulation package for ATLAS*,.
- [75] K. Edmonds, S. Fleischmann, T. Lenz, C. Magass, J. Mechnich, et al., *The fast ATLAS track simulation (FATRAS)*,.
- [76] ATLAS Collaboration , J. Boyd, M. Costa, and A. Tonoyan, *Commissioning of the ATLAS reconstruction software with first data*, [J.Phys.Conf.Ser. \*\*219\*\* \(2010\) 032059](#).
- [77] T. Cornelissen, M. Elsing, S. Fleischmann, W. Liebig, E. Moyse, et al., *Concepts, Design and Implementation of the ATLAS New Tracking (NEWT)*,.
- [78] ATLAS Collaboration , *Muon reconstruction performance of the ATLAS detector in proton–proton collision data at  $\sqrt{s}=13$  TeV*, [Eur.Phys.J. \*\*C76\*\* no. 5, \(2016\) 292](#), [arXiv:1603.05598 \[hep-ex\]](#).
- [79] J.Illingworth and J.Kittler, *A survey of the Hough transform*, [Computer Vision, Graphics, and Image Processing \*\*44\*\* \(1988\) 87](#).
- [80] ATLAS Collaboration , *Reconstruction of primary vertices at the ATLAS experiment in Run 1 proton–proton collisions at the LHC*, [Eur.Phys.J. \*\*C77\*\* no. 5, \(2017\) 332](#), [arXiv:1611.10235 \[hep-ex\]](#).
- [81] ATLAS Collaboration, *Vertex Reconstruction Performance of the ATLAS Detector at  $\sqrt{s}=13$  TeV*, Tech. Rep. ATL-PHYS-PUB-2015-026, CERN, Geneva, July, 2015.
- [82] ATLAS Collaboration, “Electron identification measurements in atlas using  $\sqrt{s} = 13$  tev data with 50 ns bunch spacing.” ATL-PHYS-PUB-2015-041, 2015. <http://cdsweb.cern.ch/record/2048202>.
- [83] ATLAS Collaboration, “Electron efficiency measurements with the ATLAS detector using the 2015 LHC proton-proton collision data.” Atlas-conf-2016-024, 2016. <https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2016-024/>.
- [84] W. Lampl, S. Laplace, D. Lelas, P. Loch, H. Ma, et al., *Calorimeter clustering algorithms: Description and performance*, Tech. Rep. ATL-LARG-PUB-2008-002, 2008.

- [85] T. Cornelissen et al., *The global  $\chi^2$  track fitter in ATLAS*, [J.Phys.Conf.Ser. \*\*119\*\* \(2008\) 032013](#).
- [86] A. Collaboration, *Electron efficiency measurements with the ATLAS detector using the 2012 LHC proton-proton collision data*, Tech. Rep. ATLAS-CONF-2014-032, CERN, Geneva, Jun, 2014. <https://cds.cern.ch/record/1706245>.
- [87] ATLAS Collaboration , *Topological cell clustering in the ATLAS calorimeters and its performance in LHC Run 1*, [Eur.Phys.J. \*\*C77\*\* \(2017\) 490](#), [arXiv:1603.02934 \[hep-ex\]](#).
- [88] ATLAS Collaboration , *Jet energy scale measurements and their systematic uncertainties in proton-proton collisions at  $\sqrt{s}=13$  TeV with the ATLAS detector*, [Phys.Rev. \*\*D96\*\* \(2017\) 072002](#), [arXiv:1703.09665 \[hep-ph\]](#).
- [89] ATLAS Collaboration, “Optimisation of the ATLAS  $b$ -tagging performance for the 2016.” ATL-PHYS-PUB-2016-012, 2016. <http://cdsweb.cern.ch/record/2160731>.
- [90] M. Cacciari, G. P. Salam, and G. Soyez, *The Anti- $k(t)$  jet clustering algorithm*, [JHEP \*\*0804\*\* \(2008\) 063](#), [arXiv:0802.1189 \[hep-ph\]](#).
- [91] M. Cacciari, G. P. Salam, and G. Soyez, *FastJet user manual*, [Eur. Phys. J. \*\*C 72\*\* \(2012\) 1896](#).
- [92] M. Cacciari and G. P. Salam, *Pileup subtraction using jet areas*, [Phys. Lett. B \*\*659\*\* \(2008\) 119](#), [arXiv:0707.1378 \[hep-ph\]](#).
- [93] ATLAS Collaboration , A. Collaboration, *Commissioning of the ATLAS high-performance  $b$ -tagging algorithms in the 7 TeV collision data*, Tech. Rep. ATLAS-CONF-2011-102, 2011.
- [94] G. Piacquadio and C. Weiser, *A new inclusive secondary vertex algorithm for  $b$ -jet tagging in ATLAS*, [J.Phys.Conf.Ser. \*\*119\*\* \(2008\) 032032](#).
- [95] P. Speckmayer, A. Hocker, J. Stelzer, and H. Voss, *The toolkit for multivariate data analysis, TMVA 4*, [J.Phys.Conf.Ser. \*\*219\*\* \(2010\) 032057](#).
- [96] ATLAS Collaboration, *Performance of missing transverse momentum reconstruction with the ATLAS detector using proton-proton collisions at  $\sqrt{s}=13$  TeV*, submitted to Eur. Phys. J. **C** (2018), [arXiv:1802.08168 \[hep-ex\]](#).

- [97] ATLAS Collaboration, “Performance of missing transverse momentum reconstruction for the ATLAS detector in the first proton-proton collisions at  $\sqrt{s}=13$  TeV.” ATL-PHYS-PUB-2015-027, 2015.  
<http://cdsweb.cern.ch/record/2037904>.
- [98] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer, and T. Stelzer, *MadGraph 5 : going beyond*, *JHEP* **06** (2011) 128, [arXiv:1106.0522 \[hep-ph\]](#).
- [99] R. D. Ball, V. Bertone, S. Carrazza, C. S. Deans, L. Del Debbio, et al., *Parton distributions with LHC data*, *Nucl.Phys.* **B867** (2013) 244–289, [arXiv:1207.1303 \[hep-ph\]](#).
- [100] S. Frixione, P. Nason, and C. Oleari, *Matching NLO QCD computations with parton shower simulations: the POWHEG method*, *JHEP* **11** (2007) 070, [arXiv:0709.2092 \[hep-ph\]](#).
- [101] H.-L. Lai, M. Guzzi, J. Huston, Z. Li, P. M. Nadolsky, et al., *New parton distributions for collider physics*, *Phys.Rev.* **D82** (2010) 074024, [arXiv:1007.2241 \[hep-ph\]](#).
- [102] P. Z. Skands, *Tuning Monte Carlo Generators: The Perugia Tunes*, *Phys. Rev. D* **82** (2010) 074018, [arXiv:1005.3457 \[hep-ph\]](#).
- [103] J. Pumplin, D. Stump, J. Huston, H. Lai, P. M. Nadolsky, et al., *New generation of parton distributions with uncertainties from global QCD analysis*, *JHEP* **0207** (2002) 012, [arXiv:hep-ph/0201195 \[hep-ph\]](#).
- [104] D. J. Lange, *The EvtGen particle decay simulation package*, *Nucl. Instrum. Meth.* **A462** (2001) 152–155.
- [105] ATLAS Collaboration, “ATLAS Pythia 8 tunes to 7 TeV data.” ATL-PHYS-PUB-2014-021, 2014. <http://cds.cern.ch/record/1966419>.
- [106] ATLAS Collaboration, “Selection of jets produced in 13TeV proton-proton collisions with the ATLAS detector.” ATLAS-CONF-2015-029, 2015.  
<https://cds.cern.ch/record/2037702>.
- [107] ATLAS Collaboration, “Tagging and suppression of pileup jets with the ATLAS detector.” ATLAS-CONF-2014-018, 2014.  
<https://cds.cern.ch/record/1700870>.

- [108] Particle Data Group , C. Patrignani et al., *Review of Particle Physics*, [Chin. Phys. C](#) **40** no. 10, (2016) 100001.
- [109] LHC Higgs Cross Section Working Group, S. Dittmaier, C. Mariotti, G. Passarino, and R. Tanaka (Eds.), *Handbook of LHC Higgs Cross Sections: 1. Inclusive Observables*, [CERN-2011-002](#) (CERN, Geneva, 2011), [arXiv:1101.0593 \[hep-ph\]](#).
- [110] LHC Higgs Cross Section Working Group, S. Dittmaier, C. Mariotti, G. Passarino, and R. Tanaka (Eds.), *Handbook of LHC Higgs Cross Sections: 2. Differential Distributions*, [CERN-2012-002](#) (CERN, Geneva, 2012), [arXiv:1201.3084 \[hep-ph\]](#).
- [111] D. de Florian, G. Ferrera, M. Grazzini, and D. Tommasini, *Higgs boson production at the LHC: transverse momentum resummation effects in the  $H \rightarrow 2\gamma$ ,  $H \rightarrow WW \rightarrow l\nu l\nu$  and  $H \rightarrow ZZ \rightarrow 4l$  decay modes*, [JHEP](#) **06** (2012) 132, [arXiv:1203.6321 \[hep-ph\]](#).
- [112] M. Grazzini and H. Sargsyan, *Heavy-quark mass effects in Higgs boson production at the LHC*, [JHEP](#) **09** (2013) 129, [arXiv:1306.4581 \[hep-ph\]](#).
- [113] LHC Higgs Cross Section Working Group, S. Heinemeyer, C. Mariotti, G. Passarino, and R. Tanaka (Eds.), *Handbook of LHC Higgs Cross Sections: 3. Higgs Properties*, [CERN-2013-004](#) (CERN, Geneva, 2013), [arXiv:1307.1347 \[hep-ph\]](#).
- [114] ATLAS Collaboration , G. Aad et al., *Luminosity Determination in pp Collisions at  $\sqrt{s} = 7$  TeV Using the ATLAS Detector at the LHC*, [Eur.Phys.J.](#) **C71** (2011) 1630, [arXiv:1101.2185 \[hep-ex\]](#).
- [115] CMS Collaboration , *Measurement of differential cross sections for Higgs boson production in the diphoton decay channel in pp collisions at  $\sqrt{s} = 8$  TeV*, [Eur. Phys. J. C](#) **76** (2016) 13, [arXiv:1508.07819 \[hep-ex\]](#).
- [116] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, *Asymptotic formulae for likelihood-based tests of new physics*, [Eur. Phys. J. C](#) **71** (2011) 1554, [arXiv:1007.1727 \[physics.data-an\]](#). [Erratum: [Eur. Phys. J. C](#) **73** (2013) 2501].
- [117] A. L. Read, *Presentation of search results: The  $CL(s)$  technique*, [J. Phys. G](#) **28** (2002) 2693.

- [118] CMS Collaboration, “Search for the standard model Higgs boson decaying into two muons in  $pp$  collisions at  $\sqrt{s}=13$  TeV.” CMS-PAS-HIG-17-019, 2017.  
<https://cds.cern.ch/record/2292159>.
- [119] C. Anastasiou, L. J. Dixon, K. Melnikov, and F. Petriello, *High precision QCD at hadron colliders: Electroweak gauge boson rapidity distributions at NNLO*, *Phys. Rev. D* **69** (2004) 094008, [arXiv:hep-ph/0312266](#).
- [120] S. Dulat, T.-J. Hou, J. Gao, M. Guzzi, J. Huston, P. Nadolsky, J. Pumplin, C. Schmidt, D. Stump, and C. P. Yuan, *New parton distribution functions from a global analysis of quantum chromodynamics*, *Phys. Rev. D* **93** (2016) 033006, [arXiv:1506.07443 \[hep-ph\]](#).
- [121] J. Butterworth et al., *PDF4LHC recommendations for LHC Run II*, *J. Phys. G* **43** (2016) 023001, [arXiv:1510.03865 \[hep-ph\]](#).
- [122] P. Motylinski, L. Harland-Lang, A. D. Martin, and R. S. Thorne, *Updates of PDFs for the 2nd LHC run*, [arXiv:1411.2560 \[hep-ph\]](#).
- [123] NNPDF , R. D. Ball et al., *Parton distributions for the LHC Run II*, *JHEP* **04** (2015) 040, [arXiv:1410.8849 \[hep-ph\]](#).
- [124] ATLAS , ATLAS Collaboration, *Measurement of the Inelastic Proton-Proton Cross Section at  $\sqrt{s} = 13$  TeV with the ATLAS Detector at the LHC*, *Phys. Rev. Lett.* **117** no. 18, (2016) 182002, [arXiv:1606.02625 \[hep-ex\]](#).
- [125] E. Gross and O. Vitells, *Trial factors or the look elsewhere effect in high energy physics*, *Eur. Phys. J. C* **70** (2010) 525–530, [arXiv:1005.1891 \[physics.data-an\]](#).
- [126] S. Wilks, *The large-sample distribution of the likelihood ratio for testing composite hypotheses*, *Ann. Math. Statist.* **9** (1938) 60–62.
- [127] A. Caldwell, D. Kollar, and K. Kroninger, *BAT: The Bayesian Analysis Toolkit*, *Comput. Phys. Commun.* **180** (2009) 2197–2209, [arXiv:0808.2552 \[physics.data-an\]](#).
- [128] CMS Collaboration, *Search for high-mass resonances in dilepton final states in proton-proton collisions at  $\sqrt{s}=13$  TeV*, submitted to JHEP (2018), [arXiv:1803.06292 \[hep-ex\]](#).