

THE CATHOLIC UNIVERSITY OF AMERICA

Search for resonant WZ production in the fully leptonic final state at 13 TeV with the CMS
detector

A DISSERTATION

Submitted to the Faculty of

The Department of Physics

School of Arts and Sciences

Of The Catholic University of America

In Partial Fulfillment of the Requirements

For the Degree

of Doctor of Philosophy

By

Andrés Mateus Vargas Hernández

Washington, D.C.

2023



Search for resonant WZ production in the fully leptonic final state at 13 TeV with the CMS
detector

Andrés Mateus Vargas Hernández, Ph.D.

Director: Rachel Bartek, Ph.D.

Co-Director: Aaron Dominguez, Ph.D.

A search for an electrically charged, narrow-width diboson (WZ) resonance in the fully leptonic final state using 137.65 fb^{-1} of data collected by the CMS experiment during the 2016-2018 run period, at the LHC and a center of mass energy of $\sqrt{s} = 13 \text{ TeV}$ is presented. The search focuses on a channel where the resonance decays to a pair of standard model vector bosons: W and Z . The Z boson subsequently decays to a pair of leptons, either electrons (e) or muons (μ). While the W boson decays to a lepton and a neutrino (ν). As ν escapes undetected, the neutrino is reconstructed from the missing transverse momentum (P_t^{miss}) of the event. The analysis is based on a bump-hunt search strategy with background estimation based on stochastically generated simulation events. No significant excess of events is observed above the expected background from the Standard Model and limits are set on the production cross-section of the diboson resonance as a function of the resonance mass at 95% confidence level. Results are interpreted in the context of the Heavy Vector Triplet (HVT) framework.

This dissertation by Andrés Mateus Vargas Hernández fulfills the dissertation requirement for the doctoral degree in Physics approved by Rachel Bartek, Ph.D., as Director, Aaron Dominguez, Ph.D. as Co-Director, and Grzegorz Kalicy, Ph.D., as Reader.

Rachel Bartek, Ph.D., Director

Aaron Dominguez, Ph.D., Co-Director

Grzegorz Kalicy, Ph.D., Reader

A mis padres, por su amor y apoyo incondicional.

ACKNOWLEDGEMENTS

I am grateful for all the people that provided support, in its wide variety of forms, during the execution of this research project and the completion of this thesis. I would like to specially acknowledge with appreciation my advisors, and the closest group of colleagues at The Catholic University of America: Prof. Aaron Dominguez, Prof. Rachel Bartek, Dr. Ali Eren Simsek, Rishabh Uniyal, Conett Huerta, Rhea Khatri, and Shivam Raj. Without access to the resources provided by Prof. Dominguez, Prof. Bartek, the Physics faculty and CUA staff, this thesis would not have been ever planned, let alone completed. Prof. Dominguez and Prof. Bartek provided continuous support, guidance and encouragement throughout this process and were always willing to go the extra mile to push forward my professional goals. I am in debt of gratitude to them for their trust and the autonomy they gave me to pursue my interests and to work on projects within the collaboration that were meaningful to me.

Visiting CERN and seeing the magnitude of this human endeavor is a humbling experience. CERN is a unique place, with remarkable people working in different areas of research. It is not an overstatement that every single contributing member of the CMS collaboration should be acknowledged. With that being said, I want to highlight my gratitude to the B2G group, specially to Dr. Louis Moureaux, Dr. Arne Christoph Reimers and Dr. Andreas Hinzmann, for providing friendly access to their expertise and for their continuous feedback during the development of the physics analysis. I am fortunate enough to have had the opportunity to serve CMS, and I am grateful I was able to engage in a wide variety of projects and drawing on the knowledge and insight of those I have interacted with. I would like to extend my thank-you message to Ianna Osborne,

Gabrielle Hugo, Dr. Sergio Lo Meo, Dr. Fabio Cossutti, and Dr. Marguerite Tonjes. Working with them taught me valuable lessons that will stick with me for the rest of my professional journey.

I appreciate having people in my career that, in pursuit of their own goals, were willing to help in mine. I owe the opportunity to work at the Thomas Jefferson National Accelerator Facility, where I also met bright and highly driven people, to Prof. Tanja Horn, Dr Edwin Munévar and Dr Julian Salamanca. Their confidence in my abilities to succeed was a great motivator to learn as much as I could and to define and set my own goals.

I want to thank my fellow graduate students and friends: Skarleth, Luiz, Rishabh, Amrit, Conett, Shivam and all other CUA graduate students with whom I had the fortune to do my coursework and to share all the different experiences and stages of graduate school. My partner Amrine for her sweet love, kind support and for fruitful morning discussions that fed me with energy for the day ahead. She dealt with my absence, mood swings, and stress with a loving understanding difficult to compare to. I am grateful to all of you for your friendship and for providing a safe space to share my thoughts, ideas, concerns and straight-up frustrations. This phase of my career came with ups and downs, they were there to lift me in my downs and ground me in my ups.

Last but not least, I am blessed, lucky and eternally grateful for having a loving and caring family: my conscientious sister Johanna Marcela, my driven brother Cristian Felipe and my parents. Tomas Vargas and Maria Hernandez neither had nor needed a college degree to be the best teachers from whom I could learn the values of hard work, dedication, and perseverance. They are complementary forces in my life, my father pushes me forward in his thoughtful way, and my mother offers me the reliable safety of an unconditional love. Both forces were needed to get me to this point, and they are God's gift to me.

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CHAPTER 1

Introduction

*"Living is worthwhile if one can contribute
in some small way to this endless chain of progress."*

— Paul Dirac

Human curiosity is one of the driving forces behind the pursuance of the understanding of the environment we live in. It is remarkable that an abstract language such as mathematics can be used to create models that reproduce the behavior of processes that are observed in nature. Physics has been extraordinarily successful in the development of conceptual and mathematical frameworks that predict the outcome of experiments, and even though there has been continuous challenges to the models, the interaction between theorists and experimentalists has allowed to continuously refine our understanding of nature. Physics has overcome these challenges in creative ways, even when they implied to radically change the way we think about the nature of reality, the ability to adapt to new paradigms has been key to its success.

Scientific progress has inevitably impacted and shaped the development of humanity and the way we live our lives even though it may take decades for technology to catch up and fully exploit every single aspect that a new scientific development has to offer. Little our ancestors knew about the consequences of understanding gravitational forces, even in their most basic form. Little they knew about the possibilities that opened up by the development of Electromagnetic or Atomic

Theory, it is therefore fair to say that little we know about the possibilities that will open with our most current models in Quantum Field Theory.

Scientific research is by definition located at the edge of knowledge, pushing forward its boundaries and even though its process is not linear it is in an upward trend. Every new discovery particularly those which disagrees with our current models and paradigms, is a welcomed challenge by the scientific community. As part of the development of theories and the outcome of experimental results, the need to set up experimental facilities has been a constant and not surprisingly as the complexity of the challenges has increased, so has the size and complexity of these facilities.

Experimental research continuously push forward the development of new technology, the design of new materials, the development of new techniques, and the usage of existing ones in the most creative ways. The Large Hadron Collider (LHC) and its experiments are prime example of this. Achieving the collision of subatomic particles at high energies is a way to probe the predictions of the most current model of particle physics, the Standard Model. The experimental requirements to achieve these collisions and to be able to reproduce and control their initial conditions are some of the most demanding in the history of physics research as they involve the acceleration of particles at speeds close to the speed of light and to recreate scenarios that are close to the conditions that existed in the very first stages of the universe, where the temperature was extremely high, and the fundamental forces are thought to be unified.

This achievement is only possible by bringing together different fields of science and the most cutting edge technology, particularly in magnet technology, cryogenics, and computing. A wide variety of expertise knowledge is required to be able to design, build, operate and maintain the experiments and the LHC. This need for a wide variety of expertise is true not only from the experimental aspect of the particle physics field but also from the theoretical side. As the mathematical complexity of the models increases and analytical solutions are no longer known, numerical simulations and stochastic methods are used in order to be able to provide observable predictions from the mathematical equations provided by theory. These stochastic methods involve

the use of Probability Theory and random sampling from probability distribution functions that, at scale, is only achievable by the use of computers.

Computing infrastructure at the hardware and software level plays an important role in the theoretical and experimental development of the field of particle physics: the development of algorithms that allow scientists to simulate particle physics processes given a set of initial conditions, parameters and the assumptions of new models is as important as the development of the algorithms needed to perform the reconstruction of physical properties based on the billions of outgoing signals captured by the detectors, amplified by the electronics and stored in specialized data structures that are optimized for later network retrieval and made available to scientists around the globe.

The work of experimental scientists in a large collaboration of particle physicists can be generally divided into three different categories: First, there is continuous need to design, build, test and bring to production, detectors that are able to handle the extreme radiation environment of the experiments; in this category we could also include activities related to the installation, calibration and commissioning of the detectors. Second, there is the need to develop and maintain computing tools that allow scientist to produce simulations of both speculated new physics models and well known physics processes in particle physics, and also to perform simulations of the detector response to the particles produced in the collisions. Third, there is the need to perform the data taking process and to analyze the data produced by the experiments to extract physics results and new knowledge. During the execution of this PhD research program I have been involved in these three areas. This dissertation aims to provide an overview of the research work that has been done as well as the context, the motivation and the results achieved in each of these areas.

An important amount of the work done in this dissertation comes from the analysis of data taken by the CMS collaboration during the 2016-2018 (Run2) time period. The data collected by the detector is unbiased and not targeted to a specific physics process. Instead, high energy physics events are recorded and then analyzed in a variety of decay channels by different analysts in the search of new physics or to perform precision measurements of the Standard Model.

Here, I perform a search for new physics in the context of the Heavy Vector Triplet (HVT) framework, this theoretical framework synthesizes different models predicting a diboson resonance. The framework itself opens up the possibility of the existence of a set of heavy particles W' and Z' while conserving the predictive validity of the Standard Model. One important aspect of these resonances is that they can be probed through the well-known vector bosons responsible for the electroweak interaction, $W^\pm$ and Z . This dissertation focuses on the fully leptonic decay channel of the $W^\pm$ boson. The results are interpreted in the context of a weakly coupled (model A) and a strongly coupled (model B) scenario.

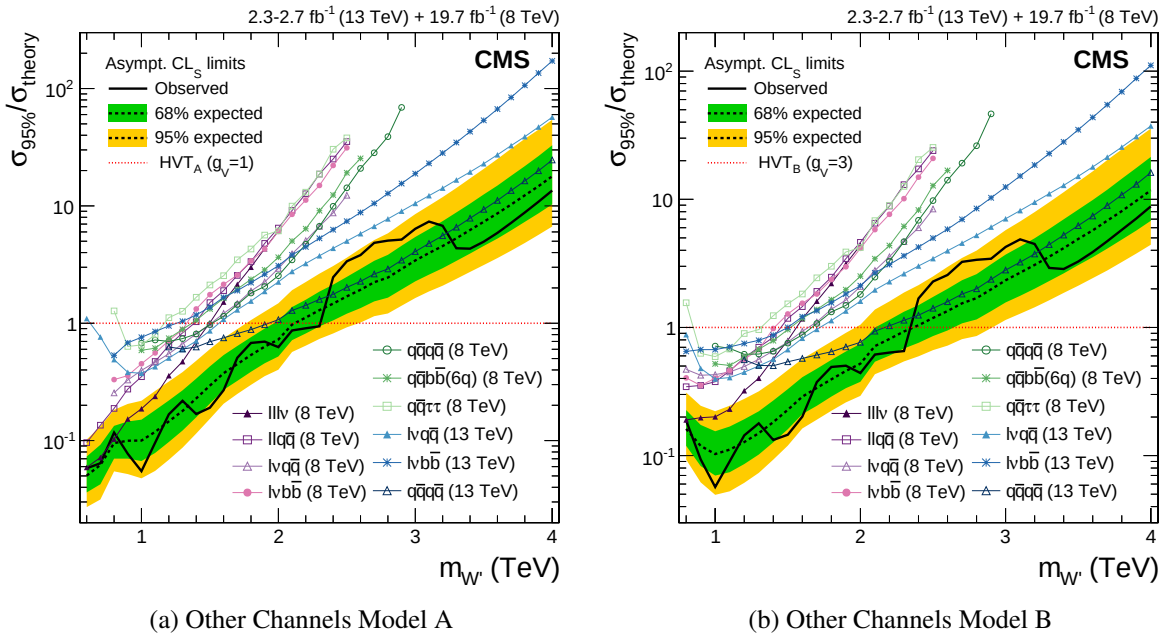


Figure 1.1: Exclusion limits at 95% CL for HVT models A (left) and B (right) on the signal strengths for $W' \rightarrow WZ$ and WH as a function of the resonance mass, obtained by combining the 8 and 13 TeV analyses. The signal strength is defined as the ratio of the excluded cross-section and the theoretical prediction. The curves with symbols refer to the different inputs to the combinations. (Sirunyan *et al.*, 2017)

Figure 1.1 shows the exclusion limits at 95% CL for HVT models A (left) and B (right) on the signal strengths for $W' \rightarrow WZ$ in different decay channels and at different center of mass energies as well as their combination. As it can be seen, performing this search at the 13 TeV center

of mass adds to the body of current knowledge pertaining to the exclusion limits of the electrically charged diboson resonance.

In [chapter 2](#) a brief overview of some of the most important experimental results that lead to the development of the field of particle physics is presented as well as a brief introduction to the Standard Model of Particle Physics. Some of the shortcomings of the Standard Model are briefly discussed in [chapter 3](#) along with an introduction to the Heavy Vector Triplet framework that compose the theoretical foundations for the search for new physics performed in this dissertation (see [chapter 6](#)). In [chapter 4](#) the reader will find an overview of CERN as an organization and the LHC facility, as well as a description of the CMS experiment. In [chapter 5](#) a brief description of the contribution to the upgrade process of the Pixel detector is provided. Finally, [chapter 7](#) summarizes the main results of the diboson resonance analysis performed and overall conclusions that are drawn from the work done in this dissertation.

CHAPTER 2

Particle Physics: An experimentalist's perspective

*"The test of all knowledge is experiment.
Experiment is the sole judge of scientific truth."*

— Richard Feynman

The scientific study of the structure of matter has its roots in the early 20th century. Even though Greek philosophers such as Democritus were among the first to speculate about the existence of indivisible basic building blocks of matter, naming them atoms back in the 5th century BCE, it was not until experiments performed by John Dalton, J.J. Thomson, Ernest Rutherford and others that jumpstarted the field of atomic physics. These experiments took the concept of building blocks of matter from an abstract philosophical discussion to a scientific study of nature. This chapter will provide an overview of the development of the field of particle physics, its main ideas and the experimental evidence that supports them. In [section 2.1](#) I briefly describe the outcomes from the first experimental studies that provided evidence for the existence of atomic and sub-atomic structures. In [subsection 2.1.1](#) I talk about the experiments and theoretical developments that led to the understanding of the discrete nature of energy and matter. In [section 2.2](#) an overview of the framework of the Standard Model and the most fundamental building blocks of matter will

be provided. [subsection 2.2.1](#) will describe the weak interaction and the experimental evidence that forms the basis for an understanding of the vector bosons $W^\pm$ and Z^0 . In [subsection 2.2.2](#) I describe the concerns that led to the concept of the Higgs field and in . I describe the main motivations for the search of physics beyond the Standard Model with a focus on the search for diboson resonances at the LHC.

2.1 The inception of Particle Physics

Dalton's study about the behavior of gases, and his conclusion about the law of partial pressures in 1803, was one of the firsts experiments that provided evidence for the idea that gases in a mixture behave as if they are composed of independent particles ([Thackray, 1966](#)). Later on, J.J. Thomson, in his famous experiment with a cathode ray tube, provided evidence on the existence of particles that were lighter than atoms while carrying electric charge. The concept of a stream of particles emitted from an electrode successfully explained the behavior of cathode rays and ignited the idea of the existence of a substructure beyond what was considered, previously indivisible, atoms ([Griffiths, 1997](#)).

$$E_n = -\frac{m_e e^4}{8\epsilon_0^2 h^2 n^2} \quad (2.1)$$

Equation 2.1: The energy levels of the hydrogen atom, as described by Bohr's model. The energy E_n of the atom is inversely proportional to the square of the principal quantum number n . m_e , e , ϵ_0 and h are all constants representing the mass of the electron, the charge of the electron, the permittivity of free space and the Planck constant respectively.

The atomic model proposed by Thomson failed to explain later experiments such as the large deflection of α particles when interacting with a thin gold foil. This experiment, initially performed in 1909 by Hans Geiger and Ernest Marsden was then explained by Ernest Rutherford in 1911. The explanation involved the idea of a dense nucleus surrounded by a cloud of electrons ([Rutherford, 1911](#)). It was not until Niels Bohr, where the idea of electrons orbiting the nucleus, in quantized levels, was introduced. This was a response to the observance of spectra

from atoms in experiments performed by Robert Bunsen and Henry Cavendish, during the 1860s, and it was aligned with the idea of the existence of quantized energy levels later proposed by Max Planck, when explaining the phenomenon of black body radiation ([Planck, 1901](#)).

The idea of quantized levels of energy was revolutionary, because there was a significant conceptual jump in the departure from the continuous nature of energy to a discrete one. Models that assumed a continuous nature of energy, such as the Rayleigh-Jeans law or the Wien displacement law failed to fully describe the observed spectra of a seemingly innocuous phenomenon such as the emanation of light from a hot surface.

$$B(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda kT}} - 1} \quad (2.2)$$

Equation 2.2: The black body radiation formula describes the spectral radiance $B(\lambda, T)$ of an object as a function of the wavelength λ and the temperature T of the object.

The idea of quantized energy levels contradicted the view of the classical physical laws where energy could take any value and any amount could be transferred continuously between different systems. The scientific community initially had difficulty accepting the idea that energy could only be absorbed or emitted in discrete packets. However, this concept was consistent with the idea of the existence of a discrete nature of matter, as quantization was also seen in the electric charge with experiments such as those performed by Robert Millikan in 1909, where the elementary electric charge was measured for the first time ([Millikan, 1913](#)). Further evidence in the search for a consistent discrete view of the nature of energy could be found in the discovery of the photoelectric effect, when a series of experiments by Heinrich Hertz in 1887 showed that light could be used to eject electrons from a metallic surface, for an in-depth description of Hertz contribution to the development of electromagnetic theory see ([Hertz, 1893](#)).

$$E = hf - \phi \quad (2.3)$$

Equation 2.3: The photoelectric effect shows the relationship between the energy E of the ejected electron, the frequency f of the incident photon, and the ϕ , the minimum energy required to eject an electron from the surface. ϕ is known as the work function and depends on the electric properties of the surface's material.

The photoelectric effect showed that there is a minimum amount of energy required to eject an electron from a metallic surface. However, this threshold couldn't be surpassed by an increase in the intensity of light, as expected from classical physics, but only by increasing the frequency of the light shone on the surface. In 1905, Albert Einstein, based on the notion of discrete packets of energy, explained the photoelectric effect. In his explanation, Einstein showed that the amount of energy in each packet is proportional to the frequency of the light and therefore there's no need to change the intensity of the light to surpasses the energy threshold of the material, but instead a change in frequency is enough (Arons and Peppard, 1965).

$$\lambda = \frac{h}{p} \quad (2.4)$$

Equation 2.4: The de Broglie wavelength of a particle with momentum p . The De Broglie wavelength λ is proportional to the inverse of the momentum p of the particle. The proportionality constant is given by the Planck constant h .

2.1.1 Evidence of the Discrete Nature of Matter

In 1924, in his doctoral thesis, Louis de Broglie proposed that there was not only duality in the behavior of light, but also in the behavior of matter. He proposed that matter could behave as waves, and that the wavelength of such wave was related to the momentum of the particle as described in equation 2.4. This hypothesis was tested and confirmed to be successful three years later by experiments done by Clinton Davisson and Lester Germer, in which a diffraction pattern was observed when electrons were fired at a crystal of nickel, an unexpected behavior for a particle but a totally expected one for a wave (Davisson and Germer, 1927).

Two years earlier, in 1922, Otto Stern and Walther Gerlach performed an experiment in which electrically neutral silver atoms were deflected by the presence of a magnetic field, and surprisingly the pattern seen in the deflection was not continuous but discrete (Friedrich and Herschbach, 2003). This experiment not only showed that particles possessed an intrinsic angular momentum (spin) but also that the nature of the angular momentum is discrete, just like energy.

$$i\hbar \frac{\partial}{\partial t} \psi(x, t) = \hat{H} \psi(x, t) \quad (2.5)$$

Equation 2.5: The Schrödinger equation describes the evolution of the wave function $\psi(x, t)$ over time. The equation relates the time derivative of the wave function to the Hamiltonian operator $\hat{H}$, which describes the energy of the system.

Erwin Schrödinger published in 1926 his paper *Quantization as an eigen value problem* where he showed that the temporal evolution of the wave function of a particle could be described by a wave equation. In this equation, the behavior of a particle is described by its wave function $\psi(x, t)$. The meaning of this wave function is still a matter of debate, but it has been shown by experiments that it can describe the probability density of observing a particle in a certain position at a given time, or equivalently, the statistical results when performing a large number of measurements in the same experiment.

$$\mu_B = \frac{e\hbar}{2m_e} \quad (2.6)$$

Equation 2.6: The Bohr magneton μ_B is the magnetic moment of the electron. e represents the charge of the electron, $\hbar$ represents the reduced Planck constant, and m_e represents the mass of the electron.

The discrete nature of energy and angular momentum, the particle-wave duality and Einstein's theory of special relativity, came to meet with Paul Dirac's theory of quantum mechanics. Dirac's equation is a relativistic, generalized version of the Schrödinger equation. This mathematical description is successful at explaining the so-called *fine structure* which is the additional

splitting of spectral lines in the spectrum of atoms due to the spin of the electron. Later, Dirac showed how the discreteness of quantities such as angular momentum and energy could be applied to the description of electromagnetic fields, which are traditionally described with a continuous function. This set the stage for the origin of Quantum Electrodynamics (QED). In QED, photons are the product of the quantization of the electromagnetic field. Numerous experiments have been performed to test QED, one of the most accurate prediction of the theory is the value of momentum of the magnetic moment of the electron which was measured by Polykarp Kusch in 1957 and slightly deviated from the Bohr magneton 2.6 which was derived from Bohr's atomic model (Heilbron and Kuhn, 1969). Current experiments are aiming at measuring the magnetic moment of the muon (Albahri *et al.*, 2021) and have identified slight deviations from the value initially predicted by QED. However, the predicted theoretical values are being revisited (Borsanyi *et al.*, 2021), and it is a matter of current research.

2.2 The Standard Model

One of the most remarkable consequences of Dirac's equation was the prediction of the existence of antimatter, which was first considered a complementary mathematical artifact of the theory. Anti-particles such as the positron are a consequence of solutions to Dirac's equation representing negative energy states. Later experiments by Carl Anderson in 1932 confirmed the existence of positrons. On the other hand, the idea of the quantization of the electromagnetic field developed by Dirac was one of the first steps in the evolution of Quantum Field Theory (QFT). In QFT, particles are described as excitations in a corresponding quantum field. These excitations can have two different flavors characterized by their spin: On one hand, the Fermions with spin $1/2$, which obey the Fermi statistics, and on the other hand, the Bosons with integer spin, which follow the Bose statistics. Fermions and Bosons contribute to model the behavior of matter in complementary ways: Fermions represent matter quantum fields such as the electrons, muons, or quarks, while Bosons act as the carriers of the different forces. For instance, the photon is the particle in charge of carrying or mediating the electromagnetic force, the gluons are the particles in

Standard Model of Elementary Particles

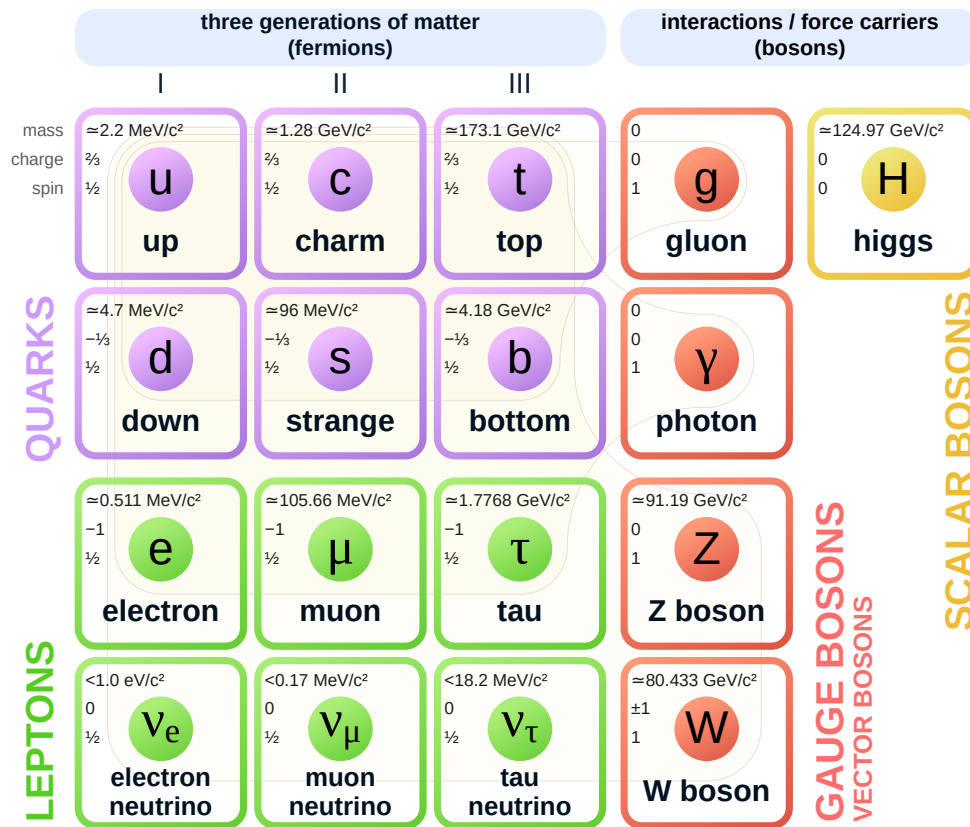


Figure 2.1: The Standard Model of Particle Physics ([Wikipedia, 2022](#))

charge of carrying the strong force, and the W and Z bosons are the mediators for the weak force; Fermions exclude each other from having the same quantum state, and serves as the basis for the Pauli exclusion principle, explaining for instance, why electrons can't occupy the same orbital in an atom which it itself makes matter stable and life possible, while bosons can be in the same quantum state modeling behaviors such as the Bose-Einstein condensate in which atoms, by virtue of being in the same quantum state, act highly coherent giving rise to macroscopic phenomena such as superconductivity, where electricity can flow with virtually no resistance or superfluidity, where a fluid can move without dissipating energy or flow up and out of its container.

Within the fermions, there are two subcategories of particles: the leptons and the quarks. Quarks, as opposed to leptons, participate in the strong interaction and are the building blocks of

subnuclear particles such as protons and neutrons. Leptons, on the other hand, participate only in the weak and electromagnetic interaction. Figure 2.1 summarizes the particles discovered so far and some of its properties including mass, charge and spin, if the charge flips in the image the result is corresponding to each anti-particle. Other quantum numbers as the isospin, weak hypercharge and color charge are not included.

$$SU(3) \times SU(2) \times U(1) \quad (2.7)$$

Equation 2.7: The three symmetry groups in the Standard Model of Particle Physics. $SU(3)$ is the symmetry group of the strong interaction, $SU(2)$ is the symmetry group of the weak interaction and $U(1)$ is the symmetry group of the electromagnetic interaction.

The Standard Model of Particle Physics (SM) is the most complete theoretical description of the fundamental particle and the interactions between them. It has been able to describe the inner workings of an atom at the largest energy scales achieved experimentally, thanks to the LHC at CERN these scales are as high as 13 TeV. SM makes use of three symmetry groups as indicated by equation 2.7. The standard model is able to model three out of the four fundamental forces of nature: the weak, strong and electromagnetic interactions.

The variational principle of least action can be rewritten to incorporate the quantization of The fields by means of the Lagrangian density $\mathcal{L}$ and the quantum field ϕ :

$$S = \int_{\mathcal{V}} \mathcal{L}(\phi, \partial_{\mu}\phi; x) d^4x \quad (2.8)$$

This principle is used to calculate the rates in which different particle principle processes occur and therefore providing a way to experimentally test the theory. The process is expressed in terms of an initial state, for instance the production of an unstable particle in a proton-to-proton collision, and its final state which is the product of its decay. This process can then be described as the temporal evolution of the field ϕ by using the Taylor expansion of the Lagrangian density of the interaction and the so called LSZ reduction formula (Shi and Sun, 2009). This perturbative

approach of the theory distinguishes different orders of contribution to the process defining the level of accuracy. An alternative way to approach the problem is by the use of Feynman diagrams, which, apart from providing a graphical representation of the process, they also provide a set of rules to calculate the amplitude of its cross-section by means of the scattering matrix (S -matrix) (Mattuck, 1992).

The dynamic and continuous interaction between theory developments and experimental results is how the problem of defining the SM Lagrangian has been tackled. Conserved quantities such as the energy and momentum of particles have been essential in the interpretation of experimental results and, from a theoretical point of view, the Noether's theorem has been a support and fundamental tool to identify symmetries in the Lagrangian while the conservation of associated quantities are continuously proved in experimental settings: In the SM, the symmetry group $SU(3)$ from Quantum Chromodynamics (QCD), sets the existence of a property called color charge to describe the interaction among quarks and gluons. Particles, such as the electron or the muon has no color charge and therefore are not affected by the strong interaction. Quantum confinement, on the other hand, states that only particles which components add to a neutral color charge can be observed. This is equivalent to say that quarks and gluons are confined to be part of composite particles, such as protons, neutrons and others hadrons. The symmetry group $SU(2)$ from the weak interaction presents the weak isospin as a conserved quantity while the electromagnetic interaction, described by the symmetry group $U(1)$ is found to be linked to the conservation of electric charge. $SU(2)$ and $U(1)$ were unified by the electroweak interaction where the hypercharge Y quantity is conserved. The electric charge Q , the weak isospin I and the Y hypercharge are related by the following equation:

$$Q = I + \frac{Y}{2} \quad (2.9)$$

2.2.1 The Weak Interaction

Experiments performed by Ernest Rutherford identified different kind of radiation based mainly on the depth of penetration by each kind in matter. α , β and γ radiation were later associated with fundamental particles such as protons and neutrons for the α radiation, electrons for the β radiation and photons for the γ radiation.

Carbon-14, a well known element, specially for its use in the process of *radiocarbon dating*, contains six protons and eight neutrons in its nucleus and is unstable. When a Carbon-14 atom decays it transforms into a Nitrogen-14 atom which contains seven protons and seven neutrons. While the number of nucleons in the nucleus remains the same, the number of protons and neutrons changes suggesting that a proton is transformed into a neutron, taking into account the conservation of charge we can conclude that a particle with a negative electric charge should be emitted in the process. In a need of a precise description for this process, the Fermi interaction was introduced by Enrico Fermi in 1934, and it was the precursor for the weak interaction. A complete theoretical description was written by Richard Feynman ([Feynman and Gell-Mann, 1958](#)). The weak interaction introduced three new bosons, two of them are the electrically charged W , with positive and negative charge, and the Z boson which is electrically neutral. In the beta decay, the quark content of the neutron changes, from udd , transforming into a proton, udu , with u representing the up quark and d the down quark. This change in the quark content is mediated by the W^- boson. The W^- boson then decays into an electron and anti-neutrino. The Z boson, on the other hand, becomes a mediator in the exchange of momentum, energy and spin when neutrinos interact with electrons, it also exercises a fundamental role in neutrino detection.



Equation 2.10: The cobalt-60 nucleus decays producing a nickel-60 nucleus, an electron, and an antineutrino. This is an example of the beta decay process, in which the quark content of

the neutron changes to transform into a proton plus additional particles to ensure the conservation properties of the weak interaction.

There are a number of striking experiments that have been performed to test and study the properties of the weak interaction, one of them is the Wu experiment ([Wu *et al.*, 1957](#)), which deserves a special mention. The experiment was performed in order to test the conservation of parity in the β decay. Parity is a symmetry operation that involves the inversion of the sign of the position coordinates of a particle, and it is commonly described as the mirror reflection of a particle. The experiment used a conceptually simple setup but a challenging experimental achievement to perform. Mainly because of the need to lower the temperature of the experiment close to absolute zero. The experiment used a sample of Cobalt-60 with a polarization of nuclear spins determined by the orientation of a strong magnetic field. As shown in equation [2.10](#), the Cobalt-60 nucleus decays through the emission of an electron and an antineutrino into a Nickel-60 nucleus. Parity conservation would imply that the number of the electrons emitted in the decay process should be the same for parallel and antiparallel directions to the magnetic field. Instead, the experiment showed that there were more electrons emitted in the opposite direction to the magnetic field, than in the parallel direction. This result is evidence of the violation of parity in the weak interaction, but more fundamentally, it shows that nature can differentiate between left and right-handed systems. Later experiments and theoretical understanding showed that even though there is violation of parity symmetry. There has not been experiments that have shown a violation of the CPT symmetry, which includes charge conjugation, parity and time reversal simultaneously. CPT symmetry is a consequence of the invariance under Lorentz transformations ([Greenberg, 2006](#)).

2.2.2 The Electroweak Symmetry Breaking

As suggested initially by Schwinger ([Schwinger, 1957](#)), and later developed by Weinberg ([Weinberg, 1967](#)) a gauge theory could provide a unification of the electromagnetic and weak forces into the electroweak interaction. Experimental evidence supporting this theory through the discovery of the $W^\pm$ and Z^0 vector bosons was first captured by CERN ([Hasert *et al.*, 1974](#); [Arnison](#)

et al., 1983; Banner *et al.*, 1983). The unification of electromagnetic and weak interactions brings with it symmetry requirements, which yields massless gauge bosons; however, massless W and Z were not consistent: neither with the short range of the weak interaction nor the experimental evidence.

In order to overcome this inconsistency between the mathematical description of the standard model and the outcome of the experiments, the *Higgs mechanism* was introduced by Peter Higgs (Higgs, 1964). The Higgs mechanism was later developed to explain not only the origin of mass of the $W^\pm$ and Z^0 bosons but also the mass of fermions. The cost of the Higgs Mechanism is the addition of a scalar field to the SM Lagrangian:

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

This contribution to the standard model Lagrangian comes with a prediction for the existence of the Higgs field ϕ and its associated boson, the Higgs boson. The successful finding of the widely expected Higgs Boson (Chatrchyan *et al.*, 2012; Barton *et al.*, 2012), and its 125 GeV, lighter than expected mass, was the experimental evidence supporting the Higgs mechanism and gave Higgs and Englert, who independently developed the theory, the 2013 Nobel Prize in Physics (Higgs, 2014).

CHAPTER 3

Beyond the Standard Model

*"The only way to make sense out of change is to
plunge into it, move with it, and join the dance."*

— Alan Watts

The Standard Model of Particle Physics have been shown to be successful in numerous experiments and to be resilient to some of the most stringent tests in experimental physics. However, the SM does not provide a complete description of nature, which physicist have always aimed for. There are many unanswered questions that the SM does not provide an explanation for. The SM from its foundation, does not provide a description of gravity, which is the dominant force at large scales and a fundamental force in nature. It is not possible to derive the gravitational interaction from the SM and there is a large discrepancy among the orders of magnitude of the electroweak, strong and gravitational forces. This discrepancy is known as the *hierarchy problem*. For a more detailed discussion on the hierarchy problem, see ([Arkani-Hamed, Dimopoulos, and Dvali, 1998](#)).

Dark matter is a way to explain the discrepancy between the observed orbital velocity of stars around their galactic center and its expected value due only to the observed matter density distribution in the galaxy. This theorized form of matter that does not interact with matter either through electroweak or strong interactions, making it difficult to detect at the length and energy scales of the LHC, interacts through gravity and its presence can be inferred through the phe-

nomenon known as gravitational lensing, in which light bends due to the distortions of space-time caused by the presence of matter, either regular or dark, according to Einstein's general relativity principles. The direct detection of dark matter has not been achieved yet, but there are an increasing number of efforts to detect it. An important review on the LHC efforts towards the search of dark matter can be found in ([Kahlhoefer, 2017](#)).

From Cosmology, it is known that the universe is in a phase of accelerated expansion. Experimental evidence of this expansion is provided by the measurement of the redshift of galaxies. The rate in which the galaxies are moving away from the earth is proportional to its relative distance to the earth. This phenomenon is known as the Hubble expansion can not be explained by current theories of gravity or the SM, but instead the hypothesis of the existence of dark energy is used to explain it. A review is left to the reader for a more detailed discussion on the subject ([Copeland, Sami, and Tsujikawa, 2006](#)).

Dark matter and dark energy are estimated to make up 95% of the universe ([Aghanim et al., 2020](#)) and the physical nature of these is still unknown. One of the implications of this estimate is that there is plenty of room for new physics to be discovered.

3.1 Simplified Models

Currently, there are a variety of theoretical extensions to the SM that have been proposed to account for its theoretical shortcomings. These extensions present themselves in the form of frameworks and not as a single, complete model. Frameworks are founded on a set of general assumptions and usually propose the existence of either new particles, interactions, or both. Based on these general assumptions different theoretical models can be developed, but an experimental test of each specific model is beyond the capabilities of the scientific community due to the large number of possible models in each framework and within each model the search of the specific space of parameters would generate an unmanageable amount of hypothesis and would be impossible to test all of them in a reasonable amount of time with a limited amount of resources. One way to overcome this problem is the use of simplified models ([Alves et al., 2012](#)).

Simplified models look for a subset within general new physics scenarios. These physics scenarios are described by an effective Lagrangian dependent on a defined energy scale. Restricting the number of particles from those physics scenarios that are considered for the search implies that the number of parameters is also reduced but does not make a search model independent as it is still tied to the assumptions within the framework. If a predicted particle is found to be consistent with the experimental data, then it would imply that the assumptions of the framework were made in a fruitful way and will signal the need to concentrate resources to investigate and develop a specific model within the given framework.

When it comes to the search for resonances at the LHC, what counts the most are the parameters that determine on one hand, the kind of decay and on the other, the mass of the resonance. These parameters can be used to build a phenomenological Lagrangian that fulfill symmetry constraints and describes the part of the process that satisfy the energy-momentum relation, i.e. it is not concerned with off-shell effects involving virtual particles. Focusing on the on-shell observables such as the cross-section, branching ratios and the decay width allows for an effective simplification leading to the ability to extract limits for the production rate of the process.

The parameter space of the simplified Lagrangian can then be scanned experimentally and later translated into a specific model. One of the characteristic features of the simplified model approach is that it is mainly concerned with the resonant peak, an important experimental signature, and not so much with the tails of the distribution as the latter can come from a variety of sources, including new physics effects or the presence of heavier resonances decaying into the same channel, which are not included in the simplified model.

3.2 The Heavy Vector Triplet Framework

Some of the most promising hypotheses addressing the Electroweak Symmetry Breaking (EWSB) propose that the Higgs field emerges from a new strongly-interacting composite sector. An unavoidable consequence of these theories is the existence of Spin-1 vector resonances decaying to heavy vector bosons. Broadly speaking these resonances fall into two categories: electrically

charged resonances, commonly referred as W' , and neutral resonances Z' (de Blas, Lizana, and Pérez-Victoria, 2013). These resonances might be available at the TeV scale (Khachatryan *et al.*, 2014), the current energy scale of the Large Hadron Collider (LHC).

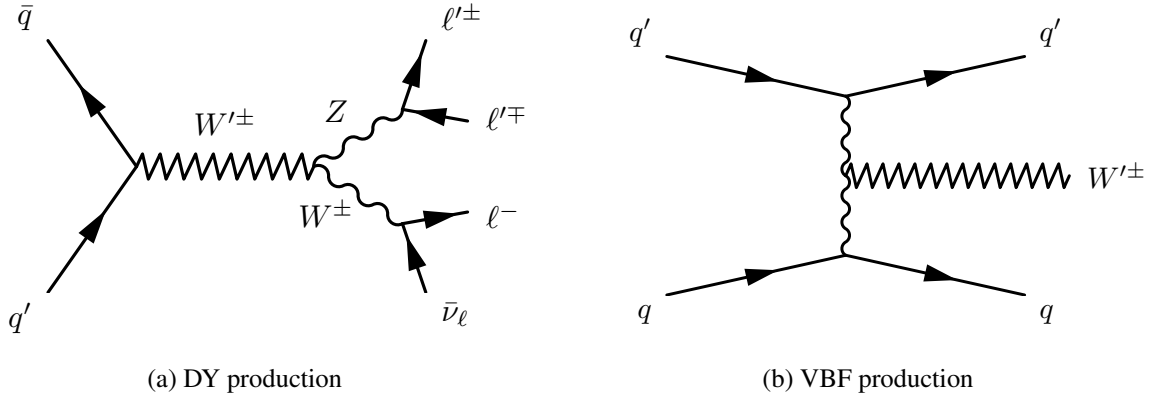


Figure 3.1: Drell-Yan (left) and Vector Boson Fusion (right) production modes for a W' resonance. The Feynman diagram for Drell-Yan production also displays the fully leptonic decay studied in this dissertation.

As shown in (Pappadopulo *et al.*, 2014) the new vector resonance simplified Lagrangian, relevant to LHC searches is given by Equation 3.1.

$$\begin{aligned}
 \mathcal{L}_V = & -\frac{1}{4}D_{[\mu}V_{\nu]}^a D^{[\mu}V^{\nu]a} + \frac{m_V^2}{2}V_\mu^a V^{\mu a} \\
 & + ig_V c_H V_\mu^a H^\dagger \tau^a \overleftrightarrow{D} H + \frac{g^2}{g_V} c_F V_\mu^a J_F^{\mu a} \\
 & + \frac{g_V}{2} c_{VVV} \epsilon abc V_\mu^a V_\nu^b D^{[\mu}V^{\nu]c} + g_V^2 c_{VVHH} V_\mu^a V^{\mu a} H^\dagger H - \frac{g}{2} c_{VVW} \epsilon abc W^{\mu\nu a} V_\mu^b V_\nu^c
 \end{aligned} \tag{3.1}$$

Where c_H accounts for the resonance interactions with the standard model vector bosons $W^\pm$ and Z , but also the scalar Higgs field H . c_F , on the other hand, accounts for the interaction with fermions which can be expressed in a more general way (see Equation 3.4) to take into consideration the differences between leptons, and light and heavy quarks. By varying the coupling g_V , different scenarios can be tested from values $g_V \sim 1$ to values $g_V \sim 4\pi$ to denote both weakly to

strongly coupled scenarios as it will be seen in [subsection 3.2.1](#) and [subsection 3.2.2](#). The vector V_μ^α accounts for both neutral and charged vector resonances. Where:

$$V_\mu^\pm = \frac{V_\mu^1 \mp iV_\mu^2}{\sqrt{2}}, \quad V_\mu^0 = V_\mu^3 \quad (3.2)$$

The first and second terms from [Equation 3.1](#) contain the kinetic and mass terms as well as further interactions with vector bosons by means of the covariant derivative D_μ :

$$D_\mu \rightarrow \partial_\mu V_\nu^\alpha + g\epsilon_{abc}W_\mu^bV_\nu^c \quad (3.3)$$

The third term on the other hand, expresses the dynamics of the interaction of the vector resonance with the Higgs currents. For more generality, the coupling of V to fermions can be decomposed into the following form:

$$c_F V_\nu^\alpha \cdot J_F = \sum_{i=l,q,3} c_i V_\nu^\alpha \cdot J_i \quad (3.4)$$

Where l represents leptons, q light quarks and 3 the third generation quarks. c_i , typically of order one, and J_i are the coupling constant and the current respectively. There are two production modes for the diboson resonance: the Drell-Yan (DY) mode, in which a quark from one of the colliding protons interacts with an anti-quark of its counterpart, and the Vector Boson Fusion, commonly abbreviated as VBF, in which a quark from each of the colliding protons radiates a vector boson and the two vector bosons subsequently interact to produce a resonance while the initial quarks further decay into jets. Feynman diagrams for both production modes are shown in [Figure 3.1](#). In this dissertation, the DY production mode will be studied. For more details on VBF in the context of LHC searches see ([Baker et al., 2022](#)).

3.2.1 Model A: Extended Gauge Symmetry

The benchmark A, corresponds to a model where the HVT emerges from weakly-coupled extensions of the SM gauge group in $SU(2)_1 \times SU(2)_2 \times U(1)_Y$ ([Barger, Keung, and Ma, 1980](#)). This

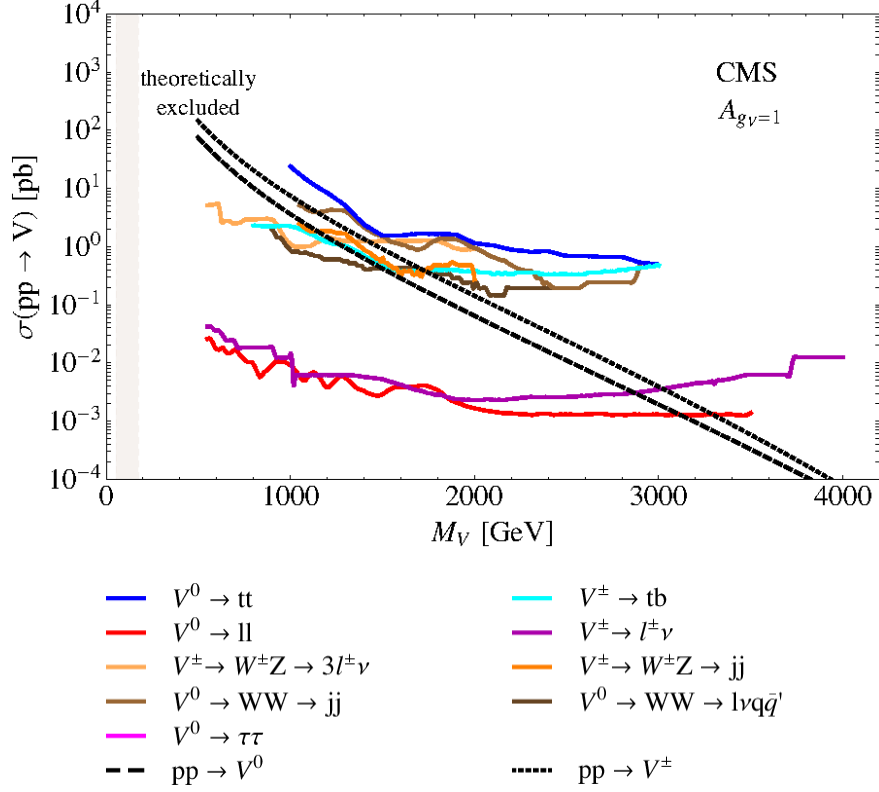


Figure 3.2: Bounds on the production cross-section for available searches at the time of publication for the models $A_{g_V=1}$ for the CMS collaboration. The black dashed curves represent the theoretical prediction. $V^\pm$ corresponds to the HVT $W^\pm$ while V^0 corresponds to the HVT Z^0 (Pappadopulo *et al.*, 2014)

is achieved by introducing a scalar field Φ with a vacuum expectation value (VEV) equivalent to $\langle \Phi \rangle = f\mathbb{I}$. This VEV breaks the gauge symmetry, from where the HVT and the SM vector bosons, $W^\pm$ and Z emerge.

As shown in (Pappadopulo *et al.*, 2014) the couplings required to reproduce Equation 3.1 are:

$$c_H \sim -g^2/g_V; c_F \sim 1 \quad (3.5)$$

The region of g_V in which model A is considered corresponds to $g_V \sim 1$.

3.2.2 Model B: Minimal Composite Higgs Model

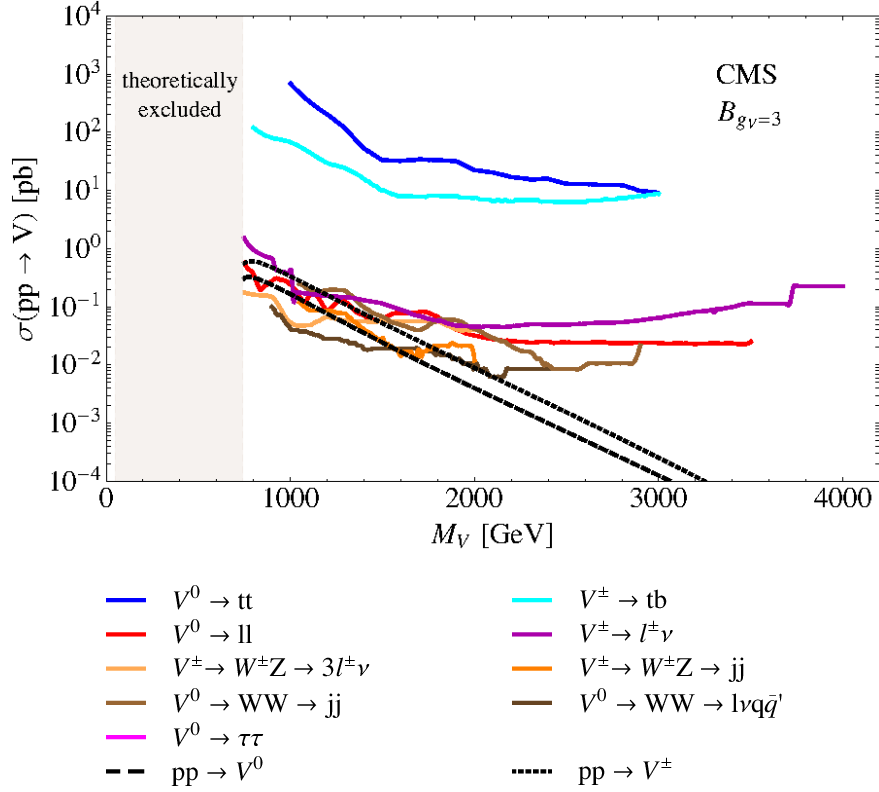


Figure 3.3: Bounds on the production cross-section for available searches at the time of publication for the models $B_{g_V=3}$ for the CMS collaboration. The black dashed curves represent the theoretical prediction. $V^\pm$ corresponds to the HVT $W^\pm$ while V^0 corresponds to the HVT Z^0 (Pappadopulo *et al.*, 2014)

A Minimal Composite Higgs Model (MCHM), referred as Model B corresponds to a model where heavy vectors emerge from a strongly-coupled Composite Higgs scenario (Contino *et al.*, 2011) where the bosonic and fermionic couplings are of the same order of magnitude:

$$c_H \sim 1; c_F \sim 1 \quad (3.6)$$

In the current study the region of g_V in which model B is considered corresponds to $g_V \sim 3$.

CHAPTER 4

CERN, The LHC, and The CMS Experiment

*”What we observe is not nature itself,
but nature exposed to our method of questioning.”*

— Werner Heisenberg

4.1 The European Organization for Nuclear Research

The European Organization for Nuclear Research, CERN (by its French acronym) was established 67 years ago, in 1954. Its headquarters are located on the French-swiss border and runs the highest energy particle physics laboratory in the world. As of 2019, 2660 staff members supported CERN activities, 45% of them employed as Engineers and applied scientists ([CERN, 2020](#)). CERN is home of dozens of experiments in a wide range of physics areas across its large infrastructure: from radio-astronomy experiments such as the CERN Axion Solar Telescope (CAST) ([CAST collaboration, 2004](#)), passing through fixed-target nuclear physics experiments such as COMPASS ([Abbon *et al.*, 2007](#)) or NA61 ([Abgrall *et al.*, 2014](#)) to Particle physics experiments such as CMS ([CMS Collaboration, 2008](#)) or ATLAS ([Aad *et al.*, 2008](#)). In addition to the staff, more than 12.4 thousand scientific users from over 110 nationalities perform research at CERN through institutes located in 70 different countries affiliated to the experiments. The number of users is led by the United States, followed by Italy and Germany ([CERN, 2020](#)). CERN scientific

program is mainly supported by contributions from the member states, with a fiscal budget for 2021 close to (USD)\$1.4 billion.

4.2 The Large Hadron Collider

The Large Hadron Collider (LHC) is a circular particle accelerator for protons and heavy ions with a circumference of *27 km*: the diameter of the accelerator is approximately equivalent to the distance between the Basilica of the National Shrine of the Immaculate Conception in Washington, DC, and The Pentagon administrative building in Arlington, Virginia. The LHC building process was finished in the 44th CERN anniversary, in 2008, and the first set of collisions took place in 2010.



Figure 4.1: Timeline for the LHC and HL-LHC (High Luminosity LHC) (CERN, 2016).

Figure 4.1 shows a timeline for the LHC/HL-LHC, the names, the center of mass energy and luminosity projected for the different periods. Long shutdowns (LS) are also shown where major changes are expected either on the LHC or the main experiments. The data used in the physics analysis presented in this thesis was collected during Run 2, from 2016 to 2018. The data is split on a per-year basis to account for changes in the conditions of the detector and the collisions.

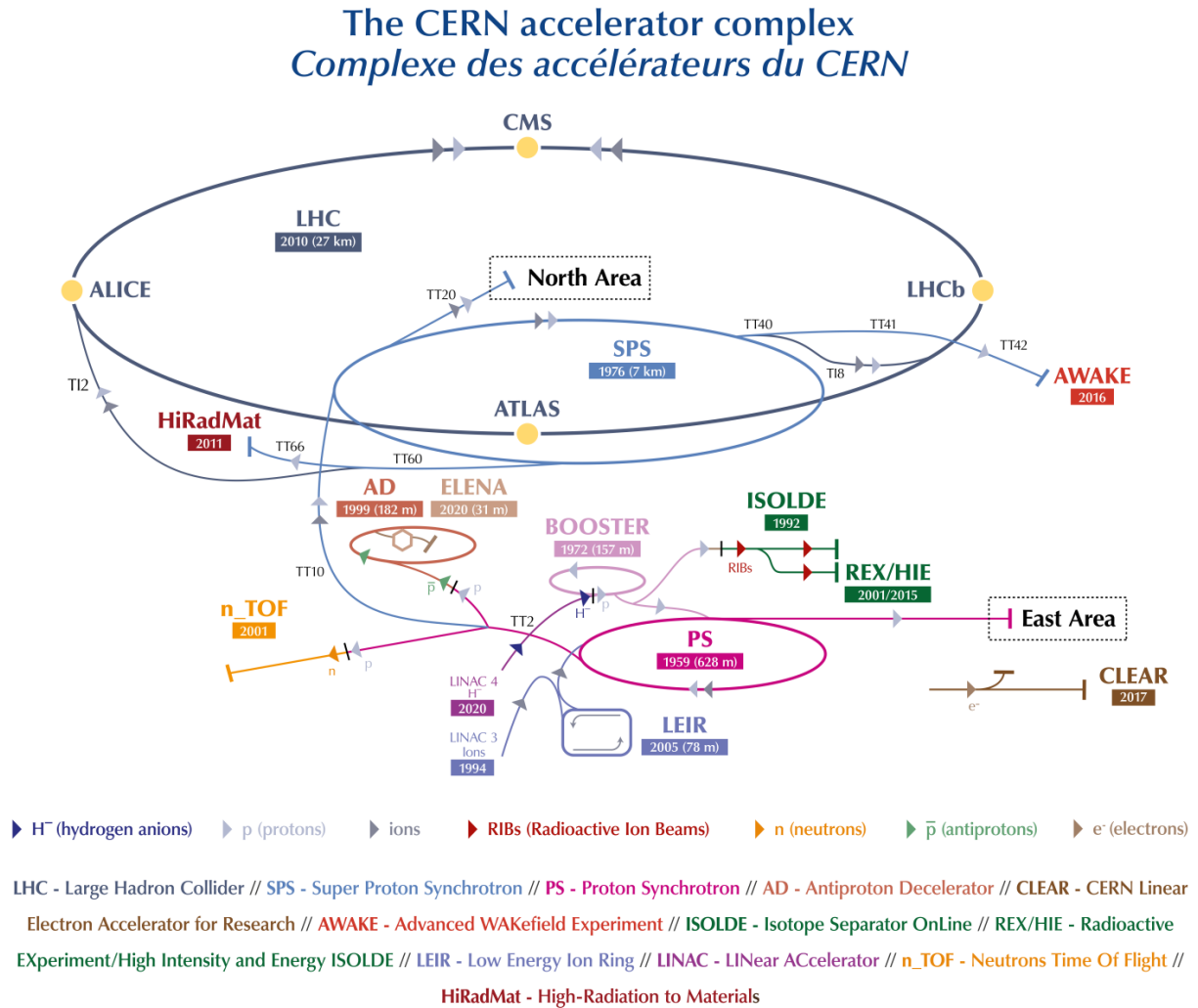


Figure 4.2: The CERN accelerator complex. The picture displays the complete acceleration process from the source of hydrogen nuclei to the location of the collision points in the experiments. Labels indicate the year(diameter) and shows how the LHC has been built on top of existing infrastructure.

The protons are accelerated in a set of stages, taking advantage of existing infrastructure within CERN. [Figure 4.2](#) the process of acceleration begins with a small bottle of hydrogen gas, electrons from the hydrogen atoms are stripped leaving space for protons on the source chamber of the linear accelerator LINAC2 (built in 1972 and replaced by LINAC4 in 2020), which is the first stage of acceleration; at the end of this stage protons will be traveling at roughly one third of the speed of light c . The protons are then injected into the booster (1972): a circular accelerator of about 24 m of radius where the continuous beam of protons is split into packages; the four different rings of the booster, handle the acceleration and compression of each proton package by means of a combination of electric and magnetic fields. The booster's output are protons accelerated to a speed of about $0.91 c$. These protons will be injected into the Proton Synchrotron (1959); another circular accelerator of about 100 m of radius where the packages reach $0.999 c$ in about 1.2 seconds, representing an energy per proton of 25 GeV. The packages of protons then proceed to the Super Proton Synchrotron (1976) with a radius of 1.1 km where they reach an energy of 450 GeV finally reaching the Large Hadron Collider LHC (2008). At this point there are two vacuum pipes within the LHC as packages are accelerated in opposite directions, clockwise and anticlockwise. A proton package with such energy is able to complete about 11.000 cycles in the LHC ring in less than 1 second. This acceleration process makes available to the experiments two proton beams of about 6.5 TeV resulting in a collision with a center of mass energy $\sqrt{s} = 13$ TeV, which is the energy at which the collisions studied in this thesis took place.

4.3 The CMS Detector

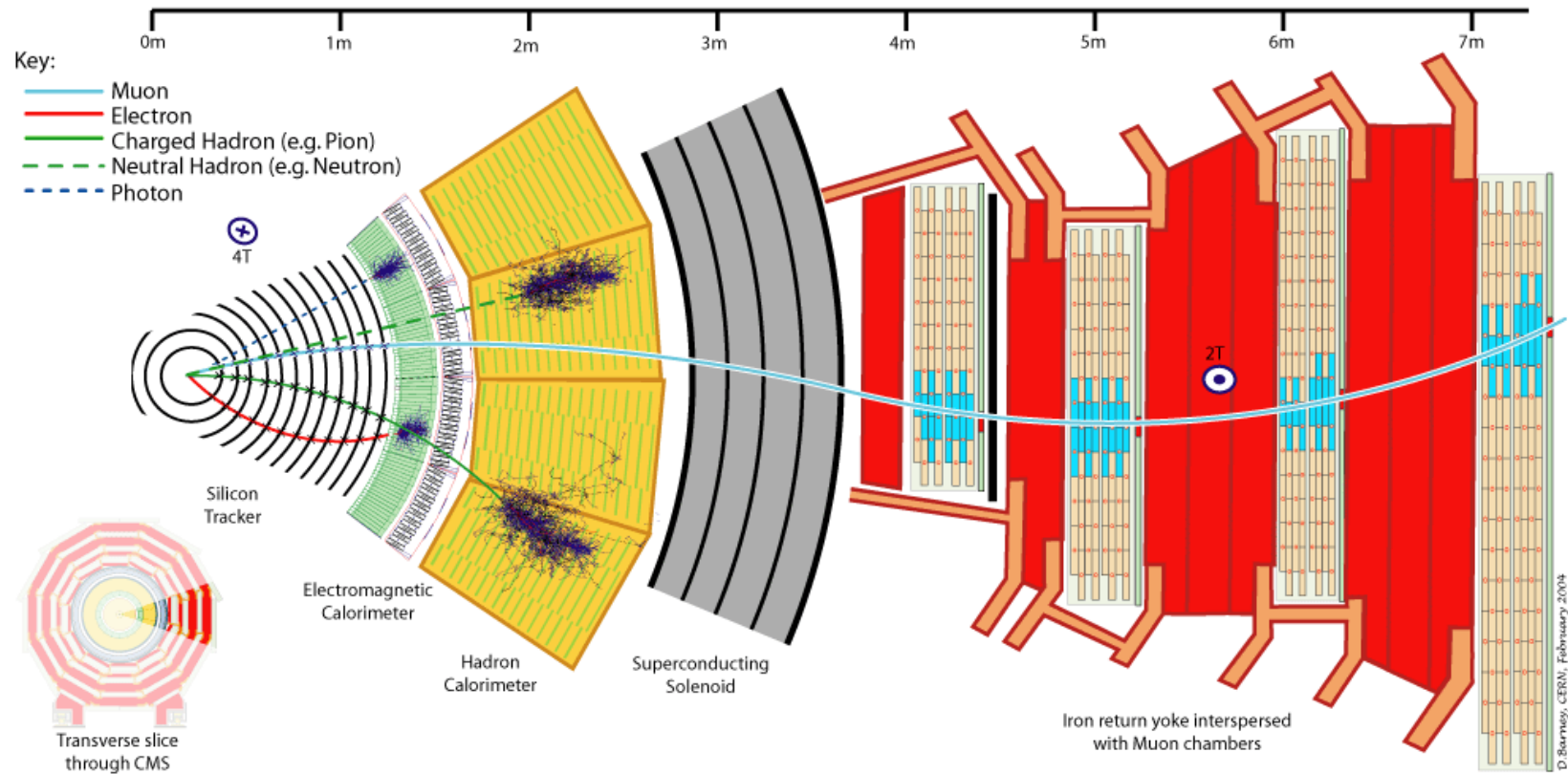


Figure 4.3: Slice of a cross-sectional view of the CMS detector displaying the different subsystems, from left to right: the tracker, the electromagnetic (green) and hadronic (yellow) calorimeters, the superconducting solenoid (blue) and the muon system. The point of convergence of the concentric layers of the silicon tracker is the area in which the interaction point is found. The effect in the trajectory of different particles due to the presence of the magnetic field is also shown. (CMS Collaboration, 2016)

The Compact Muon Solenoid (CMS) is a cylindrical, general purpose detector. Although, the acronym CMS is used to simultaneously denote, the detector, the scientific collaboration and the experiment. The detector is 21 m long with a diameter of 15 m, and it weights about 14kt. The average density of CMS is close to 855 kg/m^3 and hence the word *compact* in its name. The CMS set of sub-detectors, allow to measure the physical properties of different particles. Among these particles, Muons place an important role in the search for new physics. Muons are the product of high energy head-on collisions and therefore their presence is signature of interesting physics events. For instance, one of the main channels in the Higgs boson discovery contained four muons in the final state $H \rightarrow ZZ$ ([Chatrchyan et al., 2012](#)). The CMS detector features a superconducting solenoid generating a 3.8T magnetic field, which is a hundred thousand times stronger than that of the Earth (see Section [4.3.3](#)).

The CMS experiment is located in the commune of Cessy (France), close to the border between France and Switzerland, where CERN's main campus is based. The scientific collaboration is composed by more than four thousand people from two hundred and six institutions. The Catholic University of America is, as of 2022, the only institution representing the District of Columbia in the CMS collaboration.

The CMS experiment is one of the four points along the LHC in which hadronic collisions take place. Every 25 ns, hundreds of thousands of millions of protons (or heavy ions, depending on the collision configuration) are injected from the beam pipe into the center of the detector. From this vast number of protons only a handful collide. For instance, during the 2016 data taking period an average of 23 collisions per bunch crossing occurred. Once the hadrons collide, the products of each collision make their way through the different subdetectors. The very first detector, the Tracker detector, keeps track of the trajectory followed by charged particles generated during the collision. The trajectory is reconstructed from hits in the different layers of silicon detectors allowing us to assign identities to the particles and a given curvature in each trajectory (due to the presence of the magnetic field) allow us to measure their momentum.

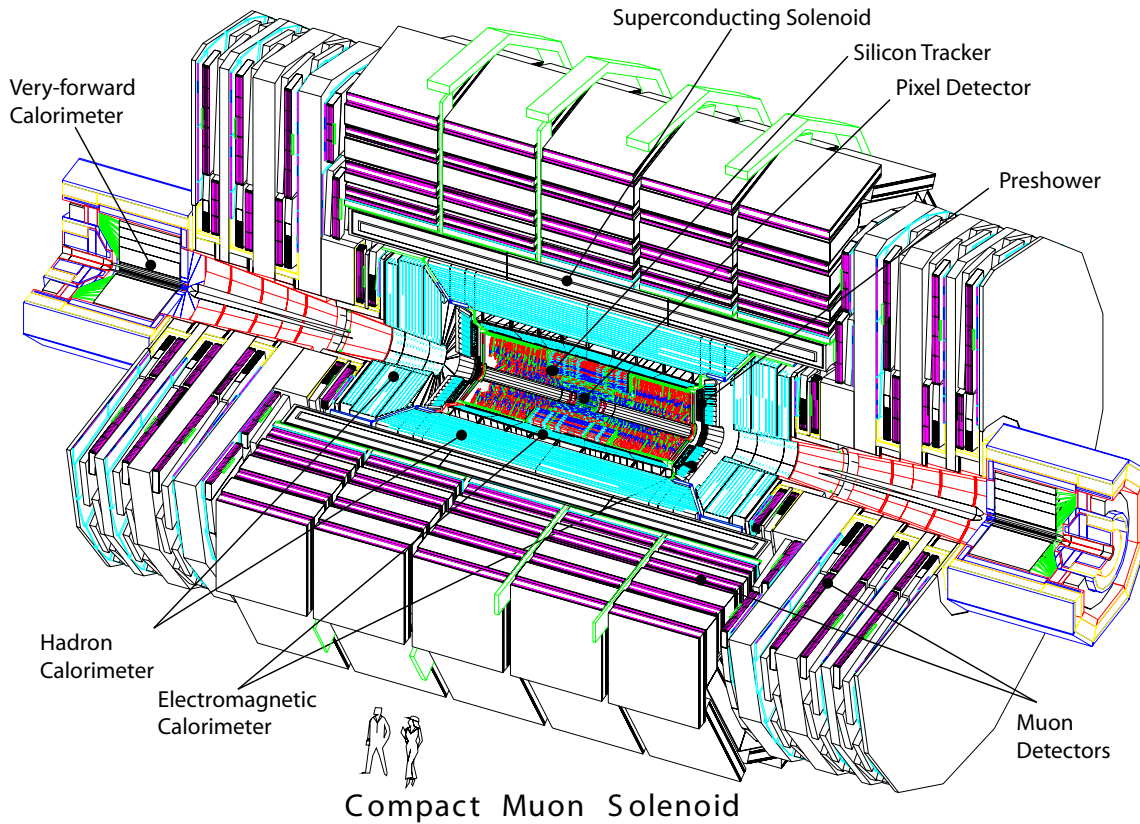


Figure 4.4: An exploded view of the CMS detector. (CMS Collaboration, 2006)

A detailed description of the Tracker system is provided in section 4.3.1. Right after the tracker we can find the Electromagnetic Calorimeter (ECAL), where light showers produced on lead-tungstate crystals are captured allowing the measurement of the energy deposited by charged particles like electrons, positrons, and neutral particles such as photons. An overview of the electromagnetic calorimeter is given in section 4.3.2. The next stage in the process is the Hadronic Calorimeter (HCAL), where hadronic showers take place. Energy measurements are possible by using multiple layers of brass and plastic scintillators. The brass acts as an absorber material while the plastic scintillators emit blue-violet light that is then captured by light collectors. Additional details on the HCAL subdetector can be found in section 4.3.2.

The superconducting solenoid, described in section 4.3.3 is located after the HCAL. It provides the detector with an up to 3.8T magnetic field. The last sub-detector in the chain is the

Muon system. Muons, being charged particles, leave hits on the tracker detector. However, as opposed to other particles, Muons are not stopped by neither of the calorimeters and therefore its trajectory is captured by four chambers of gas-ionization detectors interspersed with iron yokes, further description of the Muon system can be found in section [4.3.4](#).

4.3.1 The Tracker Detector

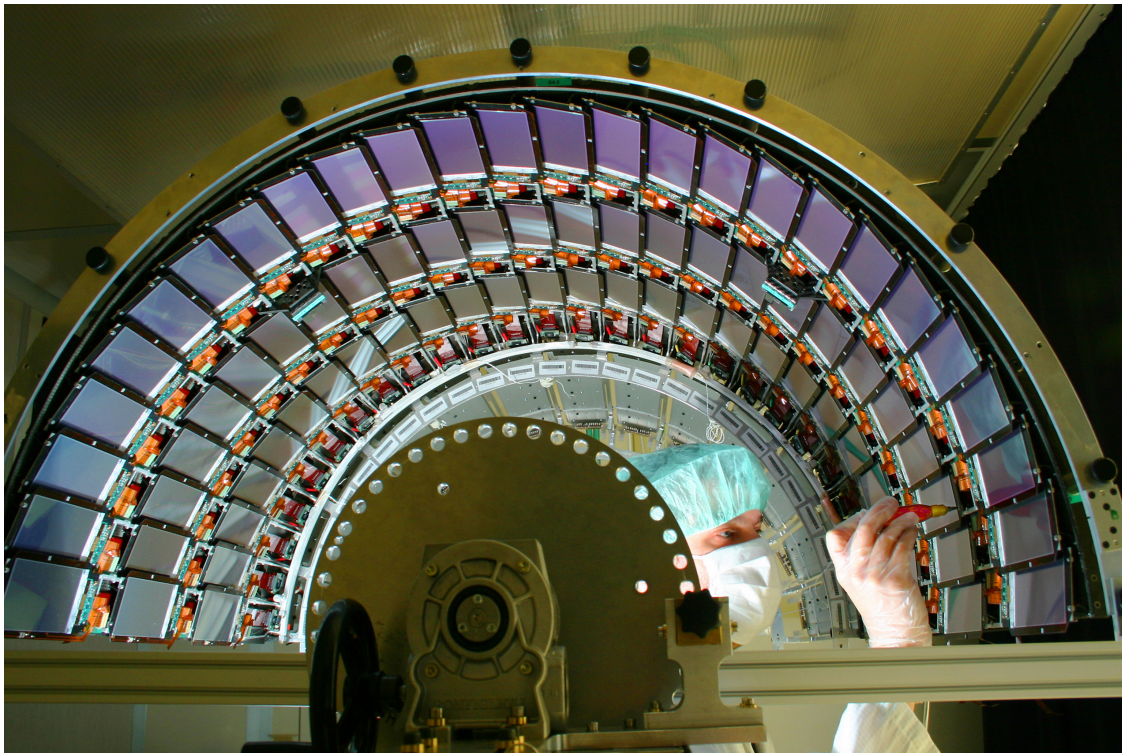


Figure 4.5: Half of the Layer 4+ shell for the Tracker Inner Barrel. ([CMS Collaboration, 2006](#))

The tracker sub-detector keeps track of the trajectories of charged particles that are either product of the collision or product of the decay of particles produced during the collision. Each charged particle interacts with individual modules of silicon detectors arranged in concentric layers, this interaction is referred to as a *hit*. A set of hits form a *track*. The reconstruction of these *tracks* is made by combining the hits in the different layers of silicon modules as the outgoing particle makes its way through the detector. The amount of material that goes into the tracker needs to

be kept to a minimum in such a way that physical phenomena that may affect the detection of the final products of the collision, including nuclear interactions, bremsstrahlung, multiple scattering, and photon conversion, remains low. The use of silicon provides a rapid response and high sensitivity to energy depositions. This is mainly due to its low ionization threshold. Granularity is an important characteristic of the tracker as it helps improve the spatial resolution of hits.

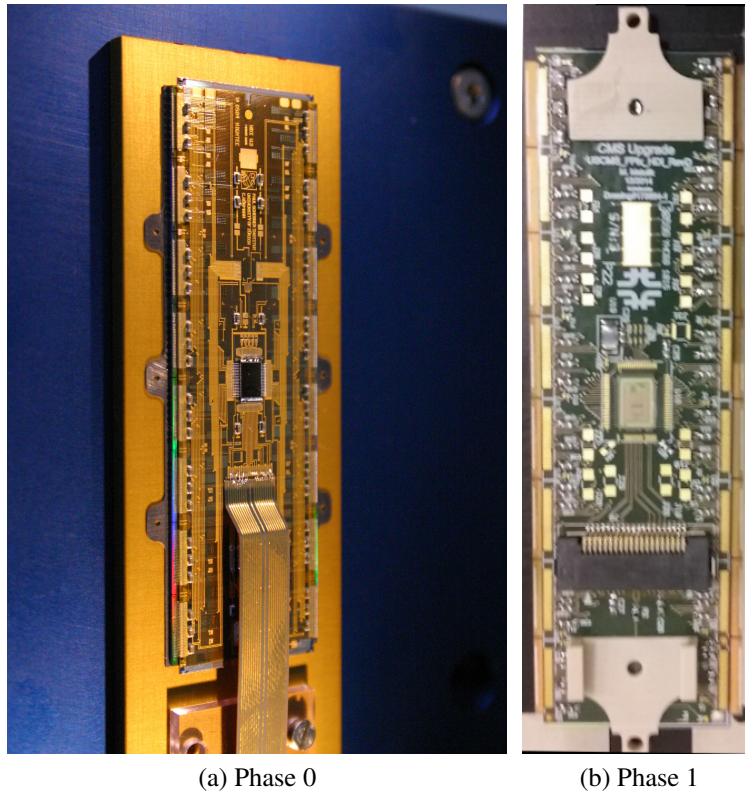


Figure 4.6: Photo of pixel module (CMS Collaboration, 2006). Phase 0 is the first version of the pixel detector, and it was used during 2016 data taking period while 2017 and 2018 data taking periods benefited from the Phase 1 upgrade.

Due to the presence of the homogeneous magnetic field, the tracks allow us to determine not only the charge of the particle (different electric charges will bend in opposite directions) but also determine its transverse momentum P_T , as well as the reconstruction of the primary and secondary vertices. The primary vertices are the positions where proton-to-proton collisions took place, while the secondary vertices are common origins for tracks from particles that are generated as part of the decay of a particle with a long enough lifetime to travel a small distance from the

collision point prior to encountering the first detector. A typical example of this behavior, is the production of a bottom quark that after a small displacement decays hadronically, semileptonically or other exotic decay modes.

The acceptance of the tracker is within the range of $|\eta| = 2.5$. The tracker diameter is 2.5 m and a total length of 5.8 m.

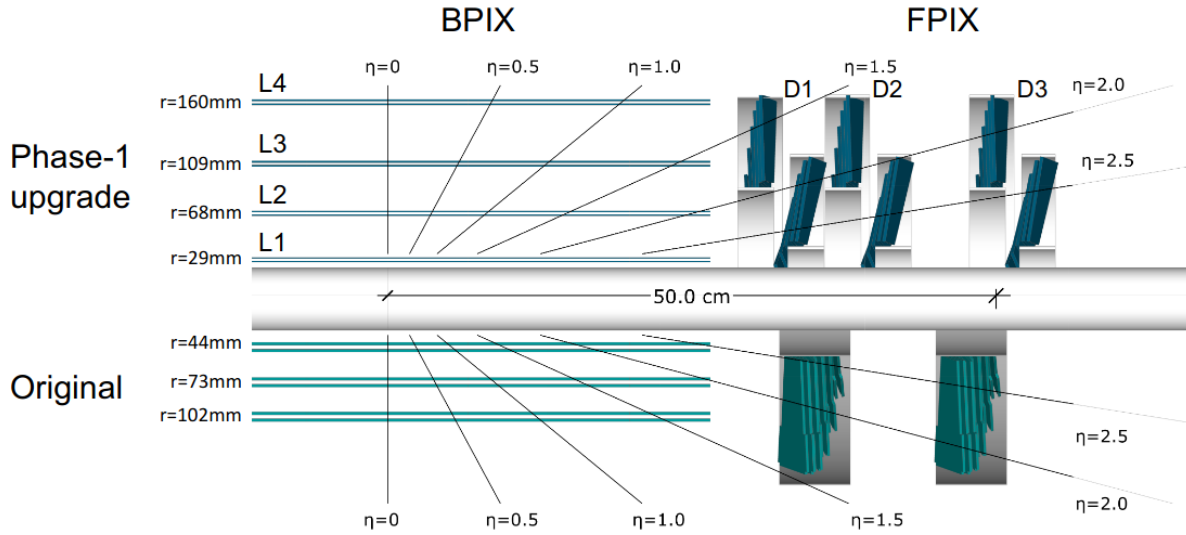


Figure 4.7: The Barrel and Forward Pixel detectors, the upper part displays the layout of the phase-1 upgrade and the bottom the original detector replaced during the upgrade period in 2016. The Phase-1 increased spatial coverage was possible due to the installation of a smaller beam pipe (7mm difference in the radius respect to the original one). ([Adam et al., 2021](#))

The tracker is composed by two silicon sub-detectors: pixel and strips. The pixel is the innermost sensitive device in CMS, with a spatial resolution of about $10 \mu\text{m}$ in $r - \phi$ and up to $40 \mu\text{m}$ in z . The pixel detector was replaced by the end of 2016 as a safeguard of the tracking and vertex resolution. [Figure 4.6](#) and [Figure 4.8](#) shows both of the pixel detector versions used in the CMS detector during the Run 2 data taking period. An additional layer of silicon modules in the barrel and the endcap, and an overall reduction of the material budget as measured in hadronic interaction length was also achieved by this upgrade.

The pixel features high granularity thanks to around 124 million silicon sensors. The pixel detector is divided into two mechanically and electrically independent sections: the pixel barrel

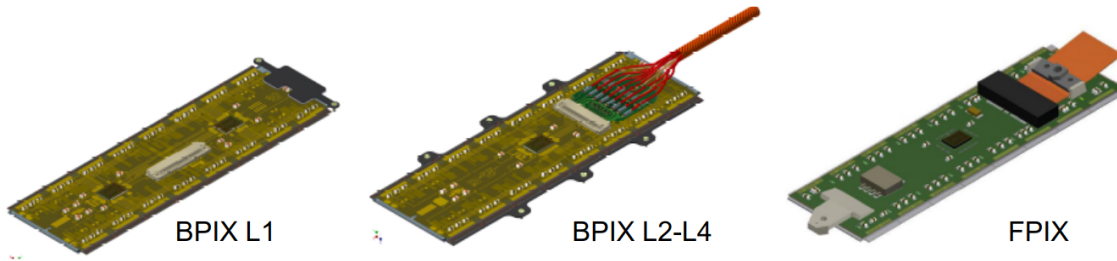


Figure 4.8: Pixel detector modules' design for the first layer of the pixel barrel (left), the second through the fourth barrel layers (middle) and the forward pixel (right). ([Adam *et al.*, 2021](#))

(BPIX) and the forward pixel (FPIX). The BPIX is made of four coaxial layers parallel to the beamline containing 1184 modules, three module designs were needed to address the challenges that come at different distances from the beamline axis. In contrast, the 672 FPIX modules have the same design and are arranged in three end cap disks.

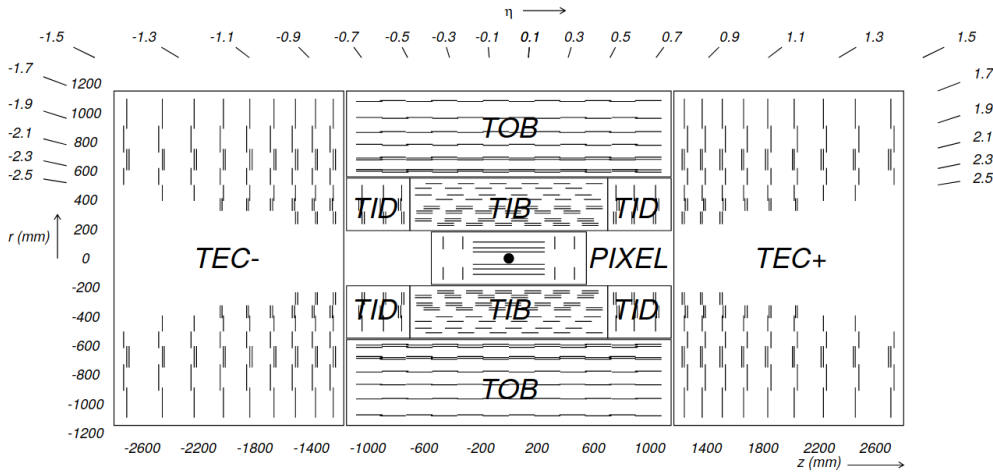


Figure 4.9: Cross-sectional view of the CMS Tracker, single lines represent a detector module while double lines indicate back-to-back modules, which allows measurements of the hits in the $\rho - \phi$ plane and z-direction. ([CMS Collaboration, 2008](#)).

The strip silicon detector consists of 15148 modules, distributed between four areas: the tracker inner barrel (TIB), the tracker outer barrel (TOB), the tracker inner disks (TID) and the

tracker endcaps (TEC), As shown in [Figure 4.9](#). The strip silicon detector is located right after the pixel and contains close to 9.3 million of micro-strips ([Dirkes *et al.*, 2007](#)). The barrel is composed by five cylindrical layers and six disks while the endcap features ten disks.

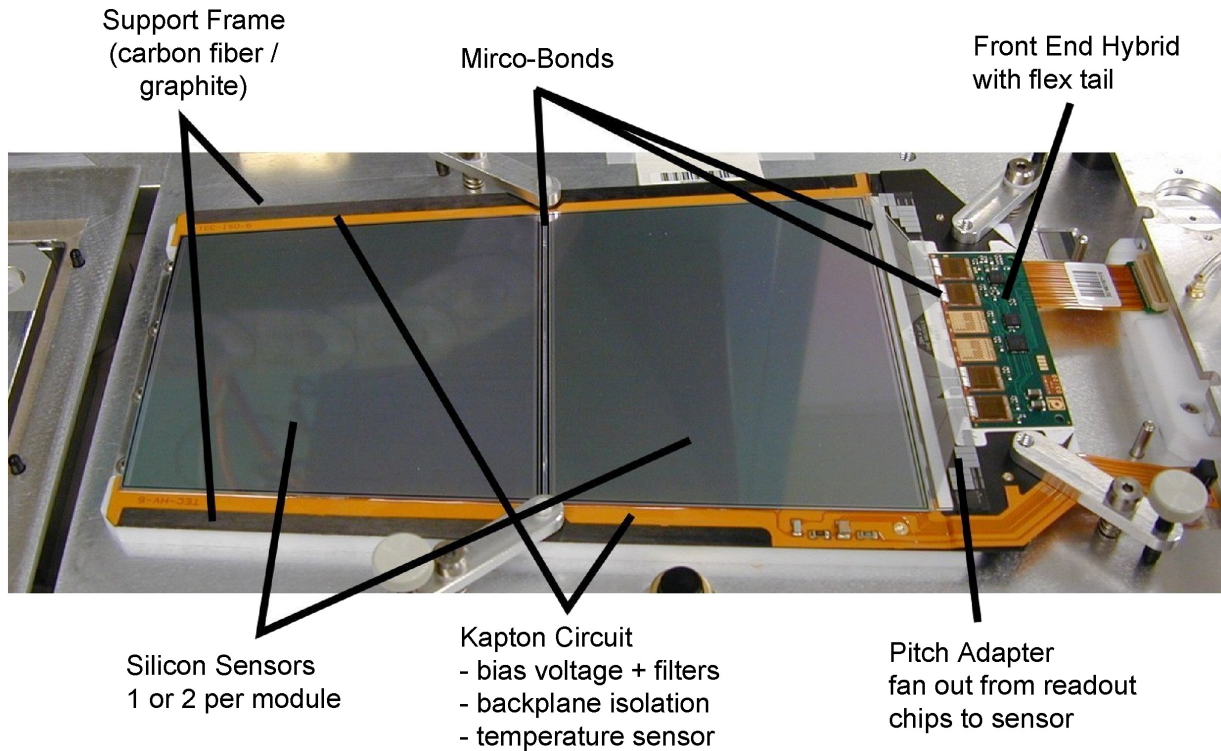


Figure 4.10: Strip Silicon module highlighting its main mechanical, active and electrical components ([Dirkes *et al.*, 2007](#)).

An instance of a strip silicon module is presented on figure [4.10](#). Further information about the tracker system can be found in its technical report design ([Karimäki, 1997](#)).

4.3.2 CMS Calorimeters

The tracker allows to reconstruct the measurement of the trajectory, charge, and transverse momentum of electrically charged particles. The calorimeters on the other hand enable CMS to perform energy measurement of neutral and electrically charged products of the collision by complete absorption. The energy measurement provided by the calorimeters relies on the properties of the showers produced on homogeneous and sampling calorimeters. Homogeneous calorimeters

make use of sensitive material exclusively, while sampling calorimeters include also a passive component that produces cascading effects than are then captured by a layer of sensitive material. Both calorimeter types are used in CMS sections. The electromagnetic calorimeter is a homogeneous one (see section 4.3.2) while the hadronic Calorimeter is a sampling one (see section 4.3.2).

The Electromagnetic Calorimeter

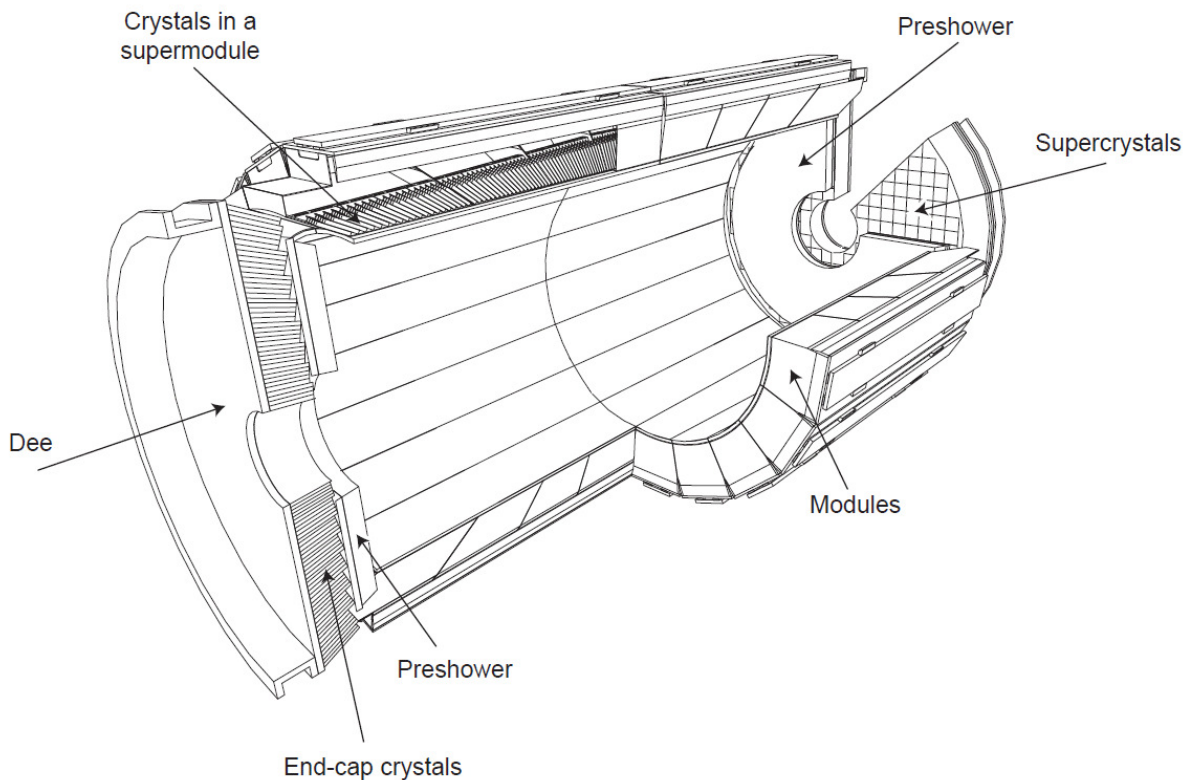


Figure 4.11: The CMS electromagnetic calorimeter's components detailed view. The barrel and the endcaps crystal composition

The Electromagnetic Calorimeter (ECAL) allows us to accurately measure the energy of electrons, positrons and photons. ECAL has a larger coverage than the tracker with $|\eta| \leq 3.0$. It uses cylindrical arrays of 61200 scintillating crystals made from lead-tungsten ($PbWO_4$), providing not only high granularity but also compactness and a fast response. The continuous ionization produced by the interaction of the crystal's lead-tungsten atoms with the incoming electrons and photons produces light in the de-excitation of ions until the electrons/photons are fully absorbed.

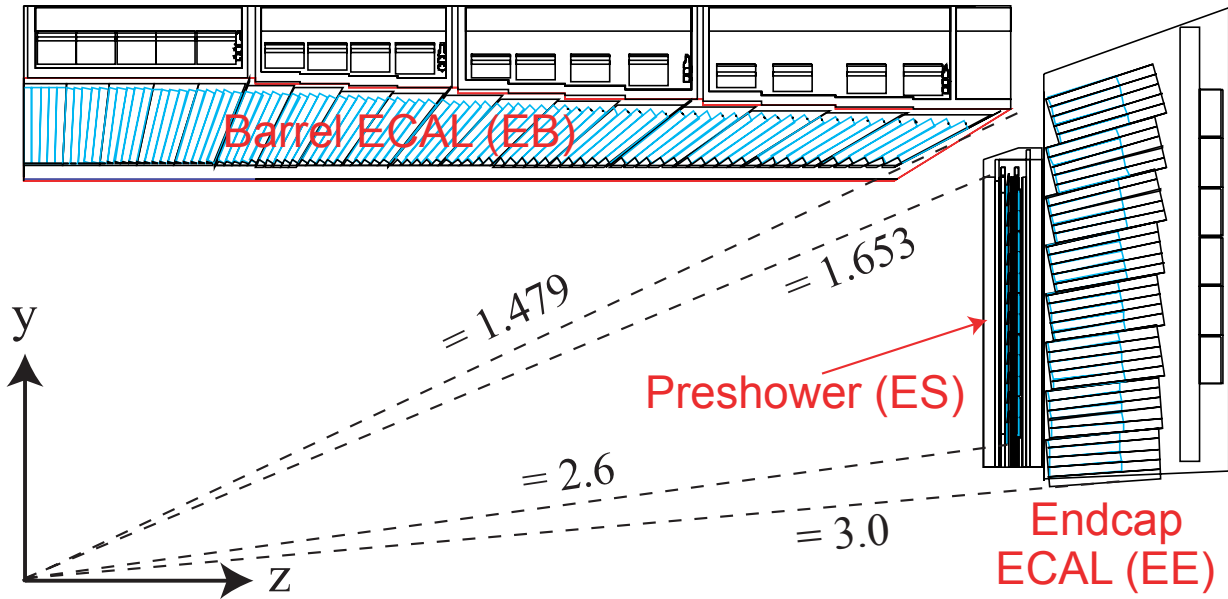


Figure 4.12: Transverse section through the ECAL, showing geometrical configuration. (CMS Collaboration, 2006)

Lead-tungsten is a high-density material (8300 kg/m^3) emitting blue-green scintillating light, 80% of this light is emitted within a 25ns time window, which makes it an adequate time frame to guarantee the fast response required for the collision frequency of the LHC. The trade-off by using lead-tungsten is the sensitivity of the light output by an increasing temperature, this is handled by placing a heat dissipation system through the ECAL allows it to run on a stable temperature of $\pm 0.05 \text{ }^\circ\text{C}$. The scintillating signals product of this interaction are then converted into an electric signal by two kinds of photodetectors depending on the region: In the barrel, where $|\eta| = 1.479$, avalanche photodiodes made of silicon (APDs) are used while in the remaining region ($1.479 < \eta < 3.0$) corresponding to the endcap, vacuum photo-diodes (VPTs) are used. The avalanche effect guarantees that despite the low light yield of the lead-tungsten crystals the gain is sufficient for an accurate measurement. Another trade-off by using lead-tungsten is the production of absorption bands due to the high flux of ionizing particles, this is reflected in the formation of colored areas and needs to be corrected independently for each crystal as the flux is highly dependent on the η

region. The correction is done by accounting for the transparency loss, measured with laser light ([CMS Collaboration, 2006](#)).

The granularity of the endcap is improved by a sampling calorimeter with layers of lead and silicon; this preshower detector located in front of the endcaps as shown in figure [4.12](#) helps identify decays where photons/electrons are produced close together.

The Hadronic Calorimeter



Figure 4.13: Assembling of the hadronic calorimeter brass wedge. Plastic scintillators are inserted between the brass plates ([Brice, Vaillet, and Lazic, 2008](#)).

The Hadronic Calorimeter (HCAL) is designed to measure the energy deposits and direction of hadronic decays. HCAL has a larger pseudorapidity range with acceptance for η up to 5.0. Most of the HCAL sits inside the superconducting solenoid, with a similar structure than previous subdetectors: barrel (HB) and endcaps (HE). Both of these are designed as a sampling calorimeter, with brass absorbers and plastic scintillators as the sensitive material. The non-magnetic nature of

brass and short interaction length, makes it an adequate candidate for absorption while keeping the active material to an equilibrated minimum (see Figure 4.13).

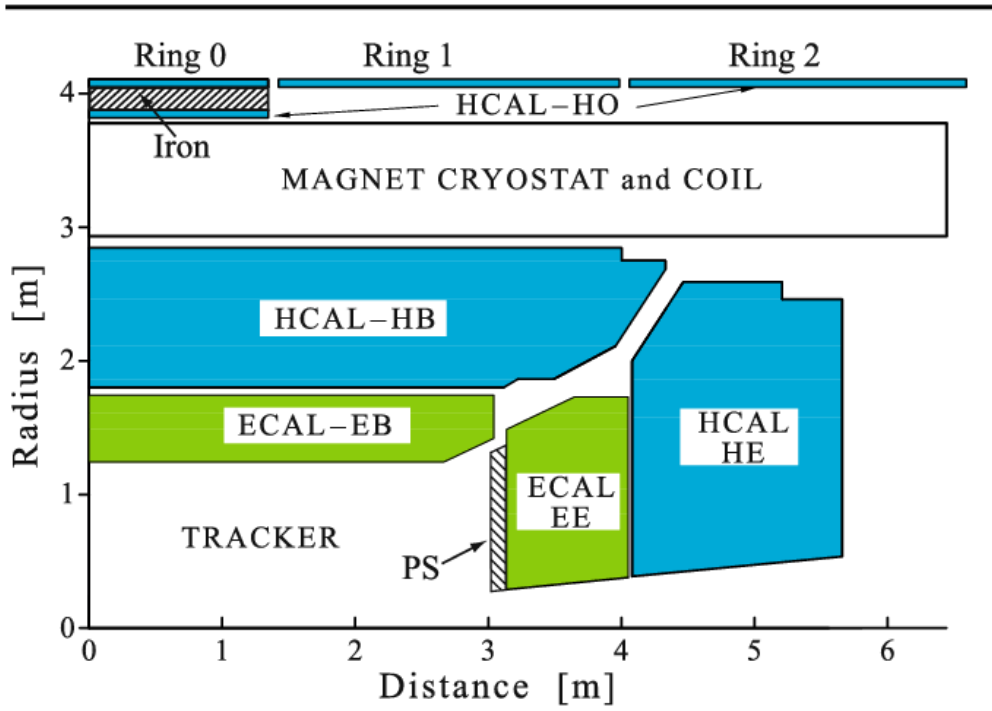


Figure 4.14: A quarter of the cross-sectional view showing the geometrical configuration of the electromagnetic and hadronic calorimeter (Abdullin *et al.*, 2008).

One of the central requirements of the HCAL is to provide containment and hermiticity in order to accurately measure the hadronic showers. As seen in figure 4.3, the HCAL is contained within the magnet coil. However, an additional 10 mm layer of a homogeneous detector made of plastic scintillators (the hadron outer detector HO) is located outside the coil (see Figure 4.14). The containment requirement allows for an increase accuracy in the measurement of missing energy E_T^{miss} .

4.3.3 The Magnet

The CMS detector possesses a superconducting solenoid coil magnet which reaches a maximum of 3.8 T, with a 6.3 m diameter, 12.5 m length and a 220 t weight (see Figure 4.15). The maximum magnetic field is reached inside the solenoid, covering the inner tracker system and both

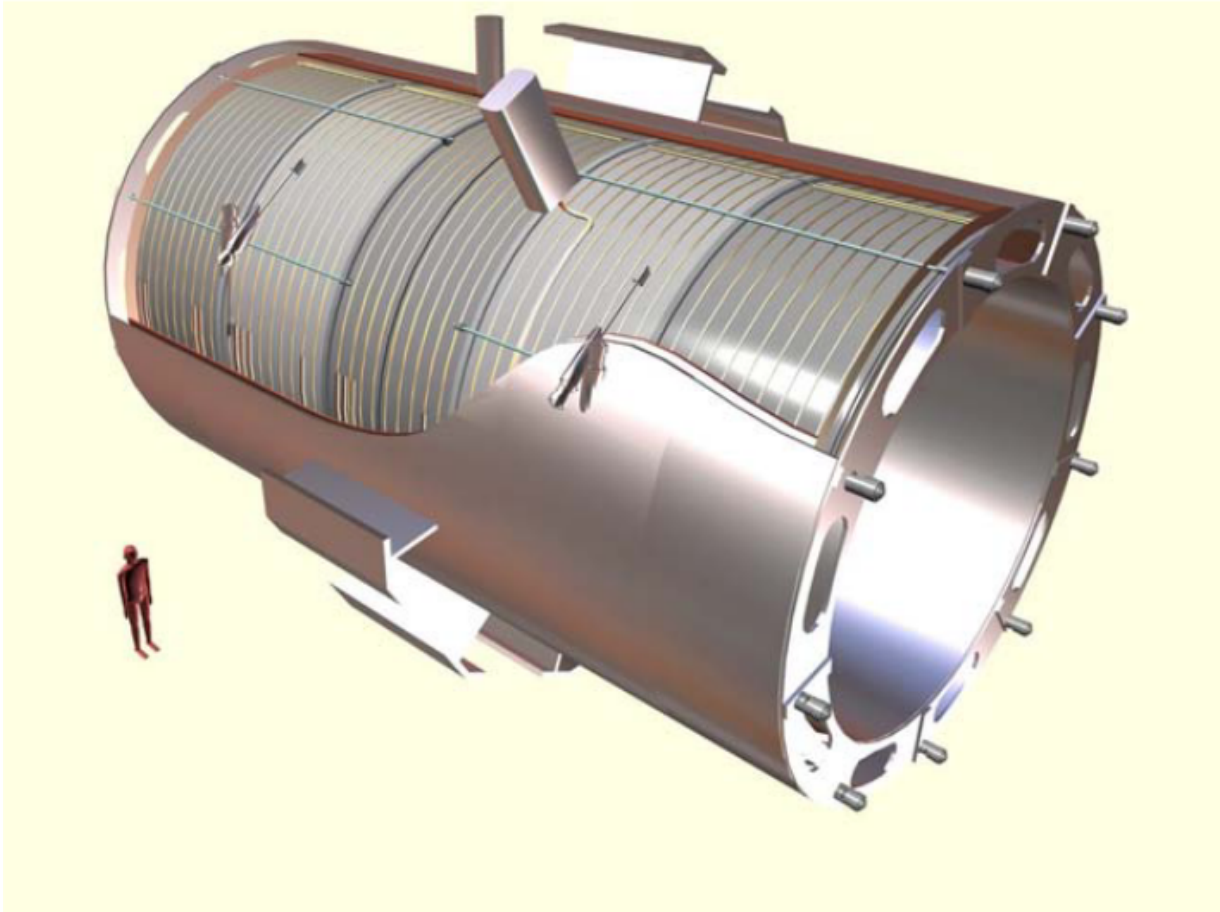


Figure 4.15: Artistic view of the CMS magnet, its support system. ([CMS Collaboration, 2006](#)).

calorimeters, bending the trajectory followed by charged particles thus aiming to determine their identity and momentum accurately.

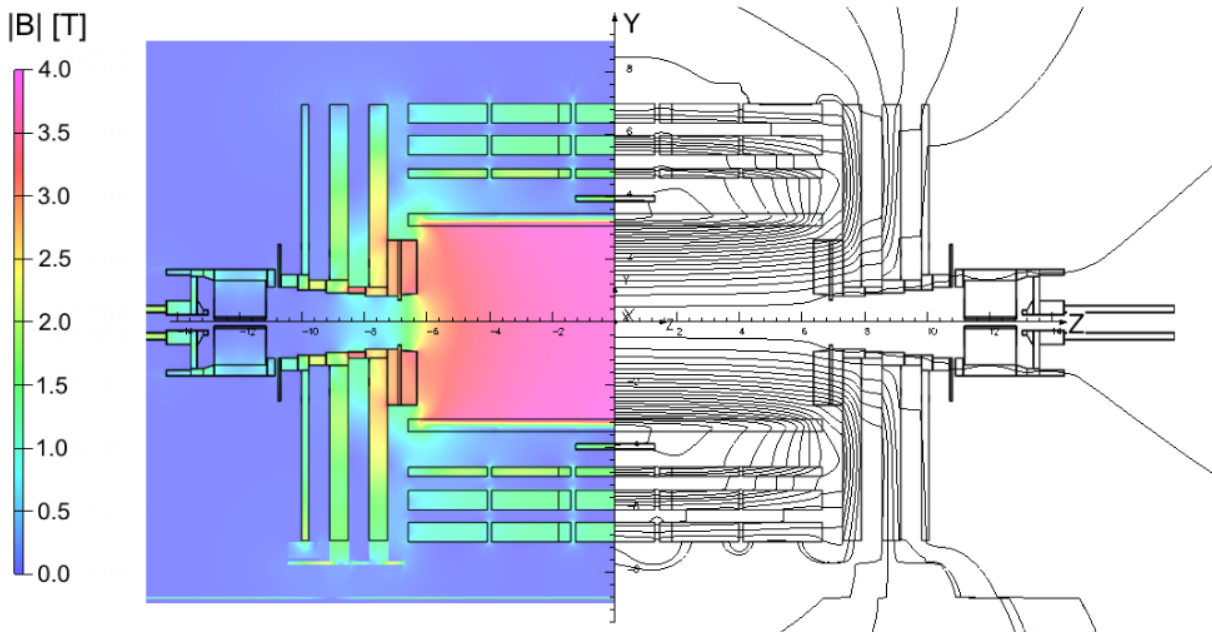


Figure 4.16: Predicted value of the magnetic field (left) and field lines (right) on a longitudinal section of the CMS detector. (CMS Collaboration, 2010b).

The magnet was assembled first, and then lowered 90 m underground for installation in the CMS cavern and is kept to a temperature of 1.8K. A map of the strength of the magnetic field can be seen in Figure 4.16, this is done by direct measurements that were taken during the installation but also through the deflection of cosmic rays muons (CMS Collaboration, 2010b). Figure 4.16 shows how uniform is the magnetic field in the inner part of the solenoid. This uniformity in the magnetic field allows the trajectory of charged particles to be approximated to helices. However, an accurate mapping of the B field is required for reconstruction and for simulation purposes. Specially, in the outer part of the solenoid where the magnetic field lines are non-uniform which has to be taken into account for the reconstruction of the muon tracks. The magnetic field is strengthened in the muon system by means of the steel yoke which is interspersed with the muon chambers (see 4.3.4) reaching a magnetic field of 2.0 T and providing a tracker-independent mean to increase the accuracy of the muon momentum measurement.

4.3.4 The Muon System

Muons are close to 200 times heavier than electrons. Because of its higher mass, the extent in which they are affected by radiative effects is greatly reduced. Therefore, Muons leave very little to no trace in the electromagnetic and hadronic calorimeters. In contrast to electrons, Muons are unstable particles, with a mean lifetime of about $2.2\mu\text{s}$. This time is enough for the muons to travel through the CMS detector prior to decaying. Muons are the only particle that penetrates the outer region of the CMS detector therefore the last subsystem is optimized to detect them.

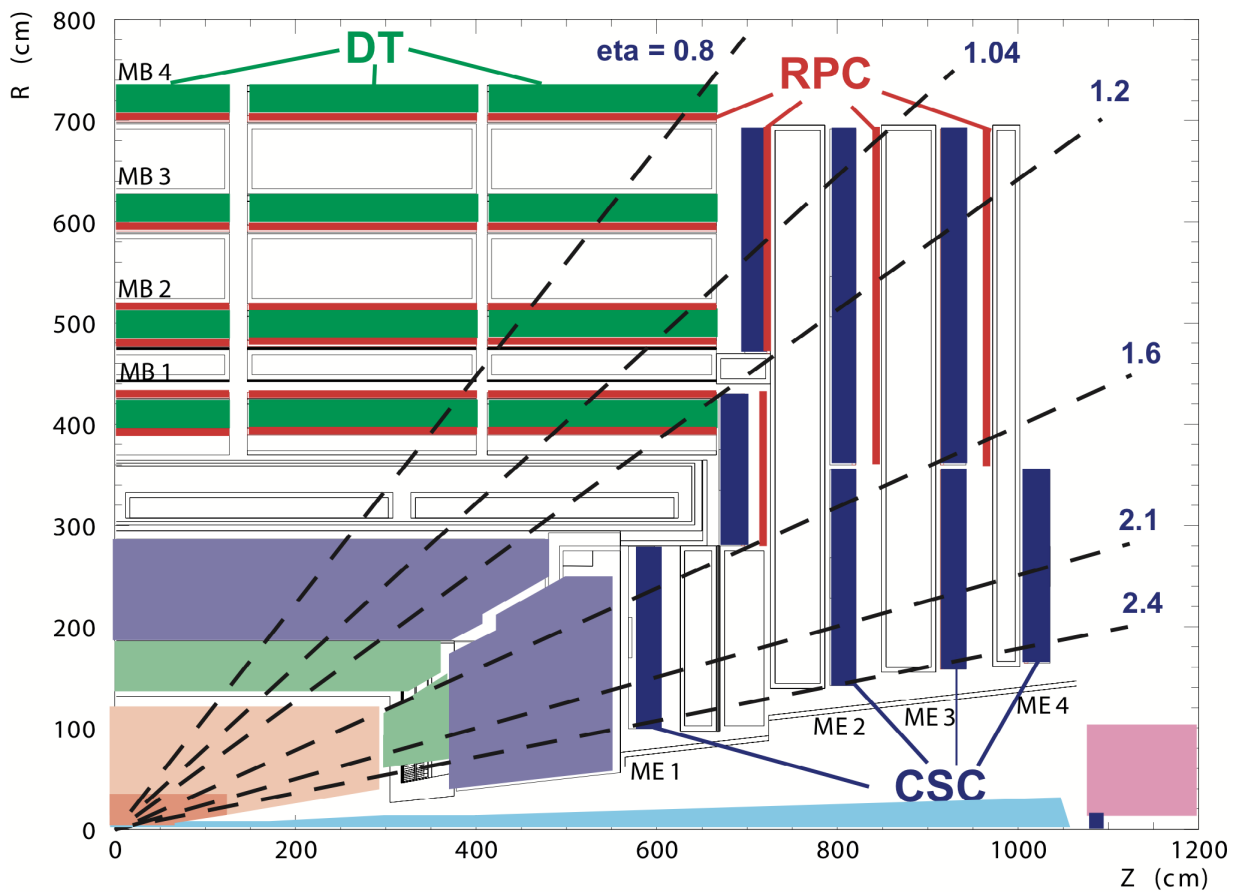


Figure 4.17: A quarter of the cross-sectional view of the muon system showing the spatial distribution of the muon chambers (CMS Collaboration, 2006).

The muon system is composed of three types of gaseous detectors located in the most outer part of CMS: the drift tube chambers (DT), the resistive plate chambers (RPC) and the cathode strip chambers (CSC), see Figure 4.18. Figure 4.17 shows the spatial distribution of the muon

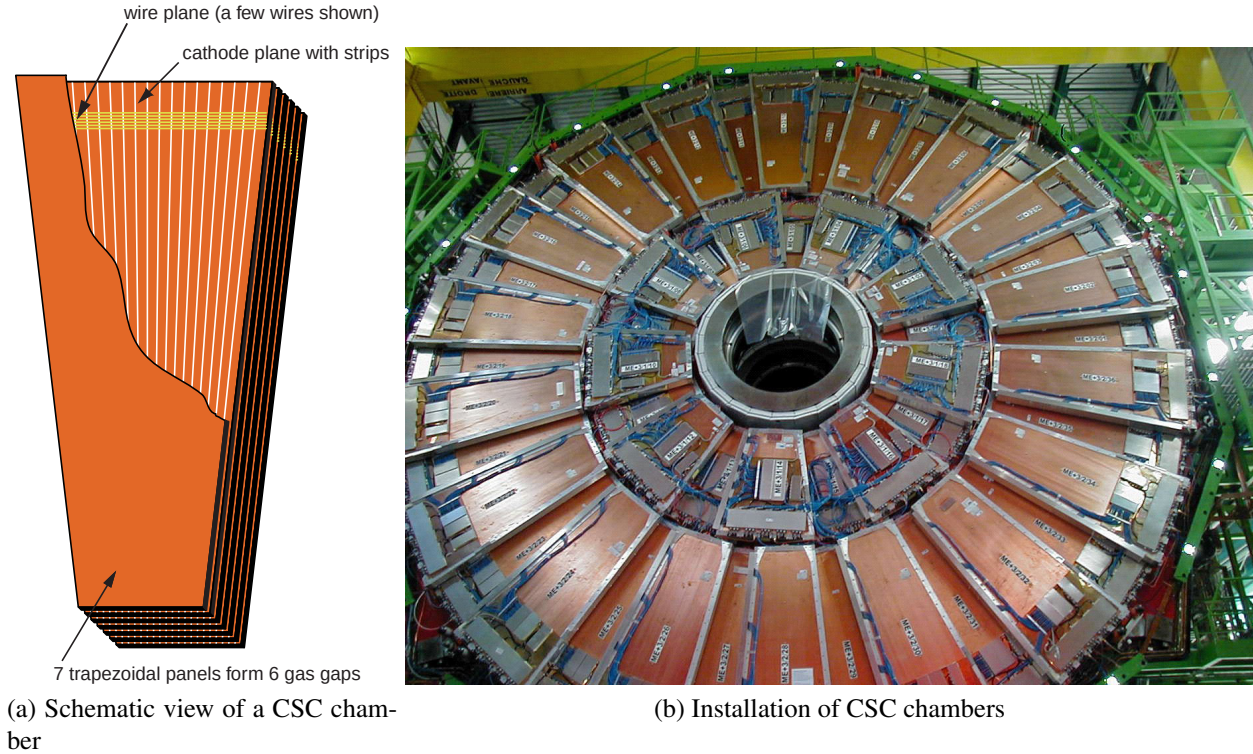


Figure 4.18: The Cathode Strip Chambers at CMS. (CMS Collaboration, 2006)

chambers. The muon chambers are located in the outermost layer of the CMS detector, right after the solenoid magnet.

Gaseous detectors use the ionization of the gas atoms due to the passage of a charged particle. This ionized atoms, in the presence of an electric field, are then subject to a drift, creating a signal in the readout electrodes.

The gas is a mixture of Argon Ar , carbon dioxide CO_2 and Carbon tetrafluoride CF_4 . The arrangement of these three subdetectors along with four muon stations provide the muon system with a coverage in the pseudorapidity range of $|\eta| < 2.4$: the barrel provides a coverage of $|\eta| < 1.2$, while the endcaps extend it to $|\eta| < 2.4$.

The muon system provides an additional source of information for the reconstruction of muon tracks and therefore an improvement in the transverse momentum resolution, which is crucial for the measurement of high transverse momentum muons ($> 200 GeV$) where the curvature of the tracks is negligible.

4.3.5 Trigger

Every 25 ns the CMS experiment injects a bunch of protons from the LHC into the center of the detector, where they collide. This implies that the CMS detector is handling the products of 40 million collisions per second (a *frequency* of 40 MHz). As the amount of data per event is large and the experiment ran continuously for three years (2016-2018) the complete storage of the data is not feasible and unaffordable. However, not every interaction comprises a high energy collision. In fact, most of the collisions constitute low energy transfers that are not relevant for the physics goals of the experiment. Taking this into account, not every single event is worth storing.

The amount of data generated at such frequency in the LHC collisions is a stress test for even the most current technology available in the market. Due to limitations in the electronics, data transfer speed and others. This challenge is overcome by a trigger system that uses a series of hardware and software filters to select events that are then stored for further analysis.

The trigger system is composed of a hardware and a software component. The hardware component, the so called Level-1 (L1) trigger consists of a hardware logic that takes the 40 MHz input and reduces it to 100 kHz, a reduction of a factor of 400. Subsequently, the software component, the High Level Trigger (HLT), takes the 100 kHz input and reduces it to 100s Hz.

The L1, or *online* trigger exploits the technological capabilities of FPGAs (Field Programmable Gate Arrays). FPGAs are integrated circuits that can be programmed to perform a determined set of operations using a hardware description language. This means that the electrical functionality in the circuit can be modified without the need to physically modify the device itself (programmable hardware). FPGAs provide to the L1 trigger the flexibility of being able to change the logical sequence of the trigger chain as needed and the speed of having specialized hardware to perform the task, achieving a latency of just 4 μ s ([CMS Collaboration, 2020](#)). Once programmed the FPGAs analyze information coming mainly from the readout electronics in the calorimeters and the muon chambers. The L1 trigger decides which events are taken to the next trigger level, the HLT that in a few hundred milliseconds will determine which events are stored for further analysis. A more detailed description of the L1 trigger can be found in ([CMS Collaboration, 2020](#)).

The HLT takes from the L1-Trigger 100 kHz of events and reduces it to 1 kHz. The main difference between the L1 trigger and the HLT is that the latter is exclusively software based. This bandwidth reduction is done by initially performing a simplified version of the reconstruction using a cluster of computers, and then, using the results of this reconstruction to look for a variety of signatures of physics processes. The trigger decision is at the same time inclusive, so to acquire an unbiased dataset but also highly exclusive in order to achieve a reduction in the data rate. In contrast to the L1 trigger, the HLT accesses tracker information, which is not available to the L1 trigger. This allows the HLT to perform a simplified version of the vertex reconstruction with information from the pixel detector. A series of selection and reconstruction algorithms better known as *HLT paths* are applied to the events. There are more than 500 paths in the trigger menu, each one of them looking for a specific signature of a physics. An event is stored if it passes at least one of the paths.

The raw data of the events passing the HLT are stored in the Tier 0 infrastructure at CERN. From here, it is available to perform a full reconstruction of the events. With algorithms that are continuously being improved in terms of efficiency, speed, and accuracy, the CMS experiment is able to reprocess the raw data and produce refined versions of the datasets.

4.4 CMS Computing infrastructure

CMS makes use of the computing infrastructure of the LHC grid. The LHC computing grid is a worldwide network that provides storage and processing capabilities to its different experiments. Four layers support the grid. The first layer is the Tier 0 (T0), which is located at CERN, is in charge of storing the events that fulfill the requirements of the trigger system. T0 also stores the raw data and performs a *prompt* reconstruction of the objects present in each event. Then, the data is distributed to the Tier 1 (T1) centers, which are located in multiple countries, including the US, France, Germany, and others. T1 centers further process the data, including the application of calibration sequences, and distributes the produced outputs to Tier 2 (T2) centers. T2 centers are hosted by universities and research institutes. T2 centers also contribute to the generation

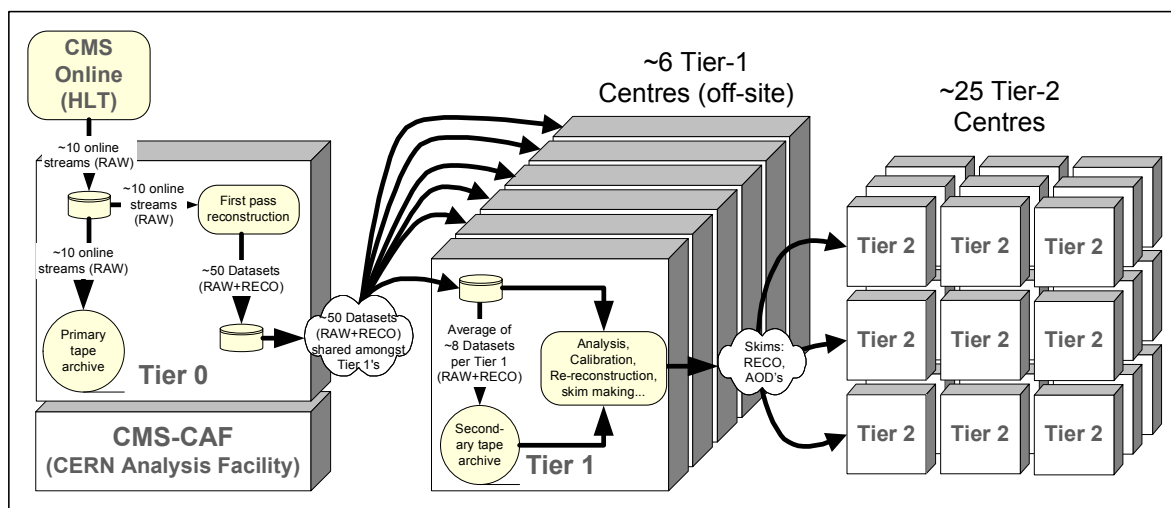


Figure 4.19: Schematic flow of event data in the CMS Computing Model. (Bayatyan *et al.*, 2005)

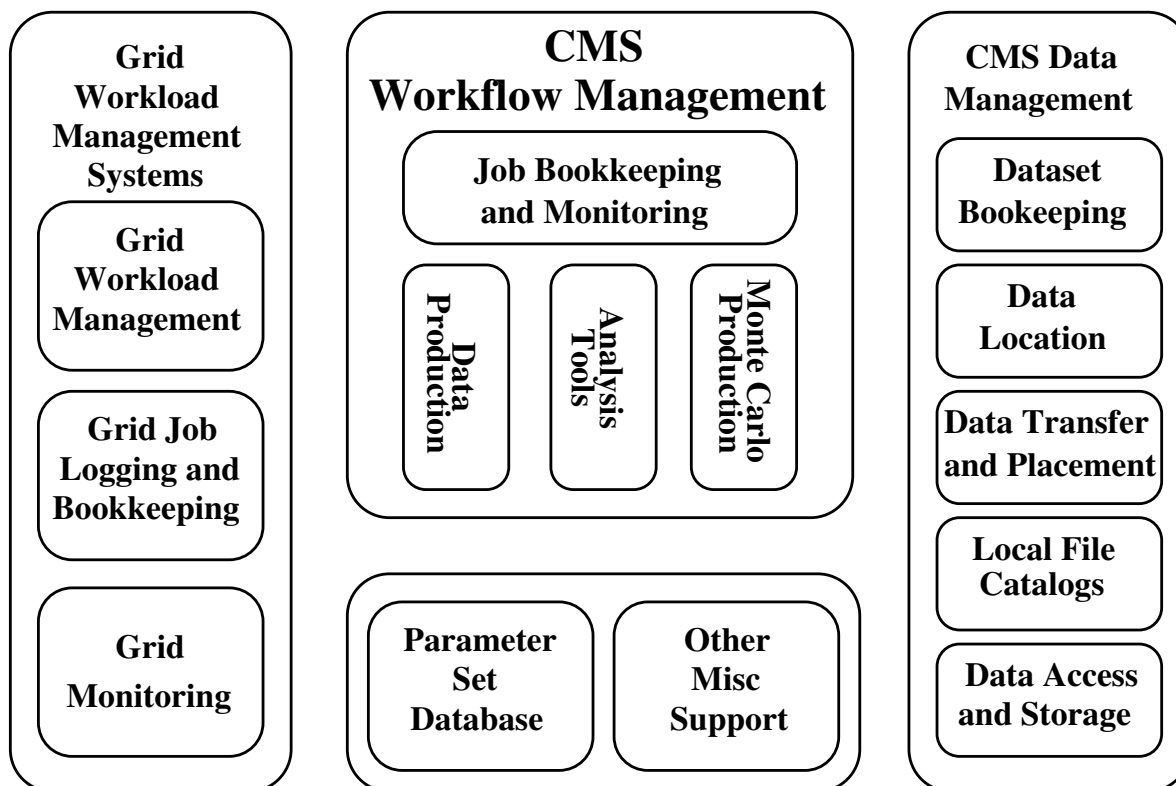


Figure 4.20: Systems and services supporting the CMS workflow data management system. (Bayatyan *et al.*, 2005)

of Montecarlo events, the simulation of the detector response and the production of fully reconstructed datasets for further analysis. Finally, numerous Tier 3 (T3) centers provide computing resources to physics analysts to perform searches of new physics, the precise measurements of physical variables in the standard model, and the execution of different studies aimed at improving the performance and quality of the simulation, reconstruction algorithms and the detector itself. Further details regarding the LHC computing infrastructure can be found in ([Bos *et al.*, 2005](#)).

CHAPTER 5

The Phase-2 Pixel Upgrade

*” We are rather like children,
who must take a watch to pieces
to see how it works.”*
—Ernest Rutherford

Rare collision events are of great interest for the high energy physics community. Its rare nature makes them difficult to detect and study, and therefore, there is a continuous need to increase the statistics available for the search of new physics. The discovery of the Higgs boson ([Chatrchyan et al., 2012](#)) and the measurement of its couplings to the other particles in the Standard Model such as the muon ([CMS collaboration, 2020](#)) and the top quark ([CMS collaboration, 2018](#)) are challenging, not only because of the low cross-section of the processes but also due to the large background involved in the searches. Despite these challenges, the measurement of the so-called Yukawa couplings are of great importance as an instrument to test experimentally the limits of the Standard Model. With more statistics, a better understanding of the fundamental building blocks of the universe can be achieved. In order to shine light on these low cross-section processes, the LHC is required to increase its luminosity even further and the experiments are expected to be upgraded to face the challenges that come with it.

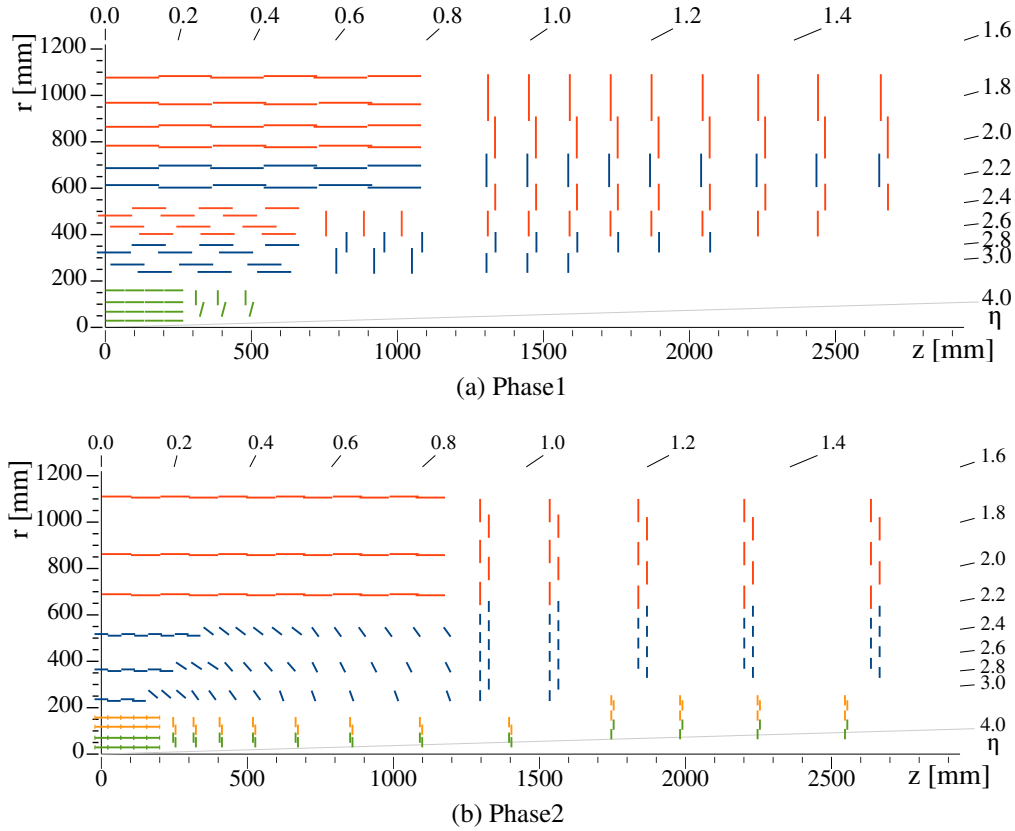


Figure 5.1: Sketch of one quarter of the tracking system in r - z view the Phase-1 (top) and Phase-2 (bottom) CMS tracking system. The pixel detector is shown in green, while single-sided and double-sided strip modules are depicted as red and blue segments.

As mentioned in [chapter 1](#), the LHC will be facing a significant increase in luminosity in the next years with the high luminosity LHC (HL-LHC) upgrade, heading towards a peak luminosity as big as seven times the current one, which is about $1.5 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. This new luminosity regime, will allow the experiments to collect an integrated luminosity of about 300 fb^{-1} per year ([CMS Collaboration, 2017b](#)). While the time between collisions will be kept at 25 ns , the expected center of mass energy will be higher at 14 TeV and the pile-up, the number of simultaneous collisions per bunch crossing, will increase five-fold to about 200. This new level of radiation does not have counterparts in the history of high energy physics with a total ionizing dose of 12 MGy and a hit rate of 3.2 GHz/cm^2 ([CMS Collaboration, 2017b](#)).

The increase in luminosity imposes new challenges to the different experiments, and with them the need to develop new designs, materials, and technologies that are able to cope with

harsher radiative environments, specially subsystems that are located in the innermost regions of the detectors, such as the Pixel in the case of CMS. This Phase-2 upgrade, which is currently under development, will be part of a series of improvements done to the detector during the third long shutdown (LS3) of the LHC (see [Figure 4.1](#)).

	1st Generation	2nd Generation	3rd Generation
Hit memory per chip	0.1 Mb	1 Mb	16 Mb
Chip output bandwidth	40 Mb/s	320 Mb/s	3 Gb/s

Table 5.1: Comparison between the different generation of the pixel readout chips. ([Chistiansen and Garcia-Sciveres, 2013](#))

The Tracker and in particular the inner tracker, where the Pixel is located, will be replaced by a brand-new detector. The new silicon sensors will be composed by about two billion pixels with a size of either $25 * 100 \mu m^2$ or $50 * 50 \mu m^2$ and a maximum thickness of $150 \mu m$, in contrast with the $300 \mu m$ thickness in the current sensor. Thickness plays an important role, mainly because of trapping, where charges generated from the interaction of the particles from the collision with the sensor, are temporarily immobilized in the defects or impurities of the sensor material.

The signals produced by silicon sensors are generally weak and noisy, making them difficult to measure accurately. Therefore, an interface between the sensor and the readout electronics is required. This is the main function of the readout chip: it accumulates the photocurrent from the sensor, amplifies it, and digitizes it, and makes it available to the readout electronics. The design of the readout chip comes with its own challenges. A combined effort between the CMS and ATLAS experiments, gave rise to the creation of the RD collaboration, which is tasked with the development of the third generation of hybrid pixel readout chips. The main differences among generations can be seen on [Table 5.1](#).

The pixel detector layout and the differences between the Phase-1 and Phase-2 spatial distributions are shown in figure [5.1](#). The extended coverage in η , with up to $\eta \sim 4.0$, as opposed to the current 2.4 maximum coverage, on top of providing additional forward acceptance, is expected to improve the b-tagging efficiency of forward jets and to provide improved measurements in the

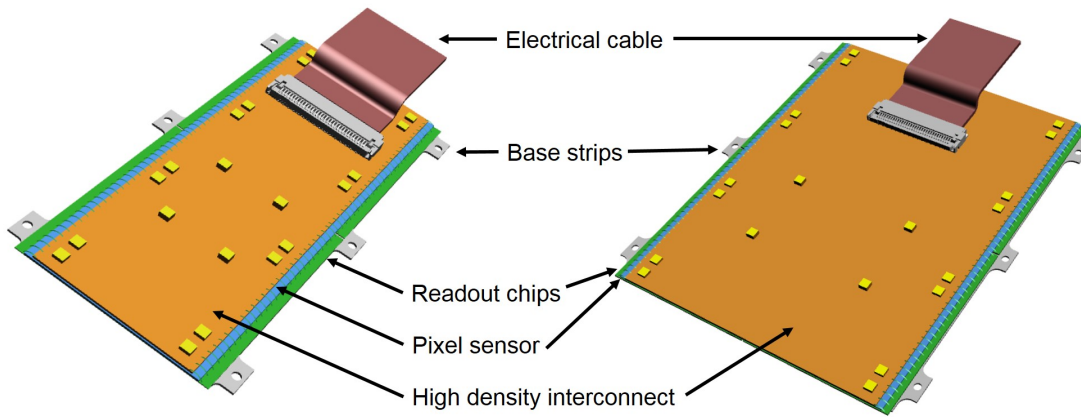


Figure 5.2: Sketch of the 1x2 (left) and 2x2 (right) pixel modules. The dimensions are roughly $1.8 \times 4.4 \text{ cm}^2$ and $3.7 \times 4.4 \text{ cm}^2$ for the 1x2 and 2x2 modules, respectively. (CMS Collaboration, 2017b)

Higgs boson four-muon decay channel. The η distribution of this important decay channel shows a gain in sensitivity in the $2.4 < \eta < 3.0$ region (CMS Collaboration, 2017b).

The Catholic University of America, as a research institution is part of the upgrade effort of the Pixel detector. The main goal of the group at Catholic is to be able to produce Pixel modules able to withstand the higher radiation levels expected in the HL-LHC. This goal implies the development of new procedures and study of different alternatives to the ones currently used.

The laboratory at Catholic is now equipped with a clean room capable, which is needed due to the high level of cleanliness and precision required to produce the modules. In the clean room there three different work stations: the first one is the assembly station, where the main equipment is a robotic gantry arm, a customized equipment from the Aerotech company. The *gantry*, as it is commonly referred to, has a 4-axis motion system, which allows it to move horizontally in the $X - Y$ plane, vertically, and a rotation around the Z axis. The motion, which is controlled by using National Instruments (NI) LabVIEW software and allow us to have a high level of precision and repeatability. However, this was not always the case, as the Gantry was brought to the lab from University of Nebraska-Lincoln and it required to be set up and calibrated. The setup was performed by the CUA-HEP group, and consisted in plugging back up the machine, testing up

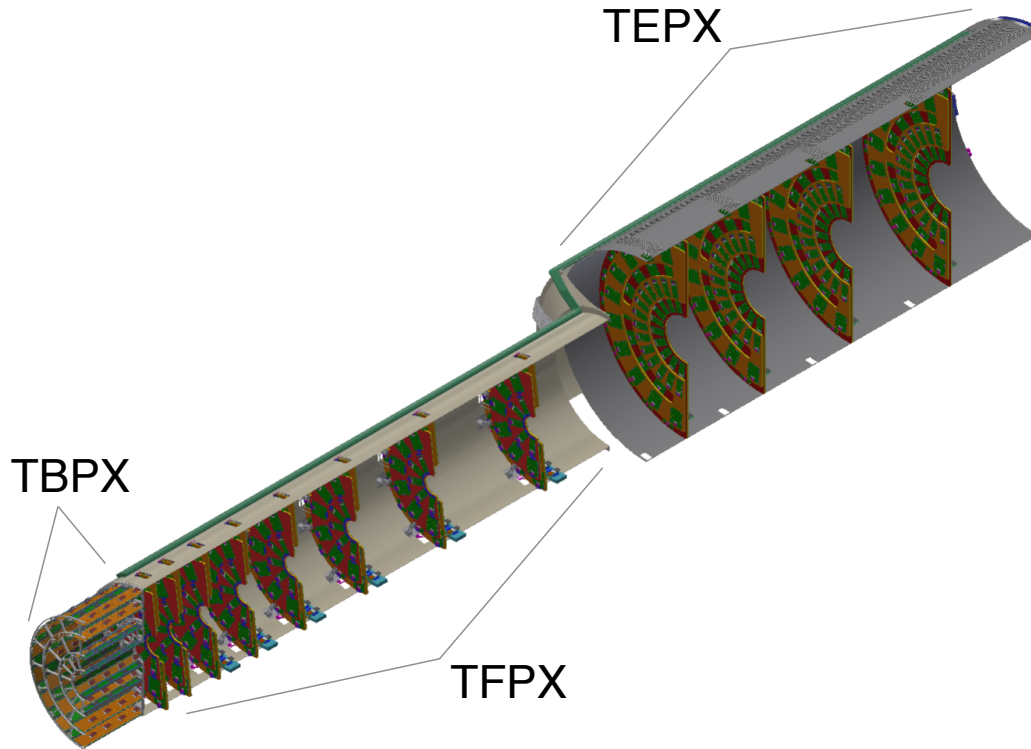


Figure 5.3: View of one quarter of the inner tracking, showing the TBPX, TFPX and TEPX dees inside the supporting structures. The pixel modules are shown as orange elements in TBPX and as green elements in TFPX and TBPX. The dees are depicted as red and orange surfaces.(CMS Collaboration, 2017b)

the quality of the electrical connections, and configuring and preparing a brand-new workstation with the latest version of LabVIEW, NI drivers, and the Aerotech software. Once the gantry was set up, an Aerotech technician came to the lab to perform a first calibration procedure. Even though the Gantry is able to move around, it is not able to pick up any object by itself. As it was previously designed (but still needed to be implemented at CUA) the gantry functionality was extended by adding a vacuum gripper, to do this we used a vacuum pump and a vacuum manifold. The manifold is a device that allows us to control the vacuum in different ports and it sits to the side of the left wall of the gantry, while the vacuum pump is located outside the clean room, helping to reduce noise and vibrations inside the clean room. The separated location of these two devices required the use of vacuum pipes, valves and tubing. The piping was performed by CUA facilities

department while the details of the tubing connections were done by the CUA-HEP group. Once the Gantry was able to move around with high precision and able to pick up objects, the process of assembling the modules can be realized.

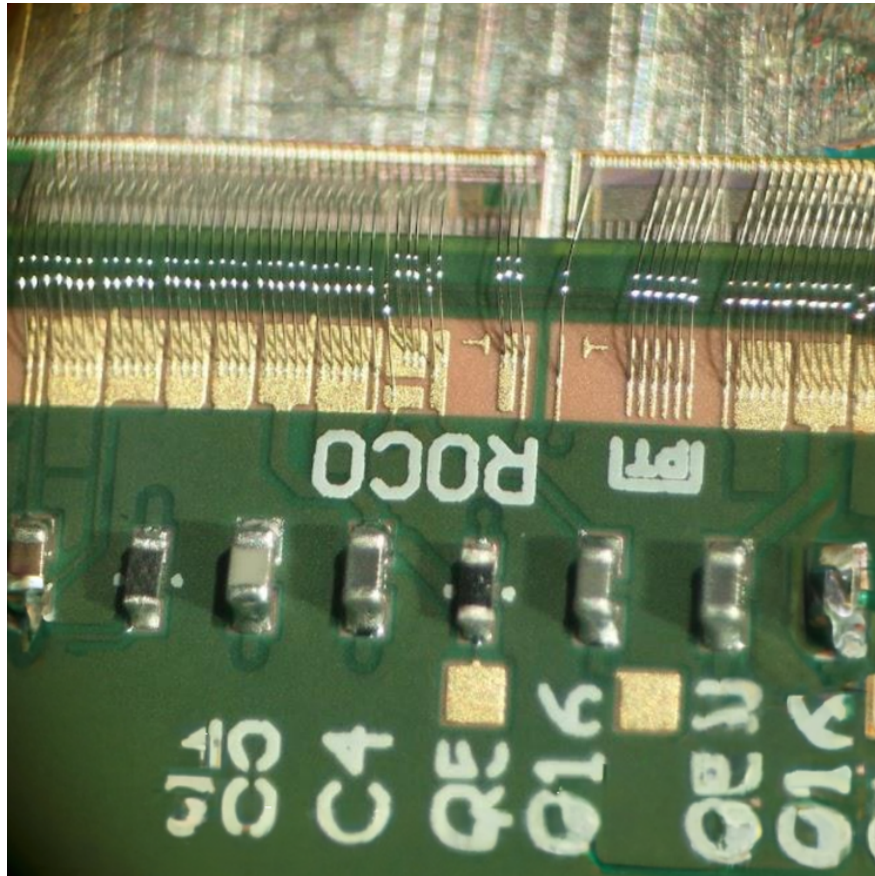


Figure 5.4: Grid of wires bonded to a sensor/HDI interface. The detailed view of the grid shows the different bond pad sizes, and the top part shows the sensor. The blurred image details are due to the zooming effect created by the microscope.

Once the HDIs are glued to the sensors, the next step involves the careful connection of the HDIs to the which involves the use of a wire bonding machine. The wire bonding machine was brought to the lab from Hesse-Mechatronics, a German company. This equipment allows us to create electrical connections using a wire, which is then bond to the sensor/HDI interface using ultrasonic waves. A detailed view of the bond pads and wire patterns can be seen in figure [5.4](#).

The electrical connections are created by surveying the HDI and locating the pads where the connections should take place. Once the pads are located, a drawing schematic is created from

the user interface of the machine, which proceeds to create the bond. In order to check the quality of the connections, the wire bonding machine is equipped with a microscope that allows us to see the connections and identify any possible defects. On top of a visual inspection of the bonds, a pull-test is performed with an older wire bonder with double functionality. The pull-tester allows us to have a metric for the strength of the bond by pulling the wire and measuring the force required to break it. The pull-tester also comes with a microscope, allowing the user to not only inspect the bond but verify that the pull needle is properly aligned with the bond in such a way that a consistent procedure is applied to all the bonds.

The labor at the wire bonding machine is now performed by Rhea Kathri, a technician from CUA, contributing member to the CUA-HEP program. The pull tester is highly demanding to the operator's eyesight, and has been designed to be performed by high-school students from the QuarkNet program.

Search for a Diboson resonance

*"I never see what has been done,
I only see what remains to be done."*

— Marie Curie

The present chapter discusses a search for new physics in the context of the HVT framework, as presented in [chapter 3](#). The search is performed in the fully leptonic final state where a hypothesized electrically charged resonance W' decays into an SM diboson system composed of a W boson and a Z boson, these two bosons further decay into leptons (either electrons e or muons μ), with Z decaying to a pair of same flavored leptons $Z \rightarrow \ell\ell$ and W decaying to a lepton, which flavor can be different from the one of the Z boson, and a neutrino $W \rightarrow \ell'\nu$. As the CMS detector does not have a dedicated subsystem for neutrino detection, the neutrino is reconstructed from the missing transverse momentum of the event.

Previous studies in different channels have been performed at CMS, and the same channel was studied with previously acquired data at 8 TeV. These individual studies were combined and results are shown for Model A and Model B in [Figure 1.1](#). The search presented in this chapter aims to extend the search to the 13 TeV energy scale and to provide input to a future combination of the results.

6.1 Analysis strategy

The strategy applied to the current resonance search is commonly known as a *bump-hunt* search, in which, based on the distribution of a discriminant variable the existence of a possible resonance is inferred by the presence of a disturbance or *bump* in a gradually decreasing background. The bump-hunt strategy is an approach that has been used extensively in the past to perform search for new physics. Robust analysis such as the Higgs-boson search ([Chatrchyan et al., 2012](#)) made use of this strategy.

There are multiple ways to perform a physics analysis in a bump-hunt search, from signal and background processes estimated from Montecarlo simulation, to data-driven methods that perform a fit in defined signal-depleted regions of the phase space, to the use of modern techniques such as supervised and unsupervised machine learning models which are trained to identify patterns in the phase space and produce as an outcome a probability of the event being either categorized as signal or background, see for instance ([Collins, Howe, and Nachman, 2019](#)).

The analysis presented in this dissertation make use of the invariant mass of a resonance candidate M_{WZ} as the discriminant variable. Although, if present, the signal is expected to affect all the distribution of the kinematic variables for the signal-like events, the invariant mass is the most sensitive to the presence of a resonance as it involves the cumulative and coherent effect of all the kinematic variables of the objects involved in the reconstruction of the resonance candidate.

Both the signal and the background are estimated from stochastic simulations of the physics processes. The modelling of the signal is done through a set of samples taken on the mass spectrum of the resonance from $M_{WZ} = 600$ GeV to $M_{WZ} = 4.5$ TeV. In order to prioritize and efficiently consume available computing resources, signal samples are specifically generated for the channel of interest; In this case, $W' \rightarrow WZ \rightarrow \ell\ell\ell'\nu$. The simulation of background processes is performed by generating a set of samples for Standard Model processes. These samples are usually shared among a wide range of analyses not only to reduce the amount of computing resources needed to generate the simulation but also to take advantage of the fact that different groups may look at different sections of the phase space and therefore study the quality of the simulation from

different angles. An improvement identified by a single analysis can benefit other analyses within the collaboration that make use of the same background samples.

Once the signal samples have been generated a set of studies are performed on the phase space in order to find sections of it where the signal is prone to be detected. An obvious example for the current analysis is an event in which three leptons are identified. These studies produce as an output a set of *cuts*, on different physical and detector variables such as the transverse momentum, the impact parameter of the collision, or the number of muon stations generating signal in the muon detector. The cuts are expressed as either threshold values, lower and upper limit in the range of values of a given variable, or in the most basic case, a boolean that determines whether an event passes or fails the cut. The latter is the case of *flags* where events are flagged as passing or failing certain criteria defined by the analyst. These cuts are further optimized to maximize the ratio between the signal and the background in the phase space. The optimization is performed through a series of iterations in which cuts are modified not only to increase the presence of the signal but also to take into account the quality or reliability of the background simulation in that particular region of the phase space.

The set of cuts that maximize the signal to background ratio is known as the *signal region* (SR). During the execution of the optimization processes the signal region remains *blinded* to the analyst, meaning the analyst is not able to see the *physics data* (the data collected by the detector) in this region of the phase space. This is done in order to prevent the analyst from introducing bias in the definition of the set of cuts in such a way that the presence of a disturbance in the background is interpreted as a signal.

As the signal region is being blinded, the quality of the background simulation is evaluated in a set of *control regions* (CR) where the signal, based on simulation, is expected to be negligible. SR and CR are mutually exclusive, meaning an event can belong to either one of them but not to both. In contrast to the signal region, the physics data in the control regions is available to the analyst, and the analyst is allowed to study the physics data in these regions. The quality of the simulation is then evaluated by comparing the distributions of different physics and detector

variables in both simulation and data. This comparison is performed by using a series of statistical metrics that are used to measure the difference between the two distributions, taking into account not only the shape of both distributions but also the sources of uncertainty in the simulation and data.

Once the signal region has been defined and the quality of the background simulation has been evaluated and accepted by the collaboration, the analysis goes through a review process by the B2G group ¹ in which an assigned expert reviews the use of the physics objects and check that it is consistent with the requirements from the different Physics Object Groups (POGs)². This *Object Review* process is concluded with a green light from the B2G group in order to proceed with the unblinding of the analysis and the production of the final results.

The following sections aim to describe in detail the different technical aspects of the analysis. Starting with [section 6.1](#) where the Montecarlo Simulation process is described, followed by [section 6.2](#) where the analysis-specific physics data samples are listed and characterized. [section 6.3](#) describes the event selection criteria while [section 6.4](#) describes how the physics objects are reconstructed and the criteria used to select them. The control regions are described and analyzed in [section 6.6](#). The signal region in [section 6.7](#) and the final results are presented in [section 6.9](#). A discussion on the statistical and systematic uncertainties is presented in [section 6.8](#).

MonteCarlo simulation

The analysis' background estimation is based on the Montecarlo (MC) simulation of standard model irreducible processes where three leptons can be found as a product of the collision and reducible processes that leaves similar signatures in the detector, including processes where there is a chance that one or more leptons could have been misidentified in the reconstruction process.

1. B2G stands for Beyond 2 Generations, a group within the CMS collaboration specialized in the search for physics beyond the Standard Model. Particularly, the search for new particles decaying to Heavy standard model objects such as the electroweak bosons, the top quark, or the Higgs boson.

2. The POGs are groups within the CMS collaboration that are responsible for reporting the status of the reconstructed data related to a specific physics object, such as muons, electrons, MET, etc.

In broad terms the MC simulations are produced in different stages: First, a simulation of the physics of the collision where the particles are produced is performed. This is known as the generation of the event. And among the output of this process, the kinematic variables of each particle is found. The generation of the event is performed by well known and validated physics software packages, such as Pythia ([Sjöstrand, 2008](#)) and MadGraph ([Alwall *et al.*, 2011](#)). This simulation step contains the complete chain of the generation process, where, from the output of the generator the parents of each particle can be identified by performing a look-up in the data entries of the generator step, this is a useful feature for the studies of the accuracy of the reconstruction process. Generating particle decays is a complex field of study in itself, involving aspects such as the modelling of the collision beams or the diffusion of the primary vertex where the interaction occurs, a process that is known as vertex smearing. The second step consists of the simulation of the detector response to the particles produced in the generator step. This process is performed by using the Geant4 package ([GEANT4 Collaboration, 2003](#)). As part of the work performed in this dissertation, a contribution was made to the CMS Geometry package, which is used by every simulation sample generated by the CMS collaboration. This contribution consisted in migrating the CMS Tracker algorithms that allowed to reconstruct a 3D model of the detector from a solution initially written to work for CMS to the DD4hep open-source toolkit ([Frank *et al.*, 2014](#)), further details of this contribution can be found in the 24th International Conference on Computing in High Energy and Nuclear Physics conference proceedings ([Vuosalo *et al.*, 2020](#)).

Geant4 is a physics validated package widely used in different areas of physics to perform the study of the interaction between radiation and matter, and accounts for different processes such as photon conversion, electron Bremsstrahlung, energy loss by ionization of charged particles, nuclear interactions, etc. The third step consists of the reconstruction of the particles based on the outcome of the detector simulation. This step is performed by executing the particle flow algorithm ([Beaudette, 2014](#)), a specific implementation of the algorithm is contained in the CMSSW framework and this is the software package used to perform the reconstruction. This framework provides a set of tools to perform a variety of tasks in the study of the detector, its configuration,

model description and physics output among others. CMSSW is a product of the CMS collaboration and receives contributions from numerous developers. As part of the development of this research projects multiple contributions were made to the CMSSW framework, particularly in the area of the geometry model of the Tracker [subsection 4.3.1](#).

As the analysis relies heavily on the accuracy of the MC simulations, its quality is evaluated by performing a comparison between the output of the simulation and the data in two signal-depleted regions (see [Section 6.6](#)).

6.1.1 Signal Simulation

Signal events for electrically charged diboson resonances in the 600 GeV to 4.5 TeV mass range under the theoretical framework of the HVT model ([Pappadopulo *et al.*, 2014](#)) have been generated using MC simulations with MadGraph5_aMC@NL ([Alwall *et al.*, 2011](#)) interfaced with Pythia 8 ([Sjöstrand, 2008](#)) for showering and hadronization, and a full detector response simulated with the Geant4 toolkit ([GEANT4 Collaboration, 2003](#)). Physics objects are then reconstructed using the Particle-flow algorithm ([Beaudette, 2014](#)).

The signal and background samples [6.1.2](#) are generated centrally by the CMS collaboration from a set of text configuration files commonly referred as *datacards*. These datacards are used to configure the input of the generation process, the datacards used to produce the signal samples can be found in ([CMS Collaboration, 2017a](#)).

A complete list of the centrally generated signal samples used is shown in [Table A.1](#).

6.1.2 Background Simulation

Background processes have been generated using MadGraph ([Alwall *et al.*, 2011](#)), Pythia ([Sjöstrand, 2008](#)) and Powheg ([Oleari, 2010](#)). These backgrounds include irreducible processes which produce the same final state as the signal and also reducible processes which produce different physics, but lead to similar signatures in the detector. The backgrounds are dominated by the production of electroweak heavy vector boson pairs (WZ), but also include ZZ production where

one of the leptons is either outside the detector acceptance or misreconstructed. Other backgrounds such as Z +Jets, $t\bar{t}$, $Z\gamma$, are included as they may contain misidentified lepton candidates coming from jets or photons.

The full list of background samples, including their dataset name and cross-section, are presented in Tables [A.2](#) (2016), [A.3](#)(2017), [A.4](#) (2018).

6.1.3 Simulation accuracy enhancements

In order to better account for the differences seen between simulation and data, a series of corrections are applied to the Montecarlo generated events in signal and background processes.

³ These corrections are applied in the form of event weights known as *scale factors* and their accumulated effect equates to a slight reshape of the distributions and take into consideration a variety of phenomena that was or could not be fully assessed when simulating the events. For instance, in case of the partial failure of a subsystem within the detector during the data taking process. Additional details of these corrections can be found in [section 6.8](#)

6.2 Data Samples

The physics datasets used for the analysis presented in this note were collected using the CMS detector during the 2016, 2017 and 2018 data-taking years. This period of is officially known as *RunII*. Data was recorded at the center-of-mass energy $\sqrt{s} = 13$ TeV and a total integrated luminosity of 137.65 fb^{-1} was collected and reconstructed with the 10.2.18 version of the CMSSW framework. [Table 6.3](#) shows the integrated luminosity collected during each year. As mentioned earlier the physics data acquired by the CMS detector is collected and stored in the CMS storage infrastructure, as the amount of data collected is extensive, the data is split into smaller datasets determined by the HLT paths that were triggered by the event. If an event containing a muon

3. In the vast majority of cases corrections are only applied to simulated events; however, in *rare* circumstances, some corrections are also applied to reconstructed data events. In either scenario the corrections go through validation, review and approval process by the relevant object group within the CMS collaboration

Table 6.1: This table shows the list of Physics Datasets used in this analysis: each year contains a list of datasets as they are officially named in the CMS database and the corresponding HLT path that will be used to select the events from each specific dataset.

Year	Dataset	HLT
2016	SingleMuon	HLT_TkMu50
		HLT_Mu50
	SingleElectron SinglePhoton	HLT_Ele27_WPTight_Gsf HLT_Photon175
2017	SingleMuon	HLT_Mu50
		HLT_OldMu100
	SingleElectron SinglePhoton	HLT_TkMu100 HLT_Ele35_WPTight_Gsf HLT_Photon200
2018	SingleMuon	HLT_Mu50
		HLT_OldMu100
	EGamma	HLT_TkMu100 HLT_Ele32_WPTight_Gsf HLT_Photon200

triggers one of the Muon HLT paths and at the same time triggers another HLT path, such an HLT path involving the presence of an electron, the event will be stored in both datasets: Single Muon and Single Electron. To account for this behavior, prior to running the analysis on physics data, an index of unique events is built to keep track of already seen events and avoid double counting.

During the data-taking period, active CMS personal and collaborators monitor the condition of the detector and log special events that may impact the quality of the data. Part of the data quality control process is performed online, during the time of collection of the data, and part of it is performed offline, after the data has been taken, reconstructed and analyzed by different groups within the collaboration. This implies that different versions of the physics data but also of the MC simulations are available. The work presented in this dissertation began in 2019 with the so-called *Legacy* datasets. However, as a newer, more refined version of the data was released the analysis was updated to use the UL Datasets (short for *Ultra-Legacy* datasets). This version is considered one of the most accurate and precise versions of the data and MC available to analysts. At this point, it is important to mention an important contribution made during the execution of this re-

Table 6.2: List of datasets used in the analysis. This table shows the name of the dataset, the year it was collected, the name of the *era* and the numeric version.

Year	Dataset	Era	Version
2016	SingleMuon	B	ver2-v1
		C, D, E, F, G, H	v1
	SingleElectron	B	ver2-v1
		C, D, E, F, G, H	v1
	SinglePhoton	B	ver2-v1
		C, D, E, F, G, H	v1
2017	SingleMuon	B, C, D, E, F	v1
	SingleElectron	B, C, D, E, F	v1
	SinglePhoton	B, C, D, E, F	v1
2018	SingleMuon	A, B, C, D	v1
	EGamma	A, B, C, D	v1

search project: in the summer of 2022 in the study of the corrections to the MC simulation for the muon object, differences in the predictions between physics data and MC simulations for muons with high transverse momentum were observed. This lead to a revision of the muon reconstruction process and to the release of a newer UL version of the SingleMuon dataset. For a more detailed description of the contribution made on this particular dataset see [Appendix 2](#).

Table 6.3: Run 2 Luminosity

Year	Luminosity [fb^{-1}]
2016	36.33
2017	41.48
2018	59.83

This analysis makes use of datasets which combine several High Level Trigger paths ([Table 6.1](#)). See [subsection 4.3.5](#). The complete list of datasets used are shown in [Table 6.2](#), each dataset contains in the order of hundreds of millions events. Due to the use of unique events mentioned earlier, after the final selection no overlap is found between channels.

6.3 Event Selection

6.3.1 Event cleanup and HLT Efficiency

Events with at least one primary vertex passing a logical OR combination of the HLT paths shown on table 6.1, and containing at least three *preselected* leptons (number of muons plus number of electrons) are selected. This is done so provided that its missing transverse energy E_T^{Miss} is greater than 40 GeV. Due to the presence of multiple leptonic flavors in the final state, each event is required to pass either the Muon or Electron triggers based on the high-Pt recommendations from the CMS Physics Objects group (POG, 2020; EGamma POG, 2020). The combined HLT efficiency was found to be higher than 85% as shown in Figure 6.1.

Additionally, for the HEM treatment (JER POG) events are excluded if any electron or jet fall within the region $-1.57 < \phi < -0.87, -2.5 < \eta < -1.3$.

To clean up the event selection according to the latest recommendations from the physics object groups (POGs) the following flags are required for the event:

- Flag_goodVertices
- Flag_globalSuperTightHalo2016Filter
- Flag_HBHENoiseFilter
- Flag_HBHENoiseIsoFilter
- Flag_EcalDeadCellTriggerPrimitiveFilter
- Flag_BadPFMuonFilter
- Flag_eeBadScFilter
- Flag_hfNoisyHitsFilter
- Flag_BadPFMuonDzFilter

One additional flag is required for the year 2017 and 2018:

- Flag_ecalBadCalibFilterV2

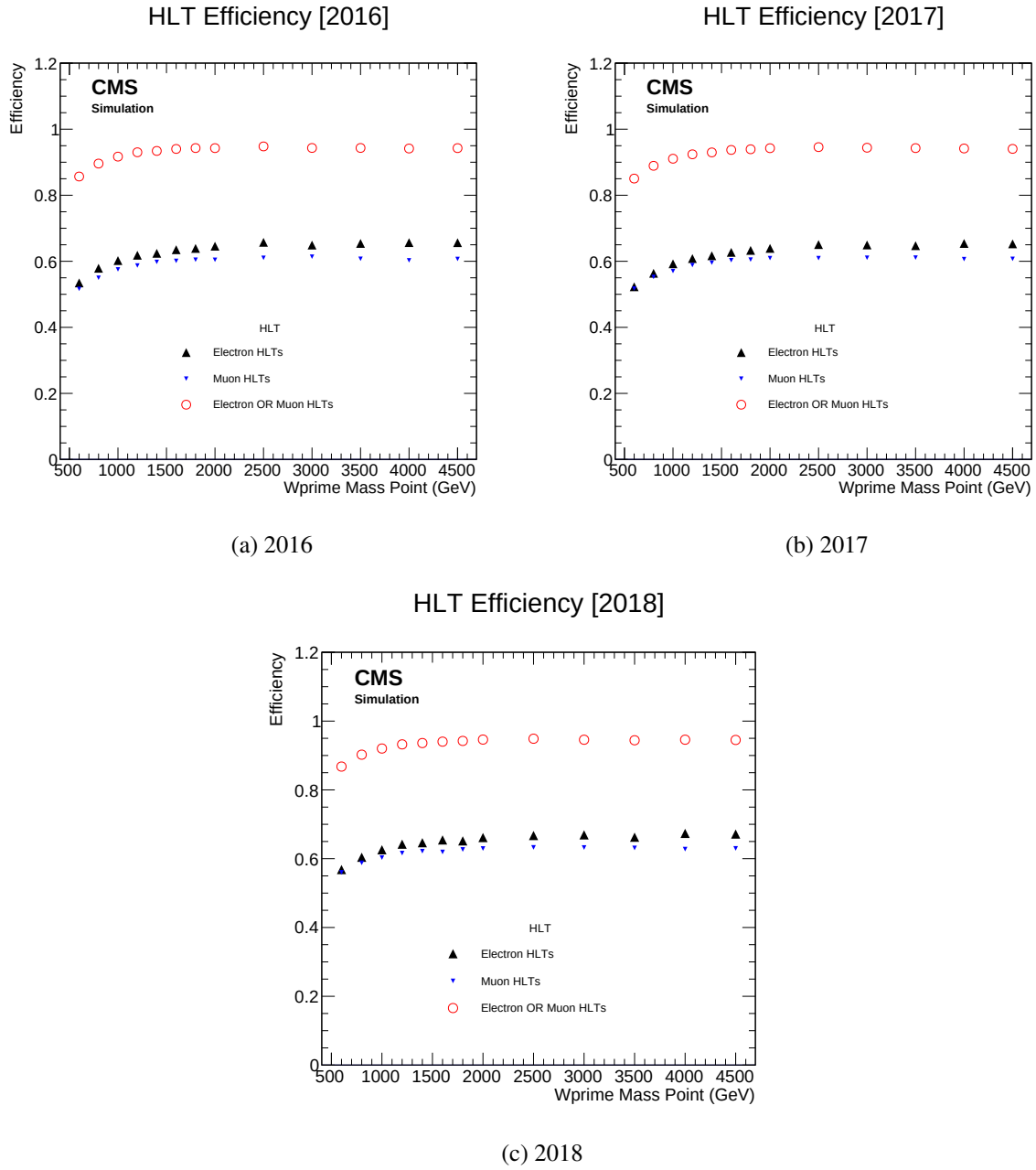


Figure 6.1: Signal efficiency for individual and combined HLT paths chosen for the present analysis, for the 2016 [6.1a](#), 2017 [6.1b](#) and 2018 [6.1c](#). The complete list of electron and muon HLT paths is shown in Table [6.1](#).

As their name suggests, these flags filter out events that are considered noisy from a particular subsystem and were identified as problematic for the proper reconstruction of the physics objects.

6.4 Object Selection

6.4.1 Electron Preselection

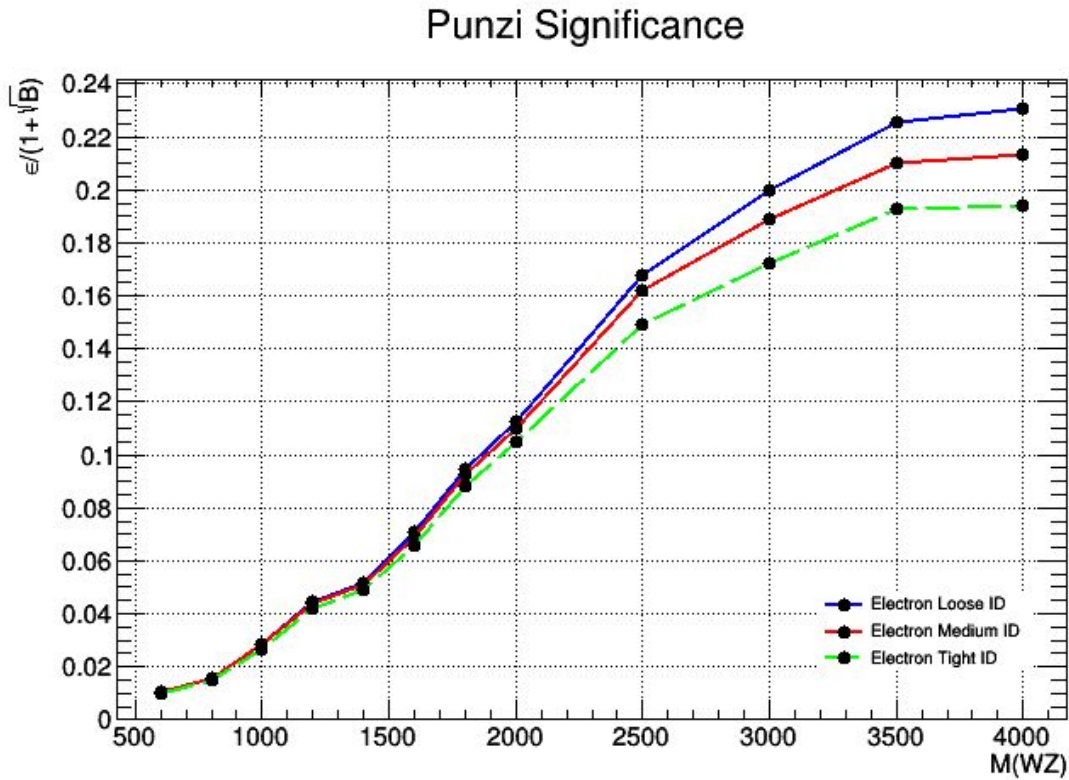


Figure 6.2: Punzi significance for the different Electron's cut-based IDs for the electron decay $Z \rightarrow e + e$. The cut-based loose ID shows high efficiency specially at high masses where the distance in the $\eta - \phi$ plane is expected to be small.

Electrons are reconstructed from hits in the different layers of the tracker and energy deposits in the scintillating crystals across the $\eta - \phi$ plane in the Electromagnetic Calorimeter. The electron's charge can be identified by its signature in the tracker due to the presence of the strong magnetic field in the CMS detector.

Electrons in this analysis are required to be within the ECAL fiducial region i.e. $|\eta| < 2.5$ excluding the transition region between the barrel and the endcaps $1.4442 < |\eta| < 1.5660$.

Electron identification is based on a cut based ID as defined by the EGamma POG (EGamma POG). Depending on the channel, the analysis, uses *loose*, *medium* or *tight* electrons, with loose electrons having an efficiency of 90%, medium electrons an efficiency of 80% and tight electrons an efficiency of 70% (EGamma POG): channels with a $Z \rightarrow e + e$ decay ($ee\nu\nu$ and $ee\mu\nu$) require two electrons passing at least the *loose* ID, due to its high efficiency specially at high resonant mass where the electrons are expected to be highly collimated (see Figure 6.2). The electron corresponding to the $W \rightarrow e\nu$ decay is required to pass the cut-based *tight* ID.

The leading electron in the event (electron with the highest P_t) is required to pass a minimum threshold of 50 GeV while other electrons can have a minimum of 10 GeV. It is assumed that the leading electron has the highest probability of firing the EGamma triggers while the probability of the subleading leptons is negligible.

6.4.2 Muon Preselection

The muon objects in this analysis can be divided into two categories: Tracker and Global high-Pt muons, a detailed cut based description of these IDs is provided by the Muon POG (Muon POG). Tracker muons are reconstructed from hits in the tracker matched with hits in the first muon station, while global high-Pt muons leave hits in the tracker and multiple layers in the muon subsystem.

Muons are required to be within the pseudorapidity range $|\eta| < 2.4$ and to have a minimum transverse momentum of $P_t = 20$ GeV. Additionally, the leading muon is required to have a transverse momentum $P_t > 70$ GeV. The Muon transverse momentum is measured by using the TuneP algorithm, which chooses the best muon reconstruction between tracker-track, tracker-plus-first-muon-station, picky, and dynamic truncation (CMS Collaboration, 2018).

For events portraying a $Z \rightarrow \mu + \mu$ decay a stricter cut is applied on the leading muon $P_t > 70$ GeV. The muon pair is required to be a composite of a cut-based global high-Pt ID muon

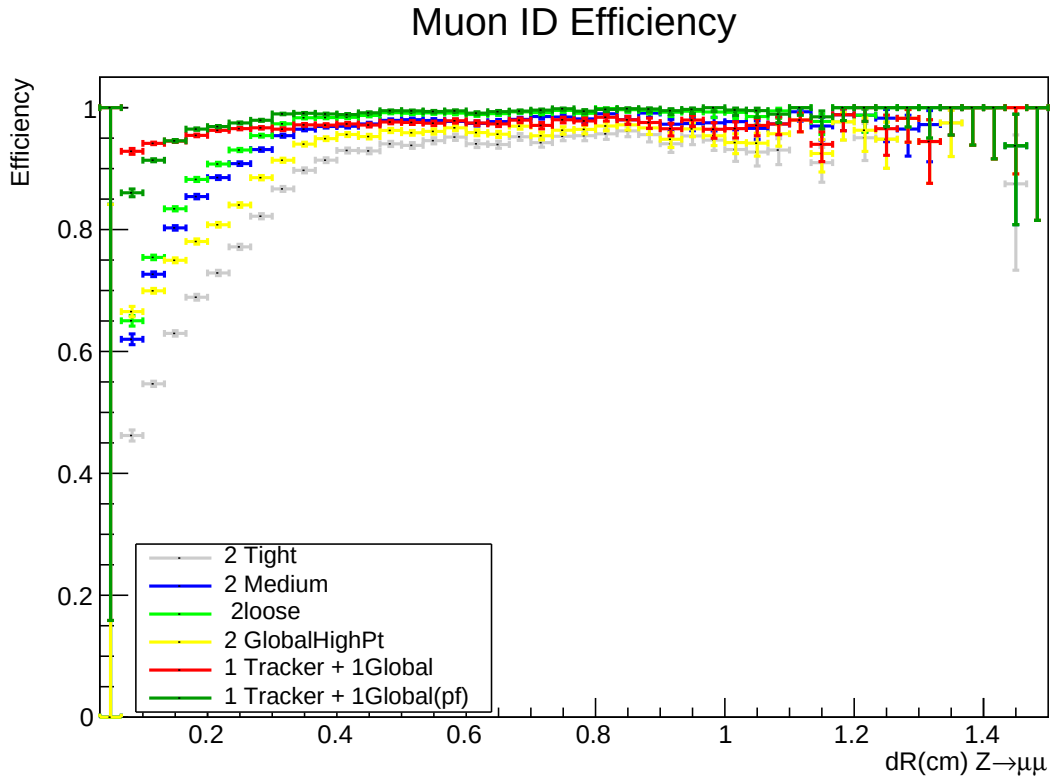


Figure 6.3: Signal Efficiency for different Muon ID combinations for the product of the decay $Z \rightarrow \mu + \mu$. The less efficient combination is requiring the Muon pair to be a cut-based Tight ID pair, increasing efficiency towards less strict cut-based requirements (Loose and Medium ID). The most efficient combination in the signal reconstruction is the combination of one global high-Pt ID Muon with another muon that can be either a tracker or global High-Pt ID.

and either a tracker or global high-Pt ID muon that is simultaneously a particle-flow candidate, following recommendations from a previous B2G analysis with a boosted Z topology (CMS Collaboration, 2019). This combination of high-Pt muons shows the second-highest efficiency, see Figure 6.3.

6.4.3 Lepton Misidentification

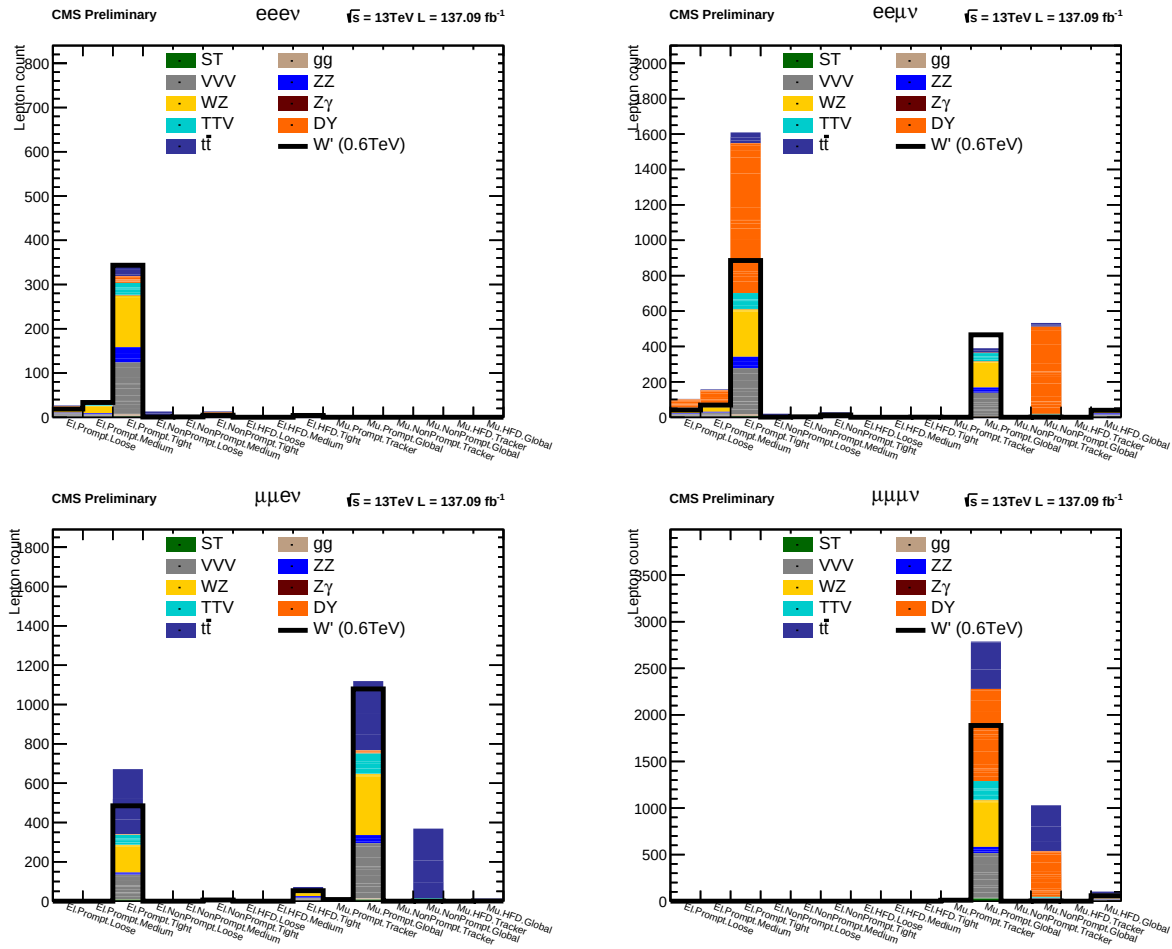


Figure 6.4: Lepton origin classification according to simulation prior to constraining the impact parameter $ip3D < 0.01$ cm. Each lepton is considered individually when filling the histogram. The main contribution to non-prompt leptons come from Muons in Drell-Yan and $t\bar{t}$ events.

The nature of the reconstruction process may lead to some objects being wrongly identified.

A dedicated study was performed in order to evaluate the effects on misreconstructed objects on the

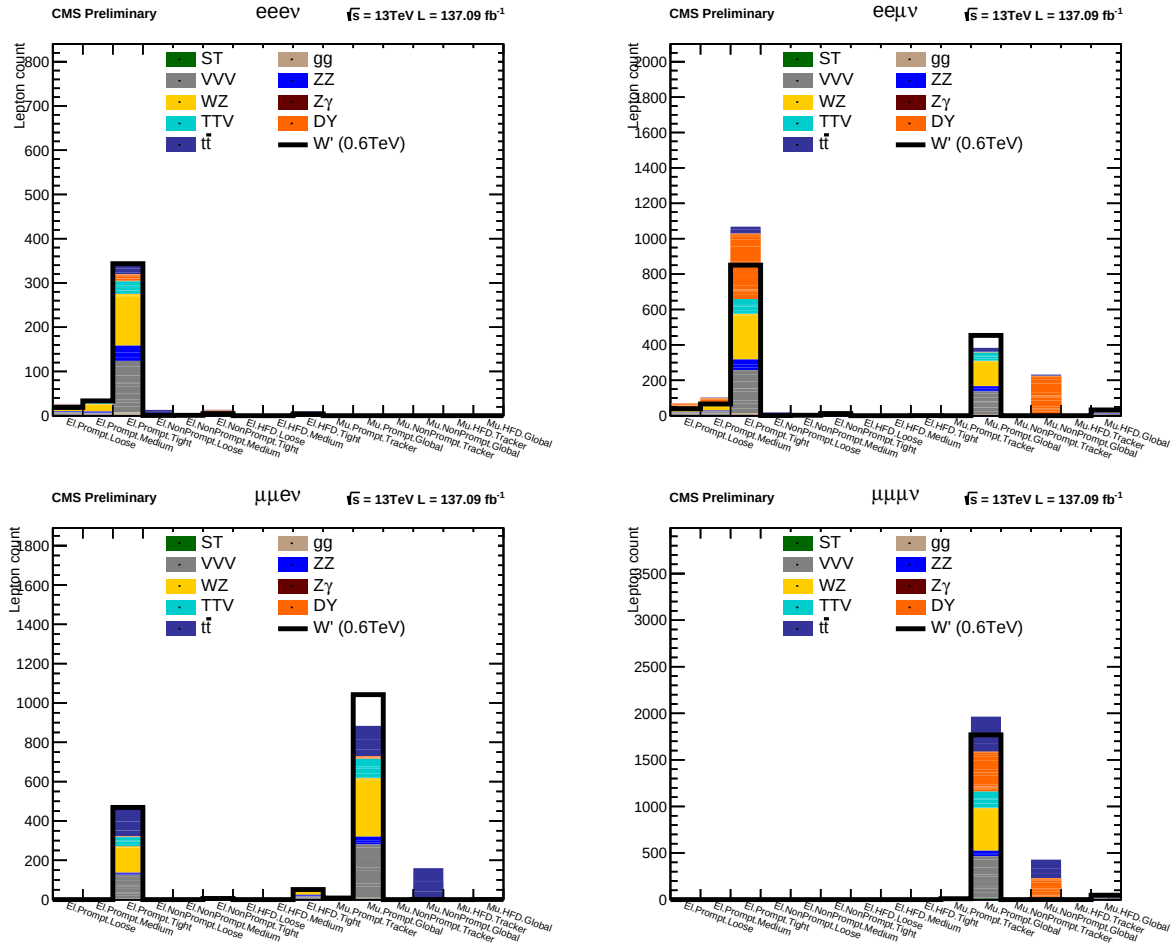


Figure 6.5: Lepton origin classification according to simulation after constraining the impact parameter $ip3D < 0.01$ cm. Each lepton is considered individually when filling the histogram. The main contribution to non-prompt leptons come from Muons in Drell-Yan and $t\bar{t}$ events.

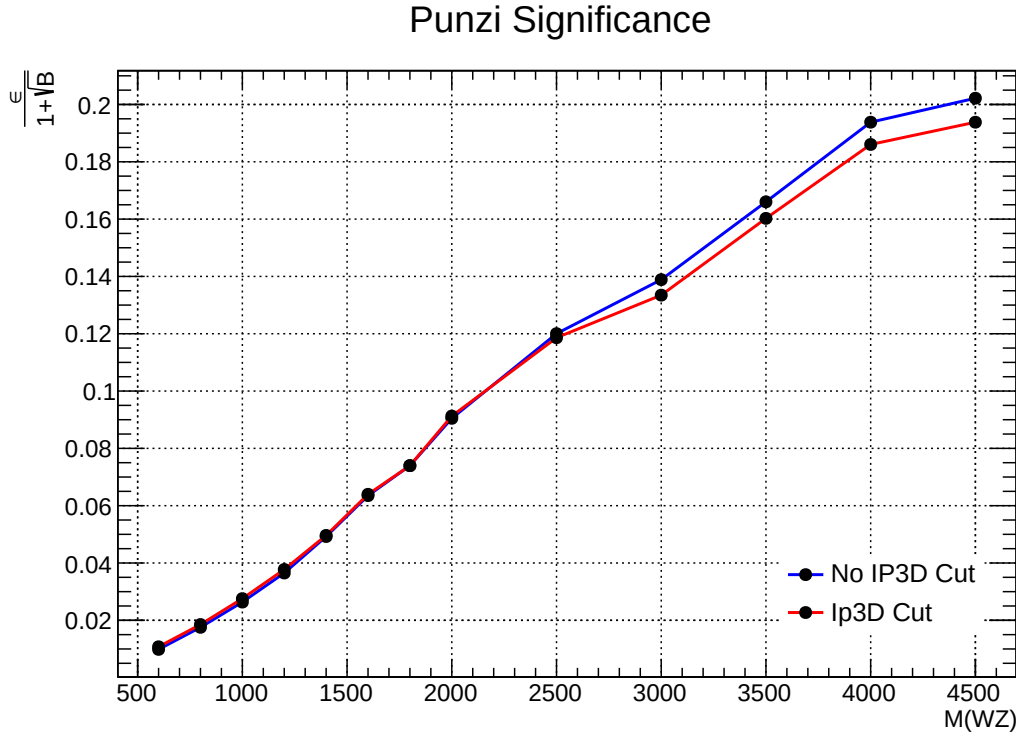


Figure 6.6: Punzi significance as a function of the mass resonance prior to and after implementing the cut on the impact parameter in order to reduce the number of non-prompt muons

counting experiment. Misreconstructed leptons are also commonly referred as fake leptons. It is assumed that if the number of MC generated electrons (muons) match the number of reconstructed electrons (muons) there are no misreconstructed objects. A fake lepton is a lepton that is non-prompt that didn't arise from a τ lepton or from a heavy flavor decay (HFD). Figure 6.4 shows how the Drell-Yan and $t\bar{t}$ processes are susceptible to present reconstructed non-prompt muons. To account for this, we impose a cut on the 3D impact parameter of the muons such that $ip3D < 0.01$ cm, Figure 6.5 shows the effect of the cut on reducing the number of non-prompt muons. The Punzi significance of the impact parameter requirement as a function of the WZ resonance mass is shown in figure 6.6.

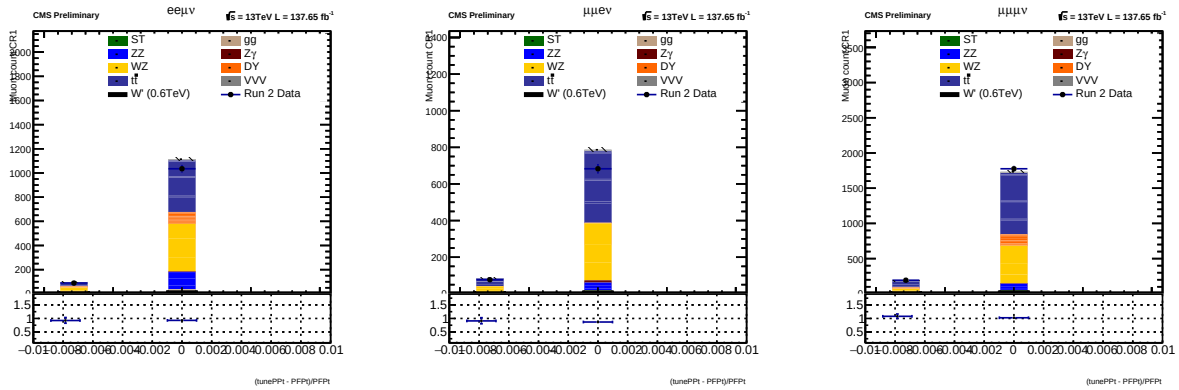


Figure 6.7: Relative difference between the transverse momentum as measured by the TuneP and Particle flow algorithms in each final signature as seen in the $dr_{l_1 l_2} > 1.5$ control region (subsection 6.6.1). Right: $Z(\rightarrow e + e)W(\rightarrow \mu + \nu)$ Middle: $Z(\rightarrow \mu + \mu)W(\rightarrow e + \nu)$ Left: $Z(\rightarrow \mu + \mu)W(\rightarrow \mu + \nu)$

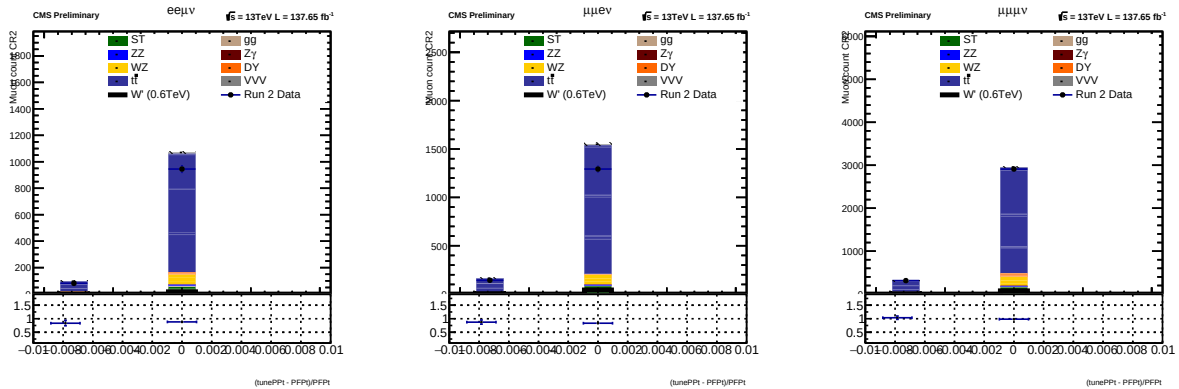


Figure 6.8: Relative difference between the transverse momentum as measured by the TuneP and Particle flow algorithms in each final signature as seen in the $70\text{GeV} < Z_{\text{mass}} < 110\text{GeV}$ control region (subsection 6.6.2). Right: $Z(\rightarrow e + e)W(\rightarrow \mu + \nu)$ Middle: $Z(\rightarrow \mu + \mu)W(\rightarrow e + \nu)$ Left: $Z(\rightarrow \mu + \mu)W(\rightarrow \mu + \nu)$

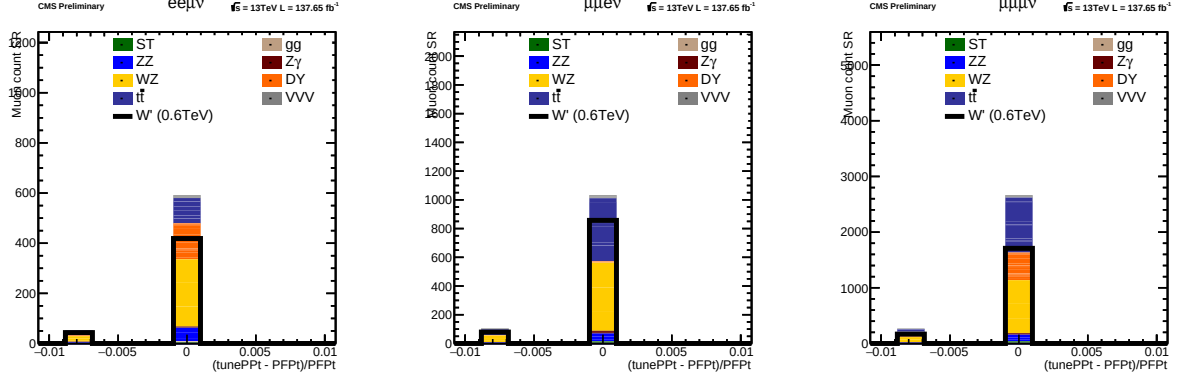


Figure 6.9: Relative difference between the transverse momentum as measured by the TuneP and Particle flow algorithms in each final signature as seen in the $dr_{l_1 l_2} < 1.5$ signal region (Section 6.7). Right: $Z(\rightarrow e + e)W(\rightarrow \mu + \nu)$ Middle: $Z(\rightarrow \mu + \mu)W(\rightarrow e + \nu)$ Left: $Z(\rightarrow \mu + \mu)W(\rightarrow \mu + \nu)$

6.4.4 Missing Transverse Energy

The missing transverse energy E_T is reconstructed with the particle flow algorithm (Beaudette, 2014) and events are required to have at least a missing transverse energy of $E_T^{miss} = 40$ GeV.

As shown in figures 6.7, 6.8, 6.9 the relative difference between the muon transverse momentum as measured by the TuneP and the Particle Flow algorithm is always less than 1% and most of the time both quantities are equivalent, this makes safe the use of the high-Pt Muon IDs with MET as computed by the particle flow algorithm.

6.5 Reconstructed Candidates

6.5.1 Z Candidate

Two same flavored, opposite charged leptons are required to reconstruct a Z candidate. If more than one pair is found, the one with reconstructed mass closer to the nominal mass $M_Z = 91.1876$ GeV is chosen. The pair's mass is required to fall in the Z mass window $70 \text{ GeV} < M_Z < 110 \text{ GeV}$. In favor of an increase in the signal efficiency the opposite charged requirement is dropped for the $ee\nu\nu$ and $ee\mu\nu$ categories.

If the Z candidate is formed from a muon pair, one of the muons is required to pass two additional requirements: being a global high-Pt muon and a particle-flow candidate. In the case of electrons, the requirement is to pass at least the selection criteria of the cut-based *loose* ID. I.e the electrons can have either loose, medium or tight cut-based ID.

The event is rejected from the signal region if the distance in the $\eta - \phi$ plane for the two leptons product of the decay of the Z is greater than 1.5. This requirement is also used to define the WZ control region, see [subsection 6.6.1](#).

6.5.2 W Candidate

The W candidate is reconstructed from the remaining lepton and the missing energy of the event E_T^{miss} . The remaining lepton is required to be either a cut based *tight* ID electron or a global High-Pt muon with a transverse momentum of at least $P_t > 50$ GeV.

The neutrino from the $W \rightarrow l\nu$ decay escapes undetected, and therefore the following assumptions are made in order to perform a kinematic reconstruction of the W candidate: there are no additional sources of missing energy, and consequently E_T^{miss} is considered the transverse momentum corresponding to the undetected neutrino. The longitudinal momentum P_z can be recovered by imposing the $M_W = 80.379$ GeV nominal mass and assuming a massless neutrino $M_\nu = 0$.

As η is unknown for the missing transverse energy, the neutrino 4-vector is not well-defined. However, by assuming the mass of W the longitudinal component of the neutrino is reduced to a quadratic equation:

$$P_z^\nu = \frac{P_Z^l(M_W^2 - M_t^{W^2} + 2P_t^l P_t^\nu) \pm P_t^l \sqrt{(M_W^2 - M_t^{W^2})((M_W^2 - M_t^{W^2}) + 4P_t^l P_t^\nu)}}{2P_t^{l^2}}$$

Where the transverse mass M_t^W is defined as $M_t^W = \sqrt{2P_t^l P_t^\nu (1 - \cos\phi_{lv})}$. Due to detector resolution effects and systematic uncertainties on the reconstruction of missing transverse energy,

the transverse mass may exceed the mass of the W boson M_W and the longitudinal component of the momentum would remain undefined, in these cases we set the transverse mass equal to the nominal value $M_t^W = M_W$.

The less energetic of the solutions gives the correct value 70% of the time according to simulation (Khachatryan *et al.*, 2015). When no real solutions are available ($W_{mt} > Wm$), the invariant mass is set to the reconstructed transverse mass and we are left with two real identical solutions.

6.5.3 WZ Candidate

The W' is reconstructed from the W and Z candidates. Events are rejected if the sum of the leptonic masses are less than 120 GeV and if the sum of the transverse momentum $L_t < 110$ GeV, where L_t is defined as:

$$L_t = \sum_{n=1}^3 Pt_{ln}$$

Events are split in four channels depending on the leptonic flavor of the diboson decay:

eeev three electrons and missing transverse energy are found, two of the electrons correspond to the decay of the Z boson and the remaining electron corresponds to the decay of the W boson. $Z \rightarrow e^+e^-$, $W \rightarrow e + \nu$ The three electrons are expected to leave hits on the tracker subsystem with low curvature due to their high transverse momentum and energy depositions are expected in the electromagnetic calorimeter The signature left on the CMS detector is shown on figure 6.10.

ee μ ν two electrons, one muon and missing transverse energy are found, the two electrons correspond to the decay of the Z boson and the muon corresponds to the decay of the W boson. $Z \rightarrow e^+e^-$, $W \rightarrow \mu + \nu$ The two electrons are expected to leave hits on the tracker subsystem with low curvature and energy depositions are expected in the electromag-

netic calorimeter while the muon leaves hits in the tracker and muon subsystem. The signature left on the CMS detector is shown on figure 6.11.

$\mu\mu e\nu$ two muons, one electron and missing transverse energy are found, the two muons correspond to the decay of the Z boson and the electron corresponds to the decay of the W boson. $Z \rightarrow \mu^+\mu^-$, $W \rightarrow e+\nu$ The two muons leave hits on the tracker and muon subsystems with negligible curvature due to its high transverse momentum while the electron is expected to leave hits in the tracker and energy deposition in the electromagnetic calorimeter. The signature left on the CMS detector is shown on figure 6.12.

$\mu\mu\mu\nu$ three muons and missing transverse energy are found, the muon pair correspond to the decay of the Z boson and the remaining muon corresponds to the decay of the W boson. $Z \rightarrow \mu^+\mu^-$, $W \rightarrow \mu + \nu$. The three muons are expected to leave hits on the tracker subsystem and muon chambers with low curvature due to their high transverse momenta. The signature left on the CMS detector is shown on figure 6.11.

Signal Efficiency

The selection of events as previously described define the signal region which provides a total yield of events per channel that can be used to estimate the efficiency in the reconstruction and selection of the events and an overall efficiency for the combined statistics in the four channels. As shown in Table A.1 each resonance mass point has its own Montecarlo sample. The Montecarlo sample for each mass point in the simulated range, contain a total of 50,000 events. Each event is generated to contain a signal-like collision, however different factors such as the detector resolution or the fact that not each outgoing particle will be within the acceptance of the detector reduce the number of events that end up being reconstructed as a signal-like event and passing the selection criteria. The efficiency is then calculated as the ratio between the number of events passing the signal region selection and the total number of events generated in the simulation for each mass point.

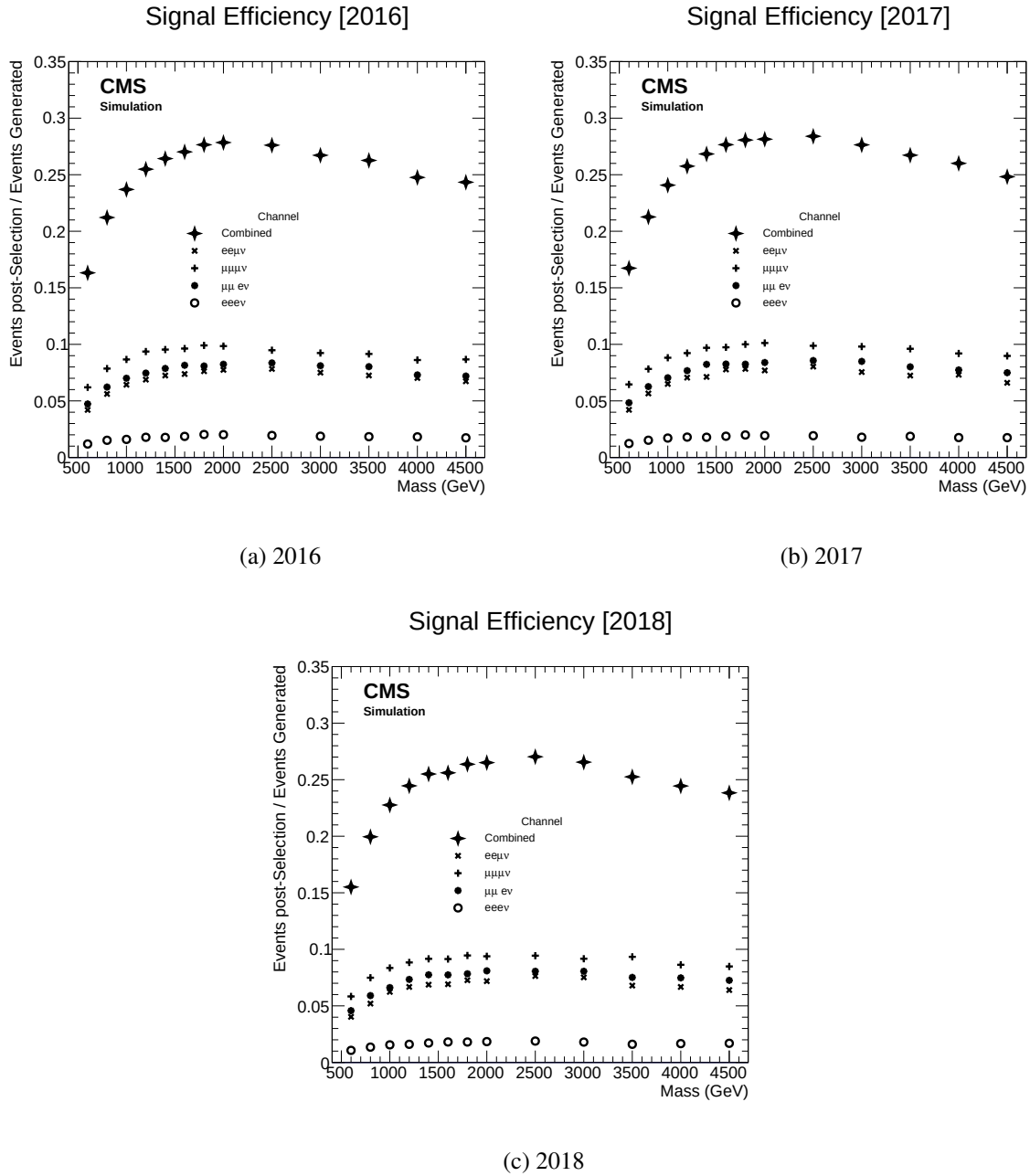
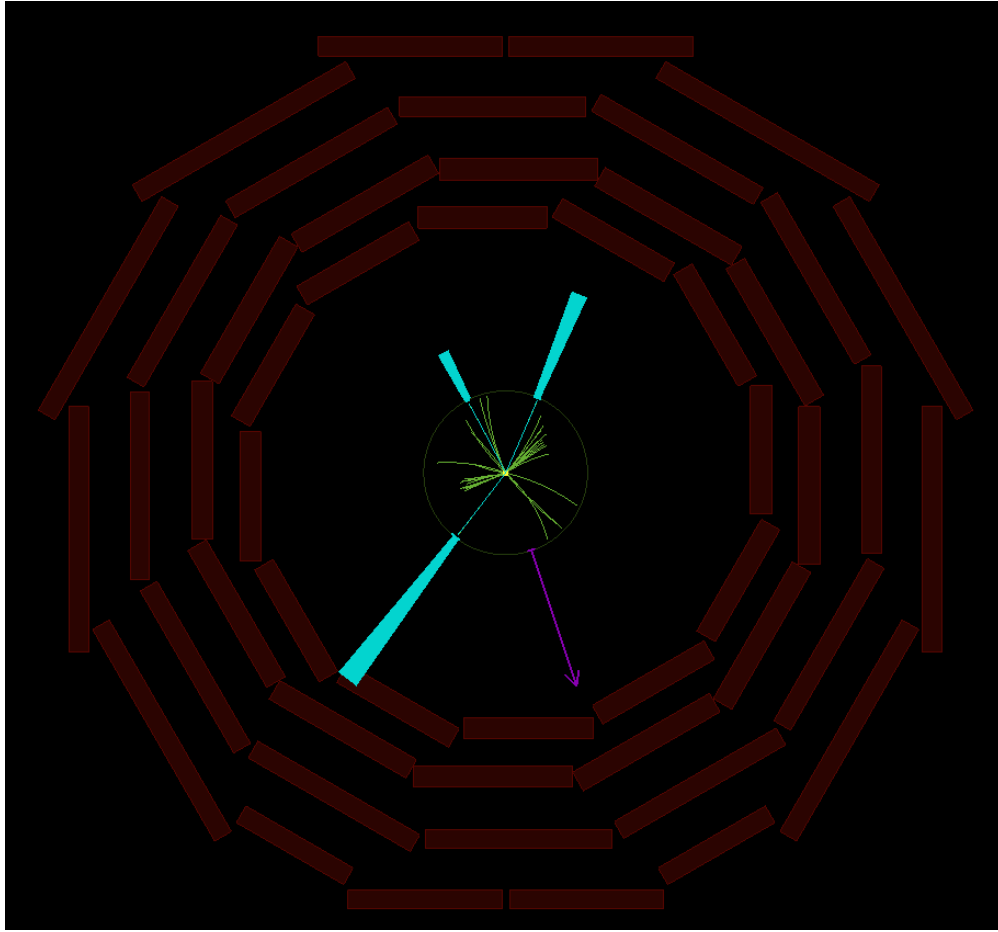
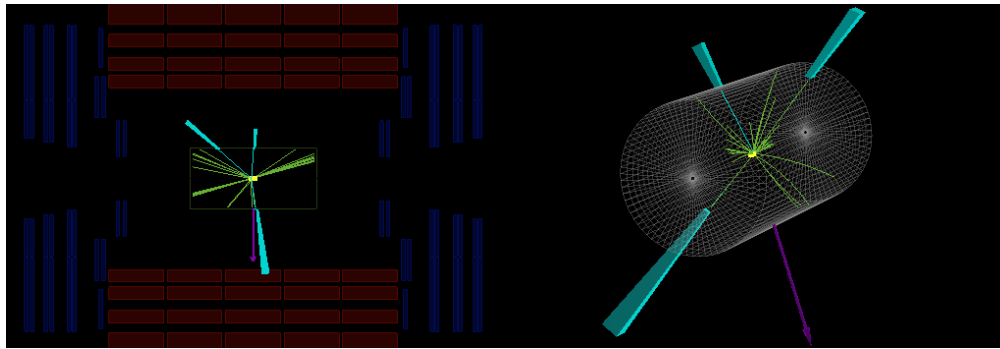


Figure 6.14: The signal selection efficiency for individual and combined channels as a function of the mass of the resonance candidate. The efficiency is calculated as the ratio between the number of events passing the selection and the total number of the events generated in the simulation. The different figures show the efficiency per year 2016 [6.14a](#), 2017 [6.14b](#) and 2018 [6.14c](#).

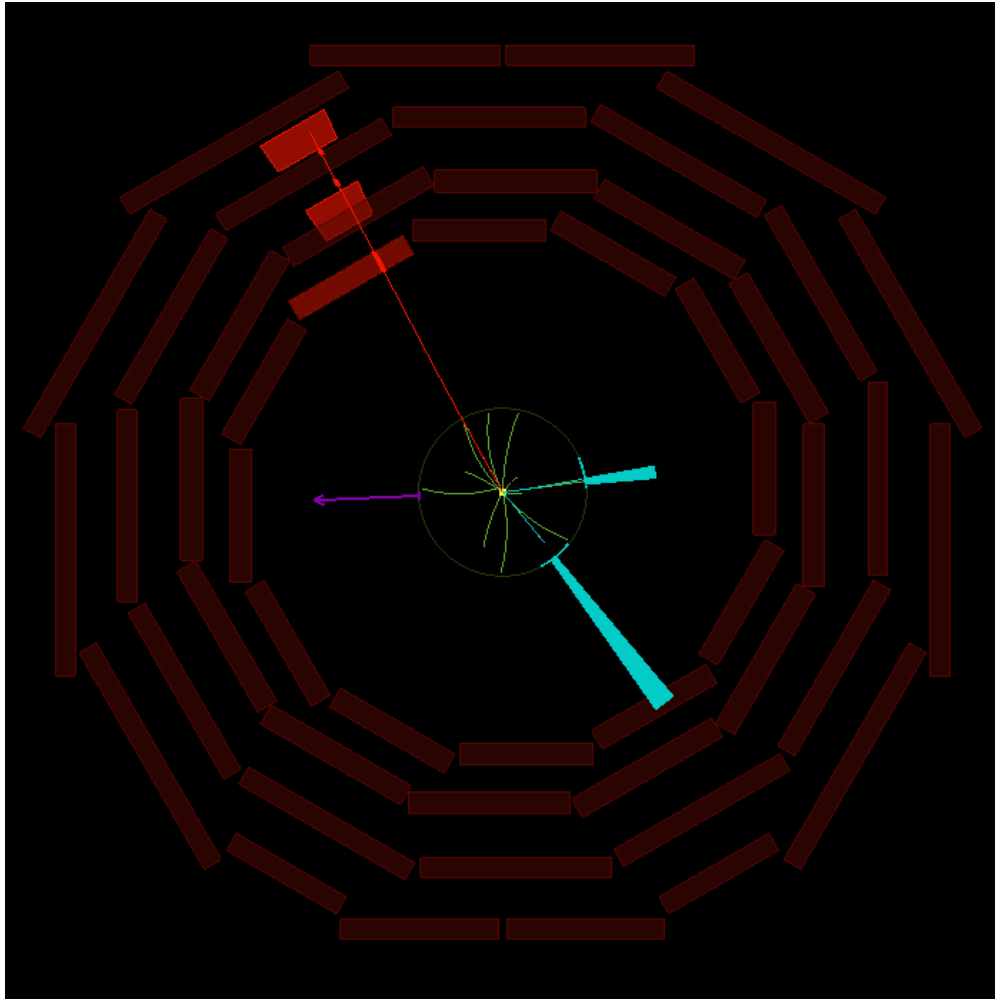
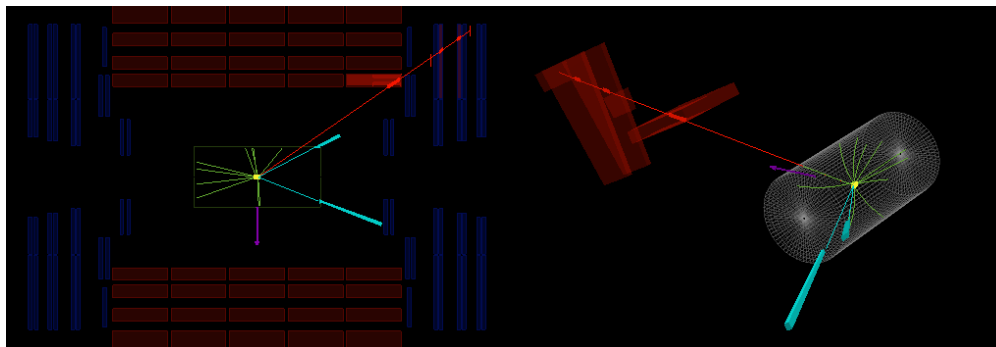
As shown in [Figure 6.14](#) the efficiency for the combined channels is between 16% and 28% and is higher as the number of muons in the channel increases, the lowest being in the $ee\nu$ channel with an efficiency in the range of 1% to 2% and the highest in the $\mu\mu\nu$ channel with an efficiency in the range of 6% to 10%. The efficiency is calculated per year keeping consistency with the simulated samples as each year has its own CMS/LHC configuration, including characteristics such as detector alignment and pileup profiles that can affect the efficiency and also provides a higher level of granularity in the analysis of Montecarlo (but also data) samples. Despite this breakdown, the efficiency is consistent and the difference between the years is negligible.

A lower efficiency in the low mass region is expected as a lower invariant mass of the resonance candidate means a lower energy and momentum of the outgoing particles. A plateau in the efficiency is observed around $M_{WZ} = 2.0 \text{ TeV}$ and the efficiency slightly drops at higher masses, this can be due to different factors. In particular, the constraints in the detector resolution, and in particular the tracker subsystem, as the higher the mass of the resonance the higher the probability for the Z boson to decay to a pair of highly energetic and collimated leptons. These collimated leptons form an aligned beam that could be misinterpreted as a single lepton, in particular in the case of the $ee\nu$ channel where the electrons travel a shorter distance in the detector (when compared to μ) for their trajectory to be deflected by the magnetic field enough to facilitate the identification of two separate particles.

(a) Projection on the $\rho - \phi$ plane.(b) Projection on the $\rho - z$ plane

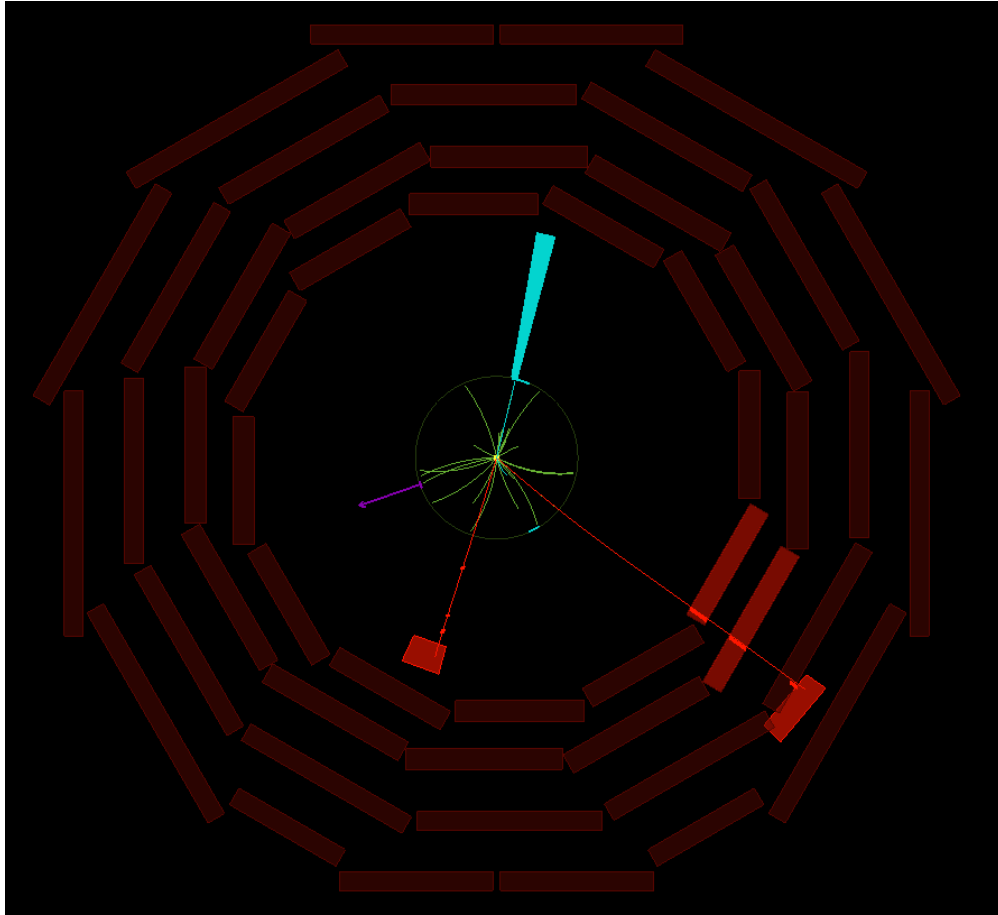
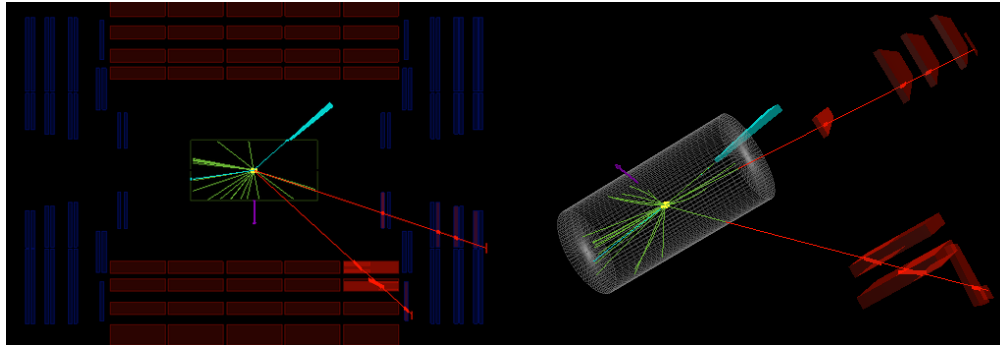
(c) 3D view

Figure 6.10: Example of the signature left on the detector by a signal-like event for the $eee\nu$ channel. This event was taken on July 13th 2018. Run: 319579, Lumiblock: 2957, Event: 4487890911. The reconstructed primary vertex is shown in yellow. Depositions on the electromagnetic calorimeter and tracks left by the three electrons are shown in cyan, their area is proportional to the amount of energy deposited, the negligible curvature shown by their tracks is a reflection of their high transverse momentum. The amount of missing transverse energy is proportional to the length of the purple arrow. Low momentum tracks for particle-flow candidates in the inner tracker are shown in green for reference, these PF candidates are filtered by the preselection.

(a) Projection on the $\rho - \phi$ plane.(b) Projection on the $\rho - z$ plane

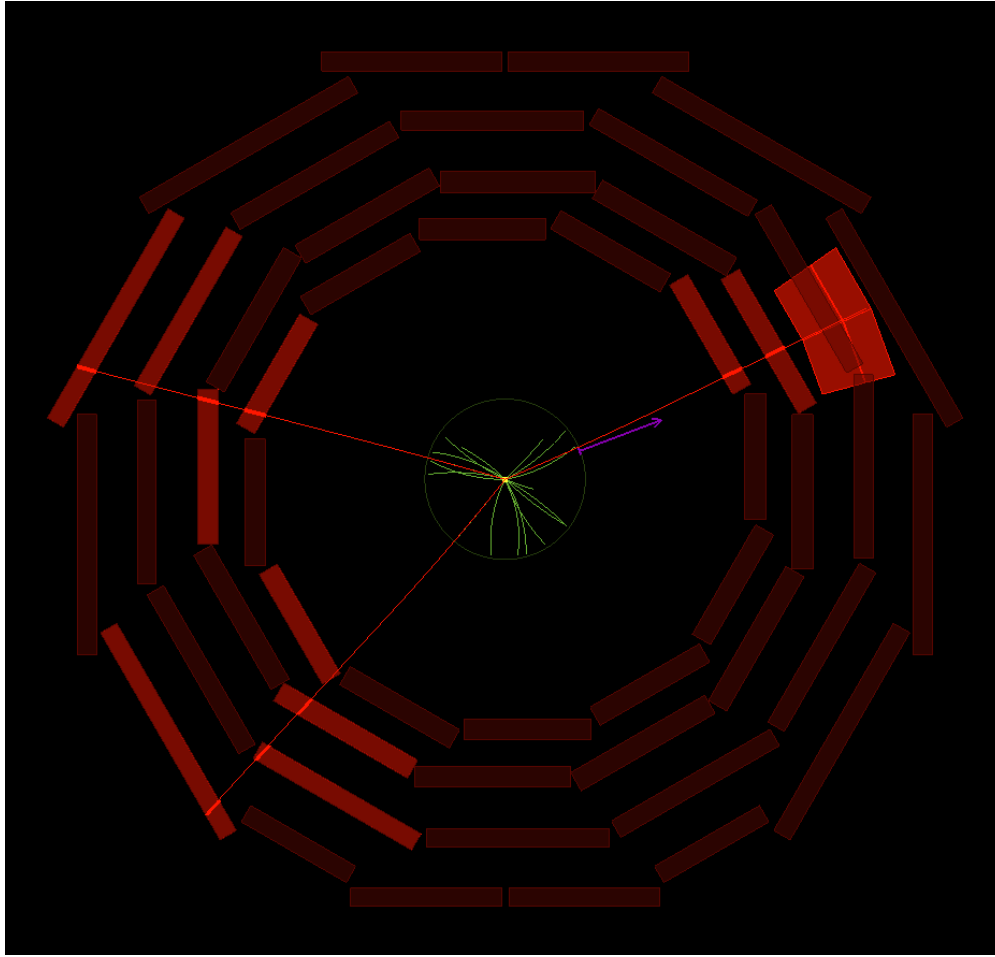
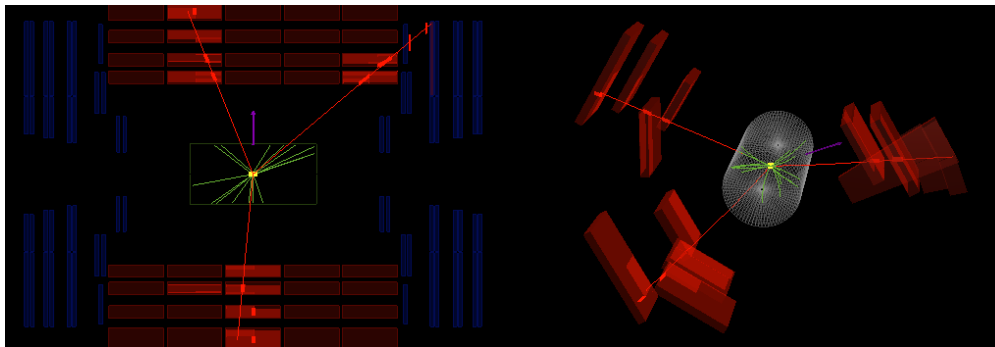
(c) 3D view

Figure 6.11: Example of the signature left on the detector by a signal-like event for the $ee\mu\nu$ channel. This event was taken on October 21st 2018. Run: 32500, Lumiblock: 188, Event: 346288517. The reconstructed primary vertex is shown in yellow. Depositions on the electromagnetic calorimeter and tracks left by the electronic pair are shown in cyan, the negligible curvature shown by their tracks is a reflection of their high transverse momentum, the cyan area is proportional to the amount of energy deposited in the calorimeter. Tracks left by the muon in the tracker detector and muon chambers are shown in red, in this particular event it is possible to see the muon will be classified as a global-High Pt muon as its hits are found in the tracker system and beyond the first station of the muon subsystem. The amount of missing transverse energy is proportional to the length of the purple arrow. Low momentum tracks for particle-flow candidates in the inner tracker are shown in green for reference, these PF candidates are filtered by the preselection.

(a) Projection on the $\rho - \phi$ plane.(b) Projection on the $\rho - z$ plane

(c) 3D view

Figure 6.12: Example of the signature left on the detector by a signal-like event for the $\mu\mu e\nu$ channel. This event was taken on October 1st 2018. Run: 323790, Lumiblock: 376, Event: 646065569. The reconstructed primary vertex is shown in yellow. The deposition on the electromagnetic calorimeter and tracks left by the electron are shown in cyan, the negligible curvature shown by their tracks is a reflection of their high transverse momentum. Tracks left by the muon pair in the tracker detector and muon chambers are shown in red. Both muons would be classified as global-High Pt Muon as their hits go beyond the first station of the muon subsystem. The amount of missing transverse energy is proportional to the length of the purple arrow. Low momentum tracks for particle-flow candidates in the inner tracker are shown in green for reference, these PF candidates are filtered by the preselection.

(a) Projection on the $\rho - \phi$ plane.(b) Projection on the $\rho - z$ plane

(c) 3D view

Figure 6.13: Example of the signature left on the detector by a signal-like event for the $\mu\mu\mu\nu$ channel. This event was taken on July 21st 2018. Run: 320024, Lumiblock: 211, Event: 355149645. The reconstructed primary vertex is shown in yellow. Tracks left by the muon pair in the tracker detector and muon chambers are shown in red, the negligible curvature shown by their tracks is a reflection of their high transverse momentum. It is possible to see the muon will be classified as a global-High Pt muon as their hits are found in the tracker system and beyond the first station of the muon subsystem. The amount of missing transverse energy is proportional to the length of the purple arrow. Low momentum tracks for particle-flow candidates in the inner tracker are shown in green for reference, these PF candidates are filtered by the preselection.

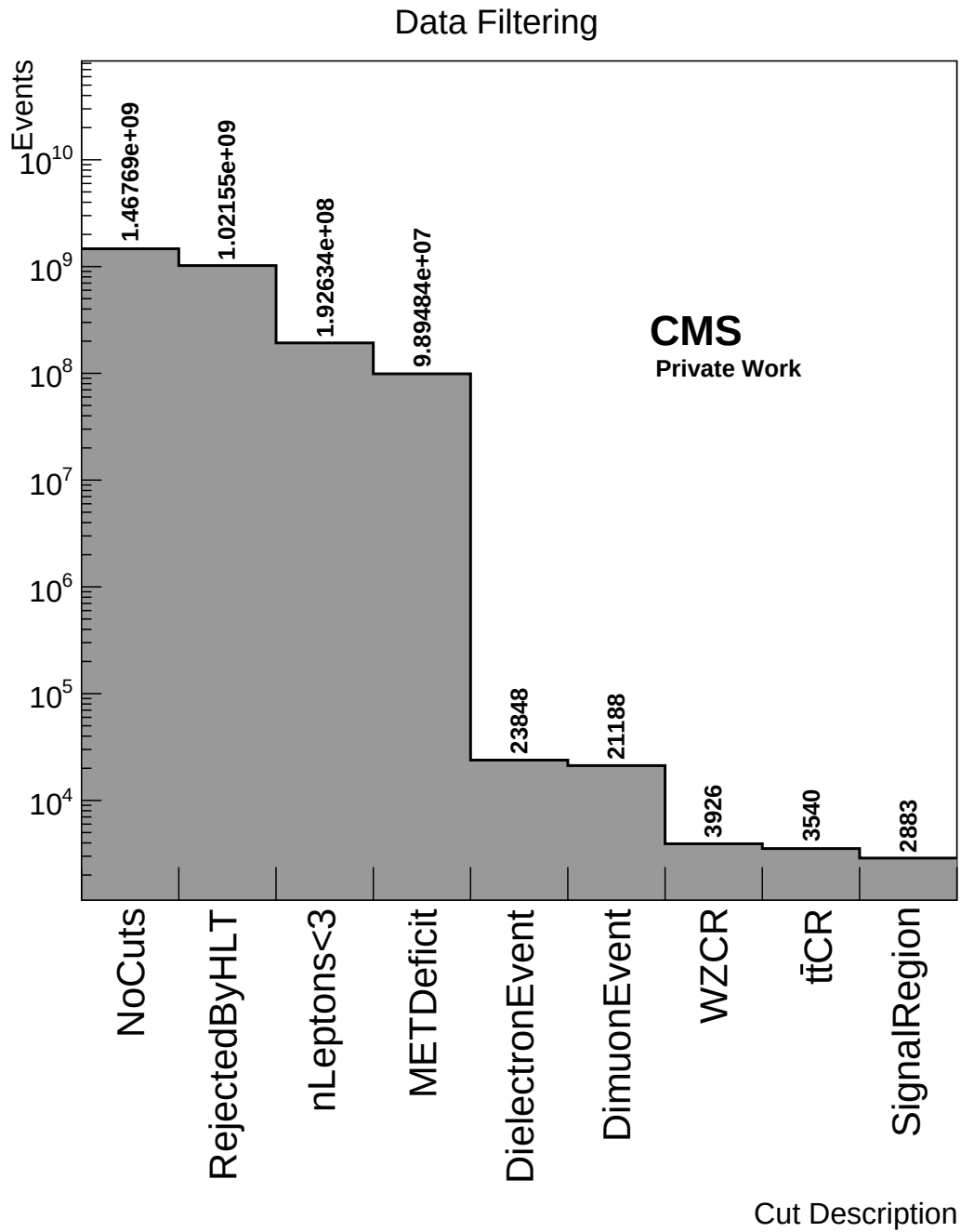


Figure 6.15: Number of Run II recorded events as the event filtering progresses. This plot is shown for illustrative purposes and contains only a partial sample of the filtering steps.

6.6 Control Regions

As mentioned earlier in [chapter 6](#), the quality of the simulation is evaluated by performing a data/MC comparison in two control regions. In [subsection 6.6.1](#) and [subsection 6.6.2](#) relevant distributions for the kinematic variables of the reconstructed objects and resonance candidate are shown. It is important to note that these distributions are shown, unless otherwise stated, prior to the fitting procedure which is held off until [section 6.8](#). The control regions are defined as follows:

6.6.1 WZ Control Region

The first control region is defined as the set of events that pass the selection criteria for the signal region except for the requirement on the distance in the $\eta - \phi$ plane between the leptons that are product of the Z boson decay: while the signal region requires $dR_{l_1, l_2} \leq 1.5$, the control region requires $dR_{l_1, l_2} > 1.5$. dR is the euclidean distance in the $\eta - \phi$ plane between the two leptons, it is computed as the square root of the sum of the squared differences in η and ϕ between the two leptons:

$$dR = \sqrt{(\eta_2 - \eta_1)^2 + (\phi_2 - \phi_1)^2} \quad (6.1)$$

An example of the dR distribution for the different channels is shown in [Figure 6.16](#). The larger the resonance's mass, the narrower the signal distribution gets, and it is shifted towards the lower dR region as the leptons that are product of the Z decay get closer forming a boosted topology. This feature applies to all the channels regardless of the lepton flavor. [Figure 6.16](#) also allow to clearly identify the different contributions from the SM processes to the background in both, the control and signal region. This control region shares the common feature with the signal region of being dominated by the WZ process and therefore the study of the quality of the simulation of this process is of particular interest.

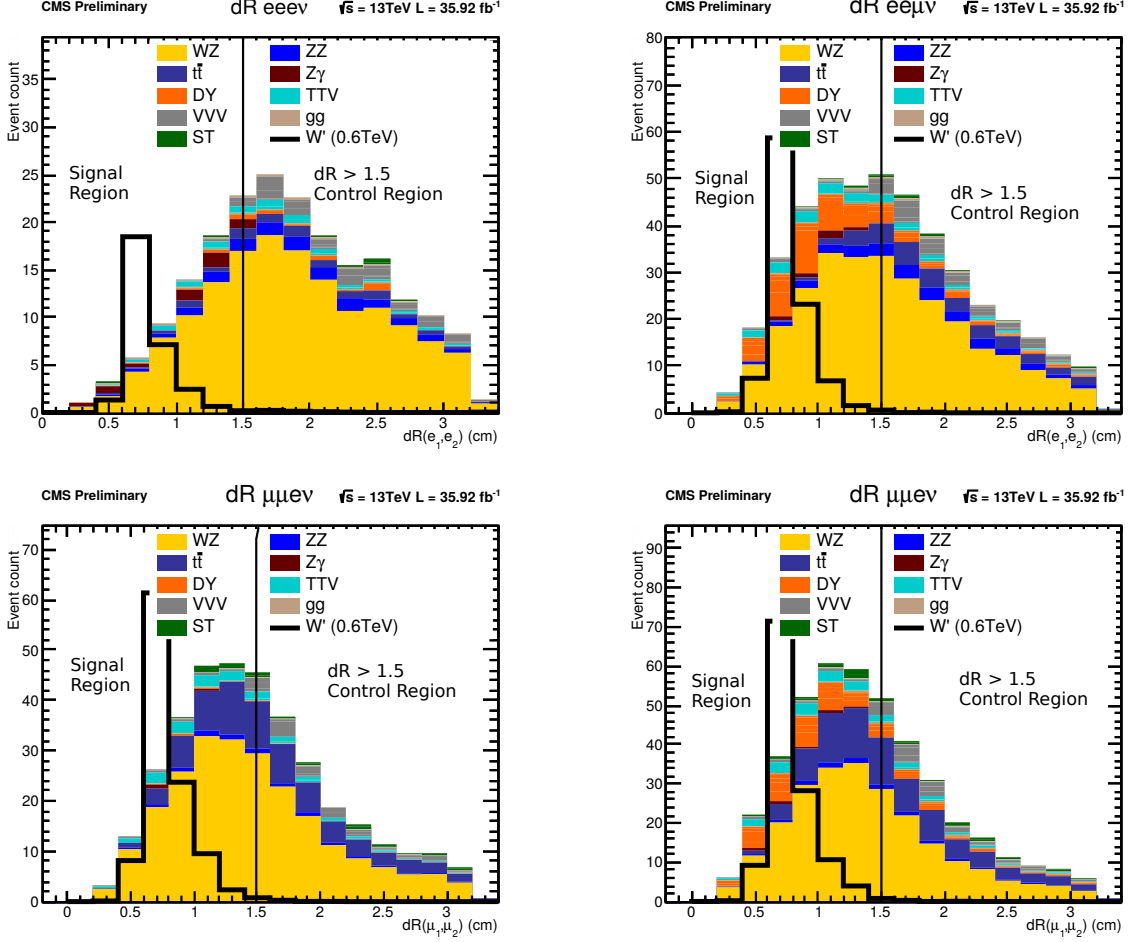


Figure 6.16: Definition of the signal and WZ control region. All the channels show how the region $dr_{l_1 l_2} > 1.5$ is signal-depleted. A 600 GeV mass resonance is used for illustration purposes. Top left: $Z(\rightarrow e+e)W(\rightarrow e+\nu)$ Top right: $Z(\rightarrow e+e)W(\rightarrow \mu+\nu)$ Bottom left: $Z(\rightarrow \mu+\mu)W(\rightarrow e+\nu)$ Bottom right: $Z(\rightarrow \mu+\mu)W(\rightarrow \mu+\nu)$

Data and Montecarlo Simulation Agreement

The agreement between the data obtained from the CMS detector and the simulation is evaluated by comparing the kinematic distributions for the different objects in the final state as well as the reconstructed mass of the WZ system.

Figure 6.17 shows the postfit distribution of the M_{WZ} distribution in the WZ control region for the fully leptonic final state combining all Run2 years. A more granular view of the agreement between data and simulation is shown in Figure 6.18 where the postfit distributions for each of

the four final states are shown. The agreement between data and simulation was found to be satisfactory in all cases, specially factoring in the low statistics of the channels studied.

Information about the agreement in the form of yields is also provided in [Table 6.4](#). The table displays the yields for the WZ control region in each of the four final states and also the total number of events per background process and data. The yields are obtained by integrating the postfit distribution for each background process and data in the M_{WZ} region of interest. The yield uncertainty is obtained by propagating the uncertainty of the postfit distribution to the total yield in each background contribution and then the yields are added in quadrature to obtain the total uncertainty. The yield uncertainty in the data is computed as the square root of the number of observed events, as it is the case for Poisson statistics.

Background	$ee\nu$	$e\bar{e}\mu\nu$	$\mu\mu e\nu$	$\mu\mu\mu\nu$	Total
WZ	332.50 ± 7.08	235.56 ± 5.78	211.31 ± 5.58	500.72 ± 10.51	1280.10 ± 15.01
$t\bar{t}$	269.40 ± 8.28	314.14 ± 8.83	217.22 ± 7.26	813.92 ± 19.46	1614.68 ± 24.04
DY	66.48 ± 8.67	45.48 ± 0.91	4.41 ± 0.42	208.37 ± 2.89	324.73 ± 9.19
ZZ	87.88 ± 1.97	76.24 ± 1.93	55.59 ± 1.45	138.86 ± 3.25	358.56 ± 4.50
ST	13.48 ± 0.58	18.24 ± 0.92	11.80 ± 0.81	40.67 ± 1.13	84.20 ± 1.76
$Z\gamma$	73.62 ± 1.54	4.33 ± 0.86	33.29 ± 1.33	19.51 ± 0.47	130.76 ± 2.26
VVV	8.36 ± 0.21	8.92 ± 0.23	5.15 ± 0.15	13.37 ± 0.35	35.80 ± 0.49
gg	7.23 ± 0.07	6.68 ± 0.10	5.47 ± 0.20	11.54 ± 0.09	30.92 ± 0.25
Total Bkg	858.94 ± 14.16	709.59 ± 10.84	544.25 ± 9.42	1746.96 ± 22.58	3859.74 ± 30.27
Data	903 ± 30	721 ± 27	536 ± 23	1766 ± 42	3926 ± 63

Table 6.4: RunII yields in the WZ Control Region for the different channels in the fully leptonic final state

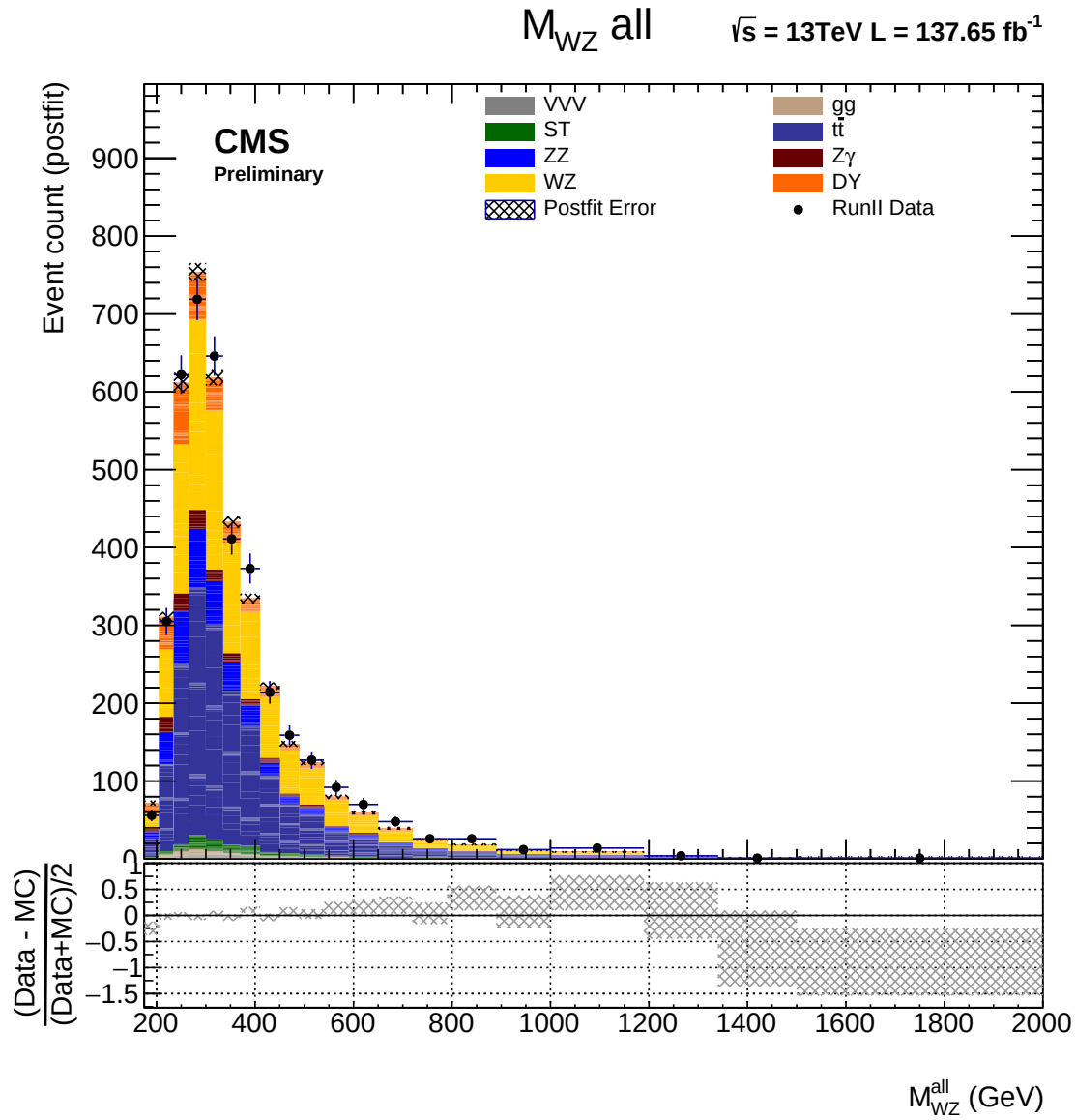


Figure 6.17: M_{WZ} Postfit distribution in the WZ control region for the fully leptonic final state combining all Run2 years.

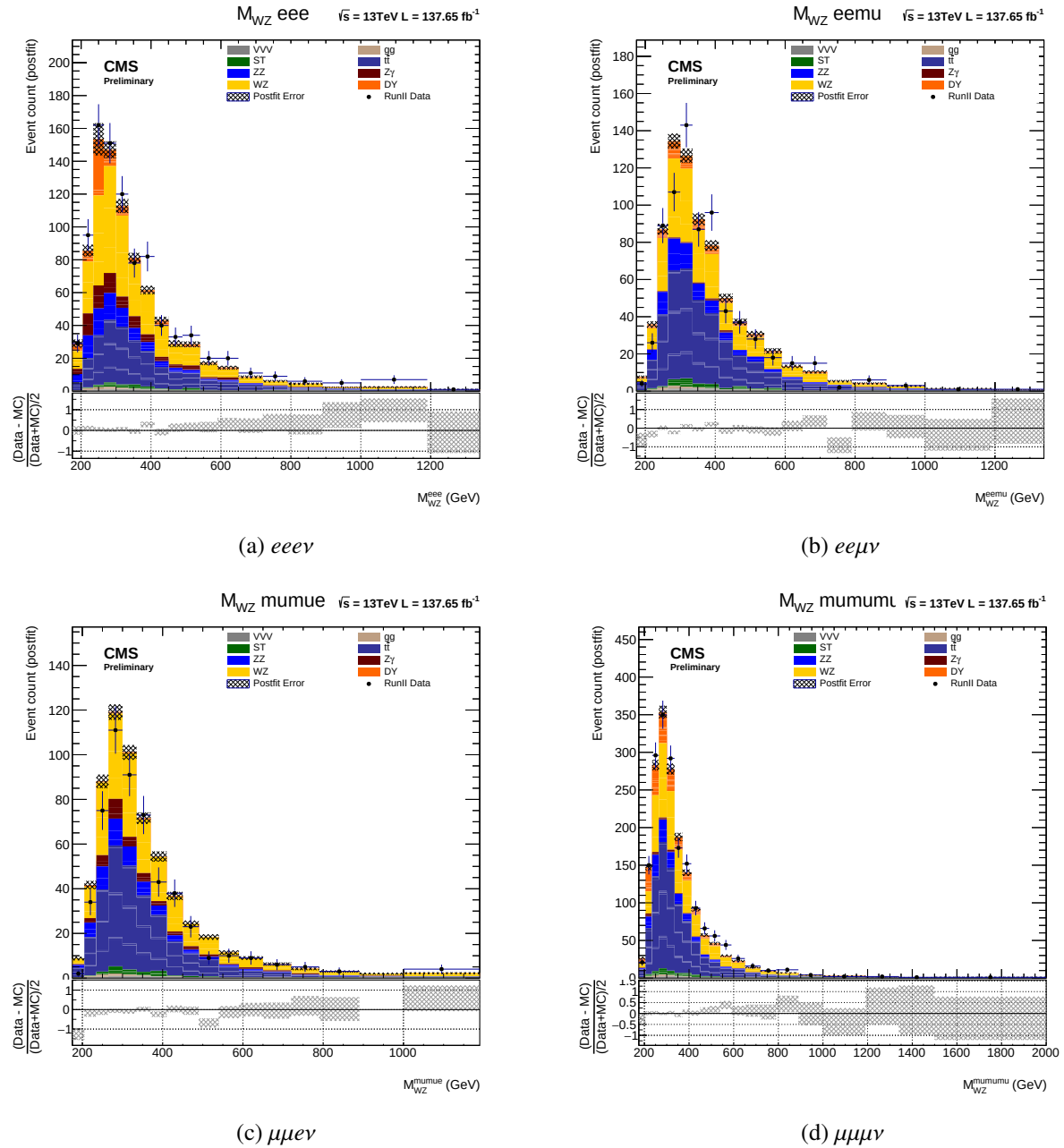


Figure 6.18: M_{WZ} Postfit distribution in the WZ control region for the different final states combining all Run2 years.

6.6.2 The $t\bar{t}$ Control Region

The second control region is defined as the set of events that pass the selection criteria for the signal region except for the requirement on the mass of the reconstructed Z boson: while the signal region requires $M_{l_1 l_2} \in [70, 110]$ GeV, the $t\bar{t}$ control region requires $M_{l_1 l_2} \notin [70, 110]$ GeV. As mentioned seen in [Figure 6.16](#) the $t\bar{t}$ process contributes to the background in the signal region and therefore the study of the quality of the simulation of this process is of particular interest.

[Figure 6.19](#) shows the $M_{l_1 l_2}$ distribution for the $t\bar{t}$ control region in the different channels, where the Z mass window is visible as the empty bins in the distribution.

Data and Montecarlo Simulation Agreement

Just as in the WZ control region, the $t\bar{t}$ control region shows a satisfactory agreement between data and simulation as evidenced in [Figure 6.20](#). A more granular comparison of the different channels is shown in [Figure 6.21](#).

Yields for the $t\bar{t}$ control region are shown in [Table 6.5](#).

Background	$ee\nu\nu$	$e\bar{e}\mu\nu$	$\mu\bar{\mu}e\nu$	$\mu\bar{\mu}\mu\nu$	Total
WZ	44.09 ± 1.55	53.79 ± 1.71	61.13 ± 1.75	110.06 ± 2.52	269.06 ± 3.84
$t\bar{t}$	158.15 ± 3.99	593.49 ± 8.90	660.37 ± 11.05	1444.85 ± 14.71	2856.85 ± 20.82
DY	12.49 ± 1.11	11.79 ± 0.49	2.57 ± 0.37	63.89 ± 1.13	90.74 ± 1.70
ZZ	7.33 ± 0.21	10.29 ± 0.24	9.29 ± 0.21	20.77 ± 0.41	47.68 ± 0.56
ST	7.00 ± 0.67	42.88 ± 1.88	47.15 ± 1.94	91.09 ± 2.45	188.13 ± 3.71
$Z\gamma$	28.12 ± 1.02	5.04 ± 0.52	11.43 ± 0.50	15.52 ± 0.52	60.11 ± 1.35
VVV	2.37 ± 0.07	8.15 ± 0.23	5.49 ± 0.15	5.75 ± 0.14	21.76 ± 0.31
gg	0.22 ± 0.00	0.32 ± 0.01	0.30 ± 0.01	0.85 ± 0.01	1.70 ± 0.01
Total	259.78 ± 4.59	725.74 ± 9.29	797.73 ± 11.37	1752.78 ± 15.18	3536.03 ± 21.61
Data	272 ± 16	726 ± 27	789 ± 28	1753 ± 42	3540 ± 59

Table 6.5: RunII yields in the $t\bar{t}$ Control Region for the different channels in the fully leptonic final state

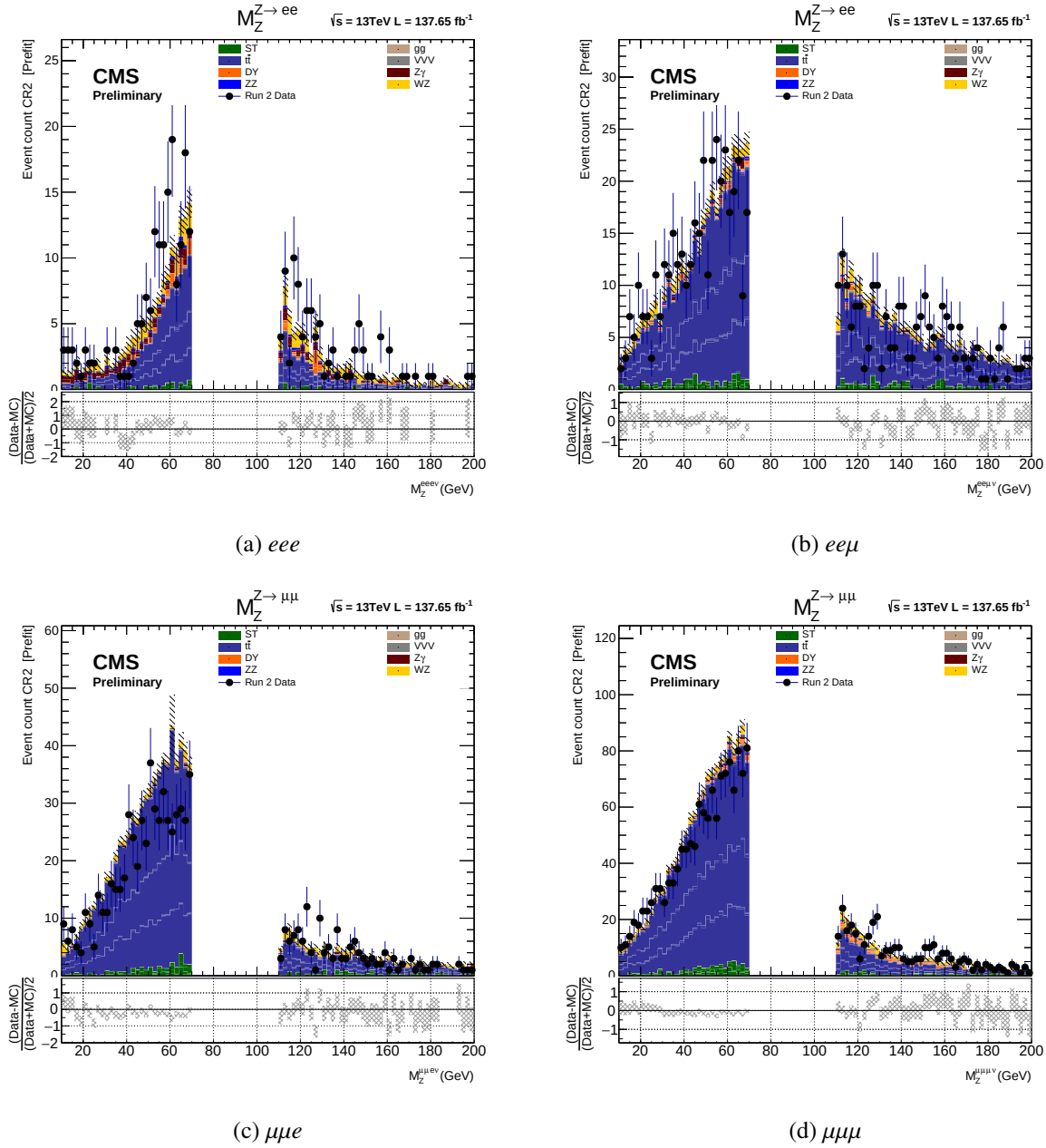


Figure 6.19: M_Z distributions of $Z \rightarrow \ell\ell$ candidates for each final signature as seen in the $70\text{GeV} > Z_{mass} > 110\text{GeV}$ control region. Top left: $Z(\rightarrow e+e)W(\rightarrow e+\nu)$ Top right: $Z(\rightarrow e+e)W(\rightarrow \mu+\nu)$ Bottom left: $Z(\rightarrow \mu+\mu)W(\rightarrow e+\nu)$ Bottom right: $Z(\rightarrow \mu+\mu)W(\rightarrow \mu+\nu)$

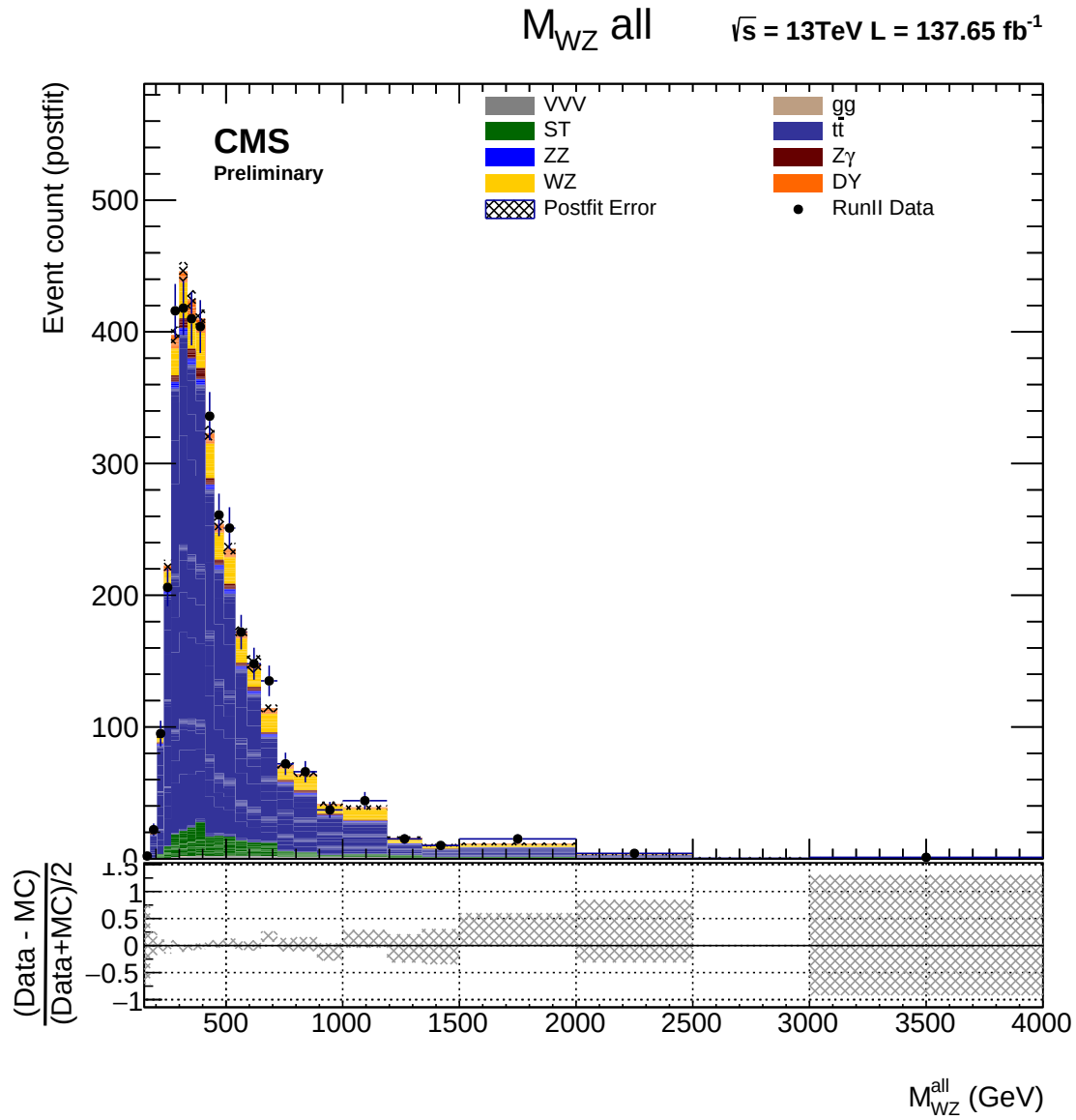


Figure 6.20: M_{WZ} postfit distribution for the $t\bar{t}$ control region combining all the channels and the different years of data taking.

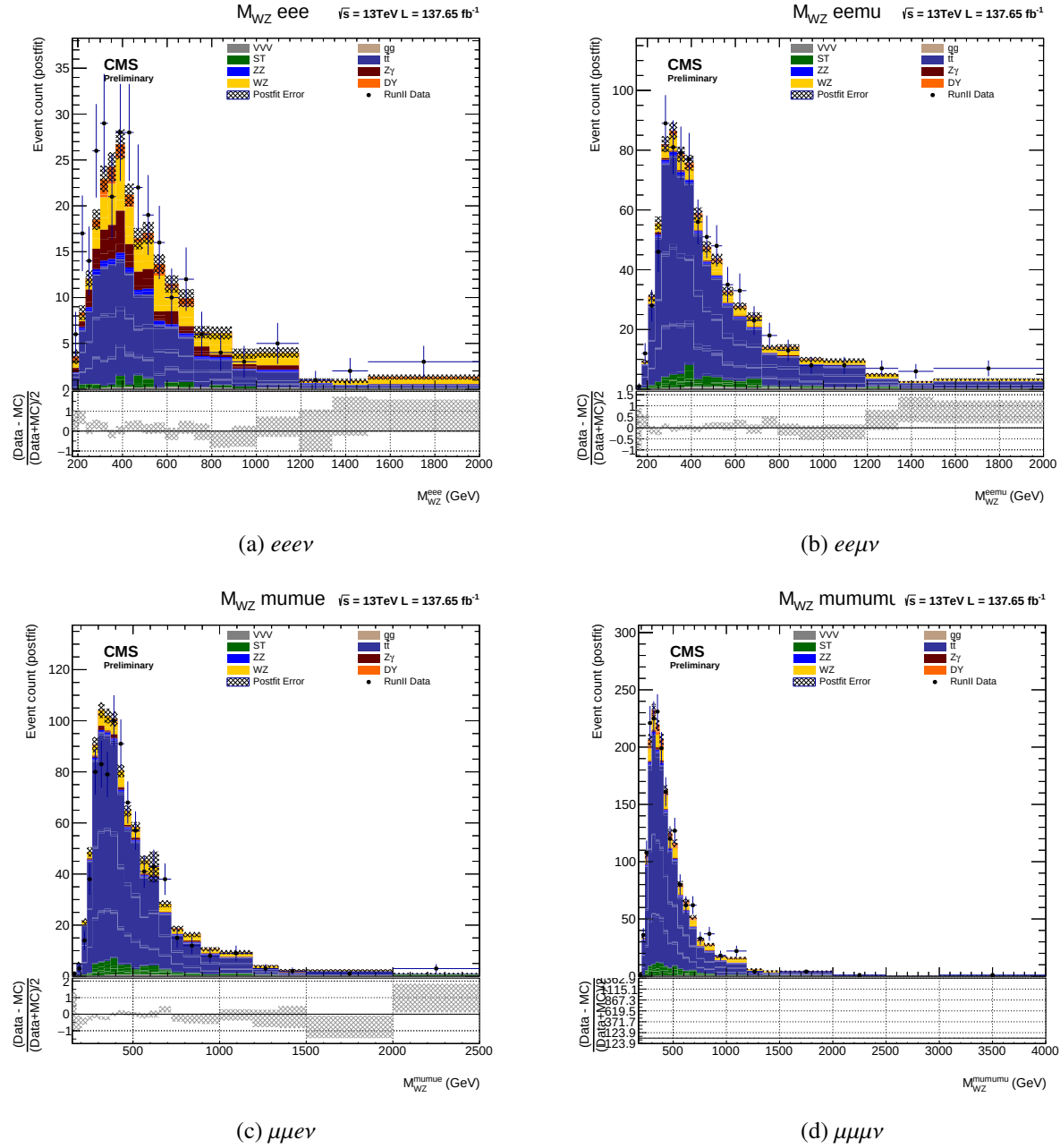


Figure 6.21: M_{WZ} Postfit distribution in the $t\bar{t}$ control region for each of the different channels.

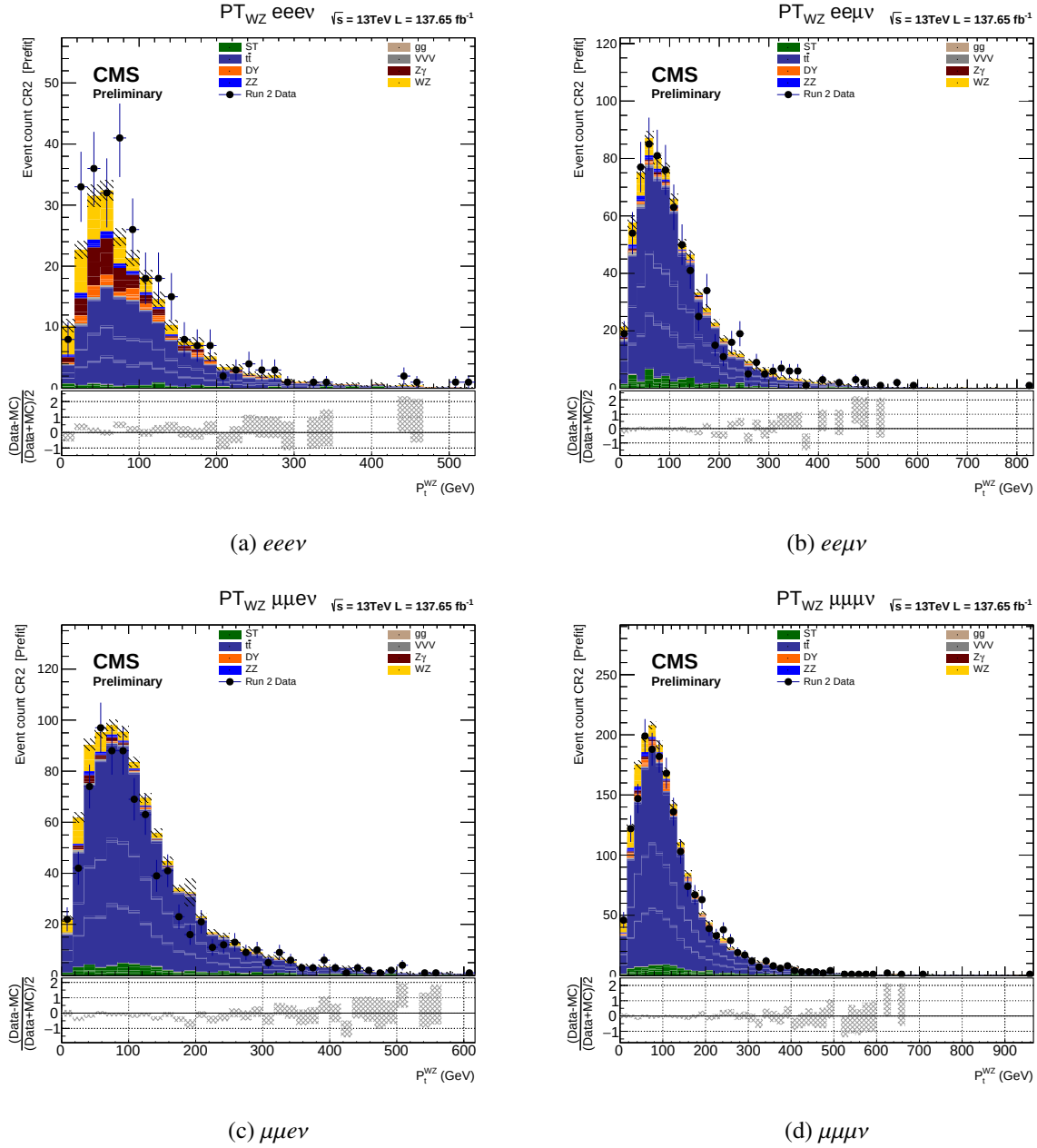


Figure 6.22: p_T distributions of WZ candidates for each final signature as seen in the $70\text{GeV} > Z_{mass} > 110\text{GeV}$ control region. Top left: $Z(\rightarrow e+e)W(\rightarrow e+\nu)$ Top right: $Z(\rightarrow e+e)W(\rightarrow \mu+\nu)$ Bottom left: $Z(\rightarrow \mu+\mu)W(\rightarrow e+\nu)$ Bottom right: $Z(\rightarrow \mu+\mu)W(\rightarrow \mu+\nu)$

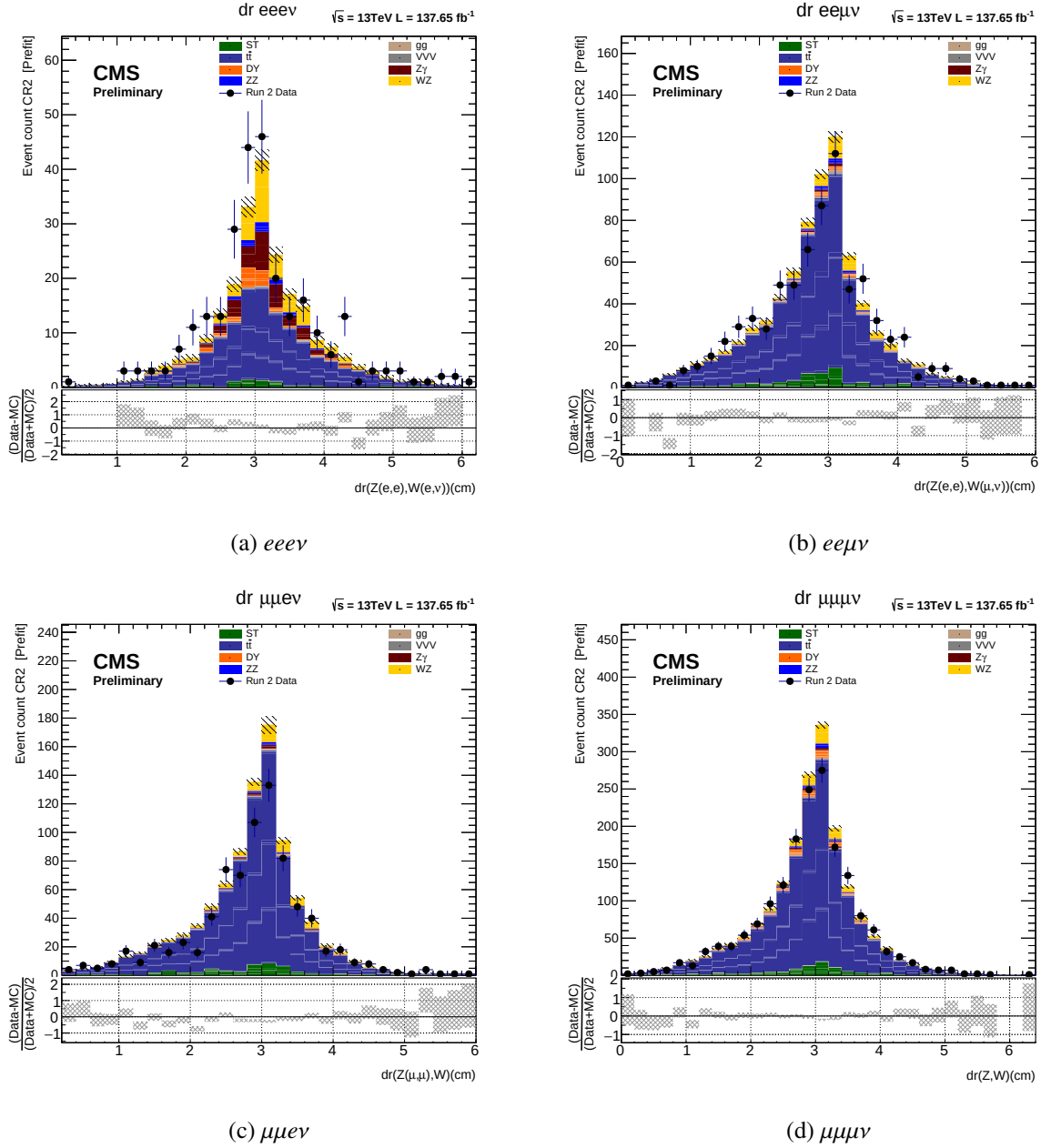


Figure 6.23: Distance in the $\eta - \phi$ plane between the W and Z candidates for each final signature as seen in the $70\text{GeV} > Z_{\text{mass}} > 110\text{GeV}$ control region.

6.7 Signal Region

section 6.3 described the event selection criteria and the set of cuts that optimizes the signal in the presence of the background. In order to study the quality of the simulation the WZ and the $t\bar{t}$ control regions were defined and studied in subsection 6.6.1 and subsection 6.6.2. It is important to emphasize that the study of the quality of the simulation lead to changes to the definition of the signal region in such a way that the relative difference between the data and the simulation is minimized in the control regions and, as these regions are kinematically close to the signal region, we can expect that the simulation also exhibits a high level of accuracy in the signal region.

In this section the distributions of the kinematic variables of the initial and the reconstructed objects are shown. The transverse momentum of the leptons used in the reconstruction of the Z vector boson is shown in Figure 6.24, Figure 6.25, Figure 6.26 and Figure 6.27 for the $ee\nu$, $ee\mu\nu$, $\mu\mu\nu$ and $\mu\mu\mu\nu$ channels, respectively. Similarly, Figure 6.28, Figure 6.29, Figure 6.30 and Figure 6.31 show the transverse momentum of the lepton used in the reconstruction of the W vector boson and the missing transverse momentum of the event for the same channels. These distributions display the combined results for the three years available in Run2.

The fit is performed on the distribution for the invariant mass of the WZ resonance candidate, and the post-fit distributions are shown in Figure 6.40 and Figure 6.41. A yield table is also available on Table 6.6.

Background	$ee\nu$	$ee\mu\nu$	$\mu\mu\nu$	$\mu\mu\mu\nu$	Total
WZ	102.19 ± 3.20	219.31 ± 4.65	290.69 ± 6.01	446.31 ± 7.44	1058.50 ± 11.11
$t\bar{t}$	38.33 ± 1.31	76.06 ± 2.08	250.46 ± 10.80	466.07 ± 11.50	830.92 ± 15.96
DY	9.74 ± 0.70	111.04 ± 2.57	9.65 ± 0.62	416.71 ± 5.34	547.14 ± 6.00
ZZ	24.49 ± 0.54	47.57 ± 0.92	54.68 ± 1.02	85.13 ± 1.65	211.88 ± 2.22
ST	0.98 ± 0.29	3.67 ± 0.36	10.33 ± 0.59	20.50 ± 0.67	35.50 ± 1.01
$Z\gamma$	28.04 ± 1.21	5.88 ± 0.41	38.69 ± 1.62	26.94 ± 0.76	99.56 ± 2.20
VVV	4.36 ± 0.12	10.95 ± 0.28	13.89 ± 0.35	20.77 ± 0.48	49.98 ± 0.67
gg	1.85 ± 0.02	3.88 ± 0.03	4.37 ± 0.03	5.42 ± 0.03	15.52 ± 0.06
Total Bkg	209.98 ± 3.78	478.38 ± 5.81	672.78 ± 12.54	1487.86 ± 14.84	2849.00 ± 20.63
Data	240 ± 15	485 ± 22	667 ± 26	1491 ± 39	2883 ± 54

Table 6.6: RunII yields in the Signal Region for the different channels in the fully leptonic final state

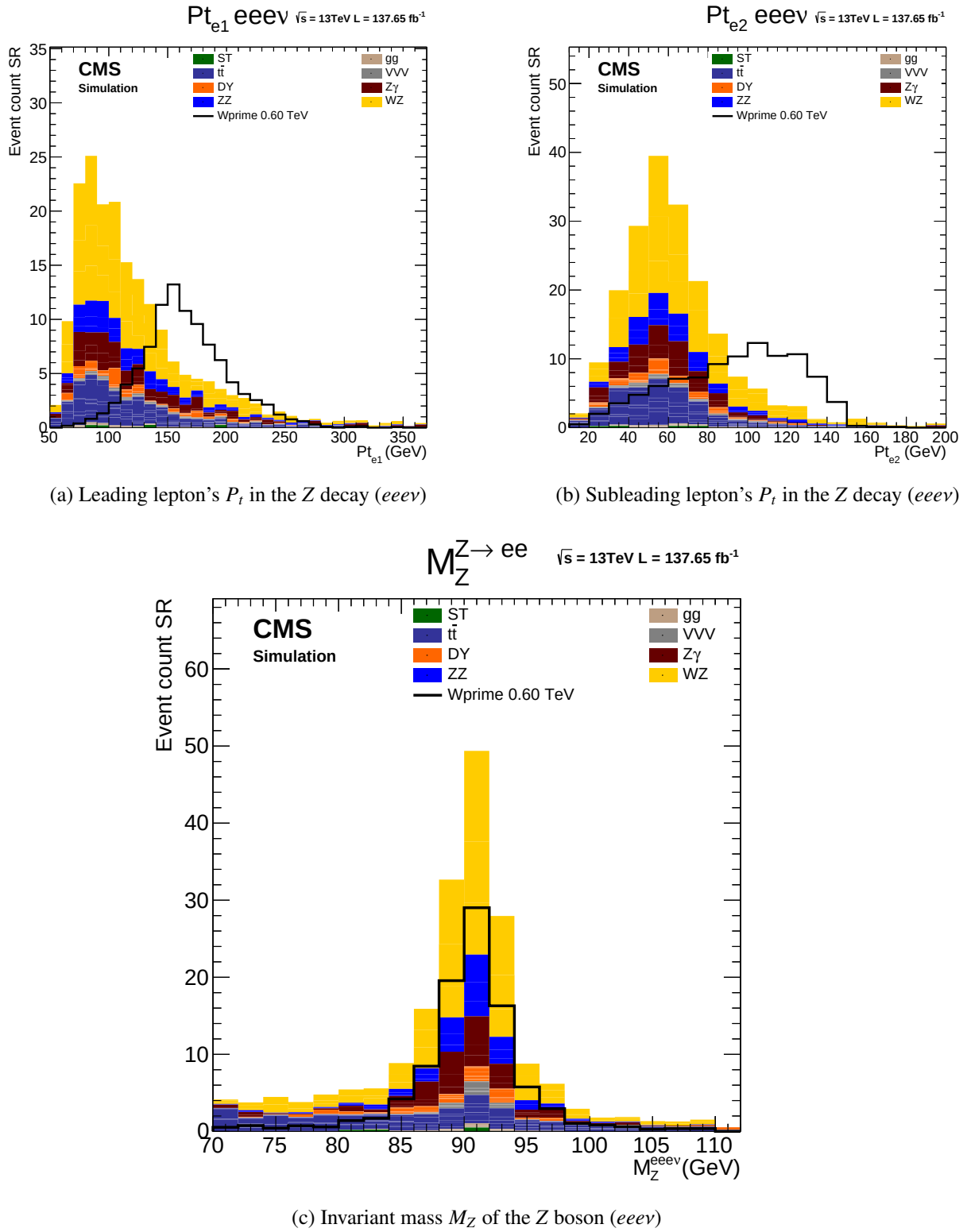


Figure 6.24: The top panel shows the transverse momentum (P_t) distribution for the pair of lepton objects that are used to reconstruct the neutral Z vector boson in the signal region for the $ee\nu\nu$ channel. The bottom plot shows the invariant mass distribution of the Z boson which is reconstructed from the two lepton objects.

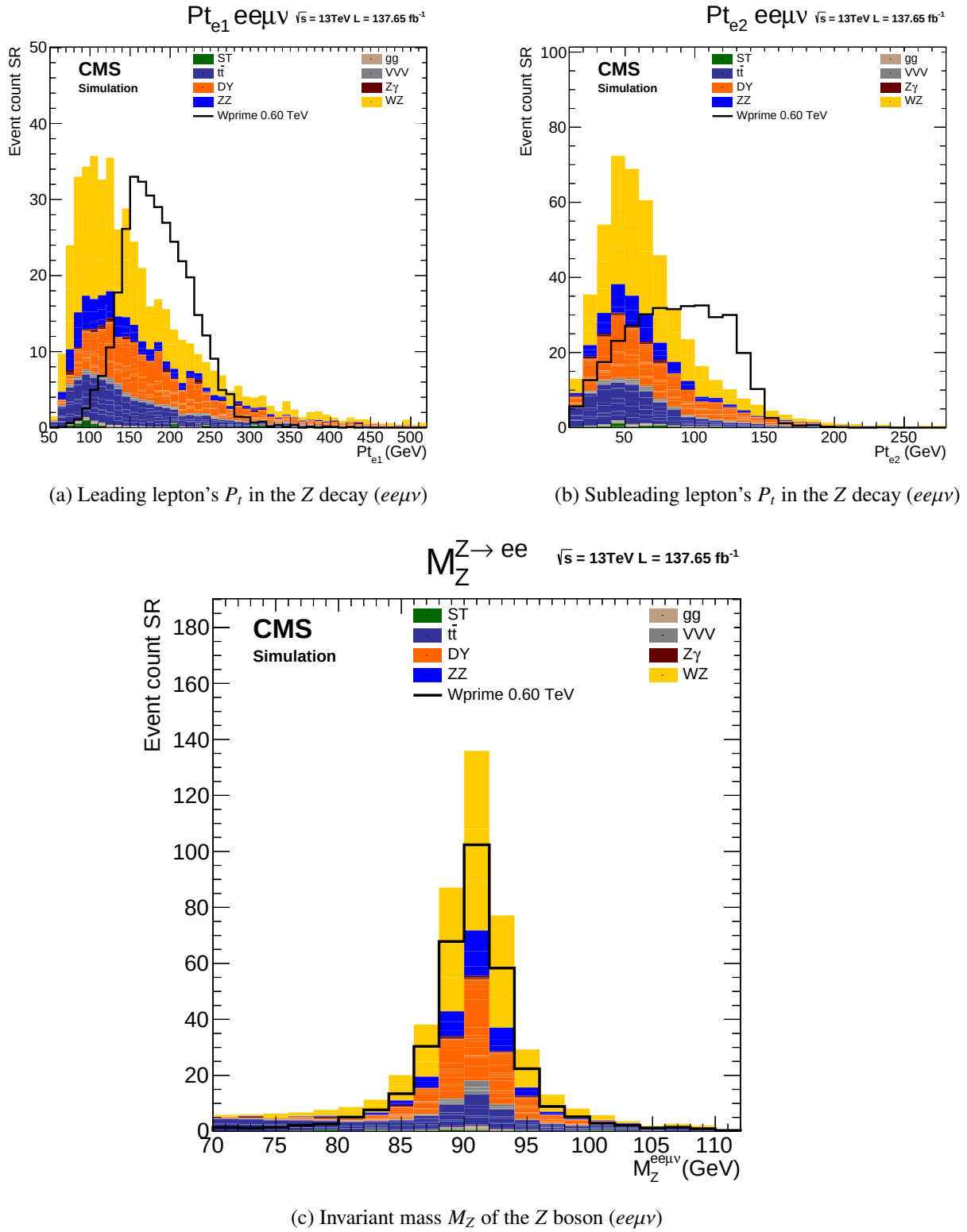


Figure 6.25: The top panel shows the transverse momentum (P_t) distribution for the pair of lepton objects that are used to reconstruct the neutral Z vector boson in the signal region for the $ee\mu\nu$ channel. The bottom plot shows the invariant mass distribution of the Z boson which is reconstructed from the two lepton objects.

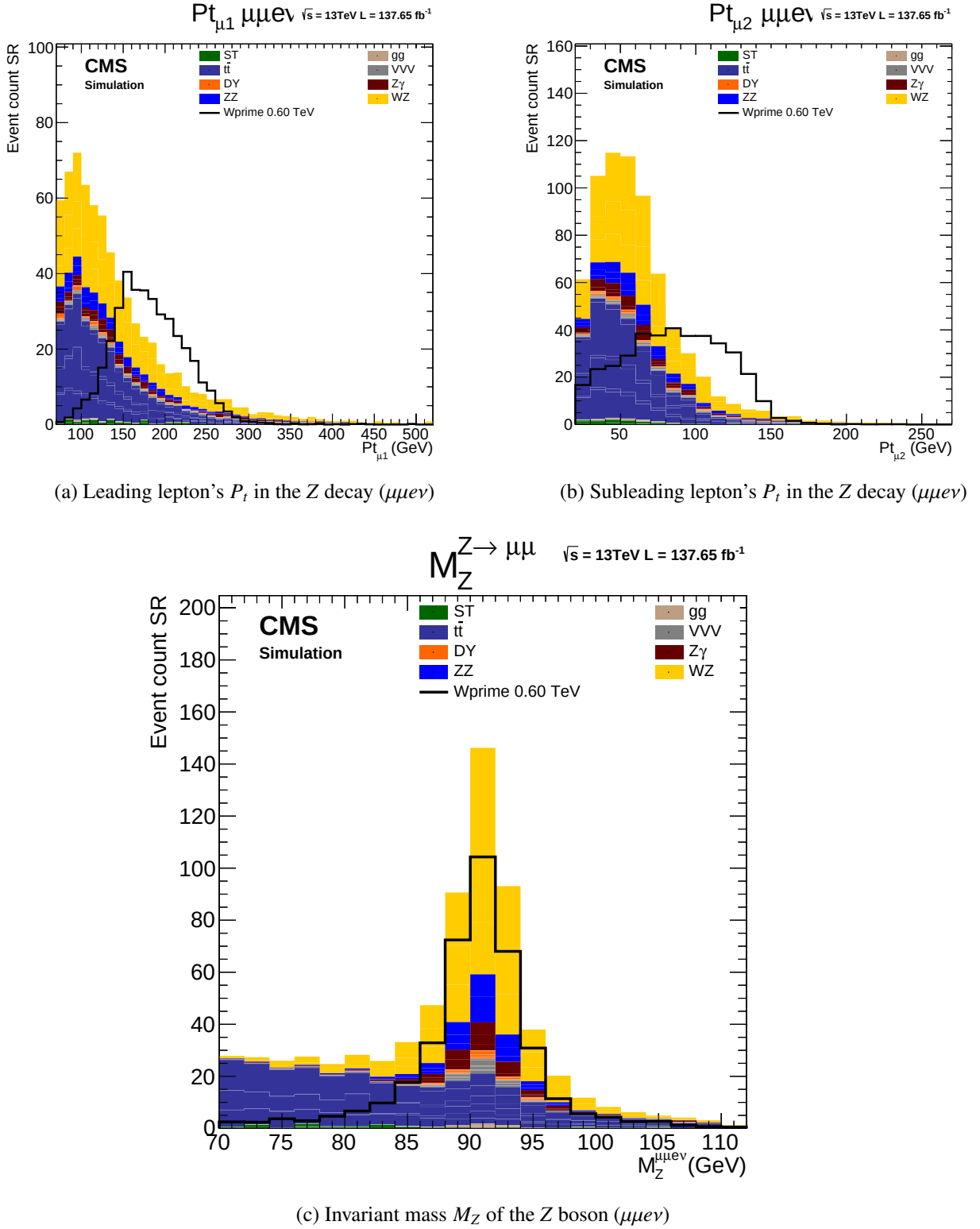


Figure 6.26: The top panel shows the transverse momentum (P_t) distribution for the pair of lepton objects that are used to reconstruct the neutral Z vector boson in the signal region for the $\mu\mu\nu$ channel. The bottom plot shows the invariant mass distribution of the Z boson which is reconstructed from the two lepton objects.

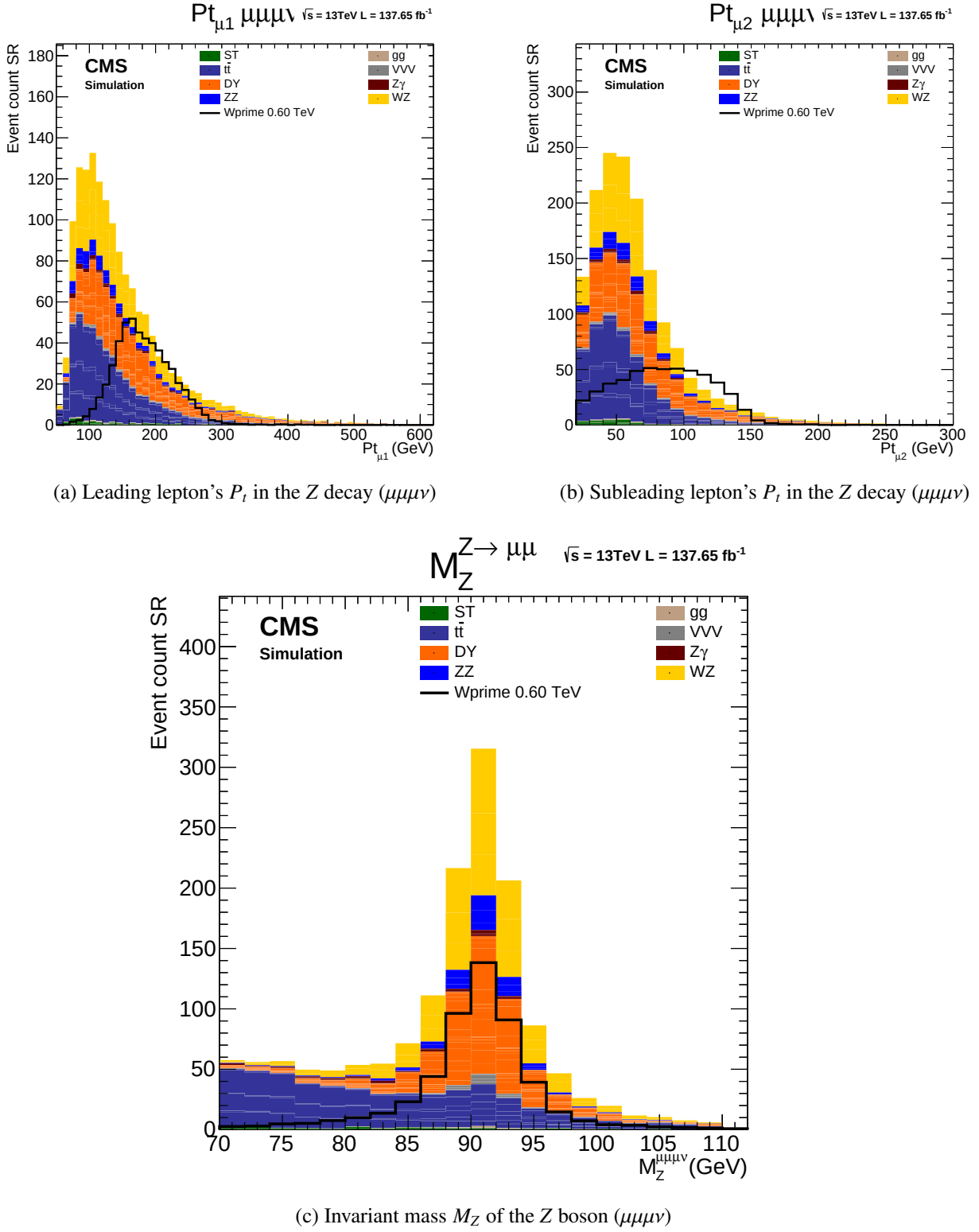


Figure 6.27: The top panel shows the transverse momentum (P_t) distribution for the pair of lepton objects that are used to reconstruct the neutral Z vector boson in the signal region for the $\mu\mu\nu$ channel. The bottom plot shows the invariant mass distribution of the Z boson which is reconstructed from the two lepton objects.

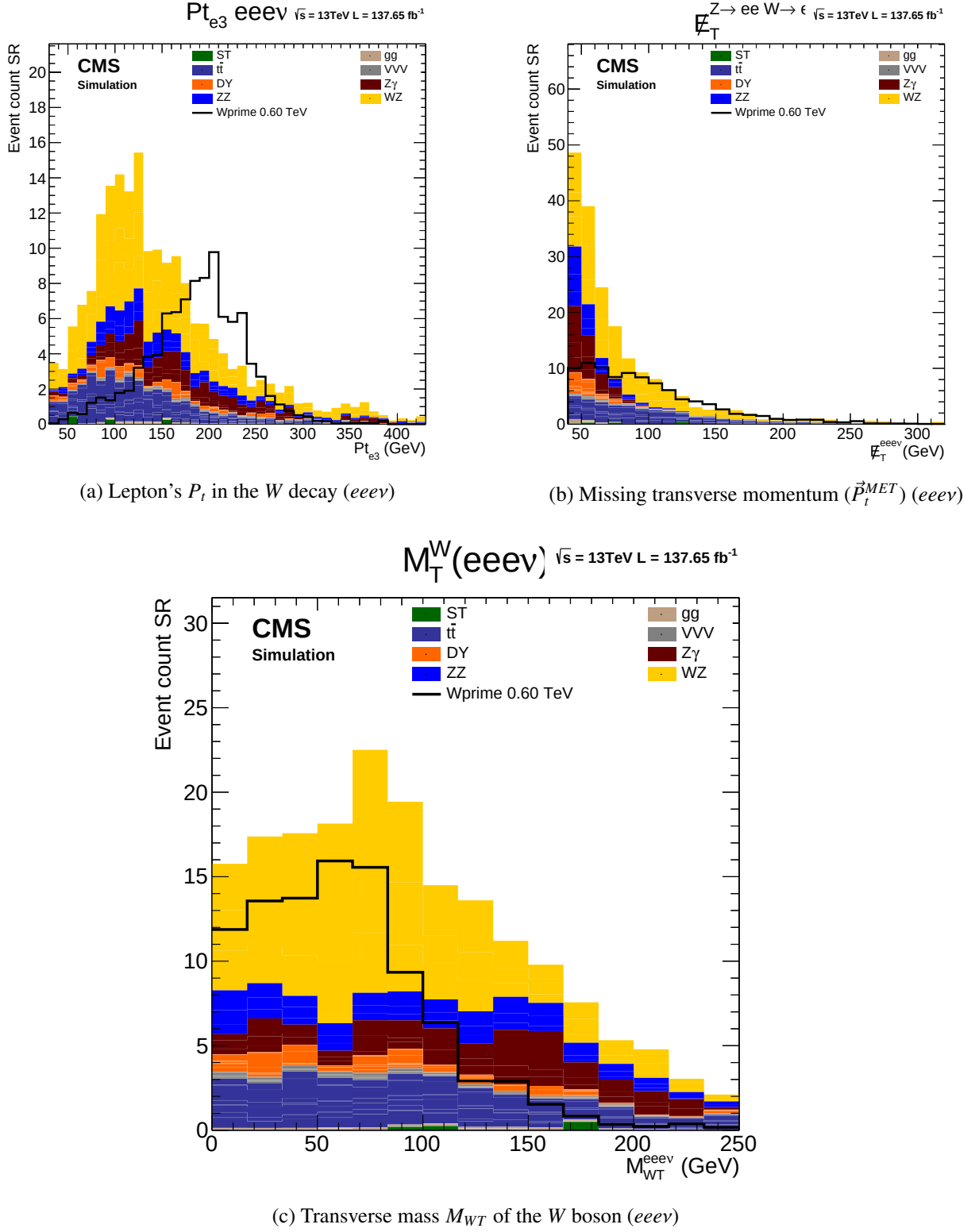


Figure 6.28: The top panel shows the transverse momentum (P_t) distribution for the lepton (left) and the missing transverse momentum ($\vec{P}_t^{MET}$) of the event (right) for the $eee\nu$ channel. The W boson is reconstructed from the lepton and the missing transverse momentum. The bottom plot shows the transverse mass distribution for the W boson.

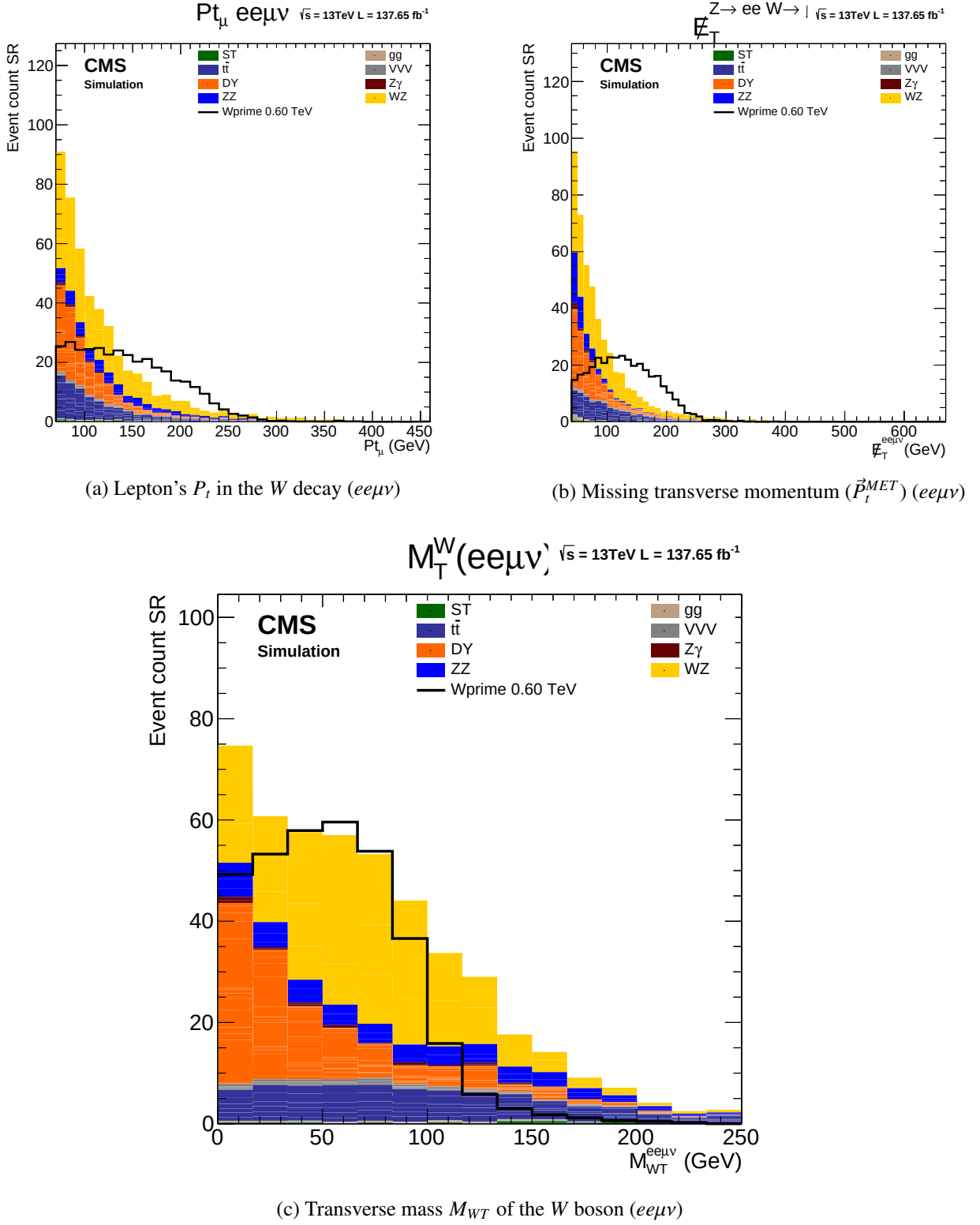


Figure 6.29: The top panel shows the transverse momentum (P_T) distribution for the lepton (left) and the missing transverse momentum ($\vec{P}_T^{MET}$) of the event (right) for the $ee\mu\nu$ channel. The W boson is reconstructed from the lepton and the missing transverse momentum. The bottom plot shows the transverse mass distribution for the W boson.

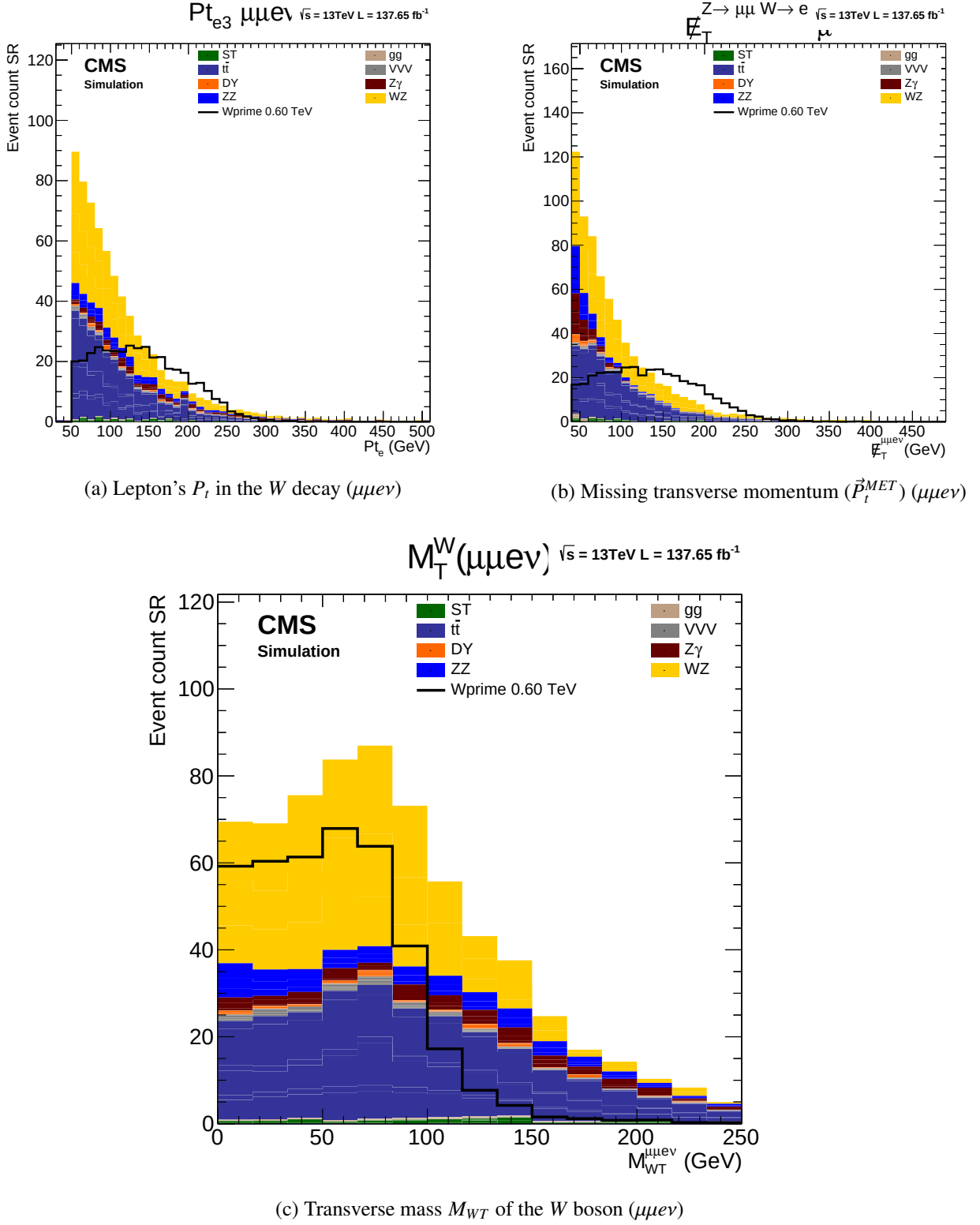


Figure 6.30: The top panel shows the transverse momentum (P_t) distribution for the lepton (left) and the missing transverse momentum ($\vec{P}_t^{MET}$) of the event (right) for the $\mu\mu\nu$ channel. The W boson is reconstructed from the lepton and the missing transverse momentum. The bottom plot shows the transverse mass distribution for the W boson.

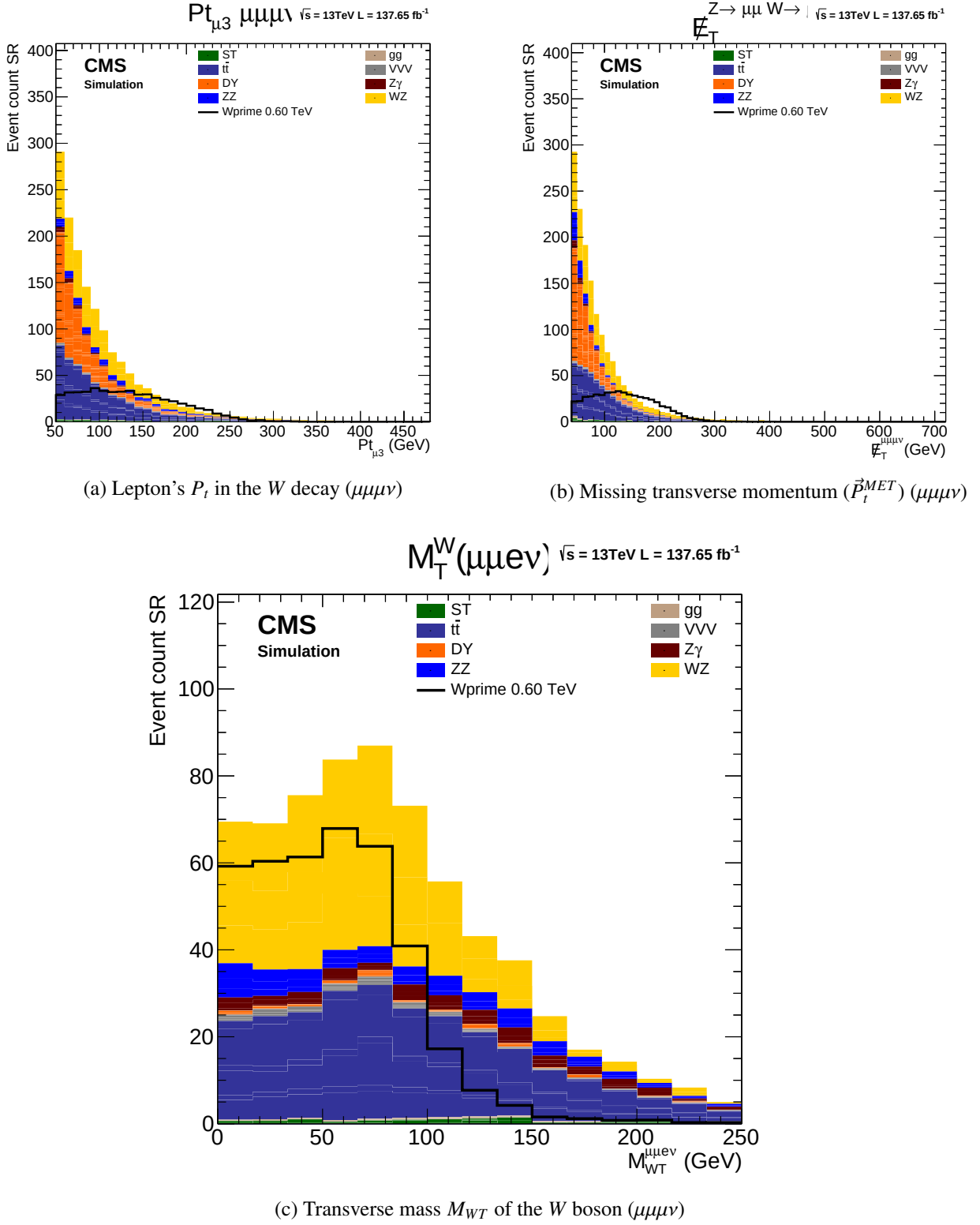


Figure 6.31: The top panel shows the transverse momentum (P_T) distribution for the lepton (left) and the missing transverse momentum ($\vec{P}_t^{MET}$) of the event (right) for the $\mu\mu\nu$ channel. The W boson is reconstructed from the lepton and the missing transverse momentum. The bottom plot shows the transverse mass distribution for the W boson.

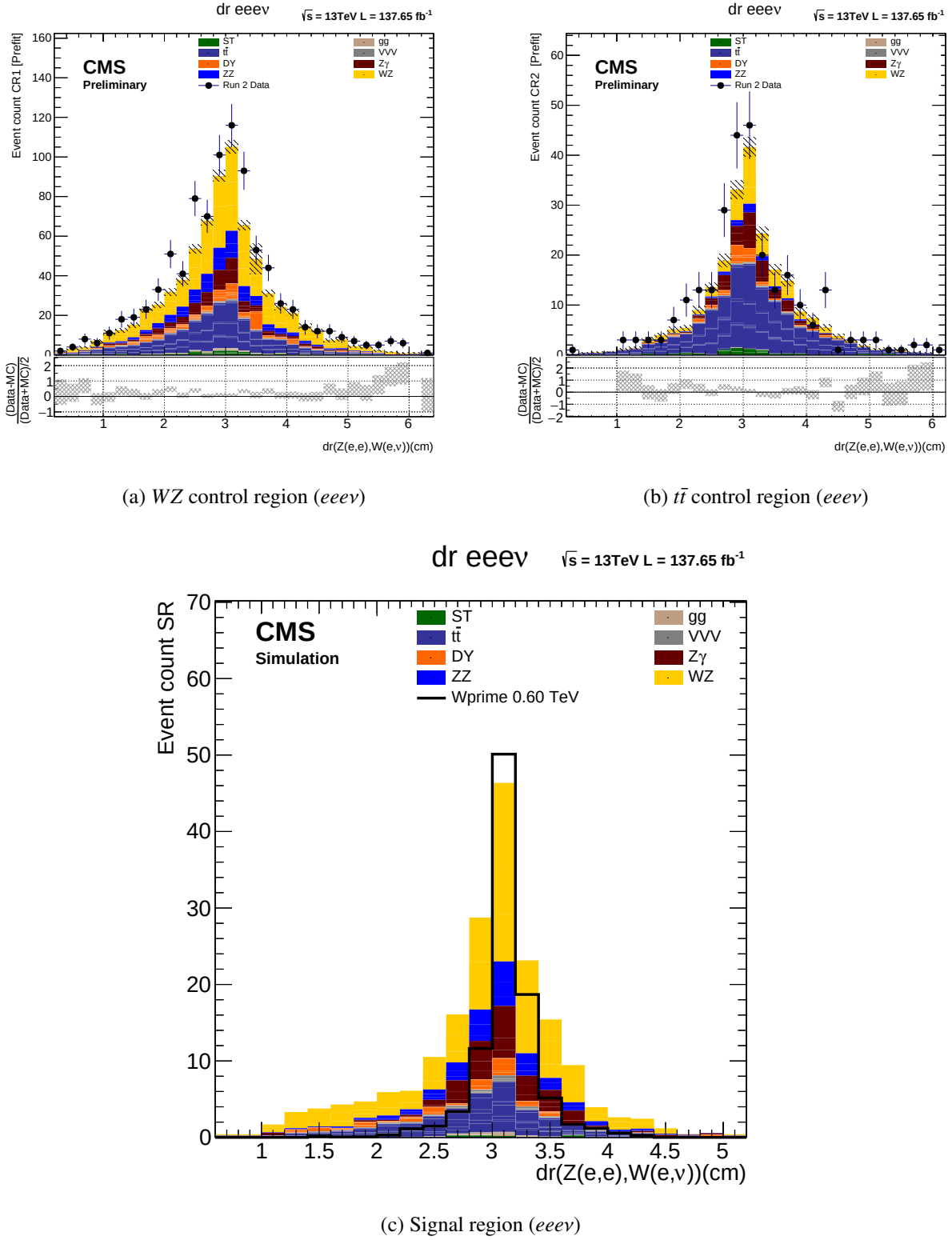


Figure 6.32: The distance in the $\eta - \phi$ plane between the Z boson and the W boson used to reconstruct the WZ resonance candidate in the WZ control region (left), the $t\bar{t}$ control region (middle) and the signal region (right) for the $eee\nu$ channel.

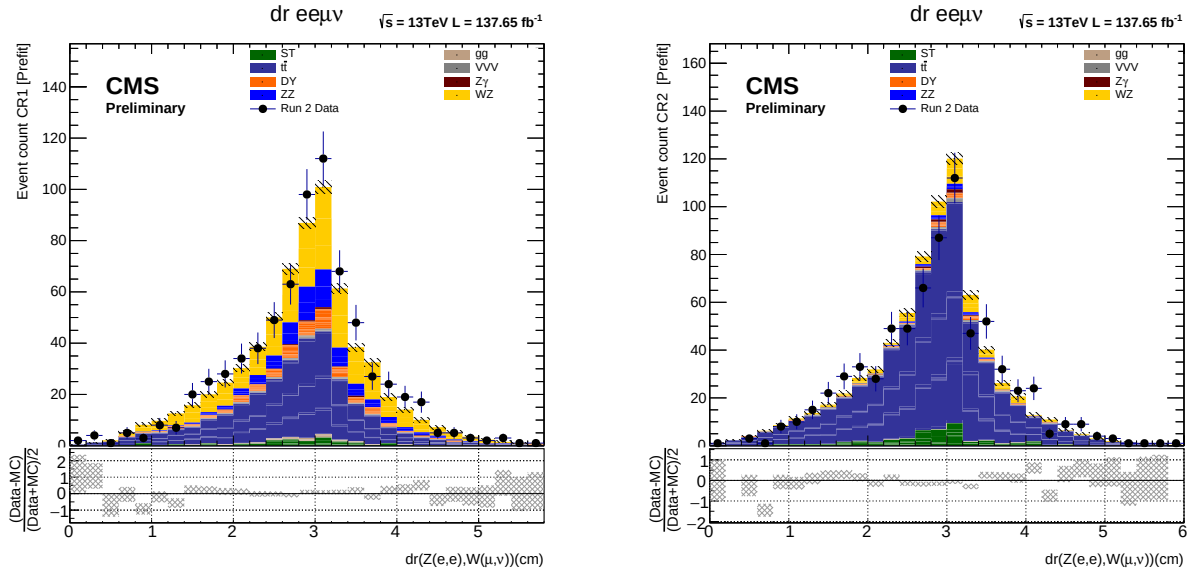
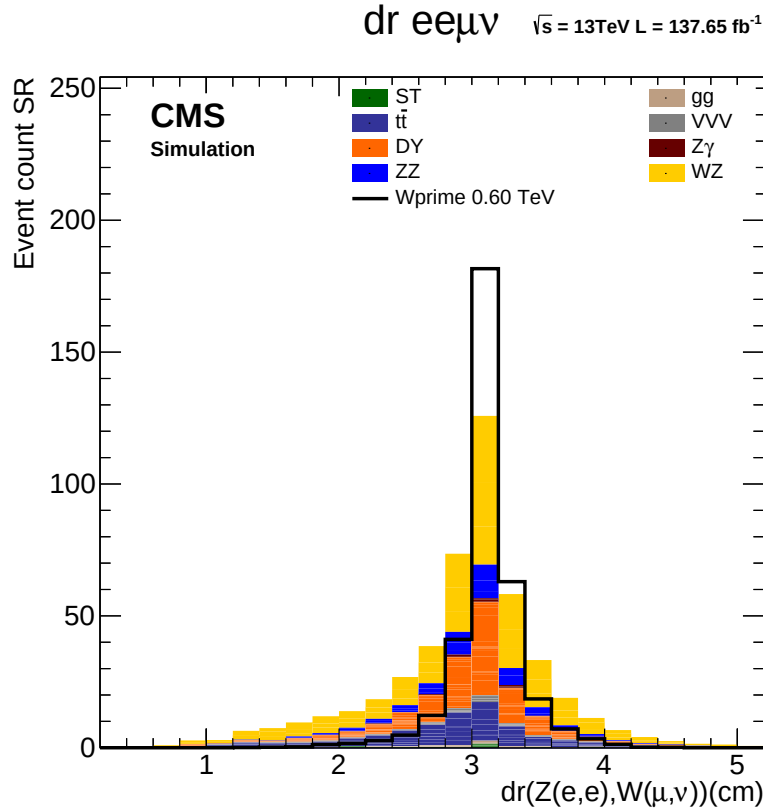
(a) WZ control region ($ee\mu\nu$)(b) $t\bar{t}$ control region ($ee\mu\nu$)(c) Signal region ($ee\mu\nu$)

Figure 6.33: The distance in the $\eta - \phi$ plane between the Z boson and the W boson used to reconstruct the WZ resonance candidate in the WZ control region (left), the $t\bar{t}$ control region (middle) and the signal region (right) for the $ee\mu\nu$ channel.

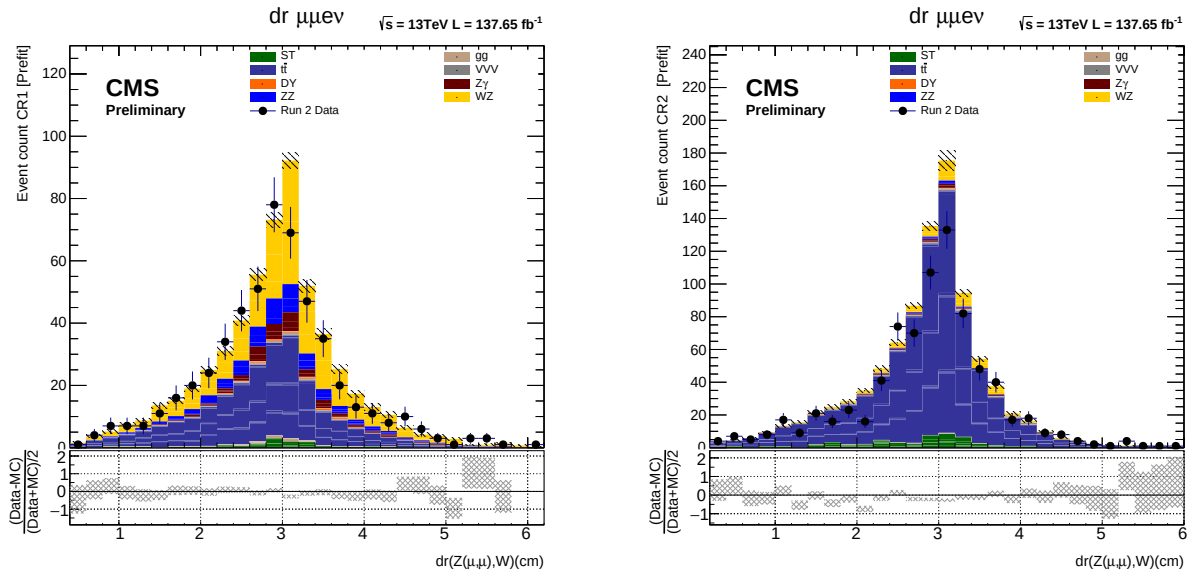
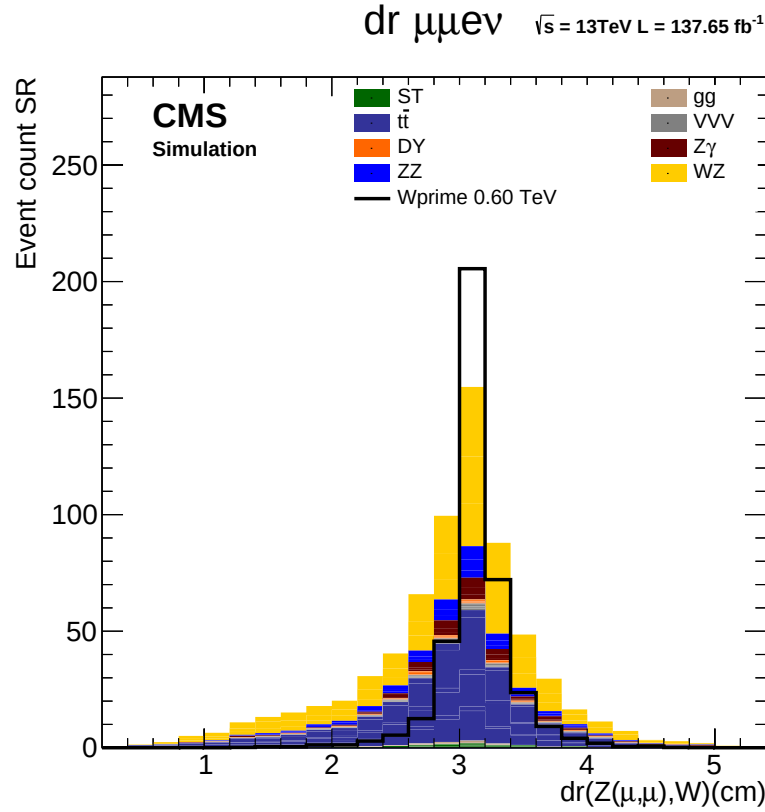
(a) WZ control region ($\mu\mu\nu\nu$)(b) $t\bar{t}$ control region ($\mu\mu\nu\nu$)(c) Signal region ($\mu\mu\nu\nu$)

Figure 6.34: The distance in the $\eta - \phi$ plane between the Z boson and the W boson used to reconstruct the WZ resonance candidate in the WZ control region (left), the $t\bar{t}$ control region (middle) and the signal region (right) for the $\mu\mu\nu\nu$ channel.

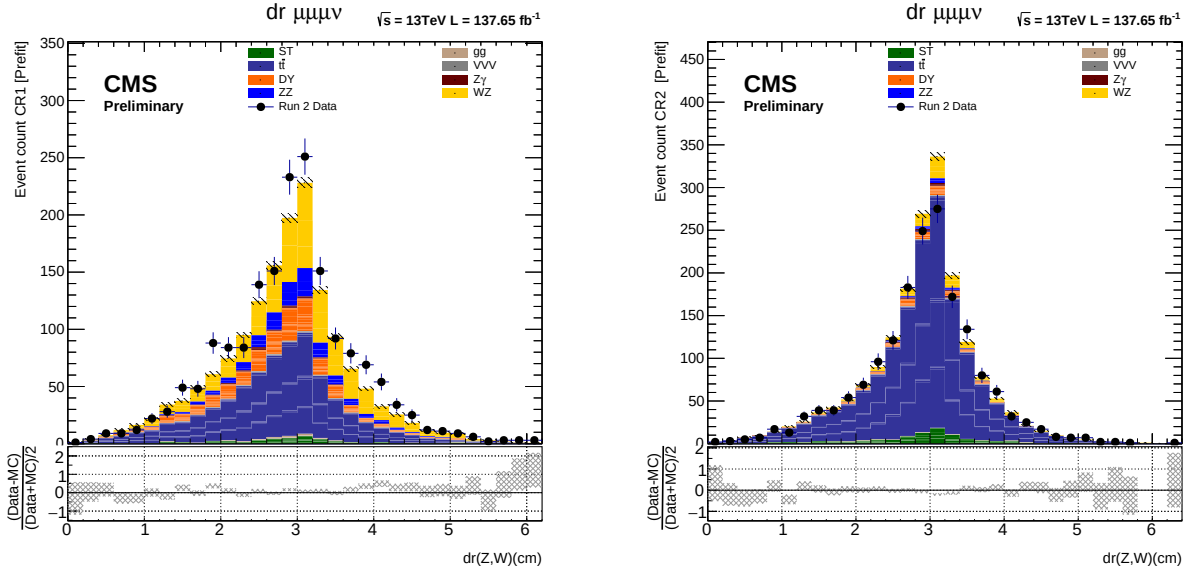
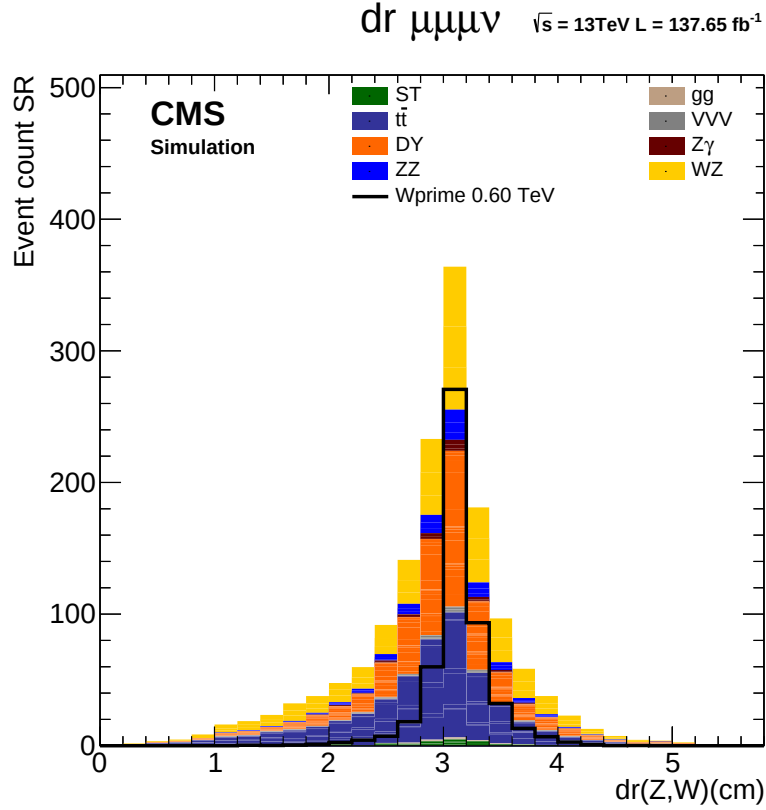
(a) WZ control region ($\mu\mu\nu$)(b) $t\bar{t}$ control region ($\mu\mu\nu$)(c) Signal region ($\mu\mu\nu$)

Figure 6.35: The distance in the $\eta - \phi$ plane between the Z boson and the W boson used to reconstruct the WZ resonance candidate in the WZ control region (left), the $t\bar{t}$ control region (middle) and the signal region (right) for the $\mu\mu\nu$ channel.

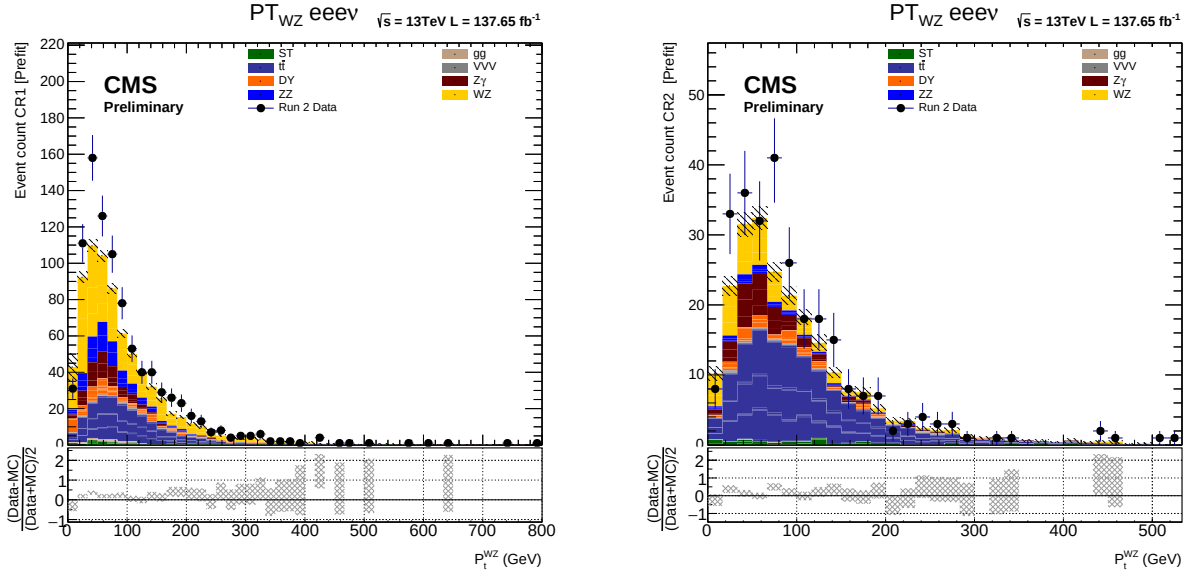
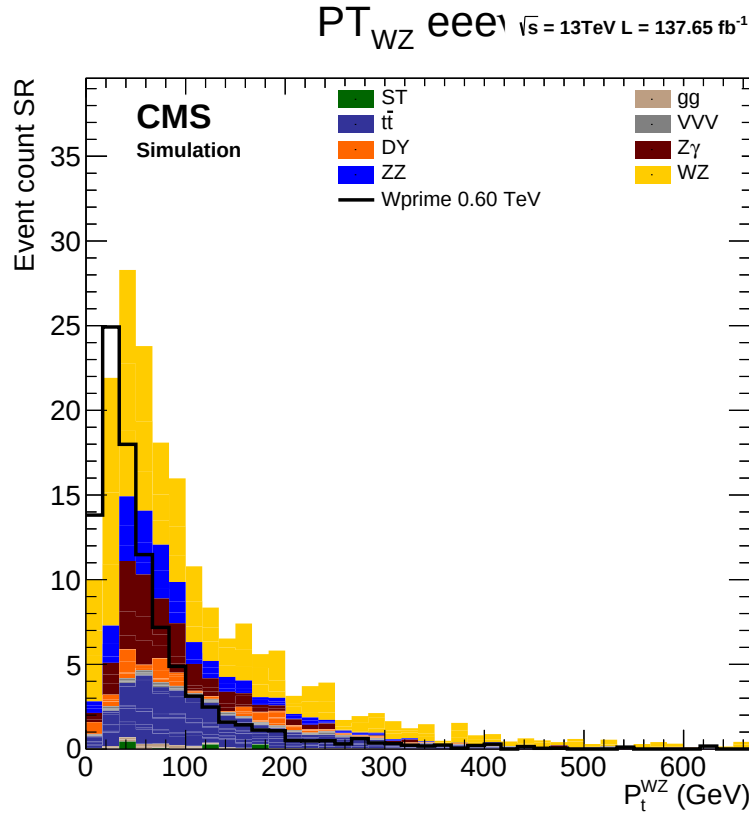
(a) WZ control region ($ee\nu\nu$)(b) $t\bar{t}$ control region ($ee\nu\nu$)(c) Signal region ($ee\nu\nu$)

Figure 6.36: The transverse momentum distribution of the reconstructed WZ resonance candidate in the WZ control region (left), the $t\bar{t}$ control region (middle) and the signal region (right) for the $ee\nu\nu$ channel.

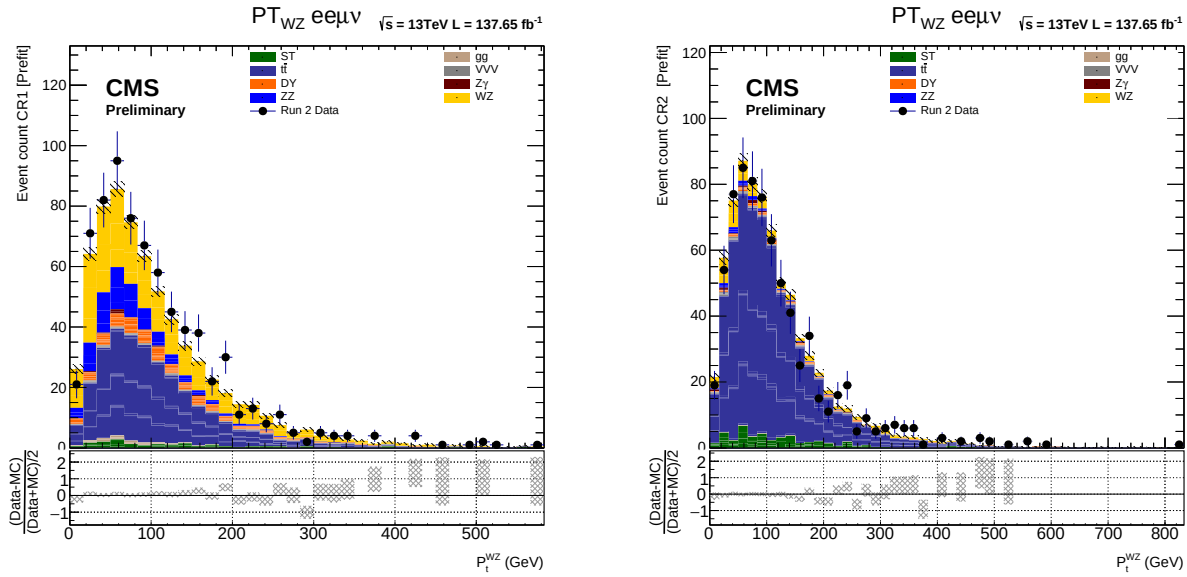
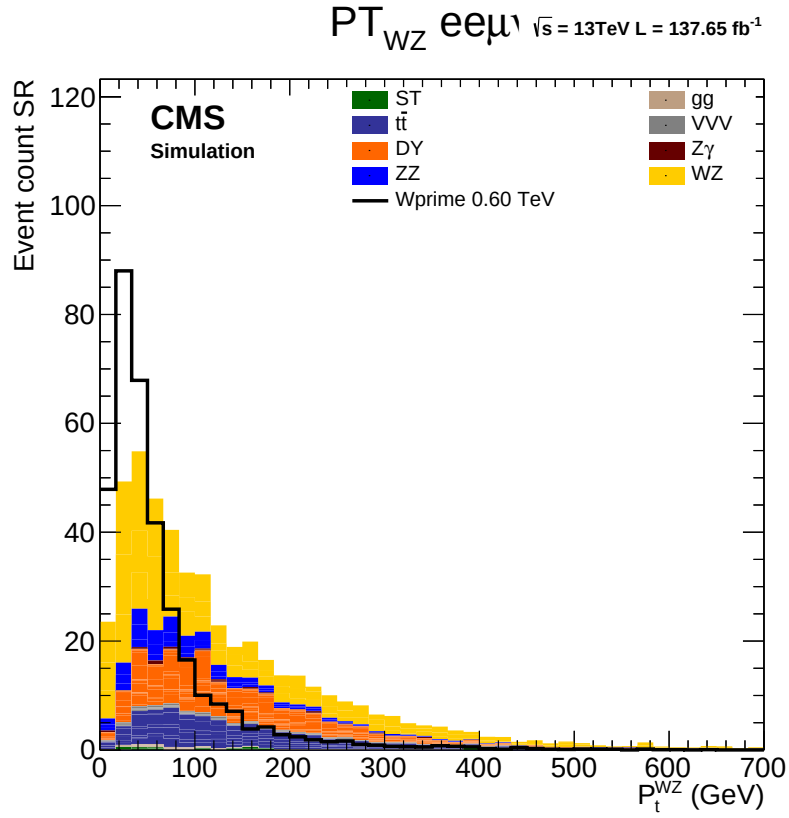
(a) WZ control region ($ee\mu\nu$)(b) $t\bar{t}$ control region ($ee\mu\nu$)(c) Signal region ($ee\mu\nu$)

Figure 6.37: The transverse momentum distribution of the reconstructed WZ resonance candidate in the WZ control region (left), the $t\bar{t}$ control region (middle) and the signal region (right) for the $ee\mu\nu$ channel.

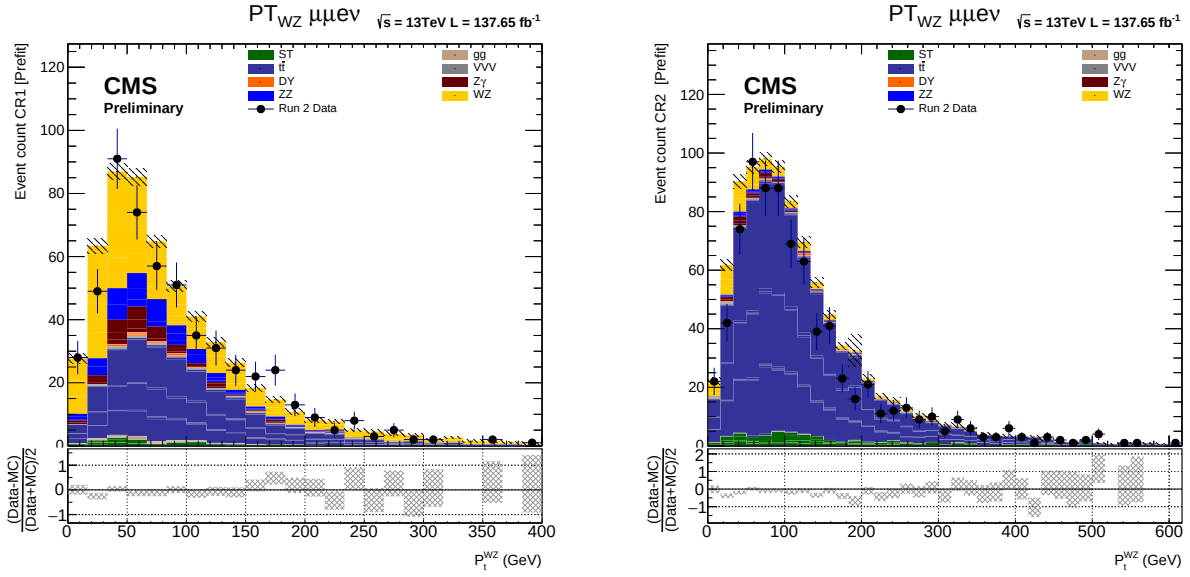
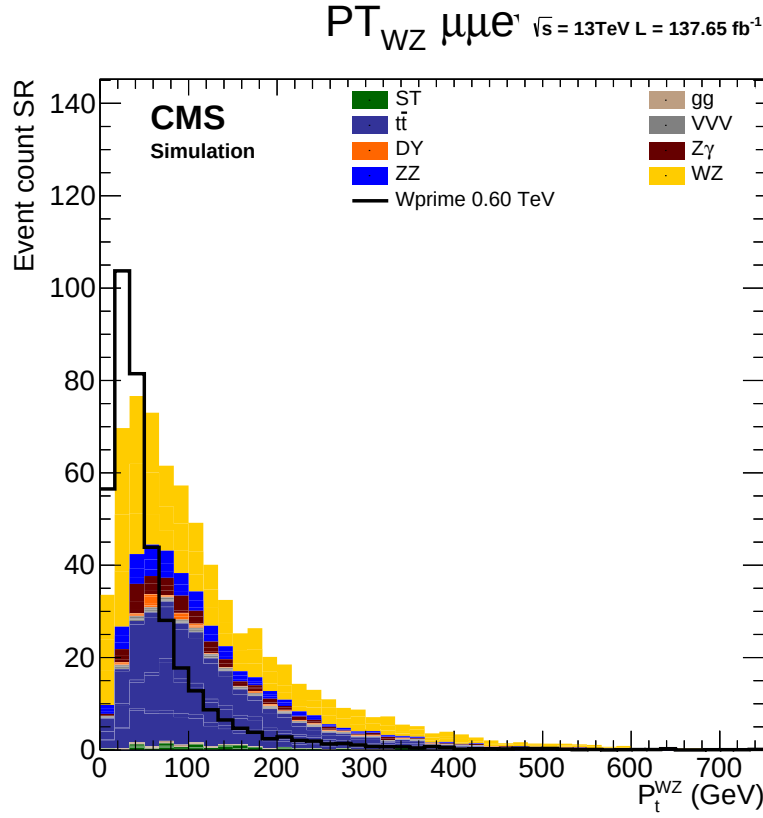
(a) WZ control region ($\mu\mu\nu$)(b) $t\bar{t}$ control region ($\mu\mu\nu$)(c) Signal region ($\mu\mu\nu$)

Figure 6.38: The transverse momentum distribution of the reconstructed WZ resonance candidate in the WZ control region (left), the $t\bar{t}$ control region (middle) and the signal region (right) for the $\mu\mu\nu$ channel.

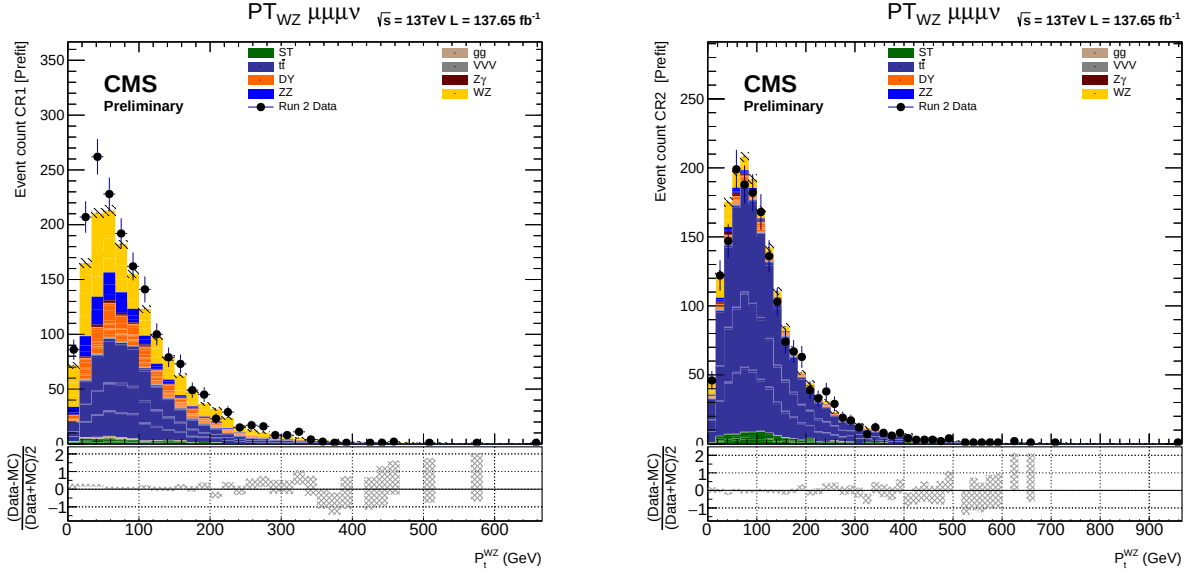
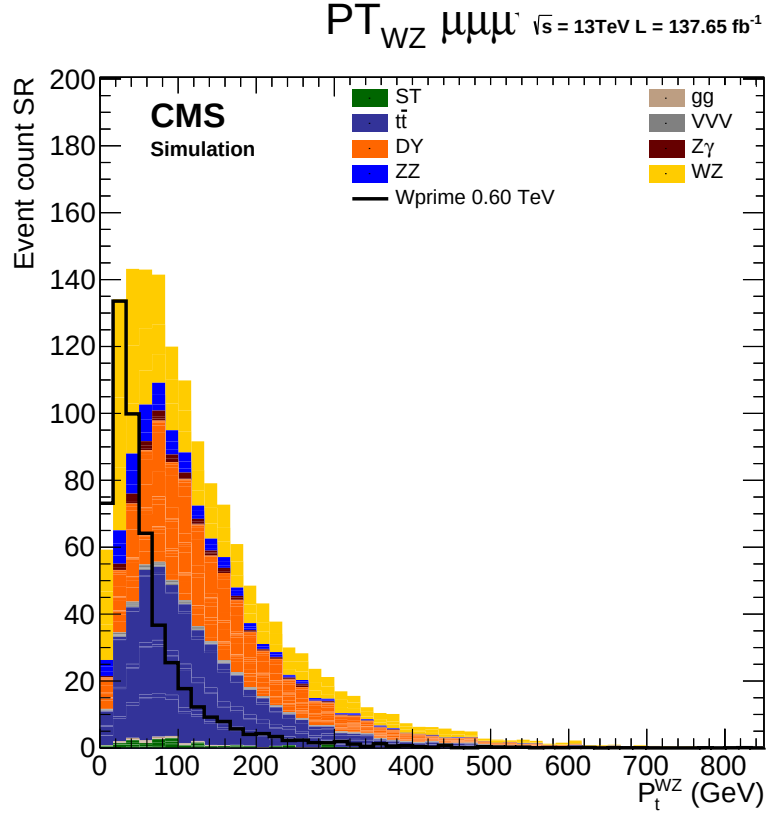
(a) WZ control region ($\mu\mu\nu$)(b) $t\bar{t}$ control region ($\mu\mu\nu$)(c) Signal region ($\mu\mu\nu$)

Figure 6.39: The transverse momentum distribution of the reconstructed WZ resonance candidate in the WZ control region (left), the $t\bar{t}$ control region (middle) and the signal region (right) for the $\mu\mu\nu$ channel.

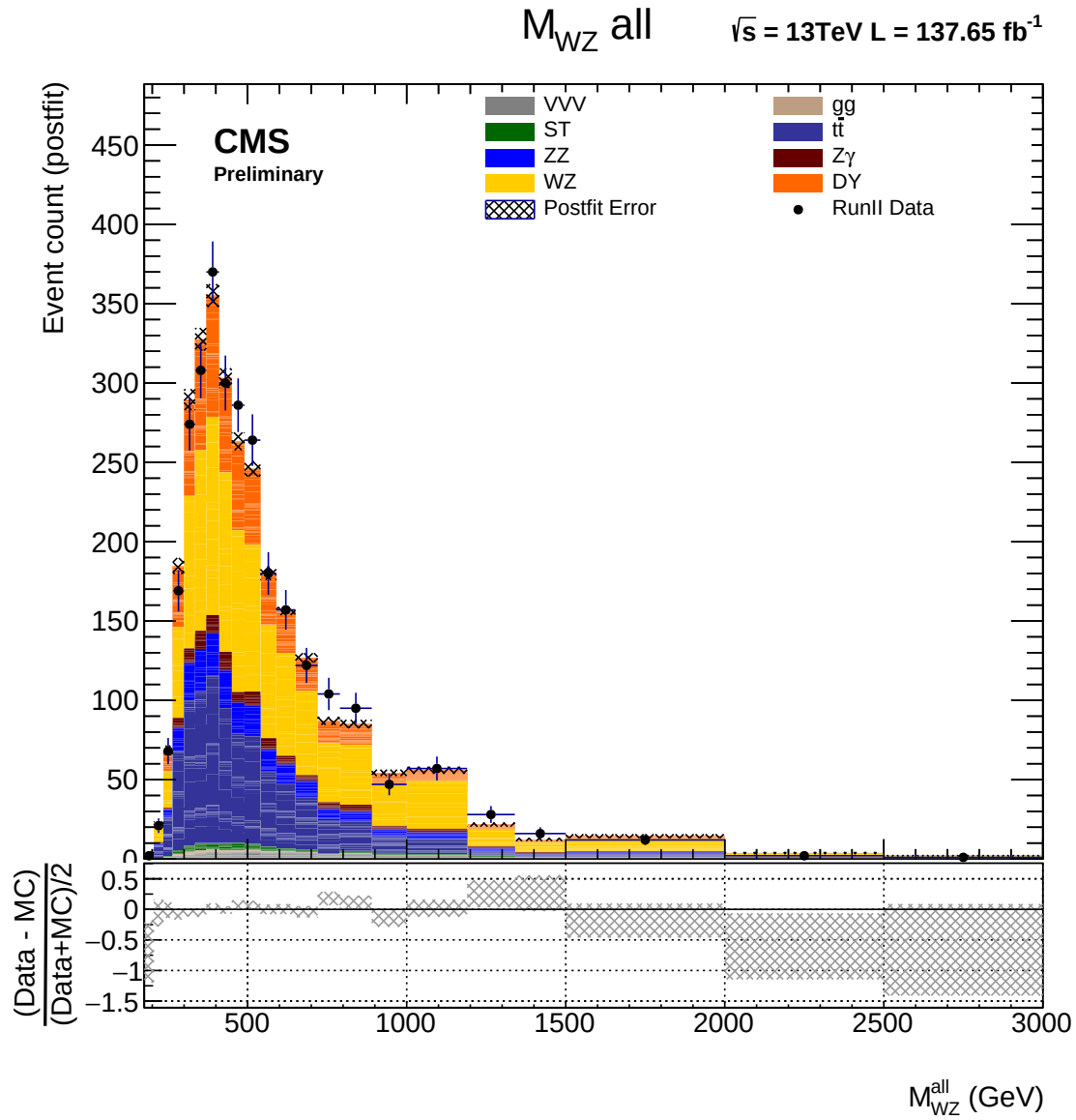


Figure 6.40: M_{WZ} postfit distribution for the signal region combining all the channels and the different years of data taking.

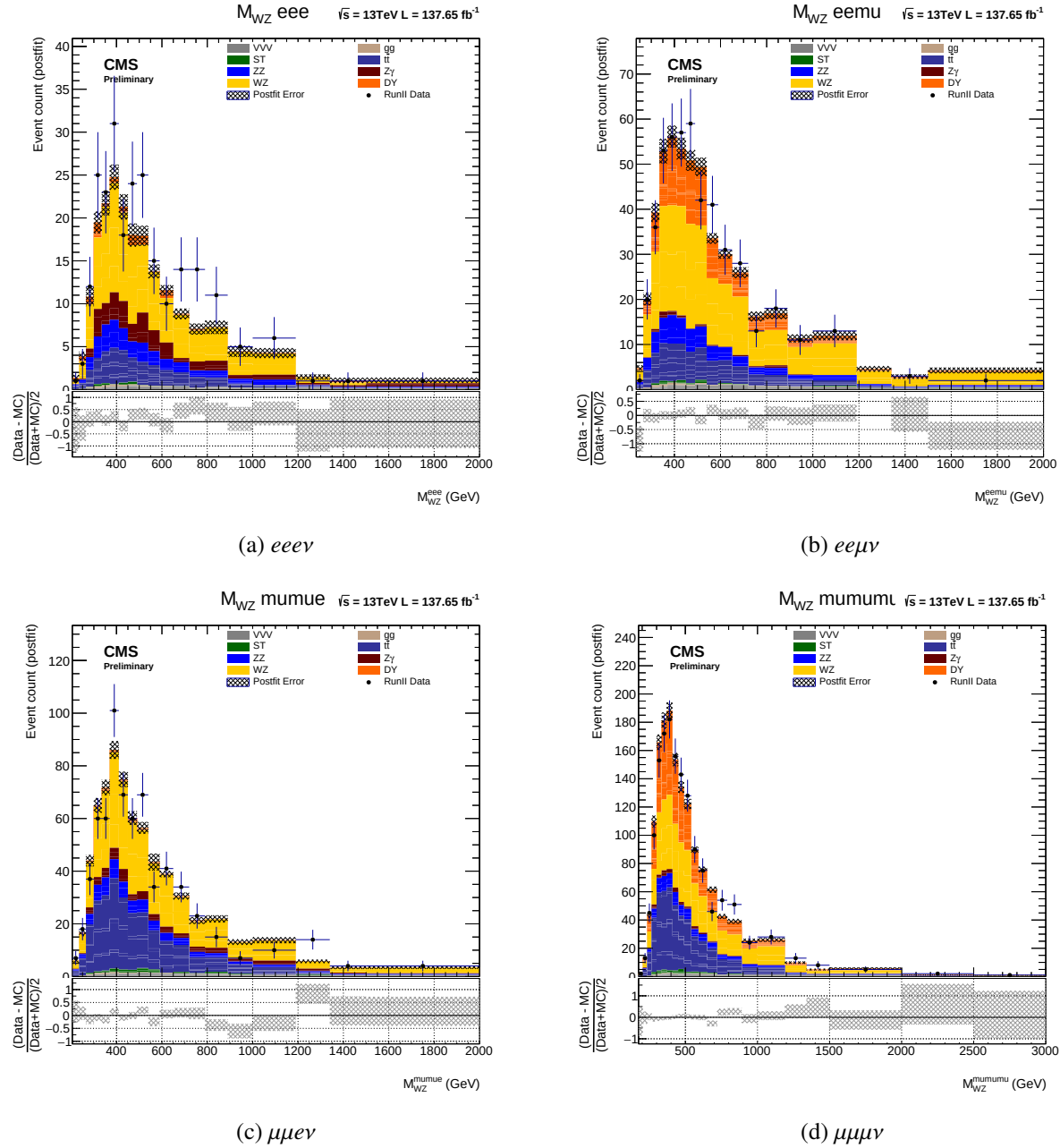


Figure 6.41: M_{WZ} Postfit distribution in the signal region for each of the different channels.

6.8 Systematic Uncertainties

As seen in [section 6.1](#), the process of counting the number of events in the different selection regions includes taking into account possible corrections to the simulation samples. These corrections include uncertainties that should be accounted for. As the scale factor is applied directly as a correction to the nominal weight of the event, a mechanism to keep track of the uncertainty in computing the scale factor is needed. Generally speaking, the type of systematic uncertainties can be split into two categories: Shape-based systematics and log-normal systematics. Shape-based systematics are those that change the shape of the distribution and as such are more granular than log-normal systematics, which are those that account only for changes in the normalization of the distribution. As expected, the shape based systematics are provided as variation bin by bin, for this, two versions of the distributions are stored for each scale factor to represent the lower and upper limit that the scale factor can take. It is important to note that this is done for each scale factor individually, but also for each individual contribution to the overall background (or signal) by the different physics processes, see for instance [Figure 6.42](#).

The uncertainty does not only apply to the scale factors, but also to other sources, such as the theoretical uncertainty in the cross-section for each process, or the uncertainty in the measurement of the luminosity. What follows is a list of sources of uncertainty in the analysis performed and how they are accounted for.

Pileup reweighting

As mentioned in [chapter 5](#) the LHC injects a *bunch* of protons into the CMS detector every 25 ns. The number of protons in each bunch is approximately 1.5×10^{11} ([Baudreghien and Mastoridis, 2012](#)) and only a small fraction of these protons will collide to produce interactions that will be recorded by the detector. The number of interactions per bunch crossing is known as *pileup*.

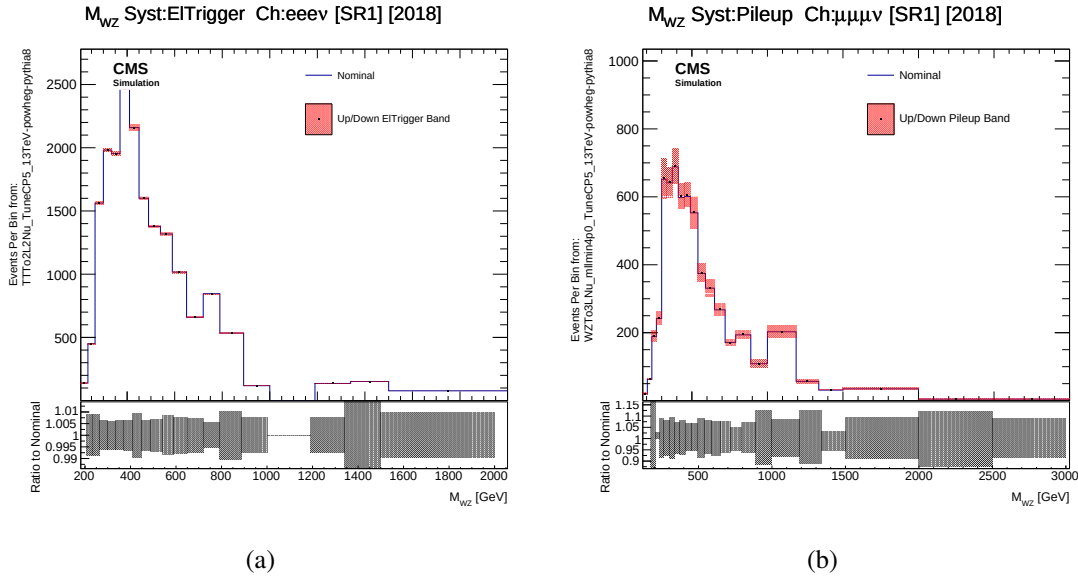


Figure 6.42: Example of the uncertainty in the scale factor for the trigger efficiency for electrons (left) and the pileup scale factor (right). The uncertainty is represented by the red band while the blue line represents the nominal distribution. The distributions are not scaled by the luminosity or cross-section event and are only for illustration purposes. The bottom plot shows the ratio relative variation of the upper and lower limit of the scale factor with respect to the nominal value.

In order to generate the simulation of the events an initial distribution for this pileup is required, and a reliable estimation is made and then used to generate the physics events in the first step of the simulation process (see [section 6.1](#)).

This distribution is commonly referred as *pileup profile*. Once the data is collected, both profiles, the one fed into simulation and the one that has been obtained in the reconstruction of the events from the detector are compared. A scale factor is created as a function of the number of true interactions.⁴ The scale factor per bin represents the ratio between the number of events in the measured profile and the number of events in the simulated profile. This scale factor is then applied to the simulated events to account for the difference between the two profiles.

4. Here, *true* interactions mean the number of interactions that is taken by the event generator not as the number of interactions as seen by the reconstruction process after the simulation of the detector response.

ECAL Prefiring

During the late stages of the 2016 and the whole 2017 data taking periods, an issue with the ECAL L1 trigger occurred which lead to a series of physics events being bypassed by the trigger and therefore not recorded by the detector. This issue, known as *ECAL prefiring* was found to be caused by detector aging evident in the distortion of the pulse shape of a group of ECAL crystals in the $2.1 < |\eta| 3.0$ regions. This distortion was due to degraded transparency of the crystals and caused the association of the L1 trigger primitives to the wrong bunch crossing, so instead of being associated with the event n , they were associated with the $n + 1$ event, causing the information from the relevant event to be discarded ([L1 Trigger DPG, 2018](#)). A scale factor is applied to the simulated events to account for this effect.

Leptons' HLT efficiency

The performance of the HLT efficiency is evaluated for the combination of the triggers for each lepton flavor. The study of the efficiency is performed through a data-driven method known as *tag and probe* ([CMS Collaboration, 2010a](#)). The tag and probe method exploits the decays of well-known resonances such as the Z boson, J/ψ or Υ mesons. These resonances can decay to a pair of particles, in our analysis either muons or electrons and in each pair one of the particles is labeled as a *tag* muon(electron) fulfilling a well restricted selection criteria while the *probe* muon(electron) fulfills a more lenient selection criteria. The efficiency is then computed as the ratio of muons/electrons that pass the HLT selection over the total number of probes while the tag is used to identify the presence in the event of the resonance of interest. The efficiency is computed as a function of the p_T and η of the probe particle. This efficiency is then taken as a scale factor and applied to the simulated events.

Leptons' ID efficiency

The efficiency of the lepton identification is also evaluated through the tag and probe method and scale factor is computed and applied to simulated events as a function of p_T and η .

Electron Reconstruction

The electron reconstruction scale factors and uncertainties are provided centrally by the EGamma POG. The scale factors are computed as a function of the p_T and η of the electron and are applied to the simulated events. As multiple electrons are found in the same event the scale factors corresponding to each electron are multiplied together to obtain the corresponding weight for the event:

$$SF_e = \prod_{i=1}^{n_e} [SF_{e_k}(P_t^{e_i}, \eta^{e_i})] \quad (6.2)$$

Where k represents the type of scale factor applied (i.e HLT, ID, Reconstruction, etc.) and n_e is the number of electrons in the event. An equivalent expression can be built for the muon(s) found in the event.

Temporary issue with dead modules in HCAL

During the 2018 data taking period, two modules in the Hadronic Calorimeter lost power due to a faulty power supply. These modules were located in the $-3.0 < \eta < -1.3$ and $-1. < \phi < -.87$ regions, occasioning an inaccurate measurement of the energy deposited in this region of the HCAL, and therefore a propagated effect in the reconstruction of the Missing Transverse Energy. Aiming to correct for this effect, events with a reconstructed Jet in this region during 2018 are excluded from the analysis.

Unclustered MET

The missing transverse momentum P_T^{miss} is not directly measured by the detector, but instead, it is reconstructed from the kinematics measured for the different particles in the event. Therefore, the uncertainty in the reconstruction of the P_T^{miss} is the propagated uncertainty of the kinematics of the other particles. The Unclustered MET is the object built from the particles that are not associated to any reconstructed jet. In order to account for this uncertainty, CMS provides a symmetric variation in each component of the transverse plane:

$$P_{t \cdot (x||y)}^{miss} \rightarrow P_{t \cdot (x||y)}^{miss} \pm \Delta P_{t \cdot (x||y)}^{miss} \quad (6.3)$$

Where $\Delta P_{t \cdot (x||y)}^{miss}$ is provided centrally by the JetMET POG. This variation gives rise to two values for the P_T^{miss} in the event and therefore a definition of an upper and lower bound. Once the two limits of P_T^{miss} is defined, the results are propagated to the distribution of discriminant variable M_{WZ} and a corresponding shape uncertainty is produced.

Bin wise uncertainties

The limited statistics in the final state of the analysis can affect the results of the fit and therefore the final results. This effect is due to the fact that background yields are subjected to statistical uncertainties based on the limitations of finite sampling of the true distribution. In order to account for this effect, bin-by-bin uncertainties are computed for each bin of the M_{WZ} distribution. This is handled by the autoMCStats method from the Higgs Combine tool. The technique to build the bin uncertainties is based on the Barlow-Beeston method ([Barlow and Beeston, 1993](#)). Even though, the uncertainties in each Bin depends on the individual contribution of each background process, the Barlow-Beeston method allows to reduce the number uncertainties by factoring in a single bin uncertainty which is constrained by the total uncertainty of the overall contribution from each process.

Drell-Yan subleading orders

The Drell-Yan process makes a non-negligible contribution to the overall background in the analysis. The Drell-Yan process initially accounts for the quark-antiquark annihilation producing a dilepton pair. However, the contribution to this process is not limited to the electromagnetic interaction of the quarks and antiquarks. In order to account for this effect, QCD corrections need to be applied. This is done through the scaling of the event by a factor, known as the *K-factor*. The K-factor is a function of the invariant mass and its value also introduces an additional source of uncertainty in the analysis, which is accounted for through a *shape* uncertainty that reflects the cumulative effect of the K-factor in the M_{WZ} distribution.

Statistical Analysis

As mentioned earlier the bump-hunt search is performed on the distribution for the invariant mass of the resonance candidate M_{WZ} . The distribution of the resonance candidate mass provides a way to articulate the existence of two hypotheses and then perform a hypothesis test. The two hypotheses are the following: the null hypothesis H_0 states that the resonance candidate mass distribution is consistent with the predictions of the SM and therefore with the distribution of backgrounds, this is known as the background-only hypothesis. The alternative hypothesis H_1 state that the distribution is not consistent with the SM and therefore allow us to reject the background-only hypothesis and further study the significance of the deviation from the SM. In particle physics, the significance of the deviation from the SM is commonly expressed in terms of a given number of standard deviations σ from the mean of the distribution, with a significance of 3σ is considered to be evidence for the existence of a new physics process while a significance of 5σ is considered to be a discovery (Barlow, 2019). On the other hand, if no deviation from the background-only hypothesis is observed, an upper limit on the cross-section of a signal process can be derived.

The hypothesis test is based on a frequentist method, where probability is interpreted as the frequency of an event in a large number of experiments performed under the same conditions. In particle physics the CL_s method (Read, 2002) is commonly employed as a way to present the

results for the search for evidence or discovery of new physics processes. For this, a likelihood function is defined, this likelihood function $\mathcal{L}$ will evaluate the realization of the data given a set of statistical parameters, in our case the nuisance parameters $\hat{\theta}$ which are the numerical representation of the uncertainties in our experiment (see [section 6.8](#)), and a new parameter known as the *signal strength modifier* r . r as a metric, scales the signal process in the distribution.

$$\mathcal{L}(data|\theta, r) = P(data|r \cdot s(\theta) + b(\theta)) \cdot p(\tilde{\theta}|\theta) \quad (6.4)$$

Where $P(data|\hat{\theta} \cdot r)$ is the probability density function of the data given the signal strength modifier r . s and b are the signal and background event yields. The events yield are affected, and therefore a function of the nuisance parameters. On the other hand, $p(\tilde{\theta}|\theta)$ is the probability of obtaining a particular nuisance parameter value $\tilde{\theta}$ for the nuisance parameter θ . A typical probability density function for binned data is the Poisson distribution:

$$\text{Poisson}(n|\lambda) = \frac{\lambda^n \cdot e^{-\lambda}}{n!} \quad (6.5)$$

Where n is the number of events in a particular bin and λ is the expected number of events in that bin. Taken this into account, the likelihood function is expressed as:

$$\prod_{i_1}^k \frac{(r \cdot s_i + b_i)^{n_i}}{n_i!} e^{-(r \cdot s_i + b_i)} \quad (6.6)$$

Where k is the total number of bins in the distribution, n_i is the number of events in bin i , s_i and b_i are its corresponding signal and background yields. Once defined the probability density function, a statistical metric is needed in order to objectively determine the agreement between the observed in data and the predictions of both of the hypotheses:

$$\tilde{q}_r = -2 \ln \frac{\mathcal{L}(n_{obs}|r, \hat{\theta}_r)}{\mathcal{L}(n_{obs}|r, \hat{\theta})} \quad (6.7)$$

Where n_{obs} is the observed number of events, which can be either the number of events in the physics data, or in a pseudodata distribution (toy) generated from either the background-only or signal-plus-background hypothesis given a set of nuisance parameters $\hat{\theta}$. $\hat{\theta}_r$ represents the set of nuisance parameters that best describe the hypothesis under the assumption of a signal strength r . The denominator of the Equation 6.7 is the maximum likelihood function where $\hat{r}$ and $\hat{\theta}$ represent the maximum of the function. The higher the value of $\tilde{q}_r$, the more significant the deviation from the hypothesis being tested (given r), the signal strength is constrained to be positive, and therefore the null hypothesis is represented by a null signal strength $r = 0$.

For a given value of r , and a given *data* (or pseudodata) distribution, the test statistic $\tilde{q}_r$ is evaluated. The importance of pseudodata distributions come to play when building the p-value distribution for the test statistic $\tilde{q}_r$:

$$p_{\tilde{q}_r} = CL_{s+b} = P\left(\tilde{q}_r \geq \hat{q}_{\mu}^{obs} | \mu s(\theta_{\mu}^{obs}) + b(\theta_{\mu}^{obs})\right) = \int_{\tilde{q}_r}^{\infty} f(\tilde{q}_r | r, \theta_r^{obs}) d\tilde{q}_r \quad (6.8)$$

And for the probability of rejection of null hypothesis:

$$p_0 = CL_b = P\left(\tilde{q}_r \geq \hat{q}_0^{obs} | b(\theta_{\mu}^{obs})\right) = \int_{\tilde{q}_r}^{\infty} f(\tilde{q}_r | 0, \theta_0^{obs}) d\tilde{q}_r \quad (6.9)$$

Where $f(\tilde{q}_r | r, \theta_r^{obs})$ is the probability density function of the test statistic $\tilde{q}_r$.

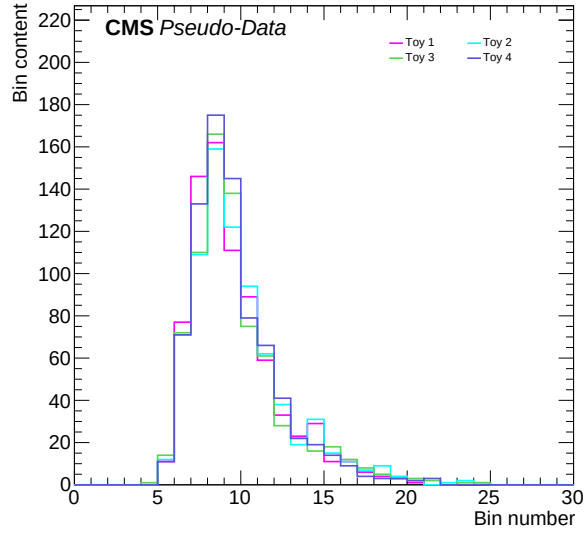


Figure 6.43: Examples of pseudodata distributions generated for the $Z(\rightarrow \mu\mu) + W(\rightarrow \mu\nu)$ channel. The distributions are generated using the signal and background templates from the WZ control region. Each distribution is generated using a different set of nuisance parameters.

6.8.1 Pulls

The systematic uncertainties described in [section 6.8](#) are embedded into the computation of the limits for the signal strength as nuisance parameters (see [section 6.9](#)). After the fit, the nuisance parameters are constrained to the best fit values to minimize the test statistic ([Equation 6.7](#)). The pulls for each nuisance parameter are then computed as the difference between the post-fit value $\hat{\theta}$ and the nominal (pre-fit) value θ divided by its uncertainty σ_{θ} :

$$\text{pull} = \frac{\hat{\theta} - \theta}{\sigma_{\theta}} \quad (6.10)$$

The pulls can either be computed on the data or an Asimov dataset. Asimov dataset are specially useful in the blinded analysis, where the data is not available. [Figure 6.44](#) shows a representative example of the pulls. A pull measurement is generated by nuisance parameter, and

the fit was performed per channel, per control region and per year to obtain a more granulate description of the fit.

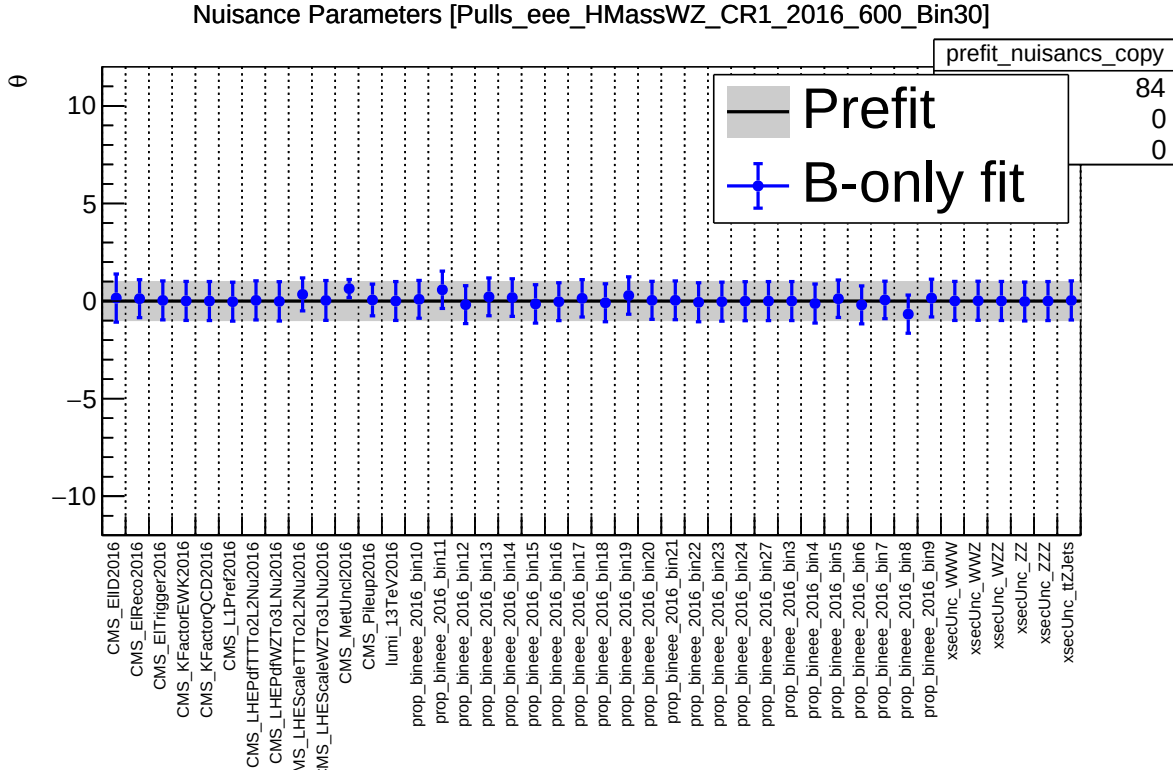
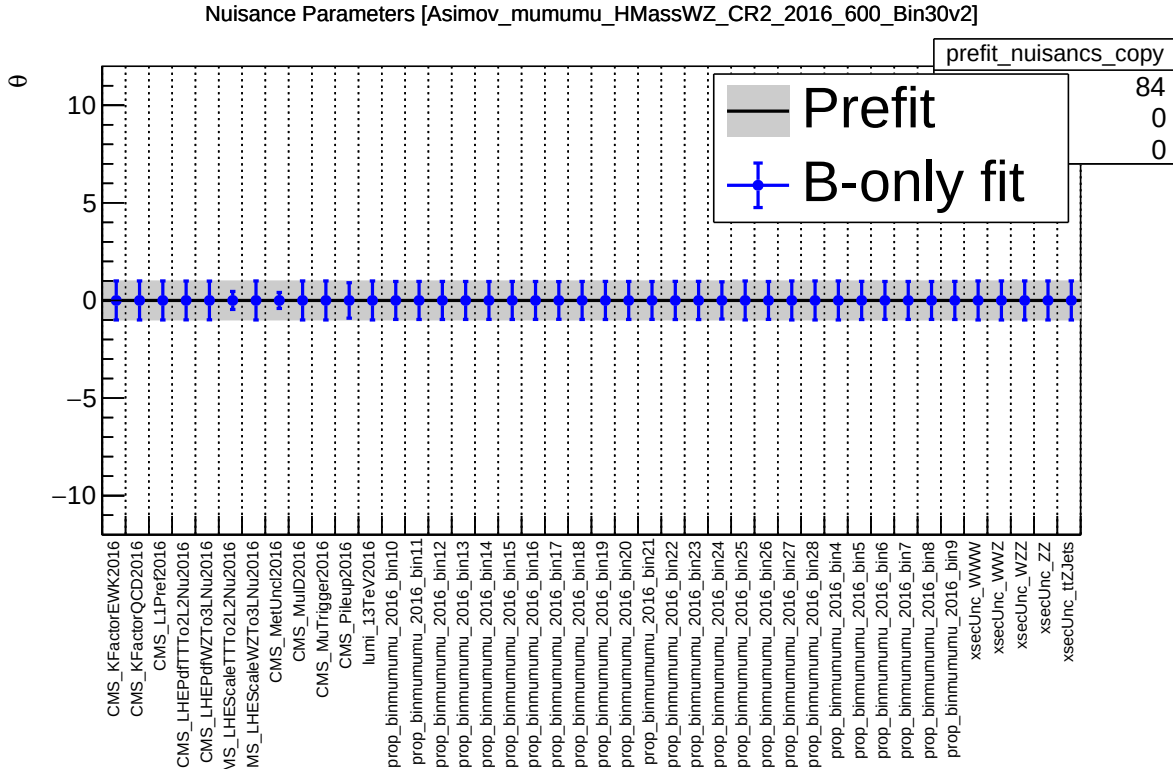


Figure 6.44: Pulls for the $eee\nu$ channel, WZ control region, year 2016.

6.8.2 Impacts

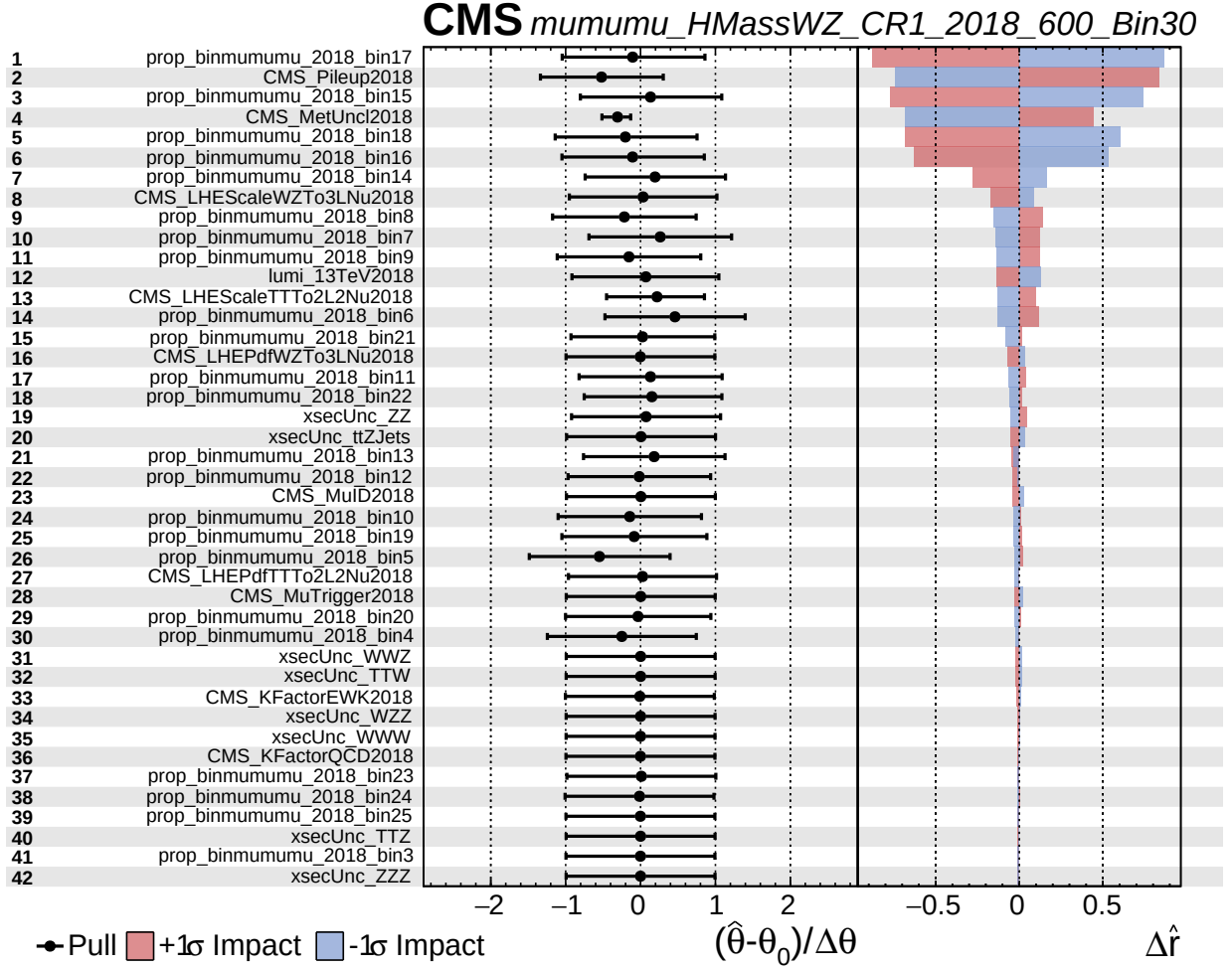


Figure 6.45: Impacts on the signal strength from the nuisance parameters for the $\mu\mu\mu\nu$ channel, WZ control region, year 2018.

As multiple nuisance parameters are used to describe the systematic uncertainties that play a role in the limit setting procedure, it is important to know the relative *impact* of each nuisance parameter in the likelihood fit. This *impact* is a measure of how much the signal strength is affected by the variation of each nuisance parameter. The calculation of the impact is done by shifting the nuisance parameter by $\pm 1\sigma$ and computing the change in the signal strength (called Parameter of Interest, POI). A given shift of a nuisance parameter is performed while keeping all other nuisance

parameters fixed at their post-fit values. [Figure 6.45](#) displays a typical example of the impact ranking and the relative impact of each nuisance parameter on the computation of the signal strength.

6.8.3 Goodness of fit

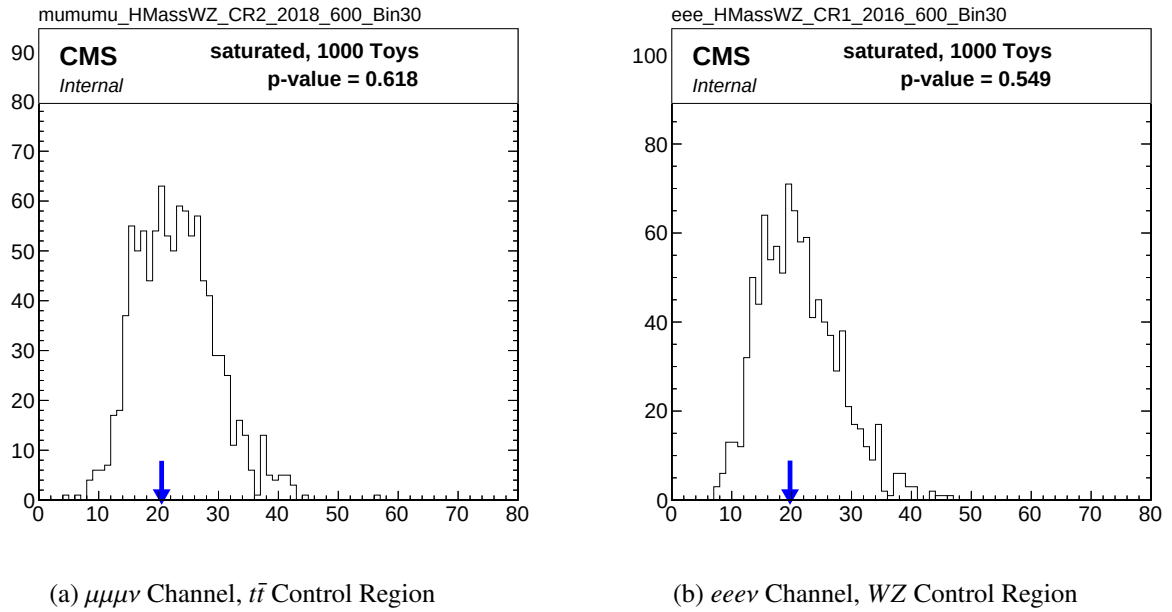


Figure 6.46: Goodness of fit, and p -value illustrative examples.

In general, the Goodness of Fit (GoF) assess the quality of the fit to the observed data. The fit can be done using either the background or signal plus background model. In the case of the control regions, where the contribution from the signal is negligible, the fit is performed using the background-only model and therefore the metric allows us to assess the quality of the background simulation in the control regions and by extension to estimate how well the background has been modelled in the analysis, including the signal region. This is done on the basis of the similar kinematic distributions of the resonance candidate in the signal and control regions as seen in [section 6.7](#).

The GoF is performed by using the *saturated model* algorithm. The saturated model as the name suggests, is a model that perfectly describes the data and then, it can be used as a reference

to compare a given fit. A set of one thousand pseudo-experiments are generated and the fit is performed on each of them, giving a test statistic for each pseudo-experiment which helps us building a distribution of it, which is then compared to the observed test statistic. After this process, the p -value is calculated providing a measurement of the probability of rejecting the null hypothesis (i.e. the background-only model) when it is true. If the p -value is either too small or too large, it indicates poor quality of the fit because there's not enough evidence to reject the null hypothesis. [Figure 6.46](#) shows a typical example of the GoF test results, the blue arrow represents the observed test statistic and the integral from this point to the right of the distribution is the p -value. The goodness of fit is performed per channel, per control region and per year to evaluate the quality of the fit in each of the possible regions, in order to have a granular description of the fit and to be able to identify possible issues in specific regions.

6.8.4 Signal Injection Test

The signal injection tests are a set of bias tests where the signal strength modified is set to a specific value. Since the amount of signal in the acquired data is unknown, a set of pseudodata distributions are generated for a given signal strength modifier r and then a fit is performed to each of pseudodata distribution in order to obtain the best fit value of the signal strength modifier $\hat{r}$. A comparison is made between the best fit value of the signal strength modifier $\hat{r}$ and the signal strength modifier r used to generate the pseudodata distribution:

$$\frac{\hat{r} - r}{\sigma_{\hat{r}}} \quad (6.11)$$

This quantity is commonly referred to as a pull, and in the ideal distribution where no bias is present, the pull should be closely distributed around zero. The error $\sigma_{\hat{r}}$ is obtained by accounting for the upper and lower uncertainties:

$$\sigma_{\hat{r}} = \sigma_{r_{\text{up}}} \times (\hat{r} - r < 0) + \sigma_{r_{\text{down}}} \times (\hat{r} - r > 0) \quad (6.12)$$

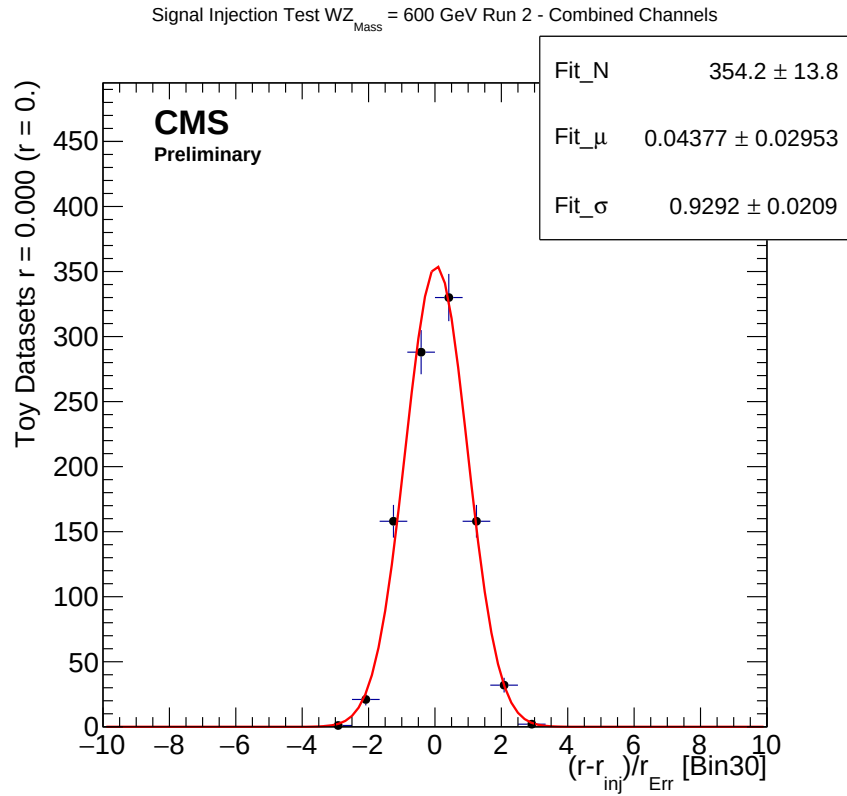
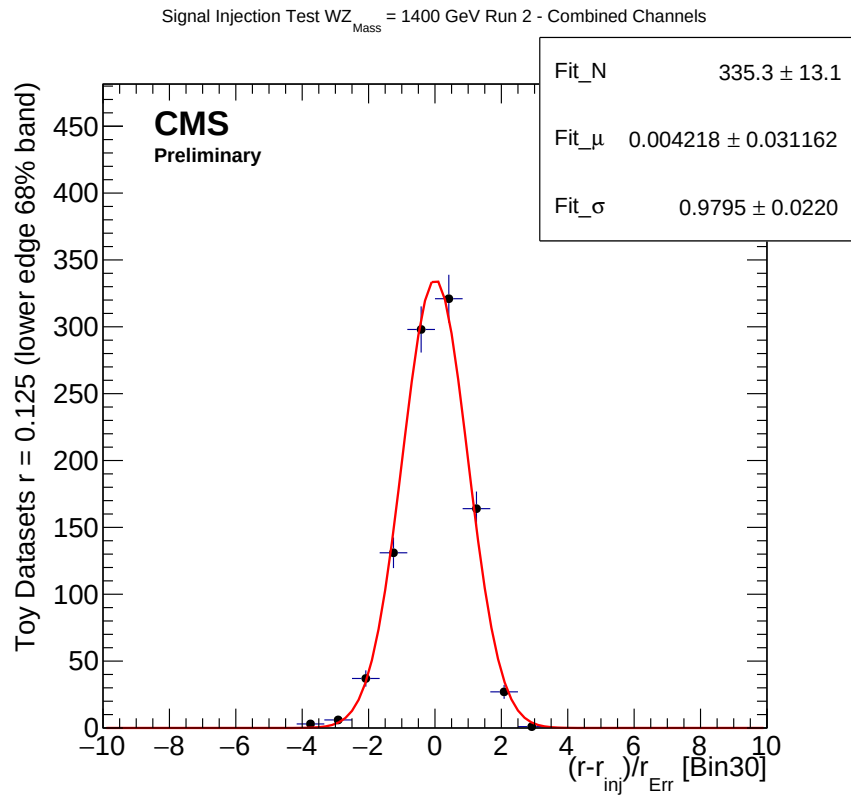
(a) $M_{WZ} = 600 \text{ GeV}$ (b) $M_{WZ} = 1400 \text{ GeV}$

Figure 6.47: Signal injection test results illustration

For the current analysis, the signal strength is set to $r = 0$, the lower, median and upper expected limits, a common test for B2G analyses and part of the B2G statistics review process. The test is performed for three resonance masses (600 GeV, 1000 GeV and 1400 GeV). A total of 1000 pseudodata distributions are generated per resonance mass at a given signal strength modifier r . A distribution for the pull is then generated and a fit to a gaussian distribution is performed. A mean value of zero and a standard deviation of one is expected for the pull distribution if no bias is present. [Figure 6.47](#) shows an illustrative example of the typical results obtained from the signal injection test, where it can be seen that the pull distribution is centered around zero as measured by the mean value of the fitted gaussian distribution and a standard deviation close to one.

6.9 Limits

As stated in [Equation 6.9](#) and [Equation 6.8](#), the p-values are associated with CL_{s+b} and CL_b respectively. In the modified frequentist approach ([Read, 2002](#)), the p-values are used to determine the confidence level of the null hypothesis:

$$CL_s = \frac{CL_{s+b}}{CL_b} = \frac{\int_{\tilde{q}_r}^{\infty} f(\tilde{q}_r|r, \theta_r^{\hat{o}bs})d\tilde{q}_r}{\int_{\tilde{q}_r}^{\infty} f(\tilde{q}_r|0, \theta_0^{\hat{o}bs})d\tilde{q}_r} \quad (6.13)$$

With $CL_s \leq 0.05$ representing a 95% confidence level for the null hypothesis. In order to find the r value that will provide a CL_s of 0.05 an iterative process is performed, where the value of r is changed and the p-values are re-evaluated in order to find the appropriate ratio. The same process can be performed to find the 68% confidence level. For the current analysis, limits on the cross-section are obtained by scaling the signal strength r to the cross-section provided by theory, see [Table A.1](#). r is computed by applying the asymptotic approximation ([Cowan *et al.*, 2011](#)) which resembles the CL_s method in the large statistics limit, but providing a computationally more efficient method.

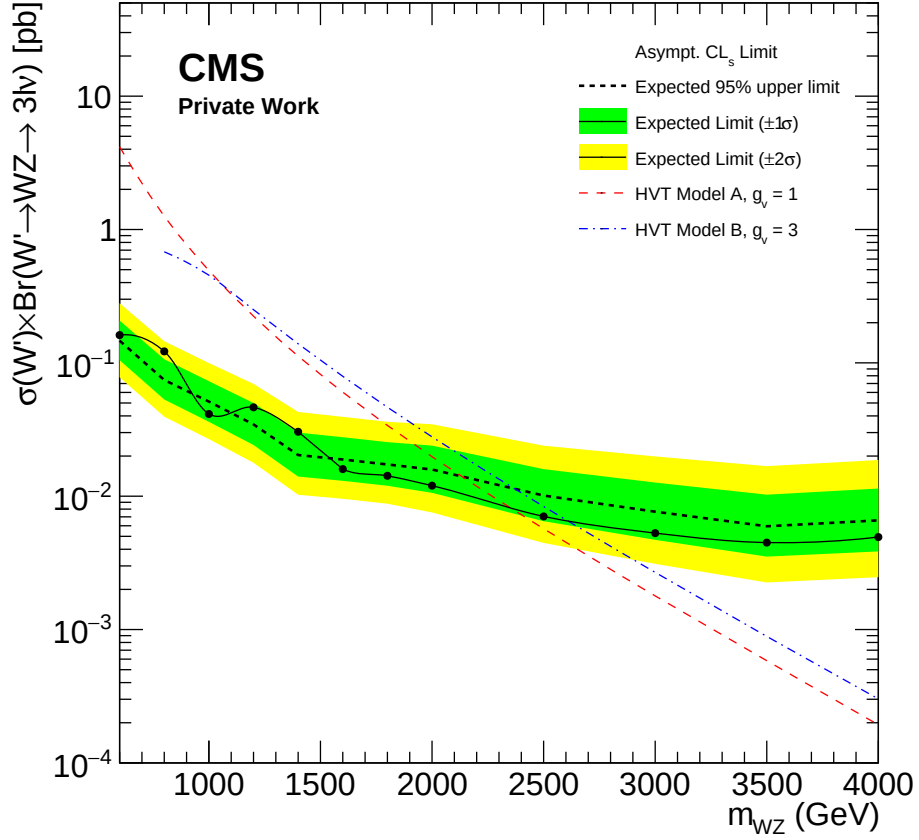


Figure 6.48: Exclusion limits at 95% CL for the signal strength of $W' \rightarrow WZ \rightarrow \ell\ell\nu$ as a function of the resonance mass. The dashed (solid) black line represents the expected (observed) exclusion limit. The green and yellow bands represent the 1σ and 2σ expected exclusion limits, respectively.

Figure 6.48 shows the exclusion limit plot for the $W' \rightarrow WZ \rightarrow \ell\ell\nu$ signal and provides a measurement for the lower bound of the exclusion limit for the W' mass in the HVT scenarios treated in the current dissertation. The observed (expected) exclusion limit is 2.45 TeV (2.15 TeV) for model A and 2.52 TeV (2.4 TeV) for model B. The slight difference between the observed and expected exclusion limits is not statistically significant and remains well within the 1σ band.

Conclusion

In this dissertation a new search for an electrically charged resonance decaying to a standard model diboson WZ system in the fully leptonic final state has been presented. The analysis involved an integrated luminosity of 137.65 fb^{-1} collected by the CMS experiment at the LHC during the 2016-2018 (Run2) period at a center-of-mass energy of $\sqrt{s} = 13 \text{ TeV}$. The analysis presented made use of the bump-hunt strategy, a time-tested technique for the search of new physics. The background estimation was based on MonteCarlo Simulations of irreducible standard model processes where three leptons (either e or μ) can be found as a product of the collision and also reducible processes that leave similar signatures in the detector and therefore lead to the reconstruction of the same final state. No significant excess of events was observed in the data and the obtained results are consistent with the standard model predictions. The current analysis represents an improvement over previous searches with CMS data. The 8 TeV search set a limit of 1.55 TeV at 95% CL on the mass of the resonance and the 13 TeV search presented in this dissertation sets a limit of 2.45 TeV (2.52 TeV) for model A (model B).

In addition to the physics search presented in this dissertation, there were contributions in different areas that will greatly benefit the field of particle physics in the short, medium and long term: In the short term, while studying the quality of the simulation in the control regions of the analysis and applying the necessary corrections, a significant discrepancy between the predictions for the Z peak resolution in the muon channel was found in the 2018 dataset. This discrepancy was

attributed to a bias in the reconstruction process and based on these studies the Muon POG further investigated, finding the cause of the bias to be coming from geometrical effects within the acceptance of the Muon subsystem, this led to the reprocessing of the 2018 dataset and the generation of a new dataset accounting for these effects. Studies like the one performed, are important to ensure the correctness of the data used in all the analyses and the new dataset is now available to be used by other CMS analyses, using high-Pt muons, a relevant object for a wide range of searches for new physics. Another significant contribution, that will benefit the field, and particularly the CMS collaboration in the medium term, was made in the upgrade of the CMS Geometry Description package, which is used by every simulation sample generated by the CMS collaboration, these are of vital importance with the upcoming Run 3 of the LHC physics program. This contribution was made by migrating from an in-house solution to a more robust open source solution that is used by other experiments such as ATLAS and LHCb. This upgrade will allow the CMS collaboration to benefit from the latest developments in the field of detector modeling and also allow for a more efficient collaboration with other experiments. Every CMS analysis uses some form of detector simulation and therefore each of them will benefit from this contribution. Finally, in the long term, the contribution made performing different studies required for the development of new assembly techniques for the CMS Pixel detector are a key step towards the growth, development, and maintenance of the Catholic University of America High Energy Physics lab as an assembly facility for the upcoming CMS Pixel Phase 2 upgrade.

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APPENDIX A

Centrally produced Signal and Background

MC samples

Table A.1: Ultra-Legacy Signal samples used in this analysis, their associated cross section times the branching ratio

Year	Sample	XSec Model A [pb]	XSec Model B [pb]
2016	WprimeToWZToWlepZlep_narrow_M600_TuneCP5_13TeV-madgraph-pythia8	6.252E-2	0.
	WprimeToWZToWlepZlep_narrow_M800_TuneCP5_13TeV-madgraph-pythia8	1.886E-2	1.02E-02
	WprimeToWZToWlepZlep_narrow_M1000_TuneCP5_13TeV-madgraph-pythia8	7.381E-3	6.81E-03
	WprimeToWZToWlepZlep_narrow_M1200_TuneCP5_13TeV-madgraph-pythia8	3.356E-3	3.75E-03
	WprimeToWZToWlepZlep_narrow_M1400_TuneCP5_13TeV-madgraph-pythia8	1.684E-3	2.08E-03
	WprimeToWZToWlepZlep_narrow_M1600_TuneCP5_13TeV-madgraph-pythia8	9.036E-4	1.19E-03
	WprimeToWZToWlepZlep_narrow_M1800_TuneCP5_13TeV-madgraph-pythia8	5.087E-4	6.97E-04
	WprimeToWZToWlepZlep_narrow_M2000_TuneCP5_13TeV-madgraph-pythia8	2.967E-4	4.18E-04
	WprimeToWZToWlepZlep_narrow_M2500_TuneCP5_13TeV-madgraph-pythia8	8.548E-5	1.25E-04
	WprimeToWZToWlepZlep_narrow_M3000_TuneCP5_13TeV-madgraph-pythia8	2.680E-5	4.02E-05
	WprimeToWZToWlepZlep_narrow_M3500_TuneCP5_13TeV-madgraph-pythia8	8.754E-6	1.33E-05
	WprimeToWZToWlepZlep_narrow_M4000_TuneCP5_13TeV-madgraph-pythia8	2.893E-6	4.53E-06
2017	WprimeToWZToWlepZlep_narrow_M4500_TuneCP5_13TeV-madgraph-pythia8	9.543E-7	1.49E-06
	WprimeToWZToWlepZlep_narrow_M600_TuneCP5_13TeV-madgraph-pythia8	6.252E-2	0.
	WprimeToWZToWlepZlep_narrow_M800_TuneCP5_13TeV-madgraph-pythia8	1.886E-2	1.02E-02
	WprimeToWZToWlepZlep_narrow_M1000_TuneCP5_13TeV-madgraph-pythia8	7.381E-3	6.81E-03
	WprimeToWZToWlepZlep_narrow_M1200_TuneCP5_13TeV-madgraph-pythia8	3.356E-3	3.75E-03
	WprimeToWZToWlepZlep_narrow_M1400_TuneCP5_13TeV-madgraph-pythia8	1.684E-3	2.08E-03
	WprimeToWZToWlepZlep_narrow_M1600_TuneCP5_13TeV-madgraph-pythia8	9.036E-4	1.19E-03
	WprimeToWZToWlepZlep_narrow_M1800_TuneCP5_13TeV-madgraph-pythia8	5.087E-4	6.97E-04
	WprimeToWZToWlepZlep_narrow_M2000_TuneCP5_13TeV-madgraph-pythia8	2.967E-4	4.18E-04
	WprimeToWZToWlepZlep_narrow_M2500_TuneCP5_13TeV-madgraph-pythia8	8.548E-5	1.25E-04
	WprimeToWZToWlepZlep_narrow_M3000_TuneCP5_13TeV-madgraph-pythia8	2.680E-5	4.02E-05
	WprimeToWZToWlepZlep_narrow_M3500_TuneCP5_13TeV-madgraph-pythia8	8.754E-6	1.33E-05
2018	WprimeToWZToWlepZlep_narrow_M4000_TuneCP5_13TeV-madgraph-pythia8	2.893E-6	4.53E-06
	WprimeToWZToWlepZlep_narrow_M4500_TuneCP5_13TeV-madgraph-pythia8	9.543E-7	1.49E-06
	WprimeToWZToWlepZlep_narrow_M600_TuneCP5_13TeV-madgraph-pythia8	6.252E-2	0.
	WprimeToWZToWlepZlep_narrow_M800_TuneCP5_13TeV-madgraph-pythia8	1.886E-2	1.02E-02
	WprimeToWZToWlepZlep_narrow_M1000_TuneCP5_13TeV-madgraph-pythia8	7.381E-3	6.81E-03
	WprimeToWZToWlepZlep_narrow_M1200_TuneCP5_13TeV-madgraph-pythia8	3.356E-3	3.75E-03
	WprimeToWZToWlepZlep_narrow_M1400_TuneCP5_13TeV-madgraph-pythia8	1.684E-3	2.08E-03
	WprimeToWZToWlepZlep_narrow_M1600_TuneCP5_13TeV-madgraph-pythia8	9.036E-4	1.19E-03
	WprimeToWZToWlepZlep_narrow_M1800_TuneCP5_13TeV-madgraph-pythia8	5.087E-4	6.97E-04
	WprimeToWZToWlepZlep_narrow_M2000_TuneCP5_13TeV-madgraph-pythia8	2.967E-4	4.18E-04
	WprimeToWZToWlepZlep_narrow_M2500_TuneCP5_13TeV-madgraph-pythia8	8.548E-5	1.25E-04
	WprimeToWZToWlepZlep_narrow_M3000_TuneCP5_13TeV-madgraph-pythia8	2.680E-5	4.02E-05
	WprimeToWZToWlepZlep_narrow_M3500_TuneCP5_13TeV-madgraph-pythia8	8.754E-6	1.33E-05
	WprimeToWZToWlepZlep_narrow_M4000_TuneCP5_13TeV-madgraph-pythia8	2.893E-6	4.53E-06
	WprimeToWZToWlepZlep_narrow_M4500_TuneCP5_13TeV-madgraph-pythia8	9.543E-7	1.49E-06

Table A.2: List of Ultra-Legacy background samples for the Summer20UL16 campaign, their associated cross-section times branching ratio and the plotting group in which each one is included.

Background	Sample	XSec [pb]
$WZ \rightarrow \ell\nu\ell\ell$	WZTo3LNU_mllmin4p0_TuneCP5_13TeV-powheg-pythia8	4.664e+00
$ZZ \rightarrow 4\ell$	ZZTo4L_M-1toInf_TuneCP5_13TeV-powheg-pythia8	1.381e+01
$t\bar{t}$	TTTo2L2Nu_TuneCP5_13TeV-powheg-pythia8	88.29
	TTToSemiLeptonic_TuneCP5_13TeV-powheg-pythia8	365.9744
	TTZToLL_M-1to10_TuneCP5_13TeV-amcatnlo-pythia8	0.283
	TTWJetsToLNU_TuneCP5_13TeV-amcatnloFFX-madspin-pythia8	2.161e-01
	ttZJets_TuneCP5_13TeV-madgraphMLM-pythia8	5.916e-01
$Z\gamma \rightarrow \ell\ell\gamma$	ZGToLLG_01J_5f_TuneCP5_13TeV-amcatnloFFX-pythia8	5.148e+01
Z+Jets	DYJetsToLL_M-50_HT-70to100_TuneCP5_PSweights_13TeV-madgraphMLM-pythia8	1.399e+02
	DYJetsToLL_M-50_HT-100to200_TuneCP5_PSweights_13TeV-madgraphMLM-pythia8	1.401e+02
	DYJetsToLL_M-50_HT-200to400_TuneCP5_PSweights_13TeV-madgraphMLM-pythia8	3.839e+01
	DYJetsToLL_M-50_HT-400to600_TuneCP5_PSweights_13TeV-madgraphMLM-pythia8	5.217e+00
	DYJetsToLL_M-50_HT-600to800_TuneCP5_PSweights_13TeV-madgraphMLM-pythia8	1.267e+00
	DYJetsToLL_M-50_HT-800to1200_TuneCP5_PSweights_13TeV-madgraphMLM-pythia8	5.682e-01
	DYJetsToLL_M-50_HT-1200to2500_TuneCP5_PSweights_13TeV-madgraphMLM-pythia8	1.324e-01
	DYJetsToLL_M-50_HT-2500toInf_TuneCP5_PSweights_13TeV-madgraphMLM-pythia8	2.974e-03
	WWW_4F_TuneCP5_13TeV-amcatnlo-pythia8	2.158e-01
VVV	WWZ_4F_TuneCP5_13TeV-amcatnlo-pythia8	1.707e-01
	WZZ_TuneCP5_13TeV-amcatnlo-pythia8	5.709e-02
	ZZZ_TuneCP5_13TeV-amcatnlo-pythia8	1.476e-02
	GluGluToContInToZZTo4e_TuneCP5_13TeV-mcfm701-pythia8	2.7e-3
$gg \rightarrow 4\ell\ell$	GluGluToContInToZZTo4mu_TuneCP5_13TeV-mcfm701-pythia8	2.7e-3
	GluGluToContInToZZTo2e2mu_TuneCP5_13TeV-mcfm701-pythia8	5.4e-3
	GluGluToContInToZZTo4tau_TuneCP5_13TeV-mcfm701-pythia8	2.7e-3
	GluGluToContInToZZTo4e_TuneCP5_13TeV-mcfm701-pythia8	2.7e-3
Single Top	ST_s-channel_4f_leptonDecays_TuneCP5_13TeV-amcatnlo-pythia8	3.549e+00
	ST_tW_antitop_5f_inclusiveDecays_TuneCP5_13TeV-powheg-pythia8	3.251e+01
	ST_tW_top_5f_inclusiveDecays_TuneCP5_13TeV-powheg-pythia8	3.245e+01
	ST_t-channel_antitop_5f_inclusiveDecays_TuneCP5_13TeV-powheg-pythia8	7.174e+01
	ST_t-channel_top_5f_inclusiveDecays_TuneCP5_13TeV-powheg-pythia8	1.197e+02

Table A.3: List of Ultra-Legacy background samples for the Summer20UL17 campaign, their associated cross section times branching ratio and the plotting group in which each one is included.

Background	Sample	XSec [pb]
$WZ \rightarrow \ell\nu\ell\ell$	WZTo3LNU_mllmin4p0_TuneCP5_13TeV-powheg-pythia8	4.664e+00
$ZZ \rightarrow 4\ell$	ZZTo4L_M-1toInf_TuneCP5_13TeV-powheg-pythia8	1.381e+01
$t\bar{t}$	TTTo2L2Nu_TuneCP5_13TeV-powheg-pythia8	88.29
	TTToSemiLeptonic_TuneCP5_13TeV-powheg-pythia8	365.9744
	TTWJetsToLNU_TuneCP5_13TeV-amcatnloFFFX-madspin-pythia8	2.162e-01
	TTZToLL_M-1to10_TuneCP5_13TeV-amcatnlo-pythia8	0.283
	ttZJets_TuneCP5_13TeV-madgraphMLM-pythia8	5.912e-01
$Z\gamma \rightarrow \ell\ell\gamma$	ZGToLLG_01J_5f_TuneCP5_13TeV-amcatnloFFFX-pythia8	5.557e+01
Z+Jets	DYJetsToLL_M-50_HT-70to100_TuneCP5_PSweights_13TeV-madgraphMLM-pythia8	1.393e+02
	DYJetsToLL_M-50_HT-100to200_TuneCP5_PSweights_13TeV-madgraphMLM-pythia8	
	DYJetsToLL_M-50_HT-200to400_TuneCP5_PSweights_13TeV-madgraphMLM-pythia8	3.836e+01
	DYJetsToLL_M-50_HT-400to600_TuneCP5_PSweights_13TeV-madgraphMLM-pythia8	5.222e+00
	DYJetsToLL_M-50_HT-600to800_TuneCP5_PSweights_13TeV-madgraphMLM-pythia8	1.267e+00
	DYJetsToLL_M-50_HT-800to1200_TuneCP5_PSweights_13TeV-madgraphMLM-pythia8	5.692e-01
	DYJetsToLL_M-50_HT-1200to2500_TuneCP5_PSweights_13TeV-madgraphMLM-pythia8	1.330e-01
	DYJetsToLL_M-50_HT-2500toInf_TuneCP5_PSweights_13TeV-madgraphMLM-pythia8	2.975e-03
VVV	WWW_4F_TuneCP5_13TeV-amcatnlo-pythia8	2.158e-01
	WWZ_4F_TuneCP5_13TeV-amcatnlo-pythia8	1.707e-01
	WZZ_TuneCP5_13TeV-amcatnlo-pythia8	5.709e-02
	ZZ_TuneCP5_13TeV-amcatnlo-pythia8	1.476e-02
$gg \rightarrow 4\ell\ell$	GluGluToContInToZZTo2e2mu_TuneCP5_13TeV-mcfm701-pythia8	5.4e-3
	GluGluToContInToZZTo4e_TuneCP5_13TeV-mcfm701-pythia8	2.7e-3
	GluGluToContInToZZTo4mu_TuneCP5_13TeV-mcfm701-pythia8	2.7e-3
	GluGluToContInToZZTo4tau_TuneCP5_13TeV-mcfm701-pythia8	2.7e-3
Single Top	ST_s-channel_4f_leptonDecays_TuneCP5_13TeV-amcatnlo-pythia8	3.549e+00
	ST_tW_antitop_5f_inclusiveDecays_TuneCP5_13TeV-powheg-pythia8	3.251e+01
	ST_tW_top_5f_inclusiveDecays_TuneCP5_13TeV-powheg-pythia8	3.245e+01
	ST_t-channel_antitop_5f_inclusiveDecays_TuneCP5_13TeV-powheg-pythia8	7.174e+01
	ST_t-channel_top_5f_inclusiveDecays_TuneCP5_13TeV-powheg-pythia8	1.197e+02

Table A.4: List of Ultra-Legacy background samples for the Summer20UL18 campaign, their associated cross section times branching ratio and the plotting group in which each one is included.

Background	Sample	XSec [pb]
$WZ \rightarrow \ell\nu\ell\ell$	WZTo3LNU_mllmin4p0_TuneCP5_13TeV-powheg-pythia8	4.664e+00
$ZZ \rightarrow 4\ell$	ZZTo4L_M-1toInf_TuneCP5_13TeV-powheg-pythia8	1.381e+01
$t\bar{t}$	TTTo2L2Nu_TuneCP5_13TeV-powheg-pythia8	88.29
	TTToSemiLeptonic_TuneCP5_13TeV-powheg-pythia8	365.9744
	TTWJetsToLNU_TuneCP5_13TeV-amcatnloFFFX-madspin-pythia8	2.166e-01
	TTTo2L2Nu_TuneCP5_13TeV-powheg-pythia8	6.871e+02
	ttZJets_TuneCP5_13TeV-madgraphMLM-pythia8	5.901e-01
$Z\gamma \rightarrow \ell\ell\gamma$	ZGToLLG_01J_5f_TuneCP5_13TeV-amcatnloFFFX-pythia8	5.557e+01
Z+Jets	DYJetsToLL_M-50_HT-70to100_TuneCP5_PSweights_13TeV-madgraphMLM-pythia8	1.398e+02
	DYJetsToLL_M-50_HT-100to200_TuneCP5_PSweights_13TeV-madgraphMLM-pythia8	1.405e+02
	DYJetsToLL_M-50_HT-200to400_TuneCP5_PSweights_13TeV-madgraphMLM-pythia8	3.839e+01
	DYJetsToLL_M-50_HT-400to600_TuneCP5_PSweights_13TeV-madgraphMLM-pythia8	5.213e+00
	DYJetsToLL_M-50_HT-600to800_TuneCP5_PSweights_13TeV-madgraphMLM-pythia8	1.265e+00
	DYJetsToLL_M-50_HT-800to1200_TuneCP5_PSweights_13TeV-madgraphMLM-pythia8	5.683e-01
	DYJetsToLL_M-50_HT-1200to2500_TuneCP5_PSweights_13TeV-madgraphMLM-pythia8	1.328e-01
	DYJetsToLL_M-50_HT-2500toInf_TuneCP5_PSweights_13TeV-madgraphMLM-pythia8	2.987e-03
VVV	WWW_4F_TuneCP5_13TeV-amcatnlo-pythia8	2.158e-01
	WWZ_4F_TuneCP5_13TeV-amcatnlo-pythia8	1.707e-01
	WZZ_TuneCP5_13TeV-amcatnlo-pythia8	5.709e-02
	ZZZ_TuneCP5_13TeV-amcatnlo-pythia8	1.476e-02
$gg \rightarrow 4\ell\ell$	GluGluToContInToZZTo2e2mu_TuneCP5_13TeV-mcfm701-pythia8	5.4e-3
	GluGluToContInToZZTo4e_TuneCP5_13TeV-mcfm701-pythia8	2.7e-3
	GluGluToContInToZZTo4mu_TuneCP5_13TeV-mcfm701-pythia8	2.7e-3
	GluGluToContInToZZTo4tau_TuneCP5_13TeV-mcfm701-pythia8	2.7e-3
Single Top	ST_s-channel_4f_leptonDecays_TuneCP5_13TeV-amcatnlo-pythia8	3.549e+00
	ST_tW_antitop_5f_inclusiveDecays_TuneCP5_13TeV-powheg-pythia8	3.251e+01
	ST_tW_top_5f_inclusiveDecays_TuneCP5_13TeV-powheg-pythia8	3.245e+01
	ST_t-channel_antitop_5f_inclusiveDecays_TuneCP5_13TeV-powheg-pythia8	7.174e+01
	ST_t-channel_top_5f_inclusiveDecays_TuneCP5_13TeV-powheg-pythia8	1.197e+02

Muon Momentum Resolution Studies

By travelling in Iron, High-Pt muons ($P_t > 200\text{GeV}$) suffer from high energy loss due to radiative processes. The transverse momentum measurement relies on sagitta ($s \propto 1/Pt$) which is associated with the number of hits found on the Tracker and the Muon subsystems. As the number of hits is lower on the so-called tracker muons, i.e. muons that were reconstructed from hits in the tracker and the first station of the muon system, a study is needed to determine the resolution of the transverse momentum measurement for `trackerHighPt` ID muons.

From MC simulations it is possible to access the true momenta of the muons and a comparison with the reconstructed momentum can be given in terms of the residual momentum:

$$\frac{P_{GEN}}{P_{RECO}} - 1 = \frac{\frac{1}{P_{RECO}} - \frac{1}{P_{GEN}}}{\frac{1}{P_{RECO}}} \quad (\text{B.1})$$

The resolution can be extracted by fitting the event profile with a Double-Sided Crystal Ball (DSCB) distribution which consists of three different regions: a Gaussian center described by a mean μ and standard deviation σ with two exponential tails modelling the effects of radiative processes in the detector. The two tails are controlled by four parameters, n_L and α_L for the left tail and n_R and α_R for the right tail. α describes how far away (as a factor of *sigma*) from the Gaussian

mean the exponential decay intersects the Gaussian core, while n controls the growth (decay) of the left (right) exponential tail.

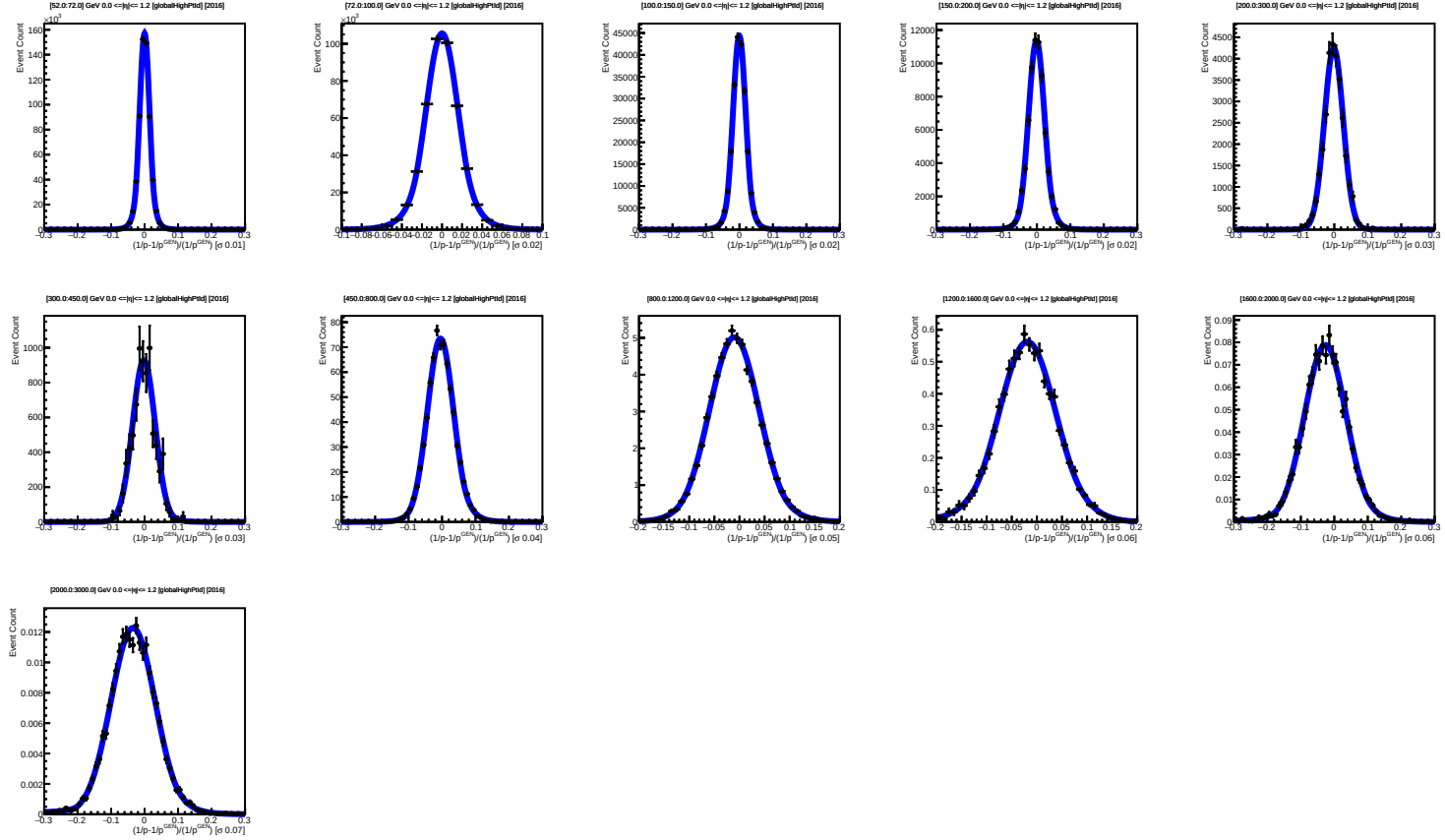


Figure A.1: Residual momentum for different transverse momentum bins for globalHighPt muons in the muon barrel ($0.0 < \eta < 1.2$). The double-sided crystal ball fit is shown with a blue solid line, the number of events as counted from MC samples are shown in black markers. The width (σ) of the Gaussian portion of the distribution is shown on the bottom label, it shows evidence of how the resolution increases as the momentum range gets higher. The comparison is shown for 2016 data and MC samples.

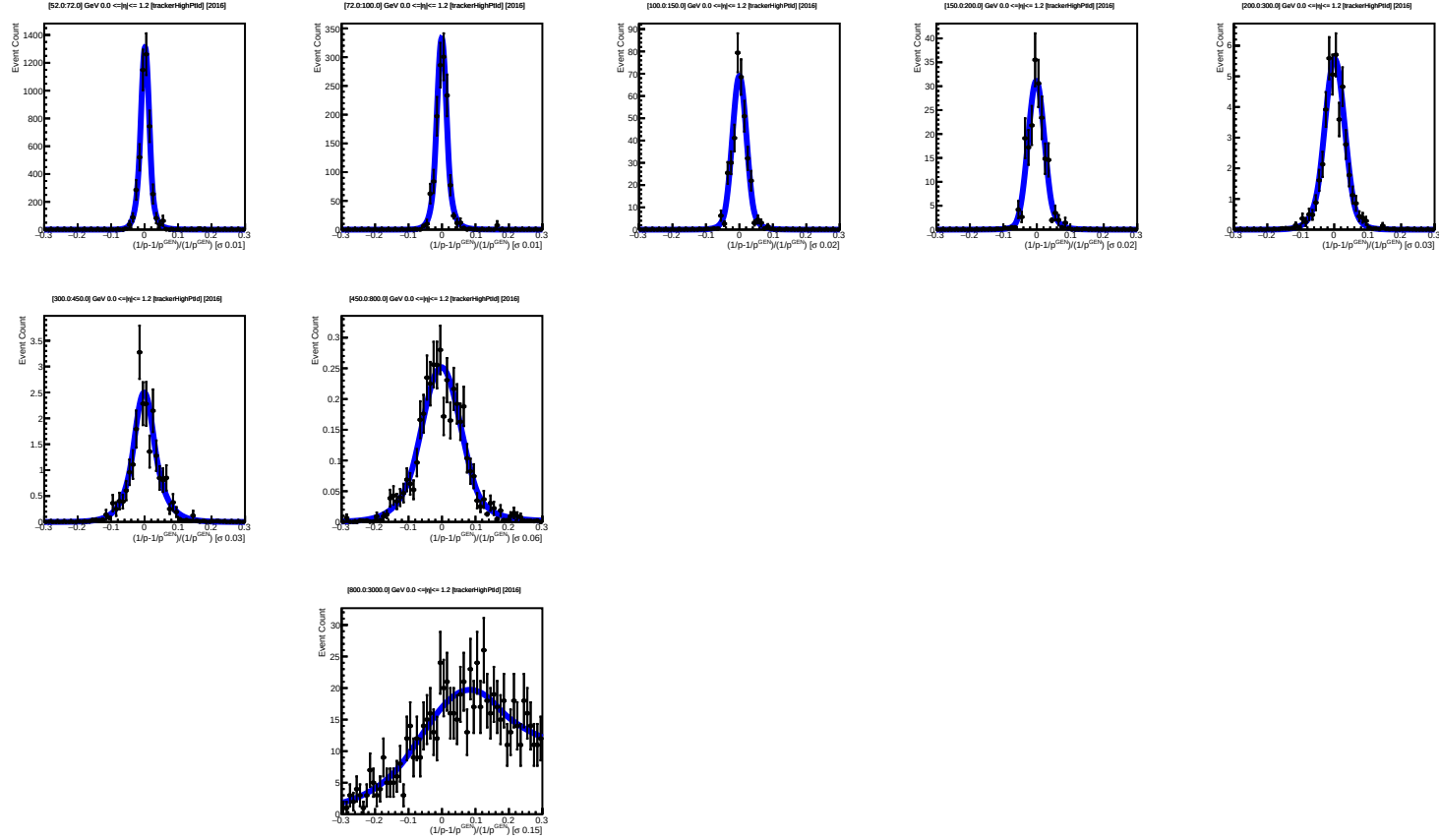


Figure A.2: Residual momentum for different transverse momentum bins for trackerHighPt muons in the muon barrel ($0.0 < \eta < 1.2$). The double-sided crystal ball fit is shown with a blue solid line, the width (σ) of the Gaussian portion of the distribution is shown on the bottom label. The comparison is shown for 2016 data and MC

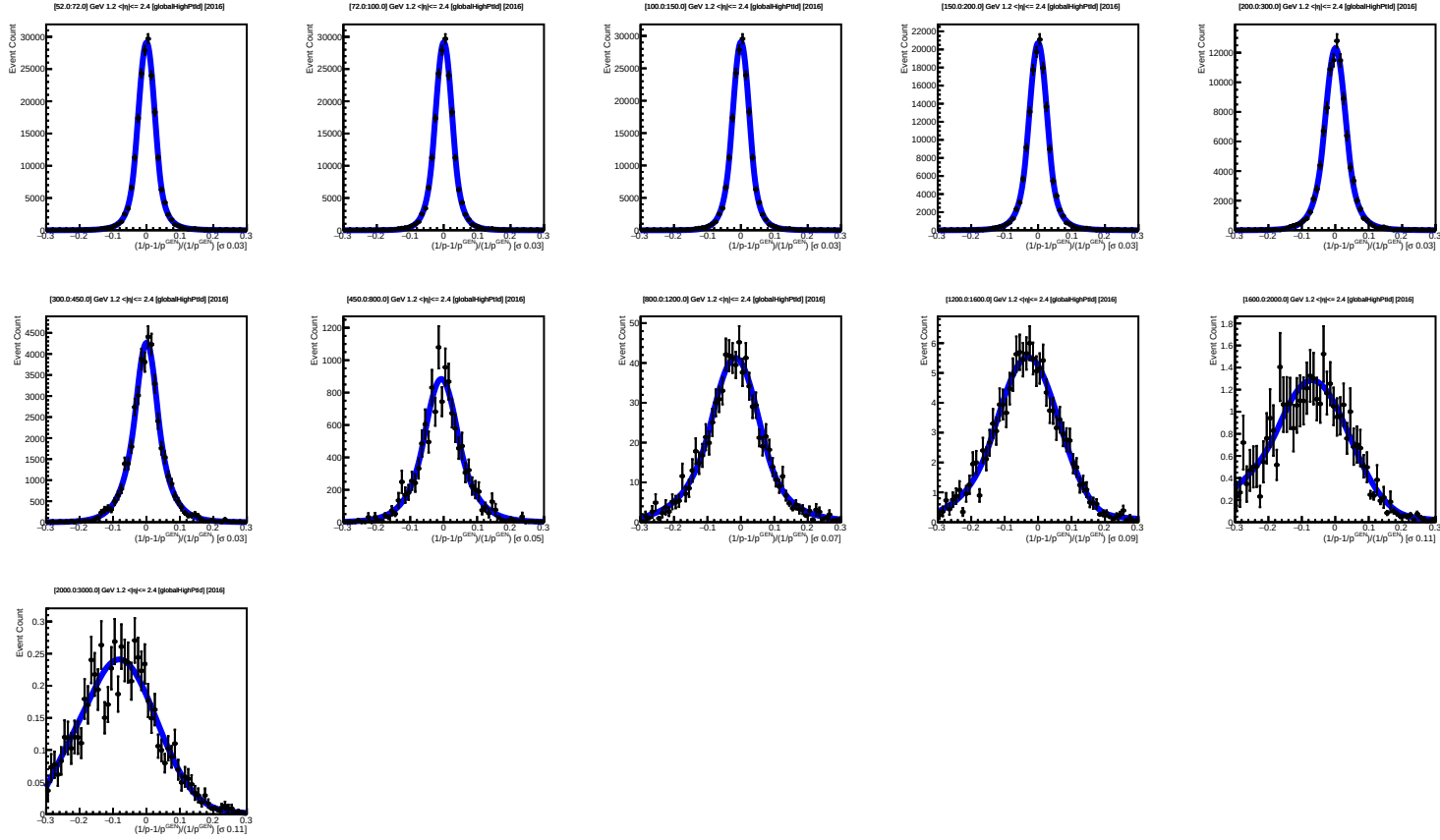


Figure A.3: Residual momentum for different transverse momentum bins for globalHighPt muons in the muon endcap ($1.2 < \eta < 2.4$). The double-sided crystal ball fit is shown with a blue solid line, the number of events as counted from MC samples are shown in black markers. The width (σ) of the Gaussian portion of the distribution is shown on the bottom label. The comparison is shown for 2016 data and MC.

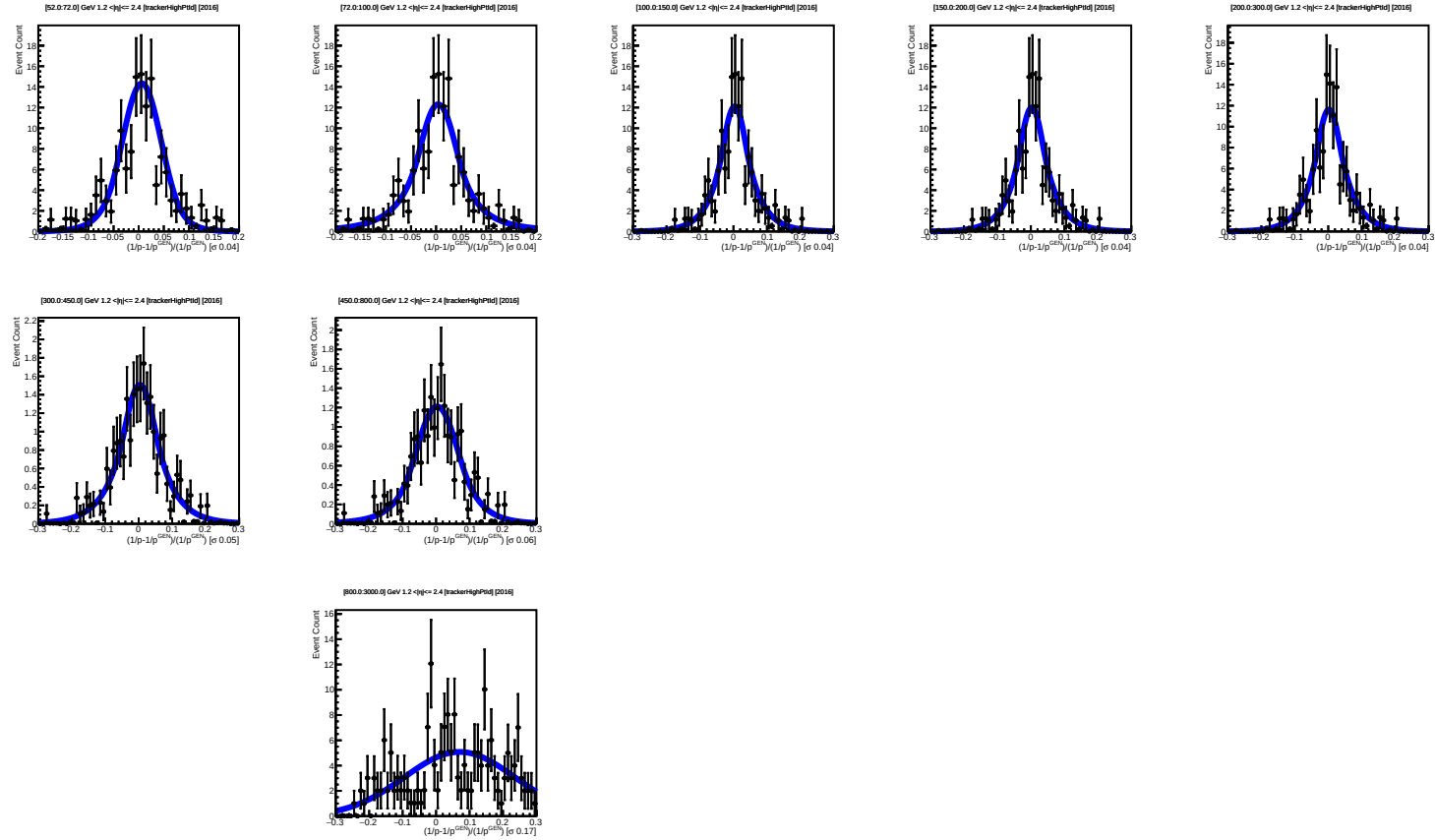


Figure A.4: Residual momentum for different transverse momentum bins for trackerHighPt muons in the muon endcap ($1.2 < \eta < 2.4$). The double-sided crystal ball fit is shown with a blue solid line, the width (σ) of the Gaussian portion of the distribution is shown on the bottom label. The comparison is shown for 2016 data and MC.

These studies were performed by simulating the standard model Z boson production decaying to a pair of Muons ($Z \rightarrow \mu\mu$). The complete list of samples is provided on [Table A.5](#). Z-Mass binned samples were used in order to increase the number of available statistics in a wide range of transverse momentum, specially on the High-Pt sector.

A counting experiment following the trigger and muon selection described on [subsection 6.3.1](#) and [subsection 6.4.2](#) collects the momentum resolution for each individual muon which is then classified in different bins depending on their ID, either global or tracker High-Pt; the η region in the Muon detector, i.e. the barrel ($|\eta| < 1.2$) or the endcap ($1.2 < |\eta| < 2.4$); and its transverse momentum range (see [Figure A.6](#)).

A fit is performed on the distribution by using a Double-Sided Crystal Ball (DSCB) (`RooCrystalBall` in `RooFit`). The width of the Gaussian portion of the DSCB provides the resolution (as a percentage) while the mean accounts for any bias present on the momentum measurements. Distributions with their fits are shown for `globalHighPt` within the muon barrel on [Figure A.1](#), the muon endcap on [Figure A.3](#); and `trackerHighPt` muons on the barrel ([Figure A.2](#)) and the endcap ([Figure A.4](#)). The results from the fits are shown in [Figure A.5](#).

As shown by [Figure A.1](#) and [Figure A.2](#) the amount of statistics available for `globalHighPt` muons is greater than for `trackerHighPt` muons.

Z-Mass Resolution

The dimuon mass can be used to validate simulation in data, where the true momentum of the muon is unknown. For this, a Data/MC comparison is done over the distributions for the reconstructed dimuon mass. The distributions are built from the reconstructed mass as a function of the muon transverse momentum and obtained for each individual muon. The mass resolution distribution is then fitted with a Breit-Wigner convolution of the Double-Sided crystal ball, from this fit the standard deviation of the Gaussian portion of the DSCB equates the dimuon mass resolution. The fits for Montecarlo simulation are shown in [Figure A.7](#) and fits in physics data

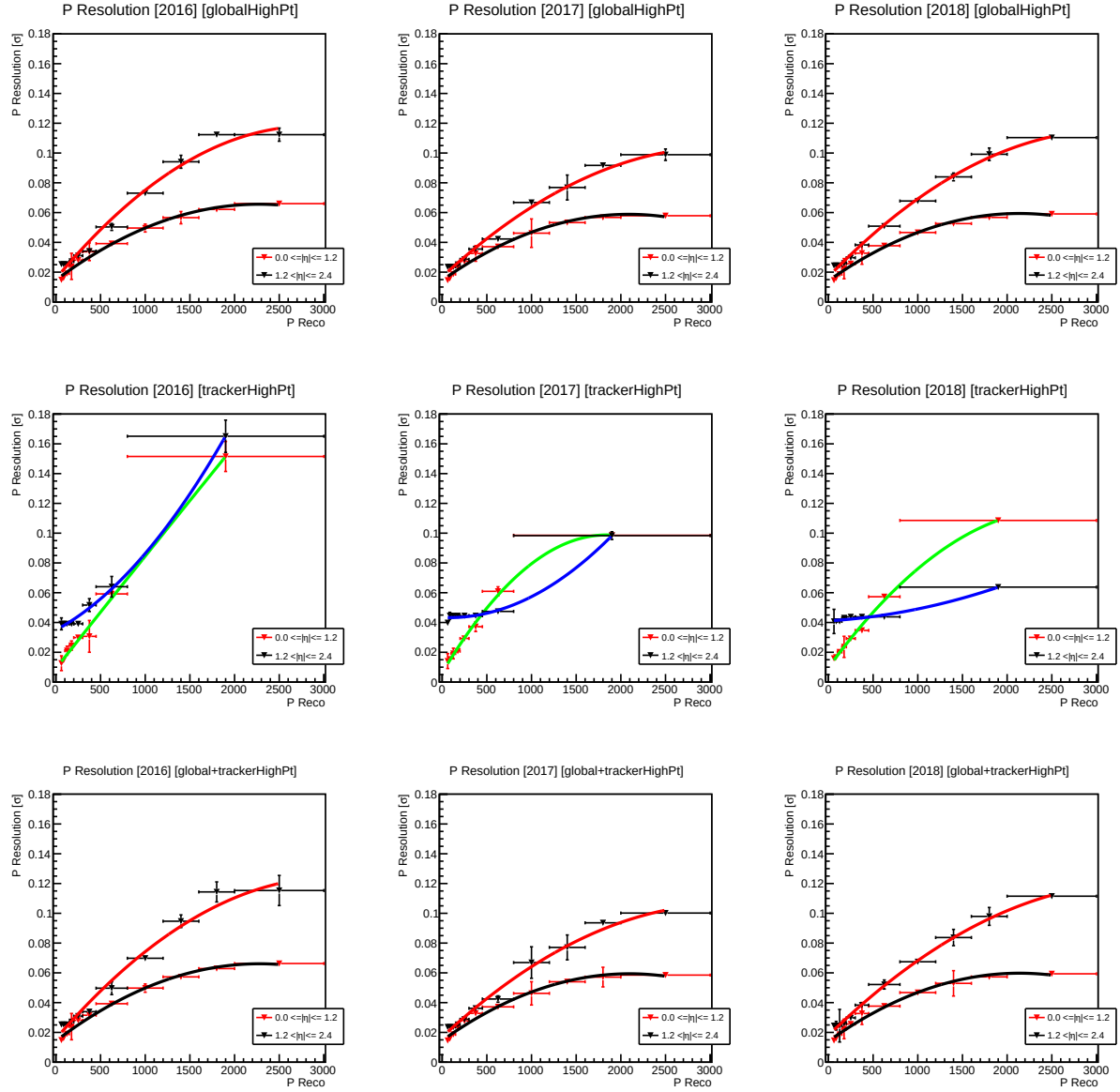


Figure A.5: Momentum resolution for Run II. A second degree polynomial shown in colored solid lines is used to fit the momentum resolution as a function of the reconstructed momentum.

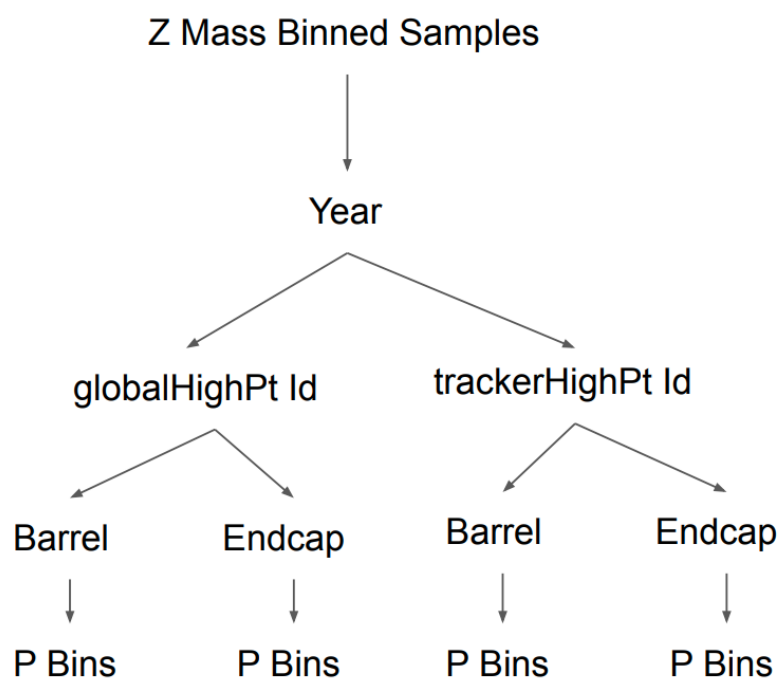


Figure A.6: Categorical distribution of the histogram binning used for the momentum resolution studies.

in [Figure A.8](#). The relevant measurement extracted from the fit and the Data/MC comparison is shown in [Figure A.9](#).

As seen in [Figure A.9](#), there is a consistent agreement between data and MC for the 2016 period. However, the 2017 and 2018 periods show a significant difference between data and MC (see [Figure A.12](#) and [Figure A.15](#)).

Table A.5: Montecarlo Samples used to study the Muon Momentum Resolution

Year	Sample	XSec [pb]
2016	ZToMuMu_NNPDF30_13TeV-powheg_M_50_120	2.116e+03
	ZToMuMu_NNPDF30_13TeV-powheg_M_120_200	2.058e+01
	ZToMuMu_NNPDF30_13TeV-powheg_M_200_400	2.890e+00
	ZToMuMu_NNPDF30_13TeV-powheg_M_400_800	2.515e-01
	ZToMuMu_NNPDF30_13TeV-powheg_M_800_1400	1.709e-02
	ZToMuMu_NNPDF30_13TeV-powheg_M_1400_2300	1.370e-03
	ZToMuMu_NNPDF30_13TeV-powheg_M_2300_3500	8.282e-05
	ZToMuMu_NNPDF30_13TeV-powheg_M_3500_4500	3.414e-06
	ZToMuMu_NNPDF30_13TeV-powheg_M_4500_6000	3.650e-07
	ZToMuMu_NNPDF30_13TeV-powheg_M_6000_Inf	2.526e-08
2017	ZToMuMu_NNPDF31_TuneCP5_13TeV-powheg-pythia8_M_50_120	2.116e+03
	ZToMuMu_NNPDF31_TuneCP5_13TeV-powheg-pythia8_M_120_200	2.058e+01
	ZToMuMu_NNPDF31_TuneCP5_13TeV-powheg-pythia8_M_200_400	2.890e+00
	ZToMuMu_NNPDF31_TuneCP5_13TeV-powheg-pythia8_M_400_800	2.515e-01
	ZToMuMu_NNPDF31_TuneCP5_13TeV-powheg-pythia8_M_800_1400	1.709e-02
	ZToMuMu_NNPDF31_TuneCP5_13TeV-powheg-pythia8_M_1400_2300	1.370e-03
	ZToMuMu_NNPDF31_TuneCP5_13TeV-powheg-pythia8_M_2300_3500	8.282e-05
	ZToMuMu_NNPDF31_TuneCP5_13TeV-powheg-pythia8_M_3500_4500	3.414e-06
	ZToMuMu_NNPDF31_TuneCP5_13TeV-powheg-pythia8_M_4500_6000	3.650e-07
	ZToMuMu_NNPDF31_TuneCP5_13TeV-powheg-pythia8_M_6000_Inf	2.526e-08
2018	ZToMuMu_NNPDF31_TuneCP5_13TeV-powheg-pythia8_M_50_120	2.116e+03
	ZToMuMu_NNPDF31_TuneCP5_13TeV-powheg-pythia8_M_120_200	2.058e+01
	ZToMuMu_NNPDF31_TuneCP5_13TeV-powheg-pythia8_M_200_400	2.890e+00
	ZToMuMu_NNPDF31_TuneCP5_13TeV-powheg-pythia8_M_400_800	2.515e-01
	ZToMuMu_NNPDF31_TuneCP5_13TeV-powheg-pythia8_M_800_1400	1.709e-02
	ZToMuMu_NNPDF31_TuneCP5_13TeV-powheg-pythia8_M_1400_2300	1.370e-03
	ZToMuMu_NNPDF31_TuneCP5_13TeV-powheg-pythia8_M_2300_3500	8.282e-05
	ZToMuMu_NNPDF31_TuneCP5_13TeV-powheg-pythia8_M_3500_4500	3.414e-06
	ZToMuMu_NNPDF31_TuneCP5_13TeV-powheg-pythia8_M_4500_6000	3.650e-07
	ZToMuMu_NNPDF31_TuneCP5_13TeV-powheg-pythia8_M_6000_Inf	2.526e-08

Table A.6: Montecarlo Samples for Z Mass Resolution studies

Year	Sample	XSec [pb]
2016	DYJetsToMuMu_M-50_Zpt-150toInf_TuneCP5_13TeV-madgraphMLM_pdfwgt_F-pythia8	6.178e+00
2017	DYJetsToMuMu_M-50_Zpt-150toInf_TuneCP5_13TeV-madgraphMLM_pdfwgt_F-pythia8	6.182e+00
2018	DYJetsToMuMu_M-50_Zpt-150toInf_TuneCP5_13TeV-madgraphMLM_pdfwgt_F-pythia8	6.178e+00

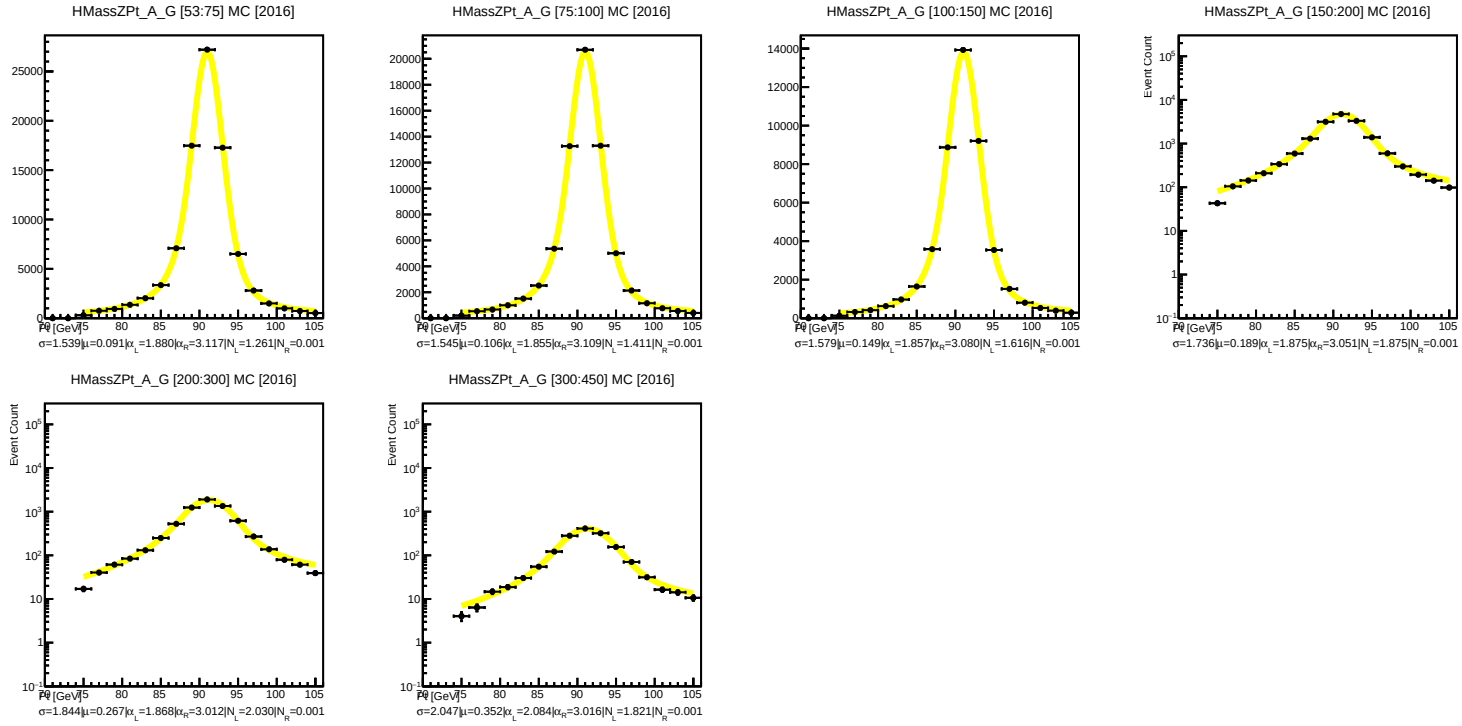


Figure A.7: Dimuon mass resolution (2016) for different transverse momentum bins from 2016 MC simulation for globalHighPt muons. The Breit-Wigner convoluted with the double-sided crystal ball fit is shown in solid yellow line and parameters of the fit are shown on the bottom of each plot.

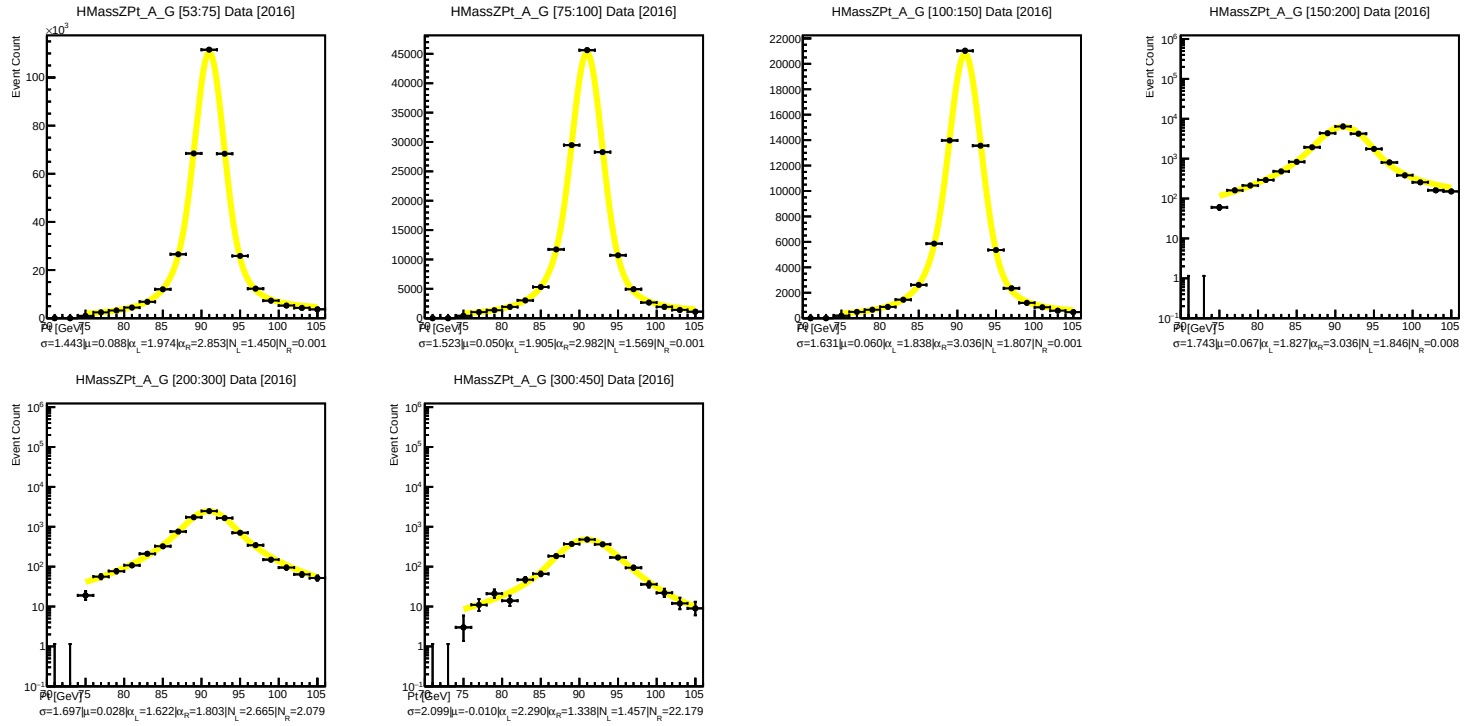


Figure A.8: Dimuon mass resolution for different transverse momentum bins from 2016 Data for globalHighPt muons. The Breit-Wigner convoluted with the double-sided crystal ball fit is shown in solid yellow line and parameters of the fit are shown on the bottom of each plot.

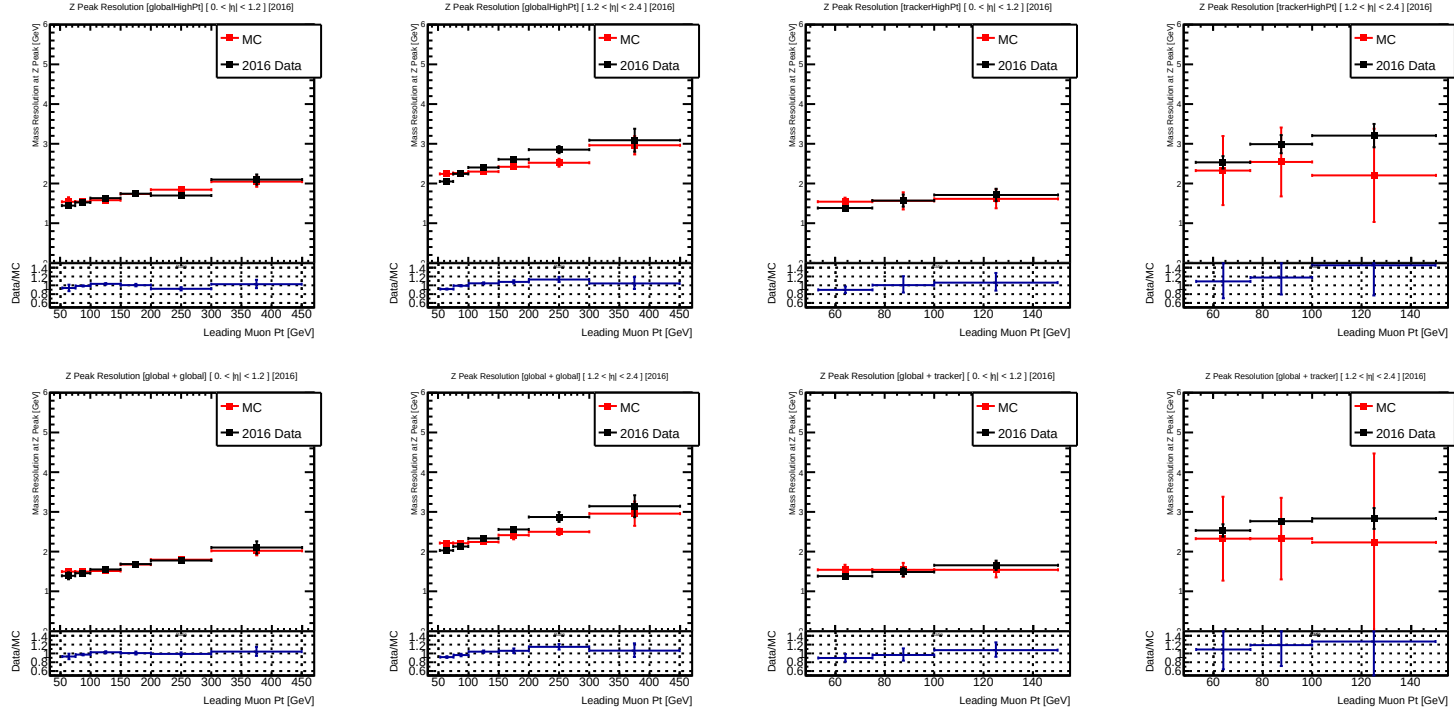


Figure A.9: Mass resolution (2016) at Z peak as a function of the leading muon's transverse momentum for the global and trackerHighPt found in the barrel and endcaps on the muon systems

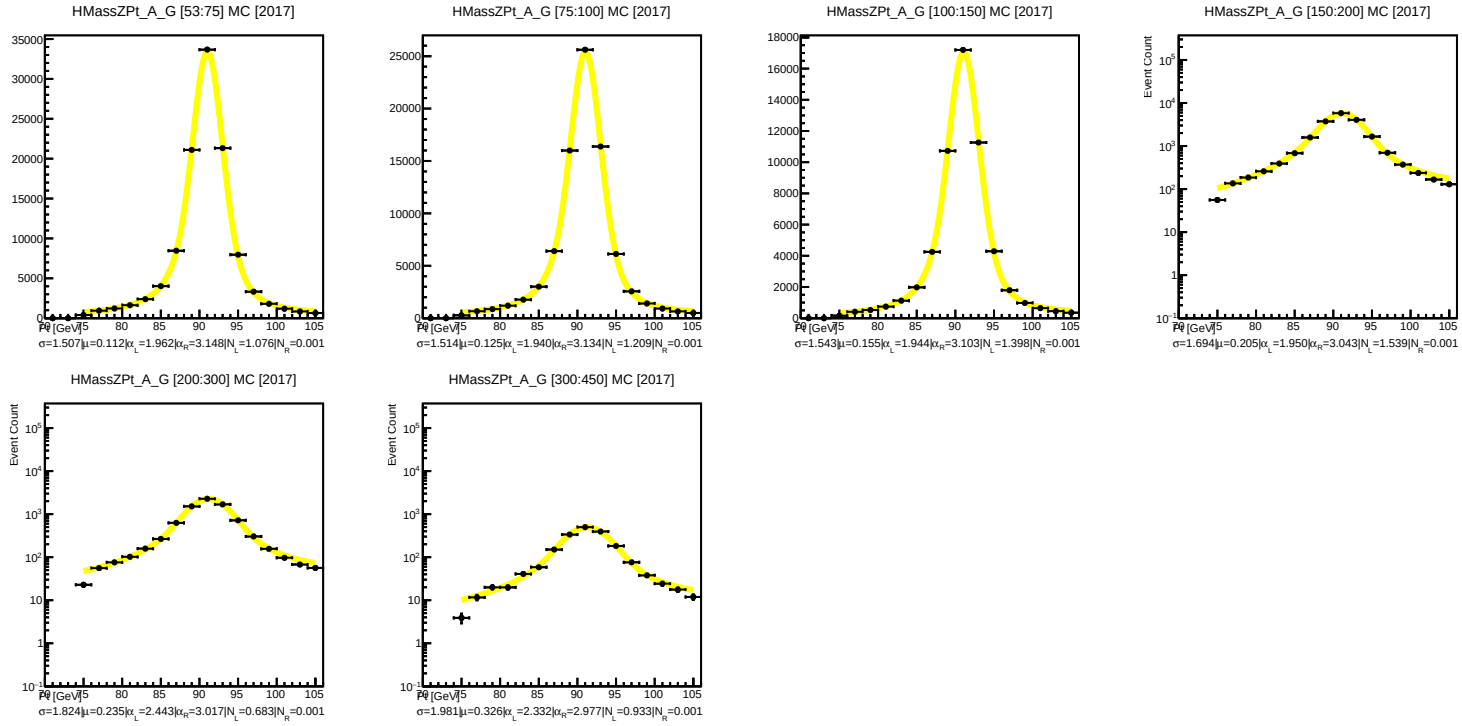


Figure A.10: Dimuon mass resolution for different transverse momentum bins from 2017 MC simulation for globalHighPt muons. The Breit-Wigner convoluted with the double-sided crystal ball fit is shown in solid yellow line and parameters of the fit are shown on the bottom of each plot.

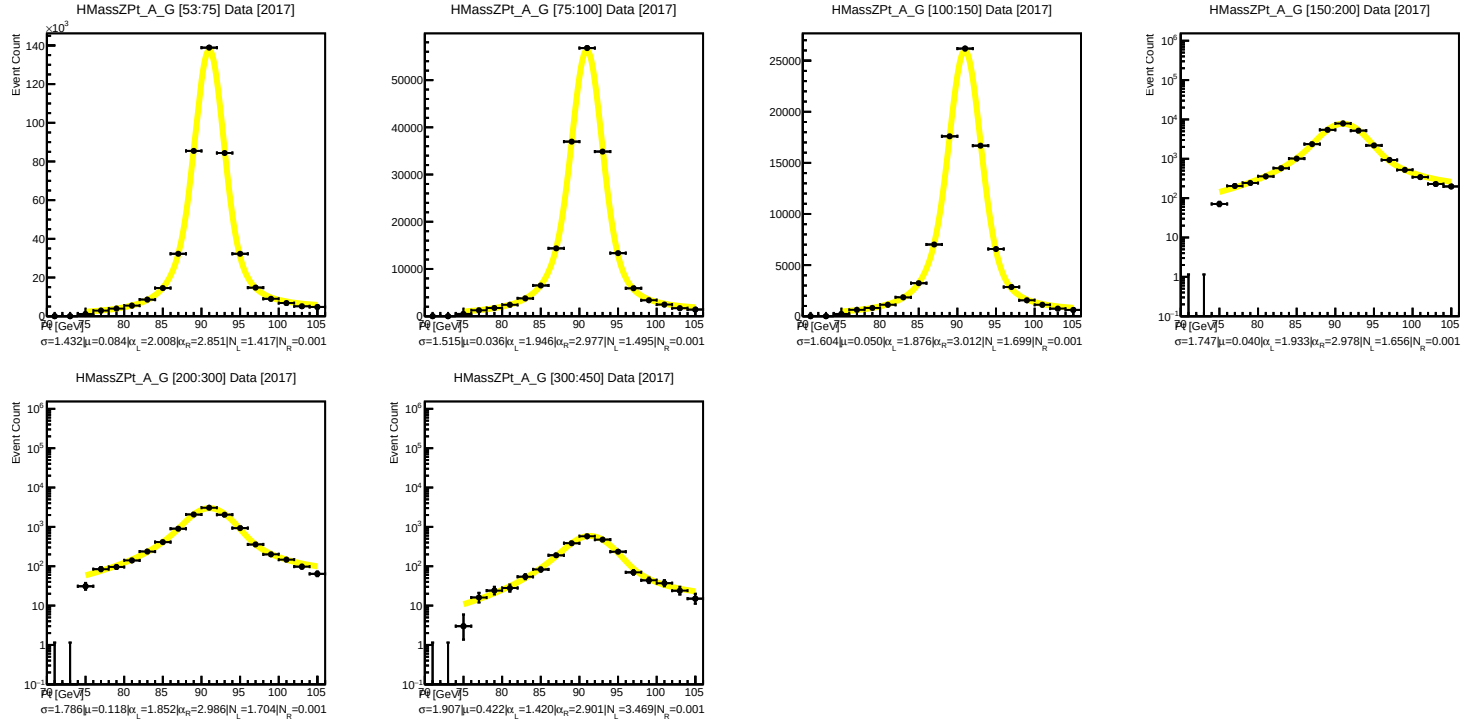


Figure A.11: Dimuon mass resolution for different transverse momentum bins from 2017 Data for globalHighPt muons. The Breit-Wigner convoluted with the double-sided crystal ball fit is shown in solid yellow line and parameters of the fit are shown on the bottom of each plot.

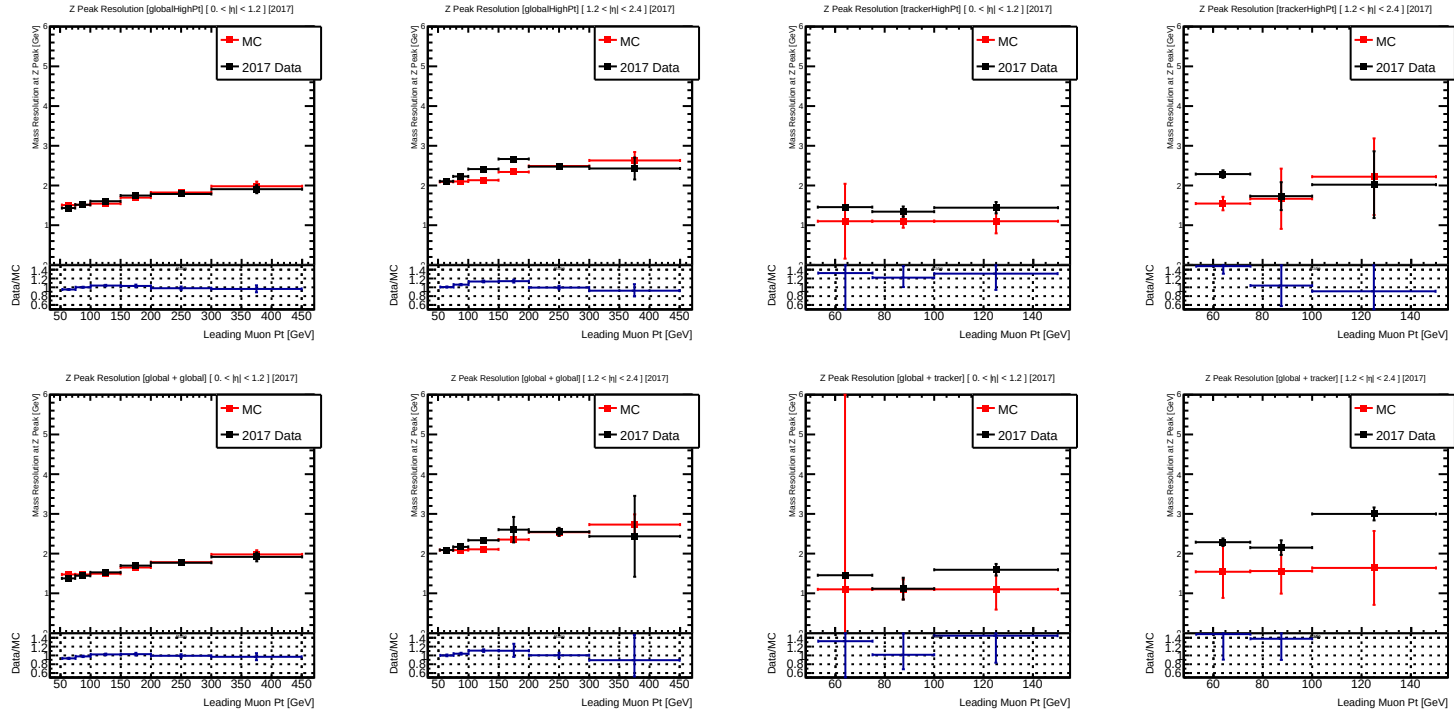


Figure A.12: Mass resolution at Z peak (2017) as a function of the leading muon's transverse momentum for the global and trackerHighPt found in the barrel and endcaps on the muon systems

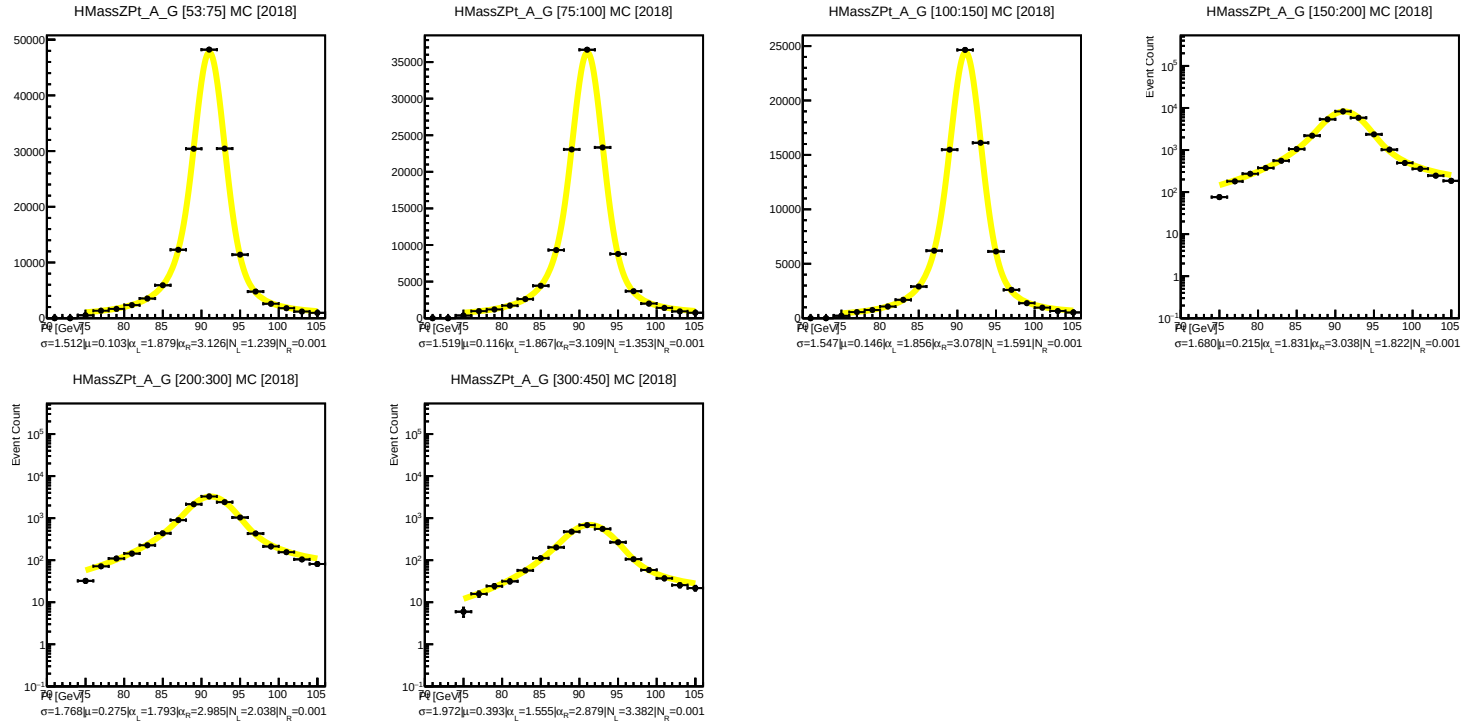


Figure A.13: Dimuon mass resolution for different transverse momentum bins from 2018 MC simulation for globalHighPt muons. The Breit-Wigner convoluted with the double-sided crystal ball fit is shown in solid yellow line and parameters of the fit are shown on the bottom of each plot.

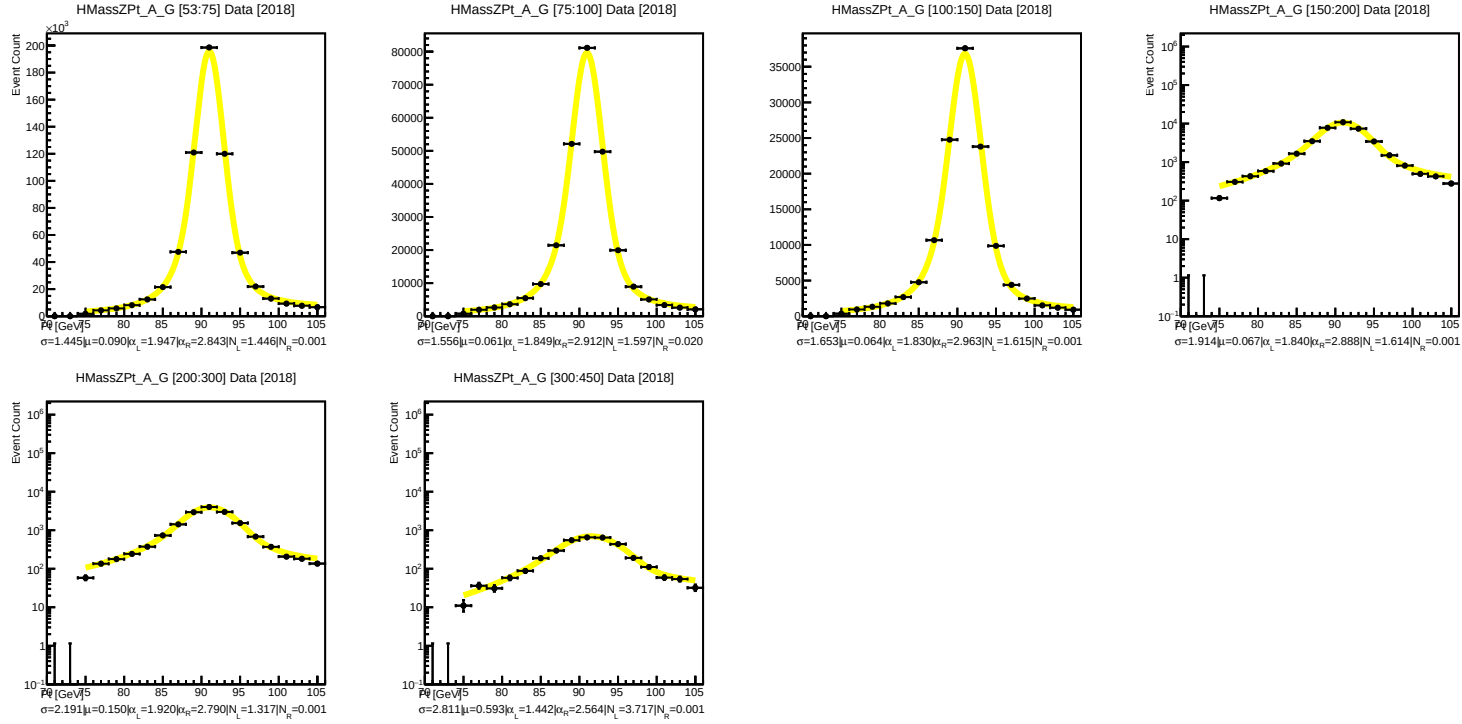


Figure A.14: Dimuon mass resolution for different transverse momentum bins from 2018 Data for globalHighPt muons. The Breit-Wigner convoluted with the double-sided crystal ball fit is shown in solid yellow line and parameters of the fit are shown on the bottom of each plot.

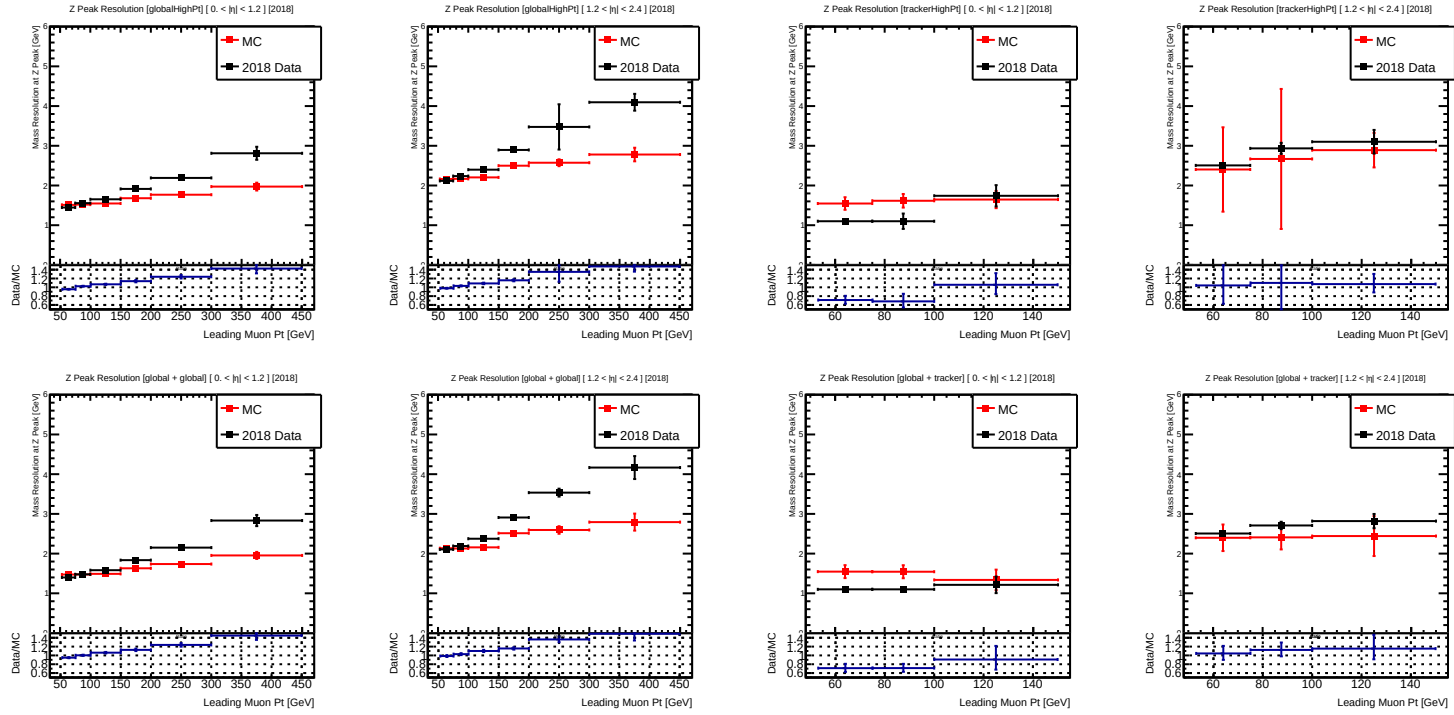


Figure A.15: Mass resolution at Z peak (2018) as a function of the leading muon's transverse momentum for the global and trackerHighPt found in the barrel and endcaps on the muon systems