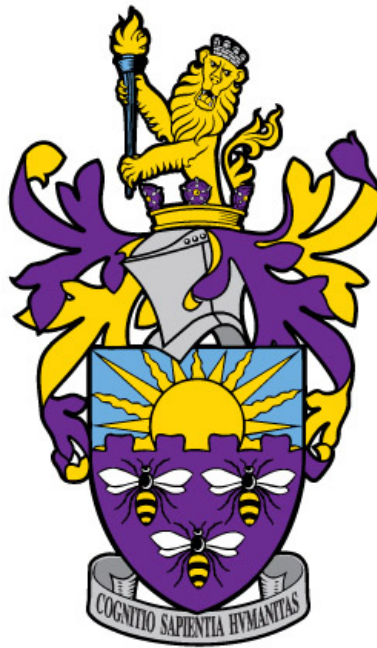


Tau lepton universality test in the vector boson fusion topology using the ATLAS detector at the LHC

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*A thesis submitted to the University of Manchester
for the degree of Doctor of Philosophy
in the Faculty of Science and Engineering*

School of Natural Sciences
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Abstract

Tau lepton universality test in the vector boson fusion topology using the ATLAS detector at the LHC

by Diego A. Baron Moreno

This thesis presents a lepton universality test using the data collected by the ATLAS experiment in proton-proton collisions at a centre-of-mass energy of $\sqrt{s} = 13$ TeV and an integrated luminosity of 139 fb^{-1} . We probe the production of di-leptons across all lepton families in the vector boson fusion (VBF) topology. First, at di-lepton invariant masses around the Z pole, we derive a correction for the simulation of the production of lepton pairs coming from Z decays in association with jets initiated by QCD radiation (QCDjj) — this is the main background for the VBF production mode, where the two jets are coming from pure electroweak interactions (EWjj). We derive the corrections in the $Z \rightarrow ll$ ($l = e, \mu$) final states and use them as input to correct the $Z \rightarrow \tau\tau$ final states. At the Z pole, we compute ratios between the EWjj signal strengths for the $e\text{-}\mu$ and $l\text{-}\tau$ final states ($l = e + \mu$); our results are $R_{e\mu} = 1.050 \pm 7.4\%(\text{Stat.}) \pm 2.9\%(\text{Syst.})$ and $R_{l\tau} = 1.092 \pm 18.5\%(\text{Stat.}) \pm 6.8\%(\text{Syst.})$, respectively. These results are consistent with the lepton universality hypothesis. The measurement uncertainties are dominated by the number of events collected by the ATLAS detector. Additionally, we present partially unblinded data-to-MC comparisons for events that have a high-invariant mass. The motivation is to look for hypothetical heavy resonances that only couple to the third generation of fermions and the W boson; if this is the case, they would be produced in the VBF mode. In the high-mass region, we discuss an unblinded Higgs control region — containing events with $116 \leq m(\tau_{\text{had}}, \tau_{\text{lep}}) < 160$ GeV; and a partially unblinded region including events with a higher di-lepton invariant mass than the Higgs region.

Furthermore, this work includes a measurement of the performance of the tau identification (tauID) algorithm for high- p_T taus using an alternative approach to the usual ATLAS tag-and-probe method in $t\bar{t}$ events. From the physics perspective our approach offers the advantage of being safer from lepton universality violation effects because our tau sample is populated from boosted Z boson decays. We measure data-to-MC ratios after applying the tauID criterion and then compute ratios between the $Z \rightarrow \tau\tau$ and $Z \rightarrow ll$ final states. This results in the partial cancellation of experimental systematics coming from the calibration of physics objects common to the light-lepton and tau final states; additionally, modelling and luminosity uncertainties are also reduced in the double ratio approach. The results have an uncertainty of $\approx 4\%$ for 1-prong and $\approx 5\%$ for 3-prong taus.

Declaration of Authorship

I, Diego A. Baron Moreno, declare that this thesis titled, “Tau lepton universality test in the vector boson fusion topology using the ATLAS detector at the LHC” and the work presented in it are my own. I confirm that no portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

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*To all the people who love me, thanks for helping me make my dreams
come true...*

Declaration of Contributions

I, Diego A. Baron Moreno, declare that the list of contributors and their corresponding contributions in this thesis titled, “Tau lepton universality test in the vector boson fusion topology using the ATLAS detector at the LHC” are the following:

- *Diego Baron Moreno*, main analyser.
- *Prof. Terry Wyatt FRS*, supervisor of Diego Baron Moreno and main analyser.
- *The ATLAS collaboration*, the two main analysers are active members of the ATLAS experiment. The ATLAS collaboration members built the ATLAS detector, run the experiment to collect the datasets that are used in this work, provide simulations of the proton-proton collisions and analyse the data.

Chapter 1

Introduction

The Standard Model (SM) is the most complete theory of the fundamental constituents of matter and their interactions. It has been thoroughly tested in particle physics experiments like the Large Hadron Collider. In 2012 a milestone in the history of particle physics was achieved. That year the ATLAS [1] and the CMS [2] collaborations simultaneously announced the discovery of the Higgs boson, which was the only particle left to be observed from the particle content of the SM. However, many different experimental observations and theoretical questions cannot be explained by the SM — dark matter, neutrino masses and a quantum theory of gravity are some examples. This is one of the reasons that has led the high-energy physics community to perform *high-precision measurements*. In these studies, the structure and predictions of the SM are tested to the per cent or even the per mille level. A high-precision measurement is designed to be sensitive to possible deviations from the SM, which could lead to the discovery of new physics.

The lepton flavour universality (LFU) hypothesis is an accidental symmetry included in the SM. It states that the couplings between the leptons and the gauge bosons are independent of the lepton flavour. It is accidental in the sense that the SM was not designed with LFU in mind. Different measurements of LFU, consistent with the SM predictions, have been performed in experiments like LEP, Tevatron and the LHC. However, studies made at BaBar, Belle and LHCb hint at a possible violation of this hypothesis — a review of these measurements can be found in [3]. In these experiments the decays of B hadrons into D hadrons plus leptons are measured. Comparisons between the different lepton generations are performed and the results are compared with the SM predictions. The tau lepton plays an important role in these measurements because this particle is used to probe if lepton universality holds for the third generation of leptons.

The work presented in this thesis is divided into two main research topics. First, a novel calibration method of the efficiency of the tau identification algorithm used in the ATLAS collaboration is discussed — the calibration is specifically targeted at high transverse momentum taus. A lepton universality test is presented in the second part of this work. This study compares the production of di-leptons in the Vector Boson Fusion (VBF) mode across the three lepton generations. The study shows the observation of the Z production in the VBF mode and its subsequent decay into tau pairs. Additionally, we test LU at the Z -peak by computing ratios between the different lepton generations. Finally, we explore the high di-lepton mass range in the VBF process. This is an interesting phase space to look for new resonances that might only couple to the third generation of SM fermions.

This thesis is organised as follows: Chapter 2 presents the SM, describes some of the most important and recent LFU tests and presents an overview of the searches for high-mass resonances that decay to tau pairs. The LHC and the ATLAS detector are described in Chapter 3; additionally, the ATLAS physics objects are reviewed as well. A more detailed description of the tau lepton, in the ATLAS experiment context, is given in Chapter 4. Chapter 5 presents the calibration measurement of the tau identification algorithm. The VBF LFU analysis is detailed in Chapter 6 and 7. The measurements for di-leptons with an invariant mass close to the Z-peak are detailed in Chapter 6 and the high-mass studies are presented in Chapter 7. Finally, the conclusions of this work are given in Chapter 8.

Chapter 2

Theoretical framework

Since the early beginnings of our civilization, humans have been trying to understand the composition of matter and how its fundamental pieces interact with each other. Even before science evolved into the highly technical subject of these days, people have been thinking about this problem. For instance, Democritus (460 BC - 370 BC) proposed the concept of *atom* as an eternal, indivisible, incompressible and homogeneous unit of matter. This is one of the first attempts we have a record of at elaborating a fundamental theory of matter.

Today, our theories of the fundamental nature of matter are more elaborated than Democritus' ideas — first principles and reductionist ideas are the building blocks of modern theories. The current scientific consensus is that the Standard Model (SM) is the best framework to explain the most fundamental aspects of nature. The SM defines a set of fundamental particles and the rules they follow when interacting with each other. It has been extensively tested and many of its predictions have been verified.

The SM is based on two theoretical frameworks: Quantum Field Theory (QFT) [4] and Group Theory (GT) [5]. QFT describes the evolution and dynamics of a quantum system of particles whose velocities can be relativistic and the particle interactions are described in the language of GT. Particles interact via the exchange of other particles, and in those processes physical quantities are conserved. Which quantities are unchanged depends on the system symmetries. For instance, if two particles exchange linear momentum, we observe that this quantity for the whole system is conserved. The reason for linear momentum being a constant of motion lies behind the fact that the structure of space-time is unchanged under spatial translations.

The connection between symmetries and conserved quantities was first described in the work of Emmy Noether [6]. She demonstrated that for every conserved physical quantity, an associated continuous symmetry must exist. The SM was built based on this notion. This chapter contains a review of the ideas behind the SM construction.

2.1 Classic field theory

Isaac Newton published his theory of gravitation in July of 1687. Newton's law states that two bodies separated by a distance r , with masses m_1 and m_2 , experience a gravitational attraction,

$$\vec{F}_g = -\frac{Gm_1m_2}{r^2}\hat{r}, \quad (2.1)$$

where $\hat{r}$ is a unit vector pointing along the straight line connecting the bodies and G is a proportionality constant known as the Cavendish gravitational constant. One can also interpret this law as if each body defined a *gravitational field* around it. The force produced from the interaction of a test body with the gravitational field (produced by a source) should be proportional to the mass of the test body and the strength of the gravitational field of the source. However, Newton had reservations about his theory. Equation 2.1 implies that any change in the mass or position of the gravitational field source would be reflected immediately on its surroundings. This was later called the *action at a distance* problem and led to the development of field theories.

The idea of fields as physical entities was further developed by Gauss, Ampere, Faraday and Maxwell in their studies of electric and magnetic interactions. Maxwell discovered that electric and magnetic forces were manifestations of a more fundamental interaction called electromagnetism. Maxwell proved that the electromagnetic fields propagated in the vacuum as waves with a finite velocity — the speed of light. In this way, field theories solve the action at a distance problem.

Mathematically a physical field is a quantity assigned to each point of the space-time. This quantity can be a scalar, like in the case of temperature or pressure in a gas; or a vector, as in the case of the velocity in a fluid. In the electromagnetic theory, one can derive the vector fields from two functions called the *field potentials*: the vector potential $\vec{A}(x)$ and the scalar potential $\phi(x)$ [7]. They can be grouped to form a four-vector, $A_\mu = (-\phi, \vec{A})$ called the electromagnetic potential. The electromagnetic theory is Lorentz invariant, which means that the physical phenomena associated with the electromagnetic field are the same for any observer moving at a constant velocity, even at speeds close to the speed of light. Lorentz invariance is a requirement of any modern physics theory.

One can use the lagrangian formalism, defined in classical mechanics [8], to derive the equations of motion of the electromagnetic field from the potential by using the Euler-Lagrange equations,

$$\partial_\mu \left(\frac{\partial \mathcal{L}}{\partial (\partial_\mu A_\nu)} \right) - \frac{\partial \mathcal{L}}{\partial A_\nu} = 0. \quad (2.2)$$

The lagrangian of the electromagnetic field is

$$\mathcal{L}_{\text{EM}} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu}, \quad (2.3)$$

where $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ is known as the Faraday tensor. By using Equation 2.3 in Equation 2.2 we obtain the equations of motion in the vacuum,

$$\partial_\nu F^{\nu\mu} = 0. \quad (2.4)$$

Apart from being Lorentz invariant, this equation is also invariant under transformations of the form

$$A'_\mu = A_\mu + \partial_\mu \Lambda(x), \quad (2.5)$$

where $\Lambda(x)$ can be any twice continuously differentiable function that depends on the coordinates. These transformations are known as *gauge transformations* and play a fundamental role in the modern description of interactions.

Let us see how gauge transformations come into play when describing interactions by looking at an example. The Dirac equation,

$$i\gamma^\mu \partial_\mu \psi - m\psi = 0, \quad (2.6)$$

describes the dynamics of a relativistic particle of spin $\frac{1}{2}$, where m is the mass of the particle and γ^μ are the Dirac matrices. The Dirac equation can be used to describe electrons. Equation 2.6 can be derived from the following lagrangian

$$\mathcal{L}_D = \bar{\psi}(i\gamma^\mu \partial_\mu \psi - m\psi). \quad (2.7)$$

This Lagrangian is invariant under transformations of the form $\psi \rightarrow \psi' = e^{i\theta} \psi$, where θ is a parameter not dependent on the space-time coordinates. This transformation is called a *global transformation*. In general, these transformations are shifts in the phase of the spinor ψ and can be seen as rotations, parametrised by the angle θ . In GT these transformations belong to a unitary group called U(1). However, if we make the angle parameter coordinate dependent, $\theta = \theta(x)$, the lagrangian in Equation 2.7 is no longer invariant. In this case, we have

$$\delta \mathcal{L}_D = i\bar{\psi} \psi \partial_\mu \theta(x). \quad (2.8)$$

Let us see that by coupling the Dirac field to the electromagnetic field (EM), we can recover a Lorentz invariant theory. First, the Maxwell equations with sources are

$$\partial_\nu F^{\nu\mu} = J^\mu. \quad (2.9)$$

To arrive to these equations we need to add the term $A_\mu J^\mu$ to Equation 2.3. Now, we carefully choose the source term as $J^\mu = \bar{\psi} \gamma^\mu \psi$ and arrive to the following lagrangian:

$$\mathcal{L}_{D+EM} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} + \bar{\psi}(i\gamma^\mu \partial_\mu \psi - m\psi) + \bar{\psi} \gamma^\mu A_\mu \psi. \quad (2.10)$$

If we inspect this equation term by term and recall Equation 2.5, we find that it is invariant under transformations of the form

$$\psi \rightarrow \psi' = e^{i\theta} \psi, \quad (2.11)$$

$$A'_\mu = A_\mu + \partial_\mu \theta(x). \quad (2.12)$$

Thus, we learnt that by coupling the EM field to the Dirac (electron) field we end up with a theory invariant under U(1) transformations. Since the transformation parameter is now dependent on the coordinates, we say that our theory is *local gauge invariant*. Consequently, we can interpret that the electromagnetic interaction between electrons is a consequence of the U(1) local symmetry obeyed by the electron and the EM fields. Additionally, the Noether theorem ensures that for any continuous symmetry, we should have a conserved quantity. In this case, the electric charge.

But not only the electromagnetic interactions can be explained under this line of thinking. The electroweak interaction, which is responsible for radioactivity-related phenomena, was also successfully explained with a symmetry argument. Sheldon Glasgow, Abdus Salam and Steven Weinberg proposed that the fields involved in the electroweak interaction are invariant under an $SU(2) \times U(1)$ symmetry [9–11]; with the addition of a spontaneous symmetry breaking mechanism

proposed by Peter Higgs [12].

Finally, the strong interaction — responsible for holding the nucleus of the atoms together and explaining its structure, was explained with a $SU(3)$ symmetry in 1964 by Murray Gell-Mann [13].

Nonetheless, gravitational interactions have resisted the same treatment. Explaining how gravity works at the quantum level remains one of the most fundamental questions in modern physics.

2.2 Quantum field theory

Classic field theory describes how matter interacts through physical fields. However, to describe interactions at the fundamental level, we must go to the microscopic regime where we know that classical assumptions no longer work and we must use the quantum formalism. Additionally, we know that the structure of space-time is relativistic and once velocities are high enough, relativistic equations should be used. Quantum Field Theory (QFT) allows us to describe quantum phenomena that can be relativistic.

Quantum mechanics describes a system by defining its *quantum state*, and allows us to calculate observables from the expected values of operators. In Dirac notation, the quantum state of a system is denoted by a ket,

$$|\alpha\rangle = |i, j, k, \dots\rangle. \quad (2.13)$$

These objects live in a Hilbert space of complex functions. The norm in this space is defined by the introduction of the complex conjugate of $|\alpha\rangle$, in Dirac's notation is $\langle\alpha|$ and it is known as bra. The numbers $i, j, k, \dots$ are the quantum numbers of the system and they are related to the physical observables by,

$$a_i = \langle\alpha(i, j, \dots)|A_i|\alpha(i, j, \dots)\rangle. \quad (2.14)$$

Since a quantum system can be in a superposition of states, two important quantities are defined. First, the probability that the system transitions from a state $|\beta\rangle$ to a state $|\alpha\rangle$, $|\langle\alpha|\beta\rangle|^2$; and second, the probability of finding the system in a particular state $|\alpha\rangle$, $|\langle\alpha|\alpha\rangle|^2$.

But quantum mechanics cannot explain phenomena like the change in the number of particles in a given system. QFT solves this problem by introducing *quantum fields*, which represent the state of a quantum system of particles. The quantum fields are promoted to operators and commutation relations are imposed between them. This procedure is known as *canonical quantisation*. In QFT the number of particles in a system (n) is one of the quantum numbers. When $n = 0$, the system is said to be in the ground state with zero particles. Once $n > 0$, the system is at an excited state, containing n particles.

For instance, after quantising the lagrangian in Equation 2.10 we obtain the theory of quantum electrodynamics (QED). QED was the first QFT to be studied extensively and was developed by Tomonaga, Schwinger and Feynman [14–16]. QED states that electrons (as particles) are the quanta (excited states) of the electron field. They act as the source for the EM field, for which the quanta are the so-called photons. QED describes the EM interaction between electrons as the exchange of photons.

2.3 The Standard Model

In this section, we will introduce the Standard Model (SM). We will define its particle content and how those particles interact with each other. It can be argued that the history of the SM development, began with the discovery of the electron in cathode-ray tube experiments performed in 1897 by J.J. Thomson. Later, this led to the first attempts to formulate a relativistic theory of the electron. While studying this problem, Dirac postulated the existence of the positron, an electron with a positive charge, also known as the anti-electron. The positron was discovered in 1932 by Carl David Anderson [17].

In quantum field theory, particles are classified into two different types: fermions, having half-integer spin; and bosons, which have integer spin. The SM includes three fundamental interactions: electromagnetic, weak and strong interactions. The SM includes two distinctive types of fermions: leptons, which take part only in electroweak interactions and quarks which are involved in electroweak and strong interactions. The charged leptons are the electron (e^-), the muon (μ^-) and the tau (τ^-); and the neutral leptons are their associated neutrinos (ν_e, ν_μ, ν_τ). The remaining six leptons are the anti-leptons, which are the anti-particles of the leptons. The leptons are grouped into three families or generations. The first generation comprises the electron, positron and their associated neutrinos ($e^-, e^+, \nu_e, \bar{\nu}_e$). The remaining two generations are formed by the muon (anti-muon) and the tau (anti-tau), with their associated (anti)-neutrinos. The quarks are divided into three families: the quark up and down (u, d), the charm and strange (c, s) and the top and bottom (t, b).

Regarding the bosonic content of the SM, we have eight mediators of the strong interaction called gluons (g). For the electroweak interaction, four bosons are included: the neutral (Z) boson, the two charged ($W^\pm$) bosons and the photon (γ). Additionally, the SM incorporates a spin-zero boson called the Higgs boson (H). We will describe its role later in this section. The SM particles can be divided into matter constituents, which are all the fermions; and the force carriers, the gauge bosons. Figure 2.1 presents the particle content of the SM; along with the mass, electric charge and spin of each particle.

In terms of discoveries, the EW bosons ($Z, W^\pm$) were discovered by the UA1 and UA2 collaborations in 1983 [18], using collisions from the Super Proton Synchrotron [19]. The gluons were discovered by the TASSO [20], Mark J [21], JADE [22] and PLUTO [23] collaborations using the PETRA particle accelerator at the german electron synchrotron (DESY) laboratory. Finally, the Higgs boson was detected simultaneously by the ATLAS [1] and CMS [2] collaborations at the Large Hadron Collider (LHC) in 2012 [24, 25].

As mentioned before, the $W^\pm$ and Z bosons are the mediators of the EW interaction and since this is a short-range force these bosons must be massive. A possible mass term for a spin one particle is

$$\mathcal{L}_m = m^2 A_\mu A^\mu. \quad (2.15)$$

However, this term is not gauge invariant. If we make a transformation like the one in Equation 2.5, we have

$$\delta \mathcal{L}_m = \partial_\mu \Lambda A^\mu + A_\mu \partial^\mu \Lambda + \partial_\mu \Lambda \partial^\mu \Lambda. \quad (2.16)$$

Thus, we have two alternatives to give a mass to the EW bosons:

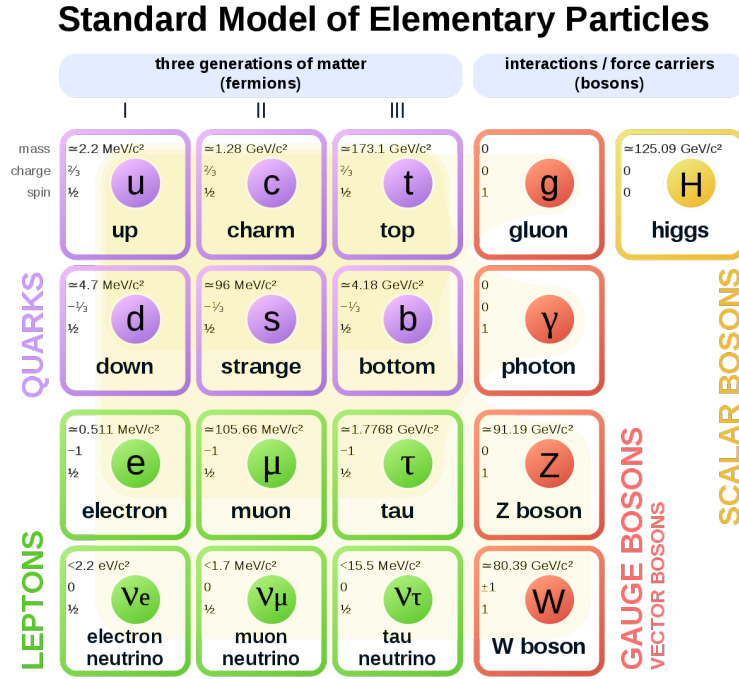


FIGURE 2.1: Particle content of the standard model. Taken from [26].

- *Explicit symmetry breaking*, introducing a term like Equation 2.15. This will result in undesired theoretical problems and it will not explain where the masses of the fermions come from — the mass would be an additional parameter of the model.
- *Spontaneous symmetry breaking*, where the ground state of the theory does not respect the symmetry. Let us see this idea in action.

To give mass to all the SM particles, the *Brout-Englert-Higgs mechanism* is introduced [27, 28]. In this mechanism, a complex doublet field is added to the SM, the Higgs field (Φ). The vacuum state of Φ will break the EW $SU(2) \times U(1)$ symmetry. The most general lagrangian invariant under this symmetry is

$$\mathcal{L}_\Phi = \partial_\mu \Phi \partial^\mu \Phi^\dagger + \mu^2 \Phi \Phi^\dagger + \lambda (\Phi \Phi^\dagger)^2, \quad (2.17)$$

with

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \quad (2.18)$$

and μ, λ parameters controlling the shape of the scalar potential $V(\Phi) = \mu^2 \Phi \Phi^\dagger + \lambda (\Phi \Phi^\dagger)^2$. The potential $V(\Phi)$ has the shape shown in Figure 2.2 for $\lambda > 0$ and $\mu^2 < 0$. It has a local unstable minimum at $\Phi = 0$ and a global minimum at $\Phi^\dagger \Phi = -\frac{\mu^2}{2\lambda}$. We can express the vacuum state as

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}. \quad (2.19)$$

Now, we can expand Φ around its minimum as

$$\Phi = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(H + v - iG^0) \end{pmatrix}, \quad (2.20)$$

where G^+, G^- and G^0 are known as the Goldstone fields. The Higgs field is coupled to the EW bosons fields B and W^j via a modification of the derivative in Equation 2.17,

$$\partial_\mu \rightarrow D_\mu = \partial_\mu - i\frac{g'}{2}YB_\mu - i\frac{g}{2}T_j W_\mu^j, \quad (2.21)$$

where Y is the weak hypercharge and T_j are the components of the weak isospin. First, we replace equations 2.20 and 2.21 in Equation 2.17 and re-define the EW fields as

$$Z = \cos \theta_W W_3 - \sin \theta_W B, \quad (2.22)$$

$$A = \sin \theta_W W_3 + \cos \theta_W B, \quad (2.23)$$

$$W^\pm = \frac{1}{\sqrt{2}}(W_1 \mp iW_2), \quad (2.24)$$

where θ_W is known as the Weinberg angle. After, we redefine the EW fields in combination with the Goldstone fields. This leads to the appearance of a mass term for the EW fields, a term proportional to the vacuum expectation value of the Higgs field (v). In this way, the Higgs mechanism gives mass to the initially massless EW bosons. Additionally, the Higgs field mass is given by $m_H = \sqrt{-2\mu^2}$.

Experimentally, by observing parity violation in beta decays [29] it has been established that only left-handed fermions and right-handed anti-fermions couple to the charged currents of the EW interaction. This leads to the representation of left-handed fermions as SU(2) doublets, considering just the first generation of leptons one writes

$$l_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, \quad (2.25)$$

and the right-handed fermions e_R, ν_R as SU(2) singlets.

One can introduce an interaction term between the Higgs field and the fermions called the Yukawa interaction. It takes the form:

$$\mathcal{L}_Y = -Y_e(\bar{l}_{Li}\phi_i e_R + \bar{e}_R\phi_i^\dagger l_{Li}), \quad (2.26)$$

where Y_e is called the Yukawa coupling constant. After using Equation 2.20 in 2.26, $\mathcal{L}_Y$ becomes

$$\mathcal{L}_Y = -\frac{1}{\sqrt{2}}vY_e\bar{e}e - \frac{1}{\sqrt{2}}Y_e H\bar{e}e, \quad (2.27)$$

with $e = e_R + e_L$, and the resulting electron mass is $m_e = Y_e v / \sqrt{2}$. The mechanism to generate the quark masses is similar. However, we can write the quark *weak* eigenstates (q') as a combination of the *mass* eigenstates (q). For the down, strange and bottom quarks

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{\text{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}, \quad (2.28)$$

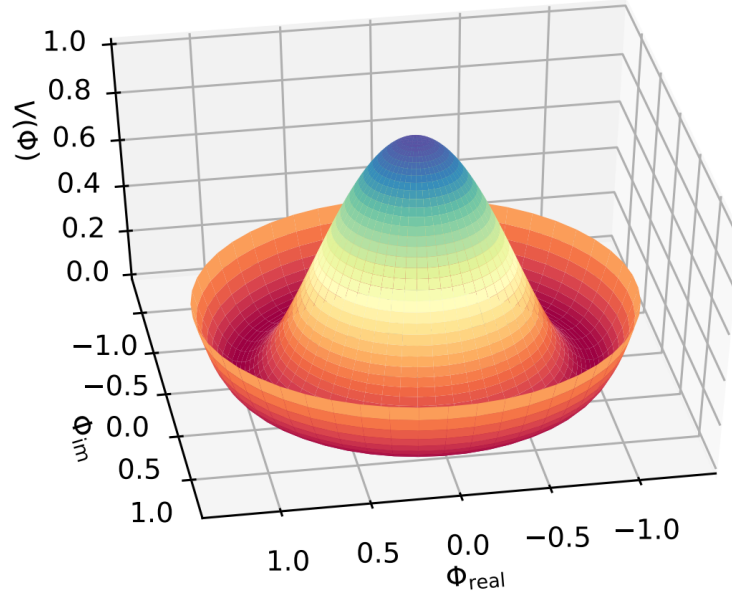


FIGURE 2.2: Higgs field potential, also called Mexican-hat potential. The global minimum of this field is not at $\Phi = 0$.

where V_{CKM} is a 3×3 matrix known as the Cabibbo–Kobayashi–Maskawa (CKM) matrix [30]. The matrix is written as

$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}, \quad (2.29)$$

and it is known to have non-diagonal terms. This leads to the mixing between different quark generations. The probability of the mixing $i \rightarrow j$ is proportional to the square of the element V_{ij} .

In summary, the Higgs field in the SM gives masses to the EW bosons and the fermions. This can be seen as the consequence of breaking the EW symmetry.

2.4 Lepton universality

In the previous section, we mentioned that the SM organises the leptons into three families or generations. In the SM the only difference between these generations is the mass of the leptons. The SM leptons couple to the EW bosons exactly with the same strength irrespective of the lepton generation. This accidental symmetry is known as Lepton Universality (LU). We say that this symmetry is accidental because the SM was not designed to include this feature. Experimental tests can be designed to probe the validity of LU, and any deviation from the SM predicted results would lead to new physics discoveries.

In this section, we will describe some LU tests. First, the ones directly involving the W and Z bosons; and later the ones related to b -quark decays.

Many experiments where the W and Z bosons are directly produced have tested LU. The most precise tests involving the Z boson were performed at the Large Electron-Positron collider (LEP). At LEP, the decay widths of $Z \rightarrow ee$, $Z \rightarrow \mu\mu$ and $Z \rightarrow \tau\tau$ were measured, and found to agree

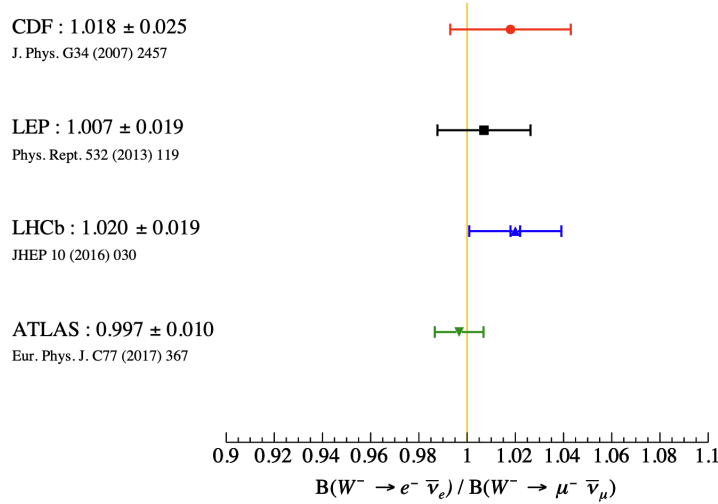


FIGURE 2.3: $R_{(e/\mu)}$ measurements from different experiments, the SM expectation is shown as the vertical yellow line. Taken from [34].

with the SM [31]. Ratios of these quantities have been measured [32],

$$\frac{\Gamma(Z \rightarrow \mu\mu)}{\Gamma(Z \rightarrow ee)} = 1.0009 \pm 0.0028, \quad (2.30)$$

$$\frac{\Gamma(Z \rightarrow \tau\tau)}{\Gamma(Z \rightarrow ee)} = 1.0019 \pm 0.0032, \quad (2.31)$$

and they are in agreement with the SM at the per mille level — it is important to note that due to the higher mass of the τ , its partial width is decreased by 0.23%.

Additionally, measurements performed by the ATLAS collaboration at the LHC support the LU hypothesis[33],

$$\frac{\Gamma(Z \rightarrow \mu\mu)}{\Gamma(Z \rightarrow ee)} = 0.9974 \pm 0.0050. \quad (2.32)$$

$W^\pm$ boson decays have been tested at the LEP, Tevatron and the LHC experiments. The measurements for the first two generations ($l = e, \mu$) are in agreement with the SM, but the precision of these (at the percentage level) is smaller compared to the Z ones [34]. A compilation of these measurements can be seen in Figure 2.3. The third generation-related LEP measurements, were in slight tension with the SM, showing a disagreement of 2.6σ with the SM prediction. However, the most recent and more precise ATLAS results discarded this tension [35]. A summary of this result can be seen in Figure 2.4.

In conclusion, the current tests of LU looking at the Z boson decays are in agreement with the theory at least at 0.3% precision. In the $W^\pm$ case, the agreement is at the 2% level taking into account all generations.

An alternative way of testing LU is by studying b -quark decays. We are going to describe two decay modes that have been tested: leading order ($b \rightarrow cl\bar{\nu}_l$) and radiative ($b \rightarrow sl^+l^-$) decays, where $l = e, \mu, \tau$. In the first case, the decays are studied by measuring the branching fractions of B hadron decays (H_b) to D hadrons (H_D), like the decay seen in Figure 2.5.

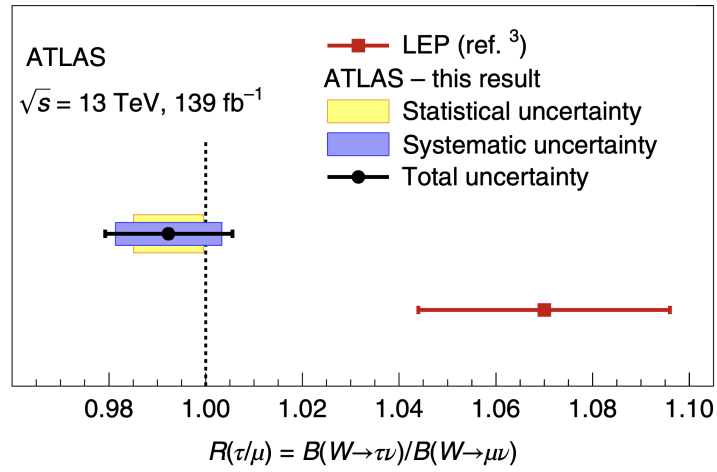


FIGURE 2.4: Comparison between the LEP and ATLAS measurements for the $R_{(\tau/\mu)}$ quantity. Taken from [35].

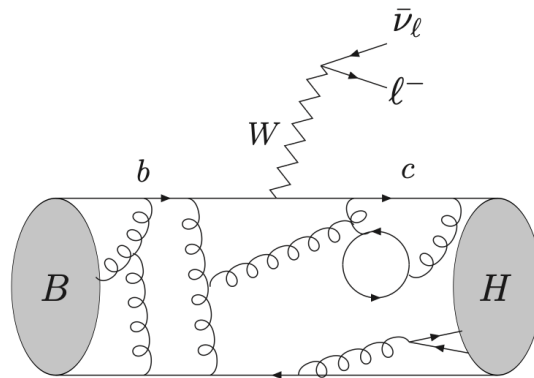


FIGURE 2.5: Illustration of the $b \rightarrow cl\bar{\nu}_l$ decay at the hadronic level. Notice how the quark transition is at tree-level. Taken from [36].

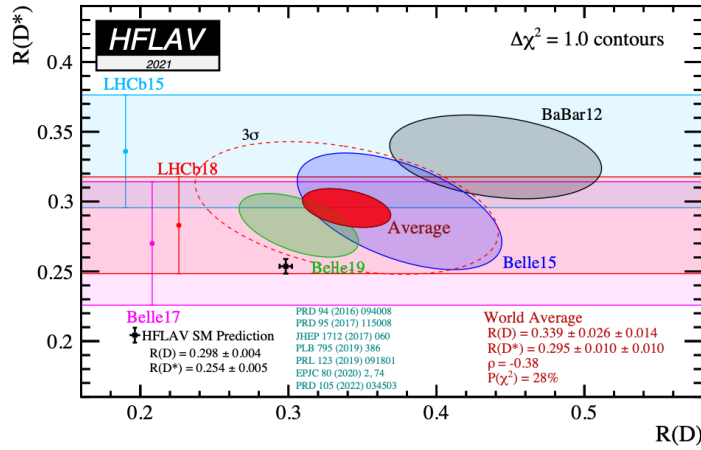


FIGURE 2.6: Review of the measurements of $R(D^*)$ and $R(D)$. The SM prediction average and the experimental average deviate from each other by 3.3σ . Taken from [3].

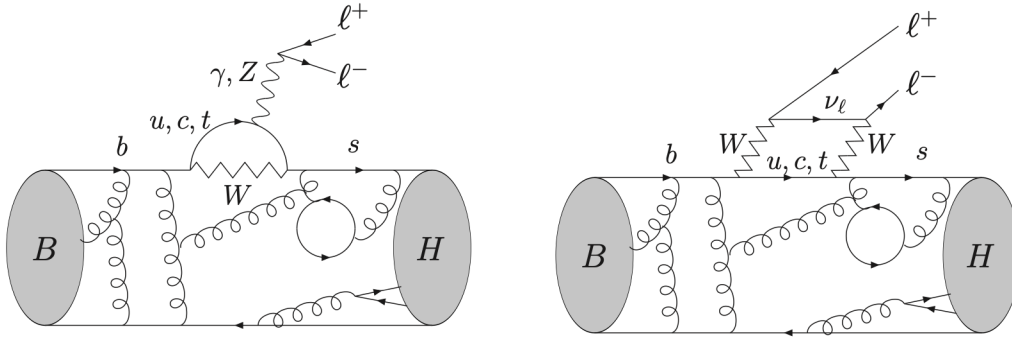


FIGURE 2.7: Illustration of the $b \rightarrow sl^+l^-$ decay at the hadronic level. Notice how the quark transition goes over a loop. Taken from [36].

The $B \rightarrow D$ transition branching fractions are measured, and ratios between different lepton generations are defined,

$$R_H = \frac{\mathcal{B}(H_b \rightarrow H_D l \bar{\nu}_l)}{\mathcal{B}(H_b \rightarrow H_D l' \bar{\nu}_{l'})}. \quad (2.33)$$

The ratios between the first two generations are in agreement with the SM [36]. Ratios involving the third generation ($l = \tau$ and $l' = e, \mu$) are of particular interest, since the values measured by the Belle [37], BaBar [38] and LHCb [39] collaborations are in tension with the SM [3]. A review of these measurements is shown in Figure 2.6.

The $b \rightarrow sl^+l^-$ measurements are also performed by measuring B hadron decays, but instead of tree-level contributions these decays are much more suppressed because they arise from processes involving loops. Some examples can be seen in Figure 2.7.

The following ratio is measured in these decays,

$$R_H = \frac{\int_{q_{\min}}^{q_{\max}} \frac{d\Gamma(H_b \rightarrow H \mu \mu)}{dq^2} dq^2}{\int_{q_{\min}}^{q_{\max}} \frac{d\Gamma(H_b \rightarrow H e e)}{dq^2} dq^2}, \quad (2.34)$$

where H is a K or K^* and q^2 is the invariant mass of the di-lepton system. The most precise

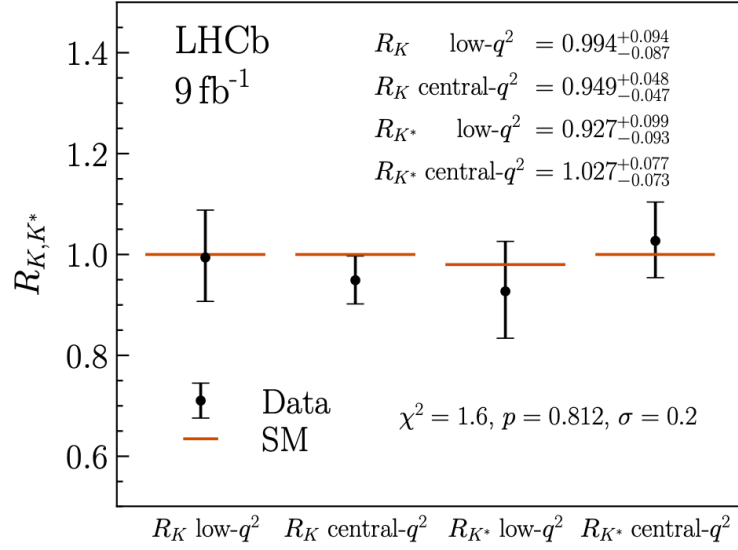


FIGURE 2.8: Values obtained for the $R(K/K^*)$ ratio by the LHCb collaboration. All four measurements are consistent with the SM expectation. Taken from [41].

measurements of these ratios have been performed recently by the LHCb collaboration and are in agreement with the SM [40, 41]. A review of these measurements can be seen in Figure 2.8.

Overall, the tests of LU show that for the first two generations, universality holds well across all measurements. This is also true for the third generation, at least for the Z boson decays and to a lower precision for W boson-related process. However, measurements from B hadron decays point to a possible violation of LU in the third generation, but the evidence is not conclusive. LU tests at much higher q^2 are complementary to this discussion, and this is the main motivation of this thesis.

2.5 Searching for heavy resonances in the di-tau mass spectrum

As outlined in the previous section, LU measurements are crucial to establish the robustness of the SM and offer a great opportunity to search for new physics. From the theoretical point of view, there are plenty of well-motivated SM extensions that include non-universal physics scenarios. In this section, we will present some of these models and searches. Additionally, experimental physicists have an additional interest in measurements that include fermions of the third generation in the final states, since the more complex nature of the signature of tau leptons and b-quark jets in the detectors poses additional experimental challenges.

The addition of a gauge boson to the SM, called Z' , is one of the most studied new physics scenarios. Specific extensions where the Z' has non-universal couplings have been studied extensively — these models explore Z' bosons that couple preferentially or exclusively to the third generation of fermions. The SM extensions include models where the fundamental symmetry is $SU(2)_1 \times SU(2)_2 \times U(1)_Y$ — including also new W' bosons to the SM [42–44]; or models where the fundamental group is $SU(2)_1 \times U(1)_1 \times U(1)_2$ and only the Z' boson is added [45].

Model-specific limits on the mass of the Z' boson can be set by fitting the model predictions to the high-precision EW measurements [45]. For the models that add a $U(1)$ symmetry to the SM, the 95% confidence lower bound for the mass of the Z' depends on the mixing angle between the

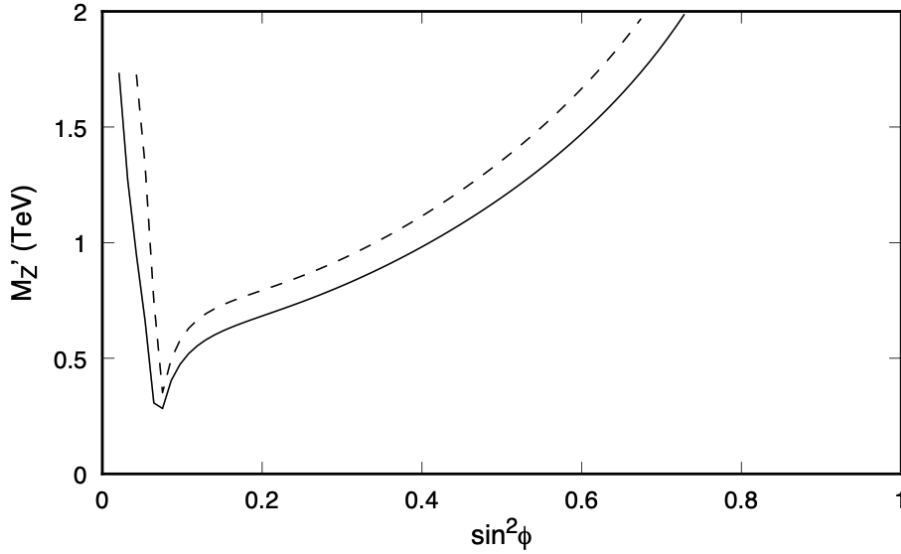


FIGURE 2.9: The solid line is the 95% confidence lower bound for the mass of the Z' as a function of $\sin^2 \phi$ for a model that adds an additional $U(1)$ symmetry to the SM. The 68% confidence lower bound is shown by the dashed line. Taken from [46].

$U(1)$ groups (ϕ) — the limits are shown in Figure 2.9. It can be noted that for $\sin^2 \phi < 0.5$ the Z' mass can be below 1 TeV.

Theories that extend the SM by adding an $SU(2)$ have been also studied in the literature. One proposal is to have a higher energy theory where two gauge groups, $SU(2)_{\text{light}} \times SU(2)_{\text{heavy}}$ couple to the first two generations and the third generation of fermions, respectively [45]. This group structure is broken at a certain energy scale into the SM $SU(2)_L \times U(1)_Y$ group. Two distinctive scenarios are defined depending on if the field that provides the symmetry breaking at the EW level is charged under $SU(2)_{\text{heavy}}$ or $SU(2)_{\text{light}}$: the "heavy" and the "light" case respectively. In the heavy case, the field responsible for generating the mass of the third generation of quarks and leptons is also responsible for the bulk of the EW symmetry breaking; in the light case, the bulk of the EW symmetry breaking is not provided by field that generates the masses of the third generation of fermions. When fits of these models to the EW precision data are performed, the resulting exclusion curves are the ones shown in Figure 2.10 — the lower bound on the Z' mass depends on the mixing angle (ϕ) between the heavy and light gauge groups. In the heavy case, the Z' mass lower bound is ≈ 3 TeV; the lower Z' mass bound in the light case is ≈ 2.3 TeV. This happens because in these models the mass of the heavier Z' and W' bosons is $M_{Z',W'} \approx \frac{\sqrt{x}}{\sin \phi \cos \phi} M_W$, where $x = \frac{u^2}{v^2}$ is the ratio between the heavy scale (u) and the EW scale (v). The best-fit value of x is greater in the heavy scenario, this yields a bigger mass for the Z' in this case.

Complementary to these indirect limits, searches for high-mass resonances decaying to di-tau final states have been performed by the ATLAS and CMS collaborations at centre-of-mass energies of 7, 8 and 13 TeV [47–52]. The searches include a varied set of final states such as: $\tau_{\text{had}} \tau_{\text{had}}$, $\tau_{\text{had}} \tau_{\text{lep}}$ and $\tau_{\text{lep}} \tau_{\text{lep}}$; where τ_{had} represents a tau decaying into hadrons and a neutrino, and τ_{lep} represents a tau decaying into two neutrinos and a light-lepton. The most recent searches by ATLAS and CMS at 13 TeV focus in topologies where the resonance is produced either in the Drell-Yan process for Z' 's or in QCD-related processes for scalar resonances. These searches set lower limits on the mass of the Z' of at least 1.5 TeV for various models as shown in Figure 2.11.

Although previous indirect and direct searches for high-mass resonances set limits on the mass

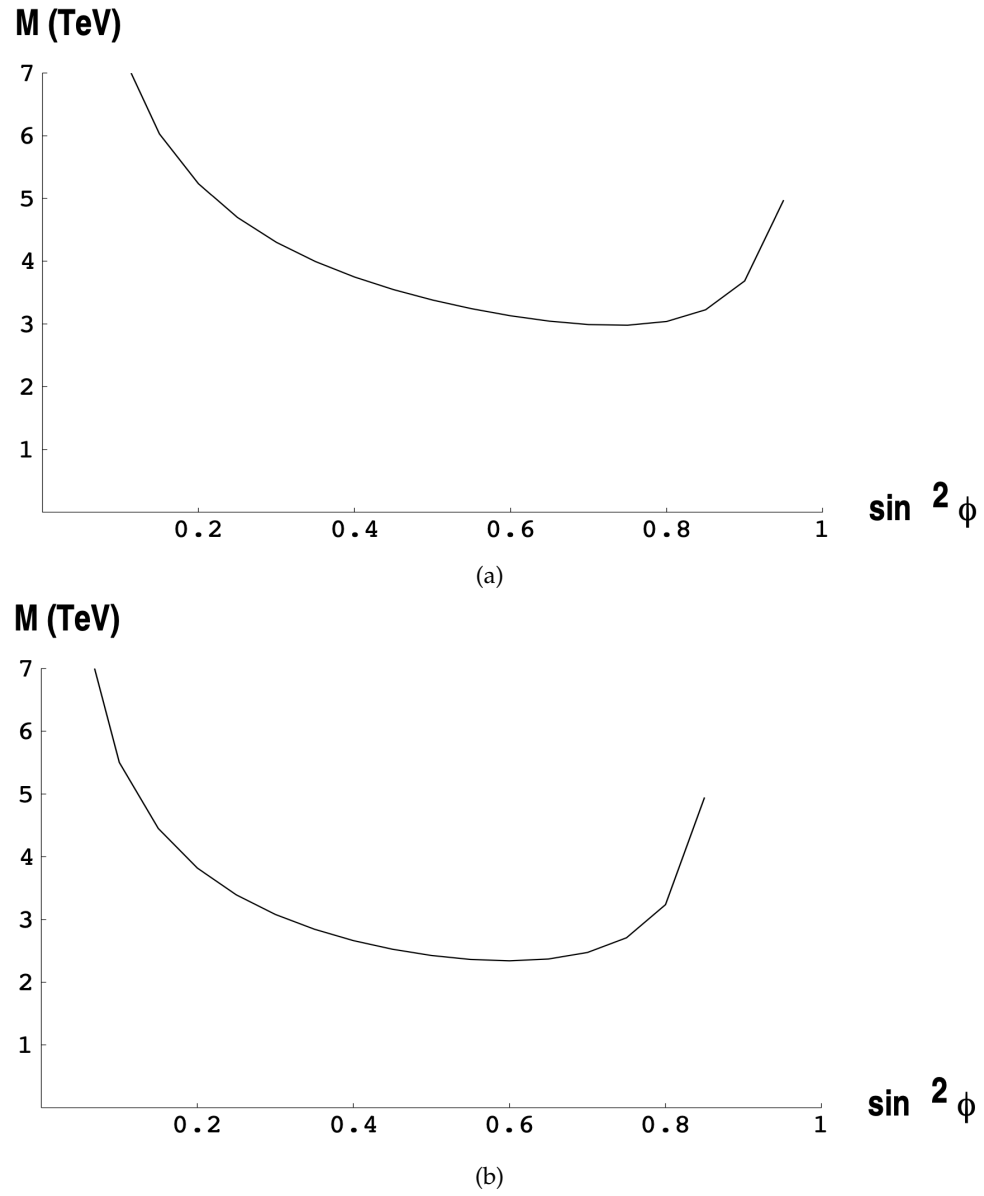
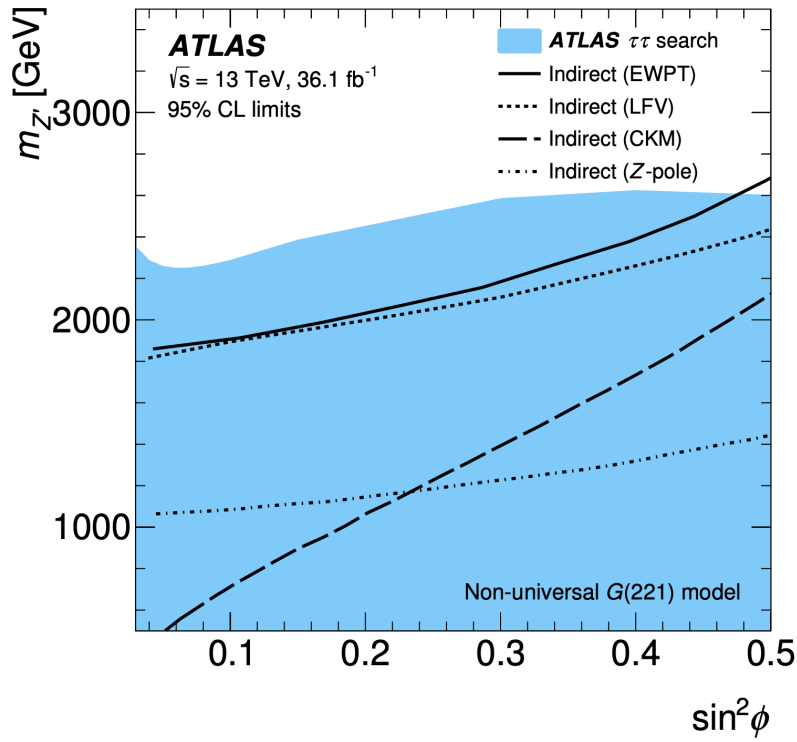
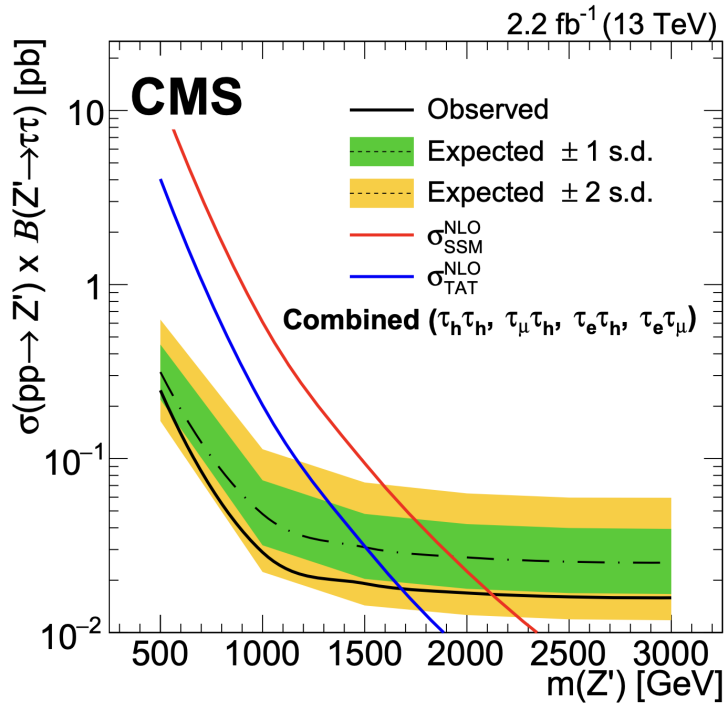


FIGURE 2.10: Lower bound for the Z' boson mass at 95% confidence level in the (a) heavy and (b) light case. These plots correspond to models where the SM is extended with an additional $SU(2)$ symmetry. Figures taken from [45].



(a)



(b)

FIGURE 2.11: (a) In blue, the 95% confidence level exclusion limit for the Z' mass derived by ATLAS as a function of the mixing angle ϕ . This limit is overlaid with indirect limits from fits to the EW precision data, the lepton flavour violation, CKM unitarity and Z-pole measurements [44, 53–55]. Figure taken from [52]. (b) The 95% confidence upper limits on the product of the cross section and branching fraction into tau lepton pairs as a function of the Z' mass. The blue and red lines are respectively the predictions of models that add a U(1) or a SU(2) gauge group to the SM as discussed above. Figure taken from [51].

of the hypothetical new particles, these limits have varying degrees of model dependence. Our motivation to perform the analysis we describe in Chapters 6 and 7 is to directly probe the possible pure EW production of the heavy resonance by looking at vector boson fusion topologies; and in addition, we probe the universality of this process by comparing the production of di-leptons across the three lepton generations.

Chapter 3

The LHC and the ATLAS detector

3.1 The Large Hadron Collider

The Large Hadron Collider (LHC) is a proton-proton collider operated by the European Centre for Nuclear Research (CERN) [56–58]. The LHC comprises an accelerator complex where two beams of protons are currently accelerated to an energy of up to 6.8 TeV. The main accelerator ring was built within a 27 km tunnel, excavated between 45 to 170 m below the ground level, in the French-Swiss border. This tunnel was previously used by the Large Electron Positron Collider (LEP) [59–61].

Four experiments are located around the LHC main ring. Two general-purpose detectors, called ATLAS [62] and CMS [63], are located in caverns excavated around 100 m below ground level. ATLAS and CMS were designed with the capabilities to perform discoveries at the energy and precision frontiers in many potential new physics scenarios. That is the reason why they are labelled as general-purpose detectors. The other two LHC experiments are called ALICE [64] and LHCb [65]. The former was designed to study the quark-gluon plasma generated at the collisions, and the latter to study the physics of the b quark and the hadrons it forms.

The LHC was designed with the idea of being able to produce proton-proton collisions with a centre-of-mass energy of $\sqrt{s} = 14$ TeV at an instantaneous luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$. It has successfully delivered two runs of data acquisition: Run I at $\sqrt{s} = 7$ and 8 TeV — between 2009 and 2013; and Run II at $\sqrt{s} = 13$ TeV — during 2015 to 2018. At the current time of writing this work, Run III is ongoing.

The LHC complex can be divided into two, the pre-acceleration chain and the main ring. In the first step of the pre-acceleration chain, negative hydrogen ions are accelerated to 160 MeV in the linear accelerator Linac4 (in 2020 Linac2 was replaced by Linac4 — the older accelerator used to produce 50 MeV protons) and passed to the Proton Synchrotron Booster (PSB). In the PSB the hydrogen ions are stripped of their two electrons and the protons are taken to an energy of 2 GeV. After, they are passed to the Proton Synchrotron (PS) where they are accelerated to 26 GeV and transferred to the Super Proton Synchrotron (SPS). Finally, the SPS pushes the beams to 450 GeV and injects them into the main ring.

Two beams of protons circulate in opposite directions in the main ring. The pressure in the beam pipe is 10^{-9} mbar. The main ring is composed of 2090 dipole superconducting magnets — each being 15 m long and operating at a temperature of 1.9 K. The magnets can produce a dipolar

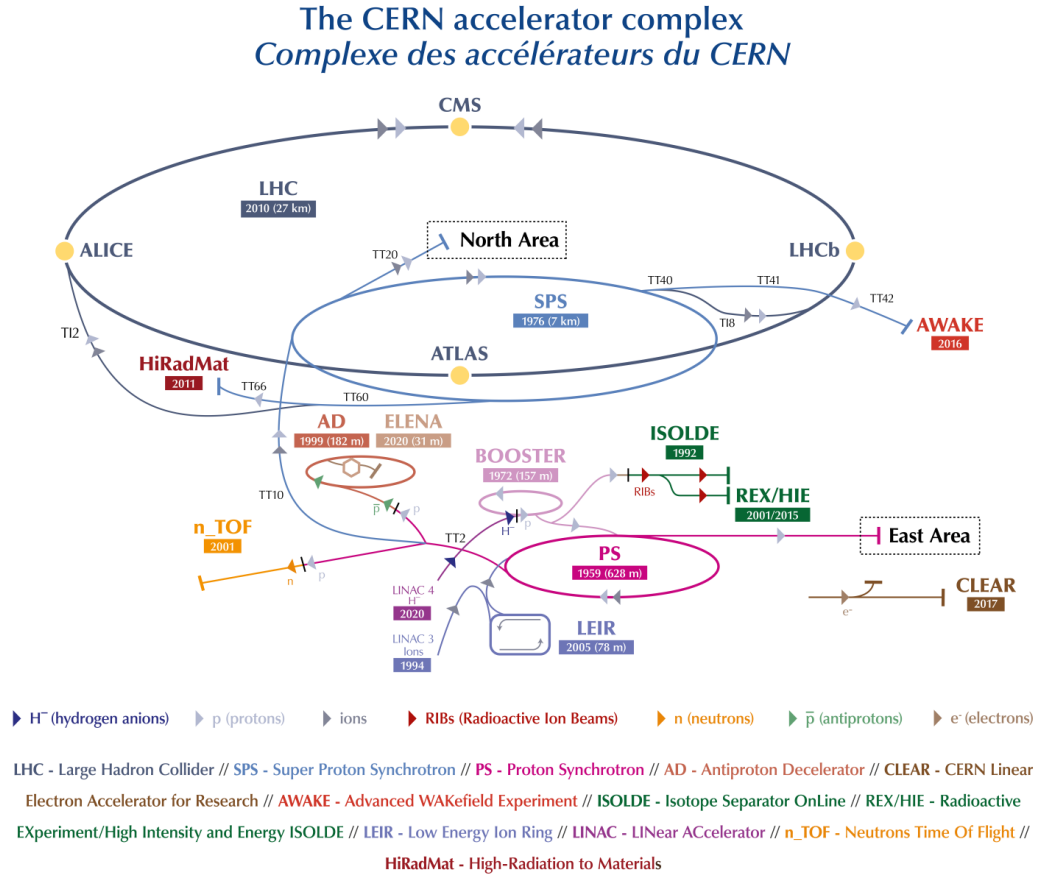


FIGURE 3.1: CERN accelerator complex in 2022. Taken from [66].

field of 8.33 T. Beam aligner magnets are placed across the ring to maintain the beams collimated. An illustration of the LHC accelerator complex is shown in Figure 3.1.

The figure that defines the performance of a particle collider is its instantaneous luminosity ($\mathcal{L}$). For a Gaussian beam, it can be written as,

$$\mathcal{L} = \frac{k_b N_b^2 f \gamma}{4\pi \epsilon_n \beta^*} F, \quad (3.1)$$

where k_b is the number of bunches in the ring, N_b is the number of protons per bunch, f is the revolution frequency, γ is the relativistic factor and ϵ_n and β^* are beam parameters: known as the normalised beam emittance and the beta function at the interaction point — the beam emittance (ϵ) is the area of the ellipse containing all the protons in the plane of: distance to the beamline versus angle with respect to the beamline, and $\epsilon_n = \beta_{\text{rel}} \gamma \epsilon$ is a quantity preserved under Lorentz boosts. In general, $\beta = \pi \sigma^2 \epsilon$, where σ is the transverse cross-section of the beam. F is a geometric correction factor due to the crossing angle of the beams.

The LHC design parameters are summarised in Table 3.1. These parameters were expected to deliver a luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. However, the LHC exceeded the design luminosity by up to a factor of two in Run II [67].

Energy	7000 GeV
f	40 MHz
k_b	2808 bunches
N_b	1.15×10^{11} protons
Half Crossing Angle	$142.5 \mu\text{rad}$
Normalised Emittance	$3.75 \mu\text{m}$
β^*	55 cm

TABLE 3.1: LHC design operation parameters.

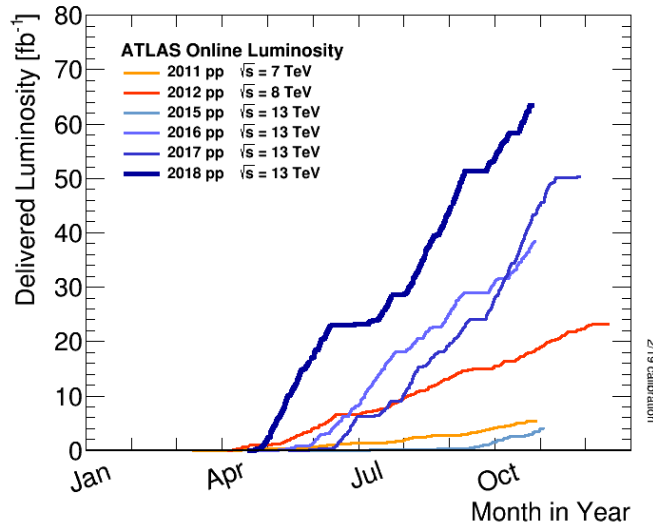


FIGURE 3.2: LHC delivered integrated luminosity across Run I and II at the ATLAS interaction point. Taken from [68].

The integrated luminosity (L) is the figure of merit for a collider, it is the sum of all the delivered luminosity over time,

$$L = \int \mathcal{L} dt. \quad (3.2)$$

It is also related to the number of events for a given physics process (N), given that the cross-section for the process is known (σ),

$$N = \sigma L. \quad (3.3)$$

A diagram showing the integrated luminosity delivered across Run I and Run II can be seen in Figure 3.2. The luminosity recorded by the ATLAS experiment is shown in Figure 3.3.

3.2 The ATLAS detector

A Toroidal LHC ApparatuS (ATLAS) is one of the two general-purpose detectors installed at the main LHC ring. It is located at Interaction Point One (IP1), close to the CERN main facilities. The ATLAS detector was designed to deliver the particle identification performance and energy-momentum measurement precision needed to make physics discoveries and high-precision measurements at the high-luminosity and high-energy LHC conditions. A very detailed description of the detector can be found in its technical design report, see [62].

The coordinate system used in ATLAS is essential to understand the detector design and performance. The origin is located at the IP. The z axis points in the direction of the beam, and the

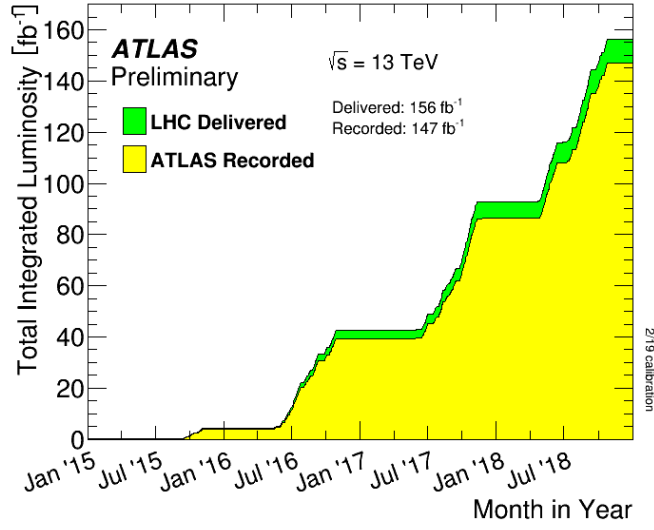


FIGURE 3.3: Comparison between the luminosity delivered by the LHC and the one recorded by the ATLAS detector during Run II. Taken from [68].

$x - y$ plane is transverse to the beam direction. The y axis points vertically upwards and the positive x axis is directed towards the centre of the LHC main ring. The azimuthal angle ϕ is measured in the transverse plane from the x axis, and the polar angle θ is measured from the beam axis.

The rapidity of a particle is defined as

$$y = \frac{1}{2} \log \left(\frac{E + p_z c}{E - p_z c} \right). \quad (3.4)$$

For ultra-relativistic particles, we have $p \gg mc$ and $E \approx pc$. Then, we define the pseudo-rapidity as

$$\eta = y = -\log \left[\tan \left(\frac{\theta}{2} \right) \right]. \quad (3.5)$$

With the help of pseudo-rapidity, the angular separation between two particles is defined as $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2}$. Additionally, the transverse energy (E_T) and momentum (p_T) of a particle are defined as the projections in the $x - y$ plane of the total energy and momentum.

The ATLAS detector was built as a set of sub-detection systems arranged in layers. Each of these sub-detectors is specialised in measuring the physical properties of a specific group of particles. The combined information taken from a single collision, from all the sub-detectors, is combined and forms an *event*. A schematic depiction of the ATLAS detector and its sub-detection systems can be found in Figure 3.4.

The closest detector to the IP is known as the *inner detector*. It allows for vertex and track reconstruction of charged particles and it uses silicon and straw-tube detection technologies. The inner detector is surrounded by a superconducting solenoid that provides an axial field of up to 2 T which helps with charge identification. The ATLAS magnet system is complemented by a barrel and two end-cap toroidal superconducting magnets.

In terms of calorimetry, ATLAS is equipped with a high-granularity liquid argon (LAr) electromagnetic calorimeter (EMCAL) which covers the range $|\eta| < 3.2$. The LAr EMCAL allows for electron and photon energy and position measurements. Additionally, for hadronic calorimetry (HCAL) ATLAS has a scintillator-tile calorimeter that covers $|\eta| < 1.7$; it is divided into a barrel

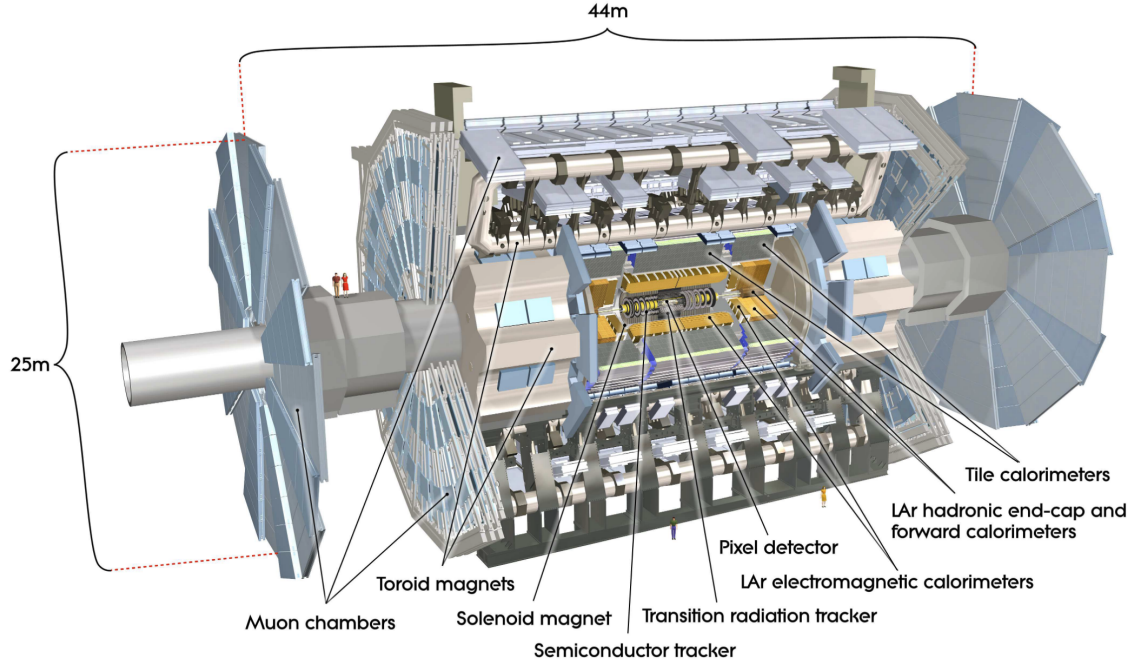


FIGURE 3.4: ATLAS detector composition. ATLAS has a cylindric geometry. Particles produced at the IP, interact with several sub-detection stations before leaving the ATLAS detector. Taken from [62].

Detector component	Required resolution	η coverage	
		Measurement	Trigger
Tracking	$\sigma_{p_T}/p_T = 0.05\% p_T \oplus 1\%$	± 2.5	
EM calorimetry	$\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$	± 3.2	± 2.5
Hadronic calorimetry (jets)			
barrel and end-cap	$\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$	± 3.2	± 3.2
forward	$\sigma_E/E = 100\%/\sqrt{E} \oplus 10\%$	$3.1 < \eta < 4.9$	$3.1 < \eta < 4.9$
Muon spectrometer	$\sigma_{p_T}/p_T = 10\% \text{ at } p_T = 1 \text{ TeV}$	± 2.7	± 2.4

FIGURE 3.5: Momentum and energy resolution of the ATLAS sub-detection systems. The pseudo-rapidity range is divided into the measurement capability and the range used for trigger purposes. Taken from [62].

and two end-caps. For $|\eta| > 1.5$, LAr calorimeters are used for hadronic calorimetry and they match the pseudo-rapidity range of the EMCAL. LAr forward calorimeters extend the electromagnetic and hadron energy measurements up to $|\eta| = 4.9$.

Finally, the muon spectrometer is the outermost sub-detection system of ATLAS and it allows for muon momentum measurements. In combination with the magnetic field produced by the air-core toroidal magnets, it can be used to determine the charge of muons. The muon detector has excellent momentum resolution and it is used by the ATLAS trigger system. The performance targets for each ATLAS sub-detection system are shown in Table 3.5.

In terms of trigger and data acquisition, ATLAS implements a two-level trigger system. Since bunches of protons collide every 25 ns, the rate at which events happen is 40 MHz. Because the permanent data storage of the experiment is not capable of recording at such a rate, and the rate of interesting physics processes is not as high, the ATLAS trigger system is designed to filter the event output. First, the Level-1 (L1) trigger decides if processing the event is interesting enough

and reduces the output to 100 kHz. After, the Level-2 trigger also called High Level Trigger (HLT) takes the final data recording rate to around 1.2 kHz. The HLT is a software-based trigger in contrast to L1, which is hardware implemented [69].

In the next subsections, each detector sub-system is described in more detail.

3.2.1 Particle interactions

ATLAS can directly detect electrons, photons, muons and charged or neutral hadrons. Each of these particles interacts with certain parts of the detector. That information is combined to reconstruct *physics objects*. At the physics object level, the detector can reconstruct particles like taus; or light and heavy flavour jets. The physics objects are constructed from signals recorded in different sub-detection components and will be discussed in Section 3.3.

The key idea behind particle reconstruction is that the detector response to different particle types is distinctive. All charged particles leave hits in the inner detector and are bent by the magnetic field. For instance, electrons deposit energy in the EMCAL and form showers via braking radiation (Bremsstrahlung) and pair production. The EMCAL is built such that electrons deposit all their energy in the material. The ATLAS EMCAL has a length of 22 radiation lengths. All charged particles interact with the EMCAL.

Hadrons deposit their energy both in the HCAL and EMCAL. If they do not have an electric charge — like neutrons, they do not leave hits in the inner detector. Photons, on the other hand, are only detected as showers in the EMCAL. Muons can travel across the whole detector volume and leave hits in the inner tracker, small energy deposits in the calorimeters and hits in the muon chambers.

The ATLAS detector is transparent to particles like neutrinos. They escape the interaction volume without leaving any trails. However, they generate momentum imbalance in the events. Thus, their presence can be inferred from lost momentum. Figure 3.6 shows a representation of the different interactions that each particle experiments with the ATLAS detector sub-systems.

3.2.2 Tracking

Several collisions take place when two bunches of protons collide at the IP and this generates lots of particles travelling through the detector. The path in space of a particle and the signature it leaves in the detector is known as its *track*. Since particles are produced at the point where a pair of protons collide, it is expected that some tracks originate from the same location in space. These points are called *vertices*. ATLAS is robust enough to resolve the tracks and vertices generated in the busy environment of high-energy pp collisions.

The Inner Detector (ID) provides ATLAS with vertex and track resolution capabilities. The ID has fine granularity and two main technologies were used for its construction: silicon-based semiconductor sensors and transition radiation detectors. Figure 3.7 shows a transverse cut of the ID. For the silicon detectors, two technologies were used: pixels and microstrip detectors (SCT). For the transition radiation tracker (TRT), straw tubes filled with gas are interleaved with transition radiation material.

The ID resides inside a central superconducting solenoid — it is 5.3 m in length and 1.25 m in radius. The solenoid produces a 2 T magnetic field. A depiction of the ID geometry can be seen in Figure 3.8. For Run 2, an additional silicon detector was inserted closer to the beam pipe: the

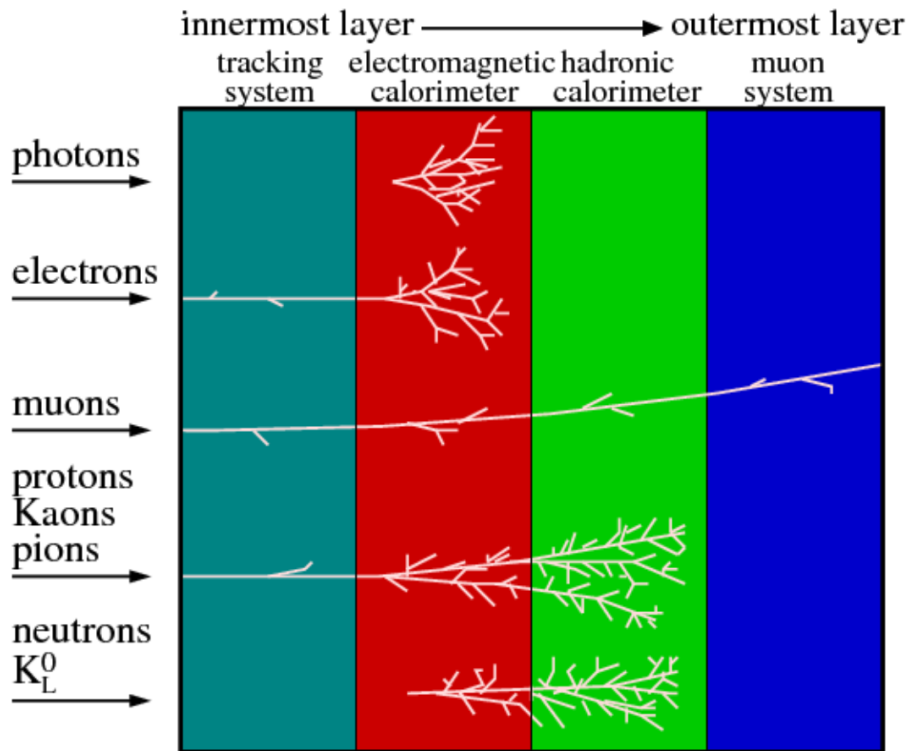


FIGURE 3.6: Different particles interact with specific ATLAS sub-detection systems. These signatures are combined to reconstruct particles at the object level. Taken from [70].

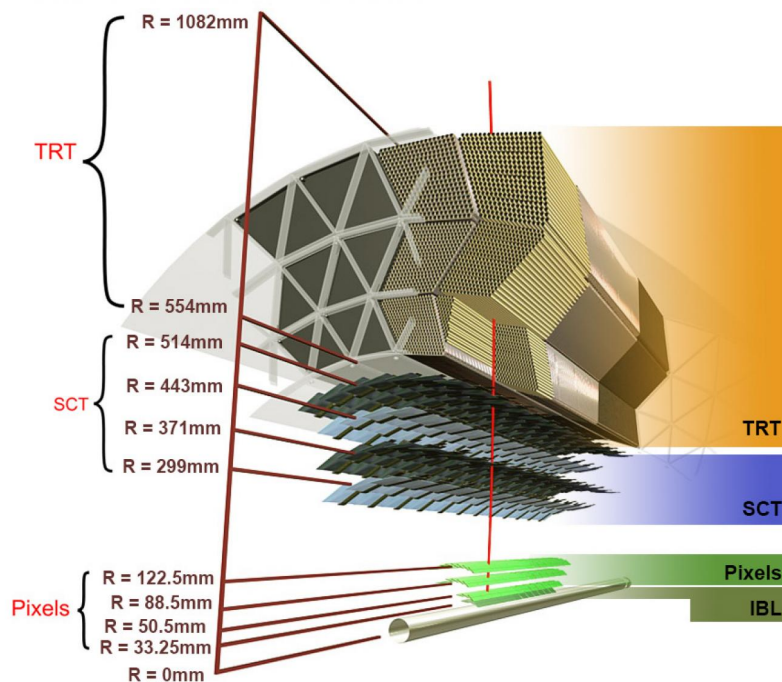


FIGURE 3.7: The ID layers distance with respect to the beam pipe. Taken from [62].

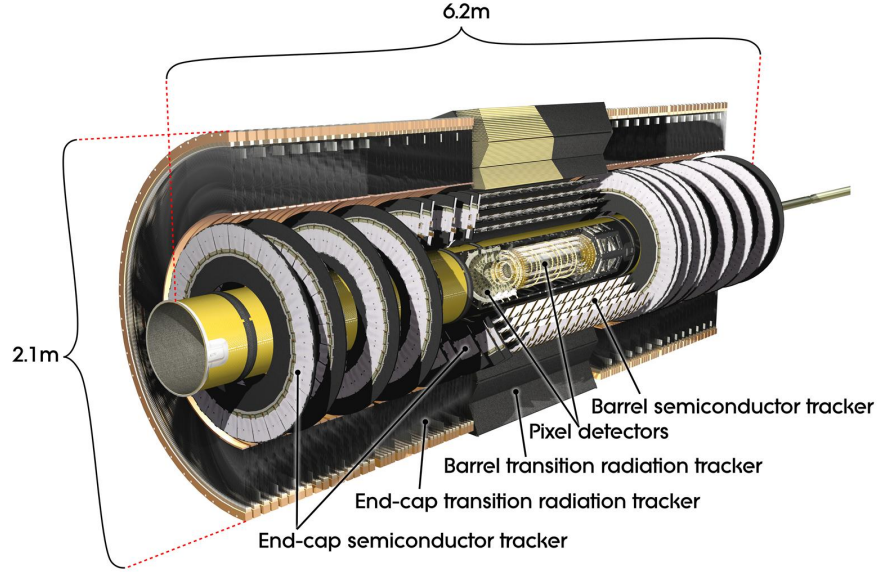


FIGURE 3.8: ID geometry showing the barrel and end-caps' instrumentation. Taken from [62].

Insertable B Layer (IBL) detector. The IBL is located 3 cm from the beam pipe and uses silicon pixel technology to record particle hits. It covers the rapidity range up to $|\eta| = 3$. The pixels have 3 layers and are arranged as three cylinders around the beam axis and six discs transverse to the beamline — three on each side of the detector. The pixels have a size of $50 \times 400 \mu\text{m}^2$. The pixel detector has approximately 80 million readout channels. The pixel detector intrinsic accuracies are $10 \mu\text{m}$ ($R-\phi$) and $115 \mu\text{m}$ (z) in the barrel, and $10 \mu\text{m}$ ($R-\phi$) and $115 \mu\text{m}$ (R) on the discs.

The working principle of the silicon sensors is the following: when a charged particle passes through the semiconductor material electron-hole pairs are generated. The charge is then driven by a bias voltage to readout sensors. These signals are interpreted as particle hits. In the SCT, four layers of instrumentation are crossed by each track. The number of channels in the SCT is approximately 6.3 million. The intrinsic accuracies of the silicon strips are $17 \mu\text{m}$ ($R-\phi$) and $580 \mu\text{m}$ (z) in the barrel, and $17 \mu\text{m}$ ($R-\phi$) and $580 \mu\text{m}$ (R) on the discs.

The TRT is the most external layer of the ID. It averages 36 hits per track. The TRT only provides $R-\phi$ information. Each straw tube is 4 mm in diameter and the accuracy is $130 \mu\text{m}$ per straw. The number of readout channels is approximately 351,000. When a charged particle passes through one of the straws, it ionizes the gas mixture and the generated charge is driven by an electric field to a wire passing through the centre of each straw tube. The TRT also provides electron identification against charged pions, since at the same particle energy the electrons and pions have different γ factors and transition radiation depends on this factor.

3.2.3 Calorimetry

ATLAS features an electromagnetic calorimeter (EMCAL) and a hadronic calorimeter (HCAL). The former was built to reconstruct the electromagnetic showers generated by electrons and photons. The latter is in charge of measuring cascades of hadrons. Both calorimeters are designed to ensure that only muons go through the material and it contains all the other types of radiation. ATLAS ECAL and HCAL are sampling calorimeters, which means that one material is used to

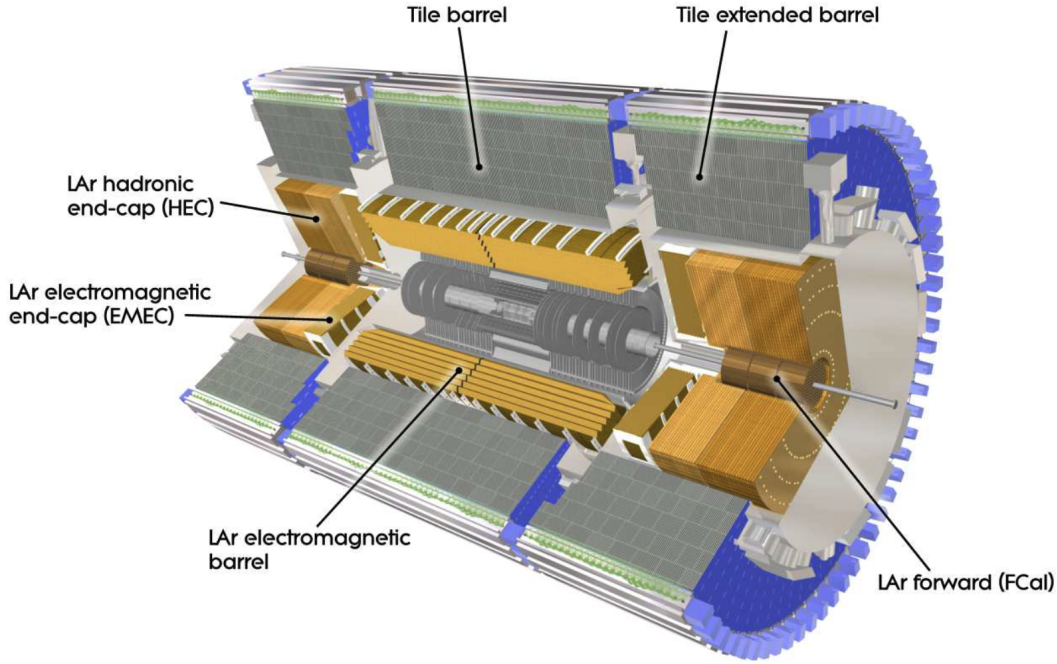


FIGURE 3.9: ATLAS calorimeter instrumentation geometry. Taken from [62].

create the particle shower (the absorber) and a different material acts as a sensor. The EMCAL has a thickness of 22 radiation lengths in the barrel and 24 in the end-caps. The size of the HCAL, given in nuclear interaction lengths is around 10 in both the end-caps and the barrel. A picture of the ATLAS entire calorimeter system can be seen in Figure 3.9. Including the forward calorimeters (FCal), the coverage in η goes up to 4.9.

The EMCAL barrel covers the pseudorapidity range $|\eta| < 1.475$ and the end-caps cover $1.375 < |\eta| < 3.2$. Lead and Liquid Argon (LAr) are used as the absorber-sensor technologies for the EMCAL, the HCAL end-caps and the FCal. The LAr calorimeters were built with accordion-shape, to prevent cracks in the azimuthal direction. The geometry of the calorimeter is split into three layers, each with different granularity in $\Delta\phi \times \Delta\eta$. Figure 3.10 shows a section of the EMCAL barrel geometry. The first layer is finely segmented in η ; the second is the longest and where most of the shower is contained; and the third layer has a coarser granularity.

When a photon or an electron interacts with the absorber material, bremsstrahlung radiation and pair production can occur — this results in the start of an electromagnetic shower. The electrons produced, ionise the LAr and the charge deposited in the sensors can be later converted into an energy measurement.

The HCAL uses LAr technology for the end-caps (HEC) and is located behind the EMCAL LAr calorimeter; they both share the same cryostat. The HEC covers $1.5 < |\eta| < 3.2$ and was constructed by combining 32 wedge-shaped modules to form each wheel. The absorber material is copper. The HEC is complemented by the LAr forward calorimeters (FCal). These calorimeters are exposed to high-radiation rates and the technology has been adapted to endure such conditions. The FCal provides coverage over $3.1 < |\eta| < 4.9$.

The outermost layer of the ATLAS calorimeters is the tile calorimeter; it uses steel as the absorber and a scintillator for the active medium. It is composed of a central barrel and two extended barrels — it covers $|\eta| < 1.7$. Hadrons that interact with the steel generate charged particles that

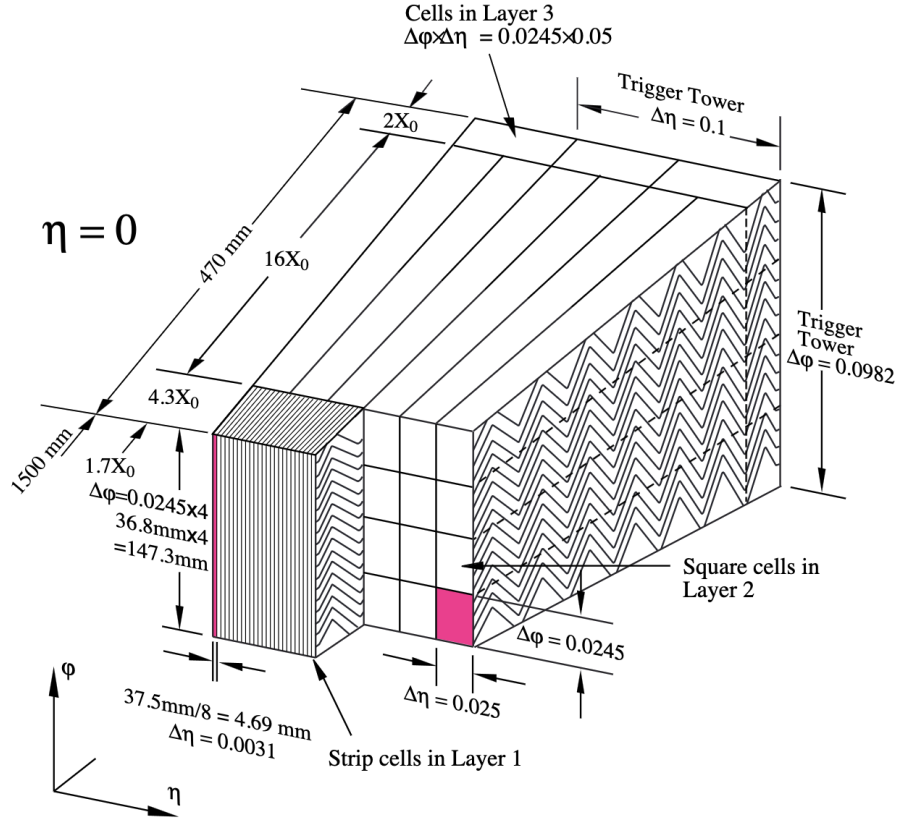


FIGURE 3.10: ATLAS EMCAL barrel geometry. Taken from [62].

later enter the scintillator material and produce photons. These photons are collected by optical fibres and are measured in photomultiplier sensors (PMTs).

The barrels are made of 64 modules, each covering an angle of $\Delta\phi \approx 0.1$. Figure 3.11 shows the geometry of the modules. The tile calorimeter granularity ranges from $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ for the internal layer to 0.2×0.1 for the external layer. The source tubes are used to insert movable radioactive sources (^{137}Cs) using a hydraulic control. The Cesium emits gamma radiation that is used to calibrate the optical components and the PMTs.

3.2.4 Muon detection

The muon spectrometer takes advantage of the track bending provided by the ATLAS magnet system. In the barrel region, $|\eta| < 1.4$, the magnetic field is generated by the large barrel toroid. In the region $1.6 < |\eta| < 2.7$, two smaller end-cap toroids produce the magnetic field. In the transition region, the magnetic field is a combination of the barrel and the end-cap toroids' fields. Different muon detector technologies are used to measure the trajectories of muons. The detectors are arranged in three cylindrical layers around the beam axis, and three disks centred around the beam for the end-caps. Figure 3.12 shows the muon spectrometer arrangement.

The momentum of charged particles exiting the calorimeters is measured by the muon spectrometer in the range $|\eta| < 2.7$. The goal is to have a resolution of 10% for 1 TeV tracks. The system is also designed to provide trigger capabilities in the range $|\eta| < 2.4$. In the centre of the detector, around $|\eta| \approx 0$, there is a gap to provide service to ATLAS systems. This lowers the performance of the muon spectrometer in that particular region.

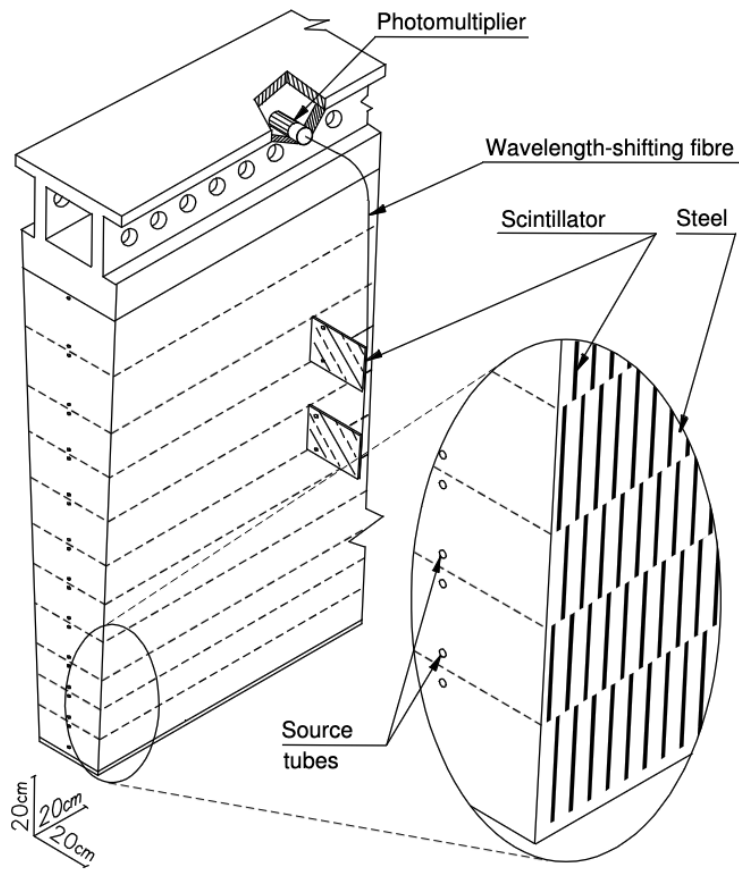


FIGURE 3.11: Diagram depicting one of the tile calorimeter modules including the locations of the detector components. Taken from [62].

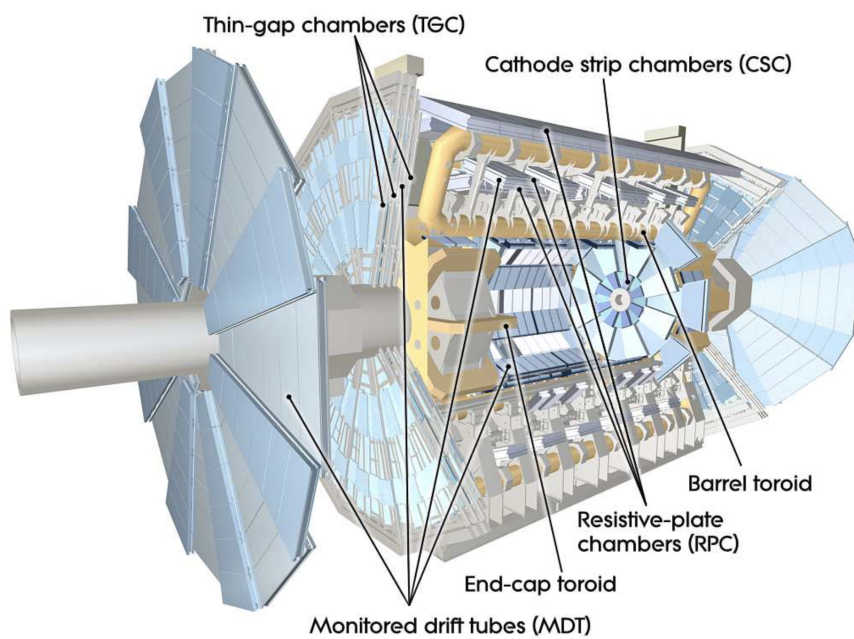


FIGURE 3.12: Muon chambers and magnet system arrangement. Taken from [62].

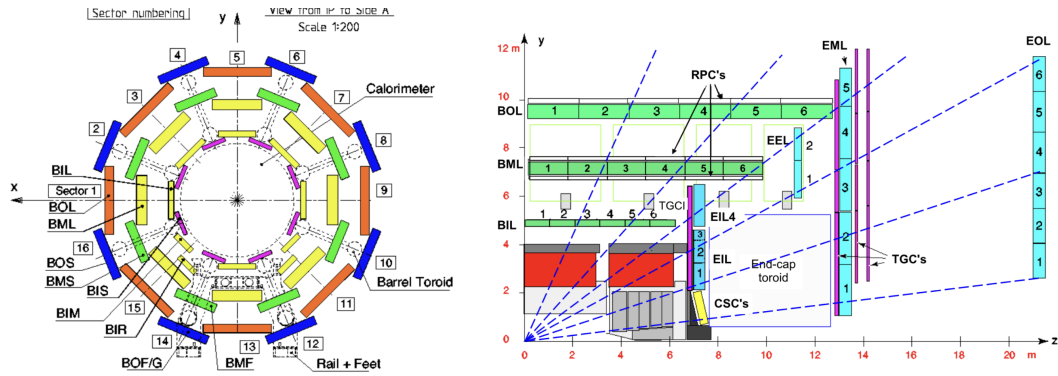


FIGURE 3.13: Muon chambers rings and disks layers, the trigger chambers cover a smaller pseudo-rapidity range. Taken from [62].

Precision momentum measurements are provided by Monitored Drift Tube chambers (MDTs) and Cathode Strip Chambers (CSCs). They cover the rapidity region $|\eta| < 2.7$ and are proportional chamber detectors. This means that when a charged particle passes through the gas contained in the drift tubes, it ionises the gas mixture and the charge is collected by wires passing across the tube axis. This signal is converted to a hit in the tube.

The muon spectrometer also serves as input for the trigger system. Fast trigger chambers, capable of providing track information in a few tens of nanoseconds after the passage of charged particles are installed in the muon detectors. For the barrel, $|\eta| < 1.05$, Resistive Plate Chambers (RPCs) have been chosen. In the end-caps, $1.05 < |\eta| < 2.4$, Thin Gap Chambers (TGCs) are installed. The chambers can help resolve beam collisions since they can emit signals with a spread of less than 25 ns. Transverse and parallel cross-section cuts of the ATLAS muon spectrometer, showing the chamber's geometry are shown in Figure 3.13.

3.2.5 Trigger and data acquisition

The ATLAS trigger system is in charge of processing all events (online) and selecting the most interesting ones to store and later process in analysis (offline) [69]. The trigger is designed as a two-level system. The first level is the Level-1 (L1) trigger, which is implemented in hardware and uses information from the calorimeters and the muon spectrometer. It selects events based on the presence of particle multiplicities above certain thresholds; event-level quantities, like the energy deposited in the calorimeters; or topological requirements, like the angle between objects. It takes the read-out rate from 40 MHz to 100 kHz — the latency of the L1 trigger is $2.5 \mu\text{s}$.

After the L1 accepts an event, the complete detector is read out and the information is passed to the High Level Trigger (HLT). The first step in the HLT is running fast trigger algorithms that provide early rejection. After that, more precise and CPU-intensive algorithms, similar to those used in offline reconstruction are run. The computing power is provided by a farm of 40000 processing units. The HLT software is based on the offline version used by the ATLAS collaboration (ATHENA) [71], which is based on Gaudi [72] — a framework for high energy physics experiments. In Run II, the output rate of the HLT was on average 1.2 kHz, corresponding to a data rate of 1.2 GB/s. After an event passes the trigger, the information is sent to the CERN computing centre, also called Tier-0. Figure 3.14 shows a diagram of the ATLAS trigger design.

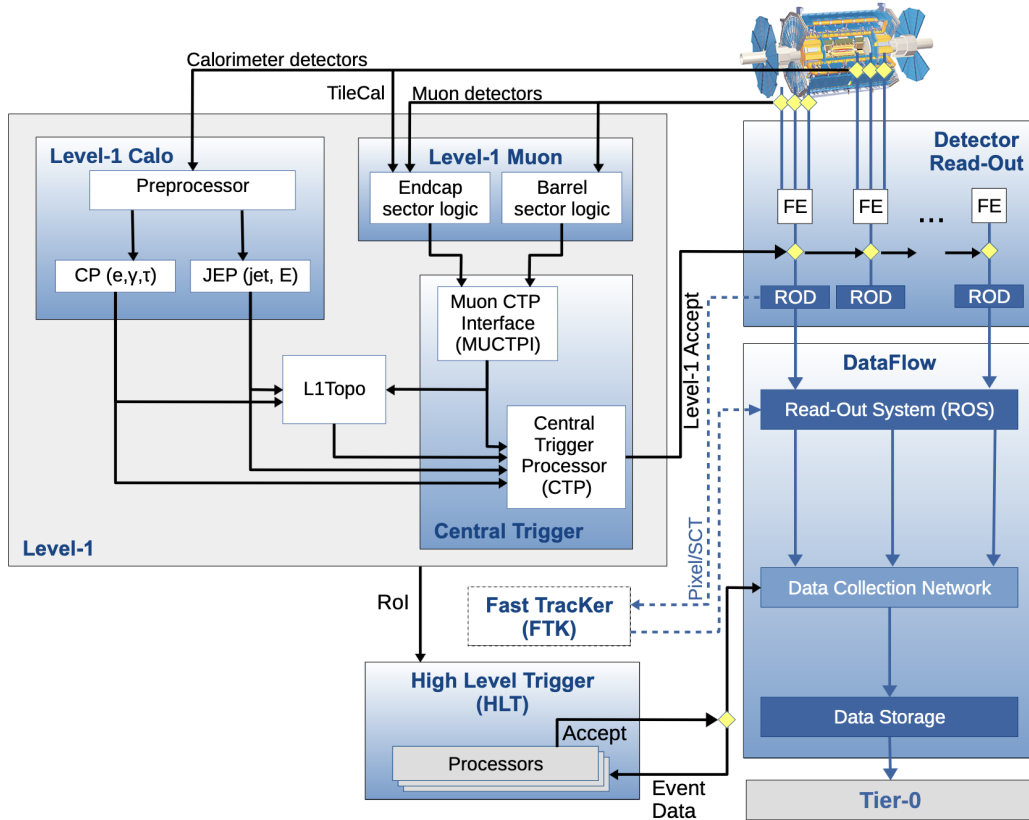


FIGURE 3.14: The ATLAS trigger system architecture for Run II. Taken from [69].

3.3 Physics objects reconstruction

3.3.1 Tracks and vertices

This section describes how the paths of charged particles (*tracks*) are reconstructed in ATLAS. Tracks are reconstructed by processing the raw measurements taken by the ID. The reconstruction starts by combining energy deposits in the silicon detectors which share an edge or a corner into clusters. These clusters represent the three-dimensional positions that a particle had when it traversed the detector. Track seeds are defined by groups of these clusters. The track seeds are required to be compatible with at least one additional hit in the ID.

To resolve the ambiguity between track candidates they are assigned a track score. The score of a track represents how likely it is to represent the path of a charged particle produced in the pp collisions. Tracks must pass some basic requirements: $p_T > 400$ MeV, $|\eta| < 2.5$, a minimum number of hits in the ID, a limited number of holes between layers of the silicon detectors and impact parameter requirements. Finally, a high-resolution fit is performed over all the tracks passing the ambiguity solver and they are added to the final track collection. A more detailed overview of the track reconstruction and performance in ATLAS can be found in [73].

Vertices are reconstructed using the information from the tracks. A vertex is a point in space where two or more tracks originate. The vertexing algorithm used in ATLAS starts by defining a seed point and then compares the compatibility of tracks with the seed [74]. The beam spot is used as the first seed for vertex reconstruction. Each track is given a weight after performing a fit to the vertex candidate. After iterating over all the tracks, the vertex candidate is calculated and

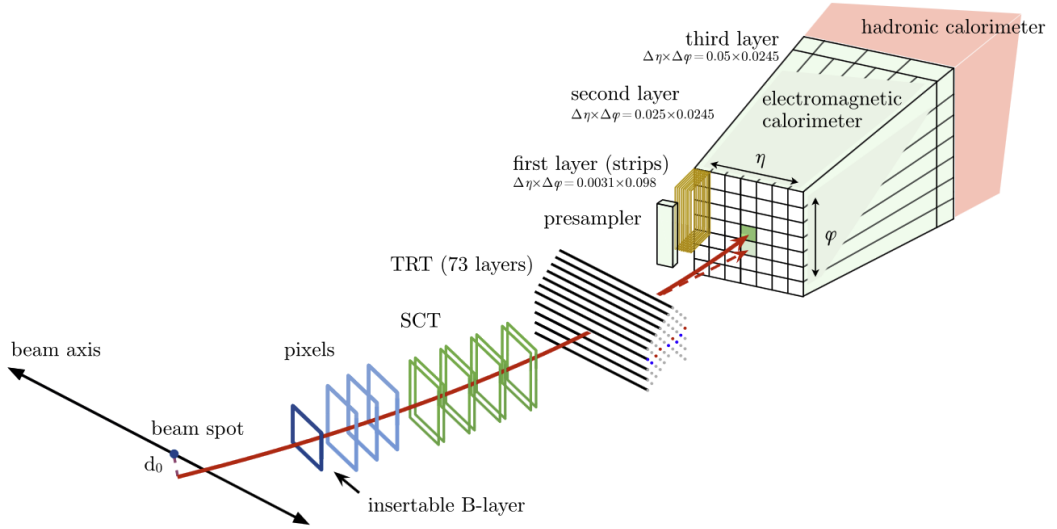


FIGURE 3.15: Trajectory of an electron across the detector sub-systems sensitive to its pass. The dotted line is used to indicate a photon radiated by the interaction of the electron with the material. Taken from [75].

the tracks that are incompatible with the vertex are grouped and considered for the next vertex candidate.

The *primary vertex* (PV) is defined as the one having the largest value for the sum of the squares of the p_T of the tracks associated with it. For each track a transverse impact parameter d_0 is defined: this is the shortest distance between the track and the vertex in the transverse plane. Additionally, the impact parameter significance is defined as d_0/σ_{d_0} , where σ_{d_0} is the uncertainty in the impact parameter.

3.3.2 Electrons reconstruction and identification

Electrons traversing the ATLAS active volume generate showers due to interactions with the material. These showers are recorded as energy deposits in the EMCAL and also leave hits in the ID which are later reconstructed as tracks. The combination of these signatures is used to reconstruct electrons in ATLAS [75]. Figure 3.15 shows an illustration of the electron interactions with the ATLAS sub-systems.

Electron reconstruction starts by forming *topo-clusters* in the EMCAL. The clusters are based on the energy deposited in cells defined by a fixed area in $\Delta\phi \times \Delta\eta$ [76, 77]. The next step is to match tracks with the topo-clusters. After the matching is made, candidates are seeded to a *supercluster* grouping algorithm: it adds secondary clusters coming from bremsstrahlung or topo-cluster splitting to the electron candidates [78]. Finally, *identification* algorithms are run over the electron candidates to increase the purity of the reconstructed electrons.

The identification algorithm is based on a likelihood discriminant that exploits variables related to the primary electron track properties, the spatial properties of the generated shower and the geometric compatibility of the primary track with the reconstructed cluster. This procedure is designed to discriminate electrons generated at the interaction vertex (*prompt electrons*), from hadronic jets, converted photons and genuine electrons generated at heavy-flavour hadron decays.

3.3.3 Muons reconstruction and identification

The muon reconstruction is based on the information provided by the ID and the Muon Spectrometer (MS) [79]. Since muons are minimum-ionising particles, their energy deposits in the calorimeters have distinctive characteristics. When just the information from the MS is used for muon reconstruction the procedure followed is: short segments are formed from the hits recorded at individual MS stations. Then, these segments are combined into tracks, requiring them to point at the IP and assuming a parabolic shape to take into account the track bending in the magnetic field. Finally, a fit of the muon trajectory that takes into account interactions with the material and possible MS misalignments is performed.

Usually, the information of the MS is combined with the other ATLAS sub-detection systems. Depending on which elements are used, different muon *types* are defined: combined muons (CB), inside-out combined muons (IO), MS extrapolated muons (ME), segment-tagged muons (ST) and calorimeter-tagged muons (CT). A brief description of each type is presented.

- Combined muons are reconstructed by combining the MS and ID tracks, taking into account energy loss in the calorimeters. For $|\eta| > 2.5$, just the information from the silicon detectors can be used in combination with the MS tracks to form a subset of CB muons called silicon-associated forward (SiF) muons.
- IO muons are defined by extrapolating ID tracks to the MS. This algorithm does not rely exclusively on MS-reconstructed tracks and targets muons that pass over limited coverage MS regions or low- p_T muons not reaching all the muon stations.
- ME muons use only the information from the MS and extrapolate the track to the beamline. These muons are aimed to recover the acceptance outside the ID coverage.
- ST muons are constructed by requiring that one ID track matches at least one MS segment. The track parameters from the ID are assigned to the muon.
- CT muons use the ID tracks to extrapolate to the calorimeters. Energy deposits consistent with a minimum-ionising particle are used to tag the muon and take its parameters from the ID tracks.

Furthermore, muon identification criteria are also defined. The goal is to discriminate prompt muons from the ones generated in heavy flavour decays and to reject fakes from light hadrons.

3.3.4 Jets reconstruction and identification

In high-energy physics a *jet* is narrow cone of hadrons produced by the hadronisation of quarks or gluons. The signature of a jet usually involves tracks recorded in the ID and deposits of energy in the calorimeters. The jet definition used by ATLAS relies on the clustering anti- k_t algorithm with a radius parameter $R = 0.4$ [80]. This algorithm uses as input any object that has a defined 4-momentum: a particle track, calorimeter energy deposits or combinations of the two. As mentioned before, energy deposits in the calorimeters are grouped into topo-clusters. For jet reconstruction, all topo-clusters are corrected to account for the position of the PV. This correction is referred to as *origin correction*.

Jets reconstructed only using calorimeter information are known as *EMtopo jets*. This was the main jet definition prior to Run II [81]. In recent years, the particle flow algorithm has been used to define *PFlow* jets [82], which use both the information from the ID and the calorimeters. Jets used for analysis are usually required to pass jet vertex tagging (JVT) requirements [83]; high JVT scores are given to jets that match with the PV.

Algorithms targeted to tag jets generated from heavy flavour decays are also used in ATLAS [84]. Hadrons formed by b-quarks often travel a few mm from the hard-scatter point before decaying. Multivariate algorithms have been designed to exploit the impact parameters and the displaced vertices that these decays generate. Since the tracking information is crucial for flavour tagging algorithms, jet flavour distinction can only be performed in the region $|\eta| < 2.5$.

3.3.5 Missing transverse momentum

Any particle escaping the ATLAS detector, without leaving any traces, will generate a momentum imbalance in the hard-scatter event — because from momentum conservation, one expects to have zero momentum in the transverse plane. One example of invisible particles is neutrinos, whose presence can be inferred by computing the quantity,

$$\vec{E}_T^{\text{miss}} = - \sum_i \vec{p}_T, \quad (3.6)$$

where i corresponds to all the visible physics objects in the event. The missing transverse energy (MET) is defined as the magnitude of the previously mentioned vector,

$$E_T^{\text{miss}} = |\vec{E}_T^{\text{miss}}|. \quad (3.7)$$

Chapter 4

The tau lepton in ATLAS

4.1 Tau lepton overview

In Section 2.3 we introduced the particle content of the SM. The tau lepton is a charged fermion that belongs to the third family of leptons. In experiments conducted at the Stanford Linear Accelerator and the Lawrence Berkley National Laboratory, the first hints of the tau existence were found [85]. The experiments discovered 64 events where

$$e^+ + e^- \rightarrow e^\pm + \mu^\mp + \geq 2 \text{ undetected particles.} \quad (4.1)$$

At the time, there was no conventional explanation for this process.

By introducing a heavier charged lepton, called the tau (τ), that could decay into the two lighter generations of leptons via electroweak interactions, one could explain the process shown in Equation 4.2. Events like

$$e^+ + e^- \rightarrow \tau^+ + \tau^- \rightarrow e^\pm + \mu^\mp + 4\nu \quad (4.2)$$

were later used to measure the mass of the tau [86, 87]; confirming the existence of a third generation of charged leptons.

4.1.1 Tau decays

The tau lepton has a mass of 1776.86 ± 0.12 MeV. This allows it to decay into electrons and muons; and also into light hadrons such as pions (π), kaons (K), rhos (ρ), etas (η) and omegas (ω) [31]. Tau decays take place through weak interactions: a tau lepton decays into a W boson producing also a tau neutrino (ν_τ); the W can later decay into a charged lepton and a neutrino, or a quark pair.

The former decays are referred to as *leptonic decays* and taus generating these final states are denoted as τ_{lep} . A Feynman diagram showing this process is shown in Figure 4.1. The latter decays are known as *semi-hadronic decays* (semi because of the presence of the tau neutrino) and are represented as τ_{had} . In high energy physics, semi-hadronic decays are commonly referred to just as hadronic tau decays. We are going to use this convention in the rest of this work. Figure 4.2 shows the Feynman diagram for the hadronic tau decay.

A rough estimate of the branching fractions of the tau decays can be done by counting the number of allowed final states. In the leptonic mode, two decays are possible. For the quarks,

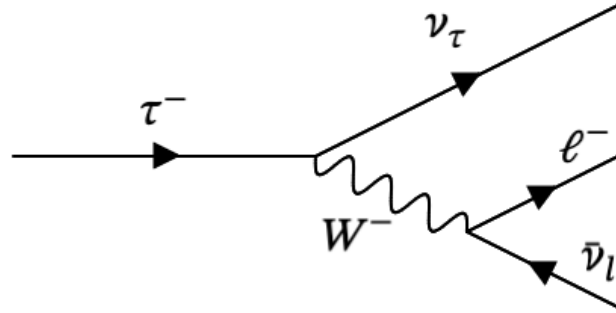


FIGURE 4.1: Leptonic tau decay mode. Two neutrinos and one light lepton ($l = e, \mu$) are produced in this final state.

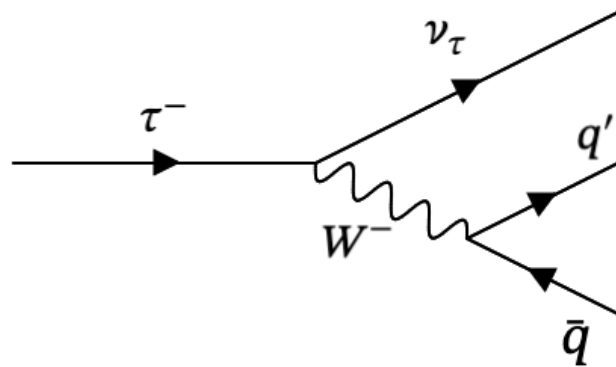


FIGURE 4.2: Hadronic tau decay mode. One neutrino and a pair of quarks are produced in these final states. Quarks later hadronise into light mesons like pions or kaons.

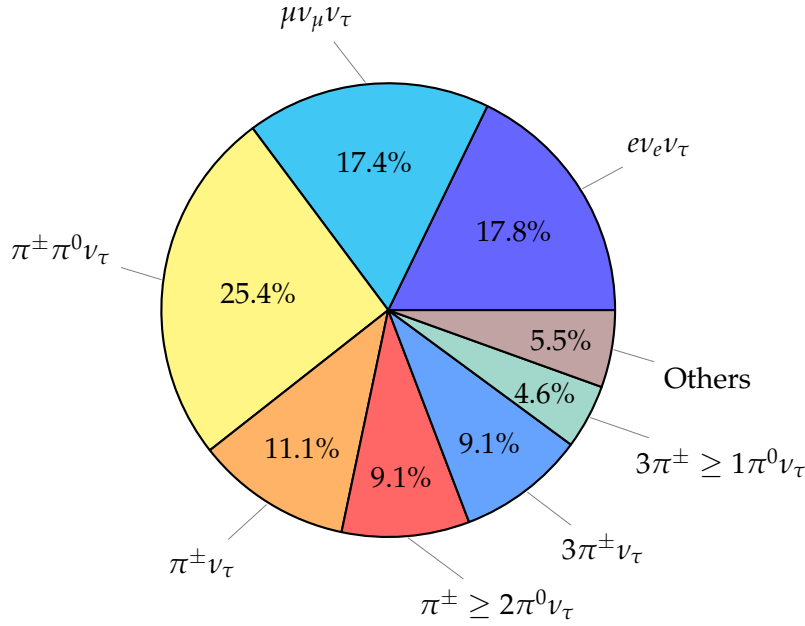


FIGURE 4.3: Tau branching fractions by decay mode. The $X\pi^\pm \geq Y\pi^0\nu_\tau$ symbol denotes decays where Y or more neutral pions are produced

since the masses of the first generation (u, d) are smaller than the second generation (c, s) the decay rate to the first generation gets enhanced — the V_{us} component of the CKM matrix allows for a not completely negligible decay rate to channels including hadrons like Kaons and other strange particles. Additionally, since quarks come in three different colours, those have to be counted in the decay possibilities. Thus, one would expect the leptonic decays to share 40% of the branching fraction, leaving 60% to the hadronic case. This naive estimation is not bad. Actual values for the leptonic branching fractions are [31]:

$$\beta(\tau \rightarrow e\nu_e\nu_\tau) = 17.82 \pm 0.04\%, \quad (4.3)$$

$$\beta(\tau \rightarrow \mu\nu_\mu\nu_\tau) = 17.39 \pm 0.04\%. \quad (4.4)$$

The reason for the difference in the branching fraction estimation is the QCD corrections in the hadronic decays [88]. The small difference between the leptonic branching fractions is due to the muon and electron mass difference. Almost 90% of the hadronic tau decays contain at least one pion. A more detailed overview of the tau decays is shown in Figure 4.3.

4.2 Reconstruction of hadronic taus in ATLAS

In general, light leptons produced in τ_{lep} decays have a softer p_T spectrum than prompt muons and electrons. They also tend to have higher impact parameters than prompt leptons. However, these features are not enough to reconstruct and identify τ_{lep} candidates as singular objects; nonetheless, the presence of a τ_{lep} can be inferred by selecting certain final states such as $Z \rightarrow \tau_{\text{had}}\tau_{\text{lep}}$ or $H \rightarrow \tau_{\text{had}}\tau_{\text{lep}}$ decays. Only τ_{had} are reconstructed and identified in ATLAS as stand-alone objects.

Tau reconstruction is seeded by jets (as defined in Section 3.3.4) if they satisfy $p_T > 10 \text{ GeV}$ and $|\eta| < 2.5$. The energy clusters are calibrated using the local hadronic calibration method [89].

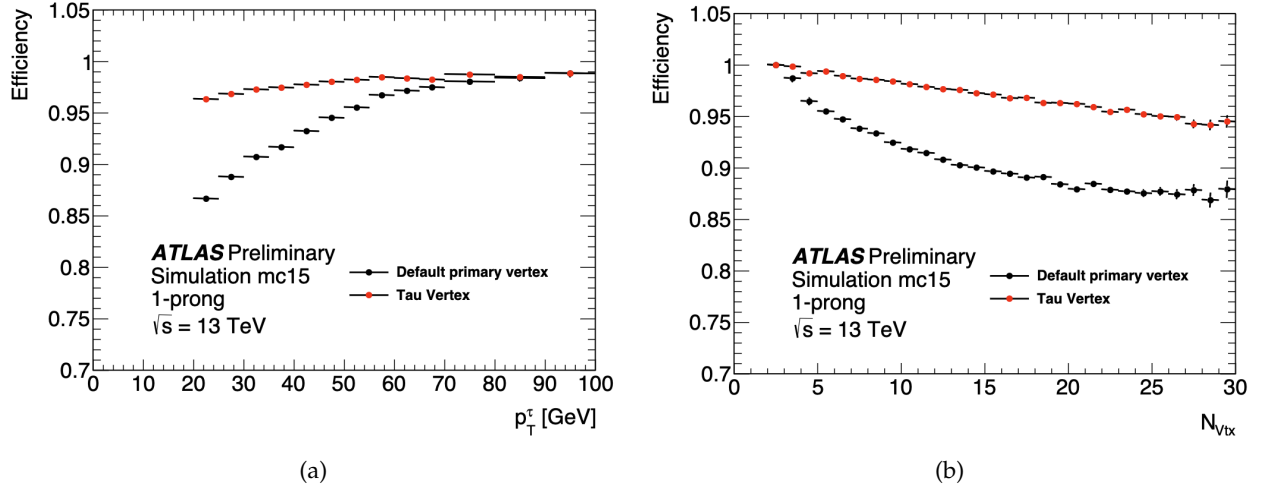


FIGURE 4.4: Efficiency comparison between default primary vertex and tau dedicated vertex algorithms. The efficiency is shown as a function of the tau- p_T (4.4a) and the number of vertices (4.4b). Taken from [90].

This accounts for energy lost in non-active material, energy discarded by algorithm thresholds and energy escaped from the calorimeters.

A dedicated tau vertex (TV) reconstruction is also performed. The TV algorithm uses all the tracks in a cone of size $\Delta R < 0.2$ around the seed jet direction. The p_T of the tracks is summed and compared with all the other primary vertex candidates. The vertex with the matched largest fraction of the p_T sum is chosen as the TV. By using the dedicated TV algorithm the efficiency of selecting the truth tau vertex is improved — both as a function of the tau- p_T and the number of interaction vertices [90]. The corresponding efficiencies are shown in Figure 4.4.

Tracks are associated with the τ_{had} candidate if they lie inside a cone of size $\Delta R < 0.2$ around the seed jet direction; have a $p_T > 1$ GeV; at least two (seven) hits are recorded in the pixel (SCT) detector; and impact parameter requirements are fulfilled with respect to the TV. Taus are split into one and three-prong candidates, depending on the number of tracks associated with the tau.

The reconstruction efficiencies for 1-prong and 3-prong τ_{had} candidates are shown in Figure 4.5 — the efficiency depends on the tau number of prongs and p_T . The efficiency for finding a tau-seed with $p_T > 20$ GeV within the pseudo-rapidity acceptance is almost 100%. The main reasons for the τ_{had} reconstruction efficiency drop are the tau track and vertex selections. High- p_T τ_{had} candidates can decay after the first pixel detector and miss the number of hits requirement, or additional tracks can be incorrectly assigned from gamma radiation that converts into electrons. These are the two main reasons for the efficiency drop at high- p_T . For 3-prongs, the reduction in efficiency at low- p_T arises from tracks missing the minimum momentum threshold. At high- p_T , the taus are more collimated and tracks can be merged and missed.

4.2.1 Hadronic decay modes

The tau reconstruction algorithm classifies the hadronic taus by the number of charged tracks. However, more than 90% of the hadronic taus yield one or three charged hadrons, up to two neutral pions and a tau neutrino. Hence, a dedicated algorithm, called *Tau Particle Flow* (TPF), is used to classify the *tau decay modes* in ATLAS [91]. First, neutral pions (π^0) are reconstructed and

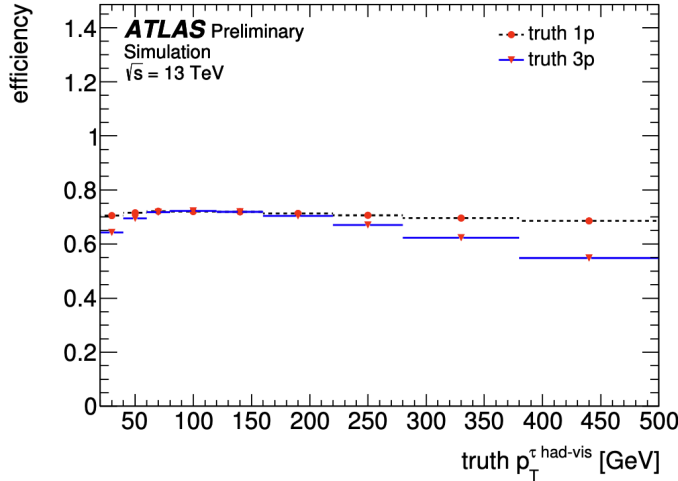


FIGURE 4.5: Tau reconstruction efficiency for 1-prong and 3-prong candidates as a function of p_T . Taken from [90].

identified from their energy deposits in the EM calorimeter. The shape and depth of the energy deposits of π^0 in the EM calorimeter are used to differentiate against charged hadrons ($h^\pm$).

The ID hits are used to reconstruct the tracks of $h^\pm$. Any tracks inside the core region of a τ_{had} are considered. Finally, multivariate algorithms, called Boosted Decision Trees (BDTs), use the kinematics, the identification scores and the multiplicities from the reconstructed π^0 and $h^\pm$ to classify the decay mode. One BDT is trained per decay mode. The efficiency of the TPF algorithm can be seen in Figure 4.6.

4.2.2 Energy calibration

A dedicated energy calibration for taus is performed in ATLAS [92]. The energy measured in the sub-detectors and used to reconstruct the tau candidates is corrected to match the energy at the generator level. The baseline calibration corrects for excess energy coming from the pileup events. At high- p_T this method results in good energy resolution. For the low- p_T range, a multivariate analysis technique called the BRT method, is applied to obtain the tau energy calibration. It uses information from: the baseline calibration, the TPF algorithm, the calorimeter and tracking measurements. The resolution of the two calibration procedures can be seen in Figure 4.7.

4.3 Tau identification

The tau reconstruction algorithm does not provide sufficient discrimination against objects that could fake the signal of a tau, such as jets produced purely from QCD radiation or electrons. Algorithms that perform this classification and allow for tau *identification* are described in this section.

4.3.1 Fakes from hadrons

Both genuine τ_{had} and hadrons generated in QCD interactions (hadronic jets) leave traces in the calorimeters and the ID. Thus, a hadronic jet can be reconstructed as a tau candidate. Algorithms that exploit the differences in the shape of the jet cone, the particle multiplicities, and the impact

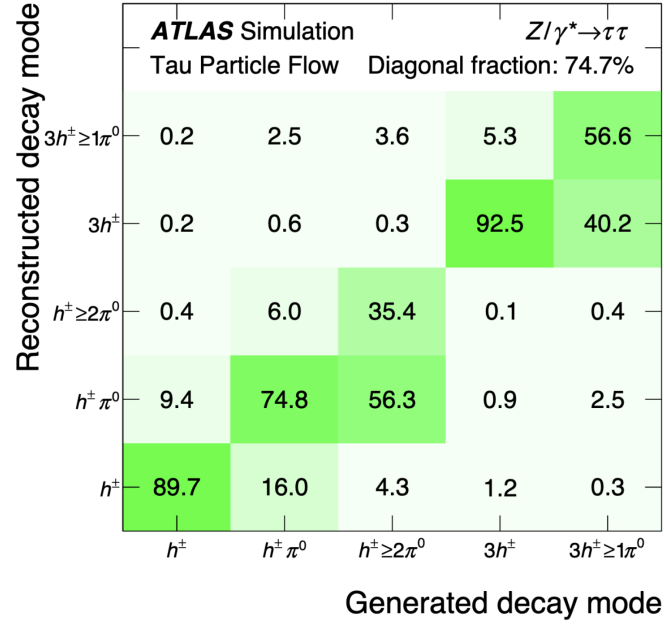


FIGURE 4.6: Tau decay mode efficiency matrix obtained from $Z \rightarrow \tau\tau$ simulated events. Taken from [91].

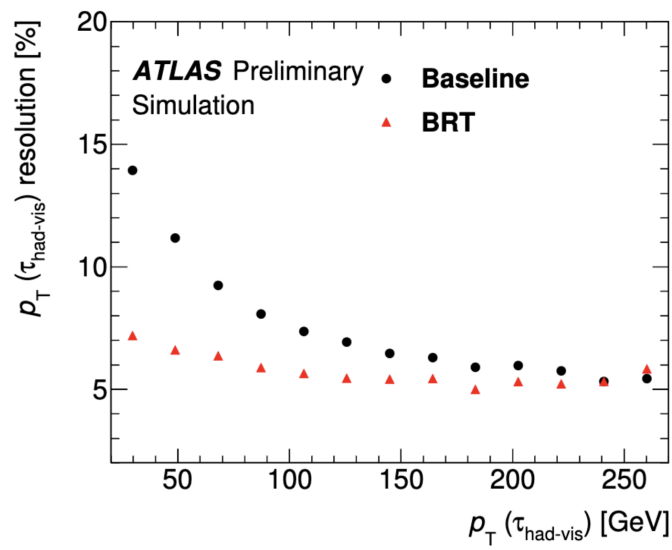


FIGURE 4.7: Comparison of the tau energy resolution between the baseline and BRT methods as a function of p_T . Taken from [92].

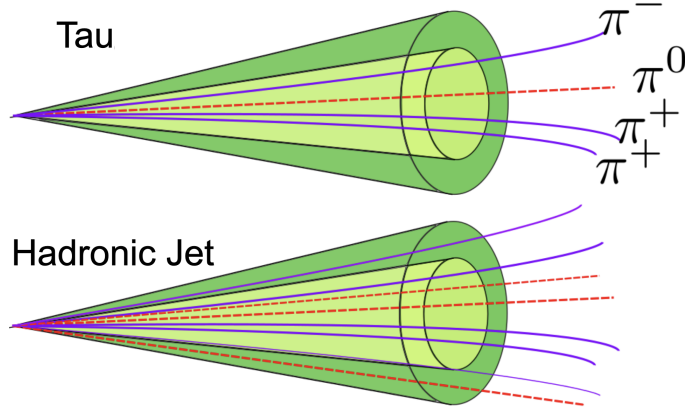


FIGURE 4.8: Differences between a 3-prong τ_{had} and a jet originated from quark or gluon radiation. Charged hadrons are shown as thick lines and dashed lines represent neutral particles. The green cone is drawn to depict how τ_{had} product decays are more collimated.

parameters of tracks associated with the seed jet are used to distinguish between genuine τ_{had} and hadronic fakes [93].

Hadronic jets tend to be broader due to the higher probability of soft gluon radiation in quark and gluon jets. They also present a higher multiplicity of hadrons when compared to genuine τ_{had} candidates. Figure 4.8 shows a pictorial representation of the differences between a τ_{had} and a hadronic jet.

Previously, ATLAS used a BDT algorithm to perform tau identification [90]. Recently, it has been superseded by a Recurrent Neural Network (RNN) classifier. A dedicated RNN is trained for 1-prong and 3-prong candidates. Before the RNN algorithm is run, the candidate tracks are classified into *core* and *isolation* tracks by a set of boosted decision trees (BDTs). These algorithms use as input track-associated variables such as the number of hits in the ID, the p_T and the impact parameters of the tracks. The following input variables are used by the RNN.

- For tracks associated with the tau candidate the following variables are included: transverse momentum (p_T^{track}), the transverse and longitudinal impact parameters ($d_0^{\text{track}}, z_0^{\text{track}} \sin \theta$), the angular distance to the τ_{had} axis ($\Delta\eta^{\text{track}}, \Delta\phi^{\text{track}}$) and the number of hits in the different ID layers ($N_{\text{Pixel hits}}, N_{\text{IBL hits}}, N_{\text{SCT hits}}$).
- The variables associated with topo-clusters are the transverse energy (E_T^{cluster}) and the angular distance to the τ_{had} axis ($\Delta\eta^{\text{cluster}}, \Delta\phi^{\text{cluster}}$).

Additionally, the following cluster moments are used [76]:

- Cluster depth (λ_{cluster}): the distance of the cluster barycentre from the calorimeter front face, measured along the cluster axis.
- Longitudinal cluster extension ($\langle \lambda_{\text{cluster}}^2 \rangle$): the second moment of the longitudinal distance of cluster cells from the cluster barycentre, along the cluster axis.
- Radial extension ($\langle r_{\text{cluster}}^2 \rangle$): the second moment of the radial distance of cluster cells from the cluster axis.

At the same time, the following high-level variables are considered:

- Transverse momentum of the original jet seed ($p_T^{\text{seed jet}}$).
- Transverse momentum at the LC scale (p_T^{uncalib}): the transverse momentum of the τ_{had} before dedicated tau energy calibration. The cluster origin is set to the tau production vertex.
- Central energy fraction (f_{cent}): the fraction of the transverse energy between the region $\Delta R < 0.1$ and $\Delta R < 0.2$ around the τ_{had} axis.
- Inverse momentum fraction of the leading track ($f_{\text{lead track}}^{-1}$): the transverse energy sum of all topo-clusters in the core region, divided by the transverse momentum of the highest- p_T core track associated with the τ_{had} candidate.
- Maximum track ΔR (ΔR_{max}): the maximum ΔR between a core track and the τ_{had} candidate.
- Transverse impact parameter significance of the leading track ($|S_{\text{Lead track}}|$): the transverse impact parameter of the highest- p_T core track associated with the τ_{had} candidate, calculated with respect to the tau vertex, divided by the uncertainty on the impact parameter itself.
- Transverse flight path significance (S_T^{flight}): the decay length of the secondary vertex in the transverse plane, calculated with respect to the tau vertex, divided by its estimated uncertainty.
- Momentum fraction of isolation tracks ($f_{\text{iso}}^{\text{track}}$): the scalar sum of the p_T of the isolation tracks, divided by the sum of the p_T of all core and isolation tracks.
- Ratio of EM energy and track momentum ($f_{\text{track}}^{\text{EM}}$): the sum of the cluster energy deposited in the EMCAL divided by the sum of the momentum of core tracks.
- Fraction of track-plus-EM-system p_T ($p_T^{\text{EM+track}}/p_T$): the ratio of the τ_{had} p_T , calculated using the vector sum of the momentum of core tracks and up to two of the most energetic EM clusters in the core region, to the calorimeter-only measurement of the τ_{had} p_T .
- Mass of the track-plus-EM-system ($m^{\text{EM+track}}$): the invariant mass of the core tracks combined with up to two of the most energetic EM clusters located in the core region.
- Mass of track system (m^{track}): the invariant mass of the core and isolation tracks, the mass of the pion is assumed for each track.

Some of the distributions of the input variables are shown in Figure 4.9.

The RNN architecture was chosen because it allows the processing of sequences of unknown length. Track, cluster and high-level variable information is treated separately in the first stages of the NN; they are later merged to produce a tau identification score.

The performance of tau identification is shown in Figure 4.10. The rejection power, defined as the reciprocal of the background selection efficiency of the RNN, exceeds the previous BDT algorithm. Different working points for the RNN are defined. These are related to the signal efficiency for genuine taus. Table 4.1 shows the different RNN working points. Figure 4.11 shows the τ_{had} identification efficiency as a function of p_T .

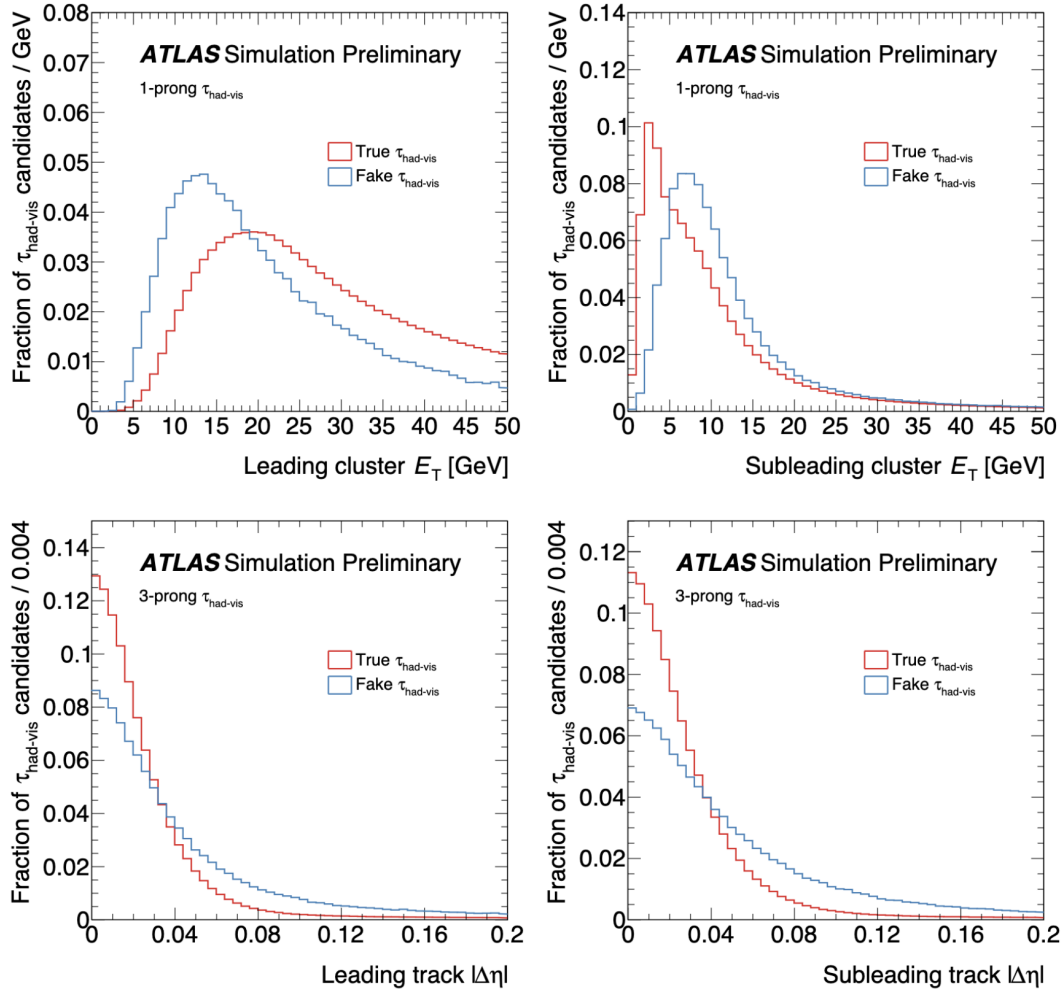


FIGURE 4.9: Distribution of the leading and sub-leading topo-cluster transverse energy (top), and pseudo-rapidity separation from the τ_{had} candidate for the leading and sub-leading track. Red histograms represent genuine τ_{had} candidates while fakes are in blue. Taken from [93].

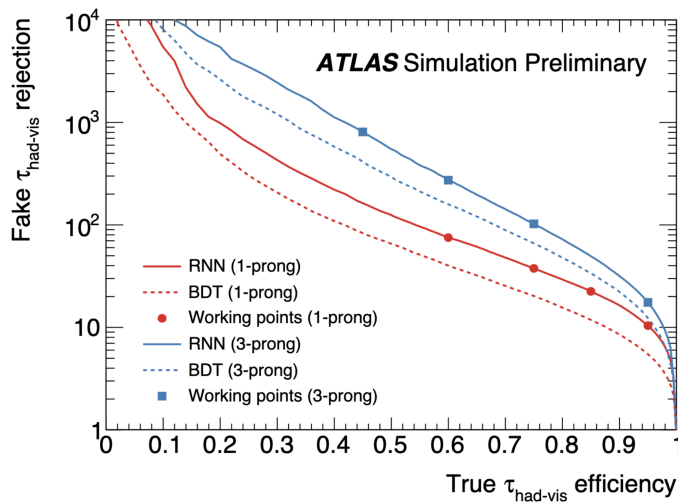


FIGURE 4.10: Rejection power of the tau identification RNN as a function of the efficiency to select genuine τ_{had} candidates. Working points are shown as solid points along the lines. The results for 1-prong and 3-prong taus are in red and blue respectively. The RNN performance is better when compared to the previous BDT algorithm — this can be observed in the plot since for any given τ_{had} efficiency the rejection power of the RNN is greater than the BDT rejection. Taken from [93].

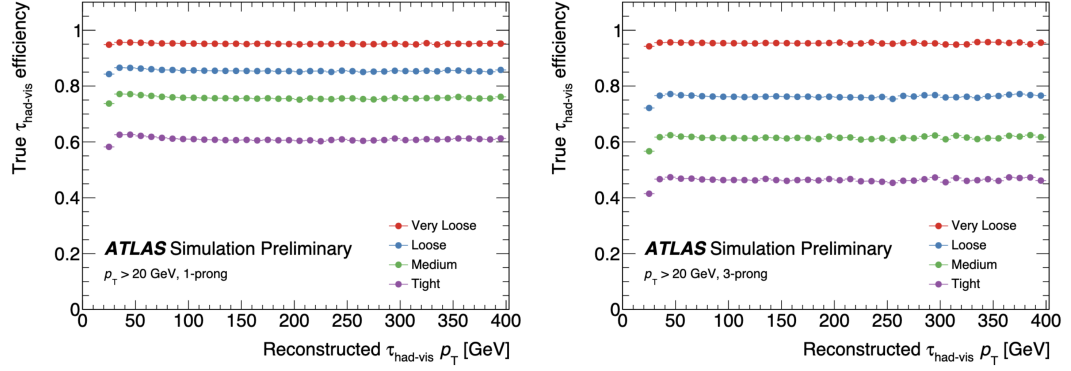


FIGURE 4.11: Efficiency for true τ_{had} identification as a function of p_T . The efficiency is flat for the different working points. Results for 1-prong and 3-prong taus are shown on the left and right, respectively. Taken from [93].

Working point	Signal efficiency (%)		Background rejection	
	1-prong	3-prong	1-prong	3-prong
Tight	60	45	70	700
Medium	75	60	35	240
Loose	85	75	21	90
Very loose	95	95	9.9	16

TABLE 4.1: Tau identification working point definitions and background rejection power. Values are shown for 1-prong and 3-prong taus separately.

4.3.2 Tau ID calibration

The performance of the BDT tau identification algorithm (tauID) is measured using a sample enriched in $Z \rightarrow \tau_{\text{had}} \tau_{\text{lep}} \rightarrow \tau_{\text{had}} \mu$ events [92] — there are not yet published results for the calibration of the new RNN algorithm presented in the previous section. The tauID performance is compared between data and simulation, and *correction or scale factors* (SFs) are applied to bring the tauID efficiency in simulation (ϵ_{MC}) to the level observed in data (ϵ_{Data}).

The calibration approach consists of selecting events where the muon fires the trigger and is used as a tag. At the same time, events must have at least one hadronic tau candidate which is used as a probe. This approach is known as the *tag-and-probe* method.

Candidate events must pass a very loose requirement (not to be confused with any of the previously presented TauID RNN working points) on the tauID BDT score. This requirement suppresses jets while being more than 99% efficient for the tau candidates. The selection requirements described in [92] are used to enhance the contribution from $Z \rightarrow \tau_{\text{had}} \tau_{\mu}$ events. After the final selection, the main background source is jets misidentified as hadronic tau decays (MJ BG).

The efficiency of the tauID in MC for a given RNN working point X is defined as:

$$\epsilon_{\text{MC}}(X) = \frac{N_{Z \rightarrow \tau_{\text{had}} \tau_{\mu}}(\text{AfterX-tauID})}{N_{Z \rightarrow \tau_{\text{had}} \tau_{\mu}}(\text{VeryLoose-tauID})}, \quad (4.5)$$

where $N_{Z \rightarrow \tau_{\text{had}} \tau_{\mu}}$ is the number of predicted $Z \rightarrow \tau_{\text{had}} \tau_{\mu}$ events.

In data, the efficiency is defined as:

$$\epsilon_{\text{Data}}(X) = \frac{(N_{\text{Obs}} - N_{\text{MJ BG}} - N_{\text{MC BG}})(\text{AfterX-tauID})}{(N_{\text{Obs}} - N_{\text{MJ BG}} - N_{\text{MC BG}})(\text{VeryLoose-tauID})}, \quad (4.6)$$

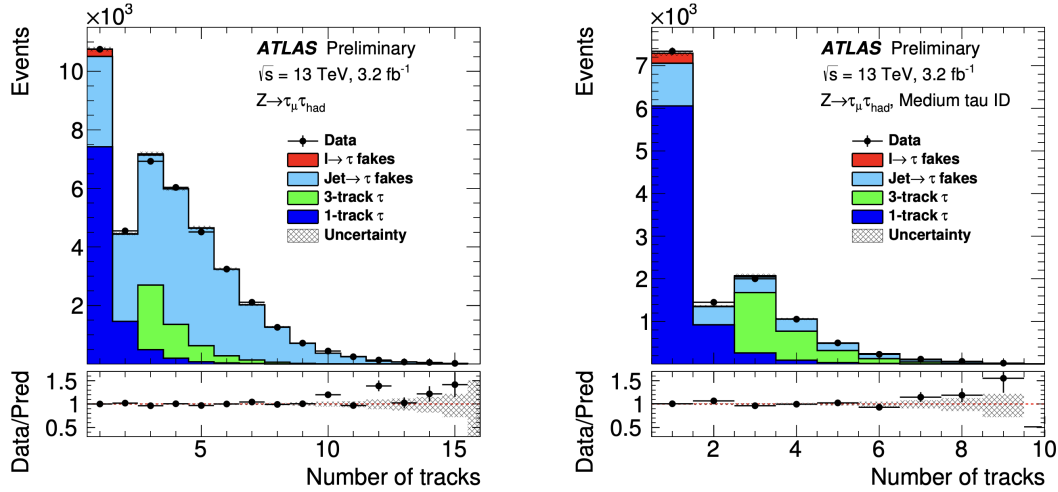


FIGURE 4.12: Track multiplicity for the $Z \rightarrow \tau_{\text{had}} \tau_{\mu}$ enriched sample. The figure on the left shows the track multiplicity distribution for candidates passing the very loose tauID requirement. The right plot shows the distribution of candidates passing the medium tauID selection. Taken from [92].

where the background contributions predicted from simulation ($N_{\text{MC BG}}$) and the number of MJ BG events are subtracted from the data. The number of MJ BG events is estimated by using the technique described in Section 5.4.1. The contribution of MJ BG and $Z \rightarrow \tau_{\text{had}} \tau_{\mu}$ events passing the very loose tauID requirement is determined by fitting these two contributions to the data using a variable with high separation between signal and background. The variable used for this purpose is the track multiplicity of the tau candidate.

To calculate the RNN efficiency in MC, given in Equation 4.5, the number of events passing a certain tauID working point is taken from the simulation. Figure 4.12 shows the track multiplicity for events passing the very loose and the medium tauID requirements.

Finally, the SFs are defined as:

$$\text{SF}_X = \frac{\epsilon_{\text{Data}}(X)}{\epsilon_{\text{MC}}(X)}. \quad (4.7)$$

The SFs results are summarised in Figure 4.13. The SFs are compatible with a value of one for both 1-prong and 3-prong candidates. These results imply that the performance of the tauID is similar in data and simulation.

4.3.3 Fakes from electrons

Single-track tau candidates can be faked by electrons. A BDT is trained to discriminate between taus and electrons in ATLAS. The algorithm exploits the shower shapes in the calorimeters, the hits in the ID and the information about the transition radiation in the TRT. Three different working points are defined: loose, medium and tight. The signal efficiency for these working points is 95%, 85% and 75%, respectively [94].

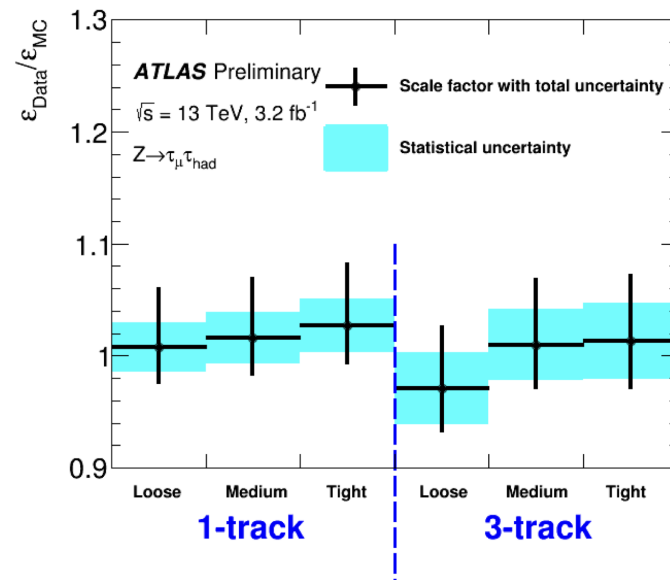


FIGURE 4.13: SFs for 1-prong and 3-prong tau candidates ($p_T > 20 \text{ GeV}$) at different levels of tauID. Taken from [92].

Chapter 5

Tau identification calibration for high- p_T taus: a lepton universality safe approach

We discussed the algorithms trained to discriminate taus from jet fakes in Section 4.3.1. As described in Section 4.3.2, the efficiencies of the algorithms are measured in data and simulation, and scale factors (SFs) are applied to the simulation in order to match the efficiencies.

For high- p_T taus, the SFs are derived using $t\bar{t}$ events. The higher mass of the top quark compared to the Z boson produces a harder tau p_T spectrum. However, by measuring the SFs with a $t\bar{t}$ enhanced sample, any hypothetical lepton universality (LU) violating effects in the W decays would be included in the SFs.

In this section, we present an alternative approach for measuring the tau identification algorithm (tauID) SFs for taus in the high- p_T region. In the new method, we select a sample of boosted $Z \rightarrow \tau_{\text{had}}\tau_{\text{lep}}$ events to measure the SFs. Since LU has been tested to far better precision in Z decays, the new approach is safer from potential LU-violating effects.

Additionally, we include boosted $Z \rightarrow ll$ events ($l = e, \mu$) as a denominator sample in the SFs calculation. By doing this, we partially cancel some of the phenomenological uncertainties such as the modelling of the transverse momentum of the Z boson; as well as reducing some of the experimental systematic uncertainties.

This chapter is structured as follows: in Section 5.1, we present the description of the data and simulation samples. Section 5.2 describes the analysis methodology: the event selection is presented and the definition of the SFs is given. The background estimation is discussed in Section 5.4. In Section 5.5 the systematic uncertainties for the analysis are presented. The analysis results and a discussion are included in Section 5.6. Finally, we conclude in Section 5.7.

5.1 Data and Monte Carlo samples

The data used for this study have been recorded during the Run-II of the LHC. They correspond to the 2015-2018 data-taking period. The total integrated luminosity is 139.2 fb^{-1} of proton-proton collisions at a centre-of-mass energy of $\sqrt{s} = 13 \text{ TeV}$.

Monte Carlo (MC) simulation samples are used for signal and background processes. For $Z \rightarrow ll$ events ($l = e, \mu, \tau$) two MC samples are used: PowHeg+Pythia8 and SHERPA 2.2.1. For the background processes, we use PowHeg+Pythia8, except for the di-boson samples which are simulated with SHERPA 2.2.11 and 2.2.2. Table 5.1 shows the MC samples used in this analysis for each physics process. The choice of this particular set of MC generators and their configurations is motivated by the input provided by the group of MC experts in ATLAS. Additionally, the use of these generators as standard in other ATLAS analyses is a motivation to measure the tauID performance in these datasets. We describe the MC samples more in-depth in the following paragraphs.

Process	Event Generator
$Z \rightarrow \tau\tau$	PowHeg+Pythia8 and SHERPA 2.2.1
$Z \rightarrow ee$	PowHeg+Pythia8 and SHERPA 2.2.1
$Z \rightarrow \mu\mu$	PowHeg+Pythia8 and SHERPA 2.2.1
$W \rightarrow l\nu_l$	PowHeg+Pythia8
$t\bar{t}$	PowHeg+Pythia8
Single t	PowHeg+Pythia8
Diboson	SHERPA 2.2.1 and 2.2.2

TABLE 5.1: List of MC event generators used in this analysis.

Two MC generators were used to simulate the Z production. The first sample was generated with the SHERPA 2.2.1 [95] generator using next-to-leading-order (NLO) matrix elements (ME) for up to two partons, and leading-order (LO) matrix elements for up to four partons calculated with the Comix [96] and OpenLoops [97–99] libraries. They were matched with the SHERPA parton shower (PS) [100] using the MEPS@NLO prescription [101–104] using the set of tuned parameters developed by the SHERPA authors. The NNPDF 3.0nnlo set of PDFs [105] was used and the samples were normalised to a next-to-next-to-leading-order (NNLO) prediction [106]. We will refer to this sample as SHERPA 2.2.1.

The second sample uses the PowHegBox MC generator [107–110] for the simulation at NLO accuracy of the hard-scattering processes of W and Z boson production and decay in the electron, muon, and τ -lepton channels. It was interfaced to Pythia 8 [111] for the modelling of the parton shower, hadronisation, and underlying event, with parameters set according to the AZNLO tune [112]. The CT 10nlo PDF set [113] was used for the hard-scattering processes, whereas the CTEQ 6L1 PDF set [114] was used for the parton shower. The effect of QED final-state radiation was simulated with Photos++ 3.52 [115, 116]. The EvtGen 1.2.0 program [117] was used to decay bottom and charm hadrons. From now on, we call these samples PowHeg+Pythia8.

Production of di-boson (VV) final states; $V=W,Z$, were simulated with the SHERPA2.2.1 or 2.2.2 [95] generator depending on the process, including off-shell effects and Higgs boson contributions, where appropriate. Fully leptonic final states and semileptonic final states, where one boson decays leptonically and the other hadronically, were generated using matrix elements at NLO accuracy in QCD for up to one additional parton and at LO accuracy for up to three additional parton emissions. Samples for the loop-induced processes $gg \rightarrow VV$ were generated using LO-accurate matrix elements for up to one additional parton emission for both the cases of fully leptonic and semileptonic final states. The matrix element calculations were matched and merged with the SHERPA parton shower based on Catani–Seymour dipole factorisation [96, 100]

using the MEPS@NLO prescription [101–104]. The virtual QCD corrections were provided by the OpenLoops library [97–99]. The NNPDF 3.0nnlo set of PDFs was used [105], along with the dedicated set of tuned parton-shower parameters developed by the SHERPA authors.

Processes including production of $t\bar{t}$, were modelled using the PowHegBox v2 [107–109, 118] generator at NLO with the NNPDF 3.0nlo [105] PDF set and the h_{damp} parameter¹ set to $1.5 m_{\text{top}}$ [119]. The events were interfaced to Pythia 8.230 [120] to model the parton shower, hadronisation, and underlying event, with parameters set according to the A14 tune [121] and using the NNPDF 2.3lo set of PDFs [122]. The decays of bottom and charm hadrons were performed by EvtGen 1.6.0 [117].

For single-top quark production, three contributions were considered. First, the associated production of top quarks with W bosons (tW) was modelled by the PowHegBox v2 [107–109, 123] generator at NLO in QCD using the five-flavour scheme and the NNPDF 3.0nlo set of PDFs [105]. The diagram removal scheme [124] was used to remove interference and overlap with $t\bar{t}$ production. The related uncertainty was estimated by comparison with an alternative sample generated using the diagram subtraction scheme [119, 124]. The events were interfaced to Pythia 8.230 [120] using the A14 tune [121] and the NNPDF 2.3lo set of PDFs [122]. Second, single-top t -channel production was modelled using the PowHegBox v2 [107–109, 125] generator at NLO in QCD using the four-flavour scheme and the corresponding NNPDF 3.0nlo set of PDFs [105]. The events were interfaced with Pythia 8.230 [120] using the A14 tune [121] and the NNPDF 2.3lo set of PDFs [122]. Finally, s -channel production was modelled using the PowHegBox v2 [107–109, 126] generator at NLO in QCD in the five-flavour scheme with the NNPDF 3.0nlo [105] parton distribution function (PDF) set. The events were interfaced with Pythia 8.230 [120] using the A14 tune [121] and the NNPDF 2.3lo PDF set.

All the MC events are passed through a GEANT4 [127] simulation of the detector [128] and reconstructed using the same algorithms used for the real data. The differences in the performance of reconstruction, isolation and identification of the physics objects, are corrected in the MC by applying p_T and η dependent scale factors. These scale factors are derived by doing MC to real data comparisons. The effect of multiple interactions in the same and neighbouring bunch crossings was modelled by overlaying the simulated hard-scattering event with inelastic proton-proton (pp) events generated with Pythia 8.186 [111] using the NNPDF 2.3lo set of parton distribution functions (PDF) [122] and the A3 set of tuned parameters [129]. The Monte Carlo (MC) events were weighted to reproduce the distribution of the average number of interactions per bunch crossing ($\langle\mu\rangle$) observed in the data.

5.2 Analysis strategy

This section presents the analysis methodology. In Section 5.2.1, we define the kinematic variables used in the event selection. Additionally, we describe the signal event topologies. Section 5.2.2 contains the tauID SFs definition.

¹The h_{damp} parameter is a re-summation damping factor and one of the parameters that controls the matching of PowHeg matrix elements to the parton shower and thus effectively regulates the high- p_T radiation against which the $t\bar{t}$ system recoils.

5.2.1 Signal events reconstruction

For this study, we consider as signal $Z \rightarrow \tau\tau$ events where one of the taus decays hadronically and the other leptonically — either into an electron or a muon. Thus, the final states include a τ_{had} candidate and one light lepton $l = e, \mu$. The presence of the light lepton is used as the tag. Generally, in $Z \rightarrow \tau\tau$ events, the taus are produced back to back and their p_T spectrum falls sharply. To enhance our sample on high- p_T taus, we select events where the opening angle in the transverse plane between the taus ($\Delta\phi(\tau_{\text{had}}, \tau_{\text{lep}})$) is smaller than usual.

The two possible topologies for the signal events are shown in Figure 5.1. For these events, the missing transverse momentum ($\vec{E}_T^{\text{miss}}$) is assumed to come from the neutrinos produced in the tau decays. Since two neutrinos are produced in the leptonic decay mode, we expect the signal events to have a larger $\vec{E}_T^{\text{miss}}$ component along the τ_{lep} direction.

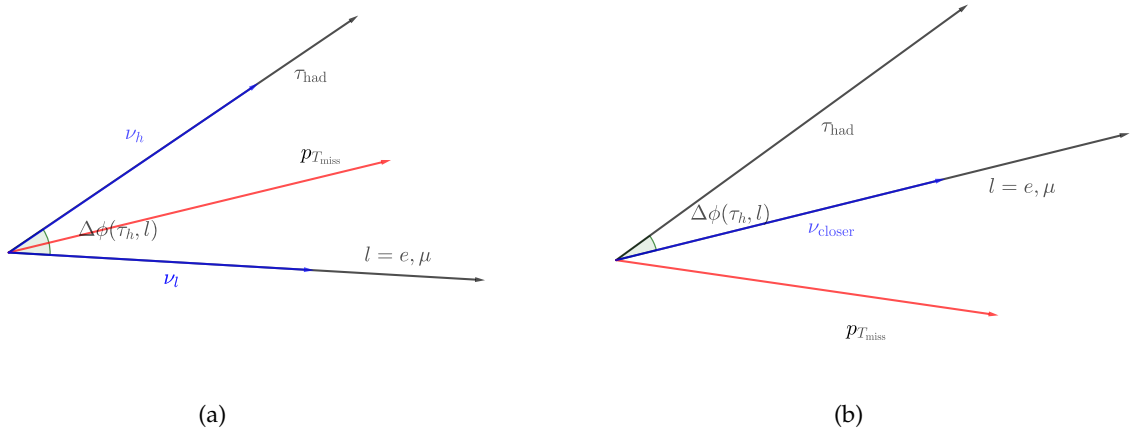


FIGURE 5.1: The two topologies that define the signal events in the transverse plane. On the left, when the missing energy is between the visible parts of the tau decays. For these events, two neutrinos are assumed to be responsible for all the missing energy. On the right, when the missing energy is outside, only one neutrino is assumed to be travelling in the direction of the closest object to the missing energy.

Let us describe the two topologies: first, for the events where the $\vec{E}_T^{\text{miss}}$ is inside the opening angle between the visible objects, we assume that the missing energy is due to a pair of neutrinos travelling in the same direction as the visible parts of the tau decays, this approach is called the *collinear approximation*. This topology is shown in Figure 5.1a. The following equation is solved to obtain the momentum of the neutrinos:

$$\vec{p}_{T_{\nu_l}} + \vec{p}_{T_{\nu_h}} = \vec{E}_T^{\text{miss}}, \quad (5.1)$$

given the following set of constraints:

$$\phi(\nu_l) = \phi(l), \quad (5.2)$$

$$\phi(\nu_h) = \phi(\tau_{\text{had}}), \quad (5.3)$$

$$\eta(\nu_l) = \eta(l), \quad (5.4)$$

$$\eta(\nu_h) = \eta(\tau_{\text{had}}). \quad (5.5)$$

In the second case, when the $\vec{E}_T^{\text{miss}}$ is pointing outside the angle formed by the visible objects, the

assumption is that only one neutrino is responsible for the majority of the $\vec{E}_T^{\text{miss}}$. We assume the neutrino is travelling along the direction of the visible object that is closest to the $\vec{E}_T^{\text{miss}}$, as is shown in Figure 5.1b. The following equations are used to obtain the neutrino momentum:

$$p_{T_\nu} = \vec{E}_T^{\text{miss}} \cos(\Delta\phi(\tau_{\text{closest}}, \vec{E}_T^{\text{miss}})), \quad (5.6)$$

$$\phi(\nu) = \phi(\tau_{\text{closest}}), \quad (5.7)$$

$$\eta(\nu) = \eta(\tau_{\text{closest}}), \quad (5.8)$$

where τ_{closest} is the visible object closest to the $\vec{E}_T^{\text{miss}}$ vector.

We define Omega (Ω) in order to classify the events into one of the previously discussed categories. First, we define

$$\omega = \frac{\Delta\phi(\tau_{\text{closest}}, \vec{E}_T^{\text{miss}})}{\Delta\phi(\tau_{\text{had}}, \tau_{\text{lep}})}, \quad (5.9)$$

and

- when $\vec{E}_T^{\text{miss}}$ is inside the opening angle between the visible objects but closer to the τ_{had} :

$$\Omega = \omega. \quad (5.10)$$

- When $\vec{E}_T^{\text{miss}}$ is still in between, but closer to the τ_{lep}

$$\Omega = 1 - \omega. \quad (5.11)$$

- If $\vec{E}_T^{\text{miss}}$ is outside and closer to the τ_{had}

$$\Omega = -\omega. \quad (5.12)$$

- Finally, if $\vec{E}_T^{\text{miss}}$ is outside and closer to the τ_{lep}

$$\Omega = \omega + 1. \quad (5.13)$$

Therefore, Ω is by construction a continuous variable that has the topological information of the event. When the $\vec{E}_T^{\text{miss}}$ is inside the visible system, Ω takes values in the interval $[0,1]$. It is exactly zero when $\vec{E}_T^{\text{miss}}$ is pointing in the τ_{had} direction and one when $\vec{E}_T^{\text{miss}}$ is pointing in the τ_{lep} direction. Ω is negative when the $\vec{E}_T^{\text{miss}}$ is outside and closer to the τ_{had} candidate, and it is positive and greater than one when $\vec{E}_T^{\text{miss}}$ is outside and closer to the τ_{lep} .

A diagram illustrating Ω is shown in Figure 5.2. The classification of the events into these topologies allows us to reconstruct the invariant mass of the di-tau system, the Z boson transverse momentum (Zp_T) and the angular distributions of the objects in the event.

5.2.2 Scale factors definition

Conventionally, the tauID scale factors (SFs) are defined as the ratio between data and simulation of the efficiencies of passing a certain level of identification for a sample of τ_{had} candidates — as described in Section 4.3.2. The main challenge of this approach is the estimation of the tau fakes background arising from QCD-initiated jets.

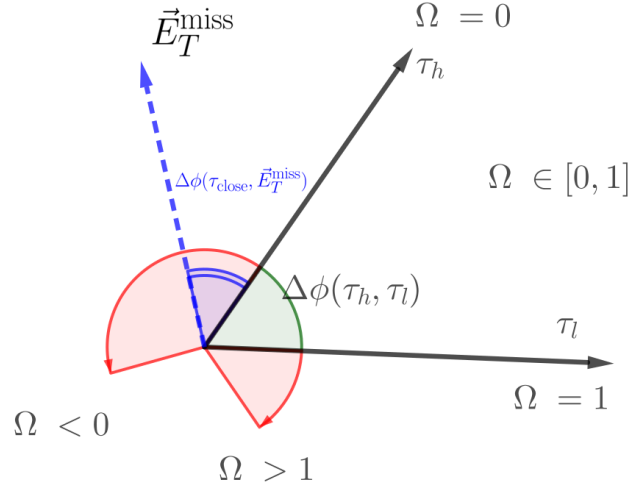


FIGURE 5.2: Graphical representation of the different values of Ω , showing its dependence on the location of the $\vec{E}_T^{\text{miss}}$.

For this study, an alternative approach has been taken. First, we define the ratio of observed to predicted signal events in $Z \rightarrow \tau_{\text{had}} \tau_{\text{lep}}$ events:

$$C_X(Z \rightarrow \tau_{\text{had}} \tau_{\text{lep}}) = \frac{N^{\text{Data}}}{N^{\text{MC}}}. \quad (5.14)$$

In Equation 5.14 X can be any of the tau-ID working points, N^{Data} is the number of observed $Z \rightarrow \tau_{\text{had}} \tau_{\text{lep}}$ events having subtracted the background predictions, and N^{MC} is the predicted number of $Z \rightarrow \tau\tau$ events with one truth-matched τ_{had} .

If the quantity in Equation 5.14 is assigned as the SF, the results would be MC-dependent, since PowHeg+Pythia8 and SHERPA 2.2.1 predict different event kinematics. To fix this problem, we can calculate the same ratio in $Z \rightarrow ll$ events:

$$C(Z \rightarrow ll) = \frac{N^{\text{Data}}}{N^{\text{MC}}}. \quad (5.15)$$

This time N^{Data} is the number of observed $Z \rightarrow ll$ events having subtracted the background predictions and N^{MC} is the number of predicted $Z \rightarrow ll$ events passing all the event selections.

Finally, we combine the two previous measurements to define the tauID SFs by taking the following ratio:

$$\text{SF}_X = \frac{C_X(Z \rightarrow \tau_{\text{had}} \tau_{\text{lep}})}{C(Z \rightarrow ll)}. \quad (5.16)$$

In this approach (referred from now on as the double ratio method), it is expected that the systematic uncertainties arising from the different descriptions of the event kinematics given by various MC generators cancel at first order. Additionally, some of the experimental systematic uncertainties should be reduced, because object calibrations are expected to affect the numerator and denominator in Equation 5.16 similarly.

However, it is important to point out that this new method does not benefit from some of the advantages offered by the traditional measurement. Since in the traditional approach it is the efficiency itself that is compared between data and MC, this helps to partially cancel the systematic uncertainties arising from the experimental calibrations, for example, the tau energy calibration.

This happens since both in the numerator and the denominator, the MC yields are similarly affected by the calibrations.

Nevertheless, the new method offers a great opportunity: since the ATLAS collaboration does not yet provide tau reconstruction scale factors; an independent measurement of the tauID performance can be combined with the double ratio method to obtain tau reconstruction SFs. This measurement could be performed because, in the double ratio method, we measure the product of the reconstruction and the identification efficiencies, whereas in the standard approach, only the identification efficiency is measured.

5.3 Event selection

5.3.1 $Z \rightarrow \tau_{\text{had}} \tau_{\text{lep}}$ events

The basic selection includes events with exactly one light lepton and one or more τ_{had} candidates that pass the loose tauID working point. The τ_{had} and light lepton are required to have opposite electric charges. The presence of the light lepton is used as our tag. A light lepton trigger is required to be fired with an online requirement on the $p_T(\mu) \geq 20$ ($p_T(e) \geq 24$) GeV for the 2015 data taking period. For 2016-2018 the online requirement is raised to $p_T(\mu, e) \geq 26$ GeV. The muon is required to pass the *medium* ID requirement and the electron has to pass the *tight* ID filter. Additionally, both muons and electrons have to pass an offline p_T requirement: $p_T > 27$ GeV.

In $Z \rightarrow \tau\tau$ events, the taus are usually produced back to back. This happens because the Z boson is usually produced at rest and conservation of momentum forces the tau decays to travel in opposite directions. This decay configuration produces tau candidates with modest values of transverse momentum. To select a sample of high- p_T tau candidates, the opening angle between the tau and the light lepton in the transverse plane is required to pass: $\Delta\phi(\tau_{\text{had}}, l) \leq 1.0$ rad. This criterion selects events where the Z boson is produced with considerable transverse momentum. This momentum is then passed to the Z decay products. Figure 5.3 shows the $\Delta\phi(\tau_{\text{had}}, \mu)$ distribution for our sample.

Events containing b-jets are vetoed to reject top-quark backgrounds. In addition, an isolation criterion is required to be passed by the light leptons: for the muon (electron), the scalar sum of the p_T of the tracks within a cone of size $\Delta R = 0.3(0.2)$ around the muon (electron) must be less than 0.06 times the muon (electron) p_T . Additionally, for the electron, the sum of the calorimeter cluster energy in a cone of size $\Delta R = 0.2$ around the electron must be 0.06 times smaller than the electron p_T .

We expect the signal events to peak around $\Omega = 1$ because more neutrinos are produced on the τ_{lep} side. We select events where $\Omega \in (-0.2, 1.6)$. Figure 5.4 shows the Ω distribution for $Z \rightarrow \tau_{\text{had}}\mu$ events.

Events with a reconstructed invariant mass (m_{reco}) close to the Z boson mass are selected ($60 \leq m_{\text{reco}} \leq 120$ GeV). The reconstructed invariant mass definition depends on the event topology. For events where $\Omega \in [0, 1]$ (*in-between events*)

$$m_{\text{reco}}^2 = (q_l + q_{\tau_{\text{had}}} + q_{\nu_l} + q_{\nu_{\tau_{\text{had}}}})^2. \quad (5.17)$$

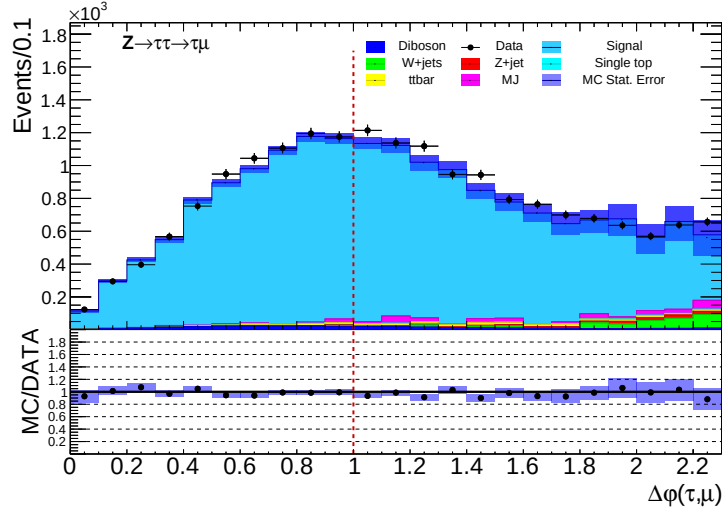


FIGURE 5.3: Distribution of $\Delta\phi(\tau_{\text{had}}, l)$ for the $Z \rightarrow \tau_{\text{had}}\mu$ final state. All the other selection requirements have been applied apart from the one being displayed. The ATLAS data are shown as points with error bars indicating the statistical uncertainties. The detector-level predictions are shown by the coloured histograms — each colour shows a particular physics process. The vertical dashed red line indicates the value used in the selection cut. The lower section of the plot shows the ratio of the prediction to the data. The statistical uncertainties in the predictions are shown as the blue-shaded regions. The SHERPA 2.2.1 generator is used to model the $Z \rightarrow \tau_{\text{had}}\tau_{\text{lep}}$ events (signal).

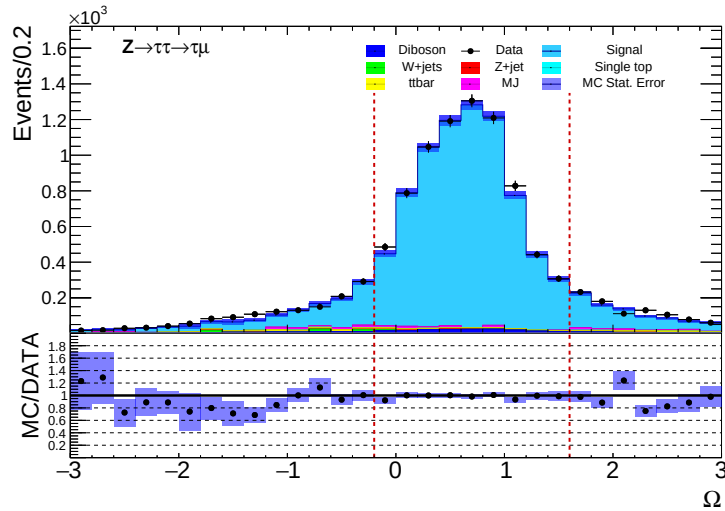


FIGURE 5.4: Distribution of Ω for the $Z \rightarrow \tau_{\text{had}}\mu$ final state. The region between the red vertical dashed lines is included in the final event selection.

When the $\vec{E}_T^{\text{miss}}$ is outside (*outside events*)

$$(m_{\text{reco}} - 5 \text{ GeV})^2 = (q_l + q_{\tau_{\text{had}}} + q_\nu)^2. \quad (5.18)$$

The RHS of Equations 5.17 and 5.18 are 4-vector sums, where q represents the four-momentum of each particle. To maintain our selection requirements consistent between the in-between and outside regions, we add 5 GeV to the reconstructed mass of the outside events, since in this region we empirically found that the di-tau mass is underestimated. Figure 5.5 shows the distribution of m_{reco} for the in-between and outside $Z \rightarrow \tau_{\text{had}}\mu$ events.

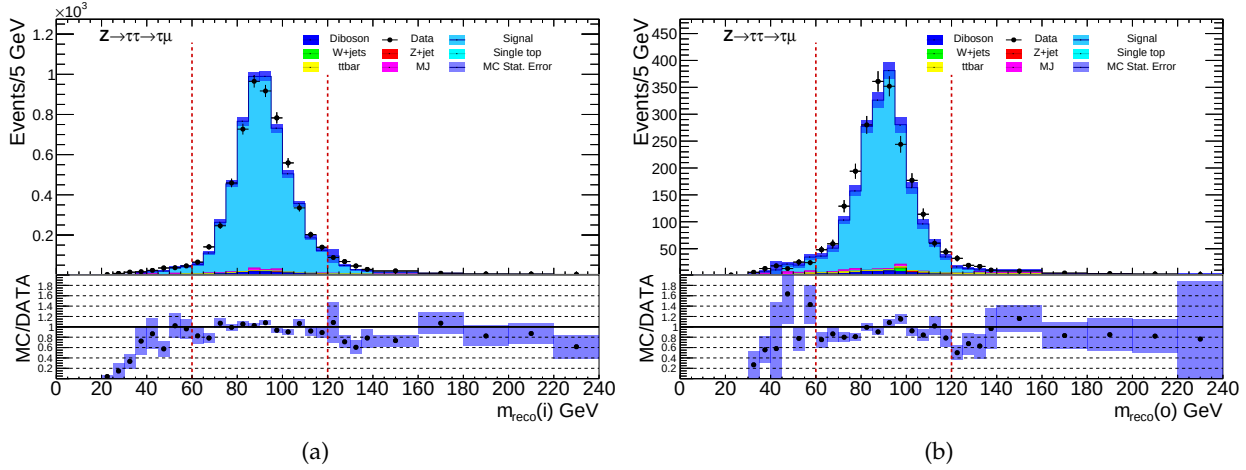


FIGURE 5.5: Distribution of m_{reco} for the in-between (a) and the outside (b) events. All the other selection requirements have been applied apart from the one being displayed.

Furthermore, for the $Z \rightarrow \tau_{\text{had}}e$ final state, we add two requirements aimed to reject events where the τ_{had} candidate is faked by an electron. First, a requirement on the visible invariant mass of the electron and the τ_{had} candidate is applied: $m(e, \tau_{\text{had}}) < 80 \text{ GeV}$ — this cut is aimed to reject $Z \rightarrow ee$ events where one of the electrons is reconstructed and identified as a τ_{had} . We also require the tau candidate to pass the loose operating point of the ATLAS ID algorithm trained to discriminate genuine taus against electrons: $\text{eBDTScore} \geq 0.05$ [94]. The distributions for these variables are shown in Figure 5.6.

Finally, to measure the tau ID SFs in the high- p_T region we select events with $p_T(\tau_{\text{had}}) \geq 45 \text{ GeV}$. The p_T distributions for τ_{had} candidates are shown in Figure 5.7 — separately for the in-between and outside topologies. A side-by-side comparison of the $Z \rightarrow \tau_{\text{had}}\mu$ and $Z \rightarrow \tau_{\text{had}}e$ kinematic distributions can be found in Appendix A.1. The kinematic predictions from the PowHeg+Pythia8 MC generator used as an alternative for the Z boson production sample can be found in Appendix A.1.3.

5.3.2 $Z \rightarrow ll$ events

The basic selection includes events with exactly two same flavour and opposite electric charge light-leptons. The same single light lepton triggers are used for these final states.

Events containing b-jets are vetoed to reject top-quark-related backgrounds. In addition, we require the same isolation and identification criterion applied in the $Z \rightarrow \tau_{\text{had}}\tau_{\text{lep}}$ selection. The

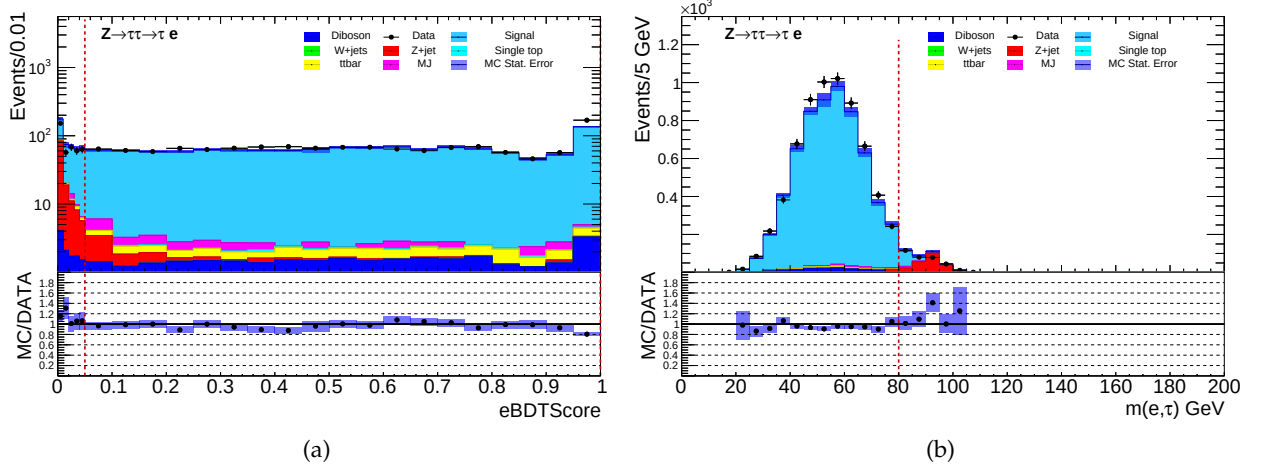


FIGURE 5.6: Distribution of the variables dedicated to reject τ_{had} fakes coming from electrons. On the right, we have the $m(e, \tau_{\text{had}})$ distribution and on the left the $eBDTScore$ distribution. All the other selection requirements have been applied apart from the one being displayed.

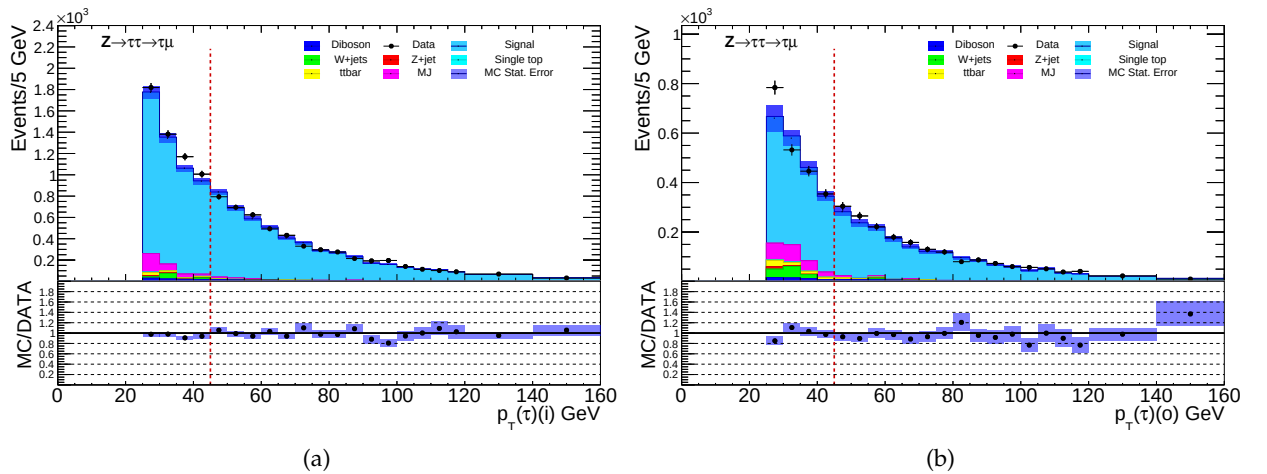


FIGURE 5.7: Distribution of $p_T(\tau_{\text{had}})$ for in-between (a) and outside (b) events. All the other selection requirements have been applied apart from the one being displayed.

invariant mass of the light lepton pair has to pass: $70 < m(l_1, l_2) < 110$ GeV. The $m(\mu_1, \mu_2)$ distribution is shown in Figure 5.8.

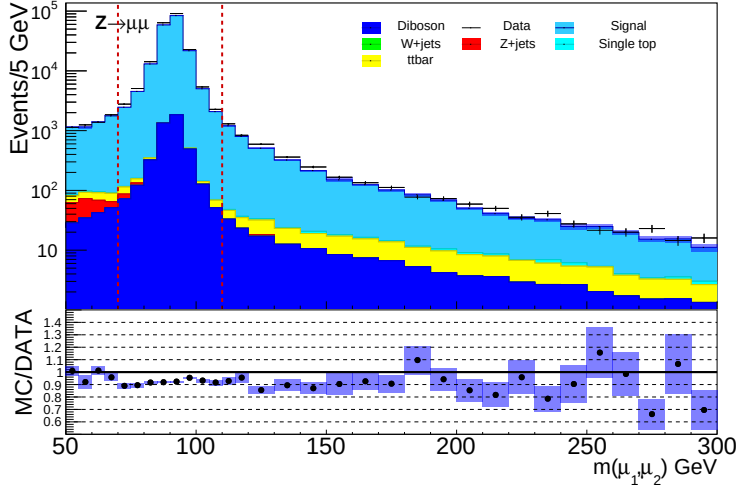


FIGURE 5.8: Invariant mass distribution for the $Z \rightarrow \mu\mu$ final state. All the other selection requirements have been applied apart from the one being displayed. In this and all subsequent figures, the ATLAS data are shown as points with the error bars corresponding to the statistical uncertainties. The detector-level predictions are shown by the coloured histograms — each colour shows a particular physics process. The region included in the final sample is the one between the dotted vertical red lines. The lower section of the plot shows the ratio of the prediction to the data. The statistical uncertainties on the predictions are shown as the blue-shaded region. The sample called *signal* is the simulation of the Z boson production decaying into a pair of light leptons, for these plots it corresponds to the SHERPA 2.2.1 MC generator.

Since the visible products of the tau decay only carry a part of the original tau momentum, we apply harder requirements on the transverse momentum in the selection of $Z \rightarrow ll$ events. To ensure a reasonable match between the kinematic phase spaces of $Z \rightarrow \tau_{\text{had}}\tau_{\text{lep}}$ and $Z \rightarrow ll$ events, different values for the $\Delta\phi(l_1, l_2)$ and the p_T of the leptons have been explored.

For the lepton's angular separation, the best match is to require the same $\Delta\phi(l_1, l_2) \leq 1.0$ rad cut. The $\Delta\phi(l_1, l_2)$ distribution is shown in Figure 5.9. For the transverse momentum of the leptons, an initial requirement of $p_T(l_1) \geq 50$ GeV and $p_T(l_2) \geq 47$ GeV is applied. Since in $Z \rightarrow \tau_{\text{had}}\tau_{\text{lep}}$ events, we cut harder on the τ_{had} candidate we need to do the same on one of the light leptons. First, we choose one of the light leptons to increase the transverse momentum cut by 30 GeV — the choice of the light lepton is done randomly. The reason for the stochastic nature of the cut is that the light-leptons are ordered in p_T and the hardest tau is not always the τ_{had} candidate. It may sometimes be the τ_{lep} candidate. The resulting light-lepton p_T distributions are shown in Figure 5.10. The detector level and truth Zp_T distributions, for selected $Z \rightarrow ll$ and $Z \rightarrow \tau_{\text{had}}\tau_{\text{lep}}$ events, are shown in Figure 5.11.

A set of alternative kinematic selections, varying the increase in the lepton p_T cut by 10 GeV, have been studied. This was done to assess the effect of having different degrees of agreement between the $Z \rightarrow ll$ and the $Z \rightarrow \tau_{\text{had}}\tau_{\text{lep}}$ event kinematics in the SFs. The corresponding truth Zp_T distribution for each particular $Z \rightarrow ll$ kinematic selection is shown in Figure 5.12. The Zp_T distribution that better matches the tau final states is shown in Figure 5.12c. This distribution corresponds to the lepton p_T requirements described above and we call this the standard selection.

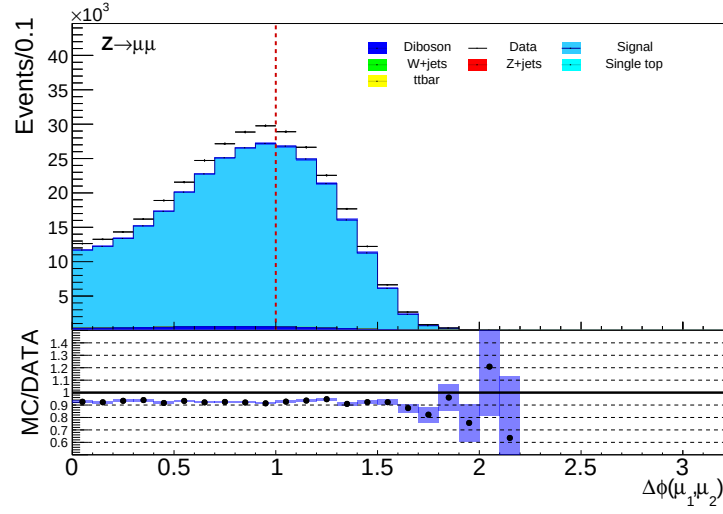


FIGURE 5.9: Distribution of $\Delta\phi(l_1, l_2)$ for the $Z \rightarrow \mu\mu$ final state. The region included in the final event selection is $\Delta\phi(l_1, l_2) \leq 1.0$ rad.

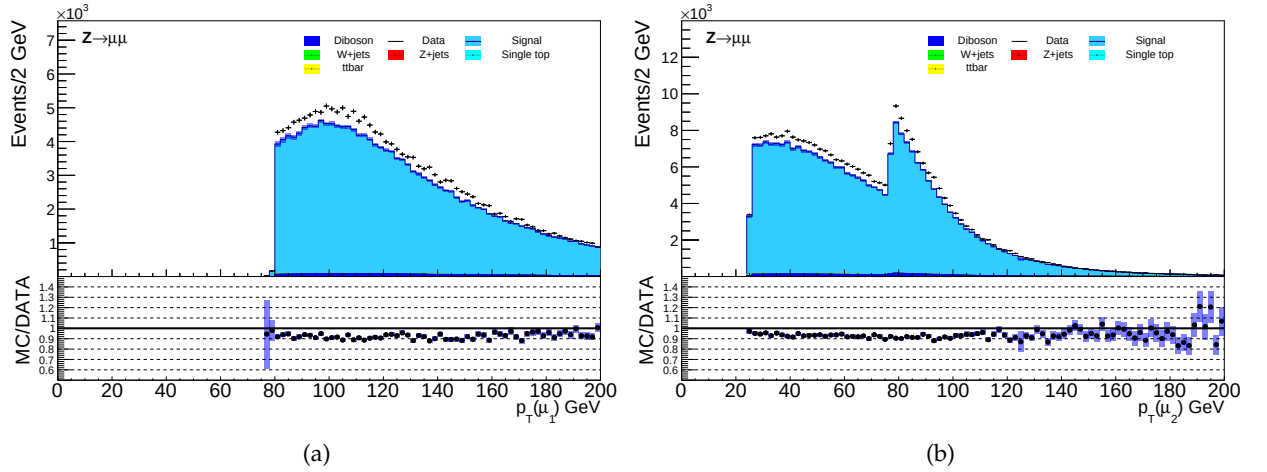


FIGURE 5.10: Leading and sub-leading muon p_T distributions in $Z \rightarrow ll$ events before the respective p_T cut is applied. When the leading (sub-leading) muon is randomly selected to add 30 GeV to the transverse momentum cut, the higher p_T cut value is 80 (77) GeV. This forces the p_T distribution of the leading muon to start at around 80 GeV — because the leptons are ordered in transverse momentum. There is enhancement in the number of selected sub-leading muons with a p_T of around 80 GeV since they are always paired with a leading muon that by definition will pass the transverse momentum requirements.

The impact of the kinematic match between the $Z \rightarrow ll$ and $Z \rightarrow \tau_{\text{had}}\tau_{\text{lep}}$ events is determined by performing comparisons of the SFs between the standard selection and the other Zp_T selections.

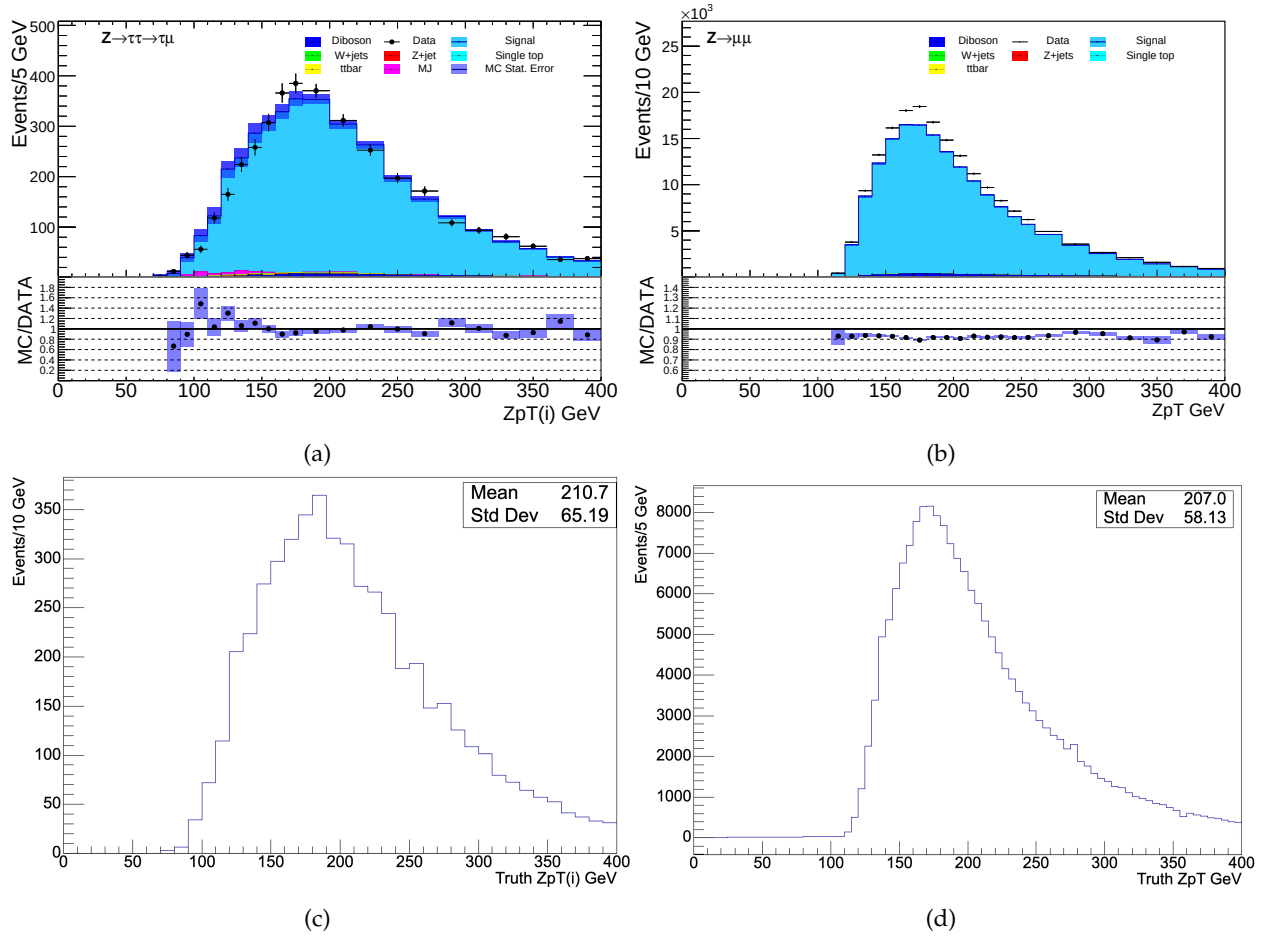


FIGURE 5.11: Left column represents the detector level (a) and truth level (c) Zp_T distributions for $Z \rightarrow \tau_{\text{had}}\mu$ events. On the right column, the same variables are shown for the $Z \rightarrow \mu\mu$ final state.

5.4 Background estimation

Jets initiated by QCD radiation are the main source of background (BG) of genuine taus. We use a *data-driven method* to estimate the multi-jet (MJ) BG. In this section, we discuss how we derived this estimation.

5.4.1 Multi-Jet Background

To obtain the MJBG prediction, we use a technique known as the ABCD method. In the ABCD method, a variable that is in principle uncorrelated with the shape of the MJBG is used to estimate the template for this process. For this study, the chosen variable is the relative sign between the charges of the τ_{had} and the light lepton.

Two regions are defined: the same sign (SS) region, where $q(\tau_{\text{had}}) = q(l)$; and the opposite sign (OS) region, where $q(\tau_{\text{had}}) = -q(l)$. The estimate of the MJBG in the SS region is obtained by subtracting from the data the BGs for which we have MC simulations, i.e., the signal and the

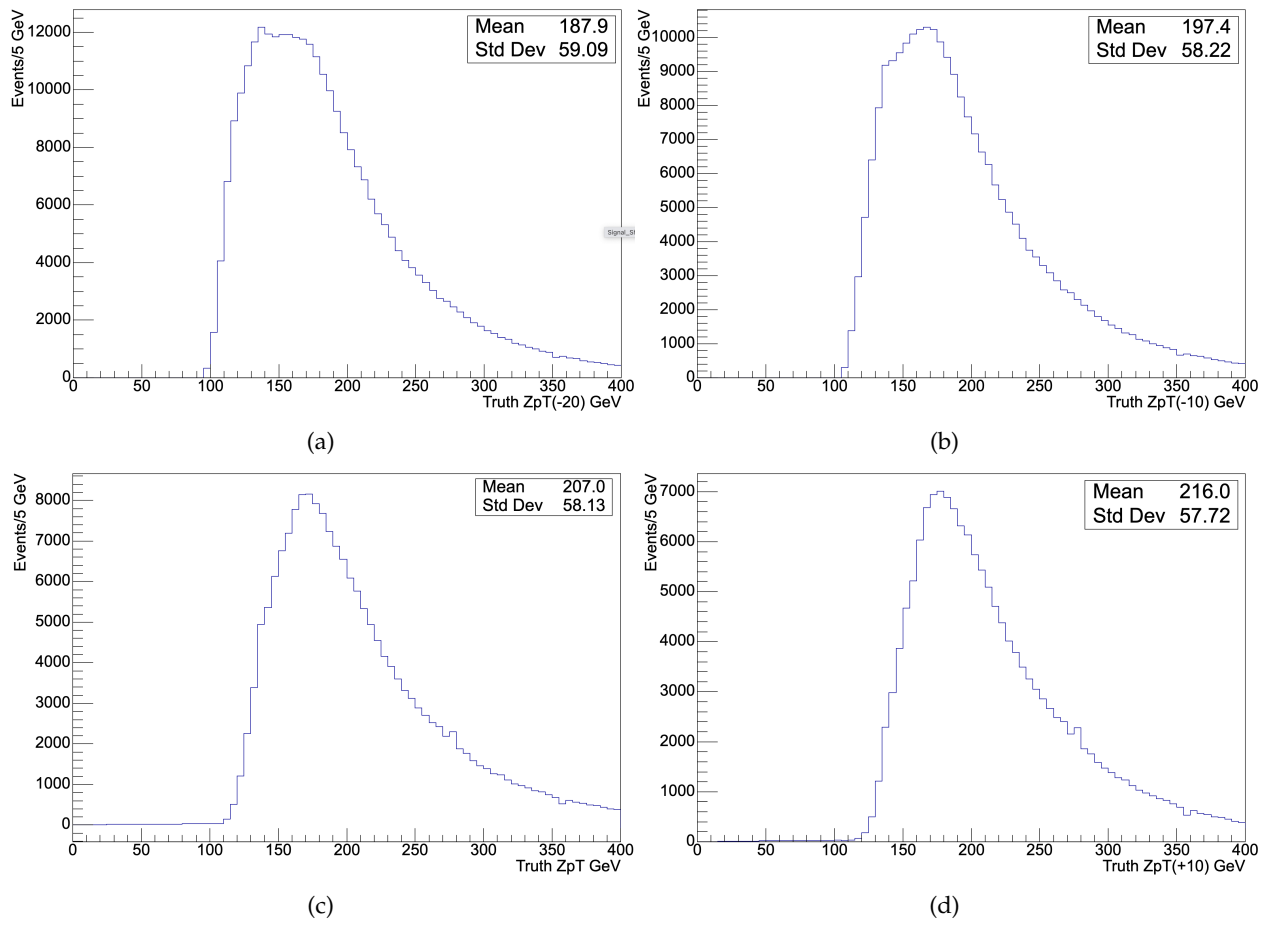


FIGURE 5.12: Truth Zp_T distributions for different values of the increased lepton p_T cut in the $Z \rightarrow \mu\mu$ sample. (a) -20 GeV selection, (b) -10 GeV selection, (c) standard selection and (d) +10 GeV selection. The (c) distribution is the one that better matches the Zp_T distribution for $Z \rightarrow \tau_{\text{had}}\tau_{\text{lep}}$ events shown in Figure 5.11c.

electroweak background (EWBG) contributions listed in Table 5.1,

$$\text{MJBG}_{\text{SS}} = \text{Data}_{\text{SS}} - \text{Signal}_{\text{SS}} - \text{EWBG}_{\text{SS}}. \quad (5.19)$$

To correct for any residual correlation between the OS and SS region, a control region (CR) for the MJBG is defined. The estimate for the MJBG in these regions is also given by Equation 5.19. The region described in Section 5.3.1, which contains the final selected events, is called the signal region (SR).

In contrast to the SR, the MJ CR is populated with events that fail the lepton isolation criterion or that fail the Tight-ID working point criterion for the τ_{had} candidate. In the MJ CR, tau candidates are required to pass a looser transverse momentum cut: $p_T(\tau_{\text{had}}) \geq 25$ GeV. This decision was made to increase the statistics in the MJ CR. A diagram conceptually showing the four analysis regions is shown in Figure 5.13.

Now, if we assume that the charge correlation is the same in the SR and the MJ CR, we have:

$$\frac{\text{MJBG}_{\text{SR OS}}}{\text{MJBG}_{\text{SR SS}}} = \frac{\text{MJBG}_{\text{CR OS}}}{\text{MJBG}_{\text{CR SS}}}. \quad (5.20)$$

We can simplify this equation to

$$\text{MJBG}_{\text{SR OS}} = \text{MJBG}_{\text{SR SS}} \times \text{RQCD}, \quad (5.21)$$

by defining

$$\text{RQCD} \equiv \frac{\text{MJBG}_{\text{CR OS}}}{\text{MJBG}_{\text{CR SS}}}. \quad (5.22)$$

Table 5.2 summarises the inputs used in the calculation of the MJBG.

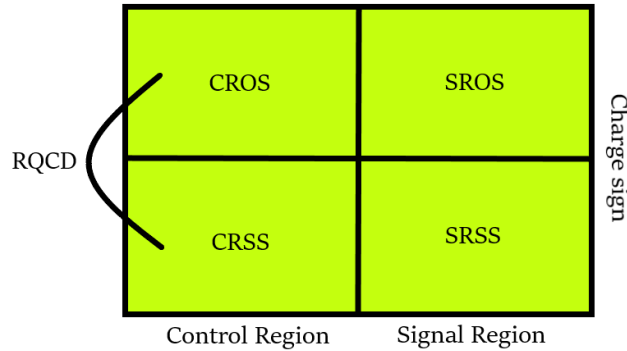


FIGURE 5.13: Regions defined to estimate the MJBG contribution in the SROS. This data-driven method is known as the ABCD method.

Figure 5.14 shows the jetRNN (tauID) score distribution in the SR SS for the $Z \rightarrow \tau_{\text{had}}\mu$ final state. Figure 5.15 shows the jetRNN score distributions for the events in the MJ CRs. In all regions the data cannot be explained by the simulated backgrounds, indicating a contribution from MJBG.

5.4.2 Electroweak Background

The electroweak background (EWBG) sources considered in this analysis are $t\bar{t}$, $Z + \text{jets}$, $W + \text{jets}$, di-boson and single-top events. For all of them, simulated samples are available and they are listed in Table 5.1.

Sample	$Z \rightarrow \mu \tau_{\text{had}}$		$Z \rightarrow e \tau_{\text{had}}$	
	1-prong	3-prong	1-prong	3-prong
CR OS Data	476.0 ± 22	270.0 ± 16	62.0 ± 8	39.0 ± 6
MC	28.608 ± 4.068	10.531 ± 1.833	21.058 ± 10.808	4.794 ± 1.558
CR SS Data	366.0 ± 19	151.0 ± 12	56.0 ± 7	28.0 ± 5
MC	3.46 ± 0.740	0.381 ± 0.229	1.152 ± 0.458	0.444 ± 0.843
RQCD	1.234 ± 0.081	1.723 ± 0.178	0.746 ± 0.208	1.260 ± 0.342
SR SS Data	95.0 ± 10	13.0 ± 4	113.0 ± 11	18.0 ± 4
MC	57.257 ± 4.799	6.761 ± 2.363	63.585 ± 4.793	19.240 ± 2.651
MJ Background	46.577 ± 13.825	10.748 ± 13.870	36.887 ± 15.695	0.0 ± 15.695

TABLE 5.2: Inputs for the calculation of the MJBG yield in the two final states: $Z \rightarrow \mu \tau_{\text{had}}$ and $Z \rightarrow e \tau_{\text{had}}$. The number of data and MC events in the SR SS, CR OS and CR SS samples are given. The excess of data with respect to simulation is assumed to arise from MJBG and it is used to calculate the value of RQCD.

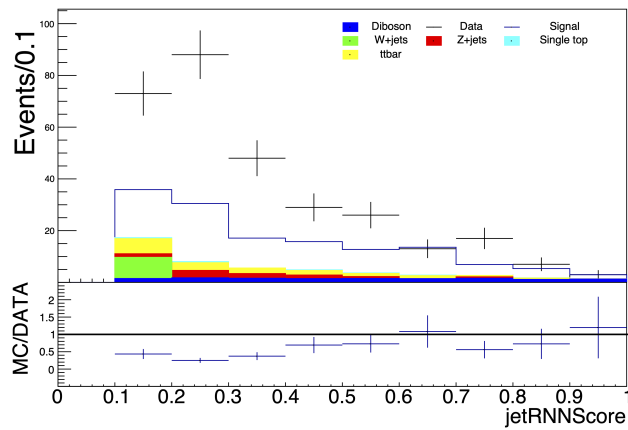


FIGURE 5.14: Distribution of jetRNNScore for 1-prong taus in the SRSS. The data-to-MC difference is the shape assigned to the MJBG. The shape is scaled by RQCD to obtain the MJBG in the SROS.

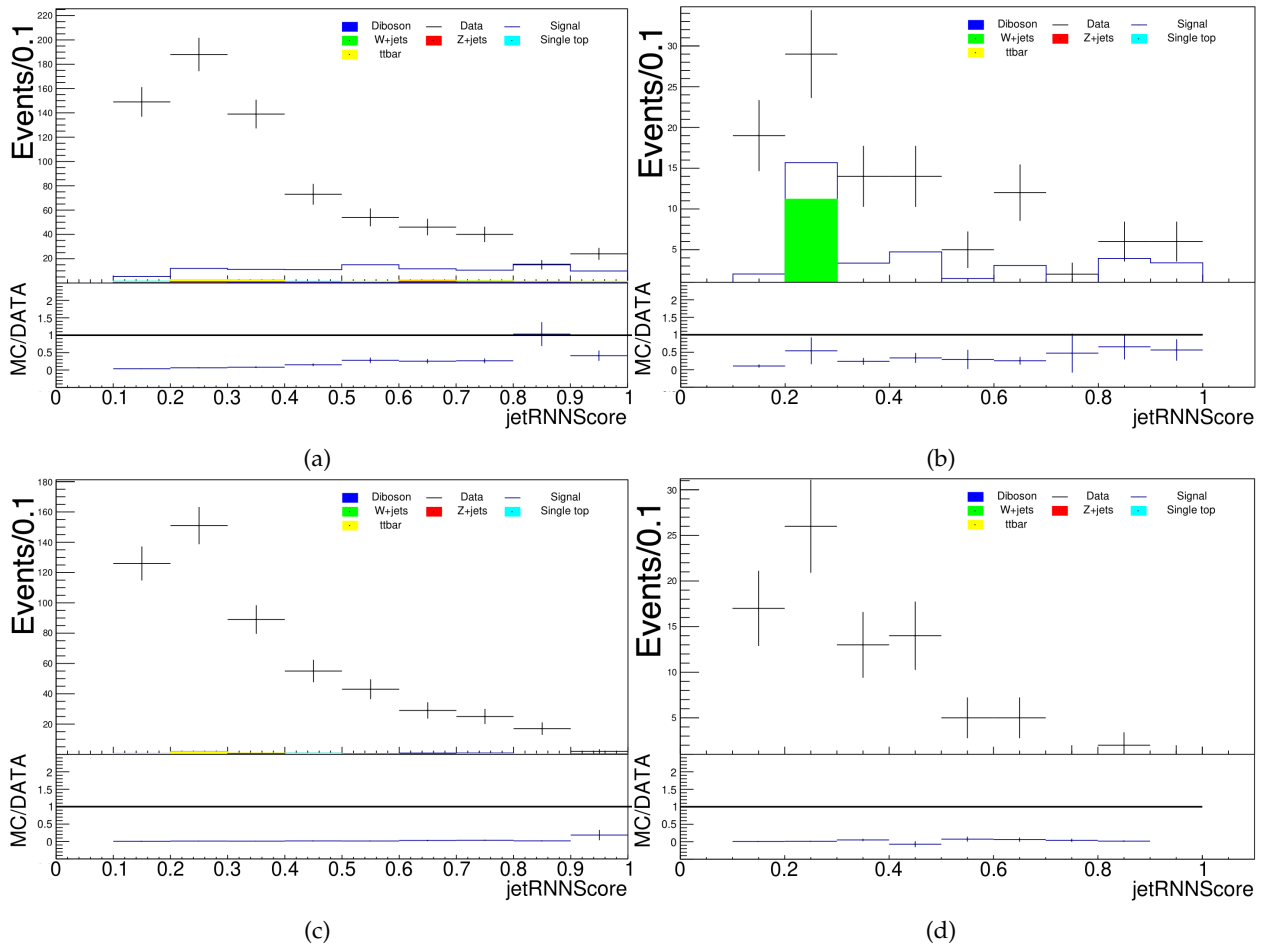


FIGURE 5.15: Left column (a, c) presents $Z \rightarrow \tau_{\text{had}}\mu$ events; $Z \rightarrow \tau_{\text{had}}e$ events are located in the right column (b, d). The two figures at the top show the CR OS and the bottom ones are the CR SS. All of the plots show the jetRNN score for 1-prong taus. In this case, the events used to calculate RQCD have jetRNN score < 0.4 .

One sample that is especially interesting to study is the $W + \text{jets}$ contribution to check if the simulation predicts the correct number of events where jets fake taus. To study the $W + \text{jets}$ contribution to the background sample, we define a CR where there is an enhanced fraction of expected $W + \text{jets}$ events. In this region, we require our events to be located in the $\Omega < 0$ or $\Omega > 1.4$ bands. We also require the transverse mass of the lepton to be, $M_T(l) \geq 60$ GeV. Finally, we require $n_{\text{jets}} \leq 2$ to reduce the $t\bar{t}$ contribution. The other selection requirements of the SR are kept.

To evaluate the MJBG contribution in the $W + \text{jets}$ CR we use the ABCD method. In the $W + \text{jets}$ enhanced region, the CR for MJBG is defined by the events that fail the light-lepton isolation or that have a τ_{had} candidate with more than 15 total tracks.

The $M_T(l)$ distributions for the $W + \text{jets}$ events in the OS and SS regions are shown in Figure 5.16. The plots show that the simulation is on average below the observed events. For this

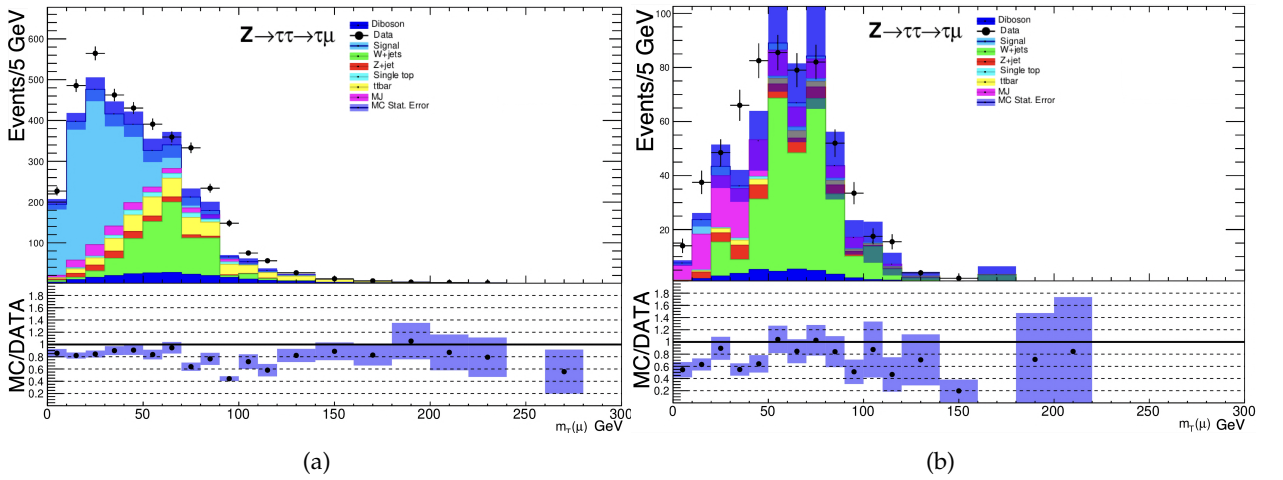


FIGURE 5.16: Distribution of $M_T(l)$ for the OS (a) and SS (b) regions. All the other requirements have been applied apart from the one being plotted. A deficit in the MC prediction is observed. This suggests that the simulation is underestimating the number of $W + \text{jets}$ events containing tau fakes.

reason, we scaled up the $W + \text{jets}$ yields in the SR by a factor of $1.2^{+0.4}_{-0.2}$.

However, we found that this correction has minimal impact on the analysis results since the $W + \text{jets}$ contribution in the SR is small.

5.5 Systematic uncertainties

Since the SFs are defined as a double ratio, we expect the reduction of systematic uncertainties arising from calibrations to shared objects between the different final states. However, some experimental systematics such as the tau energy calibrations or the MJ background estimation uncertainties do not benefit from the double ratio. Therefore, they are expected to dominate the measurement precision.

First, as discussed at the end of Section 5.3.2, different kinematic regions for $Z \rightarrow ll$ were tested to see the changes to the SFs. The variations in the C-Factor obtained from different configurations are shown in Figure 5.17. The conclusion is that by varying the match between the Zp_T distributions in $Z \rightarrow \tau_{\text{had}}\tau_{\text{lep}}$ and $Z \rightarrow ll$ events, the C-Factor changes at the most by 0.6%. We take a conservative approach and assign a 0.5% uncertainty arising from this effect.

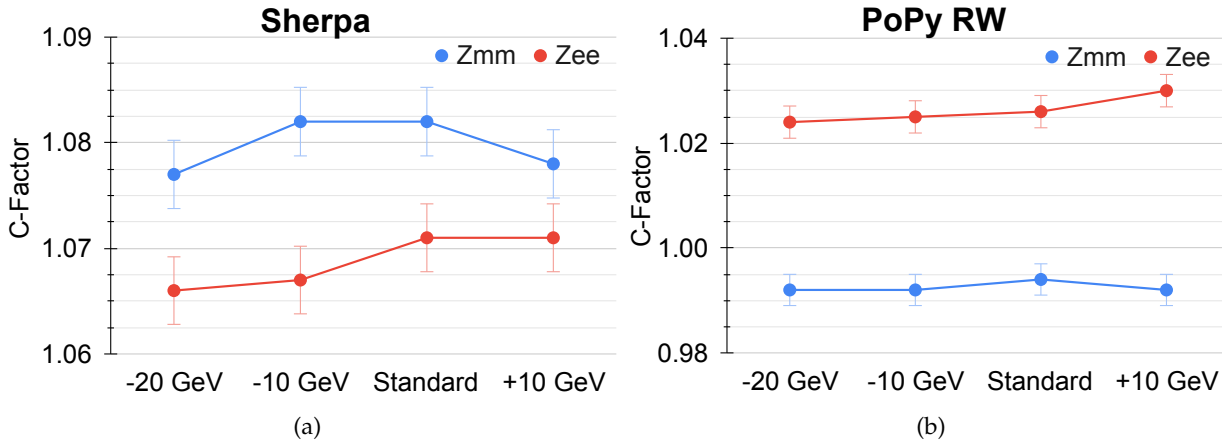


FIGURE 5.17: (a) C-Factor values for the $Z \rightarrow ll$ final states using Sherpa for the signal samples. From left to right; -20, -10, default and +10 GeV configurations for the light lepton p_T cut. Figure (b) shows the same values using PowHeg+Pythia8 for the signal sample. The error bars represent a 0.3% uncertainty in the central value.

The remaining integrated luminosity uncertainty is less than 0.07% in the double ratio, so we just discard this systematic source in the final results.

For the experimental systematic uncertainties calculation, we use the standard ATLAS procedure. In this approach, the physic objects are re-calibrated using calibration parameters one sigma away from their central value. The results are propagated through the analysis chain and compared between the central (or nominal) and the re-calibrated events (or variations). The resulting difference is quoted as the experimental systematic uncertainty.

The experimental uncertainties are split by physics objects and the corresponding calibrations (and their associated uncertainties) are provided by the so-called ATLAS Combined Performance (CP) groups. For light-leptons, the uncertainties provided account for momentum scale and resolution calibrations. In addition, uncertainties on the MC scale factors for lepton trigger, reconstruction, isolation and identification are included [78, 130]. For muons, the uncertainty on the sagitta bias is also added [79, 131]. For jets, a set of experimental uncertainties is considered; the jet uncertainties are divided into jet energy resolution and jet energy scale experimental systematics [81]. There are also dedicated experimental uncertainties for jet flavour tagging and jet vertex tagging algorithms [83, 132]. Additional experimental uncertainties are taken into account for the missing transverse momentum calculation [133]. Finally, the tau energy scale variations are also considered [90].

In this chapter, we describe the systematic uncertainties for the $Z \rightarrow \tau_{\text{had}}\mu$ final state. The systematic uncertainties for $Z \rightarrow \tau_{\text{had}}e$ events show very similar patterns and are detailed in Appendix A.2

First, for 1-prongs the uncertainties on the $\text{C-Factor}(Z \rightarrow \tau_{\text{had}}\mu)$ are broken down by source and shown in Figure 5.18. For the $\text{C-Factor}(Z \rightarrow \mu\mu)$ the same results are shown in Figure 5.19. After taking the double ratio, the uncertainties obtained for the SFs are shown in Figure 5.20. For example, when comparing the first rows of Figure 5.18 and Figure 5.20, we see that the double ratio approach reduces the uncertainties coming from these experimental scale factors — this effect is also present in other experimental systematic sources, and overall the combined effect is to reduce the total experimental systematic uncertainties.

The dominant experimental uncertainty sources are the jet, missing transverse energy (MET)

1 Prong (% Syst. Uncertainty)		
Final State	C-Factor	SF
$Z \rightarrow \tau_{\text{had}}\mu$	3.5	3.3
$Z \rightarrow \tau_{\text{had}}e$	3.6	3.7
3 Prong (% Syst. Uncertainty)		
$Z \rightarrow \tau_{\text{had}}\mu$	3.8	3.8
$Z \rightarrow \tau_{\text{had}}e$	4.2	4.2

TABLE 5.3: Total experimental systematic uncertainties for the different final states by the number of τ_{had} prongs.

and tau calibrations. The MET value is directly affected by these calibrations. This then impacts the estimation of the Z boson mass and the Ω variable. The cut values for the Ω and m_{reco} variables were chosen to minimise the size of the resulting systematic uncertainties on the SFs.

The effect of the tau energy scale variations is to move events in or out of the selection when the p_T of the taus is re-calibrated. The sensitivity to this effect is correlated with the shape of the $p_T(\tau)$ spectrum. To mitigate event migration in the p_T bins, a hard cut in $\Delta\phi(\tau_{\text{had}}, l = \mu, e)$ is imposed. This makes the $p_T(\tau)$ spectrum less rapidly falling and reduces the effect of bin migrations. A comparison of the $\tau_{\text{had}}(p_T)$ shape between two different values of the $\Delta\phi(\tau_{\text{had}}, \mu)$ cut is shown in Figure 5.21.

For the 3-prongs taus, the systematic uncertainties results are presented in Figure 5.22 and Figure 5.23.

Appendix A.2 contains the 3-prong tau results for $Z \rightarrow \tau_{\text{had}}e$ events. The conclusions are similar in this case.

Finally, the uncertainties are symmetrized and added in quadrature. The results are summarised in Table 5.3.

5.6 Results

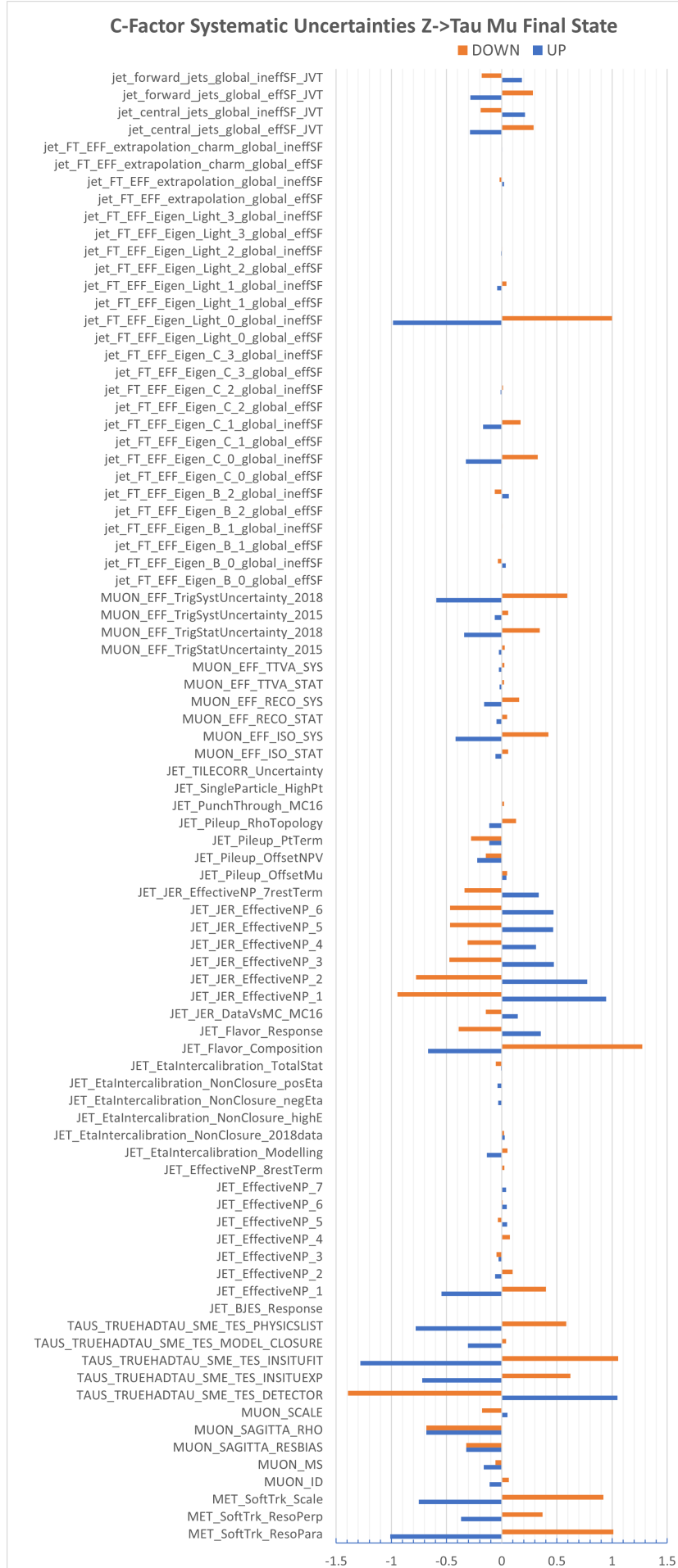
In this section, we present the tauID SFs obtained for the $Z \rightarrow \tau_{\text{had}}e$ and $Z \rightarrow \tau_{\text{had}}\mu$ final states.

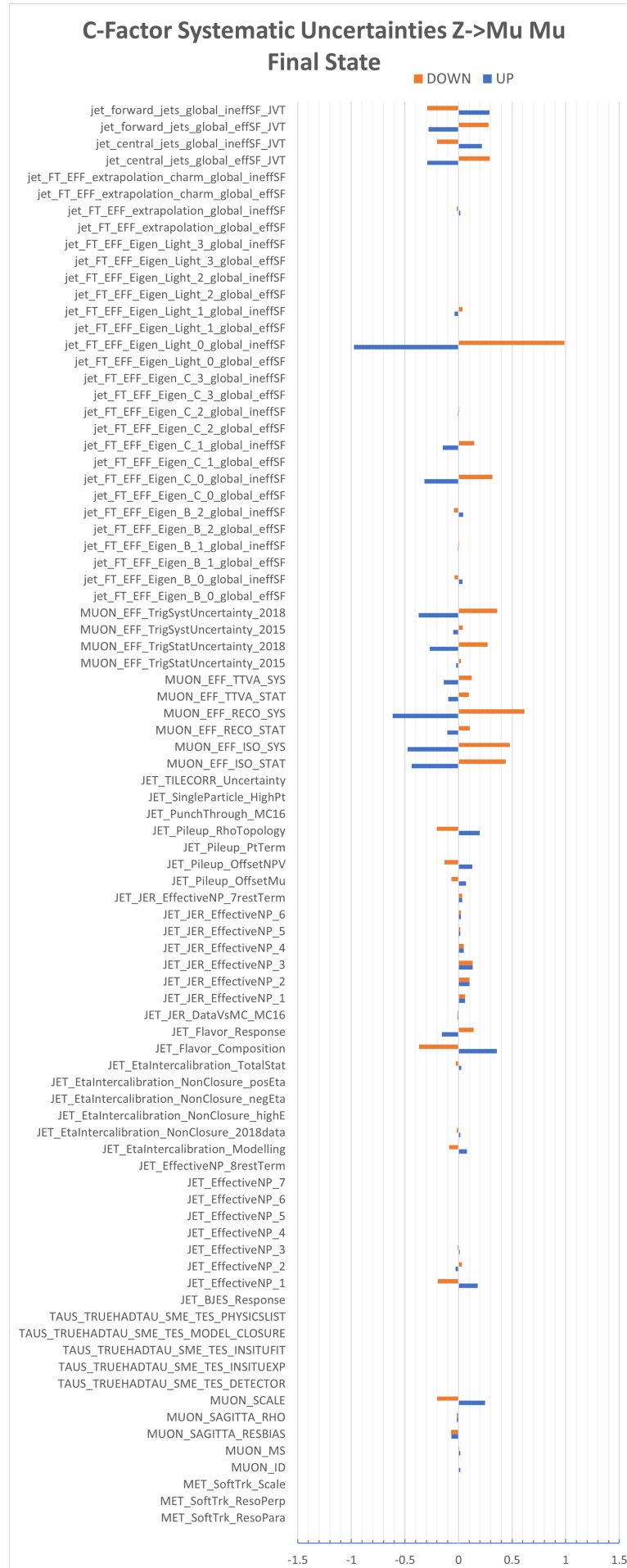
5.6.1 Zp_T study

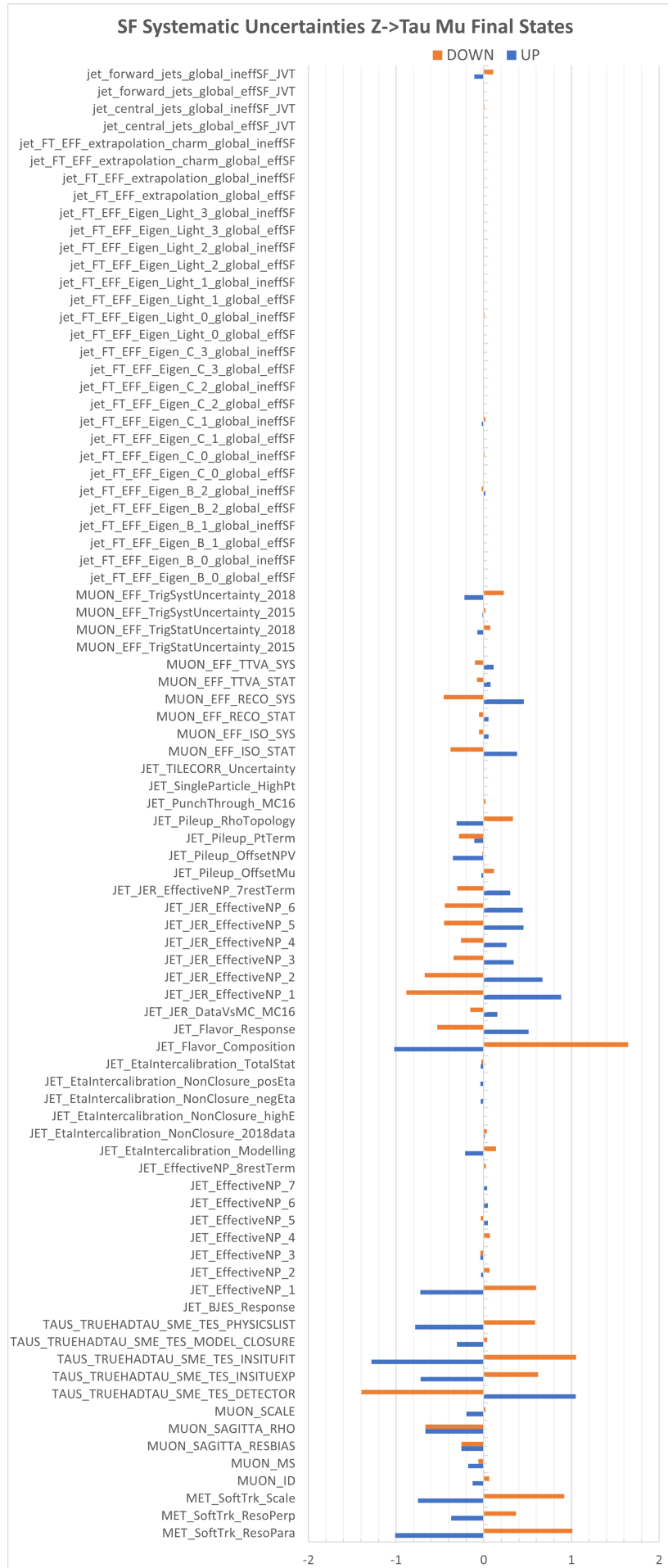
Since in this analysis, we select events with highly boosted Z bosons, the Zp_T is expected to peak at higher values than in the usual back-to-back $Z \rightarrow ll$ events. Previous results [134] have shown that different MC generators predict various shapes for the Zp_T distribution — especially in the high- p_T tail. In this analysis, we use two MC samples for the signal events: PowHeg+Pythia8 (PoPy) and SHERPA 2.2.1 (Sherpa).

As can be seen in Figure 5.24, Sherpa describes better than PoPy the Z boson transverse momentum at high values. Both generators underestimate the data below the $Zp_T = 300$ GeV region.

Figure 5.25 shows the Zp_T distribution requiring a looser $\Delta\phi(\tau, \mu) < 2.0$ criteria and a $p_T(\tau) \geq 25$ GeV requirement — the purpose of the looser selection is to observe the Zp_T distributions with better statistics. Looking at these plots we can confirm the previous ATLAS observation that Sherpa describes better the data for highly-boosted $Z \rightarrow ll$ events. If we measure the ratio

FIGURE 5.18: Percentage uncertainties in the C-Factor($Z \rightarrow \tau_{\text{had}}\mu$) for 1-prong taus.

FIGURE 5.19: Percentage uncertainties in the C-Factor($Z \rightarrow \mu\mu$).

FIGURE 5.20: Percentage uncertainties in the SF($Z \rightarrow \tau_{\text{had}}\mu$) for 1-prong taus.

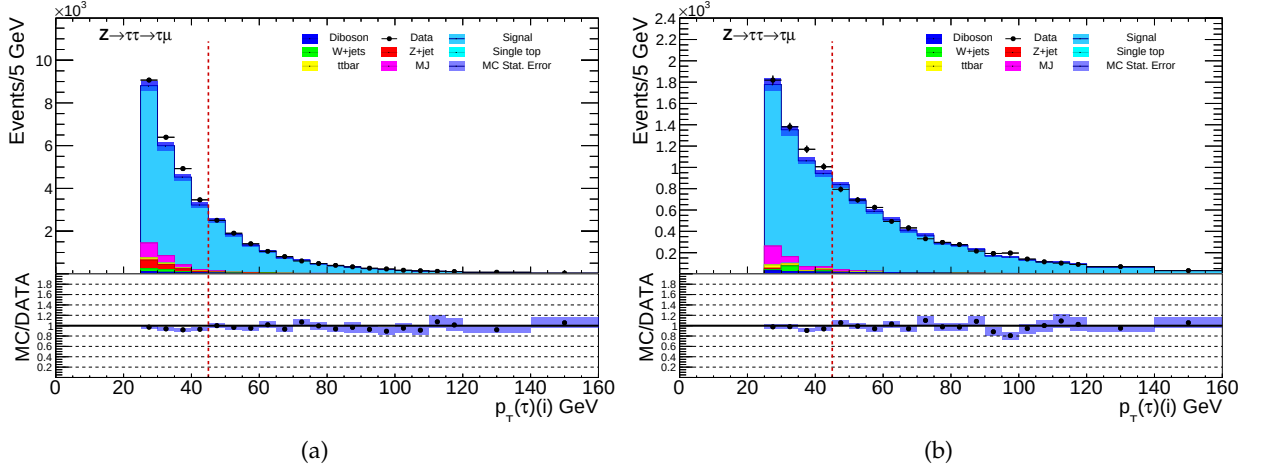


FIGURE 5.21: Figure (a) and (b) show the $\tau_{\text{had}} p_T$ spectrum for a selection requirement of $\Delta\phi(\tau_{\text{had}}, \mu) < 2.1$ and $\Delta\phi(\tau_{\text{had}}, \mu) < 1.0$, respectively. When the harder cut is applied the $\tau_{\text{had}}(p_T)$ spectrum slope is less pronounced.

defined in Equation 5.14, we would be sensitive to the Zp_T modelling. However, by taking the double ratio defined in Equation 5.16 this effect should partially cancelled.

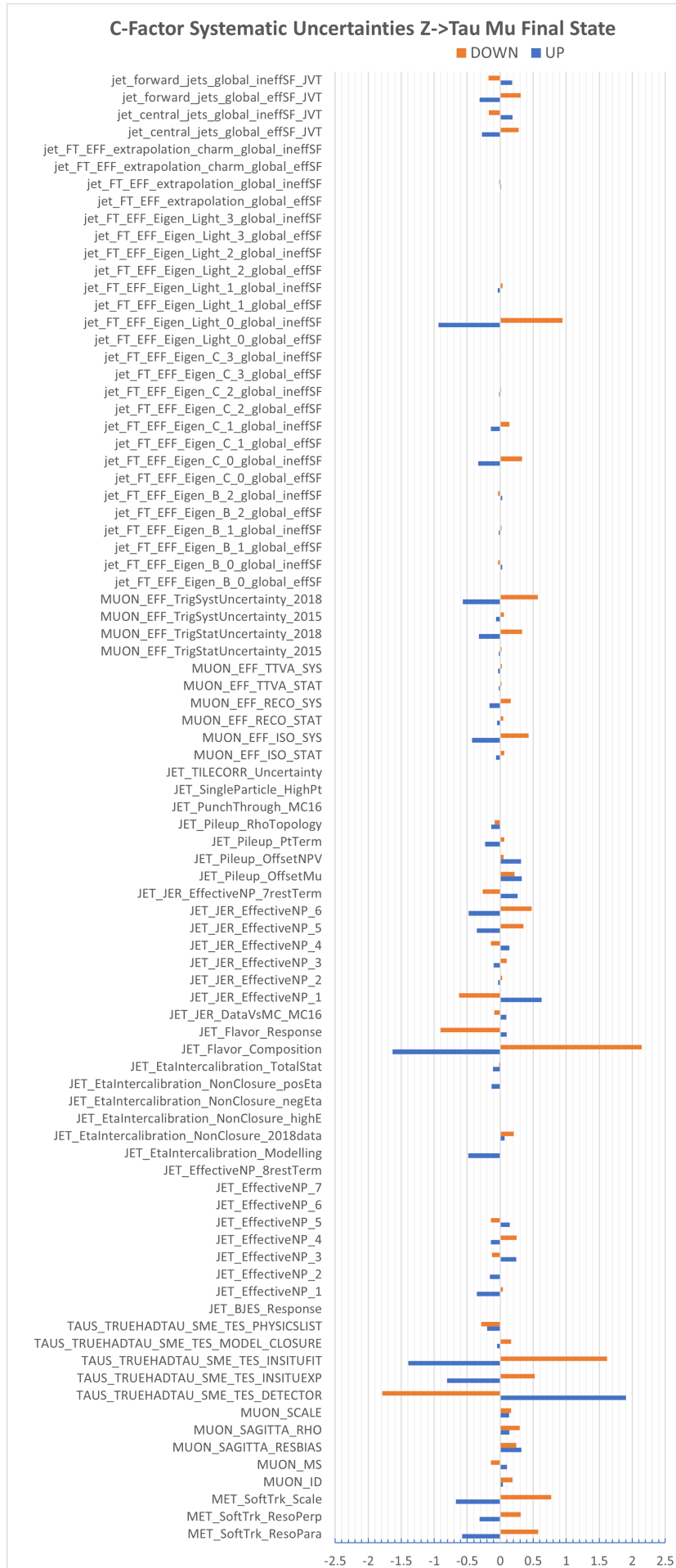
To perform a cross-check of our methodology, the $Z \rightarrow \tau_{\text{had}} \tau_{\text{lep}}$ and $Z \rightarrow ll$ PoPy samples are re-weighted according to the ratio between data and simulation presented in Figure 5.24 — we call the re-weighted samples PoPy-RW. The goal of this procedure is to show that the double ratio is not sensitive at first order to the Zp_T modelling. Appendix A.1.2 includes the kinematic predictions using the PoPy-RW samples for the Z boson production simulation.

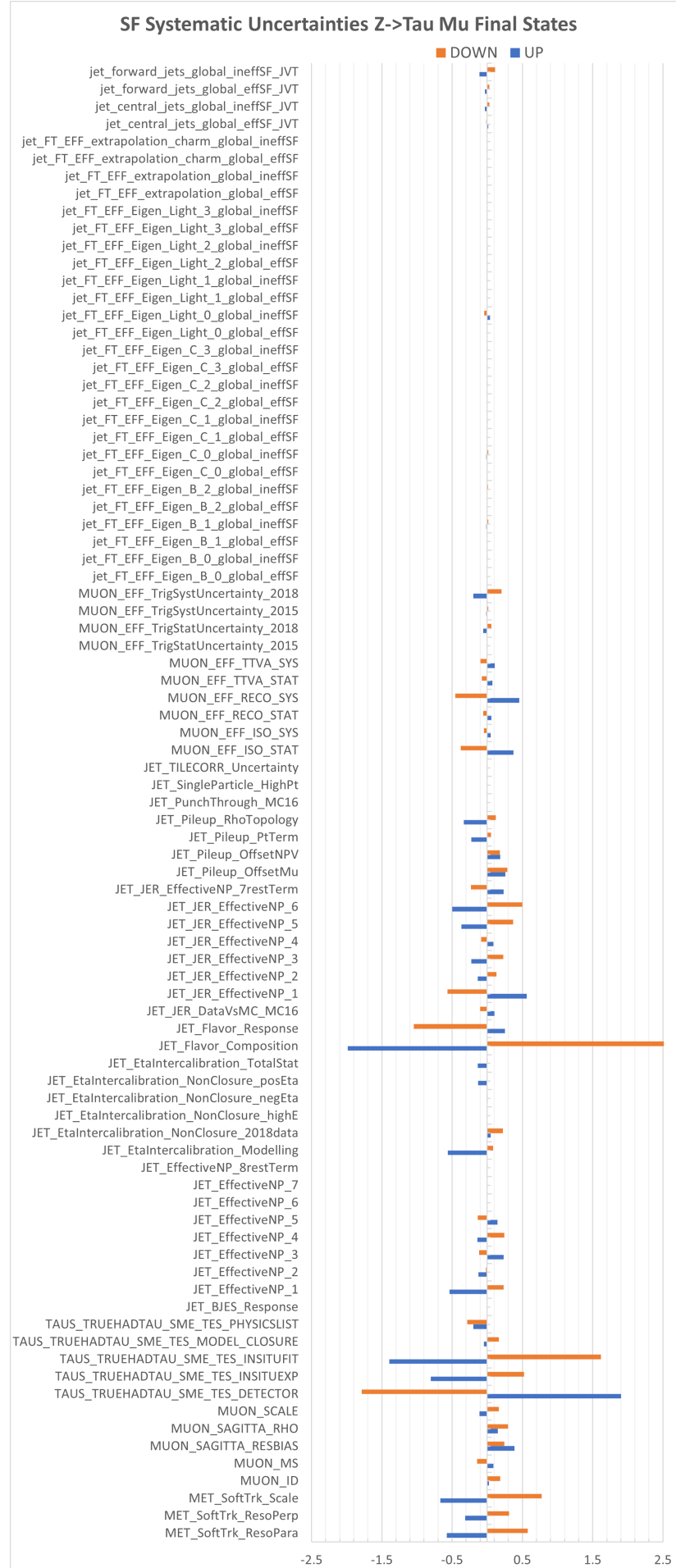
5.6.2 Scale Factors

The yields for each final state, using the Sherpa samples as the signal, are shown in Table 5.4. We calculate the C factors and the SFs; the results are given in the second column of Table 5.5 and Table 5.6. The SFs are obtained using the three alternative MC configurations, each given in a separate column. The values are reported as

$$\text{Central value} \pm \text{Uncorrelated Uncertainty} \pm \text{Correlated Uncertainty} = \text{Total}. \quad (5.23)$$

All the uncertainties reported in the tables correspond to statistical uncertainties. They are split into two categories: first, uncorrelated uncertainties which arise from the MC statistical uncertainty on the signal sample and part of the MJBG contribution since the latter is calculated taking into account the prediction for the signal in the control regions. The correlated uncertainty arises from the data statistical uncertainties and the MC statistical uncertainties of the EWBG component. The latter are fully correlated within a given final state and they should not be included when comparing different signal MC configurations (different columns). Finally, the total statistical uncertainty is calculated by adding the correlated and uncorrelated components in quadrature. This value should be used to compare between different final states.

FIGURE 5.22: Percentage uncertainties in the C-Factor($Z \rightarrow \tau_{\text{had}}\mu$) for 3-prong taus.

FIGURE 5.23: Percentage uncertainties in the $SF(Z \rightarrow \tau_{\text{had}}\mu)$ for 3-prong taus.

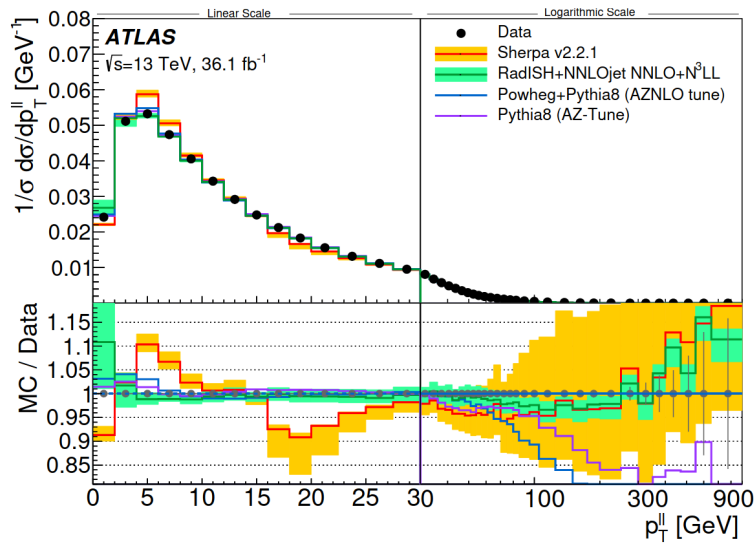


FIGURE 5.24: Comparison between different predictions for the Zp_T in Drell-Yan events. Taken from [134].

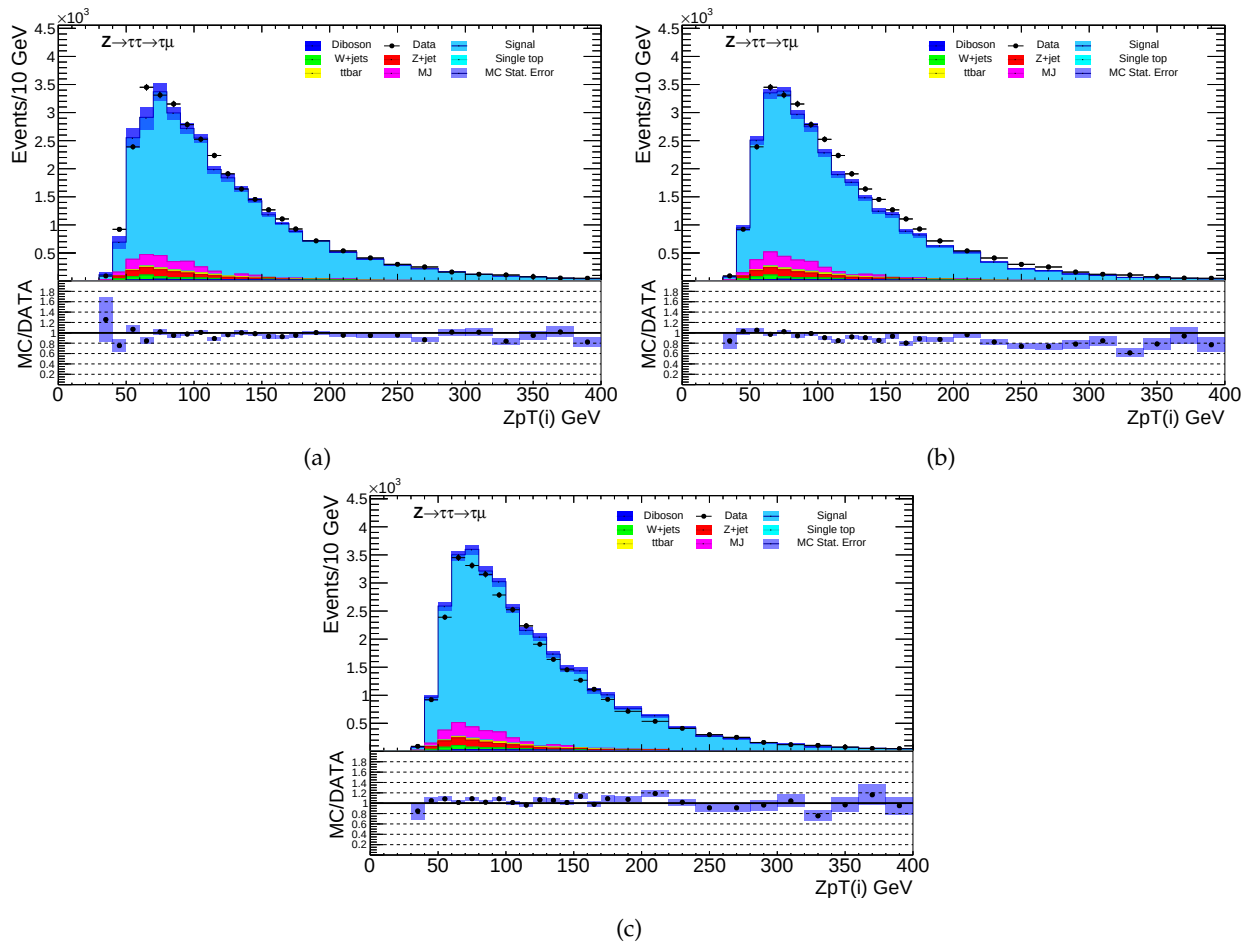


FIGURE 5.25: Distributions of Zp_T for $Z \rightarrow \tau_{\text{had}}\mu$ events requiring a looser $\Delta\phi(\tau, \mu) < 2.0$ criteria and a $p_T(\tau) \geq 25$ GeV requirement. The prediction from SHERPA 2.2.1 (a) is much closer to the data when compared with PowHeg+Pythia8 (b) which tends to underestimate the data increasingly as the Zp_T becomes higher. Figure (c) shows the PowHeg+Pythia8 Zp_T modelling after the re-weighting described in Section 5.6.1 is performed. The data-to-MC agreement is better in the re-weighted sample.

Final State Sample	$Z \rightarrow \tau\mu$		$Z \rightarrow \mu\mu$	$Z \rightarrow \tau e$		$Z \rightarrow ee$
	1-Prong	3-Prong		1-Prong	3-Prong	
Signal Truth	5658.798 ± 59.146	1463.938 ± 30.753	187038.582 ± 350.582	4656.503 ± 58.314	1233.426 ± 27.754	155746.726 ± 294.846
Signal Fake	56.596 ± 5.507	1.439 ± 1.15	0 ± 0	7.337 ± 1.598	0.473 ± 0.34	0 ± 0
Data	6156 ± 78.46	1444 ± 38	207350 ± 455.357	5280 ± 72.664	1240 ± 35.214	170783 ± 413.259
VV	130.081 ± 2.258	30.739 ± 1.061	4357.909 ± 19.042	114.437 ± 2.147	32.386 ± 1.12	3813.414 ± 12.897
W+jets	6.439 ± 6.638	0 ± 0	0 ± 0	0 ± 0	0 ± 0	8.399 ± 8.399
Z+jets	13.615 ± 1.941	0.115 ± 0.115	33.153 ± 8.899	23.516 ± 2.641	0.511 ± 0.362	50.815 ± 10.931
$t\bar{t}$	46.156 ± 2.521	14.178 ± 1.388	157.079 ± 4.772	43.25 ± 2.51	13.817 ± 1.423	134.426 ± 4.393
Single top	7.543 ± 0.939	1.366 ± 0.41	21.077 ± 1.662	4.56 ± 0.753	2.581 ± 0.595	18.488 ± 1.584
MJ	45.697 ± 13.615	9.697 ± 13.654		36.887 ± 15.695	0 ± 15.695	
RQCD	1.225 ± 0.084	1.661 ± 0.177		0.746 ± 0.208	1.26 ± 0.342	
The uncertainty reported in this table only corresponds to the statistical component.						

TABLE 5.4: Predicted yields for all the physics processes considered in this analysis — using SHERPA 2.2.1 for the $Z \rightarrow ll$ events ($l = e, \mu, \tau$). The Z+jets background sample corresponds to the production of a Z boson which decays into a pair of light leptons. This is considered as background for the $Z \rightarrow \tau\tau$ final states. For the $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ events, the Z+jets background is the $Z \rightarrow \tau\tau$ sample.

1 Prongs	Sherpa	PoPy-RW	PoPy
Muons			
$C(Z \rightarrow \mu\mu)$	$1.084 \pm 0.002 \pm 0.002 = 0.003$	$0.996 \pm 0.002 \pm 0.001 = 0.003$	$1.236 \pm 0.003 \pm 0.002 = 0.003$
$C_{\text{Tight}}(Z \rightarrow \tau\mu)$	$1.034 \pm 0.014 \pm 0.011 = 0.018$	$0.993 \pm 0.013 \pm 0.020 = 0.024$	$1.228 \pm 0.016 \pm 0.024 = 0.030$
$SF_{\text{Tight}}(Z \rightarrow \tau\mu)$	$0.954 \pm 0.013 \pm 0.010 = 0.017$	$0.997 \pm 0.014 \pm 0.020 = 0.024$	$0.993 \pm 0.014 \pm 0.020 = 0.024$
Electrons			
$C(Z \rightarrow ee)$	$1.071 \pm 0.003 \pm 0.002 = 0.003$	$1.026 \pm 0.003 \pm 0.001 = 0.003$	$1.275 \pm 0.003 \pm 0.002 = 0.004$
$C_{\text{Tight}}(Z \rightarrow \tau e)$	$1.085 \pm 0.016 \pm 0.014 = 0.021$	$1.043 \pm 0.015 \pm 0.023 = 0.028$	$1.289 \pm 0.019 \pm 0.029 = 0.034$
$SF_{\text{Tight}}(Z \rightarrow \tau e)$	$1.013 \pm 0.015 \pm 0.013 = 0.020$	$1.016 \pm 0.015 \pm 0.023 = 0.027$	$1.011 \pm 0.015 \pm 0.023 = 0.027$
Statistical uncertainty is reported as Correlated $\pm$ Uncorrelated = Total.			

TABLE 5.5: C-Factors and SFs for 1-prong taus using different MC configurations. Equation 5.23 shows how statistical uncertainties are reported.

3 Prongs	Sherpa	PoPy-RW	PoPy
Muons			
$C_{\text{Tight}}(Z \rightarrow \tau\mu)$	$0.947 \pm 0.026 \pm 0.022 = 0.034$	$0.908 \pm 0.025 \pm 0.037 = 0.045$	$1.121 \pm 0.031 \pm 0.045 = 0.055$
$SF_{\text{Tight}}(Z \rightarrow \tau\mu)$	$0.874 \pm 0.024 \pm 0.020 = 0.032$	$0.912 \pm 0.025 \pm 0.037 = 0.045$	$0.907 \pm 0.025 \pm 0.037 = 0.044$
Electrons			
$C_{\text{Tight}}(Z \rightarrow \tau e)$	$0.965 \pm 0.029 \pm 0.025 = 0.038$	$0.837 \pm 0.025 \pm 0.037 = 0.044$	$1.032 \pm 0.031 \pm 0.046 = 0.055$
$SF_{\text{Tight}}(Z \rightarrow \tau e)$	$0.901 \pm 0.027 \pm 0.024 = 0.036$	$0.815 \pm 0.024 \pm 0.036 = 0.043$	$0.81 \pm 0.024 \pm 0.036 = 0.043$
Statistical uncertainty is reported as Correlated $\pm$ Uncorrelated = Total.			

TABLE 5.6: C-Factors and SFs for 3-prong taus using different MC configurations. Equation 5.23 shows how statistical uncertainties are reported.

The first conclusion we can extract by looking at the last two columns in Table 5.5 and Table 5.6 is that the double ratio method cancels any effect due to the Zp_T modelling. The fact that the C-Factors for PoPy-RW and PoPy samples differ by 25% while the SFs agree confirms this hypothesis. When comparing the muon and electron final states for 1-prongs, we see that the PoPy results agree better between uncertainties than the Sherpa results. For 3-prongs, the situation is reversed.

Since we do not see a significant difference — greater than 2 sigma, between the SFs for the electron and muon final states, we combine the results. We assume a full correlation between the individual sources of systematic uncertainty in the combination. The results from the combination are given in Table 5.7.

Combination			
SF_{Tight}	Sherpa	PoPy	PoPy-RW
1Prong	0.978 ± 0.038	1.005 ± 0.040	1.001 ± 0.040
3 Prong	0.886 ± 0.047	0.862 ± 0.051	0.858 ± 0.051

TABLE 5.7: SFs after combining the muon and electron final states. The uncertainty accounts for both the systematic and statistical components.

1-Prong	Sherpa	PoPy-RW
$Z \rightarrow \tau\mu$	5658.798 ± 59.146	5923.081 ± 116.502
$Z \rightarrow \mu\mu$	187038.582 ± 350.582	203649.011 ± 258.455
R	33.05 ± 0.35	34.38 ± 0.68
$Z \rightarrow \tau e$	4656.503 ± 58.314	4840.89 ± 106.985
$Z \rightarrow ee$	155746.726 ± 294.846	162477.447 ± 219.923
R	33.45 ± 0.42	33.56 ± 0.74
Combination	33.21 ± 0.27	34.04 ± 0.50

TABLE 5.8: MC signal yield comparisons for 1-prong taus.

Finally, to assess the agreement between the two different MC samples we perform the following calculation: first, we take the ratio between the predicted yields for the signal processes,

$$R = \frac{Z \rightarrow ll}{Z \rightarrow \tau l} \quad (5.24)$$

— separately for electrons and muons. This ratio should be free of MC Zp_T modelling effects. Next, since we do not see big deviations between the electron and muon results, we combine them. Finally, the PoPy and Sherpa predictions are compared. These numbers can be seen in Table 5.8 for 1-prong taus. The numbers agree at the 1.4 sigma level. We do not see evidence to support the usage of different SFs for each MC generator.

For 3-prongs, the same calculation is performed and the results are shown in Table 5.9.

3-Prong	Sherpa	PoPy-RW
$Z \rightarrow \tau\mu$	1463.938 ± 30.753	1538.399 ± 58.932
R	127.76 ± 2.70	132.38 ± 5.07
$Z \rightarrow \tau e$	1233.426 ± 27.754	1419.201 ± 58.094
R	126.27 ± 2.85	114.49 ± 4.69
Combination	127.06 ± 1.96	122.73 ± 3.44

TABLE 5.9: MC signal yield comparisons for 3-prong taus.

The Sherpa predictions agree between muons and electrons, and they also agree with the PoPy-RW results for the muon final state. There is some tension with the electron final state in PoPy-RW. However, if we average the electron and muon results, the two MC samples agree between uncertainties.

5.6.3 p_T and η dependence

In addition to the inclusive study of the SFs, we split our results in p_T and η intervals. For the tau transverse momentum we measure the SFs in the following intervals: [25,45); [45,65); [65, ∞) and [45, ∞) GeV. The pseudo-rapidity bins are split into: [-2.5,1.3); [1.3,0); [0,1.3) and [1.3,2.5]. A

requirement on the transverse momentum of the taus ($p_T > 45$ GeV) is made when measuring the SFs η dependence.

The results are summarised in Figures 5.26 and 5.27. We do not observe significant evidence of a SF dependence on p_T or η .

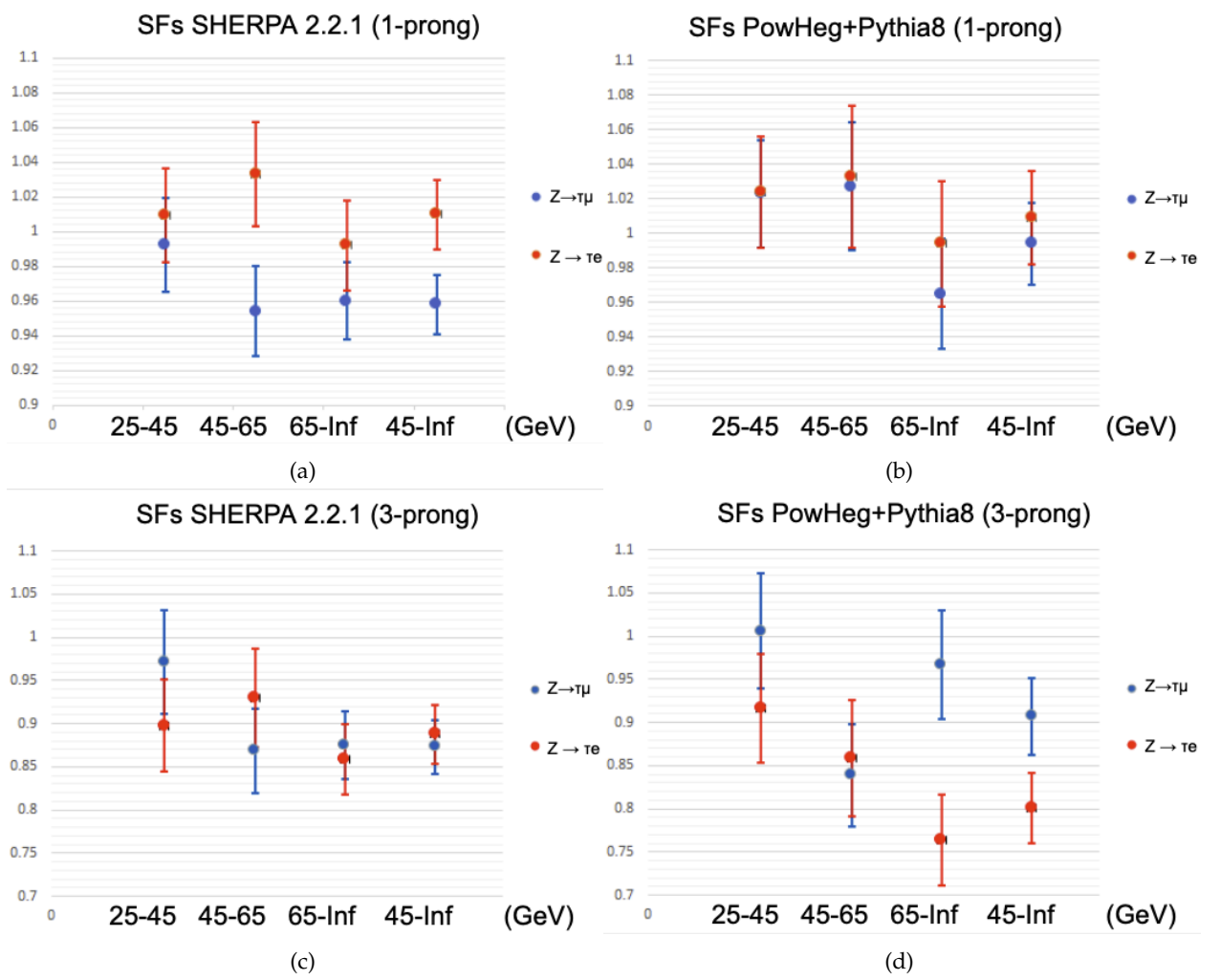


FIGURE 5.26: SFs split by p_T intervals. The plots on the top (bottom) correspond to 1(3)-prong tau candidates. The SHERPA 2.2.1 results are in the left column and the PowHeg+Pythia8 results, after the Zp_T re-weighting, are presented on the right.

Only the statistical uncertainty component is included in the error bars.

5.7 Conclusion

The ATLAS collaboration has developed algorithms to identify semi-hadronically decaying taus. Correction factors are used to account for the difference in the efficiency of these algorithms between data and simulation. The main goal of this study was to derive the correction factors for the tauID tight working point.

We used a different methodology from the usual performance tag and probe measurement. A ratio between data and MC for different lepton flavours was used to define a double ratio, which helped cancel shared systematic uncertainties between the different final states.

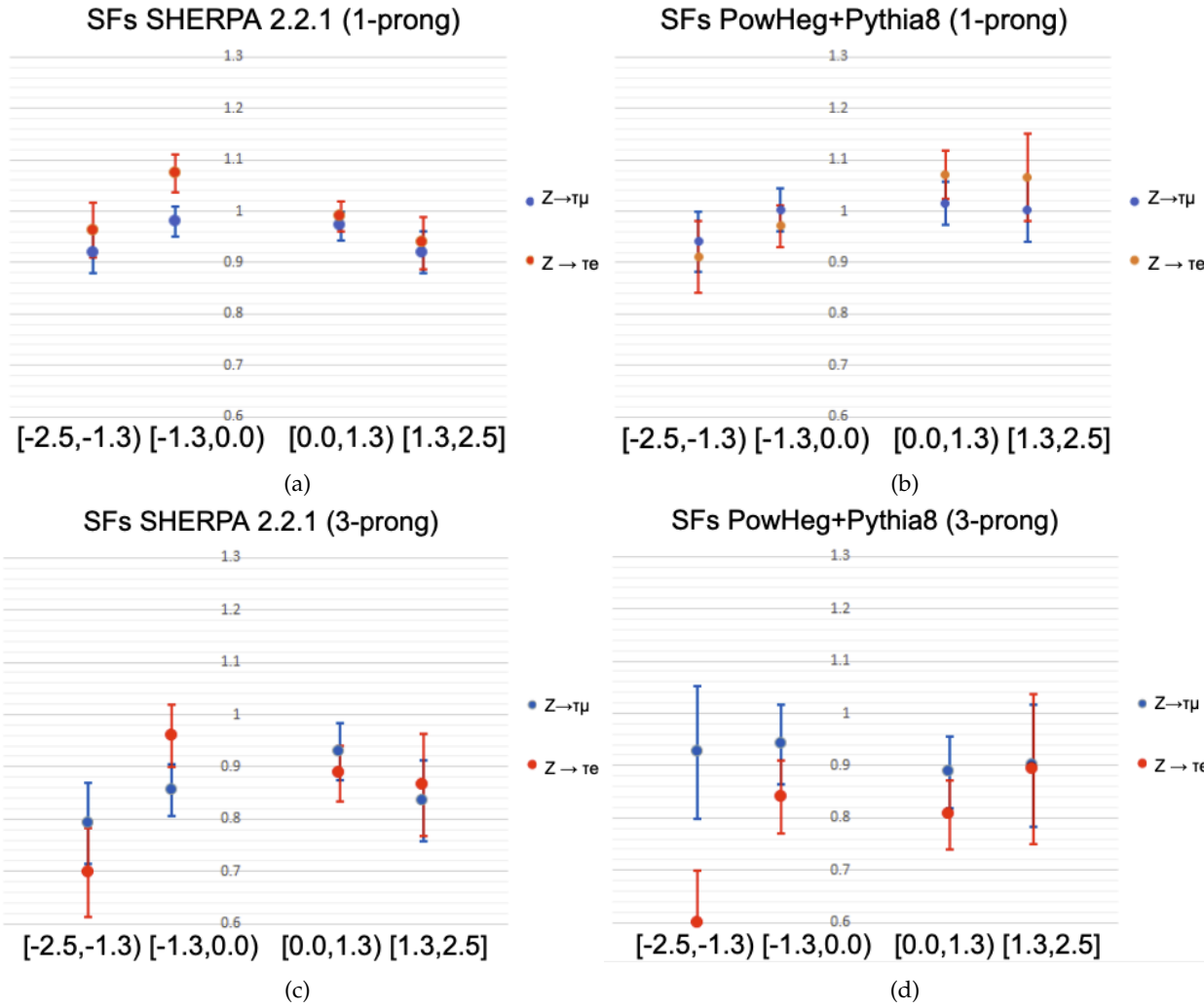


FIGURE 5.27: SFs split by η intervals. The plots on the top (bottom) correspond to 1(3)-prong tau candidates. The SHERPA 2.2.1 results are in the left column and the PowHeg+Pythia8 results, after the Zp_T re-weighting, are presented on the right.

Only the statistical uncertainty component is included in the error bars.

In order to have a sample of high- p_T taus we selected events with boosted Z bosons. The MC samples used for this study underestimate the Zp_T in the high momentum region and give varied predictions. This effect is corrected by performing the double ratio between $Z \rightarrow ll$ ($l = e, \mu$) and $Z \rightarrow \tau_{\text{had}} \tau_{\text{lep}}$ events. Our results show that there is agreement between the Zp_T re-weighted and the standard samples; confirming that the double ratio method reduces the modelling uncertainty.

As plans for the future, one could extend this study to the looser tau-ID working points. In those regions, the challenge will be to calculate a reliable estimate of the MJ background. This measurement can also be used to compare the description of the tau ID efficiency between different MC generator versions as they become available.

Chapter 6

Production of di-leptons in the Vector Boson Fusion Topology at the Z-peak

This chapter presents an observation of the Z boson production in pp collisions, in association with two jets, produced in the Vector Boson Fusion (VBF) mode (EWjj), in the $\tau\tau$ final state. A comparison between the production of the different lepton families in this process is performed. Specifically, a ratio between the total EWjj cross-sections for the light leptons $Z \rightarrow ll$ ($l = e, \mu$) and the $Z \rightarrow \tau\tau$ final states is performed. This measurement was done using the ATLAS detector Run-II data, collected from 2015 to 2018. The total integrated luminosity corresponds to 139.2 fb^{-1} of pp collisions with a centre-of-mass energy of $\sqrt{s} = 13 \text{ TeV}$.

For leptons pairs with an invariant mass close to the Z boson mass, the main background is the production of a Z boson, accompanied by QCD initiated jets (QCDjj). This background has been studied and constrained using dedicated control regions, where data-driven methods have been applied to get an estimate of the background in the signal region.

The production of EWjj events via the t-channel exchange of an electroweak boson is a much rarer process than its QCD counterpart [135]. As can be seen in Figure 6.1a, when two gluons are radiated from the quark lines to produce the final state jets, the coupling strength of the production process is proportional to $\mathcal{O}(\alpha_s^2 \alpha_{EW})$. In contrast, the pure electroweak production process is proportional to $\mathcal{O}(\alpha_{EW}^3)$ and is heavily suppressed by the two off-shell W boson propagators seen in Figure 6.1c. The VBF topology is of particular interest because it is similar to the VBF Higgs boson production mode and it is sensitive to anomalous triple gauge couplings. These additional hypothetical interactions would affect the lepton universality hypothesis depending on how the new physics couples to the leptons. This is the main motivation to look for the EWjj process in $Z \rightarrow \tau\tau$ events and specially at high di-lepton invariant masses. A detailed discussion of the status of current searches and limits on the production of high-mass resonances decaying into tau pairs can be found in Section 2.5.

Figure 6.1c shows the Feynman diagram corresponding to the EWjj process. In this topology, we expect two high-momentum jets located in opposite sides of the ATLAS detector. Since in the EWjj process there is no flow of colour between the interacting proton fragments, lower hadronic activity is expected in the rapidity interval between the jets. In contrast, Figures 6.1a and 6.1b show cases where the partons that generate the final state jets are coming from QCD radiation. This can lead to further QCD radiation in the rapidity interval spanned by the two jets.

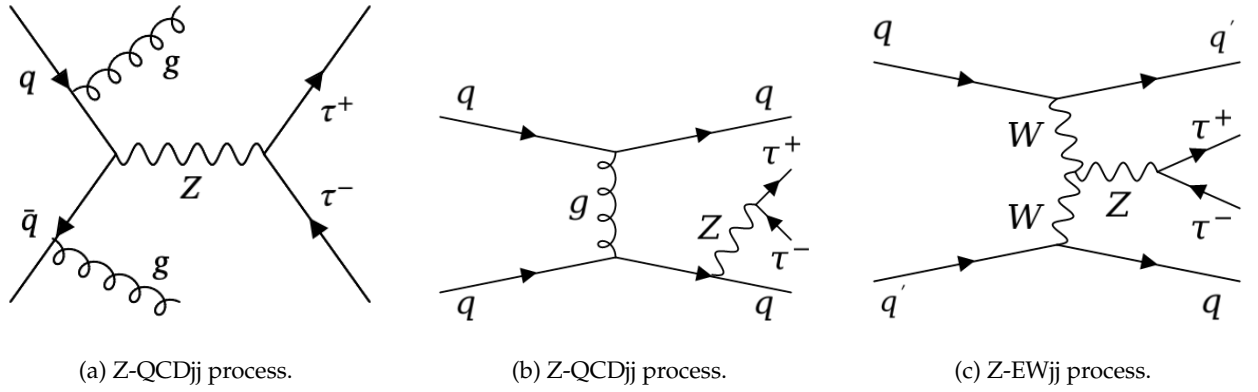


FIGURE 6.1: Two different contributions for the production of a Z boson in association with two jets. Sub-figures (a) and (b) show Feynman diagrams for the more common QCD production mode, the main background of our analysis. Sub-figure (c) shows the VBF topology, where the two out-coming quarks do not have a colour connection.

The methodology of this measurement follows similar previous ATLAS analyses [136–139]. The main difference with those studies is that we have included tau leptons in the final states. The first observation of the VBF Z production, in $Z \rightarrow ll (l = e, \mu)$ final states, was done by ATLAS at $\sqrt{s} = 8$ TeV [136]. A similar study was performed in Run-II [137]. More recently, a differential cross-section measurement for this process has been published [139]. The CMS collaboration has also measured the EWjj production cross-section at the same centre-of-mass energies [140, 141]. All of these studies put constraints on anomalous triple gauge couplings. However, an analysis that includes the third generation of leptons in the final states is complementary and can help to discover or rule out the possibility of an additional resonance that only couples to the third generation of fermions.

6.1 Data and MC samples

This analysis uses the data taken by the ATLAS detector during the LHC Run-II, from 2015 to 2018. During this period, the LHC operated at a centre-of-mass energy of $\sqrt{s} = 13$ TeV, with a bunch crossing time of 25 ns. The integrated luminosity for 2015 data taking is 3.22 fb^{-1} , for 2016 is 32.99 fb^{-1} , 2017 data accounts for 44.31 fb^{-1} and for the 2018 period is 58.45 fb^{-1} . These datasets are combined to get our final results — the total integrated luminosity is 139.2 fb^{-1} with a combined uncertainty of 1.7% [142].

Monte Carlo (MC) samples are used to estimate the backgrounds and compare the data to the Standard Model (SM) predictions. There are different samples available for each data taking period, because the conditions of the collisions and the detectors change in time. The MC samples are divided into different campaigns, in order to match the real collisions. Each MC sample is calibrated taking into account recommendations from the "combined performance" groups. These recommendations change with time as more data is taken and analysed. We describe the calibrations applied to the simulation in Section 6.2.2. Finally, the MC samples are weighted to the corresponding integrated luminosity.

Various samples for the QCDjj and the EWjj process are used in this measurement. The reason for this is that we know from previous VBF measurements that the QCDjj modelling is different

between generators and the data is not well described. Additionally, the extraction of the EWjj contribution is performed by fitting the shape of the EWjj prediction to the data — having different models for this contribution allows us to assign an uncertainty arising from the different descriptions of the EWjj process. Five MC samples are used to simulate the QCDjj background. The first two samples are described in Section 5.1, i.e., SHERPA 2.2.1 and PowHeg+Pythia8.

The third sample is an updated version of SHERPA 2.2.1. It is SHERPA 2.2.11 using next-to-leading-order (NLO) matrix elements (ME) for up to two partons, and leading-order (LO) matrix elements for up to five partons. We will refer to this sample as SHERPA 2.2.11.

The fourth sample, was simulated with MadGraph5_AMC@NLO 2.2.2 [143], using LO-accurate matrix elements (ME) with up to four final-state partons. The ME calculation employed the NNPDF 3.0NLO set of PDFs [105] (H_T -sliced) NNPDF 2.3LO set of PDFs [122] (N_{parton} -sliced). Events were interfaced to Pythia 8.186 [111] for the modelling of the parton shower, hadronisation, and underlying event. The overlap between matrix element and parton shower emissions was removed using the CKKW-L merging procedure [144, 145]. The A14 tune [121] of Pythia 8 was used with the NNPDF 2.3LO PDF set [122]. The decays of bottom and charm hadrons were performed by EvtGen 1.2.0 [117]. The V +jets samples were normalised to a next-to-next-to-leading-order (NNLO) prediction [106]. We refer to this sample as MadGraph@LO.

The fifth sample has been also generated using the MadGraph5_AMC@NLO program to generate matrix elements for $V + 0, 1$ and 2 partons at NLO accuracy. The showering and subsequent hadronisation has been performed using Pythia 8.210 with the A14 tune, using the NNPDF 2.3LO PDF set with $\alpha_s = 0.13$. The different jet multiplicities are merged using the FxFx prescription [146] implemented in the MadGraph5_AMC@NLO program (version 2.3.3 is used here). This program performs a five flavour number scheme calculation with massless b - and c -quarks in the matrix element [147], and massive quarks in the Pythia shower. The PDF input set in use for event generation is NNPDF 2.3NLO PDF set with $\alpha_s = 0.119$ and the samples have been generated with additional weights for the PDF replicas as well as scale variations of the renormalisation and the factorisation scales [148]. The samples have been generated using LHAPDF-6.1.5 [149] and FastJet-3.1.0 [150]. We refer to this sample as MadGraph@NLO.

The Z boson electroweak production (EWjj) and the W boson electroweak production, referred as W+jets EWK, are simulated with the same MC generator. The electroweak production of $\ell\ell jj$, $\ell\nu jj$ and $\nu\nu jj$ final states was simulated with SHERPA 2.2.1 [95] using leading-order (LO) matrix elements with up to two additional parton emissions. The matrix elements were merged with the SHERPA parton shower [100] following the MEPS@LO prescription [103] and using the set of tuned parameters developed by the SHERPA authors. The NNPDF 3.0NNLO set of PDFs [105] was employed. The samples were produced using the VBF approximation, which avoids overlap with semileptonic diboson topologies by requiring a t -channel colour-singlet exchange [151, 152]. This EWjj sample is referred as EWjj-SHERPA.

An alternative simulation for the EWjj process is used. The production of $\ell\ell jj$ final states was also simulated with PowHegBox v2 [107–109, 118] using the NNPDF 3.0NLO [105] parton distribution functions (PDF) and is accurate to next-to-leading order (NLO) in perturbative QCD. The sample was produced with the VBF approximation, which requires a t -channel colour-singlet exchange to remove overlap with diboson topologies. The parton-level events were passed to Pythia 8.245 to add parton-showering hadronisation and underlying-event activity, using the A14 [121] set of tuned parameters. The correct VBF-appropriate radiation pattern was achieved by using

the dipole-recoil option. The EvtGen1.7.0 program [117] was used for the properties of the bottom and charm hadron decays. This sample is referred as EWjj-PowHeg+Pythia8.

Higgs boson production via gluon–gluon fusion was simulated at next-to-next-to-leading-order (NNLO) accuracy in QCD using PowHegBox v2 [107–109, 153, 154]. The simulation achieved NNLO accuracy for arbitrary inclusive $gg \rightarrow H$ observables by reweighting the Higgs boson rapidity spectrum in Hj-MiNLO [155–157] to that of HNNLO [158]. The PDF4LHC 15nnlo PDF set [159] and the AZNLO tune [112] of Pythia 8 [120] were used.

The gluon–gluon fusion prediction from the Monte Carlo samples was normalised to the next-to-next-to-next-to-leading-order cross-section in QCD plus electroweak corrections at next-to-leading order (NLO) [160–170]. The decays of bottom and charm hadrons were performed by EvtGen [117]. The normalisation of all Higgs boson samples accounts for the decay branching ratio calculated with HDECAY [171–173] and Prophecy4f [174–176].

Higgs boson production via vector-boson fusion was simulated with PowHegBox v2 [107–109, 177] and interfaced with Pythia8 [120] for parton shower and non-perturbative effects, with parameters set according to the AZNLO tune [112]. The PowHegBox prediction is accurate to next-to-leading order (NLO) and uses the PDF4LHC 15nlo PDF set [159]. It was normalised to an approximate-NNLO QCD cross-section with NLO electroweak corrections [178–180]. The decays of bottom and charm hadrons were performed by EvtGen [117]. The normalisation of all Higgs boson samples accounts for the decay branching ratio calculated with HDECAY [171–173] and Prophecy4f [174–176].

Higgs boson production in association with a vector boson was simulated using PowHegBox v2 [107–109, 177] and interfaced with Pythia 8 [120] for parton shower and non-perturbative effects. The PowHegBox prediction is accurate to next-to-leading order for VH boson plus one-jet production. The loop-induced $gg \rightarrow ZH$ process was generated separately at leading order. The PDF4LHC 15nlo PDF set [159] and the AZNLO tune [112] of Pythia 8 [120] were used. The decays of bottom and charm hadrons were performed by EvtGen [117]. The Monte Carlo prediction was normalised to cross-sections calculated at NNLO in QCD with NLO electroweak corrections for $q\bar{q}/qg \rightarrow VH$ and at NLO and next-to-leading-logarithm accuracy in QCD for $gg \rightarrow ZH$ [181–187]. The normalisation of all Higgs boson samples accounts for the decay branching ratio calculated with HDECAY [171–173] and Prophecy4f [174–176].

The production of $t\bar{t}$, single-top quark and di-boson (VV) events is simulated with the samples described in Section 5.1. An additional sample for the electroweak production of di-boson events (EWjj-VV) is also included. EWjj-VV was simulated with the SHERPA 2.2.2 [95] generator. The LO-accurate matrix elements were matched to a parton shower based on Catani–Seymour dipole factorisation [96, 100] using the MEPS@LO prescription [101–104]. Samples were generated using the NNPDF 3.0NNLO PDF set [105], along with the dedicated set of tuned parton-shower parameters developed by the SHERPA authors.

All the processes described above are passed through a simulation of the detector, taking into account the effect of multiple interactions as described in Section 5.1.

6.2 Event and object selection

Data Sample	Single Electron	Single Muon
2015	HLT_e24_lhmedium_L1EM20VH HLT_e60_lhmedium HLT_e120_lhloose	HLT_mu20_iloose_L1MU15
2016, 2017, 2018	HLT_e140_lhloose_nod0 HLT_e26_lhtight_nod0_ivarloose HLT_e60_lhmedium_nod0	HLT_mu26_ivarmedium HLT_mu50

TABLE 6.1: List of single lepton triggers used in each data-taking period.

6.2.1 Basic selection and triggers

The events used in this analysis have to satisfy the following requirements:

- be part of the Good Run List, which describes what luminosity blocks of the data are usable,
- exclude events corrupted by any of the sub-detector systems presenting problems,
- pass the "Loose" jet-cleaning working point.

The triggers used for our selection are the unprescaled single light lepton triggers available in each data-taking period. The minimum online p_T requirement for muons and electrons changes between 2015 and the remaining data-taking periods. Trigger algorithms requiring a higher p_T threshold have looser identification and isolation requirements. The light-lepton candidate firing the trigger has to be geometrically matched to an offline reconstructed light-lepton. Table 6.1 details the triggers by data-taking period for electrons and muons separately.

6.2.2 Simulation corrections

Multiple corrections to the MC samples are applied to get a more precise description of the data. These corrections are described in this section.

Pileup correction

The Monte Carlo samples do not match perfectly the number of interactions (μ) observed in data. The ATLAS *PileupRewightingTool* is used to correct these differences. The tool is provided with a pileup reweighting configuration file for each MC sample that contains the average (μ) distributions for that sample. The tool is also provided with a file for each data period, which contains the average (μ) distributions for data. These two pieces of information are used to re-weight the MC samples to correctly describe the pileup distribution observed in the data.

An additional pileup-related correction is applied to the tagging of prompt jets. Jets are given a score according to how well they match with the principal vertex (PV). The Jet Vertex Tagging (JVT) algorithm is calibrated using $Z \rightarrow \mu\mu$ events where the leading jet in the event is back to back with the di-muon system. JVT scale factors are measured in p_T and η bins for the jet.

A more detailed description of the JVT correction can be found in [83].

Light lepton corrections

The efficiency in the reconstruction, identification and isolation of electrons and muons is different in data and simulation. A tag-and-probe method is used to select events from Z , W and J/Ψ

decays and compare the selection efficiency between data and MC. The difference is corrected by applying scale factors to the MC events parametrised in p_T and η bins.

The tag-and-probe method requires that one of the light leptons passes the tightest selection criteria (the tag). The other lepton (the probe) is selected to have a combined di-lepton mass close to the Z , W or J/Ψ ; depending on the desired p_T selection.

A more detailed description of these corrections can be found in [78, 79, 130, 131].

Tau corrections

The tau calibration scale factors are derived for the tau identification algorithms using a tag-and-probe method. For the tauID, a measurement using $Z \rightarrow \tau\tau$ events is performed, the tag object is a light lepton produced in the decay of one of the taus. The identification algorithm trained to reject electron fakes is calibrated using $Z \rightarrow ee$ events. The tau energy scale (TES) is also corrected by comparing the reconstructed tau energy and the true visible tau energy. The correction subtracts the energy of pileup interactions and corrects the response of the calorimeter due to various effects: tau decay products not reaching the calorimeter, decay products with not enough energy to create calorimeter clusters, or tau decay products being outside the $\Delta R = 0.2$ cone that defines the τ_{had} candidate.

A more detailed description of these corrections can be found in [90].

Trigger scale factors

The trigger efficiency difference between data and MC is also corrected using scale factors. Trigger scale factors are available for the single light lepton triggers described in Table 6.1. The calibration procedure follows the tag-and-probe method. The tag lepton is the one firing the trigger and then the other lepton is used to measure the trigger efficiency.

A more detailed description of these corrections can be found in [130, 188].

Jet flavour tagging correction

The algorithm used to separate b-jets from light jets is also calibrated comparing data and MC efficiencies. The sample used in the calibration is highly enriched in $t\bar{t}$ events, requiring at least two jets, opposite charge and different flavour light leptons. Additionally, one of the jets in the event has to be tagged as a b-jet with a high efficiency operating point (85%).

A more detailed description of this correction can be found in [132].

Jet energy and resolution correction

The jet energy scale (JES) correction restores the energy of the jet to the particle-level jet energy. The correction starts by removing the excess energy due to additional proton-proton interactions. After this, the jet direction and energy is corrected such that it agrees with the values obtained in MC simulation of di-jet events. Finally, a residual calibration is only applied to data events to correct for remaining data-to-MC differences.

The jet energy resolution (JER) is measured in di-jet events. The JER measurement relies on calculating the p_T difference of the two leading jets. Any difference in the momentum of the leading jets is attributed to the experimental resolution, the presence of additional radiation or biases

due to the event selection. The final JER is measured after subtracting the two latter contributing factors. The impact of these factors is measured by calculating the momentum imbalance with particle-level quantities.

A more detailed description of these corrections can be found in [81].

6.2.3 Analysis variables and event selection

This analysis follows a similar approach to the ATLAS VBF differential cross-section measurement performed with light-lepton pairs [139]. The selection is designed to reject the background processes and enhance the VBF contribution.

The two highest p_T light jets, decreasingly ordered in transverse momentum, are referred to as the leading and sub-leading jets or simply as the tagging jets. The tagging jets are denoted j_1 and j_2 , with j_1 being the leading jet. They define the "di-jet" system — the invariant mass of the di-jet system is denoted as m_{jj} . We require the leading and sub-leading jets' p_T to be greater than 75 and 70 GeV, respectively. In the EWjj process, the tagging jets are expected to be located on opposite sides of the ATLAS detector such that a considerable rapidity separation between them is expected. The rapidity separation between the tagging jets is denoted as $\Delta y_{jj} = |y_1 - y_2|$ and is required to be greater or equal than two. The interval in rapidity between the two leading jets is called the "gap". At the same time, the large rapidity separation and the high p_T requirement on the jets, produces a di-jet system with a high invariant mass — this is one of the distinctive features of the EWjj production over the QCDjj production mode. Events with more than three light jets are not allowed.

In addition to this angular observable, we define a variable for the transverse momentum balance called " p_T -balance". It is defined as the ratio between: the magnitude of the vector sum of the transverse momentum of jets and leptons in the event; and the scalar sum of the transverse momentum of the same objects. The jets included in this calculation contain any jet in the gap if present. The arithmetic definition of " p_T -balance" is

$$p_{T\text{balance}} = \frac{|\sum \vec{p}_T|}{\sum |\vec{p}_T|}. \quad (6.1)$$

In this analysis we include final states with light-leptons and taus. For the light-leptons, we consider events where the Z decays into a pair of opposite charged muons or electrons. The tau final states consist of oppositely charged tau leptons. Since the taus decay before reaching the detector volume, we consider the cases where one of the taus decays semi-hadronically (τ_{had}) and the other leptonically (τ_{lep}), producing either a muon or electron. Additionally, the case where both taus decay leptonically is considered. However, in the latter case, only the opposite charge and different flavour pairs are considered.

For all the final states, a condition on the isolation level of the light leptons has to be satisfied. For the muons (electrons), the scalar sum of the p_T of the tracks within a cone of $\Delta R = 0.3(0.2)$ around the muon (electron) must be less than 0.06 times the muon (electron) p_T . Additionally, for the electrons, the sum of the calorimeter cluster energies within a cone of $\Delta R = 0.2$ must be less than 0.06 times the electron p_T .

In the tau final states we use the collinear approximation described in Section 5.2.1 and the same definition of Ω holds.

	$Z \rightarrow \tau_{\text{had}} \tau_{\text{lep}}$	$Z \rightarrow ll$	$Z \rightarrow \tau_{\text{lep}} \tau_{\text{lep}} \rightarrow e\mu$
Tagging jets	$2 \leq n \text{ light jets} \leq 3$ $n \text{ b-jets} = 0$ $\Delta y_{jj} \geq 2.0$ $p_T(j_1) \geq 75 \text{ and } p_T(j_2) \geq 70 \text{ GeV}$		
Light leptons	$p_T(\tau_{\text{lep}}) \geq 27 \text{ GeV}$	$p_T(l_1) \geq 50 \text{ and } p_T(l_2) \geq 40 \text{ GeV}$	$p_T(e) \geq 27 \text{ and } p_T(\mu) \geq 27 \text{ GeV}$
Tau leptons	$p_T(\tau_{\text{had}}) \geq 25 \text{ GeV}$ jetRNN Working Point = Medium eBDT Working Point = Loose		
Z-peak	$66 \leq m_{\text{reco}} \leq 116 \text{ GeV}$ $m(\tau_{\text{had}}, e) \leq 80 \text{ GeV}$ $-0.2 \leq \Omega \leq 1.6$	$81 \leq m(l_1, l_2) \leq 101 \text{ GeV}$	$66 \leq m_{\text{reco}} \leq 116 \text{ GeV}$ $-0.4 \leq \Omega \leq 1.4$
VBF	$m(j_1, j_2) \geq 1000 \text{ GeV}$ $p_{T\text{bal}} \leq 0.15$		

TABLE 6.2: Event selection for the different final states.

For *in between* events ($\vec{E}_T^{\text{miss}}$ between τ candidates) the mass of the di-tau system (m_{reco}) is

$$m_Z^2(\text{in between}) = (p_{\tau_{\text{had}}} + p_{\tau_{\text{lep}}} + \nu_{\text{had}} + \nu_{\text{lep}})^2. \quad (6.2)$$

For *outside events* ($\vec{E}_T^{\text{miss}}$ outside the opening angle between the tau candidates)

$$(m_Z(\text{outside}) - 5 \text{ GeV})^2 = (p_{\tau_{\text{had}}} + p_{\tau_{\text{lep}}} + \nu_{\text{closest}})^2. \quad (6.3)$$

We added 5 GeV to the invariant mass calculation in the outside events case because we empirically found that for these events the invariant mass is underestimated.

We require the τ_{had} candidates to pass the medium identification working point of the tauID algorithm.

In the $\tau_{\text{had}} \tau_{\text{lep}}$ final state the p_T requirements are 25 and 27 GeV, respectively. For the $\tau_{\text{lep}}(e) \tau_{\text{lep}}(\mu)$ events the p_T requirement is 27 GeV for both light leptons. Muons reconstructed in the $(-0.1, 0.1)$ η region are significantly misclassified as τ_{had} ; for this reason, that region is excluded. The same exclusion is performed in di-muon events in order to match the phase spaces.

In $Z \rightarrow ll$, the lepton p_T requirements are raised to 50 and 40 GeV, for the leading and sub-leading lepton, respectively. These values are higher to match the momentum selection of the tau-lepton cases since we need to account for the momentum carried by the neutrinos that is not measured.

The events that contain a jet tagged as a b-jet are vetoed for all the final states. Two di-lepton mass ranges are defined in this analysis: the "Z-peak" region, where the invariant mass is chosen close to the Z boson mass; and the region above this value called the "high-mass" region. The Z-peak results are discussed in the remaining of this chapter and the high-mass events discussion is presented in Chapter 7.

A summary of the selection requirements described in this section for each final state, in the Z-peak region, is given in Table 6.2.

6.3 Data and MC comparisons

Plots format

First, we describe the format used in the plots included in Chapter 6 and 7 — an example plot is shown in Figure 6.2. The top part of the plot shows the number of predicted events separated by physics process as a histogram, where all physics processes are stacked one after the other. The colour codes given in the legend specify the physics process. The EWjj contribution is denoted as Signal. The di-boson processes are abbreviated as VV. The processes that include "EWK" in their names indicate the simulation for pure electroweak production of a process, such as di-boson pure electroweak contributions — denoted as VV EWK. The total statistical uncertainty of the MC samples is shown as a shaded region using inclined parallel lines. The data is shown as black points with their corresponding statistical uncertainty as vertical bars.

Plots containing red vertical dashed lines show the distribution of a variable that has been used as a selection requirement. The histogram shows the sample after applying all the other selection requirements and the region between the red lines is the one finally selected — if one of the red lines is at the right (left) histogram edge, it implies that no maximum (minimum) requirement is imposed. Finally, in the top right corner the values used to normalise the EWjj (VBF) and QCDjj (QCD) processes are shown below the final state tag.

The middle plot, labelled *MC/Data*, shows the ratio between the MC prediction and the data. The shaded region corresponds to the statistical uncertainty of this ratio. This uncertainty can be asymmetric in some bins since it is calculated as the ratio of two Poisson-distributed numbers.

Finally, the plot in the bottom, labelled *Signal/MC*, shows the signal purity which is calculated as the ratio between the signal contribution and all the expected contributions, including the signal. The vertical error bars show the statistical uncertainty of the purity.

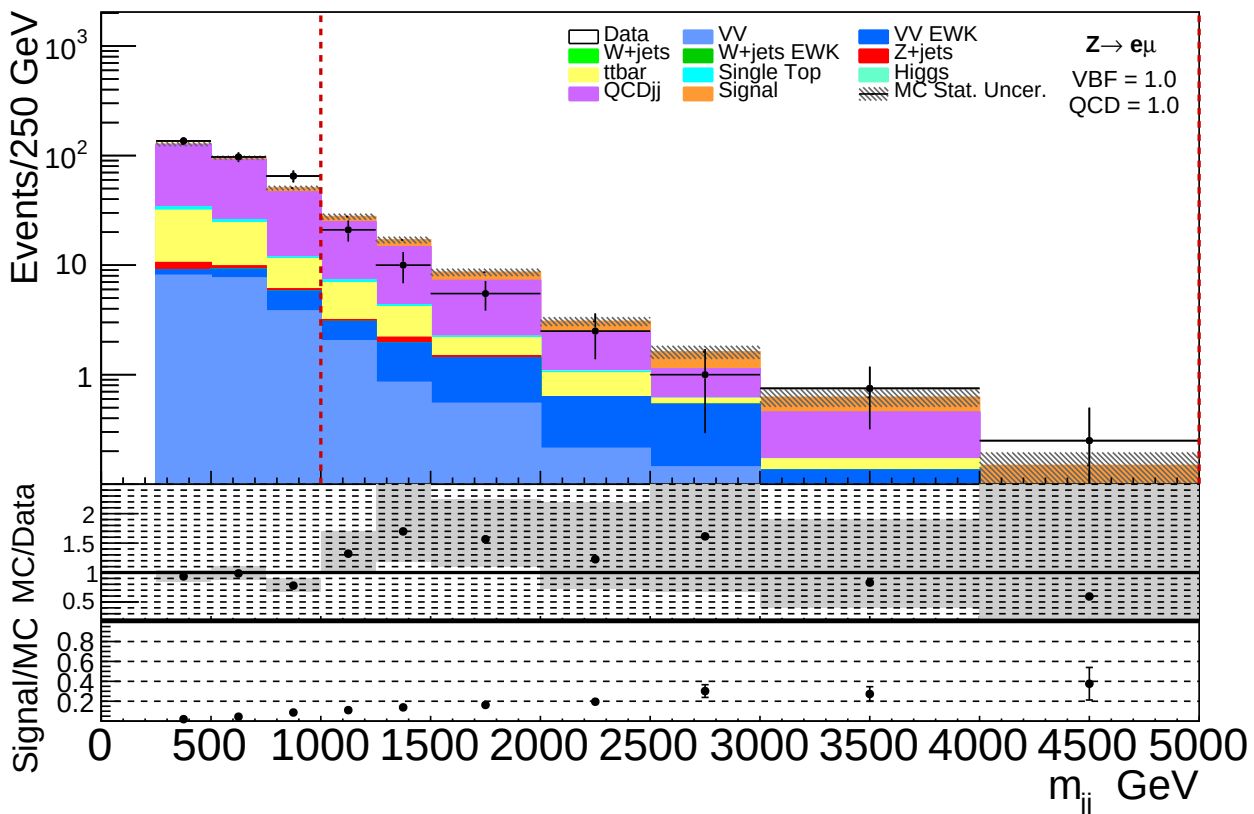


FIGURE 6.2: Example plot used in Data-to-MC comparisons in Chapter 6 and 7.

Sample	$Z \rightarrow ee$	$Z \rightarrow \mu\mu$	$Z \rightarrow \tau_{\text{had}}\tau_{\text{lep}}$	$Z \rightarrow \tau_{\text{lep}}\tau_{\text{lep}} \rightarrow e\mu$
Data	3707.0 ± 60.9	5020.0 ± 70.9	416.0 ± 20.4	53.0 ± 7.3
EWjj-SHERPA	932.1 ± 3.7	1174.6 ± 4.2	92.2 ± 1.5	11.3 ± 0.5
EWjj-PowHeg+Pythia8	1022.9 ± 3.4	1299.9 ± 3.8	103.1 ± 1.1	12.5 ± 0.4
QCDjj-MadGraph@LO	4606.2 ± 43.5	6688.8 ± 104.3	478.5 ± 32.7	66.1 ± 12.2
QCDjj-MadGraph@NLO	2466.7 ± 35.0	3369.7 ± 47.7	247.6 ± 11.5	27.9 ± 3.4
QCDjj-SHERPA 2.2.1	3516.3 ± 32.5	5072.8 ± 45.9	343.4 ± 14.6	42.7 ± 2.3
QCDjj-SHERPA 2.2.11	3277.9 ± 21.3	4741.8 ± 23.8	341.0 ± 18.7	39.0 ± 1.9
Higgs	N/A	N/A	11.9 ± 0.2	0.1 ± 0.02
$t\bar{t}$	2.3 ± 0.6	2.0 ± 0.6	7.2 ± 1.0	8.2 ± 1.1
Single Top	0.2 ± 0.2	0.4 ± 0.2	0.9 ± 0.3	0.7 ± 0.3
QCD Diboson (VV)	36.7 ± 1.0	45.4 ± 1.2	6.7 ± 0.4	4.8 ± 0.3
W+jets	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
Z+jets	N/A	N/A	0.3 ± 0.3	0.5 ± 0.3
W+jets EWK	N/A	N/A	1.4 ± 1.2	0.0 ± 0.0
EWK Diboson (VV EWK)	N/A	N/A	7.5 ± 1.4	6.0 ± 0.6

TABLE 6.3: Yields after the selection described in Table 6.2. The numbers are separated in the different analysis channels. The uncertainties correspond only to the statistical component. These figures reflect the modelling before the re-weighting described in Section 6.4.1. The Z+jets sample corresponds to the production of a Z boson which decays into a pair of light-leptons (QCDjj), and this is only considered as background for the $Z \rightarrow \tau\tau$ final states.

Table 6.3 presents the yields predicted by the different MC generators and the ones observed in data. The numbers correspond to the events passing the selection described in Table 6.2.

By looking at the yields in Table 6.3, we see that across all the final states the QCDjj process is the main background for the EWjj process. Different QCDjj MC simulators predict various yields for this process. Similarly, the EWjj predictions are different. However, the difference is less than that for the QCDjj process. The predictions not only differ in the yields, but also in the description of the event kinematics. Data-to-MC comparisons for $Z \rightarrow ll$ using SHERPA 2.2.1 or MadGraph@LO samples to model the QCDjj process and EWjj-SHERPA to model the VBF contribution are shown from Figure 6.3 to Figure 6.6 — the corresponding plots for the $Z \rightarrow \tau_{\text{had}}\tau_{\text{lep}}$ and $Z \rightarrow \tau_{\text{lep}}\tau_{\text{lep}}$ final states can be found in Appendix B.1. In these plots, the distributions for the m_{jj} , m_{ll} , Δy_{jj} , $p_{T\text{balance}}$, $p_T(j_1)$, $p_T(j_2)$ variables are shown separately for each of the analysis final states. The Ω variable is included in the tau final states plots. For the light-lepton final states, the modelling predicted by SHERPA 2.2.11 and MadGraph@NLO are presented in Appendix B.2.

Since none of the QCDjj MC generators provides a good enough description of the data, a priori MC-based signal extraction is not possible. In the next section we describe a method to correct the QCDjj simulations based on what is observed in the data. The different QCDjj shapes provide us with an estimate of the systematic uncertainty in the modelling of this background.

6.4 Extraction of the EWjj component

6.4.1 QCDjj background estimation

As seen in the previous section, the various MC predictions fail to describe the data. There is also a large variation between the QCDjj samples. This section describes how we use the data to correct

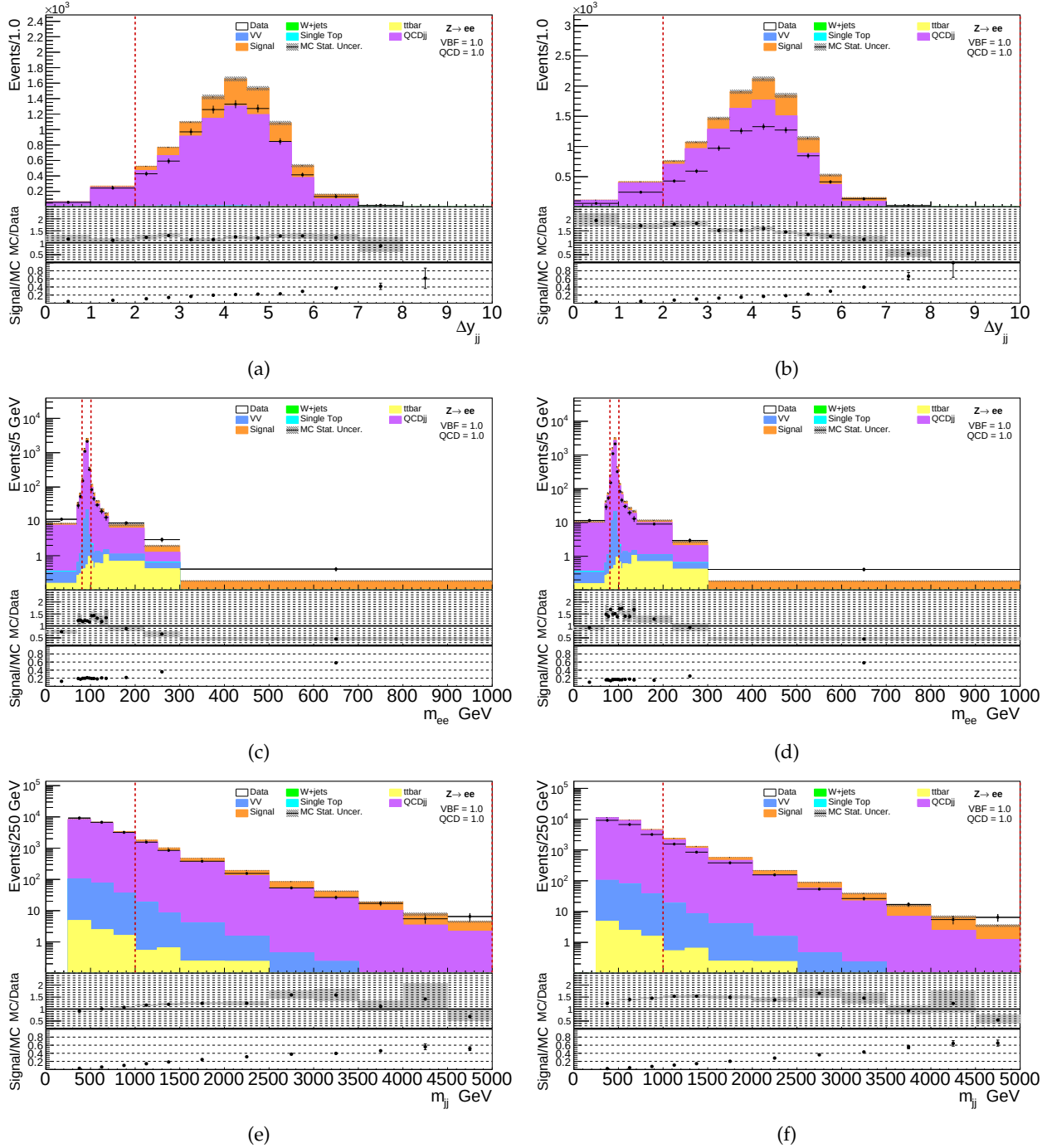


FIGURE 6.3: Data-MC comparisons for different kinematic variables in the $Z \rightarrow ee$ final state. The plots on the left column correspond to the SHERPA 2.2.1 prediction for the QCDjj process and the ones on the right to MadGraph@LO. These plots show the modelling before the re-weighting described in Section 6.4.1.

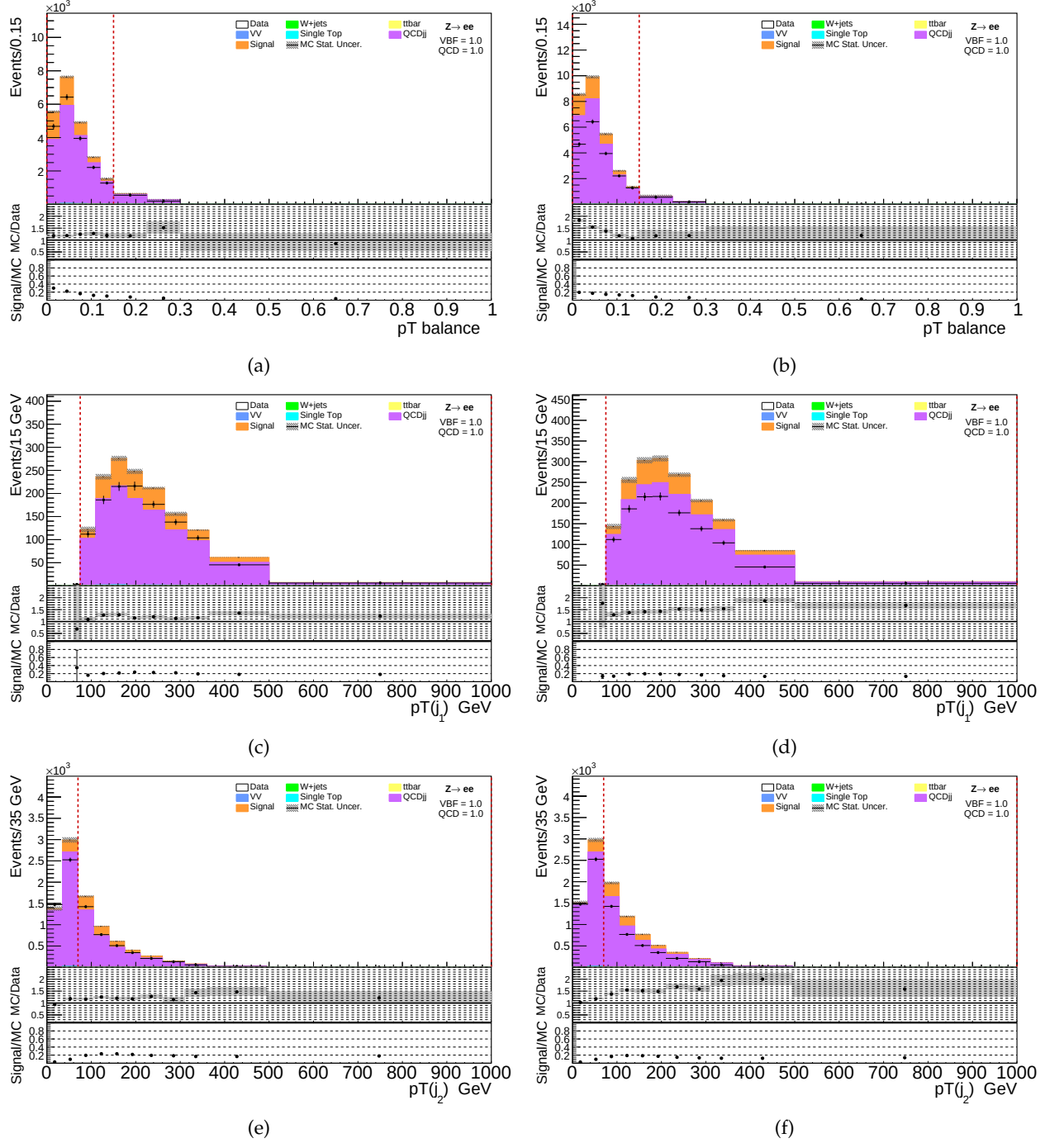


FIGURE 6.4: Data-MC comparisons for different kinematic variables in the $Z \rightarrow ee$ final state. The plots on the left column correspond to the SHERPA 2.2.1 prediction for the QCDjj process and the ones on the right to MadGraph@LO. These plots show the modelling before the re-weighting described in Section 6.4.1.

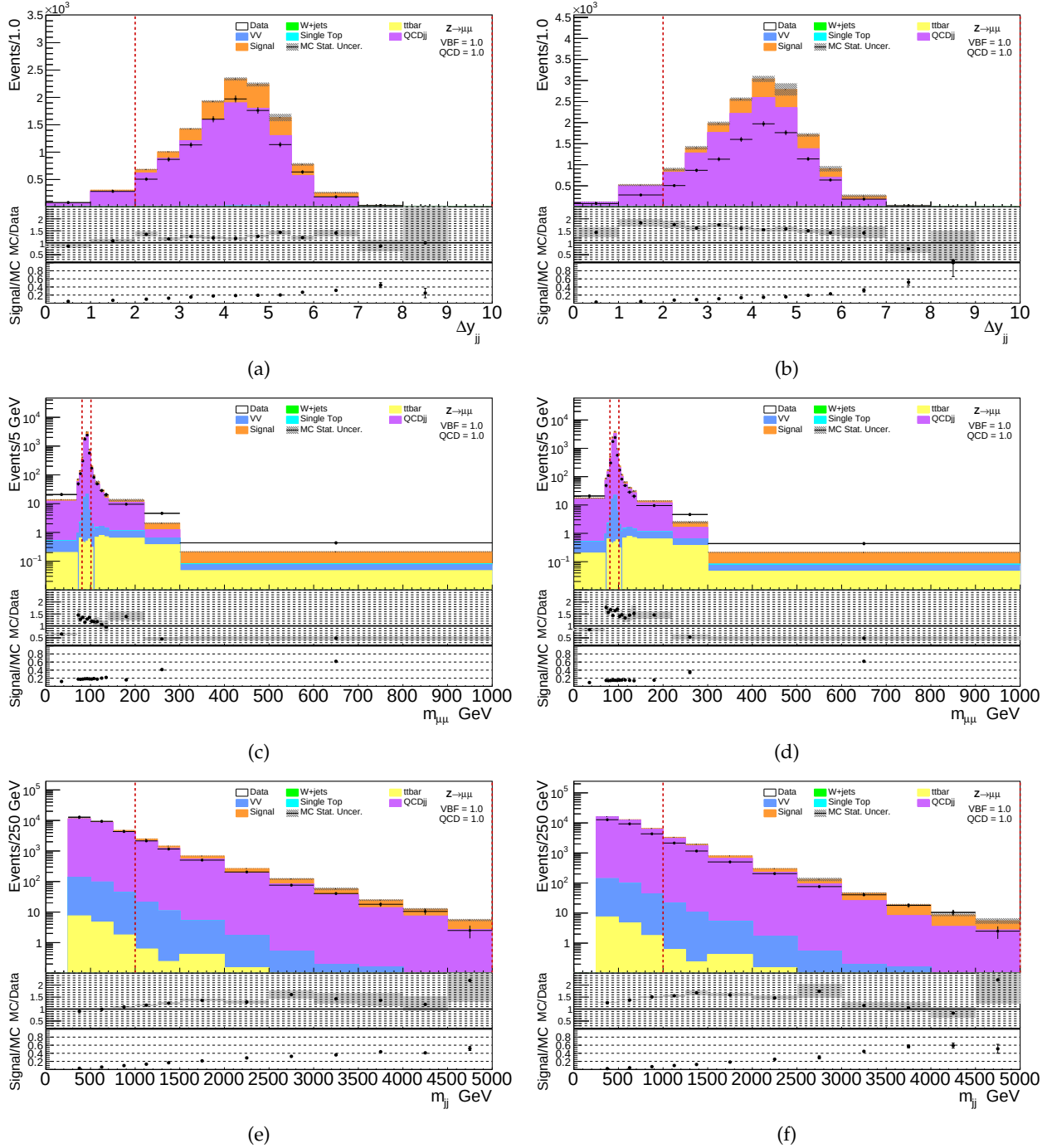


FIGURE 6.5: Data-MC comparisons for different kinematic variables in the $Z \rightarrow \mu\mu$ final state. The plots on the left column correspond to the SHERPA 2.2.1 prediction for the QCDjj process and the ones on the right to MadGraph@LO. These plots show the modelling before the re-weighting described in Section 6.4.1.

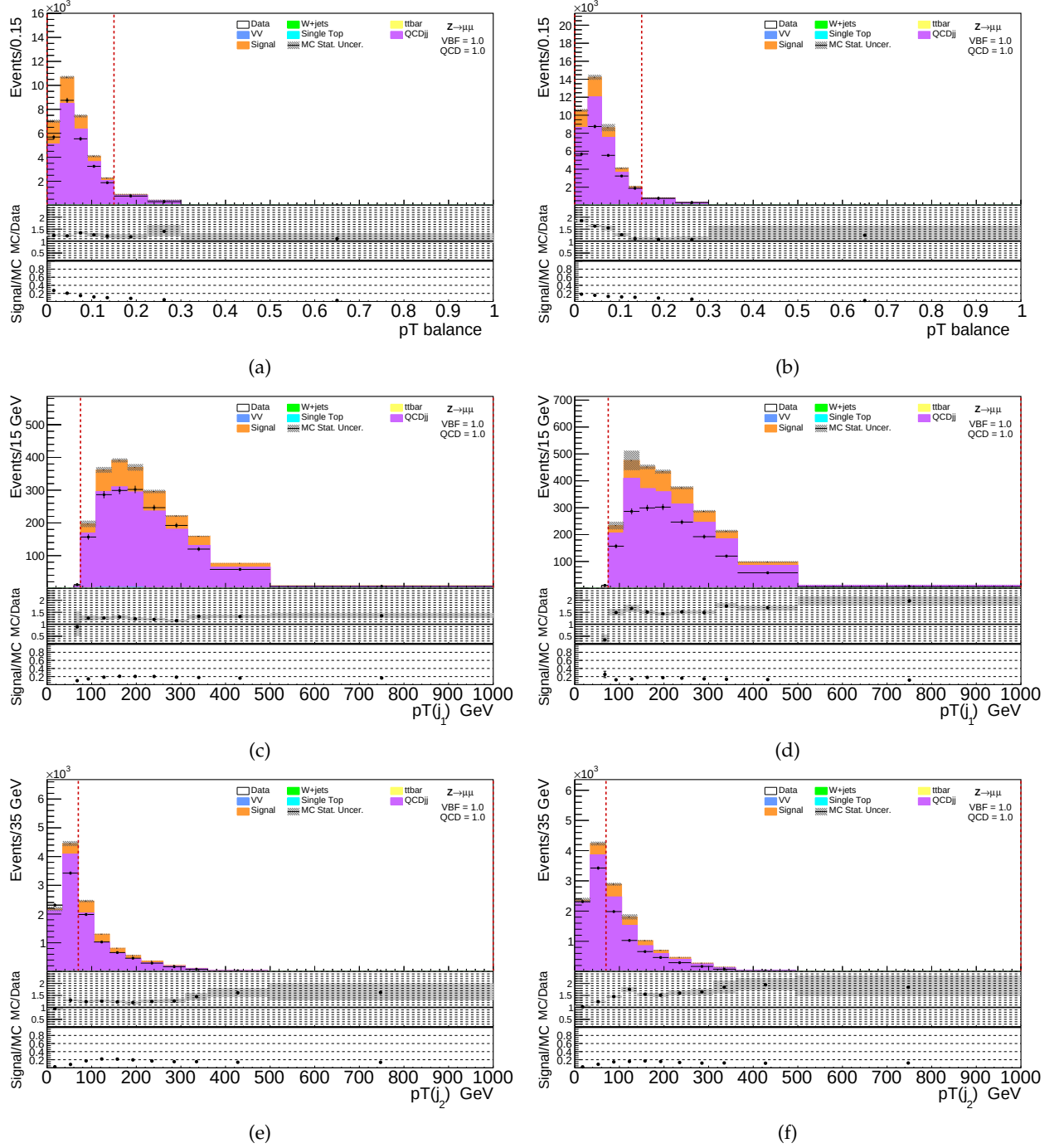


FIGURE 6.6: Data-MC comparisons for different kinematic variables in the $Z \rightarrow \mu\mu$ final state. The plots on the left column correspond to the SHERPA 2.2.1 prediction for the QCDjj process and the ones on the right to MadGraph@LO. These plots show the modelling before the re-weighting described in Section 6.4.1.

Region	Criterion
SR	$\xi_Z < 0.5$ and $N_{\text{jets}}^{\text{gap}} = 0$
CRa	$\xi_Z < 0.5$ and $N_{\text{jets}}^{\text{gap}} = 1$
CRb	$1.0 \geq \xi_Z \geq 0.5$ and $N_{\text{jets}}^{\text{gap}} = 1$
CRc	$1.0 \geq \xi_Z \geq 0.5$ and $N_{\text{jets}}^{\text{gap}} = 0$

TABLE 6.4: The signal region and three QCDjj control regions are defined in terms of the variables shown in this table.

the QCDjj background prediction.

To study the main background we define control regions (CRs); these are designed to enhance the contribution of the QCDjj background and suppress the EWjj component. We use the CRs to correct the simulation according to what is observed in the data; and then extrapolate the corrections to the signal region (SR).

Two variables are used to split the sample described in Table 6.2 into the EWjj SR and three QCDjj CRs. Let us define these variables: first, any jet located between the rapidity interval spanned by the tagging jets is called a "gap jet". Additionally, an angular variable related to the relative direction of the production of the di-lepton system with respect to the tagging jets is defined. This variable is called the centrality of the di-lepton system (ξ_Z). It is defined as

$$\xi_Z = \frac{y_{ll} - 0.5(y_{j_1} + y_{j_2})}{\Delta y_{jj}}, \quad (6.4)$$

where we have used the letter Z to indicate that the di-lepton system is expected to be produced from a Z boson decay.

For the EWjj events, the centrality of the di-lepton system (ξ_Z) is expected to take low values because the Z boson tends to be produced halfway between the tagging jets. Additionally, in the EWjj process the number of gap jets ($N_{\text{jets}}^{\text{gap}}$) is expected to be zero, because there is no colour flow between the tagging jets. The four analysis regions are defined in Table 6.4.

The CRs are used to constrain the dominant QCDjj background in the following way: first, in each CR, a re-weighting function for the QCDjj MC is extracted by comparing the data and the simulation; we combine the $Z \rightarrow \mu\mu$ and $Z \rightarrow ee$ final states in the CRs to derive the re-weighting functions. The re-weighting is based on the m_{jj} variable. The m_{jj} distribution in each CR is shown in Figure 6.7 for SHERPA 2.2.1 and MadGraph@NLO. The plots corresponding to SHERPA 2.2.11 and MadGraph@NLO are in Appendix B.3.

We extrapolate our results to the SR using the ABCD method. Finally, the m_{jj} -based re-weighting is performed in the SR. This procedure yielded MC predictions consistent with the data for SHERPA and MadGraph@LO. However, it did not work for the PowHegBox simulation — hence, we do not include PowHegBox in our results.

Let us describe the re-weighting procedure in more detail: if the weight of a MC QCDjj event with di-jet invariant mass m_{jj} in any of the regions is denoted as w_i , after the re-weighting, the corrected weight (w'_i) is

$$w'_i = w_i \times f_i(m_{jj}, a, b, c), \quad (6.5)$$

where ($i = \text{CRa}, \text{CRb}, \text{CRc}$) denotes any of the control regions and a, b, c are independent parameters for each region.

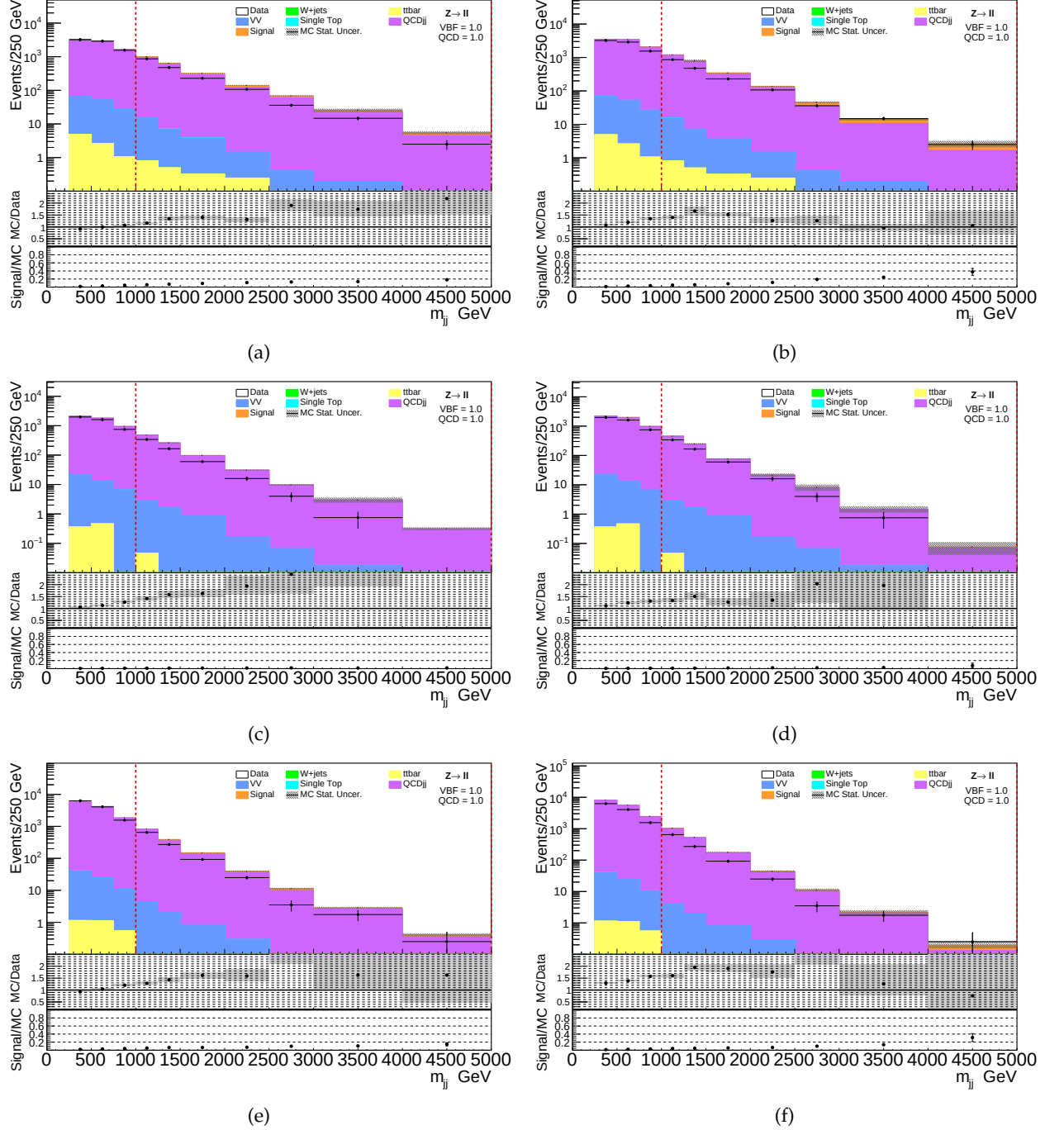


FIGURE 6.7: Data-MC comparisons for different CRs in the $Z \rightarrow ll = Z \rightarrow ee + Z \rightarrow \mu\mu$ final state. The plots on the left column correspond to the SHERPA 2.2.1 prediction and the ones on the right to MadGraph@LO. Figures (a)(b), (c)(d) and (e)(f) correspond to CRa, CRb and CRc, respectively. The dominant contribution in all the regions is from the QCDjj process.

The re-weighting function $f_i(m_{jj}, a, b, c)$ is determined by performing a least-squares fit of the ratio (r_k) defined as

$$r_k = \frac{\text{Data}_k - \text{EWjj}_k - \text{BG}_k}{\text{QCDjj}_k}, \quad (6.6)$$

where Data_k is the number of observed events, EWjj_k is the number of predicted signal events and BG_k includes all other BGs apart from the QCDjj contribution (QCDjj_k). The k index represents the k -th bin of the m_{jj} distribution.

To derive the re-weighting function in the SR ($f_{\text{SR}}(m_{jj}, a, b, c)$), we extrapolate the data-QCDjj ratio (r_k), bin by bin, using the ABCD method. Thus,

$$\frac{r_k^{\text{SR}}}{r_k^{\text{CRa}}} = \frac{r_k^{\text{CRc}}}{r_k^{\text{CRb}}}. \quad (6.7)$$

In all regions f_i is a quadratic function of the form, $f = a \times m_{jj}^2 + b \times m_{jj} + c$. Figures 6.8 and 6.9 show the r_k values as a function of m_{jj} , and the estimated functions in all the analysis regions, for both QCDjj samples.

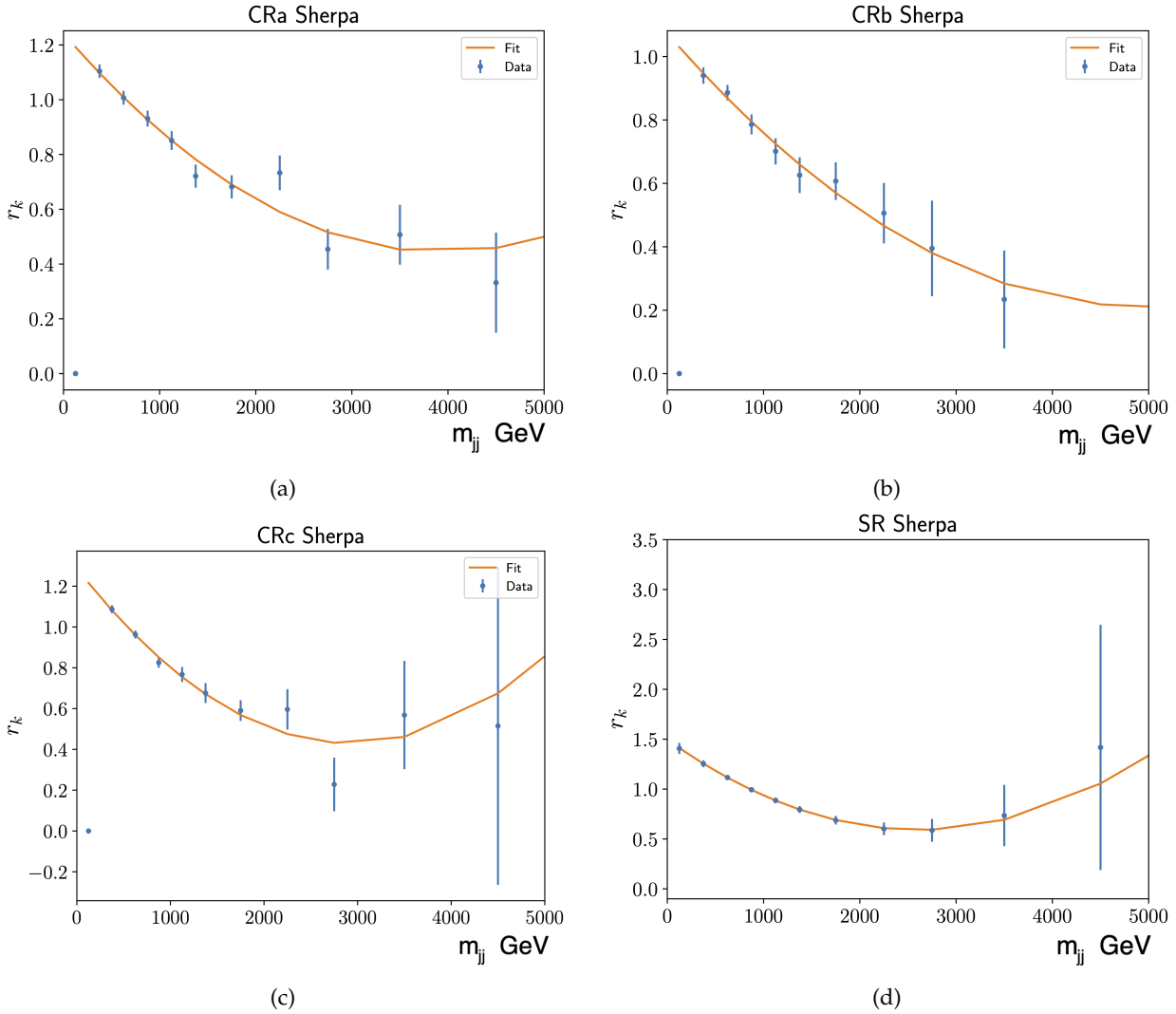


FIGURE 6.8: Functions used to re-weight the SHERPA 2.2.1 QCDjj MC in each of the analysis regions. Figures (a), (b), (c) and (d) correspond to CRa, CRb, CRc and SR, respectively. The blue points with error bars represent the r_k factors extracted from the data, and the orange line is the shape of the re-weighting function.

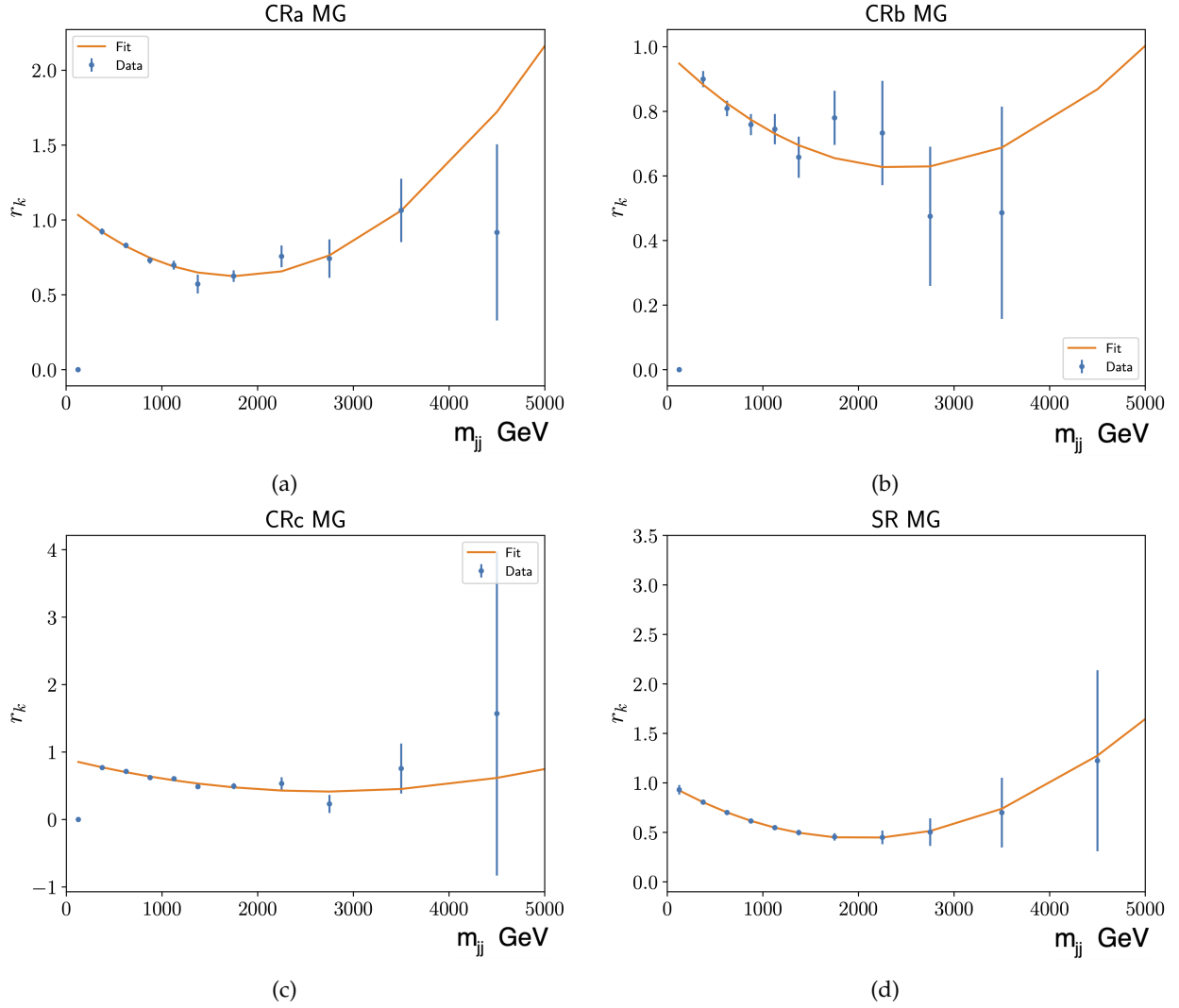


FIGURE 6.9: Functions used to re-weight the MadGraph@LOQCDjj MC in each of the analysis regions. Figures (a), (b), (c) and (d) correspond to CRa, CRb, CRc and SR, respectively. The blue points with error bars represent the r_k factors extracted from the data, and the orange line is the shape of the re-weighting function.

A cross-check is performed in the CRs to ensure that the re-weighting procedure recovers the modelling. The m_{jj} distributions after the MC correction are shown in Figure 6.10. The corresponding plots for SHERPA 2.2.11 and MadGraph@NLO are presented in Appendix B.4.

An additional measurement is performed to compare the shapes of the QCDjj samples after re-weighting in the SR: the ratio of the QCDjj corrected shapes, normalised to one, is calculated. These results are shown for the $Z \rightarrow ll$ final state in Figure 6.11.

Since there is not a particular reason to choose one of the QCDjj shapes over the other, the average shape between SHERPA and MadGraph@LO is used to extract the EWjj component. The average is calculated as

$$\text{QCDjj-Average} = \mu_{\text{SHERPA}} \times \text{QCDjj-SHERPA} + \mu_{\text{MadGraph@LO}} \times \text{QCDjj-MadGraph@LO}. \quad (6.8)$$

The μ_X factor is the corresponding normalisation (or signal strength) for the QCDjj process. It is extracted by fitting the QCDjj and EWjj components to the data using the m_{jj} distribution, since this variable offers good discrimination between the two processes. We describe how we perform

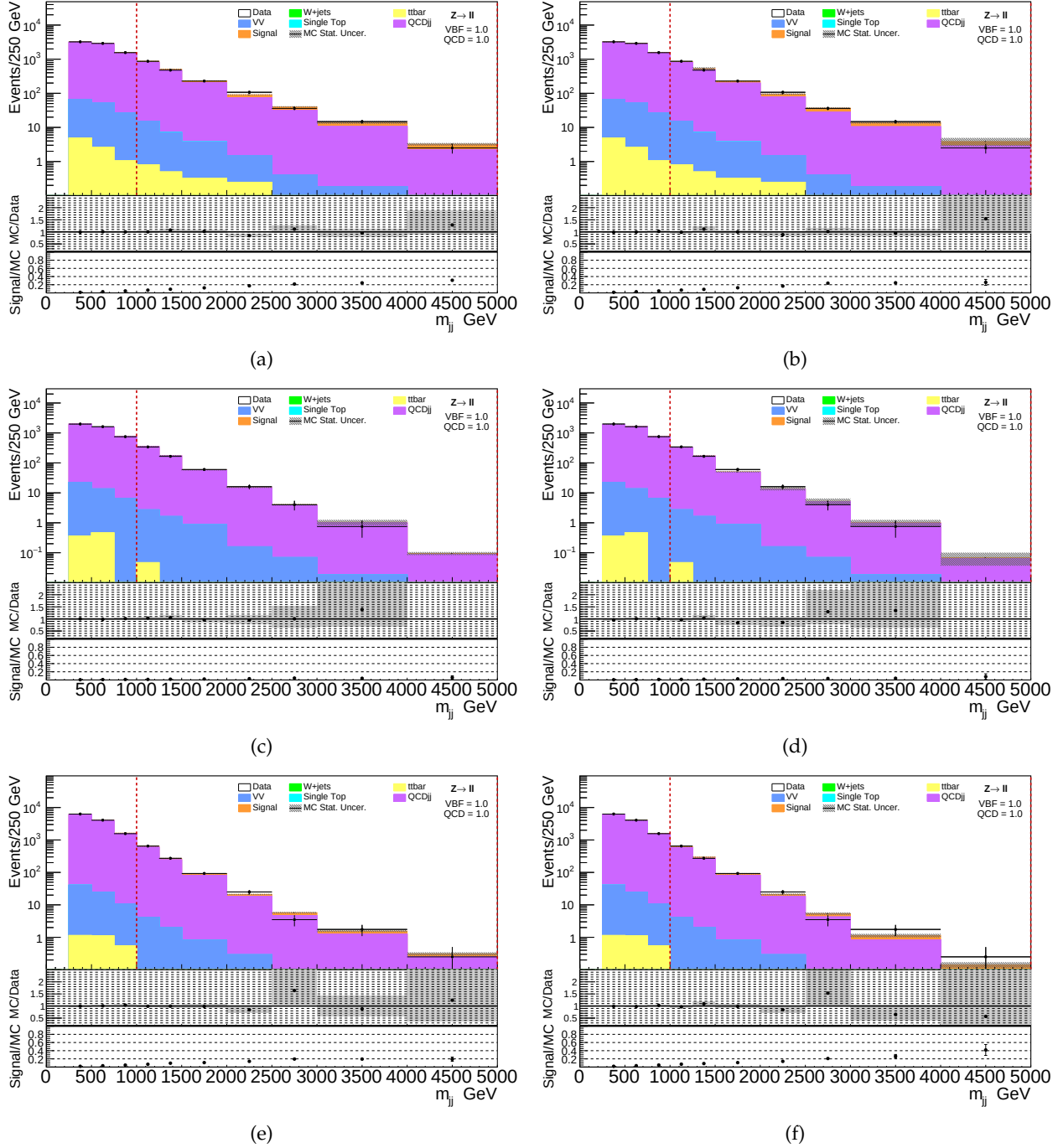


FIGURE 6.10: Data-MC comparisons after the m_{jj} -based re-weighting for the different CRs in the $Z \rightarrow ll = Z \rightarrow ee + Z \rightarrow \mu\mu$ final state. The plots on the left column correspond to the SHERPA 2.2.1 prediction and the ones on the right to MadGraph@LO. Figures (a)(b), (c)(d) and (e)(f) correspond to CRa, CRb and CRc, respectively.

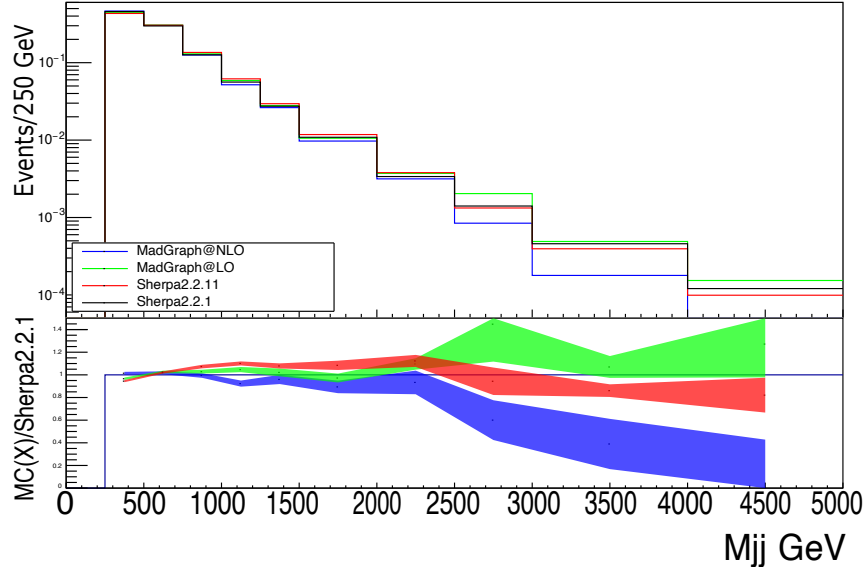


FIGURE 6.11: QCDjj shape comparison. Each shape is normalised and given a different colour. The bottom plot shows the ratio between each QCDjj MC and the SHERPA 2.2.1 shape. The coloured bands represent the statistical uncertainties on the ratio.

this procedure in the next section.

6.4.2 EWjj signal extraction

After correcting the shape of the QCDjj background, we can extract the EWjj component contribution. We perform a profile likelihood fit [189, 190] of the m_{jj} observable, with the signal strength of the QCDjj (μ_{QCD}) and EWjj (μ_{EW}) process as floating parameters. The results for the different final states are shown in Tables 6.5 and 6.6. Both tables contain the signal strengths calculated using both different QCDjj MCs. Table 6.5 contains the results using EWjj-SHERPA for the EWjj process, and Table 6.6 presents the results using EWjj-PowHeg+Pythia8.

EWjj sample	QCDjj Sample			
	SHERPA 2.2.1		MadGraph@LO	
Sample	μ_{QCD}	μ_{EW}	μ_{QCD}	μ_{EW}
$Z \rightarrow ee$	0.905 ± 0.015	1.230 ± 0.064	0.937 ± 0.015	1.144 ± 0.064
$Z \rightarrow \mu\mu$	0.942 ± 0.014	1.173 ± 0.062	0.924 ± 0.011	1.092 ± 0.060
$Z \rightarrow \tau_{\text{had}} \tau_{\text{lep}}$	0.960 ± 0.051	1.132 ± 0.224	1.046 ± 0.065	0.976 ± 0.243
$Z \rightarrow \tau_{\text{lep}} \tau_{\text{lep}} \rightarrow e\mu$	1.057 ± 0.154	1.328 ± 0.716	1.178 ± 0.233	0.344 ± 1.092

TABLE 6.5: QCDjj and EWjj signal strengths split by final state. A comparison between two choices for the QCDjj shape is displayed. The results are obtained using EWjj-SHERPA. The uncertainties correspond just to the MC and data statistical components.

EWjj sample	QCDjj Sample			
PowHeg+Pythia8	SHERPA 2.2.1		MadGraph@LO	
Sample	μ_{QCD}	μ_{EW}	μ_{QCD}	μ_{EW}
$Z \rightarrow ee$	0.930 ± 0.015	1.050 ± 0.057	0.959 ± 0.014	0.981 ± 0.056
$Z \rightarrow \mu\mu$	0.966 ± 0.014	0.989 ± 0.054	0.941 ± 0.011	0.933 ± 0.053
$Z \rightarrow \tau_{\text{had}}\tau_{\text{lep}}$	0.993 ± 0.049	0.929 ± 0.195	1.077 ± 0.062	0.793 ± 0.206
$Z \rightarrow \tau_{\text{lep}}\tau_{\text{lep}} \rightarrow e\mu$	1.071 ± 0.149	1.153 ± 0.604	1.164 ± 0.212	0.414 ± 0.885

TABLE 6.6: QCDjj and EWjj signal strengths split by final state. A comparison between two choices for the QCDjj shape is displayed. The results are obtained using EWjj-PowHeg+Pythia8. The uncertainties correspond just to the MC and data statistical components.

Looking at Tables 6.5 and 6.6 we observe some features: first, the EWjj signal strength agrees when comparing between the light lepton final states when using the same MC generator for the QCDjj and EWjj process. This is also true for the di-tau final states. Taking this into account we decide to combine the light lepton results; and also merge the $\tau_{\text{had}}\tau_{\text{lep}}$ with the $\tau_{\text{lep}}\tau_{\text{lep}}$ events — we refer to these events as $Z \rightarrow \tau\tau$. The results after the combination and re-fitting are shown in Tables 6.7 and 6.8. In addition, these tables also contain the results of extracting the EWjj contribution using the average of the QCDjj shapes — as defined in Equation 6.8. The normalisation factor for the average QCDjj shape has a value close to one because each term in Equation 6.8 is scaled by the corresponding normalisation factor (μ_{QCD}) obtained when extracting the EWjj normalisation using SHERPA 2.2.1 or MadGraph@LO individually.

EWjj sample	QCDjj Sample					
SHERPA 2.2.11	SHERPA 2.2.1		MadGraph@LO		Average	
Sample	μ_{QCD}	μ_{EW}	μ_{QCD}	μ_{EW}	μ_{QCD}	μ_{EW}
$Z \rightarrow ll$	0.922 ± 0.008	1.209 ± 0.043	0.927 ± 0.008	1.124 ± 0.043	1.001 ± 0.009	1.171 ± 0.042
$Z \rightarrow \tau\tau$	0.970 ± 0.049	1.168 ± 0.213	1.049 ± 0.061	0.990 ± 0.232	1.013 ± 0.048	1.093 ± 0.204

TABLE 6.7: QCDjj and EWjj signal strengths after final states combination. A comparison between two choices for the QCDjj shape is presented and the results for the average of the QCDjj templates is located on the rightmost two columns. The results are obtained using EWjj-SHERPA. The uncertainties correspond to the MC and data statistical components.

EWjj sample	QCDjj Sample					
PowHeg+Pythia8	SHERPA 2.2.1		MadGraph@LO		Average	
Sample	μ_{QCD}	μ_{EW}	μ_{QCD}	μ_{EW}	μ_{QCD}	μ_{EW}
$Z \rightarrow ll$	0.942 ± 0.008	1.031 ± 0.038	0.946 ± 0.008	0.964 ± 0.038	1.001 ± 0.009	1.003 ± 0.037
$Z \rightarrow \tau\tau$	1.001 ± 0.047	0.967 ± 0.185	1.077 ± 0.059	0.815 ± 0.196	1.011 ± 0.044	0.910 ± 0.177

TABLE 6.8: QCDjj and EWjj signal strengths after final states combination. A comparison between two choices for the QCDjj shape is presented and the results for the average of the QCDjj templates is located on the rightmost two columns. The results are obtained using EWjj-PowHeg+Pythia8. The uncertainties correspond to the MC and data statistical components.

We also observe a significant difference in the total cross-section when comparing the two EWjj samples across all the final states. The predicted total cross-section for EWjj-SHERPA is 0.77943 picobarns (pb) and 0.64977 pb for EWjj-PowHeg+Pythia8. After scaling the cross-section by the

corresponding signal strength (μ_{EW}), using the QCDjj-Average sample, we get the values shown in Table 6.9. The difference in the total cross-section is 28.5%. The difference in these results comes from the fact that the two EWjj templates differ substantially in predicting the m_{jj} distribution, as can be observed in Figure 6.12.

EWjj σ_{Total} (pb)	$Z \rightarrow ll$	$Z \rightarrow \tau\tau$
SHERPA 2.2.11	0.912 ± 0.028	0.852 ± 0.146
PowHeg+Pythia8	0.652 ± 0.024	0.592 ± 0.126

TABLE 6.9: Total cross-sections scaled by the extracted EWjj signal strength. The results agree comparing different final states for the same MC generator. However, the two EWjj MC samples yield a different value for the EWjj cross-section.

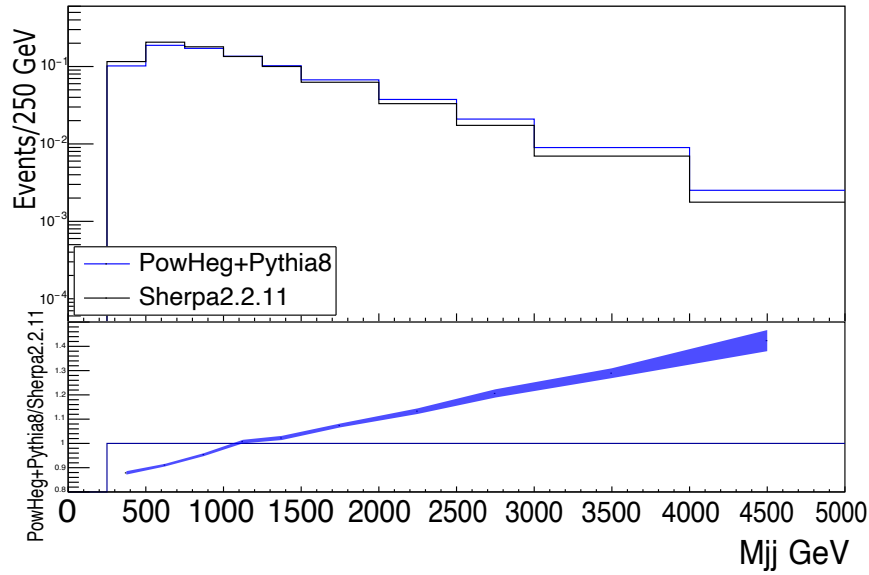


FIGURE 6.12: EWjj shape comparison. Each shape is normalised and given a different colour. The bottom plot shows the ratio between the two EWjj MC samples. The coloured bands represent the statistical uncertainties on the ratio. A big discrepancy in the description of the di-jet mass is observed.

Finally, from Figures 6.13 to 6.21, we present the data-to-MC comparisons after the QCDjj reweighting and the signal strength normalisations are applied to the different final state samples in the SR. Overall, we observe good modelling of the m_{jj} , m_{ll} , Δy_{jj} , $p_T(j_1)$, $p_T(j_2)$, ξ_Z , Ω and N_{jets}^{gap} variables. We also see how the $p_{Tbalance}$ modelling provided by SHERPA 2.2.1 is better than MadGraph@LO. This could be the result of the more accurate matrix element calculation performed by SHERPA 2.2.1 (up to two partons at NLO).

6.5 Results

6.5.1 Analysis strategy

To test the LU hypothesis, we check if the EWjj signal strength agrees between the different channels. We define the ratio

$$R_{XY} = \frac{\mu_{EW}(Z \rightarrow XX)}{\mu_{EW}(Z \rightarrow YY)}, \quad (6.9)$$

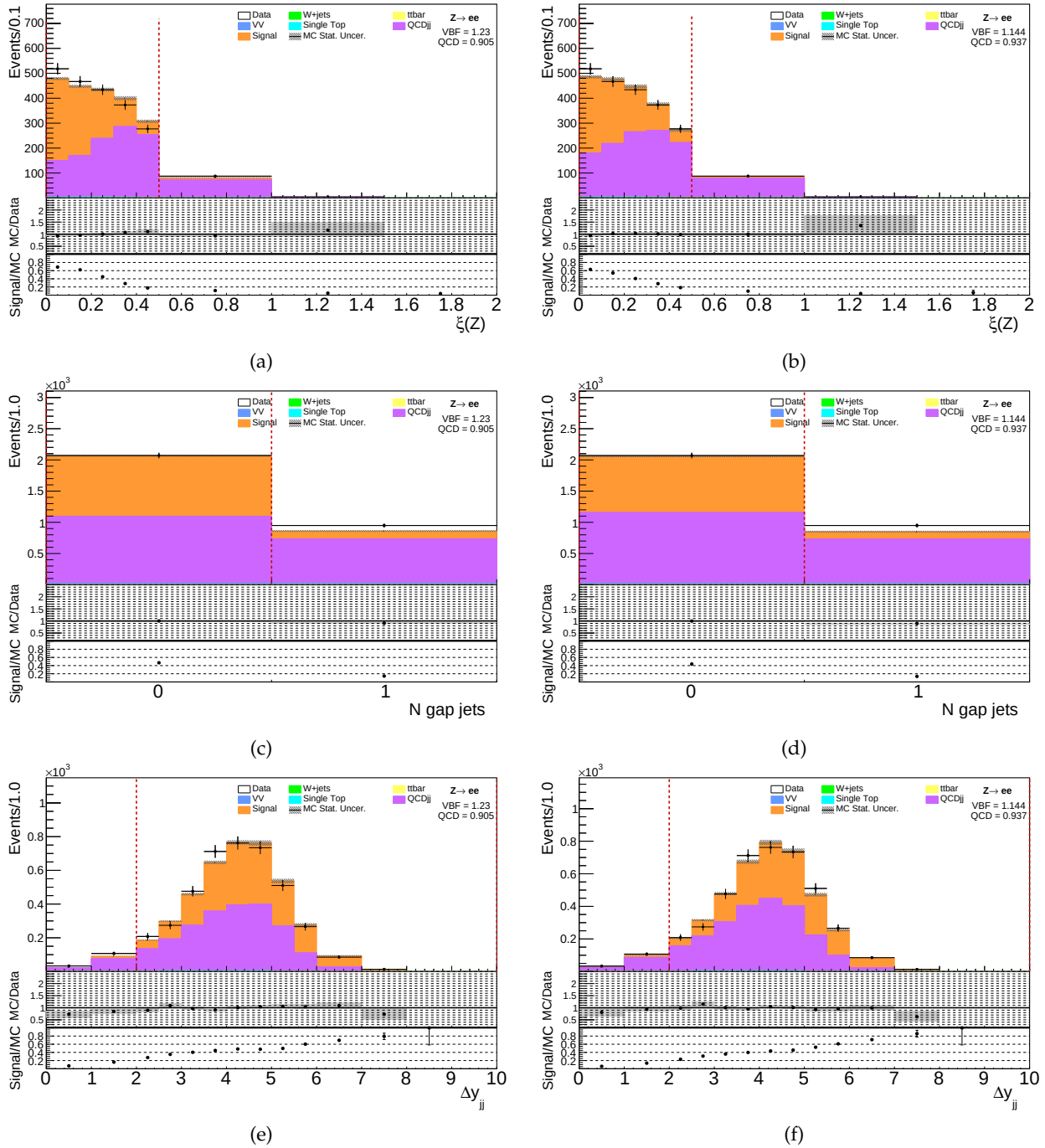


FIGURE 6.13: Data-to-MC comparisons for different kinematic variables in the $Z \rightarrow ee$ final state after performing the QCDj re-weighting and applying the signal strength normalisation factors. The plots on the left column correspond to the SHERPA 2.2.1 prediction and the ones on the right to MadGraph@LO.

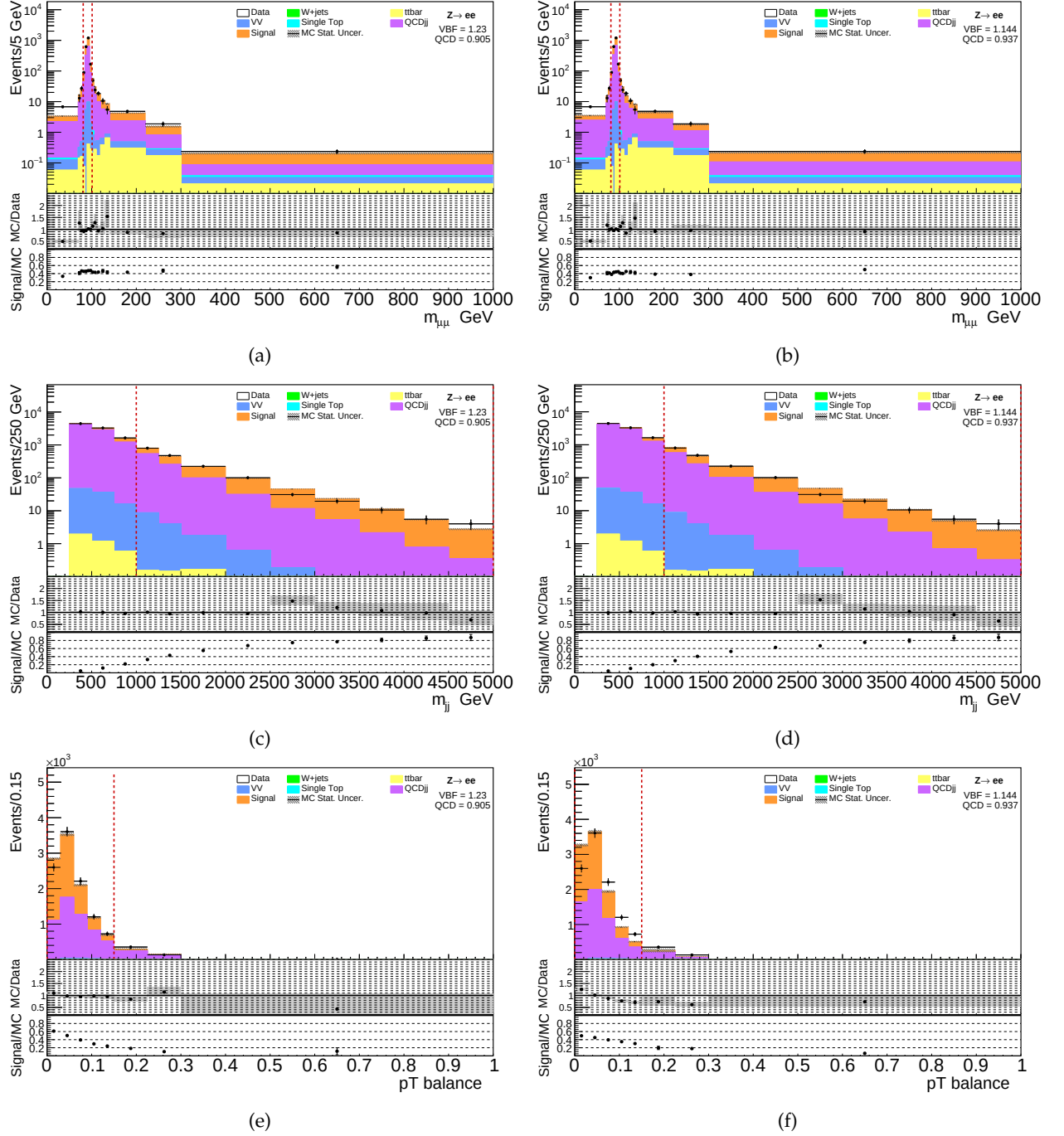


FIGURE 6.14: Data-to-MC comparisons for different kinematic variables in the $Z \rightarrow ee$ final state after performing the QCDjj re-weighting and applying the signal strength normalisation factors. The plots on the left column correspond to the SHERPA 2.2.1 prediction and the ones on the right to MadGraph@LO.

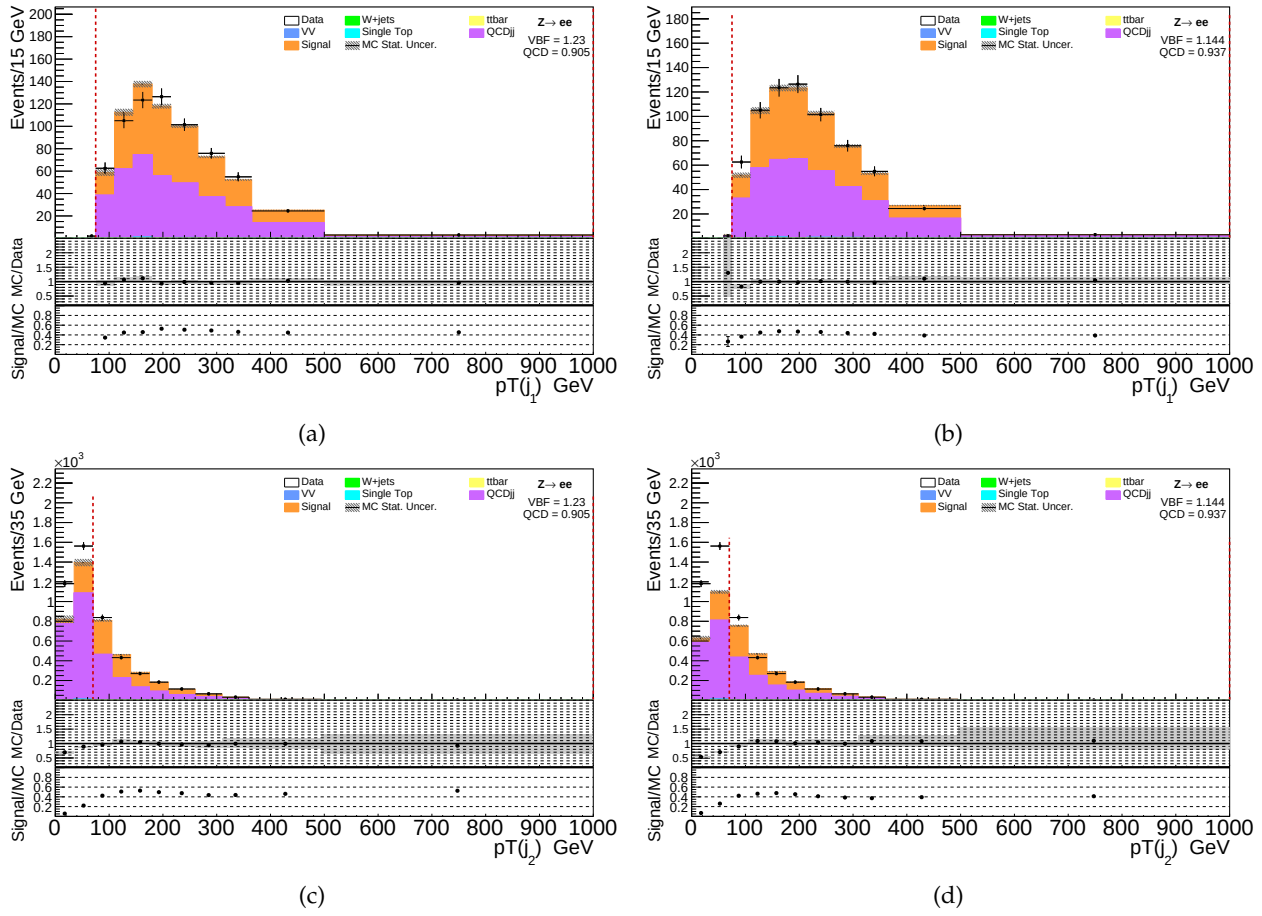


FIGURE 6.15: Data-to-MC comparisons for different kinematic variables in the $Z \rightarrow ee$ final state after performing the QCDjj re-weighting and applying the signal strength normalisation factors. The plots on the left column correspond to the SHERPA 2.2.1 prediction and the ones on the right to MadGraph@LO.

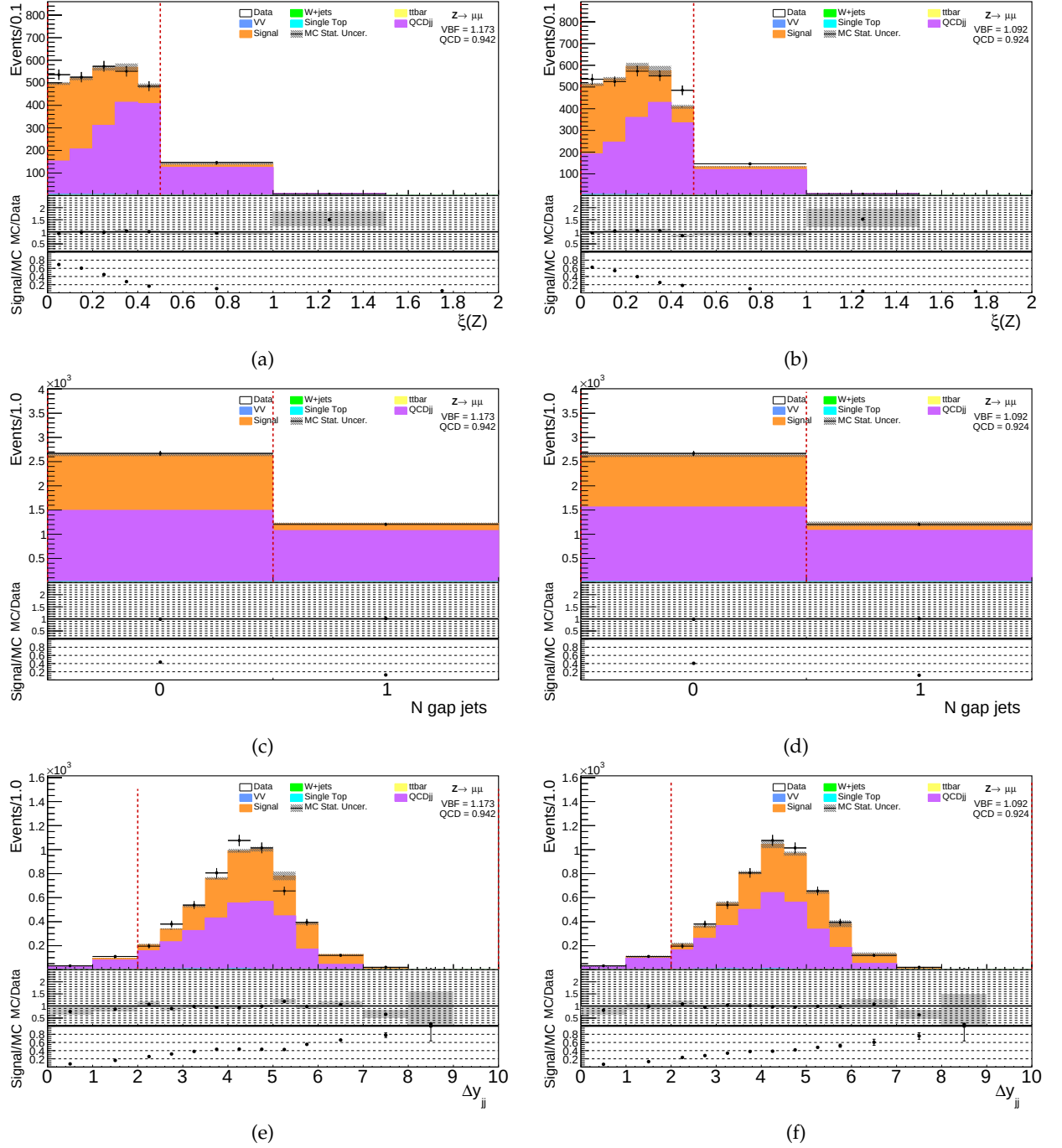


FIGURE 6.16: Data-to-MC comparisons for different kinematic variables in the $Z \rightarrow \mu\mu$ final state after performing the QCDij re-weighting and applying the signal strength normalisation factors. The plots on the left column correspond to the SHERPA 2.2.1 prediction and the ones on the right to MadGraph@LO.

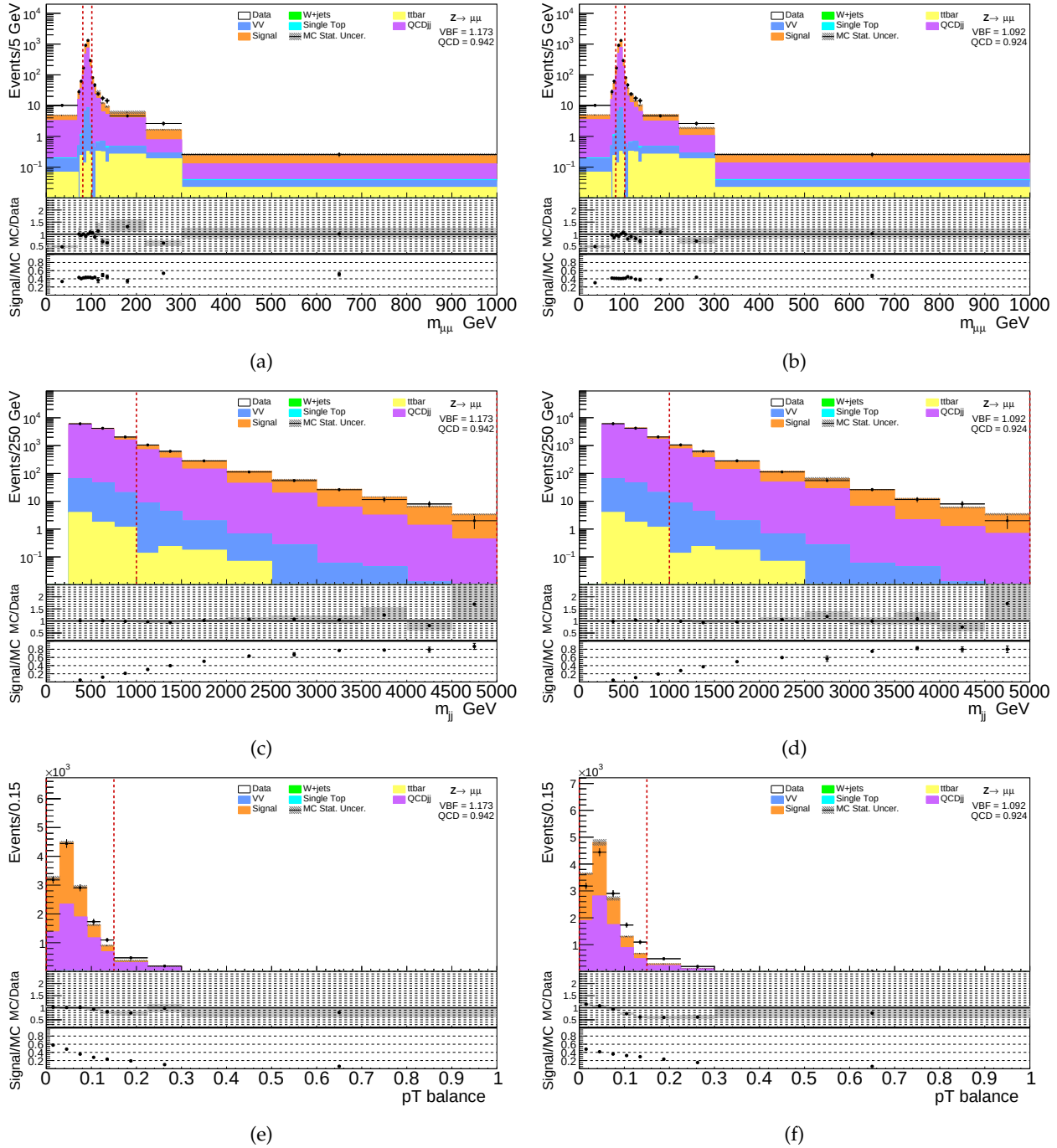


FIGURE 6.17: Data-to-MC comparisons for different kinematic variables in the $Z \rightarrow \mu\mu$ final state after performing the QCDjj re-weighting and applying the signal strength normalisation factors. The plots on the left column correspond to the SHERPA 2.2.1 prediction and the ones on the right to MadGraph@LO.

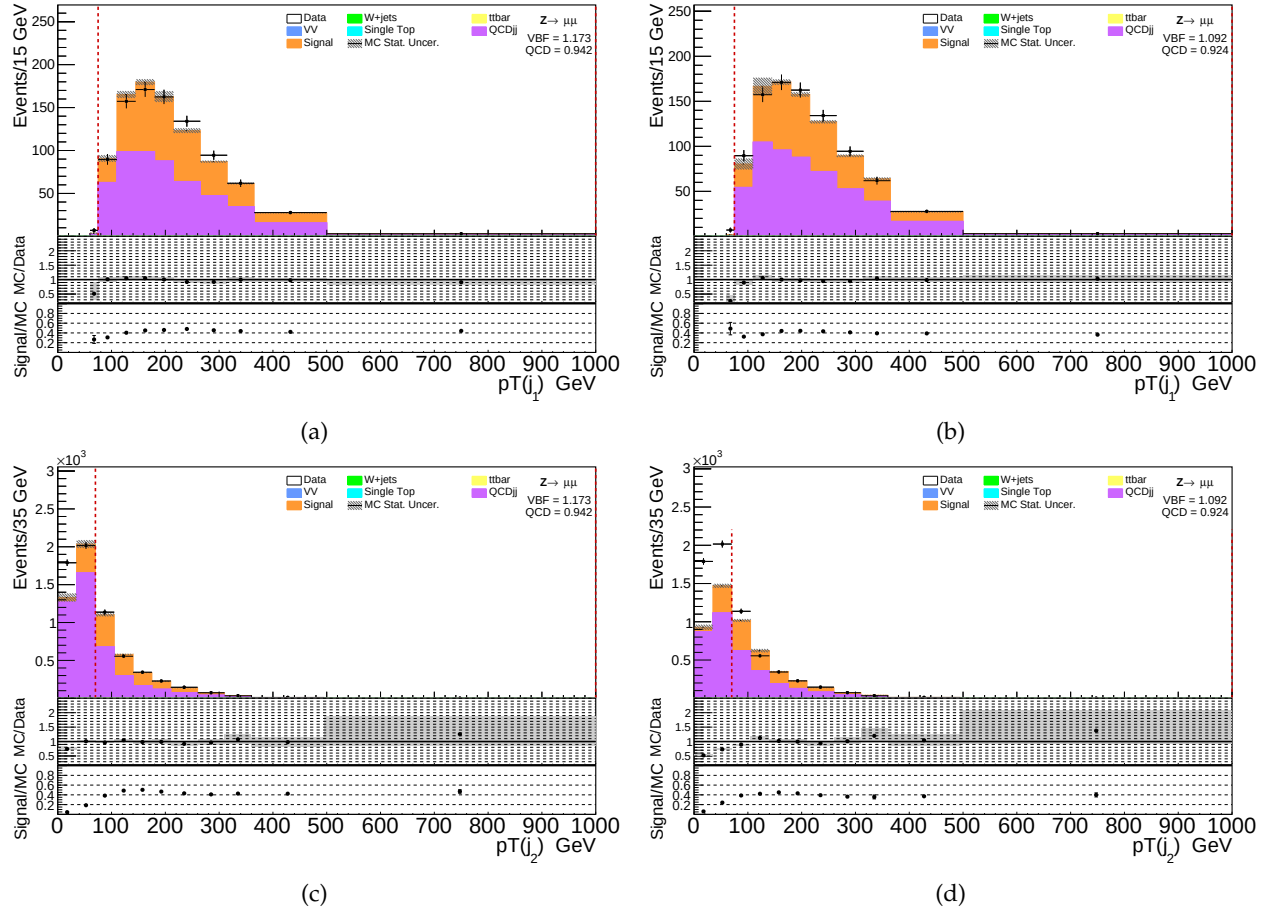


FIGURE 6.18: Data-to-MC comparisons for different kinematic variables in the $Z \rightarrow \mu\mu$ final state after performing the QCDjj re-weighting and applying the signal strength normalisation factors. The plots on the left column correspond to the SHERPA 2.2.1 prediction and the ones on the right to MadGraph@LO.

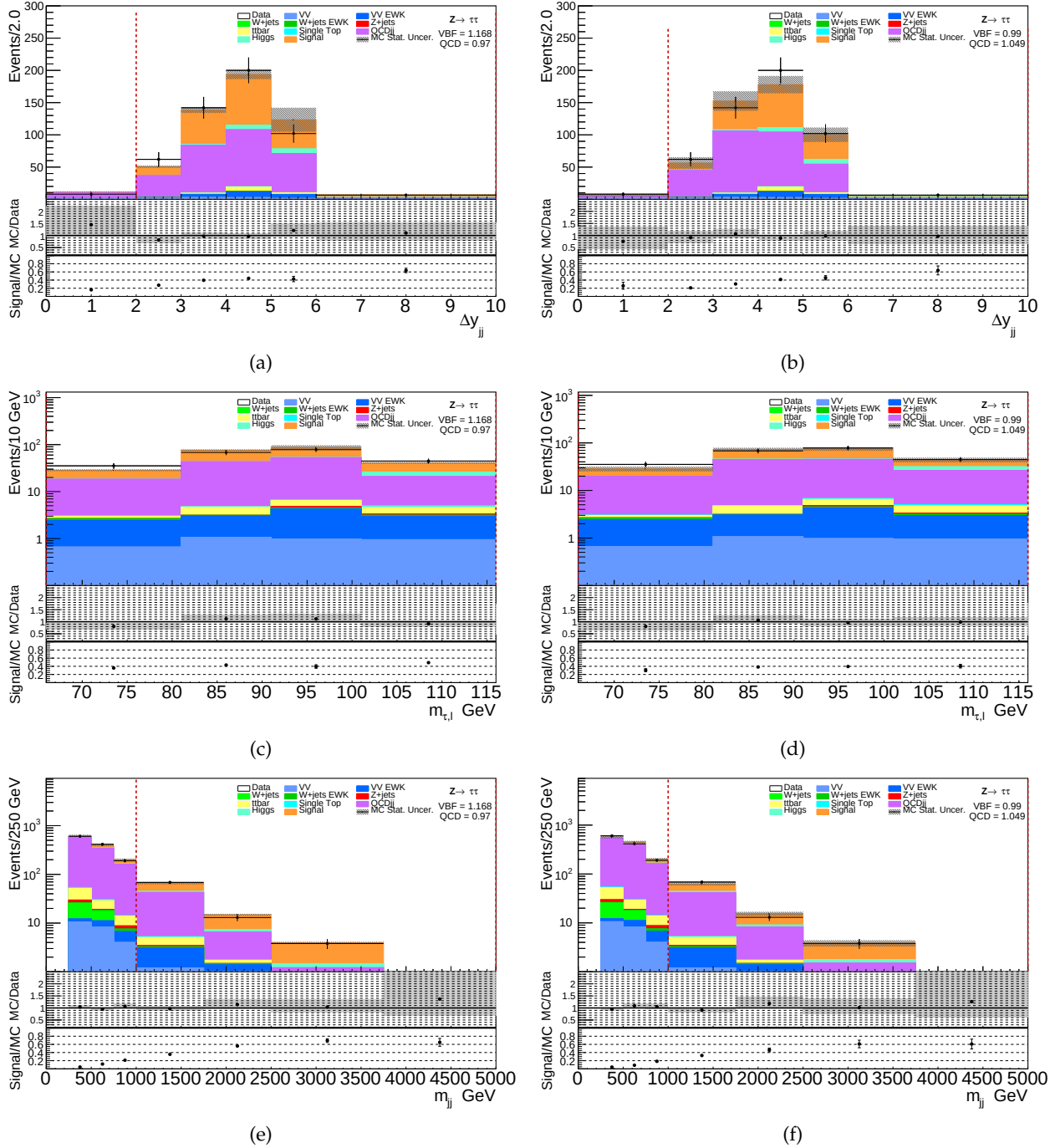


FIGURE 6.19: Data-to-MC comparisons for different kinematic variables in the $Z \rightarrow \tau\tau$ final state after performing the QCDjj re-weighting and applying the signal strength normalisation factors. The plots on the left column correspond to the SHERPA 2.2.1 prediction and the ones on the right to MadGraph@LO.

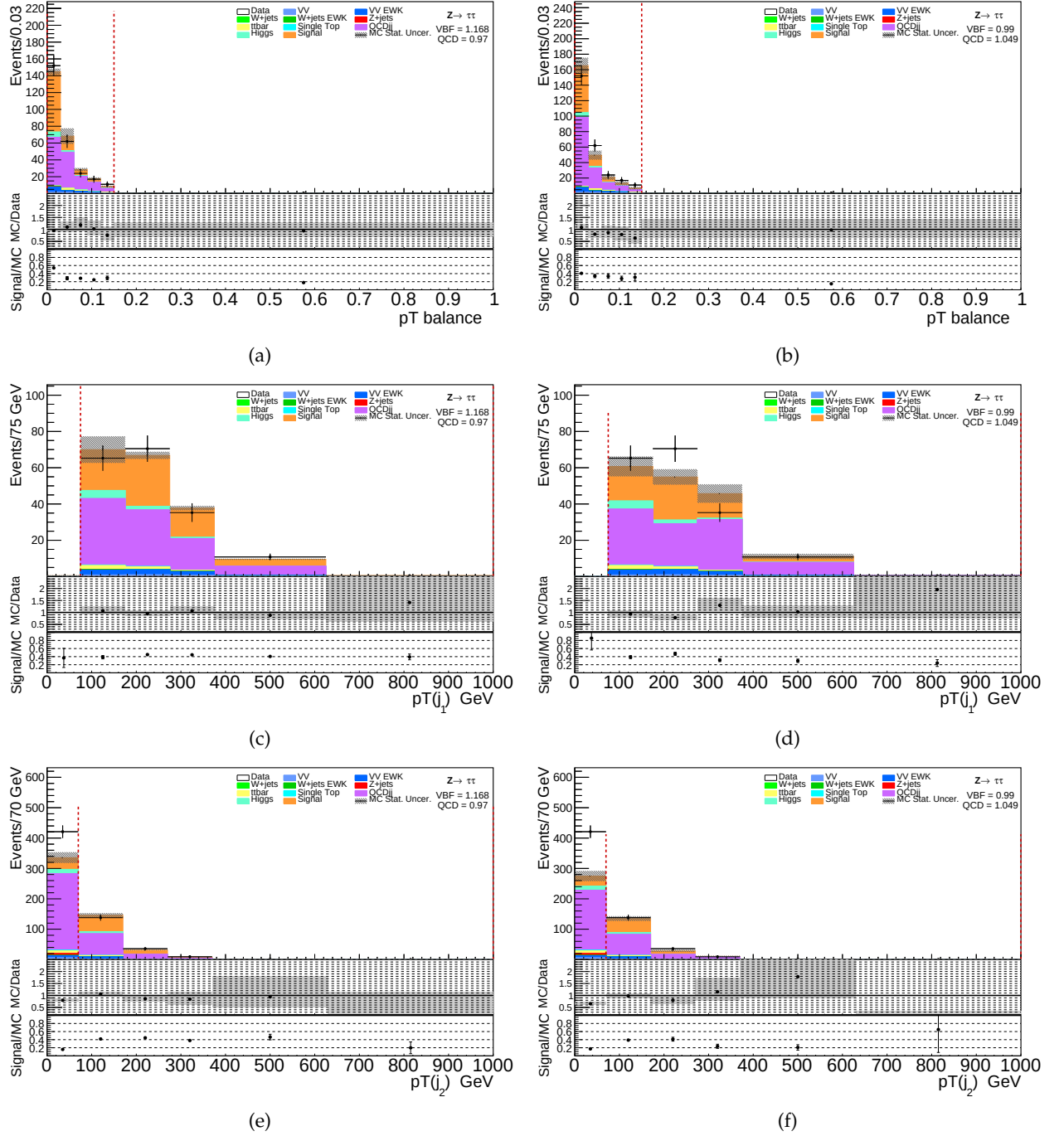


FIGURE 6.20: Data-to-MC comparisons for different kinematic variables in the $Z \rightarrow \tau\tau$ final state after performing the QCDjj re-weighting and applying the signal strength normalisation factors. The plots on the left column correspond to the SHERPA 2.2.1 prediction and the ones on the right to MadGraph@LO.

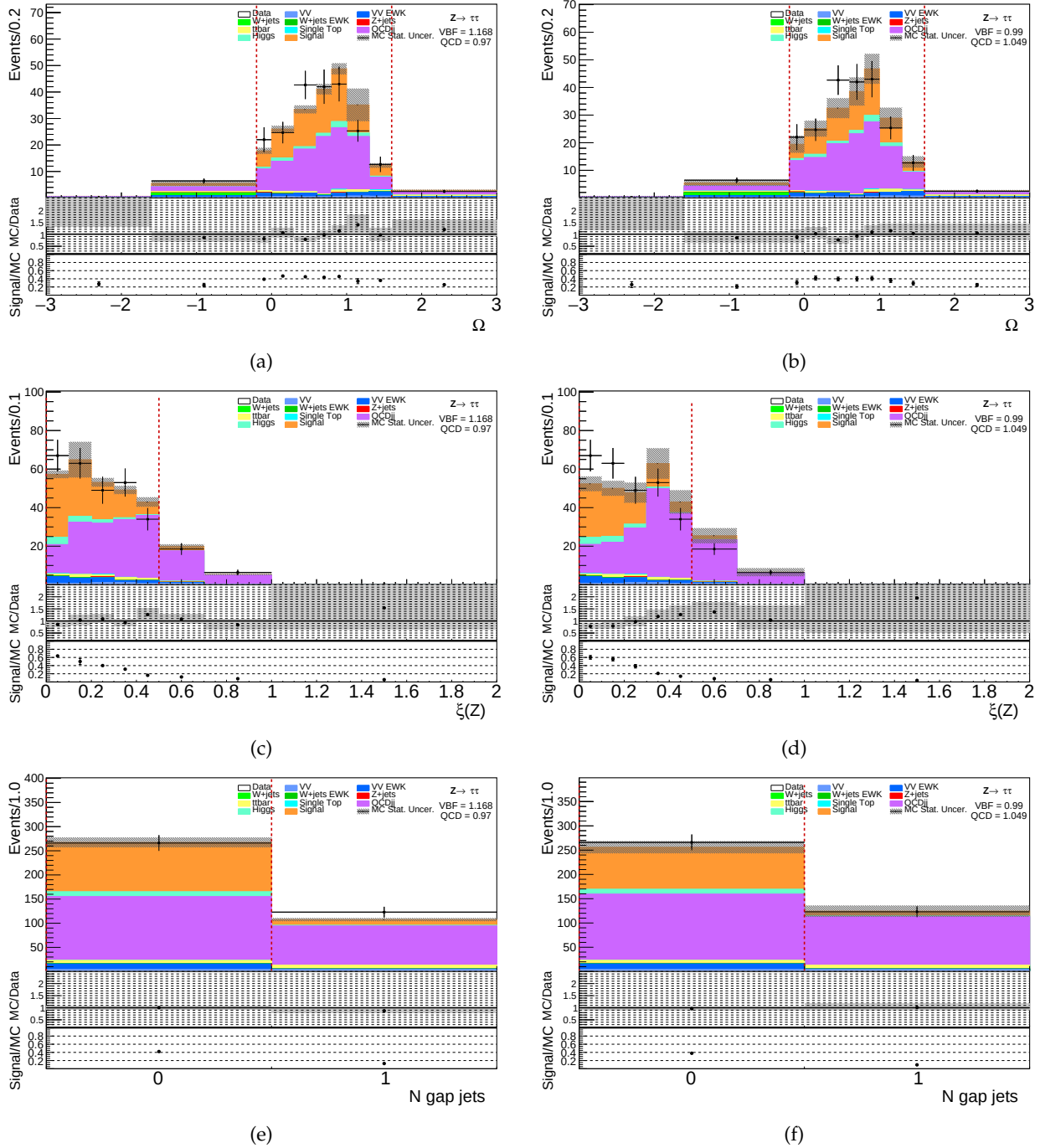


FIGURE 6.21: Data-to-MC comparisons for different kinematic variables in the $Z \rightarrow \tau\tau$ final state after performing the QCDjj re-weighting and applying the signal strength normalisation factors. The plots on the left column correspond to the SHERPA 2.2.1 prediction and the ones on the right to MadGraph@LO.

where X and Y denote different lepton flavours. We can measure R_{XY} by fitting two final states simultaneously: parametrising the fit in such a way that we normalise final state $Z \rightarrow XX$ by the product of the EWjj signal strength of final state $Z \rightarrow YY$ ($\mu_{EW}(YY)$) and the ratio R_{XY} . At the same time, channel $Z \rightarrow YY$ is normalised by the $\mu_{EW}(YY)$ signal strength.

We measure $R_{e\mu}$ and $R_{l\tau}$. In the latter ratio l denotes the combination of the light lepton final states and τ is the combination of the two tau decay modes.

6.5.2 Systematic uncertainties

So far, the results we have presented include only the statistical uncertainties of the data and the MC samples. The sources of systematic uncertainty are split into the experimental systematics and the theoretical uncertainties. These uncertainties are discussed in this section.

Experimental systematics are related to the energy scale and resolution calibrations for the different objects used in the analysis such as jets, leptons and taus. Additionally, the experimental systematics include the trigger efficiency, the pile-up modelling and the luminosity determination uncertainties. The object calibration systematics are evaluated using variations of the MC templates that are produced using alternative calibrations performed with calibration parameters one standard deviation ($\pm\sigma$) from their nominal value — the calibration parameters are provided by the ATLAS Combined Performance groups as explained in Section 5.5. These variations are propagated through the analysis chain, and for every kinematic variable of interest two shapes that correspond to the $\pm\sigma$ calibrations associated with a particular experimental systematic source are saved.

Each experimental systematic source is included in the profile likelihood fit with a nuisance parameter that interpolates between the $+\sigma$ and $-\sigma$ variations of the respective experimental calibration; to constrain the nuisance parameter a Gaussian term is included.

The impact of each systematic source on the parameter of interest (POI) is calculated by fixing all the other fit parameters to their best fit value, and then fitting again with the $\pm\sigma$ values for the parameter controlling the systematic source. The difference in the values for the POI between the two fits is taken as the impact. We prune all the systematic sources which result in a variation of the POI of less than 0.5%. Figures 6.22 and 6.23 show the impact of the different systematic sources in the POI.

The experimental systematics are the ones represented by black points. The horizontal bars are the size of the uncertainty of each particular nuisance parameter after the fit. Prior to the fit the uncertainty is set to one unit, and it should be around the same after the fit — for measurements that are not sensitive to a particular experimental effect. The red points are the nuisance parameters used in the normalisation of the EWjj or the QCDjj processes — the ones also used to define the R_{XY} ratios. The impact of each nuisance parameter ($\Delta\mu$) is calculated pre-fit and post-fit, with the pre-fit (post-fit) impacts represented with the empty (filled) blue bars. The pre-fit impact is calculated as described in the previous paragraph, setting the uncertainty of each nuisance parameter to one. In the post-fit case, the uncertainty of the nuisance parameter is fixed to the value resulting from the fit.

The total experimental systematic uncertainty on the signal strength for the $Z \rightarrow ll$ and $Z \rightarrow \tau\tau$ final states is 3.6% and 5.3%, respectively. The dominant experimental systematics are jet-related calibrations. Table 6.10 presents a breakdown of the systematic uncertainty sources.

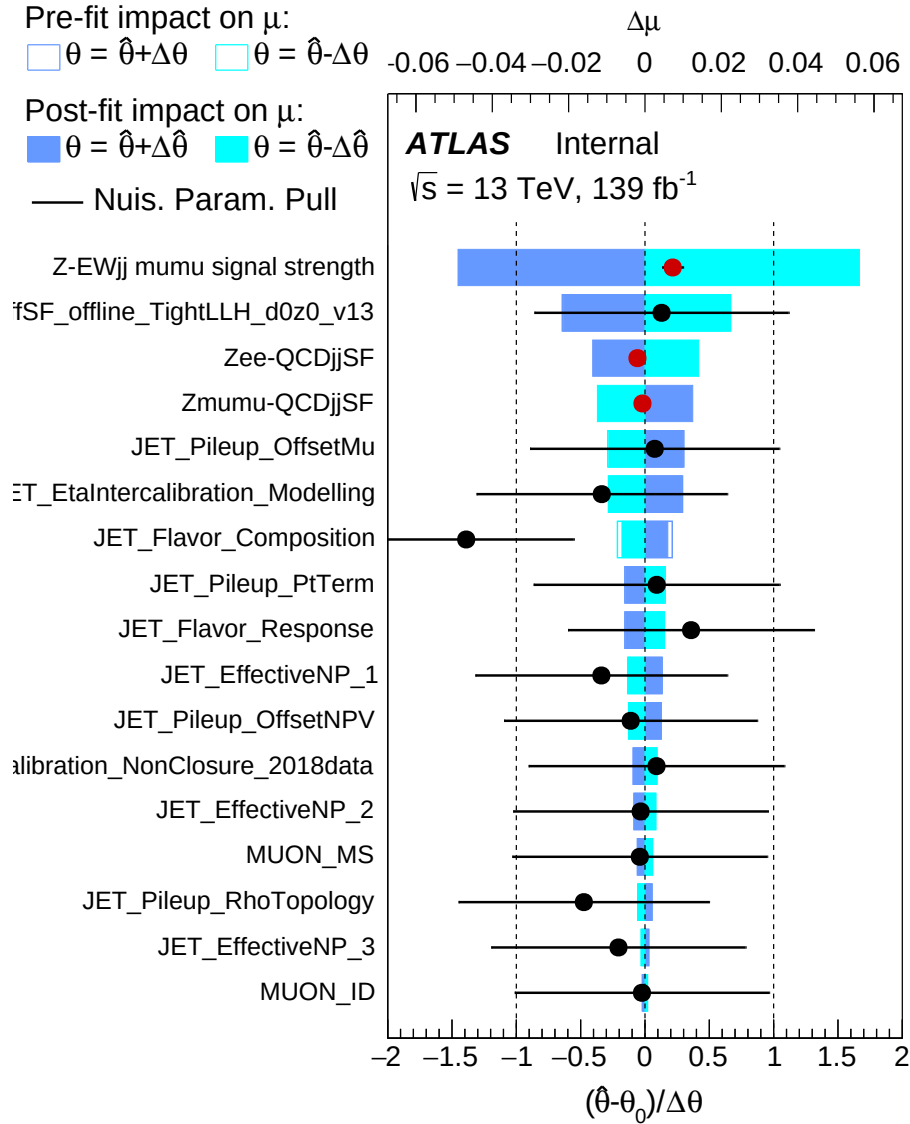


FIGURE 6.22: Breakdown of the impact on the $R_{e\mu}$ ratio of the different experimental systematic uncertainties. In this plot, the parameter of interest ($R_{e\mu}$) is denoted as μ . The parameter $\hat{\theta}$ represents the best fit value of the nuisance parameter controlling each systematic variation and θ_0 is the pre-fit value of the nuisance parameter. The difference between $\hat{\theta}$ and θ_0 is divided by the pre-fit uncertainty on the nuisance parameter.

Systematic Uncertainty (%)	$Z \rightarrow ee$	$Z \rightarrow \mu\mu$	$R_{e\mu}$	$Z \rightarrow ll$	$Z \rightarrow \tau\tau$	$R_{l\tau}$
Jet	3.0	4.3	1.9	3.5	4.9	3.5
Electron	2.2	N/A	2.1	0.7	< 0.5	0.7
Muon	N/A	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
Tau	N/A	N/A	N/A	N/A	1.7	2.2
Missing energy	N/A	N/A	N/A	N/A	1.3	1.7
Pileup	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
QCDjj modelling	3.9	4.2	0.1	3.5	7.6	4.8
EWjj modelling	14.1	14.3	0.4	14.3	15.3	1.5
Luminosity	1.7	1.7	N/A	1.7	1.7	N/A

TABLE 6.10: Breakdown of systematic uncertainties in percent.

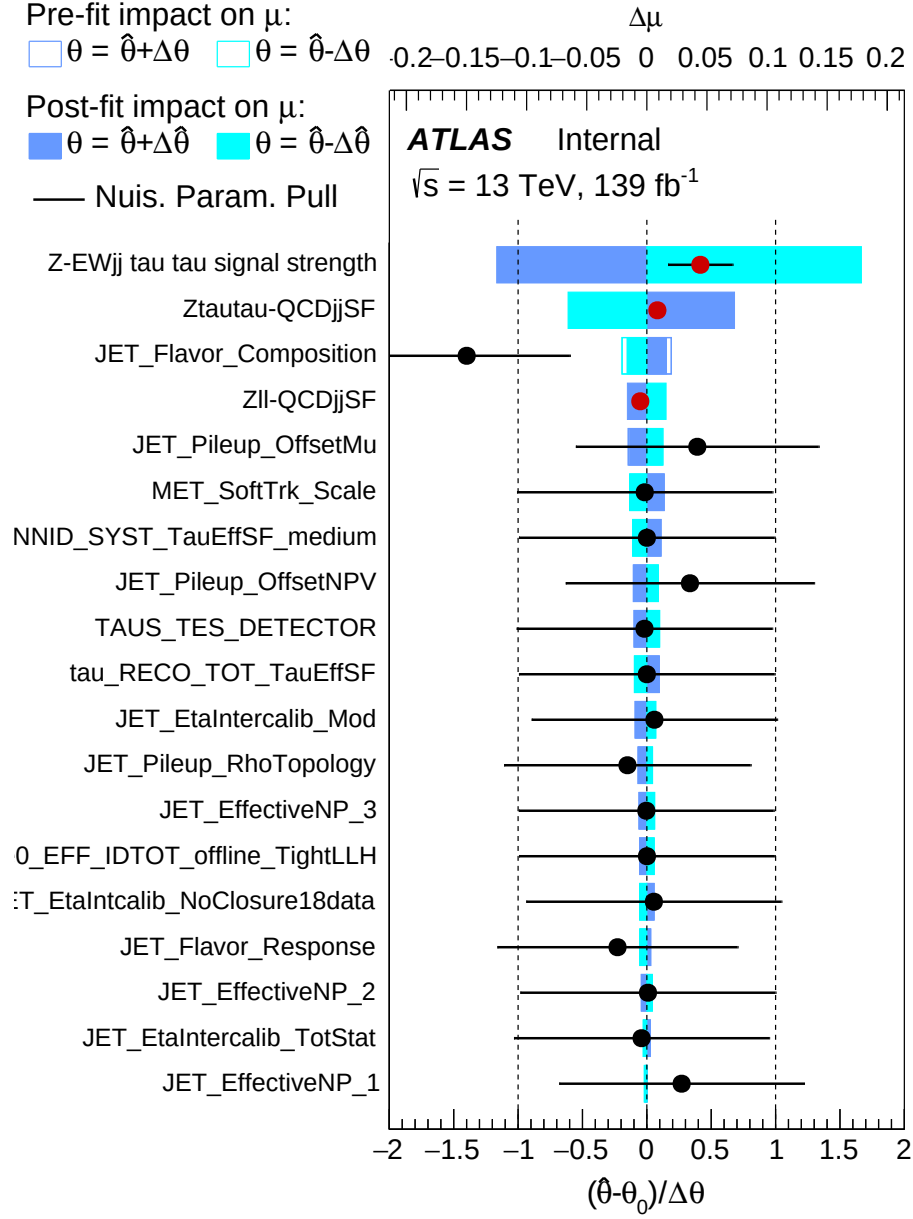


FIGURE 6.23: Breakdown of the impact on the $R_{l\tau}$ ratio of the different experimental systematic uncertainties. In this plot, the parameter of interest ($R_{l\tau}$) is denoted as μ . The parameter $\hat{\theta}$ represents the best fit value of the nuisance parameter controlling each systematic variation and θ_0 is the pre-fit value of the nuisance parameter. The difference between $\hat{\theta}$ and θ_0 is divided by the pre-fit uncertainty on the nuisance parameter.

EWjj sample	$R_{e\mu}$	$R_{l\tau}$
SHERPA 2.2.11	$1.046 \pm 0.077 \pm 0.005$	$1.071 \pm 0.209 \pm 0.022$
PowHeg+Pythia8	$1.053 \pm 0.078 \pm 0.004$	$1.102 \pm 0.224 \pm 0.015$

TABLE 6.11: Signal strength ratios with the uncertainties arising from the MC EWjj sample separated from the other sources of statistical uncertainty — which are correlated, such as the uncertainty on the data and the other MC samples. The second uncertainty component is the MC statistical uncertainty of the corresponding EWjj sample.

$R_{e\mu}$	$R_{l\tau}$
$1.050 \pm 7.4\%(\text{Stat.}) \pm 2.9\%(\text{Syst.})$	$1.092 \pm 18.5\%(\text{Stat.}) \pm 6.8\%(\text{Syst.})$

TABLE 6.12: Final results for the ratios between the signal strength for the EWjj process in different lepton generations. The results are reported with their percentage uncertainties broken down into the systematic and statistical components. The systematic component is computed by adding in quadrature the systematic uncertainty contributions shown in Table 6.10.

When measuring the R_{XY} ratios, we assume that the experimental systematics are fully correlated between the different final states. This results in a partial cancellation of the effect of some of the systematic uncertainties such as the integrated luminosity determination or the jet-related systematics. The cancellation is 3.4% and 1.8% for $R_{e\mu}$ and $R_{l\tau}$, respectively — the reduction in the systematic uncertainties is calculated comparing two scenarios: the case where the nuisance parameters are fully correlated between the $Z \rightarrow XX$ and $Z \rightarrow YY$ channels; and the case where the R_{XY} ratio is calculated assuming that the nuisance parameters in both channels are completely uncorrelated.

The theoretical uncertainties arise from the different predictions of the QCDjj and EWjj processes that are used to extract the total cross-sections. To estimate the impact of the choice of the QCDjj description, we extract the parameter of interest using the shape defined by Equation 6.8 and take the $\pm\sigma$ envelopes from the results given by using the individual shapes of each MC generator. The uncertainty on the EWjj modelling is obtained by calculating the difference in the reported cross-section between EWjj-SHERPA and EWjj-PowHeg+Pythia8 and symmetrising the result.

6.5.3 Ratios results

One advantage of measuring the ratios between the various final states is the partial cancellation of the theoretical systematic uncertainties. For instance, the EWjj modelling difference is partially cancelled when we compute the R_{XY} ratio. Table 6.11 contains the ratios — taking apart the uncertainty component arising from the EWjj description. When comparing the results obtained for different EWjj MC generators; assuming full correlation for: the experimental and the remaining theoretical systematic uncertainties, and the statistical uncertainties coming from the data, the QCDjj and the other BG MC samples; we see agreement at the 1.1σ and 1.2σ level for the $R_{e\mu}$ and $R_{l\tau}$ ratios, respectively. This is an important result since it demonstrates that the results obtained for the ratios are robust against the choice of EWjj simulation sample.

The final results for the R_{XY} ratios are reported in Table 6.12. We see agreement with the SM prediction within one standard deviation.

6.6 Conclusions

In this chapter we presented the comparison between the three lepton families for the production of di-leptons in the VBF topology at the Z-peak. The dominant background for the three channels is the production of the Z boson in association with jets initiated by QCD radiation. The QCDjj background has been constrained using dedicated control regions and the MC modelling has been corrected to describe the data better. The corrections are extrapolated to the signal region and the EWjj normalisation is extracted independently for each channel.

The experimental systematic uncertainties and the modelling uncertainties are evaluated when performing the ratios between the different final states — these sources of uncertainty are subdominant. The precision of the final results is limited by the number of recorded events.

Our final results are consistent with the LU hypothesis. In the next chapter we explore the region where the mass of the di-lepton system is greater than the Z boson mass.

Chapter 7

Probing the anomalous production of di-leptons at high-mass

In this chapter, we analyse the events that have a pair of leptons with an invariant mass greater than the region described in the previous chapter (the Z-peak). First, we describe the high-mass measurements in the $Z \rightarrow ll$ sample ($l = e, \mu$) in Section 7.1. Section 7.2 presents the results obtained in $Z \rightarrow \tau\tau$ events by applying the same selection requirements. Since measuring the $Z \rightarrow \tau\tau$ final state is found to be much more challenging at high di-tau mass we introduce a multivariate discriminant in Section 7.3. The algorithm trained to discriminate the EWjj process at high-mass is tested in a control region with events having a di-tau mass around the Higgs boson mass and the results are presented in Section 7.4. The partially blinded results for the region above the Higgs control region are discussed in Section 7.5. We present the conclusions of this study in Section 7.6.

7.1 $Z \rightarrow ll$ control region

The $Z \rightarrow ll$ baseline sample includes all the events passing the selection requirements presented in Table 6.2, apart from the di-lepton mass requirement, and classified as signal region (SR) in Table 6.4. Our sample is split into a medium-range (MR) and high-range (HR) region with respect to the mass of the di-lepton system. The regions are defined as:

$$\begin{aligned} \text{Medium Range : } 101 \leq m(l, l) < 160 \text{ GeV,} \\ \text{High Range : } 160 \text{ GeV} \leq m(l, l), \end{aligned} \tag{7.1}$$

and are shown in Figure 7.1.

The QCDjj samples are re-weighted using the same functions described in Section 6.4.1. The normalisation factors applied to the QCDjj and EWjj samples are the ones derived in the Z-peak region — the values are shown in Table 6.7. The kinematic distributions for m_{jj} , $\xi(Z)$, $p_{T\text{balance}}$ and Δy_{jj} are shown in Figures 7.2 and 7.3. We observe good agreement between the data and the MC predictions using the prescriptions obtained at the Z-peak. Two background contributions become more prominent as the mass of the di-lepton system increases: the $t\bar{t}$ and the di-boson production electroweak processes (VV EWK).

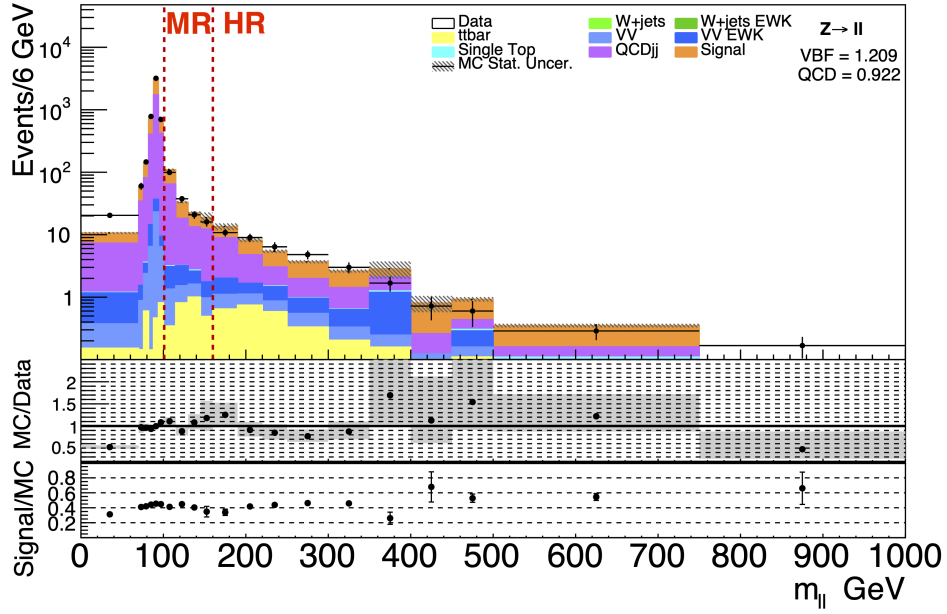


FIGURE 7.1: Di-lepton mass distribution and regions.

A cross check of the normalisation factors is done by performing an independent fit of the MR and HR regions to the data. The results are shown in Tables 7.1 and 7.2. These numbers agree reasonably well with the Z-peak results.

EWjj Sample	QCDjj Sample: Sherpa 2.2.1			
Sherpa 2.2.11	Mid Range	$\frac{\Delta\mu}{\sigma(\Delta\mu)}$	High Range	$\frac{\Delta\mu}{\sigma(\Delta\mu)}$
μ_{EW}	1.136 ± 0.159	0.44	1.301 ± 0.213	0.43
μ_{QCD}	0.877 ± 0.038	1.15	0.928 ± 0.066	0.09
QCDjj Sample: MadGraph				
μ_{EW}	1.125 ± 0.156	0	1.035 ± 0.209	0.42
μ_{QCD}	0.915 ± 0.035	0.32	1.012 ± 0.060	1.42

TABLE 7.1: Normalisation factors obtained by fitting the MR and HR independently. The difference $\Delta\mu$ is the normalisation factor difference with respect to the Z-peak normalisation factors.

EWjj Sample	QCDjj Sample: Sherpa 2.2.1			
PowHeg+Pythia8	Mid Range	$\frac{\Delta\mu}{\sigma(\Delta\mu)}$	High Range	$\frac{\Delta\mu}{\sigma(\Delta\mu)}$
μ_{EW}	0.945 ± 0.136	0.61	0.946 ± 0.164	0.51
μ_{QCD}	0.901 ± 0.037	1.07	0.969 ± 0.065	0.41
QCDjj Sample: MadGraph				
μ_{EW}	0.942 ± 0.136	0.15	0.766 ± 0.159	1.21
μ_{QCD}	0.938 ± 0.035	0.22	1.042 ± 0.058	1.65

TABLE 7.2: Normalisation factors obtained by fitting the MR and HR independently. The difference $\Delta\mu$ is the normalisation factor difference with respect to the Z-peak normalisation factors.

We also test the modelling of the QCDjj process at high-mass by combining the events that belong in any of the QCDjj CRs described in Table 6.4 and that have $m(l, l) \geq 101$ GeV. The

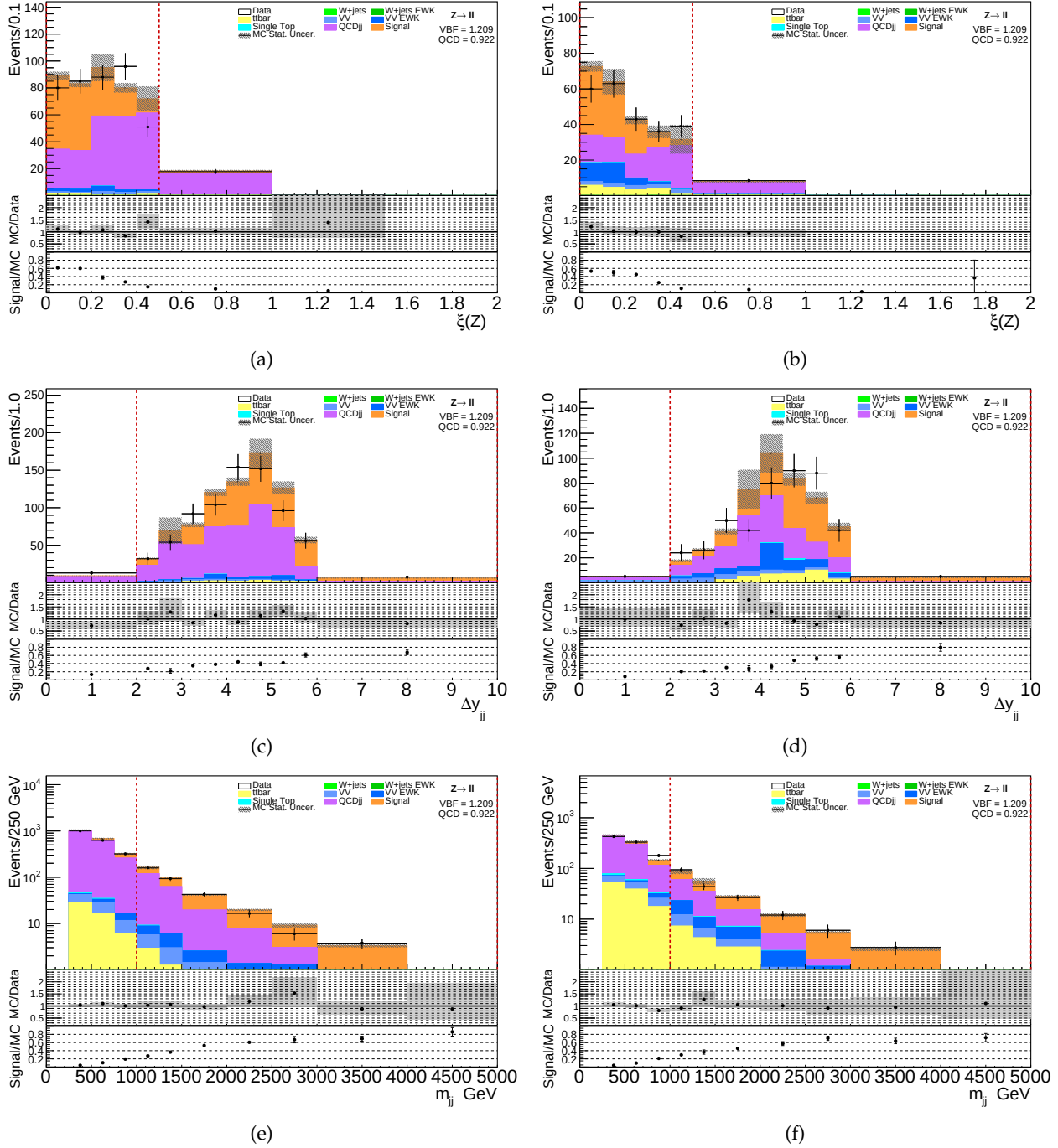


FIGURE 7.2: Data-to-MC comparisons for different kinematic variables in the $Z \rightarrow ll$ final state for the two di-lepton mass ranges. The plots on the left column correspond to the MR region and the ones on the right to HR region. In both regions QCDjj-SHERPA 2.2.1 and EWjj-SHERPA are used. The normalisation factors used for the QCDjj and EWjj processes are the ones derived in the Z-peak region.

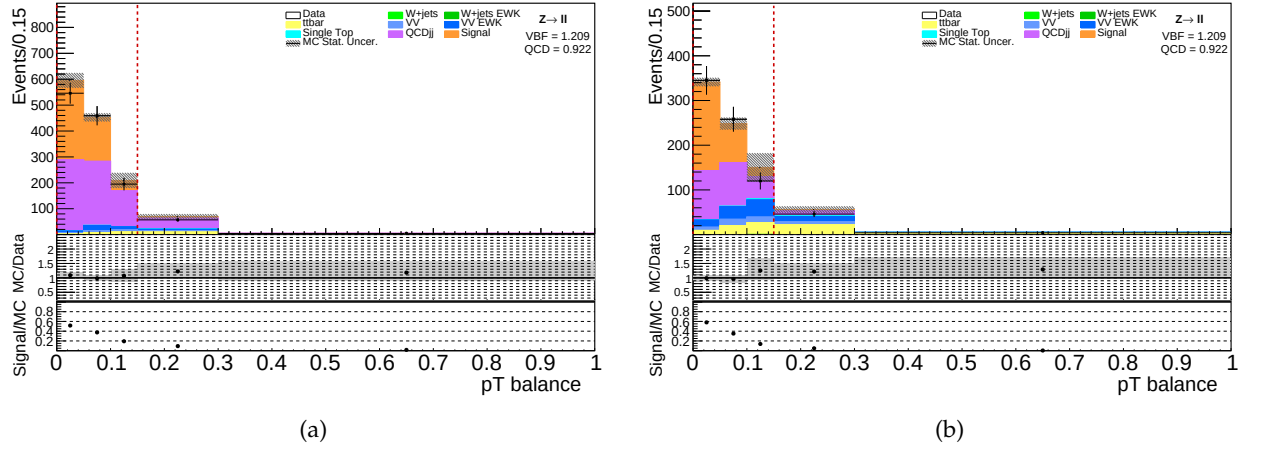


FIGURE 7.3: Data-to-MC comparisons for the $p_{T_{\text{balance}}}$ variable in the $Z \rightarrow ll$ final state for the two di-lepton mass ranges. The plots on the left column correspond to the MR region and the ones on the right to HR region. In both regions QCDjj-SHERPA 2.2.1 and EWjj-SHERPA are used. The normalisation factors used for the QCDjj and EWjj processes are the ones derived in the Z-peak region.

kinematic distributions for $\zeta(Z)$, Δy_{jj} , m_{jj} , and $p_{T_{\text{balance}}}$ are shown in Figure 7.4. Overall, the data-to-MC agreement in this region is also good.

The results presented above prove that we can be confident that the EWjj and QCDjj samples, after the re-weighting, give a good description of the data at high-mass.

7.2 $Z \rightarrow \tau\tau$ cut-based analysis

For the $Z \rightarrow \tau\tau$ events, the same selection used in $Z \rightarrow ll$ events is maintained and the reconstructed mass cut is moved to $m_{\text{reco}} \geq 160$ GeV to avoid the Higgs resonance. This selection is detailed in Table 7.3 and we will refer to this analysis approach as *cut-based*. The signal region is blinded by not running our analysis chain in the data. Additionally, in analysis regions where only one requirement is failed we do not unblind the data if the predicted signal purity is more than 10%.

Cut-based selection	
Baseline	Table 6.2
Signal Region	$-0.2 < \Omega < 1.4$
	$N_{\text{jets}}^{\text{gap}} = 0$
	$\zeta(Z) < 0.5$

TABLE 7.3: Selection requirements for the cut-based analysis approach.

The predicted distributions for the kinematic variables used in the selection requirements are shown in Figures 7.5 and 7.6 for $Z \rightarrow \tau_{\text{had}}\tau_{\text{lep}}$ events, and Figures 7.7 and 7.8 show the same distributions for $Z \rightarrow \tau_{\text{lep}}\tau_{\text{lep}}$ events. We can see that at high-mass the sample is dominated by background processes. The purity of the samples is less than 10% in $Z \rightarrow \tau_{\text{had}}\tau_{\text{lep}}$ and approximately 1% in $Z \rightarrow \tau_{\text{lep}}\tau_{\text{lep}}$ events. There is no sensitivity to the EWjj process using the same cut-based approach that worked well at the Z boson peak. We can also see how for the tau final states the $t\bar{t}$ and the VV EWK processes become an important background at high-mass.

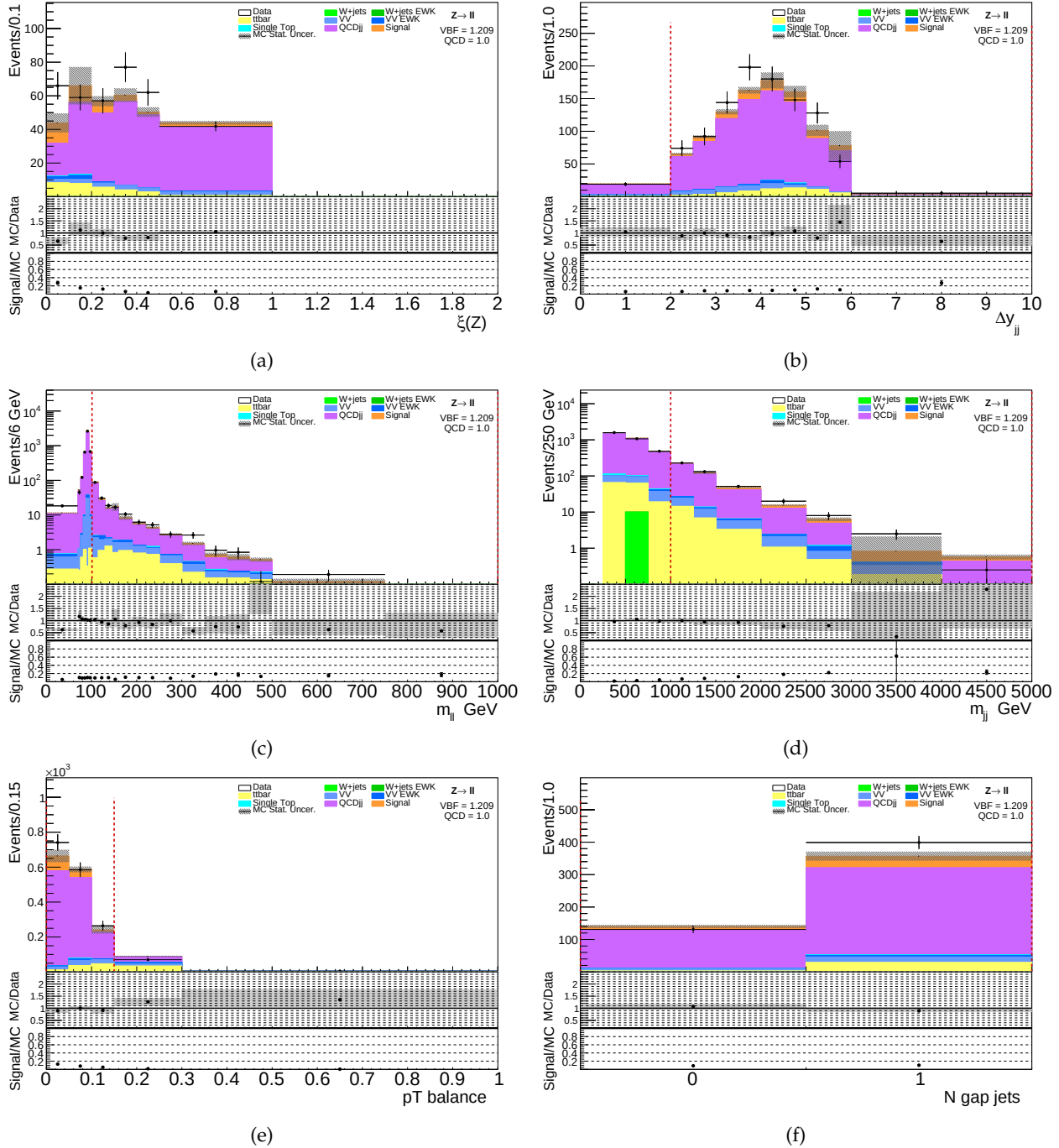


FIGURE 7.4: Data-to-MC comparisons for different kinematic variables in the $Z \rightarrow ll$ final state for the QCDjj CR at high-mass. The SHERPA 2.2.1 sample is used to model the QCDjj contribution.

Additionally, Figure 7.6c shows that as the reconstructed mass of the candidate events increases, the Multi Jets (MJ) background contribution also increases. The source of the MJ backgrounds has been discussed in Section 4.3.1 and the way their contribution is estimated for this analysis follows the same approach described in Section 5.4.1 — essentially, we select same-sign tau pairs with the kinematic features of the signal region to extract the shape of the MJ background, and then scale this shape by a factor that accounts for the residual charge correlation (RQCD). At high-mass, we set $RQCD = 1.3 \pm 0.3$. The value used for RQCD is empirical since we do not have enough statistics to define the MJ CRs and to calculate the ratio between same-sign and opposite-sign events. Furthermore, since at high-mass the W+jets sample suffers from poor statistical precision, we do not subtract this component in the MJ estimation. We rely on the data to calculate the MJ and W+jets contributions all together. In this chapter, when we refer to the MJ contribution we are actually referring to the MJ + W+jets backgrounds.

The regions that fail the requirements and have an expected signal purity of less than 10% have been unblinded to test the data-to-MC agreement and the validity of the MJ estimation.

In contrast to the Z-peak region, the performance of the cut-based approach is not good and this situation motivates a change of strategy in the analysis for the high-mass $Z \rightarrow \tau_{\text{had}} \tau_{\text{lep}}$ events. In the next section we define a multivariate analysis approach (MVA). The $Z \rightarrow \tau_{\text{lep}} \tau_{\text{lep}}$ final state is not used from this point onwards since it has a negligible contribution to the EWjj process at high-mass and the purity of this channel is poor.

7.3 Multi-variate analysis approach

In the previous section, we saw that by applying the cut-based approach to the $Z \rightarrow \tau_{\text{had}} \tau_{\text{lep}}$ events the selected sample was dominated by backgrounds. However, Figure 7.5 and 7.6 show that variables such as Ω , $p_{T\text{balance}}$, m_{jj} , Δy_{jj} and $\xi(Z)$ have signal-to-background discriminating power — this can be seen by looking in each plot at the ratio labelled Signal/MC($\times 4$), which shows the percentage of EWjj events in each bin scaled up four times. A similar signal-to-background discriminating power can be observed for the same kinematic variables in the $Z \rightarrow ll$ sample discussed in Section 7.1. One additional variable that has separating power is the transverse mass of the light-lepton in $Z \rightarrow \tau_{\text{had}} \tau_{\text{lep}}$ events ($m_T(l)$) — the distribution for $m_T(l)$ is shown in Figure 7.9. The $m_T(l)$ variable helps to discriminate the signal against events where the light-lepton was produced in a W boson decay.

7.3.1 Boosted Decision Trees

We use these variables to train a Boosted Decision Tree (BDT) using the TMVA ROOT package [191]. A BDT is a collection of decision trees which are combined using a process known as *boosting* to obtain a final decision [192, 193]. A *decision tree* is a binary structured classifier. A set of boolean decisions are applied to the data until a stop criterion is fulfilled. The data is then partitioned into many different regions which are classified according to the proportion of signal and background events in each final node (also known as leaf) — the schematic representation of a decision tree is shown in Figure 7.10.

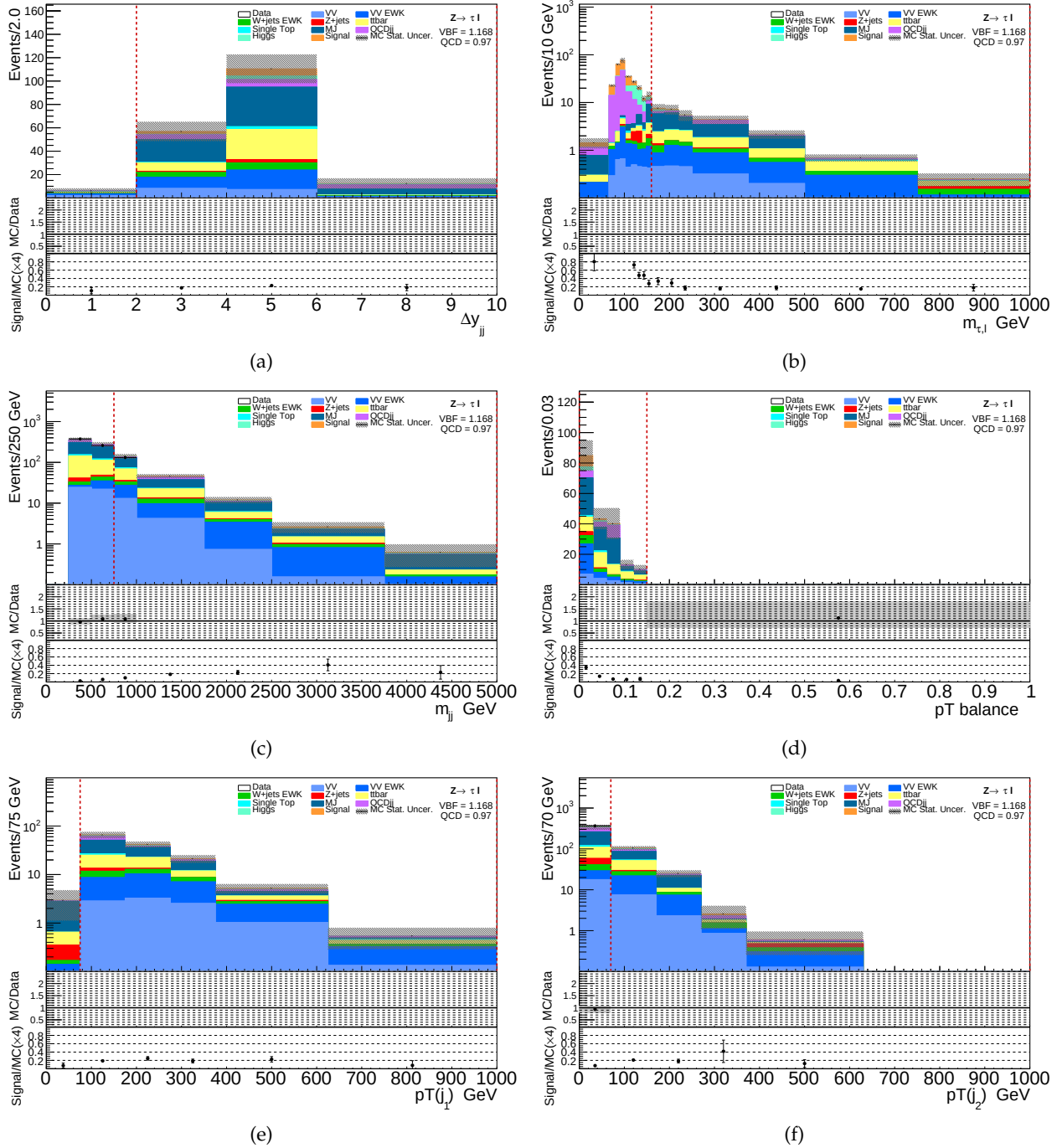


FIGURE 7.5: $Z \rightarrow \tau_{\text{had}} \tau_{\text{lep}}$ selected sample after applying the cut-based selection detailed in Table 7.3. The resulting sample is dominated by backgrounds. In all the the distribution bins that are part of the signal region or close to it, with an expected signal purity above 10%, the data are blinded.

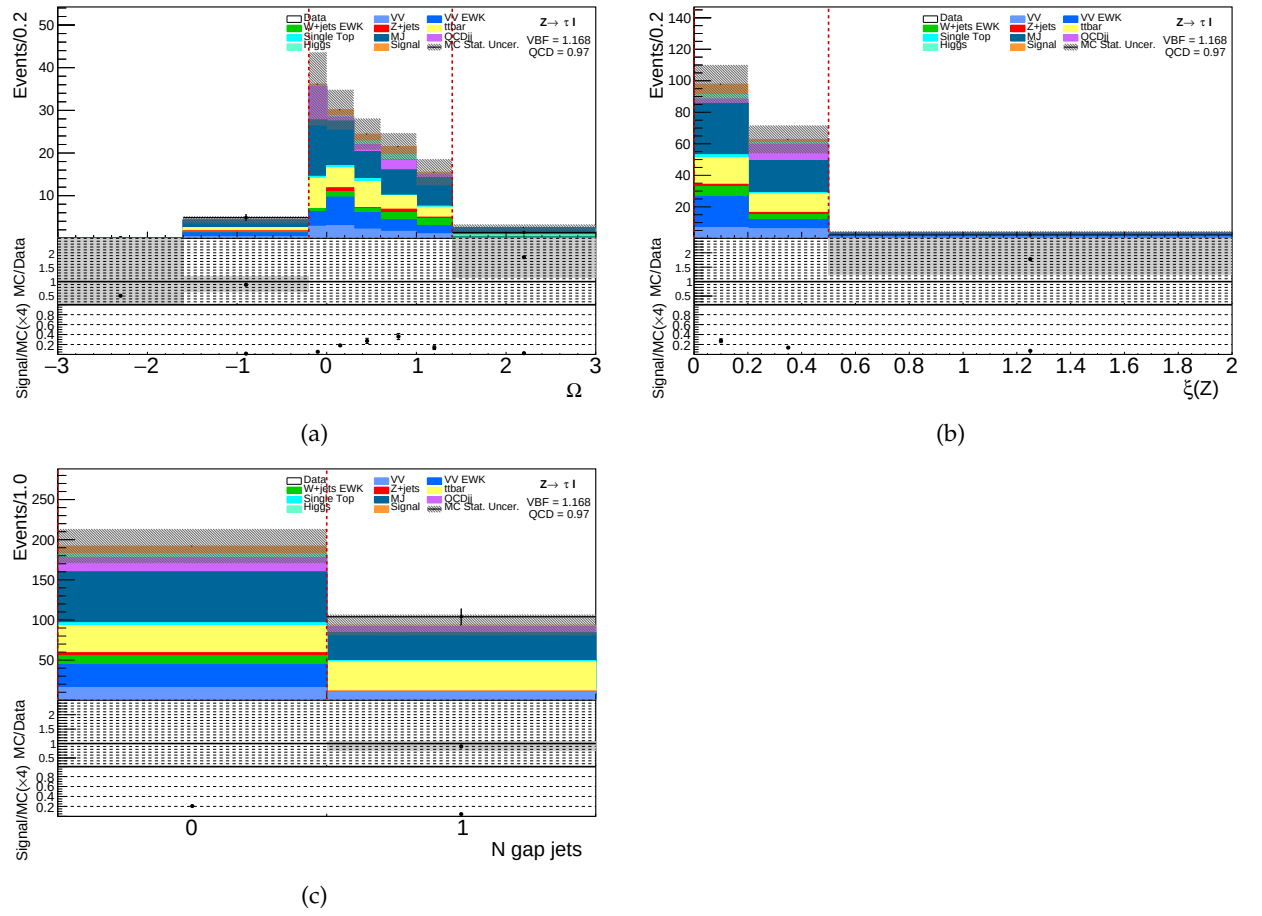


FIGURE 7.6: $Z \rightarrow \tau_{\text{had}}\tau_{\text{lep}}$ selected sample after applying the cut-based selection detailed in Table 7.3. The resulting sample is dominated by backgrounds. In all the distribution bins that are part of the signal region or close to it, with an expected signal purity above 10%, the data are blinded.

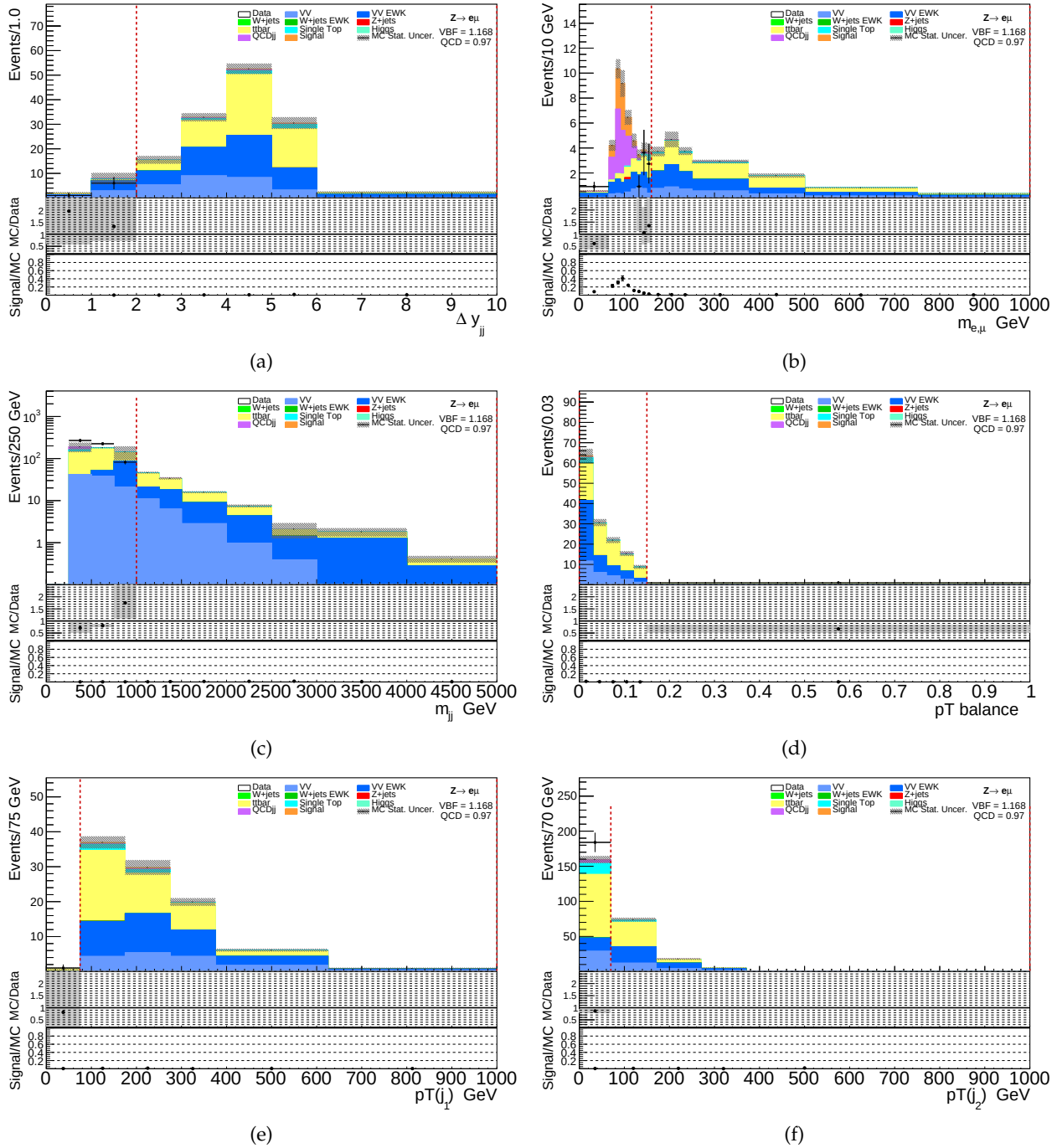


FIGURE 7.7: $Z \rightarrow \tau_{lep} \tau_{lep} \rightarrow e\mu$ selected sample after applying the cut-based selection detailed in Table 7.3. The resulting sample is dominated by backgrounds. In all the the distribution bins that are part of the signal region or close to it, with an expected signal purity above 10%, the data are blinded.

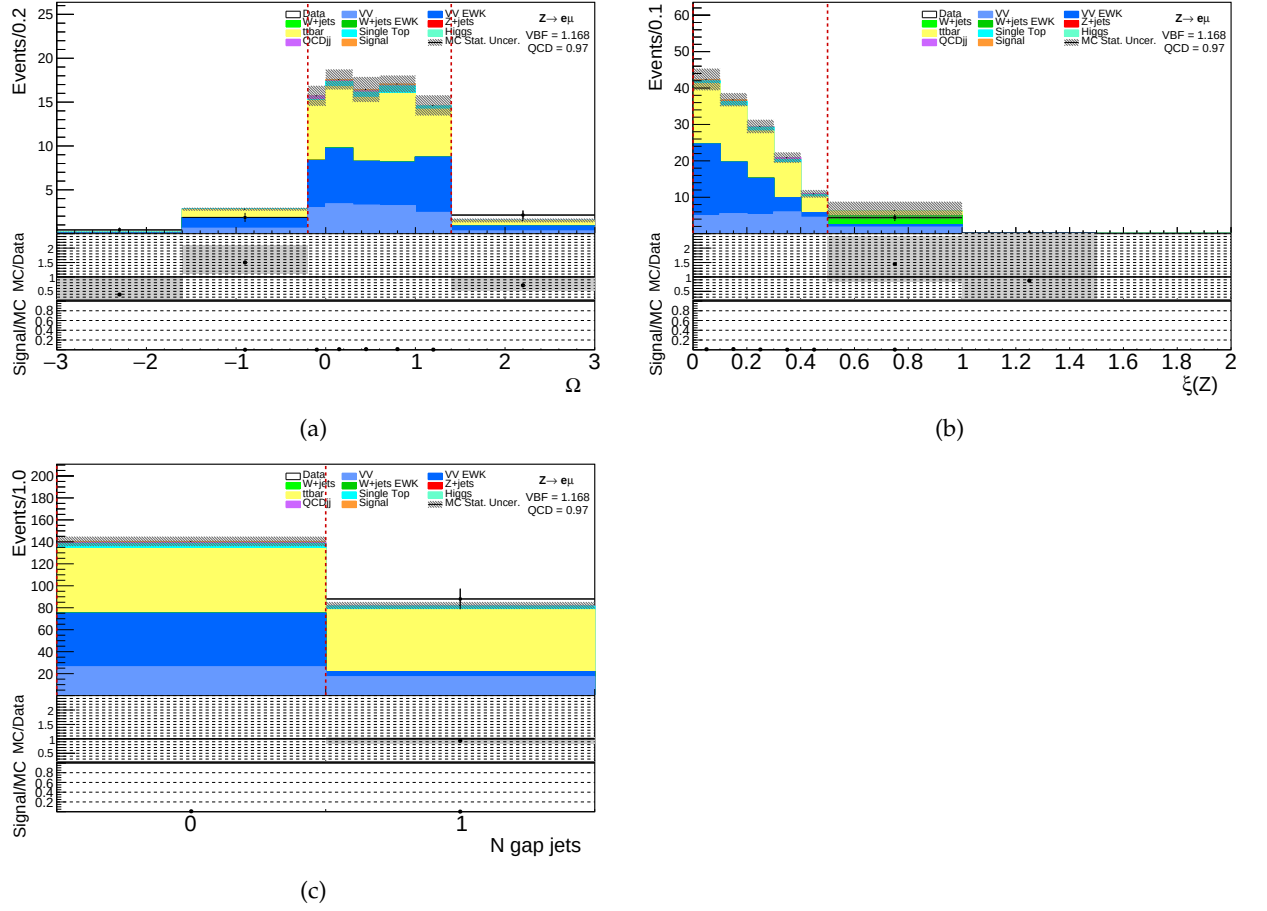


FIGURE 7.8: $Z \rightarrow \tau_{\text{had}} \tau_{\text{lep}}$ selected sample after applying the cut-based selection detailed in Table 7.3. The resulting sample is dominated by backgrounds. In all the the distribution bins that are part of the signal region or close to it, with an expected signal purity above 10%, the data are blinded.

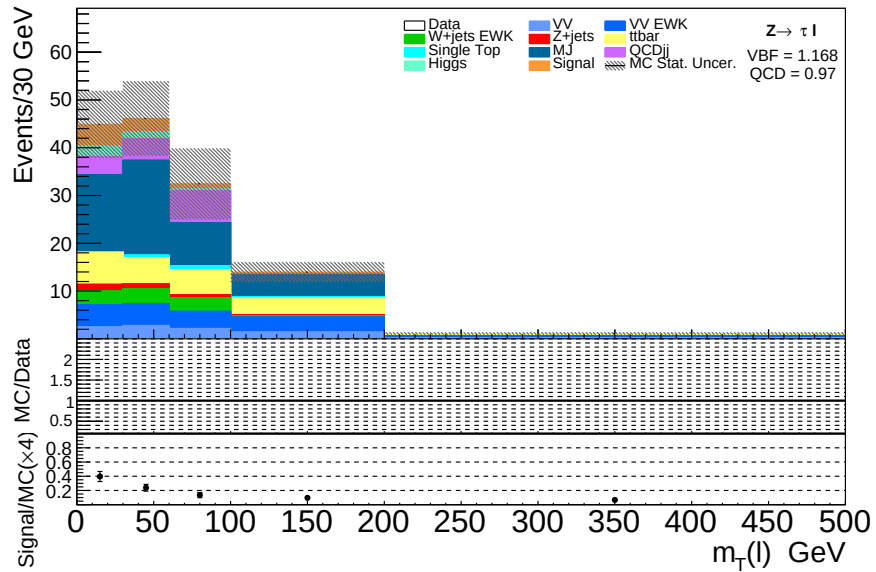


FIGURE 7.9: Distribution of $m_T(l)$ in $Z \rightarrow \tau_{\text{had}} \tau_{\text{lep}}$ events. The displayed sample has the selection requirements described in Table 7.3 applied.

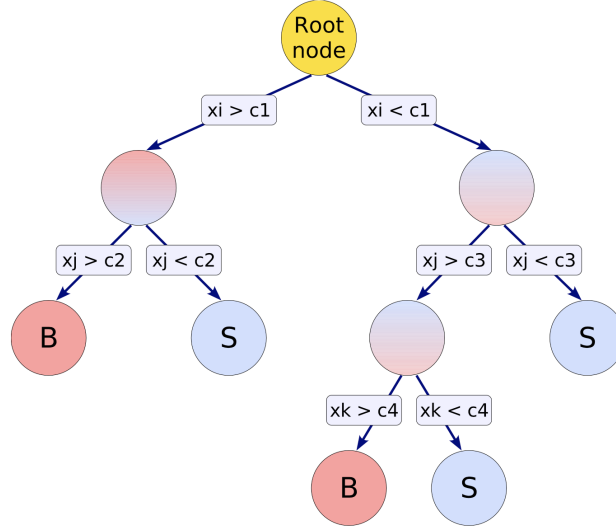


FIGURE 7.10: Schematic view of a decision tree. At each node a variable x_i is used to split events based on a given selection value c_j . The same separation variable might be used in several nodes, but also some features of the dataset could not be used at all. At the end of the decision chain, the leaf is classified as signal or background depending on which category dominates the sample at the leaf. Figure taken from [194].

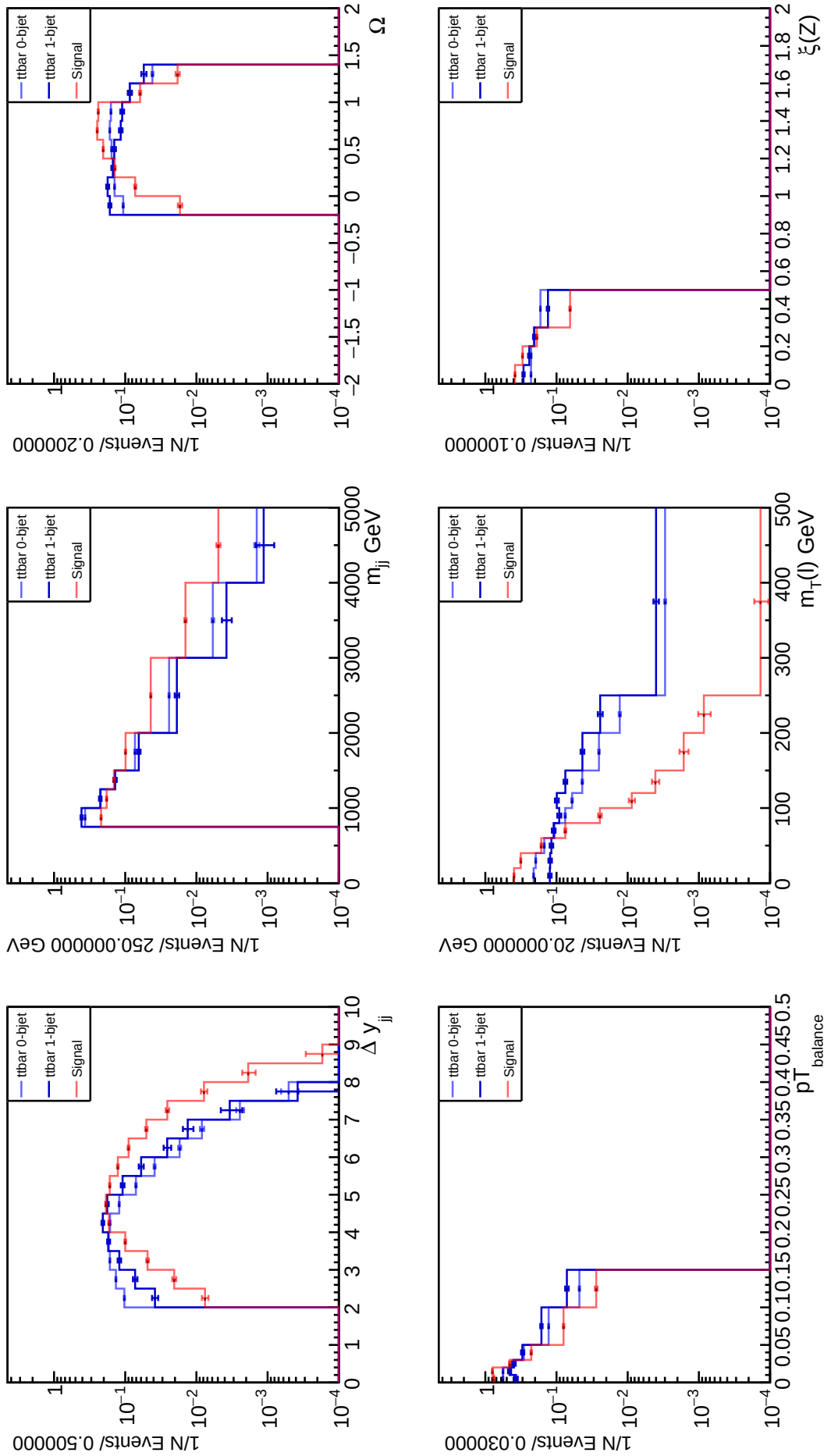
In the boosting process the training data is re-weighted for every additional decision tree that is trained. The final classifier outputs a weighted average of the individual decision trees. The boosting process results in a more robust classification algorithm (i.e, the BDT) with regards to fluctuations in the data, and provides enhanced classification performance as well [192, 195, 196].

7.3.2 VBF BDT

All events included in the BDT training must pass the selection described in Table 7.3 and are required to have $m_{\text{reco}} > 135$ GeV. For the BDT training the *signal* category is defined as the EWjj events simulated with any of the two MC generators available for this process and described in Section 6.1; additionally, the simulated VBF production of a Higgs boson decaying into a tau lepton pair is also considered as signal. For the *background* category all the other physics processes which have MC simulations available are considered. We include the various QCDjj simulation alternatives in the training.

To enhance the number of events in the background sample we also include QCDjj events with $N_{\text{jets}}^{\text{gap}} = 1$ and $t\bar{t}$ events with one b-tagged jet as part of the training — these samples are referred to as *alternative samples*. The comparisons of the BDT input variables between the alternative background samples and the signal samples can be seen in Figure 7.11 and 7.12. The kinematic distributions in these plots show that in general, the alternative and standard background samples have similar kinematic features; and they are different to the signal kinematics. The comparisons of the BDT input variables between the total signal and background samples can be seen in Figure 7.13.

The BDT hyper-parameters are given in Table 7.4. We use cross-validation to assess the performance and overtraining tendency of the BDT. We split our full training dataset into 10 sub-samples and train 10 different BDTs; each training iteration using one sub-sample as the test sample and the remaining nine samples for training. The benchmark metrics derived in our studies are the following:

FIGURE 7.11: Input variables distribution densities used to train the BDT. $tt\bar{t}$ without and with one b-tagged jet compared to the signal sample.

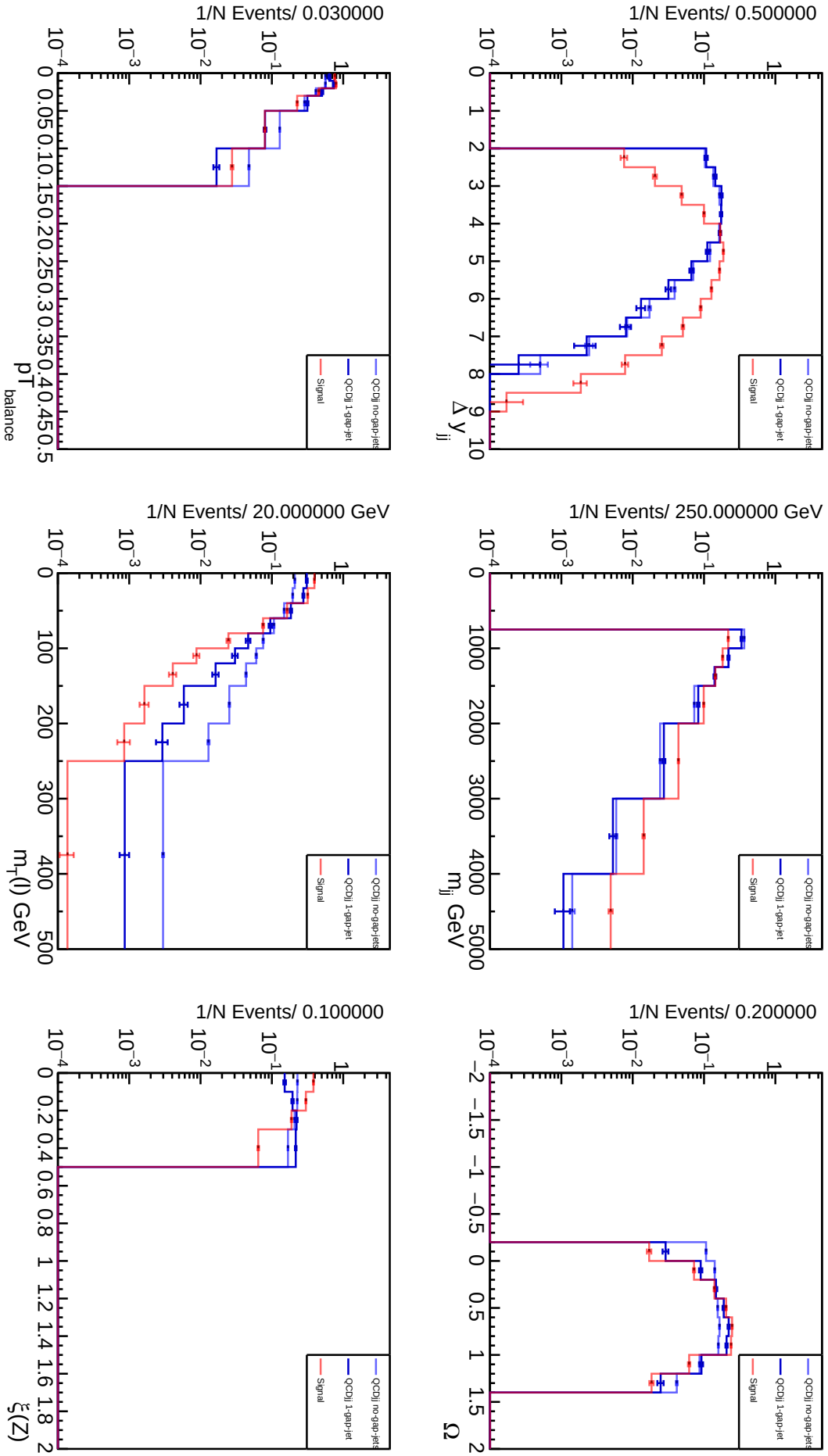


FIGURE 7.12: Input variables distribution densities used to train the BDT. QCDj without and with one jet in the rapidity gap between the tagging jets compared to the signal sample.

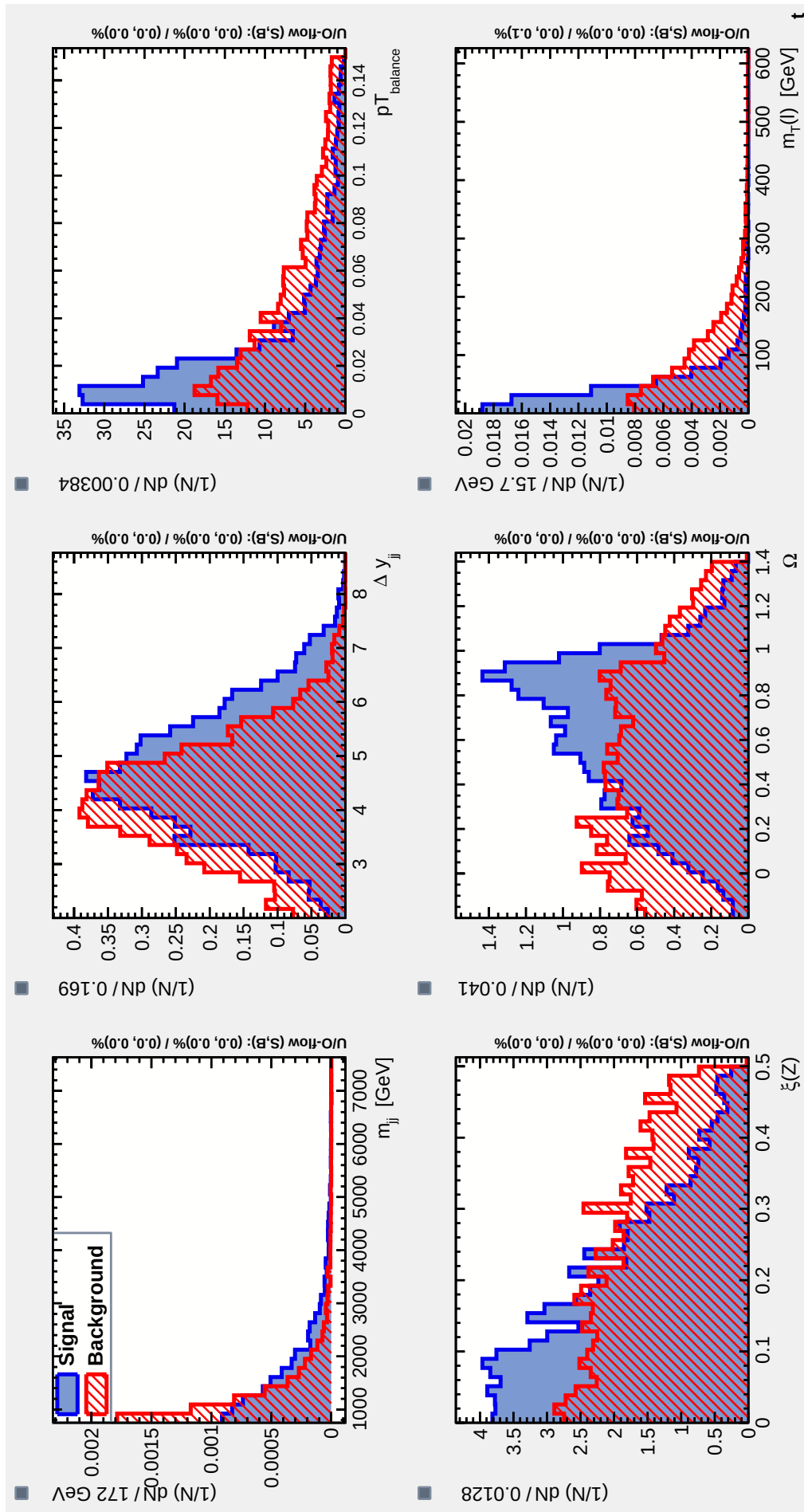


FIGURE 7.13: Input variables used to train the BDT. The distribution of the signal and background samples for each variable is shown.

BDT training hyper-parameters	
Number of trees	125
Maximum depth	2
Separation type	$S/\sqrt{S+B}$
Shrinkage	0.1
Number of variables	2
Number of cuts	80
Minimum node size	3%
Boosting type	Gradient
Bagged sample fraction	0.5

TABLE 7.4: Hyper-parameters used to train the BDT. The meaning of each of the parameters can be found in [194].

BDT Performance	
ROC Integral	0.813 ± 0.034
Separation	0.300 ± 0.061
KS Signal	0.485 ± 0.295
KS Background	0.262 ± 0.326

TABLE 7.5: Benchmark metrics derived using cross-validation with 10 train-test sets.

- **ROC Integral:** the area under the Receiver Operating Characteristic (ROC) curve can be used to measure the performance of a binary classifier. A single point in the ROC curve represents the classifier true positive rate and false positive rate at a given classifier threshold. The area under the ROC curve increases as the classifier performance increases.
- **KS test:** the Kolmogorov-Smirnov (KS) test can be used to compare the compatibility of two probability distributions. In the context of training and testing the BDT algorithm, it can be used to assess the degree to which the responses of the test and training samples to the BDT algorithm are compatible. A high KS test score suggests that no significant overtraining is observed for the classification algorithm being evaluated.
- **Separation:** this metric assesses the overlap between the background and signal probability distributions for the classifier score. The separation is zero for identical signal and background shapes, and it is equal to one for distributions with no overlap.

The metrics obtained for the BDT algorithm are shown in Table 7.5. The uncertainties reported correspond to the standard deviation derived from the results of the 10 different training-test sets. From these results we can conclude that the BDT is able to discriminate the EWjj and Higgs VBF processes against the backgrounds, and that overtraining is not a problem.

The performance of the BDT and the degree to which the MC describes the data are tested at the Z-peak in the EWjj signal region and in the QCDjj control region — the BDT score distributions can be seen in Figure 7.14. This is a sample that the BDT has never seen in the training. Discrimination power against the QCDjj process can be observed and a good BDT score description of the data is provided by the MC. In the next section we test the BDT performance in a region with a higher $m(\tau_{\text{had}}, \tau_{\text{lep}})$ value.

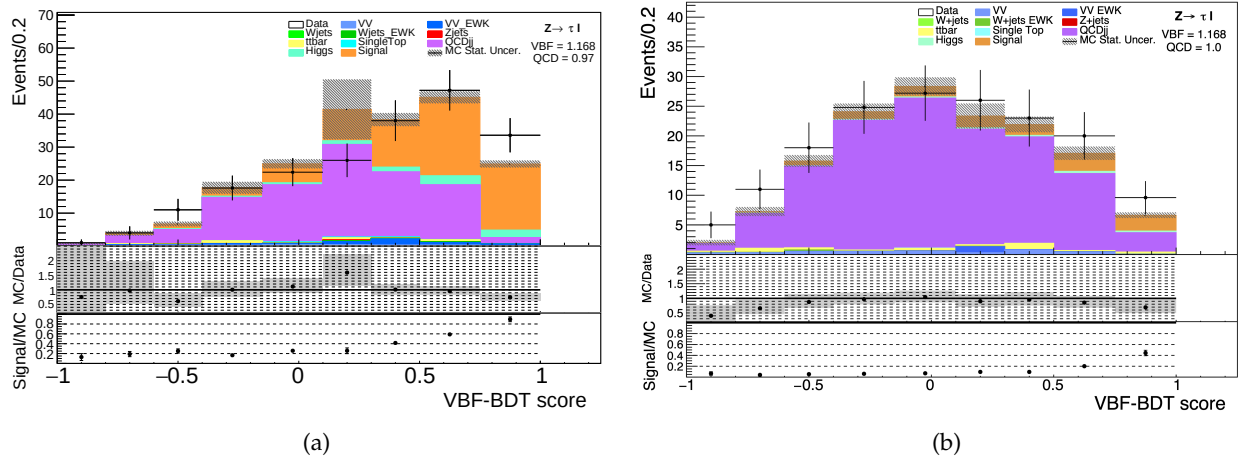


FIGURE 7.14: BDT score distribution in the EWjj signal region (a) and the QCDjj control region (b) in $Z \rightarrow \tau_{\text{had}} \tau_{\text{lep}}$ events at the Z-peak.

7.4 Higgs control region

To further test the performance of the BDT defined in the previous section we define a *Higgs* control region where,

$$\text{Higgs Region : } 116 \leq m_{\text{reco}}(\tau_{\text{had}}, \tau_{\text{lep}}) < 160 \text{ GeV.} \quad (7.2)$$

This region is highly populated by events coming from the VBF production of a Higgs boson. Some kinematic distributions after applying the cut-based selection, described in Table 7.3, to this region can be seen in Figure 7.15 — in this section, the purity shown in the plots includes the Higgs and EWjj contributions as signal.

The performance of the BDT algorithm is shown in Figure 7.16. The BDT can discriminate the EWjj and VBF-Higgs processes from the backgrounds since the majority of the signal events are grouped on the right of the BDT distribution.

Motivated by the good performance of the BDT, we test an alternative approach for selecting the Higgs region. In the new method events are required to have a BDT-Score > 0.3 , the m_{jj} cut is relaxed to 750 GeV and all the other requirements described in Table 7.3 are applied. The kinematic distributions of the selected sample are shown in Figure 7.17 and the corresponding BDT distribution is shown in Figure 7.18.

The purity of the selected sample is improved by using the BDT-based approach. This can be seen by comparing the first bin of the $N_{\text{jets}}^{\text{gap}}$ distributions shown in Figures 7.15f and 7.17f. Additionally, after applying the BDT cut, the signal-to-MC ratio is much more flat in the variables used as input in the BDT such as m_{jj} , p_{Tbalance} , Ω and $\xi(Z)$. This is an indication that the BDT is exploiting the input variables efficiently.

The Higgs control region offers a testing ground to assess various aspects of the MVA-based approach: the performance of the BDT, the ability of the MC to describe the BDT output and the improvement of the discrimination power against the background processes at higher di-lepton invariant mass by applying the MVA-based approach.

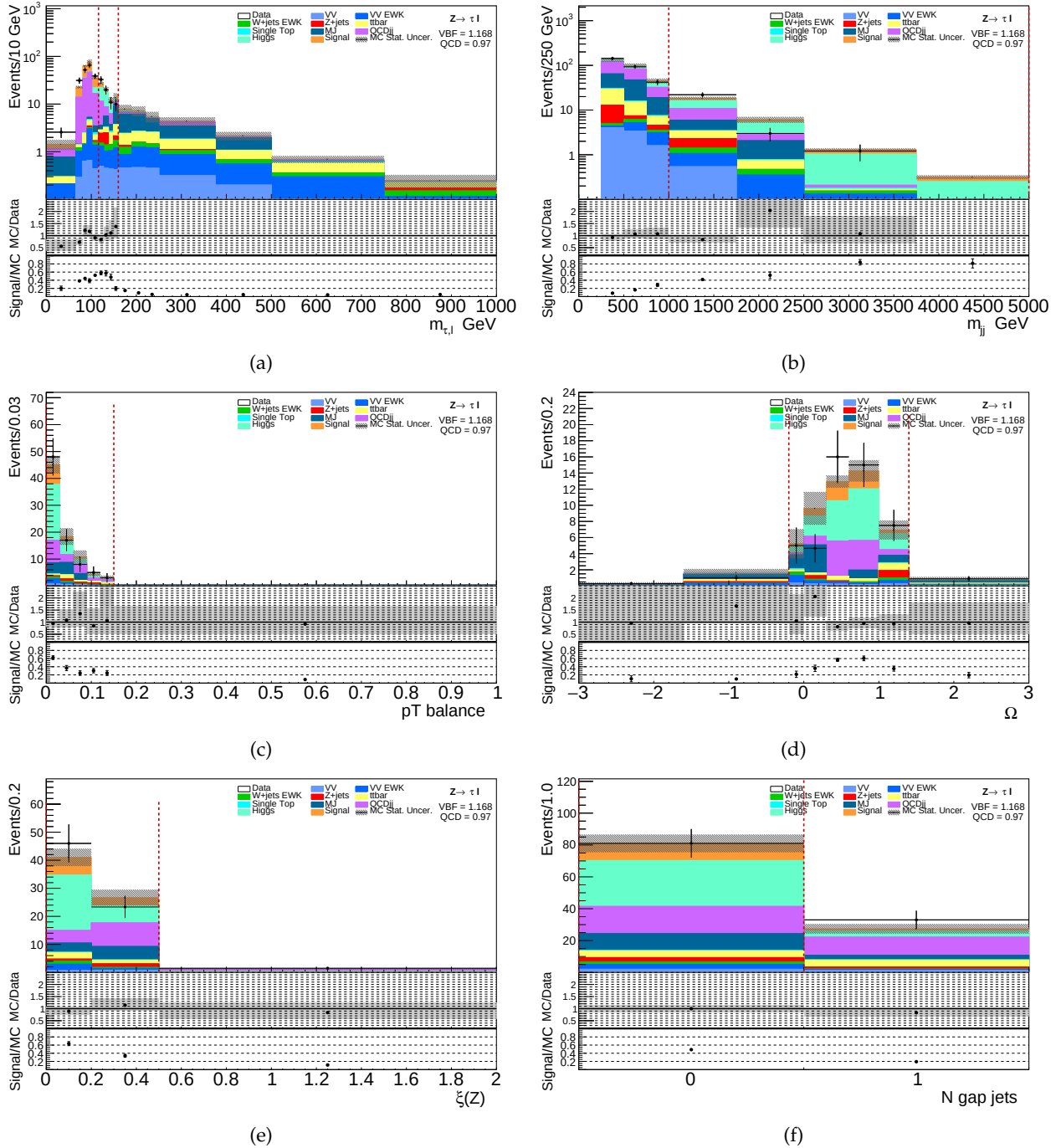


FIGURE 7.15: Data-to-MC comparisons for various kinematic variables in the Higgs control region. This is a sample of $\tau_{had}\tau_{lep}$ events passing the selection described in Table 7.3.

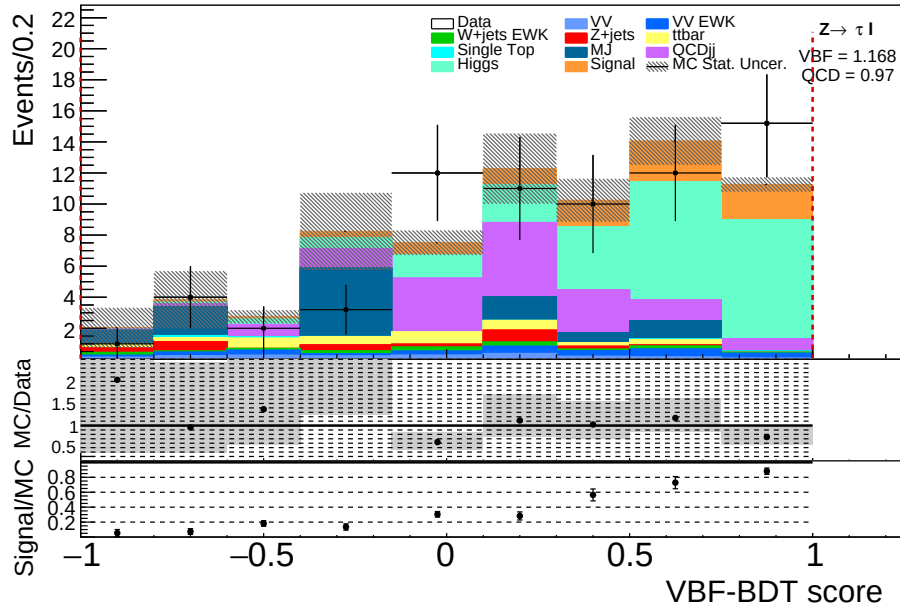


FIGURE 7.16: BDT distribution after applying the selection requirements described in Table 7.3 and the mass selection presented in Equation 7.2.

7.5 High-mass blinded results

Finally, in this section we present the partially unblinded results in the region where the $Z \rightarrow \tau_{\text{had}} \tau_{\text{lep}}$ events have $m_{\text{reco}} \geq 160$ GeV. We describe the new analysis strategy which includes additional kinematic requirements and a requirement on the score of the BDT defined in Section 7.3.

The collinear approximation used to estimate the mass of the di-tau events has one limitation: when the taus are close to being back-to-back in the transverse plane and the MET vector is pointing in between the two taus, we can overestimate the momentum of the neutrinos — this situation is represented in Figure 7.19. If the neutrinos' momentum is overestimated, the reconstructed mass is as well. We can prevent this from happening by removing events with a high-ratio of reconstructed to visible mass ($m_{\text{vis}} = m(\tau, l)$). Our final selection only includes events with $\frac{m_{\text{reco}}}{m_{\text{vis}}} < 4.0$.

The nature of the tau decays can be exploited by noticing that the τ_{had} candidate should have on average higher momentum than the lepton produced in the τ_{lep} decay. This happens since the latter decay produces two neutrinos in contrast to the hadronic decay which only produces one neutrino. We define the transverse momentum asymmetry variable as:

$$p_{\text{Tasymmetry}} = \frac{p_{\text{T}}(\tau) - p_{\text{T}}(l)}{p_{\text{T}}(\tau) + p_{\text{T}}(l)}, \quad (7.3)$$

where $l = e$ or μ . We select events with $p_{\text{Tasymmetry}} > -0.3$.

Additionally, as discussed in Section 7.2 the MJ and W+jets background is very important at high-mass. Two variables that offer good discrimination against the MJ backgrounds are the estimated momenta of the neutrinos produced in the tau decays. We require our selected sample to have $p_{\text{T}}(\nu_l) \geq 30$ GeV and $p_{\text{T}}(\nu_\tau) \geq 15$ GeV¹.

¹ $p_{\text{T}}(\nu_l)$ is the sum of the momenta of the two neutrinos produced in the leptonic tau decay.

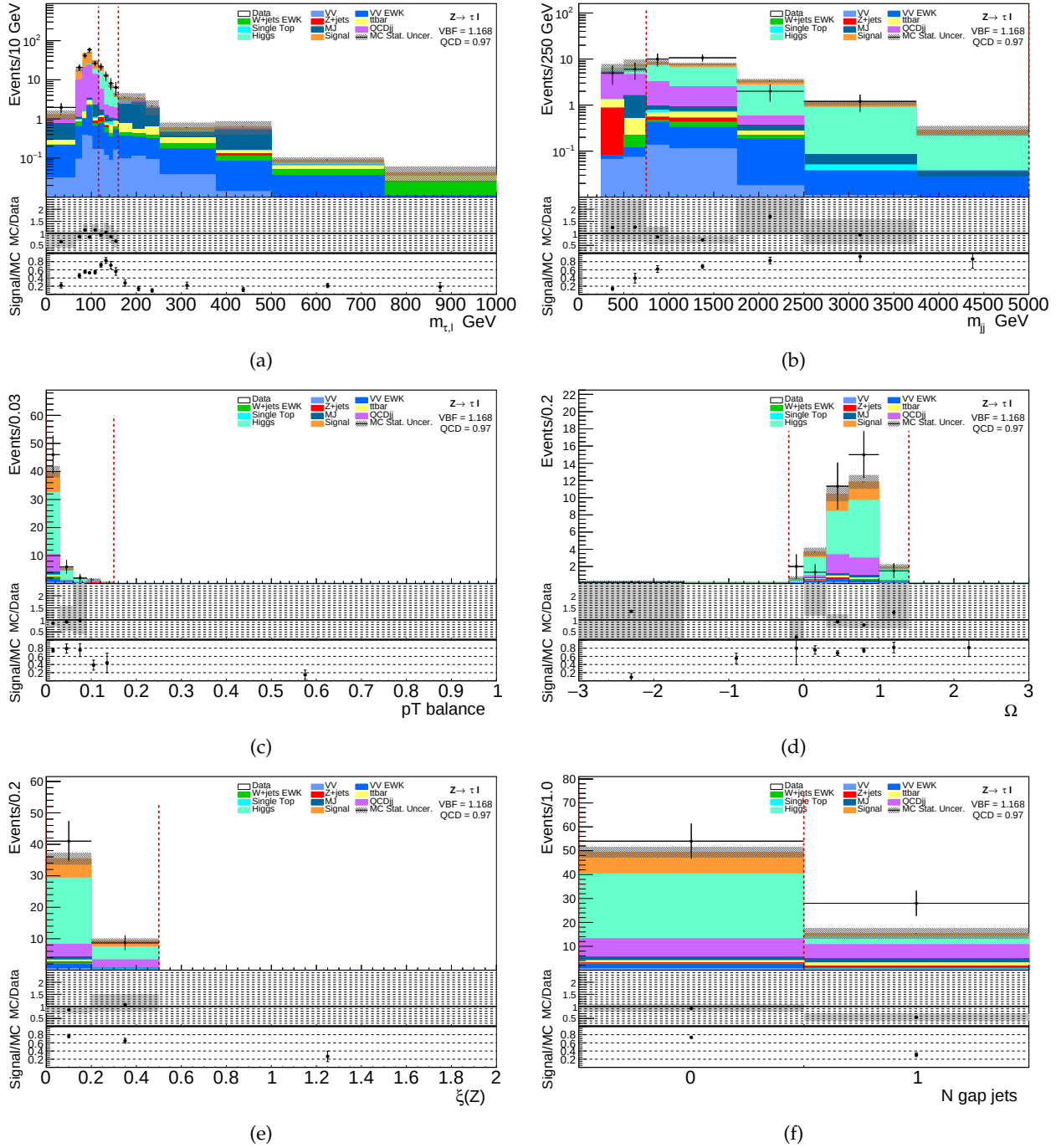


FIGURE 7.17: Data-to-MC comparisons for various kinematic variables in the Higgs control region after applying the BDT cut and relaxing the m_{jj} requirement.

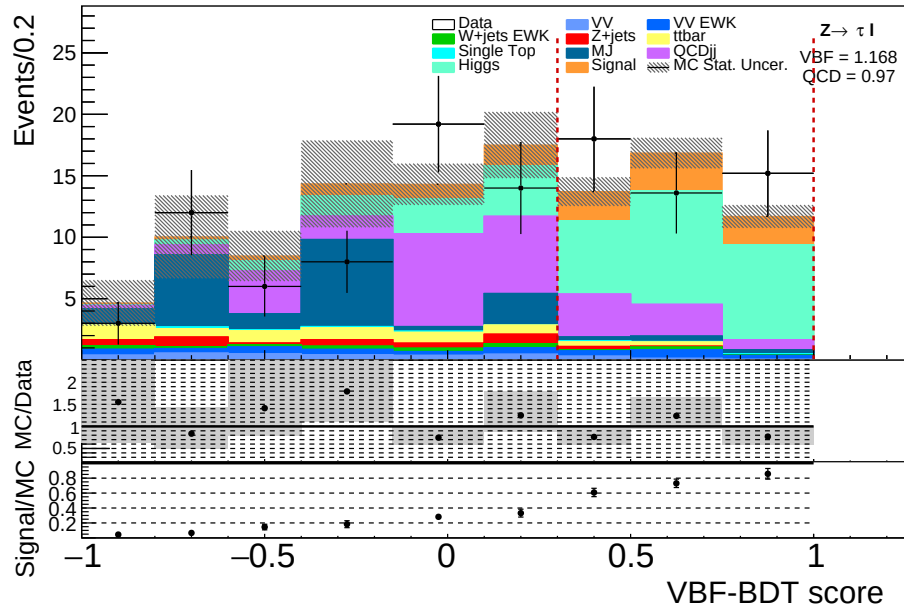


FIGURE 7.18: BDT distribution for Higgs region events with $m_{jj} > 750$ GeV. The non-VBF backgrounds proportion increases as the BDT score decreases.

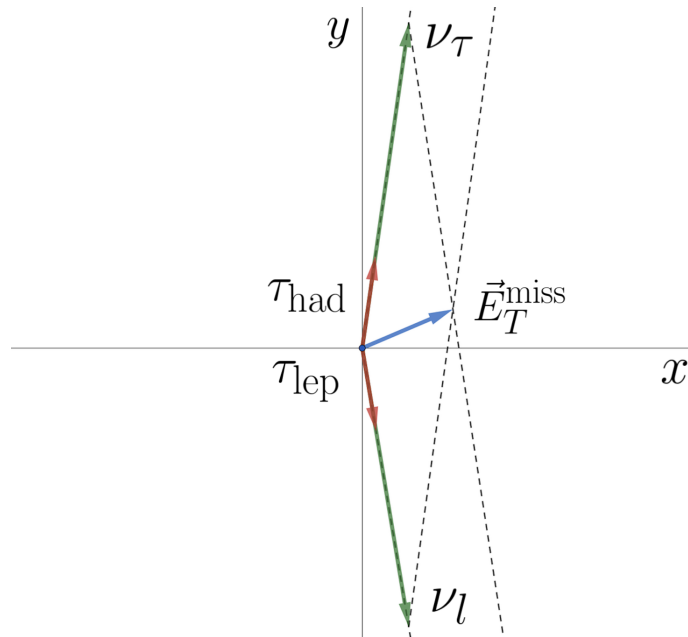


FIGURE 7.19: Topology of an event with a potential overestimated reconstructed mass.

Finally, we select events with a BDT score > 0.3 . The final selection for the high-mass $Z \rightarrow \tau_{\text{had}} \tau_{\text{lep}}$ events is detailed in Table 7.6. The distributions of $p_T(\nu_\tau)$, $p_T(\nu_l)$, $p_{T\text{asymmetry}}$, $\frac{m_{\text{reco}}}{m_{\text{vis}}}$ and BDT score can be seen from Figure 7.20 to 7.22. The bins with less than ten percent signal purity have been unblinded. In the final selected sample the estimate of the MJ and W+jets background contribution is consistent with zero. The uncertainty of this estimate is distributed in the signal region bins by following the predicted density of MC background events.

MVA-based selection	
Baseline	Table 7.3
High-mass	$m_{\text{reco}} \geq 160 \text{ GeV}$
	$p_T(\nu_\tau) \geq 15 \text{ GeV}$
	$p_T(\nu_l) \geq 30 \text{ GeV}$
	$\frac{m_{\text{reco}}}{m_{\text{vis}}} < 4.0$
	$p_{T\text{asymmetry}} > -0.3$
	BDT score > 0.3

TABLE 7.6: MVA-based analysis selection requirements for the high-mass region.

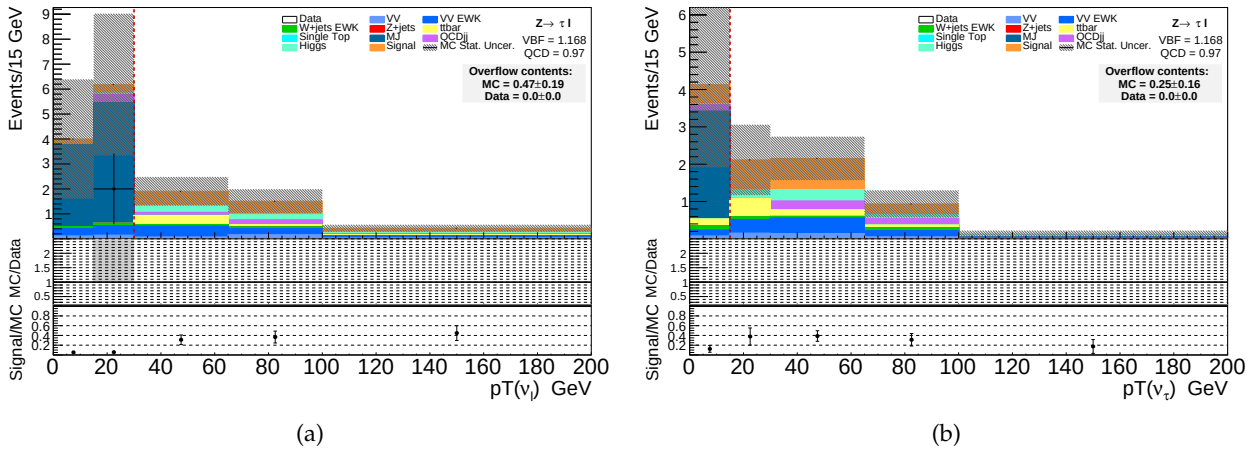


FIGURE 7.20: Estimated momentum of the ν_τ and ν_l in the high-mass sample. The selection requirements shown in the plots are targeted to suppress the MJ backgrounds. Apart from the selection cut being displayed, all the selection requirements presented in Table 7.6 have been applied.

The value of the $p_T(\nu_l)$ and $p_T(\nu_\tau)$ selection requirements is validated in an independent sample enhanced in MJ contributions. This sample is populated with events that pass the loose but not medium tauID criterion or have a non-isolated light-lepton or both. The neutrino momentum distributions for this sample are shown in Figure 7.23. We can see that in the $p_T(\nu_\tau)$ distribution the MJ background is predominantly located below the cut value; and although the MJ predicted shape is flatter in the $p_T(\nu_l)$ distribution the QCDjj and EWjj processes are predominantly located above the cut line. Additional kinematic distributions for this sample are shown in Appendix B.5.

The kinematic variables used as input in the BDT training are shown in Figure 7.24. The signal purity shows a flat distribution for the final selected sample — this is sign that the BDT is efficiently exploiting the discrimination power of the input variables. Figure 7.25 shows additional distributions: Figure 7.25e shows that the predicted BDT score distribution reasonably agrees with

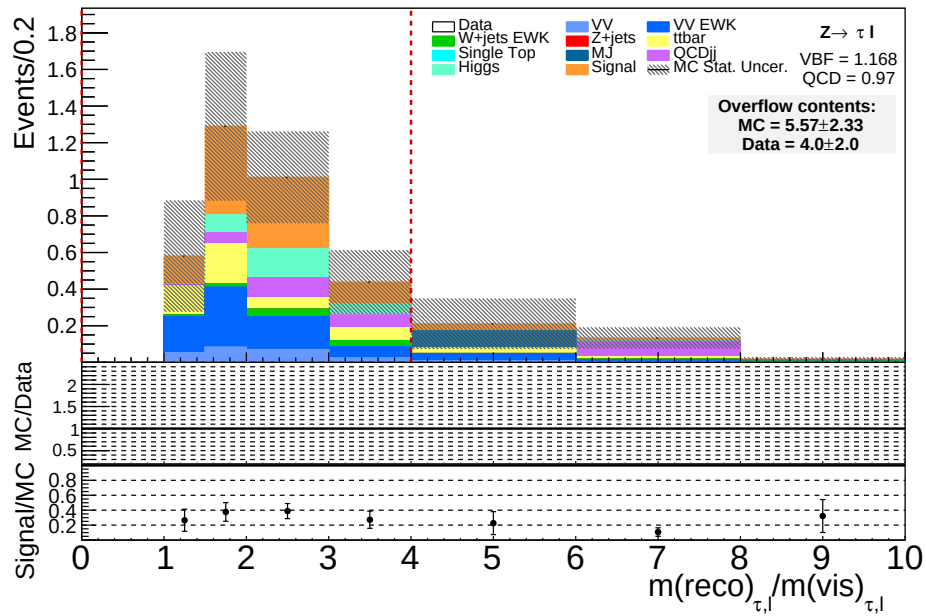


FIGURE 7.21: Distribution of $\frac{m_{\text{reco}}}{m_{\text{vis}}}$. Apart from the selection cut being displayed, all the selection requirements presented in Table 7.6 have been applied.

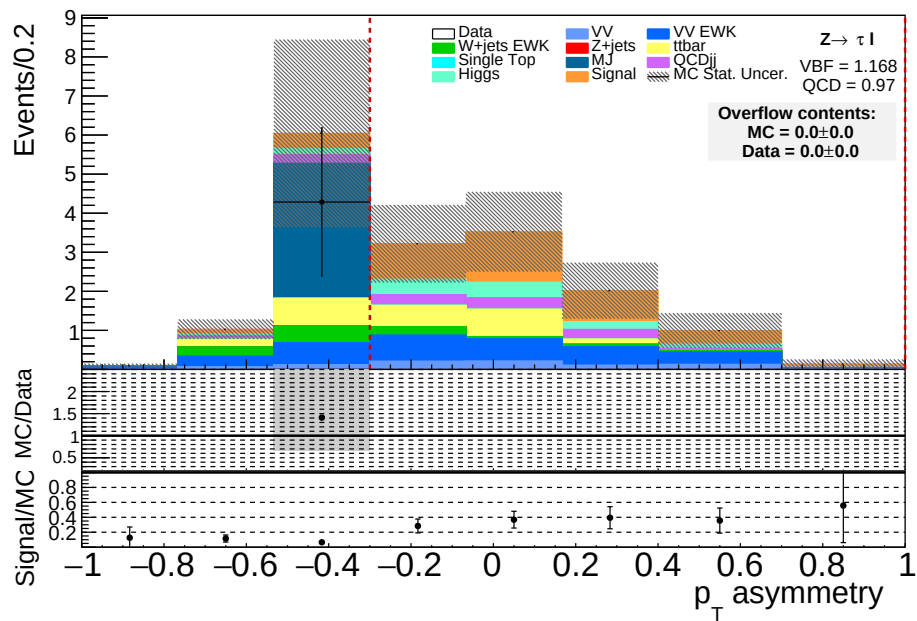


FIGURE 7.22: Distribution of $p_{T\text{asymmetry}}$ showing that signal events tend to have larger values of $p_T(\tau)$. Apart from the selection cut being displayed, all the selection requirements presented in Table 7.6 have been applied.

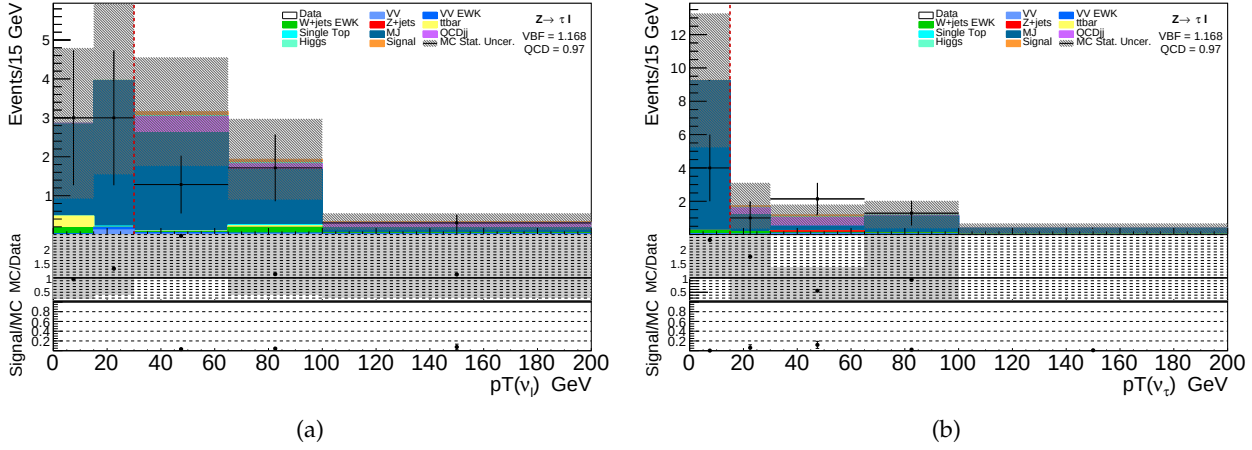


FIGURE 7.23: Estimated momentum of the ν_τ and ν_l in the high-mass sample enhanced in MJ backgrounds.

data in the unblinded bins. Figure 7.25d shows the number of jets in the gap distribution where the expected composition of our final sample can be seen.

When comparing Figure 7.25d and Figure 7.6c we see that the MVA-based approach improves the signal purity when compared to the cut-based analysis.

As an additional test of the background modelling and the BDT performance, we select the events that passed all the selection requirements detailed in Table 7.3 and that fail any of the high-mass dedicated requirements described in Table 7.6. The distributions of the key analysis variables are presented from Figure 7.26 to Figure 7.28 — we observe good modelling in all the distributions, apart from some of the bins in the number of b-tagged jets distribution.

Looking at the MC truth-level information of the EWjj sample we can measure the proportion of low-mass events that leak into the high-mass selection. Figure 7.29 shows the true invariant mass of the di-tau system — in this context, tau refers to the particle directly produced in the Z boson decay. The proportion of events passing the high-mass requirements with $m_{\text{true}}(\tau, \tau) < 130$ GeV in the EWjj-Sherpa (PoPy) sample is 35 (28)%.

For high-mass events ($m_{\text{true}}(\tau, \tau) > 130$ GeV), we can set an expected limit on the total SM cross-section for the EWjj process ($\sigma_{\text{SM}}(\text{EWjj})$). The total expected number of events in the signal region is $N_{\text{Total}} = 11.46 \pm 2.04$ with the EWjj predicted yield being $N_{\text{EWjj}} = 3.70 \pm 0.48$ — including the 35% contamination from low-mass EWjj events; the reported uncertainties include the statistical and the systematic components added in quadrature. By performing 30000 pseudo-experiments, also known as toy experiments, sampling the number of expected events from a Gaussian distribution to account for systematic uncertainties; followed by sampling the number of expected observed events from a Poisson distribution we obtain the results shown in Figure 7.30. The 95% confidence limit (C.L.) on the number of expected observed events is 19. This allows us to set a limit of

$$\sigma_{\text{EWjj Total Expected}}(95\% \text{ C.L.}) = 4.14 \times \sigma_{\text{SM}}(\text{EWjj}). \quad (7.4)$$

This value is obtained using EWjj-Sherpa MC. If we repeat the same calculation with the EWjj-PowHeg+Pythia8 yields we obtain an expected limit of $4.01 \times \sigma_{\text{SM}}(\text{EWjj})$.

Additionally, we can evaluate the performance of the BDT algorithm as a function of $m_{\text{true}}(\tau, \tau)$

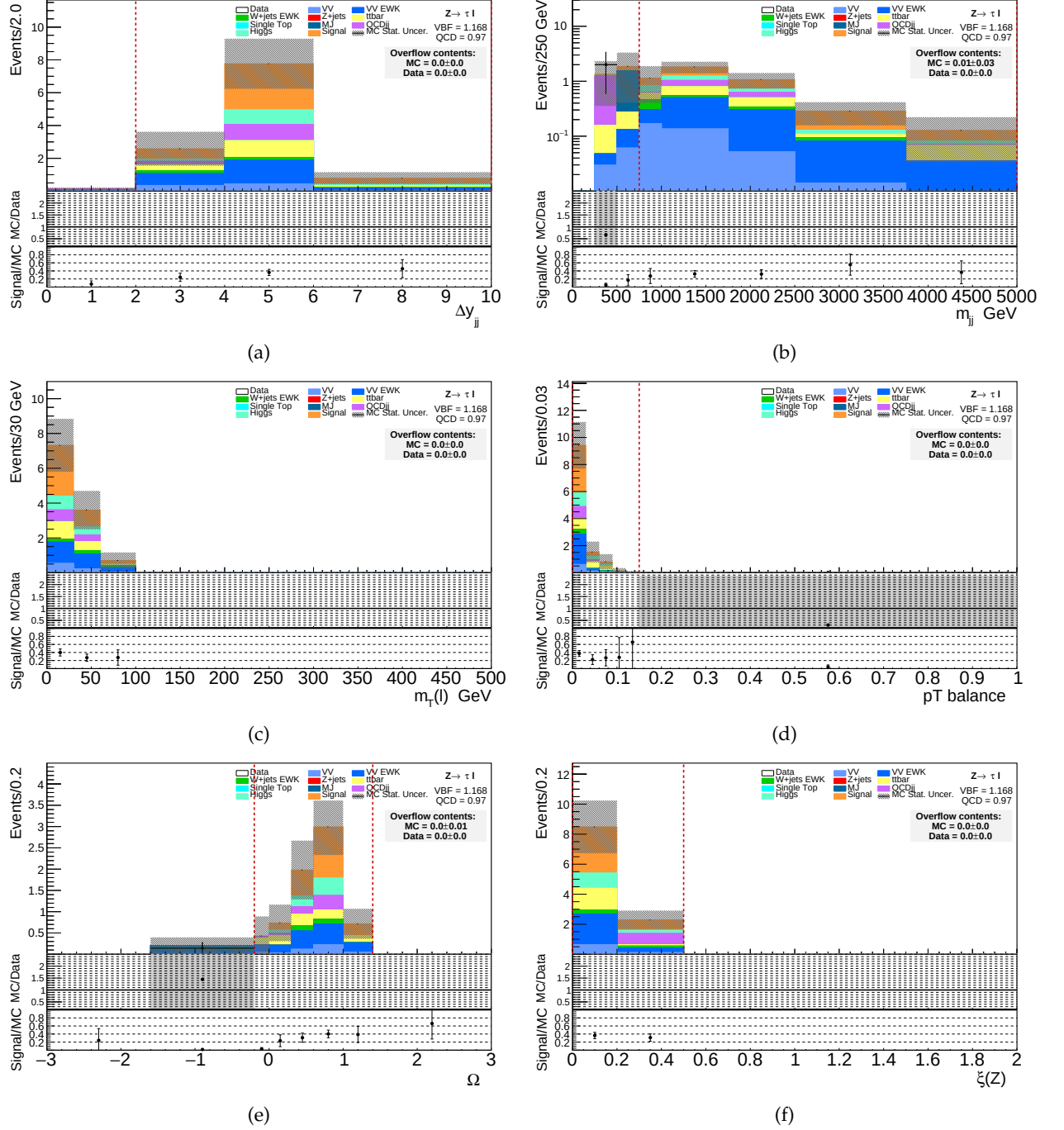


FIGURE 7.24: Data-MC comparisons for various kinematic variables in the $Z \rightarrow \tau_{\text{had}} \tau_{\text{lep}}$ high-mass region after applying the BDT cut and relaxing the m_{jj} requirement. In all the the distribution bins that are part of the signal region or close to it with an expected signal purity above 10% the data are blinded.

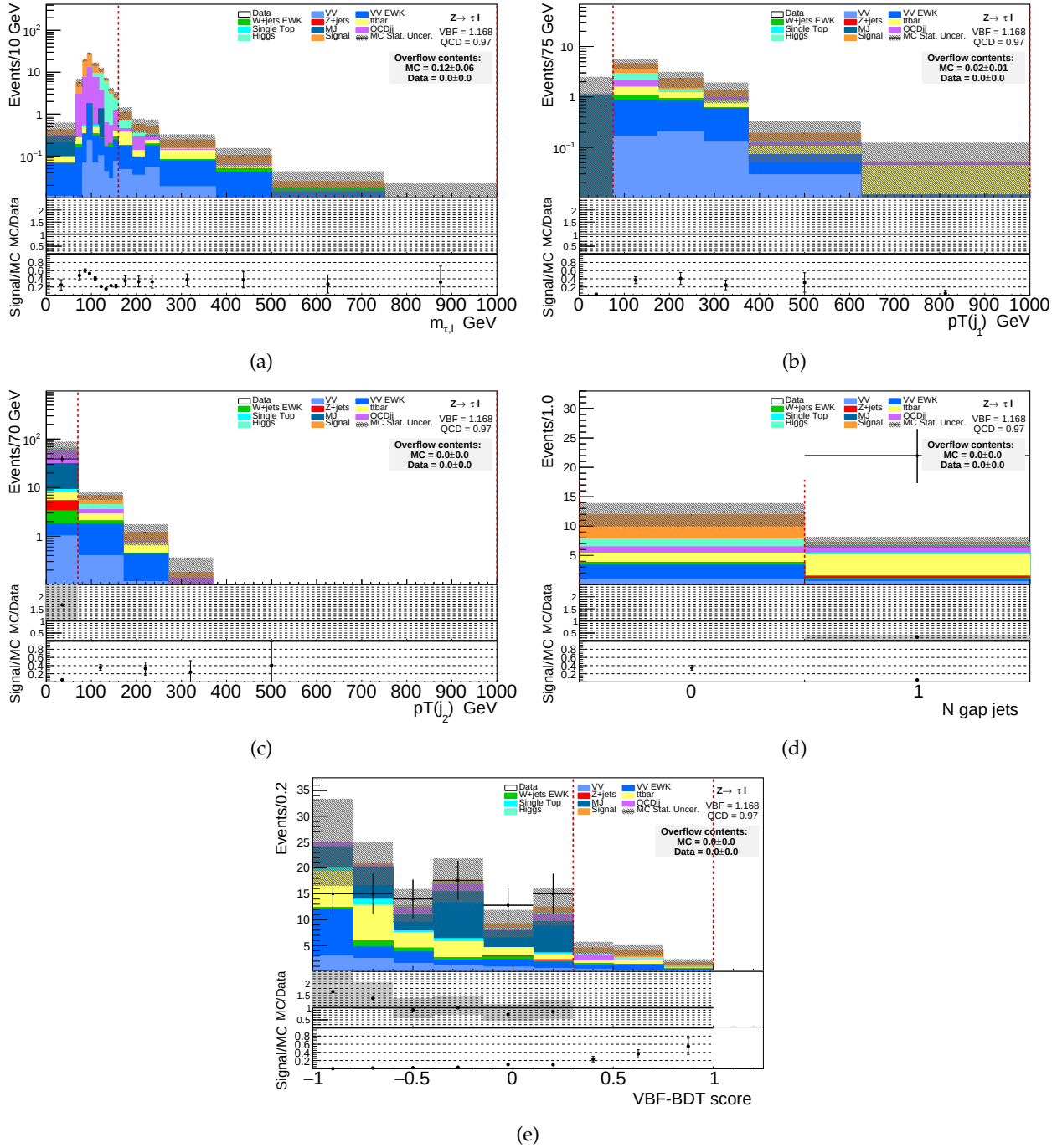


FIGURE 7.25: Data-MC comparisons for various kinematic variables in the $Z \rightarrow \tau_{\text{had}} \tau_{\text{lep}}$ high-mass region after applying the BDT cut and relaxing the m_{jj} requirement. In all the the distribution bins that are part of the signal region or close to it with an expected signal purity above 10% the data are blinded.

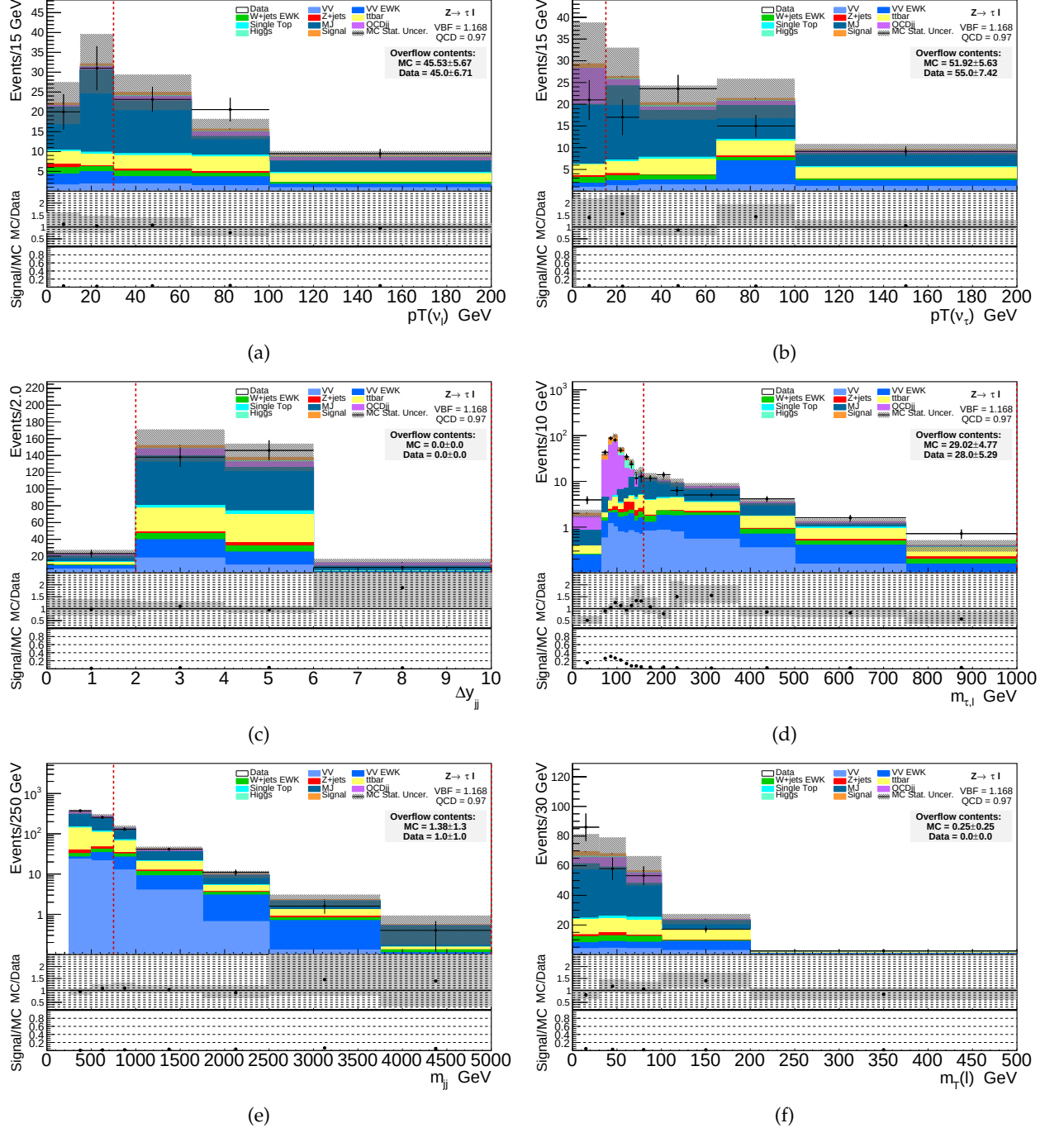


FIGURE 7.26: Data-MC comparisons for various kinematic variables in the $Z \rightarrow \tau_{\text{had}} \tau_{\text{lep}}$ high-mass for events that pass the selection requirements defined in Table 7.3 and fail any of the high-mass dedicated criteria presented in Table 7.6.

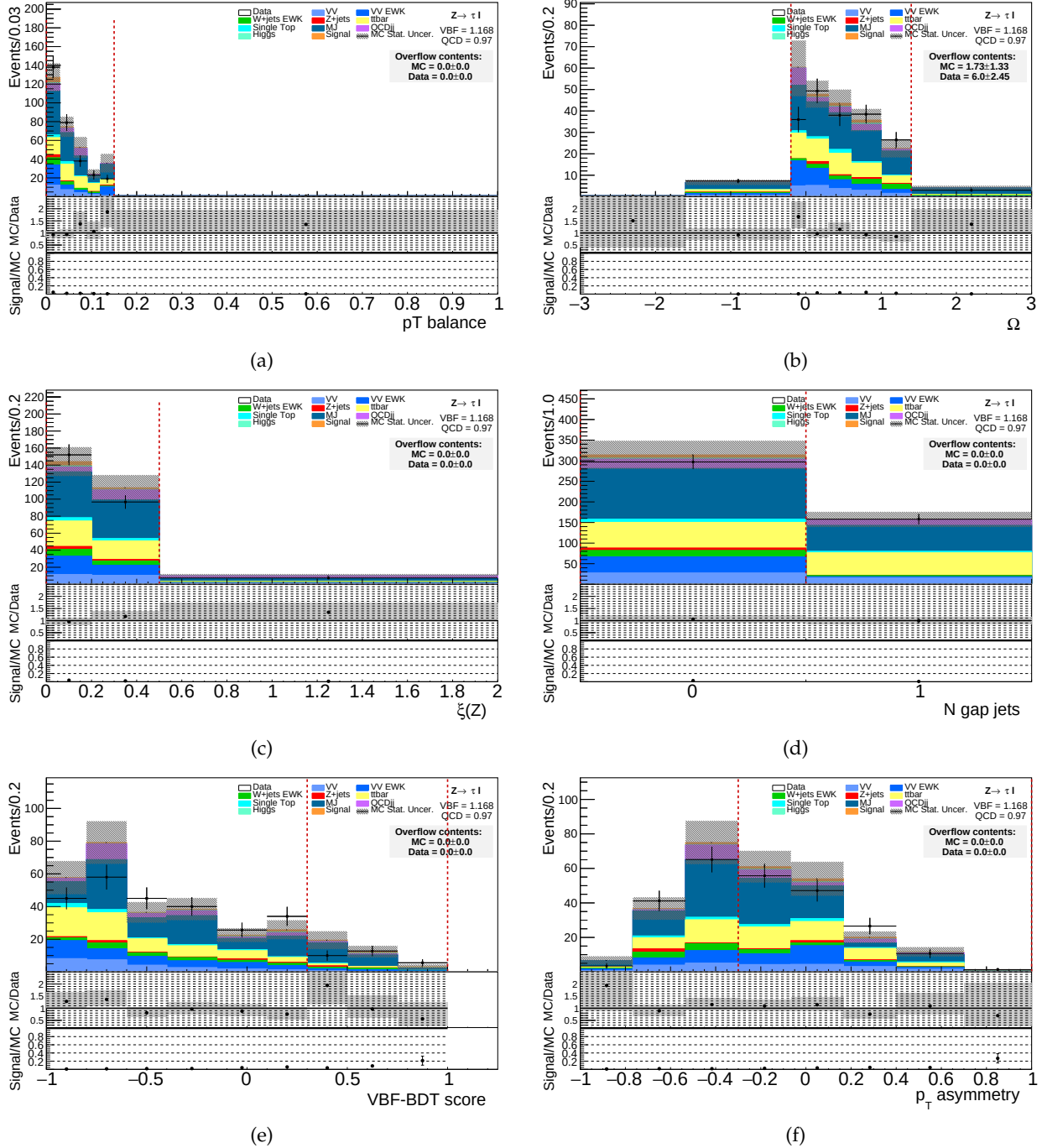


FIGURE 7.27: Data-MC comparisons for various kinematic variables in the $Z \rightarrow \tau_{\text{had}} \tau_{\text{lep}}$ high-mass for events that pass the selection requirements defined in Table 7.3 and fail any of the high-mass dedicated criteria presented in Table 7.6.

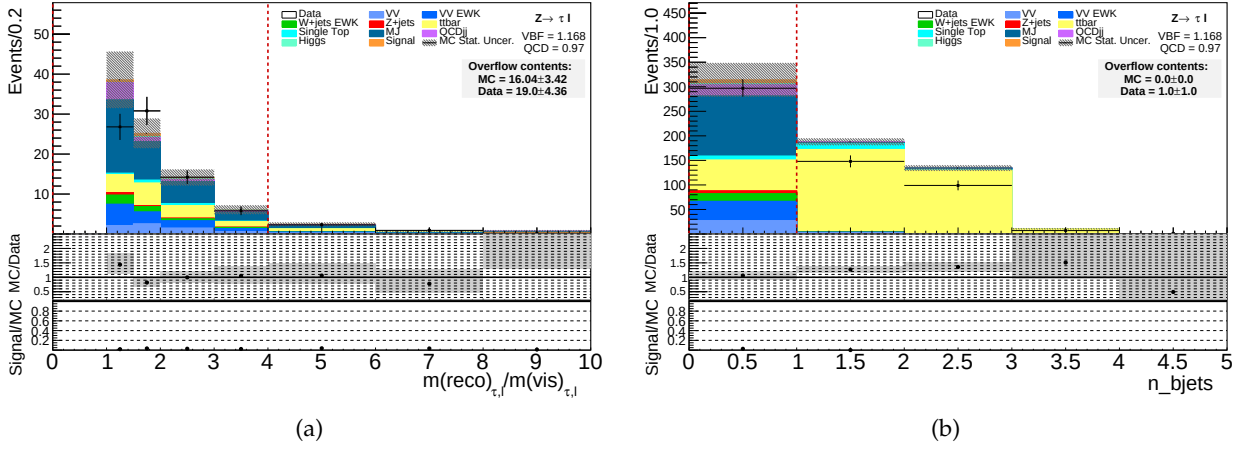


FIGURE 7.28: Data-MC comparisons for the BDT score and the Δy_{jj} distributions in the $Z \rightarrow \tau_{\text{had}} \tau_{\text{lep}}$ high-mass for events that pass the selection requirements defined in Table 7.3 and fail any of the high-mass dedicated criteria presented in Table 7.6.

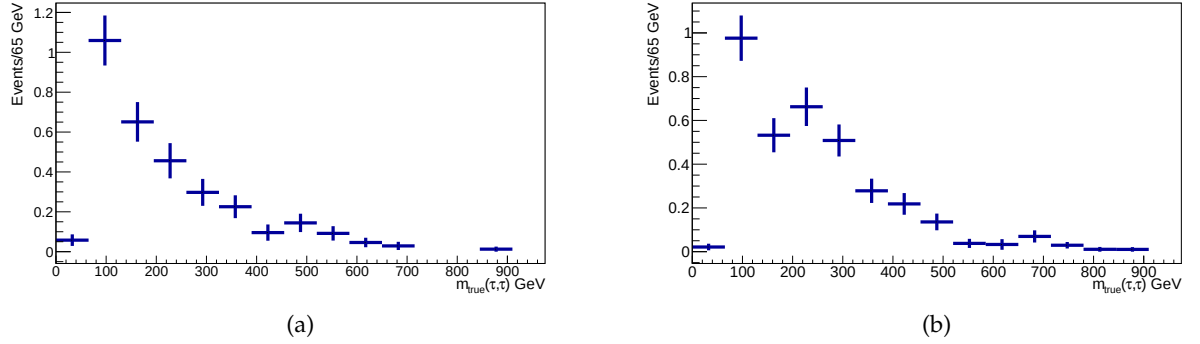


FIGURE 7.29: Distribution of $m_{\text{true}}(\tau, \tau)$ for final selected high-mass events in (a) EWjj-Sherpa and (b) EWjj-PoPy. The distributions are not normalised by the corresponding EWjj signal strength.

Expected number of events density (toy experiments)

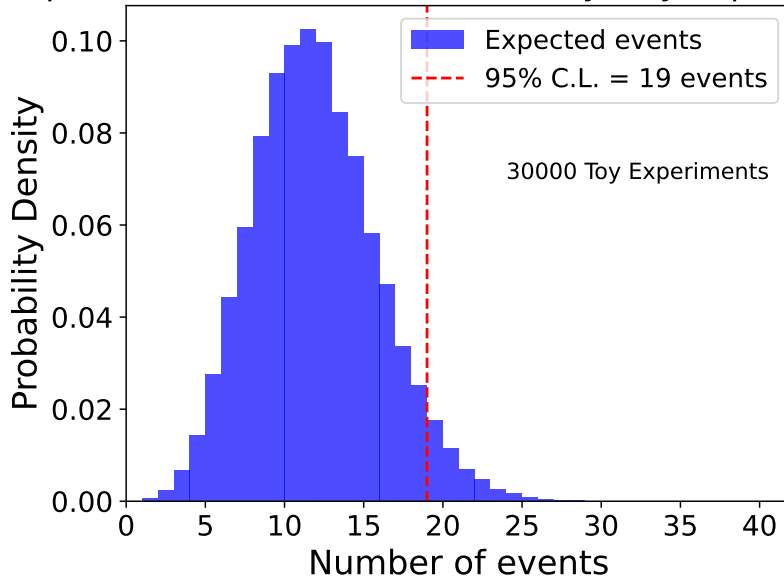


FIGURE 7.30: Probability density for the total expected number of events observed in the SR with 30000 toy experiments. The 95% C.L. is shown with the vertical red dashed line. This plot was generated using the total yields predicted by EWjj-SHERPA MC.

in our signal samples (EWjj + VBF Higgs). Figure 7.31 shows the efficiency of the BDT ($\epsilon_{\text{VBF-BDT}}$) calculated as:

$$\epsilon_{\text{VBF-BDT}} = \frac{\text{Number of events passing the kinematic requirements + BDT cut}}{\text{Number of events passing the kinematic requirements}}, \quad (7.5)$$

where the kinematic requirements refers to the selection presented in Table 6.2 — apart from the reconstructed mass, which now is required to pass $m_{\text{reco}} \geq 66$ GeV. We can see how the BDT performance is degraded as the true mass increases. This is not ideal because we want to retain high BDT efficiency at high-mass in order to have more sensitivity to heavy resonances. After investigating the reason for the efficiency drop, we found that the training variable responsible for this behaviour is the transverse mass of the light lepton ($m_T(l)$). If we remove $m_T(l)$ from the input variables used in the BDT training, the resulting efficiency can be seen in Figure 7.32 — we see how the BDT response is flatter than in the previous case. The $m_T(l)$ has a high-impact in the efficiency of the BDT because $m_T(l)$ extends to larger values as $m_{\text{true}}(\tau, \tau)$ increases, as can be seen in Figure 7.33. This plot shows that if a cut in $m_T(l)$ is used by the BDT to discriminate between the background and signal events, it will remove more high-mass signal events compared to low-mass ones.

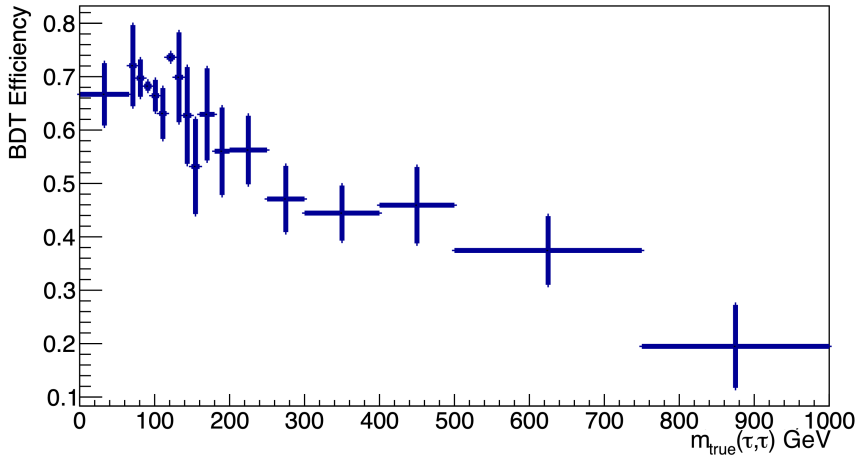


FIGURE 7.31: BDT efficiency, defined in Equation 7.5, as a function of $m_{\text{true}}(\tau, \tau)$. The $m_T(l)$ variable is included in the BDT training.

However, when $m_T(l)$ is removed from the BDT, we observe that the performance of the BDT is degraded. As a future outlook, we will investigate if we can define a training variable that takes into account the transverse mass of the light lepton and is less sensitive to the true mass of the signal events.

7.6 Conclusions

Our results in the $Z \rightarrow ll$ events show that the EWjj and QCDjj MC samples describe well the data in the high-mass region — using the corrections derived at the Z-peak. However, by following the same analysis prescription in the $Z \rightarrow \tau\tau$ events the selected sample at high mass is dominated by backgrounds such as $t\bar{t}$, multi-jet and VV processes.

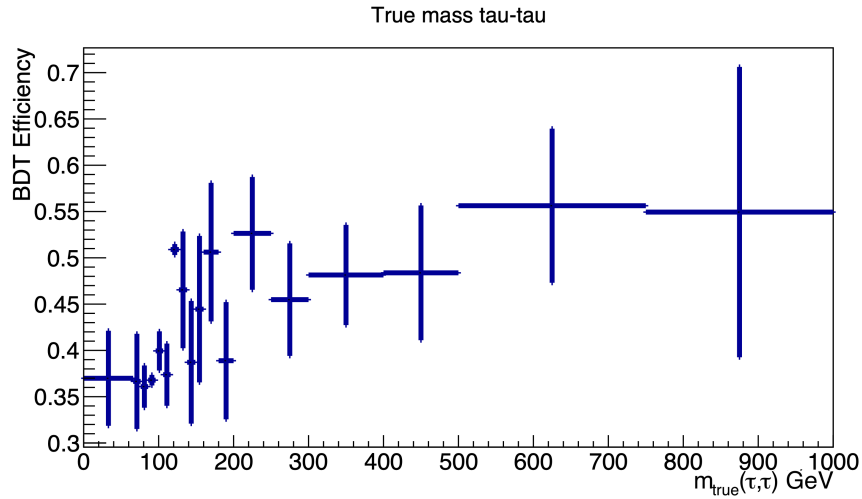


FIGURE 7.32: BDT efficiency, defined in Equation 7.5, as a function of $m_{\text{true}}(\tau, \tau)$. The $m_T(l)$ variable is not included in the BDT training.

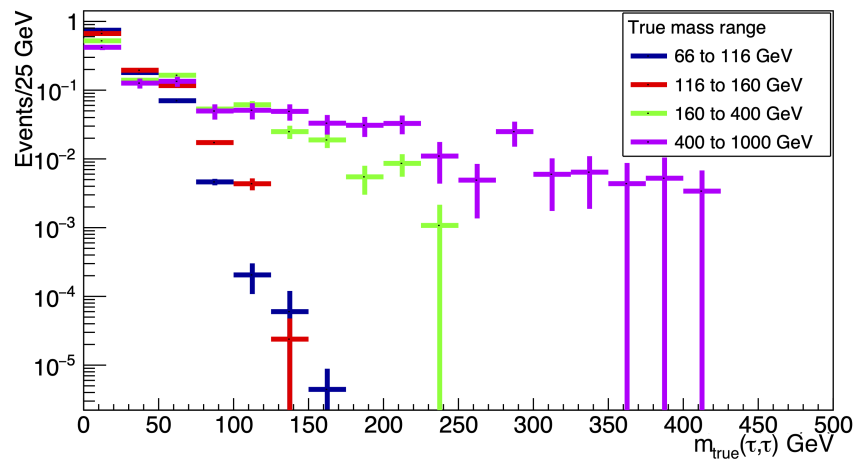


FIGURE 7.33: The $m_T(l)$ variable density for different ranges of $m_{\text{true}}(\tau, \tau)$.

We change the analysis strategy by introducing a BDT algorithm and a set of additional selection requirements to perform the high-mass selection. The performance of the BDT is tested at the Z-peak and in the Higgs control regions. Our results show good discrimination power and Data-to-MC agreement in these regions.

Finally, we present the partially unblinded results for the $Z \rightarrow \tau_{\text{had}} \tau_{\text{lep}}$ events using the MVA-analysis approach and we show how the purity of the selected sample is improved. As plans for the future, the $Z \rightarrow \tau_{\text{had}} \tau_{\text{had}}$ final state can be included to improve the number of candidate events at high-mass. We will also investigate the possibility of training a BDT that keeps a flatter performance as a function of the di-tau mass.

The high-mass signal region will be unblinded following the completion of ATLAS internal review of the analysis procedures.

Chapter 8

Conclusions

This thesis presents a measurement of the performance of the tau identification algorithm and an analysis of the production of di-leptons in the vector boson fusion topology.

The tau ID measurement was performed using a sample of boosted $Z \rightarrow \tau_{\text{had}} \tau_{\text{lep}}$ events where the τ_{lep} candidate is used as a tag and the τ_{had} candidate has high- p_T (> 45 GeV). The method we presented deviates from the traditional tag-and-probe ATLAS measurement in favour of a double ratio approach. We compare the data-to-MC agreement of the rates for the production of leptons between the $Z \rightarrow ll$ ($l = e, \mu$) and the $Z \rightarrow \tau_{\text{had}} \tau_{\text{lep}}$ final states by computing a ratio between these channels. We measure the ratio between data and MC after applying the tight tauID working point. Following this procedure we derive scale factors for the MC. In ATLAS these scale factors are used to match the tauID MC efficiency to the value observed in the data. The results have an uncertainty of $\approx 4\%$ for 1-prong and $\approx 5\%$ for 3-prong taus. The advantages of our method are the partial cancellation of experimental systematics coming from the calibration of physics objects common to the light-lepton and tau final states; additionally, modelling and luminosity uncertainties are also reduced in the double ratio approach.

From the physics perspective, the double ratio approach offers the advantage of being safer from lepton universality violation effects, since the tau sample is populated from Z boson decays. In the future, we can use this approach to extend the performance measurement to looser tau ID working points and use the results as inputs in analysis that test lepton universality in tau final states with percent level precision.

One example of such lepton universality analysis, is the work described in the second part of this thesis. We test the production of di-leptons of all three generations in the VBF topology. The $Z \rightarrow ll$ sample, in a region with di-leptons having an invariant mass around the Z boson resonance, is used as a control sample to extract the signal strength normalisation factors for the QCDjj and EWjj processes; additionally, we correct the modelling of the various QCDjj samples by comparing the predictions with the data in dedicated control regions. We use the QCDjj modelling corrections as inputs in the $Z \rightarrow \tau\tau$ final states. Finally, we extract ratios of the signal strength between light-lepton and tau final states. The results we obtain are consistent with the lepton universality hypothesis at the Z-peak — with a precision of $\approx 20\%$ which is dominated by the available statistics in the Run II data sample.

Furthermore, motivated by the possible existence of new resonances that are produced in the pure electroweak process and which only couple to the third generation of fermions, we probe the VBF phase space where the di-lepton system has high invariant mass. First, we cross-check that

the signal strength normalisations and the QCDjj re-weighting holds at high-mass by looking at the $Z \rightarrow ll$ sample. Then, we apply the same selection requirements to the $Z \rightarrow \tau\tau$ final states but we find that the sample is dominated by backgrounds. An alternative analysis technique with further selection requirements and the addition of a multi-variate algorithm is applied for the $Z \rightarrow \tau\tau$ high-mass events. Our results include the validation of the alternative analysis approach in dedicated control regions. The results are blinded in the signal region and partially unblinded in the kinematic regions close to the final signal region. Expected limits on the total cross-section for the EWjj process are calculated in the high-mass region.

We leave the signal region blinded at the moment to follow the standard ATLAS procedure for physics analysis, which includes a wider collaboration review before the data in the signal region is unblinded. A paper signed by the collaboration is being prepared for publication based on the results described in this thesis.

Appendix A

Tau ID scale factors measurement

A.1 Final state MC comparisons

The distribution of the variables used to select our events and that have importance to the analysis are presented. In the left column, the distributions for events with muons in the final state are displayed. Events with electron, appear on the right side. This convention is followed everywhere, except where specified. For all the plots, all the other selection cuts have been applied apart from the one being displayed. The conventions used in the main section of the text are followed.

A.1.1 Sherpa

$$Z \rightarrow \tau_{\text{had}} \tau_{\text{lep}}$$

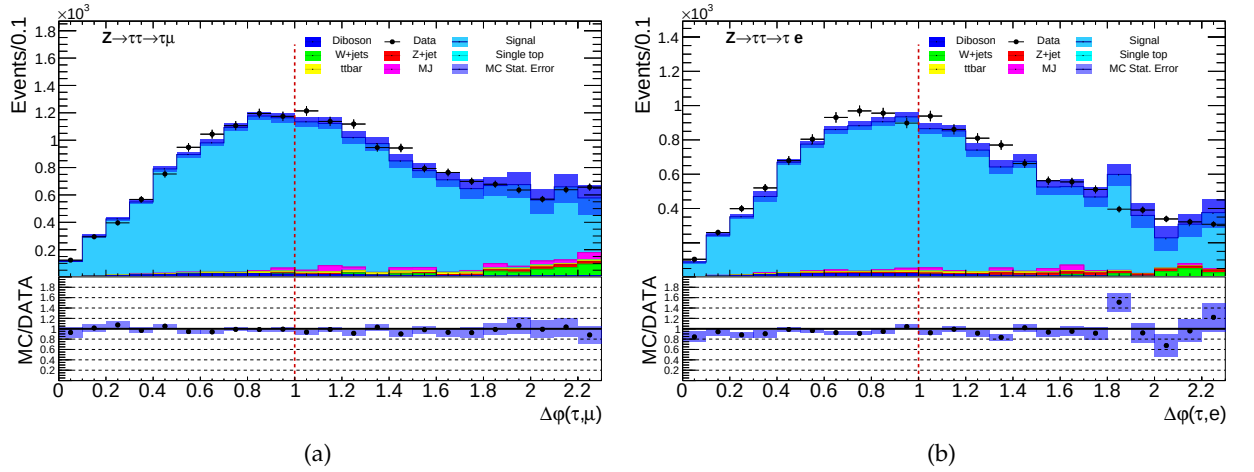
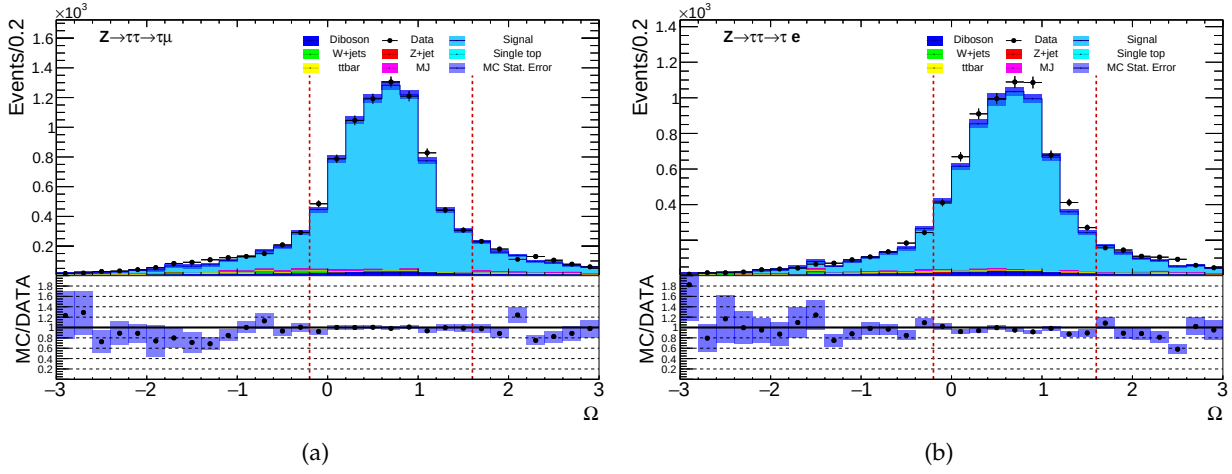
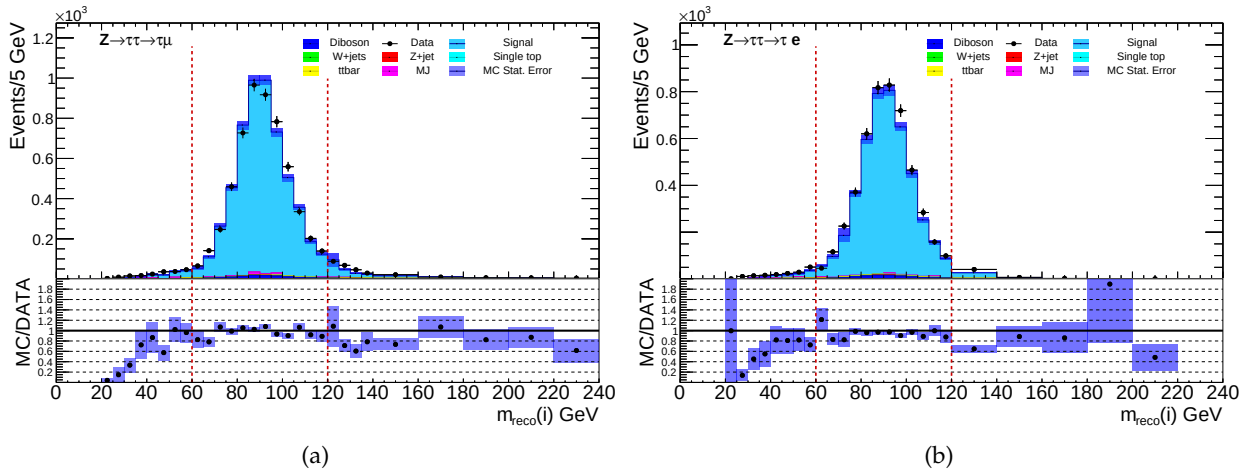
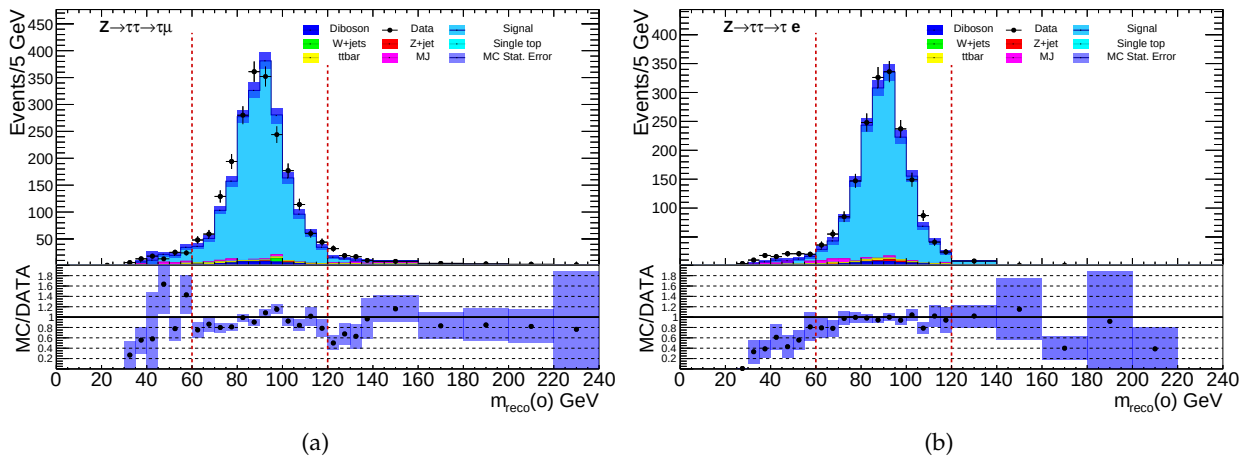
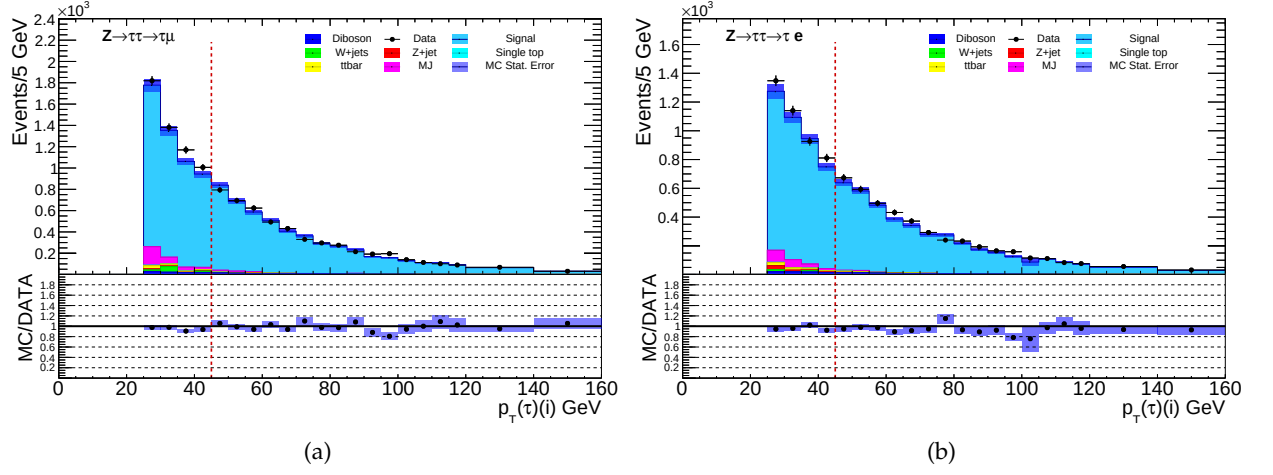
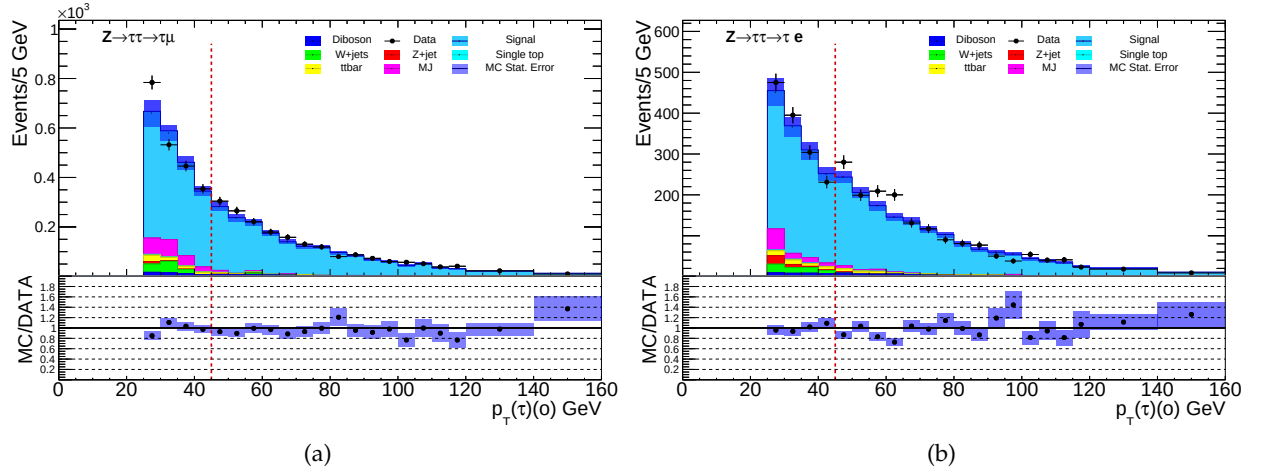
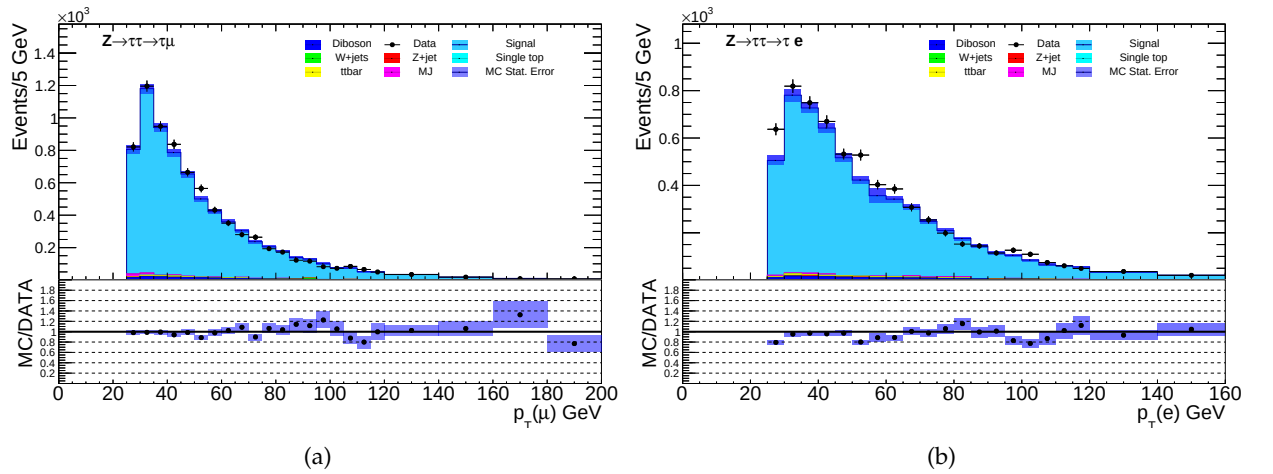
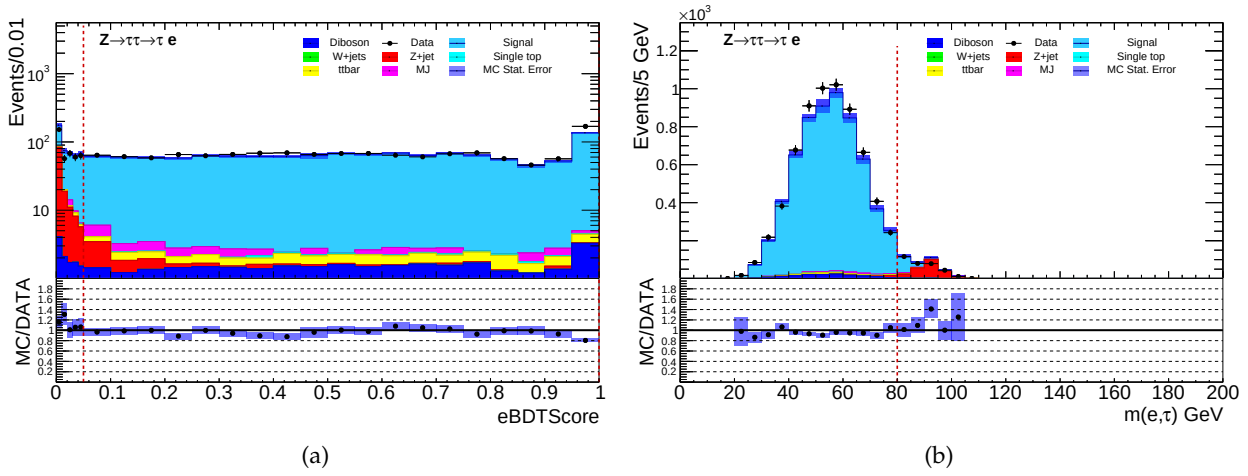
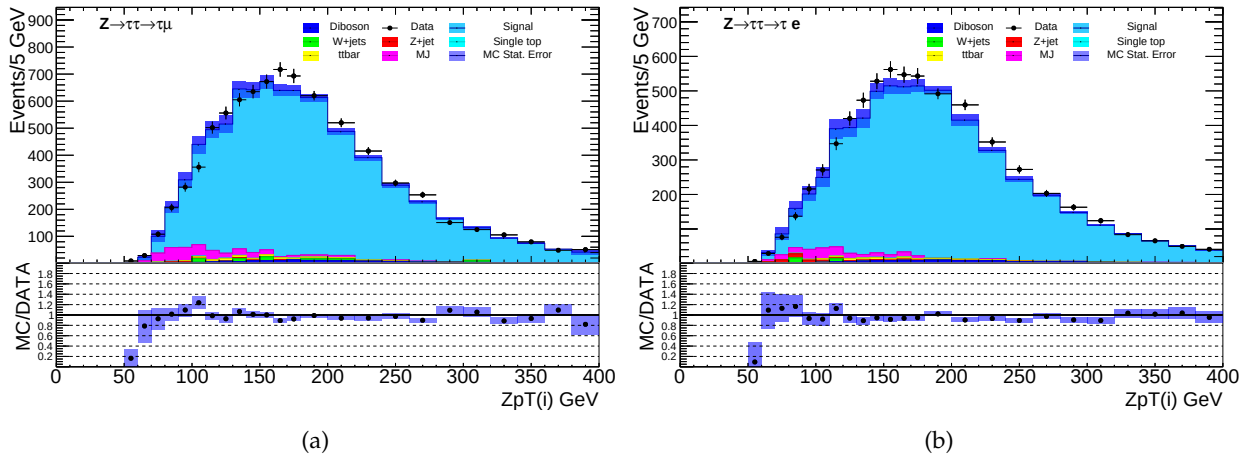
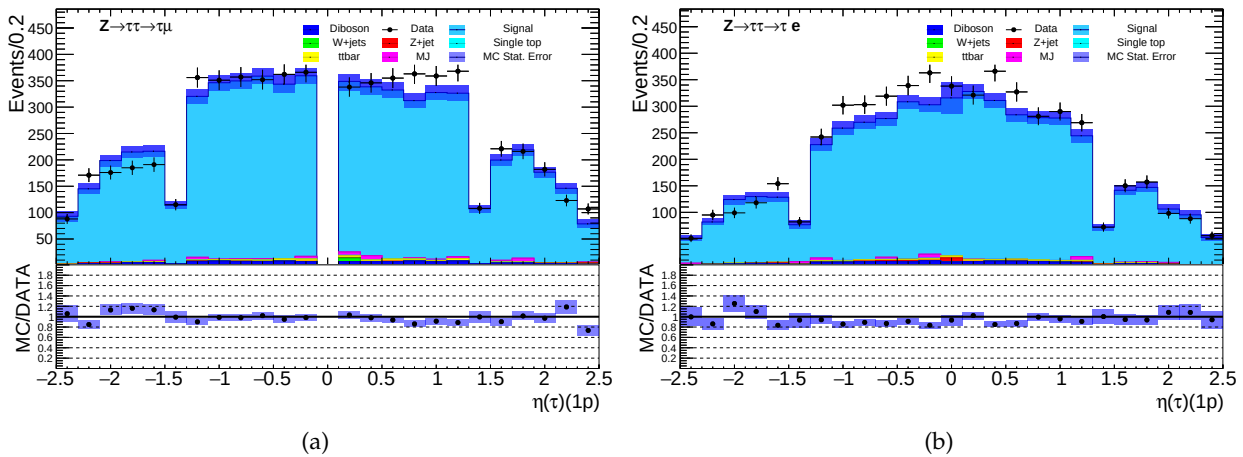
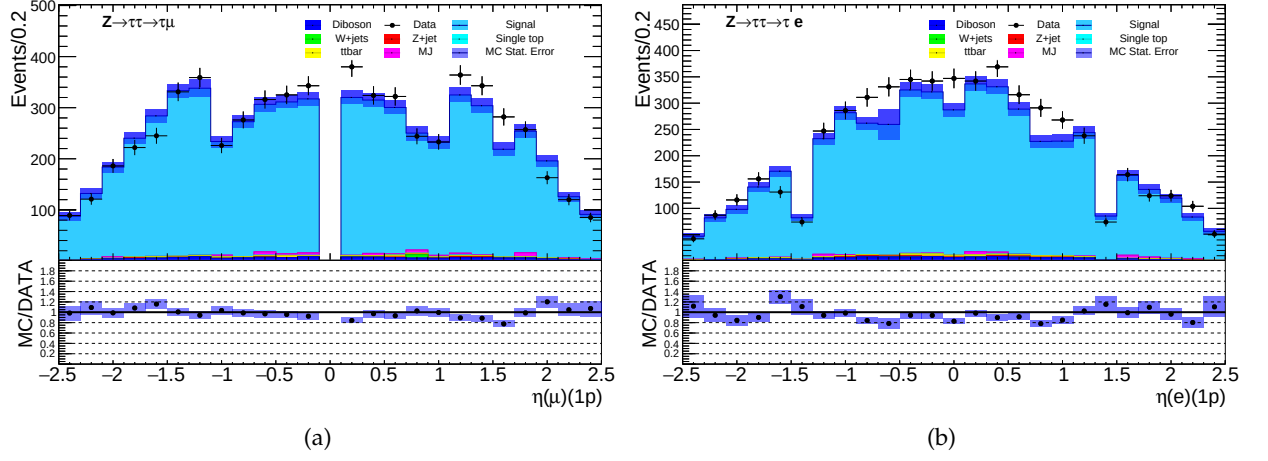
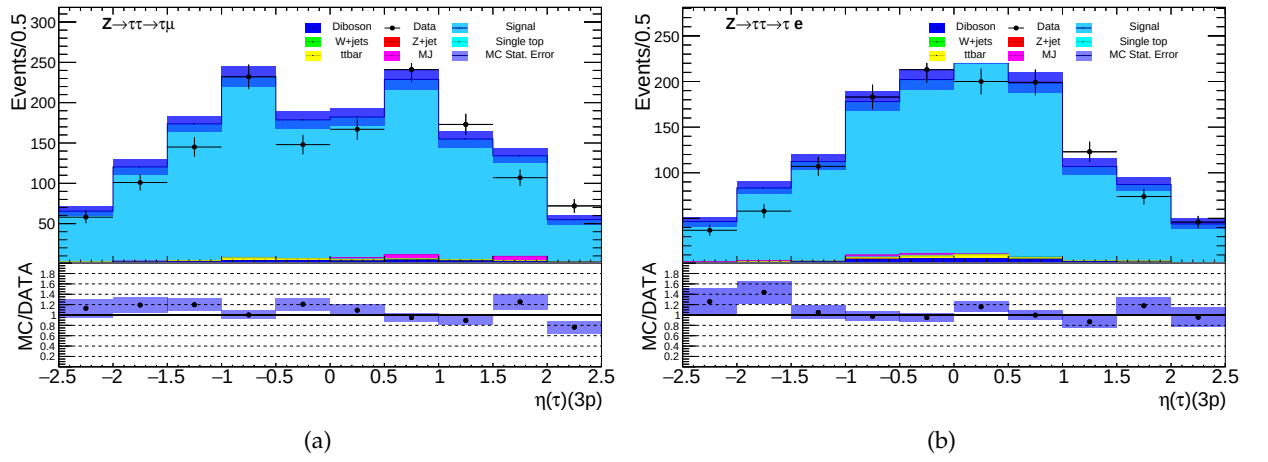
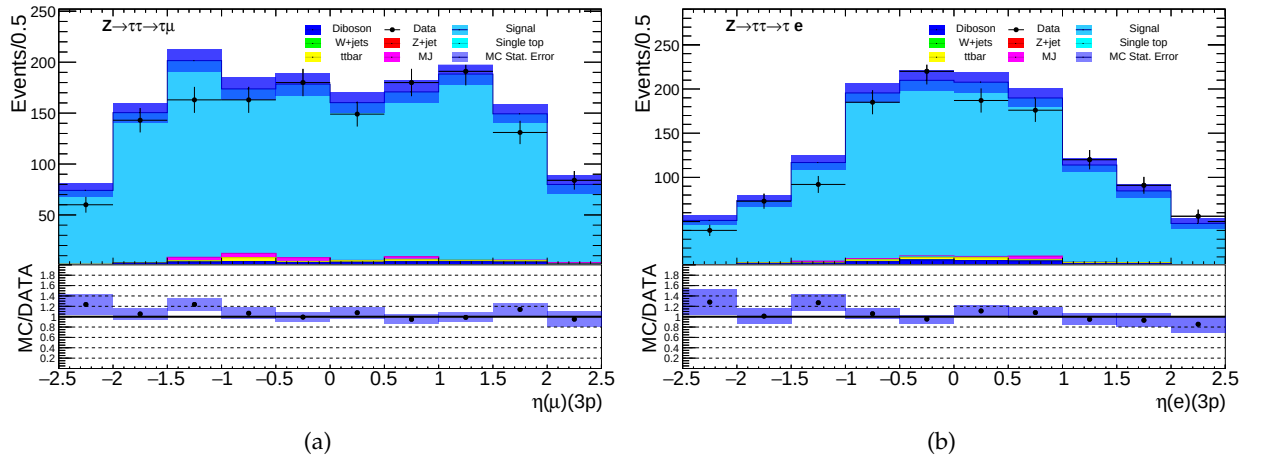


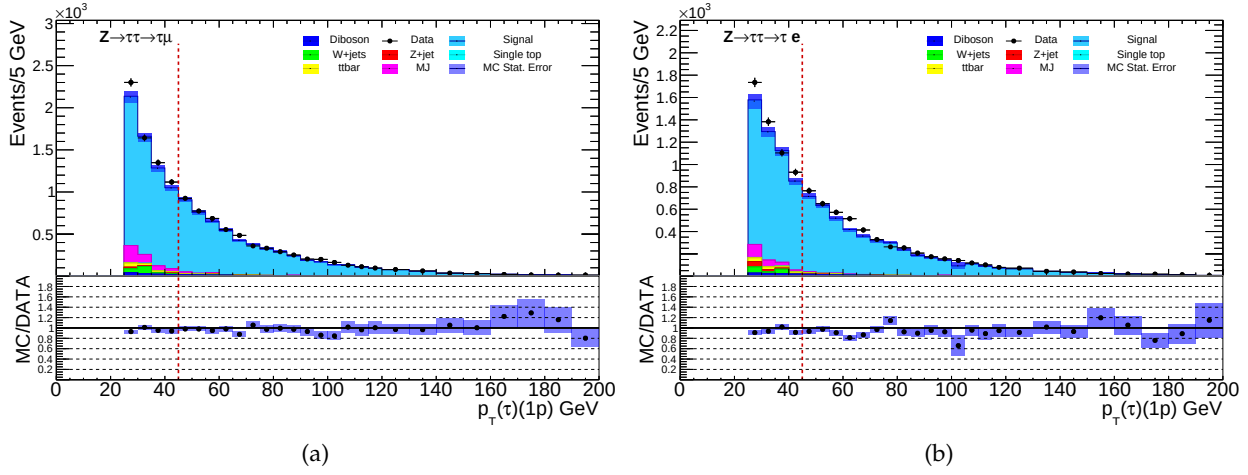
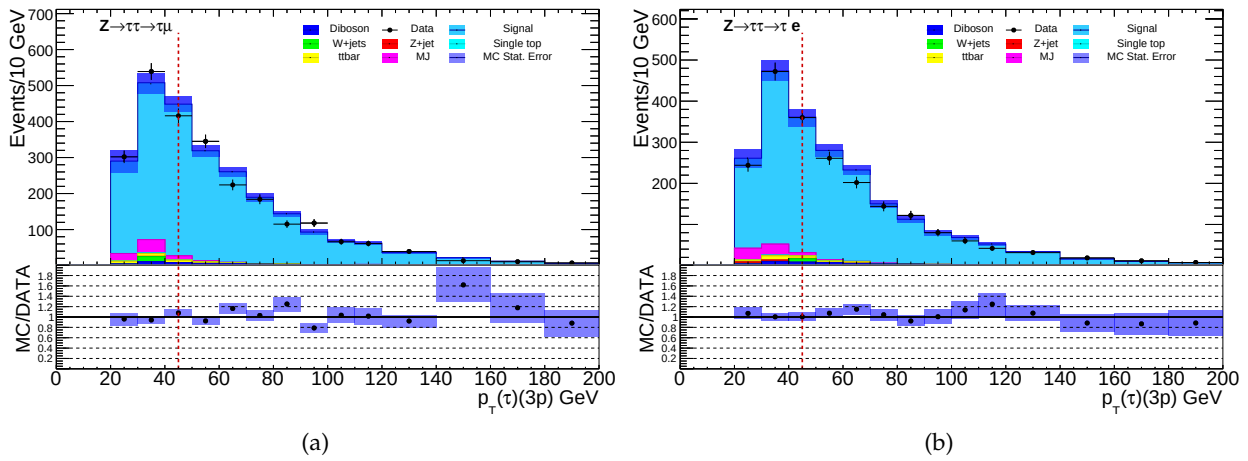
FIGURE A.1: $\Delta\phi(\tau_{\text{had}}, l)$ distribution. Sherpa used for MC signal.

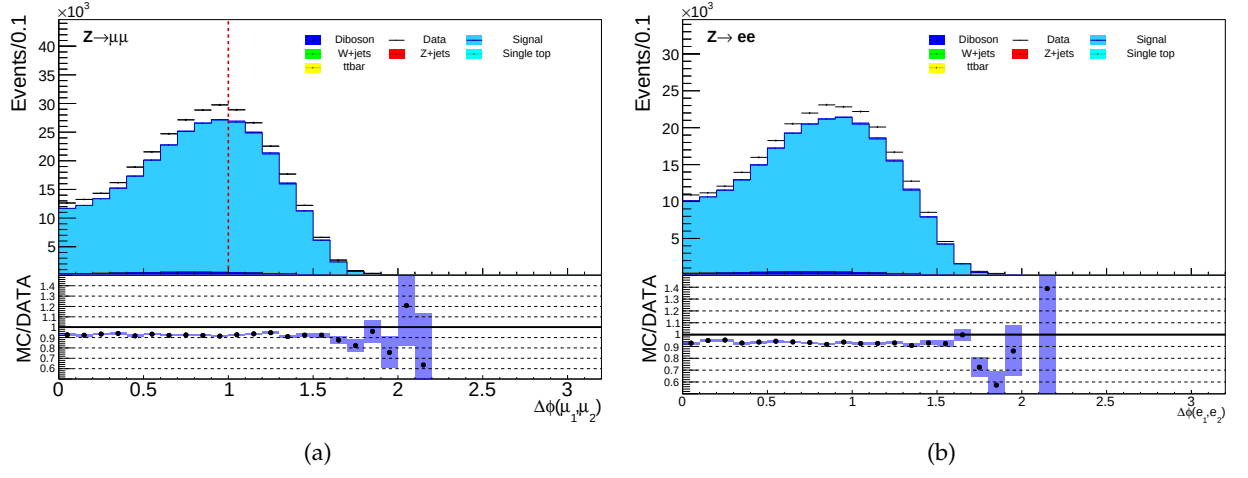
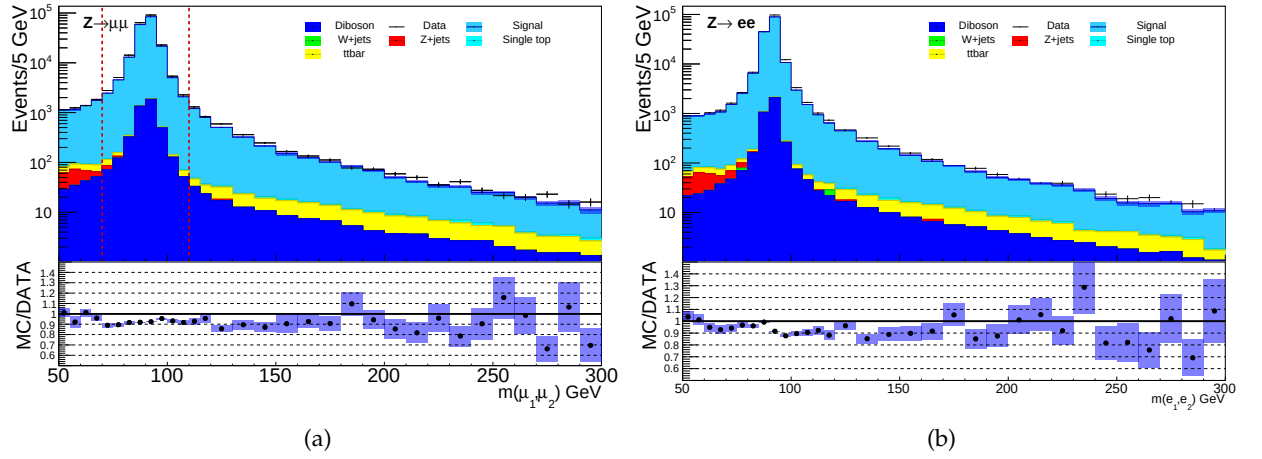
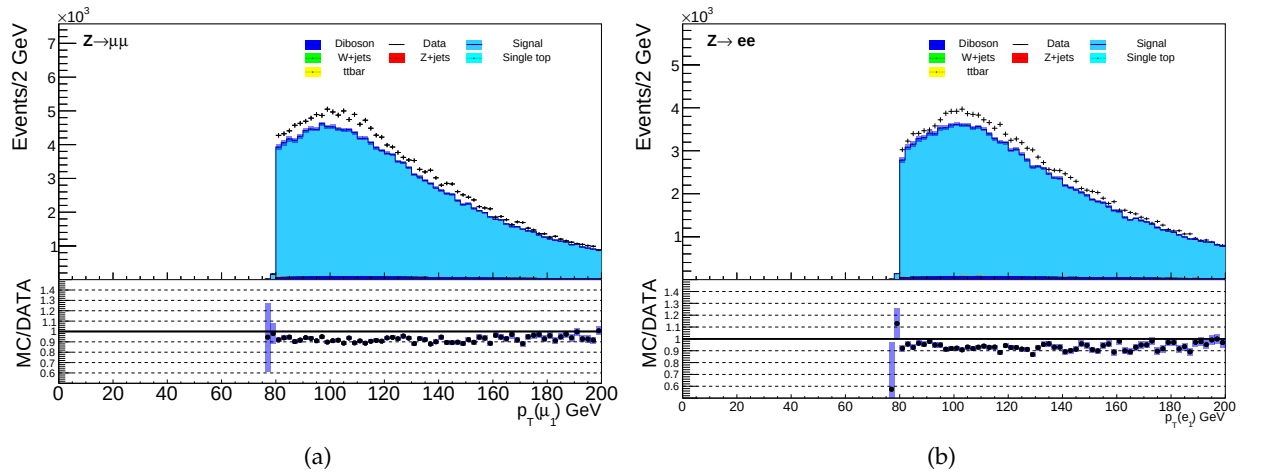
FIGURE A.2: Ω distribution. Sherpa used for MC signal.FIGURE A.3: $m_{\text{reco}(i)}$ distribution. Sherpa used for MC signal.FIGURE A.4: $m_{\text{reco}(o)}$ distribution. Sherpa used for MC signal.

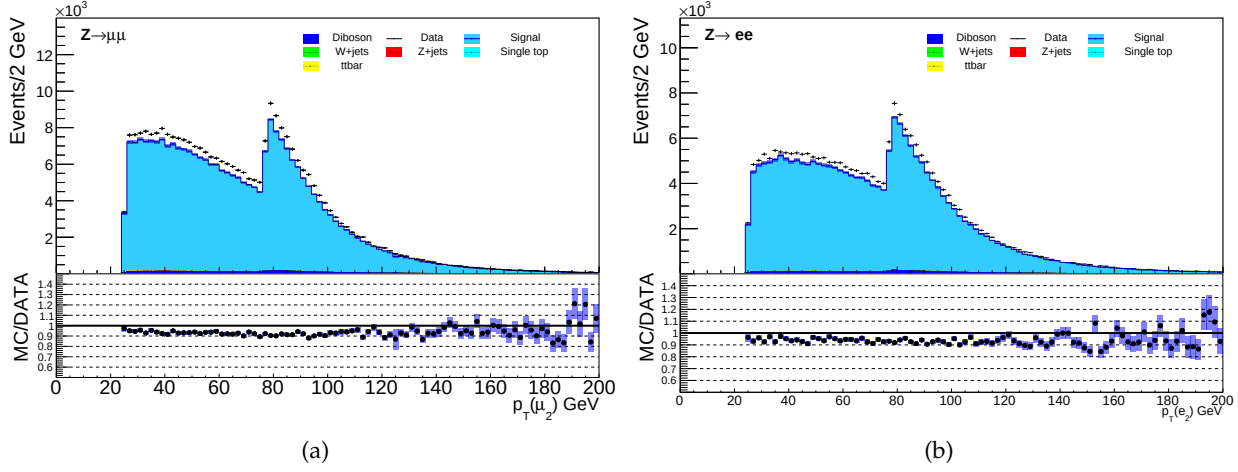
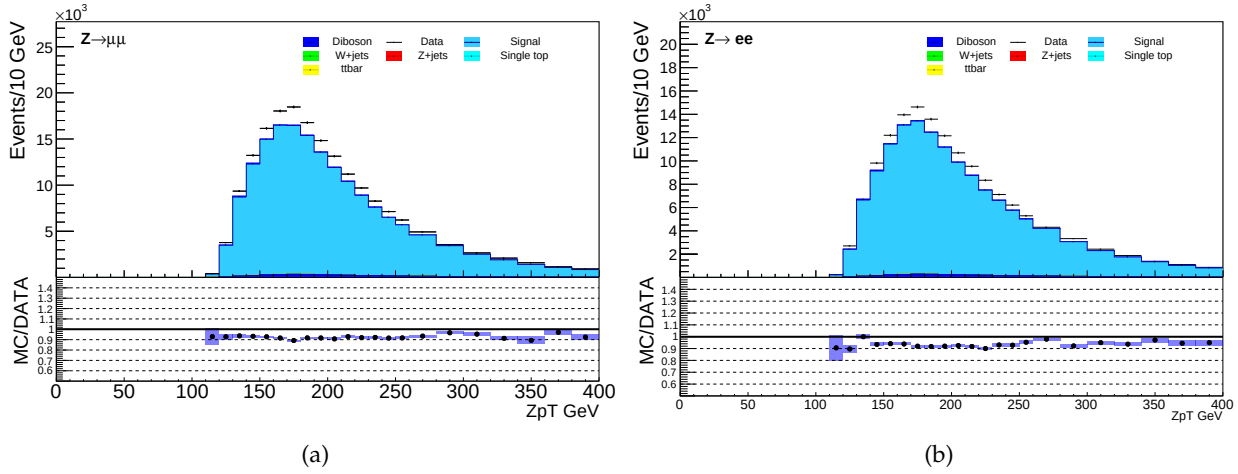
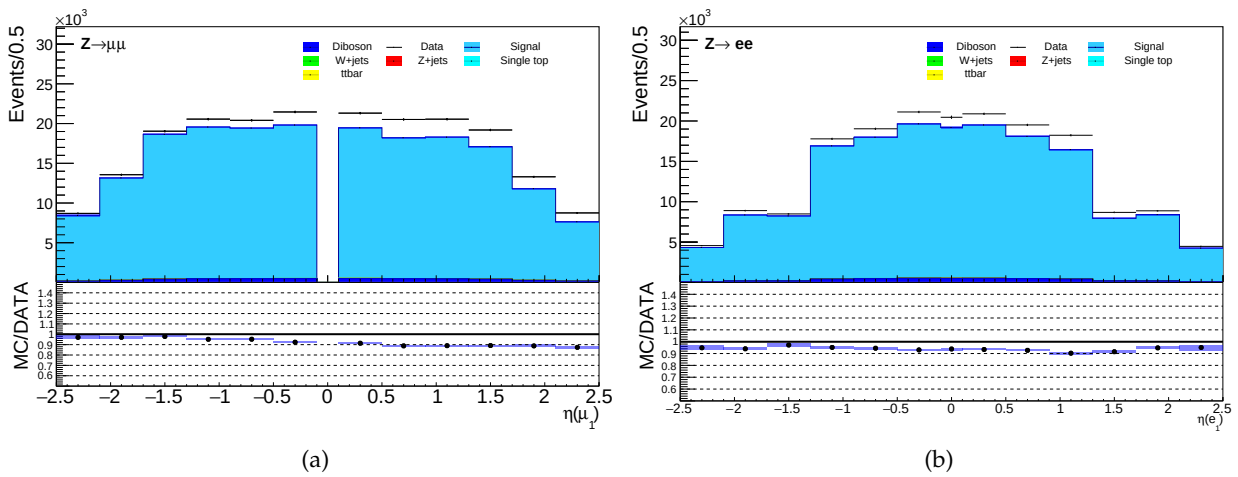
FIGURE A.5: $\tau p_T(i)$ distribution. Sherpa used for MC signal.FIGURE A.6: $\tau p_T(o)$ distribution. Sherpa used for MC signal.FIGURE A.7: Light lepton p_T distribution. Sherpa used for MC signal.

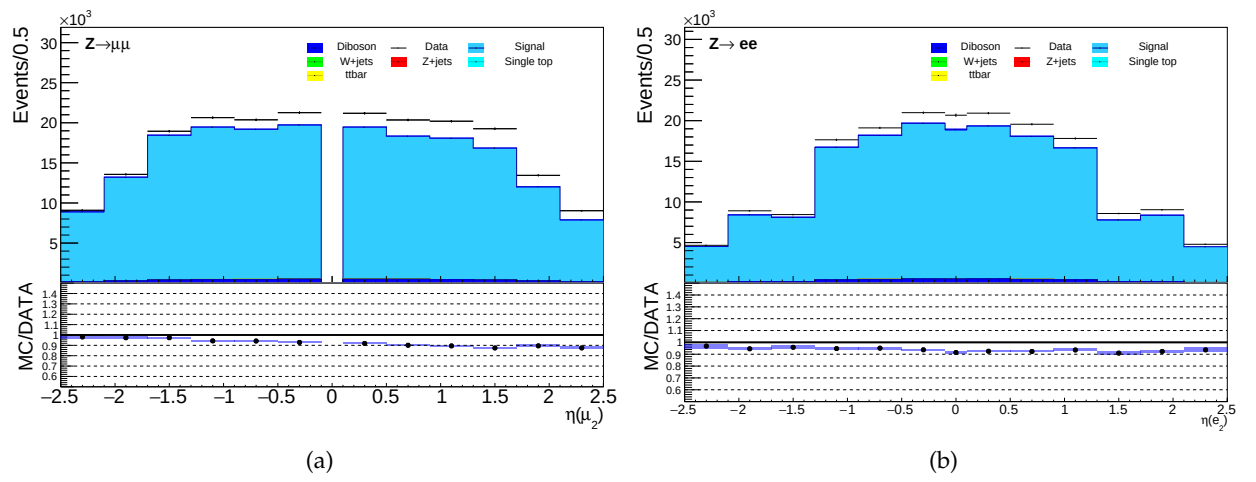
FIGURE A.8: $m(e, \tau_{had})$ and $eBDTScore$ distributions. Sherpa used for MC signal.FIGURE A.9: $Z-p_T$ distribution. Sherpa used for MC signal.FIGURE A.10: Tau η distribution. 1-Prong taus. Sherpa used for MC signal.

FIGURE A.11: Light lepton η distribution. 1-Prong taus. Sherpa used for MC signal.FIGURE A.12: Tau η distribution. 3-Prong taus. Sherpa used for MC signal.FIGURE A.13: Light lepton η distribution. 3-Prong taus. Sherpa used for MC signal.

FIGURE A.14: Tau p_T distribution. 1-Prong taus. Sherpa used for MC signal.FIGURE A.15: Tau p_T distribution. 3-Prong taus. Sherpa used for MC signal.

$Z \rightarrow ll$
FIGURE A.16: $\Delta\phi(l, l)$ distribution. Sherpa used for MC signal.FIGURE A.17: $m(l, l)$ distribution. Sherpa used for MC signal.FIGURE A.18: $p_T(l_1)$ distribution. Sherpa used for MC signal.

FIGURE A.19: $p_T(l_2)$ distribution. Sherpa used for MC signal.FIGURE A.20: $Z-p_T$ distribution. Sherpa used for MC signal.FIGURE A.21: Leading lepton η distribution. Sherpa used for MC signal.

FIGURE A.22: Sub-leading lepton η distribution. Sherpa used for MC signal.

A.1.2 PowHeg+Pythia8 Z- p_T re-weighted

$$Z \rightarrow \tau_{\text{had}} \tau_{\text{lep}}$$

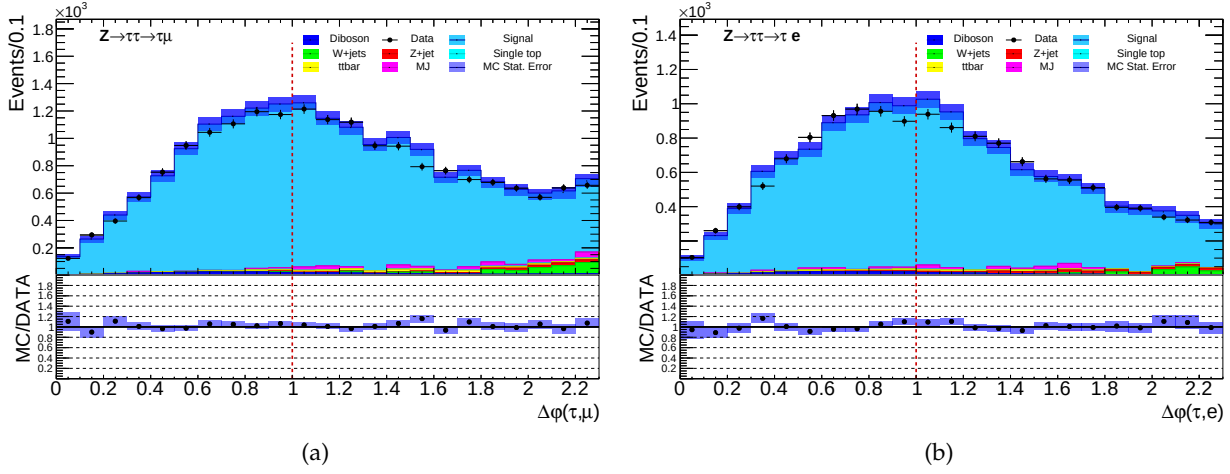


FIGURE A.23: $\Delta\phi(\tau_{\text{had}}, l)$ distribution. PowHeg+Pythia8 + Z- p_T re-weight used for MC signal.

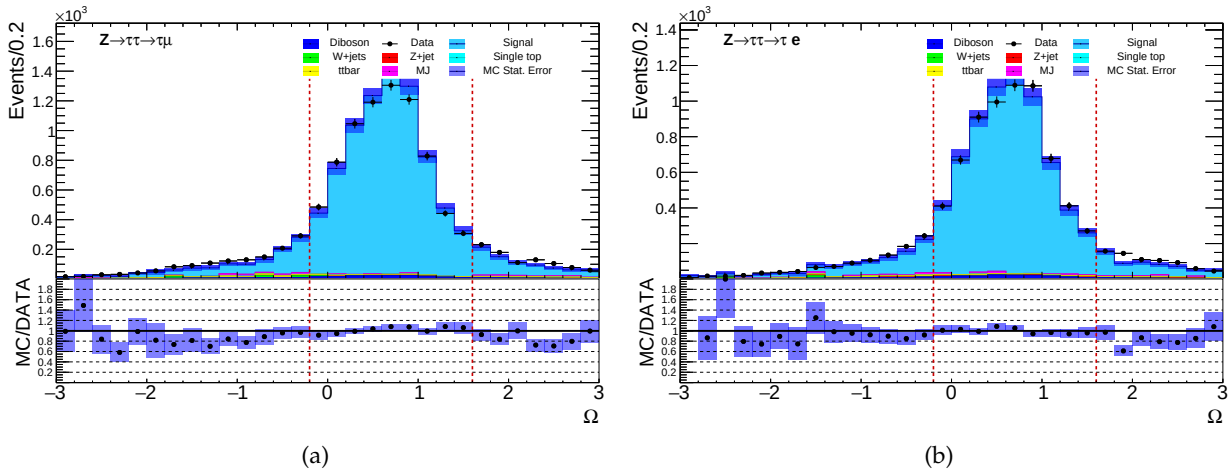


FIGURE A.24: Ω distribution. PowHeg+Pythia8 + Z- p_T re-weight used for MC signal.

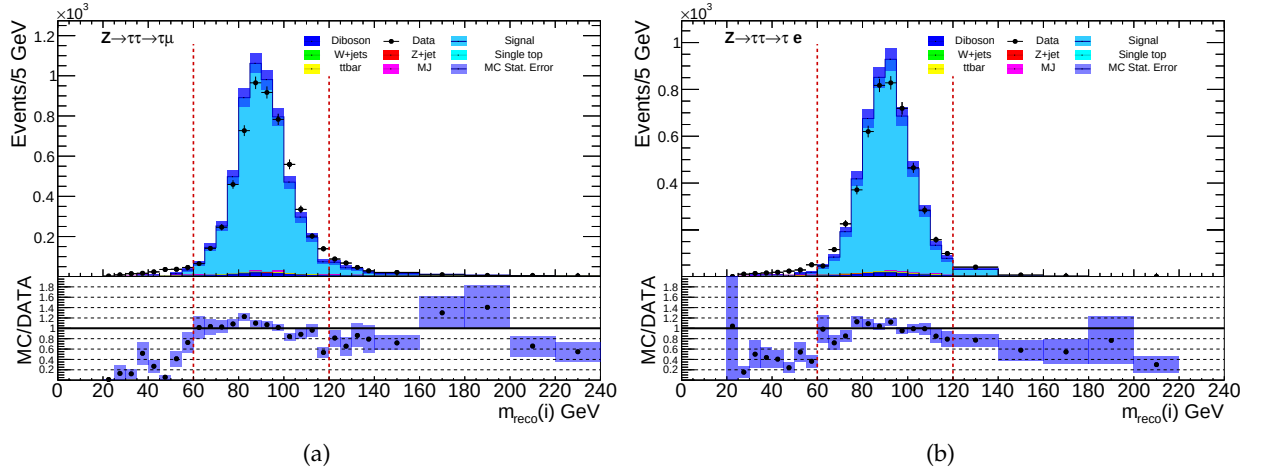


FIGURE A.25: $m_{\text{reco}(i)}$ distribution. PowHeg+Pythia8 + Z - p_T re-weight used for MC signal.

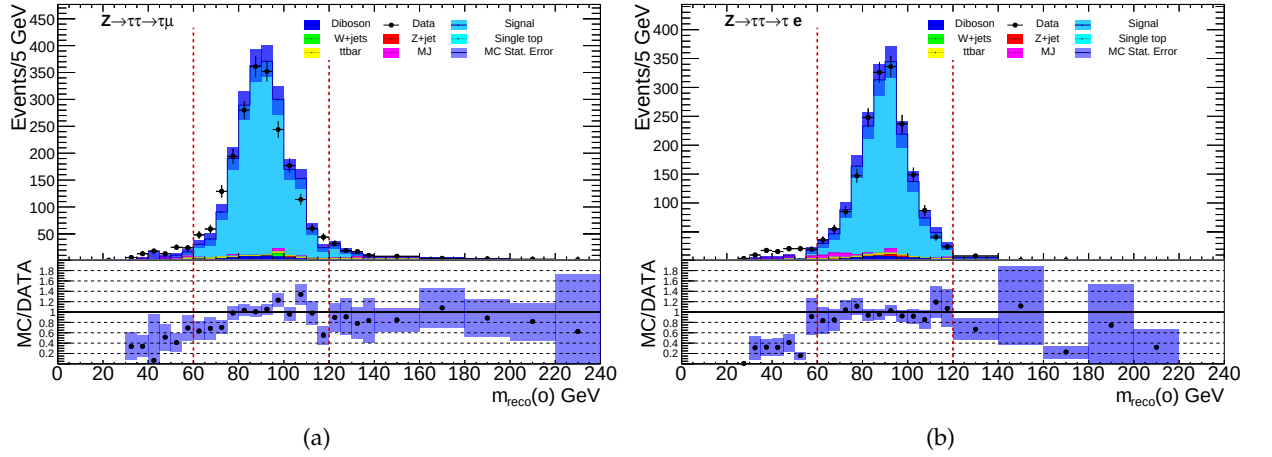


FIGURE A.26: $m_{\text{reco}(o)}$ distribution. PowHeg+Pythia8 + Z - p_T re-weight used for MC signal.

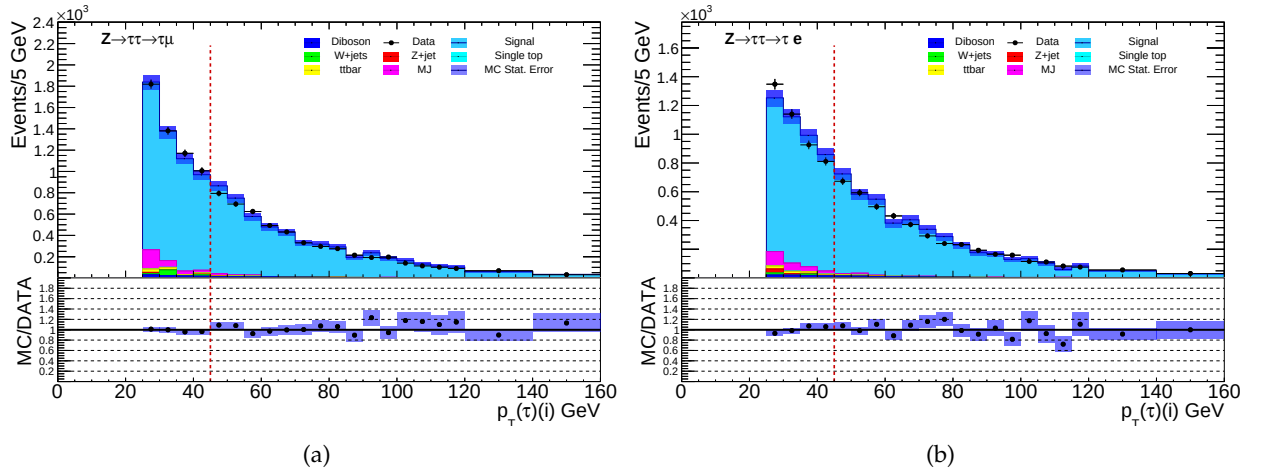


FIGURE A.27: $\tau p_{T(i)}$ distribution. PowHeg+Pythia8 + Z - p_T re-weight used for MC signal.

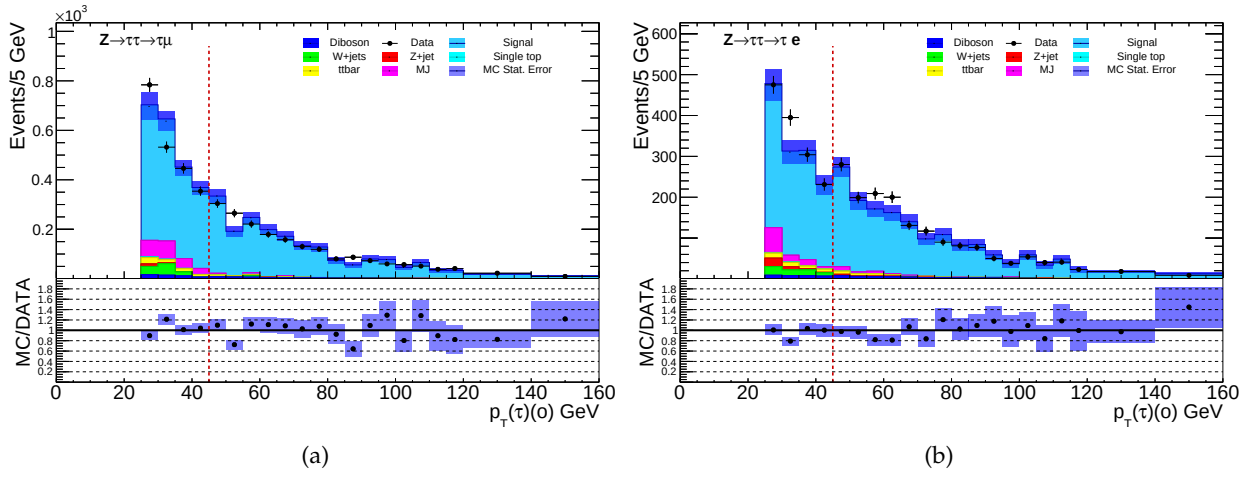


FIGURE A.28: $\tau p_T(o)$ distribution. PowHeg+Pythia8 + Z- p_T re-weight used for MC signal.

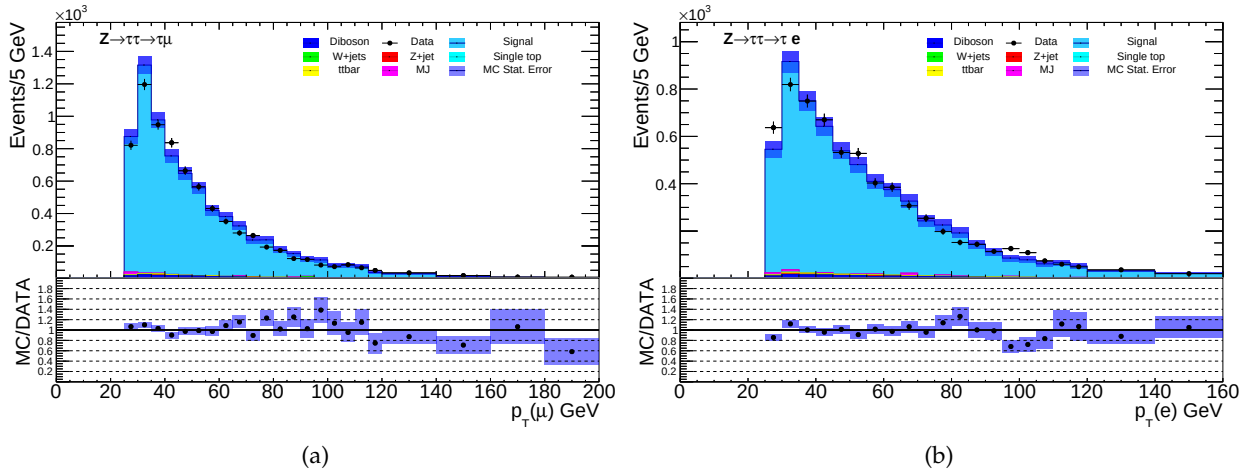


FIGURE A.29: Light lepton p_T distribution. PowHeg+Pythia8 + Z- p_T re-weight used for MC signal.

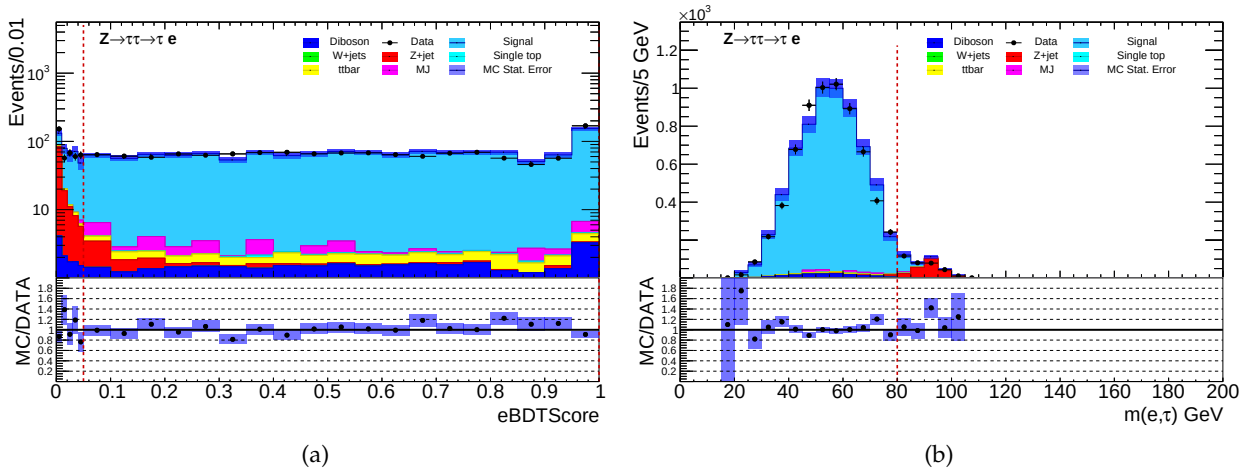


FIGURE A.30: $m(e, \tau_{\text{had}})$ and eBDTScore distributions. PowHeg+Pythia8 + Z- p_T re-weight used for MC signal.

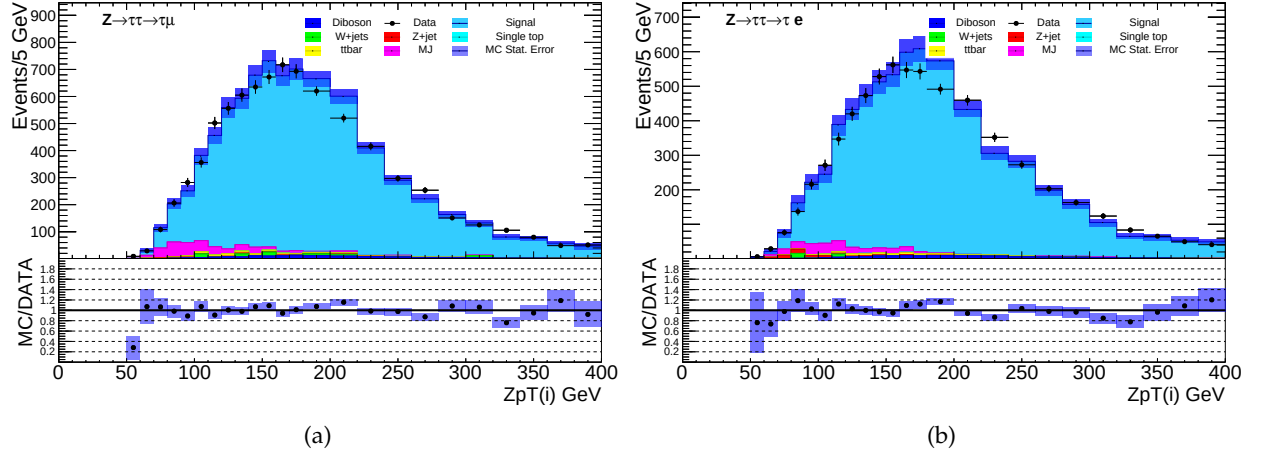


FIGURE A.31: $Z-p_T$ distribution. PowHeg+Pythia8 + $Z-p_T$ re-weight used for MC signal.

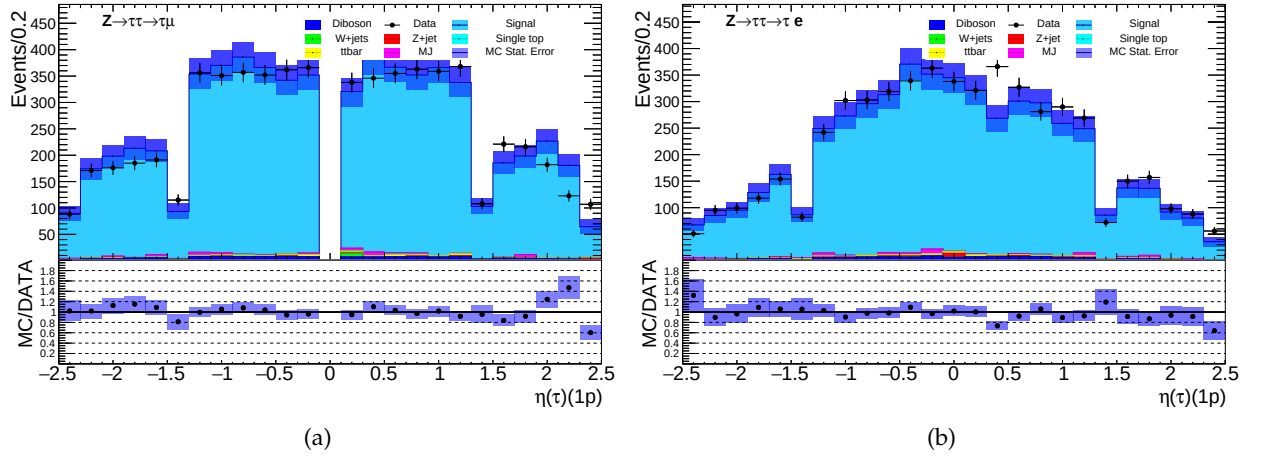


FIGURE A.32: Tau η distribution. 1-Prong taus. PowHeg+Pythia8 + $Z-p_T$ re-weight used for MC signal.

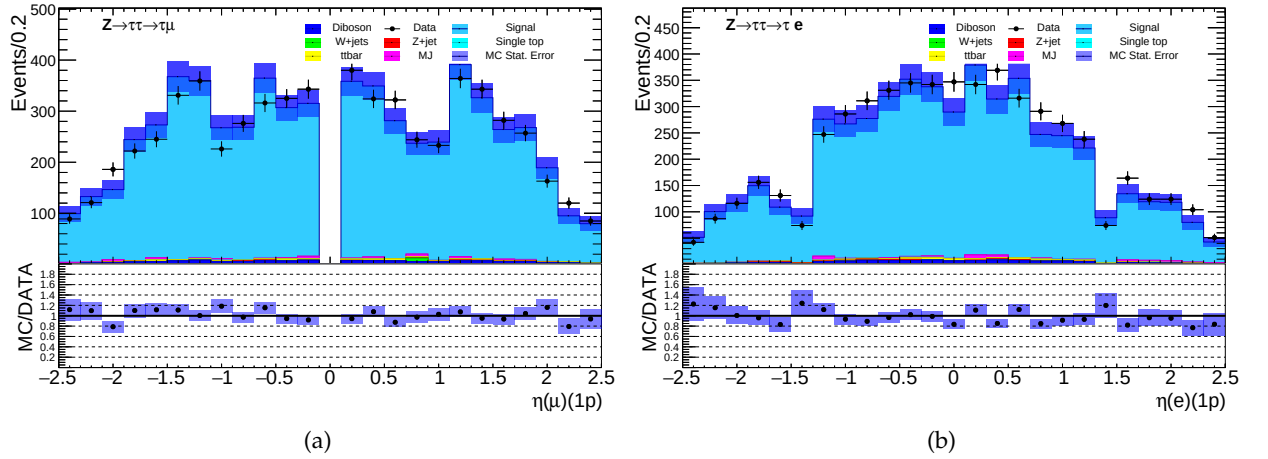


FIGURE A.33: Light lepton η distribution. 1-Prong taus. PowHeg+Pythia8 + $Z-p_T$ re-weight used for MC signal.

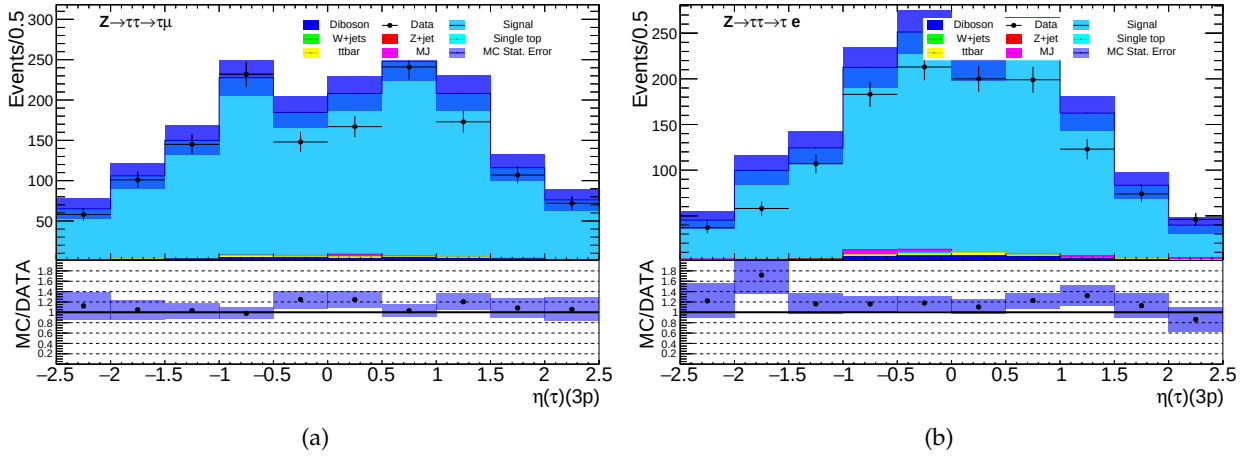


FIGURE A.34: Tau η distribution. 3-Prong taus. PowHeg+Pythia8 + Z - p_T re-weight used for MC signal.

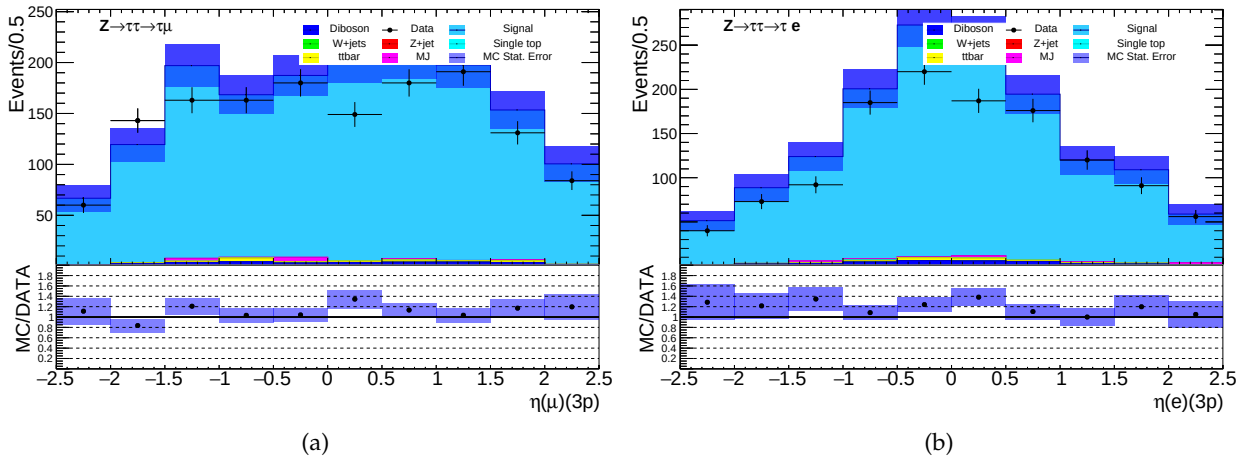


FIGURE A.35: Light lepton η distribution. 3-Prong taus. PowHeg+Pythia8 + Z - p_T re-weight used for MC signal.

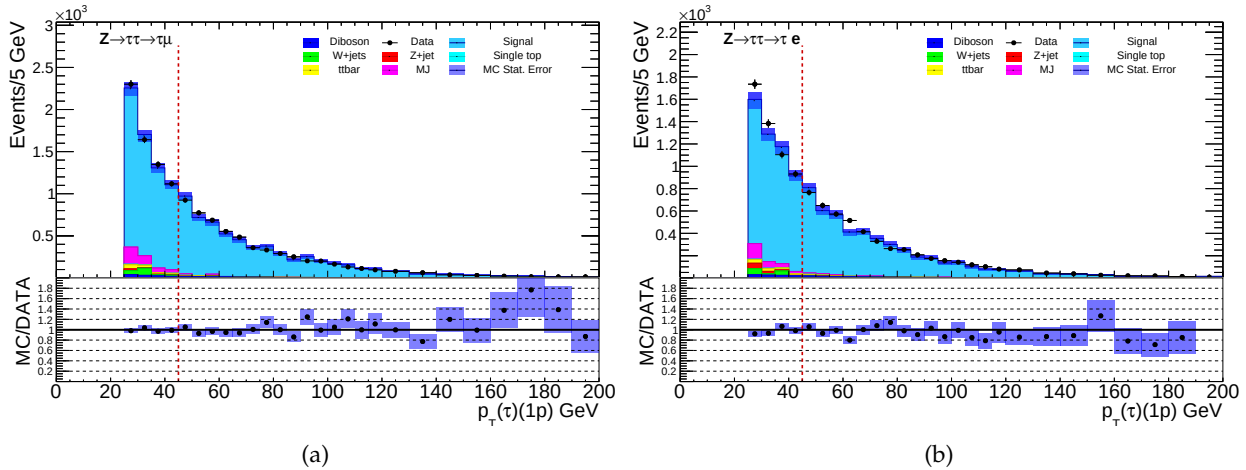


FIGURE A.36: Tau p_T distribution. 1-Prong taus. PowHeg+Pythia8 + Z - p_T re-weight used for MC signal.

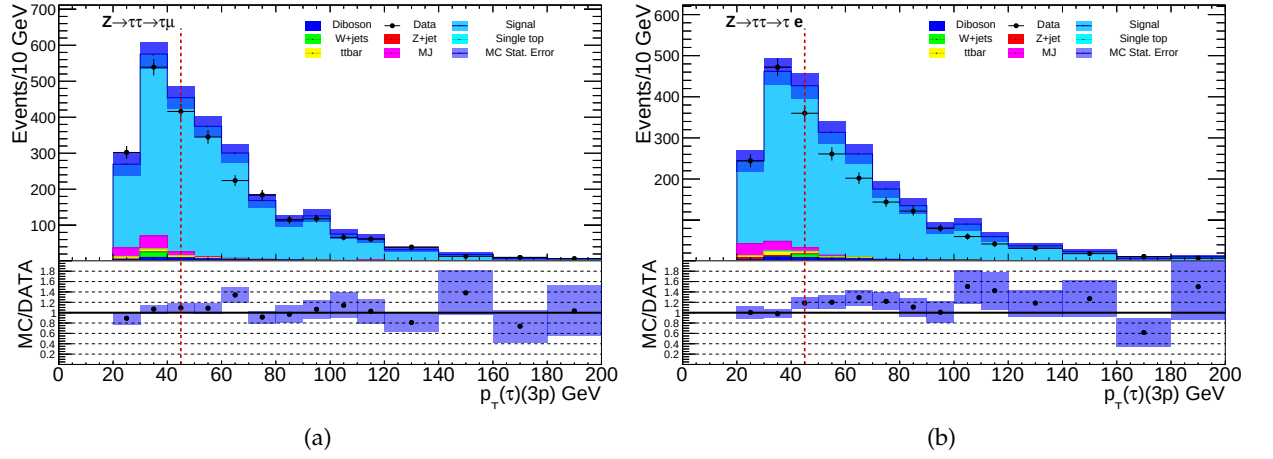


FIGURE A.37: Tau p_T distribution. 3-Prong taus. PowHeg+Pythia8 + Z - p_T re-weighted for MC signal.

$Z \rightarrow ll$

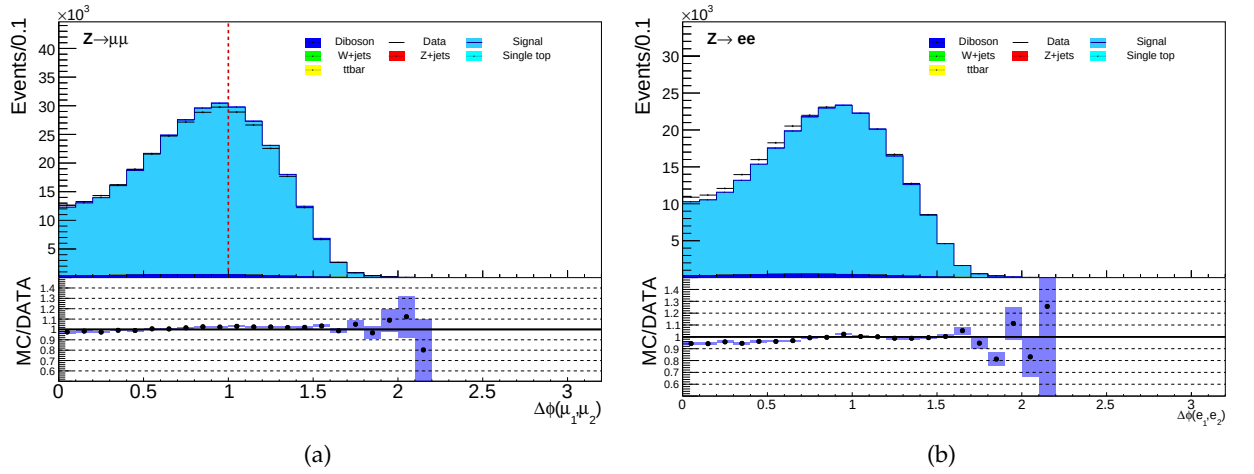


FIGURE A.38: $\Delta\phi(l, l)$ distribution. PowHeg+Pythia8 + Z - p_T re-weight used for MC signal.

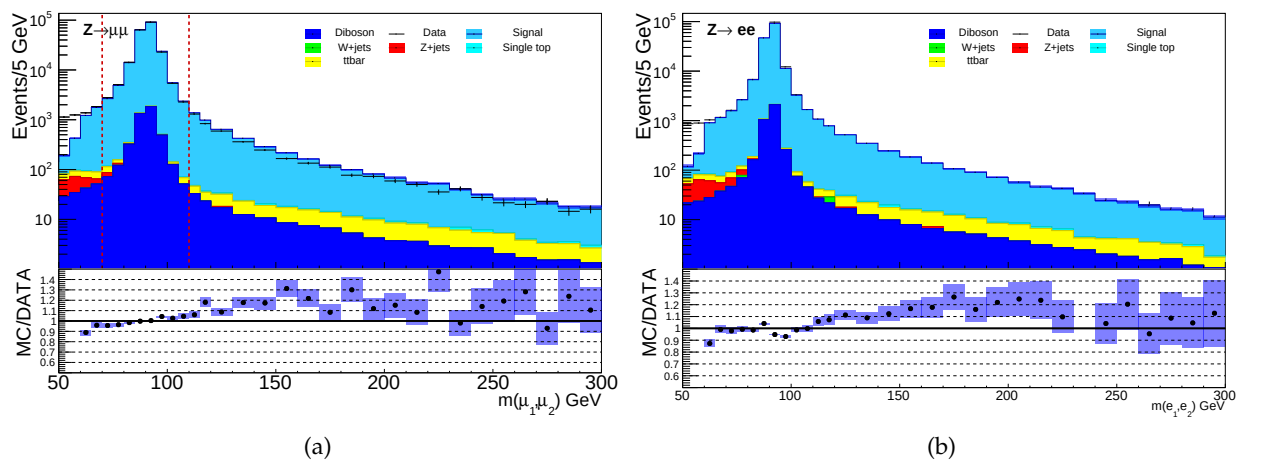


FIGURE A.39: $m(l, l)$ distribution. PowHeg+Pythia8 + Z - p_T re-weight used for MC signal.

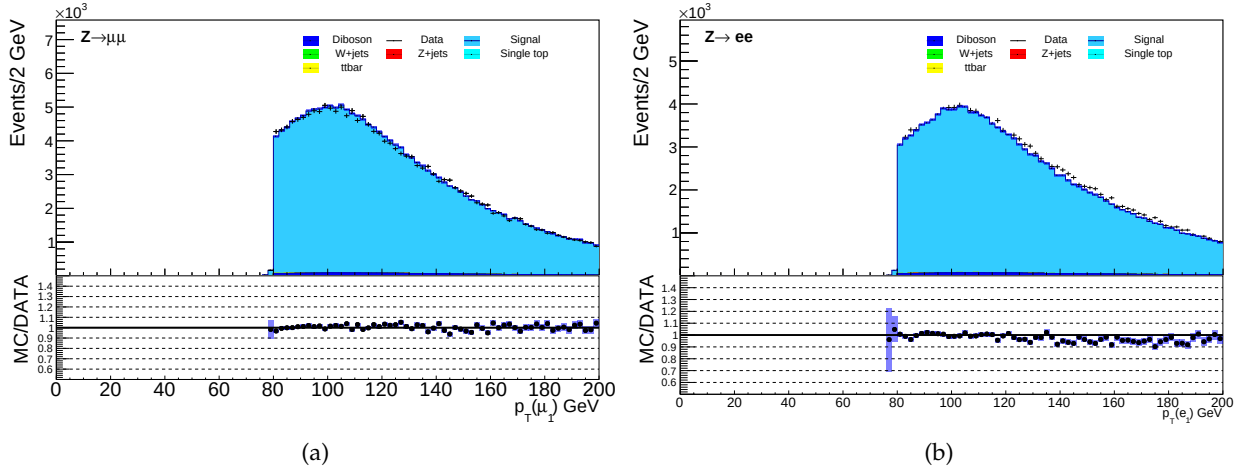


FIGURE A.40: $p_T(l_1)$ distribution. PowHeg+Pythia8 + Z- p_T re-weight used for MC signal.

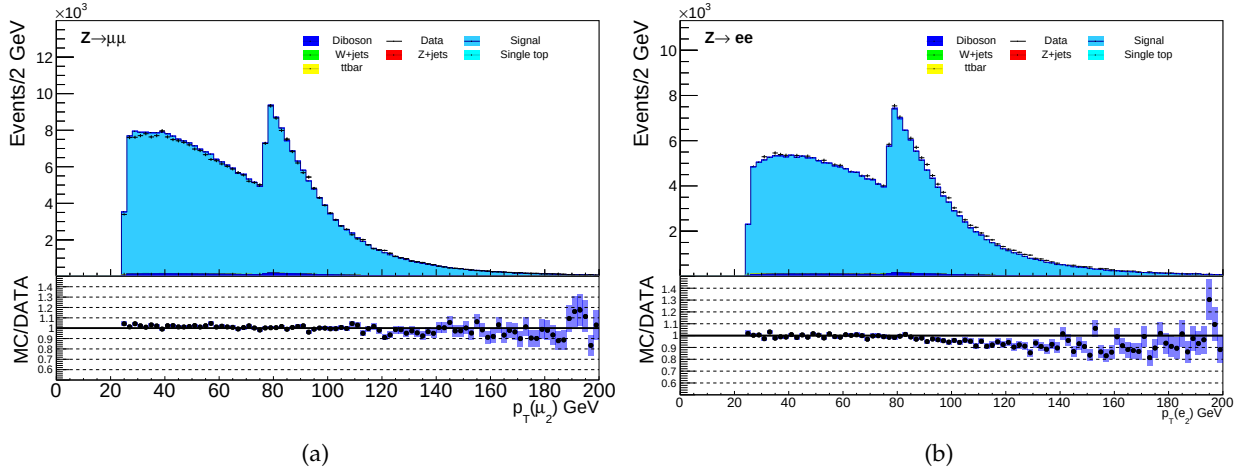


FIGURE A.41: $p_T(l_2)$ distribution. PowHeg+Pythia8 + Z- p_T re-weight used for MC signal.

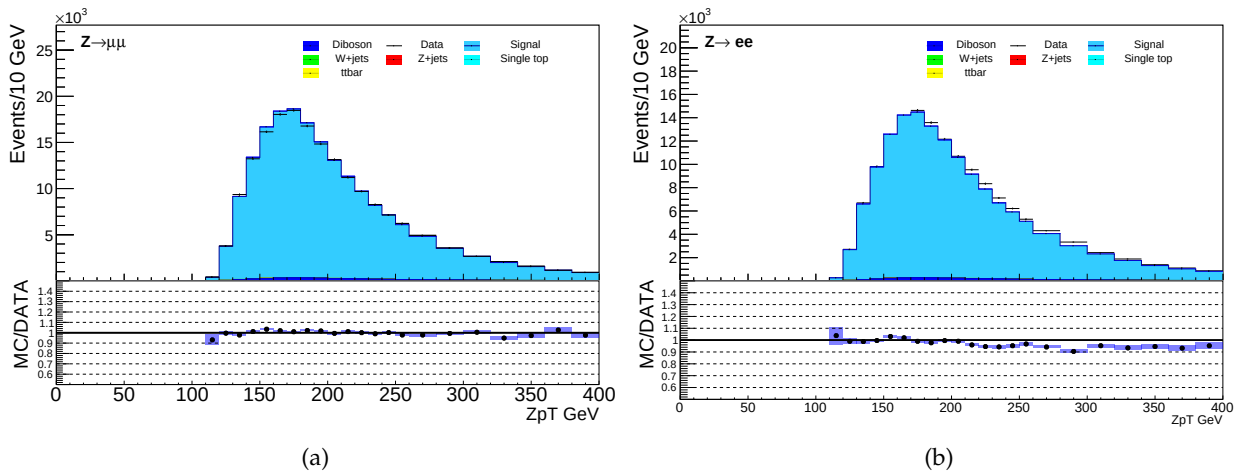


FIGURE A.42: Z- p_T distribution. PowHeg+Pythia8 + Z- p_T re-weight used for MC signal.

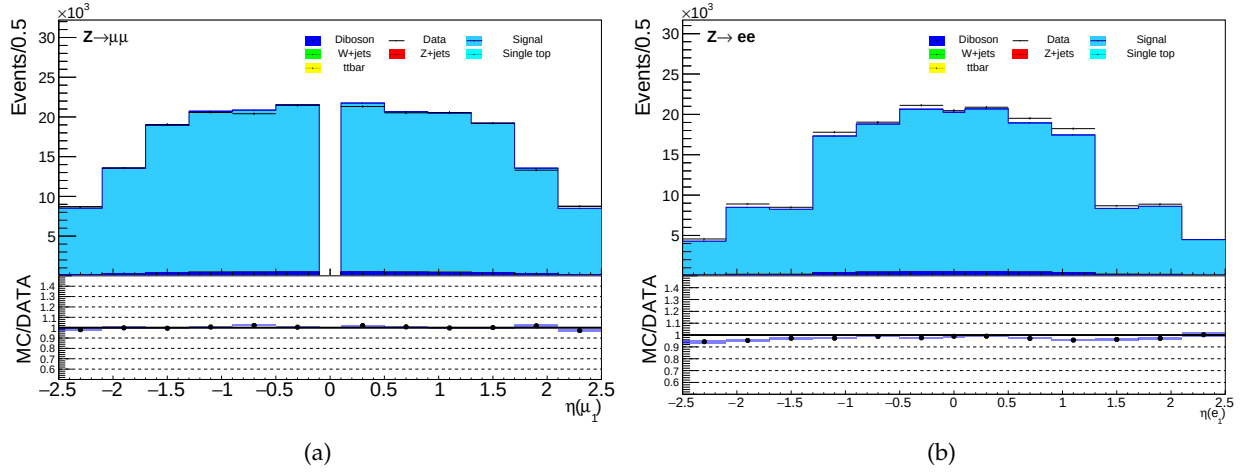


FIGURE A.43: Leading lepton η distribution. PowHeg+Pythia8 + Z - p_T re-weight used for MC signal.

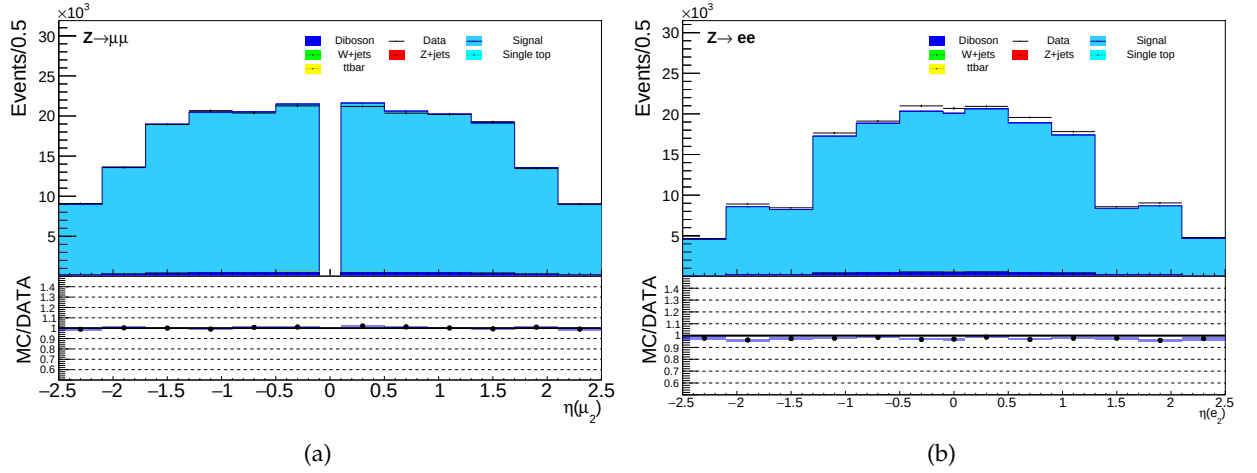


FIGURE A.44: Sub-leading lepton η distribution. PowHeg+Pythia8 + Z - p_T re-weight used for MC signal.

A.1.3 PowHeg+Pythia8

$Z \rightarrow \tau_{\text{had}} \tau_{\text{lep}}$

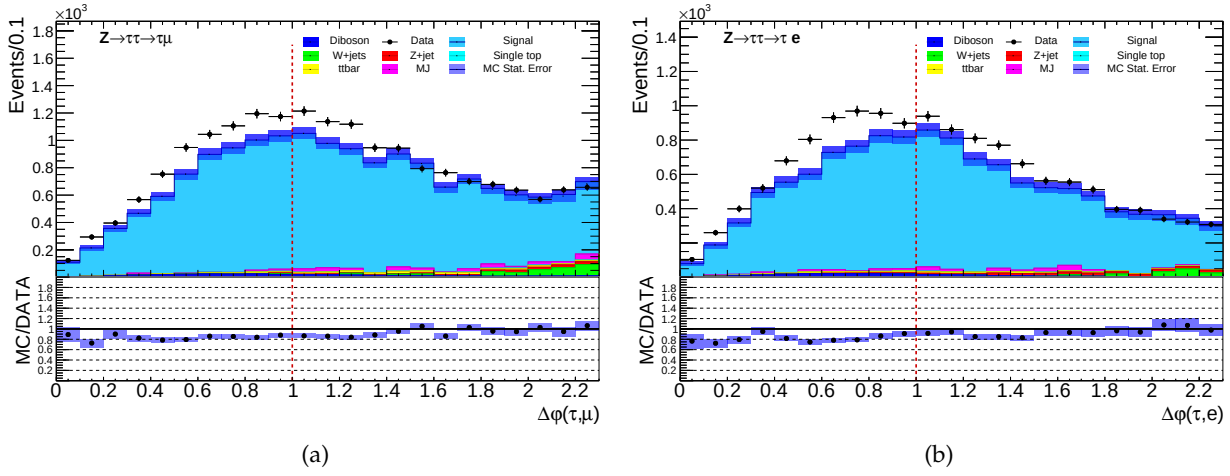


FIGURE A.45: $\Delta\phi(\tau_{\text{had}}, l)$ distribution. PowHeg+Pythia8 used for MC signal.

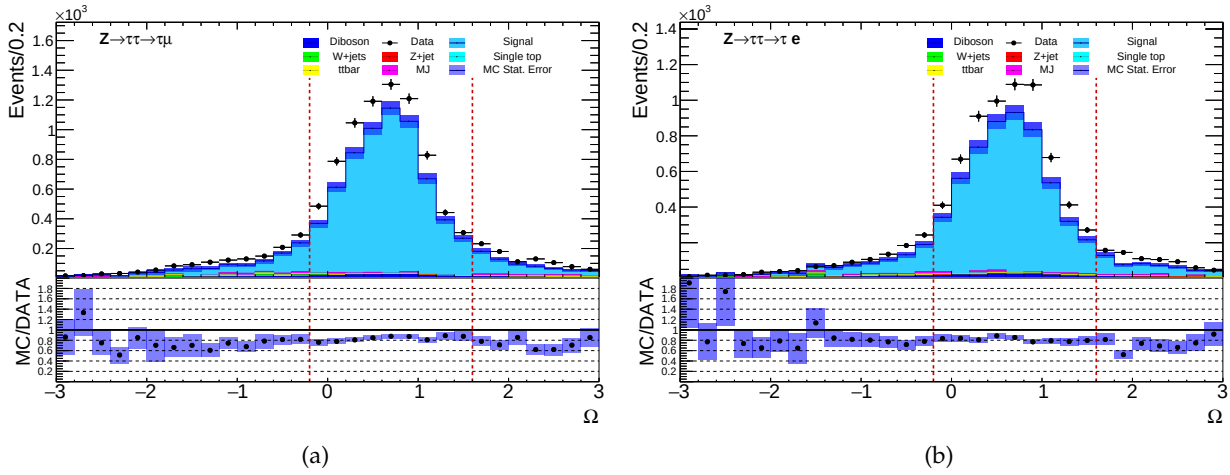


FIGURE A.46: Ω distribution. PowHeg+Pythia8 used for MC signal.

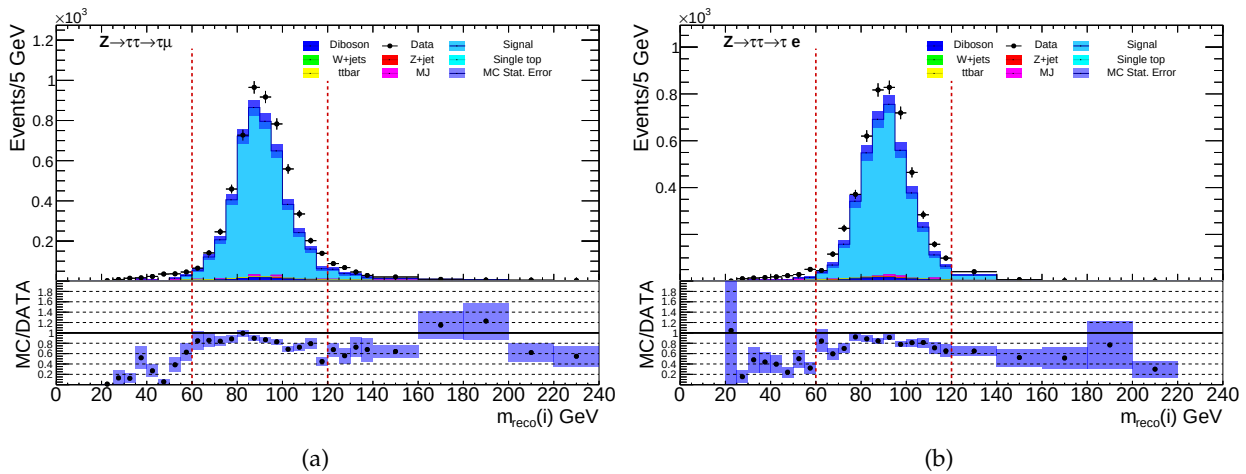
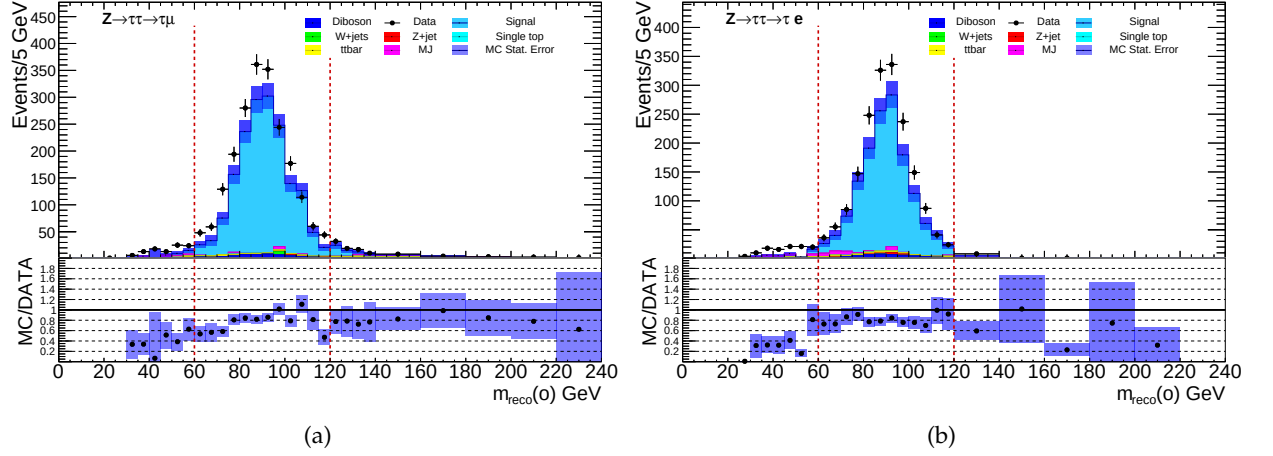
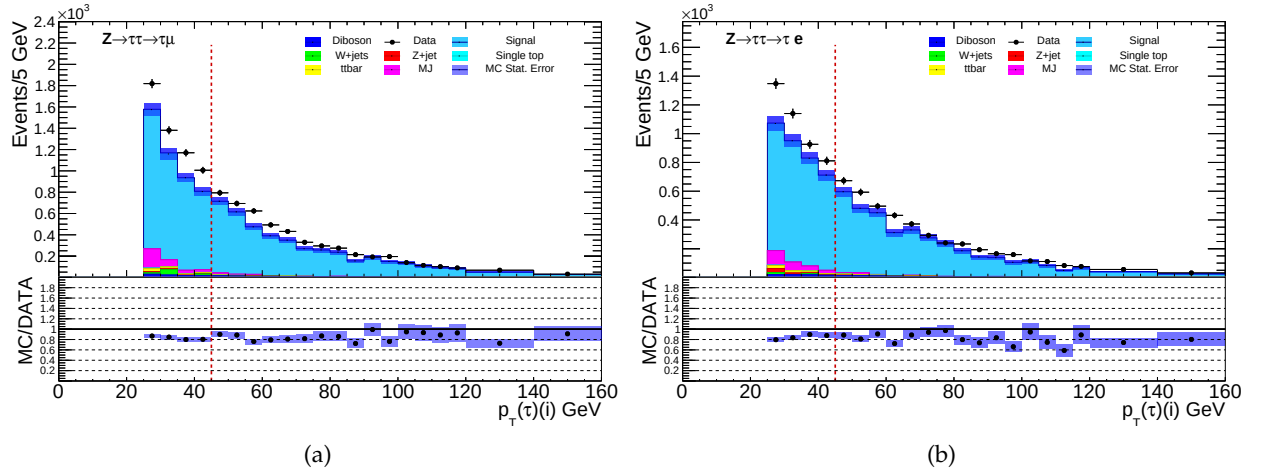
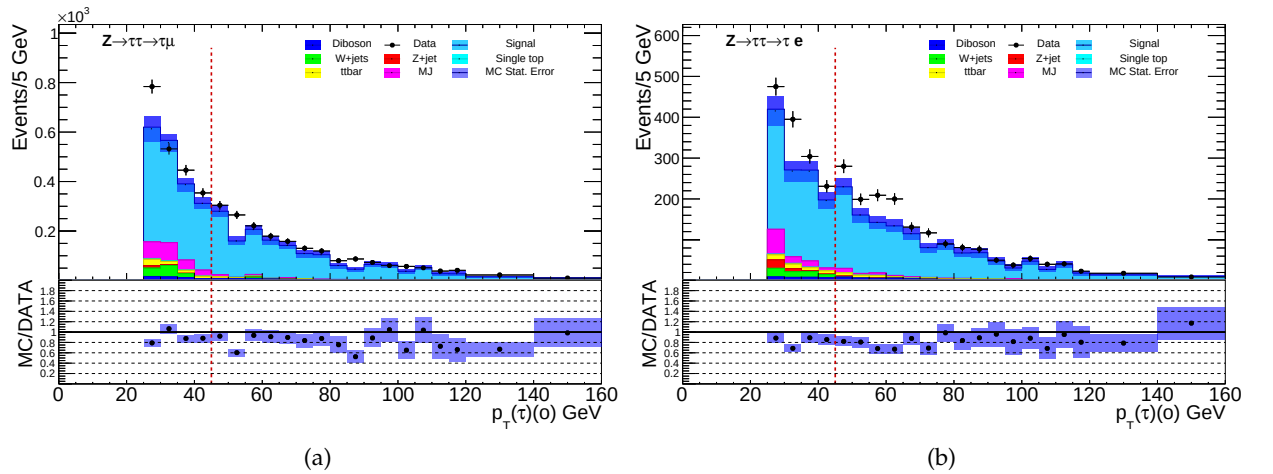
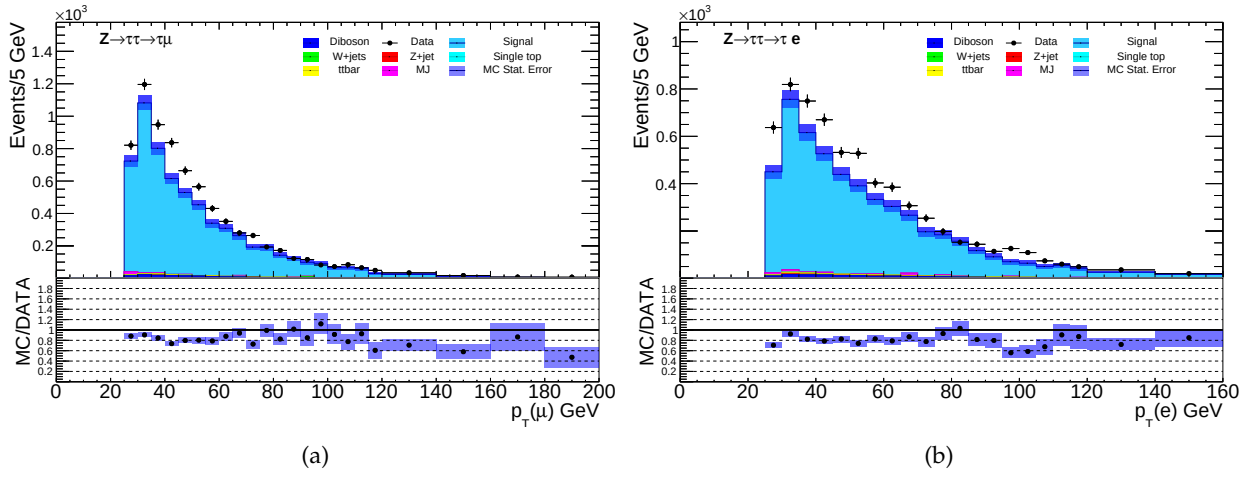
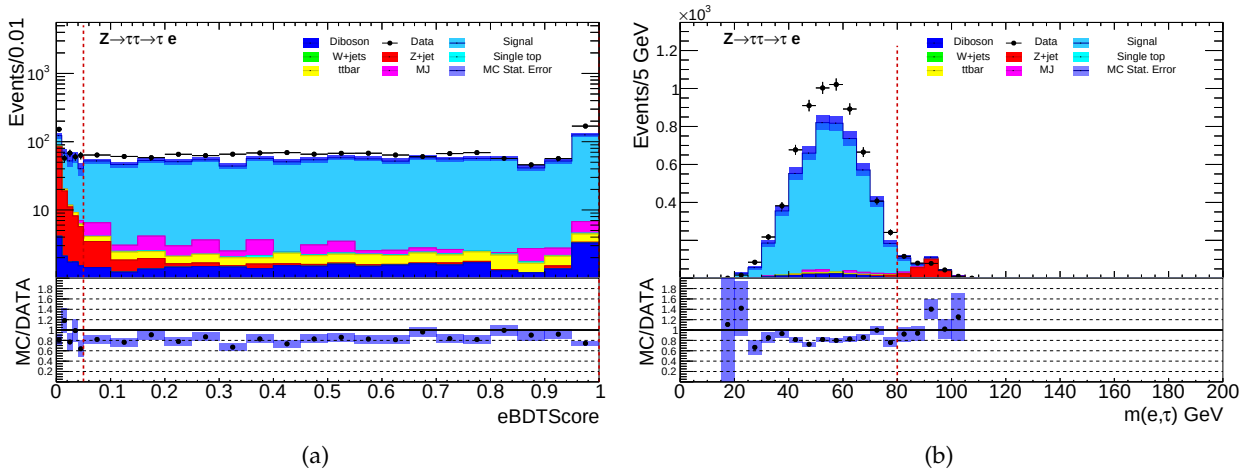
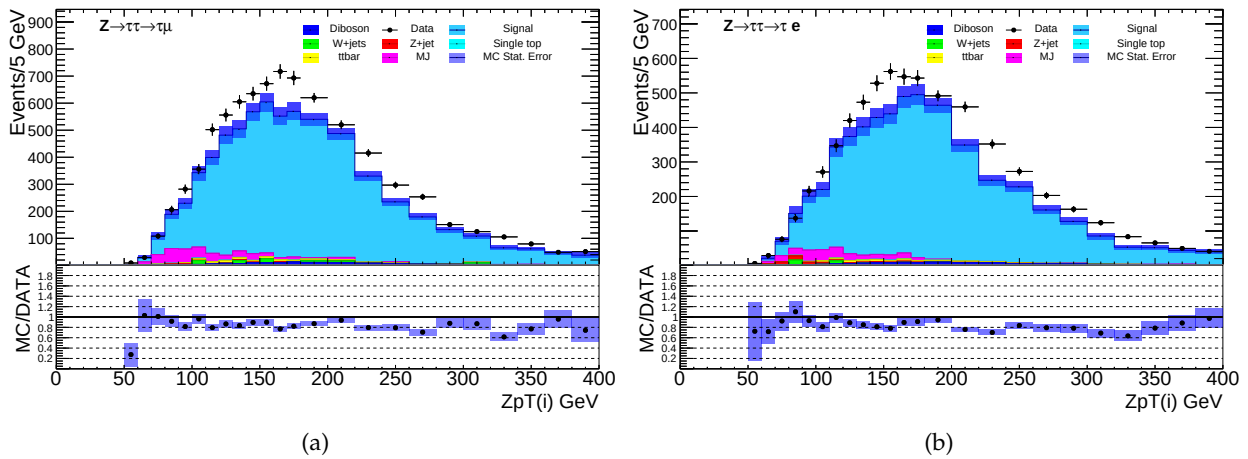


FIGURE A.47: $m_{\text{reco}(i)}$ distribution. PowHeg+Pythia8 used for MC signal.

FIGURE A.48: $m_{\text{reco}(0)}$ distribution. PowHeg+Pythia8 used for MC signal.FIGURE A.49: $\tau p_{\text{T}}(i)$ distribution. PowHeg+Pythia8 used for MC signal.FIGURE A.50: $\tau p_{\text{T}}(o)$ distribution. PowHeg+Pythia8 used for MC signal.

FIGURE A.51: Light lepton p_T distribution. PowHeg+Pythia8 used for MC signal.FIGURE A.52: $m(e, \tau_{\text{had}})$ and eBDTScore distributions. PowHeg+Pythia8 used for MC signal.FIGURE A.53: Z- p_T distribution. PowHeg+Pythia8 used for MC signal.

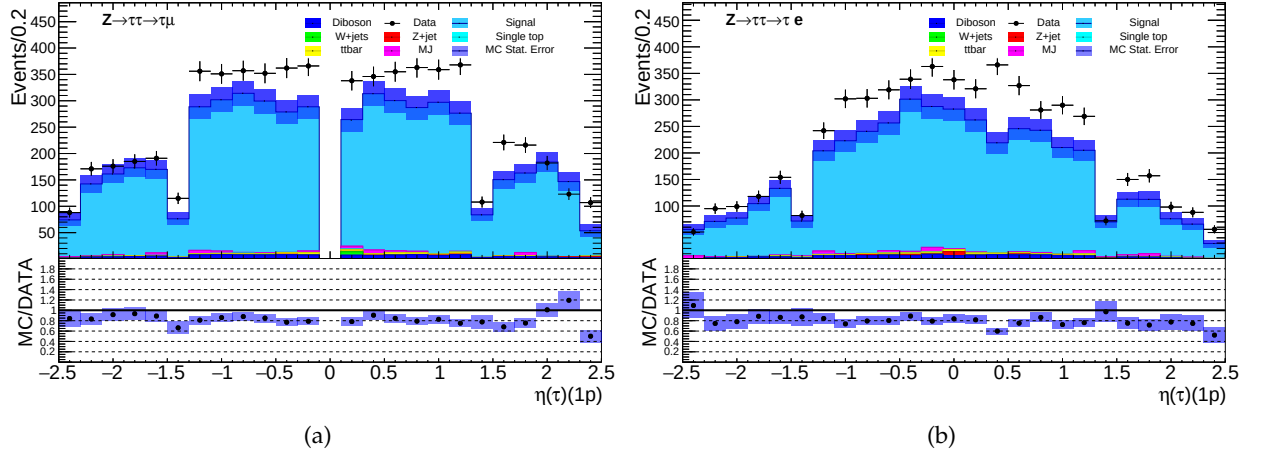


FIGURE A.54: Tau η distribution. 1-Prong taus. PowHeg+Pythia8 used for MC signal.

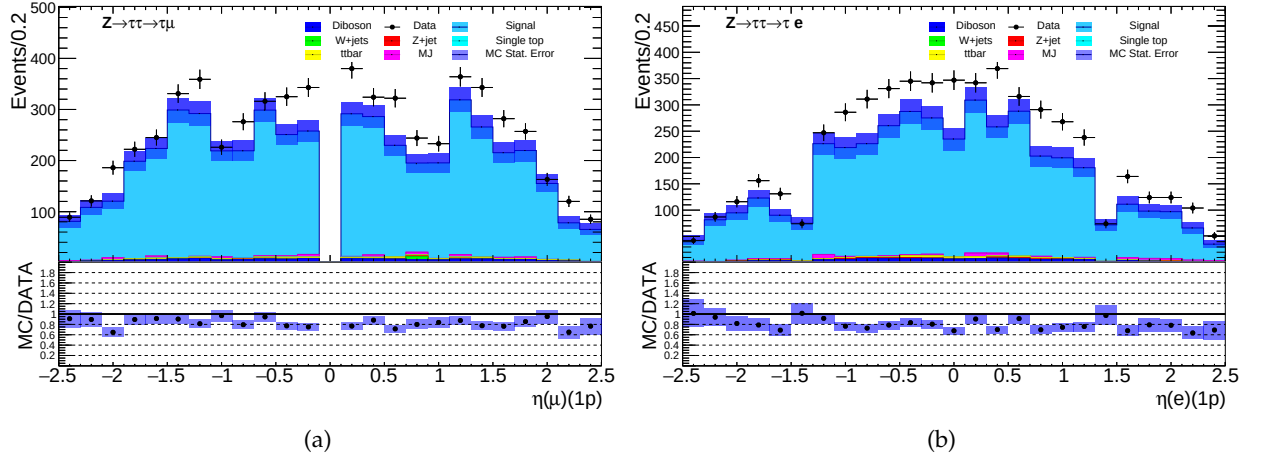


FIGURE A.55: Light lepton η distribution. 1-Prong taus. PowHeg+Pythia8 used for MC signal.

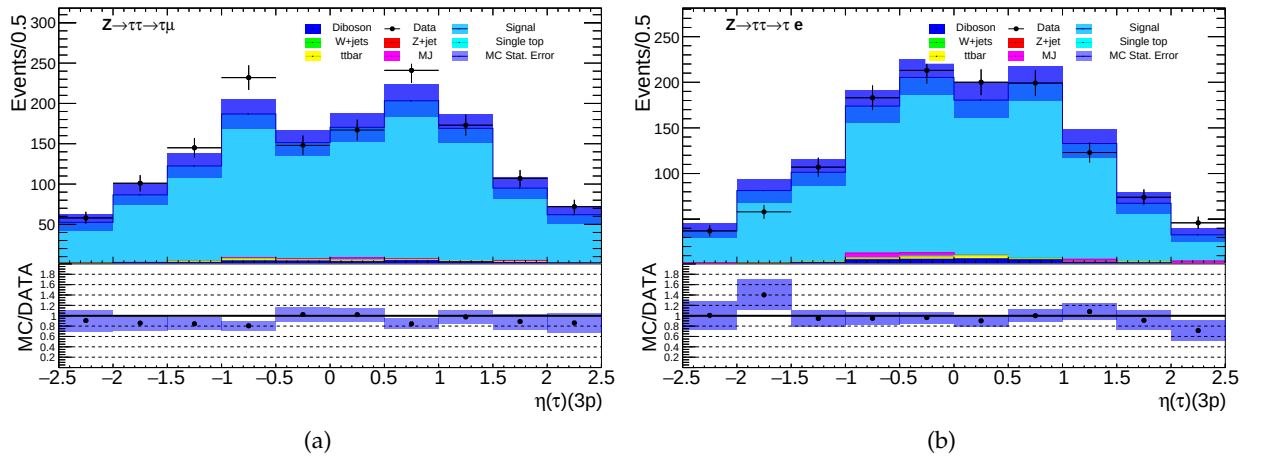


FIGURE A.56: Tau η distribution. 3-Prong taus. PowHeg+Pythia8 used for MC signal.

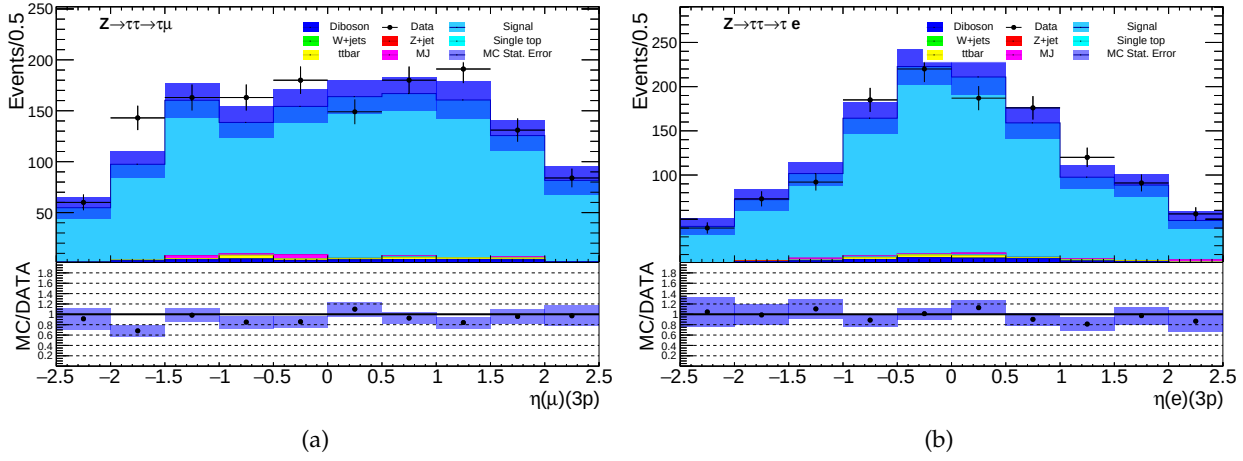


FIGURE A.57: Light lepton η distribution. 3-Prong taus. PowHeg+Pythia8 used for MC signal.

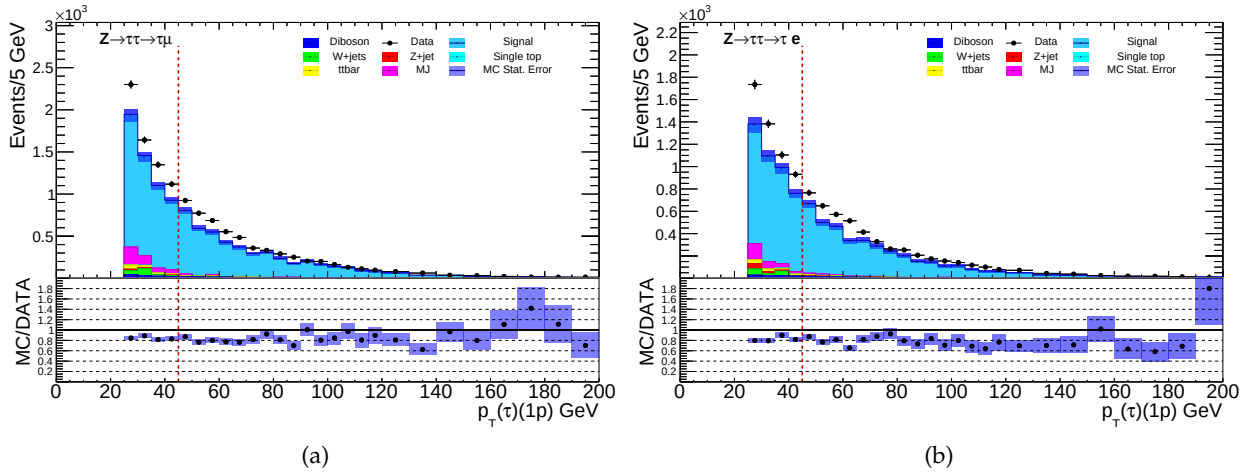


FIGURE A.58: Tau p_T distribution. 1-Prong taus. PowHeg+Pythia8 used for MC signal.

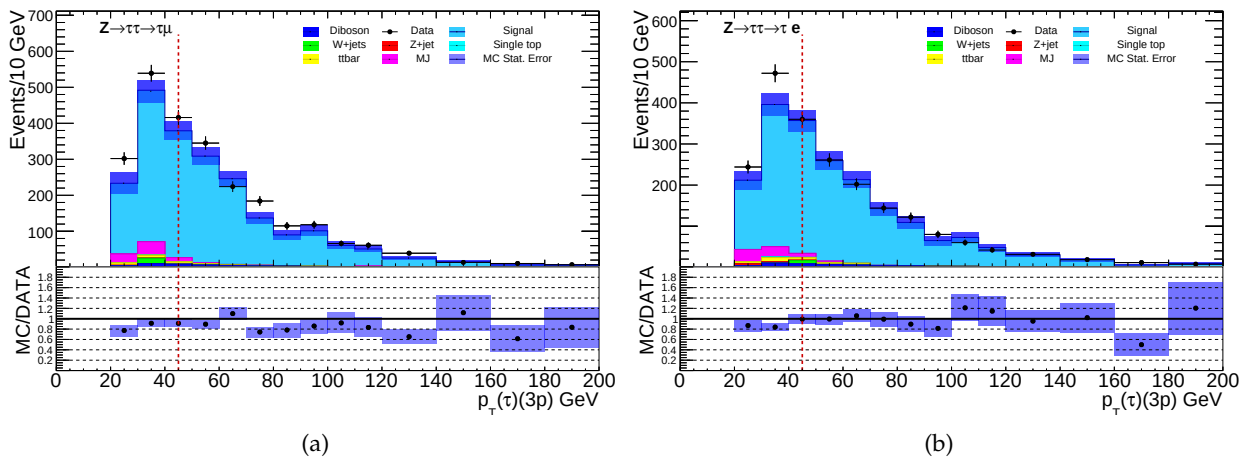
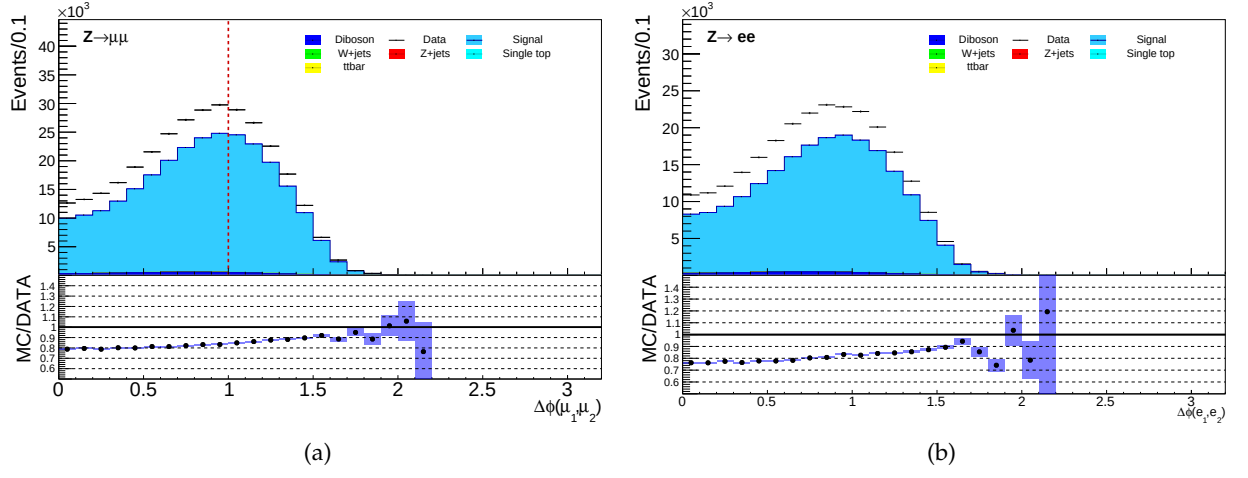
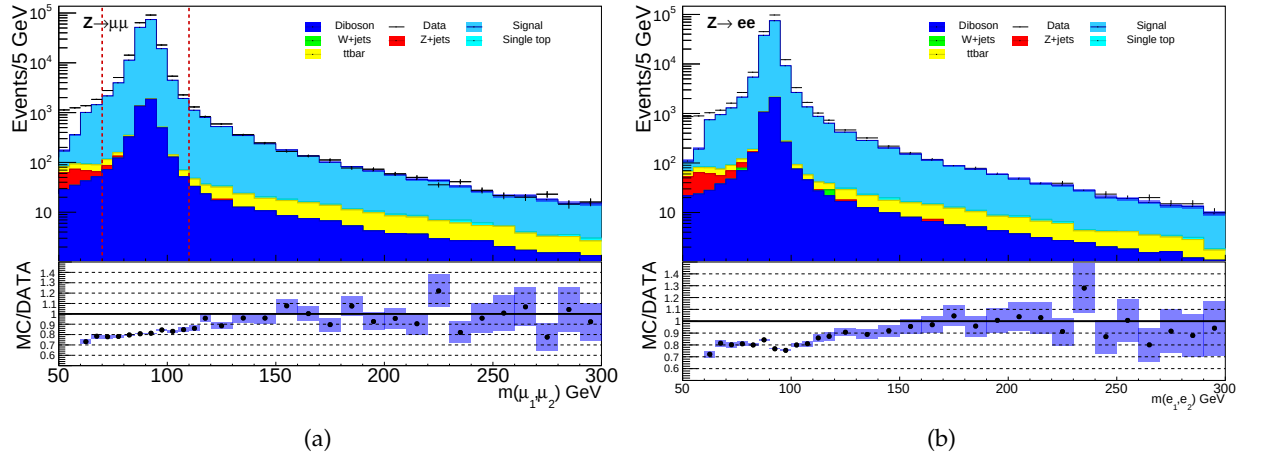
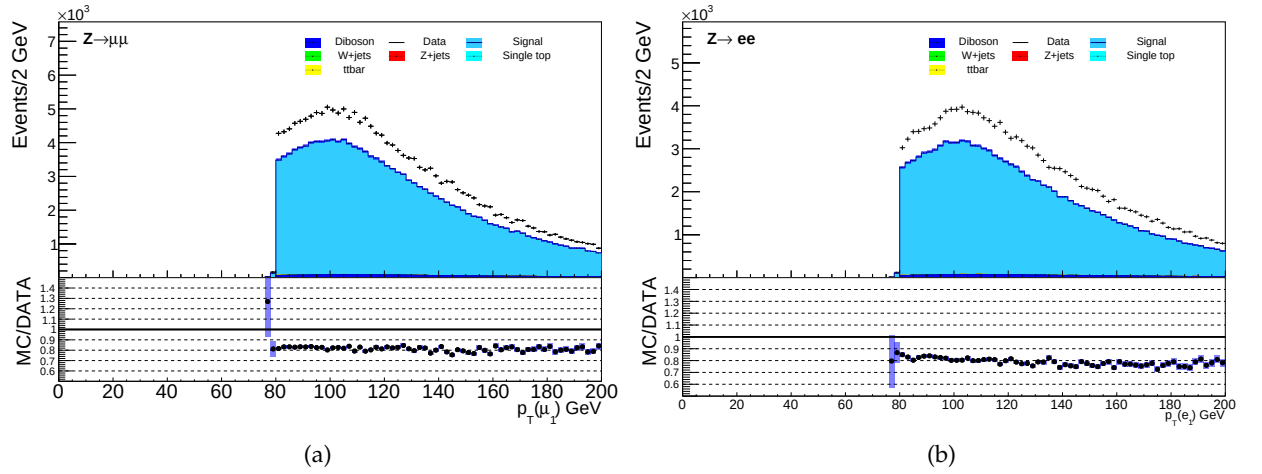
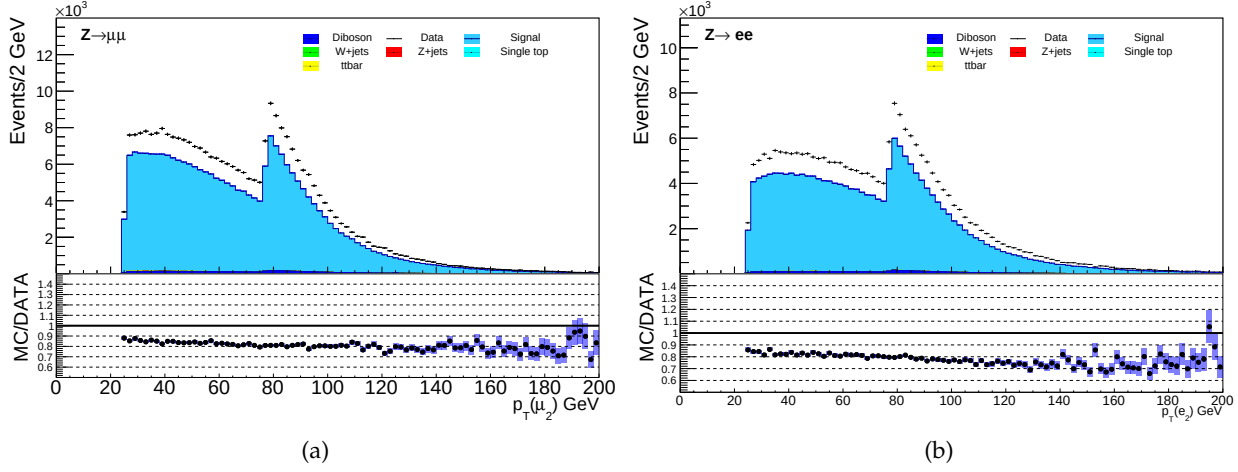
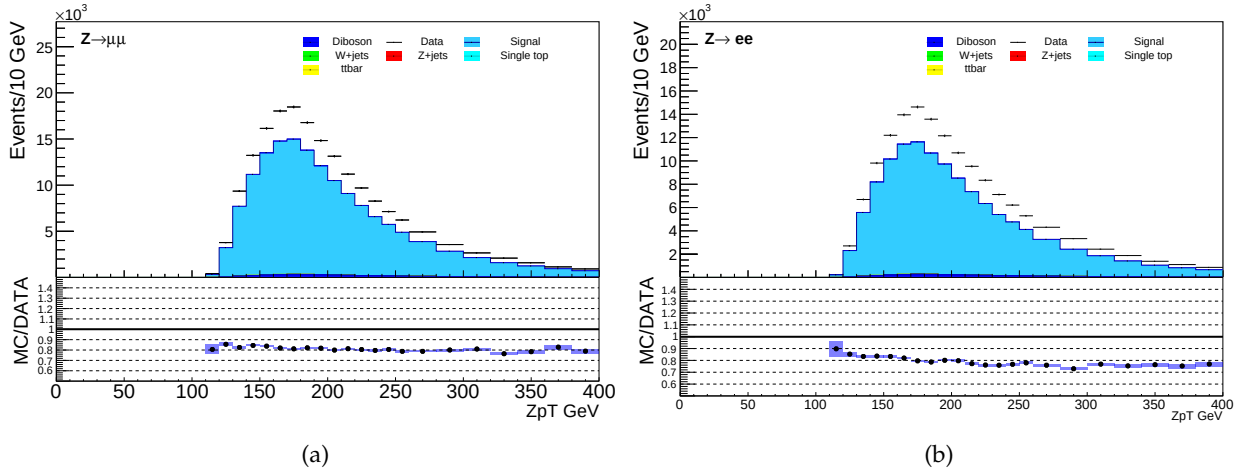
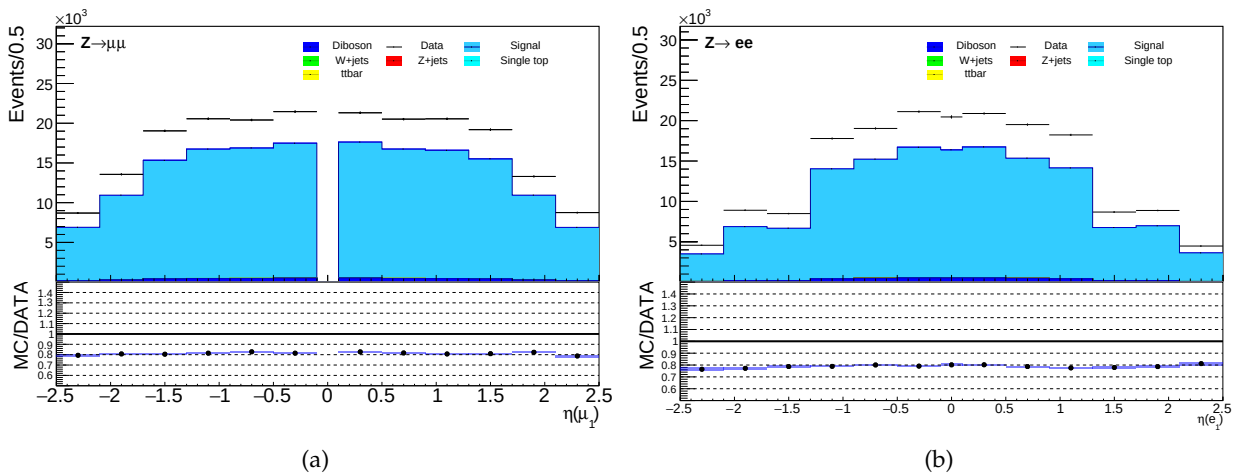


FIGURE A.59: Tau p_T distribution. 3-Prong taus. PowHeg+Pythia8 used for MC signal.

$Z \rightarrow ll$
FIGURE A.60: $\Delta\phi(l, l)$ distribution. PowHeg+Pythia8 used for MC signal.FIGURE A.61: $m(l, l)$ distribution. PowHeg+Pythia8 used for MC signal.FIGURE A.62: $p_T(l_1)$ distribution. PowHeg+Pythia8 used for MC signal.

FIGURE A.63: $p_T(l_2)$ distribution. PowHeg+Pythia8 used for MC signal.FIGURE A.64: $Z-p_T$ distribution. PowHeg+Pythia8 used for MC signal.FIGURE A.65: Leading lepton η distribution. PowHeg+Pythia8 used for MC signal.

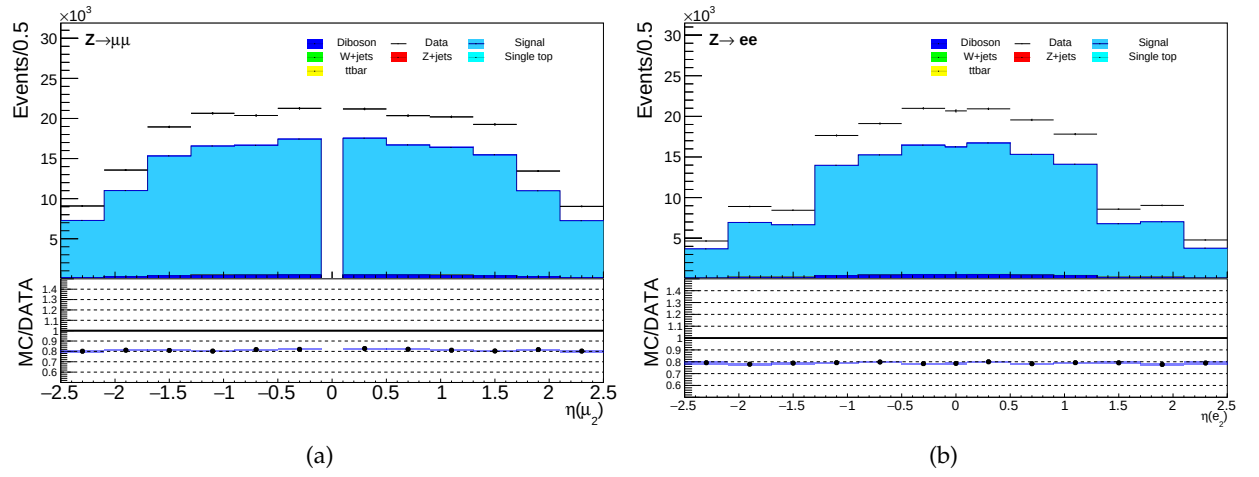


FIGURE A.66: Sub-leading lepton η distribution. PowHeg+Pythia8 used for MC signal.

A.2 $Z \rightarrow \tau_{\text{had}} e$ uncertainties

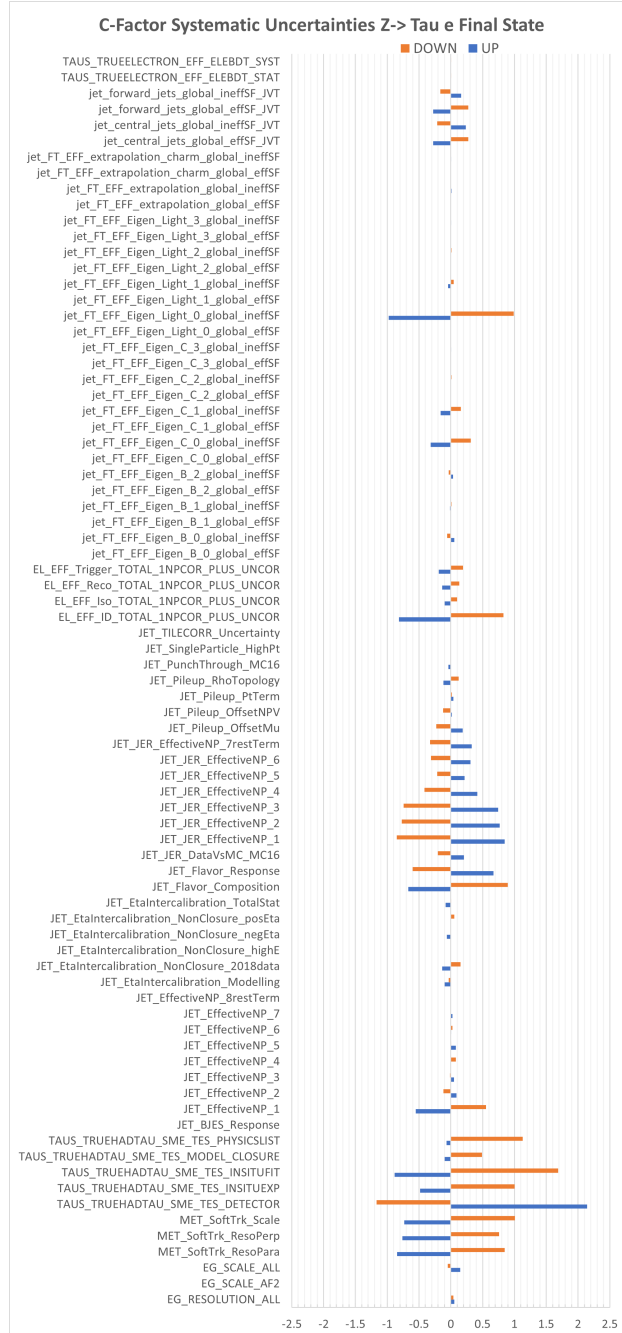
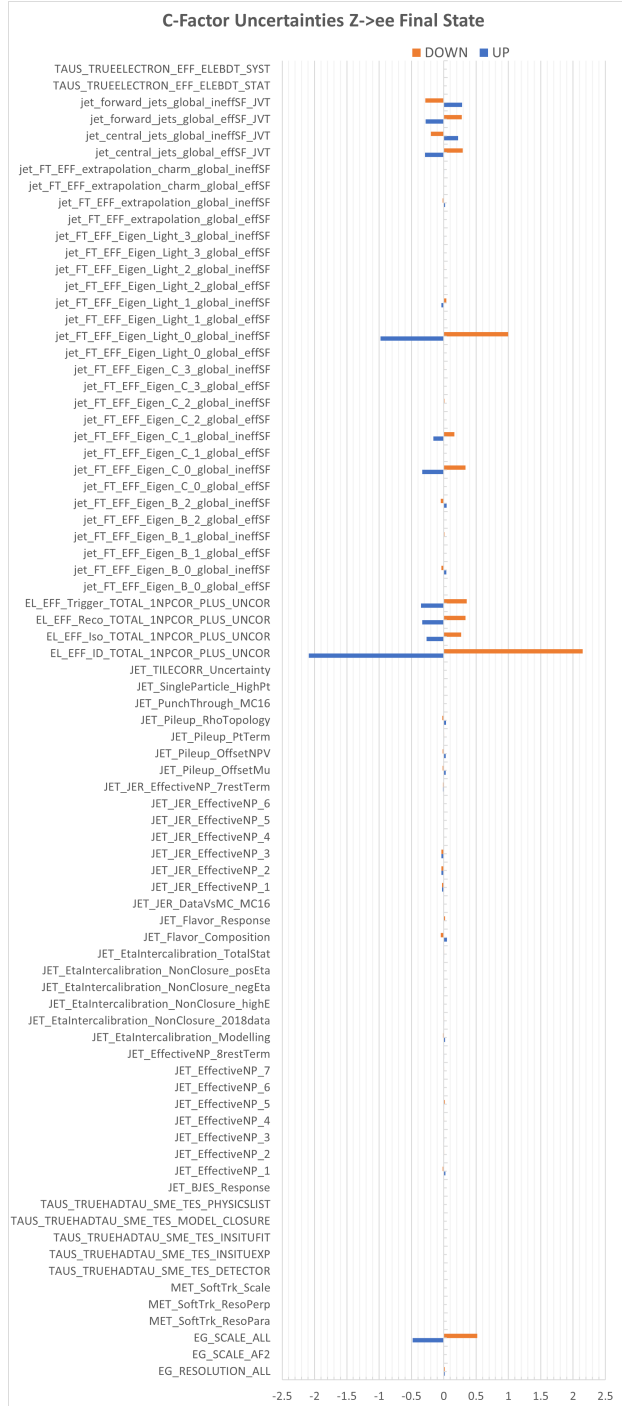
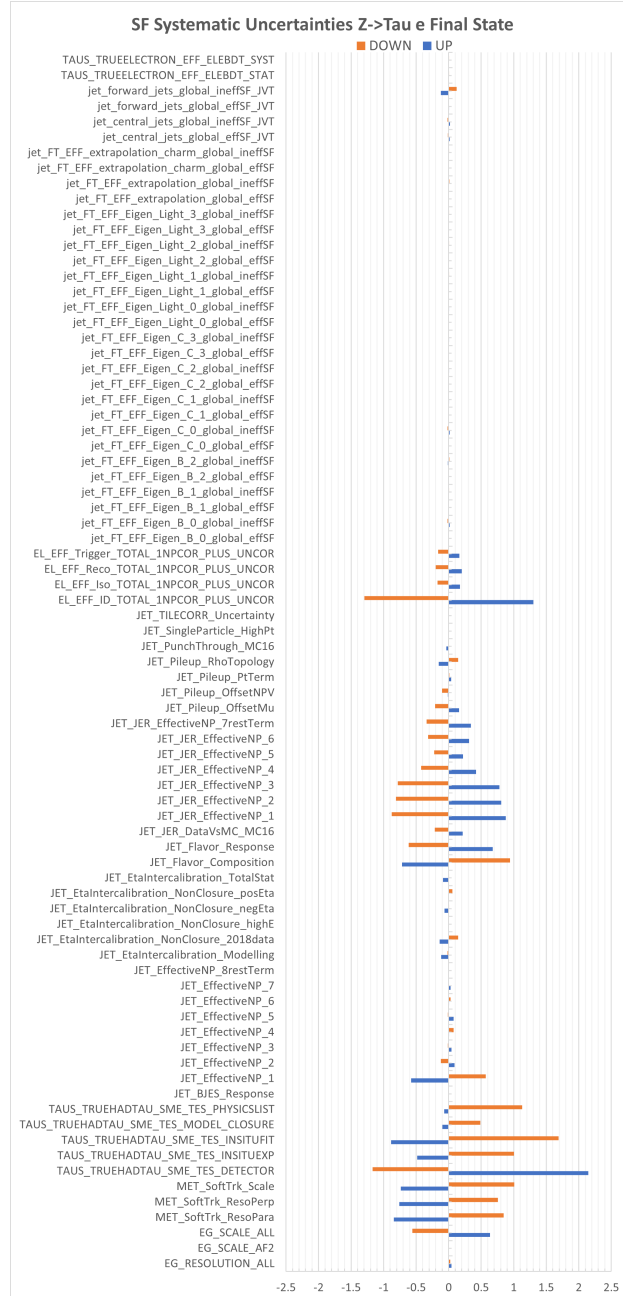
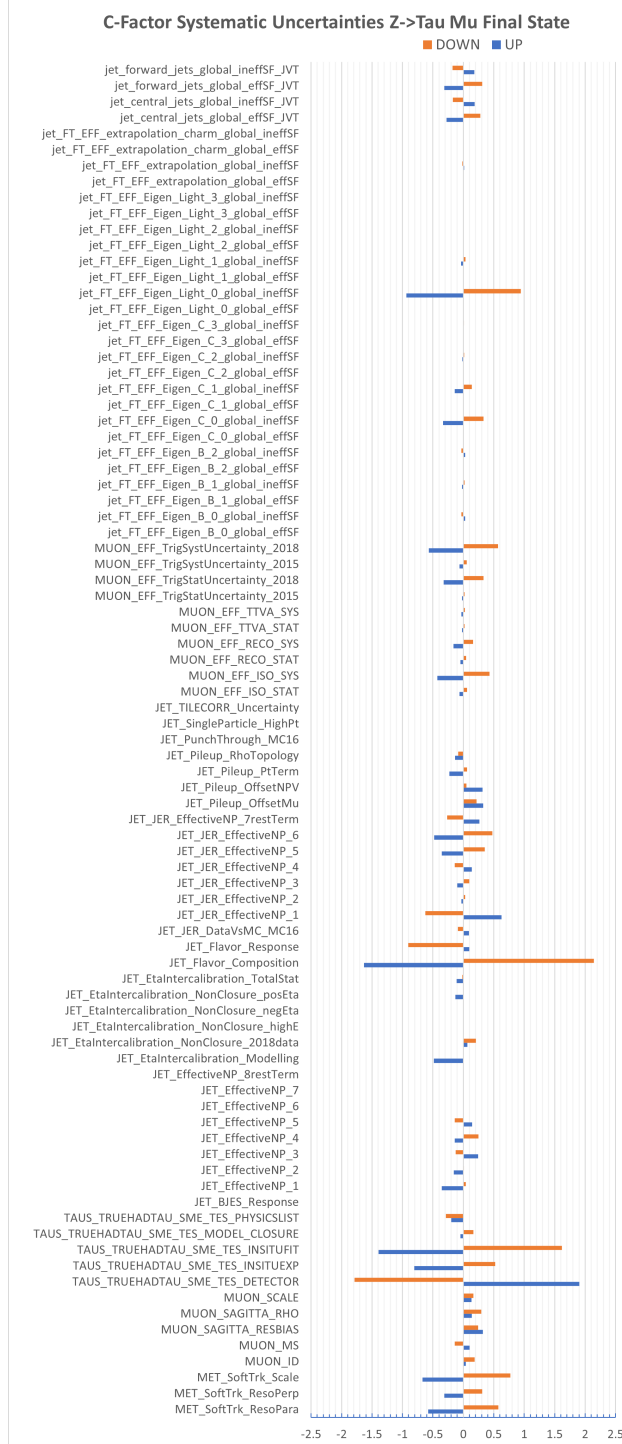
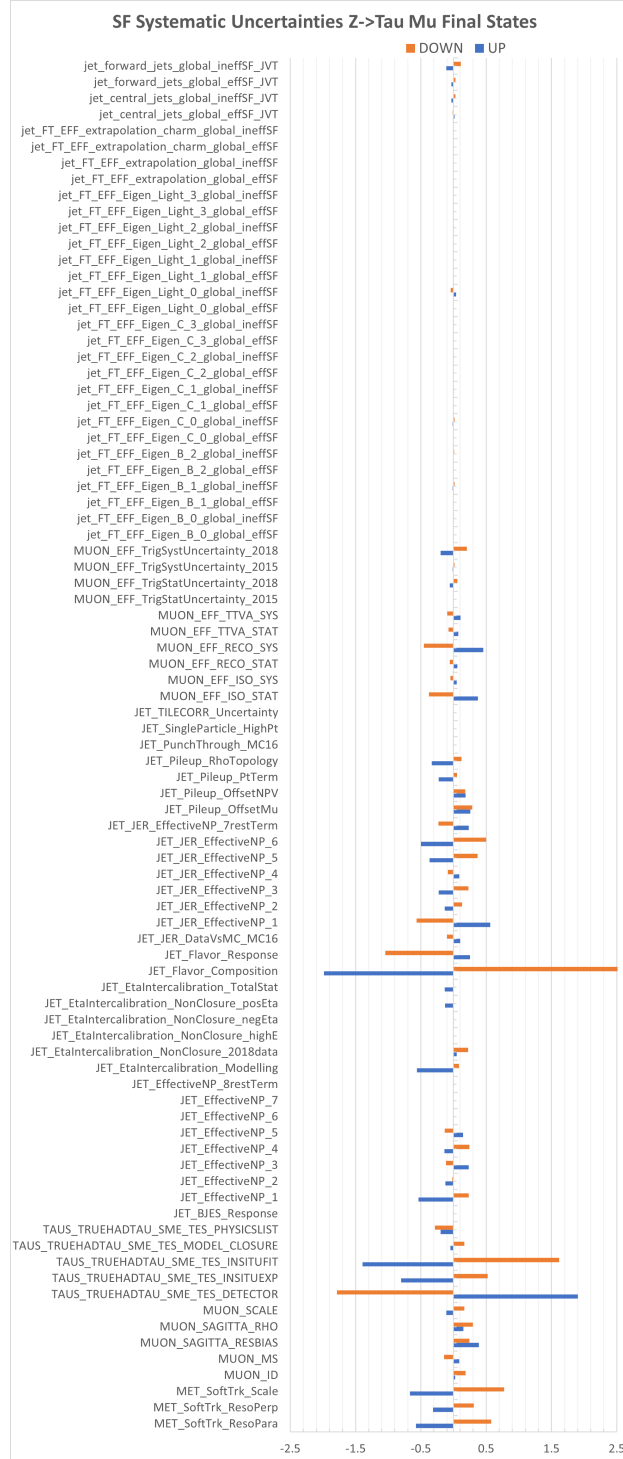


FIGURE A.67: Percentage uncertainties in the C-Factor($Z \rightarrow \tau_{\text{had}} e$) for 1-prong taus.

FIGURE A.68: Percentage uncertainties in the C-Factor($Z \rightarrow ee$).

FIGURE A.69: Percentage uncertainties in the SF($Z \rightarrow \tau_{\text{had}}e$) for 1-prong taus.

FIGURE A.70: Percentage uncertainties in the C-Factor($Z \rightarrow \tau_{\text{had}} e$) for 3-prong taus.

FIGURE A.71: Percentage uncertainties in the SF($Z \rightarrow \tau_{\text{had}} e$) for 3-prong taus.

Appendix B

VBF lepton universality measurement

B.1 Data and MC $Z \rightarrow \tau\tau$ out of the box comparisons

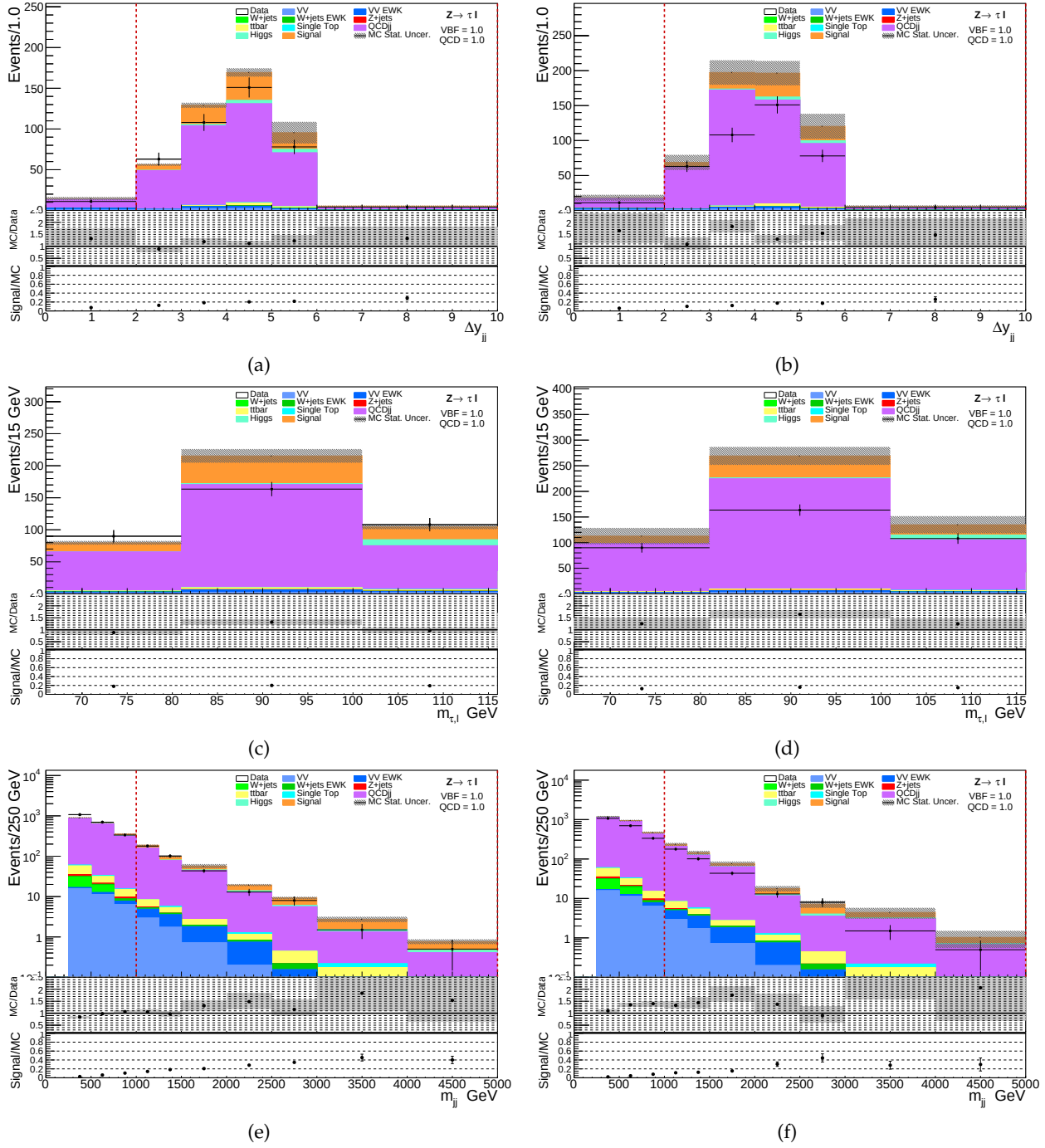


FIGURE B.1: Data-MC comparisons for different kinematic variables in the $Z \rightarrow \tau_{\text{had}} \tau_{\text{lep}}$ final state. The plots on the left column correspond to the SHERPA 2.2.1 prediction for the QCDij process and the ones on the right to MadGraph@LO. These plots show the modelling before the re-weighting described in Section 6.4.1.

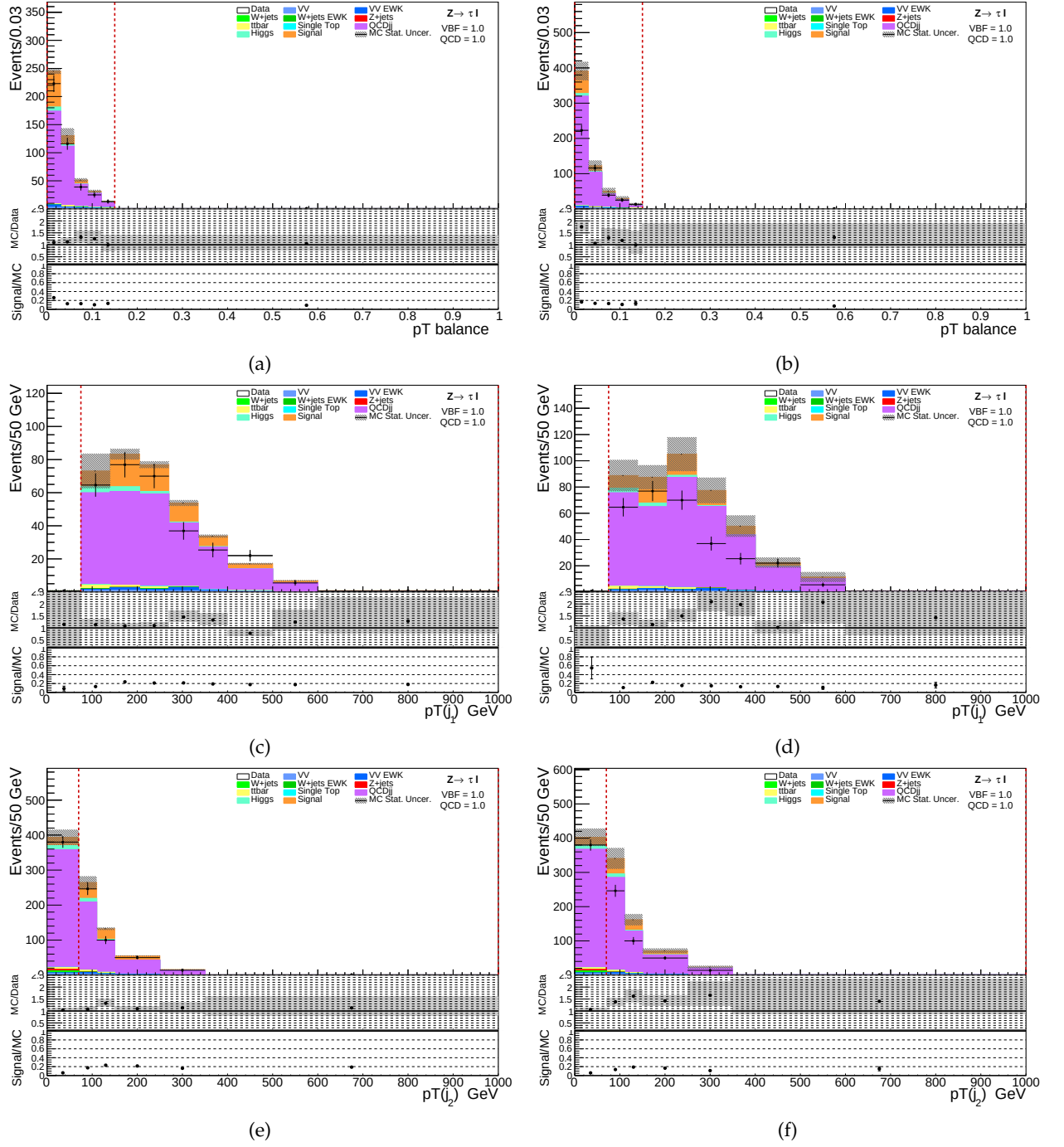


FIGURE B.2: Data-MC comparisons for different kinematic variables in the $Z \rightarrow \tau_{\text{had}} \tau_{\text{lep}}$ final state. The plots on the left column correspond to the SHERPA 2.2.1 prediction for the QCDjj process and the ones on the right to MadGraph@LO. These plots show the modelling before the re-weighting described in Section 6.4.1.

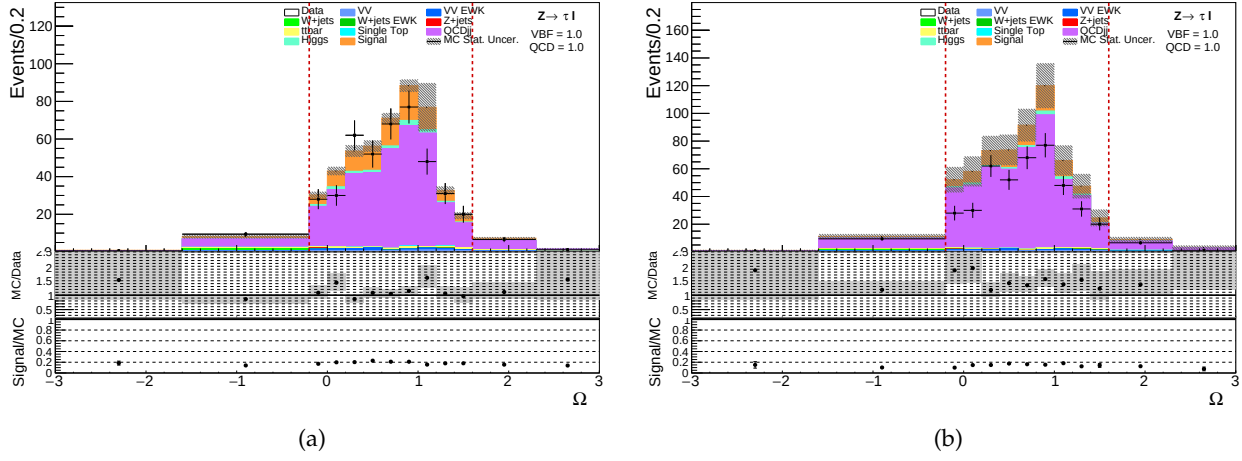


FIGURE B.3: Data-MC comparisons for different kinematic variables in the $Z \rightarrow \tau_{\text{had}} \tau_{\text{lep}}$ final state. The plots on the left column correspond to the SHERPA 2.2.1 prediction for the QCDjj process and the ones on the right to MadGraph@LO. These plots show the modelling before the re-weighting described in Section 6.4.1.

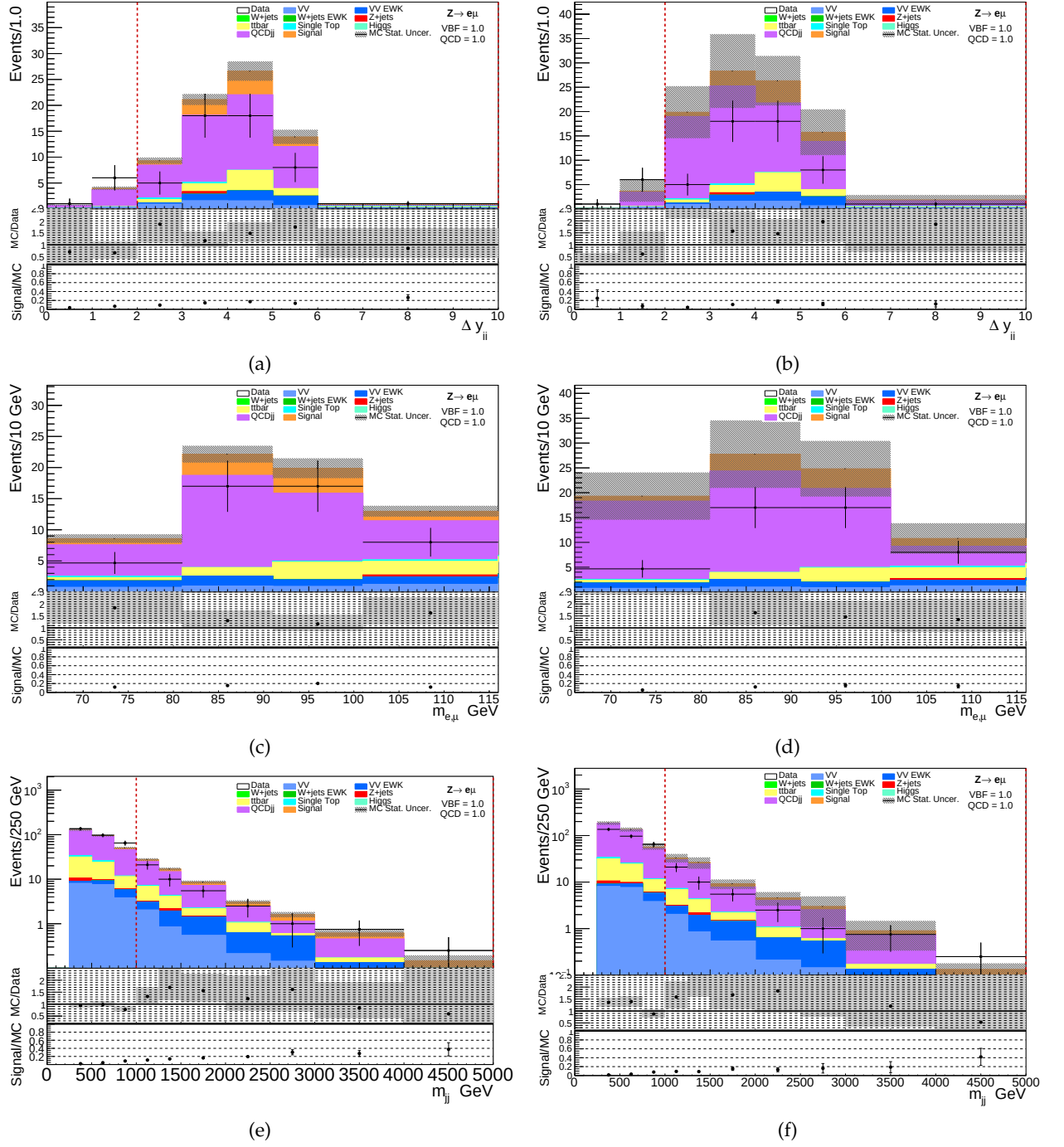


FIGURE B.4: Data-MC comparisons for different kinematic variables in the $Z \rightarrow \tau_{\text{lep}}\tau_{\text{lep}}$ final state. The plots on the left column correspond to the SHERPA 2.2.1 prediction and the ones on the right to MadGraph@LO. These plots show the modelling before the re-weighting described in Section 6.4.1.

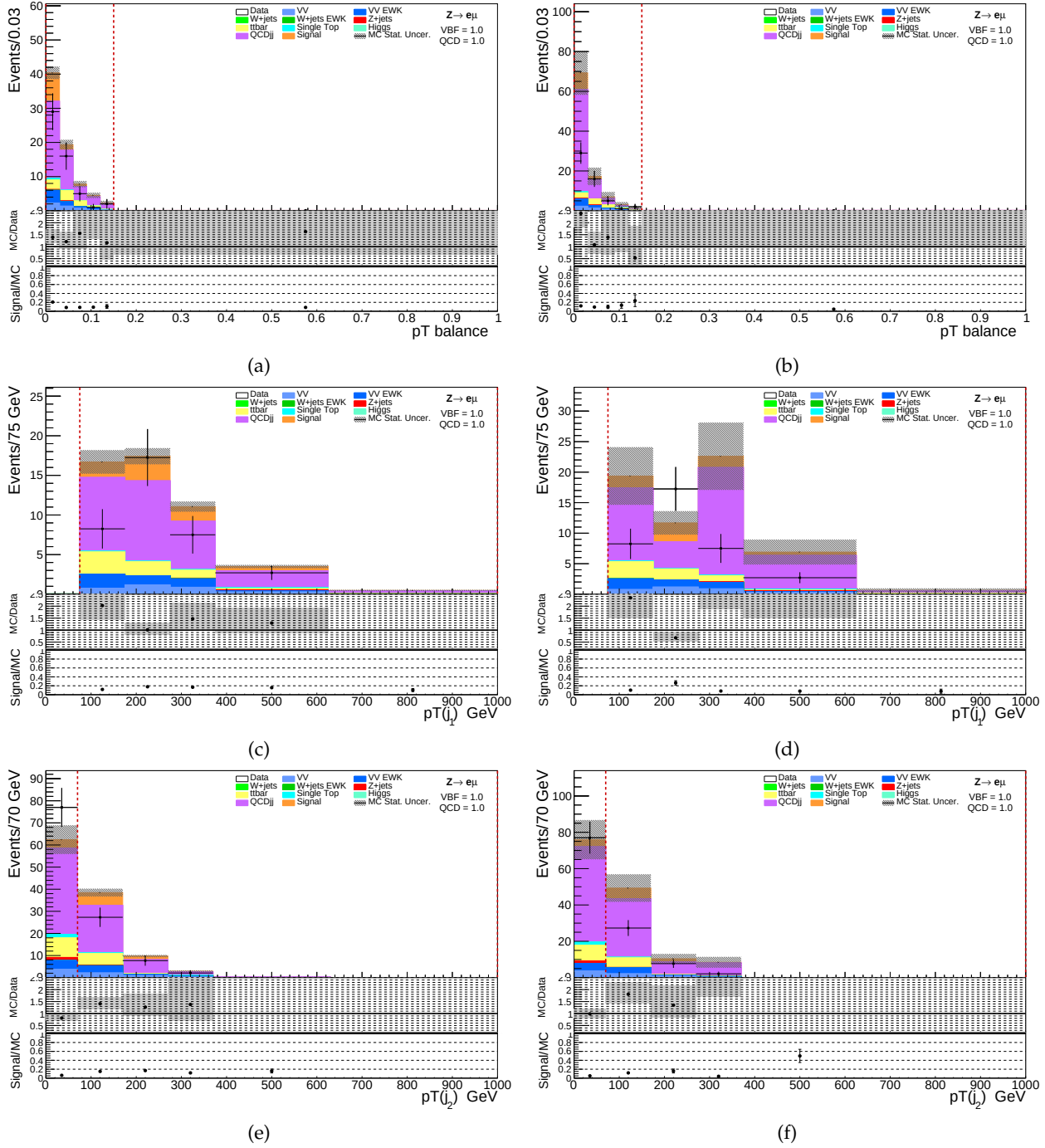


FIGURE B.5: Data-MC comparisons for different kinematic variables in the $Z \rightarrow \tau_{\text{lep}} \tau_{\text{lep}}$ final state. The plots on the left column correspond to the SHERPA 2.2.1 prediction and the ones on the right to MadGraph@LO. These plots show the modelling before the re-weighting described in Section 6.4.1.

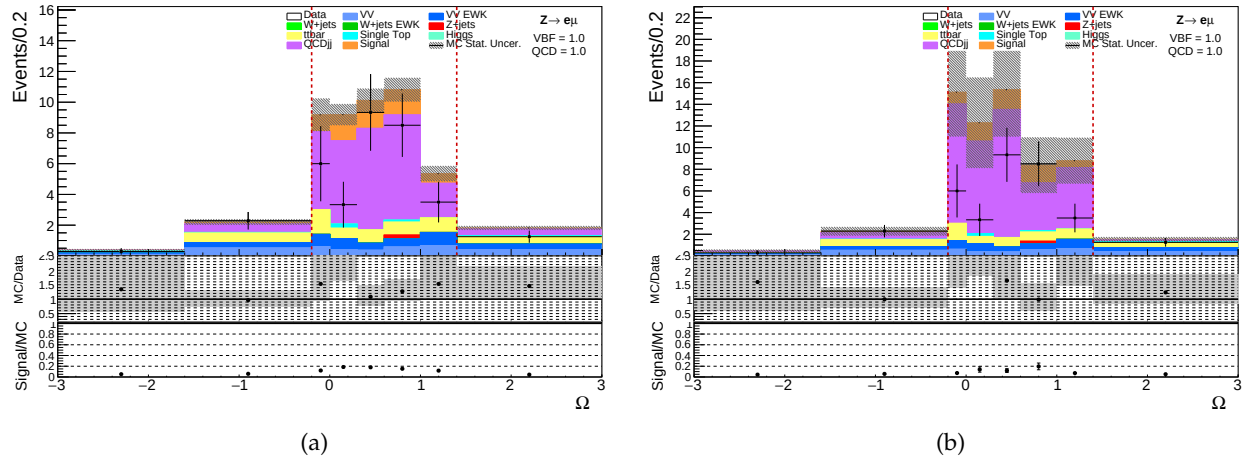


FIGURE B.6: Data-MC comparisons for different kinematic variables in the $Z \rightarrow \tau_{\text{lep}} \tau_{\text{lep}}$ final state. The plots on the left column correspond to the SHERPA 2.2.1 prediction and the ones on the right to MadGraph@LO. These plots show the modelling before the re-weighting described in Section 6.4.1.

B.2 Data-to-MC (alternative) out of the box comparisons

These plots correspond to the selection described in Table 6.2.

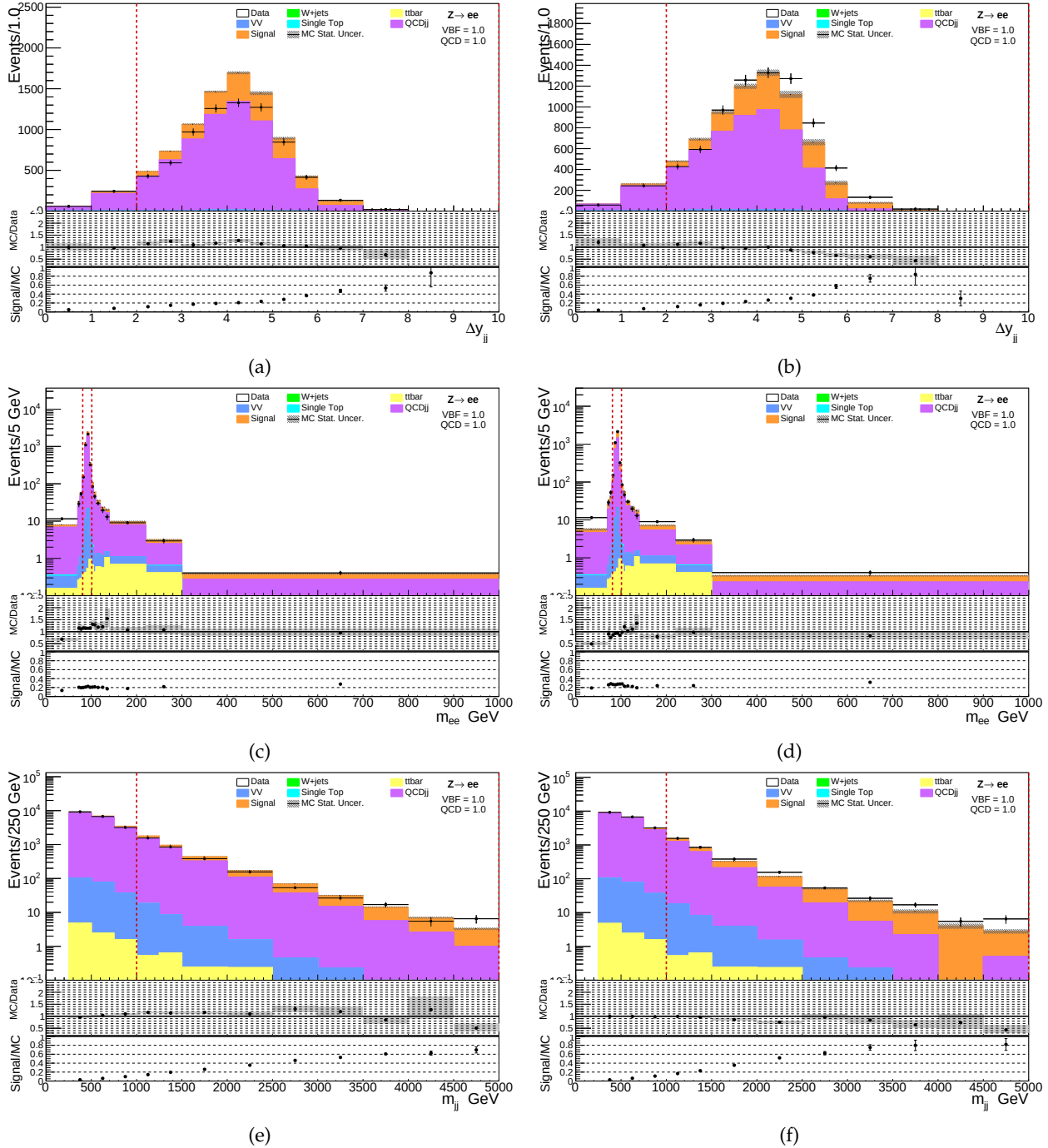


FIGURE B.7: Data-MC comparisons for different kinematic variables in the $Z \rightarrow ee$ final state. The plots on the left column correspond to the SHERPA 2.2.11 prediction and the ones on the right to MadGraph@NLO.

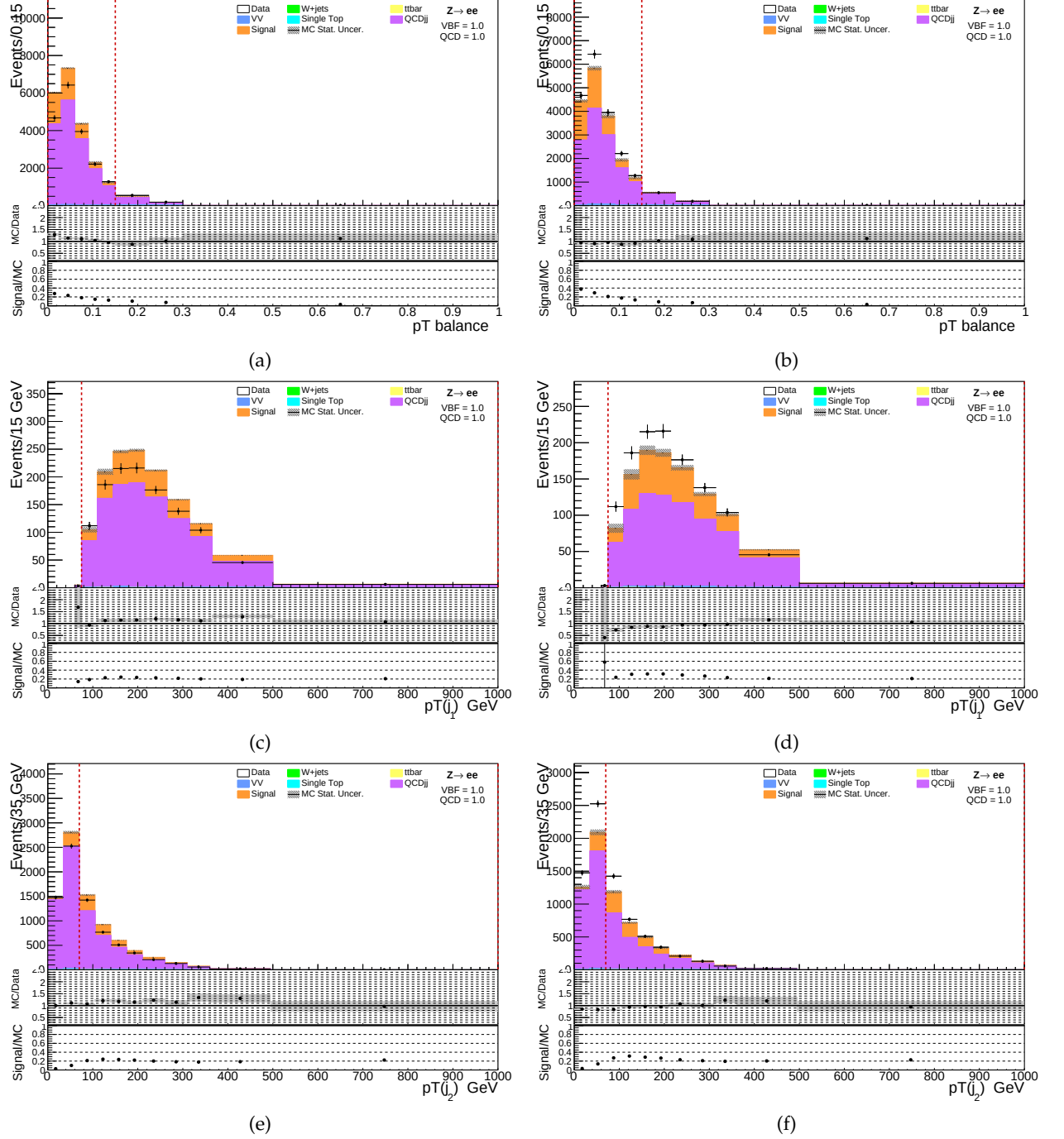


FIGURE B.8: Data-MC comparisons for different kinematic variables in the $Z \rightarrow ee$ final state. The plots on the left column correspond to the SHERPA 2.2.11 prediction and the ones on the right to MadGraph@NLO.

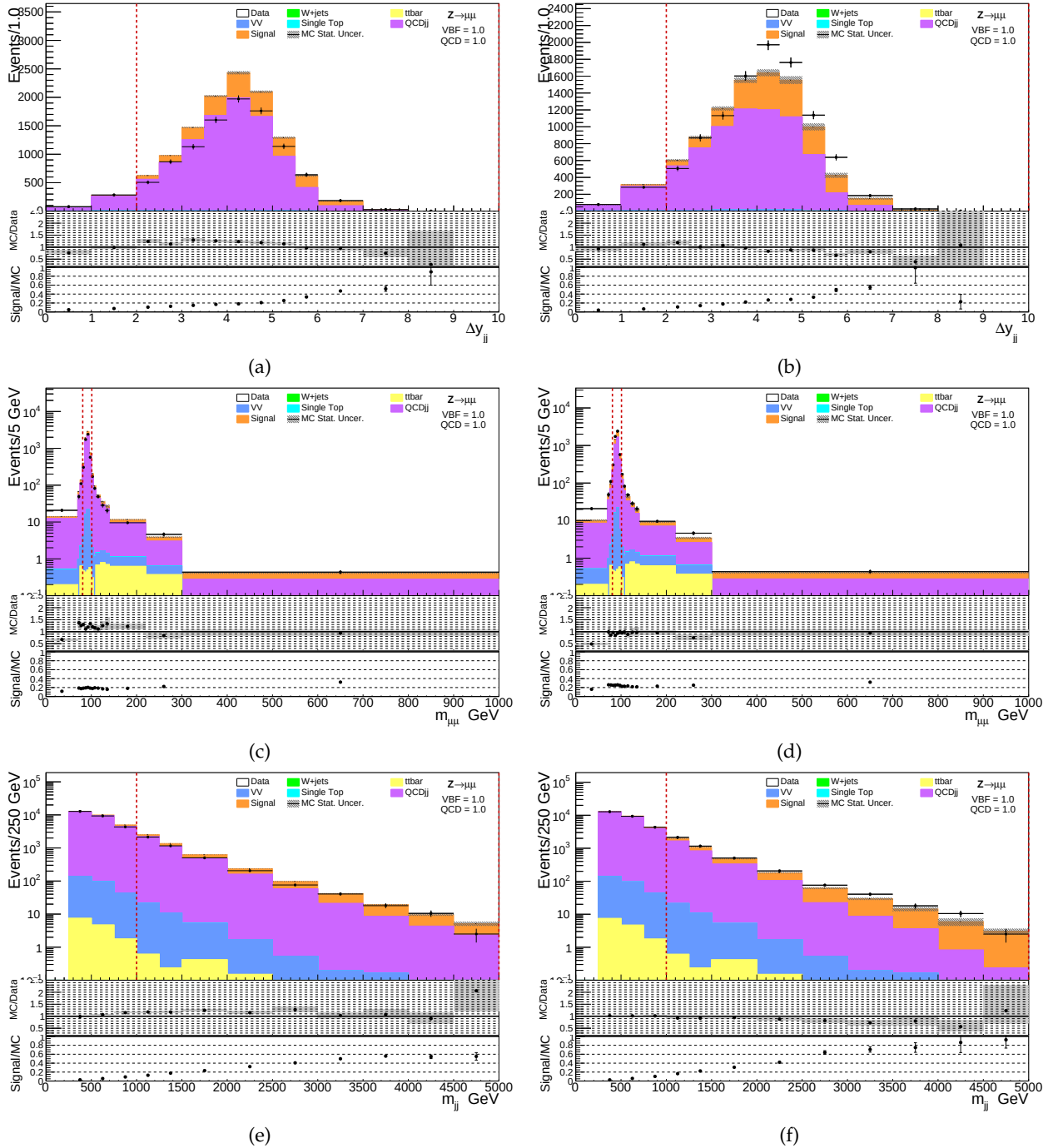


FIGURE B.9: Data-MC comparisons for different kinematic variables in the $Z \rightarrow \mu\mu$ final state. The plots on the left column correspond to the SHERPA 2.2.11 prediction and the ones on the right to MadGraph@NLO.

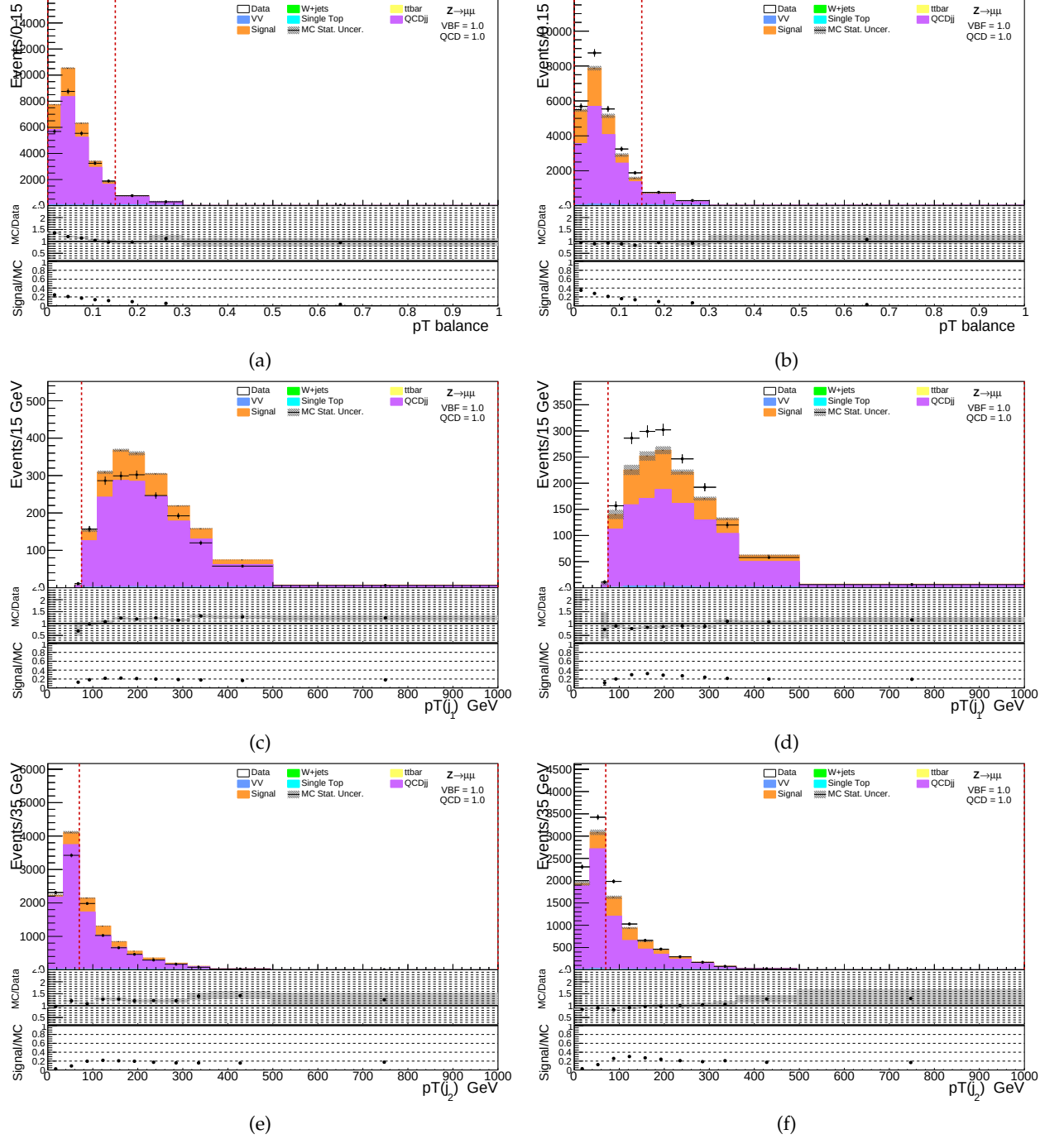


FIGURE B.10: Data-MC comparisons for different kinematic variables in the $Z \rightarrow \mu\mu$ final state. The plots on the left column correspond to the SHERPA 2.2.11 prediction and the ones on the right to MadGraph@NLO.

B.3 Data-to-MC out of the box comparisons QCDjj control regions

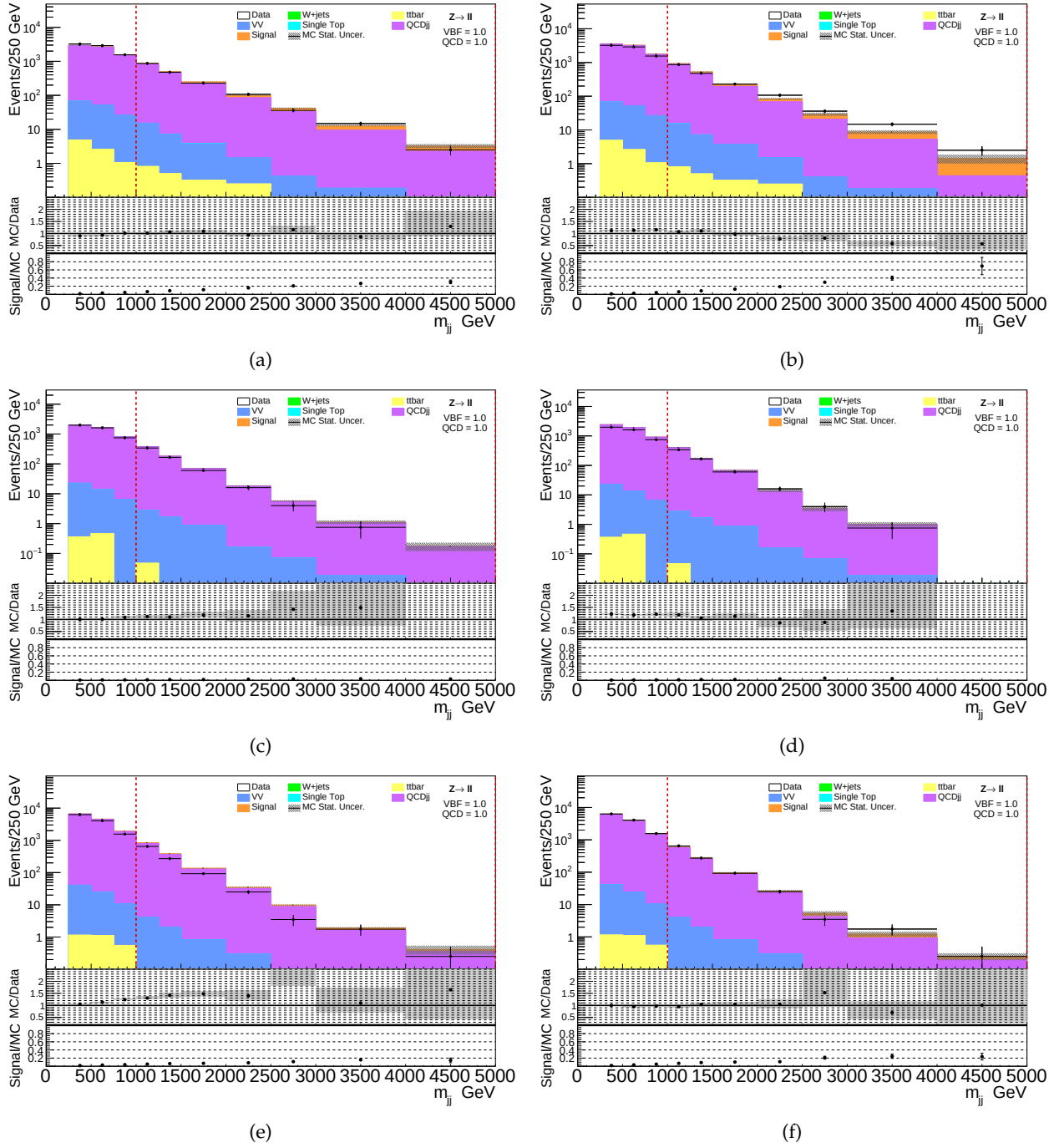


FIGURE B.11: Data-MC comparisons for different CRs in the $Z \rightarrow ll = Z \rightarrow ee + Z \rightarrow \mu\mu$ final state. The plots on the left column correspond to the SHERPA 2.2.11 prediction and the ones on the right to MadGraph@NLO. Figures (a)(b), (c)(d) and (e)(f) correspond to CRa, CRb and CRc, respectively. The dominant contributions in all the regions is from the QCDjj process.

B.4 Data-to-MC (alternative) after re-weighting comparisons QCDjj control regions

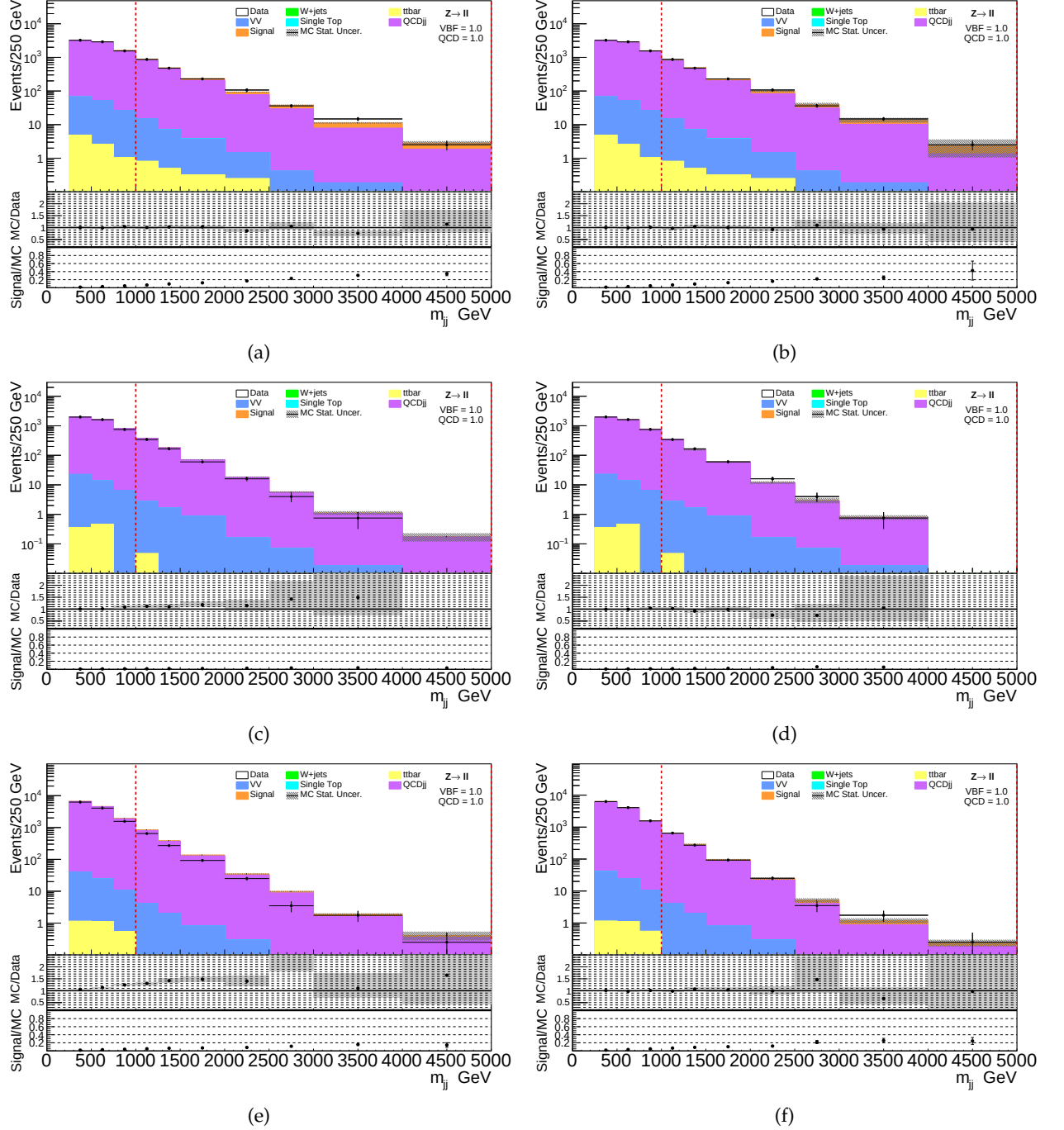


FIGURE B.12: Data-MC comparisons after the m_{jj} -based re-weighting for the different CRs in the $Z \rightarrow ll = Z \rightarrow ee + Z \rightarrow \mu\mu$ final state. The plots on the left column correspond to the SHERPA 2.2.11 prediction and the ones on the right to MadGraph@NLO. Figures (a)(b), (c)(d) and (e)(f) correspond to CRa, CRb and CRc, respectively.

B.5 Data-to-MC comparisons in MJ enhanced region at high-mass in $Z \rightarrow \tau_{\text{had}} \tau_{\text{lep}}$

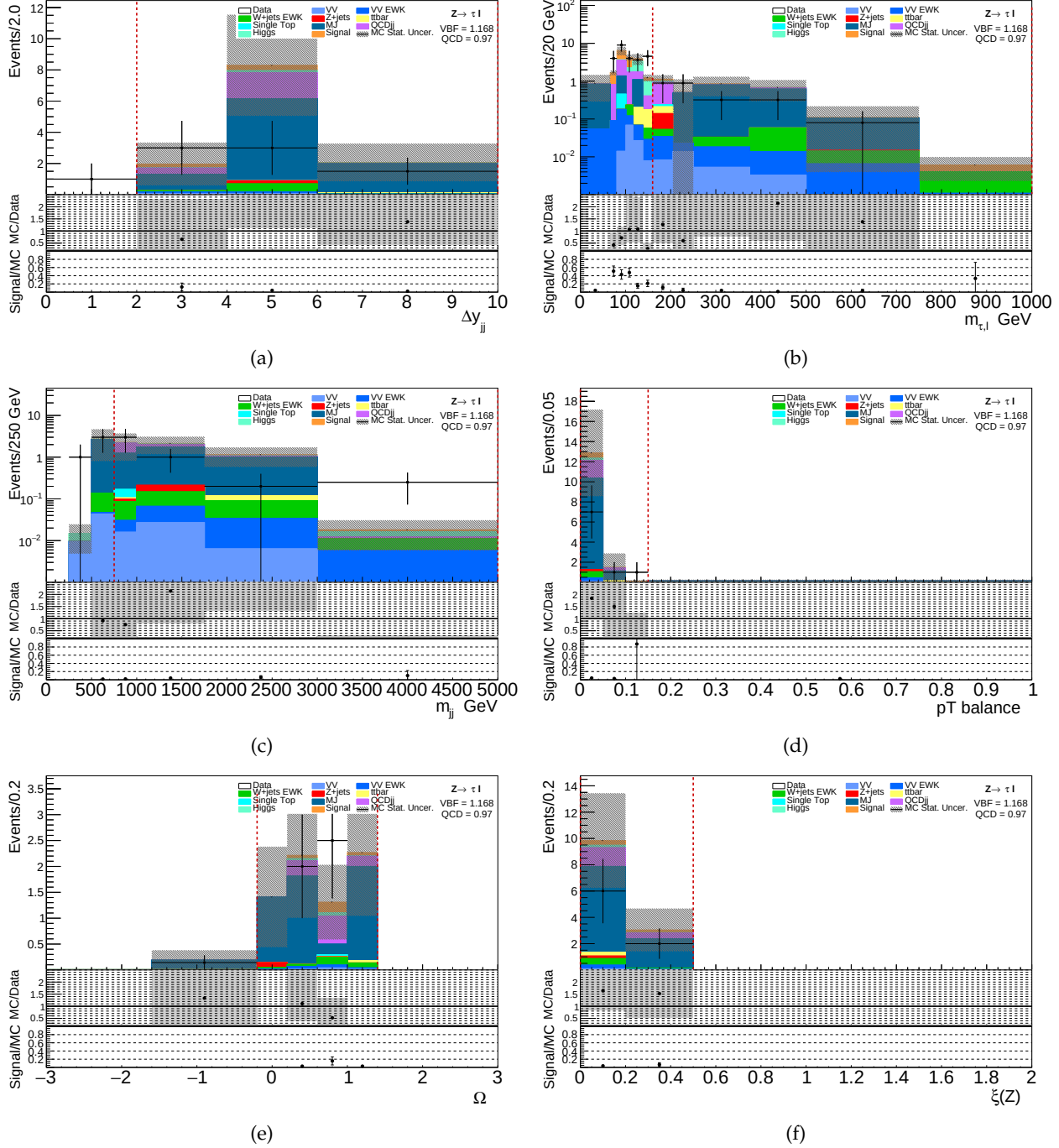


FIGURE B.13: Data-MC comparisons for various kinematic variables in the $Z \rightarrow \tau_{\text{had}} \tau_{\text{lep}}$ high-mass region enhanced in MJ events. This sample is composed of events that pass the selection described in Table 7.6 but have a loose-not-medium τ_{had} candidate, or a non-isolated light-lepton, or both.

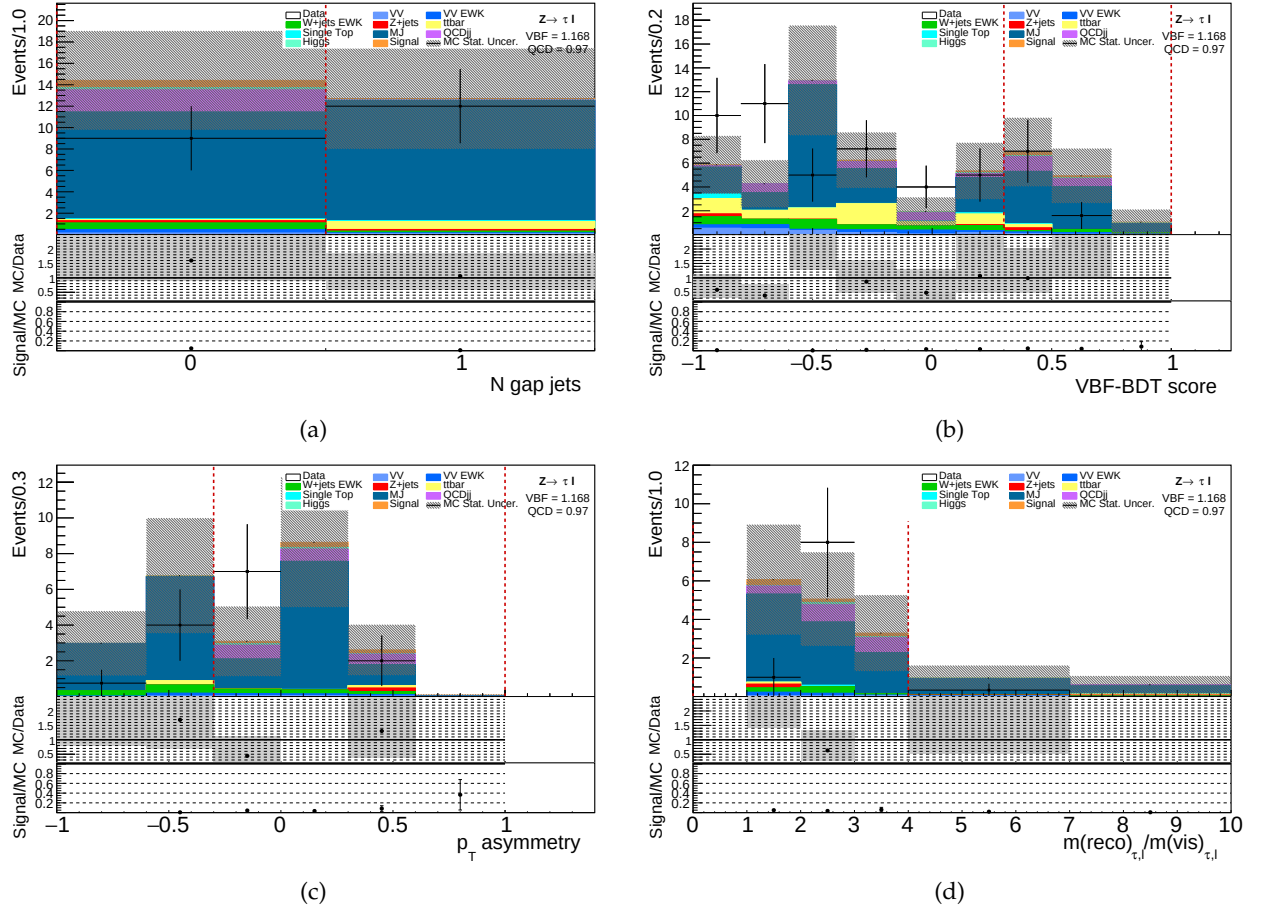


FIGURE B.14: Data-MC comparisons for various kinematic variables in the $Z \rightarrow \tau_{\text{had}} \tau_{\text{lep}}$ high-mass region enhanced in MJ events. This sample is composed of events that pass the selection described in Table 7.6 but have a loose-not-medium τ_{had} candidate, or a non-isolated light-lepton, or both.

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