



DEPARTAMENTO DE FÍSICA MODERNA
UNIVERSIDAD DE CANTABRIA



INSTITUTO DE FÍSICA DE CANTABRIA
IFCA (CSIC-UC)

MEDIDA DE LA SECCIÓN EFICAZ
DE PRODUCCIÓN DE DIBOSONES WZ
A 7 TeV Y 8 TeV
DE ENERGÍA DEL CENTRO DE MASAS
EN EL EXPERIMENTO
CMS

Memoria presentada por

Jordi Duarte Campderrós

para optar al título de Doctor por la Universidad de
Cantabria

Santander, Diciembre de 2013



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WZ PRODUCTION CROSS-SECTION
MEASUREMENT AT
7 TeV AND 8 TeV
CENTER OF MASS ENERGIES WITHIN
THE COMPACT MUON SOLENOID
EXPERIMENT

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

by

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CERTIFICAN que la presente memoria

WZ production cross-section measurement at 7 TeV and 8 TeV center of mass energies within the Compact Muon Solenoid experiment

ha sido realizada por Jordi Duarte Campderrós bajo nuestra dirección en el Instituto de Física de Cantabria, para optar al título de Doctor por la Universidad de Cantabria. Consideramos que esta memoria contiene aportaciones científicas suficientemente relevantes como para constituir la Tesis Doctoral del interesado.

En Santander, a 3 de Diciembre de 2013,

Iván Vila Álvarez

Teresa Rodrigo Anoro

A la meva cara Núria i al nostre preciós fill, Nuc.

Abstract

The WZ associated diboson production is studied by measuring both inclusive cross section and, for the first time, the ratio between the W^-Z and the W^+Z cross sections. The measurements are performed using data samples of proton-proton collisions collected during the years 2011 and 2012, at 7 and 8 TeV of centre-of-mass energies, respectively, by the CMS experiment at the LHC, updating the 7 TeV cross section measurement available in CMS, and presenting the new cross section measurement in CMS at 8 TeV. The data sample used for the 7 TeV measurements correspond to an integrated luminosity of 4.9 fb^{-1} , whence the data for the 8 TeV correspond to $\mathcal{L}_{int} = 19.6 \text{ fb}^{-1}$.

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Notation and Conventions

List of selected symbols

$\mathcal{A}$	acceptance
σ	cross section
ε	efficiency
N_X	event yields (of process X)
$\mathcal{F}$	fake lepton
f	fake rate
M_X, m_X	mass (of particle X)
$E_T^{\text{miss}}, \cancel{E}_T$	missing transverse energy
$\mathcal{L}$	luminosity
$\mathcal{P}$	prompt lepton
p	prompt rate
η	pseudorapidity
sf	scale factor
E_T	transverse energy
m_T	transverse mass
p_T	transverse momentum
y	rapidity

The *natural units* are used along this dissertation except where it is explicitly indicated. The natural units in high energy particle physics are defined through

$$\hbar = c = 1$$

being $\hbar$ the Planck's constant and c the speed of light in the vacuum. Therefore in this system

$$[\text{length}] = [\text{time}] = [\text{energy}]^{-1} = [\text{mass}]^{-1}$$

Preface

This dissertation is submitted for the degree of Doctor of Philosophy at the University of Cantabria. The research described herein was conducted under the supervision of Doctor Iván Vila Álvarez and Professor Teresa Rodrigo Anoro in the *Instituto de Física de Cantabria* (IFCA) between October 2011 and November 2013.

This work is ultimately based on the experimental apparatus and data of the CMS experiment from proton-proton collision provided by the LHC at CERN. Although none of the text of the dissertation is taken directly from previously published or collaborative articles, except where acknowledgements and references are made, the collaborative efforts with other members of the the CMS collaboration have made possible this research.

CHAPTER 1

Theoretical Framework

The Standard Model (SM) [1] is the current theory accepted nowadays in particle physics. The SM is written down in the language of quantum mechanics where a physical system is described by its *state* and a physical process is understood as the *transition* from one state to different state. Moreover, the quantum mechanics language does not allow to ask for any predictions other than probabilities. In this context, we can calculate the probability for a given transition to occur, i.e. cross sections and decay rates. Those are the only observables we can expect to predict using the quantum mechanics formalism [2].

The SM of particle physics is a relativistic Quantum Field Theory (QFT), a Lagrangian ($\mathcal{L}$) fully describes the theory [3] and the system described by the Lagrangian is composed by quantum fields and interpreted as particles. The fields are split in the interaction (boson) fields and fermion fields which receive those interactions. In this picture, the interaction fields are bosons carrying the quanta of the forces and the fermion fields are interpreted as excited states of the medium (vacuum). The Lagrangian describes the coupling between forces and fermionic fields and how they modify their internal and/or dynamical state as a consequence of the interactions. Therefore, the SM of particle physics describes matter as a collection of particles, called fermions (*quarks* and *leptons*) interacting between them by interchanging quanta of force (particles called *bosons*). Note that in order to keep the theory inside the special relativity scope, the Lagrangian has to be built assuring its invariance under Lorentz transformations.

The SM describes three of the four known fundamental forces in nature: electromagnetism, weak force and strong force¹ by using the concept of *local gauge invariance*. The Lagrangian of the system has to be invariant under some internal or local gauge transformations that in fact determine the interaction: *gauge theories*.

This chapter reviews the main features of the SM of particle physics without entering in full details. The subject is widely covered by many books, in particular [3], [1] and [2] have been used as references for this chapter. The chapter starts up with a panoramic view of gauge theories, then provides a qualitative description of the SM of particle physics and its component constituents. A brief summary of the Quantum Chromodynamics Lagrangian and its properties is described. Also, a brief description of the Electroweak sector is shown introducing the Higgs mechanism to give mass to the gauge bosons and to the fermionic fields. After this summary of the SM, some shortcomings of the theory are exposed giving theoretical support to believe that the SM is not the ultimate theory, although it works remarkably well at the energies in which have been tested. Finally, a qualitative introduction to physics at hadron colliders is described in order to contextualise the theory with our particular experiment.

1.1. Gauge Theories and the Standard Model

The gauge theories rely essentially on the assertion that every physical system should be invariant under any artifice used to describe it. In special or general relativity, that statement is applied to the coordinates used to describe nature, which should play no role in the formulation of the physical laws [4]. This is closely related to the fact that the position of any system must be given with respect, *relative* to, any other system (observer, reference frame, ...). This is what we understand as *gauge variables*; once you fixed the arbitrariness (choose a gauge), you can use this variables to describe a physical system through a Lagrangian [5]. But if you choose another gauge, the Lagrangian, i.e. the physical laws, has to keep exactly the same structure (using the new gauge variables, of course). We

¹The fourth fundamental force, the gravity, is still not described using a gauge theory as the SM is.

say, then, that the Lagrangian is *gauge-invariant*.

Every local transformation of the gauge variables that keeps the Lagrangian invariant is associated to a conserved current, called *Noether current*, carrying a conserved charge, called *Noether charge* (Noether's theorem [6]). That group of local transformations can be described using group theory through a symmetry group¹, being the generators of that group the Noether charges. In turn, Noether current describes the interaction resulting from the considered symmetry. This idea was used to formulate the SM of particle physics using some internal degrees of freedom for the quantized fields which can be represented by $SU(3)_C \times SU(2)_L \times U(1)_Y$.

To elucidate these ideas, let's assume a Lagrangian description of a quantum system built from free quantum fields, $\Psi(x^\mu) \in \mathbb{C}$, which are interpreted as probability density fields. The terms of the Lagrangian should use only $|\Psi(x^\mu)|^{2n}$ ($n = 1, \dots$) combinations in order to assure the invariance of the Lagrangian, therefore whether we use $\Psi(x^\mu)$ or $\Psi'(x^\mu) = e^{i\xi^a(x^\mu)T_a}\Psi(x^\mu)$, the Lagrangian is going to describe the same physical system². This is the natural way in which gauge theories³ emerge. Since the Lagrangian depends also on the space-time derivatives of the field, $\mathcal{L}(\Psi, \partial_\mu \Psi)$, once the phase transformation is decided, we should check how the space-time derivatives behave in order to assure the Lagrangian invariance. The covariant requirement generalises the derivative introducing the *covariant derivative* as [3],

$$D_\mu = \partial_\mu - igA_\mu^a T_a \quad (1.1)$$

which is the derivative operator to use in the Lagrangian instead of ∂_μ only. Notice that the inclusion of the transformation group introduces one field for each generator of the group, $A_\mu^a \equiv \frac{1}{g}\partial_\mu \xi^a$, for the sake of Lagrangian invariance. Hence, the starting Lagrangian describing a free particle system becomes a Lagrangian describing a particle interacting with the fields A_μ^a as soon as a local gauge transformation has been introduced. Postulating that a quantum field obeys

¹In particular, a continuous local transformation is described by Lie groups. Lie groups contain an infinite number of elements, but the elements can be written in terms of a finite number of parameters [7].

²Note that T_a are the generators of the local transformation.

³A better name for these theories would be *phase* theories, but the historical misconception of the term remains.

a local symmetry, a vector field must appear and interact with the quantum field. Furthermore, there will be conserved currents, as consequence of Noether's theorem, and its associated conserved charge which characterises the system and so a quantum number will emerge.

1.2. Quantum fields: matter and interactions

Matter and interactions are described as fields, spinors $\psi \in \mathbb{C}^4$, using relativistic QFT. Those fields live in a Minkowskian space-time¹ defined by the Dirac matrices, γ^μ , and are interpreted as probability density fields², such that the observables associated with those fields depend of $\bar{\psi}\psi$, where the *adjoint spinor* $\bar{\psi} = \psi^\dagger \gamma^0$ is defined in order to obtain Lorentz scalars. Therefore, invariant requirement on the Lagrangian implies that the terms in the Lagrangian should be formed by functions of $\bar{\psi}\psi$ or even combinations with/of other fields.

The fermionic fields describing matter are represented by 4-component Dirac spinors. The Lagrangian associated to a free fermion of mass m and the derived Dirac equation of motion are:

$$\mathcal{L} = i\bar{\psi}\gamma^\mu\partial_\mu\psi - m\bar{\psi}\psi \quad (i\gamma^\mu\partial_\mu - m)\psi = 0 \quad (1.2)$$

The solutions of the Dirac equations forming a eigenvalue problem are of the form: $\psi(x) = u(x)e^{\pm ip \cdot x}$, which are eigenstates of the *helicity* operator

$$\hat{h} \equiv \frac{\hat{\mathbf{p}} \cdot \hat{\mathbf{S}}}{|\hat{\mathbf{p}}|} \quad (1.3)$$

where $\hat{\mathbf{p}}$ is the momentum operator and $\hat{\mathbf{S}}$ the spin operator. Spin-1/2 particles with its spin direction parallel to the linear momentum have +1/2 helicity and they are called *right-handed* states, and spin-1/2 particles with its spin direction anti-parallel to the linear momentum have -1/2 helicity, *left-handed* states. As we will see in next section, the right- and left-handed states do not behave in the same

¹Using a Geometric Algebra approach, it is possible to describe the Dirac equation in terms of a space-time algebra (STA) where the usual Dirac matrices are an explicit basis for the STA [8].

²The fields can be interpreted as excitation states of the vacuum [3].

way when weakly interacting. Obviously, the two states are not disconnected since it is always possible to perform a Lorentz transformation to a reference system where the particle momentum has the same value but opposite sign, keeping the spin invariant. However, this is not possible for massless particles as the neutrinos. Thus, it is possible to project each fermion, except for the neutrinos which only exist as left-handed states, into its left-handed (ψ_L) and right-handed (ψ_R) components, the so called Weyl representation, using the projection operators $P_L = \frac{1}{2}(1 - \gamma^5)$ and $P_R = \frac{1}{2}(1 + \gamma^5)$, where $\gamma^5 = i\gamma^0\gamma^1\gamma^2\gamma^3$

$$\psi_L = P_L\psi = \frac{1}{2}(1 - \gamma^5)\psi \quad \psi_R = P_R\psi = \frac{1}{2}(1 + \gamma^5)\psi \quad (1.4)$$

and $\psi = \psi_R + \psi_L$.

The fermionic elementary particles have been classified according their properties and quantum numbers in leptons and quarks and organised in families of identical structure differing only for their mass. Table 1.1 shows the fermion classification in the SM and the relevant quantum numbers for each particle ¹: the electric charge (Q_{EM}), the third component of the weak isospin T_3 and the weak hypercharge Y , defined by the Gell-Mann and Nishijima relation $Q_{EM} = T_3 + Y/2$. Note that all the leptons and quarks have spin $1/2$.

The interactions between fermions are described by bosonic vector fields, which in turn are related to a local symmetry in the system. A free scalar boson with mass m is represented by a scalar field $\phi \in \mathbb{C}$, dynamically described by the Klein-Gordon Lagrangian, from which its equation of motion is derived,

$$\mathcal{L} = (\partial_\mu \phi)^\dagger (\partial^\mu \phi) - m\phi^\dagger \phi \quad (\square - m) \phi = 0 \quad (1.5)$$

In the case of a vector boson B_μ of mass m , the dynamics for the free boson is obtained with the Lagrangian,

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}B_\mu B^\mu \quad (1.6)$$

¹The anti-particle related to each particle is described by the same mass and quantum numbers but the charge reversed.

			Q_{EM}	Y	T_3	Interactions
LEPTONS						
$\begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix}$	$\begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix}$	$\begin{pmatrix} \nu_{\tau L} \\ \tau_L \end{pmatrix}$	0	-1	+1/2	weak
			-1	-1	-1/2	weak,EM
QUARKS						
$\begin{pmatrix} u_L \\ d'_L \end{pmatrix}$	$\begin{pmatrix} c_L \\ s'_L \end{pmatrix}$	$\begin{pmatrix} t_L \\ b'_L \end{pmatrix}$	+2/3	+1/3	+1/2	weak,EM,strong
			-1/3	+1/3	-1/2	weak,EM,strong
u_R	c_R	t_R	+2/3	+4/3	0	weak,EM,strong
d_R	s_R	b_R	-1/3	-2/3	0	weak,EM,strong

TABLE 1.1: Fermionic fields in the SM. The main quantum numbers and the interaction that are sensitive to feel are shown, but the colour charge. All the fermions have spin 1/2 and for each listed particle, there is a corresponding antiparticle with same mass but with opposite value of Q . The left-handed states are grouped into weak isospin doublets represented by one-array columns.

where $F_{\mu\nu}$ is the dynamic term of the field,

$$F_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu \quad (1.7)$$

The SM describes three of the four elementary interactions between particles. The interactions are modelled with the $U(1)_Y \times SU(2)_L \times SU(3)_C$ symmetry group describing the fermion fields transformation in the different internal spaces. The $SU(3)_C$ group of Quantum Chromodynamics (QCD) deals with the colour charge content of the quarks mediated by eight massless coloured bosons called gluons. Every quark can be represented in the colour charge space as a $SU(3)_C$ triplet and the leptons are colourless $SU(3)_C$ singlets, therefore quarks are sensible to the strong force whereas leptons are not. The QCD Lagrangian characterising the quark coupling with the colour charge current is,

$$\mathcal{L}_{\text{QCD}} = \bar{\psi} (i\gamma^\mu D_\mu - m) \psi - \frac{1}{4} G_{\mu\nu}^a G_a^{\mu\nu} \quad (1.8)$$

where $G_{\mu\nu}^a$ are the gluon field strength,

$$G_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + g_c f^{abc} A_\mu^b A_\nu^c, \quad a = 1, \dots, 8 \quad (1.9)$$

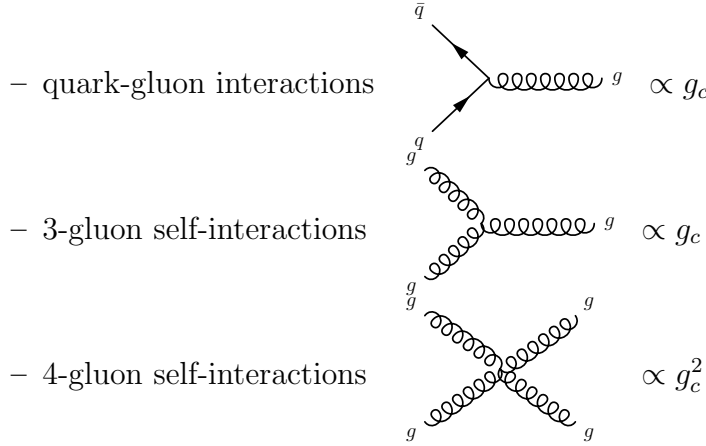
built from the *structure constants* f_{abc} of the $SU(3)_C$ group; the 8 gauge field

gluons A_μ^a and the dimensionless coupling strength g_c . The covariant derivative to keep gauge invariance is defined as

$$D_\mu = \partial_\mu - ig_c A_\mu^a T_a \quad (1.10)$$

where T_a are the generators of the non-Abelian $SU(3)_C$ group. The essential properties and features of QCD are summarised as:

- Quarks carry colour and electric charge
- Colour charge is exchanged by eight bicoloured, spin-1 and massless *gluons*
- Gluons themselves carry colour charge, so they can interact with other gluons
- The fundamental QCD vertices are:



- Colour confinement: the coupling strength¹ α_s increases with decreasing energies (or large distances), as a consequence only colour neutral hadrons can be observed in nature [1]
- Asymptotic freedom: the coupling strength α_s decreases with increasing energies (or short distances) becoming small enough to treat coloured particles as free [1]. The coupling can be approximated as $\alpha_s \simeq 1/(\beta_0 \ln(k^2/\Lambda_{QCD}))$, being β_0 a constant, k the energy of the process and Λ_{QCD} the QCD scale.

¹The coupling strength can be renormalised as $\alpha_s = \frac{g_c^2}{4\pi}$

Therefore in this regime the QCD calculations can be performed as expansions of α_s , perturbatively.

The role played by QCD in high energy proton colliders, such as the Large Hadron Collider (LHC), is fundamental. Section 1.3 offers a brief summary of the underlying physics used to describe high energy collisions at hadron colliders.

1.2.1. The Electro-Weak Interaction

The electroweak interaction was postulated¹ through the introduction of the symmetry group $SU(2)_L \times U(1)_Y$ for the fermionic fields, emerging a set of four vector fields W_μ^i ($i = 1, 2, 3$) related to the $SU(2)_L$ group and B_μ corresponding to the $U(1)_Y$ symmetry. The fermionic fields are split into isospin doublets for the left-handed states and isospin singlets for right-handed states, meaning that the doublets couple to the $SU(2)_L$ gauge bosons while the singlet states do not. As a consequence of requiring gauge invariance the covariant derivative is defined as:

$$D_\mu = \partial_\mu - igT_i W_\mu^i - ig' \frac{Y}{2} B_\mu \quad (1.11)$$

where T_i, g and Y, g' are the generators and coupling strengths of the $SU(2)_L$ and $U(1)_Y$ groups, respectively. The kinematic terms for the gauge fields included in the Lagrangian make use of the field strength tensors,

$$W_{\mu\nu}^i = \partial_\mu W_\nu^i - \partial_\nu W_\mu^i + g\epsilon^{ijk} W_\mu^j W_\nu^k \quad (1.12)$$

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu \quad (1.13)$$

¹The electroweak theory as unified theory of Quantum Electrodynamics (QED) and weak force was first described by Glashow [9], Weinberg [10] and Salam [11].

where ϵ^{ijk} is the total antisymmetric tensor. The Yang-Mills (YM) Electro-Weak (EW) Lagrangian can be expressed in the following form:

$$\begin{aligned}\mathcal{L}_{YM} = \mathcal{L}_{kin} + \mathcal{L}_{charged} + \mathcal{L}_{neutral} = \\ -\frac{1}{4}W_{\mu\nu}^i W_i^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} \\ -\bar{\psi}_L i\gamma^\mu \left(\partial_\mu - igT_i W_\mu^i - ig'\frac{Y}{2}B_\mu \right) \psi_L \\ -\bar{\psi}_R i\gamma^\mu \left(\partial_\mu - ig'\frac{Y}{2}B_\mu \right) \psi_R\end{aligned}\quad (1.14)$$

The experimental constraint of having two neutral currents [3], only one of them with parity conserved, was resolved by transforming the original basis. Defining the weak mixing angle as,

$$\sin\theta_W = \frac{g'}{\sqrt{g^2 + g'^2}} \quad (1.15)$$

$$\cos\theta_W = \frac{g}{\sqrt{g^2 + g'^2}} \quad (1.16)$$

it is possible to perform a rotation by an angle θ_W in the neutral sector revealing new physic vector fields (with mass=0),

$$W_\mu^\pm = \frac{1}{\sqrt{2}}(W_\mu^1 \pm W_\mu^2) \quad (1.17)$$

$$Z_\mu = \cos\theta_W W_\mu^3 - \sin\theta_W B_\mu \quad (1.18)$$

$$A_\mu = \cos\theta_W B_\mu + \sin\theta_W W_\mu^3 \quad (1.19)$$

Rearranging the Lagrangian using those new fields after the rotation angle the neutral sector is expressed as,

$$\begin{aligned}\mathcal{L}_{neutral} = -A_\mu \left\{ \bar{\psi}_L \gamma^\mu \left(gT^3 \sin\theta_W + g'\frac{Y}{2} \cos\theta_W \right) \psi_L + \bar{\psi}_R \gamma^\mu \left(g'\frac{Y}{2} \cos\theta_W \right) \psi_R \right\} \\ -Z_\mu \left\{ \bar{\psi} \gamma^\mu \left(gT^3 \cos\theta_W - g'\frac{Y}{2} \sin\theta_W \right) \psi - \bar{\psi}_R \gamma^\mu \left(g'\frac{Y}{2} \sin\theta_W \right) \psi_R \right\}\end{aligned}\quad (1.20)$$

The relations (1.15) and (1.16) materialise the electroweak unification with the

link between the elementary electromagnetic charge e and the weak mixing angle θ_W and the coupling strengths of the weak isospin and the hypercharge,

$$e = g \sin \theta_W = g' \cos \theta_W \quad (1.21)$$

Making use of it and the Gell-Mann and Nishijima relation $Q = T^3 + Y/2$ in the equation (1.20),

$$\begin{aligned} \mathcal{L}_{neutral} = & A_\mu \{e \bar{\psi} \gamma^\mu Q \psi\} + \\ & + Z_\mu \left\{ \frac{g}{\cos \theta_W} \bar{\psi} \gamma^\mu \left(T^3 \frac{1}{2} (1 - \gamma^5) - Q \sin^2 \theta_W \right) \psi \right\} \end{aligned} \quad (1.22)$$

where it is assumed that T^3 is zero when applied over a right-hand fermion, so using only the left-hand components $\frac{1}{2}(1 - \gamma^5)\psi$ of the fermion field. The electromagnetic and neutral weak currents are,

$$J_\mu^{em} = e \bar{\psi} \gamma_\mu Q \psi \quad (1.23)$$

$$J_\mu^{NC} = \frac{1}{\cos \theta_W} \bar{\psi} \gamma_\mu \left(T^3 \frac{1}{2} (1 - \gamma^5) - Q \sin^2 \theta_W \right) \psi \quad (1.24)$$

where the third component of the weak isospin current is

$$J_\mu^3 = \bar{\psi} \gamma_\mu \left(T^3 \frac{1}{2} (1 - \gamma^5) \right) \psi \quad (1.25)$$

Therefore it is straightforward to find the relation between electromagnetic and neutral weak currents,

$$J_\mu^{NC} = J_\mu^3 - \sin^2 \theta_W J_\mu^{em} \quad (1.26)$$

We have successfully achieved the objective of expressing the observed neutral currents in terms of the currents J_μ^3 and J_μ^Y belonging to symmetry groups $SU(2)_L$ and $U(1)_Y$.

To complete the picture, the charged currents,

$$J_\mu^+ = \frac{1}{\sqrt{2}} \bar{\psi} \gamma_\mu (T^1 - T^2) \frac{1}{2} (1 - \gamma^5) \psi \quad (1.27)$$

$$J_\mu^- = \frac{1}{\sqrt{2}} \bar{\psi} \gamma_\mu (T^1 + T^2) \frac{1}{2} (1 - \gamma^5) \psi \quad (1.28)$$

are also expressed in terms of the J_μ^i ,

$$J_\mu^+ = \frac{1}{\sqrt{2}} (J_\mu^1 - J_\mu^2) \quad (1.29)$$

$$J_\mu^- = \frac{1}{\sqrt{2}} (J_\mu^1 + J_\mu^2) \quad (1.30)$$

Up to now the theory sketched here has been constructed requiring massless fermions and gauge bosons, since the presence of mass terms for the gauge fields destroys the gauge invariance of the Lagrangian. But experimental results prove the fermions and the $W^\pm$ and Z bosons to be massive. The inclusion of the mass terms in a gauge invariant way is provided by the spontaneous symmetry breaking mechanism.

1.2.2. The spontaneous symmetry breaking mechanism

The *Goldstone's theorem* [12] states that for every spontaneously broken continuous symmetry, the theory must contain a massless particle. The massless fields arising through spontaneous symmetry breaking are called *Goldstone bosons*. The Goldstone theorem deals with global continuous symmetries of a system and reveals a ground state which does not possess the global continuous symmetry of the Lagrangian. Choosing an explicit ground state the symmetries is *spontaneously broken*. We can visualise this effect using a theory with a complex scalar self-interacting field ϕ described by the Lagrangian,

$$\mathcal{L} = T - V(\phi) = (\partial_\mu \phi)^* (\partial^\mu \phi) - (\mu^2 \phi^* \phi + \lambda (\phi^* \phi)^2), \quad (\lambda > 0) \quad (1.31)$$

which is invariant under the transformation $\phi \rightarrow e^{i\alpha} \phi$, i.e., the Lagrangian possesses a $U(1)$ global symmetry. The ϕ^4 term shows that the four-particle

vertex exists with coupling λ , so ϕ is a self-interacting field. There are two possible forms of the potential depending the sign of μ . The case $\mu^2 > 0$ is simply describing a scalar field with mass μ^2 . The ground state of the system (the vacuum) corresponds to $\phi = 0$. However, the case $\mu^2 < 0$ introduces a wrong sign for the mass term (ϕ^2) of the field, since the relative sign of the mass term and the kinetic energy T is always negative. We can express ϕ in its real and complex components $\phi = \frac{1}{\sqrt{2}}(\phi_1 + i\phi_2)$ to show that the potential $V(\phi)$ has a circle of minima in the ϕ_1, ϕ_2 plane with radius v ,

$$\phi_1^2 + \phi_2^2 = v^2, \quad v^2 = -\frac{\mu^2}{\lambda} \quad (1.32)$$

as shown in figure 1.1. Translating the field ϕ to a minimum energy position,

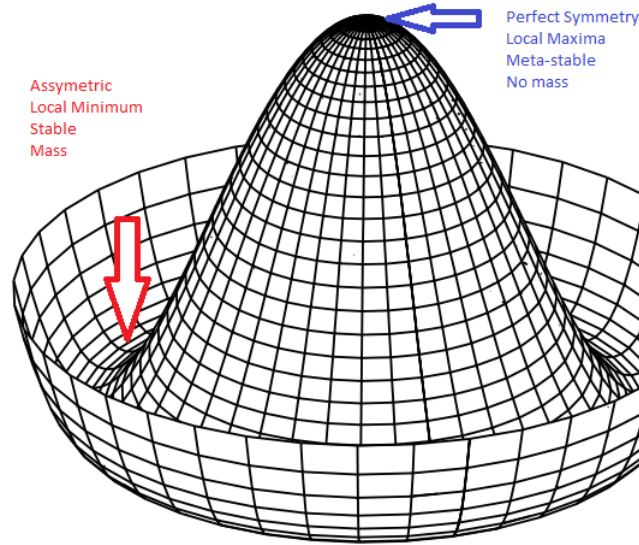


FIGURE 1.1: The potential $V(\phi)$ for a complex scalar field with $\mu^2 < 0$ and $\lambda > 0$.

which without loss of generality we may take as the point $\phi_1 = v$, $\phi_2 = 0$, and perturbing the field around the stable minima,

$$\phi(x) = \sqrt{\frac{1}{2}}[v + \eta(x) + i\xi(x)] \quad (1.33)$$

we can expand the original Lagrangian (1.31) in terms of η and ξ and obtain,

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \xi)^2 + \frac{1}{2}(\partial_\mu \eta)^2 + \mu^2 \eta^2 + \mathcal{O}(\eta^3, \xi^3, \dots) \quad (1.34)$$

Therefore, the third term of the Lagrangian (1.34) has the form of a mass term with the right sign, $-1/2m_\eta\eta^2$, so the η -mass is $m_\eta = \sqrt{-2\mu^2}$. Note that the two first terms represent the kinetic energy of the ξ and η fields respectively, but there is no mass term for ξ , the massless Goldstone boson. The theory contained a symmetry, i.e. the field ϕ was invariant under rotation represented by the circle of minima ground states, but that symmetry of the Lagrangian has apparently been broken by our choice of the ground state ($\phi_1 = v$, $\phi_2 = 0$) around which to do our perturbation calculations. Thus, the Lagrangian using the field around the ground state do not possess that symmetry, we say that the symmetry has been *spontaneously broken*¹. And due to the spontaneous symmetry breaking the mass of the η field has been *revealed*. So far, the theory still contains a massless gauge boson, but demanding local invariance we shall see that the Goldstone boson is *absorbed*. This is known as the Higgs mechanism [13].

1.2.2.1. The Higgs Mechanism

The spontaneous symmetry breaking mechanism of a *local* gauge symmetry, in particular $SU(2)_L \times U(1)_Y$ forces to include the covariant derivative (1.11). Also we need to introduce a scalar field in the multiplet spinor representation belonging to $SU(2)_L \times U(1)_Y$,

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \quad \text{with} \begin{cases} \phi^+ = \frac{1}{\sqrt{2}}(\phi_1 + i\phi_2) \\ \phi^0 = \frac{1}{\sqrt{2}}(\phi_3 + i\phi_4) \end{cases} \quad (1.35)$$

and add a term to the Yang-Mills electroweak Lagrangian (1.14),

$$\mathcal{L}_h = (D_\mu \phi)^\dagger (D^\mu \phi) - V(|\phi|), \quad (1.36)$$

¹Or more accurately, the symmetry is not apparent in the ground state.

being the Higgs potential $V(|\phi|) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$, and $\mu^2 < 0$, $\lambda > 0$ as we have seen in the previous section. Analogously to section 1.2.2 the potential $V(\phi)$ has its minimum at a finite value of $\phi^\dagger \phi$ where

$$\phi^\dagger \phi = \frac{1}{2}(\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2) = -\frac{\mu^2}{2\lambda},$$

We can choose a particular minimum,

$$\phi_1 = \phi_2 = \phi_4 = 0, \quad \phi_3^2 = -\frac{\mu^2}{\lambda} \equiv v^2$$

and substituting in equation (1.35), the value of the field ϕ in the minimum is

$$\phi_0 = \sqrt{\frac{1}{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \quad (1.37)$$

It is possible to expand $\phi(x)$ about this particular vacuum

$$\phi(x) = \sqrt{\frac{1}{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix} \quad (1.38)$$

where the only remaining scalar field is $H(x)$, the Higgs field. The expanded $\phi(x)$ field is substituted into the Lagrangian (1.36). The broken Lagrangian obtained turns out to be invariant under $U(1)_{EM}$, i.e. the vacuum is still invariant under electromagnetic interaction and therefore the associated gauge boson, the photon, remains massless. But the choice of the vacuum described in equation (1.37) breaks both $SU(2)_L \times U(1)_Y$ and therefore mass terms appear for the associated gauge bosons. Re-expressing the Higgs Lagrangian (eq. (1.36)) around the minimum,

$$\begin{aligned} \mathcal{L}_h &= (D_\mu \phi)^\dagger (D^\mu \phi) - V(|\phi|) = \\ &= \frac{1}{2} \left(\left(\partial_\mu - ig T_i W_\mu^i - ig' \frac{B_\mu}{2} \right) \begin{pmatrix} 0 \\ v + H \end{pmatrix} \right)^\dagger \left(\left(\partial_\mu - ig T_i W_\mu^i - ig' \frac{B_\mu}{2} \right) \begin{pmatrix} 0 \\ v + H \end{pmatrix} \right) \\ &\quad + \frac{\mu^2}{2} (v + H)^2 - \frac{\lambda}{16} (v + H)^4 \end{aligned} \quad (1.39)$$

The first term in equation (1.39) is expressing the kinetic energy associated to the Higgs boson, its interaction with the gauge bosons and, we will see, it is also expressing the gauge boson masses. The second term is the quadratic term of the Higgs boson, i.e. the mass term,

$$\frac{\mu^2}{2} (v + H)^2 = \mu^2 \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & v + H \end{pmatrix} \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix} = \mu^2 |\phi|^2 = -\frac{1}{2} m_H^2 |\phi|^2 \quad (1.40)$$

Thus, recalling the vacuum expectation value, $v = -\mu^2/\lambda$, the mass for the Higgs field is $m_H = v\sqrt{2\lambda}$. The vacuum expectation value can be re-expressed as a function of the Fermi constant $v = \frac{1}{G_F\sqrt{2}} \simeq 246.22 \text{ GeV}$. The coupling λ is a free parameter of the theory, so the mass is not predicted by the theory and has to be measured experimentally. Note that the last term is expressing the Higgs self-coupling .

Once we have obtained the mass term for the Higgs field, we develop equation (1.39) focusing on the Higgs interactions with the gauge bosons,

$$\begin{aligned} \mathcal{L}_{h_i} = & \frac{(v + H)^2}{8} g^2 (W_\mu^1 (W^1)^\mu + W_\mu^2 (W^2)^\mu) + \\ & + \frac{(v + H)^2}{8} g^2 \begin{pmatrix} B_\mu & W_\mu^3 \end{pmatrix} \begin{pmatrix} g^2 & g'g \\ g'g & g'^2 \end{pmatrix} \begin{pmatrix} B_\mu \\ W_\mu^3 \end{pmatrix} \end{aligned} \quad (1.41)$$

Now, equation (1.41) reveals why the basis transformation using the weak angle defined at equations (1.15) and (1.16) and therefore explains the definitions of the physical gauge bosons $W_\mu^\pm$, Z_μ and A_μ (equations (1.17), (1.18) and (1.18)). Thus, we can express the interaction Lagrangian (1.41) in terms of these bosons,

$$\mathcal{L}_{h_W} = \frac{v^2 g^2}{4} W_\mu^+ (W^-)^\mu + \frac{v g^2}{2} H W_\mu^+ (W^-)^\mu + \frac{g^2}{4} H^2 W_\mu^+ (W^-)^\mu \quad (1.42)$$

$$\mathcal{L}_{h_{AZ}} = \frac{v^2}{8} (g^2 + g'^2) Z_\mu Z^\mu + \frac{v}{4} (g^2 + g'^2) H Z_\mu Z^\mu + \frac{(g^2 + g'^2)}{8} H^2 Z_\mu Z^\mu \quad (1.43)$$

where we have split the interaction Lagrangian in two terms, each one referring to the involved gauge boson, $\mathcal{L}_{h_i} = \mathcal{L}_{h_W} + \mathcal{L}_{h_{AZ}}$. The $\mathcal{L}_{h_W}$ Lagrangian contains a quadratic term in the gauge field plus the interaction with the Higgs field. The

quadratic term is identified as the mass,

$$m_{W^\pm}^2 W_\mu^+ (W^-)^\mu = \frac{v^2 g^2}{4} W_\mu^+ (W^-)^\mu \implies m_{W^\pm} = \frac{1}{2} v g \quad (1.44)$$

and analogously for the Z boson, $m_Z = \frac{1}{2} v \sqrt{g^2 + g'^2}$. Notice that the Lagrangian does not contain mass terms for the A_μ field neither any coupling term between the Higgs and A_μ , meaning that the Higgs mechanism in the SM predicts a massless photon and no direct couplings between the Higgs and the photon. Summarising the gauge boson masses:

$$m_{W^\pm} = \frac{1}{2} v g \quad (1.45)$$

$$m_{Z^0} = \frac{1}{2} v \sqrt{g^2 + g'^2} \quad (1.46)$$

$$m_A = 0 \quad (1.47)$$

On the other hand, both Lagrangians contain coupling terms between the Higgs and the gauge bosons, where it can be observed that the coupling strength is proportional to the gauge boson mass,

$$\frac{v g^2}{2} H W_\mu^+ (W^-)^\mu \implies y_W = \frac{v g^2}{2} = g m_W \quad (1.48)$$

$$\frac{v g^2}{2} H Z_\mu Z^\mu \implies y_Z = \frac{v}{4} = \frac{g m_Z}{2 \cos \theta_W} \quad (1.49)$$

$$(1.50)$$

Summarising, the mass acquired by the gauge bosons in the SM is because of their interaction with the Higgs boson, i.e. $y_W, y_Z \neq 0$, and because of its non-vanishing vacuum expectation value, $v \neq 0$.

1.2.3. The Fermionic sector

So far, the Higgs mechanism has been useful to generate massive gauge bosons in a gauge invariant way. But fermions mass terms have not been put into the Lagrangian because the left- and right-handed components of the various fermion fields have different gauge quantum numbers and so simple mass terms violate

gauge invariance. But the great feature of the Higgs mechanism is that the same Higgs multiplet which generates $W^\pm$ and Z^0 masses is also sufficient to give masses to the leptons and quarks. It is possible to link the left-handed fermions weak isospin doublets $\psi_L \equiv \chi_L^1$, the right-handed fermions weak isospin singlet $\psi_R \equiv \ell_R \equiv q_R$ and the spinor under $SU(2)$ scalar field ϕ , i.e. the Higgs field,

$$\begin{aligned} \mathcal{L}_{Yukawa} = & - \sum_{\substack{\chi_L=1,2,3 \\ \ell=e,\mu,\tau}} Y_\ell [(\bar{\chi}_L \cdot \phi) \ell_R + h.c.] \\ & - \sum_{\substack{\chi_L=1,2,3 \\ q=d,s,b}} Y_q [(\bar{\chi}_L \cdot \phi) q_R + h.c.] \\ & - \sum_{\substack{\chi_L=1,2,3 \\ q=u,c,t}} Y_q \left[\epsilon^{ab} \bar{\chi}_{La} \phi_b^\dagger q_R + h.c. \right] \end{aligned} \quad (1.51)$$

where the ϵ^{ab} is the total antisymmetric tensor, the indices 1,2,3 refer to the lepton and quark generations and q_R , ℓ_R indices refer to the quark and lepton flavour, respectively (see Table 1.1). The Y_ℓ , Y_q are dimensionless couplings called *Yukawa couplings*, they are the coupling terms of the fermions with the scalar field ϕ . Replacing the field ϕ with this expression about its vacuum expectation value (1.38),

$$\mathcal{L}_{Yukawa} = - \sum_{\substack{f=e,\mu,\tau \\ d,s,b \\ u,c,t}} \frac{1}{\sqrt{2}} Y_f [v \bar{f} f + \bar{f} f H] \quad (1.52)$$

and the mass terms of the fermions are

$$m_f = \frac{1}{\sqrt{2}} Y_f v, \quad f = e, \mu, \tau, d, s, b, u, c, t \quad (1.53)$$

The derivation used above does not make use of the fact that additional coupling terms mixing generations can exist. In fact we did an implicit diagonalisation of the Higgs couplings by choosing a new basis for the quark fields, so in this basis, we choose the weak states (u,c,t) to have definite masses, but then (d,s,b) will

¹Note $\psi_L = \begin{pmatrix} a_L \\ b_L \end{pmatrix}$, where a_L , b_L are the the left-handed states of lepton and quarks. The explicit doublets can be found in Table 1.1.

not. Nevertheless the flavour or weak states (d,s,b) can be expressed as a linear combination of the mass eigenstates (d',s',b') through a 3×3 Cabibbo–Kobayashi–Maskawa (CKM) unitary matrix in the form,

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}, \text{ where } V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \quad (1.54)$$

The off-diagonal terms in CKM allow weak-interaction transitions between quark generations. The picture for the leptons is different due to the fact that right-handed neutrinos are not charged under any SM group, but including a Higgs coupling with the right-handed neutrinos would give a neutrino mass comparable to that of the electron. But we know from experiment that neutrino masses are extremely small, $\mathcal{O}(eV)$. This extreme suppression of the neutrino mass would be naturally explained if the right-handed neutrino states do not exist¹. Therefore, there is no right-handed states for neutrinos in the SM and there is no equivalent to the CKM matrix in the lepton sector. Thus, there are no transition between leptons of different generations.

The $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge theory of quarks and leptons plus the Higgs mechanism to provide mass to the fermions and $W^\pm$ and Z^0 gauge bosons do an excellent job of accounting for the symmetries and conservation laws that are observed in elementary particle phenomena. By imposing gauge invariance and renormalizability the Lagrangian built is able to predict which symmetries should be exact, as lepton flavour for instance, and which should be approximate, as P or C violation in weak currents. Furthermore, the SM has predicted the existence of W , Z boson, gluons and top and charm quarks before these particles were observed. The predicted properties of the SM have resisted many experimental precision tests with high accuracy. In July 2012, CMS [14] and ATLAS [15] reported the observation of a new particle compatible with the SM Higgs, the last

¹In generalisation of the SM, neutrinos can acquire Majorana mass terms that are naturally very small respecting the constraints of lepton flavour mixing. In this case the weak states chosen to have definite masses are (e, μ, τ) and, as the quarks case, it is possible to express the flavour states $(\nu_e, \nu_\mu, \nu_\tau)$ using a linear combination of the mass eigenstates (ν_1, ν_2, ν_3) using a 3×3 matrix called *Pontecorvo-Maki-Nakagawa-Sakata* (PMNS) matrix.

missing ingredient predicted by the SM. Therefore, the SM of particle physics has turned out to be an impressive theory which uses relatively few constituents to explain our current known universe. Figure 1.2 summarises the building blocks of the SM showing the matter content (spin-1/2 fermions) and the gauge interaction mediators (spin-1 bosons) of the forces with some of its main features.

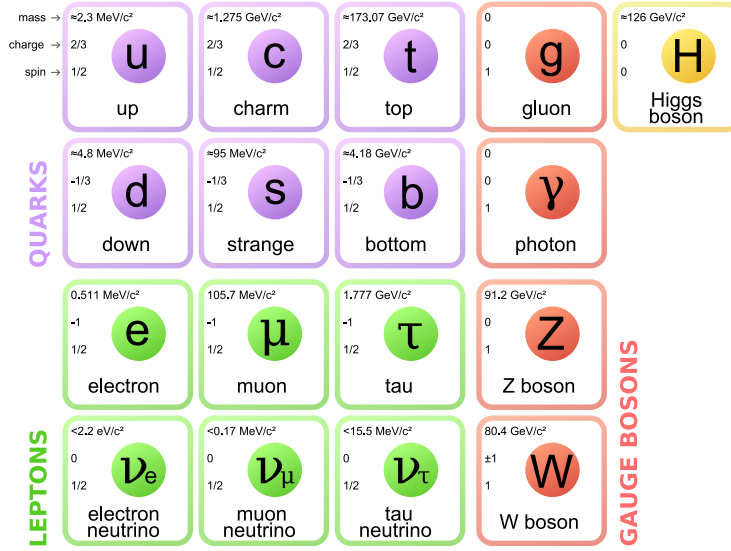


FIGURE 1.2: Constituents of the SM summarised.

However, in the theory remain a wide range of unresolved issues [16]:

- The SM does not include the remaining force of the Nature: gravity
- Hierarchy problem. Attempting the extension of SM as a broken symmetry of a larger symmetry, a Grand Unification Theory (GUT) at some energy scale, one would expect a Higgs mass comparable to the underlying mass scale of the fundamental interactions. If not it seems to require dramatic and even bizarre cancellations in the renormalised value of the Higgs boson mass.
- Strong CP problem. Experimentally, the CP symmetry is an exact symmetry in the strong interaction sector. Theoretically, however, the strong interaction naturally contains a term that breaks CP symmetry, relating matter to antimatter. There is no explanation in the SM for the absence of this term.

- High number of unrelated and arbitrary parameters. The SM is described by nineteen numerical constants which have to be taken from experiments
- Matter-antimatter asymmetry. There is an asymmetry in our universe favouring matter against the antimatter which it is not present in the SM. The CP-violation of the SM provides an effect far too small to account for the original imbalance in the early Universe.
- Dark matter and dark energy are not described neither predicted in the SM

Although the above sketched shortcomings support the belief that the SM is not the ultimate theory, it is a good model at relatively low energies (at least far away from the Planck scale). So far, all the precision tests performed have been passed with high accuracy.

1.3. Physics at Hadron Colliders

Hadron collisions are governed by the strong interaction force, given that hadrons are described as bound states of strongly interacting quarks and gluons (*partons*). There, QCD plays a fundamental role in the attempt to describe the physics produced by a proton-proton collision. The theoretical calculations of the low-energy regime of the interacting partons inside the proton are subject to non-perturbative (or *soft*) QCD. However, when considering a high-energy collision, the interactions take place at small distances between the partons of the two incoming protons giving rise to collisions with a high-momentum transference, called *hard scatterings*. The partons involved in the hard scattering can be considered as free partons¹ and a perturbative expansions in α_s can be used in order to calculate the observables of the hard scattering. Both the soft and hard aspects of hadron collider collisions can be split by virtue of the *factorisation theorems* [17] [18]. The perturbative and process-dependent scattering can be separated from the non-perturbative but universal (i.e. process-independent) structure inside the proton. Qualitatively, the hard scattering taking place with a momentum transfer Q^2 has typical interaction timescale of $\sim 1/Q$. The soft interactions inside the

¹See *asymptotic freedom* in previous section.

proton have an energy typically close to the QCD scale, i.e. Λ_{QCD} , therefore with a typical interaction timescale of $1/\Lambda_{QCD}$. Hard scattering processes, as vector boson production, usually have $Q \gg \Lambda_{QCD}$, the time scale of the hard scattering is much shorter than the soft physics inside the proton. Therefore, during hard scattering interaction, the internal structure of the proton is not going to change significantly and thus can be determined before the interaction took place. The internal structure of a hadron is summarised with a set of probability distributions of quarks and gluons, called Parton Distribution Functions (PDF). These PDFs encapsulate all the non-perturbative QCD that determines the probability of finding a parton of a given flavour and momentum inside a hadron. The calculation of an interaction cross section of a hard scattering involves the amplitudes for hard scattering between partons which must be convoluted with the PDF in order to incorporate the probability of finding the necessary partons and their energies for the hard scattering.

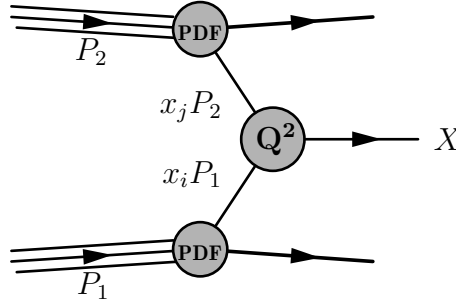


FIGURE 1.3: Hard scattering process representation. Two partons interact exchanging Q momentum from the incoming protons and as a result of the hard scattering the particle X is produced. The PDFs are encapsulating the soft QCD content, a parton is selected out of each hadron carrying a fraction of the hadron momentum, xP described by the PDFs.

Any hadron is composed by *valence* quarks, which in the case of the proton are two u and one d quarks, confined within the hadron. The total sum of valence quarks charge yields the overall charge of the hadron. Those valence quarks are continuously interacting by exchange of gluons and those gluons can also self-interact to produce more gluons or produce additional quark-antiquark pairs, called *sea quarks*. The momentum of the hadron is distributed amongst the valence quarks, the sea quarks and the gluons and the PDFs describe the

probability to find a parton with a given fraction of the hadron momentum, i.e. $p_i = xP$, being p_i the momentum of the parton i carrying a fraction x of the hadron momentum P . At low energies, the three valence quarks essentially carry all of the hadron's momentum. But when the energy transfer is large, $Q^2 \gtrsim 1 \text{ GeV}^2$, the other substructure components of the hadron, sea quarks and gluons, can be resolved. The hadron substructure depends on Q because partons at high x tend to radiate and drop down to lower values of x , while at the same time additional new partons at low x arise from radiation. Therefore, when increasing the energy of the hadron, the hadron momentum is shared amongst a larger number of constituents, although the valence quarks tend to carry a significant fraction of the hadron momentum. The PDFs take the form $f_i(x, Q^2)$, where i is the parton type, x is the momentum fraction and Q^2 is the scale. The PDF cannot be calculated from first principles due to the presence of non-perturbative effects, but the evolution of the PDFs with Q^2 can be calculated. The PDFs are obtained by a fit to experimental data at one scale and then evolved to different scales. An example of PDFs at $Q = \sqrt{10} \text{ GeV}$ and $Q = 100 \text{ GeV}$ from the MSTW group can be found in Figure 1.4.

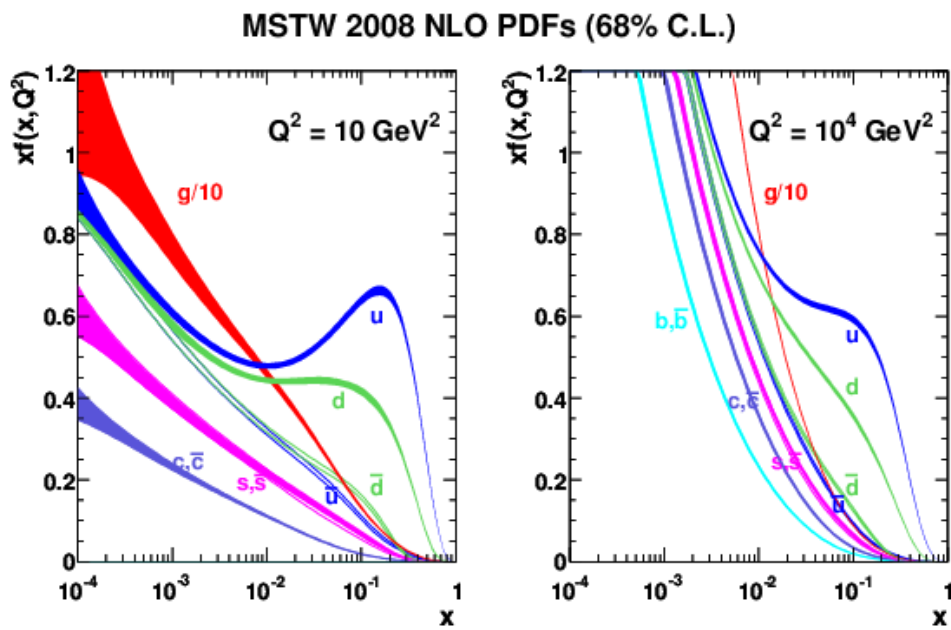


FIGURE 1.4: Parton distribution functions calculated by the MSTW group [19]. The PDFs are shown for two different energy scales.

CHAPTER 2

WZ production at hadron colliders

This chapter is a phenomenological and experimental review of the $W^\pm Z$ production mechanisms at hadron colliders. The main production Feynman diagrams are revisited and the up-to-date $W^\pm Z$ cross section and W^+Z/W^-Z ratio theoretical predictions for $W^\pm Z$ are surveyed. Some explicit calculations for the analysis phase space are done using standard tools. Then, the motivations for the study and measurement of $W^\pm Z$ and ratio are pinpointed before finalising the chapter with the status of all $W^\pm Z$ measurements performed so far.

2.1. The WZ diboson production

The $W^\pm Z$ pairs are produced at hadron colliders mainly at Leading Order (LO) in α_s , by quark-antiquark annihilation which proceeds via t- and u-channel quark exchange and s-channel W-boson exchange as seen in the Feynman diagrams of Figure 2.1. Charge conservation requires a quark up-type and an antiquark down-type for the W^+Z production. Conversely, a down-type quark and an up-type antiquark are needed for the W^-Z . Note that the quark and antiquark are not required to be from the same generation, but the small off-diagonal elements of the CKM matrix highly suppress cross-generation WZ production. In a proton-proton machine as the LHC, the predominance of u quarks enhances the W^+Z production¹ via $u\bar{d}$ type interactions taking the antiquark among the sea-quarks. Therefore it

¹Recall the quark valence content of the proton: uud .

is expected more W^+Z production than W^-Z , i.e. $\sigma_{W^-Z}/\sigma_{W^+Z} < 1$.

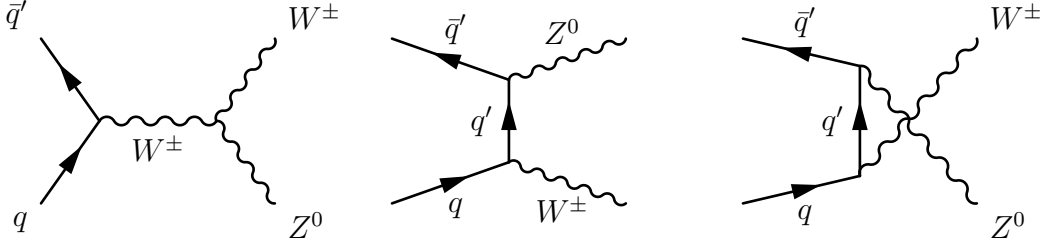


FIGURE 2.1: Feynman diagrams for the LO quark-antiquark annihilation for WZ production. It is shown from left to right the s-channel, t-channel and u-channel. Diagrams interchanging the W and Z are not shown.

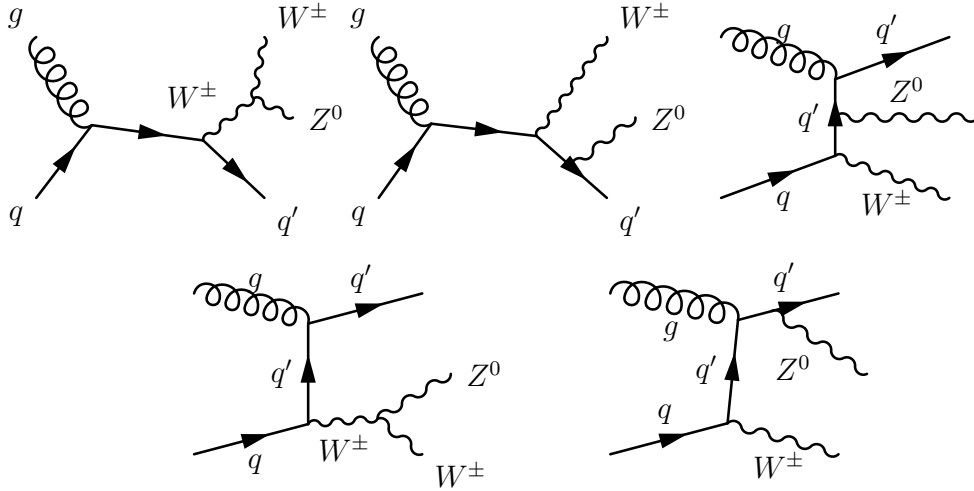


FIGURE 2.2: Feynman diagrams with NLO corrections: gluon-(anti)quark interactions for the WZ production process. Diagrams obtained by interchanging the W and Z and equivalent diagrams using antiquarks are not shown.

The inclusion of Next to Leading Order (NLO) corrections from QCD allows WZ production to be induced by gluon-quark or gluon-antiquark interactions [20] where a quark is present in the final state. Additional NLO corrections include quark-antiquark interactions with virtual corrections and with gluon bremsstrahlung [21] in the final state. The Feynman diagrams for these NLO corrections are shown in Figure 2.2, Figure 2.3 and Figure 2.4. These diagrams

must be convoluted with the proton PDFs in order to calculate the full cross section for $W^\pm Z$ production at a pp collider.

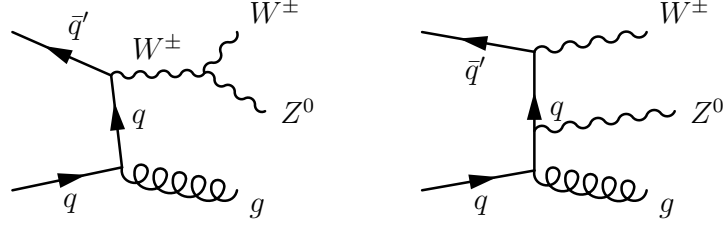


FIGURE 2.3: Feynman diagrams with NLO corrections: quark-antiquark contributions with gluon bremsstrahlung in the final state. Diagrams obtained by interchanging the W and Z and equivalent diagrams using antiquarks are not shown.

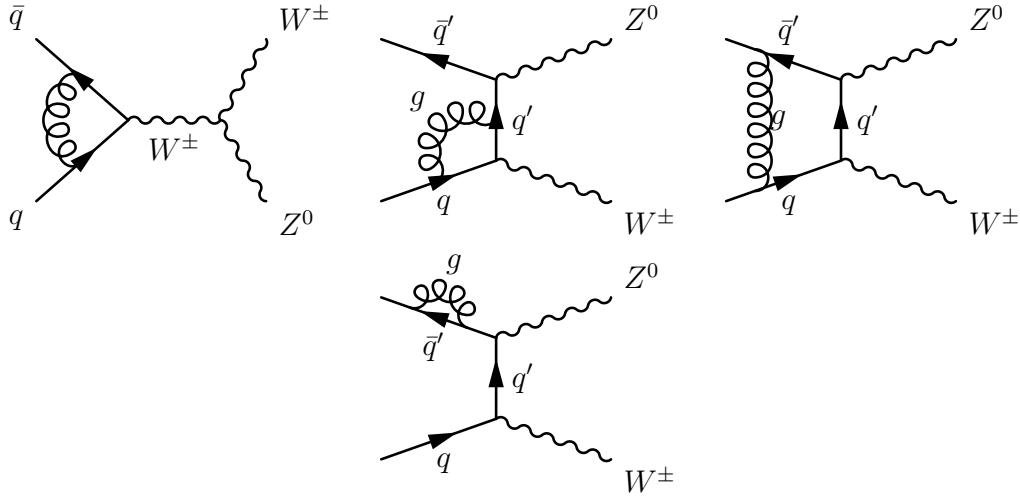


FIGURE 2.4: Feynman diagrams with NLO corrections: virtual contributions with internal gluon loops to the WZ production through quark-antiquark annihilation. Diagrams obtained by interchanging the W and Z and equivalent diagrams with the loop affecting other legs are not shown.

The most updated cross section predictions for the W^+Z , W^-Z , $W^\pm Z$ and the ratio $\sigma_{W-Z}/\sigma_{W+Z}$ at NLO [22] for 7 TeV and 8 TeV of centre of mass proton-proton collisions are reported in Table 2.1. The cross section values were obtained including full spin correlations, the Z and W widths and keeping the vector bosons on-shell. Including the Z/γ^* interference introduces divergences to the $W^\pm Z$ cross

section at very low m_{Z/γ^*} , however it is possible to define a mass window around the Z mass-pole as the phase space to be used. In Table 2.2 the $W^\pm Z$ cross section is obtained using the MCFM software [23] and PDF Martin–Stirling–Thorne–Watt (MSTW8) [19] doing the same procedure as reference [22] but including the Z/γ^* interference. In this case, the bosons are allowed to be off-shell and therefore singly resonant boson diagrams are included in the calculations. This prediction has been calculated because the analysis phase space is exactly defined in this Z mass window.

	7 TeV	8 TeV
σ_{W+Z} (pb)	$11.88(1)^{+0.65}_{-0.50}$	$14.28(1)^{+0.75}_{-0.57}$
σ_{W-Z} (pb)	$6.69(0)^{+0.37}_{-0.29}$	$8.40(0)^{+0.45}_{-0.34\%}$
$\sigma_{W^\pm Z}$ (pb)	$18.57(1)^{+0.75}_{-0.58}$	$22.88(1)^{+0.88}_{-0.66}$
$\sigma_{W-Z}/\sigma_{W+Z}$	$0.563^{+0.002}_{-0.001}$	$0.588^{+0.001}_{-0.001}$

TABLE 2.1: NLO cross section predictions for WZ production and ratio between W^-Z and W^+Z at pp collisions with a centre of mass energy of 7 TeV and 8 TeV extracted from [22]. Renormalisation and factorisation scales are set equal to the average mass of the W and Z. The vector bosons are kept on-shell, with no decays included.

	7 TeV	8 TeV
σ_{W+Z} (pb)	$11.37(1)^{+0.55}_{-0.47}$	$13.86(1)^{+0.73}_{-0.40}$
σ_{W-Z} (pb)	$6.40(1)^{+0.36}_{-0.27}$	$8.05(1)^{+0.43}_{-0.33}$
$\sigma_{W^\pm Z}$ (pb)	$17.77(2)^{+0.66}_{-0.54}$	$21.91(2)^{+0.85}_{-0.52}$
$\sigma_{W-Z}/\sigma_{W+Z}$	$0.563^{+0.002}_{-0.001}$	$0.581^{+0.001}_{-0.001}$

TABLE 2.2: NLO cross-section for WZ production and ratio between W^-Z and W^+Z at pp collisions with a centre of mass energy of 7 TeV and 8 TeV calculated using MCFM and PDF MSTW8 sets in the Z mass window $91.1876 \pm 20 \text{ GeV}/c^2$ phase space. The upper and lower deviations are obtained by varying the renormalisation and factorisation scales around the central value, $(M_Z + M_W)/2$, by a factor two.

These calculations show that the QCD NLO contributions to the $W^\pm Z$ are important and cannot be avoided. The MCFM program estimates about a 85% of the cross section comes from the quark-antiquark annihilation and the remainder from quark-gluon interactions. Note that antiquark-gluon contributions are found

negligible which is expected due to the larger availability of quarks than anti-quarks in the proton PDFs.

Due to the centre of mass energy and the charged initial state needed, and the low probability of occurrence, diboson production measurements are relatively new. In particular, the $W^\pm Z$ production was observed for the first time at the Tevatron in a $p\bar{p}$ collisions at a centre of mass energy of 1.96 TeV. These $W^\pm Z$ cross section measurements are valuable to test the SM through the constraining of its parameters and at the same time, high precision measurements could yield information of New Physics processes. Furthermore, the $W^\pm Z$ production is found to be an important background to several Higgs production and other channels in Beyond SM theories. An accurate knowledge of the $W^\pm Z$ production is therefore needed to control the search analyses. The derived observable W^+Z/W^-Z allows to reach more precision because some experimental uncertainties are cancelled or highly suppressed. Also the ratio is more sensitive to the PDF used, therefore it is a potential observable to constrain the PDF fits.

	channel	BR [%]
W	$e\nu_e$	10.75 ± 0.13
	$\mu\nu_\mu$	10.57 ± 0.15
	$\tau\nu_e$	11.25 ± 0.20
	hadrons	67.60 ± 0.27
Z	e^+e^-	3.363 ± 0.004
	$\mu^+\mu^-$	3.366 ± 0.007
	$\tau^+\tau^-$	3.370 ± 0.008
	hadrons	69.91 ± 0.06
	$\nu_\ell\bar{\nu}_\ell$	20.00 ± 0.06

TABLE 2.3: Decay probabilities, i.e. branching ratios, for W and Z. Hadrons tag is including all decays involving at least one (anti)quark. The value are obtained from ref. [24]

The aim of this thesis is to measure the cross section and ratio observable for the WZ production using the fully leptonic decay of the W and Z gauge bosons. Despite the fact that leptonic decays only represent a small fraction of possible W and Z decays, as can be seen in Table 2.4, they produce a clean 3-lepton signature in detectors, having relatively small backgrounds. Almost 90% of the time W and/or Z decays to hadrons but this signature has very large experimental

backgrounds as QCD multi-jet production and a fuzzy experimental signature full of jets, missing energy and no higher momentum leptons make the event reconstruction an intricate and challenging process.

	channel	BR [%]
	$\ell' \nu_{\ell'} \ell^+ \ell^-$	3.29 ± 0.08
WZ	$\ell^\pm + \nu_{\ell'} \bar{\nu}_{\ell'}$	6.51 ± 0.06
	hadrons	90.34 ± 0.07

TABLE 2.4: Decay probabilities for WZ. Hadrons tag is including all decays involving at least one (anti)quark. ℓ indicate sum over all type of lepton (e, μ, τ).

2.2. Previous Measurements

The WZ cross section production was measured for the first time at the $p\bar{p}$ Tevatron collider experiments D0 and CDF with a centre of mass energy of $\sqrt{s}=1.96$ TeV. After the LHC successfully started, the A Toroidal Large ApparatuS (ATLAS) and Compact Muon Solenoid (CMS) experiments have also measured the WZ production cross section at pp collisions with $\sqrt{s}=7$ TeV and $\sqrt{s}=8$ TeV. Only the analyses considering a fully leptonic signature are reported here.

The latest measurement of the WZ cross section production at Tevatron experiment's D0 [25] reported 75 candidate events in the fully leptonic decay channel $WZ \rightarrow \ell' \nu \ell^+ \ell^-$ (where $\ell', \ell \in e, \mu$) using 8.6 fb^{-1} integrated luminosity. The WZ cross section measured in the phase space¹ $M_{\ell+\ell-} \in [66, 116]$ was $\sigma_{WZ} = 4.50 \pm 0.61(\text{stat})_{-0.25}^{+0.16}(\text{sys})$ pb, in agreement with the SM NLO prediction from MCFM [26] $\sigma_{WZ}^{\text{theo}} = 3.21 \pm 0.19$ pb.

The CDF experiment has also measured the WZ production cross section at $\sqrt{s}=1.96$ TeV using in that case $\mathcal{L}=7.1 \text{ fb}^{-1}$. The production cross section in the phase space $M_{\ell+\ell-} \in [60, 120]$ was measured to be $\sigma_{WZ} = 3.9_{-0.5}^{+0.6}(\text{stat})_{-0.4}^{+0.6}(\text{sys})$ pb, also in agreement with the SM NLO prediction from MCFM, $\sigma_{WZ}^{\text{theo}} = 3.46 \pm 0.21$ pb.

New centre of mass energies have become available with the LHC pp collider and its experiments have presented results at the reached energies. ATLAS

¹Due to Z/γ^* interference, the $W^\pm Z$ cross section diverges at very low m_{Z/γ^*} , therefore an appropriate phase space must be defined to avoid the divergences at low mass when the cross section is calculated.

collaboration has published WZ cross section measurements at $\sqrt{s}=7$ TeV [27], [28] using almost the full available integrated luminosity $\mathcal{L}=4.6\text{fb}^{-1}$, obtaining a measurement in the phase space $M_{\ell+\ell-} \in [66, 116]$ of $\sigma_{WZ} = 19.0^{+1.4}_{-1.3}(\text{stat}) \pm 0.9(\text{sys}) \pm 0.4(\text{lumi})$ pb compatible within uncertainty errors with the SM prediction $\sigma_{WZ}^{\text{theo}} = 17.6^{+1.1}_{+1.0}$ pb. ATLAS has also presented results [29] at $\sqrt{s}=8$ TeV in the same phase space using an integrated luminosity of 13fb^{-1} . Its result $\sigma_{WZ} = 20.3^{+0.8}_{-0.7}(\text{stat})^{+1.2}_{-1.1}(\text{sys})^{+0.7}_{-0.6}(\text{lumi})$ pb is also compatible with SM prediction of $\sigma_{WZ}^{\text{theo}} = 20.3 \pm 0.8$ pb.

The CMS collaboration has published a public note [30] based on $\mathcal{L}=1.1\text{fb}^{-1}$. The phase space was defined to be $M_{\ell+\ell-} \in [60, 120]$, the WZ cross section was measured to be $\sigma_{WZ} = 17.0 \pm 2.4(\text{stat}) \pm 1.1(\text{sys}) \pm 1.0(\text{lumi})$ pb. Notice that the theoretical prediction was not reported in the reference. This thesis is in fact the core of the CMS public measurement using the full 2011 and 2012 luminosity [31], which at the time of this writing the analysis was in preparation process.

	$\sqrt{s}$ (TeV)	$\mathcal{L}$ (fb^{-1})	$M_{\ell+\ell-}$ (GeV/c^2)	Measured σ_{WZ} (pb)	Theoretical σ_{WZ} (pb)
D0	1.96	8.6	[66,116]	$4.50 \pm 0.61(\text{stat})^{+0.16}_{-0.25}(\text{sys})$	3.21 ± 0.19
CDF-II	1.96	7.1	[60,120]	$3.9^{+0.6}_{-0.5}(\text{stat})^{+0.6}_{-0.4}(\text{sys})$	3.46 ± 0.21
ATLAS	7	4.6	[66,116]	$19.0^{+1.4}_{-1.3}(\text{stat}) \pm 0.9(\text{sys}) \pm 0.4(\text{lumi})$	$17.6^{+1.1}_{+1.0}$
CMS	7	1.09	[60,120]	$17.0 \pm 2.4(\text{stat}) \pm 1.1(\text{sys}) \pm 1.0(\text{lumi})$	—
ATLAS	8	13	[66,116]	$20.3^{+0.8}_{-0.7}(\text{stat})^{+1.2}_{-1.1}(\text{sys})^{+0.7}_{-0.6}(\text{lumi})$	20.3 ± 0.8

TABLE 2.5: Latest available WZ cross section production measurements through the fully leptonic decay. Each row shows the cross section measured in each experiment quoting the centre of mass energy, the integrated luminosity used and the theoretical SM cross section predicted at NLO in QCD using mainly the MCFM generator

Table 2.5 summarises all the latest available WZ cross section measurements up to now and the corresponding theoretical SM predictions. In summary, all the measured values up to now are in agreement with the SM predictions within uncertainty errors. However, the central values are slightly shifted with respect to the predicted ones, although always within 2σ in the worst of the cases.

Notice that there are no previous measurements of the ratio $\sigma_{W+Z}/\sigma_{W-Z}$ to be reported; this thesis is the first measurement of this ratio observable.

CHAPTER 3

The Experiment

The experiment used for the WZ cross section measurement is introduced in this chapter. The chapter is split in two sections, one section describing the main features of the LHC machine and the experiments located therein, and the other section focused on the CMS experiment. The aim of the LHC section is to show some of the machine parameters and the performance of the last three years of running relevant to the analysis performed in this thesis. The section is mainly based on the technical references [32] and [33], so the reader is invited to look at the references for more technical and interesting details. The CMS section describes the main characteristics of the detector, introducing some physical quantities used in the analysis. The section enumerates the different subdetector systems and their main features relevant to the analysis. As the LHC section, the level of detail is kept in a mere description of the main components, nevertheless the interested reader can find more details in the technical references [34] and [35].

3.1. The Large Hadron Collider

The LHC is a proton-proton collider with a nominal design centre of mass energy of 14 TeV [32] [33] expected be reached in 2014-2015 when restarting the machine after the upgrade stop of 2013. Its primary motivation is to elucidate the nature of electroweak symmetry breaking, for which the Higgs mechanism is presumed to be responsible. However, there are alternatives that invoke more symmetry,

such as supersymmetry, or invoke new forces or constituents, such as strongly-broken electroweak symmetry, technicolor, etc or even a yet unknown mechanism. Furthermore, there are high hopes for discoveries that could pave the way toward a unified theory. These discoveries could take the form of supersymmetry or extra dimensions, the latter often requiring modification of gravity at the TeV scale. Hence, there are many compelling reasons to investigate the TeV energy scale. Hadron colliders are well suited to the task of exploring new energy domains, and the region of 1 TeV constituent $\sqrt{s}$ can be explored if the proton energy and the luminosity are high enough. The beam energy (7 TeV) and the design luminosity ($\mathcal{L} = 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$) of the LHC have been chosen in order to study physics at the TeV energy scale.

The LHC machine is installed in the tunnel where the Large Electron–Positron Collider (LEP) was previously installed. The underground infrastructure of LEP [36] basically consisted of a 26.7 km long ring tunnel lined with concrete. It included experimental areas at four points (2, 4, 6 and 8), each incorporating experimental and service caverns. For the LHC project, the existing LEP tunnel has been re-used after the complete dismantling of the LEP machine. In addition, new structures have been added, including experimental and service caverns destined to accommodate two new experiments at points 1 and 5.

The LHC produces proton-proton collisions at high centre of mass energy. For this, protons must be accelerated to velocities close to the speed of light and be focused at some points (where detectors are placed). In order to achieve this, a large variety of magnets are set in the LHC ring: dipoles, quadrupoles, sextupoles, decapoles, etc. The trajectory of the beam is curved using superconducting magnets. The LHC has more than 1200 superconducting magnetic dipoles of 8.3 Tesla operating at a temperature of 1.9 Kelvin, so the accelerator has a large cryogenic system, with superfluid Helium pumped into the magnet systems. The machine parameters relevant for the operation of the CMS detector are listed in Table 3.1. The nominal parameters, corresponding to the nominal design to reach a centre of mass energy of 14 TeV, are compared with the 2010, 2011 and 2012 running periods.

Each of the 1232 dipole magnets has radio frequency cavities providing a kick that results in an increase in the proton energy of 0.5 MeV/turn. The

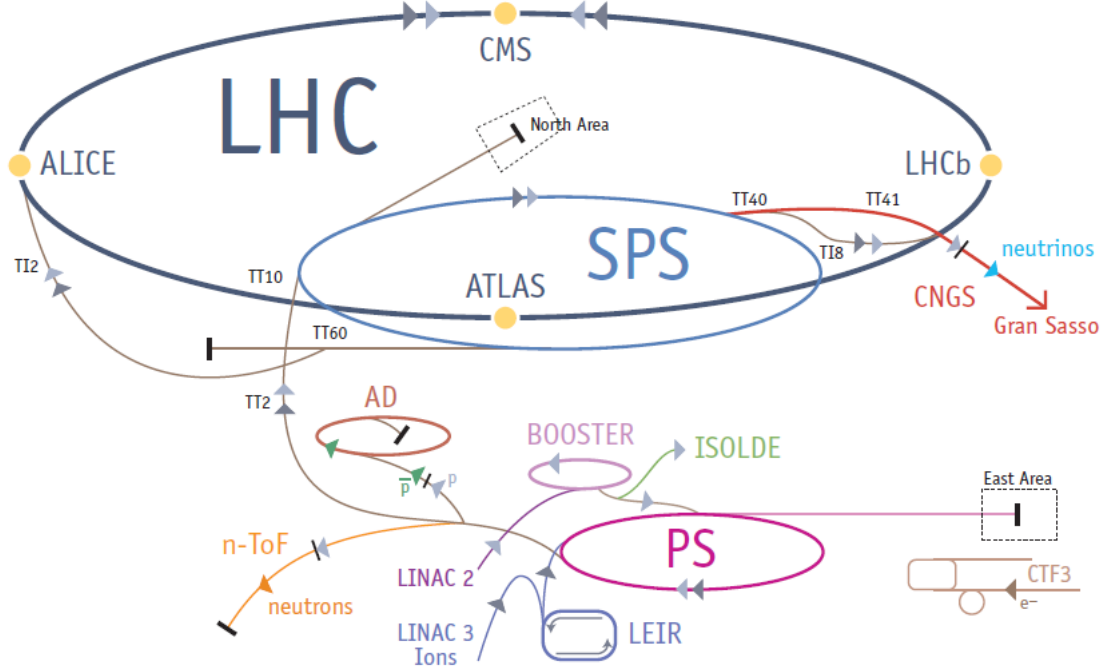


FIGURE 3.1: Schematic overview of the CERN accelerator complex.

Parameter	2010	2011	2012	Nominal
Energy per proton, E [TeV]	3.5	3.5	4	7
Peak Luminosity [$10^{33} \text{ cm}^{-2} \text{ s}^{-1}$]	0.2	3.6	7.7	10
Bunch separation [ns]	150	75/50	50	25
Maximum number of bunches, k_B	368	1380	1380	2808
Particles per bunch, N_p [10^{11}]	1.2	1.5	1.7	1.15
Beta value at IP, β^* [m]	3.5	1.0	0.6	0.55

TABLE 3.1: LHC parameters for 2010, 2011 and 2011 compared with the nominal values. The point dependent parameter values (β^* , peak luminosity) are taken at point 5, i.e. at CMS.

nominal energy of each proton beam is 7 TeV and the design luminosity of $\mathcal{L} = 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ leads to around 1 billion proton-proton interactions per second. The luminosity is given by:

$$L = \frac{\gamma f k_B N_p^2}{4\pi \epsilon_n \beta^*} F \quad (3.1)$$

which gives the main parameters at the LHC:

- γ : Lorentz factor.
- f : revolution frequency.
- k_B : number of proton bunches per beam.
- N_p : number of protons per bunch.
- ϵ_n : normalised transverse emittance (with a design value of $3.75 \text{ } \mu\text{m}$).
- β^* : betatron function at the Interaction Point (IP).
- F : reduction factor due to the beam crossing angle at the IP

Particles to be injected to the LHC are first prepared in a set of previous accelerators, to rise the energy gradually. LINAC-2 is a linear particle accelerator that increases the proton energy up to 50 MeV. Protons are accelerated up to 1.4 GeV at the next system, the Proton Synchrotron Booster (PSB). They reach an energy of 26 GeV at the Proton Synchrotron (PS) before they enter the last accelerator previous to the LHC, the SPS, where the final energy is 450 GeV. This operation is repeated 12 times for each counter-rotating beam. Finally, protons are transferred to the LHC ring. A schema of the LHC and the previous accelerators can be seen in Figure 3.1.

Along the LHC circumference there are six detectors installed: A Large Ion Collider Experiment (ALICE) [37], ATLAS [38], CMS [35] [34], Large Hadron Collider beauty (LHCb) [39], Large Hadron Collider forward (LHCf) [40] and TOTal Elastic and diffractive cross section Measurement (TOTEM) [41]. The first four detectors are installed in huge underground caverns, built in points 2,1,5 and 8 respectively, around the four collision points.

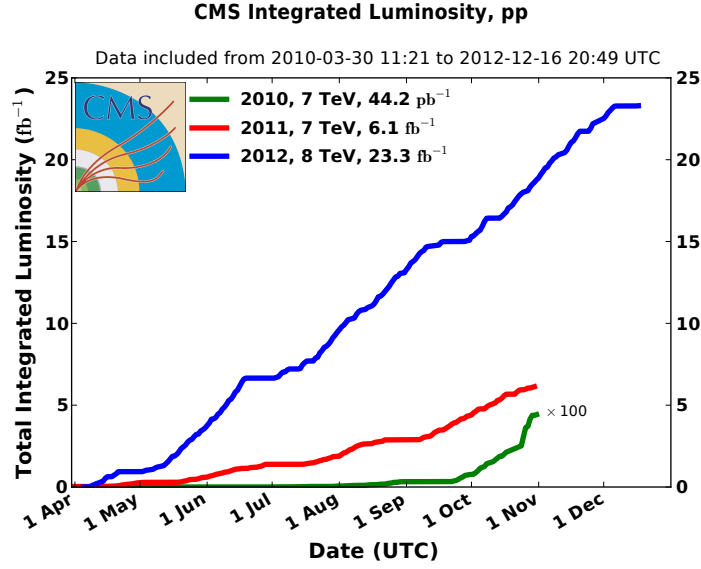


FIGURE 3.2: Cumulative luminosity delivered to CMS versus day during stable beams and for proton-proton collision. This is shown for 2010 (green), 2011 (red) and 2012 (blue) data-taking.

CMS and ATLAS are general purpose detectors that share the same physics goals, so a cross-check between their results can be made, although they have different designs. The other experiments are specialised in different topics, such as heavy flavor physics and precise measurements in the case of the LHCb or heavy ion studies for ALICE.

3.1.1. Performance

In September 10th 2008, the LHC started up with proton beams circulating successfully in the main ring for the first time. Nevertheless, nine days later a faulty electrical connection caused a chain of damages which delayed further operations for fourteen months. On November 2009 the machine came back to work and the first proton-proton collision at 450 GeV per beam were recorded. In March 2010, the LHC provided the world's highest energy collisions of 2.36 TeV and quickly increased the collision energy to 7 TeV. One of the first events recorded by the CMS detector on 30th March can be seen in Figure 3.3. The intensity of the beams was progressively increased up to reach a peak luminosity of

$2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$, around 2% of the design luminosity, at the end of the run. The

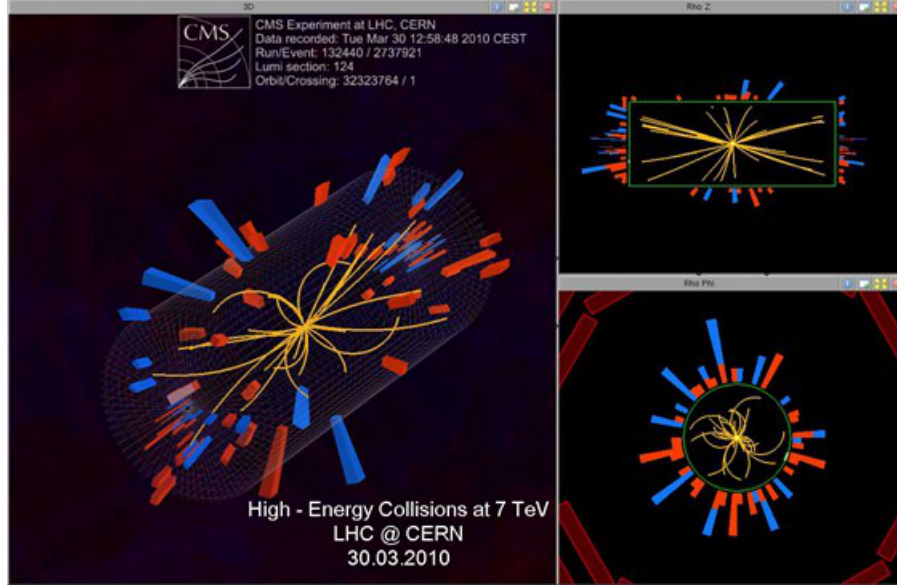


FIGURE 3.3: First CMS Event recorded at 7 TeV $\sqrt{s}$.

total integrated luminosity delivered to the CMS experiment for proton-proton collisions was 47.03 pb^{-1} , from which 43.17 pb^{-1} were recorded. The maximum instantaneous luminosity recorded was $\sim 205 \mu\text{b}^{-1}$ per second. More details for the 2010 Run are summarised in Table 3.2. For Heavy Ion collisions the total integrated luminosity delivered was $9.56 \mu\text{b}^{-1}$ and $8.7 \mu\text{b}^{-1}$ recorded.

Parameter	Value
Peak Instantaneous Stable Luminosity	$198.8 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$
Max Luminosity Delivered in one Fill	6.2 pb^{-1}
Maximum Luminosity Delivered in one Day	5.4 pb^{-1}
Maximum Luminosity Delivered in one Week	15.2 pb^{-1}
Maximum Luminosity Delivered in one Month	30.0 pb^{-1}
Maximum Colliding Bunches	348

TABLE 3.2: LHC and CMS report for 2010 Run

During 2011 the LHC delivered 5.74 fb^{-1} and CMS recorded 5.21 fb^{-1} of data, reaching a detector recording efficiency of about 91%. The 2011 proton-proton Run started in mid March and ended at the end of October, when the Heavy Ion

run started. Information about the 2011 year records of the LHC and CMS for pp collisions are reported in Table 3.3. The Technical Stop (TS) for accelerator

Parameter	Value
Peak Instantaneous Stable Luminosity	$3547.6 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$
Max Luminosity Delivered in one Fill	123.1 pb^{-1}
Maximum Luminosity Delivered in one Day	135.6 pb^{-1}
Maximum Luminosity Delivered in one Week	537.9 pb^{-1}
Maximum Luminosity Delivered in one Month	1614.9 pb^{-1}
Maximum Colliding Bunches	1331
Maximum Interactions per Crossing (pileup)	31

TABLE 3.3: LHC and CMS report for 2011 Run.

maintenance done in September 2011 divides the data in two different periods: before the TS (Run2011A) and after (Run2011B). After the TS the accelerator conditions changed (i.e. more colliding bunches and smaller β^*), giving as a result an increase of the instantaneous luminosity, which raised the pileup conditions in the detector. A maximum value of 31 pileup events per bunch crossing was reached. This increase of the instantaneous luminosity also gave a gain in the total luminosity delivered by LHC and recorded by CMS, as can be seen in Figure 3.2 as a function of time.

Parameter	Value
Peak Instantaneous Stable Luminosity	$7670.2 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$
Max Luminosity Delivered in one Fill	246.3 pb^{-1}
Maximum Luminosity Delivered in one Day	286.1 pb^{-1}
Maximum Luminosity Delivered in one Week	1300.6 pb^{-1}
Maximum Luminosity Delivered in one Month	3693.1 pb^{-1}
Maximum Colliding Bunches	1380
Maximum Interactions per Crossing (pileup)	35

TABLE 3.4: LHC and CMS report for 2012 Run.

The 2012 run started with an increased centre of mass energy of 8 TeV reaching a new record in centre of mass energy. The data taking started in April 2012 and 23.30 fb^{-1} were delivered by the LHC whilst CMS recorded 21.79 fb^{-1} . Three TS in April, June and September 2012 split the data in

four different periods: Run2012A-B-C-D. After every TS, as the 2011 run, the accelerator conditions changed, increasing its performance. As example, the peak instantaneous luminosity was doubled with respect to the previous year. The impressive performance obtained in the 2012 run is shown in Table 3.4

Several of the parameters have already reached their nominal value during the 2010-2012 running period. Some of the machine parameters are shown in Table 3.1, where the nominal design values are compared with the values of the 2010, 2011 and 2012 running. In particular, the number of protons per bunch was overcome already in 2010. The 2011 and 2012 have been a high pileup environment because the higher separation between bunches with respect to the nominal one was compensated with a low value of β^* and a higher number of protons per bunch, achieving a high instantaneous luminosity (almost the nominal one) but increasing the pileup environment.

3.2. The Detector

The Compact Muon Solenoid (CMS) is a general purpose detector designed to see a wide range of particles and phenomena produced in high-energy proton-proton collisions in the LHC. The main goal of the experiment is the discovery of new particles, such as the Higgs boson or supersymmetric partners of the Standard Model particles [35]. The scale of the experiment would make impossible to deal with it unless the efforts for building, managing and studying the results would be shared along a wide world collaboration. The CMS Collaboration is composed of about 181 institutions from 38 countries, a total of more than 3000 people.

The experiment name shows the importance given to the muon system and to the relative compactness of the detector as a result of a novel design fitting both the electromagnetic and hadronic calorimeters inside of its solenoidal magnet. With a length of 21.6 m and a diameter of 14.6 m, these dimensions make CMS smaller than the other main purpose detector at the LHC, ATLAS, but much more dense, with a total weight of 12500 tons; CMS follows the standard cylindrical symmetry topology where the detector's subsystems are disposed in concentric layers, like a cylindrical onion. The detector is divided mainly in two different regions: barrel and endcaps.

CMS is composed, from the beam line outward, of a vertex detector, a silicon tracker, Electromagnetic and Hadronic Calorimeters (ECAL and HCAL) and muon spectrometer. Figure 3.4 shows a schematic view of the detector. CMS

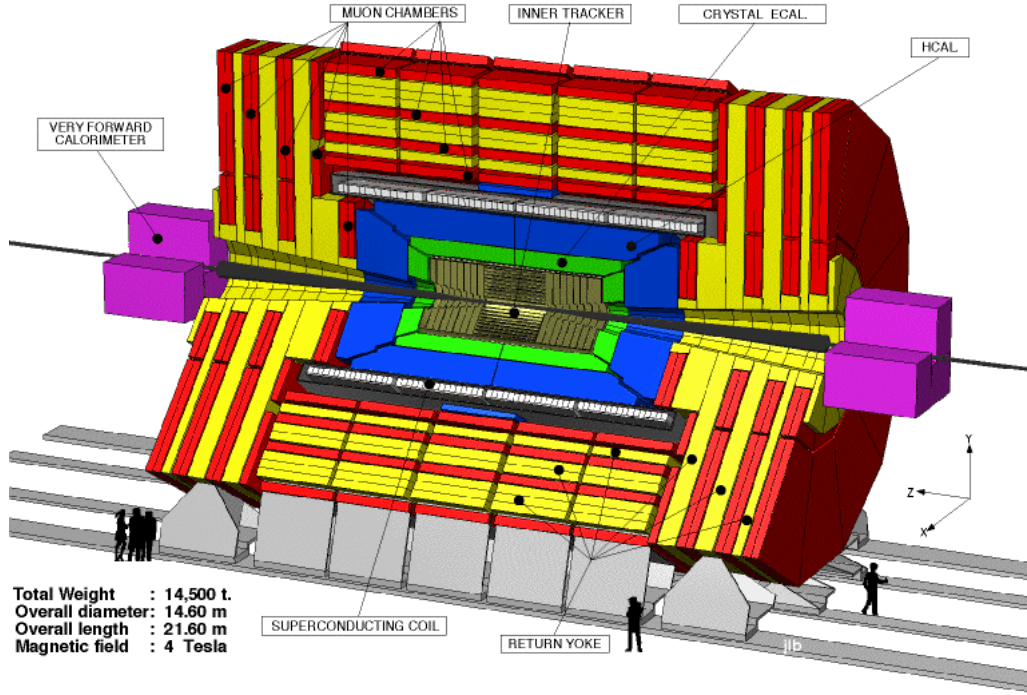


FIGURE 3.4: A cut-away view of the CMS detector, showing the main components and subdetector systems.

adopted a coordinate system where the origin is centred at the nominal collision point inside the experiment, the y-axis points vertically upward, and the x-axis points radially inward toward the centre of the LHC. The azimuthal angle ϕ is measured from the x-axis in the XY plane, $\phi = \arctan(y/x)$ and the polar angle θ is measured from the z-axis, $\theta = \arctan(\sqrt{x^2 + y^2}/z)$. The Figure 3.4 contains the reference frame along with the detector.

The largest group of collisions produced at LHC, two protons interacting via strong force, tend to carry almost all the momenta along the z-axis, so particle physicists have traditionally defined a more convenient quantity to describe the

particle deflection from the beam pipe, the *rapidity*,

$$y \equiv \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right) \quad (3.2)$$

which in the relativistic limit, $E \simeq |\vec{p}|$, reduces to a simple function of the polar angle,

$$\eta \equiv -\ln \left(\tan \frac{\theta}{2} \right) \quad (3.3)$$

This quantity is called *pseudorapidity* and it is an interesting observable because the occupancy of the detector is approximately equal in η intervals.

The momentum and energy measured transverse to the beam direction, denoted by p_T and E_T respectively, are computed from the x and y components. The imbalance of energy measured in the transverse plane is denoted by E_T^{miss} (missing transverse energy) [34]. These are convenient quantities since in hadron colliders the energy balance of an event is known only in the transverse plane.

The detector requirements for CMS to meet the goals of the LHC physics program can be summarised as follows:

- Good muon identification and momentum resolution over a wide range of momenta in the region $|\eta| < 2.5$, good dimuon mass resolution ($\sim 1\%$ at 100 GeV), and the ability to determine unambiguously the charge of muons with $p < 1$ TeV.
- Good charged particle momentum resolution and reconstruction efficiency in the inner tracker. Efficient triggering and offline tagging of τ and b-jets, requiring pixel detectors close to the interaction region.
- Good electromagnetic energy resolution, good diphoton and dielectron mass resolution ($\sim 1\%$ at 100 GeV), wide geometric coverage ($|\eta| < 2.5$), measurement of the direction of photons and correct localisation of the primary interaction vertex, π_0 rejection and efficient photon and lepton isolation at high luminosities.
- Good missing transverse energy and dijet mass resolution, requiring hadron calorimeters with a large hermetic geometric coverage ($|\eta| < 5$) and with

fine lateral segmentation ($\Delta\eta \times \Delta\phi < 0.1 \times 0.1$).

3.2.1. Magnetic Field

The magnetic field at CMS is designed to achieve a momentum resolution of $\Delta p/p \sim 10\%$ at $p = 1\text{ TeV}$, as part of the physics requires an unambiguous determination of the muon charge for muons with a momentum of $\sim 1\text{ TeV}$ and the measurement of narrow states decaying into muons.

For a particle of charge q moving inside a magnetic field B , the transverse momentum can be inferred from the radius of curvature of its trajectory, r ,

$$p_T = qrB$$

Therefore, in order to achieve the design requirements, a powerful magnet was installed. A magnetic field of 4 Tesla is given by a superconducting solenoid about 14 meters long with an inner diameter of 5.9 meters. The return field is large enough to saturate 1.5 m of iron, providing a consistent 2 T field throughout the outer muon system and allowing 4 muon stations to be integrated to ensure robustness and full geometric coverage [42]. Table 3.5 shows the design parameters for the CMS Solenoid. The CMS collaboration decided to start to operate the

Parameter	Nominal value
Field	4 T
Length	12.9 m
Inner diameter	5.9 m
Number of turns	2168
Current	19.14 kA
Stored energy	2.6 GJ

TABLE 3.5: Main parameters of the CMS superconducting solenoid.

magnet at a central magnetic field intensity of 3.8 T. After the first years of operation, once the ageing of the coil is better understood, the collaboration may decide to increase the operation mode to its nominal value.

3.2.2. Inner Tracker System

A robust tracking and detailed vertex reconstruction are able to identify and precisely measure vertices, muons, electrons, and the charged tracks within the jets over a large energy range. The inner tracker system [43] is based on silicon semiconductor technology. The actual technological implementation is driven by the detector occupancy; we can differentiate three radial regions:

- Closest to the interaction vertex where the particle flux is the highest ($\sim 10^7$ / cm/s at $r \sim 10$ cm), pixel detectors are placed. The size of a pixel is $\sim 100 \times 150 \mu\text{m}^2$, giving an occupancy of about 10^{-4} per pixel per LHC crossing.
- In the intermediate region ($20 < r < 55$ cm), the particle flux is low enough to enable use of silicon microstrip detectors with a minimum cell size of $10 \text{ cm} \times 80 \mu\text{m}$, leading to an occupancy of $\sim 2\text{-}3\%$ per LHC crossing.
- In the outermost region ($r > 55$ cm) of the inner tracker, the particle flux drops sufficiently to allow use of larger-pitch silicon microstrips with a maximum cell size of $25 \text{ cm} \times 180 \mu\text{m}$, whilst keeping the occupancy at $\sim 1\%$.

Providing precise measurements of the trajectories of all charged particles is the main goal of the inner tracker. Nevertheless, its resolution is also sufficient to distinguish a secondary vertex in a single collision event corresponding to displaced tracks. This displaced tracks are the distinctive characteristic of long-lived hadrons containing b or c quarks. Therefore, this allows to discriminate between prompt leptons produced from the decay of vector bosons and secondary leptons coming from the semileptonic decay of heavy flavour hadrons.

The closest region to the interaction vertex is the barrel region, which consists of 3 layers of hybrid pixel detectors, situated at radii of 4.4, 7.3 and 10.2 cm from the beam line. The size of these pixels is $100 \times 150 \mu\text{m}^2$. The pixel detector provides tracking points in both the $r - \phi$ (with resolution of $10 \mu\text{m}$) and $r - z$ (resolution $20 \mu\text{m}$) planes. This design, providing a z resolution on par with the $r - \phi$ resolution allows a successful secondary vertex reconstruction in three dimensions.

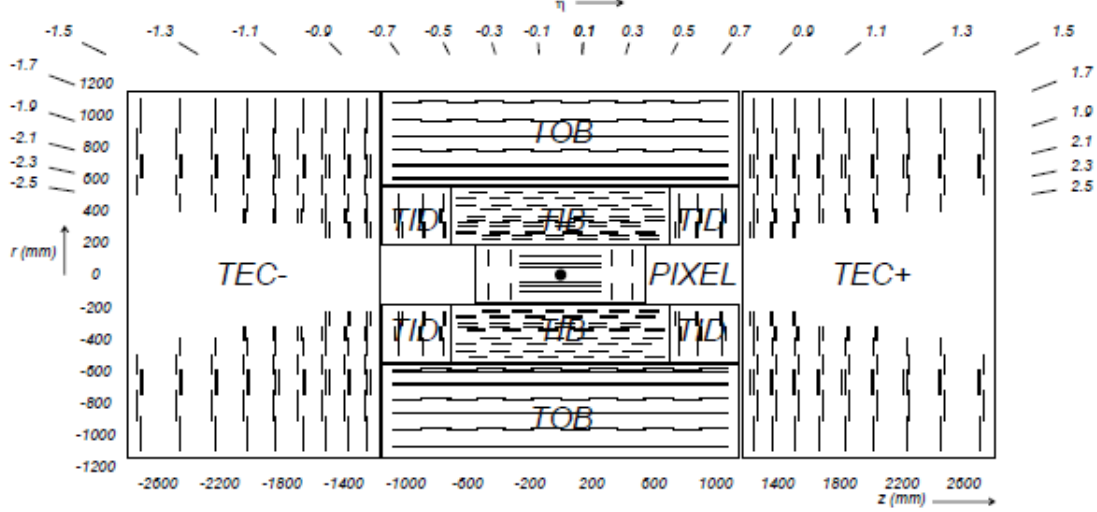


FIGURE 3.5: Schematic vision of the CMS Tracker. Single lines represent detector modules, double lines indicate back-to-back modules which deliver stereo hits.

Ten layers of silicon microstrip detectors are placed at radii between 20 and 110 cm. Each strip has a length between 10 cm and 25 cm and with a width of 180 μm . The forward region is formed by 2 endcaps (Tracker Endcap, i.e. TEC), each having 2 pixel and 9 microstrip layers. In total, the inner tracker comprises 66 million pixels and 9.6 million silicon strips. The barrel part is separated into an Inner (TIB) and an Outer Barrel (TOB). In order to avoid excessively shallow track crossing angles, the TIB is shorter than the TOB, and there are an additional 3 Inner Disks (TIC) in the transition region between the barrel and endcap parts, on each side of the TIB. The total area of the pixel detector is $\sim 1 \text{ m}^2$, whilst that of the silicon strip detectors is 200 m^2 , providing coverage up to $|\eta| < 2.4$. This is the largest silicon microstrip detector ever built. The material inside the active volume of the tracker increases from $\sim 0.4 X_0$ at $\eta = 0$ to around $1 X_0$ at $|\eta| \sim 1.6$, before decreasing to $\sim 0.6 X_0$ at $|\eta| = 2.5$. The layout of the CMS tracker is shown in Figure 3.5.

Hits in the silicon pixel and strips are used as input to reconstruction algorithms which connect them together into tracks and calculate the associated momenta.

The momentum resolution of the tracker for $|\eta| < 1.6$ is,

$$\frac{\sigma(p_T)}{p_T} = \left(\frac{p_T}{\text{GeV}/c} \right) \cdot 0.015\% \oplus 0.5\% \quad (3.4)$$

and with the relative error increasing in the forward region to a maximum in $|\eta| = 2.5$ of,

$$\frac{\sigma(p_T)}{p_T} = \left(\frac{p_T}{\text{GeV}/c} \right) \cdot 0.060\% \oplus 0.5\% \quad (3.5)$$

The first term accounts for the curvature measurement which becomes less precise for high-momentum tracks that bend only slightly in the magnetic field. The second term, the interactions with the tracker material such as multiple scattering.

The impressive performance of the tracker detector is illustrated in Figure 3.6.

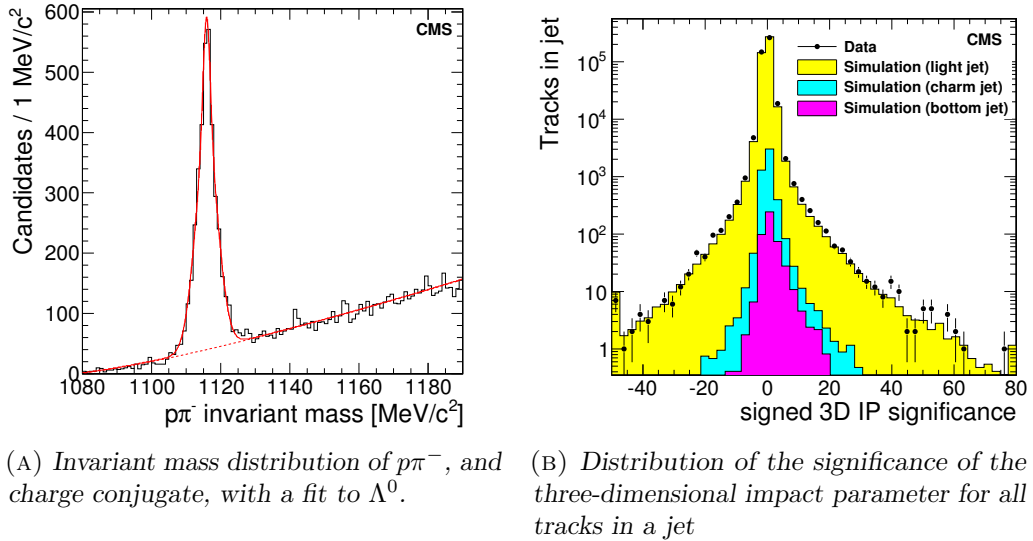


FIGURE 3.6: Tracker performance plots from early LHC operations (2010) with centre-of-mass energies of 0.9 and 2.36 TeV. Figures extracted from Reference [44]

3.2.3. Electromagnetic Calorimeter

The CMS Electromagnetic CALorimeter (ECAL) is designed to measure precisely the energy of photons and electrons and measure the energy of jets

as a result of electromagnetic showers. Also, it provides hermetic coverage for measuring missing transverse energy [45]. The other important task for the ECAL is to achieve good efficiency for electron and photon identification as well as excellent background rejection against hadrons and jets. The large solenoid radius allows the calorimetry to be located inside the solenoid. A scintillating crystal calorimeter offers the best performance for energy resolution since most of the energy from electrons or photons is deposited within the homogeneous crystal volume of the calorimeter. High density crystals with a small Molière radius allow a very compact electromagnetic calorimeter system. Lead tungstate (PbWO_4) crystals provide a high density (8.28 g/cm^3), short radiation length (0.89 cm) and small Molière radius (2.2 cm), leading to rapidly progressing, tightly contained showers for high-energy electrons and photons. Also, lead tungstate is a fast scintillator (80% of the light is emitted within 25 ns) and it is relatively easy to produce from readily available raw materials. Furthermore, substantial experience and production capacity were available. These characteristics drove the choice for the technology in the ECAL detector. The ECAL is a hermetic, homogeneous calorimeter comprising 61200 PbWO_4 crystals mounted in the central barrel part and closed by 7324 crystals in each of the two endcaps. In Figure 3.7 a layout of the ECAL is shown.

The crystals emit a blue-green scintillation light peaking near 425 nm , which is collected by silicon avalanche photodiodes (APD) in the barrel and vacuum phototriodes (VPTs) in the endcaps. The APDs and VPTs produce electrical signals which correlate with the multiplicity of detected photons, allowing the calculation of *energy deposits* left in each crystal.

The barrel section (EB) has an inner radius of 129 cm . It is structured as 36 identical supermodules, each covering half the barrel length and corresponding to a pseudorapidity interval of $0 < |\eta| < 1.479$. The crystals are quasi-projective (the axes are tilted at 3° with respect to the line from the nominal vertex position) and cover 0.0174 (i.e. 1°) in $\Delta\phi$ and $\Delta\eta$. The crystals have a front face cross section of $\sim 22 \times 22 \text{ mm}^2$ and a length of 230 mm , corresponding to $25.8 X_0$.

The endcaps (EE), are situated at a distance of 314 cm from the vertex and cover a pseudorapidity range of $1.479 < |\eta| < 3.0$. They consist of semi-circular aluminium plates from which are cantilevered structural units of 5×5 crystals,

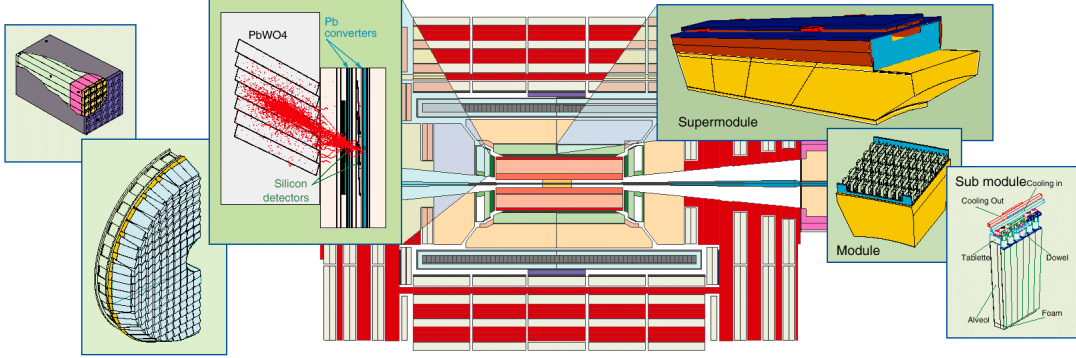


FIGURE 3.7: Layout of the CMS Electromagnetic Calorimeter showing several features.

known as supercrystals. The endcap crystals, like the barrel crystals, off-point from the nominal vertex position, but are arranged in an x-y grid (i.e. not an η - ϕ grid). They are all identical and have a front face cross section of $28.6 \times 28.6 \text{ mm}^2$ and a length of 220 mm ($24.7 X_0$). Neutral pions (π^0) can inadvertently mimic high-energy photons when they decay into two closely-spaced lower energy photons that ECAL picks up together. This problem is localised mostly in the endcap regions, thus a preshower detector, with finer granularity than ECAL, has been installed in front of the crystal calorimeter over much of the endcap pseudorapidity range. The active elements of this device are 2 planes of silicon strip detectors, with a pitch of 1.9 mm, which lie behind disks of lead absorber at depths of $2 X_0$ and $3 X_0$.

Energy deposits in individual crystals are combined into clusters of energy, which are further grouped into superclusters in the reconstruction algorithms, serving as starting point for identification of photons and electrons in the detector. The ECAL achieves an energy resolution given as

$$\frac{\sigma(E)}{E} = \frac{1}{\sqrt{E/\text{GeV}}} \cdot 2.8\% \oplus \frac{1}{E/\text{GeV}} \cdot 12\% \oplus 0.3\% \quad (3.6)$$

being the first term the stochastic term, the second one the electronic noise and the last one due to detector non-uniformity and calibration uncertainties.

Figure 3.8 shows the performance of the ECAL through the dielectron invariant

mass distributions for Z boson decays with both electrons in the barrel (Figure 3.8a) and both in the endcap (Figure 3.8b).

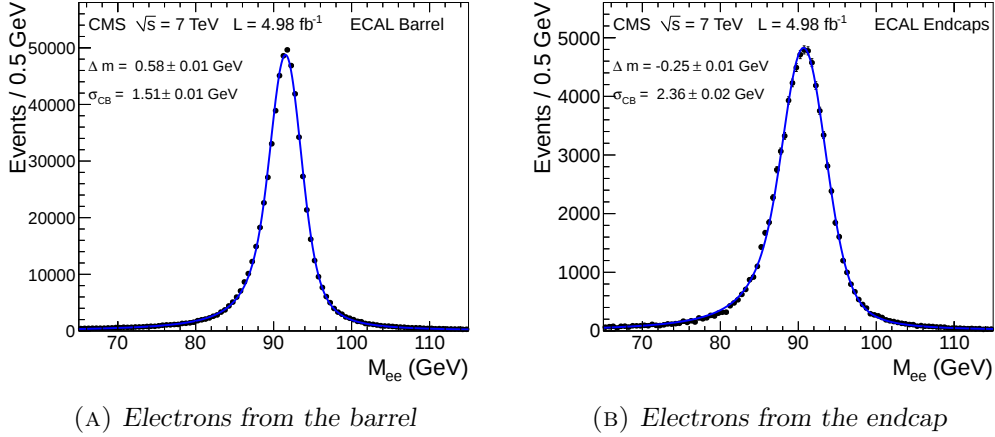


FIGURE 3.8: Dielectron invariant mass distributions extracted from 2011 data taking period.

3.2.4. Hadron Calorimeter

The Hadronic CALorimeter (HCAL) [46] surrounds the electromagnetic calorimeter and acts in conjunction with it to measure the energies and directions of jet particles. Also, it provides hermetic coverage for measuring energy. It is strongly influenced by the choice of magnet parameters since most of the CMS calorimetry is located inside the magnet coil. The HCAL is designed to detect particles which primarily interact with atomic nuclei via the strong force. An important requirement of the HCAL is to minimise the non-Gaussian tails in the energy resolution and to provide good containment and hermeticity for the E_T^{miss} measurement. Hence, the HCAL design maximises material inside the magnet coil in terms of interaction lengths. This is complemented by an additional layer of scintillators, referred to as the hadron outer (HO) detector, lining the outside of the coil. Brass has been chosen as absorber material, as it has a reasonably short interaction length, is easy to produce and is non-magnetic. The HCAL is a sampling calorimeter with alternating layers of brass and scintillator. The brass acts as a non-ferromagnetic absorber, capable of withstanding the intense

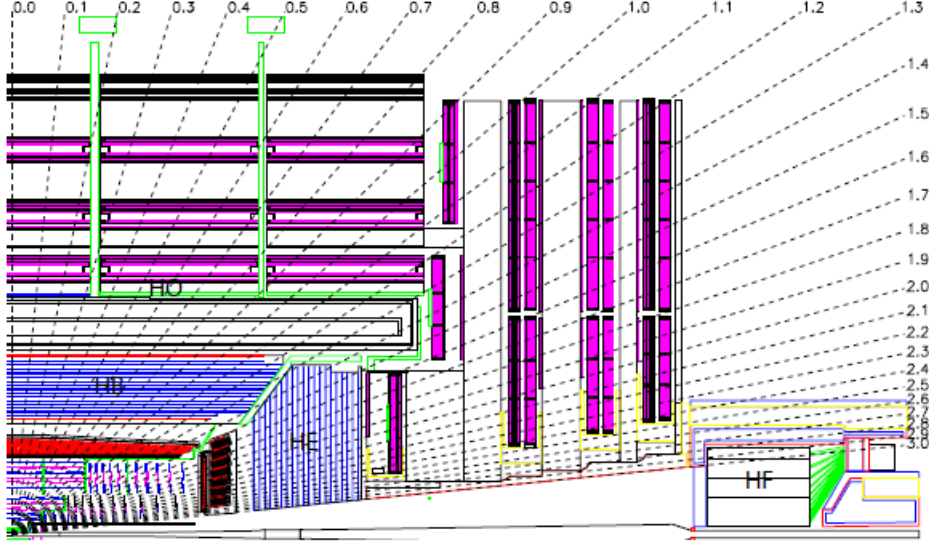


FIGURE 3.9: Layout of the CMS Hadron Calorimeter showing the different modules which are composed.

magnetic field and providing 5.82 interaction lengths of material in the barrel to facilitate the development of hadronic showers. The scintillator consists of tiles along with wavelength-shifting fibre. Hadrons leaving the ECAL interact with the scintillating material to produce a broad spectrum of photons which are then absorbed in the fibre and re-emitted in a more narrow range to which the photodetectors are sensitive. Brass is replaced with steel and scintillating fibre with quartz in the endcap, which are both better able to withstand the higher radiation dose in that region.

The HCAL is formed by the hadron barrel (HB), the hadron outer (HO), the hadron endcap (HE) and the hadron forward (HF) calorimeters, see Figure 3.9. The full system covers a pseudorapidity range of $|\eta| < 5$.

The granularity of the sampling in the 3 parts of the HCAL (HB, HO and HF) has been chosen such that the jet energy resolution, as a function of E_T , is similar in all 3 parts. The resolution for the barrel and endcap has been measured to be,

$$\frac{\sigma(E)}{E} = \frac{1}{\sqrt{E/\text{GeV}}} \cdot 85\% \oplus 7.4\% \quad (3.7)$$

with statistical fluctuations and constant terms in analogy to those discussed in the ECAL section. The inferior performance relative to the ECAL is due both to its operating principle of sampling the shower rather than absorbing all produced energy in high-resolution crystals and also to the intrinsically lower particle multiplicity in hadronic showers with respect the electromagnetic showers, leading to wider statistical fluctuations.

3.2.5. Muon System

The main purposes of the muon system are to identify muons, to be able to do it quickly in order to select the event with muon content for recording (*muon trigger*) and to measure muon momentum. Performance requirements follow the physics goals, including the maximum reach for unexpected discoveries, and the background environment of LHC at its highest luminosity. A robust 4 T solenoid-based system is the key to the CMS design [47]. The advanced muon spectrometer has the following functionality and performance:

- Muon identification: at least 16 layers of material is present up to $|\eta| = 2.4$ with no acceptance losses.
- Muon Trigger: the combination of precise muon chambers and dedicated fast trigger detectors provide unambiguous beam crossing identification and trigger on single and multi-muon events with well defined p_T thresholds from a few GeV to 100 GeV up to $|\eta|=2.1$.
- Standalone momentum resolution from 8 to 15% $\Delta p_T/p_T$ at 10 GeV and 20 to 40% at 1 TeV.
- Global momentum resolution after matching with the Central Tracker: from 1.0% to 1.5% at 10 GeV, and from 6% to 17% at 1 TeV. Momentum-dependent spatial position matching at 1 TeV less than 1 mm in the bending plane and less than 10 mm in the non-bending plane.
- Charge assignment correct to 99% confidence up to the kinematic limit of 7 TeV.

- Capability of withstanding the high radiation and interaction background expected at the LHC.

The muon system uses three different technologies [48] [49] to detect and measure the muons; drift tubes (DT) in the barrel region, cathode strip chambers (CSC) in the endcap region, and resistive plate chambers (RPC) in both the barrel and endcap. To select events with muon content for recording, the

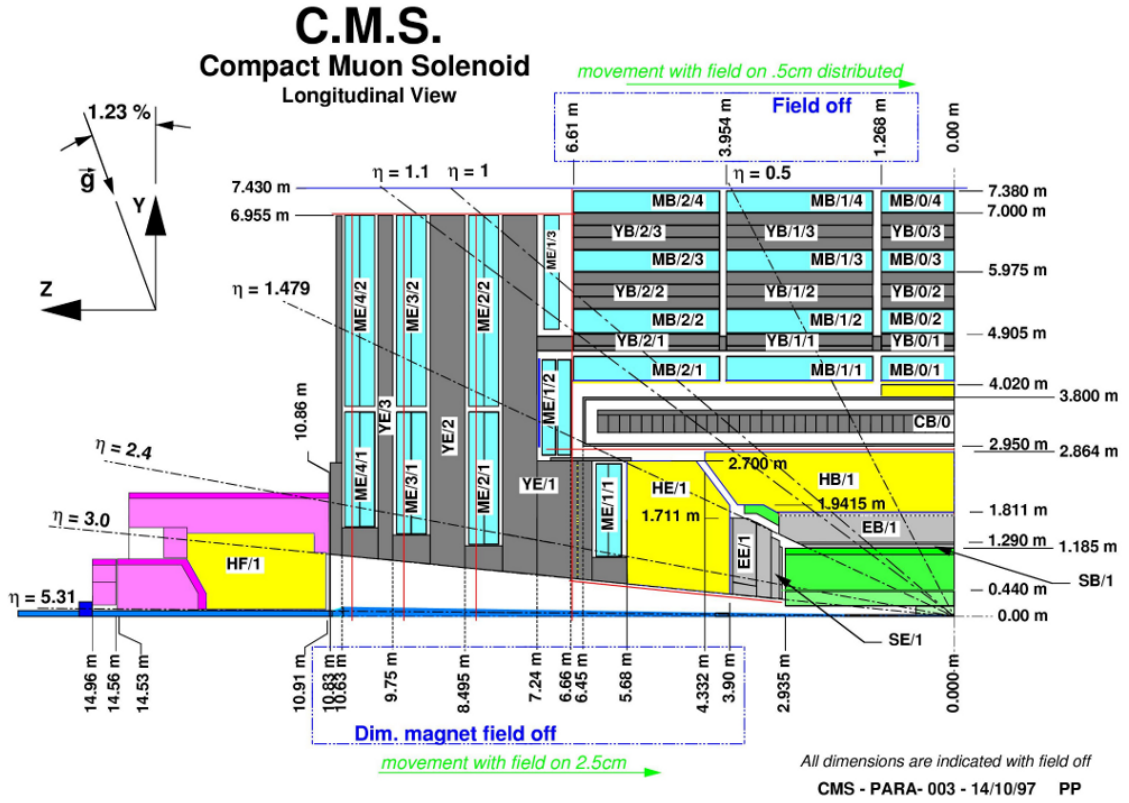


FIGURE 3.10: Layout of the CMS Muon system showing the disposed stations for barrel and endcap

trigger (see Section 3.2.6) in the barrel region is generated using a mean-timer to identify patterns. In the endcap the trigger is generated from the cathode readout patterns and the wire timing. For both barrel and endcap the RPCs provide an additional trigger signal which has a different sensitivity to backgrounds. All the muon chambers are aligned roughly perpendicular to the muon trajectories and distributed to provide hermetic coverage over the η range from 0 to 2.4. The

barrel DTs cover roughly from $|\eta| = 0$ to $|\eta| = 1.3$, where the neutron-induced background is small, the muon rate is low and the residual magnetic field in the chambers is low. The endcap CSCs cover from $|\eta| = 0.9$ to $|\eta| = 2.4$. In this region, the muon rate, as well as the neutron-induced background rate, is high, and the magnetic field is also high. The RPCs cover the region from $|\eta| = 0$ to $|\eta| = 2.1$, used both in the barrel and endcap regions. RPCs provide a fast response with good time resolution, but with a coarser position resolution than the DTs or CSCs. RPCs can therefore identify unambiguously the correct bunch crossing.

The DTs or CSCs and the RPCs operate within the first level trigger system, providing two independent and complementary sources of information. The complete system results in a robust, precise and flexible trigger device. Four stations of detectors are arranged in cylinders interleaved with the iron yoke in the muon barrel (MB) region. The segmentation along the beam direction follows the five wheels of the yoke (labelled YB-2 for the farthest wheel in -z, and YB+2 for the farthest in +z). In each of the endcaps, the CSCs and RPCs are arranged in four disks perpendicular to the beam, and in concentric rings; three rings in the innermost station, and two in the others. In total, the muon system contains of order 25000 m² of active detection planes, and nearly 1 million electronic channels. A longitudinal view of the muon system with the labelled stations is shown in Figure 3.10.

The great performance of the muon spectrometer combined with the inner tracker detector is illustrated with the dimuon invariant mass distribution for Z boson decays of Figure 3.11.

3.2.6. Trigger System and Data Acquisition

The huge amount of data delivered by LHC¹ makes it impossible for the acquisition system to record all of them. Indeed, there is no need to store every collision just due to the fact that most of them have "no physic interest": a lot of bunch crossings are going to interact inelastically or to produce low energy

¹At design luminosity of LHC, beams cross at a frequency of 40 MHz leading to collisions on the order of 10⁸ per second delivered to CMS.

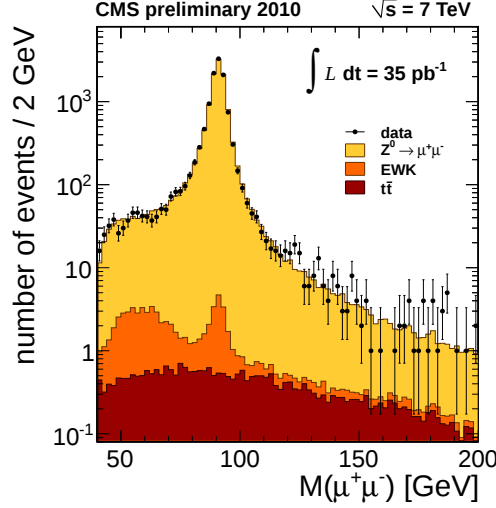


FIGURE 3.11: Dimuon invariant mass distribution for Z boson decays. Data extracted from 2011 run at $\sqrt{s}=7$ TeV using 35 pb^{-1} of data. The experimental data are compared with the expected contributions using simulated data.

interactions. Depending on what is going to be measured in a particular analysis a large number of events should be recorded before an interesting event is produced. Figure 3.12 shows the cross section or production rate of some representative processes at hadron colliders as a function of its centre of mass energy. It can be observed the huge differences along high energy processes and inelastic or low energy processes. A flexible and highly configurable system has been deployed, able to make quick decisions on which event is worth keeping and which will not be as interesting for analysis. This system is called the *trigger system* [50]. The trigger has to provide a huge event reduction factor and at the same time must maintain high efficiency for the few interesting events among millions of background ones. Furthermore, it is required to be flexible enough to easily adapt to the different running conditions and physics targets. This flexibility is accomplished by a combined hardware system made of largely programmable electronics, called *Level-1* (L1) Trigger, and a software based system for the online event filter, the so called High Level Trigger (HLT). Using the trigger system, the output rate is reduced about a factor 10^7 , delivering to the data processing centres a rate down to a few hundred Hz.

The L1 trigger is designed with an output rate of 100 kHz, using information

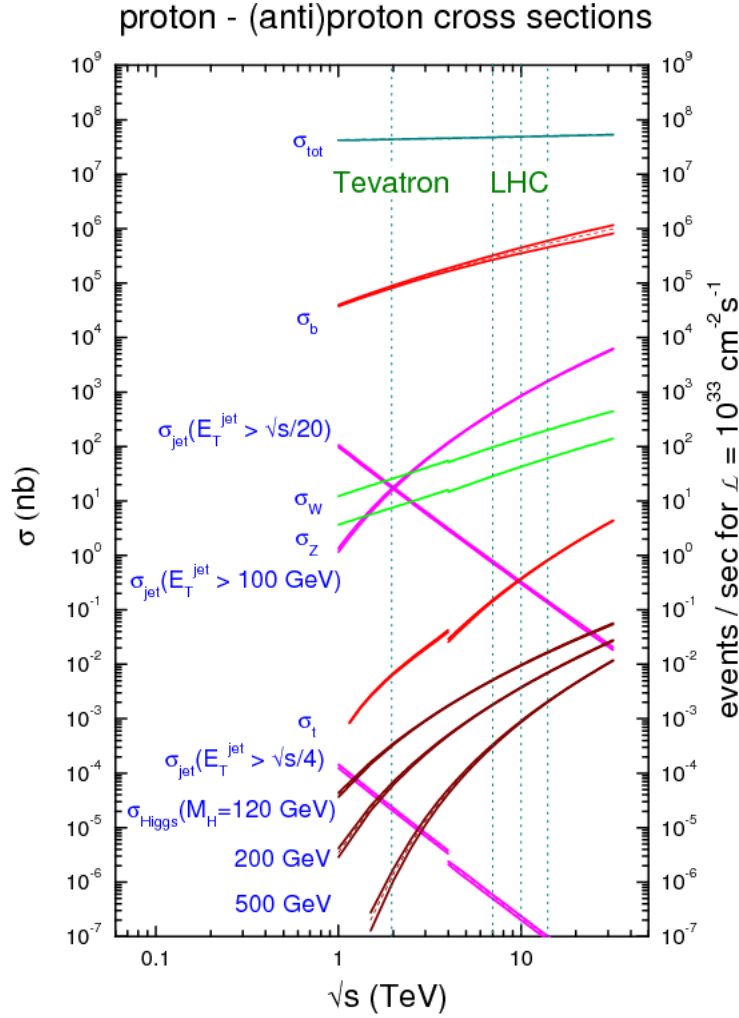


FIGURE 3.12: Production rates of some representative processes at hadron colliders as a function of its centre of mass energy. The discontinuity is due to the Tevatron being a proton-antiproton collider while LHC is a proton-proton machine. It can be appreciated the tiny production rate for high energy process with respect to the inelastic or low energy processes.

from calorimeters and muon system and some correlation of information between these systems. The L1 system is able to build some coarse high level objects, such as muons, electrons, jets, E_T^{miss} , photons, etc; which in turn are used to make decisions about whether to keep or discard a particular event. The total time allocated for the transit and for reaching a decision from a particular beam crossing is $3.2 \mu\text{s}$. This time is in part determined by the size of the LHC detectors and the underground caverns, as signals from the front-end electronics have to reach the services cavern housing the L1 trigger logic and return back to the detector front-end electronics. Given that each 25 ns a beam crossing is produced, roughly 128 beam crossings are produced while the L1 trigger is deciding about the initial event. During this latency time, the detector data must be held in buffers, while trigger data are collected from the front-end electronics and decisions reached that discard a large fraction of events while retaining the small fraction of interactions of interest (nearly 1 crossing in 1000). Of the total latency, the time allocated to Level-1 trigger calculations is less than $1 \mu\text{s}$.

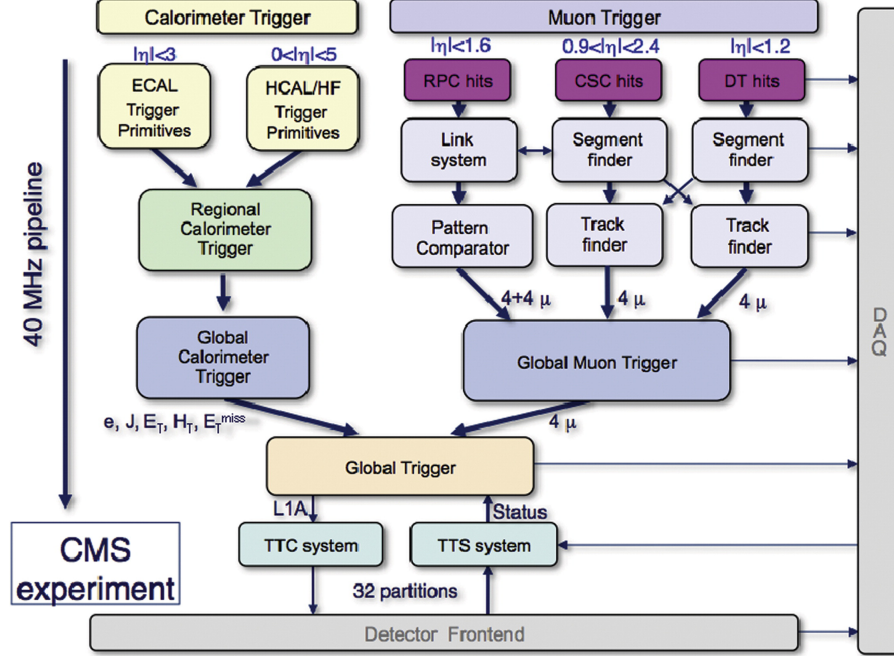


FIGURE 3.13: Scheme for the Level-1 trigger system showing the main subsystems used to make decisions.

The data from the pipelines are transferred to front-end readout buffers. After

further signal processing, zero-suppression and data-compression, the data are placed in dual-port memories for access by the data acquisition system (DAQ). Each event, with a size of about 1.5 MB (in proton-proton interactions), is contained in several hundred front-end readout buffers. Data from a given event are transferred to processors where each processor runs the same HLT software code to reduce the L1 output rate of 100 kHz to 300 or 400 Hz for massive and permanent storage. The HLT algorithms, unlike the L1, have access to the complete read-out data, with the possibility to perform complex calculations similar to those made in the offline analysis software. The strategies of HLT development are focused to discard events as soon as possible, therefore the HLT is implemented through sequential levels (Level-2 and Level-3) where stricter conditions are checked as the level is increased. The HLT system is split in *trigger paths*: each trigger path is targeting different physics processes, therefore each trigger path may deal with different physics objects. There are trigger paths requiring to have events with at least one single high- p_T electron with a p_T higher than a preselected threshold, others requiring a pair of electrons, other paths are devoted to muons or E_T^{miss} , etc. Since events firing each type of trigger path are generally independent, the data is naturally sorted into Primary Datasets (PDs) based on trigger path. Of course, the PDs are biased in favour of events with certain properties, but this is exactly what was intended when developing the trigger system. This effect has to be considered or corrected to ensure there is no bias propagation on the final result of any analysis.

CHAPTER 4

Analysis Framework

CMS was described in chapter 3 through its main subdetector systems which generate an electrical signal response when particle pass through them. As discussed in the previous chapter, the individual subdetectors can only offer a readout of hits in the tracking and muon detectors, energy deposits in the calorimeters and other basic electronic signals. Therefore, the identities and trajectories of the particles which induced that detector response should be inferred using reconstruction algorithms in order to get the ingredients, i.e. the *physic objects*, to recover and reconstruct the collision event. This chapter introduces the different algorithms used in the CMS collaboration to obtain the physics objects used in the analysis out of the raw data collected from the subdetectors. The chapter focuses on the physics objects used in this thesis work; in particular the *muons*, *electrons* and the reconstruction of the *transverse energy* is covered in detail. Previously, a brief overview of the software framework and the event data model used in the collaboration is introduced to contextualise the software physics objects and algorithms applied to the raw data.

4.1. Software Framework

The CMS collaboration designed and deployed a collection of software, called *CMSSW*, built to facilitate the development and deployment of reconstruction and analysis software. The CMSSW is based on a framework, an Event Data Model

(EDM) and the services needed by the simulation, calibration and alignment, and reconstruction modules that process the raw event data coming from the CMS detector systems [51]. Furthermore, the main reconstruction processes from raw data to final high level physics objects, as well as simulation, calibration and alignment are done in a centralised way using standard and collaboration-agreed algorithms and methods. This allows to use the same reconstructed physics objects for all analyses although the framework also allows to tune any step of the reconstruction's chain if an analysis requires so.

The readout of the detector electronics and signals, i.e. the raw data, for each proton-proton bunch crossing are stored in a C++ container called *Event*. The *Event* is the main concept in the CMS EDM. From a software point of view, an *Event* starts as a collection of the raw data from CMS or simulated data for a given collision. As the event data are processed, products are stored in the *Event* as reconstructed data objects. The *Event* thus holds all data that was taken from the detectors as well as all data derived from them. The *Event* also contains metadata describing the configuration of the software used for the reconstruction of each contained data object and the conditions and calibration data used for such reconstruction [52]. This allows to keep track of the different steps as well as to introduce any variation in the reconstruction chain. The *Event* data are output to files in ROOT [53] format, storing raw plus reconstructed data. Due to the huge amount of information dealt with in the CMS experiment and the finite available resources, the data size must be reduced. This is accomplished by selecting only interesting candidate events or by removing irrelevant information depending on the stage of an analysis. The former case is achieved by the so called Trigger system which is covered in Chapter 5, the latter defines what is called *data tier*: each data tier gathers data of each step. Thus, the RAW tier is defined by all the signals coming from the detectors, the RECO tier groups all the relevant collections processed from RAW needed for the physic reconstruction plus the collection raised from the reconstruction itself. There is another data tier designated as Analysis Object Data (AOD) which is a subset of RECO, sufficient for most kinds of physics analyses, so usually the root files delivered to physicists only contain the AOD information. Figure 4.1 shows an example of *Event* container with schematic information of its contents and the data tiers

involved.

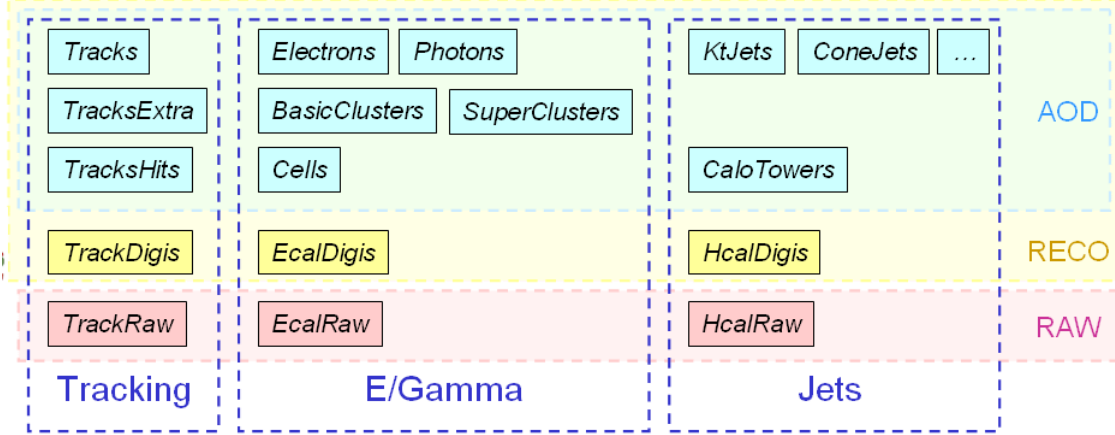


FIGURE 4.1: Event content example showing some physics objects in the C++ *Event* container. The information payload carried by each data tier is delimited by dotted lines. The "Raw" collections are the readout provided by the subdetector systems of CMS, these collections are processed to provide digitised grouped signals ("Digi" collections), which are the input for the reconstruction algorithms. After the reconstruction step, the *Event* contains intermediate level objects, as *TracksHits*, *SuperCluster* or *CaloTowers* which in turn are used to build the high level physics objects, *Tracks*, *Electrons* or *CaloJets*.

4.2. Physics Objects

All the reconstructed information is based on interpreting the readout electronics and signals from each subdetector and associating them to decay vertices, trajectories, energy or particle identities. These quantities have already physical meaning and can be grouped to form high level physics objects as electrons, muons, photons, jets and missing transverse energy. Therefore, the high level physics objects are built from intermediate level objects like tracks, superclusters of energy, etc.

4.2.1. Particle flow reconstruction

The particle flow reconstruction paradigm is becoming a new standard in the event reconstruction. The particle-flow event reconstruction [54] combines the

information from all subdetectors in CMS to identify and reconstruct individually all particles produced in a collision event. The particles reconstructed (particle flow candidates), namely charged hadrons, neutral hadrons, photons, muons and electrons, are used to construct a wide variety of higher-level particle-based objects and observables such as jets, missing transverse energy, lepton and photon isolation, tau identification, b-jet tagging, etc. The muons are reconstructed first, accounting

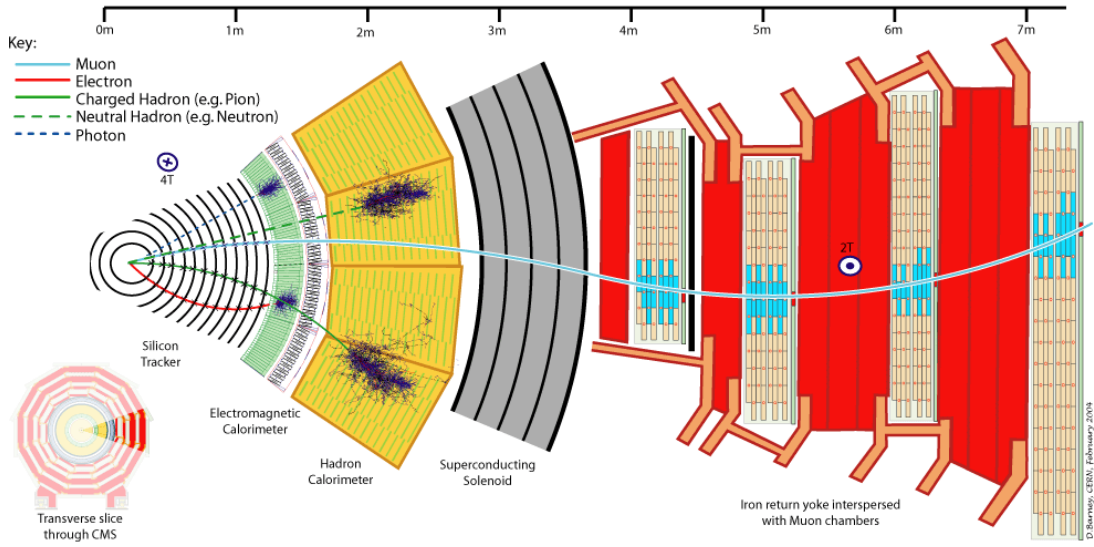


FIGURE 4.2: Detector signature of several particles showing their main interaction with the detector subsystems. The particle flow algorithm uses all the available information from all the subsystems and combine it to obtain the particle candidates.

for all segments in the muon chambers while removing related tracks in the tracker and energy deposits in the calorimeter before moving on the electrons and jets. The electron reconstruction and identification follows using the remaining energy deposits of the ECAL and the electron tracks of the tracker. The tracks are refitted with this information and the particle-flow electron is built, removing the corresponding tracks and ECAL clusters used. Tighter quality criteria are applied to the remaining tracks in order to reject fake tracks. The surviving tracks may rise to charged hadrons, photons or neutral hadrons, and more rarely to additional muons. Using several procedures to connect tracks with ECAL and HCAL energy gives rise to particle-flow charged hadrons. In the process, energy

compatibility between tracks and energy clusters in the ECAL and HCAL together with ordering algorithms allow to obtain neutral hadrons and photon candidates.

4.2.2. Muon Reconstruction

Although the muon is not a stable particle, from the point of view of CMS it behaves as such. The muon's interaction is very similar to the electron, but because of its 200 times heavier mass, and the fact that the radiated power (P) of an accelerated particle in presence of electromagnetic fields is inversely proportional to the mass of that particle (in fact, $P \propto m^{-4}$), muons do not emit as much bremsstrahlung radiation as electrons. This feature allows muons to penetrate further than electrons, barely interacting with the electromagnetic calorimeter and passing through the flux-return yoke. Thus, the main muon signature in CMS is a track in the inner tracker matched with hits in some of the muon system's detectors and a slight energy deposits in the ECAL.

Muon reconstruction starts from local pattern recognition in the muon systems and tracker, followed by the so called *stand-alone*, *tracker muon* or *global* reconstruction algorithms [55]. These three stages of reconstruction lead to objects of different levels providing by their combination a robust and efficient final muon candidate.

Stand-alone muon track (STA)

The *stand-alone* algorithm integrates information from all the muon subsystems. It starts reconstructing hit positions in the DT, CSC and RPC subsystems and building segments of the trajectory in the surface of the chambers with the hits using a pattern recognition. A vector (track position, momentum and direction) is associated to each segment. The innermost vector is used as the seed to fit the muon trajectory using a Kalman Filter technique [56]. The innermost vectors are propagated to the next chamber layer surface (prediction) and a compatible segment (measurement) is searched; once there, the predicted vector is compared with the measurement in the surface and the trajectory parameters are updated accordingly [57] (see Figure 4.3). The operation is performed until the outermost chamber is reached. Material effects like multiple scattering and energy losses

due to ionisation and bremsstrahlung in the muon chambers and return yoke are considered in the vector state prediction. At each segment a cut is applied in the quality of the track fit, a χ^2 cut, in order to evaluate the incremental χ^2 of the track fit due the new state and reject possible bad hits, mostly due to showering, delta rays and pair production. After the outward trajectory fitting, the same Kalman Filter technique is applied inward to define track parameters in the innermost muon station. From there, the trajectory is extrapolated to the point of closest approach to the beam line and optionally constrained with a vertex condition. There are additional constrains to accept a trajectory as a muon track: at least two measurements must be present in the fit, moreover, at least one of them must come from the DT or CSC chambers. This allows rejection of fake DT/CSC segments due to combinatorics.

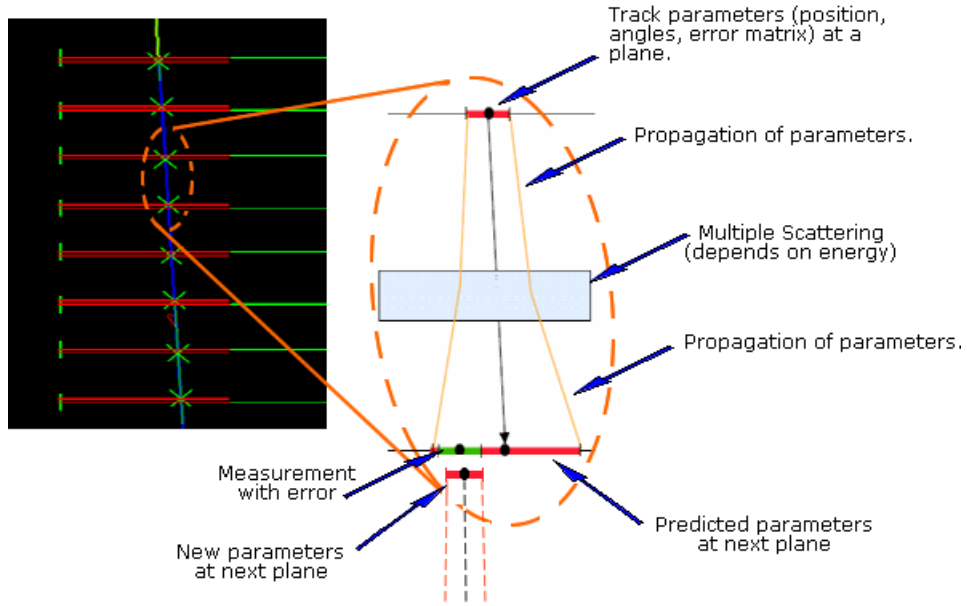


FIGURE 4.3: Description of the Kalman Filter technique used to fit the track parameters. The figure shows the extrapolation of the vector state from a surface to another in a schematic way.

Global muon track

A global muon track is obtained by combining the stand-alone muon tracks with independently-reconstructed tracks from the inner tracker. Those inner tracks are

propagated to the inside surface of the muon detector and matched with the stand-alone tracks compatible in terms of momentum, position and direction. Once the match is accomplished, the hits from both collections are used as input for a new, global fit. The final trajectory is extrapolated to the interaction region to obtain the track parameters there. Arbitration and quality algorithms are applied in order to minimise possible ambiguities and poor matches between the inner and stand-alone tracks. The global muon track takes advantage from both the tracker detector and muon spectrometer to obtain a more accurate description of muon's properties. The tracker can in general provide a much higher momentum resolution than the muon system due to its high precision and the greater multiplicity of hits available for the track fit, but at high energies, $p \sim 100$ GeV, the reduced bending of the particle limits the resolution of the inner tracker fit. At low momentum, the best momentum resolution for muons is obtained from the silicon inner tracker. At higher momentum, however, adding hits at large radii from the muon spectrometer can significantly improve the curvature measurement and thus provide a better momentum resolution. This analysis uses global muons as the primary algorithm to reconstruct muons although cross-checks with the tracker muon algorithm is also done in order to improve the quality of the object.

Tracker muon

Besides *stand-alone* and *global muons*, the third algorithm for muon reconstruction is the so called *tracker muon* which considers all tracks reconstructed from the inner tracker and looks for compatible signatures in the calorimeters and muon system. For each track in the silicon tracker, the algorithm searches for compatible segments in the muon detectors. In particular each track with $p_T > 0.5$ GeV and $p > 2.5$ GeV acts as seed and it is considered as a muon candidate if it can be matched to at least one muon segment. Energy depositions compatible with a muon hypothesis can also be used for muon identification. The tracker muon approach is particularly useful for low- p_T analyses where the global algorithm degrades.

The three algorithms cover a wide range in momentum keeping the momentum measurement and resolution within the challenging design requirements. Figure 4.4

shows the momentum resolution for the three algorithms described. For values below 200 GeV the measurement of the momentum is dominated by the tracker resolution whilst for higher values, the muon spectrometer becomes essential to achieve good resolution.

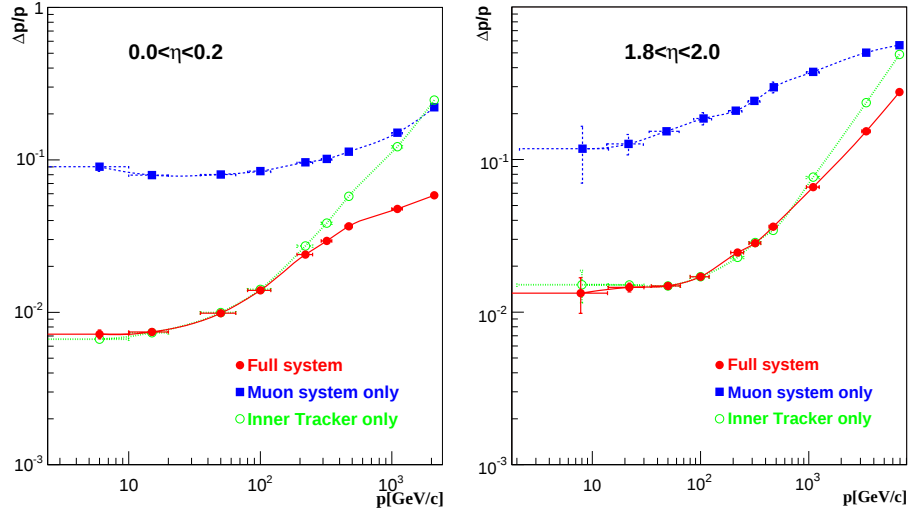


FIGURE 4.4: Momentum resolution for the tracker (green), stand-alone (blue) and global (red) algorithms for barrel (left) and endcap (right). The plots are made using simulated data.

As an example of the versatility of the muon reconstruction algorithms, Figure 4.5 shows the reconstruction of the dimuon spectrum for the first 40 pb^{-1} of data collected in 2010 at 7 TeV centre of mass energy. This plot shows the high muon momentum resolution in the detector, which is able to resolve the invariant mass of a wide range of resonances, covering a large kinematic region from $p_T \sim 500$ MeV to 1 TeV.

Another important variable in order to discriminate between prompt leptons coming from gauge bosons and leptons from heavy quark decays is the isolation of the muon. Leptons coming from jets are expected to be surrounded by hadronic activity whilst the prompt leptons from W or Z are not. The isolation of a muon is evaluated using an algorithm which checks the total energy deposited in a cone around the muon. The deposit can be the transverse energy in a calorimeter or the sum of transverse momenta of reconstructed charged-particle tracks. The cone axis

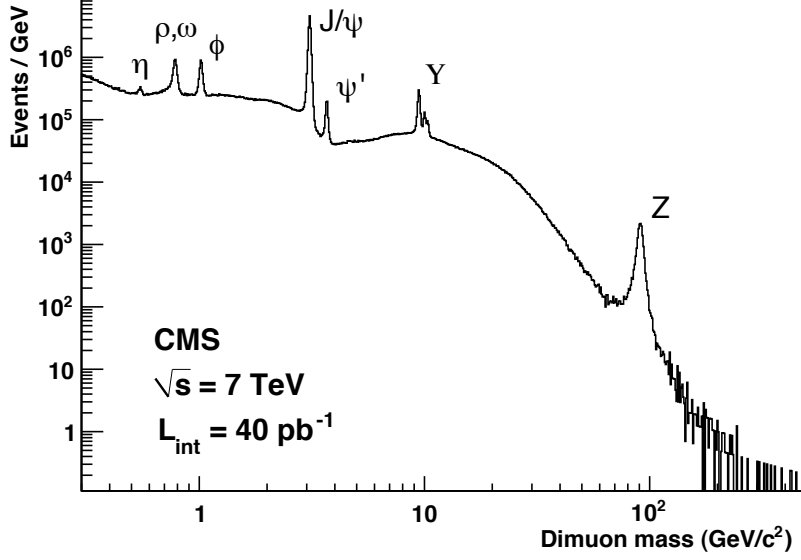


FIGURE 4.5: Invariant mass spectra of opposite-signed muon pairs using 40 pb^{-1} from 2010 run. Several mass peaks for low and high mass resonances can be appreciated.

is chosen according to the muon direction with a procedure that is tailored to the specific properties of each isolation algorithm. The geometrical definition of the cone is given by the condition $\Delta R \leq \Delta R_{\text{max}}$, where $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$, being $\Delta\eta$ and $\Delta\phi$ the distances in pseudorapidity and azimuthal angle, respectively, between the deposit and the cone axis. As the muon itself contributes to the energy measurement inside the cone, it is subtracted to improve the discriminating power of the isolation algorithm. Figure 4.6 illustrates schematically the isolation cone defined around a muon. The algorithm used for the WZ analysis performed in this thesis work is a particle flow candidate-based approach (see Section 6.3). The intense luminosity provided by the LHC creates an environment where each bunch crossing can lead to dozens of individual pp collisions. Most of the recorded events contain only one hard scattering interaction but in the same event various other proton collisions are present due to finite resolution of the data acquisition system. These other proton collisions, typically soft, are known as *pileup* (see Section 5.1.3 for details) and lead to a degradation of the event reconstruction due to the electronic signal contamination produced by its product particles. In particular, the hadronic activity is increased, especially in the forward region of the

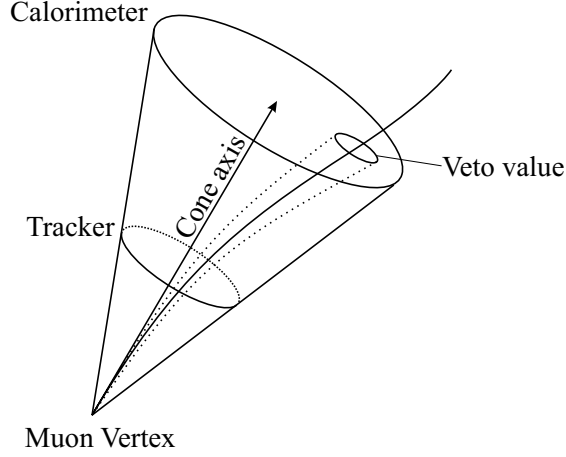


FIGURE 4.6: Schematic representation of an isolation cone around a muon. The veto value corresponds to the energy contribution of the muon itself which is going to be subtracted from the energy deposit of the cone.

detector. The high resolution of the silicon tracker allows a proper reconstruction of the hard scattering interaction point, called *primary vertex*, and other points (vertices) making possible the association of charged particles to distinct vertices. This mitigates the effect of the pileup given that the soft collisions are displaced from the primary vertex but there is no possibility to associate a neutral particle to a vertex because neutral particles leave no signature in the tracker. In this case, finding the vertex associated to a neutral particle relies on the calorimeters. Therefore, observables highly dependent on the calorimeters such as jets, missing transverse energy, etc., are very sensitive to the pileup environment. In the case of the particle flow, those effects are propagated along all the particles reconstructed. Building an isolation variable which uses particle-flow candidates allows to cope with and control the intrinsically high pileup environment of the LHC.

4.2.3. Electron Reconstruction

The primary electron signature in CMS is composed of a single track matched to an energy deposit in the ECAL. As electrons highly interact with matter, when traversing the silicon layers of the inner tracker they radiate bremsstrahlung photons and, since the electron direction can change significantly in presence of the 4 T solenoidal magnetic field, the energy reaches the ECAL with a spread in ϕ

which is p_T dependent. The amount of bremsstrahlung emitted when integrating along the electron trajectory can be very large. Furthermore, the conversion of secondary photons in the tracker material might lead to showering patterns and entail energy loss. The CMSSW software provides two complementary algorithms at the track seeding stage. The *ECAL driven* seeding and the *tracker driven* seeding, more suitable for low p_T electrons and electrons inside jets [58].

The *ECAL driven* algorithm is optimised for isolated electrons with transverse momentum $\gtrsim 10$ GeV, i.e. the relevant region of this work. It starts in the electromagnetic calorimeter by grouping one or more associated clusters of energy deposits into the so called *superclusters*. Due to the electron's trajectory bending in the magnetic field and radiating as it passes through the tracker material, the superclusters usually are spread in ϕ although narrow in η . Using the found superclusters, the algorithm matches them to pairs or triplets of hits in the innermost layers of the tracker. The *tracker driven* seeding algorithm starts from standard tracks reconstructed from the inner tracker which are extrapolated to the ECAL searching for bremsstrahlung clusters. The energy of the cluster, E , and the momentum from the track, p , are compared using the E/p ratio. The seed of the track is promoted to electron seed if E/p is close to unity. The *tracker driven* seeding has been primarily developed and optimised for low p_T , non-isolated electrons, nevertheless additional isolated electrons can be recovered using this approach combined with the *ECAL driven*, in particular in the ECAL crack regions ($\eta \simeq 0$ and $|\eta| \simeq 1.5$).

Both seeding algorithms are merged into a single collection, keeping track of its provenance. The seeds are used to initiate a dedicated electron tracking algorithm to fit the electron trajectories, the Gaussian Sum Filter (GSF) [59], which takes into account a model of the typical electron energy loss when moving through the tracker. The GSF algorithm describes the bremsstrahlung energy loss probability distributions by a superposition of several gaussians which model the Bethe-Heitler functions [60]. The momentum, energy and point of origin of the electron trajectory are assigned based on the track parameters at the distance of closest approach to the nominal beam spot, while energy is determined from a combination of tracker and ECAL information.

After the track building and fitting a preselection is applied to the electron

candidates in order to reduce the rate of jets faking electrons. The preselection is made very loose so as to maximise the reconstruction efficiency and satisfy a large number of possible analyses. In the case of electrons with *ECAL driven* seeds, some cuts have been already applied at the seeding level, requiring the transverse energy of the electron to be greater than 4 GeV and also the ratio of energy deposited in the HCAL vs. the ECAL in the supercluster region must fall below 0.15, as significant deposits in the HCAL would indicate hadronic activity from a jet. In addition, the displacement between the supercluster centroid and its associated track must satisfy $\Delta\eta < 0.02$ and $\Delta\phi < 0.15$.

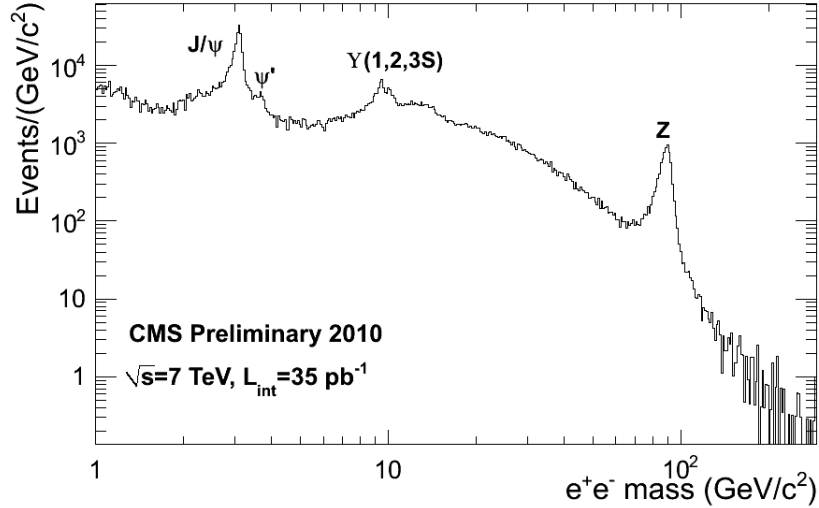


FIGURE 4.7: Invariant mass spectra of opposite-sign electron pairs using 35 pb^{-1} from 2010 run. Several mass peaks for low and high resonances can be appreciated.

The electron momentum is best estimated if the energy measured in the ECAL is combined with the momentum provided by the tracker. In accordance to the respective sensitivity to bremsstrahlung induced effects, E (calorimeter measurement) and p (tracker measurement) are either combined or only one measurement is used. The tracker measurement is more effective at low energies as well as those regions where the precision of the ECAL is poor, but in general, the ECAL dominates the measurement and resolution. Figure 4.7 shows the dielectron mass spectrum for 2010 data. The mass resolution is worse compared to the muon case (Fig. 4.5) which is able to resolve many more resonances in the

low mass region than electrons.

The isolation variable used in the electron case is analogous to the muons. More details about the concrete isolation used in the analysis are found in Section 6.4.

4.2.4. Jet Reconstruction

Jets are not used in this analysis, except indirectly in missing transverse energy reconstruction (sec. 4.2.5). The hadrons coming from the fragmentation of quarks and gluons produce signals in the ECAL and HCAL calorimeters, and if they are charged, also in the inner tracker. The calorimeter signals are clustered into collimated objects composed of stable particles, called jets. The neutral particles that partially compose a jet do not leave tracks in the inner tracker, therefore the jet reconstruction significantly relies on the calorimeters which introduces ambiguity in jet reconstruction. The CMS collaboration makes use of a wide range of jet reconstruction and clustering algorithms [61]. In particular, the particle flow jet reconstruction (through the missing transverse energy reconstruction) is used in this thesis work. The jet momentum and spatial resolutions are expected to be improved with respect to calorimeter jets, as the use of the tracking detectors and of the excellent granularity of the ECAL allows to resolve and precisely measure charged hadrons and photons inside jets, which constitute approximately 90% of the jet energy.

The input to the particle-flow jet reconstruction algorithm is a collection of energy deposits which have a high likelihood of belonging to a jet. The energy deposits are clustered by means of the "anti- k_T " clustering algorithm [62], which is based on successive pair-wise recombination of particles according to the distances between any two particles and the distance of any particle to the beam. The algorithm starts with a high-momentum particle as seed to the jet and successively adds nearby particles to the jet with weights corresponding to their momenta. The "anti- k_T " algorithm does not change its results neither by the presence of soft particles which results in QCD divergences, i.e. it is *infrared safe*, nor by collinear splitting (it automatically recombines collinear partons), i.e. *collinear safe*. These properties lead to a robust event interpretation in terms of partons allowing the application of the algorithm in theoretical calculations to arbitrary

order for meaningful comparisons with experimental data.

4.2.5. Missing Transverse Energy Reconstruction

The missing transverse energy, E_T^{miss} or $\cancel{E}_T$, is the main physics quantity used to indicate the presence of undetected neutrinos. The interacting partons of a hard interaction at a hadron collider may carry significant longitudinal boost with respect to the lab frame, but should have negligible momentum in the transverse plane. This fact can be used to infer undetected particles, such neutrinos. Therefore, a significant imbalance of the vector sum of the transverse momenta of the decay products would indicate the direction and momentum of a particle which escaped the detector without interacting. This quantity is particularly sensitive to detector malfunctions and detector resolution effects. Many sources such as finite measurement resolution, finite reconstruction efficiency, fake tracks, fake clusters, etc., can contribute to a spurious observed E_T^{miss} . Also, the pileup conditions affect the estimation of the real E_T^{miss} resolution, increasing the distribution tails.

The CMS collaboration uses several techniques to estimate the transverse missing energy in the events [63].

E_T^{miss} Calorimetric based (CaloMET)

The *CaloMET* is determined using measurements relying mostly on calorimetric information; in this case, the E_T^{miss} is defined as,

$$\left(\vec{E}_T^{\text{miss}}\right)_{\text{CaloMET}} = - \sum_n \vec{E}_T(n) - \sum_\mu \vec{p}_T(\mu) + \sum_\mu \vec{E}_T(\mu) \quad (4.1)$$

where n iterates over all energy deposits in the calorimeters, and $\vec{E}_T(n)$ is the transverse projection of a vector with magnitude equal to the selected energy deposit, pointing from the interaction point to the deposit. Explicitly,

$$\vec{E}_T(n) = -E_n \sin\theta_n \cos\phi_n \hat{\mathbf{x}} + E_n \sin\theta_n \sin\phi_n \hat{\mathbf{y}} \quad (4.2)$$

being E_n the calorimeter inputs and ϕ , θ , $\hat{\mathbf{x}}$ and $\hat{\mathbf{y}}$ the coordinates related quantities defined in Section 3.2. The index μ refers to muons and the terms associated

are correcting the muon's energy deposit in the ECAL. The muons are minimum ionising particles that transverse the calorimeters almost unaffected (the average energy deposits are a few gigaelectronvolts). Hence, to correct for the muon response the actual muon momentum measurement from the central tracker and muon system, p_T^μ , is used to replace the energy measured along the muon trajectory in the calorimeter. The calorimeter E_T^{miss} calculation can be improved by correcting for several effects. In particular, jets can be corrected to the particle level using the Jet energy correction (JEC) [64] and the E_T^{miss} is recalculated using these corrected jets. The *type-I corrections* for the E_T^{miss} use these JECs for all jets whose energies are above a threshold and having less than 90% of their energy in the ECAL. These corrections can be up to a factor of two of the initial uncorrected E_T^{miss} . The remaining soft jets below the threshold and energy deposits not clustered in any jet are considered by applying a second correction which is referred to as the *type-II correction*.

E_T^{miss} Track Corrected based (tcMET)

The *tcMET* algorithm uses the E_T^{miss} measured in the calorimeters, i.e. the CaloMET, with further corrections using information of the tracker. For each track measured in the tracker, its transverse momentum, p_T , is included in the E_T^{miss} whilst the predicted calorimetric energy deposit is removed. This approach takes advantage of the better resolution of the tracker versus the ECAL, allowing an overall resolution improvement and a better description of the E_T^{miss} distribution in the tails. For all tracks not identified as electrons or muons, the predicted energy deposition is extracted from simulations of single pions and extrapolated to the calorimeters. No correction is applied for very high p_T tracks ($\gtrsim 100$ GeV) whose energy is already well measured by the calorimeters and there is no gain from the tracker, whereas for the low- p_T tracks ($\lesssim 2$ GeV) no response from the calorimeter is assumed so the measured momentum from the tracker is taken. Therefore, the *tcMET* is defined as follows,

$$\left(\vec{E}_T^{\text{miss}}\right)_{tcMET} = \left(\vec{E}_T^{\text{miss}}\right)_{CaloMET} - \sum_{tracks} \vec{p}_T(track) + \sum_{tracks} \vec{E}_T(track). \quad (4.3)$$

Particle Flow E_T^{miss} (PFMET)

The full extent of the capabilities of the CMS detector can be reached using a particle flow approach to calculate the E_T^{miss} . All detector information is included to reconstruct the event decay products. It is simple to use the particle flow particle candidates to estimate the E_T^{miss} by subtracting vectorially all the particle flow transverse momenta.

$$\left(\vec{E}_T^{\text{miss}}\right)_{PF} = - \sum_{\text{PF-cand.}} \vec{p}_T(PF) \quad (4.4)$$

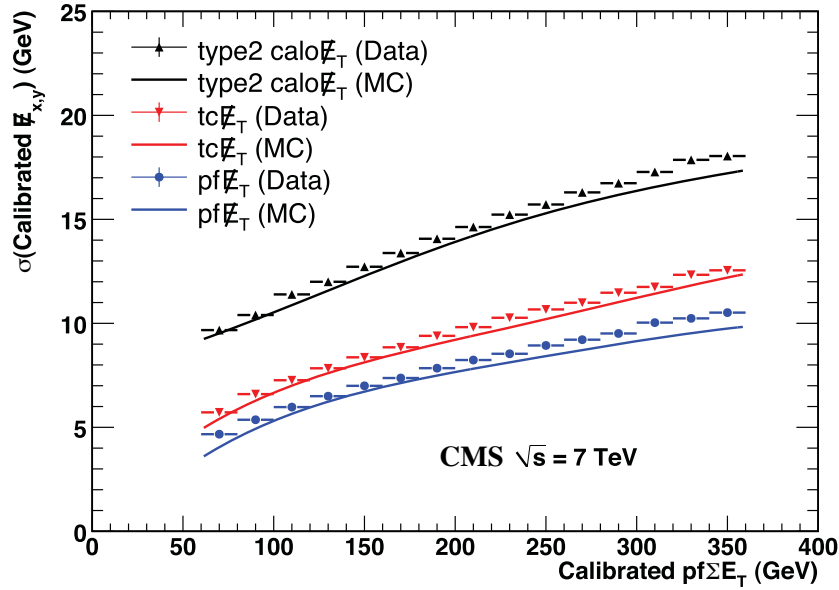


FIGURE 4.8: E_T^{miss} gaussian core resolution with respect the total transverse energy in the event ($pf\Sigma E_T$) evaluated through the particle flow algorithm. The data are selected to have at least two jets with $p_T > 25$ GeV. The plot was made using 2010 data.

Figure 4.8 shows the comparison for the E_T^{miss} resolution of the three algorithms described vs. the sum of the transverse energy of all the particles in an event using the particle flow algorithm to reconstruct the particles, i.e. $pf\Sigma E_T$. The resolution of the E_T^{miss} is improved by the $tcMET$ and $PFMET$ by a factor of 2, compared to $CaloMET$. E_T^{miss} resolution is affected by several factors: electronic

noise, pile-up, underlying events, statistical sampling nature of the energy deposits in individual calorimeter towers, systematic effects due to non-linearities, cracks and dead material, etc. As a result of this, it is clear that the higher pileup conditions of the LHC have a direct influence on the $E_{\text{T}}^{\text{miss}}$ measurement.

CHAPTER 5

Data Corrections and Monte Carlo tuning

The data provided by the detector and reconstructed by the software have to be corrected for data-taking and processing effects before they can be analysed. Furthermore, this data must be compared with theoretical predictions to allow hypothesis falsifiability. The high energy community uses the so called Monte Carlo techniques to simulate experimental outcomes to be compared with the data obtained from the experiments. The present chapter is devoted to enumerate the peculiarities of the data-taking process through the system developed to select "interesting events" and the corrections applied to the data: efficiencies, *scale factors (SFs)* and pileup effects are described. The last section of the chapter specifies the Monte Carlo approach and describes how it can be compared with the experimental data.

5.1. Data corrections

Both the PDs and the physics objects used in an analysis suffer from a biased realisation of a physical system, i.e. they are not ideal. The detector sub-systems have cracks, dead or blind zones; they have also latency times, etc. Furthermore, the algorithms used to reconstruct, identify or isolate an object, and to make decisions in the trigger system are inherently finite and usually do not use all

the available information or the information is biased by speed, storage or other computational-related requirements giving rise to inefficiencies. As an example, the trigger paths used for selecting a given PD have inefficiencies related to the coarse granularity of the decision system and the use of local reconstruction; the reconstruction algorithms to build the physics objects are also subjugated to the blind zones of the detectors and also to the intrinsic nature of reconstructing hits and energy deposits to fit trajectories, assign energies or discriminate between high-level objects. This loss of information introduces inefficiencies on the trigger selection, identification, reconstruction, and to any stage needed to obtain high level objects from raw electronic data. These inefficiencies can be split by sources and be evaluated with probabilistic theory using simulation or data techniques.

Besides the inefficiencies, the measures can also be biased due to subdetectors mis-alignments or wrong material description used by the reconstruction algorithms to scale some observables such the transverse momentum or the energy of a reconstructed particle. Also, the multiple interactions produced at each beam crossing, the so called *pileup*, are going to affect the quality of the reconstruction. These effects can be observed and properly corrected.

The corrections outlined above are described in this section. Nevertheless, there are more data corrections to be considered, but they are already included in the standard reconstruction of CMSSW, so the interested reader can see them in more detail in the references of Chapter 4.

5.1.1. Efficiencies: Tag and Probe method

As we have emphasised, after the full reconstruction process there is no warranty that all the final particles passing through the detectors have been successfully detected and/or reconstructed. Given the huge amount of variables which enter in the detection and reconstruction problems and the inherent lack of information, the efficiency problem is attacked from a probabilistic perspective in order to quantify the inefficiencies introduced by any procedure used in the data chain processing. The efficiency of some procedure can be defined as the probability that such a procedure does its job. If a frequentist approach is adopted, the probability can be interpreted as frequencies and it is possible to evaluate the rate of "work

well-done” by counting the output of the procedure with respect to the initial number of elements in which the procedure is applied. The raising problem when dealing with data is the lack of knowledge of the initial objects, as this is exactly what was lost so there is no information about it. Using simulation data, the objects are always controlled, but then introduces dependence in the simulation model, inserting in turn uncertainties in the measures. There is a tacitly generic data-driven technique to evaluate these efficiencies in order to be incorporated to the analysis: the tag and probe method.

The tag and probe method allows to select an unbiased sample of physics objects in data by exploiting di-object resonances like Z or J/ψ which can be used to measure some object efficiencies from data. In brief, the resonance is reconstructed as pairs of objects (typically leptons) with one leg passing a tight identification (*tag*) and the other one passing a loose identification (*probe*). The tight leg ”tags” the event as an event containing two same flavour leptons just because it was possible to reconstruct an invariant mass with the dilepton system around the resonance, and because the tight requirements are assuring the identity of the tag lepton. Therefore, it is possible to check any property of the probe lepton given that the event has to contain two leptons. The passing probes are defined in such a way according to whatever is the efficiency to measure. The efficiency is then evaluated considering the ratio between passing probes over the total probes.

$$\varepsilon = \frac{N_{\text{passing probes}}}{N_{\text{probes}}} \quad (5.1)$$

Equation (5.1) is barely used because of the background contamination of the experimental data; instead a complex version of it is used taking into account the data contamination through a fitting procedure. Usually, the selected probe sample is contaminated by events which do not contain a resonance, these events should be subtracted in order not to bias the measurement including non-resonant events. This is accomplished by fitting a signal-background model to the dilepton invariant mass, separately, for the passing probes and tags, and the failing probes and tags in order to calculate the efficiency as the ratio of the signal yields extracted from the fitting. The procedure is repeated in bins of some probe variables to compute efficiency histograms as function of those variables. In summary, the signal is

modelled by a probability density function describing the invariant resonance ($S(x)$, x is designing whatever dependency) and two probability density functions are used to describe the background because of the different expected origin for the passing probes ($PB(x)$) and the failing probes, ($FB(x)$). The passing distribution is modelled using the addition of signal and passing-probe background distributions, where at this point the efficiency is introduced,

$$N_S \cdot \varepsilon \cdot S(x) + N_{PB} \cdot PB(x)$$

and the failing probes, using again the efficiency, is related with the failing probe background distribution.

$$N_S \cdot (1 - \varepsilon) \cdot S(x) + N_{FB} \cdot FB(x)$$

A simultaneous fit is performed between both distributions getting as output of

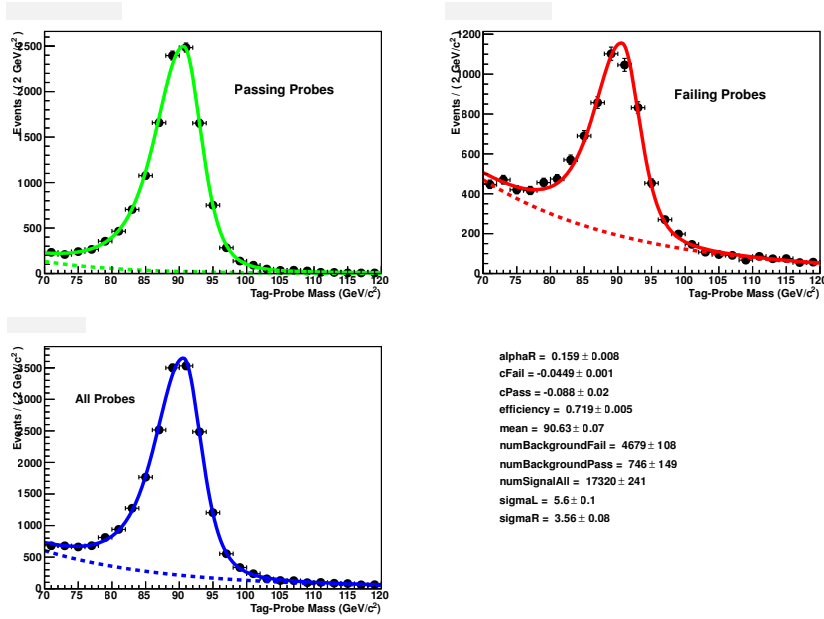


FIGURE 5.1: Passing probe and failing probe simultaneously fit for the calculation of the reconstruction efficiency of electrons. The Z mass peak and the background contribution is extracted from the fit. The fit output is shown in the table, in particular the estimated efficiency.

the fit the efficiency ε and other parameters such as the number of signal events

N_S , the number of passing background events N_{PB} , etc. Figure 5.1 illustrates the fitting procedure. Electrons from the 2011 data period have been used to extract the reconstruction efficiency. The fit is performed for a given pseudorapidity and p_T bin.

The efficiencies are not only calculated in data, the tag and probe method is also used in the simulated data and the same efficiencies than in the experimental data are obtained. As the simulation does not reflect exactly the material description of the detector, nor failures in the subdetector systems nor whatever inherent instrumental effects in the real data taking, there may be differences between the efficiencies obtained with the experimental and the simulated data. These differences are taken into account with the *scale factors*, the ratio between the efficiency obtained with simulated versus experimental data. As will be seen in Chapter 8, the analysis actually uses these scale factors instead of the efficiencies.

5.1.2. Momentum and energy scales

The momentum and energy measurement can be biased due the limited knowledge of the physical configuration of the detector¹ and the limited capability of the reconstruction algorithms. Uncertainties in the magnetic field should also be included when the tracks are used to measure the momentum. The effects of these sources in the momentum or energy measurements can be observed and therefore corrected, and the remaining systematic uncertainties are estimated after these corrections. There are several methods in CMS to accomplish this goal [58] [55] but all of them rely on the same strategy: use well-known resonances (J/ψ , Υ , Z) to correct the momentum (for muons) or energy (for electrons) scale. A bias in the (transverse) momentum of a muon or in the energy of a electron can be detected building dimuon (dielectron) systems with its invariant mass around a well-known resonance because the resonance mass peak will be displaced from its nominal value. Using this fact it is possible to correct the momentum or energy and discover all the possible biases and understand their sources by plotting the invariant mass as a function of some sensitive kinematic variables. The correction

¹Mis-alignments of the subsystems and between them, mis-calibration of the calorimeters, etc.

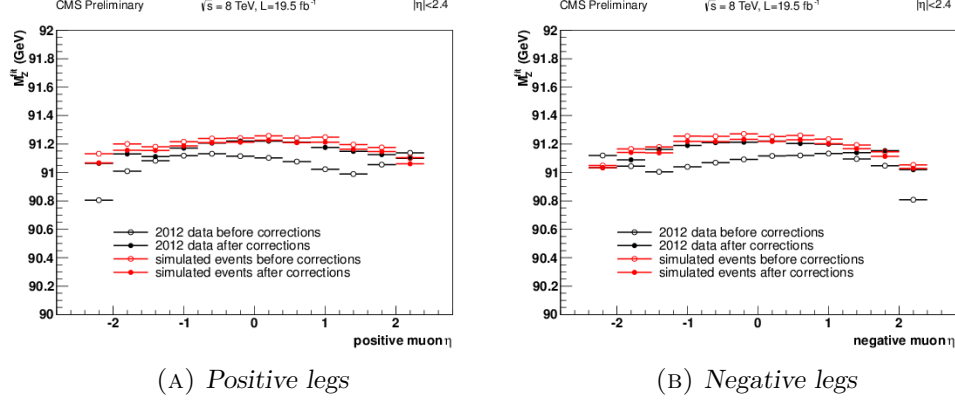


FIGURE 5.2: The dimuon mass distribution is fitted to extract the Z mass, $M_Z^{\ell\ell}$. The plots show the different $M_Z^{\ell\ell}$ obtained when fitted in different pseudorapidity bins, before (empty dots) and after (filled dots) applying the momentum scale correction. The black dots refer to data obtained during the 2012 run period whilst the red ones to simulation data.

is applied to the transverse momentum of a muon or the energy of an electron by scaling its value, $p_T^c = (1 - a(x))p_T$, where $a(x)$ is referring to any possible variable dependence of the correction. Figure 5.2 shows the fitted mean value for the invariant mass distribution of a dimuon mass system with and without the momentum scale correction applied, with respect the pseudorapidity of the muons.

5.1.3. Pileup effects

The instantaneous luminosity reached in 2011 and 2012 along with the machine parameters used by the LHC (see Chapter 3) to accomplish this high rate of collisions make each proton bunch crossing highly likely to give more than one interaction. Indeed, dozens of collisions can occur in the same bunch crossing, which the CMS detector records them as the same event; they are "piled up" together with the hard scattering. This secondary collisions are known as *pileup* events. Figure 5.3 shows the peak number of interactions per beam crossing during the 2010, 2011 and 2012 run periods. An important increment in the number of interactions can be observed along the two last periods, giving a mean number of interactions per beam crossing about 9 for the 2011 run period, and around 21 for

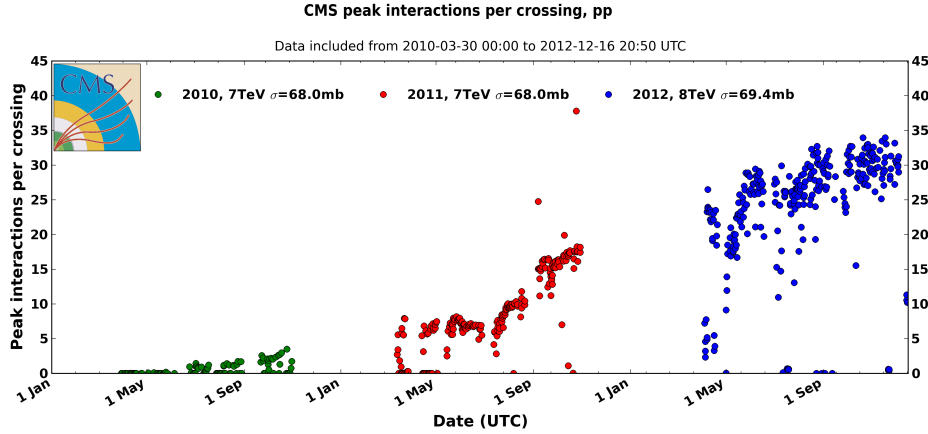


FIGURE 5.3: Peak number of interactions per beam crossing for the 2010 (green), 2011 (red) and 2012 (blue) data. The mean number of interactions integrated along the full data-period for 2011 is 9.1, and for 2012 is 20.7

2012. Therefore, besides the hard interaction, the event is populated with particles coming from secondary interactions, mostly soft, which contaminate the primary hard scattering and complicate the reconstruction process. A typical event with pileup is characterised by many primary vertices along the beam line, as can be seen in Figure 5.4. Multiple overlapping interactions lead to an enhanced detector occupancy which are almost saturated by the particles produced from different vertices. A direct consequence is that the number of jets is much increased as well as the density of the reconstructed tracks and the mean energy deposited in the detector. Calorimetric measurements result particularly sensitive to such conditions, biasing the isolation and identification of the objects.

The net effect of the pileup events presence in the main event is that the measured energy of the jets is overestimated. This is because particles coming from vertices different from the hard scattering primary vertex contribute with tracks or energy deposition in the calorimeters, leading to an increase of the total energy measured within the jet cone. Therefore, to correct these effects an event-by-event and jet-by-jet treatment is applied to the event. The main algorithm used in CMS to correct for the measured energy is the FASTJET [65] algorithm, that works correctly for any infrared safe jet reconstruction algorithm, and estimates the energy contribution due to pileup for each reconstructed jet which can then be subtracted from the jet's energy to yield a result which more

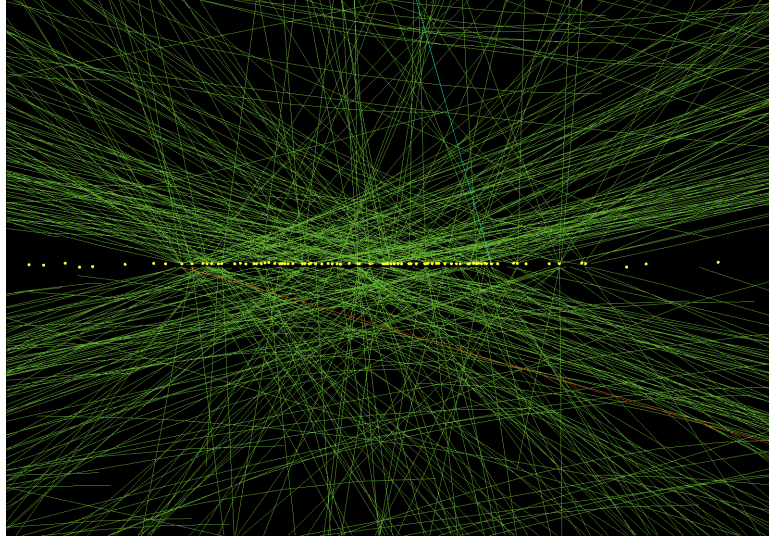


FIGURE 5.4: Reconstructed event from the 2012 run period (extracted from a high-pileup run 198609) showing 78 reconstructed vertices (yellow dots) in one beam crossing. The event is displayed in the $Rho - Z$ view, so the vertices can be seen along the beam pipe. Following the track reconstruction (green, red and blue lines), the tracks are grouped into the vertices, each one representing a proton-proton collision.

closely represents the energy of the initiating parton. The algorithm introduces an "abstract" area for each jet in order to account for the energy density of the jet. However, a jet consists of point-like particles which themselves have no intrinsic area, therefore it defines a sensible area by adding additional, infinitely soft particles (called ghosts) and identifies the region in rapidity and ϕ where the ghosts are clustered with a given jet. The extent of this region gives a measure of the dimensionless jet area, A . Figure 5.5 shows several jets clustered using the k_t algorithm; the reconstructed jets are associated to the high energy deposits in the calorimeter's cells and the shaded areas surrounding them were constructed in the way described above. This area is then a measure of the jet's susceptibility to pileup contamination. The algorithm provides also a parameter measuring the overall level of diffuse noise¹ ρ (in GeV/Area) as the median value of $p_T^{\text{jet}}/A^{\text{jet}}$ taken over all jets. The jet energy correction is done by subtracting from the

¹The pileup, although it could be some extent of the underlying event (see section 5.2.3 for definition).

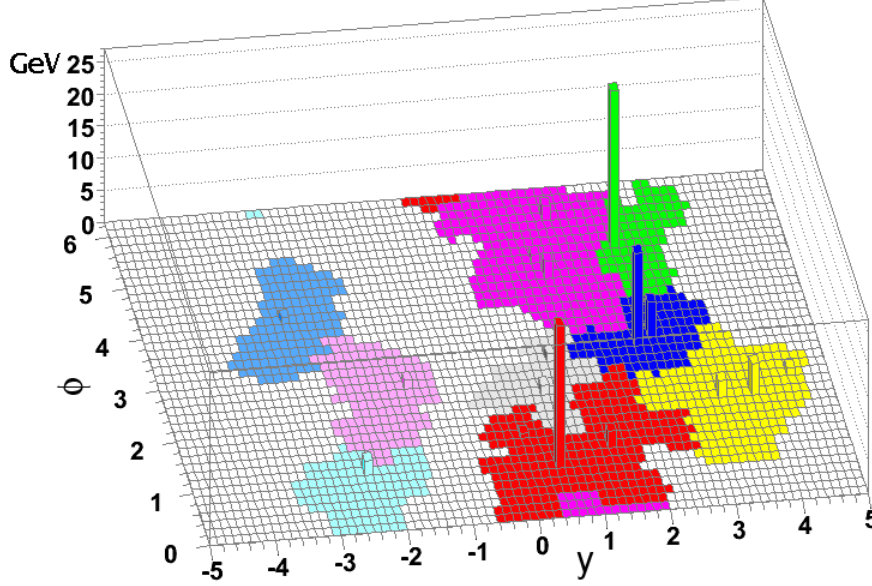


FIGURE 5.5: Calorimeter's energy deposits in the $y - \phi$ plane. Each colour is associated to a different clustered jet. The k_t algorithm was used to cluster the energy deposit cells and the FASTJET algorithm to associate to each jet an area, represented with the same colour of the jet.

measured energy of the jet the corresponding $\rho \cdot A^{jet}$.

As the FASTJET algorithm extracts the energy density per unit area ρ due to the contribution of pileup and underlying events, it can be used to correct the sensitive quantities related with the reconstructed objects, in particular isolation and identification of leptons, and the particle flow E_T^{miss} object which is built from the event's jets and other particles. The E_T^{miss} then uses directly the jet energy correction when it is calculated using jets corrected for pileup events. Moreover, the isolation of the muon and electron can also take advantage of the ρ estimation to subtract it in the isolation cones defined for the leptons. The specific pileup correction applied to the lepton objects used in this analysis is detailed in Chapter 6.

5.2. The Monte Carlo approach for event simulation

Any physics experiment is conceived to increment the knowledge on the particular field in which the experiment is designed. To that end, most of the time

the outcome of the experiment is compared with theoretical predictions based on physical models which try to describe the studied phenomenon. In high energy particle collisions, the physics involved is currently described by the SM of particle physics, as has been established in Chapter 1. The theoretical predictions offered by the SM are mainly particle production rates (or cross sections), i.e. probabilities for a particular process to occur. The comparison of that kind of theoretical predictions with the experimental data is, then, intrinsically statistical. The task to map the cross section for various processes onto the discrete event structure of the experimental data is extremely challenging. Typically hundreds of particles are produced in every high energy collision and all the species of the SM and maybe some beyond, are involved with momentum ranges that spread along several orders of magnitude. Furthermore, theoretical calculations in QCD processes involve the intrinsically non-perturbative and unsolved problem of confinement (see Section 1.3). These particular, a priori, intractable problems have been overcome with a wide range of techniques based on Monte Carlo simulation [66]. Roughly speaking, a random number generator is interfaced with the equations governing a certain process in order to produce a large number of simulated collision events. This is done through highly specialised software called *event generators*. The event generators produce as well the decays of unstable particles that do not escape from the detector. These particles are the outcomes of the event generator, apart from the history of all the decay chain, and their passage through the detector has to be simulated. The simulation step mimics the energy deposits, hits and any other material response due to the passage of the particles through the subdetectors, and again Monte Carlo methodology is applied to deal with it. The standard package used by almost the entire community in particle physics and other areas is the GEANT4 [67] framework¹. In order to obtain the same electronic signals produced by the read-out of the real detector, the emulation of the data acquisition system and read-out is also performed.

The simulation of collision events is divided in several steps by which event generators, usually different programs for each step, build up the hadron-hadron

¹In this work, we are not going to describe the physics and methodology involving the simulation stage. We point the interested reader to the cited reference and in particular the web page of the package where additional and very complete information can be found.

collision involving a hard scattering process of interest. The basic phases of the process that needs to be simulated are the primary hard subprocess (*hard scattering*), parton showers associated with the incoming and outgoing coloured participants in the subprocess (*parton showering*), non-perturbative interactions that convert the showers into outgoing hadrons and connect them to the incoming beam hadrons (*hadronisation*), secondary interactions that give rise to the *underlying event*, and the decays of unstable particles which are fed to the detector simulator. Not all stages are relevant in all processes. In particular, the soft QCD type, which are the most produced in hadron-hadron collision, rely on phenomenological models and make use of the PDF¹. The main stages of the generation of a hadron-hadron collision event are briefly described below without entering in full details. The interested reader can found a deeper development of the subject in [68].

5.2.1. Hard scattering process

The hard scattering process involves large momentum transfers between the implicated particles. These are the processes in which most of the analyses carried out at the detectors of the LHC are interested, and these are the processes able to produce heavy particles or jets with high transverse momenta. The cross section for a scattering subprocess $ab \rightarrow n$, where n denotes the number of final state particles, at hadron colliders can be computed in collinear factorisation through [69]

$$\begin{aligned}
 \sigma_{h_1 h_2 \rightarrow n} &= \sum_{a,b} \int_0^1 dx_a dx_b \int f_a^{h_1}(x_a, \mu_F) f_b^{h_2}(x_b, \mu_F) d\hat{\sigma}_{ab \rightarrow n}(\mu_F, \mu_R) \\
 &= \sum_{a,b} \int_0^1 dx_a dx_b \int d\Phi_n f_a^{h_1}(x_a, \mu_F) f_b^{h_2}(x_b, \mu_F) \\
 &\quad \times \frac{1}{2\hat{s}} |\mathcal{M}_{ab \rightarrow n}|^2(\Phi_n; \mu_F, \mu_R),
 \end{aligned} \tag{5.2}$$

where

- $f_a^h(x, \mu)$ are the PDFs, which depend on the momentum fraction x of parton

¹As was seen in Section 1.3

a with respect to its parent hadron h , and on the factorisation scale μ_F ;

- $\hat{\sigma}_{ab \rightarrow n}$ denotes the parton-level cross section for the production of the final state n through the initial partons a and b . It depends on the momenta given by the final-state phase space Φ_n , on μ_F and on the renormalisation scale μ_R . The fully differential parton-level cross section is given by the product of the corresponding matrix element squared, averaged over initial-state spin and colour degrees of freedom, $|\mathcal{M}_{ab \rightarrow n}|^2$, and the parton flux $1/(2\hat{s}) = 1/(2x_a x_b s)$, where s is the hadronic centre-of-mass energy squared.
- $d\Phi_n$ denotes the differential phase space element over the n final-state particles.

The PDFs carry the non-perturbative QCD part, which describe the probability of a parton to have some fraction of the total hadronic momentum; these functions are extracted experimentally (see Section 1.3). The parton-level probabilities are contained in the matrix element squared $|\mathcal{M}_{ab \rightarrow n}|^2(\Phi_n; \mu_F, \mu_R)$ and can be evaluated using Feynman diagrams. All multi-purpose event generators provide a comprehensive list of LO matrix elements and the corresponding phase-space parametrisations for $2 \rightarrow 1$, $2 \rightarrow 2$ and some $2 \rightarrow 3$ production channels in the SM and some of its new physics extensions. Some event generators provide NLO or even Next to Next to Leading Order (NNLO). Moreover there are a wide variety of event generators specialised in particular processes or family of processes. A couple of examples of event generators used in this work are PYTHIA [70] and MADGRAPH [71].

5.2.2. Parton showering

The hard scattering interaction is well described using perturbative QCD due to the notion of asymptotic freedom in strong interactions. Nevertheless, to give an inclusive picture of the process, including the internal structure of the jets and the distributions of accompanying particles, any fixed order, as is used in the matrix elements, is not sufficient. The effect of all higher orders can be simulated through a parton shower algorithm, which is typically formulated as an evolution in momentum transfer down from the high scales associated with the

hard process to the low scales, of order 1 GeV, associated with confinement of the partons it describes into hadrons. In summary, scattered, annihilated and created partons radiate gluons, and as gluons themselves are coloured, this radiation give rise to further gluon radiation and parton multiplication. The radiation can be produced before the parton scattering or annihilating process, the so called Initial State Radiation (ISR), or after, called Final State Radiation (FSR). The parton shower algorithms will provide the partonic final state to be added to the final state products of the hard scattering. At that point, the interaction scale of the partons has fallen during the parton showering, eventually initiating the process of *hadronisation*, i.e. the partons are bound into colourless hadrons (see Subsection 5.2.4).

5.2.3. Underlying event

Besides the gluon radiation, several parton-parton interactions can occur within a single hadron-hadron collision and can be modelled by *multiple parton interactions* which can produce additional observable jets. Most multiple parton interactions are relatively soft, however, and do not lead to easily identifiable additional jets. Instead, they contribute to building up the total amount of scattered energy and cause colour exchanges between the remnants, thereby increasing the number of particles produced in the hadronisation stage. This additional activity is known as the *underlying event*.

5.2.4. Hadronisation

The outcome of the different algorithms described above to populate and describe a hadron-hadron collision is obtained as coloured partons carrying some momentum and energy, i.e. the partonic final state. Nevertheless, the partons are coloured so they are going to bind into colourless hadrons. The description of this process is done with phenomenological models due to the non-perturbative nature of the problem¹. The event generators usually implement the Lund string model [72], in which quarks are bound together with a gluon string. For quarks

¹The only available rigorous approach, lattice-QCD, is formulated in Euclidean space-time, whereas time evolution of partons into hadrons is inherently Minkowskian.

travelling away from one another, this string becomes stretched and stores energy, eventually breaking to produce new $q\bar{q}$ pairs when an energy threshold is reached. The process is repeated until the energy available is below a threshold. The initial partons have been progressing to a collection of colourless bound states. These resulting hadrons are typically collimated along the direction of the initial hard parton, forming a coherent jet of particles.

5.2.5. Pileup

The pileup contribution (see Section 5.1.3) to a hard scattering event is copied in simulation by superimposing some number of simulated soft interaction events on top of each nominal event, following the interaction multiplicity distribution observed in the experimental data. This distribution is used to re-weight the simulated data to produce the exact data distribution.

The full process to simulate a hard scattering event at LHC starts by defining the process we want to generate defining a particular equation (5.2). With a random number generator, the chosen PDF is sampled in order to determine the initial momentum of the partons. The probability for a proton to radiate a photon before the collision is also considered (QED-ISR) modifying the initial available proton energy. Then, the random generator is used again to sample the differential cross section of equation (5.2), defining momenta for the final state particles. Once the final state particles from the hard scattering are obtained, the ISR and FSR are modelled by a parton shower algorithm which increases the gluon and quark multiplicity of the event, adding new partons to the final state. In parallel, a number generator is used again to select the number of interactions which occurred in the same bunch crossing, adding more particles to the event. The full partonic content is matched to be able to hadronise. Finally, all the final particles are evolved into stable or unstable particles ready to be detected by the detector subsystems. Figure 5.6 shows a full proton-proton event with the main stages described here. After the event generation, the final particles outcoming from the Monte Carlo programs are introduced to the GEANT4 simulator whence the particles passing through the whole CMS are simulated. The simulator returns

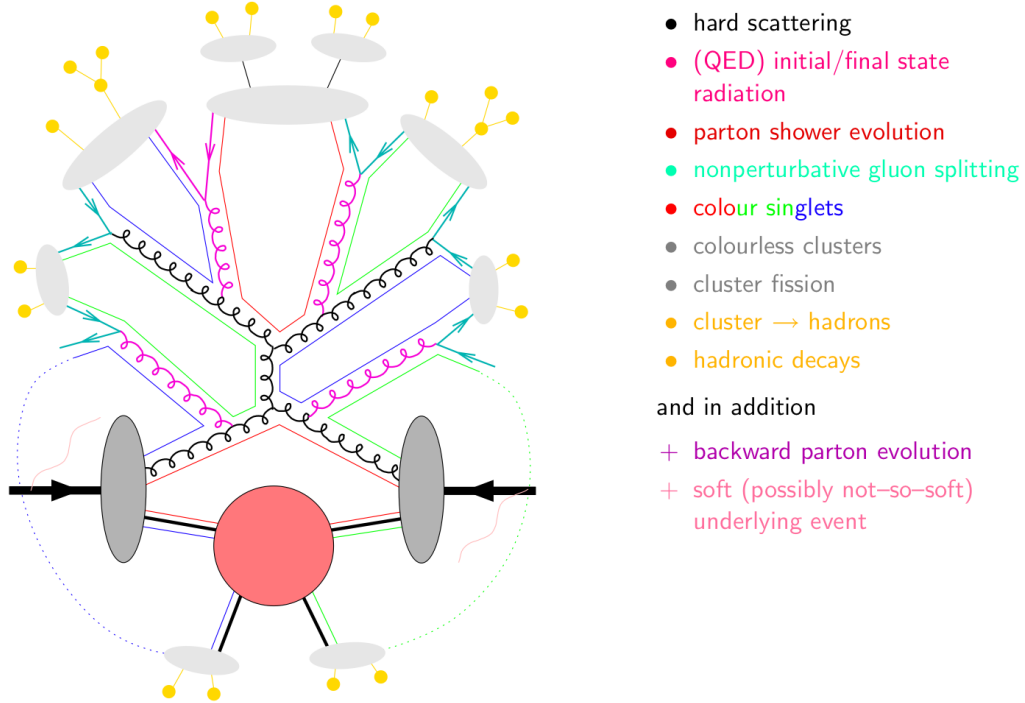


FIGURE 5.6: Schematic proton-proton collision showing a gluon-gluon hard scattering. The grey blobs are the incoming protons, the red blob represents the multiple interactions giving the underlying event. The figure was extracted from <http://www.gk-eichtheorien.physik.uni-mainz.de/Dateien/Zeppenfeld-3.pdf>.

a set of energy deposits and hits in the sensitive detectors which in turn are sent to a read-out emulator to obtain the final output as it is obtained in a real CMS collision.

CHAPTER 6

Selection of WZ events

The chapter describes the event topology and expected signature of the WZ production decaying leptonically and establishes our signal definition. The possible sources of noise, the backgrounds, are determined and it is examined how they can mimic our signal in the CMS detector. The selection strategy of muons and electrons is analysed thoroughly, detailing the several approaches of lepton identification and isolation, and also the online data selection. For each of the selection processes, their efficiencies are calculated and presented. The final step is focused in the analysis strategy which is based in sequential cuts to suppress the remnant background achieving high signal purity. In this context, the observables used and their role in the analysis are described. Several distributions are shown to control the event selection and illustrate the logic of the analysis strategy.

6.1. The signal signature and backgrounds

The $WZ \rightarrow \ell \nu \ell'^+ \ell'^-$ decay signature is defined by two opposite-charged, same-flavour, high- p_T , isolated leptons, whose invariant mass is compatible with the one of the Z boson, together with a third high- p_T , isolated lepton and a significant deficit of transverse energy, E_T^{miss} , associated with the escaping neutrino. The same signature can be obtained from other high-energy processes introducing noise to the signal WZ process we want to measure; these noise processes are called *backgrounds*. All the production processes leading to three high- p_T leptons in the

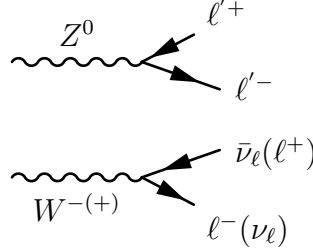


FIGURE 6.1: Schematic diagram for the leptonic decay of the WZ process. The event is characterised by a couple of high- p_T , opposite-charged, same-flavour and isolated leptons decaying from the Z boson besides a third high- p_T , isolated lepton from the W. A significant amount of E_T^{miss} is expected due to the undetected neutrino from the W.

final state should be categorised and studied in order to suppress them or, if it is not possible, to control them. Such processes are called the *physical backgrounds* in opposition with the *instrumental* background. This later background appears due to inefficiencies in the detection and/or reconstruction and to the limited coverage of the detector (*detector acceptance*); spurious leptons are reconstructed from jets or other mis-identified particles transforming an event which originally did not contain three leptons into one that does. The main physical background is the ZZ production process in its full leptonic decay, when one lepton is either no-reconstructed or falling outside the detector acceptance. The trilinear boson couplings are also physical backgrounds but due to their low production cross section they should only be considered when the accumulated data are large enough. These background have been considered in the 8 TeV analysis, however even with the large amount of data (19.6 fb^{-1}) collected they barely contribute. The instrumental sources are summarised below:

QCD production processes related with QCD, where final state particles are hadrons, therefore jets. This background is generically called QCD. Three high- p_T , isolated spurious (*fakes*) leptons should be reconstructed making it unlikely. Despite of the huge production rate of QCD processes, their contribution in this analysis is negligible.

W+jets the W production in association with jets has a very high production rate (around 31.3 nb). The W hadronic decay can be ignored as it needs three

fake leptons (and the production rate is much lower than QCD backgrounds). The leptonic decay provides a true high- p_T , isolated lepton, therefore two fakes leptons are required to mimic the signal topology. This is, again, very unlikely and the contribution is negligible.

Z+jets the production of Z/γ^* in association with jets is going to be relevant in the leptonic decay of the Z. Moreover, unlike the other two backgrounds described above, this process contains a genuine Z in the final state making more difficult to reject it through an invariant mass requirement. Thus, the process only needs one fake lepton and some E_T^{miss} to present the same signature as WZ.

Single top a top quark can be produced in association with a W boson. When the top quark decays through the weak force, it decays almost exclusively to a W boson and a bottom quark. The bottom quark can eventually decay leptonically, thus it is possible to find a third lepton, although not isolated, together with the two leptons from the Ws. The lepton coming from the quark is considered as a fake lepton because it should not pass the isolation criteria. The W and top quark hadronic decays can contribute also when the jets are mis-identified as leptons, however the low probability of reconstructing more than one fake lepton (as we will see in Chapter 7) together with the topology of the single top production makes these contributions negligible.

$t\bar{t}$ As the single top case, the weak decay of the top (anti-top) quark produces W^- (W^+) boson and anti-bottom (bottom) quark. Therefore, two high- p_T , opposite-charged, isolated leptons and E_T^{miss} from the Ws are going to be present in the final state signature, together with the non-isolated lepton from the quarks or any properly fake lepton. This background source together with the $Z + jets$ are the dominant instrumental backgrounds, as it will see in chapters 7 and 8.

WW the W diboson production in its leptonic decay mimics the topology of the signal events by acquiring a third fake lepton from the underlying or pileup

events. Given that the third lepton is not reconstructed from high energy jets and the absence of a genuine Z, this background is easily contained.

Z γ The Z production can be accompanied by a initial state radiation, where the photon is produced by the incoming partons, or a final state radiation, where the photon is radiated by one of the charged leptons from the Z decay. A photon conversion into leptons (mostly electrons) can be produced when the photon interacts with the detector, giving the third missing lepton to complete the signal signature.

The leptonic decay of the WZ process consider four possible final states. The W muonic decay and Z muonic and electronic decays, and W electronic decay and also Z muonic and electronic decays. This four possibilities with final states defined by its lepton presence (3μ , $2\mu 1e$, $1\mu 2e$ and $3e$) allow us to split the WZ final state into four independent and exhaustive channels and use them to analyse independently the WZ process.

6.2. Online selection of WZ candidate events

The LHC delivered proton-proton collisions at 7 TeV of centre of mass energy during the year 2011 splitting the data taking into two major *run periods*, A and B, separated by a short technical stop. The next year, 2012, the centre of mass energy of the collisions reached the 8 TeV and there were four major run periods (A, B, C and D) again separated by technical stops. During this period, CMS recorded 5.56 fb^{-1} of pp collision data for 2011 and 21.79 fb^{-1} for 2012. During the data taking, each subdetector of CMS experiences some amount of downtime due to equipment failures, meaning that some fraction of the recorded luminosity cannot be used for general analyses which rely on the integration of the full detector. Consequently, the collaboration certifies a list of runs suitable for physics publication, which for 2011 was an integrated luminosity of 4.9 fb^{-1} and for 2012, 19.6 fb^{-1} .

As it was explained in Chapter 5, the events selected by the trigger system are sorted in PDs based on trigger paths. The topology of the WZ process in its leptonic decay makes suitable the use of trigger paths looking for at least two

high- p_T leptons, in this analysis we consider the `DoubleMu` and `DoubleElectron` PDs where events must fire a trigger looking for a pair of muons or a pair of electrons, respectively. The 2012 period includes also the dataset selected with events with at least one muon and one electron, the `MuEG` PD. To control the recorded event rate, each of these triggers imposes momentum thresholds on the candidate objects (amongst some loose object identification and isolation requirements), with these thresholds increasing as the instantaneous luminosity increases. These HLT paths are each seeded by a L1 trigger path requiring one or two low-level detector objects with thresholds lower than those imposed at higher levels. Some loose quality cuts in identification and/or isolation are also imposed on the candidates, cuts which must become stricter in the analysis level to avoid a biased analysis. Tables 6.1 and 6.2 give the value of these thresholds corresponding to various run ranges for 2011 and 2012, respectively.

Run Range	DoubleElectron (E_T)			
	L1		HLT	
160329-170901	12	0	17	8
171050-EndYear	12	5	17	8

(A) *Double Electron trigger paths*

Run Range	DoubleMuon (p_T)			
	L1		HLT	
160329-165208	3	3	7	7
165364-178419	3	3	13	8
178420-EndYear	3	3	17	8

(B) *Double Muon trigger paths*

TABLE 6.1: L1 and HLT energy and momentum thresholds for the PDs of 2011 data period. The *EndYear* label is referring to the last run available before the end of the data taking period. Besides the energy thresholds, the trigger paths are also requiring some loose quality cuts.

Besides the signal trigger paths to select events suitable for the WZ analysis, we have selected other trigger paths, called *utility trigger*, used to perform tag and probe efficiencies. These trigger paths use further requirements for one of the leptons but very loose on the other, which is going to be used to calculate the

Run Range	DoubleElectron (E_T)			
	L1		HLT	
190456-EndYear	13	7	17	8

(A) Double Electron trigger paths

Run Range	DoubleMuon (p_T)			
	L1		HLT	
190546-196027	10	0	17	8
196046-EndYear	10	0 OR 3.5	17	8

(B) Double Muon trigger paths

Run Range	MuEG (p_T, E_T)			
	L1		HLT	
190456-EndYear	12	7	17	8
190456-196027	0	12	8	12
196046-EndYear	0 OR 3.5	12	8	12

(C) Muon-Electron trigger paths thresholds. The first column for L1 and HLT is referring to the muon object whilst the second column to the electron.

TABLE 6.2: L1 and HLT energy and momentum thresholds for the PDs of 2012 data period. Besides the energy and momentum thresholds, the trigger paths are also requiring some quality cuts. In particular, the 0 value of some muon triggers implies that there is no momentum requirement for the muon, but just the quality requirements.

efficiencies.

6.2.1. Trigger efficiencies

As it was explained in Section 5.1, the data selected by the trigger system are inherently biased to favour certain types of physical processes and, therefore, it is mandatory to take into account this bias. The usual way to proceed is by calculating the trigger efficiencies, i.e. the probability that given an object which should have been fired the trigger path, this trigger path was actually fired. There are several approaches, some involving simulation data and others just involving data from the experiment. The simulation data approach uses data samples

simulated with the Monte Carlo techniques¹ described at 5.2; also including the trigger logic and the trigger paths. Then, the simulated data will also lost some events due to trigger inefficiencies and can be compared directly with the experimental data. The drawback of this method is the high dependence on the detector simulation which in turn has to be taken into account too. Besides, the trigger paths are evolving rapidly (defining new paths, prescaling others, etc.) because of the continuously changing conditions of data taking (increasing of instantaneous luminosity, increasing pileup, detector equipment failures, etc.); as meaning that the Monte Carlo samples and the experimental data samples do not share exactly the same trigger paths. The calculation of the trigger efficiencies using the *tag and probe* method (see 5.1.1) address this problem using exclusively experimental data. Then, the extracted efficiencies can be used on the Monte Carlo samples to weight the simulated event accordingly to the trigger efficiency applicable to that event. In this way, the simulated data incorporate the trigger inefficiencies, mimicking the effect of having been "selected" through a real trigger system and becoming suitable to be trigger-comparable with the experimental data.

	$0.0 < \eta \leq 0.8$	$0.8 < \eta \leq 1.2$	$1.2 < \eta \leq 2.1$	$2.1 < \eta \leq 2.4$
$10.0 < p_t \leq 13.0$	0.0700 ± 0.0114	0.0715 ± 0.0107	0.1042 ± 0.0069	0.1307 ± 0.0141
$13.0 < p_t \leq 15.0$	0.9084 ± 0.0103	0.9050 ± 0.0108	0.8996 ± 0.0069	0.8073 ± 0.0163
$15.0 < p_t \leq 17.0$	0.9393 ± 0.0064	0.9126 ± 0.0088	0.9161 ± 0.0055	0.8478 ± 0.0128
$17.0 < p_t \leq 20.0$	0.9656 ± 0.0029	0.9504 ± 0.0044	0.9448 ± 0.0030	0.8876 ± 0.0075
$20.0 < p_t \leq 30.0$	0.9648 ± 0.0007	0.9516 ± 0.0013	0.9480 ± 0.0009	0.8757 ± 0.0026
$30.0 < p_t \leq \infty$	0.9666 ± 0.0003	0.9521 ± 0.0005	0.9485 ± 0.0004	0.8772 ± 0.0012

(A) *Leading leg*

	$0.0 < \eta \leq 0.8$	$0.8 < \eta \leq 1.2$	$1.2 < \eta \leq 2.1$	$2.1 < \eta \leq 2.4$
$10.0 < p_t \leq 13.0$	0.9604 ± 0.0092	0.9417 ± 0.0098	0.9472 ± 0.0052	0.8951 ± 0.0129
$13.0 < p_t \leq 15.0$	0.9589 ± 0.0075	0.9464 ± 0.0086	0.9519 ± 0.0050	0.8964 ± 0.0130
$15.0 < p_t \leq 17.0$	0.9711 ± 0.0047	0.9401 ± 0.0075	0.9518 ± 0.0043	0.9000 ± 0.0109
$17.0 < p_t \leq 20.0$	0.9669 ± 0.0029	0.9535 ± 0.0043	0.9576 ± 0.0027	0.9166 ± 0.0066
$20.0 < p_t \leq 30.0$	0.9655 ± 0.0007	0.9535 ± 0.0013	0.9558 ± 0.0009	0.9031 ± 0.0023
$30.0 < p_t \leq \infty$	0.9670 ± 0.0003	0.9537 ± 0.0005	0.9530 ± 0.0004	0.8992 ± 0.0011

(B) *Trailing leg*

TABLE 6.3: Muon trigger efficiencies extracted with a tag and probe method in p_T and η bins, for 2011 data. The errors shown are statistical.

¹Henceforth throughout this work, the data samples generated using Monte Carlo techniques may just be called *Monte Carlo samples*, despite of the abuse of language.

	$0.0 < \eta \leq 1.5$	$1.5 < \eta \leq 2.5$		$0.0 < \eta \leq 1.5$	$1.5 < \eta \leq 2.5$
$10.0 < p_t \leq 20.0$	0.5061 ± 0.0037	0.3176 ± 0.0059	$10.0 < p_t \leq 20.0$	0.9854 ± 0.0009	0.9938 ± 0.0011
$20.0 < p_t \leq 30.0$	0.9849 ± 0.0003	0.9774 ± 0.0007	$20.0 < p_t \leq 30.0$	0.9923 ± 0.0002	0.9953 ± 0.0003
$30.0 < p_t \leq \infty$	0.9928 ± 0.0001	0.9938 ± 0.0001	$30.0 < p_t \leq \infty$	0.9948 ± 0.0001	0.9956 ± 0.0001

(A) *Leading leg*(B) *Trailing leg*TABLE 6.4: Electron trigger efficiencies extracted with a tag and probe method in bins of p_T and η for 2011 data. The errors shown are statistical.

The trigger efficiencies can be obtained from independent PDs selected with trigger paths with looser criteria than the ones used to select the analysis sample. A tag and probe method is used, where the tag has been matched with the lepton which fired the trigger to avoid the bias on the probe lepton. The efficiencies obtained with the tag and probe are trigger efficiencies per lepton. The analysis requires two leptons to select the event (double lepton trigger paths), one lepton is the high- p_T object and it is called the *leading leg* and the other one is the low- p_T object and it is called the *trailing leg*. Therefore, the trigger efficiencies are calculated for the leading and the trailing lepton independently and are interpreted as the probability of a lepton passing one leg trigger requirement¹. Tables 6.3 and 6.4 tabulate the efficiency per leg for the 2011 analysis muon and electron object, respectively, calculated with the tag and probe method.

Figures 6.2 show the trigger efficiencies per leg for muons and electrons of the 2012 analysis in function of the transverse momentum of the lepton. Each curve is plotted for the different pseudorapidity regions considered. The figures illustrate the transverse momentum cut used in the leptons of the analysis, which are localised in the plateau of the turn-on curves.

The efficiencies per leg have been interpreted as the probability of a lepton passing one leg trigger requirement and can be used to build a probability function per event (not per leg) which takes into account the possibilities for each combination of the final state leptons to fire the double trigger. Therefore, as the experimental data is selected through the triggers, in order to be able of compare the simulated data with the experimental one, this effect is introduced in the simulated data using weights. Each Monte Carlo event is weighted with

¹The trailing efficiency is actually evaluated requiring a leading lepton in the event, therefore is a conditional probability.

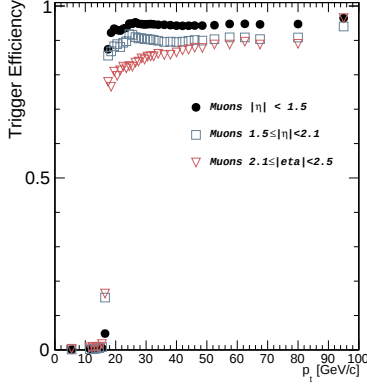
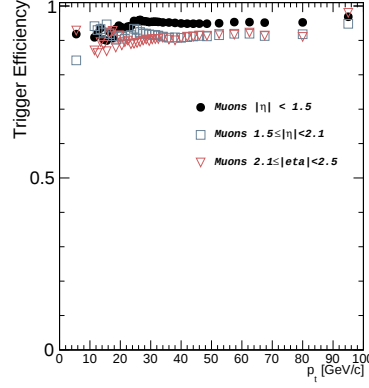
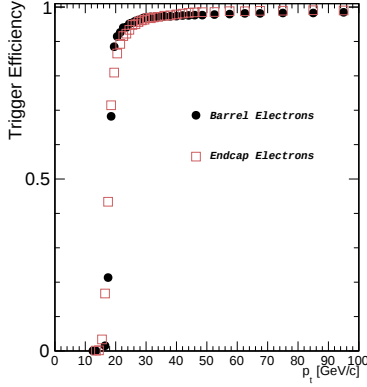
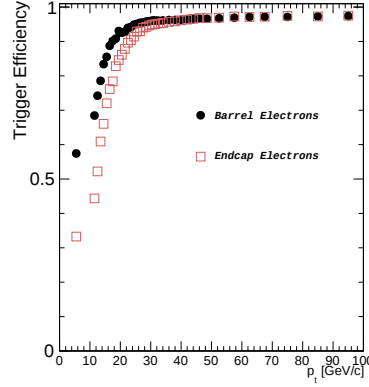
(A) *Double_Mu17_Mu8 trigger leading leg*(B) *Double_Mu17_Mu8 trigger trailing leg*(C) *Double_Ele17_Ele8 trigger leading leg*(D) *Double_Ele17_Ele8 trigger trailing leg*

FIGURE 6.2: Trigger efficiencies with respect to the offline selection for 2012 data. Each curve is plotted in function of p_T of the lepton for the different η regions considered. The turn-on curves guide the analysis transverse momentum requirements: in order to avoid biased samples the leptons should be cut in a transverse momentum placed in the plateau of the turn-on curve.

equation (6.1a) in the case of same flavour channel eee and $\mu\mu\mu$ because it is possible to use all the electrons (muons) in the event to fire the `DoubleElectron` (`DoubleMu`) trigger. And the equation (6.1b) is used for $ee\mu$ and $\mu\mu e$ channels where only the same flavour leptons may be used to fire the Double trigger path, since the third different-flavour lepton is not entering in the possible combinations.

$$\mathcal{P}(\text{Pass}|3\ell) = 1 - \left[(1 - \varepsilon_1^L)(1 - \varepsilon_2^L)(1 - \varepsilon_3^L) + \sum_{\substack{i,j,k=1 \\ i \neq j \neq k}}^3 \varepsilon_i^L(1 - \varepsilon_j^T)(1 - \varepsilon_k^T) \right] \quad (6.1a)$$

$$\mathcal{P}(\text{Pass}|2\ell) = 1 - \left[(1 - \varepsilon_1^L)(1 - \varepsilon_2^L) + \sum_{\substack{i,j=1 \\ i \neq j}}^2 \varepsilon_i^L(1 - \varepsilon_j^T) \right] \quad (6.1b)$$

where $\varepsilon_i^L = \varepsilon_i^L(p_T^i, \eta^i)$ is the efficiency per leg of the trailing leg, evaluated on the i-lepton of the event and $\varepsilon_i^T = \varepsilon_i^T(p_T^i, \eta^i)$ is the efficiency per leg of the leading leg, evaluated on the i-lepton of the event.

After the event weighting, the simulated data incorporate the trigger inefficiencies and, thus, the probability to "store" the event by a trigger system.

6.3. Muon selection

Muon selection is designed to achieve high efficiency for muons coming from W or Z decays, hereafter called *prompt muons*, keeping a high rejection in those which are not. Muons are restricted to be within the pseudorapidity acceptance ($|\eta| < 2.4$) of the muon and tracking system, and have to fulfil various track quality requirements. To avoid any bias introduced by the trigger thresholds, the transverse momentum is chosen to be higher than trigger thresholds used and in the plateau of the trigger efficiency turn-on curve. The muons are required to be reconstructed (see Section 4.2.2) using the tracker and the muon spectrometer, i.e. a *Global* muon, and the relative χ^2 over the degrees of freedom (normalised χ^2) of the global fit has a quality cut; this is useful to reject muons from hadrons decaying in flight and kaons punching through the calorimeter. In addition, for a track, more than 10 hits in the inner tracker are required to guarantee a good fit of the track, at least another hit is required in the pixel detector and at least one hit in the muon spectrometer. Moreover, the muon must be matched to track segments in two different muon stations which suppress accidental track-to-segment matches and punch-through. The transverse impact parameter of the track is also restricted around the beam spot in order to reject cosmic ray muons;

the longitudinal impact parameter is also restricted to be around of the beam spot to further suppress cosmic muons, muons from decays in flight and tracks from pileup. Finally, the requirement of the relative error fit $\Delta p_T/p_T$ better than 10% is applied to reject poorly measured muons. The requirements described

	2011	2012
Max. relative p_T resolution, $\Delta p_T/p_T$	0.1	0.1
Max. normalised χ^2 for global fit	10	10
Min. number of pixel hits	1	1
Min. number of inner tracker hits	11	–
Min. number of layers in the inner tracker with hits	–	6
Min. number of matched muon segments	2	2
Max. transverse impact parameter, $ d_0 $ [cm]	0.2	0.01 (0.02)
Max. longitudinal impact parameter, $ d_z $ [cm]	0.1	0.1
Max. relative particle flow isolation ISO_{PF}/p_T	0.12	–
	$(p_T \leq 20 \text{ GeV, MB})$	–
	$(p_T \leq 20 \text{ GeV, ME})$	0.86
Min. MVA isolation output	$(p_T \leq 20 \text{ GeV, ME})$	–
	$(p_T > 20 \text{ GeV, MB})$	–
	$(p_T > 20 \text{ GeV, ME})$	0.82
		0.86

TABLE 6.5: Selection requirements imposed on muons in the 2011 and 2012 analyses. Besides these requirements, in the case of 2012 analysis, the muon object must be reconstructed with a particle flow algorithm and it can be a global or a tracker muon, not just a global as in the 2011 case. The d_0 value in the 2012 column is shown for muons with $p_T < 20 \text{ GeV}$ and for muons with $p_T > 20 \text{ GeV}$ in parentheses. The isolation requirements are also included. The *MB* and *ME* labels are referring to barrel and endcap muons, i.e. muons with $|\eta|$ lower or higher than 1.479.

above have been used for the 2011 analysis, the 2012 muon objects use the same requirements and add new ones. The muon is also required to be reconstructed using a particle flow algorithm and, therefore, the global requirement is relaxed and it also admitted a tracker muon. Furthermore, the minimum number of inner tracker hits is substituted by the equivalent cut in the number of tracker layers with hits. Also the impact parameter cuts have been tight. Table 6.5 shows the quality cuts for the 2011 and 2012 muon objects.

Besides the aforementioned quality requirements, the muon is required to be isolated. For this purpose, a particle flow isolation is used. The isolation variable

is built using the particle flow candidates found in the event through,

$$Iso_{PF} = \sum_{PF} E_T^{ChHad} + \max \left(0, \sum_{PF} p_T^{NeutHad} + \sum_{PF} E_T^\gamma - d\beta \right), \quad (6.2)$$

where $\sum_{PF} p_T^{ChHad}$ is the p_T sum of the charged hadron candidates with $|d_z^{candidate} - d_z^\mu| < 0.1 \text{ cm}$, $\sum_{PF} E_T^{NeutHad}$ is the scalar sum of transverse energy of the neutral hadron candidates and $\sum_{PF} E_T^\gamma$ is the scalar sum of transverse energy of the photon candidates. The charged, neutral and photon candidates have been defined within a $\Delta R < 0.3$ cone around the muon candidate. The $d\beta$ correction is defined as $d\beta = 0.5 \sum p_T^{PU}$ being $\sum p_T^{PU}$ the p_T sum of the charged particles in the $\Delta R < 0.3$ cone around the muon, but with particles not originating from the primary vertex¹. The 0.5 factor corresponds to a naive average of neutral to charged particles (which has been measured in Reference [73] and Higgs searches [74] and [75]). In summary, the muon isolation is calculated by estimating all the charged hadrons around the isolation cone and adding the neutral candidates which have been corrected by the pileup, avoiding possible pileup over corrections (when the correction is negative).

The increasing pileup conditions in the 2012 running period have motivated a change in the isolation strategy in order to reduce the dependence of this variable with the number of pileup vertices and increase both prompt efficiency and fake muon rejection. It is accomplished with a particle flow isolation variable implemented using a Multivariate Analysis (MVA): the discrimination power of the ΔR between the muon and other particles are used to discriminate between isolated and non-isolated muons. Some of the input variables are $\sum_{PF} E_T^{ChHad}$, $\max(0, \sum_{PF} p_T^{NeutHad} + \sum_{PF} E_T^\gamma - d\beta)$, $\sum \Delta R(\mu, PF^{ChHad})$, etc. Once the Boosted Decision Tree (BDT) is trained in a enriched sample of isolated muons (sample defined with a Z resonance similar to the tag and probe method) in order to discriminate between prompt and non-isolated muons, it can be used to classify the muons between prompt and non-isolated. The improvement accomplished using this MVA approach for isolation versus the sequential cut isolation approaches are shown in Figures 6.3. The BDT output is dependent

¹Note that this is a pileup correction similar to that provided by the FASTJET algorithm of Section 5.1.3.

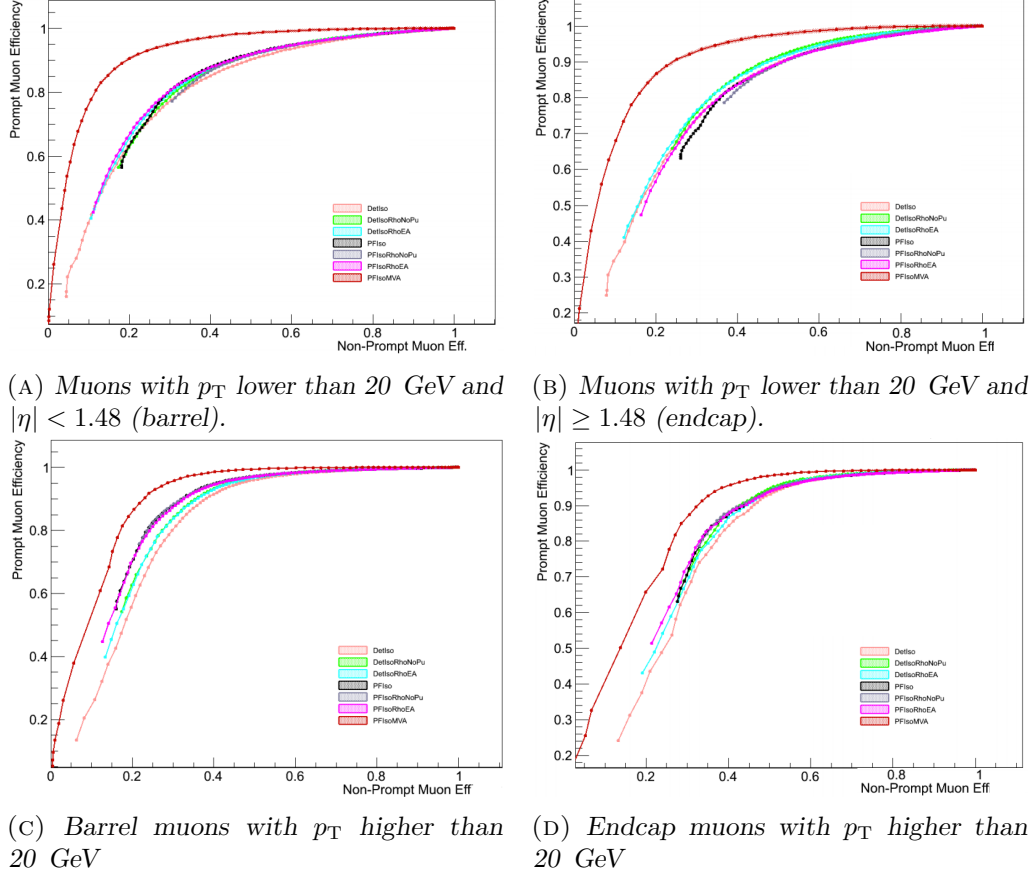


FIGURE 6.3: The prompt muon efficiency with respect to the fake muon efficiency is shown in the plots. The curve is build by varying the cuts thresholds of the MVA output and evaluating the signal and background efficiency in each point (the so called ROC curves, from Receiver Operating Characteristic in signal detection theory). The MVA approach used in this analysis is labelled as "PFIsoMVA" and represented by red lines and dots. There are several muon isolation strategies compared, in particular the one used in 2011 analysis is represented by black lines and dots and labelled "PFIso". It may be observed the improvement reached with the MVA-isolation approach with respect the sequential 2011 one, the purity of the 2012 muons is substantially higher.

of the kinematics of the muon, thus it has been split the muons into barrel and endcap and between lower and higher than $p_T = 20$ GeV as it can be seen in Table 6.5.

The values of the requirements used to identify and isolate the muon objects have been optimised by the CMS collaboration providing a few different baseline

selection and isolation working points suitable for different target analyses [76]. The main advantage of this approach is that efficiencies related with the muon objects are provided in a centralised way for the whole collaboration. A dedicated working group¹ is in charge to define, optimise and support the recommended muon selections.

6.3.1. Muon efficiencies and scale factors

From the hits in the tracker and muon spectrometer systems up to the high level physic object used for analysis, the final muon has been built in three main stages: the reconstruction, explained in Section 4.2.2, the identification and the isolation (both described in the previous sections). Each process introduces inefficiencies which may be calculated using the tag and probe method. The efficiency of the final selected muon object can be factorised as the efficiencies of each stage, given that the output of one process is the input of the next, and they are applied sequentially. Thus,

$$\varepsilon_{\mu} = \varepsilon_{hlt|iso} \cdot \varepsilon_{iso|id} \cdot \varepsilon_{id|reco} \cdot \varepsilon_{reco}$$

where ε_{reco} stands for the efficiency of the reconstruction process, using as probes the available inner and stand-alone tracks and evaluating how many global muon tracks are obtained. Note that an extra term should be included before the reconstruction efficiency, it is the track reconstruction efficiency, but it has been measured to be compatible with the unity, thus it is not shown explicitly. The $\varepsilon_{id|reco}$ is the identification efficiency which can be calculated using as probes the previous global tracks and checking how many pass the identification criteria described in previous section. The $\varepsilon_{iso|id}$ stands for the efficiency of isolation, and analogously the probes are defined as the identified leptons and the passing probes, those passing the isolation criteria. And finally $\varepsilon_{hlt|iso}$ is the trigger efficiency (both L1 and HLT) and it is calculated from a tag and probe using as probe sample the identified and isolated muons, then it is checked if they pass the trigger leg.

¹Muon Physics Object Group (POG), there are analogous working groups for each of the physics objects used in the CMS analysis framework.

	$0 < \eta \leq 1.2$	$1.2 < \eta \leq 2.5$
$10 < p_t \leq 20$	0.933 ± 0.009	0.964 ± 0.007
$20 < p_t \leq 30$	0.951 ± 0.002	0.944 ± 0.002
$30 < p_t \leq 40$	0.971 ± 0.001	0.954 ± 0.001
$40 < p_t \leq 50$	0.980 ± 0.008	0.965 ± 0.001
$50 < p_t \leq 60$	0.985 ± 0.001	0.968 ± 0.002
$60 < p_t \leq 80$	0.978 ± 0.002	0.967 ± 0.004
$80 < p_t \leq \infty$	0.979 ± 0.006	0.984 ± 0.016

(A) *Muon scale factors for 2011 data.*

	$0.0 < \eta \leq 0.9$	$0.9 < \eta \leq 1.2$	$1.2 < \eta \leq 2.4$
$10 < p_t \leq 15$	0.9923 ± 0.012	0.971 ± 0.358	1.002 ± 0.005
$15 < p_t \leq 20$	0.9611 ± 0.006	0.951 ± 0.005	0.995 ± 0.003
$20 < p_t \leq 25$	0.9821 ± 0.002	0.982 ± 0.001	1.020 ± 0.002
$25 < p_t \leq 30$	1.0000 ± 0.001	0.993 ± 0.002	1.019 ± 0.001
$30 < p_t \leq 50$	0.9928 ± 0.0002	0.9911 ± 0.0004	1.0018 ± 0.0003
$50 < p_t \leq \infty$	0.994 ± 0.001	0.991 ± 0.001	1.005 ± 0.001

(B) *Muon scale factors for 2012 data*

TABLE 6.6: Muon reconstruction, isolation and identification scale factors applied to the Monte Carlo sample events in bins of pseudorapidity and transverse momentum. Scale factors calculated for the 2011 analysis.

The efficiencies are calculated both in the simulated samples and in the experimental data in the way described above using a tag and probe method as it was explained in Section 5.1.1. The cross section measurement is performed by keeping the experimental observed data uncorrected, as it will be explained in Chapter 8, whereas the simulated data is assuming the efficiency corrections through the application of the SFs¹ in the simulated samples. Table 6.6 shows the total SF, i.e. reconstruction, identification and isolation, for the selected muons to be applied to the Monte Carlo samples. Notice that the trigger efficiency is not introduced in the SFs due to the weight method technique described at Section 6.2.1. The effect of the trigger in the Monte Carlo samples is simulated by the equations (6.1) which make use of the trigger efficiencies per leg evaluated in experimental data.

¹*Id est*, the ratio between the efficiencies calculated in Monte Carlo versus experimental data

6.4. Electron selection

The electron objects, after the reconstruction process (see Section 4.2.3), are selected on a basis of few discriminating variables in terms of identification, selection and photon conversion rejection. The main discriminating variables used are described in Table 6.7. The CMS collaboration has developed two

$\sigma_{i\eta i\eta}$	supercluster η width
$\sigma_{i\phi i\phi}$	supercluster ϕ width
$\Delta\eta_{in}$	distance in the η -plane between the track and the supercluster
$\Delta\phi_{in}$	distance in the ϕ -plane between the track and the supercluster
f_{brem}	the fraction of the total momentum carried away by bremsstrahlung
$E_{HCAL}/E_{ECAL} \equiv H/E$	Ratio between energy deposited in the HCAL vs. ECAL
N_{SC}^a	Number of additional clusters from supercluster
$1/E_{SC} - 1/p_{TRK}$	The difference between the inverse of the Energy in the supercluster and the momentum measured with the tracker

TABLE 6.7: Main discriminating variables for electron identification, used in both cut based and MVA approach. Note the i label in the calorimeter's supercluster related variables is indicating that any measurement (distance or width) is taken as a number of crystals rather than distance.

main approaches to identify electrons: a cut based approach [58] and a MVA discriminator approach [77]. Both of them have been optimised to select electrons from Z and W (*prompt* electrons) and reject fakes from jets or photon conversion. Threshold cuts in the discriminant variables can be tuned, defining Working Point (WP) of different efficiency on the prompt and rejection on the fakes. This analysis uses the MVA approach using BDT to identify prompt electrons given the optimal efficiency in selecting signal keeping a low rate of selected fakes, with respect the cut based approach as it can see in Figures 6.4.

The training of the multivariate algorithm is performed with the combination of those variables in a BDT. Since the calorimeter response is different between

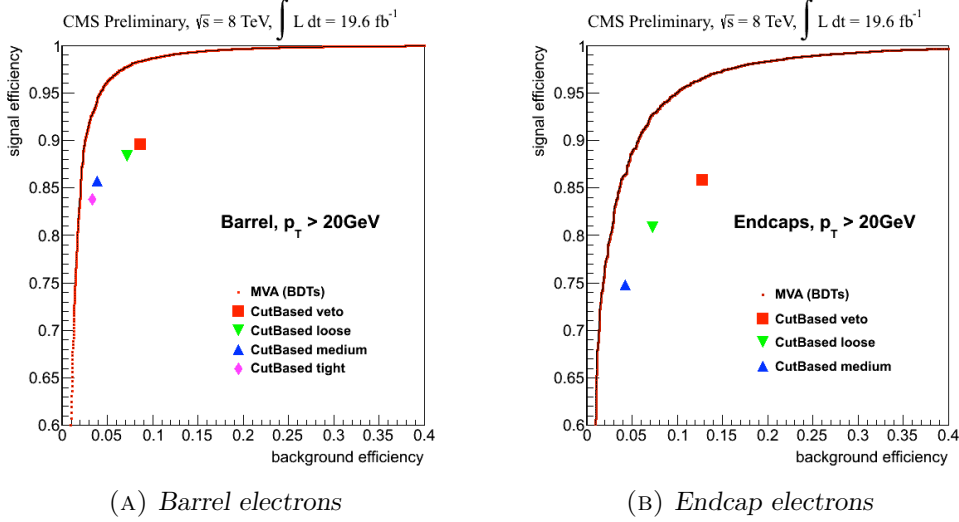


FIGURE 6.4: The prompt electron efficiency with respect to the fake lepton efficiency is shown in the plots. The curve is built by varying the cuts thresholds of the MVA output and evaluating the signal and background efficiency in each point. The cut based points are referring to different WP. The MVA-based identification improves significantly the purity of the electrons.

endcap and barrel, and also the track reconstruction differs for low- p_T and high- p_T electrons, the training is done in different regions of η and p_T . Further details can be obtained from Reference [77]. Besides the electron identification, all electrons are required to be within detector acceptance ($|\eta| < 2.5$) and further requirements are applied in order to avoid a possible bias due to the trigger selection; the trigger paths for electrons use some loose cuts in some of the variables of Table 6.7 which have to be taken into account in the analysis. These extra requirements are shown in Table 6.8 and it summarises as follows. The electromagnetic shower shape (see Section 4.2.3) is checked to test the compatibility with the isolated electron hypothesis. Therefore, the shower is evaluated for the width of the electromagnetic cluster in terms of pseudorapidity ($\sigma_{i\eta i\eta}$), the difference between the measured position of the ECAL supercluster and the associated track ($\Delta\phi_{in}$ and $\Delta\eta_{in}$) and the ratio of the energy deposited in the HCAL over the ECAL (E_{HCAL}/E_{ECAL}). Furthermore, it is required that electron tracks have no missing hits in the innermost regions in order to reject e^+e^- pair created from photons of the hard interaction. These photon have a high probability to convert to an

e^+e^- pair in the tracker, thus those tracks are likely to miss hits in the innermost region of the tracker.

		2011		2012	
		EB	EE	EB	EE
Max.	$\sigma_{i\eta i\eta}$	0.01	0.03	0.01	0.03
Max.	$ \Delta\phi_{in} $	0.15	0.1	0.15	0.1
Max.	$ \Delta\eta_{in} $	0.007	0.009	0.007	0.009
Max.	E_{HICAL}/E_{ECAL}	0.12	0.1	0.12	0.1
Max.	transverse impact parameter, $ d_0 $ [cm]	0.02		0.02	
Max.	longitudinal impact parameter, $ d_z $ [cm]	0.1		0.1	
Max.	$\sum_{HICAL} E_T p_T$	0.2		0.2	
Max.	$\sum_{ECAL} E_T/p_T$	0.2		0.2	
Max.	$\sum_{tracker} E_T/p_T$	0.2		0.2	
Min. MVA identification output	$(p_T \leq 20 \text{ GeV}, \eta \leq R1)$	0.14		0.0	
	$(p_T \leq 20 \text{ GeV}, \eta \in (R1, 1.479])$	0.53		0.1	
	$(p_T \leq 20 \text{ GeV}, \eta \in (1.479, 2.5])$	0.54		0.62	
	$(p_T > 20 \text{ GeV}, \eta \leq R1)$	0.95		0.94	
	$(p_T > 20 \text{ GeV}, \eta \in (R1, 1.479])$	0.95		0.85	
	$(p_T > 20 \text{ GeV}, \eta \in (1.479, 2.5])$	0.88		0.92	
Max.	relative particle flow isolation Is_{OPF}/p_T	0.13	0.09	0.15	

TABLE 6.8: Selection requirements imposed on electrons in the 2011 and 2012 analyses. The electrons are split in barrel electrons (EB), for those having a $|\eta| < 1.479$ and endcap electrons (EE). The detector based isolation variables are the scalar sum of the energy deposits in the electromagnetic ($\sum_{ECAL} E_T$) and hadronic ($\sum_{HICAL} E_T$) calorimeters and also the sum of the transverse momentum in the tracker ($\sum_{tracker} E_T$). Those sum are performed around the electron candidate by defining a $\Delta R = 0.3$ cone around it.

The electron isolation is computed using a particle flow approach [77] similar to the muon case (Equation (6.2)) but using the density noise estimation ρ and the jet area A_{eff} approach from the FASTJET method described at Section 5.1.3 to control the pileup environment. This pileup correction in the isolation is especially important in the 2012 analysis.

$$Is_{OPF} = \sum_{PF} E_T^{ChHad} + \max \left(0, \sum_{PF} p_T^{NeutHad} + \sum_{PF} E_T^\gamma - \rho \cdot A_{eff} \right) \quad (6.3)$$

6.4.1. Electron efficiencies and scale factors

Analogously to the muon case (Section 6.3.1), the efficiencies for the electron selection were calculated with the tag and probe method. At each stage of the selection, it has been evaluated its efficiency in experimental and simulated data, and compared both values to obtain the SFs. Table 6.9 shows the electron SFs for the total selection process.

	$0 < \eta \leq 1.44$	$1.44 < \eta \leq 1.56$	$1.56 < \eta \leq 2.5$
$10 < p_t \leq 15$	0.96 ± 0.03	0.92 ± 0.15	1.0 ± 0.7
$15 < p_t \leq 20$	0.96 ± 0.02	1.01 ± 0.12	1.0 ± 0.6
$20 < p_t \leq 25$	0.95 ± 0.01	0.99 ± 0.04	1.01 ± 0.02
$25 < p_t \leq 50$	0.99 ± 0.01	1.01 ± 0.02	1.01 ± 0.02
$50 < p_t \leq \infty$	0.98 ± 0.01	1.00 ± 0.11	1.01 ± 0.02

(A) *Electron scale factors for 2011 data.*

	$0 < \eta \leq 0.8$	$0.8 < \eta \leq 1.44$	$1.44 < \eta \leq 1.56$	$1.56 < \eta \leq 2.0$	$2.0 < \eta \leq 2.5$
$10 < p_t \leq 15$	0.66 ± 0.02	0.73 ± 0.03	0.81 ± 0.09	0.61 ± 0.04	0.64 ± 0.03
$15 < p_t \leq 20$	0.901 ± 0.009	0.942 ± 0.014	0.86 ± 0.07	0.83 ± 0.02	0.76 ± 0.02
$20 < p_t \leq 30$	0.943 ± 0.003	0.950 ± 0.004	0.92 ± 0.01	0.923 ± 0.005	0.972 ± 0.006
$30 < p_t \leq 40$	0.9614 ± 0.0009	0.94 ± 0.15	0.965 ± 0.005	0.9249 ± 0.0015	1.0 ± 0.6
$40 < p_t \leq 50$	0.9763 ± 0.0006	0.97 ± 0.09	0.954 ± 0.004	0.9608 ± 0.0011	0.982 ± 0.002
$50 < p_t \leq \infty$	0.9742 ± 0.0012	0.9698 ± 0.0013	0.986 ± 0.009	1.0 ± 0.2	0.970 ± 0.003

(B) *Electron scale factors for 2012 data*

TABLE 6.9: Electron reconstruction, isolation and identification scale factors applied to the Monte Carlo sample events in bins of pseudorapidity and transverse momentum. Errors are statistical.

6.5. Neutrino selection

The neutrino leaves no signal in the detector systems, nevertheless is possible to infer its presence by the E_T^{miss} observable (introduced and described in Section 4.2.5) which is constructed employing the energy-momentum conservation in the transverse plane of the proton beams. The signal events are expected to have a significant amount of E_T^{miss} because of the W leptonic decay $W \rightarrow \ell \nu_\ell$ whilst the main backgrounds (as Drell-Yan) are restricted to measure spurious E_T^{miss} , coming from detector resolution and/or from E_T^{miss} not properly reconstructed.

The analysis makes use of the particle flow algorithm to estimate the E_T^{miss} which takes advantage of the full detector information to reconstruct the event decay products. The E_T^{miss} is estimate by subtracting vectorially all the particle flow candidates in the transverse plane,

$$\left(\vec{E}_T^{\text{miss}}\right)_{PF} = - \sum_{\text{PF-cand.}} \vec{p}_T(PF) \quad (6.4)$$

Notice that this observable is considerably sensitive to the pileup environment and some corrections are needed to avoid fake missing transverse energy reconstruction. Further details about such corrections and performance behaviour description have been explained at Section 4.2.5.

6.6. Event selection

The WZ cross section analysis is essentially based in counting events. Counting how many events we have recorded that have the expected signature of the WZ production when the gauge bosons decay leptonically. The signal was classified in four different categories depending the final state leptons considered (see Section 6.1) allowing us to perform four independent counting analysis using four orthogonal samples. The leptonic signature $\ell^\pm \ell'^+ \ell'^-$ is going to be defined by the gauge bosons decays $W \rightarrow \ell^\pm \nu_\ell$ and $Z \rightarrow \ell'^+ \ell'^-$, being these final state leptons high- p_T isolated muons and electrons. In the previous section we have focused precisely on optimising the selection requirements in order to select such kind of leptons. Notice that we are also considering as signal the τ decay of the gauge bosons as long as they decay leptonically, getting a muon or electron in the final state. In Chapter 7 we will see how to deal with this kind of signal.

The three high- p_T lepton final state is in fact a remarkably restrictive requirement. We have detailed the potential sources of noise in Section 6.1 and we have anticipated that the only (important) irreducible background is the ZZ production which, however, has a production rate almost an order of magnitude lower than the WZ process. Therefore, the analysis has such a clean signature than the signal-to-noise ratio is considerably high. Furthermore, the presence of the Z resonance and the W allows to reduce the remnant instrumental background. The

Z resonance is tested using the invariant mass of the two same flavour, opposite charged leptons, being the invariant mass defined as,

$$M_{\ell_1\ell_2} = \sqrt{E_1^2 + E_2^2 - |\mathbf{p}_1 + \mathbf{p}_2|^2}, \quad (6.5)$$

where E_i is the energy and $\mathbf{p}_i$ the 3-momentum of the i -lepton. In the highly relativistic regime of the collider experiments, the energy of the lepton is much higher than its rest mass ($E \gg m$), therefore the previous expression becomes

$$M_{\ell_1\ell_2} = 2p_{t_1}p_{t_2} (\cosh(\eta_1 - \eta_2) - \cos(\phi_1 - \phi_2)), \quad (6.6)$$

being η_i and ϕ_i the pseudorapidity and the azimuthal angle of the i -lepton, respectively.

Since it is not possible to reconstruct the invariant mass of the W gauge boson because of the neutrino's presence, which it is not leaving any electronic signal in the detector, the transverse mass is defined through the missing transverse energy and a lepton to build the W mass in the transverse plane [24],

$$M_T(W) = \sqrt{2p_T^\ell E_T^{\text{miss}} \left(1 - \cos\phi_{\vec{p}_T^\ell, \vec{E}_T^{\text{miss}}}\right)}, \quad (6.7)$$

where $\phi_{\vec{p}_T^\ell, \vec{E}_T^{\text{miss}}}$ is the angle between the transverse momentum vector of the lepton with the transverse missing energy vector. Note that this observable is invariant under Lorentz boosts in the z direction.

The analysis is performed in three main sequential steps filtering events that have to fulfil some requirements. The main stages of the analysis are:

1. Lepton preselection

- The event contains exactly three leptons fulfilling the requirements of Sections 6.3.
- Two of the event leptons must have at least a transverse momentum higher than 20 GeV and the third higher than 10 GeV.
- The leptons must be inside the detector acceptance which implies $|\eta| < 2.4$ (2.5) for muons (electrons).

As it will show along this chapter, these requirements filters most of the instrumental background events with more than one fake lepton, meaning *QCD* and *W + Jets* mostly, leaving a sample mainly composed by instrumental background with one fake lepton, i.e. $Z/\gamma^* + jets$ and $t\bar{t}$, besides of the irreducible background.

2. Z candidate selection

- The event must contain two opposite-charged, same flavour leptons. The invariant mass of these leptons must be compatible with the Z resonance, meaning that the invariant mass of the dilepton system must be inside $M_Z \pm 20$ GeV, where the Z nominal mass [24] is $M_Z = 91.1876$ GeV. In case that more than one lepton pair satisfies these requirements, the pair with invariant mass closer to the nominal one is chosen.

These stage of the analysis rejects the remnant background without a real Z resonance: $t\bar{t}$ and single top and *WW*.

3. W candidate selection

- The available third lepton not associated with the Z is required to have a transverse momentum higher than 20 GeV. This implies that whenever a lepton has a $p_T < 20$ GeV it must come from the Z decay.
- This lepton is required to be outside a cone of $\Delta R = 0.1$ around either of the Z candidate leptons. The requirement is rejecting asymmetric internal photon conversions¹ mainly from $Z/\gamma^* + Jets$. The Z lepton candidate, which radiates the virtual photon, is going to be close to the lepton created from the asymmetric conversion [79].

¹Asymmetric conversions [78] is a process whereby one lepton takes most of the photon energy and the second lepton is very soft and not measured. There are two types of photon conversion important for this analysis. The first type is an external conversion in which a photon radiated by the collision interacts with the detector material and produces a lepton pair, primarily electrons but very rarely muons. The second type of conversion is the internal photon conversion, where the photon is virtual and does not interact with the detector. Internal photon conversion can produce muons almost as often than electrons.

- The missing transverse energy of the event must be higher than 30 GeV in order to take into account the undetected neutrino.

This final selection tries to reject events with the presence of spurious E_T^{miss} due to its resolution as the the Drell-Yan process and the ZZ background.

Any event that does not fulfil these requirements is rejected. These cuts are applied to the experimental data previously obtained with the double lepton trigger paths (see Section 6.2) and to the simulated data¹ to which the corrections described before (scale factors, trigger weights, pileup reweighting, etc.) have been applied. The simulated predictions are compared with the experimental data at each stage of the analysis mainly by comparing the event distributions of sensitive observables. Figures 6.5 show the transverse momentum and pseudorapidity of the three leptons selected imposing the preselection requirements. It can be observed that the dominant background consists of the so called *Data-driven background* which is primarily composed by $Z/\gamma^* + \text{Jets}$ and $t\bar{t}$ (see Chapter 7 where the background treatment is detailed). The instrumental background coming from more than one fake lepton is already mitigate at the preselection level. The number of signal events is essentially of the same order than the background.

After the Z candidate selection, it is possible to build the invariant mass of the dilepton system selected and check some other interesting observables. At this point, the non-peaking backgrounds should have diminished and it can be observed that the predicted signal is primarily composing the experimental data. See for instance, Figures 6.6 where the invariant mass and the transverse momentum of the dilepton system is plotted. The Figure 6.7a displays the E_T^{miss} distribution at Z-candidate selection. This figure illustrates the E_T^{miss} cut which is applied when requiring the W candidate; the remnant background populates the low E_T^{miss} region, likely due to the non-presence of real E_T^{miss} , whilst the signal trends to be in higher E_T^{miss} regions.

Using the remaining lepton which is going to be assigned as W candidate, it is possible to build the transverse mass of the E_T^{miss} and this W-candidate lepton. The Figure 6.8a shows this transverse mass just before requiring the E_T^{miss} cut. The $m_T(\ell_W, E_T^{\text{miss}})$ distribution exhibits the Jacobian peak in the WZ Monte Carlo

¹The simulated data used in this analysis are explained in detail in Chapter 7

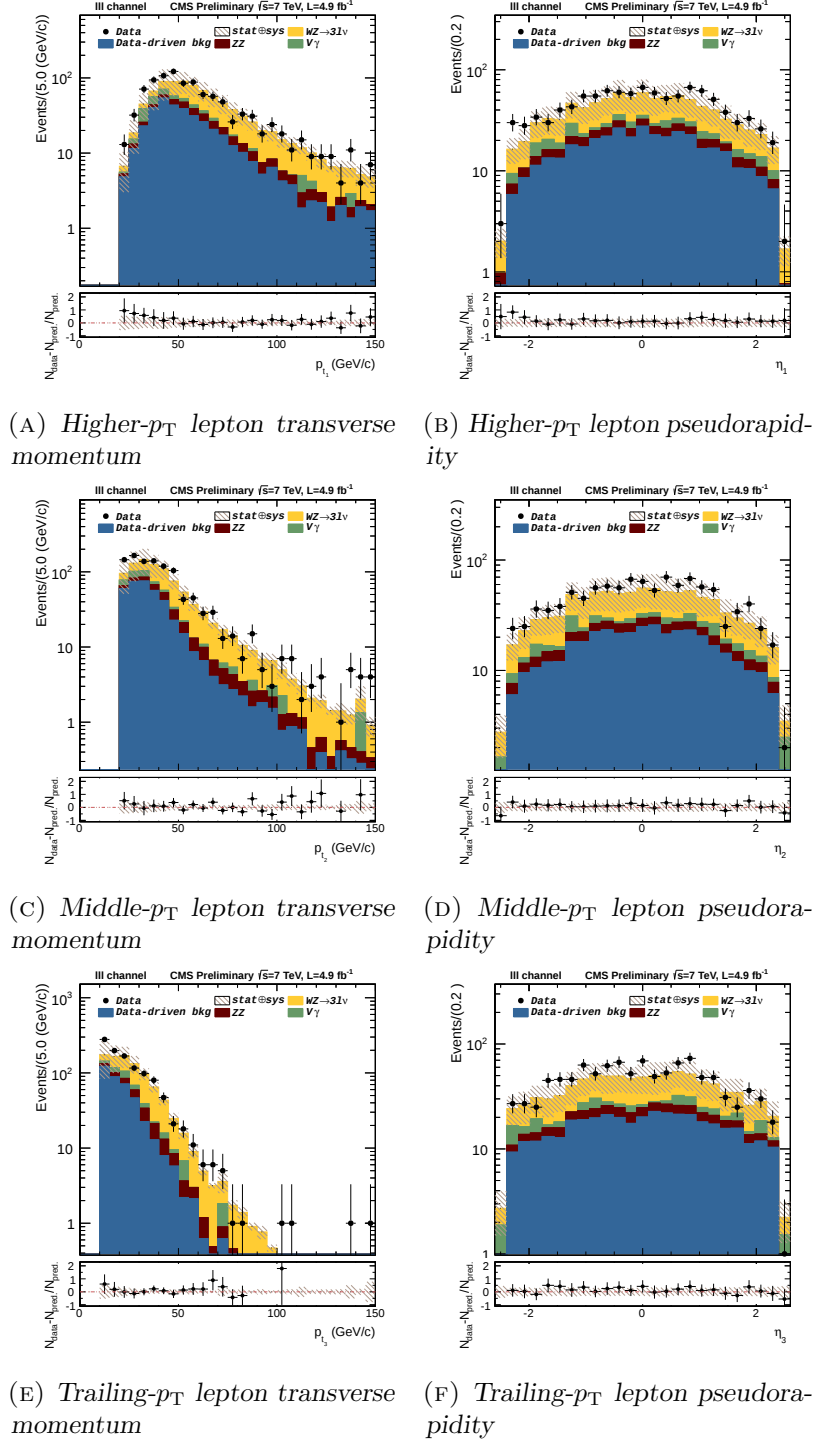
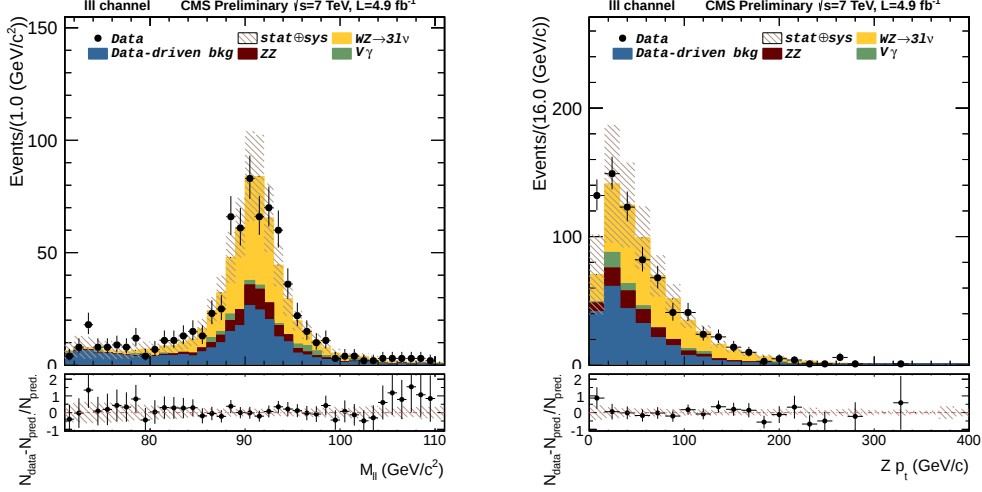


FIGURE 6.5: Lepton kinematic distributions at preselection level. The distributions are built adding up the four final state channels. Statistical and systematic uncertainties are included. The data versus Monte Carlo prediction is shown in the lower plot. Data corresponding to 2011 analysis.



(A) Invariant mass of the Z-candidate dilepton system (B) Transverse momentum of the Z-candidate dilepton system

FIGURE 6.6: Z-candidate dilepton system related distributions after applied the Z selection step. The distributions are built adding up the four final state channels. Statistical and systematic uncertainties are included. The experimental data versus the Monte Carlo prediction is shown in the lower plot. Data corresponding to 2011 analysis.

prediction whilst the background are mainly focused to low regions because of the spurious E_T^{miss} , due to resolution, used to build the observable. In the Figure 6.8b when all the requirements of the W selection stage are applied, and in particular the E_T^{miss} cut, almost all the background has disappeared, clearing the transverse mass around the W invariant mass. Figures 6.9 show the transverse momentum of the Z and W system after all the selection is applied.

Furthermore, Figures 6.10 shows the angular distances between the two Z-candidate leptons with the W-candidate lepton in order to check the internal photon conversion. The angular distance is estimated with,

$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} \quad (6.8)$$

where $\Delta\eta = \eta_1 - \eta_2$ is the difference in pseudorapidity and $\Delta\phi = \phi_1 - \phi_2$ the azimuthal angle difference between the two leptons. This ΔR defines a cone generated by the revolution in the three-dimensional space of the surface created

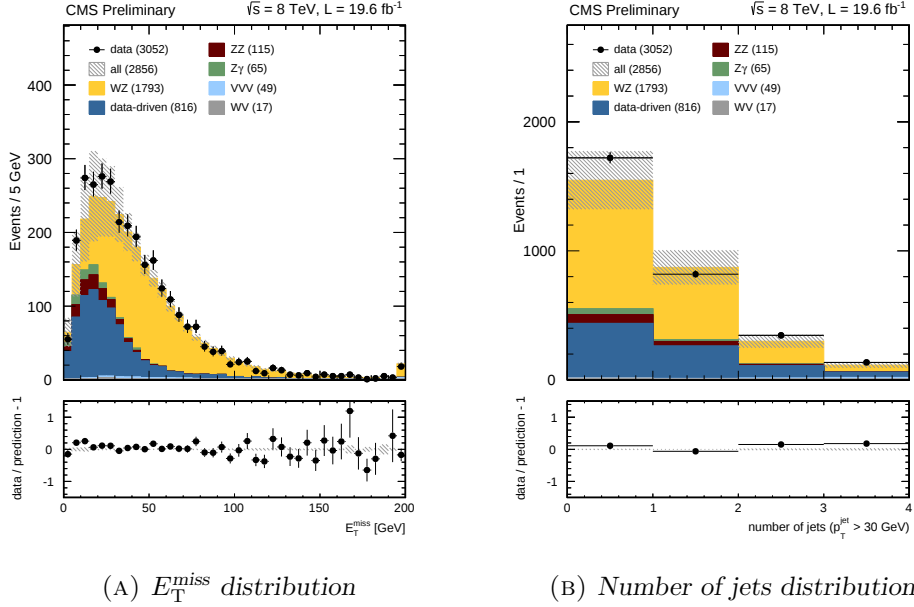


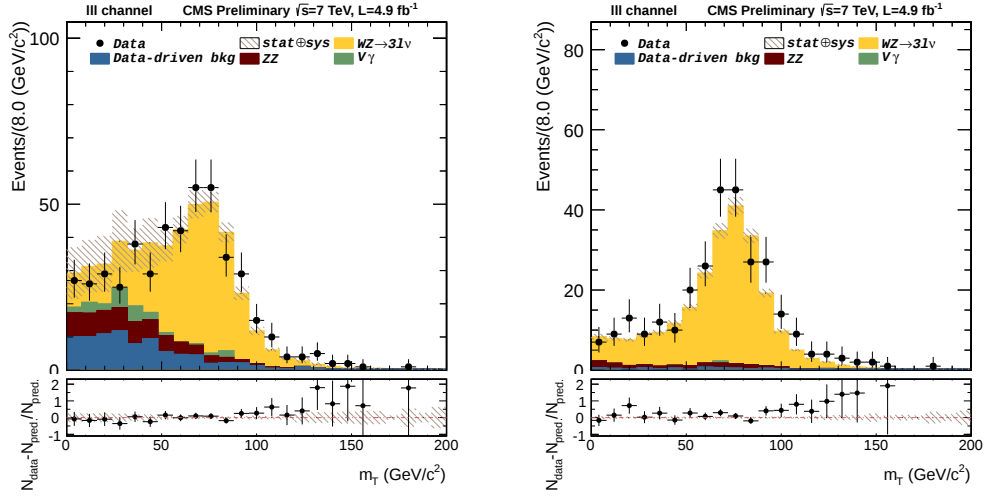
FIGURE 6.7: Distributions at the Z-candidate selection stage. The distributions are built adding up the four final state channels. Statistical and systematic uncertainties are included. The experimental data versus the Monte Carlo prediction is shown in the lower plots. Data corresponding to 2012 analysis.

by the two linear momentum vectors of the leptons. Hence, the figures are showing the angular separation between the Z-candidates and the W-candidate leptons: the lowest region of ΔR is likely notifying an internal photon conversion. As expected this region is populated only by Drell-Yan events.

The control distributions plots reveal a good agreement between the Monte Carlo prediction for the SM processes and the experimental data. All the distributions are consistent within the statistical and systematic¹ uncertainties. The Appendix A is filled with more detailed distributions, both for the 7 and 8 TeV analyses, at each stage of the selection and for each final lepton state channel separately.

Finally, a quantitative view of the analysis is given in Tables 6.10 and 6.11, showing the experimental and Monte Carlo prediction data events obtained for the four lepton final state channels.

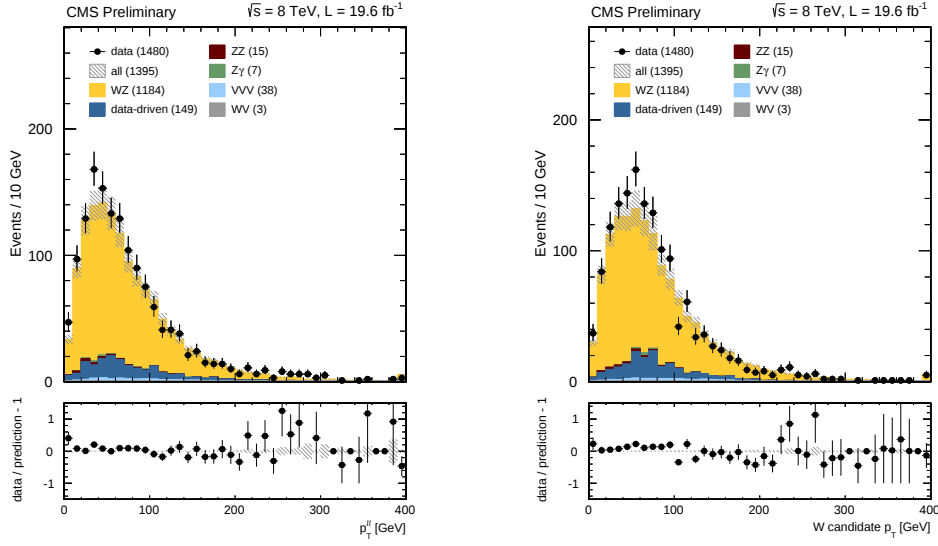
¹A detailed treatment of the systematic uncertainties considered in this analysis is elaborated in Chapter 8.



(A) All the W-selection requirements are applied but the E_T^{miss} cut.

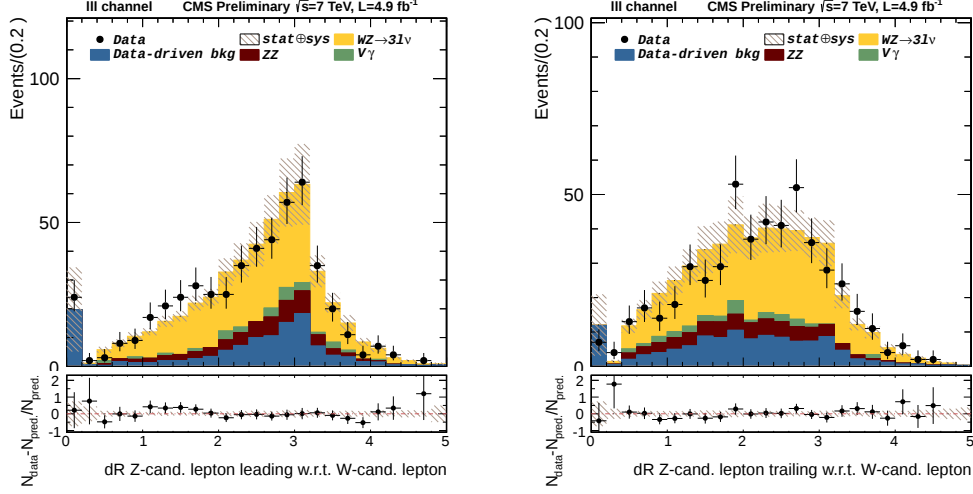
(B) All the W-selection requirements are applied

FIGURE 6.8: Transverse mass of the W lepton candidate and the E_T^{miss} at W selection stage. The distribution is built adding up the four final state channels. Statistical and systematic uncertainties are included. The experimental data versus the Monte Carlo prediction is shown in the lower plot. Data corresponding to 2011 analysis.



(A) *Transverse momentum of the Z system* (B) *Transverse momentum of the W system*

FIGURE 6.9: Distributions after all the selection stages are applied. The distributions are built adding up the four final state channels. Statistical and systematic uncertainties are included. The experimental data versus the Monte Carlo prediction is shown in the lower plots. Data corresponding to 2012 analysis.



(A) Leading Z lepton candidate checked with the W lepton (B) Trailing Z lepton candidate checked with the W lepton

FIGURE 6.10: ΔR distribution between the Z and W candidates. The distribution is built adding up the four final state channels. Statistical and systematic uncertainties are included. The experimental data versus the Monte Carlo prediction is shown in the lower plot. Data corresponding to 2011 analysis.

	Z cand.	W cand.
Data-driven bkg.	32 ± 2	2.1 ± 0.4
ZZ	14.07 ± 0.06	1.95 ± 0.02
$V\gamma$	12 ± 4	0.00 ± 0.00
$WZ \rightarrow 3l\nu$	66.2 ± 0.6	44.8 ± 0.5
Total expect.	124 ± 4	48.8 ± 0.6
Data	117	64

(A) Three electron final state

	Z cand.	W cand.
Data-driven bkg.	46 ± 3	1.44 ± 0.3
ZZ	13.87 ± 0.07	3.46 ± 0.04
$V\gamma$	$(9 \pm 9) \cdot 10^5$	0.00 ± 0.00
$WZ \rightarrow 3l\nu$	78.7 ± 0.6	50.4 ± 0.5
Total expect.	139 ± 3	55.3 ± 0.5
Data	162	62

(B) Two electron and one muon final state

	Z cand.	W cand.
Data-driven bkg.	97 ± 3	2.5 ± 0.4
ZZ	21.66 ± 0.09	2.68 ± 0.03
$V\gamma$	15 ± 4	0.5 ± 0.5
$WZ \rightarrow 3l\nu$	83.3 ± 0.6	55.7 ± 0.5
Total expect.	217 ± 5	61.4 ± 0.8
Data	178	70

(C) Two muons and one electron final state

	Z cand.	W cand.
Data-driven bkg.	68 ± 3	1.70 ± 0.2
ZZ	18.85 ± 0.07	4.83 ± 0.03
$V\gamma$	0.00 ± 0.00	0.00 ± 0.00
$WZ \rightarrow 3l\nu$	117.2 ± 0.7	75.07 ± 0.6
Total expect.	204 ± 3	81.6 ± 0.6
Data	272	97

(D) Three muons final state

TABLE 6.10: Number of events at the different stages of the signal selection in the four leptonic channels investigated for the 2011 analysis. The data driven background (mainly $t\bar{t}$ plus Drell-Yan) estimation and the Monte Carlo background samples used are described in Chapter 7. The WZ signal event yields are obtained from applying the signal selection to Monte Carlo simulated events. The errors shown are statistical only.

	Z cand.	W cand.
Data-driven bkg.	75 ± 3	14.8 ± 1.4
ZZ	19.0 ± 0.1	2.43 ± 0.04
$V\gamma$	22 ± 3	2.4 ± 0.9
WV	1.7 ± 0.8	0.1 ± 0.1
VVV	7.6 ± 0.3	6.1 ± 0.3
$WZ \rightarrow 3\ell\nu$	281.0 ± 1.7	193.9 ± 1.4
Total expect.	406 ± 5	220 ± 3
Data	442	235

(A) *Three electron final state*

	Z cand.	W cand.
Data-driven bkg	150 ± 5	48 ± 3
ZZ	31.5 ± 0.2	3.9 ± 0.1
$V\gamma$	41 ± 4	3.8 ± 1.2
WV	0.7 ± 0.2	0.2 ± 0.1
VVV	13.1 ± 0.4	10.4 ± 0.4
$WZ \rightarrow 3\ell\nu$	466 ± 2	316 ± 2
Total expect.	703 ± 7	382 ± 4
Data	790	400

(C) *Two muons and one electron final state*

	Z cand.	W cand.
Data-driven bkg	214 ± 7	27 ± 3
ZZ	22.7 ± 0.2	3.11 ± 0.04
$V\gamma$	1.2 ± 0.7	0.4 ± 0.4
WV	0.5 ± 0.1	0.1 ± 0.1
VVV	10.7 ± 0.4	7.9 ± 0.3
$WZ \rightarrow 3\ell\nu$	380 ± 2	245.8 ± 1.6
Total expect.	629 ± 7	284 ± 3
Data	613	288

(B) *Two electron and one muon final state*

	Z cand.	W cand.
Data-driven bkg	377 ± 10	59 ± 5
ZZ	42.1 ± 0.2	5.8 ± 0.1
$V\gamma$	0.8 ± 0.5	0.0 ± 0.0
WV	14 ± 2	2.2 ± 0.7
VVV	18.0 ± 0.5	13.4 ± 0.4
$WZ \rightarrow 3\ell\nu$	666 ± 3	428 ± 2
Total expect.	1118 ± 10	508 ± 5
Data	1207	557

(D) *Three muons final state*

TABLE 6.11: Number of events at the different stages of the signal selection in the four leptonic channels investigated for the 2012 analysis. The data driven background (mainly $t\bar{t}$ plus Drell-Yan) estimation and the Monte Carlo background samples used are described in Chapter 7. The WZ signal event yields are obtained from applying the signal selection to Monte Carlo simulated events. The errors shown are statistical only.

CHAPTER 7

Background Studies

The main background processes which contaminate the WZ signal are classified in two categories depending on their origin: instrumental and irreducible physics backgrounds. The instrumental background, mostly jet-induced, is estimated using a method based on the experimental data which exploits the WZ lepton isolation and identification criteria. In this chapter, the method is explained in detail and the main formulae obtained, then the results of the method are validated and subsequently applied, obtaining the jet-induced background contribution to the WZ signal. The second part of this Chapter is devoted to explain the irreducible physics background components, which are estimated using a Monte Carlo simulation.

7.1. Contamination of the WZ signal

In the previous Chapter, Section 6.1, the main sources of noise were identified for the WZ leptonic final state signature. In summary, the background processes contributing to the three lepton final states were categorised into two groups.

- Backgrounds where some of the identified final three lepton states are originated by leptons not promptly produced by W or Z decays, meaning particles misidentified as leptons or leptons in jets, mostly coming from heavy flavour decays. The main processes contributing to this jet-induced source of background are:

- QCD, with three non-prompt leptons or fakes;
- W+Jets, with two fake leptons;
- Drell-Yan plus jets, WW+Jets, $t\bar{t}$ and single top, providing one fake lepton
- Backgrounds with one or more prompt leptons no-reconstructed, or other backgrounds,
 - ZZ production, where one lepton is lost or outside acceptance
 - VVV ($V = \gamma, W, Z$) production, triple gauge boson decays can mimic exactly the signal selection, as WWW; or one decay leptons is outside the fiducial volume, as in WWZ. Nevertheless, the production rate of this processes is very small compared with the WZ production rate; the 2012 data taking period achieved enough integrated luminosity to observe some of this processes. Thus, this background is just considered for 2012 data.
 - $V\gamma$ ($V = Z, W$), mostly a third electron¹ appears because of the photon interaction with the detector material (external photon conversion) and one of the leptons of the created pair is lost.

The jet-induced background is not well modelled in the simulations, therefore it has been estimated using a method based upon experimental data, i.e. a *data-driven* method. The method is called fakeable object method (FOM). The contribution of the second category, i.e. signal-like events where the three lepton are prompts, is estimated with a Monte Carlo simulation.

7.2. The fakeable object method

The fakeable object method is a method used to estimate the background contribution caused by the so called *fake* leptons. The method is based in the *matrix* method [80, pp. 334–337], widely used in high energy physics to estimate the composition of collected data. In brief, the matrix method starts from a set

¹Although it can be a muon, but with much lesser probability.

of cuts S which have been applied to a dataset in order to enhance the number of signal events. After applying these selection cuts to a dataset $N(S)$ events are selected. The number of signal events ν_S can be estimated by considering the efficiency of the selection cuts,

$$\nu(S) = \varepsilon_S \nu_S \quad (7.1)$$

being $\nu(S)$ the number of events after the selection, and it may be estimated by $\hat{\nu}(S) = N(S)$, being $N(S)$ the number of events measured after applying the selection cuts.

The selected sample is not only composed by signal events, as Equation (7.1) is assuming. Indeed, a realistic scenario would consider that before the selection, n different sources of background processes contribute to the expected number of events, and the selection criteria S do not totally reject all background contributions. Therefore, the number of selected events after the selection cuts is

$$\nu(S) = \varepsilon_S \nu_S + \varepsilon_{S|B_1} \nu_{B_1} + \cdots + \varepsilon_{S|B_n} \nu_{B_n} \quad (7.2)$$

where ν_{B_i} is the number of events of the i -background and $\varepsilon_{S|B_i}$ is the efficiency of the selection cuts S to select the i -background source. Another set of selection criteria B_i may be introduced in order to select enriched regions of the different i -background sources. Using these new selection cuts, the dataset will be split in n -different samples,

$$\nu(B_i) = \varepsilon_{B_i|S} \nu_S + \cdots + \varepsilon_{B_i} \nu_{B_i} + \cdots + \varepsilon_{B_i|B_n} \nu_{B_n} \quad (7.3)$$

being $\nu(B_i)$ the number of selected events using the selection cuts B_i , $\varepsilon_{B_i|S}$ is the efficiency of the selection cuts B_i to select the signal events, ε_{B_i} is the efficiency of the selection cuts B_i to select the i -background source and $\varepsilon_{B_i|B_n}$ the efficiency of the selection cuts B_i to select the n -background source. Therefore, we end up with a total of $n + 1$ selection cuts each of them aiming to select a given component of the primary dataset, Equations (7.1) and (7.2) can be expressed with a linear

system of equations in matrix form

$$\begin{pmatrix} \nu(S) \\ \nu(B_i) \\ \vdots \\ \nu(B_n) \end{pmatrix} = \begin{pmatrix} \varepsilon_S & \varepsilon_{S|B_1} & \cdots & \varepsilon_{S|B_n} \\ \varepsilon_{B_1|S} & \varepsilon_{B_1} & \cdots & \varepsilon_{B_1|B_n} \\ \vdots & \vdots & \ddots & \vdots \\ \varepsilon_{B_n|S} & \varepsilon_{B_n|B_1} & \cdots & \varepsilon_{B_n} \end{pmatrix} \begin{pmatrix} \nu_S \\ \nu_{B_i} \\ \vdots \\ \nu_{B_n} \end{pmatrix} \quad (7.4)$$

or in the equivalent vector form $\mathbf{N}_{\text{sel}} = \boldsymbol{\varepsilon} \boldsymbol{\nu}$. Thus, we may use the number of measured events N_{sel} to estimate ν ,

$$\mathbf{N}_{\text{sel}} = \boldsymbol{\varepsilon} \hat{\boldsymbol{\nu}} \quad (7.5)$$

being $\mathbf{N}_{\text{sel}}$ the vector of events measured using the different criteria S and B_i , $\boldsymbol{\varepsilon}$ is the efficiency matrix, and $\hat{\boldsymbol{\nu}}$ is the vector of the actual number of events for the different processes. Therefore, inverting the efficiency matrix, it is possible to estimate the original signal and background contributions

$$\hat{\boldsymbol{\nu}} = \boldsymbol{\varepsilon}^{-1} \mathbf{N}_{\text{sel}} \quad (7.6)$$

Estimating the efficiency matrix, by Monte Carlo techniques or data-driven methods, and performing the $n + 1$ sample selection, it is possible to estimate the background contribution to a given datasample.

The FOM shares the strategy of the matrix method outlined above where the source of background to be estimated is caused by *fake leptons*. The *fake* meaning is dependent of each analysis; in the WZ context, a fake lepton could be:

- a true “fake“ lepton, for example, a jet misidentified and reconstructed as an electron,
- a real lepton from a heavy hadron decay

A prompt lepton from a W or Z gauge boson is expected not to have hadronic activity surrounding it and to fulfil the identification requirements presented in the previous Chapter (see Section 6.3 and 6.4). Conversely, a jet-induced lepton is expected to be poorly isolated, and also not coming from the primary vertex.

Therefore, it is possible to relax the isolation and identification criteria of the leptons, building a sample of *loose* or also called *fakeable* leptons, in order to study these isolation and identification properties.

In addition, the loose definition is used to build a experimental data sample of three final state fakeables in the signal region. The sample is split in four exhaustive subsamples¹ by evaluating the category of the fakeables, i.e. whether they pass or fail the analysis cuts. Therefore this sample built with three loose leptons N_{3L} is split in a subsample which all of the three loose leptons do not pass the tight analysis cuts N_{t0} , another subsample which only one of the fakeable leptons pass the tight analysis cuts N_{t1} , a further subsample which two of the fakeable leptons pass the tight analysis cuts N_{t2} , and finally the total sample is completed with the subsample which all of the three loose leptons pass the tight analysis cuts N_{t3} . This can be expressed in a succinct way by

$$N_{3L} = N_{t0} \cup N_{t1} \cup N_{t2} \cup N_{t3} \quad (7.7)$$

Notice that the identification of this notation with the one used to introduced the matrix method is straightforward. The number of selected events using the signal selection criteria $\nu(S)$, or more precisely its estimator N_{sel} , is recognised as N_{t3} , and the number of selected events using a enriched region of the i-source of background $\nu(B_i)$ may be identified with N_{ti} being $i = 0, 1, 2$.

Thus, in order to apply the Equation (7.6) the efficiency matrix has to be estimated. The probability to detect in the analysis a fake lepton is assumed to be a *universal* property only dependent on the detector acceptance and resolution by means of the transverse momentum and pseudorapidity of the lepton², and it is fundamentally determined by the lepton isolation and identification criteria. Therefore, it is possible to extract this probability using a data sample which only contains such fake leptons. This may be accomplished by generating a sample of fakeable leptons enriched of fake leptons and counting how those fakeables would

¹In the mathematical group theory sense, thus the four subsamples fully cover and complete the sample

²Throughout this Chapter is possible to find the expression “lepton kinematics“ referring to the lepton transverse momentum and pseudorapidity which determine the quality of the detector measurement.

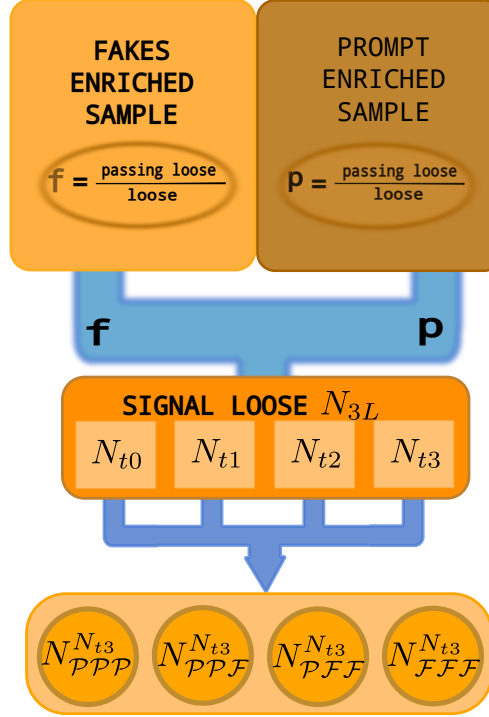


FIGURE 7.1: Schematic illustration of the fakeable object method. The Fake and Prompt enriched samples are used to obtain the fake and prompt rates, respectively. The Signal Loose sample is built by applying to the analysis the loose selection to the lepton objects; each N_{ti} subsample is defined by their content of i -tight leptons. Afterwards, each event of the four exhaustive loose subsamples is weighted with functions (Equations (7.13)) of p , f and N_{ti} and combined to obtain the several estimations of the jet-induced background and prompt content represented as $N_{PP}^{N_{t3}}$, $N_{PF}^{N_{t3}}$, $N_{FF}^{N_{t3}}$ and $N_{FF}^{N_{t3}}$.

pass or fail the full isolation and identification analysis' criteria. The ratio of the passing tight criteria leptons (*tight* leptons) over all the loose leptons is called the *fake ratio*. This fake ratio along with the *prompt rate*, i.e. the probability to a prompt lepton to pass the tight analysis cuts (which can be extracted using tag and probe methods), are the efficiency factors measured from experimental data needed to build the efficiency matrix of Equation (7.6). Therefore, the method have been built to estimate the jet-induced background contribution to the three final state WZ analysis, i.e. the ν_S and the ν_{B_i} which in the FOM notation are $N_{PP}^{N_{t3}}$ for the signal, and $N_{PF}^{N_{t3}}$, $N_{PF}^{N_{t3}}$ and $N_{FF}^{N_{t3}}$ for the backgrounds. The full workflow of the method outlined in the last paragraphs is schematised in

Figure 7.1.

A formal derivation of the method is now conducted. Some definitions are introduced here to fix the notation and nomenclature and to delimit the scope of this probabilistic problem,

- Definitions related with true information

Definition 1 (Prompt Lepton, $\mathcal{P}$). *Lepton from W or Z decay*

Definition 2 (Fake lepton, $\mathcal{F}$). *Jet-induced or misidentified lepton*

Definition 3 (N_{XYX}). *Number of events with just X,Y,Z leptons, being X,Y,Z fakes ($\mathcal{F}$) or prompt ($\mathcal{P}$)*

- Definition related with measured information

Definition 4 (Loose Lepton, L). *Lepton passing the relaxed cuts (see Tables 7.1 and 7.2) mainly related with isolation*

Definition 5 (Tight Lepton, T). *Loose lepton passing the more restrictive isolation and identification analysis cuts*

Definition 6 (Fail Lepton, F). *Loose lepton failing the isolation and identification analysis cuts, i.e. a no-tight lepton*

Definition 7 (Prompt rate, p). *Probability that a prompt lepton pass the tight cuts, $P(T|\mathcal{P})$*

Definition 8 (Fake rate, f). *Probability that a fake lepton pass the tight cuts, $P(T|\mathcal{F})$*

Definition 9 (N_{ti}). *Number of events containing just three loose leptons of which i leptons are tight*

The loose or fakeable lepton definition is accomplished by relaxing isolation and some of the identification requirements of the WZ analysis leptons whilst the other requirements are kept as in the main analysis. Tables 7.1 and 7.2 define the loose lepton for 2011 and 2012 analyses, respectively. The tables are just showing the modified requirements of the main lepton criteria of Chapter 6 (Tables 6.5 and 6.8) where it is understood that the other requirements are also applied.

	Loose	Tight	Fail
ISO_{PF}/p_T	< 1.0	< 0.12	$[0.12, 1.0)$

(A) *Muon loose definition.* The loose definition relaxes the isolation requirement, while the other requirements defined in the 2011 column of the Table 6.5 are also applied.

	Loose	Tight	Fail
ISO_{PF}/p_T	NOT REQUIRED	$< 0.13 (0.09)$	$\geq 0.13(0.09)$
		AND	OR
MVA ID	NOT REQUIRED	$> cut(p_t, \eta)$	$\leq cut(p_t, eta)$

(B) *Electron loose definition.* The loose definition removes the multivariate identification (MVA ID) and the isolation requirement, while the other requirements defined in the 2011 column of the Table 6.8 are also applied. The MVA ID values, p_T and η dependent, for the tight category are detailed in the aforementioned table. The relative isolation contains two cuts, one cut is applied to barrel electrons whereas the other one (in parenthesis) is applied to endcap electrons.

TABLE 7.1: Loose lepton definitions for 2011 analysis.

7.2.1. Fakeable object method derivation

The definitions 1, 2 and 3 specify the true composition of the sample, whereas definitions from 4 to 9 refer to measurable quantities. The first equality relating the measurable observables with the true ones is straightforward obtained,

$$N_{3L} = N_{\mathcal{P}\mathcal{P}\mathcal{P}} + N_{\mathcal{P}\mathcal{P}\mathcal{F}} + N_{\mathcal{P}\mathcal{F}\mathcal{F}} + N_{\mathcal{F}\mathcal{F}\mathcal{F}} = N_{t0} + N_{t1} + N_{t2} + N_{t3} \quad (7.8)$$

Id est, the sample selected using three loose-criteria leptons (N_{3L}) consists of four exhaustive subsamples. Regarding the origin of the true leptons, the leptons only can be prompt-prompt-prompt ($N_{\mathcal{P}\mathcal{P}\mathcal{P}}$), prompt-prompt-fake ($N_{\mathcal{P}\mathcal{P}\mathcal{F}}$), prompt-fake-fake ($N_{\mathcal{P}\mathcal{F}\mathcal{F}}$) or fake-fake-fake ($N_{\mathcal{F}\mathcal{F}\mathcal{F}}$). Furthermore, regarding the measured category of the three selected leptons, the leptons only can be classified as tight-tight-tight (N_{t3}), tight-tight-fail (N_{t2}), tight-fail-fail (N_{t1}) and fail-fail-fail (N_{t0}).

The contributions of the several prompt-fake combinations which pass the full

	Loose	Tight	Fail
$ d_0 $ [cm]	< 0.2	$< 0.01(0.02)$	$[0.01(0.02), 0.2)$
		AND	OR
MVA ISO	≥ -0.6	$\geq \text{cut}(p_T, \eta)$	$(-0.6, \text{cut}(p_T, \eta)]$

(A) *Muon loose definition.* Loose definition relaxes the transverse impact parameter and the multivariate isolation (MVA ISO), the other requirements specified in the 2012 column of Table 6.5 are also applied. The MVA ISO values for the tight category are detailed in the aforementioned table. The d_0 parameter contains two cuts, one cut is applied to muons with $p_t \leq 20$ GeV whereas the other one (in parenthesis) is applied to muons with $p_t > 20$ GeV.

	Loose	Tight	Fail
$ d_0 $ [cm]	NOT REQUIRED	< 0.02	≥ 0.02
		AND	OR
$ d_z $ [cm]	NOT REQUIRED	< 0.1	≥ 0.1
		AND	OR
ISO_{PF}/p_T	NOT REQUIRED	< 0.15	≥ 0.15
		AND	OR
MVA ID	NOT REQUIRED	$> \text{cut}(p_t, \eta)$	$\leq \text{cut}(p_t, \eta)$

(B) *Electron loose definition.* The loose definition removes the transverse and longitudinal impact parameter, the relative isolation and the multivariate identification (MVA ID), whilst the other requirements specified in the 2012 column of Table 6.8 are also applied. The MVA ID values for the tight category are detailed in the aforementioned table.

TABLE 7.2: Loose lepton definitions for 2012 analysis.

analysis cuts can be obtained using probabilistic relations,

$$N_{\mathcal{F}\mathcal{F}\mathcal{F}}^{N_{t3}} = \sum_{\text{events}}^{N_{t3}} P(\mathcal{F}\mathcal{F}\mathcal{F}|TTT)P(TTT) \quad (7.9a)$$

$$N_{\mathcal{P}\mathcal{F}\mathcal{F}}^{N_{t3}} = \sum_{\text{events}}^{N_{t3}} P(\mathcal{P}\mathcal{F}\mathcal{F}|TTT)P(TTT) \quad (7.9b)$$

$$N_{\mathcal{P}\mathcal{P}\mathcal{F}}^{N_{t3}} = \sum_{\text{events}}^{N_{t3}} P(\mathcal{P}\mathcal{P}\mathcal{F}|TTT)P(TTT) \quad (7.9c)$$

$$N_{\mathcal{P}\mathcal{P}\mathcal{P}}^{N_{t3}} = \sum_{\text{events}}^{N_{t3}} P(\mathcal{P}\mathcal{P}\mathcal{P}|TTT)P(TTT) \quad (7.9d)$$

Here, $P(TTT)$ is the probability that, given an event with three loose leptons, these leptons pass the analysis cuts, therefore $N_{t3} = \sum_{events}^{N_{t3}} P(TTT)$. The conditional probabilities $P(\mathcal{FFF}|TTT)$, $P(\mathcal{PFF}|TTT)$, $P(\mathcal{PPF}|TTT)$ and $P(\mathcal{PPP}|TTT)$ are quantifying the probability of, given three tight leptons, that these leptons are all fakes, one prompt and two fakes, two prompt and one fake and all prompt, respectively. Thus, the left side of Equations (7.9) designates the estimation of each prompt and fake contribution to the WZ three lepton final state analysis. Therefore, each event passing the WZ analysis cuts is weighted by the conditional probability (lepton kinematic dependent) for each lepton to be fake or prompt given that each lepton pass the tight analysis criteria. The problem is focused in finding these conditional probabilities.

Nevertheless, the probabilities available are the fake and prompt rates, i.e. the probabilities which have a fake or prompt lepton to be tight (as definitions 8 and 7 established),

$$P(T|\mathcal{F}) \equiv f \quad (\text{Fake rate}) \quad (7.10a)$$

$$P(T|\mathcal{P}) \equiv p \quad (\text{Prompt rate}) \quad (7.10b)$$

In an analysis with one final state lepton, the probability that a lepton passes the tight cuts, is evaluated through the full space of lepton types, i.e. prompt and fake,

$$N_T = \sum_{events}^{N_L} [P(T|\mathcal{P})P(\mathcal{P}) + P(T|\mathcal{F})P(\mathcal{F})] = pN_{\mathcal{P}} + fN_{\mathcal{F}} \quad (7.11)$$

and analogously for the fail case,

$$N_F = \sum_{events}^{N_L} [P(F|\mathcal{P})P(\mathcal{P}) + P(F|\mathcal{F})P(\mathcal{F})] = (1 - p)N_{\mathcal{P}} + (1 - f)N_{\mathcal{F}} \quad (7.12)$$

Assuming that the fake and prompt rates are independent of the number of leptons in the event, Equations (7.9) can be equivalently expressed through their

true contribution content by using the prompt and fake efficiencies,

$$N_{\mathcal{F}\mathcal{F}\mathcal{F}}^{N_{t3}} = \sum_{events}^{N_{3L}} P(TTT|\mathcal{F}\mathcal{F}\mathcal{F})P(\mathcal{F}\mathcal{F}\mathcal{F}) = f^3 N_{\mathcal{F}\mathcal{F}\mathcal{F}} \quad (7.13a)$$

$$N_{\mathcal{P}\mathcal{F}\mathcal{F}}^{N_{t3}} = \sum_{events}^{N_{3L}} P(TTT|\mathcal{P}\mathcal{F}\mathcal{F})P(\mathcal{P}\mathcal{F}\mathcal{F}) = pf^2 N_{\mathcal{P}\mathcal{F}\mathcal{F}} \quad (7.13b)$$

$$N_{\mathcal{P}\mathcal{P}\mathcal{F}}^{N_{t3}} = \sum_{events}^{N_{3L}} P(TTT|\mathcal{P}\mathcal{P}\mathcal{F})P(\mathcal{P}\mathcal{P}\mathcal{F}) = p^2 f N_{\mathcal{P}\mathcal{P}\mathcal{F}} \quad (7.13c)$$

$$N_{\mathcal{P}\mathcal{P}\mathcal{P}}^{N_{t3}} = \sum_{events}^{N_{3L}} P(TTT|\mathcal{P}\mathcal{P}\mathcal{P})P(\mathcal{P}\mathcal{P}\mathcal{P}) = p^3 N_{\mathcal{P}\mathcal{P}\mathcal{P}} \quad (7.13d)$$

Therefore, the problem has been restated to find the estimated number of background contributions, which it is resolved within the matrix method in the Equation (7.6). Thus, the equivalent equations but for the three lepton final state cases, which are, in fact, the linear system of equations of the matrix method (Equation (7.4)) particularised to the fakes backgrounds, are

$$N_{t0} = (1-p)^3 N_{\mathcal{P}\mathcal{P}\mathcal{P}} + (1-p)^2(1-f)N_{\mathcal{P}\mathcal{P}\mathcal{F}} + (1-p)(1-f)^2 N_{\mathcal{P}\mathcal{F}\mathcal{F}} + (1-f)^3 N_{\mathcal{F}\mathcal{F}\mathcal{F}} \quad (7.14a)$$

$$N_{t1} = 3p(1-p)^2 N_{\mathcal{P}\mathcal{P}\mathcal{P}} + [2p(1-p)(1-f) + f(1-p)^2] N_{\mathcal{P}\mathcal{P}\mathcal{F}} + [2f(1-f)(1-p) + p(1-f)^2] N_{\mathcal{P}\mathcal{F}\mathcal{F}} + 3f(1-f)^2 N_{\mathcal{F}\mathcal{F}\mathcal{F}} \quad (7.14b)$$

$$N_{t2} = 3p^2(1-p)N_{\mathcal{P}\mathcal{P}\mathcal{P}} + [2pf(1-p) + p^2(1-f)] N_{\mathcal{P}\mathcal{P}\mathcal{F}} + [2pf(1-f) + (1-p)f^2] N_{\mathcal{P}\mathcal{F}\mathcal{F}} + 3f^2(1-f)N_{\mathcal{F}\mathcal{F}\mathcal{F}} \quad (7.14c)$$

$$N_{t3} = p^3 N_{\mathcal{P}\mathcal{P}\mathcal{P}} + p^2 f N_{\mathcal{P}\mathcal{P}\mathcal{F}} + pf^2 N_{\mathcal{P}\mathcal{F}\mathcal{F}} + f^3 N_{\mathcal{F}\mathcal{F}\mathcal{F}} \quad (7.14d)$$

where the sum over the total events has been explicitly made. The equations are derived for same lepton pseudorapidity, transverse momentum and flavour, for the sake of clarity. The generalisation considering different η , p_T and lepton flavour is straightforward but complicates the notation and does not introduced any new insight, it will be derived later.

The linear Equations (7.14) are inverted to obtain the estimation of each

source, equivalent to Equation (7.6),

$$N_{\mathcal{P}\mathcal{P}\mathcal{P}} = \frac{1}{(p-f)^3} \left\{ (1-f)^3 N_{t3} - f(1-f)^2 N_{t2} - \right. \\ \left. - f^2(1-f) N_{t1} + f^3 N_{t0} \right\} \quad (7.15a)$$

$$N_{\mathcal{P}\mathcal{P}\mathcal{F}} = \frac{1}{(p-f)^3} \left\{ -3(1-p)(1-f)^2 N_{t3} + \right. \\ \left. + [2f(1-p)(1-f) + p(1-f)^2] N_{t2} - \right. \\ \left. - [f^2(1-p) + 2pf(1-f)] N_{t1} + 3pf^2 N_{t0} \right\} \quad (7.15b)$$

$$N_{\mathcal{P}\mathcal{F}\mathcal{F}} = \frac{1}{(p-f)^3} \left\{ 3(1-p)^2(1-f) N_{t3} - \right. \\ \left. - [f(1-p)^2 + 2p(1-p)(1-f)] N_{t2} + \right. \\ \left. + [2pf(1-p) + p^2(1-f)] N_{t1} - 3p^2f N_{t0} \right\} \quad (7.15c)$$

$$N_{\mathcal{F}\mathcal{F}\mathcal{F}} = \frac{1}{(p-f)^3} \left\{ -(1-p)^3 N_{t3} + p(1-p)^2 N_{t2} - \right. \\ \left. - p^2(1-p) N_{t1} + p^3 N_{t0} \right\} \quad (7.15d)$$

The above equations give the estimated number of events composed by the available combinations of prompt and fakes leptons to make up three lepton final states, from the isolation and identification lepton categories (tight and fail). Now, Equations (7.13) (through the inclusion of Equations (7.15) on them) have all the ingredients to estimate the contribution of each type of fake lepton background to the final analysis. In particular, the $N_{\mathcal{P}\mathcal{P}\mathcal{P}}^{N_{t3}}$ is the estimated number of signal events (because of the three prompts in the final state) before subtracting any irreducible process (ZZ , VVV), which is part of the three prompt component.

The derived Equations (7.13) and (7.15) may be expressed in form of *weighting rules* which takes into account the flavour dependence and the lepton kinematic not explicitly considered and being able to estimate not only the normalised factors of each background source but also the distribution of these processes. Each event is weighted following the reported rules of Table 7.3 depending of the category of the lepton (fail or tight) and the contribution which is being estimated (fake or prompt).

	Tight	Fail
$w(\mathcal{P})$	$\frac{1}{p-f}p(1-f)$	$\frac{1}{p-f}pf$
$w(\mathcal{F})$	$\frac{1}{p-f}f(1-p)$	$\frac{1}{p-f}pf$

TABLE 7.3: Each loose event is weighted by the combination of prompt and fake rates reported in the table depending the category of the lepton. The factors are applied lepton by lepton in each event. The table is showing the weight that should be applied to each lepton which is going to be estimated as *prompt* (first row) or *fake* (second row) given that the lepton passed the tight analysis cuts (column *Tight*) or failed these cuts (column *Fail*). The weighted event contributes to the current estimation depending of the estimation and the number of tight and fail leptons N_{ti} have, following the prescription of Equations (7.15)

7.2.2. Lepton fake and prompt rates determination

Adopting the loose lepton definition, a jet enriched sample is selected in the experimental data from a combination of single-lepton trigger paths. The trigger paths have the lowest p_T threshold in order to select the sample mainly with *QCD* events. The loose lepton identification requirements shown in Tables 7.1 and 7.2 are tighter than the trigger requirements in order to suppress a possible trigger-induced bias to the fake rate. The jet enriched sample may still contain prompt leptons from real W and Z decays. In order to suppress contamination due to signal leptons from the decay of W and Z bosons it is also required that the missing transverse energy of the event to be less than 20 GeV and the W transverse mass less than 20 GeV. The muons from Drell-Yan and Z decays are removed with the $m_{\mu\mu} > 20$ GeV and the $m_{\mu\mu} \notin [76, 106]$ GeV constraints. For electrons the W transverse mass cut is not applied, and the Z-peak veto is enlarged to $m_{ee} \notin [60, 120]$ GeV. The remaining electroweak (W/Z+jets) contribution, which clearly biases the fake rate at high p_T , is removed using the background estimations as provided by the corresponding Monte Carlo simulations.

The jet-enriched sample is composed of fakeables, leptons which pass the loose isolation and identification cuts. Thus the sample space Ω is defined as

$$\Omega \equiv \bigcup_{events} L \quad (7.16)$$

After the application of the tight cuts to the fakeables, the sample space Ω is divided with fakeables passing the tight criteria cuts T and fakeables not passing (or failing) that cuts $\neg T \equiv F$,

$$\Omega \equiv L = T \oplus \neg T = T \oplus F, \quad \text{thus } P(T) + P(F) = 1 \quad (7.17)$$

where it is implicitly included the sum over all events.

Given that the sample was biased selecting mostly jet events, all the leptons of the sample should be fakes (at least ideally). We can count how many leptons pass the tight cuts and assign this ratio, i.e. the fake rate, as the probability (using a frequentist approach to probabilities):

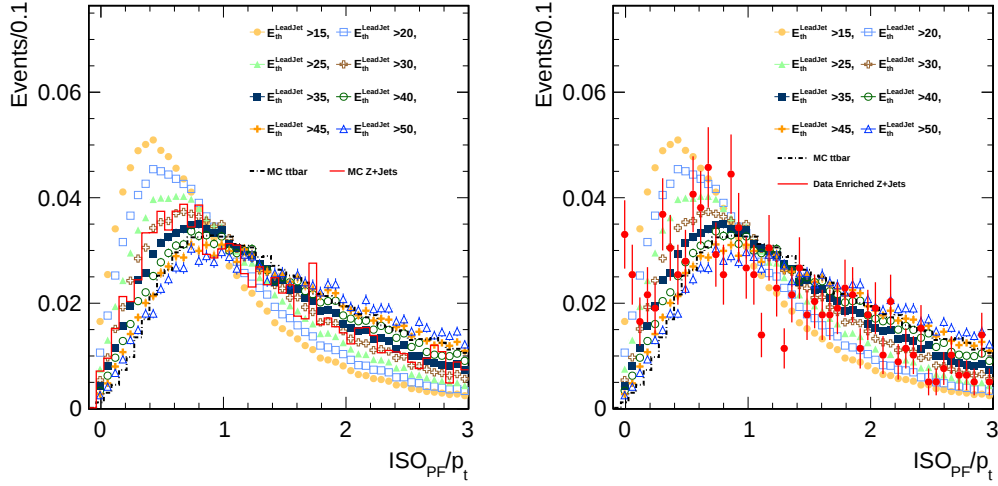
$$f(p_T, \eta) = P(T|\mathcal{F})_{p_T, \eta} = \frac{M_{t1}(p_T, \eta)}{M_L(p_T, \eta)}, \quad (7.18)$$

where M_{t1} is the number of leptons passing the tight cuts and M_L is the total number of loose leptons for a given lepton transverse momentum and pseudorapidity.

The fakeable sample should be as similar as possible to the jet content and lepton isolation distribution of the instrumental background contributions we want to estimate for our analysis. The contribution of the one fake component to the analysis, i.e. $\mathcal{PPF}$, is expected to be composed mainly by Drell-Yan, $t\bar{t}$, single top and WW. Moreover, we assume (and it will be verified along this Section) the hypothesis that before the W candidate requirement, the $\mathcal{PPF}$ contribution is essentially Drell-Yan due to the real Z boson presence. But after requiring the W candidate and therefore requiring high E_T^{miss} we would expect a strong reduction of Drell-Yan allowing the $t\bar{t}$ events emerge up. Accepting that hypothesis, the fake-enriched sample defined to extract the fake rates should follow the jet or lepton isolation distribution of Drell-Yan and $t\bar{t}$ events¹. Using the E_T of the leading jet to be above a given threshold, E_{th}^{LeadJet} , it is possible to modify the hardness of the E_T jet spectra of the sample and also the isolation of the leptons due to the high correlation between both quantities. Therefore, the E_{th}^{LeadJet} is

¹Strictly speaking, it must follow every background present but as it is shown in Table 7.9 the $\mathcal{PPF}$ and $\mathcal{FFF}$ distributions are almost negligible

cut in different values and the E_T of the jets with a lepton inside¹ are plotted and compared with the Drell-Yan and $t\bar{t}$ distributions simulated with Monte Carlo. Using the same $E_h^{LeadJet}$ cut, the relative isolation distribution of the leptons is also plotted and compared again with the Monte Carlo Drell-Yan and $t\bar{t}$ distributions.



(A) Relative isolation using a full Monte Carlo sample for Z+Jets and $t\bar{t}$ processes.

(B) Relative isolation using a Z+Jets enriched experimental data and a MC sample for the $t\bar{t}$ processes.

FIGURE 7.2: Relative isolation distribution of the loose 2011 muons in the fake-enriched sample used to calculate the fake rate. A cut in the transverse energy of the leading jet of the fake-enriched sample is applied giving as a result a variation in the relative isolation of the loose leptons. The relative isolation of the fakes for the Monte Carlo are also plotted. The curve built with leading jet with transverse energy higher than 30 GeV matches with the Z+Jets Monte Carlo distribution, whereas the curve with $E_{th}^{LeadJet} > 45$ GeV matches with the Monte Carlo $t\bar{t}$ distribution.

Figure 7.2a shows the relative isolation distribution of the 2011 muons, while Figure 7.3 is showing the transverse energy spectra of the jets associated to an electron. Although the E_T of the jets with a lepton inside can also be used to obtain the matching with the Monte Carlo distributions, the isolation distribution is preferred because is a direct observable giving information of the hadronic activity of the lepton; in contrast, looking at the E_T of the jet with a lepton inside, the information of the lepton, which is our primary goal, is obtained through the

¹In a $\Delta R=0.3$

energy of the surrounding jet, introducing the jet reconstruction, the jet-lepton matching, and other convoluted effects.

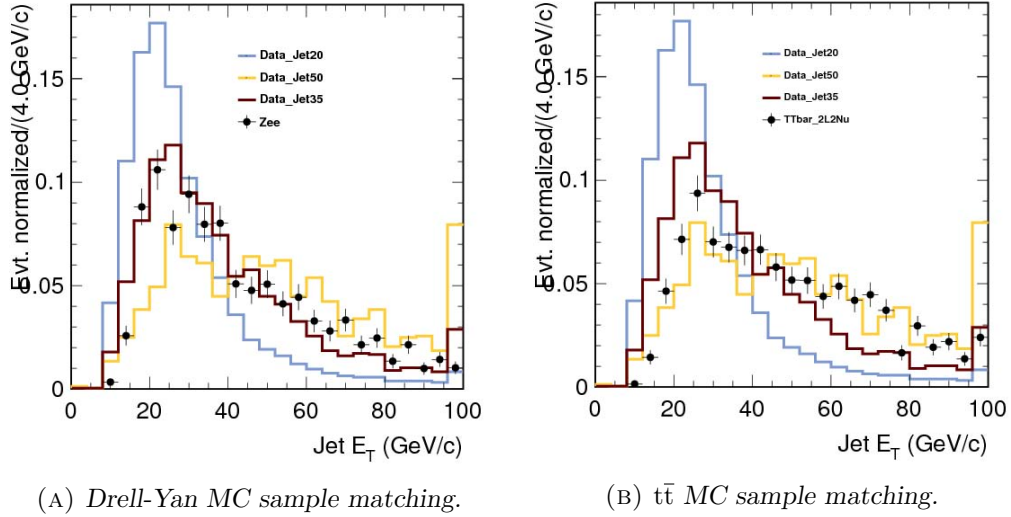


FIGURE 7.3: Transverse energy distribution of the jets which contain a fakeable lepton for 2011 electrons in the fake-enriched sample used to calculate the fake rate. A cut in the transverse energy of the leading jet of the fake-enriched sample is applied giving as a result a variation in the E_T jet distribution of the fakeable jets. The E_T jet spectra for the Monte Carlo are also plotted. The curve built with leading jet with transverse energy higher than 35 GeV matches with the Z+Jets Monte Carlo distribution, whereas the curve with $E_{th}^{LeadJet} > 50$ GeV matches with the Monte Carlo $t\bar{t}$ distribution.

Applying a Ψ -test [81, pp. 294–305] to evaluate the amount of plausibility has the Monte Carlo predicted distribution when it is found a particular set of observed data, the matching data distribution with a Z+Jets is accomplished with a transverse energy cut in the Leading jet of the fake-enriched sample higher than 30 (35) GeV for muons (electrons), whilst for the $t\bar{t}$ sample is better to use a transverse energy higher than 45-50 GeV. These values, shown for leptons on the 2011 analysis, were found to be consistent along the 2012 too. Notice that the data-driven method has been “contaminated” with the inclusion of the Monte Carlo prediction for the relative isolation distributions. Nevertheless, although there are other possibilities¹ to determine the fakeable leptons kinematics, the Monte Carlo

¹A Z+Jets and $t\bar{t}$ enriched regions could be selected using only experimental data and use

approach is simple enough and, in the case of the $t\bar{t}$, is a process well described theoretically. The $Z+Jets$ is better estimated using a control region in data, defined with events fulfilling the Z mass resonance window ($M_Z \pm 10$ GeV) and rejecting the presence of real E_T^{miss} through a cut in its resolution $E_T^{\text{miss}} < 20$ GeV. A very pure $Z + Jets$ sample is collected with these cuts where it is used the lepton not associate to the Z resonance as the fake lepton in order to be compared its isolation with the isolation of the loose leptons in the jet-enriched sample. Figure 7.2b shows the relative isolation distribution of the fakeables of the $Z + Jets$ sample; the limited number of events avoids us to extract a solid conclusion concerning the optimal E_T cut on the leading jet of the jet-enriched sample, relying on Monte Carlo for selecting this cut (Figure 7.2a).

Therefore, the fake rates have been extracted, in η and p_T of the leptons, by counting the number of passing loose leptons over the total loose leptons selected in a jet-enriched sample biased by requiring a transverse energy of the leading jet higher than 30 (35) GeV for muons (electrons) and 50 GeV for both leptons, to account for the $Z+Jets$ and $t\bar{t}$ composition, respectively. Tables 7.4 and 7.5 present the fake rate matrices for muons and electrons used in the 2011 and 2012 analyses.

The selection of the leading jet transverse energy cut depends on the jet-induced background composition in the WZ analysis. It was already argued that the major contribution of this background is going to come from the processes with one fake lepton and, thus, two prompt ($\mathcal{PPF}$ in the notation defined at the beginning of the Chapter). This hypothesis will be probed in the Section 7.2.3. The other assumption made is that the $\mathcal{PPF}$ contribution is mainly composed by Drell-Yan and $t\bar{t}$ events. This assumption has naively checked by comparing the data-driven estimation with $Z+Jets$ and $t\bar{t}$ Monte Carlo $\mathcal{PPF}$ samples. The data-driven estimation has been obtained using several fake rate matrices extracted with different E_{th}^{LeadJet} cuts trying to avoid possible bias due to the fake matrix choice. Figures 7.4 show that the fakes lepton background in the WZ analysis is mainly dominated by the Drell-Yan before the W lepton candidate requirement. After the

them to match the isolation distributions. This approach was tried in this analysis, but for the $t\bar{t}$ case there was not enough events in 2011 to reach enough accuracy for the distribution shapes.

	$ \eta \in [0, 1]$	$\eta \in (1, 1.48]$	$\eta \in (1.48, 2]$	$\eta \in (2, 2.5]$
$10 < p_t \leq 15$	3.4 ± 0.7	5.0 ± 1.2	5.7 ± 1.5	5 ± 2
$15 < p_t \leq 20$	0.8 ± 0.4	2.9 ± 1.3	6.2 ± 2.2	0.04 ± 0.03
$20 < p_t \leq 25$	1.1 ± 0.1	1.5 ± 0.2	2.5 ± 0.3	3.1 ± 0.6
$25 < p_t \leq 30$	1.0 ± 0.1	0.9 ± 0.2	1.6 ± 0.3	2.3 ± 0.6
$30 < p_t \leq \infty$	1.6 ± 0.1	1.7 ± 0.2	2.6 ± 0.3	2.2 ± 0.4

(A) Measured muon fake rates in function of transverse momentum and η of the muon. Note that values in 10^{-2} . Errors are statistical only

	$ \eta \in [0, 1]$	$\eta \in (1, 1.48]$	$\eta \in (1.48, 2]$	$\eta \in (2, 2.5]$
$10 < p_t \leq 18$	6 ± 4	4 ± 3	1 ± 1	3 ± 3
$18 < p_t \leq 26$	2.6 ± 1.2	3.4 ± 1.6	1 ± 1	4 ± 2
$26 < p_t \leq 34$	6.1 ± 1.5	6.0 ± 1.8	5.4 ± 1.8	5.1 ± 1.8
$34 < p_t \leq \infty$	5.2 ± 1.4	2.4 ± 1.2	3.3 ± 1.5	4.4 ± 1.6

(B) Measured electron fake rates in function of transverse momentum and η of the electron. Values in 10^{-2} . Errors are statistical only

TABLE 7.4: Measured lepton fakes rates from the jet-enriched sample described in the text, using a transverse energy of the leading jet higher than 50 GeV for 2011 analysis. The values in the tables are in 10^{-2} .

E_T^{miss} requirement, Figures 7.5 show the suppression of the Drell-Yan component, allowing the $t\bar{t}$ sample to contribute at the same level of events. Therefore, the $\mathcal{PPF}$ contribution is going to be composed mainly by Drell-Yan and $t\bar{t}$ events as we have already assumed.

For the prompt rate extraction, a tag and probe method is used with the fakeable leptons defining the probes. The measured prompt rates are shown in Tables 7.6 and 7.7.

7.2.3. Estimation of data-driven contribution

The jet-induced background contribution to the WZ signal is estimated through the Equations (7.13). In particular, $N_{\mathcal{PPF}}^{N_{t3}}$ is in fact the data-driven expectation signal given that the equation is estimating the contribution of three prompt leptons to the final state. It may be noticed, however, that any process with three

	$ \eta \in [0, 1]$	$\eta \in (1, 1.48]$	$\eta \in (1.48, 2]$	$\eta \in (2, 2.5]$
$10 < p_t \leq 15$	7.6 ± 1.1	7.6 ± 1.7	9 ± 3	18 ± 6
$15 < p_t \leq 20$	6.3 ± 1.9	6 ± 3	9 ± 5	38 ± 14
$20 < p_t \leq 25$	7.7 ± 1.0	9.2 ± 1.8	9 ± 3	10 ± 4
$25 < p_t \leq 30$	7.0 ± 1.5	11 ± 3	9 ± 3	13 ± 6
$30 < p_t \leq \infty$	7.4 ± 1.9	8 ± 3	7 ± 3	21 ± 11

(A) Measured muon fake rates in function of transverse momentum and η of the muon. Note that values in 10^{-2} . Errors are statistical only

	$ \eta \in [0, 1]$	$\eta \in (1, 1.48]$	$\eta \in (1.48, 2]$	$\eta \in (2, 2.5]$
$10 < p_t \leq 15$	4.3 ± 0.5	3.4 ± 0.4	0.8 ± 0.2	1.6 ± 0.5
$15 < p_t \leq 20$	4.8 ± 0.3	6.5 ± 0.3	2.7 ± 0.1	3.0 ± 0.2
$20 < p_t \leq 25$	4.1 ± 0.2	6.0 ± 0.3	3.1 ± 0.2	2.4 ± 0.2
$25 < p_t \leq 30$	3.8 ± 0.3	5.5 ± 0.5	2.2 ± 0.3	2.1 ± 0.3
$30 < p_t \leq \infty$	2.8 ± 0.6	4.8 ± 0.9	2.5 ± 0.6	2.4 ± 0.5

(B) Measured electron fake rates in function of transverse momentum and η of the electron. Values in 10^{-2} . Errors are statistical only

TABLE 7.5: Measured lepton fakes rates from the jet-enriched sample described in the text, using a transverse energy of the leading jet higher than 50 GeV for 2012 analysis. The values in the tables are in 10^{-2} .

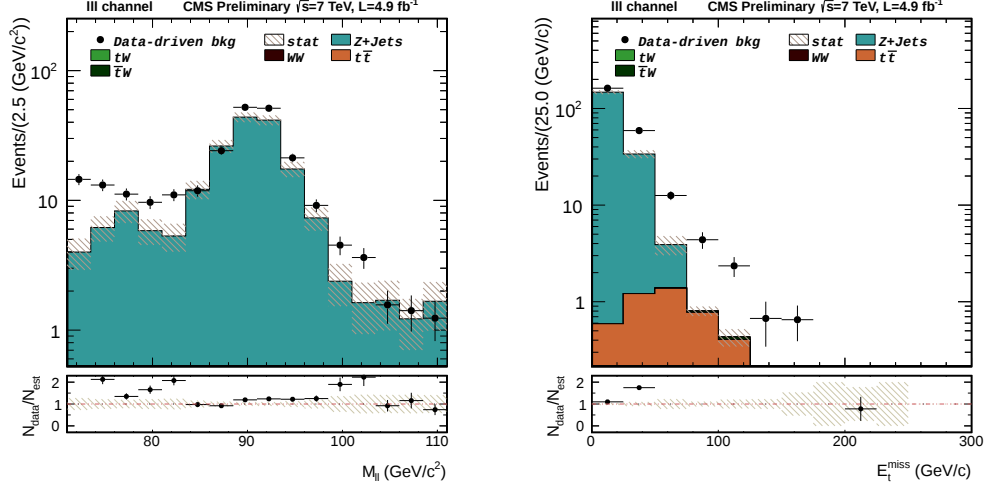
	$0.0 < \eta \leq 1.0$	$1.0 < \eta \leq 1.48$	$1.489 < \eta \leq 2.0$	$2.0 < \eta \leq 2.4$
$10 < p_t \leq 15$	0.7780 ± 0.0024	0.7780 ± 0.0024	0.7780 ± 0.0024	0.7780 ± 0.0024
$15 < p_t \leq 20$	0.7780 ± 0.0024	0.7780 ± 0.0024	0.7780 ± 0.0024	0.7780 ± 0.0024
$20 < p_t \leq 25$	0.8670 ± 0.0015	0.8670 ± 0.0015	0.8670 ± 0.0015	0.8670 ± 0.0015
$25 < p_t \leq 30$	0.9059 ± 0.0009	0.9059 ± 0.0009	0.9059 ± 0.0009	0.9059 ± 0.0009
$30 < p_t \leq \infty$	0.9489 ± 0.0002	0.9489 ± 0.0002	0.9489 ± 0.0002	0.9489 ± 0.0002

(A) Measured muon prompt rates in bins of p_t and η of the muon. Errors are statistical only

	$0.0 < \eta \leq 1.0$	$1.0 < \eta \leq 1.48$	$1.48 < \eta \leq 2.0$	$2.0 < \eta \leq 2.5$
$10 < p_t \leq 15$	0.8145 ± 0.0033	0.8145 ± 0.0033	0.6048 ± 0.0053	0.6048 ± 0.0053
$15 < p_t \leq 20$	0.8145 ± 0.0033	0.8145 ± 0.0033	0.6048 ± 0.0053	0.6048 ± 0.0053
$20 < p_t \leq 25$	0.9031 ± 0.0014	0.9031 ± 0.0014	0.8058 ± 0.0026	0.8058 ± 0.0026
$25 < p_t \leq 30$	0.9244 ± 0.0009	0.9244 ± 0.0009	0.8406 ± 0.0020	0.8406 ± 0.0020
$30 < p_t \leq \infty$	0.9572 ± 0.0002	0.9572 ± 0.0002	0.8980 ± 0.0005	0.8980 ± 0.0005

(B) Measured electron prompt rates in bins of p_t and η of the electron. Errors are statistical only

TABLE 7.6: Measured lepton prompt rates for 2011 analysis, using a tag and probe method.



(A) Invariant mass distribution of the same flavour, opposite-signed lepton system (B) Missing transverse energy event distribution

FIGURE 7.4: Jet-induced background composition after the Z-candidate analysis requirement is applied. We may appreciate that the dominant contribution is coming from the Z+Jets process. The figures are showing the four channels added up in logarithmic scale. The dot markers are the $\mathcal{PPF}$ contribution estimated with the data-driven method, the other samples are Monte Carlo based. Data from 2011 run.

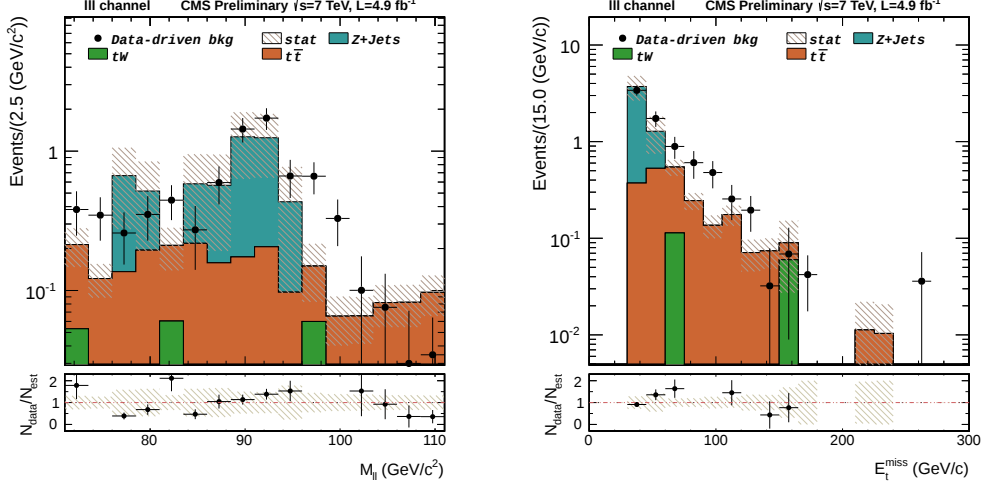
	$0.0 < \eta \leq 1.48$	$1.48 < \eta \leq 2.5$
$10 < p_t \leq 15$	0.7119 ± 0.0003	0.7582 ± 0.0006
$15 < p_t \leq 20$	0.8049 ± 0.0018	0.8495 ± 0.0001
$20 < p_t \leq 25$	0.9027 ± 0.0008	0.8948 ± 0.0012
$25 < p_t \leq 50$	0.9741 ± 0.0001	0.9627 ± 0.0002
$50 < p_t \leq \infty$	0.9900 ± 0.0001	0.9875 ± 0.0003

(A) Measured muon prompt rates in bins of p_t and η of the muon. Errors are statistical only

	$0.0 < \eta \leq 1.0$	$1.0 < \eta \leq 1.479$	$1.479 < \eta \leq 2.0$	$2.0 < \eta \leq 2.5$
$10.0 < p_t \leq 15.0$	0.8145 ± 0.0033	0.8145 ± 0.0033	0.6048 ± 0.0053	0.6048 ± 0.0053
$15.0 < p_t \leq 20.0$	0.8145 ± 0.0033	0.8145 ± 0.0033	0.6048 ± 0.0053	0.6048 ± 0.0053
$20.0 < p_t \leq 25.0$	0.9031 ± 0.0014	0.9031 ± 0.0014	0.8058 ± 0.0026	0.8058 ± 0.0026
$25.0 < p_t \leq 30.0$	0.9244 ± 0.0009	0.9244 ± 0.0009	0.8406 ± 0.0020	0.8406 ± 0.0020
$30.0 < p_t \leq \infty$	0.9572 ± 0.0002	0.9572 ± 0.0002	0.8980 ± 0.0005	0.8980 ± 0.0005

(B) Measured electron prompt rates in bins of p_t and η of the electron. Errors are statistical only

TABLE 7.7: Measured lepton prompt rates for 2012 analysis, using a tag and probe method.



(A) Invariant mass distribution of the same flavour, opposite-signed lepton system (B) Missing transverse energy event distribution

FIGURE 7.5: Jet-induced background composition after the E_T^{miss} analysis requirement is applied. The composition is almost even mixture of $t\bar{t}$ and Drell-Yan events. The figures are showing the four channels added up. The dot markers are the $\mathcal{PPF}$ contribution estimated with the data-driven method, i.e. $N_{\mathcal{PPF}}^{N_{t3}}$, the other samples are Monte Carlo based. Data from 2011 run.

prompt leptons, i.e. an irreducible background as, for instance, the ZZ full leptonic decay where one lepton is lost, will contribute to $N_{\mathcal{PPF}}^{N_{t3}}$. Therefore, such processes have to be subtracted, using the corresponding Monte Carlo. Equivalently, the WZ signal expectation may be obtained using Equation 7.14d by,

$$N_{\mathcal{PPF}}^{N_{t3}} = N_{t3} - (N_{\mathcal{PPF}}^{N_{t3}} + N_{\mathcal{PFF}}^{N_{t3}} + N_{\mathcal{FFF}}^{N_{t3}}) \quad (7.19)$$

The WZ signal expectation (plus the irreducible backgrounds) is estimated subtracting to the total events passing all the selection cuts, the estimation of the $\mathcal{PPF}$, $\mathcal{PFF}$ and $\mathcal{FFF}$ jet-induced background contributions. The estimated number of events obtained in the WZ analysis using the Equations (7.13) and the fake and prompt rates obtained in the last Section (Tables 7.4 and 7.6, respectively) are reported in Table 7.9 split by measured channels. The actual measured N_{ti} yields are given in Table 7.8. From table 7.9 one may observe that the contribution to the signal selection N_{t3} is clearly dominated by the $\mathcal{PPF}$ component, being

	$3e$	$2e1\mu$	$2\mu1e$	3μ
N_{t0}	1	8	3	6
N_{t1}	20	16	21	29
N_{t2}	63	80	98	119
N_{t3}	64	62	70	97

(A) 2011 analysis table

	$3e$	$2e1\mu$	$2\mu1e$	3μ
N_{t0}	7	1	3	5
N_{t1}	81	33	71	53
N_{t2}	270	207	497	327
N_{t3}	235	288	400	557

(B) 2012 analysis table

TABLE 7.8: Number of selected events with fakeable objects for each decay channel and selection category, where N_{ti} is the actual selected number of events with i -tight and $(3-i)$ fail leptons. Data from 2011 analysis.

	$3e$	$2e1\mu$	$2\mu1e$	3μ
$N_{\mathcal{P}\mathcal{P}\mathcal{P}}^{N_{t3}}$	61.92 ± 8.07	60.56 ± 7.93	67.67 ± 8.42	95.30 ± 9.89
$N_{\mathcal{P}\mathcal{P}\mathcal{F}}^{N_{t3}}$	2.06 ± 0.45	1.44 ± 0.28	2.32 ± 0.42	1.70 ± 0.24
$N_{\mathcal{P}\mathcal{F}\mathcal{F}}^{N_{t3}}$	0.022 ± 0.011	0.0028 ± 0.0041	0.0088 ± 0.0050	0.0060 ± 0.0028
$N_{\mathcal{F}\mathcal{F}\mathcal{F}}^{N_{t3}}$	0.0001 ± 0.0002	0.0002 ± 0.0001	0 ± 0	0 ± 0
$\sum N$	64	62	70	97

(A) 2011 analysis table

	$3e$	$2e1\mu$	$2\mu1e$	3μ
$N_{\mathcal{P}\mathcal{P}\mathcal{P}}^{N_{t3}}$	220.16 ± 15.74	260.89 ± 17.62	352.08 ± 20.82	498.00 ± 24.70
$N_{\mathcal{P}\mathcal{P}\mathcal{F}}^{N_{t3}}$	14.67 ± 1.44	27.02 ± 2.93	47.32 ± 3.44	57.11 ± 4.76
$N_{\mathcal{P}\mathcal{F}\mathcal{F}}^{N_{t3}}$	0.169 ± 0.058	0.09 ± 0.13	0.59 ± 0.24	1.86 ± 0.52
$N_{\mathcal{F}\mathcal{F}\mathcal{F}}^{N_{t3}}$	0.0008 ± 0.0010	0.0014 ± 0.0012	0.011 ± 0.013	0.030 ± 0.027
$\sum N$	235	288	400	557

(B) 2012 analysis table

TABLE 7.9: Number of events estimated in the using the fakeable object method. The last row is the analytic sum of previous rows and should be exactly N_{t3} . It can be appreciated the negligible contribution of the $\mathcal{P}\mathcal{F}\mathcal{F}$ and $\mathcal{F}\mathcal{F}\mathcal{F}$ processes, meaning the jet-induced background is mostly due to the $\mathcal{P}\mathcal{P}\mathcal{F}$ processes.

negligible in the analysis the $\mathcal{PF}\mathcal{F}$ and $\mathcal{FF}\mathcal{F}$ contributions.

7.2.4. Validation of the method

Several closure tests have been carried out to assess the validity of the data-driven approach to estimate the fake-lepton background contribution. A closure test may be performed by obtaining a pure $\mathcal{PP}\mathcal{F}$ sample, thus in that case one may eliminate all the non $\mathcal{PP}\mathcal{F}$ terms from Equation 7.14d,

$$N_{t3} = p^2 f N_{\mathcal{PP}\mathcal{F}} \equiv N_{\mathcal{PP}\mathcal{F}}^{N_{t3}} \quad (7.20)$$

We can check the method reliability and its assumptions by checking the validity of the above equation in a pure $\mathcal{PP}\mathcal{F}$ sample.

The $\mathcal{PP}\mathcal{F}$ background in the WZ analysis is expected to be dominated by $t\bar{t}$ and Drell-Yan processes (see Section 7.2.2). Therefore, it has been applied the FOM method to a $t\bar{t}$ and Drell-Yan Monte Carlo simulated samples and to a $t\bar{t}$ and Drell-Yan enriched data samples. Both approaches have caveats: the data-driven applied in the Monte Carlo samples uses a fake rate matrices extracted from a jet-enriched data sample described in Section 7.2.2 whilst it should be use fake rates matrices extracted from a simulated Monte Carlo data. Conversely, the data-driven applied to the $\mathcal{PP}\mathcal{F}$ enriched samples suffers contamination from other background contributions, due to the impossibility to select a pure $\mathcal{PP}\mathcal{F}$ sample using experimental data, thus it does not fulfil the requirements needed to apply the Equation (7.20).

The Monte Carlo-based closure tests have been performed in the 2011 analysis applying the FOM to the $Z/\gamma \rightarrow \ell^+\ell^- + Jets$ Monte Carlo sample and to the $t\bar{t} \rightarrow 2\ell 2\nu 2b$, both described in Table 7.17. The Table 7.10 shows the closure test results for the $t\bar{t}$ dileptonic sample and the results for the Drell-Yan sample are in Table 7.11. In both cases, the $\mathcal{PP}\mathcal{F}$ contribution has been obtained by applying the FOM to the simulated samples, while concurrently, the selection cuts of the main WZ analysis were applied to the same simulated sample. The closure test (Equation (7.20)) predicts the same values the $\mathcal{PP}\mathcal{F}$ contribution and for the N_{t3} yields within uncertainties, which can be tested using the *number of standard*

	$3e$	$2e1\mu$	$2\mu1e$	3μ
$N_{\mathcal{PPF}}^{N_{t3}}$	0.220 ± 0.011	0.396 ± 0.012	0.607 ± 0.014	0.843 ± 0.015
N_{t3}	0.29 ± 0.06	0.44 ± 0.07	0.65 ± 0.08	0.64 ± 0.08
$\delta\varepsilon \cdot 100$	24%	10%	7%	32%
N_σ	1.2	0.6	0.5	2.5

TABLE 7.10: Data-driven estimation ($N_{\mathcal{PPF}}^{N_{t3}}$) and yields from the nominal analysis selection (N_{t3}), obtained with the dileptonic $t\bar{t}$ simulated sample. Errors are statistical only. The $\delta\varepsilon$ is the relative difference between both central measurements and N_σ the number of standard deviations between both measures. The fake rates used for this estimation were obtained from a jet-enriched sample with a $E_{th}^{LeadJet} > 50$ GeV cut. The yields are weighted to a luminosity of 4.9 fb^{-1}

	$3e$	$2e1\mu$	$2\mu1e$	3μ
$N_{\mathcal{PPF}}^{N_{t3}}$	27.3 ± 1.1	30.27 ± 1.1	149 ± 2	42.5 ± 1.4
N_{t3}	19 ± 3	53 ± 4	106 ± 6	91 ± 6
$\delta\varepsilon \cdot 100$	33%	43%	29%	53%
N_σ	2.6	5.1	6.9	8.31

TABLE 7.11: Data-driven estimation ($N_{\mathcal{PPF}}^{N_{t3}}$) and yields from the nominal analysis selection (N_{t3}) obtained with the $Z + Jets$ MC simulated sample. Errors shown are statistical only. The $\delta\varepsilon$ is the relative difference between both central measurements and N_σ the number of standard deviations between both measures. The fake rates used for this estimation were obtained from a jet-enriched sample with a $E_{th}^{LeadJet} > 30(35)$ GeV cut. Yields weighted to an arbitrary luminosity.

deviation observable, N_σ , defined as

$$N_\sigma = \frac{|\bar{a} - \bar{b}|}{\sqrt{\sigma_a^2 + \sigma_b^2}}, \quad (7.21)$$

being $\bar{a}$ and $\bar{b}$ the central values of two measurements, and σ_a, σ_b their respective associated errors. Thus, the σ_n observable is quantifying the compatibility of two measurements, and as a rule of thumb a $N_\sigma < 3$ is implying a compatible measurements¹ (with probability of 99.7%).

The results obtained in the aforementioned tables show compatible values for

¹Assuming independent Gaussian errors

the $t\bar{t}$ closure test whereas is not the case for the $Z + Jets$ Monte Carlo sample. As it was argued in previous sections, the QCD sector of the Z+Jets Monte Carlo simulation is expected to be poorly modelled, unlike the $t\bar{t}$ process. This is illustrated by the incompatible $\mathcal{PPF}$ estimation with the main analysis results of the Z+Jets closure test, because of using a fake rate matrix extracted from a experimental dataset which was defined through the $E_{th}^{LeadJet} > 30(35)$ GeV cut matching the experimental Z+Jet enriched region. Therefore, to be conclusive it is mandatory to check the closure test in experimental data, in particular the Z+Jets region.

A $t\bar{t}$ enriched region have been extracted from the experimental data using the selection cuts given in Chapter 6 and modifying some of the selection cuts,

- same flavour, opposite-charged leptons should fulfil $M_{\ell\ell} \notin M_Z \pm 25$ GeV/ c
- number of jets in the event > 2 , at least 1 b-tagged
- $E_T^{\text{miss}} > 40$ GeV

Vetoing the Z candidate and requiring a high amount of E_T^{miss} will reduce significantly the Drell-Yan process, and the b-tagging ¹ requirement reduces the remnant WW. In addition, the WZ, ZZ and $V\gamma$ Monte Carlo samples have been processed, denoted as $N_{\mathcal{PPF}}^{MC}$, to account the possible contamination to the signal region. Table 7.12 shows the obtained yields once the Monte Carlo subtraction of $N_{\mathcal{PPF}}^{MC}$ have been done, and the data-driven estimation for the $\mathcal{PPF}$ contribution. Notice the small number of events available after the selection cuts, which although a remarkably different central values are obtained between the estimation of the method and the analysis, the measurements are completely compatible as it may see in the N_σ row.

The last closure test performed is in the $Z + Jets$ region. The experimental data have been enriched with Z+Jets processes using the nominal selection cuts of the WZ analysis but modifying some of them,

- same flavour, opposite-charged leptons should fulfil $M_{\ell\ell} \in M_Z \pm 15$ GeV,
- third lepton $p_t > 10$ GeV/ c ,

¹Method to identify jets originating from bottom quarks. See details in Reference [82]

	$3e$	$2e$	2μ	3μ
$N_{\mathcal{PPF}}^{N_{t3}}$	0.4 ± 0.2	0.56 ± 0.15	0.8 ± 0.2	0.66 ± 0.15
$ N_{t3} - N_{\mathcal{PPP}}^{MC} $	3 ± 3	0.4 ± 1.0	4 ± 2	3 ± 3
$\delta\varepsilon \cdot 100$	85%	35%	82%	78%
N_σ	0.8	0.15	1.5	0.69

TABLE 7.12: Data-driven estimation $N_{\mathcal{PPF}}^{N_{t3}}$ and yields from nominal analysis N_{t3} obtained with the $t\bar{t}$ region sample. Errors shown are statistical only. The $\mathcal{PPF}$ contribution has been obtained applying the fakeable object method to the enriched- $t\bar{t}$ region sample and subtracted the $\mathcal{PPP}$ contribution with simulated data. The selection cuts of the WZ analysis are applied to the same region to obtain the N_{t3} yields. The $\delta\varepsilon$ is the relative difference between both central measurements and N_σ the number of standard deviations between both measures. Fake rates used extracted with the $E_{th}^{LeadJet} > 50$ GeV cut in the jet-enriched sample (see Section 7.2.2). Yields correspond to the available luminosity of the 2011 run period: 4.9 fb^{-1}

- $E_T^{\text{miss}} < 20 \text{ GeV}/c$

The Z mass window have been reduced in order to assure a better quality of the Z-candidates and the transverse momentum cut of the third lepton has been lowered to increase the number of events. The Z+Jets process does not contain real E_T^{miss} , therefore the associated cut has been reverted and reduced. As in the case of the $t\bar{t}$ region, the WZ, ZZ and $V\gamma$ processes have been incorporated with a Monte Carlo simulated samples and subtracted to the N_{t3} yields. The results of the test are reported in Table 7.13. All the channels close the test, although it is worth to mention that whence the mixed channels have an impressive accuracy, the pure electronic and muonic channel present more differences between the FOM estimation and the standard analysis. Nevertheless, the results are consistent in the experimental data case of the Z+Jets sample in contrast with the Monte Carlo simulation (Table 7.11) leading to the not-well-modelled Z+Jets' initial assumption discussed previously further plausibility.

7.2.5. Systematic uncertainties

The jet-enriched sample used to built the fake rate has been selected in such a way that the relative isolation spectra of the fakeable of this sample and

	$3e$	$2e$	2μ	3μ
$N_{\mathcal{PPF}}^{N_{t3}}$	18 ± 2	23 ± 2	23 ± 2	35 ± 2
$ N_{t3} - N_{\mathcal{PPP}}^{MC} $	6 ± 5	24 ± 6	22 ± 7	63 ± 9
$\delta\varepsilon \cdot 100$	189%	3%	2%	45%
N_σ	2.4	0.1	0.1	3.0

TABLE 7.13: Data-driven estimation $N_{\mathcal{PPF}}^{N_{t3}}$ and yields from nominal analysis N_{t3} obtained with the enriched Z+Jets region sample. Errors shown are statistical only. The $\mathcal{PPF}$ contribution has been obtained applying the fakeable object method to the enriched Z+Jets region sample and subtracted the $\mathcal{PPP}$ contribution with simulated data. The selection cuts of the WZ analysis are applied to the same region to obtain the N_{t3} yields. The $\delta\varepsilon$ is the relative difference between both central measurements and N_σ the number of standard deviations between both measures. Fake rates used extracted with the $E_{th}^{LeadJet} > 30(35)$ GeV cut in the jet-enriched sample (see Section 7.2.2). Yields correspond to the available luminosity of the 2011 run period: 4.9 fb^{-1}

the background samples (mainly $t\bar{t}$ and $Z + Jets$) are as similar as possible by introducing a E_T cut in the leading jet as it was discussed in Section 7.2.2. The optimal cut value for a $t\bar{t}$ sample has found to be $E_T^{LeadJet} > 50$ GeV whilst for the case of $Z + jet$ has found a $E_T^{LeadJet} > 30(35)$ GeV cut, for muons (electrons).

Those results have been obtained by matching the E_T spectra of the fakeable jet in the jet-enriched, $Z + Jets$ and $t\bar{t}$ samples (see Figures 7.2) and confirmed by the several experimental and Monte Carlo simulated data closure tests performed in the last section. However, the background contribution is not expected to be homogeneous but a mixture of $t\bar{t}$ and $Z + Jets$ process (see Section 7.2.2). The $E_T^{LeadJet} > 50 \text{ GeV}/c$ choice as the nominal cut to extract the fake rates is taken into account by recalculating the data-driven using the $E_T^{LeadJet} > 30(35)$ GeV which mimics $Z + Jets$ and assigning a systematic using the differences between both estimations. The fake rates extracted using the $E_{th}^{LeadJet} > 30(35)$ GeV cut are shown in Tables 7.15 and 7.16. The obtained differences are shown in Table 7.14. Although it was propagated the errors associated to the Equations (7.13) of the fakeable object method, the systematic errors obtained are negligible with respect to the systematic uncertainty associated to the transverse energy of the leading jet cut, and consequently they are not considered in this analysis.

	$3e$	$2e1\mu$	$2\mu1e$	3μ
$E_T^{LeadJet} > 15 \text{ GeV}$	60 ± 8	57 ± 8	64 ± 9	91 ± 10
$E_T^{LeadJet} > 50 \text{ GeV}/c$ (nominal)	62 ± 8	61 ± 8	68 ± 8	95 ± 10
$\delta_{sys} \cdot 100$	2.4%	5.5%	5.3%	5.0%

TABLE 7.14: Signal estimation $N_{\mathcal{P}\mathcal{P}\mathcal{P}}^{N_{t3}}$ for the data-driven using different fake rate sets. The relative differences between them are used as systematic for the method, δ_{sys}

	$ \eta \in [0, 1]$	$\eta \in (1, 1.48]$	$\eta \in (1.48, 2]$	$\eta \in (2, 2.5]$
$10 < p_t \leq 15$	0.041 ± 0.003	0.052 ± 0.004	0.061 ± 0.005	0.057 ± 0.008
$15 < p_t \leq 20$	0.018 ± 0.002	0.024 ± 0.004	0.028 ± 0.005	0.019 ± 0.007
$20 < p_t \leq 25$	0.021 ± 0.001	0.032 ± 0.002	0.037 ± 0.002	0.049 ± 0.004
$25 < p_t \leq 30$	0.045 ± 0.002	0.071 ± 0.004	0.090 ± 0.005	0.112 ± 0.010
$30 < p_t \leq \infty$	0.075 ± 0.002	0.087 ± 0.003	0.109 ± 0.005	0.151 ± 0.010

(A) Measured muon fake rates in function of transverse momentum and η of the muon. Errors are statistical only

	$ \eta \in [0, 1]$	$\eta \in (1, 1.48]$	$\eta \in (1.48, 2]$	$\eta \in (2, 2.5]$
$10 < p_t \leq 15$	0.066 ± 0.015	0.040 ± 0.012	0.016 ± 0.009	0.023 ± 0.013
$15 < p_t \leq 20$	0.057 ± 0.009	0.054 ± 0.010	0.018 ± 0.007	0.041 ± 0.013
$20 < p_t \leq 25$	0.085 ± 0.009	0.064 ± 0.011	0.057 ± 0.010	0.046 ± 0.009
$25 < p_t \leq 30$	0.085 ± 0.012	0.067 ± 0.015	0.052 ± 0.012	0.070 ± 0.015
$30 < p_t \leq \infty$	0.09 ± 0.02	0.06 ± 0.02	0.07 ± 0.02	0.07 ± 0.02

(B) Measured electron fake rates in function of transverse momentum and η of the electron. Errors are statistical only

TABLE 7.15: Measured lepton fakes rates from the jet-enriched sample described in the text, using a transverse energy of the leading jet higher than 30(35) GeV for muons (electrons) for 2011 analysis.

7.3. Irreducible backgrounds

The contribution of other prompt components to the signal (ZZ, $V\gamma$ and VVV for the 2012 analysis) has been subtracted using Monte Carlo simulated samples, taking as background estimation the number of events passing the signal selection. The samples have been simulated in a centralised way for the whole CMS collaboration for the sake of coherence and consistency. Thus, any analysis performed within the collaboration makes use of the same simulation input. The massive simulation of Monte Carlo samples are structured in production campaigns, whence the detector conditions (alignment, magnetic field, dead detector regions,

	$ \eta \in [0, 1]$	$\eta \in (1, 1.48]$	$\eta \in (1.48, 2]$	$\eta \in (2, 2.5]$
$10 < p_t \leq 15$	0.084 ± 0.005	0.100 ± 0.008	0.128 ± 0.012	0.20 ± 0.02
$15 < p_t \leq 20$	0.073 ± 0.009	0.080 ± 0.014	0.10 ± 0.02	0.21 ± 0.04
$20 < p_t \leq 25$	0.098 ± 0.005	0.134 ± 0.009	0.11 ± 0.01	0.12 ± 0.02
$25 < p_t \leq 30$	0.136 ± 0.009	0.191 ± 0.016	0.16 ± 0.02	0.23 ± 0.04
$30 < p_t \leq \infty$	0.19 ± 0.02	0.25 ± 0.03	0.23 ± 0.04	0.31 ± 0.10

(A) Measured muon fake rates in function of transverse momentum and η of the muon. Errors are statistical only

	$ \eta \in [0, 1]$	$\eta \in (1, 1.48]$	$\eta \in (1.48, 2]$	$\eta \in (2, 2.5]$
$10 < p_t \leq 15$	0.045 ± 0.005	0.033 ± 0.004	0.008 ± 0.002	0.021 ± 0.005
$15 < p_t \leq 20$	0.044 ± 0.003	0.049 ± 0.003	0.017 ± 0.001	0.017 ± 0.002
$20 < p_t \leq 25$	0.041 ± 0.002	0.064 ± 0.003	0.025 ± 0.002	0.025 ± 0.002
$25 < p_t \leq 30$	0.059 ± 0.003	0.101 ± 0.005	0.041 ± 0.003	0.043 ± 0.003
$30 < p_t \leq \infty$	0.084 ± 0.006	0.111 ± 0.009	0.058 ± 0.006	0.066 ± 0.005

(B) Measured electron fake rates in function of transverse momentum and η of the electron. Errors are statistical only

TABLE 7.16: Measured lepton fakes rates from the jet-enriched sample described in the text, using a transverse energy of the leading jet higher than 30(35) GeV for muons (electrons) for 2012 analysis.

etc.) are kept frozen along the production. The generation of the physics processes is accomplished by the use of different generator programs depending the process to simulate. As is explained in detail in Section 5.2, once the process is generated, the outcome is sent to the detector simulator based in GEANT4, to simulate the particles passing through the detector. The list of the samples used in this analysis, with some relevant information as the production campaign, the Monte Carlo program used to generate the sample, the cross section considered and the internal name in CMS are detailed in Tables 7.17 and 7.18.

In order to take into account the reconstruction, identification and isolation lepton efficiencies (studied in Chapter 6) that are present in the experimental data, these efficiencies have been measured in data, ε , and in the simulation, ε_{sim} , using tag and probe methods. Each Monte Carlo simulated event has been weighted by the efficiencies scale factors $SF = \varepsilon/\varepsilon_{sim}$, mimicking the simulated events with the data inefficiencies behaviour.

As the data is selected using trigger requirements the Monte Carlo events should contain only events with the same trigger paths accepted. This approach is difficult to accomplish due to the asynchrony between Monte Carlo sample

massive production and the continuous development of the trigger paths. Instead, as it was discussed in Section 6.2.1 of the previous Chapter, it has been measured, in η and p_T bins, the lepton trigger efficiencies of any double trigger used in the analysis and interpreted as the probability of a lepton passing one leg trigger requirement. Moreover, it has been built a probability function which is used to weight each Monte Carlo event (Equations 6.1).

In addition to the object corrections, the Monte Carlo samples need to be reweighted in order to match the pileup interactions present in the data. This is needed because the simulated data is produced before the acquisition of the experimental data and, therefore, there is no clue about the number of additional interactions per bunch crossing. The approach used in the CMS collaboration to simulate the pileup is based in the last data-taking period. A distribution representing the mean number of interactions seen during the last data-taking is built and used as input for a given production campaign. For each event, the mean

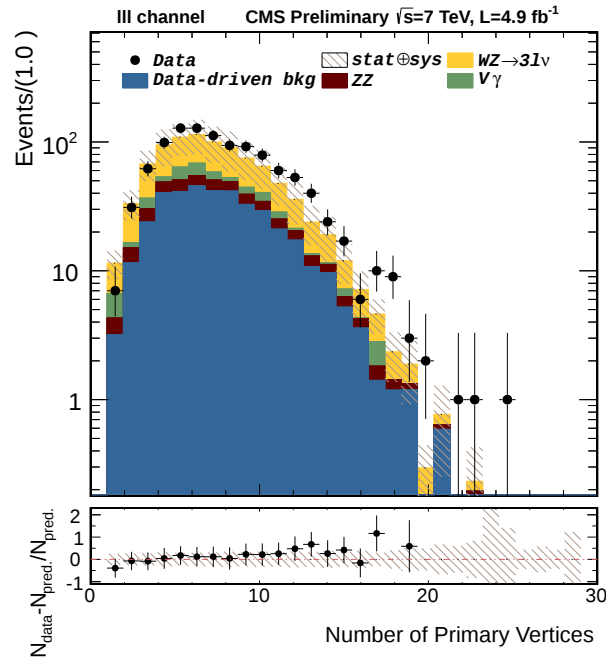


FIGURE 7.6: Number of primary vertices reconstructed per event distribution in the WZ 2011 analysis. The lepton preselection stage have been applied

number of interactions per bunch crossing is chosen from the input distribution.

This sets the instantaneous luminosity to be simulated for all of the bunch crossings in that event. For each bunch crossing, the number of interactions is randomly sampled from a Poisson distribution with a mean equal to the value chosen before. When compare the simulated with the experimental data, the number of interactions observed in the simulated data should match the experimental data, therefore a event reweighting ($N_{int.}/N_{int.}^{MC}$) is performed in the simulation to obtain the same number of interaction distribution. Figure 7.6 shows the experimental data compared with the Monte Carlo simulation for the number of primary vertices distribution at each event, which is a sensible observable for the pileup.

Signal	Nickname	MC dataset name	$\sigma \cdot BR$ [pb]
$WZ \rightarrow 3\ell 1\nu$	WZJet3L1Nu	/WZJetsTo3L1Nu_TuneZ2.7TeV-madgraph-tauola/*/AODSIM	0.879 (NLO)

Background	Nickname	MC dataset name	$\sigma \cdot BR$ [pb]
$Z/\gamma^* \rightarrow \ell\ell + Jets$	DYee	/DYToEE_M-10To20_CT10_TuneZ2.7TeV-powheg-pythia/*/AODSIM	3319.61 (NNLO)
	Zee	/DYToEE_M-20_CT10_TuneZ2.7TeV-powheg-pythia/*/AODSIM	1666 (NNLO)
	DYtautau	/DYToTauTau_M-10To20_TuneZ2.7TeV-pythia6-tauola/*/AODSIM	31319.61 (NNLO)
	Ztautau	/DYToTauTau_M-20_CT10_TuneZ2.7TeV-powheg-pythia/*/AODSIM	1666 (NNLO)
	DYmumu	/DYToMuMu_M-10To20_CT10_TuneZ2.7TeV-powheg-pythia/*/AODSIM	31319.61 (NNLO)
	Zmumu	/DYToMuMu_M-20_CT10_TuneZ2.7TeV-powheg-pythia/*/AODSIM	1666 (NNLO)
$W \rightarrow \ell\nu + Jets$	WJetsToLNU	/WJetsToLNU_TuneZ2.7TeV-madgraph-tauola/*/AODSIM	31314 (NNLO)
$V\gamma + jets$	PhotonVJets	/GVJets_7TeV-madgraph	165 (LO)
$WW \rightarrow X$	WW	/WW_TuneZ2.7TeV_pythia6_tauola/*/AODSIM	47 (NLO)
$tW \rightarrow X$	tW	/T_TuneZ2.tW-channel-DR_7TeV-powheg-tauola/*/AODSIM	7.87 (NLO)
$t\bar{W} \rightarrow X$	tbarW	/Tbar_TuneZ2.t-channel_7TeV-powheg-tauola/*/AODSIM	7.87 (NLO)
$t\bar{t} \rightarrow X$	Ttbar	/TTJets_TuneZ2.7TeV-madgraph-tauola/*/AODSIM	163 (NLO)
$t\bar{t} \rightarrow 2\ell 2\nu 2b$	TTTo2L2Nu2B	/TTTo2L2Nu2B_7TeV-powheg-pythia6/*/AODSIM	17.10 (NLO)
$ZZ \rightarrow 4\ell$	ZZ4e	/ZZTo4e_7TeV-powheg-pythia6/*/AODSIM	0.0154 (NLO)
	ZZ4mu	/ZZTo4m_7TeV-powheg-pythia6/*/AODSIM	0.0154 (NLO)
	ZZ4tau	/ZZTo4tau_7TeV-powheg-pythia6/*/AODSIM	0.0154 (NLO)
	ZZ2e2mu	/ZZTo2e2mu_7TeV-powheg-pythia6/*/AODSIM	0.0308 (NLO)
$ZZ \rightarrow 2\ell 2\ell'$	ZZ2e2tau	/ZZTo2e2tau_7TeV-powheg-pythia6/*/AODSIM	0.0308 (NLO)
	ZZ2mu2tau	/ZZTo2mu2tau_7TeV-powheg-pythia6/*/AODSIM	0.0308 (NLO)
$ZZ \rightarrow X$	ZZ	/ZZ_TuneZ2.7TeV_pythia6_tauola/*/AODSIM	7.67 (NLO)

* Fall11-PU_S6_START42.V148-v1

TABLE 7.17: Summary of Standard Model processes, Monte Carlo simulated samples and cross section times branching ratio values used for this analysis in 2011. Mostly of the samples were generated with PYTHIA, in some cases MADGRAPH was used. The parton shower was included by interfacing POWHEG to the main generator program, and the tau-lepton decays was dealt with TAUOLA.

Signal	Nickname	MC dataset name	$\sigma \cdot \text{BR}$ [pb]
$WZ \rightarrow \ell\nu\ell\ell$	WZ	/WZJetsTo3LNU_TuneZ2.8TeV-madgraph-tauola/[1]	1.058

Nickname	Background process	MC dataset name	$\sigma \cdot \text{BR}$ [pb]
top	$t\bar{t} \rightarrow 2\ell 2\nu 2b$	/TTTo2L2Nu2B.8TeV-powheg-pythia6/[3]	23.640
	tW	/T_tW-channel-DR_TuneZ2star.8TeV-powheg-tauola/[1]	11.177
	$\bar{t}W$	/Tbar_tW-channel-DR_TuneZ2star.8TeV-powheg-tauola/[1]	11.177
VVV	WZZ	/WZZNoGstarJets.8TeV-madgraph/[1]	0.0192
	ZZZ	/ZZZNoGstarJets.8TeV-madgraph/[1]	0.00459
	WWZ	/WWZNoGstarJets.8TeV-madgraph/[1]	0.0633
	WWW	/WWWJets.8TeV-madgraph/[1]	0.0822
	$t\bar{t}W$	/TTWJets.8TeV-madgraph/[1]	0.232
	$t\bar{t}Z$	/TTZJets.8TeV-madgraph/[1]	0.174
	$t\bar{t}WW$	/TTWWJets.8TeV-madgraph/[1]	0.00204
	$t\bar{t}\gamma$	/TTGJets.8TeV-madgraph/[1]	1.44
	$WW\gamma$	/WWGJets.8TeV-madgraph/[1]	0.528
WV	$W \rightarrow \ell\nu$	/WJetsToLNU_TuneZ2Star.8TeV-madgraph-tarball/[1]	37509
	$W \rightarrow \ell\nu + b\bar{b}$	/WbbJetsToLNU_Massive_TuneZ2star.8TeV-madgraph-pythia6-tauola/[1]	39.9
	$W\gamma^* \rightarrow \ell\nu e e$	/WGstarToLNU2E_TuneZ2star.8TeV-madgraph-tauola/[1]	5.873
	$W\gamma^* \rightarrow \ell\nu\mu\mu$	/WGstarToLNU2Mu_TuneZ2star.7TeV-madgraph-tauola/[1]	1.914
	$W\gamma^* \rightarrow \ell\nu\tau\tau$	/WGstarToLNU2Tau_TuneZ2star.7TeV-madgraph-tauola/[1]	0.336
	$W\gamma \rightarrow \ell\nu\gamma$	/WGToLNUG_TuneZ2star.8TeV-madgraph-tauola/[1]	553.9
	WW	/WW_TuneZ2star.8TeV-pythia6-tauola/[1]	57.07
	$WZ \rightarrow q\bar{q}\ell\ell$	/WZJetsTo2L2Q_TuneZ2star.8TeV-madgraph-tauola/[1]	2.206
	$WZ \rightarrow \ell\nu q\bar{q}$	/WZJetsTo2QLNU.8TeV-madgraph/[2]	1.584
	$Z\gamma$	/ZGToLLG.8TeV-madgraph/[1]	132.6
Z+jets	$Z/\gamma \rightarrow \ell\ell$ ($10 < m_{\ell\ell} < 50$ GeV)	/DYJetsToLL_M-10To50filter.8TeV-madgraph/[1]	860.5
	$Z/\gamma \rightarrow \ell\ell$ ($m_{\ell\ell} > 50$ GeV)	/DYJetsToLL_M-50_TuneZ2Star.8TeV-madgraph-tarball/[1]	3532.8
	$Z/\gamma \rightarrow \ell\ell + b\bar{b}$	/ZbbToLL_massive_M-50_TuneZ2star.8TeV-madgraph-pythia6-tauola/[1]	94.1
ZZ	$ZZ \rightarrow 2\mu 2\tau$	/ZZTo2mu2tau.8TeV-powheg-pythia6/[1]	0.1767
	$ZZ \rightarrow 4e$	/ZZTo4e.8TeV-powheg-pythia6/[1]	0.07691
	$ZZ \rightarrow 2e 2\tau$	/ZZTo2e2tau.8TeV-powheg-pythia6/[1]	0.1767
	$ZZ \rightarrow 4\mu$	/ZZTo4mu.8TeV-powheg-pythia6/[1]	0.07691
	$ZZ \rightarrow 2e 2\mu$	/ZZTo2e2mu.8TeV-powheg-pythia6/[1]	0.1767
	$ZZ \rightarrow 4\tau$	/ZZTo4tau.8TeV-powheg-pythia6/[1]	0.07691
	$ZZ \rightarrow \ell\ell q\bar{q}$	/ZZJetsTo2L2Q_TuneZ2star.8TeV-madgraph-tauola/[1]	1.275
	$ZZ \rightarrow \ell\ell\nu\nu$	/ZZJetsTo2L2Nu_TuneZ2star.8TeV-madgraph-tauola/[3]	0.365
	$gg \rightarrow ZZ \rightarrow 2\ell 2\ell$	/GluGluToZZTo2L2L_TuneZ2star.8TeV-gg2zz-pythia6/[1]	0.00447
	$gg \rightarrow ZZ \rightarrow 4\ell$	/GluGluToZZTo4L.8TeV-gg2zz-pythia6/[1]	0.00224
	$gg \rightarrow H \rightarrow ZZ \rightarrow 4\ell$	/GluGluToHTToZZTo4L_M-125.8TeV-powheg-pythia6/[1]	0.0524

[1] Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM
[2] Summer12_DR53X-PU_S10_START53_V7C-v1/AODSIM
[3] Summer12-PU_S7_START52_V9-v1/AODSIM

TABLE 7.18: Summary of Standard Model processes, Monte Carlo simulated samples and cross section times branching ratio values used for this analysis in 2012. Mostly of the samples were generated with PYTHIA, but in some cases MADGRAPH was used. The parton shower was included by interfacing POWHEG to the main generator program, and the tau-lepton decays was dealt with TAUOLA.

CHAPTER 8

WZ Cross section measurements

The measurement of the cross section at centre of mass energies of 7 TeV and 8 TeV is described along this chapter. The general formula to obtain a cross section from the observed events is recalled, identifying the necessary elements and describing how they are estimated. Afterwards, using the results from previous chapters, the cross section measurements in each channel are reported, along with their estimated uncertainties. A detailed description of the sources of systematic uncertainties identified are presented and propagated to the measurement. The chapter concludes with a review of the BLUE method used to combine the four measurements to finally show the final combined result.

8.1. Cross section estimation

The probability of a process is given by the *cross section*, σ . Introducing the *instantaneous luminosity*, $\mathcal{L}$, as the number of incident particles per unit area per unit time [$\mathcal{L}$] = $\text{cm}^{-2} \text{s}^{-1}$, then the event rate of a process A is given by,

$$\frac{dN_A}{dt} = P(A)\mathcal{L} \equiv \sigma_A\mathcal{L}, \quad (8.1)$$

Integrating along a period of time T , and including the effects of measuring in a real detector by introducing the probability of measure an event A in the detector,

ε_A , the number of events observed is given by,

$$N_A^{obs} = \sigma_A P(\text{Measured}|A) \left(\int_T \mathcal{L} dt \right) \quad (8.2)$$

The probability of measure an event from the process A can be decomposed into the probability that an event fall into the geometric acceptance of the detector and once the event is inside acceptance, the probability that the event is actually reconstructed and measured.

$$P(\text{Measured}) = P(\text{Measured}|\text{Inside Acc.})P(\text{Inside Acc.}) \equiv \varepsilon \mathcal{A} \quad (8.3)$$

where it has been renamed,

$$\begin{aligned} P(\text{Inside Acc.}) &\equiv \mathcal{A}, \text{ and} \\ P(\text{Measured}|\text{Inside Acc.}) &\equiv \varepsilon \end{aligned}$$

The production cross section of a process is measured in a fiducial region constrained by the geometric acceptance of the detector. The number of events observed from the signal selection, correcting for the efficiency that an event inside acceptance is reconstructed, are then extrapolated to the full phase space of events which includes events outside the detector and selection acceptance. Thus, the production cross section in the full phase space is given by

$$\sigma = \frac{N_S}{\mathcal{A} \cdot \varepsilon \cdot \mathcal{L}_{int}} \quad (8.4)$$

being N_S the number of signal observed in the fiducial region, $\mathcal{A}$ and ε represents the kinematic and geometric acceptance and the selection efficiency for the fiducial events, respectively, as it has been described above, and $\mathcal{L}_{int}$ is the integrated luminosity.

The $\mathcal{A}$ is determined using Monte Carlo simulation. A sample of WZ process is simulated in the full phase space, then a fiducial volume is defined to count how many events enters in this volume. The frequentist approach of probabilities allows to measure the $\mathcal{A}$ as the ratio between the events in the fiducial region over the total generated events. The Table 8.1 defines the fiducial volume in the

Monte Carlo simulated WZ process by cutting the generated objects.

$p_T^\ell > 20, 20, 10 \text{ GeV}$	for the three leptons decaying from Z and W
$p_T^\nu > 30 \text{ GeV}$	for the neutrino decaying from W
$ \eta^\ell < 2.4 (2.5)$	for the W, Z-muons (electrons)

TABLE 8.1: Fiducial and kinematic region definition in the MC simulated sample for the WZ process. The cuts are applied to the generated objects.

Therefore,

$$\mathcal{A} = \frac{N_{\text{Generated WZ} \rightarrow 3\ell\nu}^{\text{MC Fiducial Volume}}}{N_{\text{Generated WZ} \rightarrow 3\ell\nu}^{\text{MC Phase Space}}} \quad (8.5)$$

where the $N_{\text{Generated WZ} \rightarrow 3\ell\nu}^{\text{MC Fiducial Volume}}$ is the number of events generated in the WZ Monte Carlo sample fulfilling Table 8.1, and $N_{\text{Generated WZ} \rightarrow 3\ell\nu}^{\text{MC Phase Space}}$ is the total number of events in the WZ Monte Carlo sample with $|m_{\ell\ell} - m_z| < 20 \text{ GeV}$ defining the analysis measurement phase space¹. Notice that each generated event shall be corrected or reweighted by the pileup correction described in Section 7.3 from Chapter 7.

Analogously, the ε term in Equation (8.4) takes account of the probability that a WZ event is actually measured due to detector effects. In particular, the reconstruction, isolation, identification and trigger efficiencies are included in this term, as well as the efficiency of the selection cuts described in Chapter 6. This correction factor essentially gives the probability of reconstructing an event, given that all objects in the event would have been in the detector. The efficiency can be factorised as,

$$\varepsilon \equiv P(\text{Measured}|\mathcal{A}) = P(\text{PAC}|LS)P(LS|TF)P(TF|\mathcal{A}) \quad (8.6)$$

where the abbreviation used in the above formula stands for,

- PAC: *Pass analysis event cuts* described in Section 6.6 of Chapter 6 to select the events.

¹The generation of the WZ process includes the interference term of Z/γ^* which introduces divergences in the $W^\pm Z$ cross section theoretical calculation and, consequently, in the event generation, at very low m_{Z/γ^*} . See details in Section 2.1 of Chapter 2.

- LS: *Lepton object selection*, which are the quality cuts in reconstruction, identification and isolation specified in Sections 6.3 and 6.4 from Chapter 6 to select the leptons objects to be used in the analysis.
- TF: *Trigger fired*, i.e. an event was stored by the trigger paths described in Section 6.2 of Chapter 6.

Therefore, the probability that an event inside acceptance has actually been measured is split in the probability that an event inside acceptance has been stored because the trigger decision, and once the event is stored, the probability that the lepton objects in the event fulfil the quality criteria of the analysis, and once there are three good-quality leptons, the probability that the event pass all the analysis cuts. Again, the probabilities are renamed,

$$P(PAC|LS) \equiv \varepsilon_{event}$$

$$P(LS|TF) \equiv \varepsilon_{leptons}$$

$$P(TF|\mathcal{A}) \equiv \varepsilon_{trigger}$$

Notice that $\varepsilon_{leptons} \cdot \varepsilon_{trigger}$ may be factorised into individual lepton efficiencies, $\varepsilon_{leptons} \cdot \varepsilon_{trigger} = \varepsilon_{\ell_1} \varepsilon_{\ell_2} \varepsilon_{\ell_3}$. In turn, each individual lepton efficiency is decomposed in the product of the efficiencies of the full reconstruction chain of each object:

$$\varepsilon_{\ell_i} = \varepsilon_{trigger|iso} \cdot \varepsilon_{iso|id} \cdot \varepsilon_{id|reco} \cdot \varepsilon_{reco} \quad (8.7)$$

The lepton object efficiencies have already been introduced and calculated in Sections 6.3.1 and 6.4.1 using tag and probe methods.

The probability of any event to pass the analysis cuts, ε_{event} , may be extracted again using Monte Carlo simulated data by re-expressing the corrections $\mathcal{A} \cdot \varepsilon$ as,

$$\mathcal{A} \cdot \varepsilon = (\mathcal{A} \cdot \varepsilon^{sim}) \left(\frac{\varepsilon}{\varepsilon^{sim}} \right) \equiv \mathcal{C} \cdot \rho, \quad (8.8)$$

where ε^{sim} is the efficiency to measure an event inside acceptance in simulation. The factor ρ corrects the differences in between efficiencies evaluated in experimental with respect to the simulation data. This factor involves the lepton SFs introduced in Chapter 6, and allows to leave the observed experimental

data uncorrected whereas it is the simulated data which assume the efficiency corrections. The factor $\mathcal{C}$ deals with Monte Carlo simulation only and allows to use the WZ Monte Carlo simulated sample to count how many generated events pass the analysis cuts, and with a frequentist approach of probabilities, to measure the acceptance and efficiency as the ratio between passing-analysis events over generated events. Therefore, the calculation of event efficiency is not made explicitly in order to avoid resolution effects of the detector, but it is embedded in the $\mathcal{C}$ factor together with the acceptance. In practice, as the event reconstruction in Monte Carlo simulation also involves the reconstruction efficiencies of the leptons in the events; the acceptance, efficiency and the ρ factor are extracted at once using the WZ Monte Carlo simulated sample as,

$$\mathcal{A} \cdot \varepsilon^{sim} \cdot \rho = \mathcal{C} \cdot \rho = \frac{N_{\text{Reconstructed } WZ \rightarrow 3\ell\nu}^{\text{MC Pass Analysis Cuts}} \cdot SF_{leptons}}{N_{\text{Generated } WZ \rightarrow 3\ell\nu}^{\text{MC Phase Space}}} \quad (8.9)$$

where $SF_{leptons}$ are the scale factors used to account the discrepancies of the $\varepsilon_{leptons}$ efficiencies between data and simulation¹ and it is understood to be applied on an event-by-event level. As the Monte Carlo sample used to simulate the signal is not an inclusive sample, but $WZ \rightarrow \ell'\nu\ell^+\ell^-$ ($\ell, \ell' = \mu, e, \tau$), in order to obtain the inclusive cross section with the acceptance and efficiencies $\mathcal{C} \cdot \rho$ extracted from this sample, the cross section calculated shall be corrected explicitly by the branching ratio,

$$\sigma = \frac{N_S}{\mathcal{C} \cdot \rho \cdot \mathcal{BR}(WZ \rightarrow \ell'\nu\ell^+\ell^-) \cdot \mathcal{L}_{int}} \quad (8.10)$$

where $\mathcal{BR}(WZ \rightarrow \ell'\nu\ell^+\ell^-) = \mathcal{BR}(W \rightarrow \ell'\nu) \cdot \mathcal{BR}(Z \rightarrow \ell^+\ell^-) = 0.0329 \pm 0.0003$ [24].

The uncertainty associated to the cross section measurement is reported regarding the source of uncertainty,

$$\Delta\sigma = (\Delta\sigma)_{\text{stats}} \oplus (\Delta\sigma)_{\text{sys}} \oplus (\Delta\sigma)_{\text{lumi}} \quad (8.11)$$

where $(\Delta\sigma)_{\text{stats}}$ is referring to the statistical uncertainty, $(\Delta\sigma)_{\text{sys}}$ is the systematic uncertainty described in Section 8.3, and $(\Delta\sigma)_{\text{lumi}}$ the systematic uncertainty

¹See detailed description and obtained values in Sections 6.3.1 and 6.4.1 in Chapter 6.

associated with the measurement of the luminosity.

8.2. Cross section measurements results

The WZ analysis performed in this thesis work is based in the Equation (8.4). The several ingredients composing the aforementioned equation, described in previous section, have been measured along the previous Chapters, therefore the last stage of the analysis is to harvest them to obtain the cross section measurement.

	$3e$	$2e1\mu$	$1e2\mu$	3μ
$N_{\mathcal{P}\mathcal{P}\mathcal{P}}^{N_{t3}}$	62 ± 8	61 ± 8	68 ± 8	95 ± 10
N_{ZZ}^{MC}	1.95 ± 0.02	3.46 ± 0.04	2.68 ± 0.03	4.83 ± 0.03
$N_{V\gamma}^{MC}$	–	–	0.51 ± 0.51	–
N_S	60 ± 8	57 ± 8	65 ± 8	90 ± 10

TABLE 8.2: Number of observed signal N_S for each measured channel, given the data-driven estimation of the prompt-prompt-prompt sample and the subtracted MC-simulated background ZZ and $V\gamma$. Errors shown are originated from the finite number of events simulated in the MC samples and from the statistical errors of the prompt and fake rates used to estimate the $\mathcal{P}\mathcal{P}\mathcal{P}$ contribution. The MC samples are normalised to the integrated luminosity achieved in 2011 data of $\mathcal{L} = 4.9 \text{ fb}^{-1}$.

The number of signal observed after the selection cuts is obtained by the data-driven FOM¹, and subtracting the Monte Carlo-estimated background yields²

$$N_S = N_{\mathcal{P}\mathcal{P}\mathcal{P}}^{N_{t3}} - N_{bkg}^{MC} \quad (8.12)$$

The N_{bkg}^{MC} is composed by the Monte Carlo-simulated processes ZZ , $Z\gamma$ (and VVV [$V=W,Z,\gamma$] in the 2012 analysis). The obtained yields for the 2011 and 2012 analyses and the four measured channels are summarised in Tables 8.2 and 8.3.

The correction factors have been extracted using the procedure explained at previous section, in particular, expressions (8.5) and (8.8), and they are reported

¹Described in detail in previous Chapter 7

²See detailed description of corrections applied to simulated samples in Section 7.3 from Chapter 7.

	$3e$	$2e1\mu$	$1e2\mu$	3μ
$N_{\mathcal{P}\mathcal{P}\mathcal{P}}^{N_{t3}}$	220 ± 15	260 ± 16	352 ± 19	498 ± 22
N_{VVV}^{MC}	6.1 ± 0.3	7.9 ± 0.3	10.4 ± 0.4	13.4 ± 0.4
N_{ZZ}^{MC}	2.42 ± 0.08	3.10 ± 0.09	3.9 ± 0.1	5.8 ± 0.1
$N_{V\gamma}^{MC}$	2.5 ± 0.9	0.4 ± 0.4	4.0 ± 1.2	2.2 ± 0.7
N_S	209 ± 15	249 ± 16	334 ± 19	477 ± 22

TABLE 8.3: Number of observed signal N_S for each measured channel, given the data-driven estimation of the prompt-prompt-prompt sample and the subtracted MC-simulated background VVV, ZZ, $V\gamma$. Errors shown are originated from the finite number of events simulated in the MC samples and from the statistical errors of the prompt and fake rates used to estimate the $\mathcal{P}\mathcal{P}\mathcal{P}$ contribution. The MC samples are normalised to the integrated luminosity achieved in 2012 data of $\mathcal{L} = 19.6 \text{ fb}^{-1}$.

in Tables 8.4.

Therefore, the Equation (8.4) is used to perform the cross section measurement $\sigma(pp \rightarrow WZ \rightarrow \ell'\nu\ell^+\ell^-)$ in four different and exhaustive channels: eee , μee , $e\mu\mu$ and $\mu\mu\mu$. The final state channels are defined by the leptonic decay of the $W \rightarrow \ell'\nu_\ell$ and $Z \rightarrow \ell^+\ell^-$ ($\ell, \ell' = e, \mu, \tau$), where the τ -decay is accounted to a given channel when decays to electron or muon. The results for each channel are given in Tables 8.4 and 8.5.

	$\mathcal{A} [\%]$	$\mathcal{C} [\%]$	ρ	N_S	$\sigma(pp \rightarrow WZ + X) [\text{pb}]$
eee	5.09 ± 0.03	1.595 ± 0.014	1.01 ± 0.01	60 ± 8	$23.00 \pm 3.10_{\text{stat}} \pm 1.39_{\text{sys}} \pm 0.51_{\text{lumi}}$
μee	5.04 ± 0.03	1.868 ± 0.016	0.96 ± 0.01	57 ± 8	$19.67 \pm 2.73_{\text{stat}} \pm 1.50_{\text{sys}} \pm 0.43_{\text{lumi}}$
$e\mu\mu$	5.04 ± 0.03	2.312 ± 0.017	0.87 ± 0.01	65 ± 8	$19.81 \pm 2.60_{\text{stat}} \pm 1.55_{\text{sys}} \pm 0.44_{\text{lumi}}$
$\mu\mu\mu$	4.89 ± 0.03	2.859 ± 0.019	0.93 ± 0.01	91 ± 10	$21.02 \pm 2.30_{\text{stat}} \pm 1.47_{\text{sys}} \pm 0.46_{\text{lumi}}$

TABLE 8.4: Acceptance ($\mathcal{A}$), acceptance and event efficiency in simulation ($\mathcal{C}$), experimental-simulation efficiency factor (ρ), number of signal observed and inclusive WZ cross section, measured by channel. The cross section errors are split in statistical, systematic and luminosity origin (see next section). The errors reported for the other factors are statistical only. Notice that the low acceptance is due to the wide signal definition, where each channel final state is defined from the whole leptonic WZ decay. Results for 7 TeV.

	$\mathcal{A}$ [%]	$\mathcal{C}$ [%]	ρ	N_S	$\sigma(pp \rightarrow WZ + X)$ [pb]
eee	4.57 ± 0.02	1.46 ± 0.05	0.89 ± 0.05	209 ± 15	$24.92 \pm 1.83_{\text{stat.}} \pm 1.25_{\text{syst}} \pm 1.10_{\text{lumi}}$
μee	4.58 ± 0.02	1.78 ± 0.07	0.93 ± 0.05	249 ± 16	$23.42 \pm 1.59_{\text{stat.}} \pm 1.11_{\text{syst}} \pm 1.03_{\text{lumi}}$
$e\mu\mu$	4.53 ± 0.02	2.22 ± 0.09	0.96 ± 0.06	334 ± 19	$24.40 \pm 1.46_{\text{stat.}} \pm 1.33_{\text{syst}} \pm 1.07_{\text{lumi}}$
$\mu\mu\mu$	4.46 ± 0.02	2.90 ± 0.12	0.99 ± 0.06	477 ± 22	$25.71 \pm 1.27_{\text{stat.}} \pm 1.34_{\text{syst}} \pm 1.13_{\text{lumi}}$

TABLE 8.5: Acceptance ($\mathcal{A}$), acceptance and event efficiency in simulation ($\mathcal{C}$), experimental-simulation efficiency factor (ρ), number of signal observed and inclusive WZ cross section, measured by channel. The cross section errors are split in statistical, systematic and luminosity origin (see next section). The errors reported for the other factors are statistical only. Note that the low acceptance is due to the wide signal definition, where each channel final state is defined from the whole leptonic WZ decay. Results for 8 TeV.

8.3. Systematic uncertainty

Each measured observable used to calculate the cross section per channel have been determined with a degree of uncertainty. Besides of the statistical uncertainty, related with the finite number of measurements performed, sources of systematic uncertainties have been identified and evaluated for each term of Equation (8.10) and subsequently propagated to the cross section measurement per channel. The factorisation performed to the efficiency term, $\mathcal{A} \cdot \varepsilon = \mathcal{C} \cdot \rho$, allows to evaluate separately the theoretical and experimental sources of systematic uncertainty. The $\mathcal{C} = \mathcal{A} \cdot \varepsilon^{\text{sim}}$ factor concerns both sources of uncertainty in the theoretical models used to generate the WZ Monte Carlo simulated sample and in the detector performance such the scale factors and resolution of the final-state objects. The $\rho = \varepsilon/\varepsilon^{\text{sim}}$ factor, which corrects the detector efficiency in the simulation $\mathcal{C}$ with the detector efficiency in experimental data, is mainly characterised by the SFs of the trigger, reconstruction and identification requirements of the lepton objects of the analysis, and consequently, affected by the uncertainties of those SFs. The N_S observable, built as $N_S = N_{\mathcal{P}\mathcal{P}\mathcal{P}}^{N_{t3}} - N_{bkg}^{MC}$, involves the systematic uncertainty assigned to the data-driven method for the $N_{\mathcal{P}\mathcal{P}\mathcal{P}}^{N_{t3}}$ measurement, and the same sources of systematic considered in the $\mathcal{C}$ factor but applied to the Monte Carlo background samples. In addition, the cross section uncertainties of each simulated sample is also considered. Finally, the uncertainty of the integrated luminosity measurement is included as a source of systematic uncertainty as well

and propagated to the cross section measurement along with all the aforementioned sources.

Systematic uncertainties affecting $\mathcal{C}$

The considered theoretical uncertainties on $\mathcal{A}$ arises from the PDF set choice to simulate the WZ Monte Carlo sample and the uncertainties quoted for the PDF, in addition to the QCD renormalisation and factorisation scales used to generate the WZ Monte Carlo simulation. The PDF are fit to a phenomenological function using several parameters ($i = 1, \dots, N$) from available experimental data (see Section 1.3 of Chapter 1). The best fit is used as the central value PDF, but by modifying $\pm 1\sigma_i$ each fitted parameter separately is possible to obtain as many PDFs functions as parameters the function have. Therefore, each PDF collaboration provides a set of $N + 1$ PDF, one for the best fit, used to the Monte Carlo simulations, and the other N used to propagate the uncertainties. Further details may be obtained from Reference [83]. The effect of the PDF uncertainties in the acceptance is studied by recalculating the acceptance using the N -subset of functions¹. The maximum and minimum variation with respect the acceptance calculated with the central PDF is taken as systematic uncertainty. The other theoretical systematic associated to the modelling of the Monte Carlo samples is the choice of the QCD renormalisation μ_R and factorisation μ_F scales [84]. The nominal values used in the WZ simulated sample are $\mu_R^0 = \mu_F^0 = (M_W + M_Z)/2$. The usual variation by a factor of two up and down with respect the nominal values ($2\mu_R^0$, $\mu_R^0/2$, $2\mu_F^0$ and $\mu_F^0/2$) is evaluated independently in the acceptance, taking the biggest difference between the nominal and the varied scales as the systematic uncertainty due to the QCD scales choice.

The detector performance uncertainties are studied by the uncertainties of each involved parameter used to correct the data (see Chapter 5, Section 5.1), namely the muon momentum and electron energy scales, the E_T^{miss} scale and resolution and the pileup re-weighting. The muon momentum and the electron energy scale have been corrected (see Chapter 5, Section 5.1.2), introducing an associated uncertainty in the measurement: 1% for muon momentum scale and 2% (5%) for

¹In fact, the effect is obtained using the *master equations* of Reference [83].

barrel (endcap) electron energy scale. These variations have been used to shift up and down the measured momentum (energy) in the signal and background simulated samples and the recalculated yields have been compared with the nominal ones, taking as systematic uncertainty the difference between them. The E_T^{miss} scale and resolution is evaluated from their components. Since the E_T^{miss} is inferred from the sum of the transverse momenta of all the observed particles in the event, the E_T^{miss} is broken into its components (jets, leptons, unclustered energy) and their scales and resolutions are varied by their uncertainties. The maximum and minimum values for the recalculated E_T^{miss} are used to perform again the analysis selection with all the Monte Carlo samples obtaining new yields. The relative yields difference with respect the nominal ones is accounted as the systematic uncertainty. Finally, the weighting process done in the simulated samples in order to match the interaction multiplicity distribution observed in the experimental data assumes a inelastic proton-proton cross section of $\sigma_{pp} = 73.5$ mb with a 5% of uncertainty. This uncertainty is used to shift up and down the inelastic p-p cross section, resulting in a $\pm 1\sigma$ variation in the Poisson distribution of the mean number of interactions (see Chapter 7, Section 7.3), and therefore, obtaining a new weights to use with the simulated samples. Using these new weights the yields obtained are compared with the yields using the nominal Poisson distribution, and the relative differences are assigned as systematic of the re-weighting process.

Systematic uncertainties affecting ρ

The ρ factor, which takes into account the discrepancies in the experimental versus simulated data efficiencies, is described by the correction factors, i.e. the SFs, of the efficiencies of the trigger and final-state objects selection outlined in Section 5.1.1. The SFs have been estimated by the ratio of experimental over simulated data efficiencies as it is described in Sections 6.3.1 and 6.4.1. The uncertainties of the efficiencies determination by the tag and probe method are propagated to the ratio. The sources of uncertainties are the limited statistics for the different categories used to extract the efficiencies, and the different shapes used for the fits of the Z resonance and backgrounds. The statistical error is of the order of 1%. The systematic uncertainty from the shapes used to fit the mass

peak is about another 1-2%. The shape systematic was calculated in two different ways: varying the parameters that defined the fitting function and, conversely, using different functions for the shapes. Nevertheless, this systematic is partially cancelled out when calculating the scale factors because of the fact that the fitting functions for data and simulated samples were change in the same way.

The effect of this uncertainty to the analysis is studied by varying each SF independently, using the varied SF to weight the simulated samples. The obtained yields with the modified scale factor is compared with the nominal SF's yields being the relative difference estimated as systematic uncertainty.

Systematic uncertainties affecting N_S

The estimated number of signal is obtained by subtracting to the $\mathcal{PPP}$ estimation of the data driven method the background estimated with Monte Carlo simulation. Therefore, the systematic uncertainties introduced by the FOM and the theoretical or measured uncertainties on the cross sections assigned to the Monte Carlo simulated backgrounds are considered as systematic sources of N_S . The systematic uncertainty assigned to the $\mathcal{PPP}$ estimation emerges because of the particular choice of the leading jet transverse energy cut used to bias the jet-induced enriched region as it is described in Section 7.2.5. The theoretical uncertainty on the cross section assigned to the background estimated with Monte Carlo simulations are 14% (15%) for the 2011 (2012) ZZ sample extracted from CMS measurements results in experimental data [85], [86]; and 7% (15%) for the $Z\gamma$ 2011 (2012) cross section¹, also extracted from CMS results [87].

Systematic uncertainties affecting $\mathcal{L}$

The integrated luminosity $\mathcal{L}_{int}$ is measured by a dedicated group in the CMS collaboration, providing a centralised measure of $\mathcal{L}_{int}$ to be used by all the analyses performed. The last 2011 measure [88] of the total integrated luminosity is affected by 2.2% of uncertainty, while for 2012 the uncertainty quoted [89] is 4.4%.

The systematic uncertainties described above have been propagated to the cross section measurement. Tables 8.6 and 8.7 reports the relative uncertainty on the

¹The 2012 uncertainty is in fact an extrapolation of the 2011.

cross section measurement introduced by each source of systematic uncertainty. The data-driven and E_T^{miss} scale and resolution are the dominant sources of systematic uncertainties in each cross section measured channel.

	eee [%]	$ee\mu$ [%]	$e\mu\mu$ [%]	$\mu\mu\mu$ [%]
Lepton and Trigger efficiency	2.8	2.5	1.9	1.4
Muon momentum scale	–	0.6	0.4	1.1
Electron energy scale	1.9	0.6	1.2	–
E_T^{miss} scale and resolution	3.7	3.4	4.3	3.7
Fakeable object method	2.5	5.8	5.6	5.2
pile-up re-weighting	0.3	0.5	1.0	0.7
PDFs	1.5	1.5	1.5	1.5
μ_F, μ_R scales	1.3	1.3	1.3	1.3
Theoretical MC cross-sections	0.4	0.8	0.6	0.7
Acceptance stat. error	1.0	0.9	0.9	1.6

TABLE 8.6: Summary of systematic uncertainties considered on the 2011 cross section measurement shown in each measured channel. The values report the relative uncertainty introduced by each source of systematic on the cross section showing its final impact in the measurement, $(\delta\sigma_{WZ})_{sys}^i/\sigma_{WZ} \cdot 100$.

	eee [%]	$ee\mu$ [%]	$e\mu\mu$ [%]	$\mu\mu\mu$ [%]
Lepton and Trigger efficiency	1.8	1.8	1.8	1.8
Muon momentum scale	–	0.4	0.9	1.1
Electron energy scale	0.8	0.6	0.1	–
E_T^{miss} scale and resolution	2.9	2.9	3.5	3.1
Fakeable object method	2.7	1.9	2.7	2.6
pileup re-weighting	0.8	1.1	0.6	0.9
PDFs	1.4	1.4	1.4	1.4
μ_F, μ_R scales	1.6	1.6	1.6	1.6
Theoretical MC cross sections	0.3	0.2	0.3	0.2
Acceptance stat. error	0.8	1.2	1.1	1.0

TABLE 8.7: Summary of systematic uncertainties considered on the 2012 cross section measurement shown in each measured channel. The values report the relative uncertainty introduced by each source of systematic on the cross section showing its final impact in the measurement, $(\delta\sigma_{WZ})_{sys}^i/\sigma_{WZ} \cdot 100$.

8.4. Cross section combination

The final cross section estimation is obtained by combining the cross section measurements in the different channels, taking into account the correlation in the uncertainties using the Best Linear Unbiased Estimator (BLUE) method [90]. The method defines the combined cross section as the linear combination of the measured cross sections in each channel

$$\sigma(W^\pm Z \rightarrow \ell'^\pm \nu_{\ell'} \ell^\pm \ell^-) = \sum_{i=1}^4 \alpha_i \sigma_i \quad (8.13)$$

where the i -index is referring to the four measured channels $3e$, $1\mu 2e$, $1e 2\mu$ and 3μ , σ_i are the cross section measurements in each channel and α_i are the weights to be obtained by minimising the variance. The unbiased requirement implies

$$\sum_{i=1}^4 \alpha_i = 1 \quad (8.14)$$

And from Equation (8.13), the variance is deduced as,

$$Var(\sigma) = \boldsymbol{\alpha}^T \mathbf{E} \boldsymbol{\alpha} \quad (8.15)$$

being $\boldsymbol{\alpha}$ the vector of weighting factors α_i , $\boldsymbol{\alpha}^T$ its transpose and $\mathbf{E}$ the error matrix, where its diagonal elements give the variances of the individual measurements, while the off-diagonal elements describe the correlations between pair of measurements,

$$\mathbf{E} = \begin{pmatrix} Var(\sigma_1) & Covar(\sigma_1, \sigma_2) & Cov(\sigma_1, \sigma_3) & Cov(\sigma_1, \sigma_4) \\ Cov(\sigma_2, \sigma_1) & Var(\sigma_2) & Cov(\sigma_2, \sigma_3) & Cov(\sigma_2, \sigma_4) \\ Cov(\sigma_3, \sigma_1) & Cov(\sigma_3, \sigma_2) & Var(\sigma_3) & Cov(\sigma_3, \sigma_4) \\ Cov(\sigma_4, \sigma_1) & Cov(\sigma_4, \sigma_2) & Cov(\sigma_4, \sigma_3) & Var(\sigma_4) \end{pmatrix} \quad (8.16)$$

Notice that the correlations are only considered as fully correlated or uncorrelated,

$$Cov(\sigma_i, \sigma_j) = r \cdot \sqrt{Var(\sigma_i) \cdot Var(\sigma_j)}, \quad r = 0 \text{ or } 1 \quad (8.17)$$

The minimisation of the variance is accomplished by the method of Lagrangian multipliers to give,

$$\boldsymbol{\alpha} = \frac{\mathbf{E}^{-1}\mathbf{U}}{\mathbf{U}^T\mathbf{E}^{-1}\mathbf{U}} \quad (8.18)$$

where $\mathbf{E}^{-1}$ is the inverse of the error matrix, and $\mathbf{U}$ a vector whose four components are all unity.

In order to build the error matrix, the uncertainty errors have been considered

- fully correlated between all channels:
 - E_T^{miss} energy scale and resolution
 - pileup re-weighting
 - PDF choice
 - renormalisation and factorisation scales
 - cross sections of Monte Carlo estimated backgrounds
- fully correlated between electron (muon) channels:
 - Electron energy (muon momentum) scale
 - Electron (muon) reconstruction, identification and isolation scale factors uncertainties from the tag and probe method
- fully correlated between $ee\mu$ and eee ($\mu\mu e$ and $\mu\mu\mu$) channels:
 - Double electron (muon) trigger efficiency
- uncorrelated between channels:
 - Scale factor's statistical errors
 - data driven uncertainty
 - Statistical errors

The error matrix obtained for 2011 analysis is

$$\mathbf{E} = \begin{pmatrix} 11.73 & 1.32 & 1.45 & 1.25 \\ 1.32 & 8.62 & 1.15 & 1.06 \\ 1.45 & 1.15 & 8.09 & 1.16 \\ 1.25 & 1.06 & 1.16 & 6.54 \end{pmatrix} pb^2, \quad (8.19)$$

giving a weighting factors of $\alpha_{3e} = 0.159$, $\alpha_{1\mu 2e} = 0.245$, $\alpha_{1e 2\mu} = 0.256$ and $\alpha_{3\mu} = 0.340$. The final estimated cross section for the WZ process at 7 TeV in the phase space $M_{ll} \in 91.1876 \pm 20 \text{ GeV}/c^2$ is measured to be:

$$\sigma_{7 \text{ TeV}}(pp \rightarrow \text{WZ} + X) = 20.8 \pm 1.3_{\text{stat}} \pm 1.1_{\text{sys}} \pm 0.5_{\text{lumi}} \text{ pb}$$

The measurement is compatible with the NLO prediction obtained in Chapter 2, $17.8^{+0.7}_{-0.5} \text{ pb}$, although is noticeable a $1.5\text{-}\sigma$ deviation from the theoretical value. Figure 8.1a shows the ratio between measured and predicted cross section in each of the measured channels.

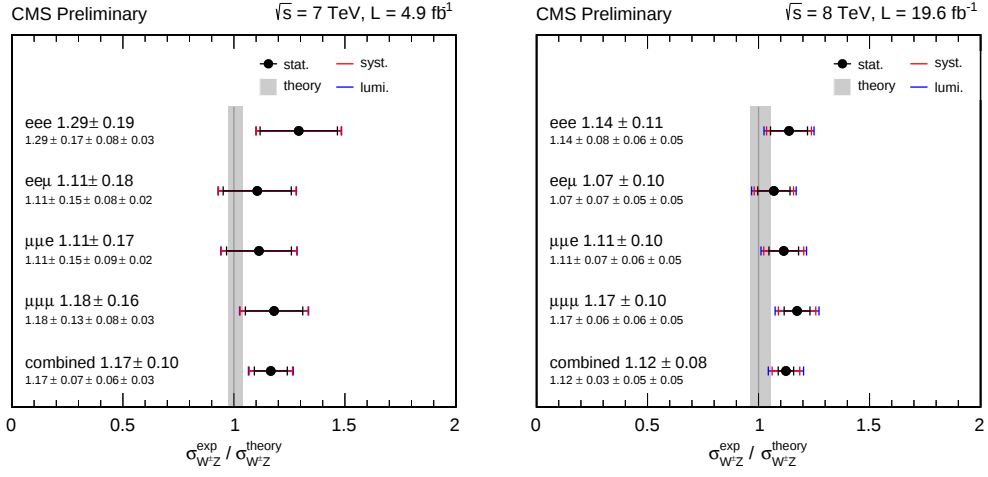
The error matrix obtained for 2012 analysis is

$$\mathbf{E} = \begin{pmatrix} 4.90 & 1.06 & 1.18 & 1.17 \\ 1.06 & 3.77 & 1.15 & 1.16 \\ 1.18 & 1.15 & 3.93 & 1.35 \\ 1.17 & 1.16 & 1.35 & 3.44 \end{pmatrix} pb^2 \quad (8.20)$$

giving a weighting factors of $\alpha_{3e} = 0.195$, $\alpha_{1\mu 2e} = 0.279$, $\alpha_{1e 2\mu} = 0.235$ and $\alpha_{3\mu} = 0.290$. The final estimated cross section for the WZ process at 8 TeV in the phase space $M_{ll} \in 91.1876 \pm 20 \text{ GeV}/c^2$ is measured to be:

$$\sigma_{8 \text{ TeV}}(pp \rightarrow \text{WZ} + X) = 24.6 \pm 0.8_{\text{stat}} \pm 1.1_{\text{sys}} \pm 1.1_{\text{lumi}} \text{ pb}$$

The measurement is compatible with the NLO prediction obtained in Chapter 2, $21.9^{+0.9}_{-0.5} \text{ pb}$, and, similar to the 7 TeV measurement, a $1.3\text{-}\sigma$ deviation from the theoretical value can be observed. Figure 8.1b shows the ratio between measured and predicted cross section in each of the measured channels.



(A) 7 TeV measurement. The NLO prediction is $17.8^{+0.7}_{-0.5} \text{ pb}$. (B) 8 TeV measurement. The NLO prediction is $21.9^{+0.9}_{-0.5} \text{ pb}$.

FIGURE 8.1: Ratio of measured cross section over the theoretical prediction for each measured channel and the BLUE method combined measurement. Each row in the plot shows the measured channel, the ratio value and the uncertainty error (also split in statistical, systematic and luminosity source in the line below each channel).

CHAPTER 9

Measurement of W^-Z and W^+Z cross sections ratio

Since the LHC is a proton-proton collider, the W^+Z and W^-Z cross sections are not equal. As it was described in chapter 2, the dominant production mechanism of W^+Z bosons involves an up-type quark and a down-type antiquark while a down-type quark and up-type antiquark is required to produce W^-Z . The predominance of the valence u-quark in the protons enhances the W^+Z production in front of the W^-Z ; therefore, an overall excess of W^+Z events over W^-Z is expected.

This chapter describes the strategy followed to measure the cross section ratio $\sigma_{W^-Z}/\sigma_{W^+Z}$ which is fully based in the WZ inclusive cross section measurement developed in the previous chapters. Therefore, the signal definitions, background description, analysis strategy and systematic uncertainties from the previous cross section analysis remain valid. Accordingly, in this chapter we will point out the peculiarities that the charge's split of the samples introduces to the analysis. Control distributions are also shown along with the event yields obtained in each measurement. Finally, the cross section ratio is calculated in four independent lepton-flavour channels which are combined to obtain the final result.

9.1. Event selection

The signal definition for the inclusive analysis (see Chapter 6) is slightly modified to define two exhaustive regions from the inclusive signal by evaluating the charge of the W candidate lepton. A positive lepton identifies the W^+Z signal whilst a negative lepton identifies the W^-Z . Therefore, the analysis strategy is entirely based in the inclusive cut-based analysis selection presented in Chapter 6 and performed in these two regions defined by the charge of the W-candidate lepton. Consequently, the *Lepton preselection* and the *Z candidate selection* stages are common to both regions given that the W-candidate lepton is still not defined at those levels of the analysis. The number of events for the four measured channels are reported in Tables 9.1 and 9.2. It is worthwhile to mention that, as expected, the yield differences between opposite-charged final states are coming from the WZ production, since every background process generates the W-candidate lepton, whether it is a fake lepton as a lost-by-acceptance lepton, with a charge democratically populated.

	W^+	W^-
Data-driven bkg.	1.0 ± 0.3	1.1 ± 0.3
ZZ	0.99 ± 0.02	0.96 ± 0.02
$V\gamma$	0 ± 0	0 ± 0
$WZ \rightarrow 3\ell\nu$	28.5 ± 0.4	16.3 ± 0.3
Total expect.	30.5 ± 0.5	18.3 ± 0.4
Data	36	28

(A) *Three electron final state*

	W^+	W^-
Data-driven bkg.	0.63 ± 0.18	0.8 ± 0.2
ZZ	1.81 ± 0.03	1.65 ± 0.02
$V\gamma$	0 ± 0	0 ± 0
$WZ \rightarrow 3\ell\nu$	32.3 ± 0.4	18.1 ± 0.3
Total expect.	34.8 ± 0.4	20.5 ± 0.4
Data	40	22

(B) *Two electron and one muon final state*

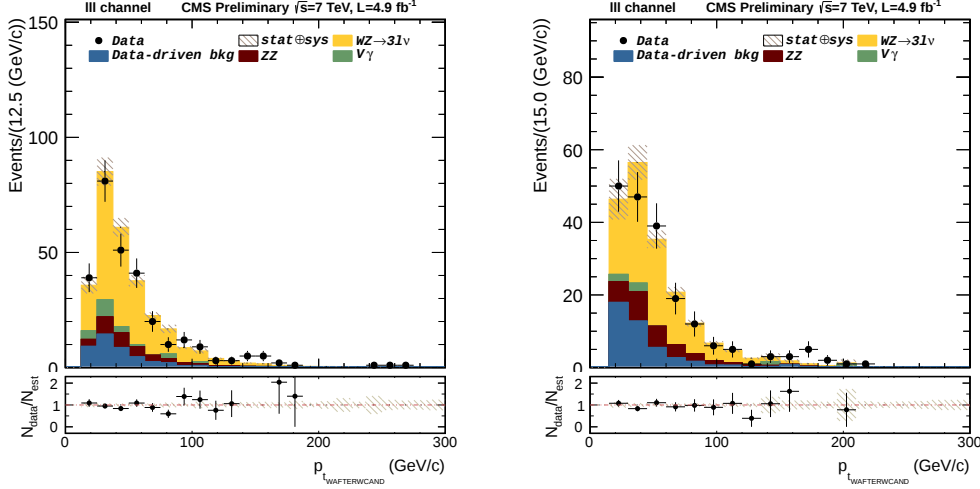
	W^+	W^-
Data-driven bkg.	1.1 ± 0.3	1.4 ± 0.3
ZZ	1.37 ± 0.02	1.32 ± 0.02
$V\gamma$	0.5 ± 0.5	0.003 ± 0.003
$WZ \rightarrow 3\ell\nu$	35.7 ± 0.4	20.1 ± 0.3
Total expect.	38.7 ± 0.7	22.8 ± 0.4
Data	48	22

(C) *Two muons and one electron final state*

	W^+	W^-
Data-driven bkg.	1.2 ± 0.2	0.56 ± 0.14
ZZ	2.53 ± 0.02	2.30 ± 0.02
$V\gamma$	0 ± 0	0.00 ± 0.00
$WZ \rightarrow 3\ell\nu$	48.2 ± 0.5	26.9 ± 0.4
Total expect.	51.9 ± 0.5	29.7 ± 0.4
Data	52	45

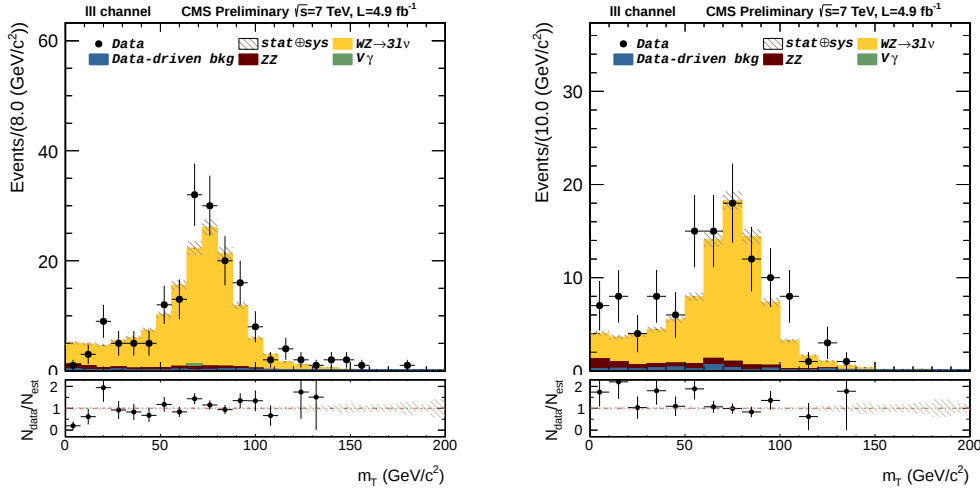
(D) *Three muons final state*

TABLE 9.1: Number of events selected in the four leptonic channels investigated for the 2011 analysis. The MC samples are normalised to $\mathcal{L}_{int} = 4.9 \text{ fb}^{-1}$. The first column of results is obtained requiring a third positive lepton as W candidate, while the second column is obtained by requiring a negative W-candidate lepton. The errors shown are statistical only.



(A) Positively charged W-candidate lepton (B) Negatively charged W-candidate lepton

FIGURE 9.1: Transverse momentum distributions for the W-lepton selected candidate once the W-candidate requirement have been applied in the selection. The MC samples are normalised to the 2011 integrated luminosity, $\mathcal{L}_{int} = 4.9 \text{ fb}^{-1}$.



(A) Positively charged W-candidate lepton (B) Negatively charged W-candidate lepton

FIGURE 9.2: Transverse mass distribution built with the W-lepton candidate and the E_T^{miss} once the W-candidate requirement have been applied in the selection. The MC samples are normalised to the 2011 integrated luminosity, $\mathcal{L}_{int} = 4.9 \text{ fb}^{-1}$.

	W^+	W^-
Data-driven bkg.	7.4 ± 1.0	7.5 ± 1.0
ZZ	1.22 ± 0.05	1.24 ± 0.05
$V\gamma$	0.9 ± 0.5	1.5 ± 0.8
WV	0 ± 0	0.1 ± 0.1
VVV	3.3 ± 0.2	2.7 ± 0.2
$WZ \rightarrow 3\ell\nu$	118.4 ± 1.1	75.5 ± 0.9
Total expect.	131.2 ± 1.6	88.5 ± 1.5
Data	138	97

(A) Three electron final state

	W^+	W^-
Data-driven bkg.	13 ± 2	14 ± 2
ZZ	1.60 ± 0.08	1.49 ± 0.07
$V\gamma$	0 ± 0	0.4 ± 0.4
WV	0 ± 0	0 ± 0
VVV	4.3 ± 0.2	3.6 ± 0.2
$WZ \rightarrow 3\ell\nu$	150.7 ± 1.3	95.2 ± 1.0
Total expect.	170 ± 2	115 ± 2
Data	179	109

(B) Two electron and one muon final state

	W^+	W^-
Data-driven bkg.	24 ± 2	24 ± 2
ZZ	2.0 ± 0.09	1.9 ± 0.09
$V\gamma$	1.8 ± 0.8	2.0 ± 0.9
WV	0.1 ± 0.1	0.1 ± 0.1
VVV	5.7 ± 0.3	4.7 ± 0.3
$WZ \rightarrow 3\ell\nu$	192.9 ± 1.5	123.0 ± 1.2
Total expect.	227 ± 3	155 ± 3
Data	254	146

(C) Two muons and one electron final state

	W^+	W^-
Data-driven bkg.	31 ± 3	29 ± 3
ZZ	3.0 ± 0.1	2.8 ± 0.1
$V\gamma$	0 ± 0	0 ± 0
WV	1.6 ± 0.7	0.6 ± 0.3
VVV	7.4 ± 0.3	6.0 ± 0.3
$WZ \rightarrow 3\ell\nu$	263.1 ± 1.7	164.9 ± 1.4
Total expect.	306 ± 4	203 ± 4
Data	344	213

(D) Three muons final state

TABLE 9.2: Number of events selected in the four leptonic channels investigated for the 2012 analysis. The MC samples are normalised to $\mathcal{L}_{int} = 19.6 \text{ fb}^{-1}$. The first column of results is obtained requiring a third positive lepton as W candidate, while the second column is obtained by requiring a negative W-candidate lepton. The errors shown are statistical only.

The observables distributions for both signals are equivalent to the inclusive analysis up to *W-candidate selection* stage when the specific charge for the W-lepton candidate is required. Thus, only distributions after the *W-candidate* stage is required are shown. Figures 9.1 show the transverse momentum of the W-lepton candidate for the W^+Z and W^-Z once the requirement is applied, just to control the possible differences in p_T spectra between both opposite-charged lepton. The p_T spectra should be a little bit harder for the positively charged lepton, as it will be explained in Section 9.2. Moreover, Figures 9.2 and Figures 9.3 summarise some of the main control distributions in both signal regions after all the analysis steps have been performed, showing a relative good agreement between the experimental data and the data-driven and Monte Carlo predictions.

The Appendix A contains a bunch of detailed distributions split by measured channel, both for 7 and 8 TeV, at each stage of the selection.

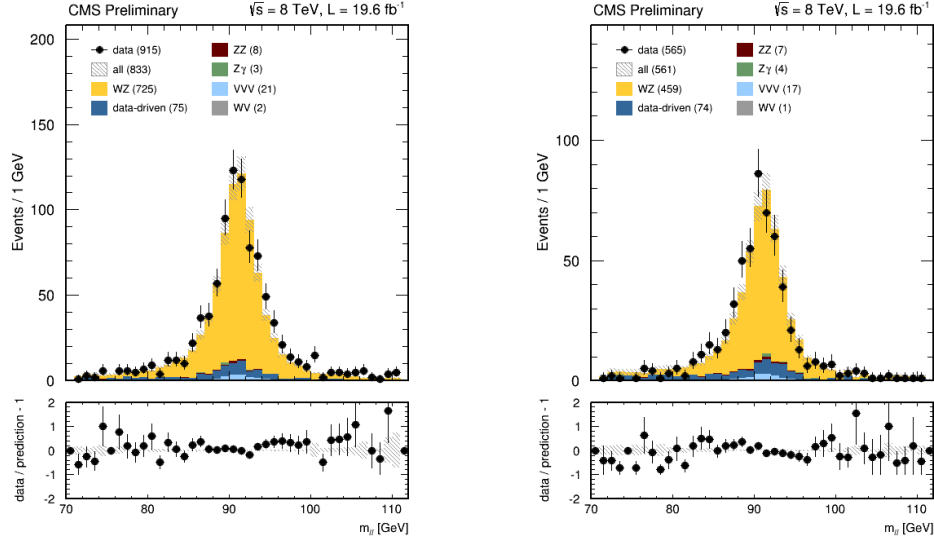
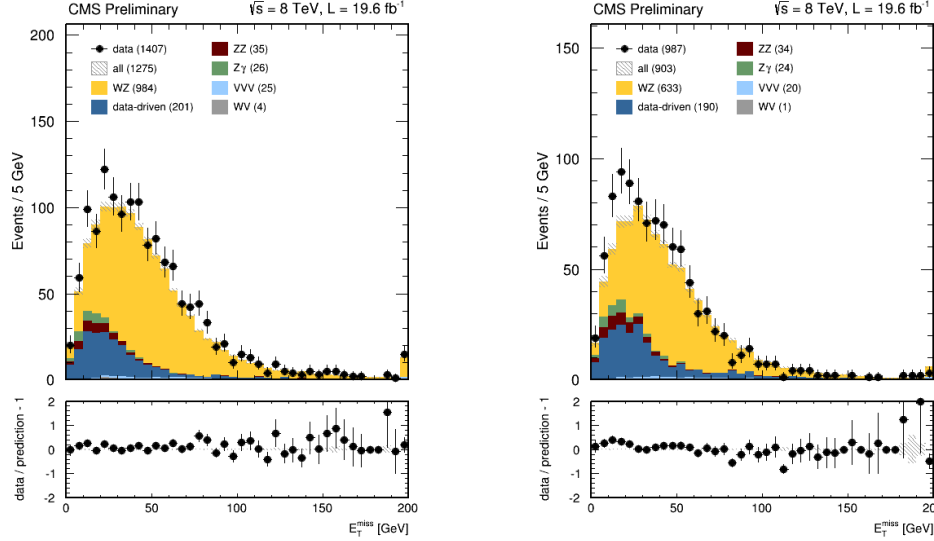
(A) Invariant mass of the Z-system for the W^+Z signal selection(B) Invariant mass of the Z-system for the W^-Z signal selection(C) E_T^{miss} distribution for the W^+Z signal selection, before the E_T^{miss} cut is applied(D) E_T^{miss} distribution for the W^-Z signal selection, before the E_T^{miss} cut is applied

FIGURE 9.3: Distributions once the full steps of the analysis cuts have been performed. The MC samples are normalised to the 2012 integrated luminosity, $\mathcal{L}_{\text{int}} = 19.6$ fb $^{-1}$.

9.2. Cross sections ratio measurements

The same technique applied to measured the inclusive cross section (Section 8.1) is exploited to measure the ratio of the W^-Z over W^+Z cross sections. Equation (8.10) applied to both W^+Z and W^-Z is divided to obtain,

$$\frac{\sigma_{W^-Z}}{\sigma_{W^+Z}} = \frac{N_S^- \mathcal{C}^+ \rho^+}{N_S^+ \mathcal{C}^- \rho^-} \quad (9.1)$$

Notice that the luminosity term is cancelled but the acceptance and efficiency in simulation, $\mathcal{C}$, and efficiency correction, ρ , are kept in the equation.

Keeping the $\mathcal{C}$ term in the above equation is mandatory because of the expected topological differences between the W^+Z and W^-Z production. The W^+Z process trends to be produced more boosted than the W^-Z due to the energy distribution of the quarks inside the proton. In particular, the up and anti-down quark pairs (W^+Z production) have been measured to carry the major fraction of the proton energy with higher probability than the down and anti-up pairs (W^-Z production), as it can be observed, for instance, in the PDF fitted by the MSTW8 group shown in Figure 1.4 at Chapter 1. Therefore, W^+Z decay products are expected to fall outside the pseudorapidity acceptance of the detector with more probability than the W^-Z decay products and, consequently, the acceptance for W^+Z process is expected to be slightly lower than the W^-Z .

By contrast, the correction efficiency factor ρ , applied to the simulated data in order to compensate the potentially overestimated efficiencies¹ of the simulated detector, are not expected to be excessively charge dependent. In fact, the lepton and trigger efficiencies ratio of negative to positive leptons, $\varepsilon^-/\varepsilon^+$, have been measured in several W charge asymmetry analysis at 7 TeV for both electrons [91] and muons [92], all of them reporting an efficiency ratio compatible with unity within the statistical uncertainty. As the same behaviour is reproduced in the simulated samples, the ratio of positively to negatively charge leptons SFs are also compatible with unity. Nevertheless, as the efficiency cancellation is valid in small pseudorapidity and p_T regions; taking a conservative approach, the ρ terms are kept in equation (9.1) and the efficiencies uncertainties estimated in

¹Because of the impossibility of reproduce with total accuracy a real detector.

the W charge asymmetry analyses referenced before, 3% for electrons and 2.3% for muons, are propagated as a systematic source of uncertainty due to the SFs differences between opposite charged leptons.

The two cross sections W^+Z and W^-Z measurements were performed, analogously to the inclusive measurement, in four exhaustive final state regions, to obtain the ingredients for the ratio Equation (9.1). Table 9.3 and 9.4 shows the number of observed signal ratio, the acceptance and efficiency ratios and the efficiency correction ratio between W^-Z and W^+Z used to obtain the cross section ratios reported. As expected, the tables show a slightly higher acceptance for the W^-Z process with respect the W^+Z production, between 5-8% depending of the measured channel. In contrast, the ρ terms are compatible with unity between the two processes, meaning that this analysis is insensitive to the potential differences in the reconstruction, isolation or trigger efficiency between different charged lepton objects.

	$\mathcal{C}^+/\mathcal{C}^-$	ρ^+/ρ^-	N_S^-/N_S^+	$\sigma_{W^-Z}/\sigma_{W^+Z}$
eee	0.926 ± 0.018	1.00 ± 0.02	0.76 ± 0.21	$0.71 \pm 0.19_{\text{stat}} \pm 0.02_{\text{sys}}$
μee	0.941 ± 0.017	1.01 ± 0.03	0.52 ± 0.15	$0.50 \pm 0.15_{\text{stat}} \pm 0.01_{\text{sys}}$
$e\mu\mu$	0.945 ± 0.015	1.00 ± 0.02	0.43 ± 0.12	$0.40 \pm 0.12_{\text{stat}} \pm 0.01_{\text{sys}}$
$\mu\mu\mu$	0.945 ± 0.014	1.01 ± 0.02	0.87 ± 0.19	$0.83 \pm 0.18_{\text{stat}} \pm 0.02_{\text{sys}}$

TABLE 9.3: Measured ratios between W^-Z and W^+Z for the acceptance, efficiencies and number of signal at 7 TeV. The last column contains the cross section ratio measured in the four considered channels. The errors are split in statistical and systematic origin. The errors reported for the other acceptance, efficiencies and signal terms are statistical only.

The four measurements are combined with the BLUE method described at Section 8.4, where the same error correlation as the inclusive cross section measurement was used along with the uncertainty originated from possible differences in lepton efficiencies because of the lepton charge, $\varepsilon^-/\varepsilon^+$, mentioned in the previous section. The charge ratio efficiency uncertainty is assumed to be fully correlated between the channels with the same flavour of the lepton W-candidate, i.e. eee and $e\mu\mu$ on one hand, and $\mu\mu\mu$ and μee on the other. The obtained error matrix

	$\mathcal{C}^+/\mathcal{C}^-$	ρ^+/ρ^-	N_S^-/N_S^+	$\sigma_{W-Z}/\sigma_{W+Z}$
eee	0.939 ± 0.022	1.01 ± 0.04	0.67 ± 0.09	$0.63 \pm 0.09_{\text{stat}} \pm 0.01_{\text{sys}}$
μee	0.948 ± 0.021	1.00 ± 0.03	0.56 ± 0.07	$0.53 \pm 0.08_{\text{stat}} \pm 0.02_{\text{sys}}$
$e\mu\mu$	0.940 ± 0.019	1.00 ± 0.03	0.52 ± 0.06	$0.49 \pm 0.06_{\text{stat}} \pm 0.01_{\text{sys}}$
$\mu\mu\mu$	0.956 ± 0.016	1.00 ± 0.02	0.58 ± 0.06	$0.55 \pm 0.06_{\text{stat}} \pm 0.01_{\text{sys}}$

TABLE 9.4: Measured ratios between W^-Z and W^+Z for the acceptance, efficiencies and number of signal at 8 TeV. The last column contains the cross section ratio measured in the four considered channels. The errors are split in statistical and systematic origin. The errors reported for the other acceptance, efficiencies and signal terms are statistical only.

for the 7 TeV analysis is

$$\mathbf{E}_{7\text{ TeV}} = \begin{pmatrix} 0.0372 & < 10^{-4} & 0.0003 & < 10^{-4} \\ < 10^{-4} & 0.02125 & < 10^{-4} & 0.0002 \\ 0.0003 & < 10^{-4} & 0.01382 & < 10^{-4} \\ < 10^{-4} & 0.0002 & < 10^{-4} & 0.0333 \end{pmatrix} \quad (9.2)$$

providing a weighting factors of $\alpha_{3e} = 0.151$, $\alpha_{1\mu 2e} = 0.268$, $\alpha_{1e 2\mu} = 0.411$ and $\alpha_{3\mu} = 0.170$. It is worthwhile to mention that due to the correlation of the systematic uncertainties in both W^+Z and W^-Z cross sections, the systematic uncertainty of the cross section ratio is highly reduced, remaining as main source of systematic uncertainty the ratio efficiency introduced. The W^-Z , W^+Z cross section ratio in the phase space defined in $M_{ll} \in 91.1876 \pm 20 \text{ GeV}/c^2$ at 7 TeV is measured to be:

$$\left(\frac{\sigma_{W-Z}}{\sigma_{W+Z}} \right)_{7\text{ TeV}} = 0.547 \pm 0.075_{\text{stat}} \pm 0.011_{\text{sys}} \quad (9.3)$$

in agreement with the NLO prediction $0.563^{+0.002}_{-0.001}$, calculated with the PDF set MSTW8, reported at Chapter 2 (Table 2.2). The arguments rising a differences in acceptance between the W^+Z and W^-Z production discussed before are applicable to argue why the ratio observable is expected to be remarkably more sensitive to the PDF-set choice than the cross section observables. Therefore, it has been used another PDF set, the CT-10 [93], with the MCFM program to obtain a NLO prediction of the ratio observable. The Table 9.5 summarises the 7 TeV NLO

predictions obtained with different PDF-sets to be compared with the measured value, and it may be noted that the prediction obtained with the CT-10 PDF set are in excellent agreement with the measured value within uncertainty errors.

PDF-set	$\sigma_{W-Z}/\sigma_{W+Z}$ (NLO)	$\sigma_{W+Z}/\sigma_{W-Z}$ (NLO)	N_σ
MSTW08	$0.563^{+0.002}_{-0.001}$	$1.776^{+0.006}_{-0.003}$	0.21
CT-10	$0.546^{+0.002}_{-0.001}$	$1.832^{+0.007}_{-0.003}$	0.01

TABLE 9.5: NLO prediction for the $\sigma_{W-Z}/\sigma_{W+Z}$ and the inverse $\sigma_{W+Z}/\sigma_{W-Z}$ ratios obtained with MCFM using different PDF sets reported in the first column. The predictions are obtained for 7 TeV centre of mass energy and compared in the last column with the $\sigma_{W-Z}/\sigma_{W+Z}$ measured value $0.547 \pm 0.075_{\text{stat}} \pm 0.011_{\text{sys}}$ or $1.83 \pm 0.25_{\text{stat}} \pm 0.04_{\text{sys}}$ for the inverse ratio, reporting the number of standard deviation (defined at Chapter 7, Equation 7.21).

For completeness, the inverse ratio is also shown and may be compared with the NLO prediction from Table 9.5

$$\left(\frac{\sigma_{W+Z}}{\sigma_{W-Z}} \right)_{7 \text{ TeV}} = 1.83 \pm 0.25_{\text{stat}} \pm 0.04_{\text{sys}} \quad (9.4)$$

The 8 TeV centre of mass energy analysis is performed analogously. The obtained error matrix is

$$\mathbf{E}_{8\text{TeV}} = \begin{pmatrix} 0.0176 & < 10^{-4} & 0.0002 & < 10^{-4} \\ < 10^{-4} & 0.0234 & < 10^{-4} & 0.0001 \\ 0.0002 & < 10^{-4} & 0.0219 & < 10^{-4} \\ < 10^{-4} & 0.0001 & < 10^{-4} & 0.0113 \end{pmatrix} \quad (9.5)$$

The ratio in the 8 TeV centre of mass energy analysis is measured to be:

$$\left(\frac{\sigma_{W-Z}}{\sigma_{W+Z}} \right)_{8 \text{ TeV}} = 0.551 \pm 0.035_{\text{stat}} \pm 0.010_{\text{sys}}, \quad (9.6)$$

and the inverse ratio

$$\left(\frac{\sigma_{W+Z}}{\sigma_{W-Z}} \right)_{8 \text{ TeV}} = 1.81 \pm 0.12_{\text{stat}} \pm 0.03_{\text{sys}} \quad (9.7)$$

The measured values are in good agreement, within the uncertainty errors, with the SM predictions reported at Table 9.6. As it may be observed in the table, the NLO prediction calculated with the MCFM tool using the CT-10 PDF set is, as in the 7 TeV case, in better agreement with the measured value.

PDF-set	$\sigma_{W-Z}/\sigma_{W+Z}$ (NLO)	$\sigma_{W+Z}/\sigma_{W-Z}$ (NLO)	N_σ
MSTW08	0.580 ± 0.001	1.724 ± 0.003	0.82
CT-10	0.563 ± 0.001	1.777 ± 0.003	0.33

TABLE 9.6: NLO prediction for the $\sigma_{W-Z}/\sigma_{W+Z}$ and the inverse $\sigma_{W+Z}/\sigma_{W-Z}$ ratios obtained with MCFM using different PDF sets reported in the first column. The predictions are obtained for 8 TeV centre of mass energy and compared in the last column with the $\sigma_{W-Z}/\sigma_{W+Z}$ measured value $0.551 \pm 0.035_{\text{stat}} \pm 0.010_{\text{sys}}$ or $1.81 \pm 0.12_{\text{stat}} \pm 0.03_{\text{sys}}$ for the inverse ratio, reporting the number of standard deviation (defined at Chapter 7, Equation 7.21).

CHAPTER 10

Conclusions

The W^-Z and W^+Z productions from proton-proton collisions have been studied in two centre of mass energies 7 and 8 TeV; and, in particular, the inclusive cross section measurement of the WZ production $\sigma(pp \rightarrow WZ + X)$ and the ratio between both processes $\sigma(pp \rightarrow W^-Z + X)/\sigma(pp \rightarrow W^+Z + X)$ have been performed. The measurements are based in data acquired with the CMS experiment, resulting from proton-proton collisions produced at the LHC. The total amount of data used for the 7 TeV analysis is equivalent to $\mathcal{L} = 4.9 \text{ fb}^{-1}$, whilst for the 8 TeV analysis is $\mathcal{L} = 19.6 \text{ fb}^{-1}$.

The final state particles, used to select the WZ candidates from collision events, are composed of three well-identified, high- p_T and isolated leptons in addition to substantial E_T^{miss} . The selected samples of WZ candidate events are compared to the estimation of the background processes, either simulated with Monte Carlo techniques or estimated from experimental data. The estimated signal along with the detector acceptance and efficiency for identifying the signal events as determined from simulation are included to obtain the cross section of the considered process. For the cross section ratio measurement, such methodology is applied to both signal samples defined by the charge of the W-candidate lepton and the obtained cross sections are divided to obtain the ratio. All the measurements are performed individually for each of the four leptonic final states, eee , μee , $e\mu\mu$ and $\mu\mu\mu$, and the final results are obtained from a best fit linear combination, giving the results reported in Table 10.1. The 7 TeV analysis is statistically

limited, however, the 8 TeV analysis is greatly benefited from the amount of recorded data allowing to measure with uncertainty errors dominated by the systematic sources considered, in particular the luminosity uncertainty error is the same size than the total of the other systematic uncertainty errors. The improvement of the luminosity uncertainty error, which was released during the redaction of this thesis work [94], will improve the precision of the measurement.

	7 TeV ($\mathcal{L}=4.9 \text{ fb}^{-1}$)	8 TeV ($\mathcal{L}=19.6 \text{ fb}^{-1}$)
$\sigma(pp \rightarrow WZ + X)$	$20.8 \pm 1.3_{\text{stat}} \pm 1.1_{\text{sys}} \pm 0.5_{\text{lumi}}$	$24.6 \pm 0.8_{\text{stat}} \pm 1.1_{\text{sys}} \pm 1.1_{\text{lumi}}$
$\frac{\sigma(pp \rightarrow W^-Z+X)}{\sigma(pp \rightarrow W^+Z+X)}$	$0.547 \pm 0.075_{\text{stat}} \pm 0.011_{\text{sys}}$	$0.551 \pm 0.035_{\text{stat}} \pm 0.010_{\text{sys}}$

TABLE 10.1: Results obtained for the measurements performed in this thesis work.

The inclusive cross section have been measured to be a slightly higher value than the SM-NLO predictions, although the number of standard deviations are 1.8 for 7 TeV and 1.5 for 8 TeV. In the case of the cross sections ratio, both for 7 and 8 TeV, are in excellent agreement with the NLO.

10.1. Analysis prospects

The data recorded in CMS from proton-proton collisions at $\sqrt{s}=7$ TeV have allowed to measure the associate WZ production cross section and, for the first time, the cross sections ratio between W^-Z and W^+Z , with results dominated by statistical errors. The amount of collected data with proton-proton collisions at $\sqrt{s}=8$ TeV, substantially increased with respect to the 2011 data, has allowed to measure with more precision the cross section and the cross sections ratio, reaching almost the same sensitivity of the SM theoretical predictions. Improving the systematic source of uncertainty's treatment, in particular the luminosity source which is already available, will allow to reach a precise measurement with lower errors than the theoretical predictions.

The available data in the 8 TeV would allow to extend the WZ electroweak measurements to differential cross sections in bins of various kinematic variables, such as p_T^Z , which present a more detailed comparison of theory to measurements. In addition, the presence of anomalous triple-gauge boson couplings (aTGC) may

also be tested via the WWZ vertex [95] and the limits significantly improved. Both, the differential cross sections as the aTGC are being calculated, during the writing of this thesis memory, in order to be included in the CMS WZ's paper in preparation. This paper is based, along with contributions of other CMS WZ team members, on the contents of this dissertation.

APPENDIX A

Extended analysis distributions

This appendix includes the full set of distributions plots performed for the cross section and the cross section ratio analyses for both 7 TeV and 8 TeV. The distributions were obtained in order to study and control the effect of each sequential cut introduced in the signal selection, allowing to compare the selected experimental data with the theoretical predictions of the signal and the irreducible backgrounds, and the data-driven estimation of the instrumental background. In addition, each distribution is joined by a bottom plot showing the difference between the observed experimental data and the estimation, normalised to the estimation. The Monte Carlo samples used were pileup re-weighted, trigger and scaled factor weighted and normalised to the luminosity of the corresponding data set, which is 4.9 fb^{-1} for the 7 TeV analysis and 19.6 fb^{-1} for the 8 TeV. The appendix is organised by showing the available distributions in each measured channel in addition to the combined channel at each stage of the selection.

A.1. Cross section analysis distributions at 7 TeV

The distributions shown in this subsection correspond to the 2011 analysis of the inclusive WZ cross section using data corresponding to an integrated luminosity of 4.9 fb^{-1} . The ZZ (red in figures) and $V\gamma$ (green) processes were estimated using simulated Monte Carlo data, whereas the prompt-prompt-fake background (blue in figures) contribution was estimated using the FOM data-driven. The

other instrumental background contributions were found to be negligible. The WZ simulated Monte Carlo sample (yellow in figures) is also shown in order to compare the theoretical predictions with the experimental data (black dots in figures). Systematic and statistical errors are also shown (grey dashed lines in figures). The distributions are grouped by observable, showing in each figure four columns corresponding to the four measured channels, and each row to a stage of the analysis.

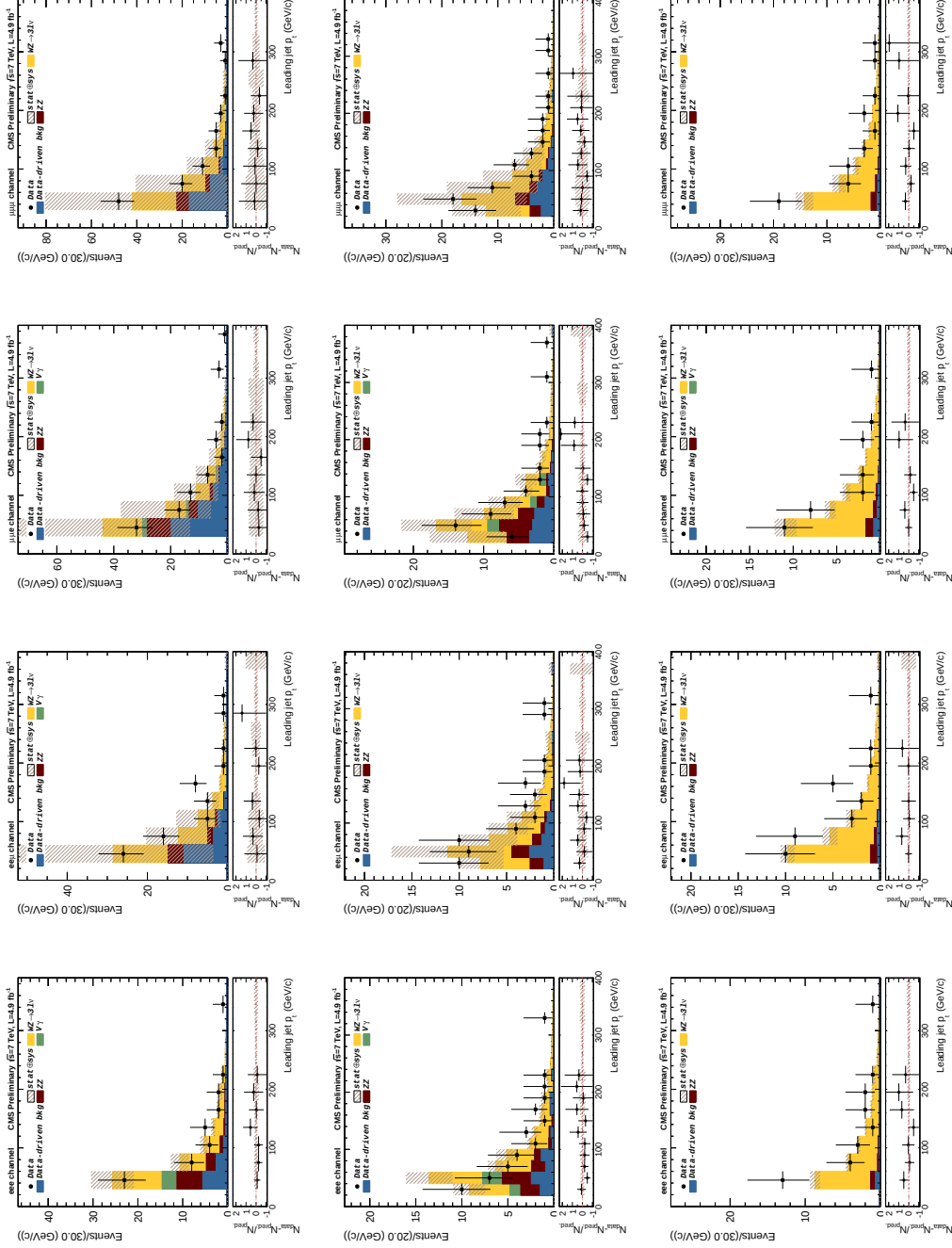


FIGURE A.1: Transverse momentum distribution of the leading jet at each event for the measured channels eee , μee , $e\mu\mu$ and $\mu\mu\mu$ (from left to right) and after each analysis selection stage: after Z-candidate requirement (up row), after W-candidate, without the E_T^{miss} cut (middle row) and after W-candidate including E_T^{miss} cut (bottom row).

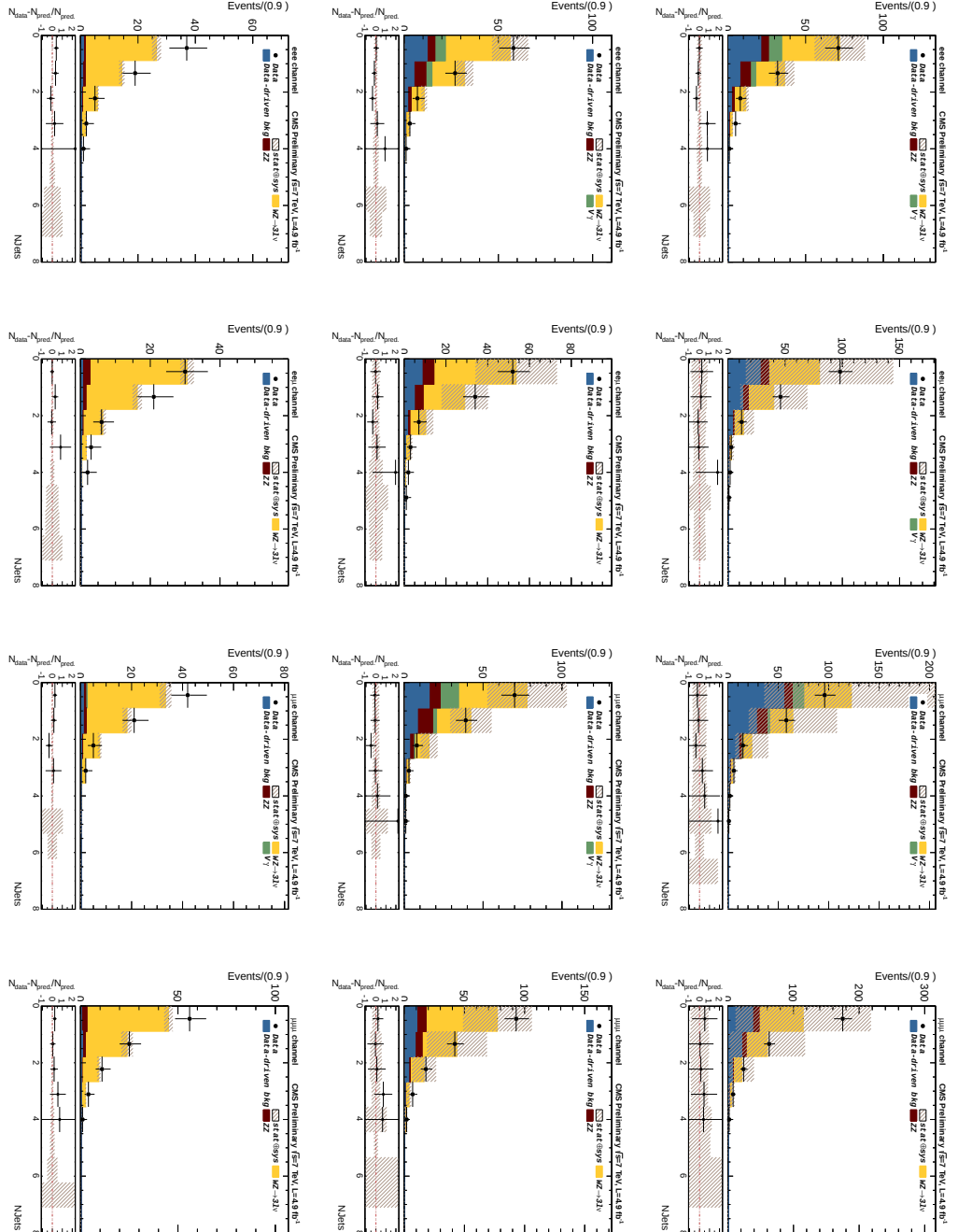


FIGURE A.2: Number of jets distribution at each event for the the measured channels ee , μee , $e\mu\mu$ and $\mu\mu\mu$ (from left to right) and after each analysis selection stage: after Z-candidate requirement (up row), after W-candidate, without the E_T^{miss} cut (middle row) and after W-candidate including E_T^{miss} cut (bottom row).

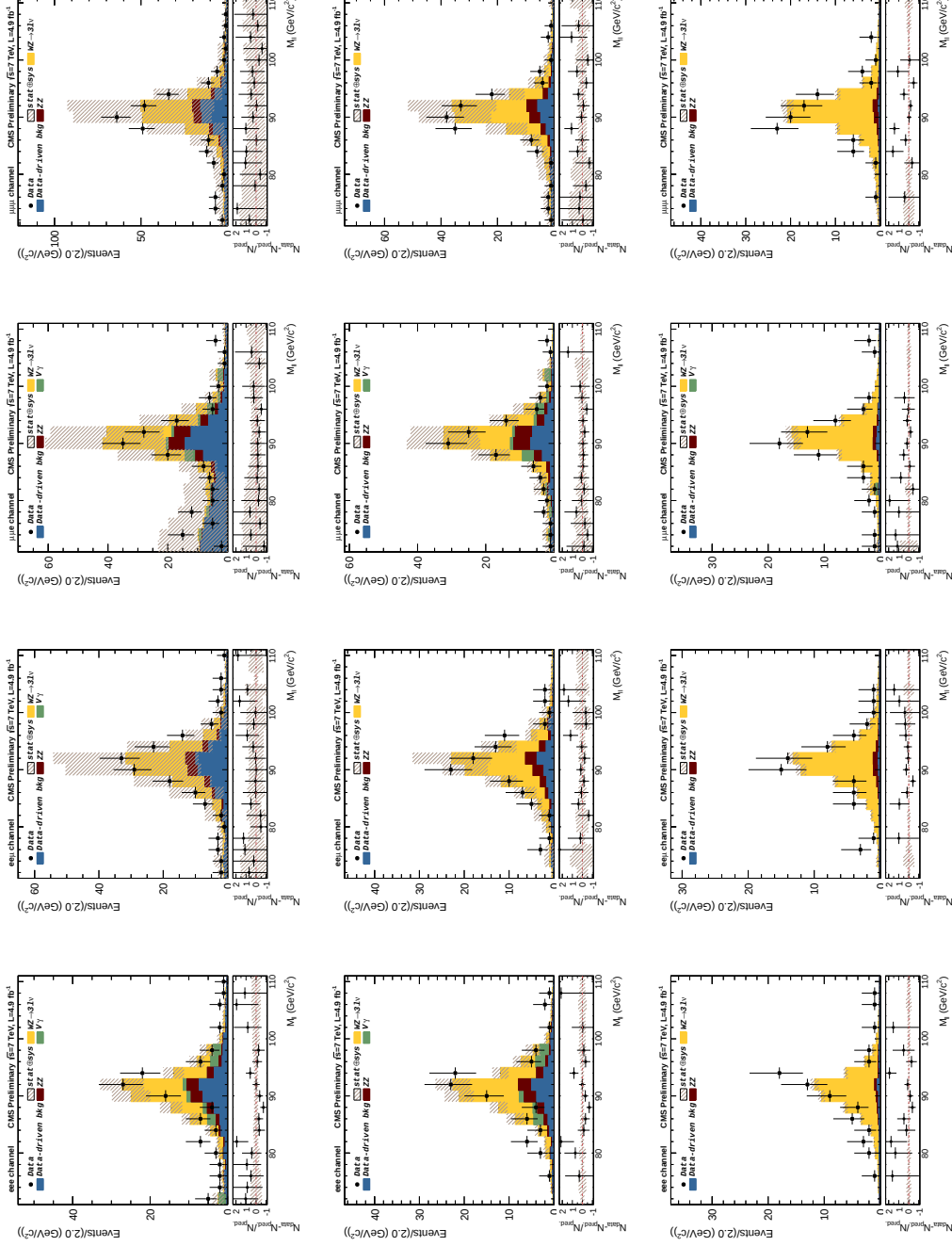


FIGURE A.3: Invariant mass of the Z-candidate dilepton system for the measured channels eee , μee , $e\mu\mu\mu$ and $\mu\mu\mu\mu$ (from left to right) and after each analysis selection stage: after Z-candidate requirement (up row), after W-candidate, without the E_T^{miss} cut (middle row) and after W-candidate including E_T^{miss} cut (bottom row).

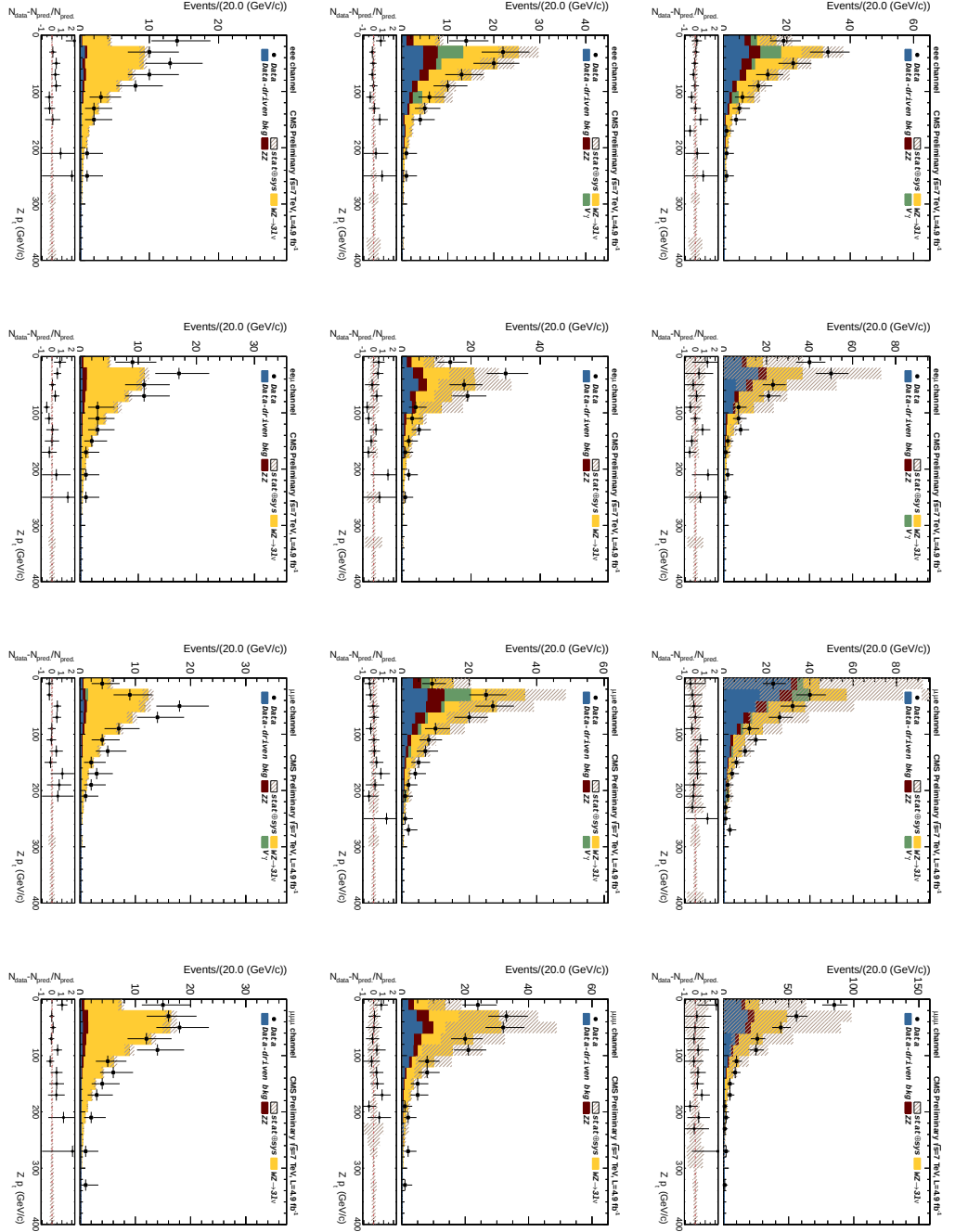


FIGURE A.4: Transverse momentum of the Z-candidate dilepton system for the measured channels eee , μee , $e\mu\mu$ and $\mu\mu\mu$ (from left to right) and after each analysis selection stage: after Z-candidate requirement (up row), after W-candidate, without the E_T^{miss} cut (middle row) and after W-candidate including E_T^{miss} cut (bottom row).

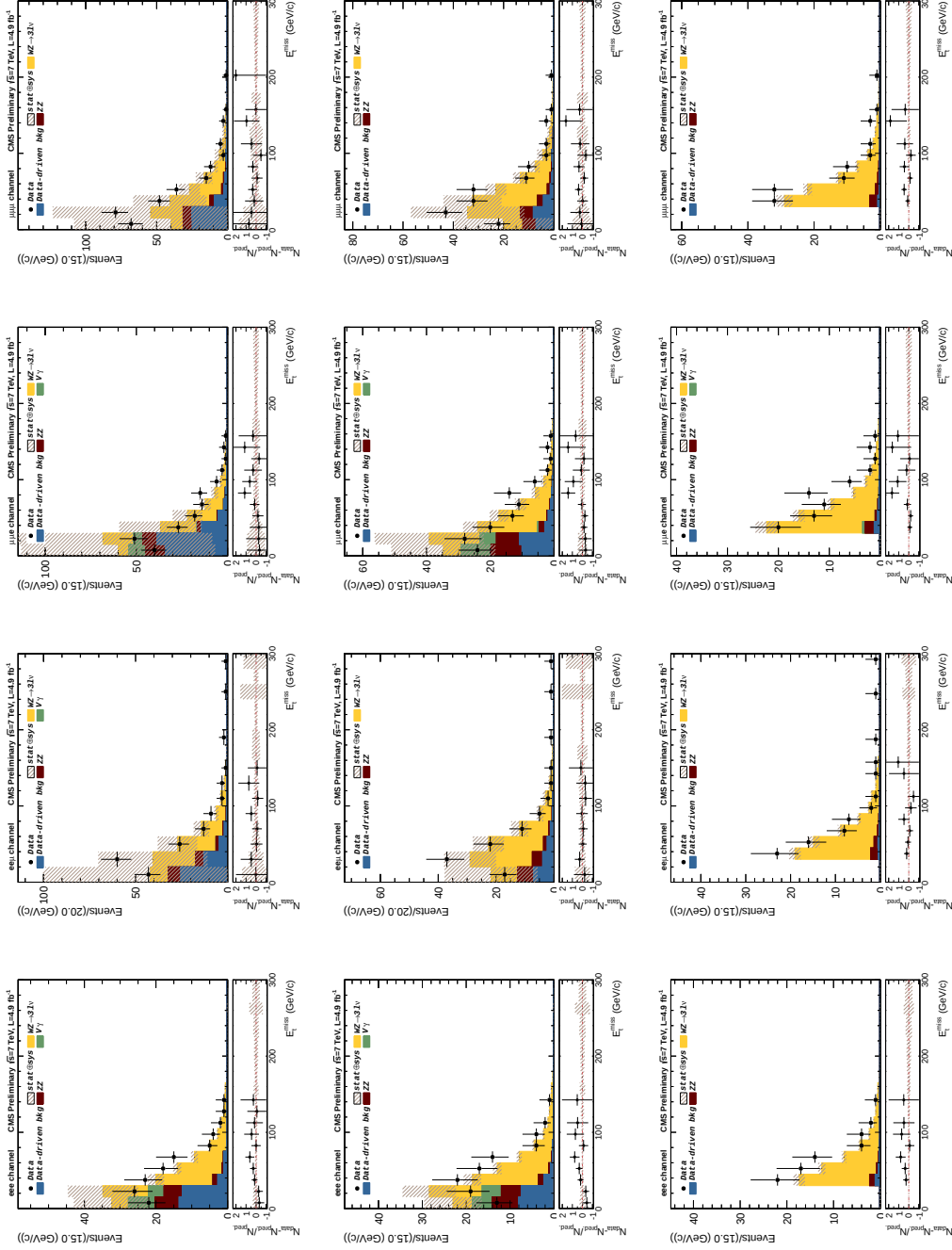


FIGURE A.5: Missing energy in the transverse plane at each event for the measured channels eee , eee , eee and eee (from left to right) and after each analysis selection stage: after Z-candidate requirement (up row), after W-candidate, without the E_T^{miss} cut (middle row) and after W-candidate including E_T^{miss} cut (bottom row).

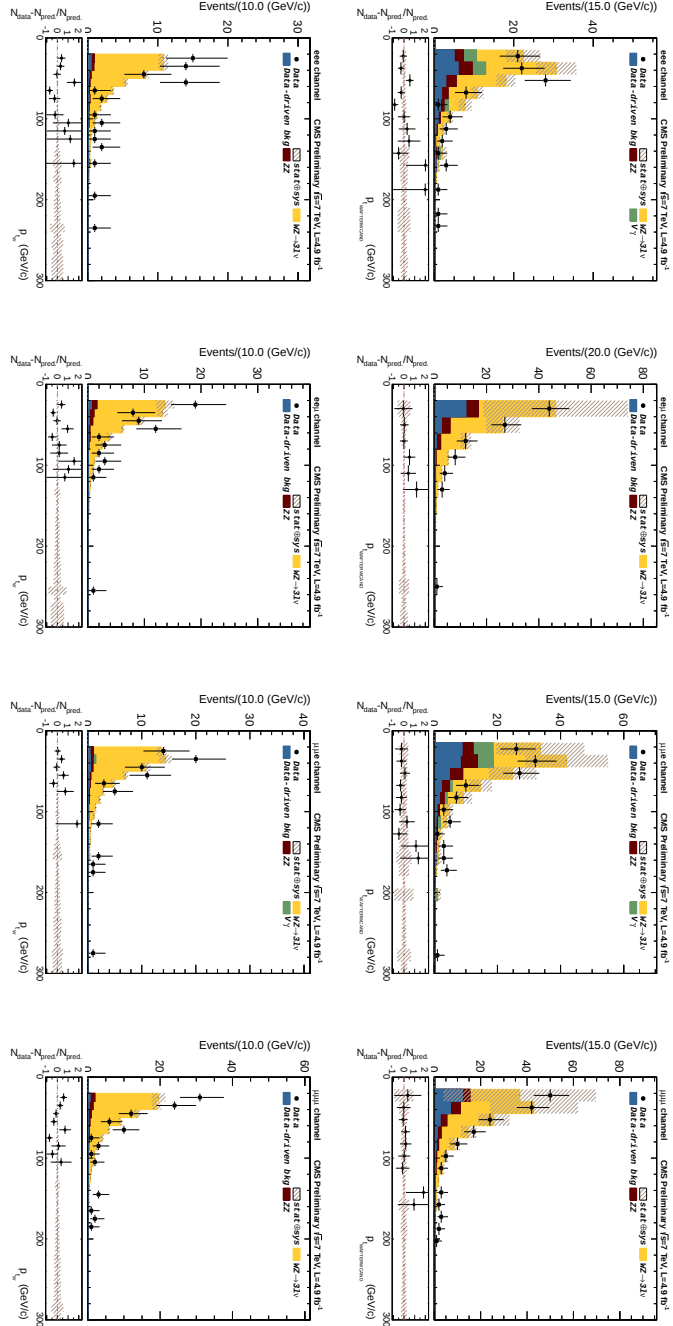


FIGURE A.6: Transverse momentum of the W-candidate system composed by the third selected lepton and E_T^{miss} at each event for the measured channels eee , μee , $e\mu\mu$ and $\mu\mu\mu$ (from left to right) and after each analysis selection stage (once the W is selected): after W-candidate requirement without the E_T^{miss} cut (up row) and after W-candidate including E_T^{miss} cut (bottom row).

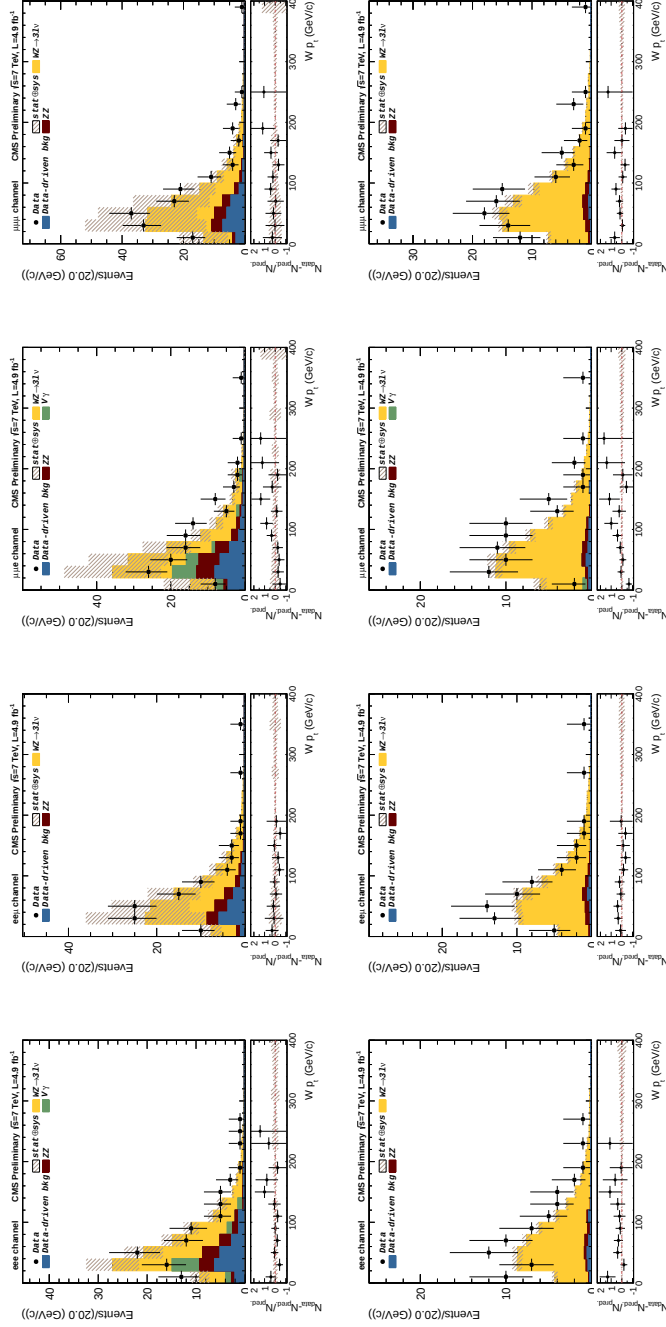


FIGURE A.7: Transverse momentum of the W-candidate lepton at each event for the measured channels eee , μee , $e\mu\mu$ and $\mu\mu\mu$ (from left to right) and after each analysis selection stage (once the W is selected): after W-candidate requirement without the E_T^{miss} cut (up row) and after W-candidate including E_T^{miss} cut (bottom row).

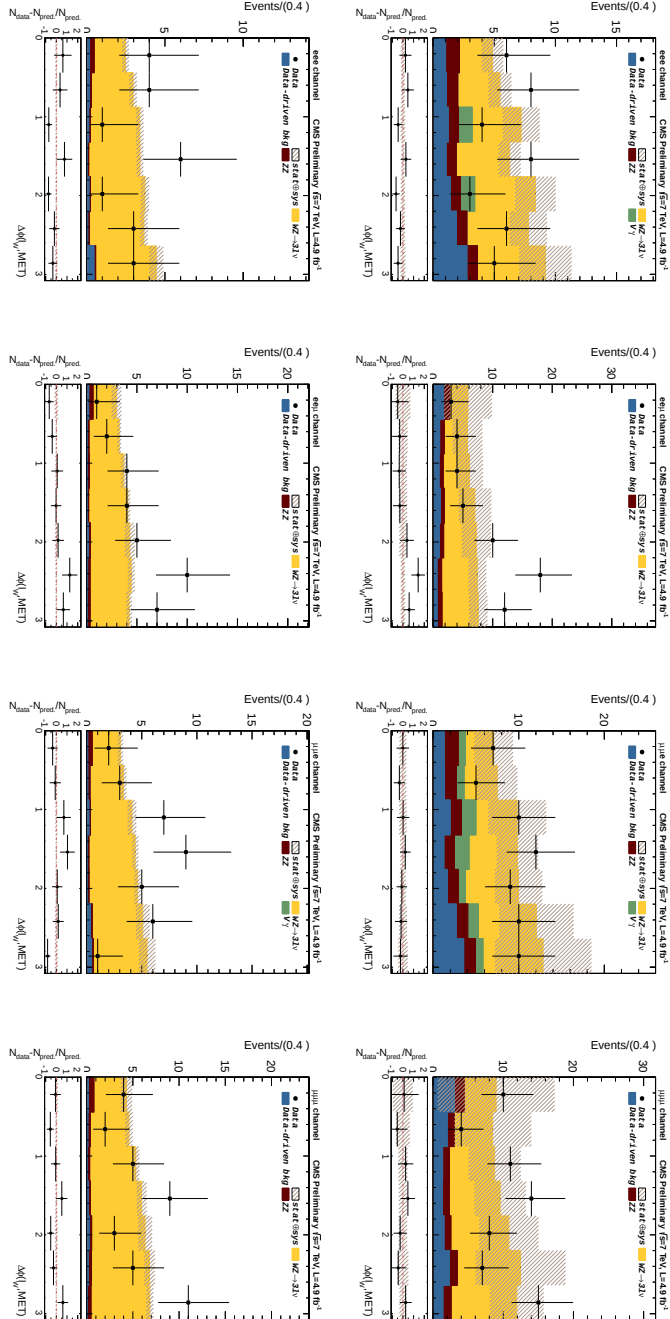
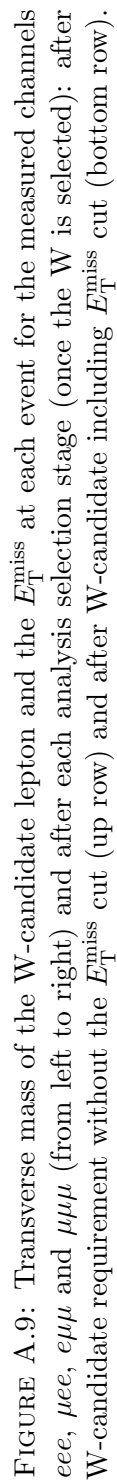


FIGURE A.8: Azimuthal angle between the W-candidate lepton and the E_T^{miss} at each event for the measured channels ee , $e\mu$, $e\mu\mu$ and $\mu\mu$ (from left to right) and after each analysis selection stage (once the W is selected): after W-candidate requirement without the E_T^{miss} cut (up row) and after W-candidate including E_T^{miss} cut (bottom row).



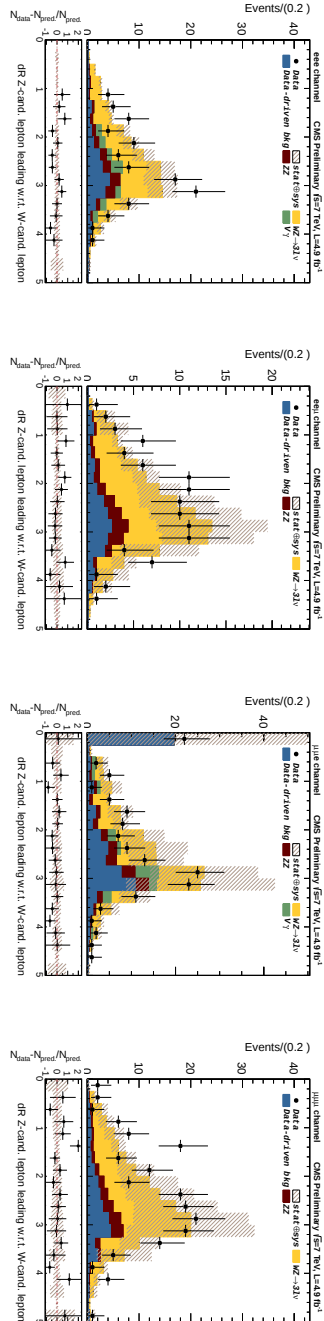


FIGURE A.10: Angular distance between the W-candidate lepton and the Z-candidate leading lepton at each event for the measured channels eee , μee , $e\mu\mu$ and $\mu\mu\mu$ (from left to right) after W-candidate requirement is applied.

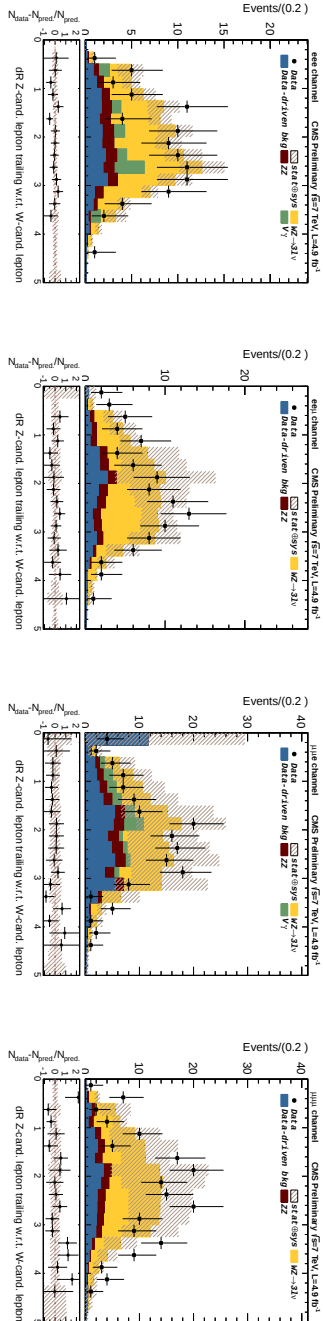


FIGURE A.11: Angular distance between the W-candidate lepton and the Z-candidate trailing lepton at each event for the measured channels eee , μee , $e\mu\mu$ and $\mu\mu\mu$ (from left to right) after W-candidate requirement is applied.

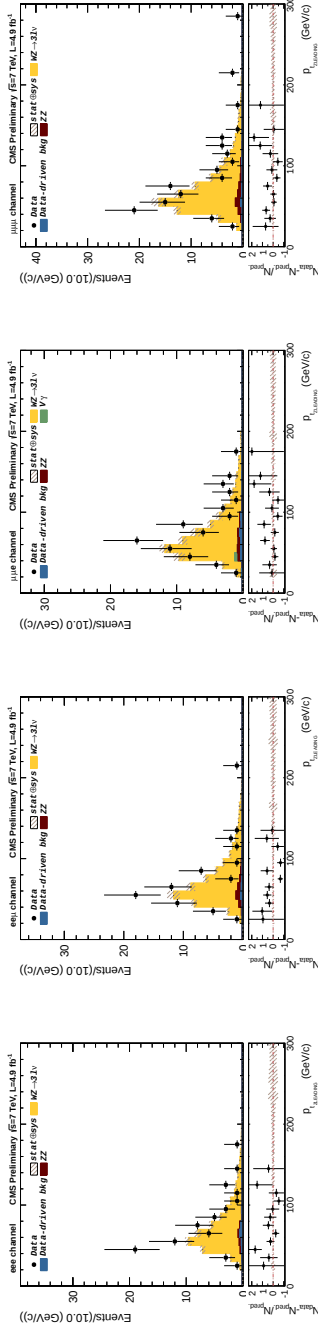


FIGURE A.12: Transverse momentum of the Z-candidate leading lepton at each event for the measured channels eee , μee , $e\mu\mu$ and $\mu\mu\mu$ (from left to right) after W-candidate requirement is applied.

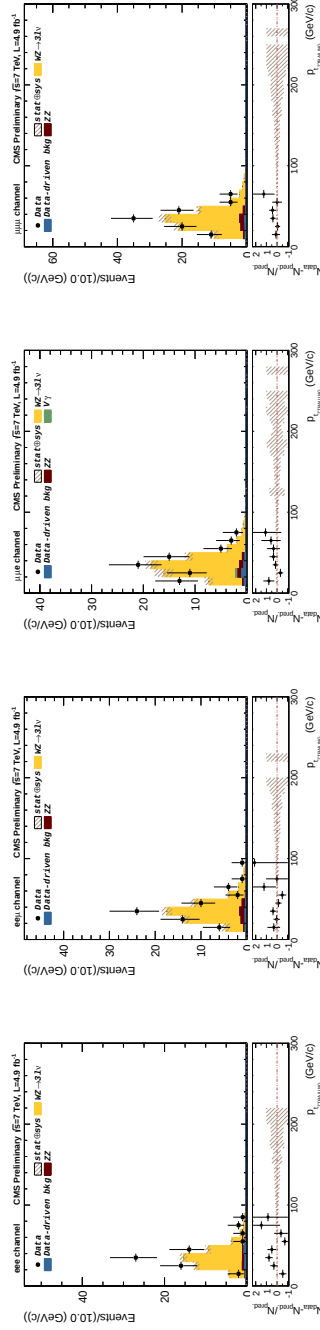


FIGURE A.13: Transverse momentum of the Z-candidate trailing lepton at each event for the measured channels eee , μee , $e\mu\mu$ and $\mu\mu\mu$ (from left to right) after W-candidate requirement is applied.

A.2. Ratio analysis distributions at 7 TeV

The distributions shown in this subsection correspond to the 2011 analysis of the cross section ratio between the W^+Z and W^-Z processes. The samples follows the colour conventions and the processing explained in the previous section. The distributions are grouped by observable, showing in each figure two columns corresponding to the combined channel of the W^-Z and W^+Z and each row to a stage of the analysis. Note that since the sample splitting by charge lies in the W-candidate, the analysis stages are shown from this requirement on.

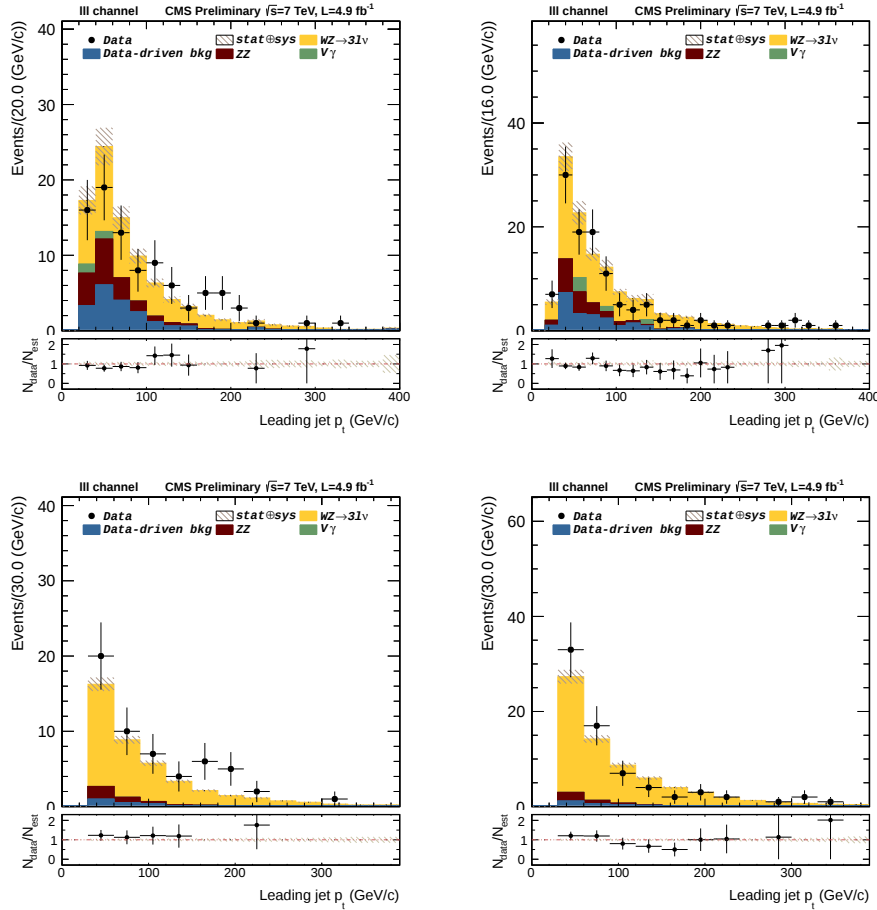


FIGURE A.14: Transverse momentum distribution of the leading jet at each event for the W^-Z (left column) and W^+Z (right column) before the E_T^{miss} cut (up row) and after (bottom row).

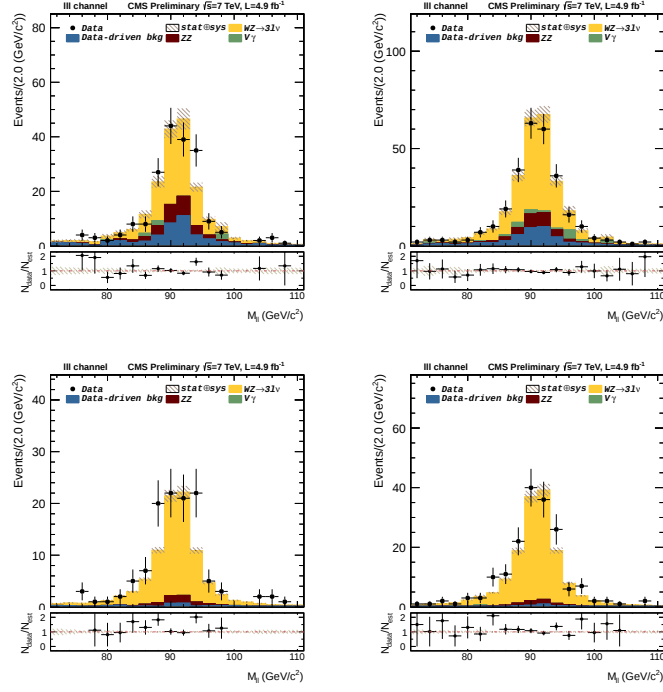


FIGURE A.15: Invariant mass of the Z-candidate dilepton system for the W^-Z (left column) and W^+Z (right column) before (up row) and after the E_T^{miss} cut (bottom row).

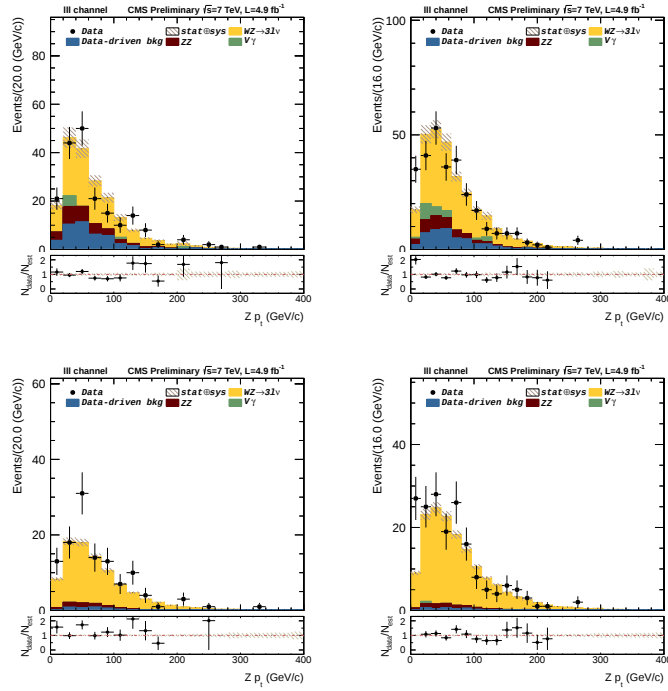


FIGURE A.16: Transverse momentum of the Z-candidate dilepton system for the W^-Z (left column) and W^+Z (right column) before (up row) and after the E_T^{miss} cut (bottom row).

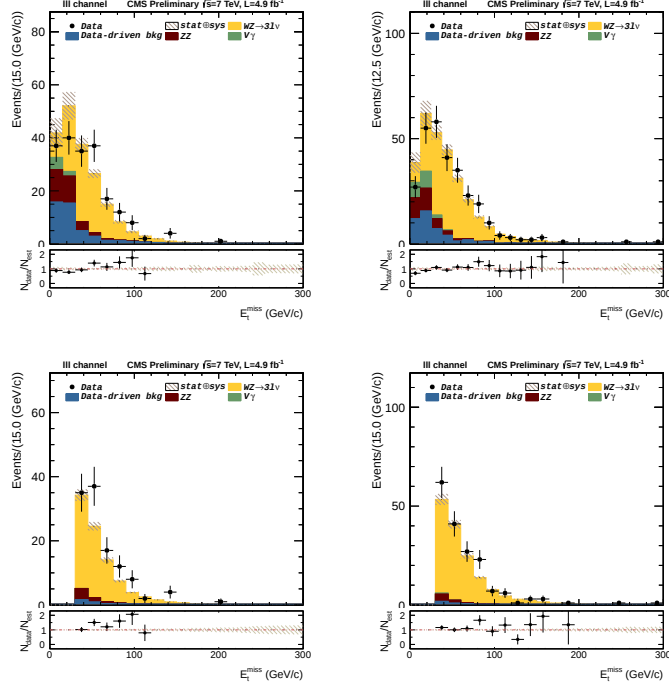


FIGURE A.17: Missing energy in the transverse plane at each event for the W^-Z (left column) and W^+Z (right column) before (up row) and after the E_T^{miss} cut (bottom row).

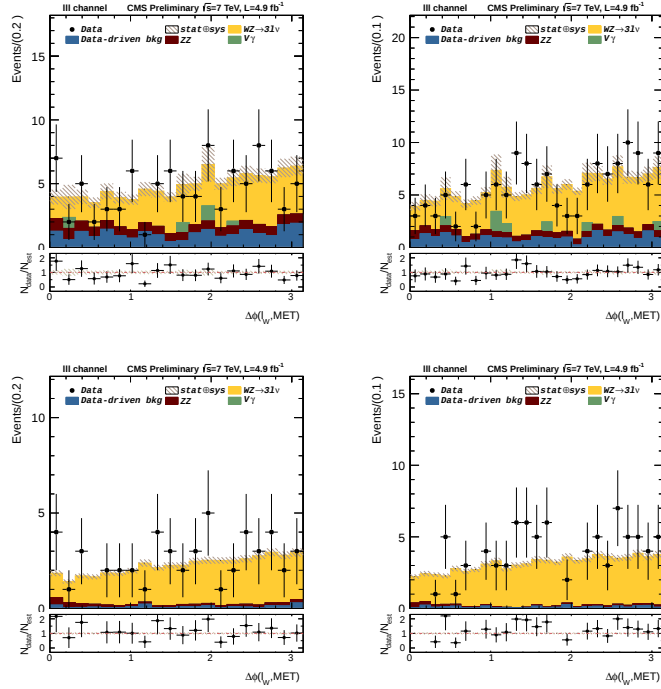


FIGURE A.18: Azimuthal angle between the W-candidate lepton and the E_T^{miss} at each event for the W^-Z (left column) and W^+Z (right column) before (up row) and after the E_T^{miss} cut (bottom row).

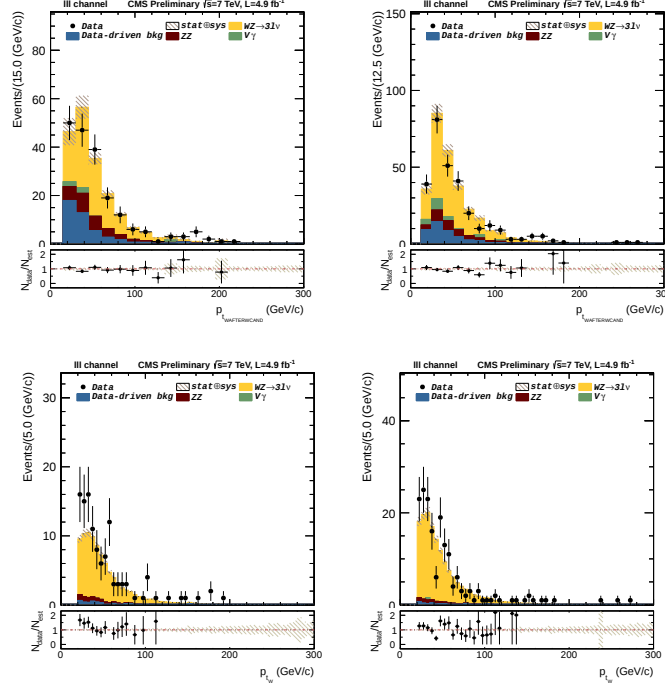


FIGURE A.19: Transverse momentum of the W-candidate system composed by the third selected lepton and E_T^{miss} at each event for the W^-Z (left column) and W^+Z (right column) before (up row) and after the E_T^{miss} cut (bottom row).

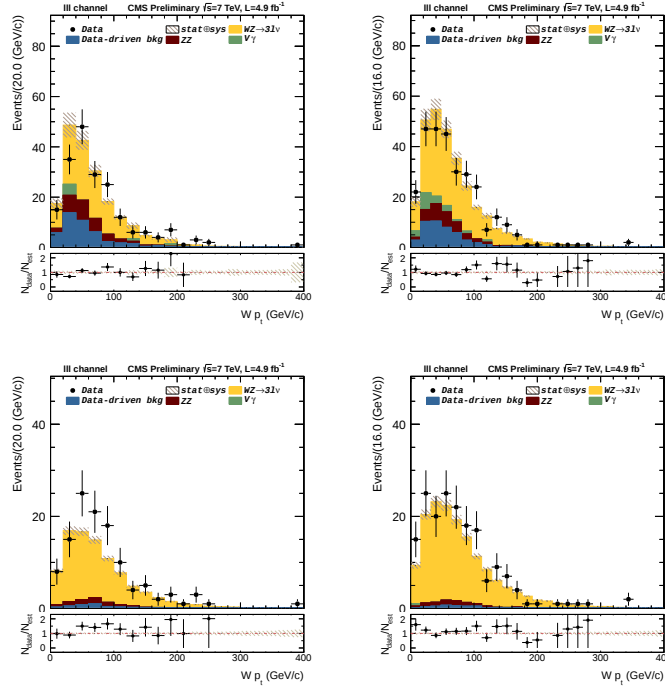


FIGURE A.20: Transverse momentum of the W-candidate lepton at each event for the W^-Z (left column) and W^+Z (right column) before (up row) and after the E_T^{miss} cut (bottom row).

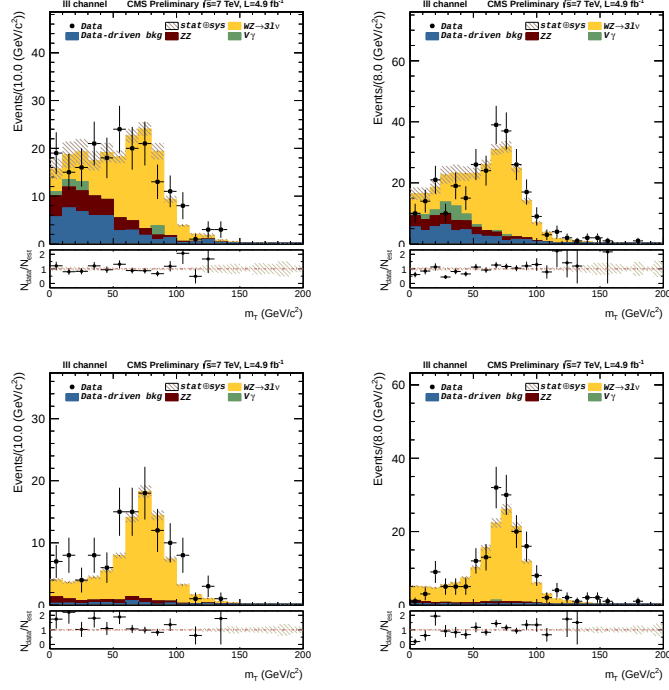


FIGURE A.21: Transverse mass of the W-candidate lepton and the E_T^{miss} at each event for the W^-Z (left column) and W^+Z (right column) before (up row) and after the E_T^{miss} cut (bottom row).

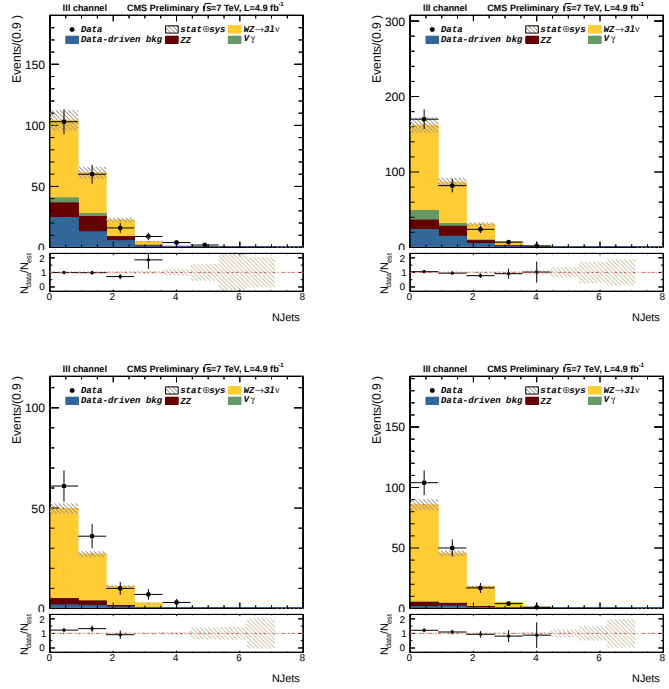


FIGURE A.22: Number of jets distribution at each event for the the W^-Z (left column) and W^+Z (right column) before (up row) and after the E_T^{miss} cut (bottom row).

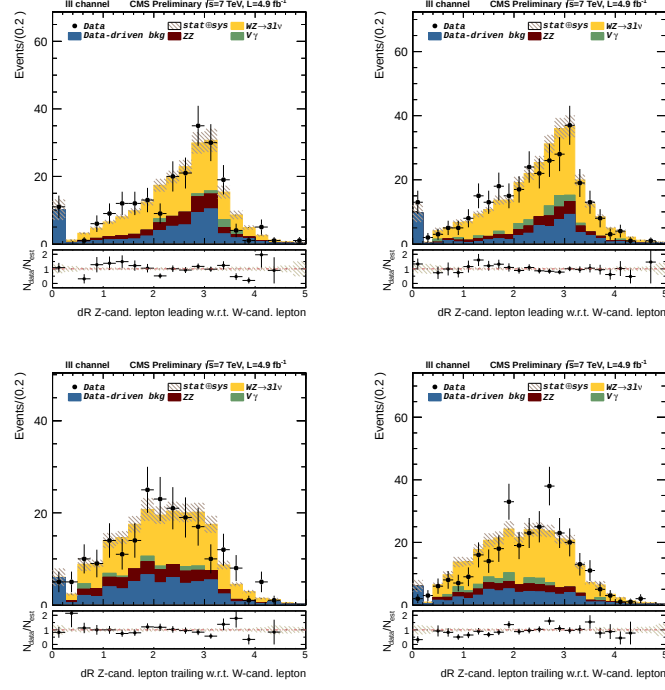


FIGURE A.23: Angular distance between the W-candidate lepton and the Z-candidate leading (up row) and trailing lepton (bottom row) at each event for the W^-Z (left column) and W^+Z (right column) before E_T^{miss} cut.

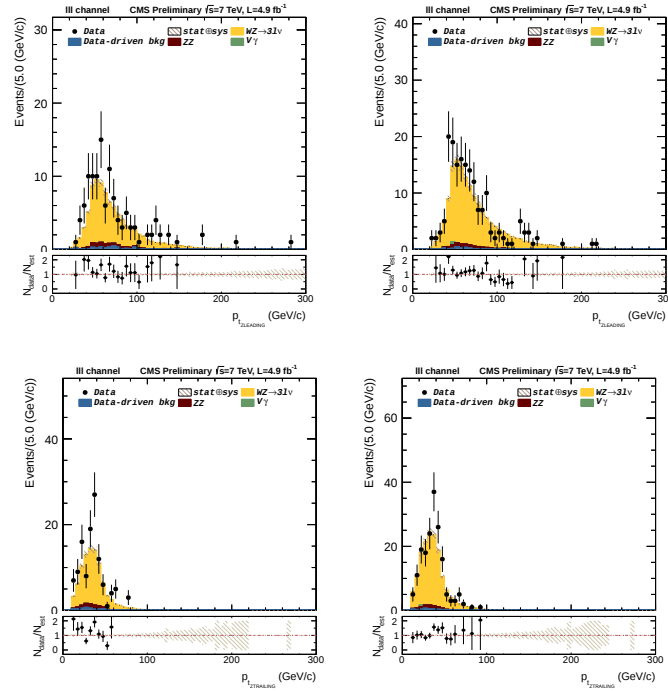


FIGURE A.24: Transverse momentum of the Z-candidate leading (up row) and trailing lepton (bottom row) at each event for the W^-Z (left column) and W^+Z (right column) after the E_T^{miss} cut.

A.3. Cross section analysis distributions at 8 TeV

The distributions shown in this subsection correspond to the 2012 analysis of the inclusive WZ cross section using data corresponding to an integrated luminosity of 19.6 fb^{-1} . In addition to the same processes used in the 7 TeV analysis estimated with simulated Monte Carlo samples, the the VVV ($V=W,Z$) processes are also considered (with light blue in figures) along with the $W\gamma$ and $W\gamma^*$ denoted as WV (grey in figures).

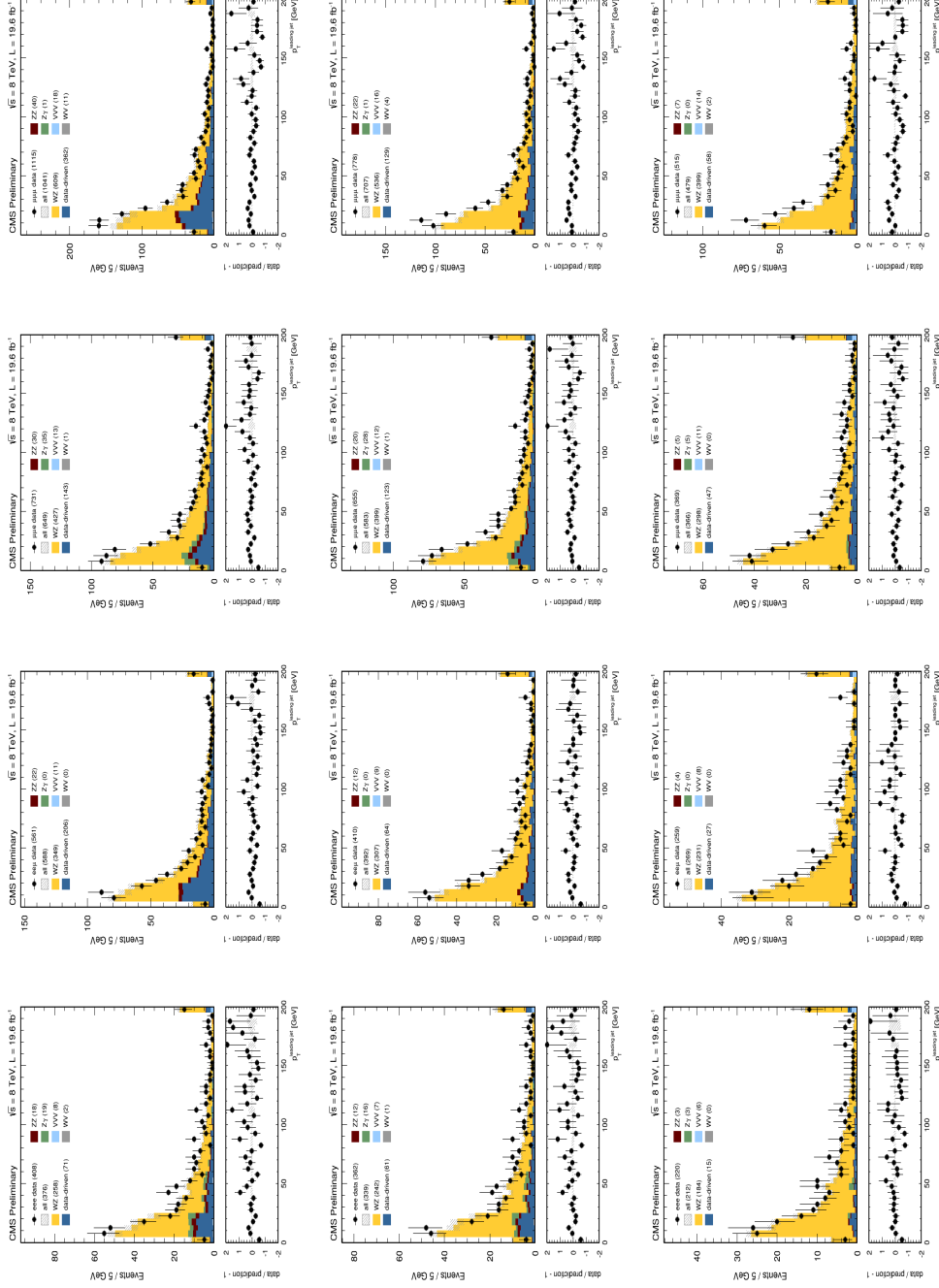
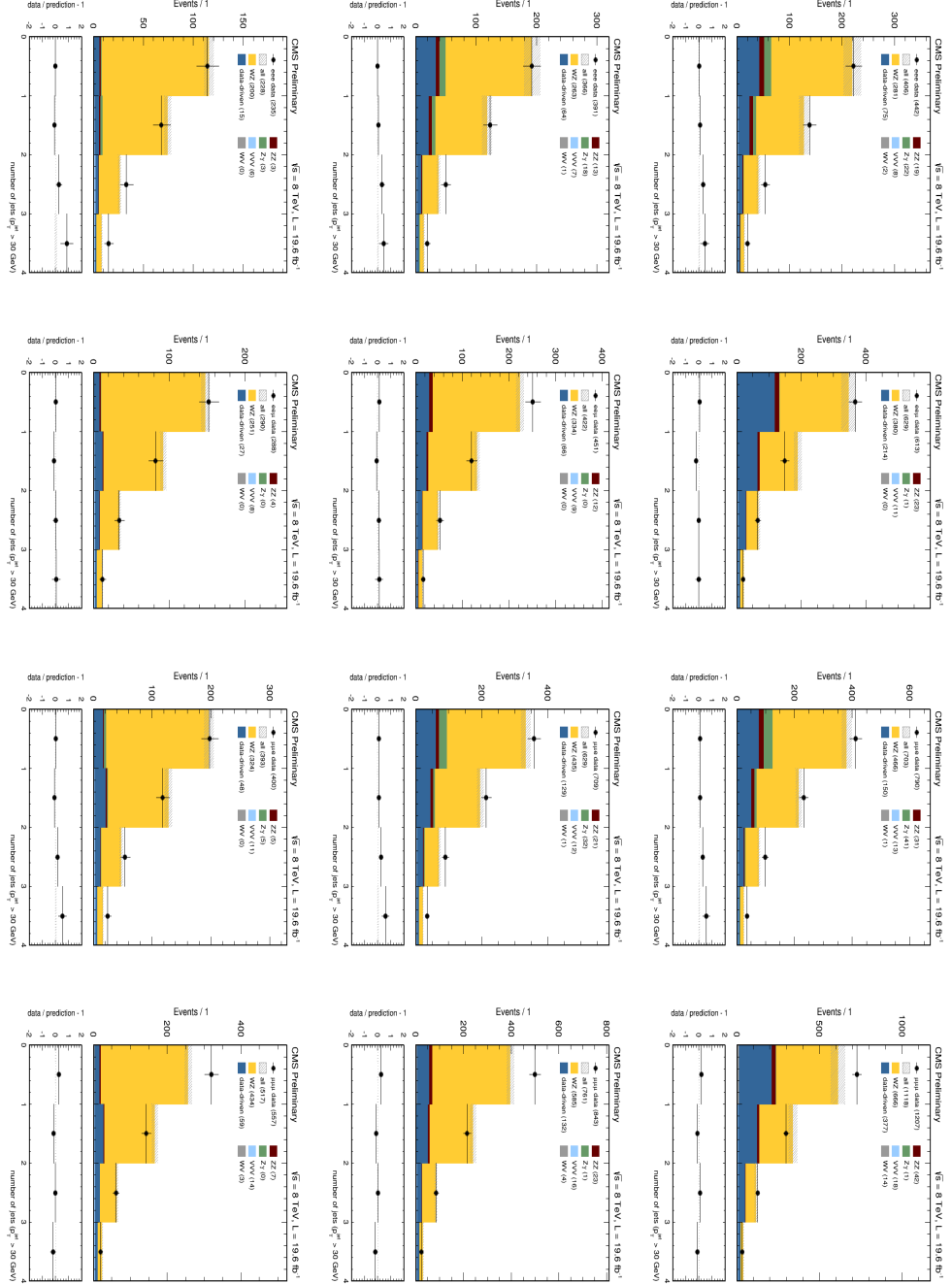


FIGURE A.25: Transverse momentum distribution of the leading jet at each event for the measured channels eee , μee , $e\mu\mu$ and $\mu\mu\mu$ (from left to right) and after each analysis selection stage: after Z-candidate requirement (up row), after E_T^{miss} cut (middle row) and after W-candidate including E_T^{miss} cut (bottom row).



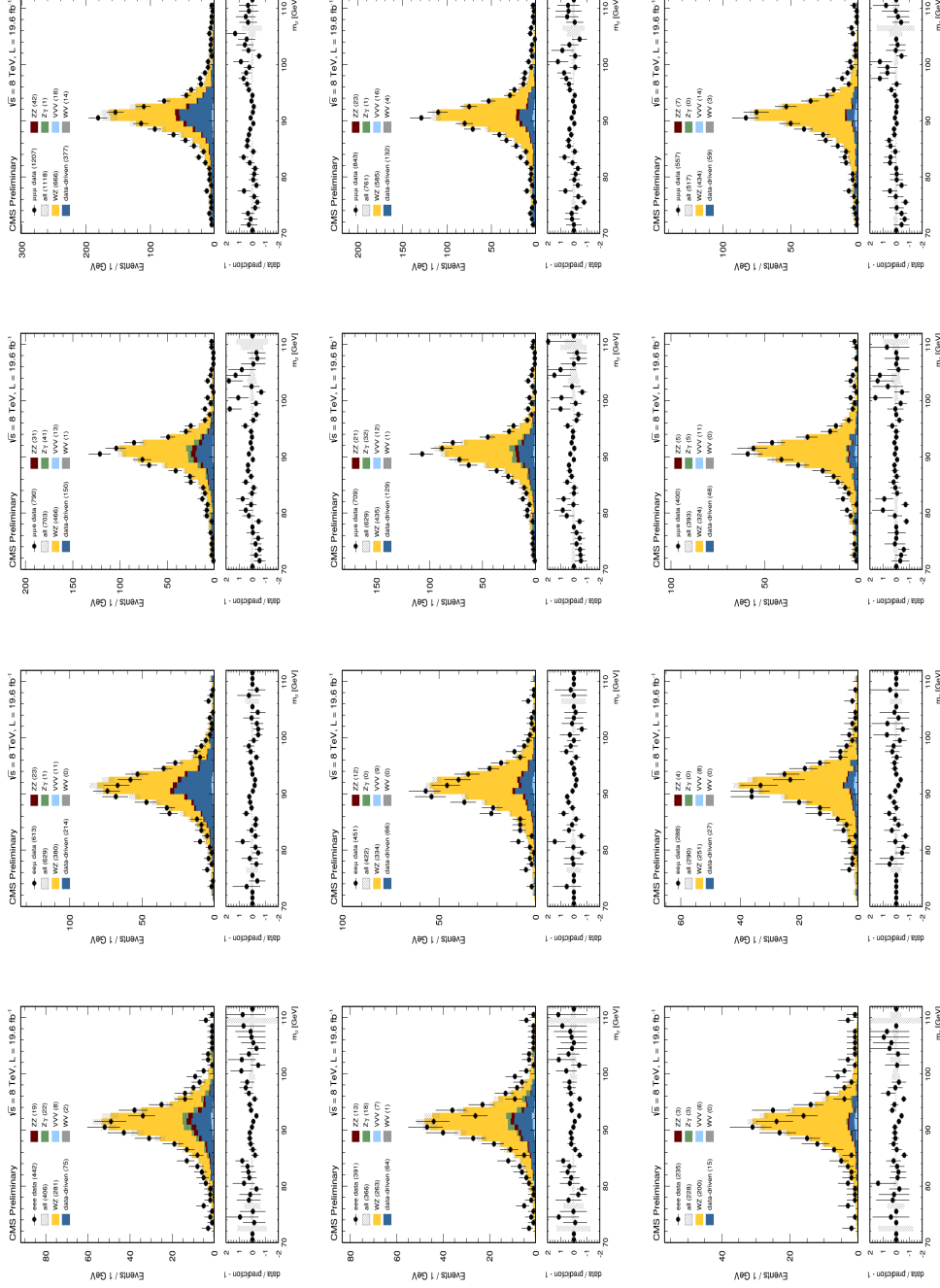


FIGURE A.27: Invariant mass of the Z-candidate dilepton system for the measured channels eee , uee , $e\mu\mu$ and $\mu\mu\mu$ (from left to right) and after each analysis selection stage: after Z-candidate requirement (up row), after W-candidate, without the E_T^{miss} cut (middle row) and after W-candidate including E_T^{miss} cut (bottom row).

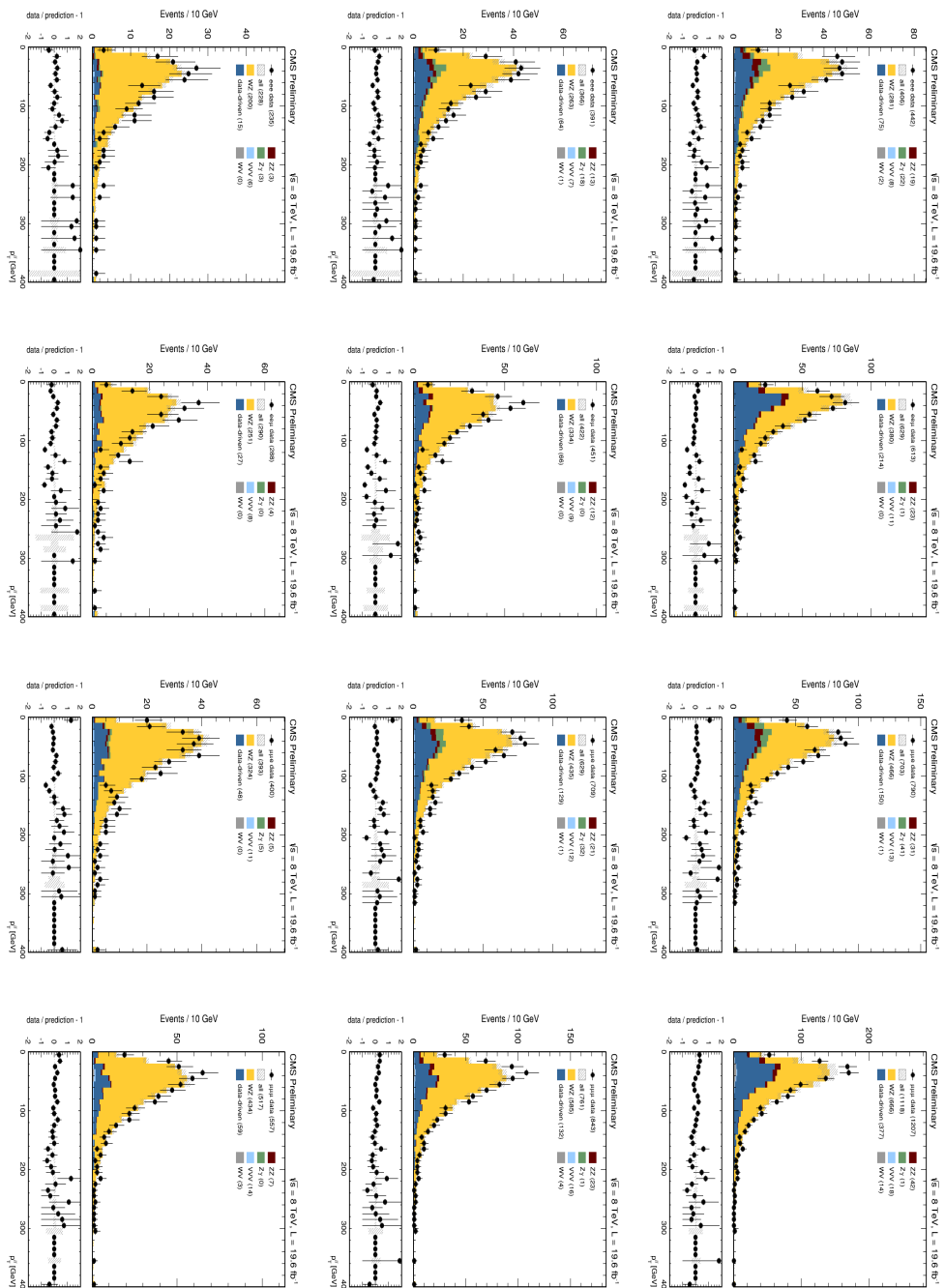


FIGURE A.28: Transverse momentum of the Z-candidate dilepton system for the measured channels ee , $ee\mu$, $e\mu\mu$ and $\mu\mu$ (from left to right) and after each analysis selection stage: after Z-candidate requirement (up row), after W-candidate, without the E_T^{miss} cut (middle row) and after W-candidate including E_T^{miss} cut (bottom row).

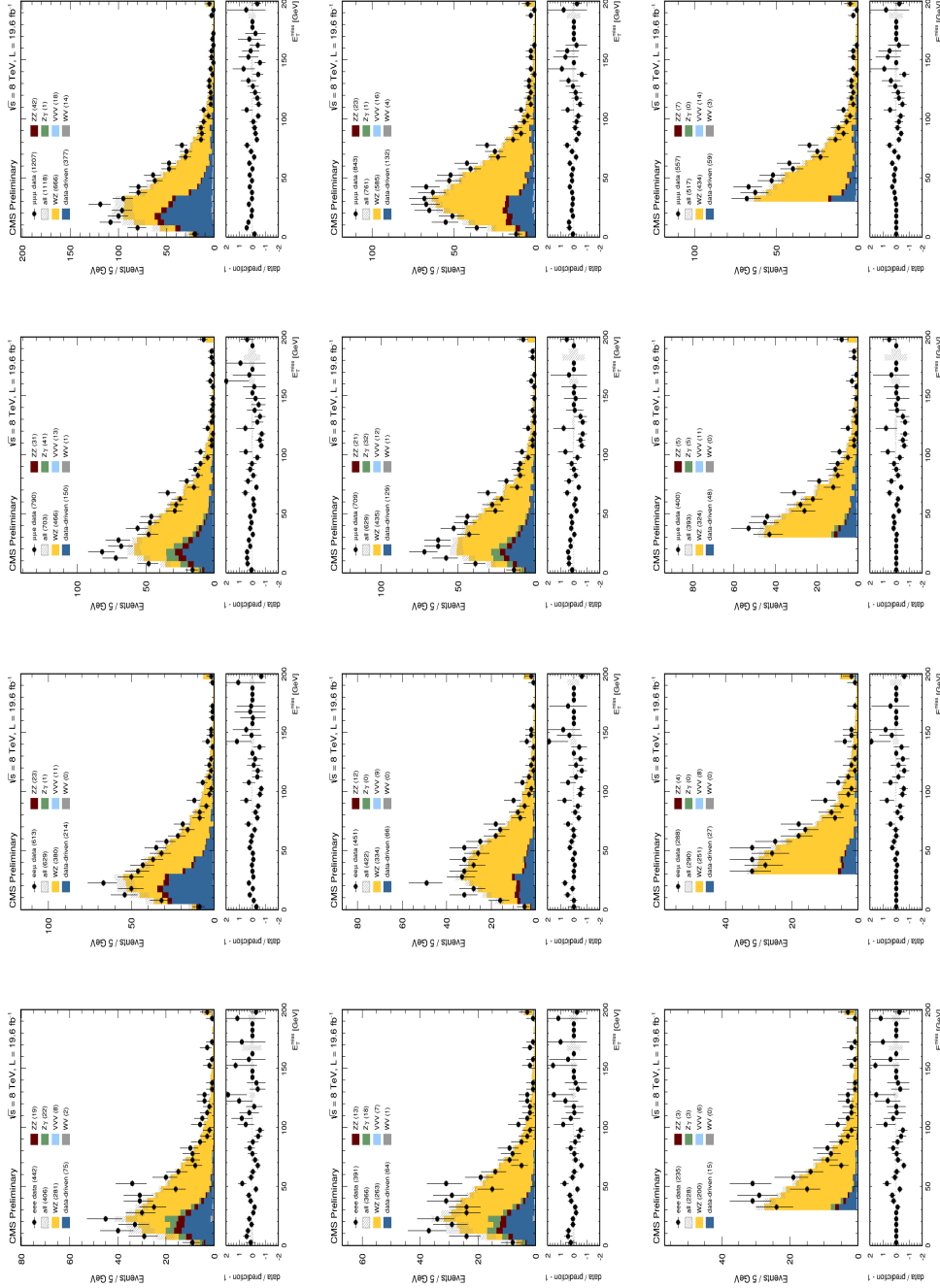


FIGURE A.29: Missing energy in the transverse plane at each event for the measured channels eee , μee , $e\mu\mu$ and $\mu\mu\mu$ (from left to right) and after each analysis selection stage: after Z-candidate requirement (up row), after W-candidate, without the E_T^{miss} cut (middle row) and after W-candidate including E_T^{miss} cut (bottom row).

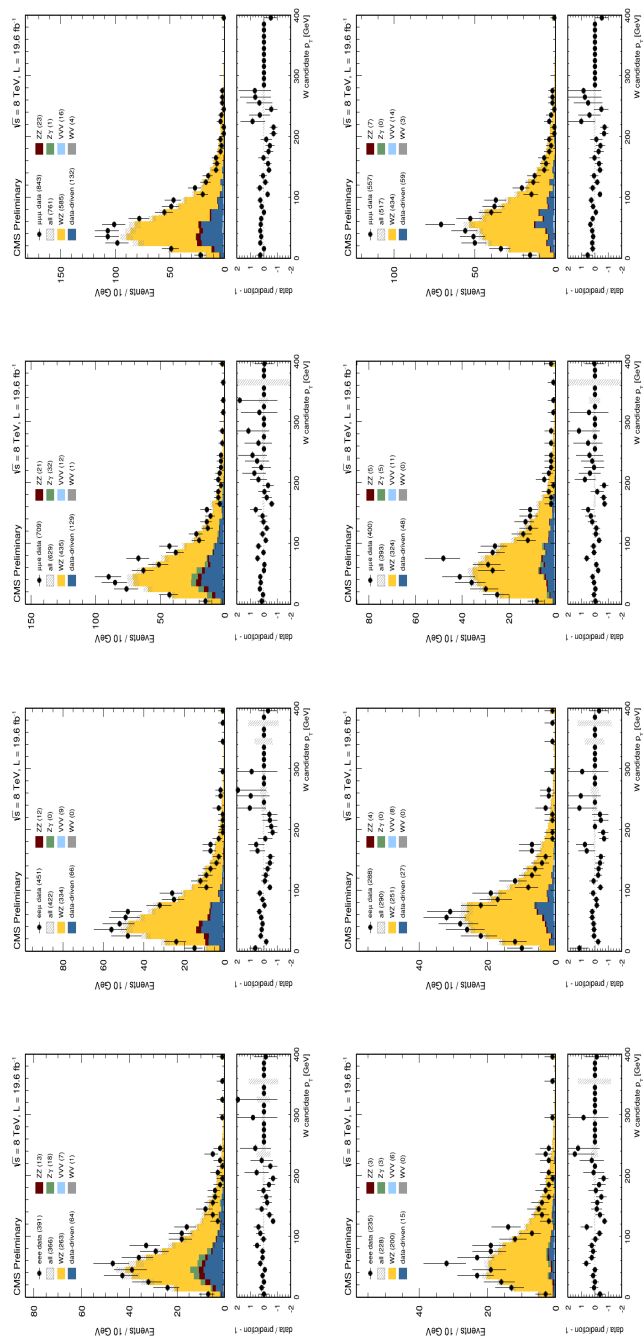
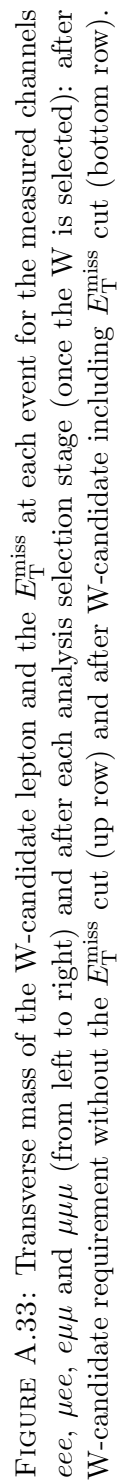


FIGURE A.31: Transverse momentum of the W-candidate lepton at each event for the measured channels eee , μee , $e\mu\mu$ and $\mu\mu\mu$ (from left to right) and after each analysis selection stage (once the W is selected): after W-candidate requirement without the E_T^{miss} cut (up row) and after W-candidate including E_T^{miss} cut (bottom row).



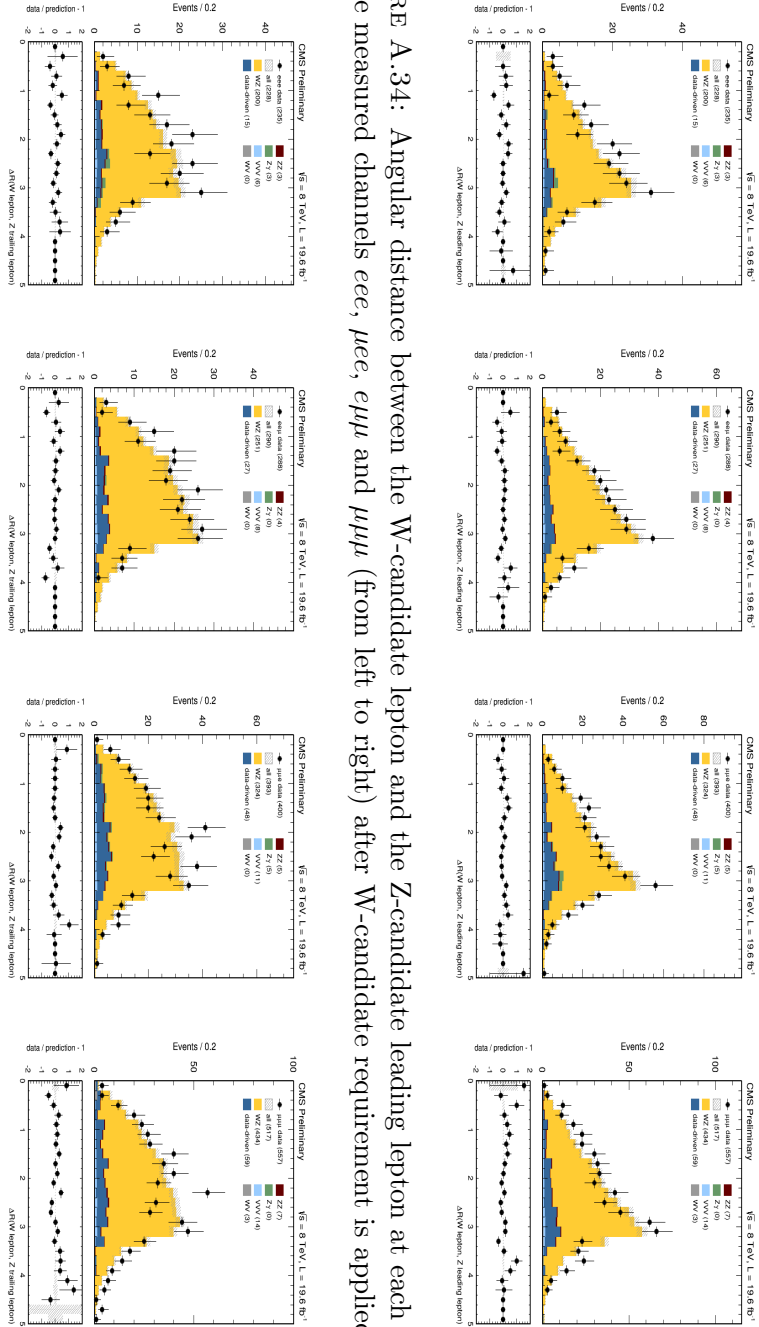


FIGURE A.34: Angular distance between the W-candidate lepton and the Z-candidate leading lepton at each event for the measured channels eee , μee , $e\mu\mu$ and $\mu\mu\mu$ (from left to right) after W-candidate requirement is applied.

FIGURE A.35: Angular distance between the W-candidate lepton and the Z-candidate trailing lepton at each event for the measured channels eee , μee , $e\mu\mu$ and $\mu\mu\mu$ (from left to right) after W-candidate requirement is applied.

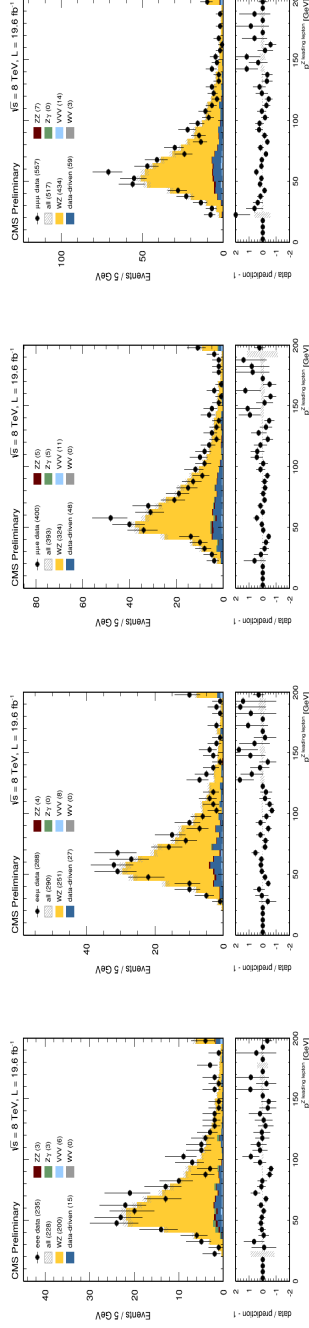


FIGURE A.36: Transverse momentum of the Z-candidate leading lepton at each event for the measured channels eee , eee , $e\mu\mu$ and $\mu\mu\mu$ (from left to right) after W-candidate requirement is applied.

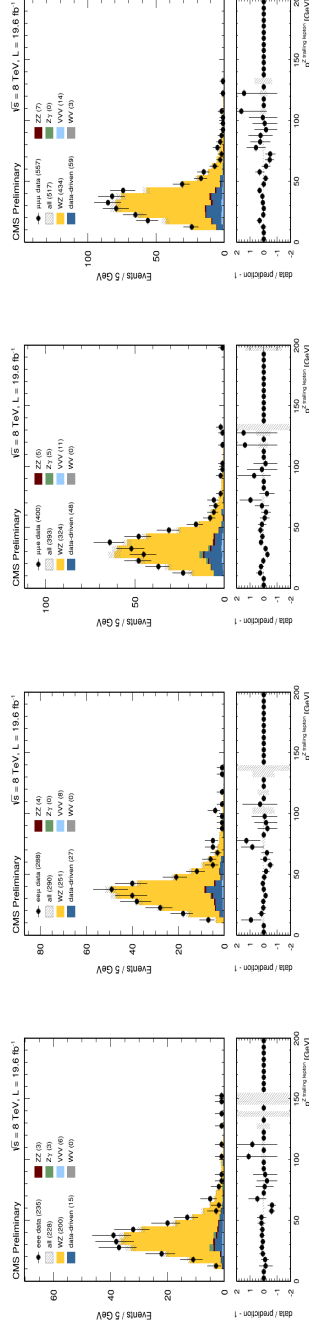


FIGURE A.37: Transverse momentum of the Z-candidate trailing lepton at each event for the measured channels eee , eee , $e\mu\mu$ and $\mu\mu\mu$ (from left to right) after W-candidate requirement is applied.

A.4. Ratio analysis distributions at 8 TeV

The distributions shown in this subsection correspond to the 2012 analysis of the cross section ratio between the W^+Z and W^-Z processes. The samples follows the colour conventions and the processing explained in the previous sections. The distributions are grouped by observable, showing in each figure two columns corresponding to the combined channel of the W^-Z and W^+Z and each row to a stage of the analysis. Note that since the sample splitting by charge lies in the W-candidate, the analysis stages are shown from this requirement on.

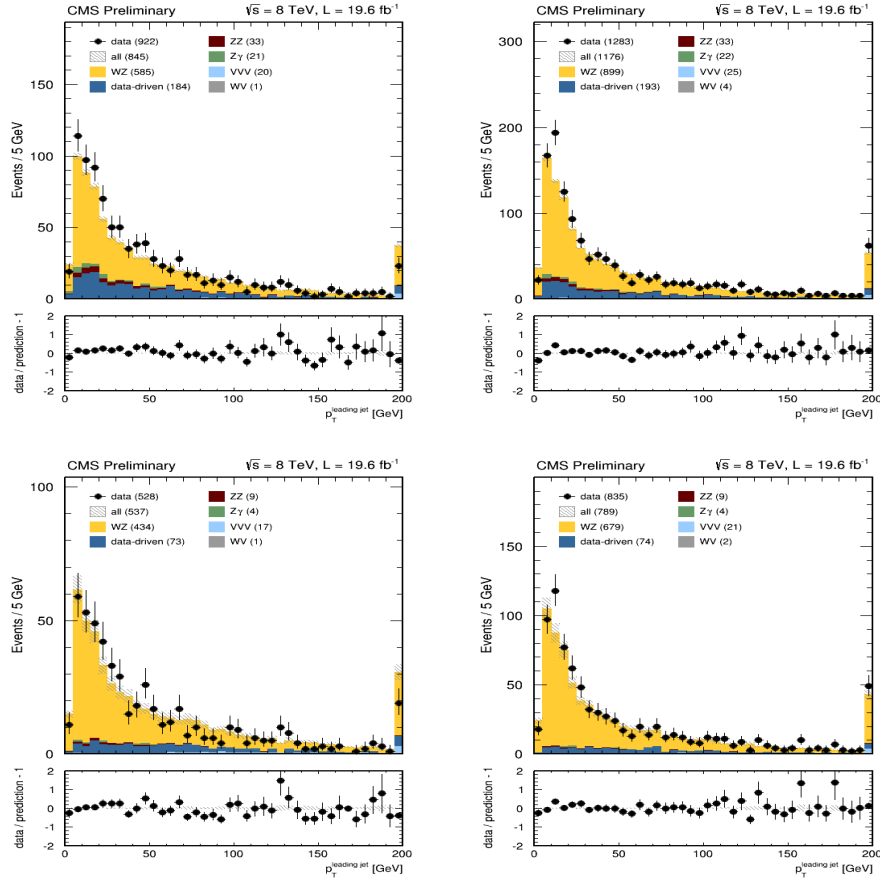


FIGURE A.38: Transverse momentum distribution of the leading jet at each event for the W^-Z (left column) and W^+Z (right column) before the E_T^{miss} cut (up row) and after (bottom row).

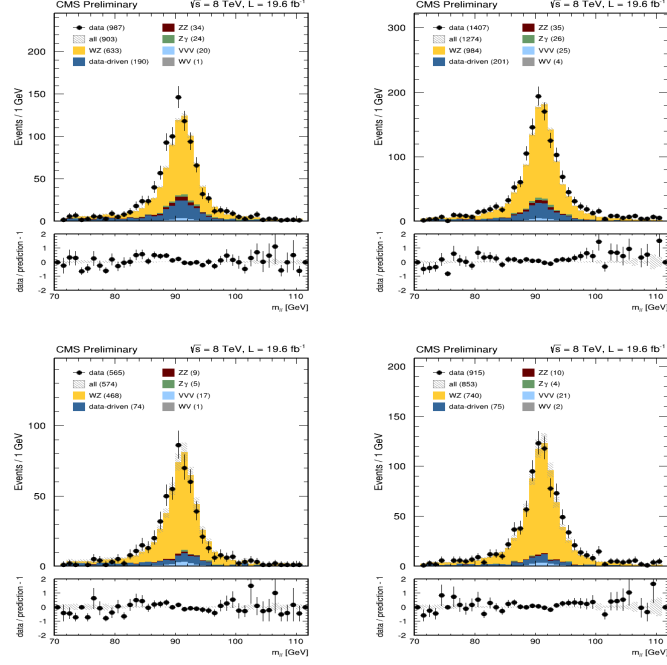


FIGURE A.39: Invariant mass of the Z-candidate dilepton system for the W^-Z (left column) and W^+Z (right column) before (up row) and after the E_T^{miss} cut (bottom row).

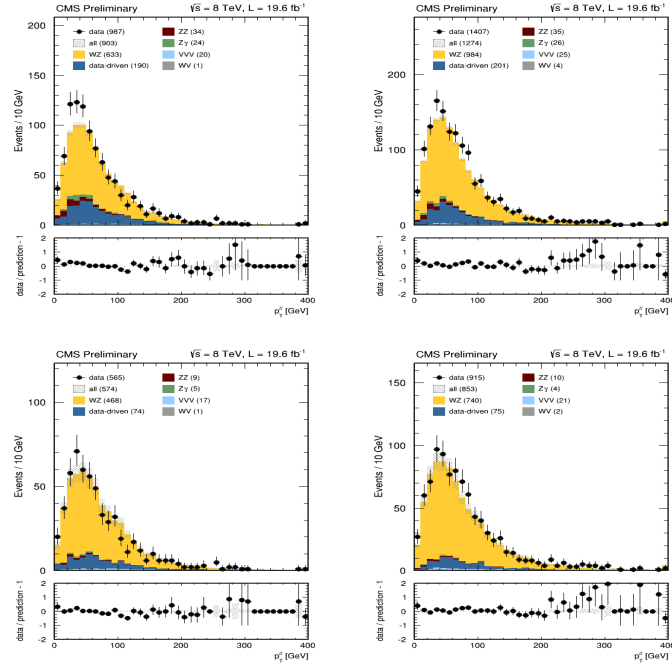


FIGURE A.40: Transverse momentum of the Z-candidate dilepton system for the W^-Z (left column) and W^+Z (right column) before (up row) and after the E_T^{miss} cut (bottom row).

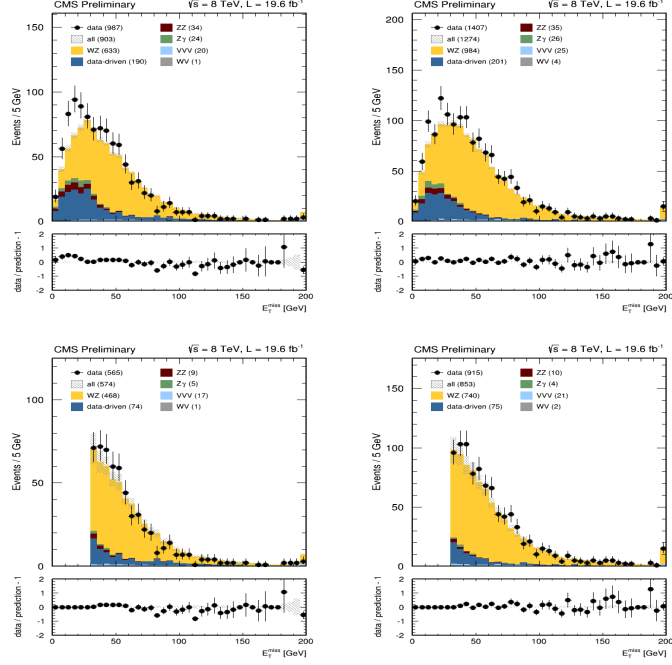


FIGURE A.41: Missing energy in the transverse plane at each event for the W^-Z (left column) and W^+Z (right column) before (up row) and after the E_T^{miss} cut (bottom row).

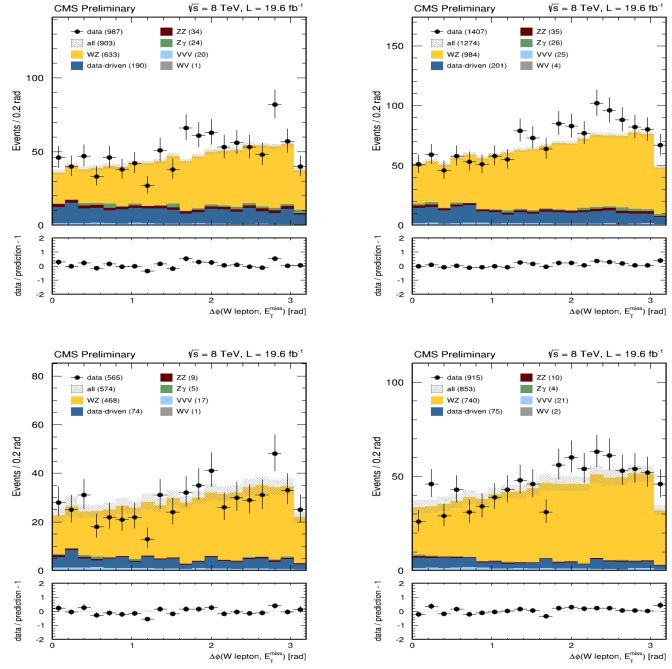


FIGURE A.42: Azimuthal angle between the W-candidate lepton and the E_T^{miss} at each event for the W^-Z (left column) and W^+Z (right column) before (up row) and after the E_T^{miss} cut (bottom row).

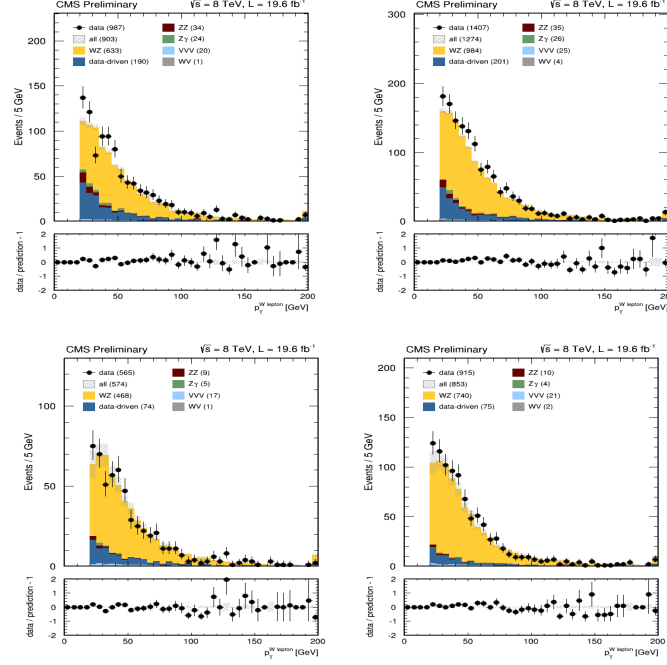


FIGURE A.43: Transverse momentum of the W-candidate system composed by the third selected lepton and E_T^{miss} at each event for the W^-Z (left column) and W^+Z (right column) before (up row) and after the E_T^{miss} cut (bottom row).

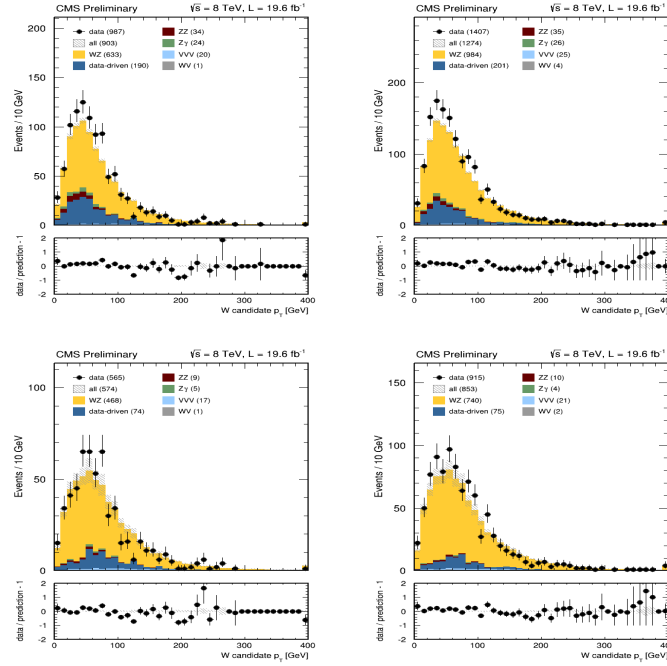


FIGURE A.44: Transverse momentum of the W-candidate lepton at each event for the W^-Z (left column) and W^+Z (right column) before (up row) and after the E_T^{miss} cut (bottom row).

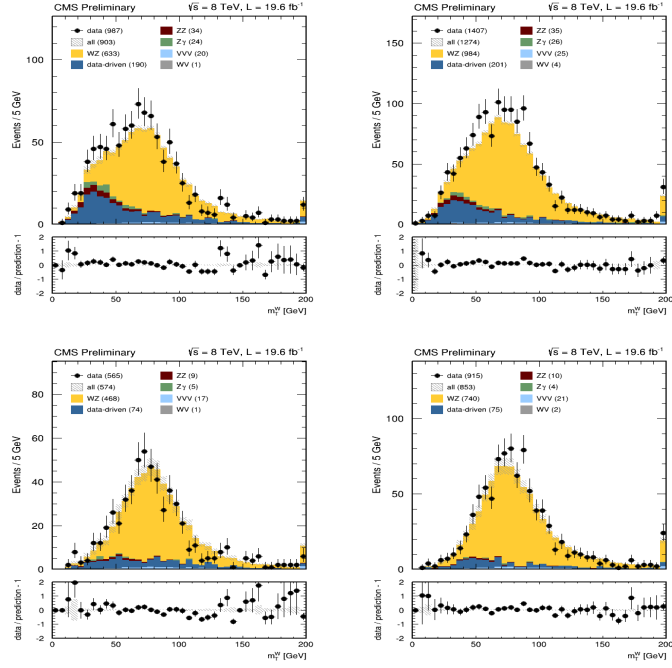


FIGURE A.45: Transverse mass of the W-candidate lepton and the E_T^{miss} at each event for the W^-Z (left column) and W^+Z (right column) before (up row) and after the E_T^{miss} cut (bottom row).

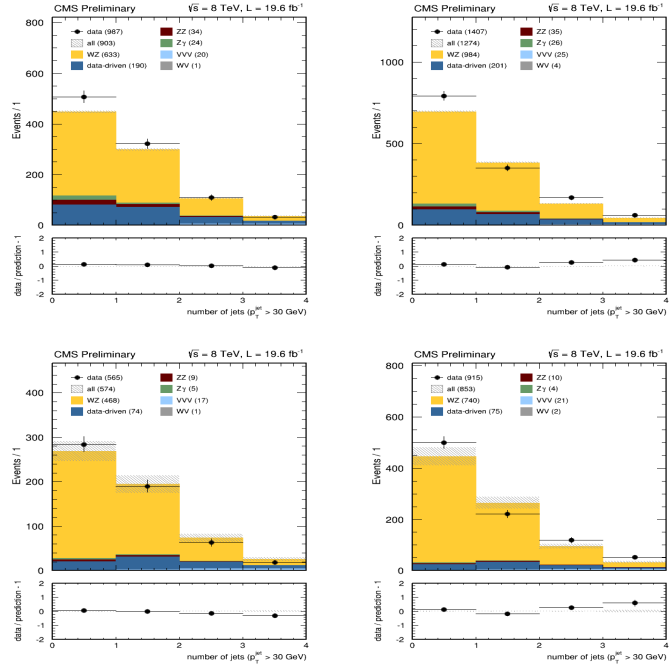


FIGURE A.46: Number of jets distribution at each event for the the W^-Z (left column) and W^+Z (right column) before (up row) and after the E_T^{miss} cut (bottom row).

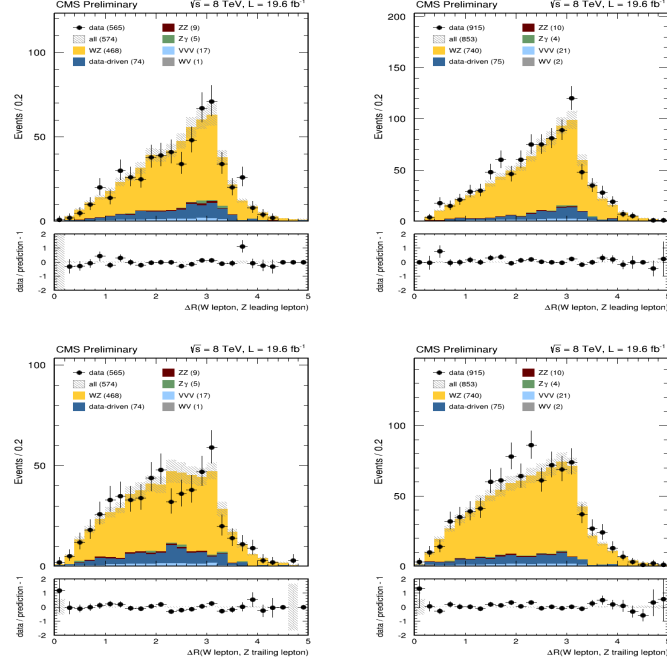


FIGURE A.47: Angular distance between the W-candidate lepton and the Z-candidate leading (up row) and trailing lepton (bottom row) at each event for the W^-Z (left column) and W^+Z (right column) before E_T^{miss} cut.

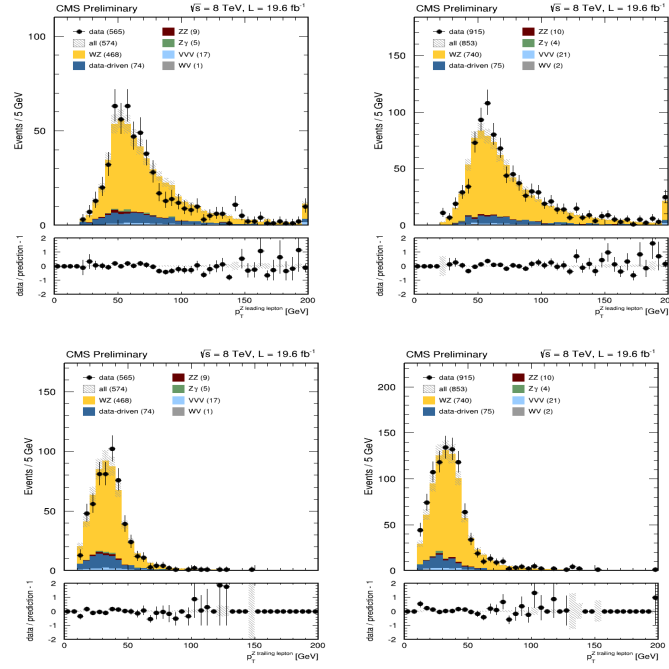


FIGURE A.48: Transverse momentum of the Z-candidate leading (up row) and trailing lepton (bottom row) at each event for the W^-Z (left column) and W^+Z (right column) after the E_T^{miss} cut.

Resumen

Había una vez, un circo...

— Los payasos de la tele

El arranque del acelerador de partículas más potente del mundo, el LHC (de sus siglas en inglés *Large Hadron Collider*), en 2009 y sus tres años de impresionante rendimiento han permitido a todos los experimentos situados en el anillo del acelerador, entre ellos CMS (del inglés *Compact Muon Solenoid*), almacenar millones de datos de colisiones protón–protón, accediendo por primera vez a la escala de energías del teraelectronvoltio (TeV). El análisis de estos datos ha reforzado las predicciones del Modelo Estándar de partículas y ha posibilitado una serie de importantes resultados destacando entre ellos el descubrimiento de una nueva partícula compuesta, el mesón $\chi_b(3P)$, la creación de plasma de quarks y gluones, la primera observación de la desintegración del mesón B_s^0 a dos muones cuyos resultados son consistentes con el Modelo Estándar y el descubrimiento de una nueva partícula elemental, un bosón cuyas propiedades medidas hasta la fecha son consistentes con el bosón de Higgs predicho por el Modelo Estándar. La obtención de tan notables resultados ha necesitado de un previo re-descubrimiento del Modelo Estándar de partículas.

El Modelo Estándar de partículas, establecido como modelo ortodoxo de las interacciones entre las partículas a mediados de los años 70 del siglo pasado, ha sido verificado experimentalmente a lo largo de estos años, confirmando las predicciones, en muchos casos con notable precisión. Este conocimiento experimental del modelo ha sido explotado para calibrar los datos, permitiendo una mejor comprensión de los complejos aparatos de medida usados para la detección de partículas. Los procesos predichos por el Modelo Estándar han sido observados de nuevo y se

han realizado nuevas medidas en el nuevo rango de energías que ha alcanzado el acelerador: 7 y 8 TeV. Estas nuevas medidas, de destacado valor científico por sí mismas, representan el primer paso hacia los descubrimientos mencionados previamente, puesto que estos procesos, ya medidos y estudiados con el Modelo Estándar, introducirán ruido a la señal del nuevo proceso que quiere medirse y, por tanto, deben entenderse y controlarse perfectamente para poder ser sustraídos o estimados de los datos observados. En particular, la producción de dibosones WZ aparece recurrentemente como fondo de diversas búsquedas del bosón de Higgs y en modelos de nueva física, siendo, por consiguiente, importante un conocimiento preciso y minucioso del proceso para controlar los análisis de búsqueda. Asimismo, la sección eficaz de producción del proceso nunca ha sido medido en los rangos de energía que ha alcanzado el LHC, proporcionando una nueva medida a confirmar por las predicciones del Modelo Estándar.

Puesto que el bosón W está cargado, el estudio del proceso de producción de WZ pasa por estudiar la producción de W^-Z y W^+Z , y en particular, un observable interesante a medir es el cociente de la sección eficaz de ambos procesos, $\sigma_{W^-Z}/\sigma_{W^+Z}$. Este cociente puede ser medido con mayor precisión que las secciones eficaces debido a que es posible cancelar en algunos casos, o reducir de forma importante en otros, algunas de las incertidumbres experimentales. Además, el cociente de secciones eficaces resulta ser más sensible a las funciones de distribución partónicas (PDFs, del inglés *Parton Distribution Functions*), unas funciones fenomenológicas que se utilizan como *inputs* en los cálculos teóricos de sección eficaz. En consecuencia, este observable puede utilizarse para validar o constreñir los diferentes conjuntos de PDFs que existen.

En esta tesis doctoral se presenta y desarrolla el trabajo realizado para medir la sección eficaz de producción de dibosones WZ en colisiones protón-protón con una energía de centro de masas de 7 y 8 TeV, junto con la medida del cociente de producción de W^-Z y W^+Z . Los datos analizados se obtuvieron durante los años 2011 ($\sqrt{s}=7$ TeV) y 2012 ($\sqrt{s}=8$ TeV) con el detector CMS, equivalente a 4.9 fb^{-1} y 19.6 fb^{-1} de luminosidad integrada para 2011 y 2012 respectivamente. La sección eficaz de producción de WZ ha sido medida con anterioridad a menor energía, $\sqrt{s}=1.96$ TeV, en los experimentos CDF [96] y D0 [96] del acelerador americano *Tevatron*, y recientemente en *ATLAS*, el otro gran experimento de

propósito general del LHC, a 7 y 8 TeV de energía de centro de masas [27–29]. CMS ha presentado resultados [30] a 7 TeV utilizando datos que corresponden a 1.1 fb^{-1} de luminosidad integrada, y que constituyen parte de varias tesis doctorales [97, 98]. Los últimos resultados actualizados a 7 TeV utilizando todos los datos disponibles, así como los nueva medida que ha presentado CMS a 8 TeV, y junto con la primera medida experimental realizada del cociente de producción de W^-Z y W^+Z [31], se han extraído fundamentalmente de esta tesis doctoral. El proceso de análisis se compartió con otro grupo de trabajo dentro de la colaboración¹, de forma que de manera independiente, aunque utilizando la misma metodología y datos iniciales, se obtuvieron los mismos resultados. Este proceso proporcionó robustez al análisis y lo protegió contra posibles (y probables) errores de código, añadiendo solidez a las medidas. Los resultados de esta tesis constituyen, pues, los resultados que la colaboración CMS ha presentado en conferencias y cuyo artículo correspondiente está en fase de preparación.

1. Marco teórico

El Modelo Estándar de partículas [1] (ME) se ha establecido, a lo largo de estos cuarenta años desde que a mitades de los años 70 del siglo XX se finalizó su formulación con la confirmación experimental de los *quarks*, como la teoría que mejor describe experimentalmente las interacciones de las partículas subatómicas. El modelo caracteriza tres de las cuatro interacciones fundamentales conocidas: la electromagnética, la débil y la fuerte. A pesar de los esfuerzos realizados para incluir la cuarta interacción, la gravitatoria, hasta la fecha no ha sido posible acomodarla a la teoría; este hecho, junto con otras cuestiones fundamentales sin resolver, evita que el ME sea una teoría completa de las interacciones fundamentales aunque sí es un modelo efectivo que proporciona predicciones teóricas consistentes con los resultados experimentales en los rangos energéticos alcanzados hasta la fecha.

El modelo describe la materia y antimateria a través de campos fermiónicos y las interacciones mediante campos bosónicos. Así, el ME incluye 61 partículas elementales, 48 fermiones de spin $1/2$ y 13 bosones mediadores de fuerza. Los fermiones, clasificados de acuerdo a cómo interaccionan, es decir qué *cargas* llevan,

¹Cuyo esfuerzo quedará plasmado en otra tesis doctoral que está fase de en preparación

se dividen en *quarks* y *leptones*. Hay seis quarks¹ (*up*, *down*, *charm*, *strange*, *top* y *bottom*) y seis leptones (*electrón*, *neutrino electrónico*, *muón*, *neutrino muónico*, *tauón* y *neutrino tauónico*), cada uno con su correspondiente antipartícula. Cada tipo de quark y leptón es designado como *sabor*. A su vez, los leptones y quarks se agrupan en *generaciones* formadas por partículas que exhiben un comportamiento físico similar. La propiedad distintiva de los quarks es que son portadores de carga de color y, por tanto, interaccionan a través de la fuerza fuerte. Los quarks, además, llevan carga eléctrica y carga de isospín débil, interactuando también mediante la fuerza electromagnética y débil. Los leptones, en cambio, no llevan carga de color, interactúan a través de la fuerza débil aunque, el electrón, muón y tauón lo hacen también a través de la electromagnética. Así, los neutrinos, al no llevar carga eléctrica e interactuar únicamente mediante la interacción débil, son extremadamente complicados de detectar.

	Interacciones			
	ν_e	ν_μ	ν_τ	débil
LEPTONES	e	μ	τ	débil, EM
QUARKS	u	c	t	débil, EM, fuerte
	d	s	b	débil, EM, fuerte

TABLA R.1: Taxonomía de los fermiones del ME, mostrando sus respectivos símbolos: ν (neutrino), e (electron), μ (muón), τ (tauón) y la inicial del nombre de cada quark. Cada quark se encuentra con tres cargas diferentes de color (carga de la interacción fuerte), siendo en total $3 \times 6 = 18$ quarks. Además, cada fermión tiene su correspondiente antipartícula (de carga eléctrica opuesta). La agrupación en filas responde a la asociación por generaciones. La última columna muestra la interacción a la que son sensibles cada fermión de la misma generación (EM=electromagnética).

Los bosones, por su parte, son las partículas de spin 1 que el modelo utiliza para mediar las interacciones. Son los portadores de las fuerzas electromagnética (fotón, γ), débil (bosones Z , W^+ y W^-) y fuerte (ocho gluones, g). Tanto el fotón como los gluones son bosones sin masa, y, en el caso de los gluones, además también pueden interaccionar consigo mismos. Los bosones Z , W^+ y W^- , responsables de mediar las interacciones débiles entre partículas de distinto sabor, son, por

¹En realidad, hay 18 quarks, cada uno de los seis con diferente carga de color: roja, verde y azul.

el contrario, bosones masivos. El bosón W , al portar carga eléctrica, también se acopla con la interacción electromagnética. Los tres bosones masivos junto con el fotón se agrupan de forma que colectivamente son los mediadores de la interacción electrodébil (EWK, del inglés electroweak), la unificación en el ME de la teoría electromagnética y débil.

El ME se formula matemáticamente a través de teoría cuántica de campos [3], donde un *lagrangiano* controla la dinámica y la cinemática de la teoría. La construcción del modelo sigue los procedimientos habituales para construir la mayoría de teorías de campo, postulando un conjunto de simetrías del sistema, que a su vez definen las interacciones del mismo. Además de la simetría global de Poincaré, puesto que el ME es una teoría relativista, el ME viene definido por la simetría interna del sistema $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$. La formulación del lagrangiano más general con la simetría interna mencionada, predice partículas sin masa, predicción inconsistente con los datos experimentales. Así, se introduce un mecanismo *ad-hoc* para proporcionar masa a las partículas y que respeta la invarianza del sistema a la simetría local, completando el ME. Este mecanismo es conocido como *mecanismo de Higgs*, cuya consecuencia directa es la introducción de un nuevo bosón en la teoría, el bosón de Higgs, encargado de proporcionar masa a los fermiones y a los bosones W y Z , mientras que permite al fotón y a los gluones no tener masa.

2. El experimento

El LHC es un acelerador de partículas que permite colisionar protones a 14 TeV de energía en el centro de masas en su diseño nominal. Durante los tres primeros años de funcionamiento ha alcanzado las energías 7 TeV y 8 TeV, proporcionando por primera vez acceso experimental a esos rangos energéticos y con una luminosidad instantánea capaz de producir millones de procesos de baja tasa de producción. En el anillo principal del acelerador, de unos 27 kilómetros de circunferencia instalado cerca de Ginebra, se sitúan cuatro grandes detectores en el centro de otros tantos puntos de colisión: ALICE, ATLAS, CMS y LHCb; estos aparatos van a detectar y almacenar las colisiones de partículas de alta energía que se produzcan.

El detector CMS [99] es un detector de propósito general, compacto y hermético de unos 21 metros de largo y 14 de diámetro, cuyo peso aproximado es de 12500 toneladas. El diseño del detector comprende un solenoide superconductor que proporciona un campo magnético uniforme de 3.8 T, en cuyo interior se emplazan diferentes sistemas de detección de partículas. En su parte más interna, rodeando al punto de colisión, se encuentra el sistema interno de detección de trazas, compuesto por un detector de píxeles de tres capas cilíndricas de radios comprendidos entre 4.4 y 10.2 cm, y un detector de bandas de silicio compuesto por diez capas cilíndricas de detección que se extienden hacia el exterior alcanzando un radio de 1.1 m. Cada sistema cilíndrico se completa con dos tapas, permitiendo extender la aceptación de detección hasta $|\eta| < 2.5$. Los detectores de trazas se rodean de un calorímetro electromagnético de cristal de tungstato de plomo (ECAL, del inglés *electromagnetic calorimeter*) de fina granularidad en el plano transversal, y de un calorímetro hadrónico basado en detectores de centelleo (HCAL, del inglés *hadron calorimeter*) que cubren la región $|\eta| < 3$. El hierro de retorno, en la parte externa del solenoide, está instrumentado con detectores gaseosos que se utilizan para identificar muones en el rango $|\eta| < 2.4$. El barril del cilindro del sistema de detección de muones está formado por cámaras de deriva (DT, del inglés *drift tube*) mientras que las tapas del cilindro montan cámaras de bandas catódicas (CSC, del inglés *cathode strip chamber*) complementadas por cámaras de láminas resistivas (RPC, *resistive plate chamber*).

Los sucesos de colisiones se seleccionan utilizando el *sistema de selección de datos*, llamado *trigger*. Debido a limitaciones de almacenamiento y velocidad de procesamiento, no todas las colisiones producidas en CMS pueden almacenarse. De hecho, dada la frecuencia de cruce de los haces de protones proporcionados por el LHC en el punto de interacción, unas 100 millones de colisiones por segundo se están produciendo en CMS, de las cuales sólo un porcentaje muy pequeño serán colisiones de altas energías e interesantes desde el punto de vista de análisis. El sistema de *trigger* es el encargado de seleccionar dichas colisiones *interesantes* a través de parte de los sistemas de detección de CMS, siendo el sistema lo suficientemente flexible para poder seleccionar sucesos dependiendo de sus propiedades medidas y organizarlos en diferentes subconjuntos de datos según el contenido del suceso.

3. Análisis del proceso WZ

La producción de dibosones WZ en un colisionador protónico se produce principalmente por la aniquilación de quarks u (d) y antiquarks $\bar{d}$ ($\bar{u}$) de los protones que colisionan para producir un boson W^+ (W^-) que a su vez pierde energía al interactuar débilmente produciendo un boson Z. La desintegración leptónica de los bosones es, entre todas las desintegraciones posibles, la más limpia experimentalmente. El W produce un leptón con su misma carga acompañado de un neutrino, indetectable en CMS pero que puede inferirse aplicando conservación de energía en el plano transversal. Por su parte, el bosón Z se desintegra leptónicamente en dos leptones del mismo sabor y carga opuesta. Así, experimentalmente la signatura del proceso se caracteriza por tres leptones, dos de ellos del mismo sabor y carga opuesta, y una cantidad apreciable de energía perdida en el plano transversal (designada como E_T^{miss}).

La sección eficaz de producción de un proceso X puede estimarse a partir de

$$\sigma(pp \rightarrow X) = \frac{N_S}{\mathcal{A} \cdot \varepsilon \cdot \mathcal{L}_{int}}, \quad (\text{R.1})$$

siendo N_S el número de sucesos observados del proceso X , i.e. la señal; $\mathcal{A}$ designa la aceptación del detector; ε es la eficiencia de detectar el proceso; y $\mathcal{L}_{int}$ es la luminosidad integrada. Así, medir una sección eficaz equivale a seleccionar sucesos de señal evaluando las eficiencias de detección, que en líneas generales define la metodología utilizada en la medida de la sección eficaz de cualquier proceso.

Específicamente, la metodología utilizada en la medida de la tasa de producción del proceso WZ y del cociente $\sigma_{W-Z}/\sigma_{WZp}$ de este trabajo de tesis sigue las siguientes líneas argumentales. Los datos proporcionados por el detector CMS se seleccionan mediante una serie de cortes de calidad sobre los objetos fundamentales del análisis, esto es, los leptones, y posteriormente se aplican una sucesión de *cortes secuenciales* optimizados para extraer sucesos de señal. Puesto que entre los sucesos seleccionados van a encontrarse contaminación de otros procesos, se utilizan métodos basados en datos (*data-driven*) y métodos basados en simulación (Monte Carlo) para estimar estos fondos. Las eficiencias de reconstrucción de objetos (donde se incluyen trigger, identificación y aislamiento) se evalúan con

métodos basados en datos experimentales llamados *tag-and-probe*. Finalmente, utilizando una muestra simulada de WZ se obtiene la aceptación y la eficiencia de selección.

3.1. Reconstrucción de objetos

Los datos recolectados por CMS se procesan de forma centralizada, proporcionando una reconstrucción genérica de los sucesos a todo análisis realizado en la colaboración. Cada análisis puede refinar el contenido de los sucesos, adecuándolos a las necesidades del análisis particular. Para la selección de los estados finales del proceso WZ, los sucesos reconstruidos son inicialmente filtrados con cortes de calidad sobre los leptones finales del suceso; en particular se requiere una buena identificación de los candidatos a muones [75] y de los candidatos a electrones [58]. Además, se comprueba que cada candidato a leptón sea compatible con el vértice primario del suceso, que se escoge como aquel cuyas trayectorias asociadas suman un mayor $\sum p_T^2$. Este criterio proporciona una asignación correcta del vértice primario en más del 99 % de los casos.

Los leptones que provienen de una desintegración de bosones W o Z tienden a estar aislados de otras partículas del suceso, mientras que hadrones que se han identificado incorrectamente como leptones, o leptones que provienen de desintegraciones de quarks pesados generalmente están cerca de un jet. Así, una forma de discriminar entre estos dos tipos de leptones es mediante el uso del *aislamiento*. El aislamiento puede definirse a través de un cono construido alrededor de la dirección de la trayectoria del leptón en el vértice del suceso; se calcula la suma escalar de la energía transversa de cada partícula reconstruida en el suceso que es compatible con el vértice primario escogido y que está contenida en el cono (sin utilizar la del propio leptón). Si dicha suma excede aproximadamente el 10 % del momento transverso del leptón, se rechaza, considerándolo no aislado (el porcentaje exacto de p_T depende del sabor del leptón, de su momento transverso y de su pseudorapidez).

La E_T^{miss} , debida al neutrino que proviene de la desintegración del W que no interactúa con el detector, se calcula mediante un método llamado *particle-flow* [73]. El algoritmo de *particle-flow* combina la información del detector de

trazas, del espectrómetro de muones y de todos los calorímetros de CMS para reconstruir objetos de acuerdo con el tipo de partículas: electrones, muones, fotones y hadrones neutros o cargados. Esta reconstrucción, utilizando todos los subsistemas de detección disponibles, permite conseguir correcciones precisas en las energías de las partículas, además de proporcionar un grado significativo de redundancia que se traduce en una medida de la E_T^{miss} menos sensible a los errores en las calibraciones calorimétricas. La E_T^{miss} se calcula como la magnitud del vector suma, cambiado de signo, de las energías transversas de todos los objetos *particle-flow*.

3.2. Selección de sucesos

La desintegración leptónica de los dibosones WZ define el estado final de la señal como tres leptones de alto momento y aislados, dos de carga opuesta y mismo sabor, además de una cantidad apreciable de E_T^{miss} debido al paso del neutrino por el detector sin interactuar con sus sistemas. La desintegración del W o Z en tauones también es considerada señal, siempre y cuando el tauón se desintegre leptónicamente. Dependiendo del sabor de los leptones finales, podemos realizar la medida utilizando cuatro estados finales, i.e. *canales*, diferentes y excluyentes: eee , μee , $e\mu\mu$ y $\mu\mu\mu$ (sobreentendiendo la presencia de E_T^{miss} en todos ellos).

Los sucesos que sobreviven a los cortes de calidad de los leptones son evaluados mediante cortes secuenciales que rechazan todo aquel suceso que no cumpla:

1. El suceso tiene que haber sido seleccionado con un trigger que requiera la presencia de dos leptones, ya sean dos muones o dos electrones.
2. El suceso tiene que contener sólo tres leptones, electrones o muones, que satisfagan los criterios de calidad descritos previamente.
3. El suceso contiene un candidato a Z, construido a partir de dos leptones de signo opuesto e igual sabor. Además el leptón de mayor p_T tiene que cumplir $p_T > 20$ GeV y el de menor, $p_T > 10$ GeV. La masa invariante del sistema de los dos leptones debe estar en una ventana de 20 GeV alrededor de la masa nominal del Z.
4. El tercer leptón, asociado al W, se requiere que cumpla $p_T > 20$ GeV.

5. La E_T^{miss} del sucesos tiene que ser mayor de 30 GeV.

Los requisitos (1) y (2) se designan a lo largo de este trabajo como corte de *preselección*, el requisito (3) como *candidato-Z* y los requisitos (4) y (5) como *candidato-W*. En el caso de la medida del cociente de secciones eficaces entre W^-Z y W^+Z , el requisito (4) es ampliado de tal forma que incluya la carga del leptón separando así la muestra en dos submuestras, cada una utilizada para medir W^-Z y W^+Z .

3.3. Estudio de fondos

El uso de los cortes secuenciales en los sucesos permite seleccionar con gran pureza una muestra con candidatos a WZ, pero quedan remanentes de sucesos que provienen de otros procesos, contaminando la señal. Estos sucesos, llamados *fondos* o *ruido*, se pueden clasificar, dependiendo de su origen, en fondos instrumentales o fondos físicos.

Los fondos físicos son aquellos procesos de producción cuyo estado final es exactamente igual al estado final del WZ, esto es tres leptones aislados de alto momento y una cantidad apreciable de E_T^{miss} . El proceso ZZ desintegrándose ambos bosones Z leptónicamente constituye un fondo físico del WZ cuando uno de los cuatro leptones no sea detectado, ya sea por aceptación o por ineficiencias de detección, presentando un estado final de tres leptones, dos de carga opuesta e igual sabor, y una cantidad apreciable de E_T^{miss} debido al leptón perdido. Así, también constituyen fondos físicos los procesos VVV (siendo $V=W,Z$), aunque estos procesos tiene una baja tasa de producción en comparación con el WZ o el ZZ, y solamente van a ser considerados en el análisis de 8 TeV, donde la cantidad de datos acumulados es lo suficientemente grande como para que aparezcan algunos de dichos procesos. Estos fondos físicos son irreducibles en el sentido que no es posible distinguirlos en su estado final de la señal; para estimarlos se genera toda la cadena de desintegración del proceso considerado a partir de cálculos teóricos y técnicas Monte Carlo, reproduciendo las posibles partículas finales del proceso y su cinemática. Se simula el paso de dichas partículas finales a través del detector obteniendo la emulación de la respuesta del detector en forma de datos equivalentes a los datos que se obtendrían experimentalmente. El proceso es generado tantas

veces como sea posible de tal forma que se consiga un número significativo de sucesos. La simulación de procesos y su desintegración se realiza a través de software especializado, llamados *generadores de sucesos*, que son utilizados ampliamente por toda la comunidad para estimar y obtener predicciones teóricas en colisiones de partículas de altas energías. Así, todos los procesos involucrados considerados, tanto señal como fondos del análisis del WZ han sido simulados y comparados, donde procediera, con los datos experimentales. Los procesos de señal y fondo han sido generados utilizando principalmente MADGRAPH [71], PYTHIA [70] y POWHEG [100]. El conjunto de PDFs utilizado para producir las muestras fueron CTEQ6L [101] y CT10 [93] dependiendo del generador. En todos los procesos, la respuesta del detector se simula utilizando una descripción detallada de CMS basada en el paquete GEANT4 [67]. Finalmente, las muestras simuladas fueron repesadas para producir la distribución del número de interacciones protón-protón en cada cruce de haces (*pileup*) observados en los datos experimentales, dado que esa información no estaba disponible en el momento de procesar las muestras de Monte Carlo.

Los fondos instrumentales son procesos cuyo estado final queda distorsionado por la medida errónea de la desintegración de una o varias partículas del proceso, siendo identificadas como leptones aislados cuando originalmente no lo eran. Estos leptones, llamados *fakes*, pueden ser jets hadrónicos que se identificaron erróneamente como leptones, o verdaderos leptones pero que se desintegraron a partir de quarks pesados. Este tipo de fondo, a su vez, pueden clasificarse según el número de leptones *fakes* creados.

- Tres *fakes* creados. Por ejemplo, en procesos de multijets en QCD, o en procesos W+jets, donde el W se desintegra hadrónicamente.
- Dos *fakes* creados. El proceso W+jets, donde el W se desintegra leptónicamente es un ejemplo de ello.
- Un *fake* creado. El proceso Z+jets, con dos leptones de alto momento, mismo sabor y signo opuesto, si el Z se desintegró leptónicamente. También el proceso $t\bar{t}$ es un ejemplo de este caso cuando los quark top se desintegran a W y estos a su vez se desintegran leptónicamente.

Los dos primeros casos, la creación de tres y dos *fakes*, es bastante improbable y, de hecho, se comprueba que en este análisis pueden negligirse. Así, los fondos instrumentales se reducen al caso de creación de un *fake*, cuya contribución principal la constituyen los procesos $Z+\text{jets}$ y $t\bar{t}$.

La estimación de los fondos instrumentales se ha realizado utilizando un método basado en datos, llamado *fakeable object method* (FOM). El FOM es un método que estima la contribución de leptones *fakes* explotando las, a priori, distintas eficiencias de identificación e aislamiento que tienen los leptones *fakes* y los leptones desintegrados de un W o Z , llamados *prompt*. Para ello, se relajan los criterios de calidad de los leptones del análisis, obteniendo un nuevo conjunto de leptones llamados *loose* o *fakeables* que son utilizados para comprobar las eficiencias de identificación e aislamiento, relacionadas directamente con la probabilidad de que sean leptones *fake* o *prompt*. El método extrae en datos experimentales las eficiencias de los leptones *prompt* y *fake* y las utiliza para estimar las diferentes contribuciones en el estado final de tres leptones, es decir, estima las contribuciones en el análisis, de fondos generados con tres leptones *fake* ($N_{\mathcal{FFF}}^{N_{t3}}$), con dos leptones *fake* y uno *prompt* ($N_{\mathcal{FFP}}^{N_{t3}}$), con un leptón *fake* y dos *prompts* ($N_{\mathcal{PPF}}^{N_{t3}}$), y con tres leptones *prompt* ($N_{\mathcal{PPP}}^{N_{t3}}$). En particular, la estimación $N_{\mathcal{PPP}}^{N_{t3}}$ está definiendo el proceso WZ , aunque también incorpora las contribuciones de los procesos irreducibles, así sustrayendo a $N_{\mathcal{PPP}}^{N_{t3}}$ las estimaciones basadas en Monte Carlo de los fondos irreducibles, obtenemos directamente la estimación del número de sucesos de señal N_S .

3.4. Sistemáticos de las medidas

La medida de cada observable utilizado en la ec. (R.1) tendrá asociadas incertidumbres debidas a efectos sistemáticos que han sido identificados, además de los errores asociados a la estadística utilizada para realizar la medida. Los efectos sistemáticos identificados en las medidas de sección eficaz pueden separarse en varios grupos. El primer grupo combina sistemáticos que afectan a la aceptación y a las eficiencias de reconstrucción e identificación de los objetos de estado final, y son determinados a través de simulaciones Monte Carlo. En este grupo se incluyen las incertidumbres asociadas a la escala y resolución de energía de los leptones

y de la E_T^{miss} , incertidumbres asociadas al rescalado del pileup en las muestras simuladas, y también las incertidumbres teóricas de las PDFs y de las escalas de renormalización y factorización utilizadas en el cálculo de la sección eficaz de la señal. El segundo grupo incluye las incertidumbres introducidas al utilizar los factores de corrección de eficiencias, factores que corrigen las eficiencias calculadas en muestras Monte Carlo con las eficiencias calculadas en datos experimentales. Las eficiencias de reconstrucción e identificación de leptones se calculan con métodos *tag-and-probe* tanto en datos experimentales como en simulaciones Monte Carlo; la diferencia en el cociente de eficiencias entre datos y Monte Carlo se toma como incertidumbre. El tercer grupo de incertidumbres sistemáticas implica al número de sucesos de fondo estimados. En particular, al número estimado por el método *data-driven* se le asigna una incertidumbre debida a la elección de la muestra experimental utilizada para estimar la tasa de *fakes*. A los fondos estimados con simulaciones Monte Carlo, se les asignan un error sistemático debido a la sección eficaz del proceso utilizada para normalizar el número de sucesos; cuando está disponible una medida experimental, se utiliza el error de la medida como error sistemático de la sección eficaz del proceso, en caso contrario se utiliza el error teórico asociado al obtener dicha sección eficaz. Finalmente, también se incluye la incertidumbre asociada a la medida de la luminosidad.

La medida del cociente de secciones eficaces entre los procesos W^-Z y W^+Z sufrirán de las mismas fuentes de errores sistemáticos descritos en el párrafo anterior, pero al realizar el cociente, la incertidumbre de la luminosidad se cancela y el resto de sistemáticos atenúan su efecto debido a que la dirección de dichos efectos sistemáticos es idéntico en ambos procesos. La única fuente de error sistemático que no se verá reducida es la debida a las diferencias en las eficiencias entre los leptones positivos y negativos asociados al W, sistemático no considerado en la medida de sección eficaz inclusiva debido a que dicha diferencia ha sido medida como compatible a la unidad dentro de errores. En el caso de la medida de $\sigma_{W^-Z}/\sigma_{W^+Z}$, los errores de la medida del cociente de eficiencias entre leptones positivos y negativos han sido propagados como sistemáticos, siendo esta fuente la que contribuye en mayor proporción a los errores sistemáticos.

4. Discusión de resultados

La aplicación de la metodología desarrollada a lo largo de este trabajo de tesis, y sintetizada en este capítulo resumen, ha permitido obtener las medidas de la sección eficaz del proceso $pp \rightarrow WZ + X$ y del cociente entre procesos $\sigma(pp \rightarrow W^-Z + X)/\sigma(pp \rightarrow W^+Z + X)$ con energías de centro de masas de 7 TeV y 8 TeV, en el espacio de fases definido en una ventana de 20 GeV alrededor de la masa nominal del bosón Z. Las medidas han sido realizadas en cuatro canales de desintegración con estados finales definidos por los leptones de los bosones W y Z: eee , μee , $e\mu\mu$ y $\mu\mu\mu$. Las cuatro medidas han sido combinadas utilizando un método lineal que tiene en cuenta las correlaciones entre los errores de la medida para obtener la mejor estimación.

El resultado obtenido para $\sqrt{s} = 7$ TeV utilizando los datos detectados por CMS durante el año 2011, que corresponden a una luminosidad integrada de 4.9 fb^{-1} es

$$\sigma_{7 \text{ TeV}}(pp \rightarrow WZ + X) = 20.8 \pm 1.3_{\text{stat}} \pm 1.1_{\text{sys}} \pm 0.5_{\text{lumi}} \text{ pb}$$

donde los errores han sido separados dependiendo de la fuente que los produce, estadístico (stat), sistemático (sys) o sistemático de la luminosidad (lumi). La medida es compatible, dentro de errores, con la predicción teórica del Modelo Estándar para este proceso, $17.8^{+0.7}_{-0.5} \text{ pb}$.

La sección eficaz medida con una energía de centro de masas de 8 TeV, utilizando los datos detectados por CMS durante el año 2012 y que corresponden a una luminosidad integrada de 19.6 fb^{-1} es

$$\sigma_{8 \text{ TeV}}(pp \rightarrow WZ + X) = 24.6 \pm 0.8_{\text{stat}} \pm 1.1_{\text{sys}} \pm 1.1_{\text{lumi}} \text{ pb}$$

siendo también compatible, dentro de errores, con la predicción teórica de $21.9^{+0.9}_{-0.5} \text{ pb}$.

El medida del cociente de secciones eficaces a 7 TeV

$$\left(\frac{\sigma_{W-Z}}{\sigma_{W+Z}} \right)_{7 \text{ TeV}} = 0.547 \pm 0.075_{\text{stat}} \pm 0.011_{\text{sys}}$$

se compara perfectamente con la predicción teórica, dentro de errores, de $0.563^{+0.002}_{-0.001}$ donde se utiliza el conjunto de PDFs MSTW8 para calcular la predicción. Utilizando otro conjunto de PDFs, CT-10, se obtiene una predicción con un valor central mucho más cercano al valor medido $0.546^{+0.002}_{-0.001}$.

En el caso del cociente a 8 TeV, se obtiene una medida de

$$\left(\frac{\sigma_{W^-Z}}{\sigma_{W^+Z}} \right)_{8 \text{ TeV}} = 0.551 \pm 0.035_{\text{stat}} \pm 0.010_{\text{sys}},$$

que también presenta un acuerdo excelente con las predicciones teóricas, 0.580 ± 0.001 utilizando el conjunto de PDFs MSTW8 y 0.563 ± 0.001 utilizando CT-10.

Los datos almacenados en CMS de colisiones protón-protón a $\sqrt{s}=7$ TeV han permitido medir la sección eficaz de producción asociada del proceso WZ, y por primera vez, el cociente de secciones eficaces entre W^-Z y W^+Z , obteniendo resultados dominados por errores estadísticos. La cantidad de datos de colisiones a $\sqrt{s}=8$ TeV, que se incrementaron sustancialmente respecto a 7 TeV, ha posibilitado unas medidas de mayor precisión, a punto de alcanzar la sensibilidad de las predicciones teóricas. Una interesante mejora del presente análisis incluiría un estudio detallado de las fuentes de error sistemáticas para intentar minimizarlas y reducir su tamaño, alcanzando así la sensibilidad teórica. Además, los datos disponibles para 8 TeV permiten extender las medidas a secciones eficaces diferenciales en *bins* de variables cinemáticas sensibles, proporcionando una comparación más detallada de la medida con la teoría. El mismo análisis está capacitado para comprobar la presencia de *acoplamientos anómalos de tres bosones gauge* a través del vértice WWZ, donde los límites, en caso de no encontrar dichos acoplamientos, podrían ser mejorados sustancialmente respecto a la literatura.

Las medidas realizadas en este trabajo de tesis son resultados originales que serán publicados por la colaboración CMS en un artículo, en fase de redacción, y que han sido presentadas en distintas conferencias especializadas. En particular, el cociente de secciones eficaces no había sido medido previamente, siendo éste el primer texto, junto con las presentaciones en conferencias, que lo contiene.

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Glossary

Background

Data events containing the theoretical expected processes which are not defined as signal, *see also Signal*.

Channel

See Decay Channel.

Data-driven

Technical term referring to the use of experimental data to obtain an estimation, avoiding the use of simulated data.

Decay Channel

Each combination of particles that a unstable particle can disintegrate.

Event

Data obtained in a particles collision.

Event Reconstruction

Software algorithms applied to the raw data acquired in order to obtain the high level objects produced in the event, *see also Event*.

Final State Radiation

Radiation produced by a particle coming from a scattering or annihilating process, usually referred to the hard scattering.

Gauge Invariance

Local invariance of a Lagrangian under some kind of transformations.

Hard Scattering

Process involving a large momentum transfer in a hadron-hadron collision.

Initial State Radiation

Radiation produced by a particle in its way to a scattering or annihilating process, usually referred to the hard scattering.

Interaction Point

Physical point where the collision between two particles occurs.

Leading Order

Calculation of the matrix element up to first order of α_s . Called also Born or tree level.

Monte Carlo

Wide set of techniques used to simulate events relying on repeated random sampling based in theoretical probabilities. Actually, the term Monte Carlo is broader, the definition given here is within the context of this dissertation.

Multivariate Analysis

Statistical technique to analyse simultaneously more than one outcome variable.

Parton Distribution Functions

Phenomenological functions fitted from experimental data, describing the probability to find a parton inside a hadron carrying a given fraction of the hadron total momentum.

Pileup

Collisions accompanying the hard scattering produced at the same bunch crossing and recorded along the hard scattering event.

Primary Dataset

Set of experimental data recorded by CMS sorted by trigger paths, *see also Trigger Path*.

Signal

Data events containing the theoretical expected process under study.

Signature

Experimental hallmark left by the particles in the detector, which characterises an event.

Tag and Probe

Technique used in high energy physics to calculate efficiency using well defined events containing resonances.

Trigger

Data-filtering system used to keep a low rate of stored events among the billions per second produced at the LHC.

Trigger Path

Sequence of hardware and software algorithms applied to the raw experimental data outcome used to reject or accept an event. Each path is optimised to select events with specific characteristics (muon, electron, hadronic content, ...).

Underlying Event

Additional parton interactions occurring in a hadron-hadron collision, apart from the hard scattering process.

Acronyms

ALICE	A Large Ion Collider Experiment.
aTGC	anomalous triple-gauge boson couplings.
ATLAS	A Toroidal Large ApparatuS.
BDT	Boosted Decision Tree.
BLUE	Best Linear Unbiased Estimator.
CKM	Cabibbo–Kobayashi–Maskawa.
CMS	Compact Muon Solenoid.
DAQ	data acquisition system.
ECAL	Electromagnetic CALorimeter.
EDM	Event Data Model.
EW	Electro-Weak.
FOM	fakeable object method.
FSR	Final State Radiation.
GSF	Gaussian Sum Filter.
GUT	Grand Unification Theory.
GWS	Glashow, Weinberg and Salam.
HCAL	Hadronic CALorimeter.

HLT	High Level Trigger.
IP	Interaction Point.
ISR	Initial State Radiation.
JEC	Jet energy correction.
LEP	Large Electron–Positron Collider.
LHC	Large Hadron Collider.
LHCb	Large Hadron Collider beauty.
LHCf	Large Hadron Collider forward.
LO	Leading Order.
MSTW8	Martin–Stirling–Thorne–Watt.
MVA	Multivariate Analysis.
NLO	Next to Leading Order.
NNLO	Next to Next to Leading Order.
PD	Primary Dataset.
PDF	Parton Distribution Functions.
POG	Physics Object Group.
PS	Proton Synchrotron.
PSB	Proton Synchrotron Booster.
QCD	Quantum Chromodynamics.
QED	Quantum Electrodynamics.
QFT	Quantum Field Theory.
SF	scale factor.
SM	Standard Model.
STA	Stand-alone muon track.

TOTEM	TOTAL Elastic and diffractive cross section Measurement.
WP	Working Point.
YM	Yang-Mills.

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