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Search for high-mass resonances
decaying into muon pairs
with the CMS experiment at LHC

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Introduction

The Standard Model (SM) of particle physics provides a successful description of all particle physics phenomena. The accuracy of the model can be tested with precision by studying the elementary particles and their interactions in high energy collisions. It is known however, that the SM does not describe the nature completely and it is usually seen as a low energy approximation of a more general theory. There exist many theories extending beyond the SM which predict new physics at an energy scale that can be probed with the Large Hadron Collider (LHC) at CERN with the highest proton-proton center-of-mass energy ever achieved.

Many different searches are performed by the experiments built at the four interaction points of the machine. One of those experiments is the Compact Muon Solenoid (CMS) detector, one of the two general purpose experiments at the LHC. In 2012, the CMS experiment, in parallel with the ATLAS experiment, discovered the scalar boson, predicted by the Brout-Englert-Higgs (BEH) mechanism in 1964.

Searches for new physics beyond the SM are also performed with the CMS experiment at the LHC. Both the ATLAS and CMS collaborations have previously reported searches for new massive resonances (Z') decaying into an electron pair or a muon pair [1,2] using approximately 20 fb^{-1} of proton-proton collisions with center-of-mass energy $\sqrt{s} = 8 \text{ TeV}$ (Run-1). The results have been found consistent with Standard Model predictions and exclude at 95% C.L. a Z'_{SSM} , from the Sequential Standard Model (SSM) with SM-like couplings, with a mass less than 2.90 TeV and a Z'_Ψ , from grand unified theories with the E_6 gauge group, with a mass less than 2.57 TeV (CMS) and 2.46 TeV (ATLAS).

In summer 2015, LHC has started colliding protons at a center-of-mass energy of 13 TeV. Since the cross section for heavy resonances increases with the collision energy, higher mass regions than before have started to be available for new physics searches and, with only a few months of data taking, the sensitivity of the searches presented in Run-1 has been reached [3]. An integrated luminosity of 2.8 fb^{-1} has been recorded by CMS in 2015.

This thesis is about the search for new massive particles decaying into dimuons¹. Such new particles would manifest themselves as a narrow resonance in the invariant mass spectra of the lepton pairs in the final state.

The muon reconstruction plays a crucial role in this analysis since the muon performance at high momentum is strongly affected by radiative processes (electromagnetic showers or hard bremsstrahlung) and by the muon detector alignment. Specialized algorithms for high-energy muon reconstruction, known as “TeV-muon” refits, have been developed in CMS and the final momentum assignment is performed by the so called “Cocktail” algorithm which chooses the best muon track candidate. These algorithms have been updated and tuned to optimize the performance in collisions at 13 TeV.

The production cross section of the new massive particles is very small compared to the one from the Z boson, but already a few reconstructed events at very high mass, on top of the small non-resonant background contribution from SM processes, can lead to a discovery. The leptonic channels with electrons and muons have the advantage that the reconstruction of those leptons is very well understood, leading to a low background from misreconstructed lepton candidates. Furthermore the Z resonance provides an excellent candle for the calibration of the analysis in the mass² range between 60 and 120 GeV. The search has been designed to be as inclusive as possible, which means that a high selection efficiency is a relevant issue in the event selection. Emphasis is also laid on an accurate simulation of the background contributions. No excess over the prediction of the SM contribution has been observed and 95% confidence level upper limits have been set on the ratio of the cross section times branching fraction of new bosons, normalized to the cross section times branching fraction of the Z boson.

The thesis is organised as follows:

Chapter 1 introduces the SM of elementary particle physics and presents various theories going beyond the SM. In particular, new models that predict additional massive resonances decaying into muon pairs are reported.

Chapter 2 describes the experimental setup: the design and operational parameters of the LHC and the CMS detector.

Chapter 3 reports the CMS track reconstruction with particular attention to muons, electrons and jets.

Chapter 4 is dedicated to the high-energy muon reconstruction: the “Cocktail” algorithm optimization and tuning procedure is reported; the new muon

¹In this thesis the term muons describes both muons and anti-muons, unless stated otherwise.

²In this thesis the kinematical units are expressed in terms of units of energy fixing $c=1$ and $\hbar=1$. Such system of units is often referred to as Natural Units.

reconstruction performance has been compared with the high-energy muon reconstruction used for the analysis at 8 TeV, the standard global muon reconstruction, and that from “TeV-muon” reconstructors.

Chapter 5 presents in detail the search for new massive particles decaying into a muon pair describing the muon and event selection, muon momentum scale and dimuon mass resolution measurement, background estimation and validation, invariant mass spectra and statistical interpretation of the results.

The results presented in Chapter 4 and 5 are part of a public CMS Physics Analysis Summary (PAS) [4], and are going to be published as a paper of the CMS collaboration in Spring 2016. Monday, December 7th 2015 I have presented the results for the search for high-mass decaying into a muon pair to the CMS collaboration. The analysis has been approved and results have been presented at CERN Jamboree (December 15th 2015) by the CMS collaboration.

Chapter 1

Physics at the Large Hadron Collider

The fundamental components of matter and their interactions are nowadays best described by the Standard Model (SM) of particle physics, which is based upon two separate quantum field theories, describing the electroweak interaction (Glashow-Weinberg-Salam model or GWS) and the strong interaction (Quantum Chromo-Dynamics or QCD).

In this chapter, a short overview of the SM and of the electroweak theory is given in Section 1.1. Physics Beyond the SM (BSM), motivations for extending the SM, and a description of the theories that lead to heavy resonances that decay to lepton-antilepton pairs are described in Section 1.2.

1.1 Standard Model of elementary particles

The SM is an elegant theory for particle physics which explains the interactions between all known particles in terms of gauge field theory, based on Lagrangian invariant under a group of local phase transformations. The model describes the matter as composed by twelve elementary particles, the *fermions*, all having half-integer spin. Fermions can be divided into two main groups according to their different behavior with respect to the four interactions: *leptons*, and *quarks*, whose classification is given in Table 1.1 [5].

Four types of interactions have been distinguished in Nature, described in terms of forces mediated by particles with an integer spin, the so-called *bosons*.

- The electromagnetic interactions, responsible for the force between electrically charged particles, are mediated by the massless and chargeless spin-one *photon*. Since the mass of the photon is zero, it can mediate interactions to infinite distances.

Leptons			Quarks		
Flavor	Charge	Mass	Flavor	Charge	Mass
ν_e	0	<2 eV	up (u)	$+2/3$	2.3 MeV
e	-1	511 keV	down (d)	$-1/3$	4.8 MeV
ν_μ	0	<2 eV	charm (c)	$+2/3$	1.275 GeV
μ	-1	105.6 MeV	strange (s)	$-1/3$	95 MeV
ν_τ	0	<2 eV	top (t)	$+2/3$	173.2 GeV
τ	-1	1.78 GeV	bottom (b)	$-1/3$	4.18 GeV

Table 1.1: The elementary fermions of the SM. Numerical values taken from [5].

- The strong interactions are responsible for the attracting force between quarks. The strong force is mediated by the *gluons* which are massless spin-one particles and, like photons, might be expected to have infinite range. Quarks do not exist as free states, but only as constituents of a wide class of particles, the *hadrons*, such as protons and neutrons.
- The weak interactions take place between fermions and describes processes like beta-decay. These interactions can involve neutrinos which have no electric and colour charge and, therefore, do not interact with the photon or gluons. The carrier particles of the weak force are the charged spin-one $W^\pm$ and the neutral spin-one Z bosons, discovered at CERN in 1983. Since they carry mass, the weak interaction is short ranged.
- All particles are affected by the gravitational force and the *graviton* G , a hypothetical, massless and chargeless elementary particle of spin-two, would be the carrier of the gravitational force in a quantum field theory that involves gravity. On the scales of particle physics, gravitational force is negligible and the SM excludes it from consideration.

The main parameters of the electromagnetic, weak and strong interactions are summarized in Table 1.2 [5].

The SM describes three fundamental interactions with two gauge theories: the theory of strong interactions or Quantum Chromo-Dynamics (QCD), and the theory of the electroweak interaction, or Electroweak Standard Model, that unifies the electromagnetic and the weak interactions.

Interaction field	Boson	Coupling constant	Charge	Mass[GeV]	Spin
Electromagnetic	(γ)	$\alpha = 1/137$	0	0	1
Weak	$W^\pm$	$\alpha_W = 1.02 \times 10^{-5}$	± 1	80.385 ± 0.015	1
	Z^0	$\alpha_W = 1.02 \times 10^{-5}$	0	91.187 ± 0.002	1
Strong	gluons	$\alpha_s = 0.1184$	0	0	1
	H^0		0	125.09 ± 0.24	0

Table 1.2: The elementary bosons of the SM. Numerical values taken from [5].

1.1.1 Gauge symmetries of the model

As claimed by the Noether's theorem, a Lagrangian invariant under a continuous group of transformations corresponds to a conservation law. For example, the symmetry of the action under translations in time and space gives rise to the energy and momentum conservation. Generally, a symmetry that leaves the Lagrangian invariant under a group of transformations is called a gauge symmetry.

In quantum electrodynamics the Lagrangian is invariant under the gauge group $U(1)_{EM}$ of local phase rotations with only one vector field involved and the phase as a scalar quantity:

$$\psi(x) \rightarrow e^{i\alpha(x)\psi(x)}, \quad A_\mu \rightarrow A_\mu - \frac{1}{e}\delta_\mu\alpha(x). \quad (1.1)$$

This symmetry leads to the conserved quantum number Q (electric charge), and to the existence of a massless vector, the photon γ .

If the phase rotation in Equation (1.1) is replaced with the non-commuting Pauli spin operators, that are the Pauli matrices, one ends up with the non-Abelian $SU(2)_I$ group, which is the group of the *isospin* quantum number that distinguishes the up quark and the down quark. The isospin symmetry is a global symmetry.

By extending the gauge symmetry to the group $SU(2)_I \times U(1)_Y$ it is possible to describe a theory reproducing both the electromagnetic and weak interaction phenomenology. In this sense, the weak and the electromagnetic interactions are said to be unified. The generators of $SU(2)_I$ are the three components of the weak isospin operator $t^a = \frac{1}{2}\tau^a$, where τ^a are the Pauli matrices. The generator of $U(1)_Y$ is the weak *hypercharge* Y operator. The corresponding quantum numbers satisfy the following relation

$$Q = I_3 + \frac{Y}{2}, \quad (1.2)$$

where I_3 is the third component of the weak isospin (eigenvalue of t^3).

One can group the fermions of the SM by their *chirality*, which can be left-handed (negative-helicity) or right-handed (positive-helicity) and is defined, respectively, with the projection operators $(1 - \gamma^5)/2$ and $(1 + \gamma^5)/2$, where, considering the Dirac matrices γ^i , $\gamma^5 = i\gamma^0\gamma^1\gamma^2\gamma^3$.

Left-handed fermions form doublets, while right-handed fermions form singlets. The left-handed quark doublets consist of up-type and down-type quarks and the left-handed lepton doublets of a charged lepton and its neutrino:

$$L_L = \begin{pmatrix} \nu_{\ell,L} \\ \ell_L \end{pmatrix}, \ell_R, \quad Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, u_R, d_R, \quad (1.3)$$

where $\ell = e, \mu, \tau$; $u = u, c, t$, and $d = d, s, b$. Up to now right-handed neutrinos have never been observed. In Table 1.3, I_3 , Y and Q quantum numbers of all fermions are reported.

	I_3	Y	Q
$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$\begin{pmatrix} 1/2 \\ -1/2 \end{pmatrix}$	$\begin{pmatrix} 1/3 \\ 1/3 \end{pmatrix}$	$\begin{pmatrix} 2/3 \\ -1/3 \end{pmatrix}$
u_R, d_R	0, 0	$4/3, -2/3$	$2/3, -1/3$
$\begin{pmatrix} \nu_{\ell,L} \\ \ell_L \end{pmatrix}$	$\begin{pmatrix} 1/2 \\ -1/2 \end{pmatrix}$	$\begin{pmatrix} -1 \\ -1 \end{pmatrix}$	$\begin{pmatrix} 0 \\ -1 \end{pmatrix}$
ℓ_R	0	-2	-1

Table 1.3: Isospin (I_3), hypercharge (Y), and electric charge (Q) of all fermions.

The weak interaction only acts on left-handed particles and, thus, violates parity, which is the invariance under mirror operation at the origin in space. Follows that the Lagrangian of the electroweak theory is invariant under transformations in $SU(2)_L \times U(1)_Y$, where the L subscript stands for left-handed.

In QCD there exists also an additional quantum number, often called the colour charge, which can have three different values and leads to the gauge symmetry of the $SU(3)_C$ group, where the C subscript stands for colour. While one representation of the generators of the $SU(2)$ symmetry were the Pauli matrices, with some additional factors, a representation of the generators of the $SU(3)$ symmetry are the eight 3×3 Gell-Mann matrices, with some factors as well.

To conclude, the SM is invariant under the gauge group:

$$SU(3)_C \times SU(2)_L \times U(1)_Y. \quad (1.4)$$

The gauge structure of the theory is of key importance, and so far it is one of the most confirmed assumption of the model. Each generator of the

group is associated with a spin-one particle, a vector boson, as said before, the mediator of a fundamental force between the fermions. The SM contains $8 + 3 + 1$ of such vector bosons.

1.1.2 Electroweak theory

As described in Section 1.1.1, the requirement of local gauge invariance with respect to the $SU(2)_I \times U(1)_Y$ group introduces four massless vector fields (gauge fields), $W_\mu^{1,2,3}$ and B_μ , which couple to fermions with two different couplings constraints, g and g' . Note that B_μ does not represent the photon field because it arises from the $U(1)_Y$ group of hypercharge, instead of $U(1)_{EM}$ group of electric charge. Physical fields are given by linear combinations of $W_\mu^{1,2,3}$ and B_μ : the charged bosons W^+ and W^- correspond to

$$W_\mu^\pm = \sqrt{\frac{1}{2}}(W_\mu^1 \mp iW_\mu^2), \quad (1.5)$$

while the neutral bosons γ and Z correspond to

$$A_\mu = B_\mu \cos \theta_W + W_\mu^3 \sin \theta_W, \quad (1.6)$$

$$Z_\mu = -B_\mu \sin \theta_W + W_\mu^3 \cos \theta_W, \quad (1.7)$$

obtained by mixing the neutral fields W_μ^3 and B_μ with a rotation defined by the Weinberg angle θ_W .

The interaction term between gauge fields and fermions, in terms of the fields $W_\mu^\pm$, Z_μ , and A_μ is:

$$\mathcal{L}_{int} = \frac{1}{2\sqrt{2}}g(J_\alpha^+ W^{(+)\alpha} + J_\alpha^- W^{(-)\alpha}) + \frac{1}{2}\sqrt{g'^2 + g^2}J_\alpha^Z Z^\alpha - eJ_\alpha^{EM} A^\alpha \quad (1.8)$$

where J^{EM} is the electromagnetic current coupling to the photon field, while J^+ , J^- , and J^Z are the three weak isospin currents. It is found that

$$J_\alpha^Z = J_\alpha^3 - 2\sin^2 \theta_W \cdot J_\alpha^{EM}. \quad (1.9)$$

The neutral gauge field A_μ can then be identified with the photon field.

The Glashow-Weinberg-Salam model thus predicts the existence of two charged gauge fields, which only couple to left-handed fermions, and two neutral gauge fields, which interact with both left and right-handed components.

At low energies, we can only observe the $U(1)_{EM}$ symmetry. Therefore, the $SU(2)_L \times U(1)$ gauge symmetry must be broken at some energy scale

E_{weak} . Processes with energies $E \ll E_{weak}$ feel only the $U(1)_{EM}$ symmetry of electrodynamics. At energies $E > E_{weak}$, the interaction has the full $SU(2)_I \times U(1)_Y$ gauge symmetry. In the language of particles, this means that the weak interaction must be mediated by gauge bosons, which have masses of the order of E_{weak} . We know experimentally that $E_{weak} = O(100)$ GeV.

1.1.3 Electroweak symmetry breaking

The SM for weak and electromagnetic interactions is constructed on a gauge theory with four gauge fields corresponding to massless bosons. Since only the photon is massless, whereas W and Z bosons are massive, something has to happen in order to preserve the electroweak unification.

The masses of the gauge fields, as well as the fermions, in the SM, are generated by spontaneous symmetry breaking. ElectroWeak Symmetry Breaking (EWSB) in the SM is described by a renormalizable theory which perfectly reproduces the low-energy phenomenology and implies the rising of a new scalar boson, the Higgs boson. The EWSB mechanism was proposed in 1964 independently by Brout and Englert [8] and Higgs [9]. The coupling of the massive particles to the Brout-Englert-Higgs field is proportional to the mass of the particles.

The Higgs boson is the latest discovered particle of the SM, first observed in 2012 by the CMS and ATLAS experiments [6, 7]. More properties are shown in Table 1.2.

1.2 Beyond Standard Model

One of the most important question in particle physics today is whether there are any new gauge bosons beyond the ones associated with the $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge group. The answer to this question is one of the goals of LHC.

Soon after the proposal of the electroweak $SU(2)_L \times U(1)_Y$ model there were many suggestions for extended or alternative electroweak gauge theories, some of which involved additional $U(1)'$ factors. The existence of heavy neutral bosons Z' is a feature of many extensions of the SM. They arise in extended gauge theories including Grand Unified Theories (GUTs), superstring theories, and multi-dimension models.

1.2.1 Motivations for physics beyond the SM

The SM of elementary particle physics is a very successful theory that is able to describe most of the known phenomena with very high precision. However, the SM is usually seen as a low energy approximation of a more general theory. Indeed, there are some observations which can not be explained by the SM, as described below.

- From the four fundamental forces, gravity is the only one not included in the SM. The theory of general relativity based on classical physics describes gravitational effects. To combine the quantum theory of the SM with general relativity, a quantum theory of gravity is necessary, which could be obtained by adding a particle carrying the gravitational force, a graviton. This proves to be difficult because of the way the gravity interacts with the geometry of spacetime. The strength of the gravitational force is much lower than the ones from the other three fundamental forces. While those have a similar strength that shows an effect at the electroweak scale of $O(100 \text{ GeV})$, the energy at which gravitational interactions become relevant is at the order of the Planck scale $E_P = 10^{19} \text{ GeV}$, which is defined by the Planck mass, $M_P = \sqrt{\hbar c/G_N}$, with G_N being the gravitational constant. The huge difference between the electroweak scale and the Planck scale is also known as a *hierarchy problem*.
- The hierarchy problem implies that the mass of the Higgs boson should be of the order of the Planck scale. In order for the observed mass value to be 125 GeV , a fine-tuned cancellation of the bare mass and the contribution from Feynman diagrams loop corrections, both of $O(10^{19} \text{ GeV})$, is necessary.
- Astronomical observations show that the visible content of matter can only be approximately 5% of the total matter and energy content of our universe. The remaining part is assumed to consist of about 25% dark matter, which is typically assumed not to interact electromagnetically or by strong interactions, and 70% dark energy, which is thought to be responsible for the observed accelerated expansion of the universe, by introducing a repellent force. The SM, however, does not offer a good candidate for a dark matter particle.
- In the SM neutrinos have no mass. The fact that neutrinos can change from one flavour to another implies that they must have non-zero mass difference, and their mass eigenstates are different from their flavour eigenstates. A mass term for the neutrinos can be added to the SM,

but it is not clear if the small masses that the neutrinos must have can arise from the same electroweak symmetry breaking mechanisms than the masses for the other particles of the SM.

- The SM contains 19 free parameters, that have to be measured. The parameters include the charged fermion masses, the mixing angles and the charge-parity (CP) violating phase of the Cabibbo-Kobayashi-Maskawa (CKM) matrix, the coupling constants of the three forces, and the mass and vacuum expectation value of the Higgs boson. However, it is widely believed that some of these parameters at least should be related to each other from a mechanism that is not described by the SM. As an example one could consider the different masses of the quark and lepton generations that may arise from a common generation in a BSM theory, that has a spontaneously broken symmetry at the scale of the SM.
- The SM coupling constants of the electromagnetic interaction, the weak interaction and the strong interaction have a similar value at an energy scale of $O(10^{16} \text{ GeV})$. However, they do not converge to a single value as shown in Figure 1.1. In order to unify the coupling constants, an extension of the SM is necessary that changes the evolution above the electroweak scale.

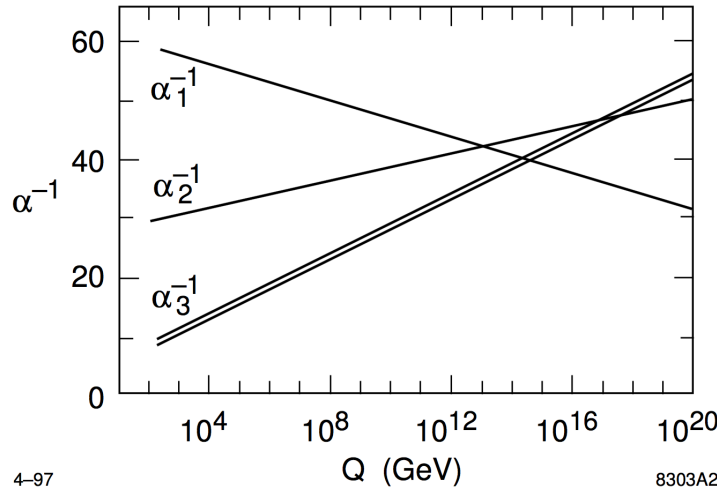


Figure 1.1: Evolution of the SM couplings $\alpha_i = \frac{g_i^2}{4\pi}$ as a function of the energy scale [10].

These problems of the SM with gravity and the matter content of the universe, as well as the other characteristics of the SM, indicate that there

must be new physics at a scale beyond the electroweak scale. What is unknown, however, is the energy scale at which this new physics will manifest itself. It could be as high as the Planck scale, but this would mean that the hierarchy problem remains unsolved. Therefore, it is rather believed that there should be new physics at the TeV scale, at which a discovery with direct searches at the LHC could be possible.

1.2.2 New massive resonances decaying into a lepton pair

If there is new physics to be found at the TeV scale, then a promising search channel at a hadron collider is the dilepton decay. New physics would manifest itself in a change of the dilepton invariant mass spectrum. Especially in the case of new heavy resonances, the low background and the resonance peak as a signal, in combination with the high accuracy of the lepton reconstruction, make the dilepton final state an experimentally well motivated channel.

From a theoretical point of view, a new massive resonance that decays to a lepton/antilepton pair arises in many different types of BSM models. Extensions of the SM gauge group in the framework of Grand Unification can lead to a new spin-one resonance [11–13], while supersymmetric models predicting a new spin-zero resonance also exist [14]. Models with extra dimensions can also lead to new particles, including spin-two particles [15, 16]. Generically, for searches for new physics, all particles that can give rise to a resonance in the dilepton spectrum are called Z' . In the following the different classes of models that lead to a Z' resonance are described.

As the SM Z boson, the Z' is expected to be a very short-lived particle. It can only be observed through its decay products or through indirect interference effects. It can be detected either in very high energy processes or in high precision experiments at lower energies. In the first kind of processes, the energy of the colliding particles must be large enough to produce a Z' . The decay products of the Z' must be then detected above the SM background. Such a background is always present because the SM Z boson or the photon are produced by the same processes, which create a Z' .

Grand unified theories

Many physicists believe that all fundamental interactions must have one common root. They suppose that strong and electroweak interactions can be described by one simple gauge group G at very high energies $E > E_{GUT}$, referred to as the GUT scale. Such theories are called Grand Unified Theories (GUTs). For energies $E \ll E_{GUT}$ the gauge group G must be broken to retain the SM gauge symmetry $SU(3)_C \times SU(2)_L \times U(1)_Y$. One can imagine this symmetry

breaking similar to the breaking of the $SU(2)_L \times U(1)_Y$ symmetry to $U(1)_{EM}$ in the SM.

The motivation for this is the scale dependency of the coupling constants of the three forces, which in the SM converge almost at one value at a very high energy scale, as shown in Figure 1.1. It is hoped therefore, that the introduction of a larger symmetry modifies the couplings in such a way to unify them in one point at the GUT scale. In this way the E_{GUT} is predicted as the energy where the three running gauge coupling constants of the SM gauge group become equal. Introducing a new gauge group implies the existence of one or more new neutral gauge bosons.

GUTs make predictions which can be tested in experiments. In particular, they predict that the proton must decay. This decay is mediated by the exchange of gauge bosons with a mass $O(E_{GUT})$. It is the analogue of the β decay described in the electroweak theory. To be consistent with present experiments on proton decay, we get the condition $E_{GUT} > 10^{15}$ GeV. This energy is much larger than E_{weak} . It is important that it is smaller than the Planck mass M_P . At energies above the Planck mass, gravity is expected to become as strong as the other interactions. At energies well below M_P , as it happens in GUTs, the effects of gravity can be neglected.

As was shown by H. Georgi and S.L. Glashow in 1974, the smallest simple gauge group G , which can contain the SM, is $G = SU(5)$ [17]. The number n of neutral gauge bosons of a GUT is given by $n = \text{rank}[G]$. We have $\text{rank}[SU(5)] = 4$. Therefore, there is no room for additional neutral gauge bosons in the $SU(5)$ GUT. However, models using the simple extension of the SM to the $SU(5)$ gauge group predict the decay of the proton to a positron and a neutral pion within a time shorter than the lower limit of current proton lifetime measurements ($\tau_p > 10^{33}$ years for this decay mode [5]).

All GUTs with gauge groups larger than $SU(5)$ predict at least one extra neutral gauge boson (Z'). It was shown by H. Fritzsch and P. Minkowski in 1975 that the next interesting gauge group larger than $SU(5)$ is $SO(10)$. The $SO(10)$ theory predicts one extra neutral gauge boson because $\text{rank}[SO(10)] = 5$. To complete the multiplet, one new fermion with the quantum numbers of the right-handed neutrino must be added. The $SO(10)$ GUT is not in contradiction with present experiments.

The symmetry of this group could be broken in a scheme

$$SO(10) \rightarrow SU(5) \times U(1) \rightarrow G_{SM} \times U(1)_\chi \quad (1.10)$$

where χ denotes the charge of the new particle coming from the additional $U(1)_\chi$ group. While in the previously discussed $SU(5)$ extension, the mass of the new bosons must be of the order $O(10^{16}$ GeV), the mass for bosons from the additional $U(1)_\chi$ can be in the TeV range. Therefore, particles coming

from such an extension could be discovered with a TeV hadron collider like the LHC.

GUTs with gauge groups larger than $SO(10)$ predict more than one extra neutral gauge bosons and many new fermions. These new (exotic) fermions must be heavy enough to make the theories consistent with present experiments.

Popular classes of models are the E_6 models, which extend the $SO(10)$ group with another unitary group to the exceptional E_6 group, so that the symmetry can be broken following

$$E_6 \rightarrow SO(10) \times U(1)_\psi \rightarrow SU(5) \times U(1)_\chi \times U(1)_\psi \rightarrow G_{SM} \times U(1)_\chi \times U(1)_\psi. \quad (1.11)$$

For the linear combination of $U(1)_\theta = U(1)_\psi \cos \theta - U(1)_\chi \sin \theta$ we can express the Z' boson as:

$$Z'(\theta) = Z'_\psi \cos \theta - Z'_\chi \sin \theta. \quad (1.12)$$

Each value of the mixing angle θ , free parameter of the theory, corresponds to a $U(1)_\theta$ group and leads to a different Z' phenomenology. The most widely used models, with their corresponding mixing angle, are: Z'_ψ ($\theta=0$), Z'_χ ($-\pi/2$), Z'_η ($\arccos(\sqrt{5/8})$) and Z'_I ($\arccos(\sqrt{5/8}) - \pi/2$) bosons that couple differently to quarks and leptons.

The mass of the Z' is not constrained by theory. A priori, it can be anywhere between E_{weak} and E_{GUT} . An observation of a Z' would provide information on the GUT group and on its symmetry breaking.

Supersymmetry

The Minimal Supersymmetric Standard Model (MSSM) contains the supersymmetric partners of the SM particles: every fermion has a SUSY partner particle which is a boson, and vice versa. The superpartner particles of fermions, called *sfermions*, are the *sleptons* $\tilde{\ell}$ and $\tilde{\nu}_\ell$ ($\ell=e,\mu,\tau$), *squarks* $\tilde{q}$, and have spin 0. The gauge bosons superpartners are the *gauginos* $\tilde{g}$, $\tilde{W}^\pm$, $\tilde{Z}$, and $\tilde{\gamma}$ with spin 1/2. It requires two Higgs doublets, which, after giving mass to W and Z bosons, lead to five scalar degrees of freedom, usually parametrized in terms of two CP-even neutral scalars, the lighter h and H_z , one CP-odd neutral pseudoscalar A and a pair of charged Higgs bosons $H^\pm$. Each Higgs will have a supersymmetric fermionic partner, named *higgsino*.

Extending the MSSM with the extra $U(1)'$ a third Higgs boson is required to break the $U(1)'$ gauge symmetry and give mass to the Z' boson.

In the SM the baryon number B and the lepton number L are conserved

quantities defined as

$$B = \frac{1}{3}(n_q - n_{\bar{q}}), \quad L = (n_l - n_{\bar{l}}), \quad (1.13)$$

where n_q , $n_{\bar{q}}$, n_l , and $n_{\bar{l}}$ are, respectively, the numbers of quarks, antiquarks, leptons and antileptons. This is generally not the case in a SUSY model, and a new quantum number called R-parity (R_p) is introduced

$$R_p = (-1)^{B-L+2s}, \quad (1.14)$$

where s is the spin of the particle, to restore the conservation laws found in experiments. With this definition all SM particles have $R_p = +1$ and all superpartners have $R_p = -1$.

While many SUSY models are R-parity conserving and do not allow for the decay of a superparticle into an ordinary dilepton, there exist R-parity violating SUSY models where this is possible [14]. Spin 0 superpartner of a neutrino, a *sneutrino* ($\tilde{\nu}$), could decay to dileptons in these R-parity violating SUSY models. In order to be able to solve the fine-tuning problem of the SM, by canceling the SM loop corrections with the loop corrections involving superpartners, the masses of SUSY particles are expected to be in the TeV range. The analysis on Z' production and decays into SM and MSSM particles depends on $U(1)'$, and MSSM several parameters, among them the Z' or MSSM masses. The experimental searches for physics BSM set exclusion limits on such quantities.

Sequential standard model

Another model which is experimentally investigated is the so-called Sequential Standard Model (SSM) [11], which predicts a new boson Z'_{SSM} heavier than the Z boson, but with the same couplings to fermions and gauge bosons as in the SM. This is often used as a benchmark model for experimental Z' searches.

Extra dimensions

Theories involving additional spatial dimensions represent a different class of models. They all emerged as solutions to the gauge hierarchy problem explaining the weakness of the gravitational force compared to the other forces by allowing the graviton, as the carrier of the gravitational force, to propagate in the extra dimensions, while the other fields of the SM must remain in the usual 4-dimensional spacetime. The overlap of the wave functions of the SM particles with the graviton is, therefore, small and this would explain the observed weakness of the gravitational force.

Large extra dimensions One of the first solutions of the hierarchy problem involving extra spatial dimensions was proposed by Arkani-Hamed, Dimopoulos and Dvali [18], is called ADD models, also known as the model with large extra dimension (LED). It is based around the observation that, while the electroweak scale has been tested at distances of the order of $1/M_{EW}$, the gravitational force is far from being explored at distanced of $1/M_{Pl} \sim 10^{-33}$ cm. This reasoning leads to the idea of abandoning the interpretation of M_{Pl} as a fundamental energy scale, and leaving only M_{EW} as fundamental scale.

To account for the observed weakness of gravity compared to electroweak interactions, new spatial dimensions are introduced, with gravity being the only fundamental interaction that sees them. The SM fields are trapped on a 4-dimansional wall, often called a *brane* in the extra dimensions, and gravitons are the only particles freely propagating in the whole space (the *bulk*).

In the case of n extra dimensions with a common compactification radius of R , the gravitational potential for two test masses m_1 and m_2 placed at a distance $r \ll R$ can be calculated writing Gauss' low in $(4+n)$ dimensions

$$V(r) \sim \frac{m_1 m_2}{M_{Pl(4+n)}^{n+2}} \frac{1}{r^{n+1}} \quad (1.15)$$

where $M_{Pl(4+n)}$ is the fundamental scale of gravity in the extra dimensions, and is assumed to be of the order of M_{EW} . When the test masses are moved away to a distance much larger that the compactification radius $r \gg R$, the gravitational flux lines no longer propagate in the extra dimensions and the potential returns to the familiar $1/r$ form,

$$V(r) \sim \frac{m_1 m_2}{M_{Pl(4+n)}^{n+2} R^n} \frac{1}{r} \quad (1.16)$$

Comparing Equations (1.15) and (1.16) follows that the observed Planck mass in 4 dimensions is an effective mass that is defined by the fundamental Planck mass in $4+n$ dimensions and R :

$$M_{Pl}^2 \sim M_{Pl(4+n)}^{n+2} R^n. \quad (1.17)$$

The fundamental Planck mass can, thus, be in the TeV range, which would solve the hierarchy problem. The observed strength of gravity can be reproduced with a suitable choice of R and n . If one assumes the mass scale at 1 TeV, a condition for the size of the extra dimension arises

$$R \sim 10^{\frac{30}{n}-17} \text{cm} \times \left(\frac{\text{TeV}}{M_{EW}} \right)^{1+\frac{2}{n}}. \quad (1.18)$$

The case with $n = 1$ corresponds to $R \sim 10^{13}$ cm, which would imply deviations from Newton's law at distances on the scale of the Solar System (the Earth's orbit has a radius of $\sim 1.5 \times 10^8$ km), at which it is well established. Hence the number of extra dimensions must be larger. For $n = 2$ the value of R is ~ 1 mm, and this is also excluded. Current limits on the size of extra dimensions from precision tests of the gravitational force are of the order of $200 \mu\text{m}$ [19]. Higher numbers of extra dimensions, up to the 10 or 11 suggested by string theory, predict deviations at smaller distances, and are not excluded by gravitational measurements.

In the ADD framework the graviton couples to other particles with a strength $\sim 1/M_{Pl}$, but since it can propagate into the extra dimensions, it can also have momentum in the new dimension. From the 4-dimensional point of view, such momentum appears as mass, and is quantized.

ADD models predict a large number of massive excitations, called Kaluza-Klein (KK) excitations or KK towers, of the graviton, where the mass difference between the different excitations is inverse proportional to R . For $M_{Pl(4+n)}$ masses in the TeV range and two extra dimensions, this mass difference between the KK excitations is so small, that physics following this model would not appear as single resonances but as a continuous distortion of the measured dilepton spectrum. In the case that the SM bosons are also allowed to propagate in the extra dimensions, this gives rise to KK towers of these bosons as well. Calculating the cross-section of a TeV scale physics process requires summing over all the states with masses smaller than the energy available to the graviton. Due to sheer multiplicity of these states, the cross-section can be of the order of electroweak cross-sections. This way the ADD model predicts effects that can be studied in the collider experiments.

The Randall-Sundrum model A closer look at the geometric solution for the hierarchy problem proposed by ADD reveals one flaw: the discrepancy between M_{Pl} and M_{EW} is not really removed, it is moved elsewhere. A result of compactifying the extra dimensions on a circle with a radius of R is a new hierarchy between the electroweak scale, and the compactification scale $1/R$. This inspired a different approach, proposed by Randall and Sundrum [16], with only one extra dimensions and non-trivial geometry.

The authors propose a set-up with the extra dimension, denoted by $0 < \phi < 2\pi$, which is compactified on an orbifold (circle with the additional condition $(x, \phi) = (x, -\phi)$). The two fixed points of the orbifold, $\phi = 0, \pi$, hold the three normal spatial dimensions, also called 3-branes. The full space is often called the bulk, while a subset with p dimensions is denounced as p -brane.

The solution to Einstein's equations in such 5-dimensional space is an anti-

de Sitter (AdS_5) space with non-factorizable geometry, given by the metric

$$ds^2 = e^{-2kr_c\phi} \eta_{\mu\nu} dx^\mu dx^\nu + r_c^2 d\phi^2 \quad (1.19)$$

where $k \sim M_{Pl}$ is the AdS_5 curvature parameter, r_c is the compactification radius, x^μ are the standard 4-dimensional coordinates and $\eta_{\mu\nu}$ is the 4-dimensional metric tensor. Assuming that the SM fields are confined to the brane located at $\phi = \pi$, any fundamental 5-dimensional mass parameter m_0 , has an effective 4-dimensional value of

$$m = e^{-kr_c\pi} m_0. \quad (1.20)$$

This gives rise to massive leptonically decaying KK gravitons in the 4-dimensional world, with masses at the TeV scale, easily generated from parameters of order of the Planck scale, by choosing $kr_c \sim 11-12$. The compactification scale $1/r_c$ is of the order of M_{Pl} , so no additional hierarchy is introduced.

KK graviton excitations in this model have significantly different properties than in the case with large extra dimensions. The interactions of matter fields with the graviton towers are given by the Lagrangian [20]

$$L = -\frac{1}{M_{Pl}} T^{\alpha\beta} h_{\alpha\beta}^{(0)} - \frac{1}{\Lambda_\pi} T^{\alpha\beta} \sum_{n=1}^{\infty} h_{\alpha\beta}^{(n)} \quad (1.21)$$

where $h_{\alpha\beta}$ are the graviton fields, $T^{\alpha\beta}$ is the energy-momentum tensor of the matter field, and Λ_π is the coupling parameter, given by

$$\Lambda_\pi = M_{Pl} e^{-kr_c\pi} \quad (1.22)$$

and is of order of the weak scale.

As can be seen from the Lagrangian, while the massless zero-mode of the graviton couples with the usual $1/M_{Pl}$ strength, the coupling of the KK excitations, determined by the Λ_π parameter, is comparable to $1/M_{EM}$. The masses of the KK modes are

$$m_n = k x_n e^{-kr_c\pi} \quad (1.23)$$

where x_n is the n -th root of the J_1 Bessel function.

Such KK gravitons would show up in collider experiments as individual resonances, providing a good way of testing the model. The Randall-Sundrum model phenomenology is governed by two free parameters, with the mass of the first graviton excitation m_1 and the coupling parameter of the graviton to the SM, $c = k/M_{Pl}$ being the usual choice. The parameter space is strongly constrained, both by experimental data and by theoretical limits.

1.2.3 Current experimental limits

Searches for new massive resonances have been done by various experiments.

From the first period of data taking (Run-1) at the Large Hadron Collider at CERN, the ATLAS and CMS collaborations published results from pp collisions at $\sqrt{s} = 7$ TeV [21, 22], at a combination of $\sqrt{s} = 7$ TeV and early 2012 $\sqrt{s} = 8$ TeV [23], and at $\sqrt{s} = 8$ TeV [1, 2]. ATLAS [24] and CMS [25, 26] have published results on searches for signals from large extra dimensions. Table 1.4 lists lower limits obtained separately in the dielectron and the dimuon final states, and the combined dielectron and dimuon lower limits for the mass of various heavy resonances, obtained from searches at the LHC with a center-of-mass energy of 8 TeV.

Lower mass limit [TeV]				
ATLAS				
Z' model	dielectron observed	dimuon observed	combined expected	combined observed
Z'_χ			2.60	2.62
Z'_ψ			2.46	2.51
Z'_{SSM}	2.79	2.53	2.87	2.90
$G_{RS}(c/M_{Pl} = 0.01)$			1.28	1.25
$G_{RS}(c/M_{Pl} = 0.05)$			2.25	2.28
$G_{RS}(c/M_{Pl} = 0.1)$			2.67	2.68
CMS				
Z' model	dielectron observed	dimuon observed	combined expected	combined observed
Z'_ψ	2.34	2.39	2.57	2.57
Z'_{SSM}	2.67	2.73	2.90	2.90
$G_{RS}(c/M_{Pl} = 0.01)$	1.25	1.13	1.38	1.27
$G_{RS}(c/M_{Pl} = 0.05)$	2.13	2.12	2.35	2.35
$G_{RS}(c/M_{Pl} = 0.1)$	2.50	2.56	2.73	2.73

Table 1.4: Observed 95% C.L. limits in the dielectron and dimuon channels separately, and 95% C.L. limits in the combined final state, on the Z' or G_{RS} mass for various models, obtained from about 20 fb^{-1} of $\sqrt{s} = 8$ TeV LHC data, recorded in 2012.

Chapter 2

The CMS experiment

The Compact Muon Solenoid (CMS) experiment is one of two general-purpose particle physics detectors at the Large Hadron Collider LHC. This chapter introduces LHC and presents the general design of CMS with emphasis on the muon spectrometer.

2.1 The LHC collider

The Large Hadron Collider (LHC) [27] is a proton-proton superconducting accelerator and collider installed in the existing 26.7 km tunnel that was constructed between 1984 and 1989 for the CERN LEP machine.

In a circular collider of radius R , the energy loss per turn due to synchrotron radiation is proportional to $(E/m)^4/R$, where E and m are respectively the energy and mass of the particles accelerated. Protons, due to their higher mass with respect to electrons, imply a smaller energy loss for synchrotron radiation.

The LHC lies between 45 m and 170 m below the surface and is divided in eight arcs and eight straight sections, of which four house equipment needed for the accelerator and the other four contain the interaction points where the two beams are brought into collision in the four main experiments: CMS (Compact Muon Solenoid) [28] and ATLAS (A Toroidal Apparatus) [29], two big independently designed general-purpose detectors designed to investigate the largest range of physics possible, and ALICE (A Large Ion Collider Experiment) [30] and LHCb (Large Hadron Collider beauty experiment) [31] which are medium-size experiments with specialised detectors for analysing the LHC collisions in relation to specific phenomena.

The high beam intensity required by the experiments excludes the use of antiproton beams, and hence excludes the particle-antiparticle collider configuration of a common vacuum and magnet system for both circulating beams,

as used for example in the Tevatron. To collide two counter-rotating proton beams requires opposite magnetic dipole fields in both rings. The LHC is therefore designed as a proton-proton collider with separate magnet fields and vacuum chambers in the main arcs and with common sections only at the insertion regions where the experimental detectors are located.

The existing CERN infrastructure, shown in Figure 2.1, is used for injecting the protons into LHC (Linac, Booster, Proton Synchrotron (PS), Super Proton Synchrotron (SPS)). The SPS accelerates protons to an energy of 450 GeV, and the remaining acceleration is done by the LHC during the first 20 minutes after beam injections.

The machine comprises 1232 dipole magnets and is designed to have an energy per proton beam of 7 TeV, which results in a center-of-mass energy of $\sqrt{s} = 14$ TeV, 2808 bunches per ring, and the time between two bunch crossings in an impact point (IP) of 25 ns, which spaces the bunches about 7.5 m apart along the beam axis.

In the years 2010 and 2011 the LHC was operated with proton beam energies of 3.5 TeV. In 2012, the beam energy of 4 TeV was reached, resulting in a proton-proton (pp) center-of-mass energy of 8 TeV and a bunch spacing of 50 ns. This LHC running period is called Run-1. In spring 2013, the LHC was shut down for about 2 years to allow consolidation and upgrade of numerous machine systems.

In July 2015 LHC started to collide proton beams with a center-of-mass energy of 13 TeV (LHC running period called Run-2). After a short period of 50 ns operation (Run2015B), the machine collected data with a bunch spacing of 25 ns (Run2015C and D).

In this thesis, a proton-proton interaction at the LHC is called an event.

2.1.1 Luminosity

At the LHC, the number of events per second generated in the collisions is proportional to the cross section σ_{event} :

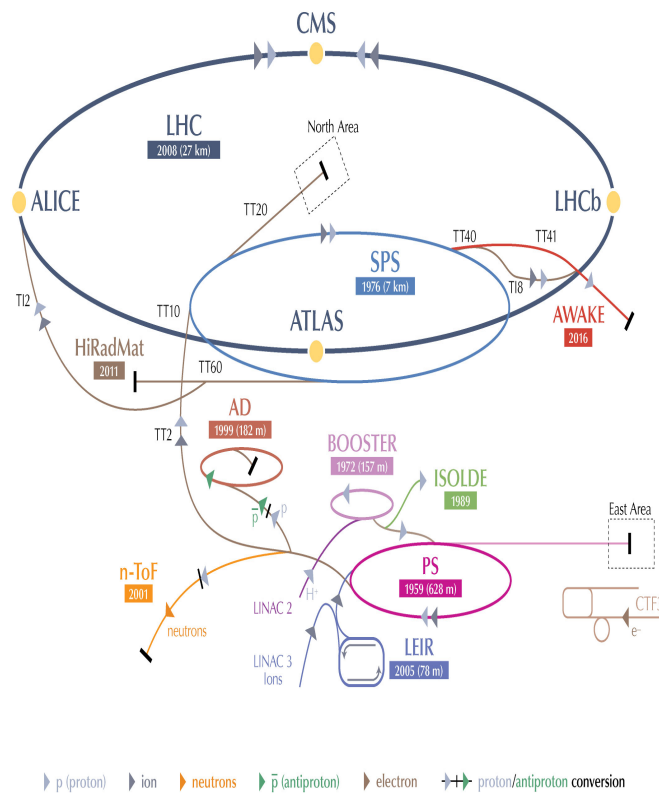
$$N_{event} = \sigma_{event} \times \mathcal{L} \quad (2.1)$$

Here, $\mathcal{L}$ is the machine instantaneous luminosity, defined as the number of collisions per unit time and cross-sectional area of the beams:

$$\mathcal{L} = \frac{N_1 N_2 n_b f_{rev}}{A} \quad (2.2)$$

where N_1 and N_2 are the number of particles in the two colliding bunches, A is the overlap area of the two bunches transverse to the beam, n_b is the

CERN's Accelerator Complex



LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron
 AD Antiproton Decelerator CTF3 Clic Test Facility AWAKE Advanced WAKEfield Experiment ISOLDE Isotope Separator OnLine DEvice
 LEIR Low Energy Ion Ring LINAC LINEar ACcelerator n-ToF Neutrons Time Of Flight HiRadMat High-Radiation to Materials

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Figure 2.1: The CERN accelerator complex.

number of bunches in one beam, and f_{rev} is the revolution frequency of one bunch (with a design value of 11245 Hz). At the LHC proton-proton collisions $N_1 = N_2 = N_p$, and, since the area of overlap is difficult to measure directly in an accelerator, for a Gaussian beam distribution $\mathcal{L}$ can be written as :

$$\mathcal{L} = N_p^2 n_b f_{rev} \frac{\gamma}{4\pi\epsilon_n\beta^*} F \quad (2.3)$$

where γ is the relativistic Lorentz factor, ϵ_n is the normalized transverse beam emittance (with a design value of $3.75 \mu\text{m}$), β^* is the so called betatron function at the IP, and F is the geometric luminosity reduction factor due to the crossing angle at the IP.

The maximum number of bunches per beam and the revolution frequency are defined by the circumference of the LHC. In order to get as many events of interest as possible, one can either increase the number of particles in a bunch or focus the two beams on a smaller area for the interaction.

The values for the LHC machine parameters are listed in Table 2.1.

		Design	Run 2015
Centre-of-mass energy [TeV]	$\sqrt{s}$	14	13
Luminosity [$\text{cm}^{-2}\text{s}^{-1}$]	$\mathcal{L}$	10^{34}	10^{33}
Bunch spacing [ns]		25	25
Num. of bunches	n_b	2808	2244
Num. of protons/bunch	N_p	1.15×10^{11}	1.1×10^{11}
Norm. Rms. Emittance [μm]	ϵ_n	3.75	3.5
β^* at the IP [m]	β^*	0.55	0.8

Table 2.1: Machine parameters of LHC

During collisions, the number of particles in a bunch, and thus also the instantaneous luminosity, decreases exponentially from the initial peak luminosity. The peak luminosity of the LHC in 2015 is shown in Figure 2.2. In general, after about ten hours, the instantaneous luminosity has decreased so much that it is more efficient to abort the fill and refill the machine with new beams.

The integrated luminosity is the luminosity integrated over time, and is shown in Figure 2.3, cumulated for all the pp fills taken during 2015.

2.1.2 Phenomenology of proton-proton interactions

Several independent proton-proton interactions can take place in a bunch crossing in the interaction point. The interaction of two protons forms a primary

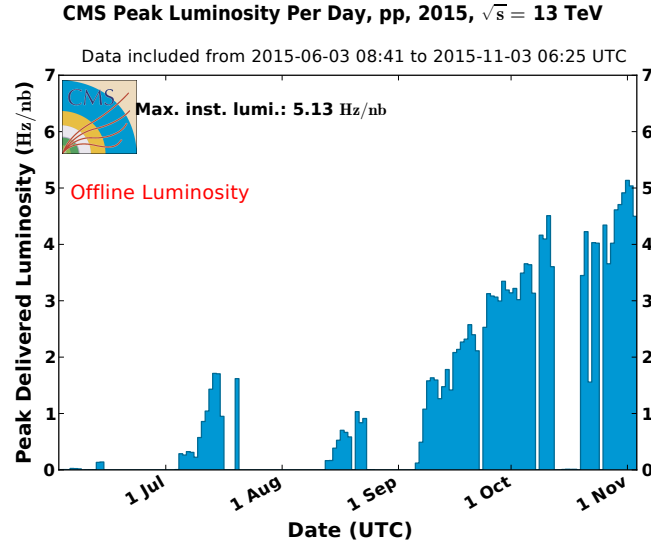


Figure 2.2: Peak delivered luminosity per day for 2015 as measured by the CMS experiment.

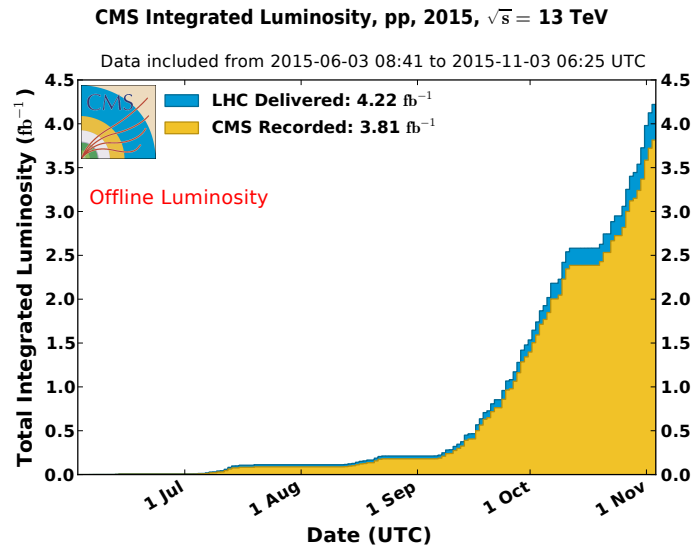


Figure 2.3: Cumulative offline luminosity versus day delivered to (blue), and recorded by CMS (orange) during stable beams and for p-p collisions at 13 TeV centre-of-mass energy in 2015 [32].

vertex, from which the particles, that were created in the interaction, originate. The number of primary vertices created on average depends on the beam parameters, e.g. how many particles are in a bunch and how small is the focusing area. In 2015 this number has been measured by the CMS experiment and corresponds to, on average, 11.4 interactions per bunch crossing, as shown in Figure 2.4. The presence of many primary vertices per bunch crossing presents

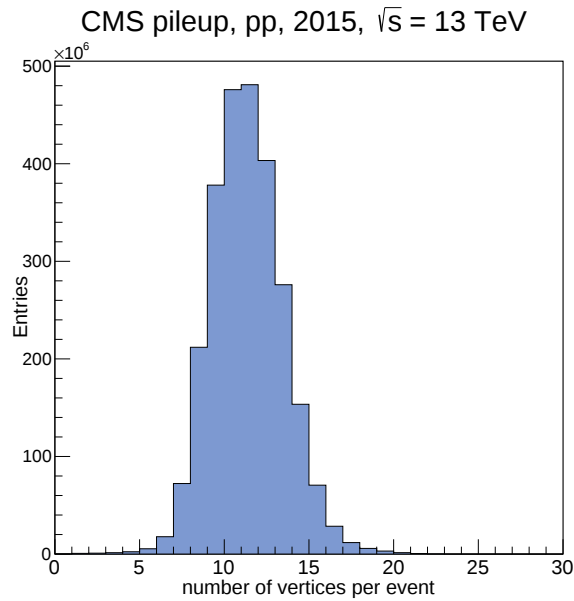


Figure 2.4: Number of reconstructed vertices per event for p-p collisions at 13 TeV centre-of-mass energy and 25 ns bunch spacing in 2015, corresponding to 2.7 fb^{-1} .

a challenge for the event reconstruction, since the particles originating from different primary vertices can be superimposed in the detector. Interactions besides the interaction of interest that one wants to study are referred to as *pileup*.

The facts that a proton bunch of the beam contains many protons, and that the proton is a composite particle, result in several processes taking place in an event.

Soft interaction

A large distance collision can take place between two incoming protons. In soft collisions only a small momentum is transferred and particle scattering at large angle is suppressed. The final state particles have small transverse momentum ($\sim 10^2 \text{ MeV}$), so that most of them escape down the beam pipe.

Hard interaction

When two protons collide, two of its partons (quarks and gluons) can take part in a hard interaction with high transferred p_T . The effective centre-of-mass energy of the hard scattering, $\sqrt{\hat{s}}$, is proportional to the fractional energies x_a and x_b carried by the two interacting partons:

$$\sqrt{\hat{s}} = \sqrt{x_a x_b s} , \quad (2.4)$$

where $\sqrt{s}$ is the centre-of-mass energy of the proton beams.

The probability density $f_p(x_p, Q^2)$ to find a parton p , with the fraction x of the longitudinal proton momentum in the proton-proton center-of-mass frame, depends on the squared four-momentum transfer Q^2 between the partons of the collision, and is described by the Parton Distribution Function (PDF). PDFs are different for gluons, u and d valence quarks and low-momentum sea quark-antiquark pairs of all flavours and depend on the energy scale at which the interaction between the partons takes place; for higher exchanged momenta a shorter distance scale is probed and the contribution of gluons and sea quarks becomes higher.

PDFs are measured in Deep Inelastic Scattering (DIS) experiments of leptons on hadrons and different models are available such as CTEQ [33, 34], MSTW [35], or NNPDF [36].

An example for parton distribution functions is shown in Figure 2.5 for two different values of the invariant momentum transfer Q^2 .

To probe physics at a certain energy scale, the value for Q^2 has to be taken in the range of the squared effective centre-of-mass energy $\hat{s}^2$ of the hard scattering which corresponds to the squared invariant mass M^2 of the system. This means, e.g. that to study physics at the TeV scale, with a collider with $\sqrt{s} = 13$ TeV, from Equation (2.4) the average x of the partons has to be around 0.1. From the corresponding PDF in Figure 2.6 it can be seen that at such values the up quark and down quark content shows an excess over the other quarks, which means that the interactions are dominated by the valence quarks and the gluons.

The probability for one particular hard interaction in an event, as expressed in Equation (2.1), depends on the cross section of that particular process. The cross section for different SM processes as a function of the centre-of-mass energies in pp collisions is shown in Figure 2.7.

Before the two partons interact with each other they can radiate other partons. Similar to this process also the decay products of the hard interaction can radiate partons or photons. This radiation of particles is called *initial state radiation* (ISR) when it happens before the hard interaction, and *final state radiation* (FSR) if it occurs with the decay products of the hard interaction.

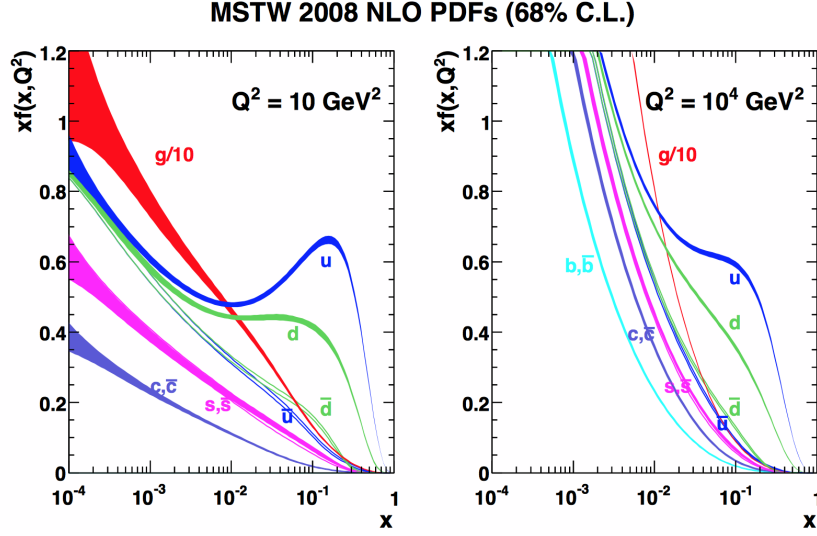


Figure 2.5: Parton density functions, including the one sigma uncertainty bands, for the partons in a proton for two different invariant momentum transfers $Q^2=20 \text{ GeV}^2$ (left) and $Q^2=10^4 \text{ GeV}^2$ (right) [35].

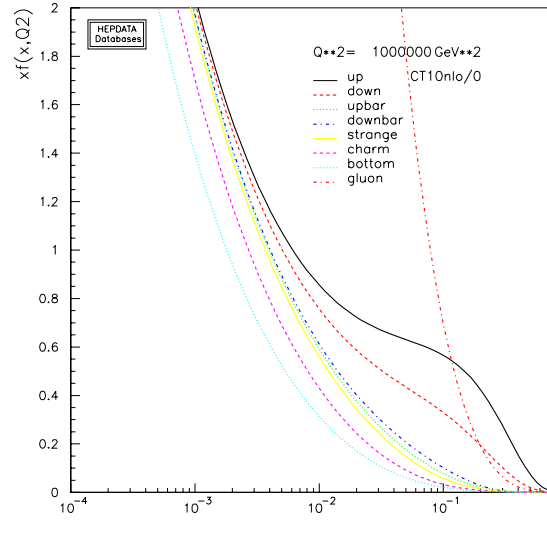


Figure 2.6: PDFs for different partons in a proton, obtained with the CT10 parametrisation [33] Q^2 is chosen for physics studies at the TeV scale. The plot was generated with the tool from the HepData project [37].

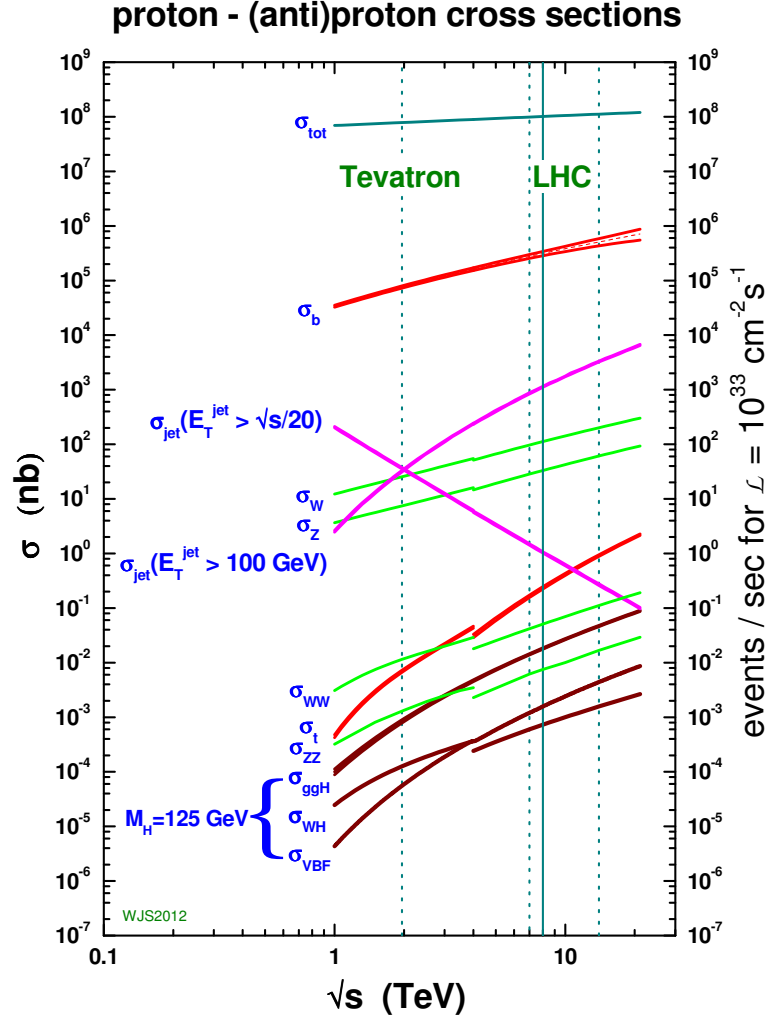


Figure 2.7: Cross section of SM processes as a function of the center-of-mass energy of proton proton collisions. The vertical lines mark the center-of-mass energies of the Tevatron and the LHC [38].

When quarks and gluons are involved in the ISR and FSR, one speaks also of *parton showering*.

If the final state of a hard interaction contains particles that carry a colour charge like e.g. quarks, they have to form new particles in order to become colour neutral. This process is called *hadronisation* and results in showers of particles that form a cone along the initial particles direction and are called

jets. The exception to this is the top quark, which has a lifetime shorter than the timescale at which the hadronisation takes place, and, therefore, decays before it hadronises. If the particles created in ISR and FSR carry a colour charge they hadronise as well. After the hard interaction, the remnants of the two protons are not colour neutral anymore and have to hadronise as well, forming jets that fly along the beam axis.

Secondary particles created in an hard interaction, which in turn can decay, form the final state of an event that can be detected. The rate of hard interactions, though, is several orders of magnitude lower than that of soft interactions.

Definition of kinematic variables

The fact that the two partons interact with unknown energies implies that the total energy of an event is unknown, because the proton remnants, that carry a sizable fraction of the proton energy, are scattered at small angles and are predominantly lost in the beam pipe, escaping detection. For this reason it is not possible to define the total and missing energy of the event, but only the total and missing transverse energies (in the plane transverse to the beams).

Moreover, the centre of mass may be boosted along the beam direction. This is the reason why it is very useful to use experimental quantities that are invariant under such boosts.

We indicate the beam direction as z axis, referred to as longitudinal, and the $x - t$ plane, orthogonal to the beam line, is called transverse plane. Based in these definitions, the momentum of a particle can be divided in two components: the longitudinal momentum p_z and the transverse momentum p_T , defined as

$$p_T = \sqrt{p_x^2 + p_y^2} . \quad (2.5)$$

The rapidity is defined as:

$$y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z} , \quad (2.6)$$

and has the property of being additive under Lorentz boosts along the z direction, i.e. it is simply shifted by a constant when subjected to such transformations. For ultrarelativistic particles ($p \gg m$) the rapidity is approximated by the pseudorapidity:

$$\eta = -\ln \tan \frac{\theta}{2} , \quad (2.7)$$

where θ is the angle between the particle momentum and the z axis. The pseudorapidity can be reconstructed from the measurement of the θ angle and can be also defined for particles whose mass and momentum are not measured.

2.2 The CMS detector

The CMS design [28] was driven by the goals of the LHC physics program. The overall layout of CMS, illustrated in Figure 2.8, is typical for a general purpose high energy particle detector. The detector has a cylindrical shape with an overall length of 28.7 m, of which 21.6 m make the main cylinder with a diameter of 15 m, and the rest of the length comes from the forward calorimeter. The total mass is 14000 t. The main detector is made of a central barrel section that is closed with an endcap section on both ends to cover most of the 4π solid angle.

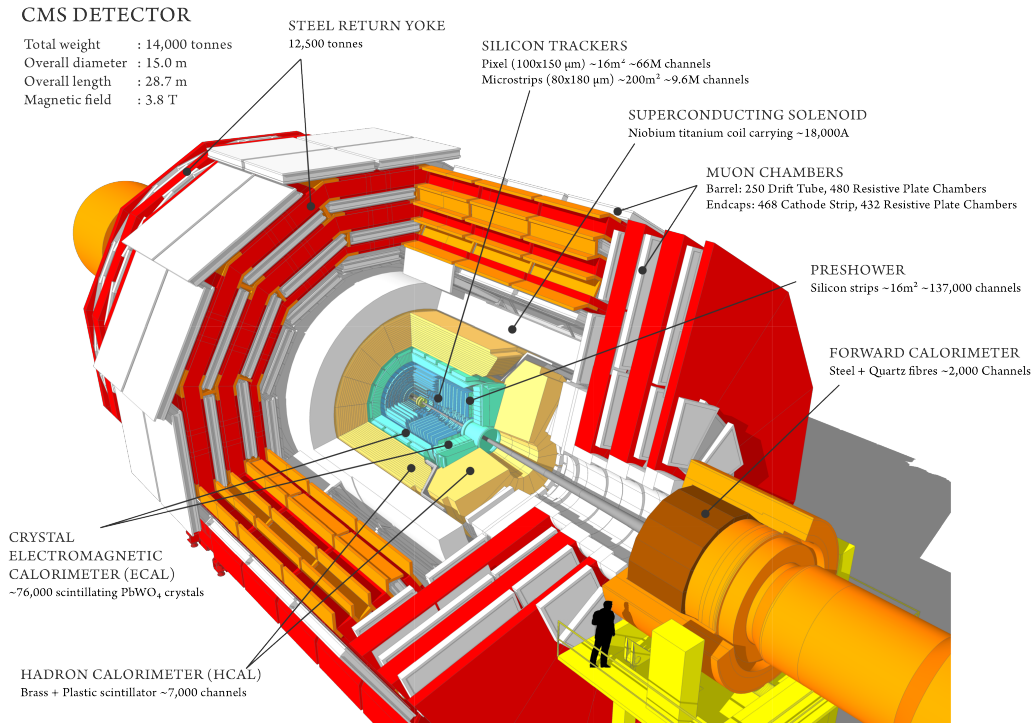


Figure 2.8: Sectional view of the CMS detector. The LHC beams travel in opposite directions along the central axis of the CMS cylinder colliding in the middle of the CMS detector.

The central features of the CMS detector are: the high-field (≈ 3.8 T) solenoid in the barrel part, the full-silicon-based inner tracker, and the homogeneous electromagnetic calorimeter. In particular, the large bending power, needed to measure precisely the momentum of high-energy charged particles, forced a choice of superconducting technology for the magnets. Inside the 6 m diameter bore of the magnet, the silicon tracking system, the Electromagnetic

CALorimeter (ECAL), and the Hadronic CALorimeter (HCAL) are located. Outside of the solenoid, the muon tracking system is sandwiched in between the layers of the steel return yoke for the magnetic field. The high magnetic field not only provides a large bending power within a compact spectrometer, but also avoids stringent demands on muon-chambers resolution and alignment. The return field is large enough to saturate 1.5 m of iron, allowing 4 muon stations to be integrated to ensure robustness and full geometric coverage.

The longitudinal view of one quarter of the CMS detector is shown in Figure 2.9. All CMS components are indicated with the standard two-letter code (the second being B for barrel and E for endcap) which will be explained and used in the following. The muon spectrometer is composed by 4 stations of Drift Tube (DT) detectors in the barrel region (MB) and 4 stations of Cathode Strip Chambers (CSCs) in the endcaps (ME). Both the barrel and the endcaps muon chambers are coupled to Resistive Plate Chambers (RPCs) to ensure redundancy and robustness to the muon trigger and reconstruction.

The origin of the coordinate system of the detector lies in the center at the nominal collision point. The x -axis points radially inward to the center of the LHC ring and the y -axis points vertically upward. The coordinate system is right-handed and so the z -axis points horizontally along the counter clockwise beam direction. Since the products of the collisions will fly outward from the collision point, it makes sense to use cylindrical coordinates for the description (used by reconstruction algorithms) based on the azimuthal angle ϕ , defined as the angle measured from the x -axis in the $x - y$ plane, the radial coordinate r is also measured in the $x - y$ plane and finally, the polar angle θ measured from the z -axis. Instead of the polar angle the pseudorapidity η is used, which is zero in the $x - y$ plane and goes to positive and negative infinity, respectively, towards the positive and negative z -axis. The forward regions of the detector mean regions of higher $|\eta|$, close to the z -axis or about $|\eta| > 3$.

2.2.1 Magnet

The solenoid of the CMS detector produces uniform field in the axial direction, while the flux return is assured by an external iron yoke with three layers, in between which the muon system is installed. The momentum analysis of charged particles is performed by measurement of particles trajectories inside the solenoid and the momentum resolution is given by:

$$\frac{\Delta p_T}{p_T} = \Delta s \frac{8p_T}{0.3BR^2} , \quad (2.8)$$

where $p = \gamma mv$ is the particle momentum, B is the magnetic induction, s is the sagitta and R is the solenoid radius. Therefore strong field and large

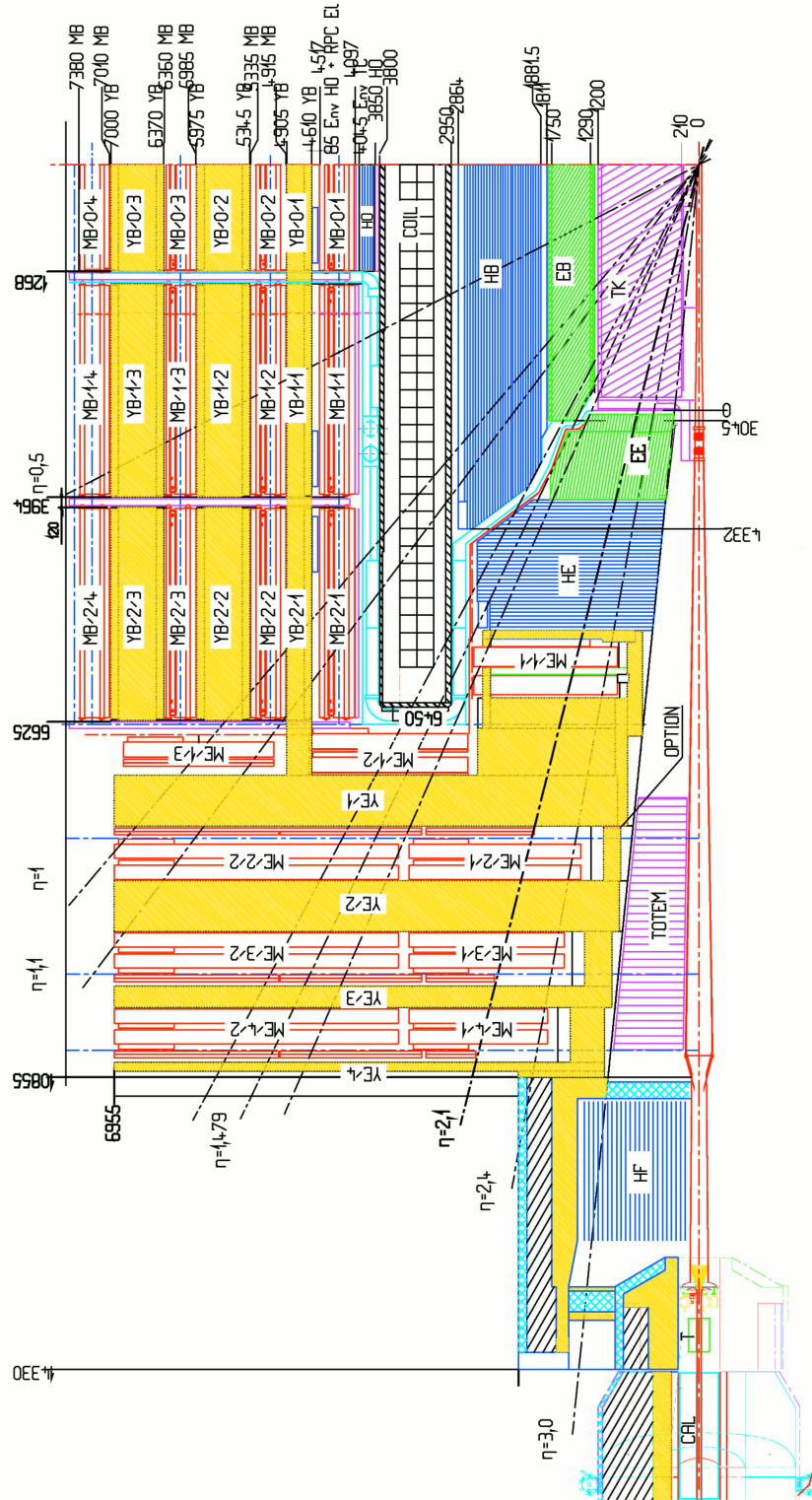


Figure 2.9: CMS longitudinal view.

radius are an efficient approach to reach optimal momentum resolution: CMS preferred a high field within a compact space.

The superconducting magnet of the CMS detector has a length of 12.5 m and a diameter of the cold bore of 6.3 m. It is made from a 4-layer winding of *NbTi* cable reinforced with aluminium, weighting a total of 220 t, and kept at a temperature of 4.5 K with liquid helium. It was designed to produce a field of 4 T but operate at a lower field of 3.8 T. The magnetic field is generated by a 18 kA current circulation in the cables. The magnet system stores an energy of 2.5 GJ.

2.2.2 Inner tracker

The aim of the inner tracker is to reconstruct the trajectories of charged particles in the region $|\eta| < 2.5$ with high efficiency and momentum resolution, to measure their impact parameter, and to reconstruct secondary vertices. For the tracker is required a detector technology featuring high granularity and fast response keeping to the minimum the amount of material in order to limit multiple scattering, bremsstrahlung, photon conversion, and nuclear interactions, since it is the detector closest to the beam line.

The longitudinal view of one quarter of the tracker is shown in Figure 2.10. The innermost tracker closest to the IP is made of three layers of silicon pixel

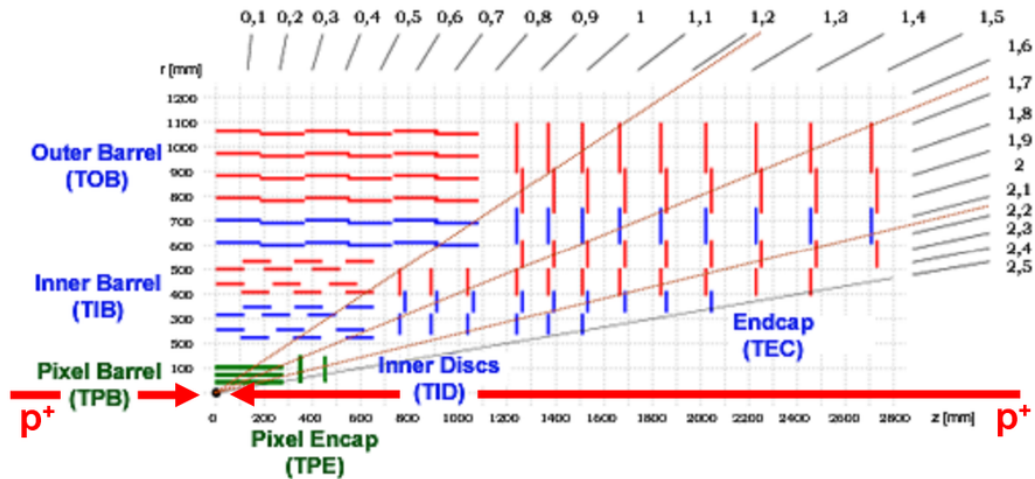


Figure 2.10: Schematic overview of the inner tracker.

detectors named Tracker Pixel Barrel (TPB), ranging from 8.8 cm to 20.4 cm diameters, and two wheels of Tracker Pixel Endcap (TPE), covering the pseu-

dorapidity range up to $|\eta| = 2.5$. TPB and TPE contain 48 million and 18 million pixels, respectively. The pixels have a size of $100 \times 150 \mu\text{m}^2$.

Thanks to the large Lorentz drift angle in the magnetic field, with a charge interpolation from the analog pulse heights, the measured hit resolution in the TPB is $9.4 \mu\text{m}$ in the $r - \phi$ coordinate and $20\text{--}40 \mu\text{m}$ in the longitudinal direction. The longitudinal resolution depends on the angle of the track relative to the sensor. For longer clusters, sharing of charge among pixels improves the resolution, with optimal resolution reached for interception angles of $\pm 30^\circ$.

The silicon strip tracker is placed outside of the pixel tracker. The barrel part of the strip tracker is divided in the 4-layers of the Tracker Inner Barrel (TIB) and the 6-layers of the Tracker Outer Barrel (TOB). Coverage in the forward region is provided by the 3 Tracker Inner Discs (TID), and the 9 disks of the tracker endcap (TEC) on each side. The pitch of the strips varies between $80 \mu\text{m}$ in the innermost layers of the TIB, and $183 \mu\text{m}$ in the outer layers of the TOB. In the disks the pitch varies between $97 \mu\text{m}$ and $184 \mu\text{m}$. Some of the modules are composed by two detectors mounted back-to-back with the strips rotated by 100 mrad . These double-sided (stereo) modules will also provide a measurement in the coordinate orthogonal to the strips. The single point resolution that can be achieved depends strongly on the size of the cluster and on the pitch of the sensor and varies not only as a function of the cluster width, but also as a function of pseudorapidity, as the energy deposited by a charged particle in the silicon depends on the angle at which it crosses the sensor plane. The measured hit resolution in the barrel strip detector varies between $\sim 20 \mu\text{m}$ and $\sim 30 \mu\text{m}$ in $r - \phi$ in the TIB and TOB.

2.2.3 Calorimeter

The CMS calorimeter system is designed to measure the energy of hadronic jets and electromagnetic cascades induced by photons and electrons, and to provide hermetic coverage to allow missing transverse energy measurement. Other requirements are good electron and photon identification efficiency and good separation between QCD jets and hadronic τ decays.

Electromagnetic calorimeter

The CMS ECAL is a scintillating crystal calorimeter, with lead-tungstate (PbWO_4) chosen as the crystal material. Lead-tungstate is a fast, radiation-hard scintillator characterised by a small Moliere radius (21.9 mm) and a short radiation length (8.9 mm), that allows good shower containment in the limited space available for the ECAL. Moreover, the scintillation decay time of these crystals is of the same order of magnitude as the LHC bunch crossing time:

$\sim 80\%$ of the light is emitted within 25 ns.

The longitudinal view of one quarter of the ECAL is shown in Figure 2.11. The ECAL consists of 61200 crystals in the barrel (EB), covering a pseudorapidity

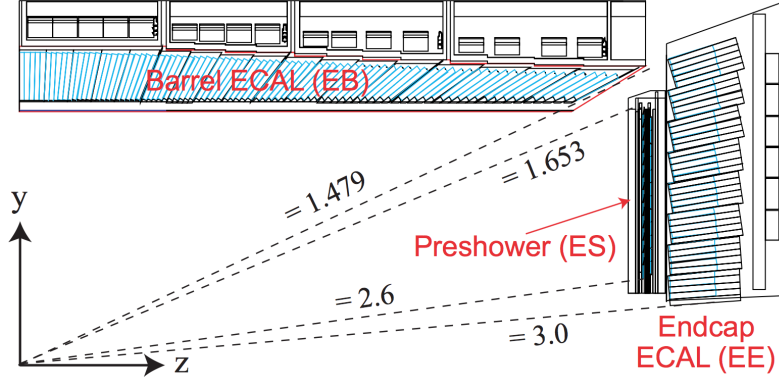


Figure 2.11: Geometry of the ECAL and the preshower detector, for a quadrant of the CMS detector.

pseudorapidity range of $|\eta| < 1.5$, and 14648 crystals in the endcaps (EE), which cover a pseudorapidity range of $1.5 < |\eta| < 3.0$. The length of the crystals is 230 mm in the barrel and 220 mm in the endcaps, corresponding to 25.8 and 24.7 radiation lengths respectively. Crystals are trapezoidal, with a square front face of $22 \times 22 \text{ mm}^2$ in the barrel and $30 \times 30 \text{ mm}^2$ in the endcaps, matching the Moliere radius. Scintillator light is collected by silicon avalanche photo-diodes in the case of barrel crystals, and vacuum photo-triodes for endcaps crystals.

In front of the EE there is a pre-shower detector (ES) that covers the pseudorapidity region of $1.65 < |\eta| < 2.6$ and consists of two lead radiators to initiate electromagnetic showers from incoming electrons and photons and two planes of silicon strip detectors to measure the energy and transverse shower profile. The ES is designed to identify photons coming from neutral pion decays and improve the estimation of the direction of photons, to improve the measurement of the two-photon invariant mass.

The energy resolution of a calorimeter can be parametrised as the quadratic sum of a stochastic term ($\sigma_s/\sqrt{E}$), a noise term (σ_n/E) and a constant term (c) [39]:

$$\frac{\sigma_E}{E} = \frac{\sigma_s}{\sqrt{E}} \oplus \frac{\sigma_n}{E} \oplus c. \quad (2.9)$$

The theoretical parametrization of the different contributions as a function of the energy are shown in Figure 2.12. The stochastic term includes the effects of fluctuations in the number of photo-electrons as well as in the shower

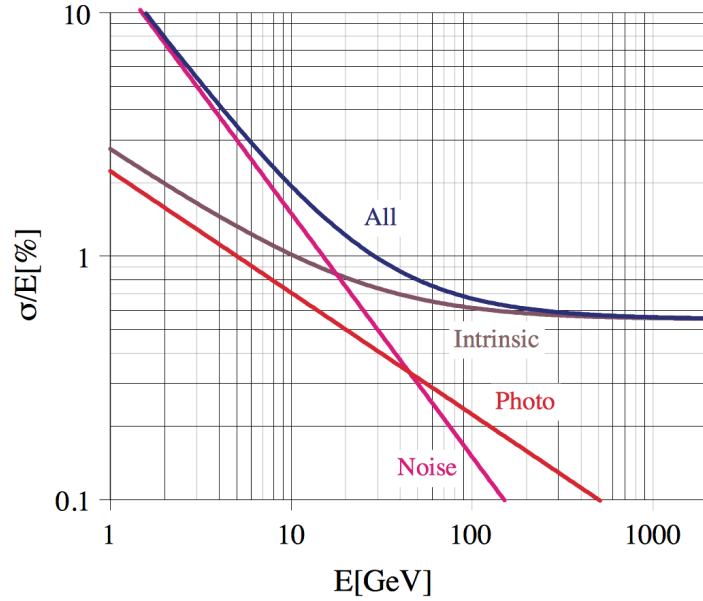


Figure 2.12: Theoretical parametrization of the different contributions to the energy resolution of the ECAL. The noise term contains the contributions from electronic noise and pileup energy. The curve labelled “intrinsic” includes the shower containment and a constant term of 0.55%.

containment, the noise term consists of electronic noise, digitisation noise, and noise from additional pp interactions (pileup), and the constant term related to the calibration of the calorimeter and non-uniformity of the longitudinal light collection of the crystals. The parameters, measured in an electron test beam, for incident electrons of seven energies from 20 to 250 GeV, with a 3×3 crystal configuration, considering E is in GeV, correspond to $\sigma_s = 0.028 \text{ GeV}^{1/2}$, $\sigma_n = 0.12 \text{ GeV}$, and $c = 0.003$ [40].

Hadronic calorimeter

The HCAL of CMS is a sampling calorimeter with brass as absorber, plastic scintillator tiles as active medium, and wavelength shifting fibers to transfer the light to the detector. This absorber material has been chosen as it has a reasonably short interaction length, and is non-magnetic. Most of the HCAL is located inside the bore of the cryostat, and consists in a barrel (HB) that extends to $|\eta| < 1.4$, and two endcaps (HE) ranging from $1.3 < |\eta| < 3$. Since the absorber depth of the ECAL barrel and the HCAL barrel in the solenoid is

not sufficient to contain the complete particle shower, an additional calorimeter (HO) is placed as a tail catcher outside the cryostat, using it as an additional absorber. In the central ring of the CMS barrel, the HO has two layers, one on each side of the first layer of iron of the yoke, while in the other 4 rings there is only one HO layer. Figure 2.13 shows a quadrant of the HCAL with the segmentation in calorimeter towers.

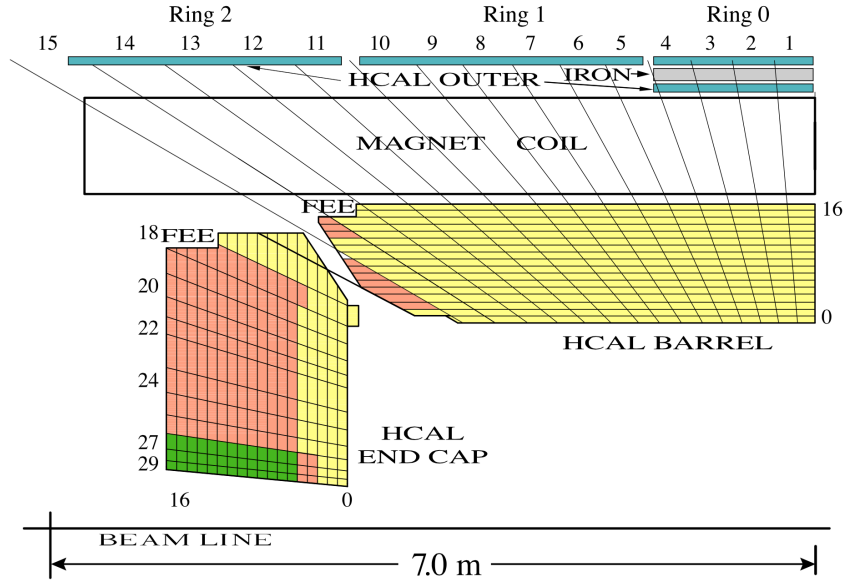


Figure 2.13: A quadrant of the HCAL with the segmentation in calorimeter towers in the r - z plane. The colours indicate the optical grouping of the readout channels [28].

Since the identification of forward jets is very important for the rejection of many backgrounds, the barrel and the endcap parts, which cover up to $|\eta| < 3.0$, are complemented by a very forward calorimeter (HF), placed at ± 11.2 m from the interaction point, which extends the pseudorapidity range of the calorimetry up to $|\eta| < 5.2$. As the particle flux in this very forward region is extremely high, a radiation hard technology, using Cherenkov light in quartz fibers, was chosen with steel as an absorber. The HF detector is also used as a real-time monitor for the luminosity on a bunch-by-bunch basis.

The HCAL baseline single-particle energy resolution is

$$\frac{\sigma_E}{E} = \frac{65\%}{\sqrt{E}} \oplus 5\% \quad (2.10)$$

in the barrel,

$$\frac{\sigma_E}{E} = \frac{83\%}{\sqrt{E}} \oplus 5\% \quad (2.11)$$

in the endcaps, and

$$\frac{\sigma_E}{E} = \frac{100\%}{\sqrt{E}} \oplus 5\% \quad (2.12)$$

in the forward calorimeter (where E is expressed in GeV).

2.2.4 Muon system

In order to provide an independent muon identification, robust trigger and accurate momentum measurement and charge, for muons with momenta from a few GeV to a few TeV, the muon spectrometer is placed outside the magnet and consists of four stations of detectors integrated into the iron return yokes so that the 3.8 T magnetic field inside the solenoid and the 1.8 T average return field can be used as bending field.

The muon spectrometer is composed of three independent sub-detectors used both for tracking and for trigger in order to guarantee robustness and redundancy. The layout of the system is presented in Figure 2.14. In the

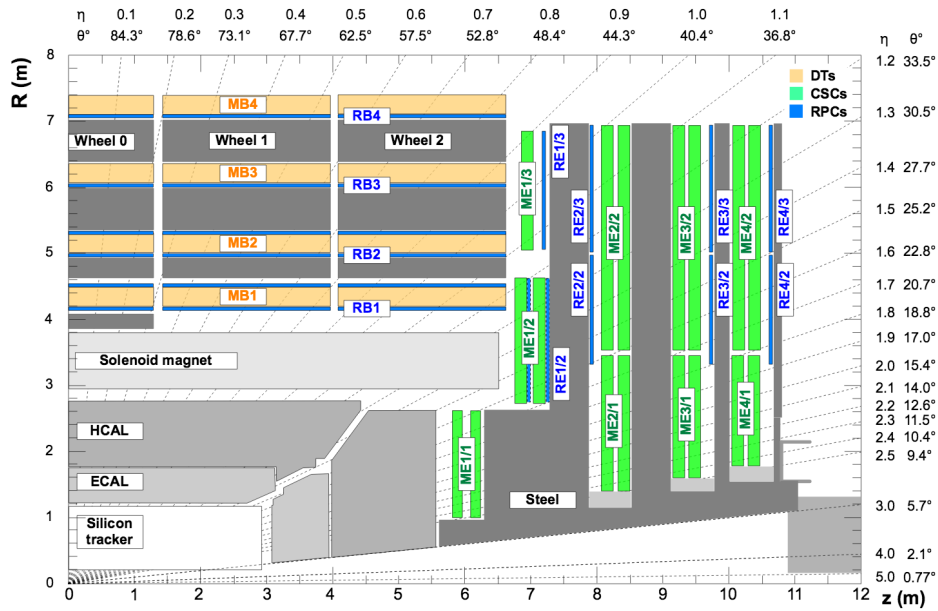


Figure 2.14: A quadrant of the CMS detector with the different muon sub-detectors highlighted [41].

barrel ($|\eta| < 1.2$), where the track occupancy and the residual magnetic field are low, DT detectors are installed. In the endcaps, where the particle rate is higher and a large residual magnetic field is present, CSCs are used. The

coverage of the DT and the CSC system goes up to $|\eta| < 2.4$. In the region $|\eta| < 2.1$ RPCs are present.

The muon identification is guaranteed by the amount of material in front of the chambers and in the return yoke of the magnet which shields the spectrometer from charged particles other than muons: more than 10 interaction length and 110 radiation length are present before the first measurement station of the spectrometer, at least 16 interaction length of material present up to $\eta = 2.4$ with no acceptance losses.

The magnetic field inside the iron of the yoke bends the tracks in the transverse plane thus allowing the measurement of their p_T . The high field is fundamental for the momentum resolution of the spectrometer but it also sets the environment in which the detector operates. The innermost endcap CSCs, the ME1/1 chambers, are exposed to the full field which, in this region, is almost entirely axial and uniform. In the following CSC stations the field is no longer axial and uniform, however, the small drift space allows these detectors to limit the degradation of the chamber resolution. In the barrel region most of the flux is contained within the iron plates of the yoke where the axial component of the field reaches ≈ 1.8 T. The space where the DT chambers are placed should ideally be field-free. However in the iron gaps and at the end of the coil the residual magnetic field is far from being negligible: there are spatially limited regions where the field in the radial direction can reach 0.8 T.

The robustness of the spectrometer is also guaranteed by the different sensitivity of DT, RPC and CSC to the backgrounds. The main sources of background particles in the LHC environment will be represented by secondary muons produced in π and K decays, from punch-through hadrons and from low energy electrons originating after slow neutron capture by nuclei with subsequent photon emission. This neutron induced background will be the responsible of the major contribution to the occupancy level in the muon detectors. The total background rate at high pseudorapidity reaches up to 1 kHz/cm² in the innermost part of the ME1/1 station. In the barrel the fluences are much lower being everywhere less than 10 Hz/cm². As described in the following sub-sections, CSC and DT chambers, in contrast with RPC detectors, are characterized by a layout which helps in reducing the effect of background hits: the request of correlation between consecutive layers is particularly effective against background hits affecting only a single layer.

More details about the muon reconstruction are provided in Section 3.2.

Drift tubes

The choice of the drift tube detector in the barrel is motivated by the relatively low particle rates and magnetic field intensity in this region. The barrel section

of the CMS iron yoke is divided into 5 wheels, forming 3 concentric layers of iron. Each wheel is divided into 12 sectors. The muon chambers are installed on the outer and inner sides of the yoke and in the pockets between layers, arranged in four stations at different radii, named MB1, MB2, MB3 and MB4. Each station consists of 12 chambers, one per sector, except for MB4 where 14 chambers are present.

The basic detector unit in this setup is a drift cell: a gas-filled tube with rectangular cross-section showed in Figure 2.15. The two shorter sides of the rectangle form cathodes, while an anode wire is strung through the middle. A charged particle passing through the detector volume ionizes the gas, producing a cloud of electrons that drifts toward the wire. The drift time is measured and converted to distance using the knowledge of drift velocity. A single drift cell has a cross-section of $42 \times 13 \text{ mm}^2$ and wire length 2-3 m. It is filled with a 85%/15% mixture of Ar/CO_2 , giving a 350 ns maximum drift time. Single wire measurement resolution is of the order of $200 \text{ }\mu\text{m}$.

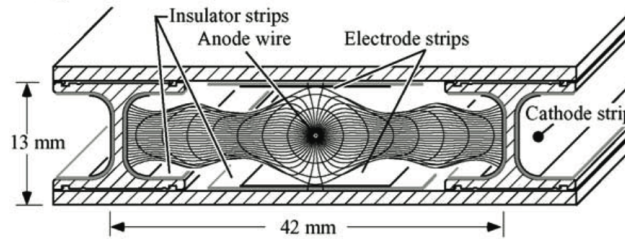


Figure 2.15: Drift tube layout.

The drift tubes in a chamber are grouped into SuperLayers (SL) consisting of four layers of tubes, staggered by half a tube. In each chamber there are two SLs with wires parallel to the beam direction, measuring muon position in the bending plane of the magnetic field. These are separated by a 128 mm thick aluminium honeycomb spacer, providing good angular resolution within one chamber. Additional SL measuring the η coordinate of the muon is present in the three inner stations. Each SL is equipped with fast pattern-recognition electronics, providing bunch crossing identification, and measuring the track segment position and angle, as described in Section 3.2.1.

Cathode strip chambers

Measurement of muon trajectories in the endcap part of the CMS muon system is performed mainly by CSCs. This type of detector has been chosen because of its capability to provide precise time and position measurement in the presence

of a high and inhomogeneous magnetic field, and high particle rates.

The detector is a multi-wire proportional chamber with one of the cathode planes being segmented in strips running orthogonally to the wires. The principle of operation is shown in Figure 2.16: a muon crossing the chamber produces an avalanche in the gas (a 40%/50%/10% mixture of $Ar/CO_2/CF_4$) collected by the wire. This induces an electrical charge on several adjacent cathode strips. Fitting the measured distribution of charge picked up by the strips gives an estimate of the position of the muon along the wire.

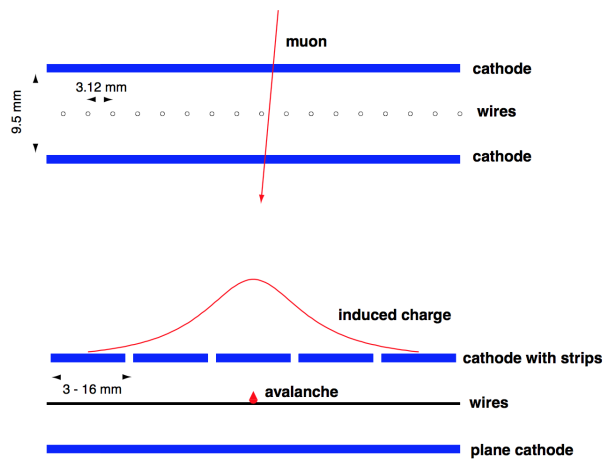


Figure 2.16: The principle of operation of a cathode strip chamber, with cross-section across the wires (top) and across the strips (bottom).

There are four muon stations integrated into each endcap of the CMS detector (ME1-ME4). The chambers are grouped into rings, with the first station (ME1) consisting of three rings, and the remaining three (ME2-ME4) having two rings of chambers. The rings are formed by 18 or 36 trapezoidal chambers that overlap in ϕ in every ring except the outermost ring of the first station (ME1/3), giving geometrical coverage close to 100%.

Each individual chamber has a trapezoidal shape and is made of seven cathode panels stacked together, forming six gas-gaps each containing an array of anode wires. The gaps are 9.5 mm thick and one of the two cathode planes for each gap is segmented into radial strips orthogonal to the wires. The strips cover a constant area in ϕ (2.33-4.65 mrad, depending on the disk). The orthogonal coordinate (r) is measured by the wires which, to reduce the number of channels, are read out in groups of 5 to 16. The inner-most CSC detector lies inside the solenoid, so the wires have to be rotated to compensate for the Lorentz drift.

Resistive plate chambers

RPCs are used throughout the CMS muon system, with the main goal of providing fast trigger signal. They are installed both in the barrel and in the endcaps and are thus complementary to the CSC and the DT systems. These detectors are characterized by an excellent time resolution and fast response providing unambiguous bunch crossing identification, but they have a limited spatial resolution (least one order of magnitude lower than DTs and CSCs) and therefore their impact on muon reconstruction performance is very low.

A single chamber consist of two bakelite planes externally coated with graphite separated by a 2 mm wide gas gap, as shown in Figure 2.17.

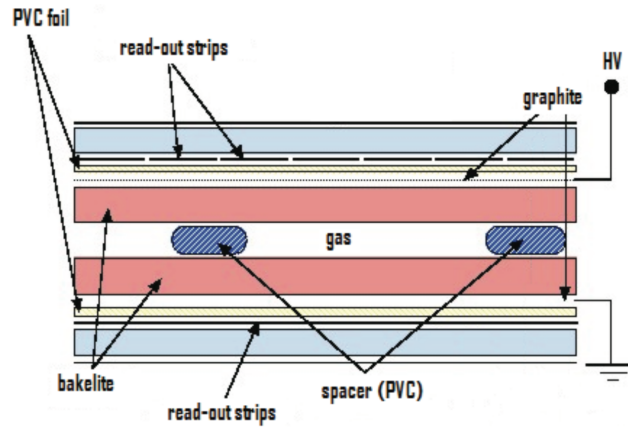


Figure 2.17: Single gap Resistive Plate Chambers layout.

Charged particles crossing the gap generate avalanches by ionizing the 96.2% $C_2H_2F_4$ (freon) + 3.5% iC_4H_{10} (isobutane) + 0.3% SF_6 + water vapour gas mixture. The signal is read out from detector by a set of aluminium strips, insulated from the electrode with a thin film. In CMS the efficiency of the detector is improved by combining two gas gaps with a common readout plane. This increases the charge induced on the strips. Moreover RPCs operate in “avalanche” mode rather than in the more common “streamer” mode, thus allowing the detectors to sustain higher rates. This mode is obtained with a lower electric field, thus the gas multiplication is reduced and an improved electronic amplification is required.

The barrel RPC chambers follow the segmentation of DT chambers. There are six layers of RPCs, two in the first and second muon station (MB1 and MB2), and one in the third and fourth (MB3 and MB4). The barrel RPCs are rectangular, with dimensions $210\text{-}375 \times 85$ cm. A total number of 96 readout

strips run parallel to the beam, with pitch increasing from the inner to the outer muon station: from 2.1 cm in the inner MB1 plane to 4.1 cm in the MB4 planes.

In the endcaps, there are four stations, covering the region up to $\eta = 1.6$. Endcap RPC chambers are trapezoids, with strips running in the radial direction. The strips are also trapezoidal in shape, with a width changing to recover a constant angle in ϕ . The dimensions of the strips vary strongly from detector to detector: they are about 25 cm long and have a pitch of 0.7 cm in the lowest detector of the ME1 chambers (at $\eta = 2.1$) whereas in the chambers at highest r in ME2,3,4 they are about 80 cm in length and have a pitch of roughly 3 cm.

2.2.5 Trigger

The recognizing of the interesting signatures, among the high track multiplicity produced at every LHC collision, is for sure one of the most challenging tasks for the CMS detector. The bunch crossing frequency at CMS interaction point is 40 MHz (bunch spacing of 25 ns) while technical difficulties in handling, storing and processing extremely large amounts of data impose a limit of about 600 Hz on the rate of events that can be written to permanent storage, as the average event size will be of about 1 MB. At the LHC nominal luminosity the total event rate for inelastic interactions is expected to be of the order of 10^9 Hz while the rate of interesting events is very small (see Figure 2.18). A sophisticated trigger system selects events of interest. The time available for the selection is very small since the bunch crossing time is 25 ns. This interval of time is not enough to read out all raw data from the detectors, and for this reason CMS uses a multi-level trigger design, where each step of the selection uses only part of the available data. In this efficient way higher trigger levels have to process fewer events and have more time available; they can go into finer detail and use more refined algorithms. The two steps of the CMS selection chain are: the Level-1 (L1) trigger, built from custom hardware, which reduces the rate to a maximum of 100 kHz, and High Level Trigger (HLT), running the CMS reconstruction software on a processor farm, which performs higher level reconstruction and reduces the rate of events selected by the L1 trigger to about 400 Hz before the events are stored on disk.

Level-1 trigger

The L1 system is built from custom designed, programmable electronics, and is located underground, both in the service and the experiment caverns. Within a time budget of $3.2 \mu\text{s}$, it has to decide if an event is discarded or kept, and

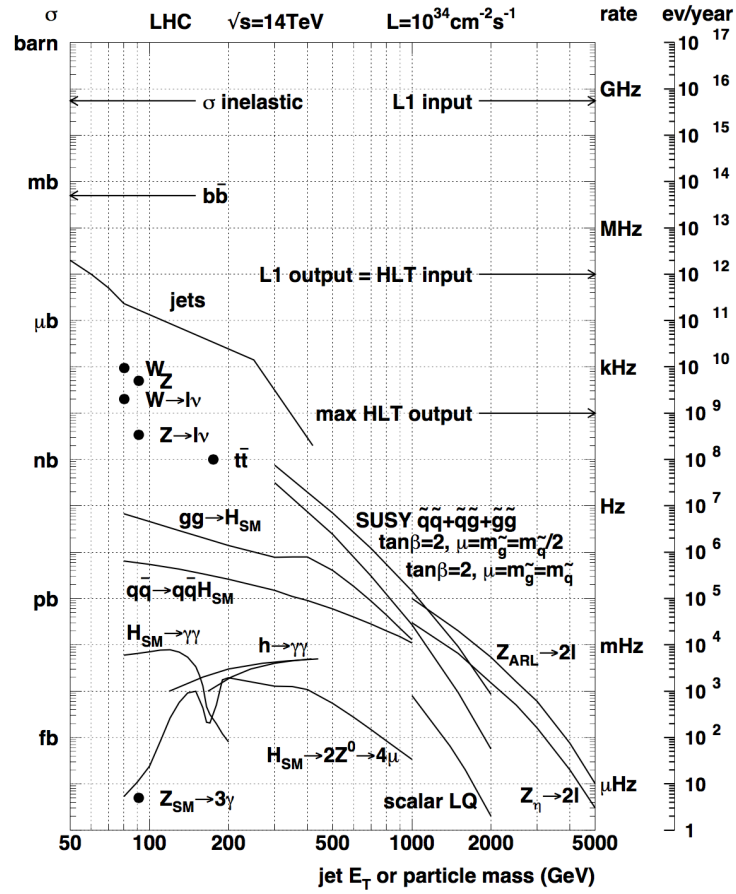


Figure 2.18: Event cross sections and rates of selected processes for the LHC design luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ as a function of the mass of produced objects.

transfer this decision back to the subdetectors, which keep the high resolution data in memory in the meantime. The L1 is divided in a muon trigger and a calorimeter trigger, which classify and rank interesting event candidates, reconstructed from low resolution data read out from the subdetectors. The rank of a candidate is determined by energy or momentum, and quality of the data. The calorimeter and muon triggers do not perform any selection themselves. They identify “trigger objects” of different types: e/γ (isolated and not), jets and muons. Based on the input from the muon trigger and the calorimeter trigger, the global trigger calculates the final trigger decision. Up to 128 trigger algorithms can be executed in parallel to generate a decision. The simplest triggers are in general those based on the presence of one object with an E_T or p_T above a predefined threshold (single-object triggers) and those based on the presence of two objects of the same type (di-object triggers) with either symmetric or asymmetric thresholds. Other requirements are those for multiple objects of the same or different types (“mixed” and multiple-object triggers). The high resolution data from the inner tracker are not used to generate the L1 decision, which means that there is no information about the vertices and no distinction between electrons and photons available at this level.

High level trigger

Once the L1 trigger has accepted an event, the data of this event are transferred from the buffer memory to the surface, where they are reconstructed in the HLT. The HLT is a special part of the CMS software and runs on a farm of several thousand processors. Each processor works on the reconstruction of one event at a time, to get to a trigger decision within on average 100 ms. Since the time budget for one event is much larger than at the L1 trigger, more complicated algorithms, including tracking, can be executed at the HLT. Once an event is accepted, it is stored on disk and fully reconstructed offline at a later time. The goal of the HLT is to reduce the event rate from the maximum Level-1 output to 600 Hz which is the maximum rate for mass storage.

The use of standard software techniques and languages makes it possible to benefit from the continuous improvements in the reconstruction software. In particular the algorithms used in the HLT, which access data with full resolution and granularity from any part of the detector, is identical to those used in the off-line reconstruction. However, in order to discard uninteresting events as soon as possible, the selection is organized in a sequence of logical steps: the Level-2 and Level-3. The Level-2 uses the full information from calorimeters and muon detectors and reduces the event rate by roughly one order of magnitude. The data from the silicon tracker represent almost 80%

of the event size and require complex and time consuming algorithms for the reconstruction. For this reason this information is used only during the Level-3 selection.

The HLT consists of approximately 400 trigger paths, which, starting from the seed of the L1 trigger, look for different objects and signatures in an event. One trigger path is built from reconstruction modules and filter modules. After some parts of the data are reconstructed, a filter module decides if the reconstructed objects pass the thresholds and the next step in reconstruction is started, or if the event is not accepted by the path. In the later case, the execution of the path is stopped and the following reconstruction steps and filter steps are not performed to save computation time. Following this concept to save computation time, the less computation intense reconstruction steps (e.g. unpacking the data from the ECAL and measuring the energy deposit) are done first. The reconstruction steps that take a lot of time, e.g. the tracking, are done at the end of a path for objects that have already passed the previous steps. If an event is not accepted by a path, it can still be accepted by a different path.

If, for some paths with low thresholds, the acceptance rate is too high, they can be prescaled to lower the rate. A prescale value of ten means, for example, that the path is executed only for every tenth event that was accepted by the L1 trigger, and, consequently, the trigger rate for that path is ten times smaller. The prescale value for one trigger path has several predefined levels, depending on the instantaneous luminosity of the LHC machine. During an LHC fill, the instantaneous luminosity decreases, and the prescale values can be changed during a CMS run to keep the global trigger rate at an optimal level.

A detailed description of the muon HLT reconstruction is provided in Section 3.2.5.

In order to cope with the conditions of the high-luminosity data taking at 13 TeV, the trigger algorithms have been improved for Run-2, to make the muon trigger efficiency less sensitive to the number of pileup events. In addition, the muon detector and trigger upgrades performed during the Long Shutdown 1 allow the analysis at 13 TeV to extend the pseudorapidity region where muons can be triggered, by including the region $2.1 < |\eta| < 2.4$.

The main trigger used to select events for the analysis described in this thesis is the unprescaled single-muon trigger with the lowest p_T threshold that does not include muon isolation requirements, without pseudorapidity restrictions. More in detail, the L1 trigger path used for this analysis is the logic OR of L1_SingleMu16 and L1_SingleMu25, which select single muons with

$p_T > 16$ and 25 GeV respectively. The HLT path used is HLT_Mu50, that selects single muons with $p_T > 50$ GeV in the pseudorapidity range of the muon detector acceptance, $|\eta| < 2.4$. A comparison with the path HLT_Mu45_eta2p1, with a restricted pseudorapidity range, but lower p_T threshold, is reported in Section 5.1.2. The L2 p_T threshold has been lowered from 16 to 10 GeV starting from the 2015C period, with a consequent $\approx 1\%$ improvement of the overall trigger efficiency.

Chapter 3

Object reconstruction

The requirement for physics analyses in CMS is based on the reconstruction of high-level physics objects (trajectory) which correspond to particles traveling through the detector. The CMS sub-detectors record the signal of a particle as it travels through the active material, and this signal is reconstructed as individual points in space known as *recHits*. The recHits are associated together to determine points on the particle trajectory. The characteristics of the trajectory are then used to define its momentum, charge, and particle identification.

For each event, collections of particles are reconstructed, as well as jets, the missing transverse energy E_T^{miss} and the primary vertices. A general description on tracking of charged particles is given in Section 3.1. The offline muon reconstruction is described in Section 3.2, while section 3.3 discusses the offline electron reconstruction. The reconstruction of jets is explained in section 3.4.

3.1 Tracking of charged particles

This Section is dedicated to the track reconstruction: in Section 3.1.1 a parametrization of a charged particle trajectory in a magnetic field $\vec{B}$ is given; in Section 3.1.2 the material effects of particle motion are shown and finally, in Section 3.1.3, the CMS track reconstruction technique is described.

3.1.1 Track parameters

The Lorentz force gives a relation between the momentum and its motion in a magnetic field, and allows the determination of the equation of motion for the trajectory of the charged particle. The measurement of the full trajectory of a charged particle in a magnetic field provides a method to determine its

momentum ($\vec{p} = m\gamma\vec{v}$) and charge q . Parameterizing the Lorentz force as a function of the distance along the trajectory, $s(t)$, the trajectory is given by the differential equation

$$\frac{d^2\vec{r}}{ds^2} = \frac{q}{p} \frac{d\vec{r}}{ds} B(r) \quad (3.1)$$

where $\frac{d\vec{r}}{ds}$ is the unit length tangent to the trajectory, and $\frac{d^2\vec{r}}{ds^2}$ is a measure of the curvature of the trajectory. So, if $\vec{B}$ is known, the momentum at a point (x, y, z) is obtained by measuring the tangent to the trajectory and the curvature of the trajectory. The tangent to the trajectory makes an angle λ with respect to the detector as illustrated in Figure 3.1.

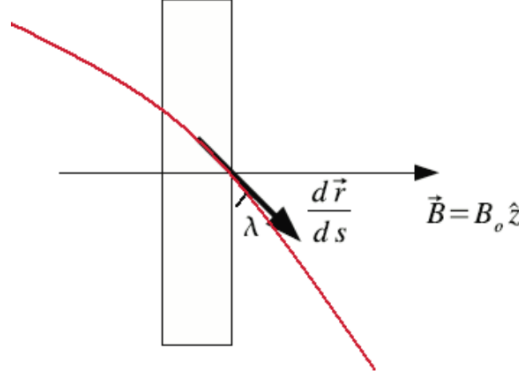


Figure 3.1: Schema for the trajectory parametrization in a magnetic field $\vec{B}$.

From the solution of Equation (3.1), for known $\vec{B}$, three relations for $x(s)$, $y(s)$, and $z(s)$ are obtained. The above relations describe a helix in space that is parameterized by $\{x, y, z, \lambda, q/p\}$. The projection in the $x-y$ plane follows a circle with fixed radius of curvature $R_T = |\vec{p}| \cos \lambda / qB$, while the z coordinate measures the stretch of the helix in the direction parallel to $\vec{B}$.

However, the previous parameterization has some limitations since it does not take into account three important factors caused by the real CMS detector:

- inhomogeneous $\vec{B}$ field;
- the energy loss by the particle through the detector;
- the multiple scattering which deflects the trajectory in a stochastic manner.

These effects affect the momentum and its direction. An accurate measurement of direction is critical in determining whether the particle came from the interaction point or a detached vertex. To take into account these effects, a set of parameters that scales with the changes mentioned is used.

The magnetic field is a function of the coordinates $\vec{B}(x, y, z)$, therefore to correctly describe the trajectory it is necessary to incorporate the magnetic field changes into the parametrization. The new set of parameters:

$$\{x, y, x', y', q/|\vec{p}|\}, \quad (3.2)$$

evaluated at a reference surface $z = z_r$ together with the derivatives with respect to z , provides the change from the ideal trajectory. This new parametrization also scales with the effects of multiple scattering and localizes the trajectory to a plane region where the $\vec{B}$ field can be expanded as a perturbation to a good approximation. Thus, a solution to the trajectory in an inhomogeneous $\vec{B}$ field can be found by using an iterative methods for the approximation of solutions of differential equations (recursive method of Runge-Kutta [42]).

As said, a trajectory of a helix in a region of known magnetic field can be uniquely specified by at least five degrees of freedom, where a unique determination would require infinite precision on the five parameters. For large momenta, the projection of the trajectories can be approximated by a straight line $y = a + bz$ in a plane containing the magnetic field and with a parabola $y = a + bx + (c/2)x^2$ in the plane normal to the magnetic field, with $c = -R_T^{-1}$. The uncertainties on the above parameters due to the intrinsic resolution of the detectors translates directly into an uncertainty on the momentum vector.

3.1.2 Material effects

A charged particle will be deflected by random Coulomb scattering with the material of the detector. For sufficient crossed material, the deflection angle from its unperturbed trajectory becomes Gaussian distributed around zero. The scattering introduces an uncertainty in the position measurements and a correlation in the measurements after the material scattering. In cases where the multiple scattering dominates the uncertainty, the momentum resolution does not depend on the momentum, but there is a weak dependence on the number of measurements for a fixed amount of material and on the length of the spectrometer.

Although ionizing single atoms in a medium requires a relatively small amount of energy transfer, the additive effects do contribute in a well understood manner. The mean rate of energy loss for moderately relativistic particles with charge ze heavier than the electron is given by the Bethe-Bloch

formula:

$$-\left\langle \frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \left(\frac{2m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} \right) - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right] \quad (3.3)$$

where $K = 4\pi N_A r_e^2 m_e c^2$, A and Z are respectively the atomic mass and atomic number of the absorber, T_{max} is the maximum kinetic energy which can be imparted to a free electron in a single collision, I is the mean excitation energy, and $\delta(\beta\gamma)$ is the density-effect correction [5]. It describes the mean rate of energy loss in the region $0.1 \lesssim \beta\gamma \lesssim 1000$ for intermediate- Z materials.

The function as computed for muons on copper is shown as the “Bethe” region of Figure 3.2 and well describes the average energy loss in the range between $[\approx 100 \text{ KeV}, \approx 100 \text{ GeV}]$. At lower energies various corrections must be made, and at higher energies, radiative effects begin to be important. These limits of validity depend on both the effective atomic number of the absorber and the mass of the slowing particle. A minimum $\approx 2 \text{ MeV cm}^2/\text{g}$ is reached at $\beta=0.96$ that for muons corresponds to $E_\mu=0.35 \text{ GeV}$. For $0.35 < E_\mu < 100 \text{ GeV}$ there is a slight rise of $\approx 10\%$.

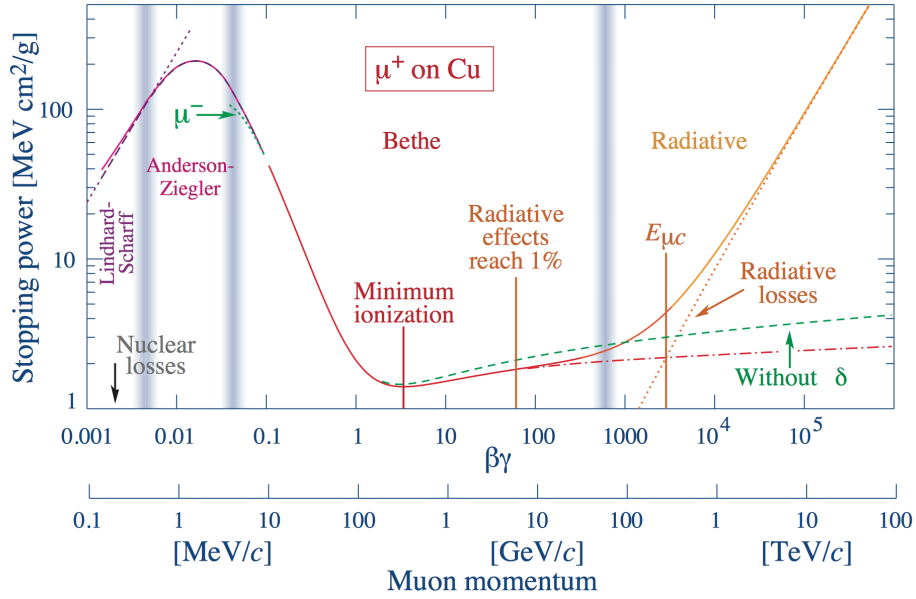


Figure 3.2: Stopping power ($\langle -dE/dx \rangle$) for positive muons in copper as a function of $\beta\gamma$ over nine orders of magnitude in momentum. Solid curves indicate the total stopping power [5].

The loss of energy has to be incorporated in the equations of motion, and the information can be introduced in an iterative manner.

3.1.3 Tracking algorithm

The recHits from the position sensitive detectors are analyzed using a pattern recognition algorithm to associate the measurements with trajectories. The procedure from recHits to tracks is independent of the sub-detector information used and follows the same logical steps: local reconstruction, which consists of estimating particle positions and uncertainties on all detectors layers, seed generation, trajectory building, ambiguity resolution, and trajectory smoothing.

Seed generation

A trajectory seed is the starting point for the reconstruction. The seed should constrain all five trajectory parameters and their estimation should be sufficiently close to their true value to allow the use of linear fitting algorithms. In CMS the Kalman filter (KF) [43] is being used [44]. Moreover, also the uncertainties of the parameters should be sufficiently small in order to reduce the region where to find compatible hits.

The most common types of trajectory seeds in CMS are hit-based seeds and state-based seeds. It is assumed that the trajectories, and therefore the trajectory seeds, are compatible with the beam spot. Hit-based seeds require a hit-pair or hit-triplet compatible with the beam spot to provide the initial vector. Additional options are that the seed direction meet certain criteria, or that the hits be located in a certain geometric region of the detector. State-based seeds do not require any hits and are specified by an initial momentum and direction.

Trajectory building

Trajectory building starts at the position specified by the trajectory seed, and the building then proceeds in the direction specified by the seed to locate compatible hits on the subsequent detector layers.

The trajectory building is based on a combinatorial Kalman filter method. The filter proceeds iteratively from the seed layer, starting from a coarse estimate of the track parameters provided by the seed. First, a dedicated navigation component determines which layers are compatible with the initial seed trajectory. The trajectory is then extrapolated to these layers according to the equations of motion of a charged particle in a constant magnetic field, accounting for multiple scattering and energy loss in the traversed material, as described in Sections 3.1.1 and 3.1.2. Radiative processes are not implemented in the Kalman filter.

Naturally more than one hit per layer can be compatible with the extrapolated track, and then several new trajectory candidates are created, one per hit, forming combinatorial trees of track candidates. In addition, one further trajectory candidate is created, in which no measured hit is used, to account for the possibility that the track did not leave any hit on that particular layer.

On each successive detection layer, each trajectory estimate and its covariance matrix are then updated with the corresponding hit. This update can be seen as a combination of the predicted trajectory state and the hit in a weighted mean, as the weights attributed to the measurement and to the predicted trajectory depend on their respective uncertainties. Afterward all resulting trajectory are propagated to the next layer and the procedure is repeated. The algorithm is stopped when the outermost layer is reached or a stopping condition is satisfied.

In order not to bias the result all trajectory candidates are grown in parallel, but in order to limit the number of combinations, only a limited number of these are retained at each step, based on their normalized χ^2 and number of valid and invalid hits. This algorithm is configurable through several parameters. Depending on their values, it can provide either a high track finding efficiency, as needed offline, or very fast CPU performance suitable for use in the HLT. By default only 5 candidates are propagated at each step and only one consecutive invalid hit is allowed [51].

Ambiguity resolution

Trajectory building produces a large number of trajectories, many of which share a large fraction of their hits. Ambiguities in track finding arise because a given track may be reconstructed starting from different seeds, or because a given seed may result in more than one trajectory candidate. These ambiguities, or mutually exclusive track candidates, must be resolved in order to avoid double counting of tracks. The ambiguity resolution is based on the fraction of hits which are shared between two trajectories. For any pair of track candidates this fraction is defined as:

$$f_s = \frac{N_s^h}{\min(N_1^h, N_2^h)} \quad (3.4)$$

where N_1^h and N_2^h are the number of hits in the first and second track candidate respectively. If this fraction exceeds a value of 0.5, the track with the least number of hits is discarded, or, if both tracks have the same number of hits, the track with the highest χ^2 value is discarded.

The ambiguity resolution is applied twice: the first time on all track candidates resulting from a single seed, and the second time on the complete set

of track candidates from all seeds [51].

Trajectory smoothing

For each trajectory, the building stage results in a collection of hits and in an estimate of the track parameters. However, the full information is only available at the last hit of the trajectory and the estimate can be biased by constraints applied during the seeding stage. Therefore the trajectory is refitted using a least-squares approach, implemented as a combination of a standard Kalman filter and smoother. The Kalman filter is initialized at the location of the innermost hit. The fit then proceeds in an iterative way through the list of hits. For each valid hit the position estimate is re-evaluated using the current values of the track parameters. The track parameters and their covariance matrix are updated with the measurements and are modified according to the estimates for energy loss and multiple scattering.

This first filter is complemented with a smoothing stage: a second backward filter is initialized with the result of the first one, except for the covariance matrix, which is scaled with a large factor, and run backwards towards the beam line. At each hit the updated parameters of this second filter are combined with the predicted parameters of the first filter, excluding the current hit.

This filtering and smoothing procedure yields optimal estimates of the parameters at the surface associated with each hit. Estimates on other surfaces, e.g. at the impact point, are then derived by extrapolation from the closest hit.

3.2 Muon reconstruction

The key of the analysis described in this thesis is the ability to trigger on, and accurately reconstruct, muons with high efficiency: muon reconstruction algorithms have been designed to achieve these goals. Moreover, for the goal of looking high-mass resonances decaying into muons the good reconstruction of high-energy muons is a crucial item as described in Chapter 4.

The muon reconstruction [45] is done with data collected by the muon system and the inner tracker. A muon trajectory is estimated as described in Section 3.1. Several muon reconstruction strategies are available in CMS, in order to fulfill the specific needs of different analysis. In general, the reconstruction of muons consists of three main stages:

- local reconstruction: in each muon chamber, the raw data from the detector read-out are reconstructed as `recHits`; in CSC and DT chambers, such `recHits` are then fitted to track stubs (segments);

- stand-alone reconstruction: recHits and segments in the muon spectrometer are collected and fitted to tracks, referred to as “stand-alone muon tracks”;
- global reconstruction: stand-alone tracks are matched to compatible tracks in the inner tracker and a global fit is performed using the whole set of available measurements (recHits or segments): the resulting tracks are called “global muon tracks”.

There is an additional complementary approach with respect to global reconstruction: the “muon identification” which starts from the inner tracker tracks and flags the particle as muons by searching for matching segments in the muon spectrometer. The muon candidates produced with this strategy are referred to as “tracker muons”.

After the completion of both algorithms, the reconstructed stand-alone, global, and tracker muons are merged into a single software object, with the addition of further information, like isolation and energy collected in matching calorimeter towers. This information can be used for further identification, in order to achieve a balance between efficiency and purity of the muon sample.

3.2.1 Local reconstruction

The particle trajectory is built starting from the recHits, which are local points on the sub-detectors layers. Ideally one recHit per layer should be produced. Details about the CMS muon system are reported in Section 2.2.4.

Drift tubes

Local reconstruction begins building mono-dimensional hits in single drift cells. The only information contained in these hits is the distance from the wire, with an intrinsic left/right ambiguity and without any information about their position along the wire. The cell hits are the starting point for the reconstruction of segments separately in the $r - \phi$ and $r - z$ projections. These two-dimensional segments still do not provide any information about the coordinate parallel to the sense wires but they add the knowledge about the track angle projected in the measurement plane. Combining the two projections, it is possible to reconstruct the three dimensional information about the track crossing the chamber, as shown in Figure 3.3. The resulting 3D segments have an angular resolution of about 0.7 mrad in ϕ and about 6 mrad in θ .

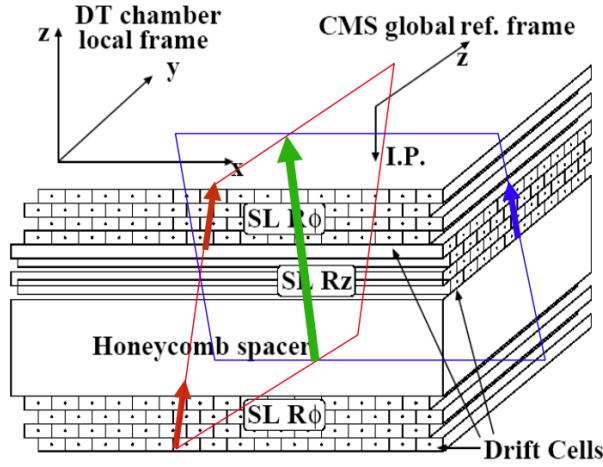


Figure 3.3: RecHits in a Drift Tube chamber. The 2D reconstructed segments in the SuperLayers are shown in red and blue, and the 4D RecHits combined from the two is shown as the green arrow.

Cathode strip chamber

Local reconstruction provides position and time of arrival of a muon hit from the distribution of charge induced on the cathode strips. Two-dimensional hits are obtained in each layer: the radial coordinate r is measured by the wires, the azimuthal coordinate ϕ by the strips, where the charge distribution of a cluster of three neighbouring strips is fitted to the so-called Gatti function to obtain a precise position measurement. These are combined to create a three-dimensional straight line segment within each chamber (made of up to 6 layers). The position resolution of segments varies from about $50 \mu\text{m}$ in the first CSC station to about $250 \mu\text{m}$ in the fourth. The direction resolution varies with the chamber type, with an average of about $40\text{-}50 \text{ mrad}$ in ϕ , slightly worse in θ .

Resistive plate chamber

Local reconstruction gives the position of a muon hit from the position of clusters of hit strips. The procedure consists of grouping all adjacent fired strips. Once all groups are formed, the reconstructed point is defined as the “center of gravity” of the area covered by the cluster of strips. In the barrel, where strips are rectangular, it is simply the center of a rectangle. In the endcap, the computation is more complicated as the area covered by the clusters are trapezoids of variable shape. The assumption here is that each group of strips is fired

as a result of a single particle crossing and that this crossing can have taken place anywhere with flat probability over the area covered by the strips of the cluster. Errors are computed under the same assumption of flat probability (length of each side of the cluster divided by $\sqrt{12}$) [51].

3.2.2 Stand-alone muon reconstruction

The stand-alone track reconstruction starts with the estimation of the seed state from track segments (DT for barrel and CSC for endcap) in the off-line reconstruction and from the trajectory parameters estimated by the Level-1 of trigger in the on-line reconstruction. The track is then extended using an iterative algorithm (based on Kalman filter as seen in Section 3.1) which updates the trajectory parameters at each step.

Once the hits are fitted and the fake trajectories removed, the remaining tracks are extrapolated to the point of closest approach to the beam line. In order to improve the p_T resolution a beam-spot constraint is applied. The track reconstruction handles the DT, CSC, and RPC reconstructed segment/hits and can be configured in such a way as to exclude the measurements from one or more muon subsystems. The independence from the subsystem is achieved thanks to a generic interface also shared with the inner tracking system. This allows the tracker and the muon code to use the same tracking tools (such as the Kalman filter) and the same track parametrization.

Seed generator

The algorithm is based on the DT and CSC segments. A pattern of segments in the stations is searched for, using a rough geometrical criteria. Once a pattern of segments has been found (it may also consist of just one segment), the p_T of the seed candidate is estimated using parametrisations of the form:

$$p_T = A - \frac{B}{\Delta\phi} \quad (3.5)$$

For DT seed candidates with segments in MB1 or MB2, $\Delta\phi$ is the bending angle of the segment with respect to the vertex direction. This part of the algorithm assumes the muon has been produced at the interaction point. If segments from both MB1 and MB2 exist, the weighted mean of the estimated p_T is taken. If the seed candidate only has segments in MB3 and MB4, the difference in bending angle between the segments in the two stations is used to calculate p_T .

In the CSC and overlap region, the seed candidates are built with a pair of segments in either the first and second stations or the first and third stations

and $\Delta\phi$ is evaluated as the difference in ϕ position between the two segments. Otherwise, the direction of the highest quality segment is used.

Pattern recognition and track fit

In the standard configuration the seed trajectory state parameters are propagated to the innermost compatible muon detector layer and a pre-filter is applied in the inside-out direction. Its main purpose is to refine the seed state before the true filter. The final filter in the outside-in direction is then applied and the trajectory built. The algorithm is flexible enough to perform the reconstruction starting from the outermost layer instead of the innermost. The pre-filter step can optionally be skipped, hence increasing the speed of the reconstruction which could be important for the High Level Trigger.

The pre-filter and filter are based on the same iterative algorithm used in two different configurations. In both cases it can be subdivided into different sub-steps: search of the next compatible layer and propagation of the track parameters to it, best measurement finding and possibly update of the trajectory parameters with the information from the measurement. The process stops when the outermost (for the pre-filter) or the innermost (for the filter) compatible layer of muon detectors is reached.

At each step the track parameters are propagated from one layer of muon detectors to the next and the best measurement is searched for on a χ^2 basis. The required precision is obtained by using smaller steps in regions with larger magnetic field inhomogeneities. The χ^2 compatibility is examined at the segment level, estimating the incremental χ^2 given by the inclusion in the fit of the track segment. In case no matching hits (or segments) are found, the search continues in the next station. For the update of the trajectory parameters the pre-filter and the filter follow two different approaches. As the pre-filter should give only a first estimate of the track parameters, it uses the segment for the fit. The parameters are almost always updated as the χ^2 cut imposed at this stage is loose (of the order of one hundred). The final filter instead uses the hits composing the segment with a tighter χ^2 cut (of the order of 25) which can reject individual hits. This results in a more refined trajectory state. The RPC measurements are not aggregated in segments, so that for them the only distinction between the pre-filter and the filter is the χ^2 cut.

In order to finally accept a trajectory as a muon track, at least two measurements, one of which must be of the DT or CSC type, must be present in the fit. This allows rejection of fake DT/CSC segments due to combinatorics.

After the fake track suppression the parameters are extrapolated to the point of closest approach to the beam line. In order to improve the momentum resolution a constraint to the nominal interaction point (IP) is imposed [51].

3.2.3 Global muon reconstruction

The reconstruction of global muon tracks begins after the completion of the reconstruction of the stand-alone tracks and the inner tracker tracks. Each stand-alone track is matched to a compatible tracker track and a fit of all the available measurements (recHits or segments) is performed.

Muon track reconstruction in the tracker

As in the muon system, the reconstruction process starts with the seed finding, but while in the muon system the trajectory is built during the pattern recognition, in the tracker the pattern recognition and the final fit are performed separately. Two or three consecutive hits, in the pixel and/or in the strip detector, are used to find the seeds. Based on the Kalman filter technique, the algorithm uses an iterative process to pass from one layer to the next and to perform the pattern recognition. The principle is very similar to that used in the muon spectrometer alone.

Track matching and global fit

The process of identify the tracker track to combine with a given stand-alone muon track is referred to as track matching and consists of two steps. The first step is to define a region of interest (ROI) in the track parameter space that roughly corresponds to the stand-alone muon track, and to select the subset of the tracker tracks inside this ROI. The determination of the ROI is based on the stand-alone muon with the assumption that the muon originates from the interaction point.

The second step is to iterate over this subset, applying more stringent spatial and momentum matching criteria to choose the best tracker track to combine with the stand-alone muon. The matching is performed by propagating the muon and the tracker tracks onto the same plane and looking for the best χ^2 value from the comparison of track parameters in the ROI.

This outside-in algorithm is accompanied by an inside-out identification algorithm, where candidate tracker tracks are extrapolated to the muon system taking into account the magnetic field, the average expected energy losses, and multiple Coulomb scattering in the detector material.

If there is a suitable match between tracker track and stand-alone muon track, then the default global fit algorithm combines hits from the tracker and the stand-alone muon track and performs a final fit over all hits. However it is also possible to combine only a subset of the hits for the global fit. In particular, choosing a subset of the muon hits provides a better momentum resolution for high energy muons, when the measurements in the muon system

are frequently contaminated by electromagnetic showers. The treatment of very energetic muons will be described in Chapter 4.

If the matching fails, the reconstruction is stopped and no global track is produced. If the matching algorithm selects more than one tracker track for a given stand-alone track, all matched tracks proceed in the reconstruction chain and the global track with the best χ^2 is chosen.

After the final global fit is made for all stand-alone track matches in the event, fake tracks are suppressed. The reconstruction of the muons ends with the matching of the global muon track and the energy deposits in the calorimeters.

3.2.4 Muon identification

Standard muon track reconstruction starts from the muon system and combines stand-alone muon tracks with tracks reconstructed in the inner tracker. This approach naturally identifies the muon tracks in the detector. However, a large fraction of muons with transverse momentum below 6-7 GeV does not leave enough hits in the muon spectrometer to be reconstructed as stand-alone muons. Moreover, some muons can escape in the gap between the wheels.

A complementary approach, which starts from the tracker tracks, has therefore been designed [46] to identify off-line these muons and hence improve the muon reconstruction efficiency: consists in considering all silicon tracker tracks and identifying them as muons by looking for compatible signatures in the calorimeters and in the muon system.

The algorithm starts extrapolating each reconstructed silicon track outward to its most probable location within each detector of interest (ECAL, HCAL, HO, muon system). After collecting the associated signals from each detector, the algorithm determines compatibility variables corresponding to how well the observed signals fit with the hypothesis that the silicon track is produced by a muon.

A very loose threshold on the compatibility variables is applied to select candidates that are saved in the muon collection; different physics analyses can apply further selections on the same variables, in order to balance the purity and efficiency of the muon identification.

In the calorimeter, the algorithm calculates and stores the energies in all the crystals (ECAL) or towers (HCAL) crossed by the track, as well as the energies in a 3×3 region. Based on these energies, a compatibility variable is determined, which describes how consistent these energies are with respect to what is expected for a muon. Muons identified through this calorimeter-based compatibility are referred to as “calo-muons”.

If at least one muon segment matches the extrapolated track, the corre-

sponding tracker track qualifies as a “tracker-muon”.

The general muon tracking has been optimized for the Run-2 [41, 47] and two additional muon-specific iterations have been implemented: the first one outside-in, seeded from the muon system to recover missing tracker tracks; the second one inside-out, to reconstruct muon-tagged tracks with looser requirements, thus improving the hit collection efficiency. The muon tracking efficiency is shown in Section 3.2.6 (Figure 3.5).

In general, particles detected as muons are produced in pp collision from different sources which lead to different experimental signatures:

Prompt muons: the majority of muon chamber hits associated with the reconstructed muon candidate were produced by a muon, arising either from decays of W, Z, and promptly produced quarkonia states, or other sources such as Drell-Yan processes or top quark production.

Muons from heavy flavour: most of muon chamber hits associated to the muon candidate were produced by a true muon. The muon’s parent particle can be a beauty or charmed meson, a tau lepton.

Muons from light flavour: most of muon chamber hits associated to the muon candidate were produced by a true muon. This muon originated from light hadron decays (π and K) or, less frequently, from a calorimeter shower or a product of a nuclear interaction in the detector.

Hadron punch-through: most of muon chamber hits of the muon candidate were produced by a particle other than a muon. The so called “punch-through” (i.e. hadron shower remnants penetrating through the calorimeters and reaching the muon system) is the source of the most of these candidates ($\sim 88\%$ for global muons) although “sail-through” (i.e. particles that does not undergo nuclear interactions upstream of the muon system) is present as well.

Duplicate: if one particle gives rise to more than one reconstructed muon candidate, the one with the largest number of matched hits is flagged according to one of the other categories. Any others are labelled as “duplicate”. These are duplicate candidates created by instrumental effects or slight imperfections in the pattern recognition algorithm of the reconstruction software [45].

The standard CMS reconstruction provides additional information for each muon, useful for muon quality selection and identification (ID) in physics analyses [45]. A list of the informations used in CMS analyses to identify good

muons from backgrounds is reported below, with a brief explanation of the motivations for using them.

- A muon is required to be identified both as a tracker (TRK) and a global muon (GLB). This is effective against decays-in-flight, punch-through and accidental matching (with noisy or background tracks or segments).
- The number of hits in the tracker track part of the muon. Generally tracks with small number of hits give bad p_T estimate. In addition decays in flight give rise in many cases to lower hit occupancy in the tracks.
- There should be at least one pixel hit in the tracker track part of the muon. The innermost part of the tracker is an important handle to discard non-prompt muons. By requiring just a minimal number of hits we introduce negligible reconstruction inefficiency.
- A minimal number of tracker layers involved in the measurements. This guarantees a good p_T measurement, for which some minimal number of measurement points in the tracker is needed. It also suppresses muons from decays in flight.
- The muon track has to have a minimum number of chamber hits in different stations with matching (consistent with the propagated to the muon chambers tracker track) segments. This is also to comply with a similar looser requirement in the trigger.
- Very bad fits are rejected by requiring reasonable global muon fit quality. If there is a decay in flight inside the tracking volume, the trajectory could contain a sizeable “kink”, resulting in a poorer χ^2 of the fit used to determine the trajectory.
- The global muon has to contain at least one “valid” muon hit. This requirement assures that the global muon is not a “bad” match between the information from the muon system and the tracker. This could happen in particular for non-prompt muons.
- The impact parameter (d_{xy}), defined as the distance of closest approach of the muon track with respect to the beamspot has to be compatible with the interaction point hypothesis (muon from the interaction point). This is effective against cosmic background and further suppress muons from decays in flight.
- Also the longitudinal impact parameter (d_z) is used to further suppress cosmic muons, muons from decays in flight and tracks from pile-up.

- Muon can be required also to be matched a Particle Flow (PF) muon. PF is a reconstruction technique widely used in CMS analyses. It makes use of the full detector information to describe the global collision event, by identifying particles individually and clustering them into more complex objects. More details about PF algorithm are available in [49, 50].

All these variables are used to define a tight identification, called “TightID”. The TightID efficiency is shown in Section 3.2.6 (Figure 3.6).

Specific selection developed for high p_T ($p_T > 200$ GeV) studies, called “High p_T ID”, does not use the PF. It is aimed to the best reconstruction of the muon track parameters for high- p_T muons without relying on external informations on the event. Moreover, the goodness of the global-muon track fit selection, based on the χ^2 of the track, is not requested, but an additional selection based on the $\sigma p_T/p_T$ for the track used for momentum determination is applied. The High p_T ID is used to select muon candidates in this analysis, as will be described in Section 5.1.3.

3.2.5 High level trigger

The reconstruction follows the same basic steps in the online HLT, described in Section 2.2.5, and in the offline reconstruction, though the online algorithms have to be faster and hence are less sophisticated [48]. Muon reconstruction at HLT starts with track fitting in the outer muon spectrometer, which builds the so called level-2 (L2) muons. The level-3 (L3) muon reconstruction is the muon HLT step that builds full muon tracks (including tracker information) starting from those L2 muons. A sequence of three algorithms is tried in cascade from the fastest to the slowest and the cascade is interrupted when a L3 candidate is reconstructed. For the first two algorithms the seeds to reconstruct the tracker tracks are built on the basis of L2 muons propagated to tracker layers with the addition of information from one tracker hit for the second algorithm. For the last algorithm, starting from inside and going outward, the L2 muons are used to build regions where to look for hits but the seeds to reconstruct tracker tracks are built using pixel/tracker hit information.

Quality cuts may be applied, in particular to test the compatibility of the muon track with the beam spot (e.g. by a 1-2 mm cut on the transverse impact parameter).

In Run-2 the pattern recognition has been improved by replacing a simple geometrical criterion with a χ^2 matching to assign hits to the tracker track. In addition the quality cuts have been moved to be applied as the last step of each branch, to avoid reconstructing fake tracks which would then be cut off at the end of the cascade. Other significant improvements have been implemented

in the inner tracking, as described in Section 3.2.4. This has also allowed to deploy tracker-muon triggers with a similar inside-out algorithm as that used in the offline muon identification. The HLT performance is shown in Section 3.2.6 (Figure 3.7).

3.2.6 Performance

The relative momentum resolution as a function of momentum is shown in Figure 3.4, for a muon emitted in the central region and in the forward region. Simulated single-muon samples with continuous values of p_T (between 10 GeV and 1 TeV), and with a flat distribution in η and ϕ are used. The muon momentum precision is essentially determined by the measurement in the transverse plane of the muon bending angle, taking the interaction point as the origin of the muon. For stand-alone muons the bending angle is measured at the exit of the 3.8 T coil. The resolution of this measurement (blue dots) is dominated by multiple scattering in the material before the first muon station up to p_T values of 200 GeV, when the chamber spatial resolution starts to dominate. For low muon momenta, the full system momentum resolution (red dots) is mainly driven by the inner tracker (green dots). At high momentum a longer lever arm is needed to measure the muon trajectory curvature and the full system muon momentum resolution improves when combining the inner tracker and muon detector measurements.

The muon tracking efficiency is evaluated for data and simulation using the “tag-and-probe” method.

The tag-and-probe method utilizes a known mass resonance (e.g. J/Ψ , Z) to select particles of the desired type, and probe the efficiency of a particular selection criterion on those particles. In general the “tag” is an object that passes a set of very tight selection criteria designed to isolate the required particle type (in this case a muon, though in principle the method is not strictly limited to these). A generic set of the desired particle type (i.e. with potentially very loose selection criteria) known as “probes” is selected by pairing these objects with tags such that the invariant mass of the combination is consistent with the mass of the resonance. Combinatoric backgrounds may be eliminated through any of a variety of background subtraction methods such as fitting, or sideband subtraction. The definition of the probe object depends on the specifics of the selection criterion being examined. The efficiency itself is measured by counting the number of “probe” particles that pass the desired selection criteria.

The performance of the muon tracking is illustrated in Figure 3.5, which shows the muon tracking efficiency as a function of the η of the probe muon, and the

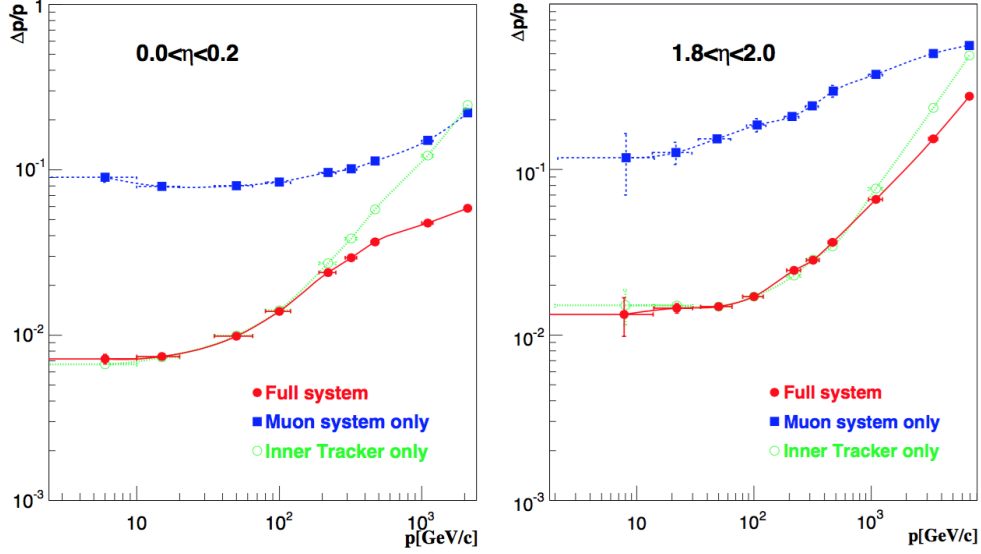


Figure 3.4: Relative resolution of the muon momentum measurement for the reconstruction with the inner tracker only, the muon system only and for the combination of the inner tracker and the muon system [51].

number of primary vertices in one event. In the region $|\eta| < 2.2$ and for events with number of reconstructed primary vertices lower than 25 (Figure 2.4 shows that this condition was satisfied during the 2015 data taking), the measured tracking efficiency of isolated muons is $> 99\%$ in both data and simulation. The tracking efficiency is constant as a function of the number of vertices per event which means that does not depend on the pileup.

In 2012 data it was noticed a small efficiency loss of muon reconstruction for muon tracker tracks, increasing with pileup. In order to recover it, two additional specific iterations have been designed for the muon tracking, as described in Section 3.2.4. In addition the new algorithm has also improved the muon track quality, in particular the number of hits per track. This is reflected in the identification efficiency of standard selections as the Tight Muon selection (“TightID”) [47], shown in Figure 3.6. The pattern of the efficiency as a function of η is related to the acceptance of the muon detector and the presence of small non instrumented regions between the barrel wheels. The Run-2 reconstruction improves the average efficiency by 1-2%, in particular in events with high multiplicity of proton-proton interactions per bunch crossing. The recovery is clearly visible across the whole tracker-eta coverage.

At the end of Run-1, a degraded performance had been observed also for

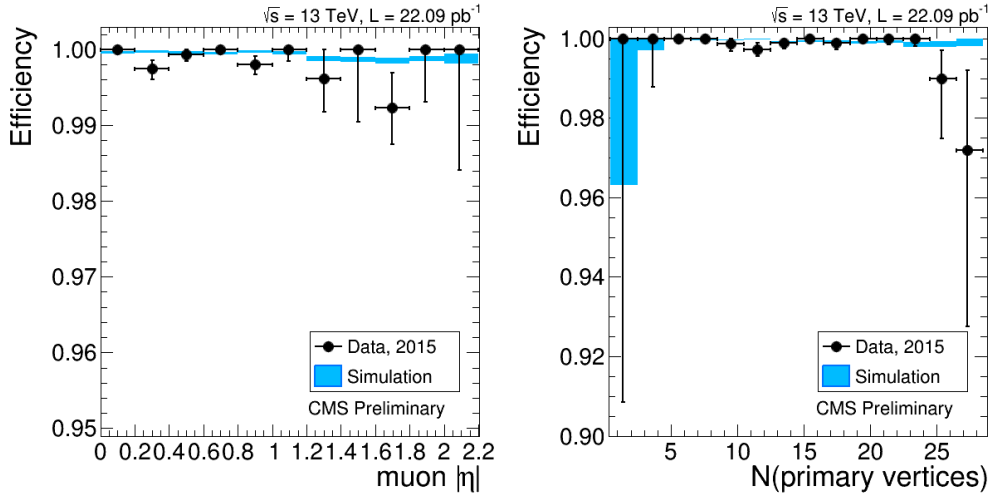


Figure 3.5: Tracking efficiency measured with a tag-and-probe technique, for muons from Z decays, as a function of the muon absolute pseudorapidity η (left) and the number of primary vertices (right), for data (black dots) and simulation (blue bands) [52].

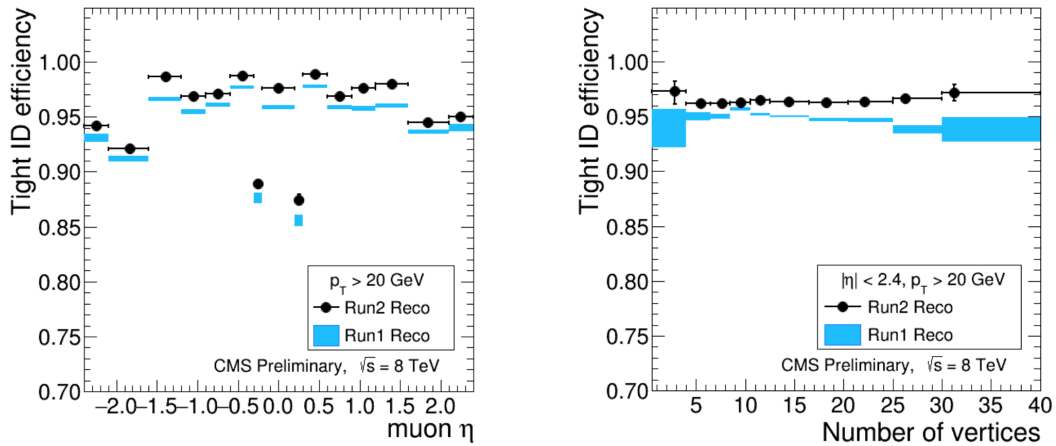


Figure 3.6: Muon reconstruction and identification (for Tight Muon ID selection) efficiency measured with a tag-and-probe technique, for muons from Z decays, as a function of the muon absolute pseudorapidity η (left) and the number of primary vertices (right), for a subsample of data recorded in the last part of the 2012 Run, reconstructed with both the Run-1 (blue bands) and Run-2 (black dots) reconstruction algorithms. Muons with $p_T > 20 \text{ GeV}$ are considered [47].

the HLT global muon reconstruction causing a significant inefficiency of 5-10% for high pileup values. As described in Section 3.2.5, the overall quality of the Run-2 trigger has been improved. The pileup-dependent inefficiency has been completely recovered, as shown by results obtained from MC simulations in Figure 3.7 (left). In general, the performance studied during Run-2 shows better efficiency and purity with respect to Run-1, while the total expected rate does not exceed the design value.

Figure 3.7 (right) shows the efficiency of selecting $Z/\gamma \rightarrow \mu^+\mu^-$ events as a function of the average number of pileup interactions, for a given rejection of the QCD backgrounds. As visible the efficiency is increased and the pileup dependence is reduced. These improvements, among others, allow to keep the same Run-1 HLT trigger thresholds for the isolated single-muon trigger path in conditions of maximum luminosity: $p_T = 24$ GeV for $|\eta| < 2.1$. The extreme endcap regions ($2.1 < |\eta| < 2.4$) requires slightly higher thresholds.

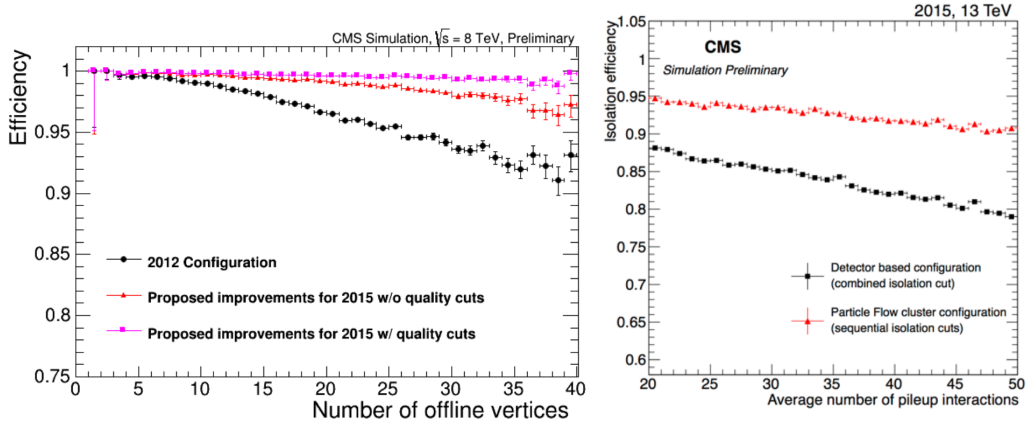


Figure 3.7: Muon HLT efficiency for the global reconstruction step as a function of the number of reconstructed vertices, from a MC simulation of $W \rightarrow \mu\nu$ events (left). Muon HLT isolation efficiency as a function of the average number of pileup interactions (right) for two working points giving a similar rate reduction [41].

The dimuon mass spectrum obtained analyzing collisions collected during the 25 ns LHC running period at 13 TeV, corresponding to an integrated luminosity of 2.7 fb^{-1} , are shown in Figure 3.8. The events were selected by both inclusive and specialized dimuon triggers.

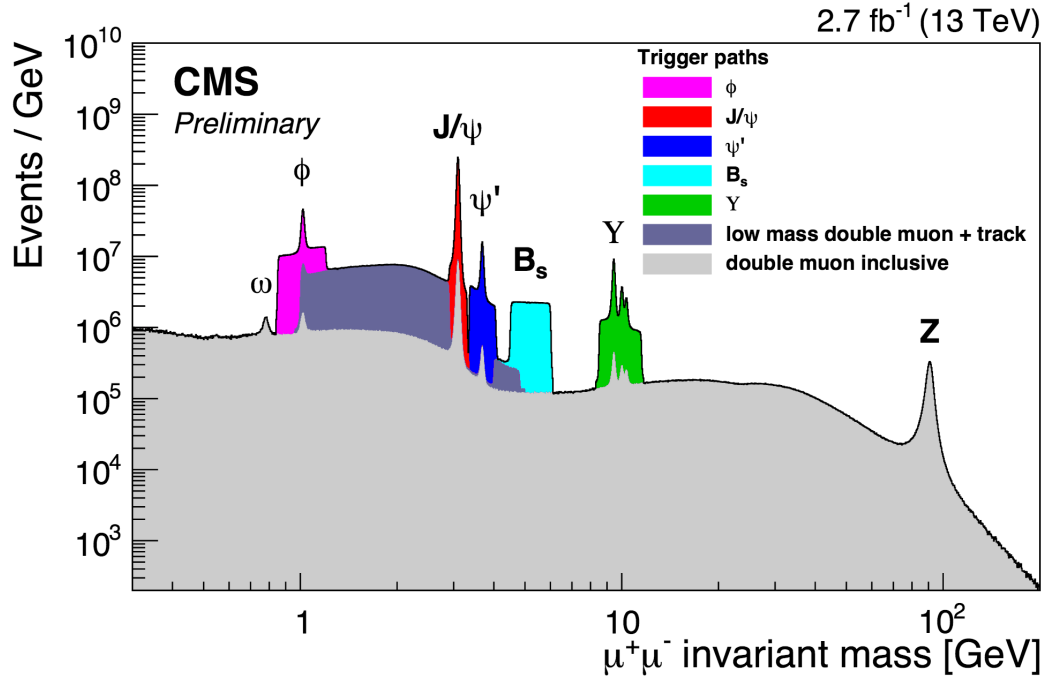


Figure 3.8: Dimuon mass distribution collected with various dimuon triggers, during the 25 ns running period at 13 TeV in 2015. The coloured paths correspond to dedicated dimuon triggers with low p_T thresholds, in specific mass windows, while the light gray continuous distribution represents events collected with a dimuon trigger with high p_T thresholds [53].

3.3 Electron reconstruction

Electrons that are produced at the interaction point fly outwards on a trajectory bent by the magnetic field, leaving hits in the inner tracker and then deposit practically all their energy in clusters of ECAL crystals. As a first step the energy deposit in the ECAL is measured and after that follow the selection of track seeds, the tracking and the association of tracks to ECAL energy deposits. A more detailed description of the electron reconstruction can be found in [54–56].

3.3.1 Energy measurement

An electron interacting in the ECAL, will deposit in average 94% (97%) of its energy in a matrix of 3×3 (5×5) crystals around the crystal with the largest energy deposit, which is called the seed crystal. However, the material

in front of the ECAL has a thickness between 0.4 and 2 radiation lengths. This means that the electrons lose energy because of bremsstrahlung in the material before they reach the ECAL crystals. At $\eta \sim 0$, on average 33% of the electron energy is lost before reaching the ECAL and in the direction of the largest material budget at $\eta \sim 1.4$ the loss is on average 86%. This energy, lost via radiated photons, has to be added to the energy deposited by the electron in the ECAL. This is done by the construction of a supercluster (SC) as defined below. Since the trajectory of the electron is curved in $r-\phi$ plane, the energy deposit in the ECAL barrel coming from radiated photons is mainly spread in the ϕ direction.

To get the energy in a SC, dominoes of 5×1 crystals in $\eta - \phi$ are produced, extending for 17 crystals (0.3 rad) in the ϕ direction around the seed crystal, which must have a transverse energy of at least 1 GeV. If the energy of the domino exceeds a threshold of 0.1 GeV it is grouped with nearby dominoes to form a cluster. The clusters themselves have to have a seed domino that exceeds an energy of 0.35 GeV to be added to the SC. In the endcaps, the energy deposit from bremsstrahlung follows a trajectory in η and ϕ . The energy is collected in a 5×5 matrix around a seed crystal that has to exceed a transverse energy threshold of 0.18 GeV. Around the seed crystal the energy is collected in 5×5 matrices along roads in η and ϕ . These roads have a range of ± 0.07 in η and ± 0.3 rad in ϕ around the seed crystal, and the transverse energy of the 5×5 cluster has to exceed 1 GeV if it is to be added to the SC. The energy collected in the pre-shower detector situated in front of the 5×5 matrix is also added to the SC energy.

As part of the particle flow (PF) reconstruction algorithm [57], which aims at identifying all particles present in an event by combining information from the different subdetectors, PF clusters are defined by adding neighbouring crystals around a seed crystal with $E^{seed} > 230$ MeV in the barrel, and $E^{seed} > 600$ MeV or $E_T^{seed} > 150$ MeV in the endcaps, depending on pseudorapidity. The crystals must have a signal that is 2σ above the electronic noise level of 80 MeV in the barrel and up to 300 MeV in the endcaps.

3.3.2 Track seed selection

Track seeds for electron tracks, which are the starting point for the electron track reconstruction, are built from doublets or triplets of hits in the pixel detector, combined with vertex positions calculated from general charged particle tracks. To select track seeds for electrons two methods are used, called ECAL driven and tracker driven.

For the ECAL driven seeding, one starts from an ECAL SC, with at least 4 GeV of transverse energy and a veto of 0.15 on the ratio of hadronic energy to

SC energy. The hadronic energy is calculated from the HCAL towers in a cone of $\Delta R = 0.15$ around the direction of the electron. Hits in the first pixel layer are searched by back propagating the trajectory from the barycenter of the SC, under both charge assumptions. If a pixel hit is found in a relatively wide window around the prediction from the back propagation, the track is refitted with the position of the hit and a second hit in the next layers is searched for with a narrower window. If the first two hits are matched with the prediction from the SC the seed is selected.

Tracker driven seeds are selected from tracks that were reconstructed with the Kalman filter algorithm. This algorithm is not suited for electrons that emit bremsstrahlung as the curvature of the track changes in that case. All seeds of KF tracks that match a PF cluster in the ECAL and pass a matching criterion of the ratio between PF cluster energy and track momentum $E/p > 0.65$ (0.75), for track momenta $2 < p < 6$ GeV ($p \geq 6$ GeV), are selected.

The seeds obtained with the ECAL driven method are combined with the tracker driven seeds.

3.3.3 Tracking

The tracking for electrons consists of the track building outward from the seed, for which a combinatorial KF method is used, and the track fitting which uses a Gaussian sum filter (GSF) method in a backward fit. For the track building, starting from the seed, the combinatorial track finding algorithm iteratively adds successive layers, using the Bethe-Heitler (BH) model [58] for the modeling of the electron losses. Owing to the possibility of emitted bremsstrahlung, a very loose requirement between the predicted hits and the found hits is applied. Not more than one layer can have no compatible hit found, and in case of multiple hits found up to five candidate trajectories are generated per layer.

The fractional loss of energy of an electron owing to bremsstrahlung when passing through a material is given by the Bethe-Heitler model. Since the distribution of the energy loss after the BH model is non-Gaussian, fitting the track with the KF algorithm that uses Gaussian distributions does not give good results. The GSF algorithm models the BH energy loss distribution as a sum of six Gaussian distributions with different mean, width and amplitude. After passing through a layer, six new trajectory components are generated with the weight according to the weight of the initial trajectory multiplied by the weight of the Gaussian component in the BH energy loss distribution estimation. To limit the maximal number of trajectories followed to 12, the ones with low weight are dropped or merged if they are similar. Finally, the track parameters obtained have their uncertainty distributed according to the

sum of Gaussian distributions from the trajectory components. For the value of the track parameter the mode of the distribution is used.

3.3.4 Track-supercluster matching

In order to build GSF electron candidates, a track has to be associated to a SC. For ECAL driven tracks, the position of the SC is taken as the energy weighted position and the position of the track is the extrapolated position at the SC from the innermost track position. The difference should be smaller than 0.02 in the η direction and 0.15 rad in the ϕ direction. For tracker driven tracks a multivariate technique, using a boosted decision tree (BDT), is used, that combines track observables and SC observables to get a global identification variable. For a successful matching, the track-SC combination should be higher than a threshold of this variable.

3.3.5 Charge and momentum measurement

The charge of the electron candidate is defined by the majority of the charge estimation by three different methods. The first method measures the charge from the curvature of the GSF track. The second estimate comes from the curvature of the KF track associated to the GSF track if they share at least one innermost hit. The third charge estimation comes from the comparison of the ϕ direction of the SC position as measured from the beam spot with the ϕ direction as measured from the first hit of the GSF track. Simulations predict a charge mis-identification rate of 1.2% for electrons with a transverse momentum $p_T \sim 35$ GeV.

The momentum of the electron candidates is measured by combining the momentum as measured by the tracking procedure with measurements from the ECAL. The weighting of the two measurements depends on the track parameters and the SC parameters. For electrons with high energies the precision of the energy measurement from the ECAL outweighs the one from the tracker, and the transverse momentum of the electron candidate is defined by the energy measurement from the ECAL SC (E_{SC}) and the polar angle of the track at the interaction point θ_{track} ,

$$p_T = E_{SC} \sin \theta_{track} \quad (3.6)$$

Since the transverse momentum measurement for high energy electrons is based on the energy measurement from the ECAL, it is in the following called E_T .

3.4 Jet reconstruction

The cross section to produce jets is by far the largest in pp collisions at the LHC: jets represent background for many analysis, but are also used to perform analysis. A jet is reconstructed using the “anti-kt” clustering algorithm [59] with a cone size parameter of $R = 0.5$, or in some cases $R = 0.7$, in the $y - \phi$ space, where the rapidity of a jet is defined by its energy and momentum as

$$y = \frac{1}{2} \ln\left(\frac{E + p_z}{E - p_z}\right) \quad (3.7)$$

Three different types of jets are reconstructed, which depend on the way information from the sub-detectors is combined [60].

- Calorimeter jets use information from the calorimeter towers in the HCAL and the corresponding ECAL crystals.
- Jet-plus-track (JPT) jets use the information from the tracker in addition to the calorimeter jets, to add tracks that are bent out of the cone defined by the calorimeter jets. The calorimeter jets parameters are corrected by taking into account these additional tracks.
- Particle flow jets are generated by the clustering of PF candidate particles and taking the vectorial sum of their four momenta.

The energy of the jet measured with the jet algorithm has to be corrected for pileup and other contributions to match the true energy of the jet. An uncertainty smaller than 3% has been found on the jet energy scale for jets with $|\eta| < 3$ and $p_T > 50$ GeV. The jet energy resolution (JER) is obtained by studying the energy resolution of jet energy scale corrected jets in data and simulation, using dijet and γ +jet events. The resolution is found to be about 10% for central PF jets with $|\eta| < 0.5$ and $p_T > 100$ GeV. Jets that originate from b-quarks are identified with several different techniques, referred to as b-tagging. b-tag methods make use e.g. of the small distance that a B meson, produced by the hadronisation of a b-quark, travels before it decays, which leads to a secondary vertex from which tracks originate.

Chapter 4

High-Energy muon reconstruction and Algorithm improvements

The importance of the goodness of high- p_T (> 200 GeV) muon reconstruction is a key item for the search for high-mass resonances decaying into muons. One of the goals of this thesis was the improvement of the reconstruction of “TeV-muon”, as described in this Chapter.

In Section 4.1 the problems related to the high-energy muon reconstruction are described and a detailed description of the “TeV-muon” refits (“TeV-refits”) and the “Cocktail” algorithm, tools specifically designed for handling the reconstruction of high-energy muons, is presented. A new improved version of the “Cocktail” algorithm, optimized in preparation for 13 TeV collisions, is described in Section 4.1.3. The impact of the detector alignment on the muon reconstruction is reported in Section 4.1.4. Section 4.2 is dedicated to the performance of new “Cocktail” algorithm.

4.1 High- p_T muon reconstruction

Momentum measurement precision in a muon spectrometer is limited by several factors. These can be divided into two categories. The first one corresponds to stochastic physics processes related to muon energy loss in material. The second category includes detector-related effects: measurement precision, magnetic field map uncertainty and detector alignment precision (described in Section 4.1.4).

There are four main processes describing muon energy loss in material:

- ionization, including production of delta rays (knock-on electrons with energies from ~ 1 eV to ~ 100 GeV);

- direct electron-positron pair production;
- bremsstrahlung;
- inelastic interaction with nuclei.

The main sources of physical uncertainty for muons with energies in the TeV range are electromagnetic showers and large energy losses, produced by radiative processes.

As discussed in Section 3.1.2, at sufficiently high energies, radiative processes become more important than ionization for all charged particles [5]. For muons, in particular, in materials such as iron, this critical energy $E_{c\mu}$, defined as the energy at which radiative and ionization losses are equal, occurs at ≈ 300 GeV. Radiative processes are characterized by hard spectra and large energy fluctuations. As a consequence, at these energies the treatment of the energy loss as a uniform and continuous process is, for many purposes, inadequate.

It is convenient to write the average rate of muon energy loss as

$$-dE/dx = a(E) + b(E)E, \quad (4.1)$$

where $a(E)$ is the ionization energy loss given by the Bethe-Bloch equation (Equation (3.3)), and $b(E)$ is the sum of e^+e^- pair production, bremsstrahlung, and photo-nuclear contributions. To the approximation that these slowly-varying functions are constant, the mean range x_0 of a muon with initial energy E_0 is given by

$$x_0 \approx (1/b) \ln(1 + E_0/E_{c\mu}), \quad (4.2)$$

where $E_{c\mu} = a/b$. Figure 4.1 shows contributions to $b(E)$ for iron. Since $a(E) \approx 0.002 \text{ GeVg}^{-1}\text{cm}^2$, $b(E)E$ dominates the energy loss above several hundred GeV, where $b(E)$ is nearly constant. The rates of energy loss for muons in hydrogen, uranium, and iron are shown in Figure 4.2.

The radiative cross sections are expressed as functions of the fractional energy loss ν . The bremsstrahlung cross section goes roughly as $1/\nu$ over most of the range, while for the pair production case the distribution goes as ν^{-3} to ν^{-2} . Large losses are therefore more probable in bremsstrahlung, and in fact energy losses due to pair production may very nearly be treated as continuous.

The probabilities for emitting electrons of different energies by muons propagating through iron, is shown in Figures 4.3. As can be seen from the plot, the cross-sections for electron production rise with muon momentum, especially the cross section for pair production. For a muon with 1 TeV energy, this process dominates for highly energetic (above 1 GeV) electrons. Electrons above 1 GeV are the source of electromagnetic showers that contaminate muon detectors. A thousand TeV muons traversing 1 meter of iron will produce an average of

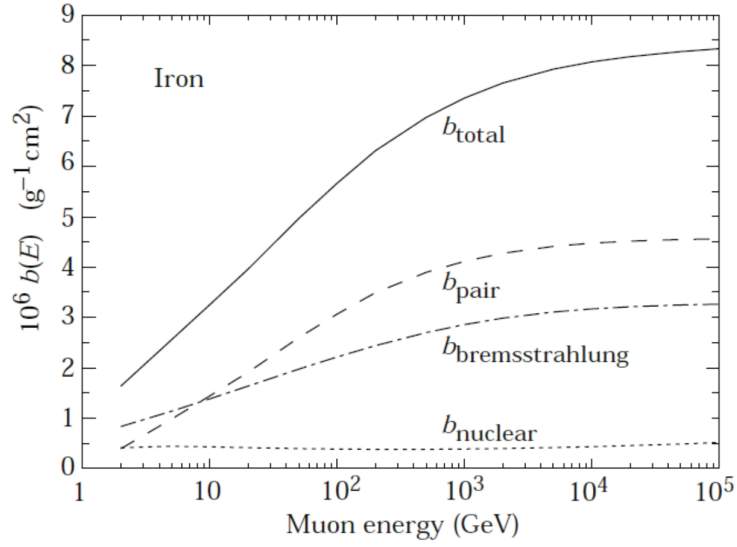


Figure 4.1: Relative contribution of the different radiative processes to the muon energy loss in iron, as a function of the muon energy.

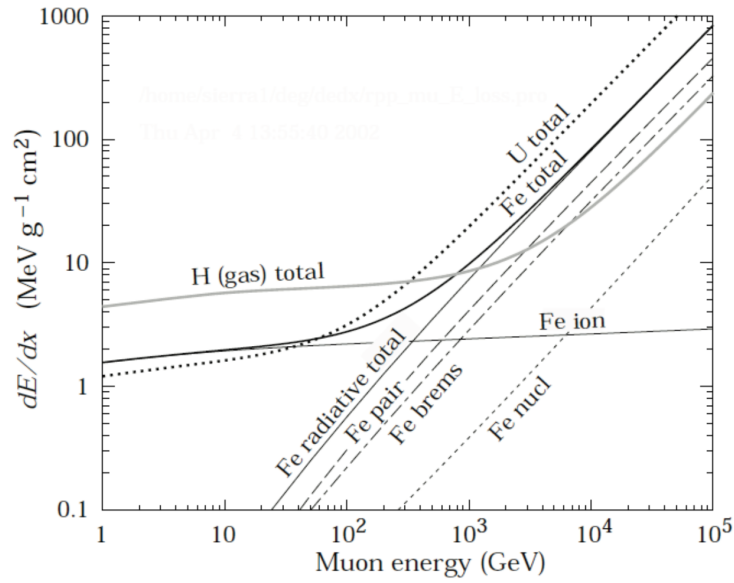


Figure 4.2: Rates of energy loss for muons in different materials.

sixty 1 GeV electrons through ionization, two through bremsstrahlung and 500 through pair production.

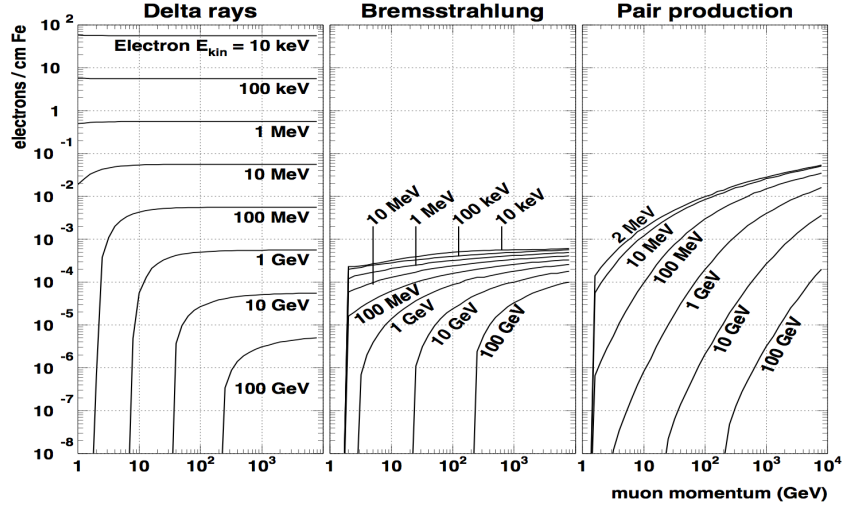


Figure 4.3: Cross sections for electron production by muons traversing matter, shown as number of electrons produced per 1 cm of iron, as a function of muon transverse momentum.

4.1.1 Muon shower

In the CMS outer muon system the possibility of showering is taken into account by placing the four muon stations between layers of iron from the CMS solenoid return yoke. The thickness of the iron (30 cm to 90 cm) is sufficient to contain most of the electromagnetic showers caused by muons [61]. This way, even if a shower in one muon station corrupts the position measurement in that station, it should not affect the next stations (except for cases where the muon lost a significant fraction of its energy and its direction change). So in principle, the station where the shower occurred should be simply removed from the track fit.

“Picky” muon reconstruction

A procedure has been set up to identify the stations containing showers and removing them from the fit, when necessary. The algorithm, called the “Picky” muon reconstructor (PMR), works as follows: first, the default global reconstruction is performed and the global track is provided. For every hit of the global track in the muon system, the multiplicity of hits in the chamber that produced it is checked. This is done considering a cone with predefined radius around the hit being used in trajectory building, to ignore random hits e.g. from neutron background. If the number of hits in the chamber is higher than

one, the chamber is flagged as contaminated. The compatibility of the hits in contaminated chambers with the trajectory is checked by performing a χ^2 cut. An additional loose χ^2 cut is applied to all hits in the tracker and the muon system. Finally, considering the set of hits that passed the compatibility cuts, the fitting procedure is repeated.

4.1.2 Large energy loss

As already seen, radiative processes do not allow a treatment of energy loss as a uniform and continuous process. For this reason the Kalman filter cannot correctly handle muons undergoing one of this kind of processes. Figure 4.4 shows an example of change in bending in the transverse plane caused by a radiative process. This causes a mismatch between the predicted state and the real measurement, worsening the reconstruction.

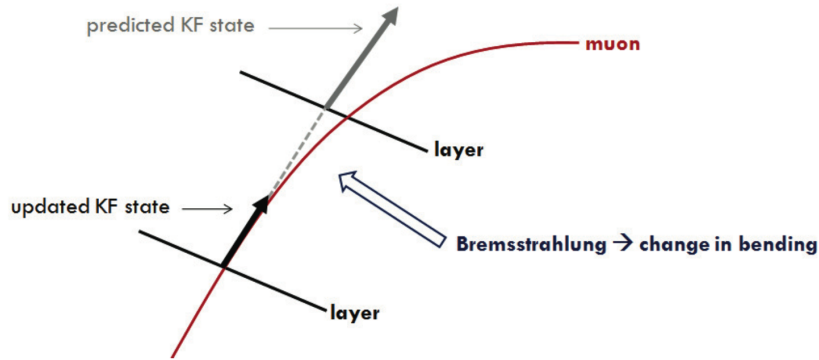


Figure 4.4: Example of muon undergoing bremsstrahlung.

Since, after a large energy loss, the remaining hits will only bias the track fit, the Kalman filter should be stopped once a large energy loss is identified. The possible strategies to recognize a large radiative energy loss are substantially two:

- to look for a high occupancy in the muon chambers or calorimeters;
- to look for a large incompatibility between the extrapolated track states and reconstructed segments in the muon chambers.

However a shower coming from a radiative process can be fully contained in passive volumes (in the iron for example), not necessarily producing high occupancy in the muon chambers. The second option is taken into account to define the following muon reconstruction algorithm.

Dynamic truncation (DYT) algorithm

The DYT algorithm, for every global muon trajectory, starts from the corresponding tracker track and propagates it out to the first muon system layer (for instance, for the barrel region, the first layer of the first super-layer of the first DT chamber). Compatible segments (or hits) in the muon chambers are found by using an estimator which takes into account the propagation of the tracker covariance matrix through the material and the magnetic field, and the covariance matrices of the candidate muon segments (or hits). The estimator performs similarly to a χ^2 between the track propagation and the segment in the muon station. If a large energy loss between the last tracker layer and the first muon system layer occurred, a large incompatibility (large estimator values) between the propagated state and the reconstructed segment is expected. If such a large incompatibility is found, the KF is stopped at previous layer (and the remaining hits are not used), otherwise the algorithm proceeds to the next station and the mechanism is repeated.

4.1.3 “Cocktail” algorithm: old and new versions

As discussed in Section 3.2.6, at high momentum, the muon momentum resolution improves when combining the inner tracker and muon detector measurements (Figure 3.4). Most of the gain comes from the first hit used in the muon system and great care is needed using more than the first good muon hit because of radiative processes.

In CMS there are specialized algorithms developed for high- p_T muon reconstruction, as already mentioned, and tuning them requires great care. Some of these algorithms, like “Picky”, are known as “TeV-muon” refits. Depending on the selection applied to the initial hits, the “TeV-refit” can work with three different options:

- default option: it just refits without any selection of the hits.
- Tracker Plus First Muon Station (TPFMS) option: it performs a refit using the tracker hits plus the hits coming from the innermost muon station.
- “Picky” option: it selects the muon hits according to the χ^2 in the chambers where a shower is supposed to be present. Afterwards it performs the refit using the tracker hits plus the selected muon hits.

Momentum assignment is then performed by the “Cocktail” algorithm which chooses the best muon reconstruction. The selection of the best available track

is made on a track-by-track basis, using the tail probability of the track fit χ^2/ndf .

For the Run-1 muon reconstruction, the “Cocktail” algorithm decision was taken between the global, tracker-only, TPFMS, and “Picky” tracks. This version of the algorithm, also known as the “Tune-P” algorithm, was the standard best muon reconstruction during Run-1.

The new “Cocktail” algorithm

The DYT algorithm provides an additional TeV muon track candidate. In preparation for Run-2, new developments and studies took place in the muon reconstruction, involving in particular the DYT fit. As a consequence the “Tune-P” algorithm and the PF algorithm were extended to include also the DYT muon candidate.

In the context of this analysis, the new version of the “Cocktail” algorithm, which includes the DYT fit, is called “Tune-P” (or “Tune-P + DYT” in some plots), while the previous version, without DYT, is labeled as “Tune-P old”.

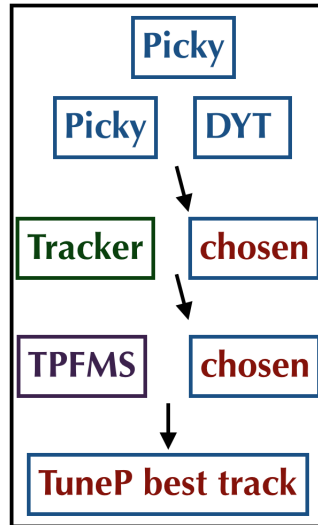


Figure 4.5: The basic logic of the new “Cocktail” algorithm.

The selection of the best available track, for the new “Cocktail” algorithm, is still made on a track-by-track basis, using both the tail probability of the track fit χ^2/ndf and the relative p_T measurement error $\delta p_T/p_T$. The basic logic is shown in Figure 4.5. The algorithm starts with the “Picky” fit, then, if the DYT track has a lower relative p_T error, it switches to DYT. It then compares the tail probability of the chosen track with that of the tracker-only fit and

picks tracker-only if its probability is significantly better (specific thresholds have been tuned for each step). Then the tail probabilities of the chosen track and TPFMS are compared and the one giving the best result is kept. At the end, if the final candidate track or the tracker-only track have p_T lower than 200 GeV, the tracker-only track is selected.

The version of the “Cocktail” algorithm described so far, which I have implemented and optimized, is currently (since May 2015) included in the official CMS standard muon reconstruction and is used in all the analyses involving high-energy muons in the final state.

4.1.4 Detector Alignment

Precise measurement of muons up to the TeV-momentum range requires the muon chambers to be aligned with respect to each other, and to the central tracking system, with an accuracy of a few hundred μm in position and about 40 μrad in orientation [62].

Considering the CMS geometry described in Section 2.2 and shown in Figure 2.8, with the exception of the CMS central wheel, which is fixed, the other wheels and disks are movable along the beam direction to allow opening the yoke for the installation and maintenance of the detectors.

Gravitational distortions lead to static deformations of the yoke elements that generate displacements of the muon chambers with respect to their design position of up to several mm. These displacements can be measured within a few hundred microns by photogrammetry when the detector is open, both in the barrel and in the endcaps. However, the repositioning of the large elements of the yoke after opening and closing of the CMS detector, though rather precise, cannot be better than a few mm given their size and weight. In addition, the magnetic flux induces huge forces that cause deformations and movements that may be as large as several mm, and must be carefully tracked by the alignment system.

In order to determine the positions and orientations of the muon chambers, the CMS alignment strategy combines precise survey and photogrammetry information, measurements from an optical-based muon alignment system, and the results of alignment procedures based on muon tracks. The muon alignment system is fast, independent of beam conditions, and can provide online monitoring of relative movements precisely. Track-based alignment needs to accumulate a large amount of data and is, therefore, intrinsically slower, but it provides very accurate alignment of the muon chambers with respect to the inner tracker, which is crucial for optimal muon momentum measurement.

The aim of the muon alignment system is to provide position information

of the detector elements with a precision comparable to the intrinsic chamber resolution. This information is used online for triggering purposes, and offline as a correction for track reconstruction. More details about the CMS alignment can be found in [62] and [63].

Since the measurement of the muon transverse momentum is sensitive to the alignment of the tracker and of the muon chambers, the tuning of the muon reconstruction algorithms, the optimization studies for the “Cocktail” algorithm together with muon reconstruction performance have been obtained using Monte Carlo (MC) simulations reconstructed with different residual misalignment scenarios (called misalignment scenarios in the following), aiming to describe the alignment of the real detector, evolving during 2015:

- the **startup** or **hardware-based** scenario (**ST** or **HW**), which describe the status at Day-1 of the 50 ns run, i.e. it should represent the conditions for the first period of 2015 data tacking (Run2015B). The inner tracker has been aligned analyzing tracks from 2015 cosmic data (Cosmic Run At Four Tesla (CRAFT15)) and collisions recorded with magnetic field off (0 T data). The misalignment scenario for the muon system has been built from the uncertainties of the hardware alignment.
- The first **realistic** or **track-based** scenario (**TB** or **TB-Sep2015**), which should represent the alignment of muon detectors during the 25 ns data tacking period (Run2015C/D). The muon system track-based alignment has been carried out using Run2015B data, starting from an alignment of the inner tracker obtained using the same dataset (in addition to CRAFT15 and 0 T data).
- The **asymptotic** or long term scenario, which should represent the status after the final track-based alignment. This best alignment is carried out with $\sim 1 \text{ fb}^{-1}$ of collision data. This is the scenario generally used for all the Run-2 MC productions.

The simulation samples used in this analysis, described in Section 5.1.1 and listed in Table 5.3, have been produced with the asymptotic misalignment scenario (tag: **Asympt25ns**), and then re-reconstructed with the realistic misalignment scenario (tag: **Startup25ns**).

In addition to CMS central MC productions, private MC samples have been processed with such misalignment scenarios, with the propose of testing the muon reconstruction performance in different conditions. In particular: 100K muon gun events, with muon η distributed flat in $[-2.5, 2.5]$ and p_T from 5 GeV to 2.5 TeV; 100K Z' events generated with PYTHIA 8 [67, 68] with $m_{Z'} = 5 \text{ TeV}$, which actually have a continuous mass spectrum extending

down to low mass values due to PDFs effects. These Z' events have been reconstructed without pileup, as this not contribute to the muon performance studies.

4.2 Performance of the new “Cocktail” algorithm

All the specific high-momentum muon reconstruction algorithms presented in Section 4.1 have similar efficiencies and differ mostly in the p_T assignment. In order to evaluate the different reconstruction algorithms performance, the reconstructed muon p_T (p_T^{rec}) has been compared with the true value at generator level (p_T^{gen}), and the impact on dimuon invariant mass has been monitored. In the contest of this analysis, the variables of interest for studying the reconstruction algorithm performance are the RMS and gaussian core width (resolution) of the relative single-muon inverse- p_T or dimuon invariant mass residual distributions $(1/p_T^{rec} - 1/p_T^{gen})/1/p_T^{gen}$ or $(M_{reco} - M_{gen})/M_{gen}$.

Example of relative mass residual distributions are plotted in Figures 4.6 and 4.7 for simulated Z' mass generated between 2.5 TeV and 3.5 TeV, and reconstructed considering tracker-only, TPFMS, “Picky”, and DYT muon candidates. The corresponding distributions for the old and new “Tune-P” algorithms are shown in Figure 4.8. The reconstruction performances are shown for the asymptotic (left column) and the TB misalignment scenario (right column). As expected, performances obtained with the TB misalignment scenario are worse, compared with the asymptotic misalignment scenario, for all the reconstructors which include muon system informations (the misalignment scenarios considered do not include changes in the tracker alignment, no differences are visible among left and right plots in Figure 4.6 (top)). The impact of the muon system in the high-mass dimuon reconstruction can be noticed looking at the worst performance (bigger RMS and Gaussian core) obtained considering tracker-only tracks in Figure 4.6. “Picky” and DYT reconstructed dimuons, as reported in Figure 4.7 (left), shown similar performances, although the improvements of including DYT inside the “Cocktail” algorithm is visible in Figure 4.8.

Figure 4.9 shows the peak width and the RMS of the relative $1/p_T$ residual distribution, as a function of muon p_T , for different reconstructors, separately for the barrel ($|\eta| < 0.9$) and the endcap regions ($1.2 < |\eta| < 2.4$). The peak width is obtained from a Gaussian fit of the core of the distribution. The RMS is sensitive to the non-Gaussian tails and is determined from a broad range. The new “Tune-P” (including DYT, purple lines) shows visible improved performance with respect to the old “Tune-P” (black lines) especially considering the realistic misalignment scenario: reduced tails and Gaussian

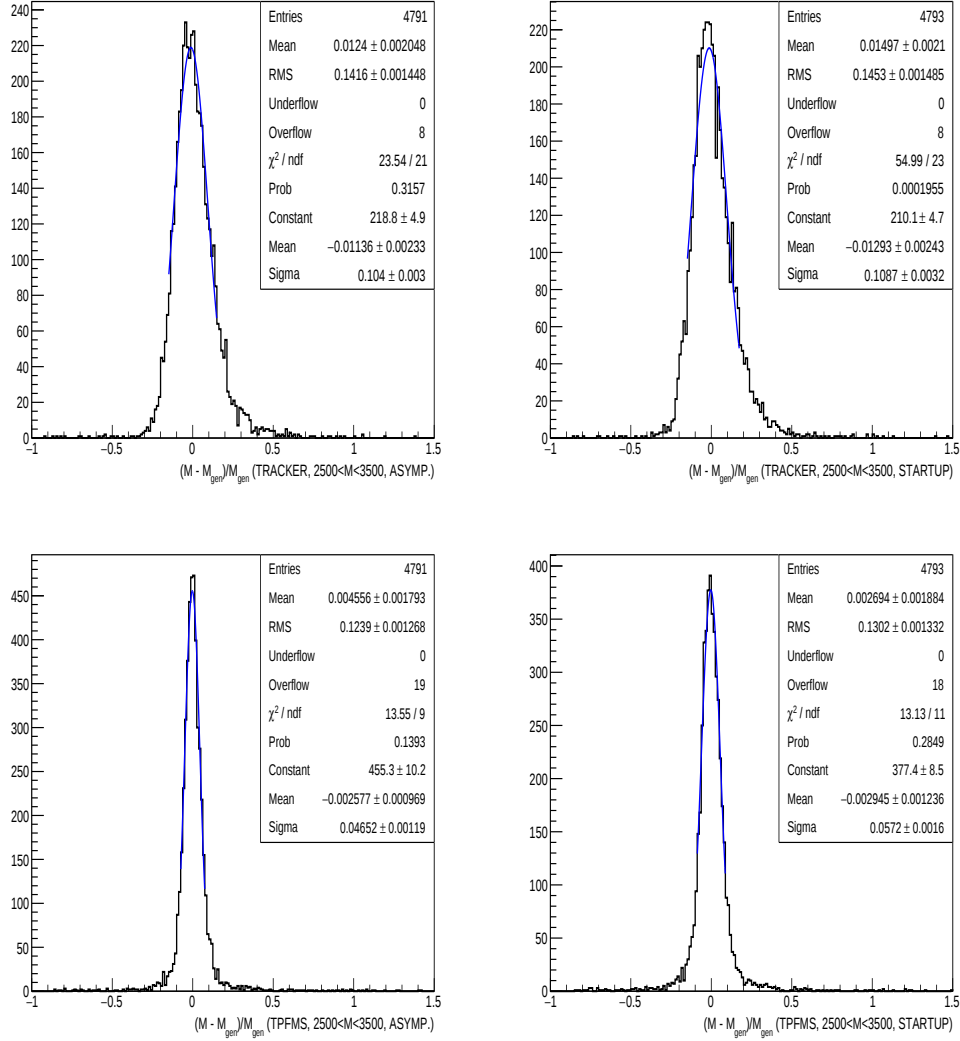


Figure 4.6: Example distributions from MC simulation showing the mass relative residuals for dimuons generated with $2.5 < M_{\mu\mu} < 3.5$ TeV. The top row refers to tracker-only muons, the bottom row refers to TPFMS. The left column shows the asymptotic misalignment scenario, the right column the track-based misalignment scenario. Gaussian fit of the peaks (to evaluate resolutions) are superimposed.

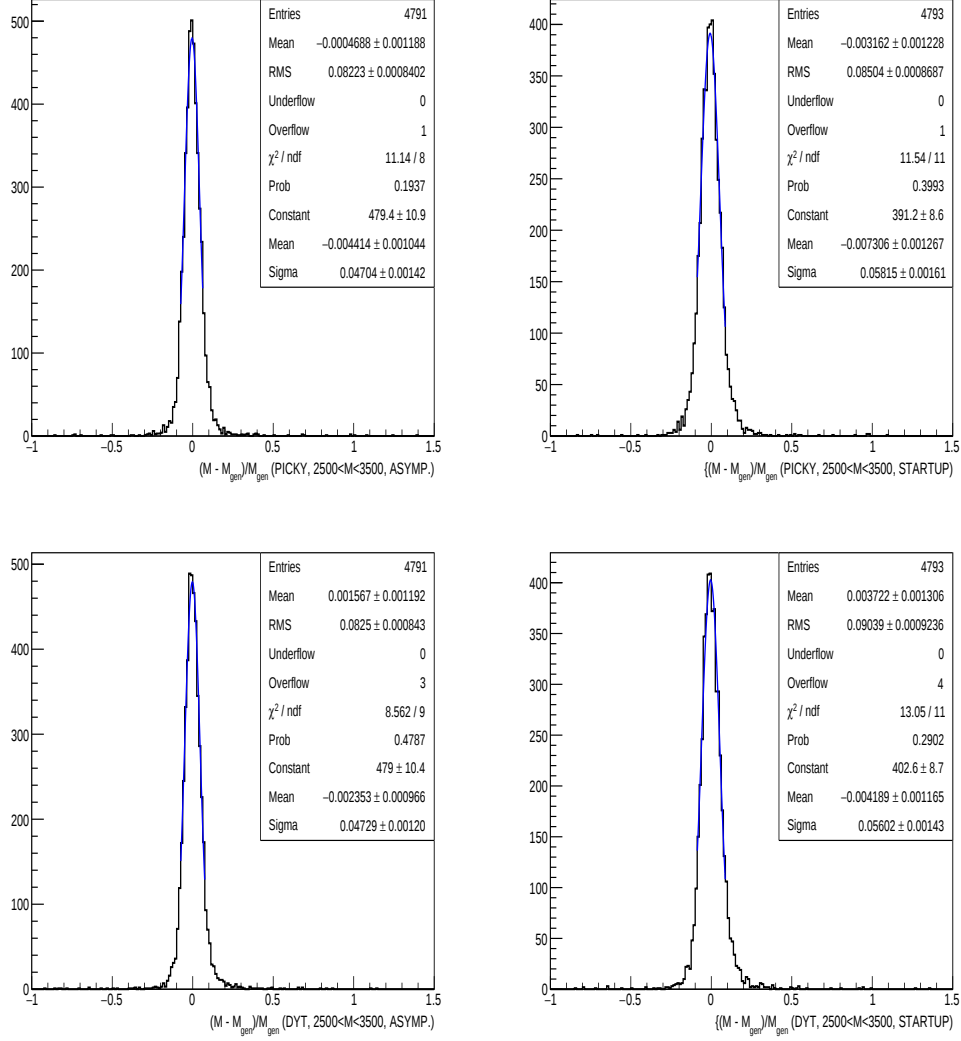


Figure 4.7: Example distributions from MC simulation showing the mass relative residuals for dimuons generated with $2.5 < M_{\mu\mu} < 3.5$ TeV. The top row refers to "Picky" muons, the bottom row refers to DYT. The left column shows the asymptotic misalignment scenario, the right column the track-based misalignment scenario. Gaussian fit of the peaks (to evaluate resolutions) are superimposed.

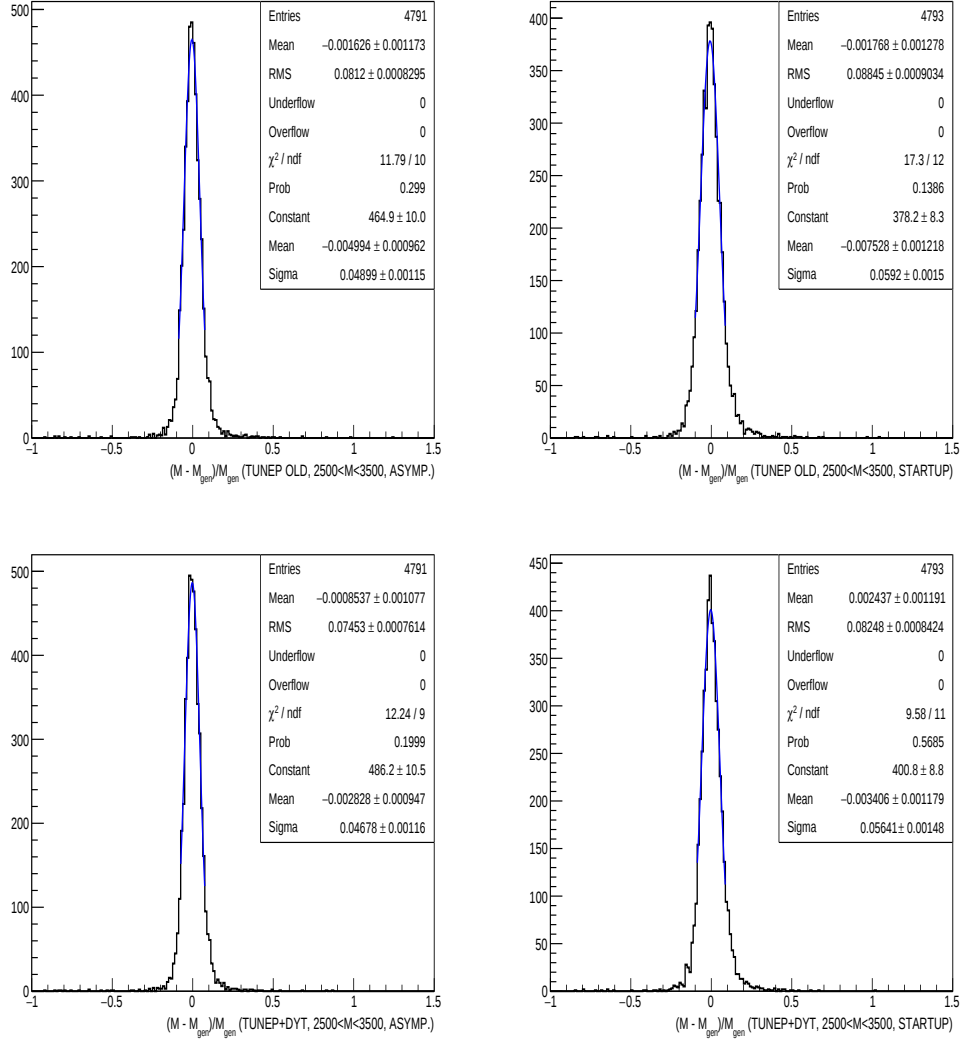


Figure 4.8: Example distributions from MC simulation showing the mass relative residuals for dimuons generated with $2.5 < M_{\mu\mu} < 3.5$ TeV. The top row refers to the old “Tune-P”, the bottom row to the new “Tune-P”. The left column shows the asymptotic misalignment scenario, the right column the track-based misalignment scenario. Gaussian fit of the peaks (to evaluate resolutions) are superimposed.

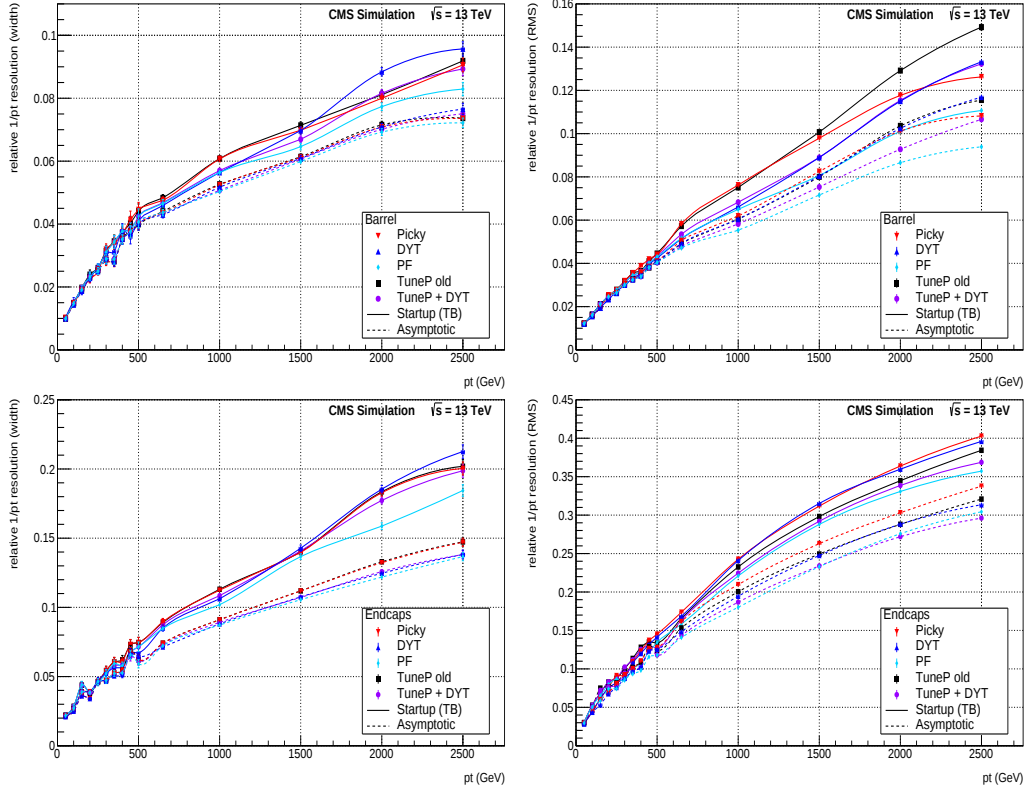


Figure 4.9: Core width (left column) and RMS (right column) of the relative $1/p_T$ residual distribution, as a function of p_T from MC simulation. The top row shows the performance in the barrel region ($\eta < 0.9$), the bottom row the endcap region ($1.2 < |\eta| < 2.4$). The results include “Picky”, DYT, Particle-Flow, old “Tune-P” and new “Tune-P”, for both the track-based scenario (solid lines) and the asymptotic scenario (dashed lines).

width. A sizable difference is observed between the TB misalignment scenario and the asymptotic misalignment scenario.

The PF p_T assignment (light blue lines) has also been tested. The new “Tune-P” version and, in general, the inclusion of the DYT reduce the tails of the momentum residual at high- p_T , which affect also the observed missing transverse energy of the event (E_T^{miss}). Therefore, the global event description, as obtained by the Particle-Flow algorithm, is improved as well.

Figure 4.10 shows the peak width and the RMS of the relative dimuon invariant mass residual distribution, as a function of the mass, for different reconstructors, from simulation of Z' events. The performance of the new “Tune-P” (purple lines) shows visible improvements with respect to the old

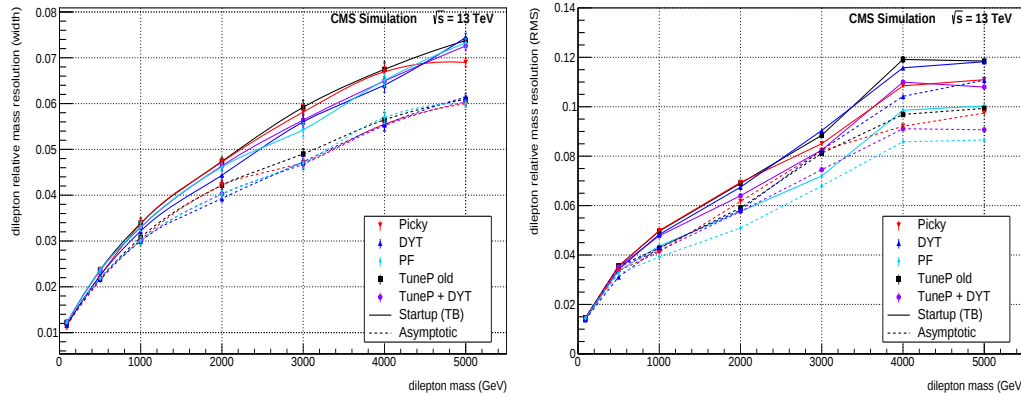


Figure 4.10: Core width (left) and RMS (right) of the relative mass residual distribution for simulated Z' events as a function of the dilepton mass. The results include “Picky”, DYT, Particle-Flow, old “Tune-P” and new “Tune-P”, for both the track-based scenario (solid lines) and the asymptotic scenario (dashed lines).

“Tune-P” (black lines).

4.2.1 Momentum resolution using cosmic muons

Important tests of the momentum reconstruction at high- p_T and related quantity such as the resolution, charge misidentification probability, uncertainty in the absolute momentum scale, can be carried out using cosmic muons.

Super-Pointing cosmic muons are defined as those tracks passing close to the nominal interaction point, such that they can be used to study the performance that would be achieved on collision tracks. The Super-Pointing cosmic muons are obtained by skimming the full cosmic muons dataset with standard cuts: tracks have to pass within 10 cm of the beam axis and 50 cm longitudinal distance from the origin of the CMS reference frame. These cuts are chosen to have tracks crossing the whole volume of the pixel tracker intersecting the beam pipe. Quality cuts are also applied on the number of tracker hits: each leg must have at least 1 pixel hit and strips fired in at least 5 different layers. To compare the various reconstructors on the very same sample of tracks the request is made to have all the TeV refits successful. Moreover the event has to contain exactly 2 tracker-only tracks and 2 global-muon tracks.

Super-Pointing cosmic muons can be reconstructed as two separate tracks in the upper and lower halves of CMS (“2-leg reconstruction”). For such a pair of tracks from the same muon, the difference in the reconstructed quantities is related to the resolution of the measurement of each leg, assuming the same performance. While the bottom part of a cosmic track can mimic a collision

track very well, the top part implies a time-reversal, hence some caveats have to be considered.

The reconstruction of the muon curvature q/p_T is tested by the relative residual distribution:

$$R(q/p_T) = \frac{(q/p_T)^{upper} - (q/p_T)^{lower}}{\sqrt{2}(q/p_T)^{lower}} \quad (4.3)$$

where the $\sqrt{2}$ accounts for the fact that the two fits are independent.

The used cosmic muons dataset for these studies is CRAFT15. Unfortunately the accumulated statistics are not satisfactory to study the high- p_T region (there are few hundred muons with $p_T > 500$ GeV collected during the 2015 data taking, more cosmic muons will be collected during 2016), nevertheless analysis of these data is a useful data-driven test.

Starting from the Super-Pointing skim the data have been re-reconstructed privately with several different misalignment conditions. The reconstruction performances (q/p_T residual and pull, quality of the track variables) using various tested conditions are compared for the “Tune-P” tracks and the scenario with muon hardware-based alignment (tag: 74X_CRAFTR_V1) is found to perform better even though the muon system hardware-based alignment is expected to give a worse performance with respect to the first track-based alignment.

This hints to some incompatibility of the CRAFT15 misaligned geometry with the track-based alignment scenario obtained from collision data, which prevents a tight comparison of the performance obtained from the CRAFT15 runs and the 2015 collision periods. In between the two eras there have been several magnetic cycles with identified movements of parts of the pixel detector, although no significant effects have been reported by the muon hardware measurements. Therefore the performance obtained from CRAFT15 data represent only a conservative (pessimistic) limit to the real performance in the barrel region for collisions in Run2015C/D.

Figure 4.11 shows the Gaussian width and the RMS of the q/p_T relative residual distribution as a function of p_T for all the reconstructors. “Picky”, DYT and the “Tune-P” seem to perform best, but the statistics are quite limited.

Resolution shown in Figure 4.9 using simulations and Figure 4.11 using cosmic muons can be compared to validate results from simulations. Figure 4.12 shown a direct comparison between resolutions obtained using cosmic muons and Drell-Yan simulations considering the same p_T binning, eta region ($|\eta| < 0.9$) and fitting range.

In the last bin the mean p_T is ~ 700 -800 GeV for cosmic muons which have a harder p_T spectrum than simulated muons from collisions. The inverse p_T

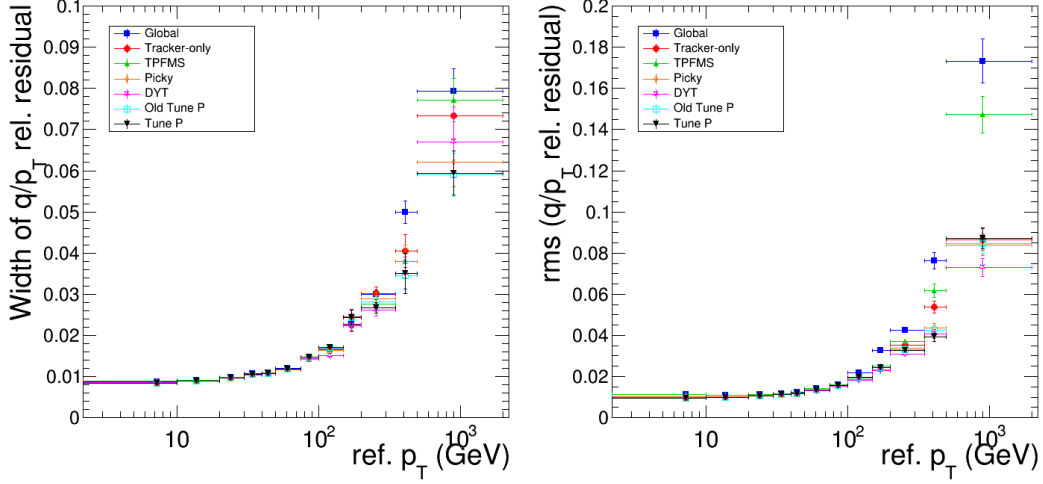


Figure 4.11: Gaussian width (left) and RMS (right) of the q/p_T relative residual distribution as a function of the reference p_T for all the reconstructors, obtained on CRAFT15 cosmic data with the HB misalignment scenario conditions.

resolution increases with muon p_T reaching a maximum of $5.9 \pm 0.5\%$ in the last bin for cosmic muons and $4.8 \pm 0.2\%$ for simulation. The difference in quadrature between σ_{data} and σ_{MC} is $\sim 4\%$ and represents the $1/p_T$ resolution uncertainty interpreted as an extra smearing effect σ_{extra} to be applied to MC, such that $\sigma_{data}^2 = \sigma_{MC}^2 + \sigma_{extra}^2$.

To account for the tendency of increasing discrepancy between data and MC with p_T , the extra smearing is assigned as a safe 80% ($\sim \sigma_{extra}/\sigma_{MC}$) of the $1/p_T$ resolution obtained from simulations. Different parametrization of $1/p_T$ resolution in the barrel and endcaps are considered separately from Figure 4.9. This result has been confirmed, for low p_T values, in the barrel and the endcaps, looking at the comparison of the Z boson width as a function of the muon p_T , for 2015 data and simulation.

4.2.2 Further optimization studies

The p_T assignment used in this analysis has been shown in Section 4.1.3, although I have further optimized the “Cocktail” algorithm as will be described in the following.

Another big effort to the high- p_T muon reconstruction comes from the inclusion of the muon chamber Alignment Position Errors (APEs) in the local muon reconstruction. These additional studies, reported in this section, are planned to be implemented in the official software of CMS for the next data-

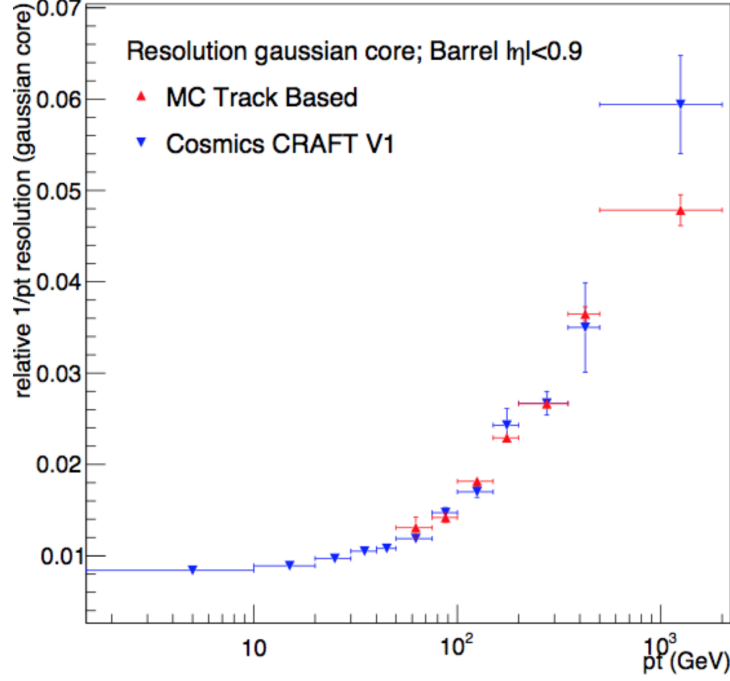


Figure 4.12: Gaussian width of the q/p_T relative residual distribution from CRAFT15 cosmic muons with the HB misalignment scenario conditions (blue dots) and $1/p_T$ relative residual distribution from Drell-Yan MC samples (red dots), as a function of the reference p_T . The same p_T binning, eta region and fitting range is considered.

tacking.

TuneR

Inside the new “Cocktail” algorithm described in Section 4.1.3 only the first step, selecting between “Picky” and DYT, has been properly tuned, while the other thresholds have been inherited by the previous tuning based on asymptotic misalignment conditions and in use since the Run-1.

I have performed further tuning of the “Cocktail” algorithm with and without the inclusion of DYT based on MC samples with the asymptotic scenario. These new tunings are called “Tune-R”. In addition to the tuned thresholds of all the “Cocktail” algorithm steps, the logic at low p_T has been changed. In the “Tune-R” algorithm the tracker-only track is finally selected only for $p_T < 150$ GeV and in case the tracker-only fit has an higher probability. The effect of the tunings in terms of frequency of selection for the different reconstructors

is reported in Figure 4.13. It is visible a strong reduction of tracks where the tracker-only fit is selected. Moreover the probability to choose “Picky” or DYT at the end of the selection is $> 35\%$ for the new “Tune-P” (including DYT) and $> 45\%$ for the associated tuning “Tune-R” (including DYT).

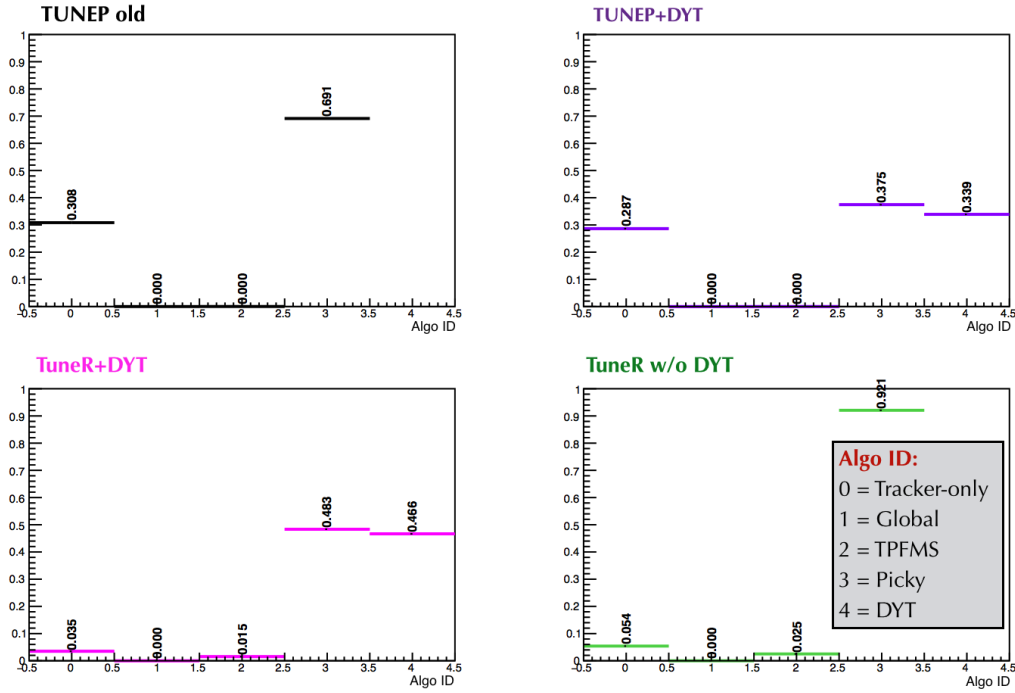


Figure 4.13: Relative frequency for each reconstructor, to be chosen by the “Cocktail” algorithm. Each reconstructor is identified by an integer number (0-4). Various “Cocktail” algorithm versions are considered: old “Tune-P”, new “Tune-P”, “Tune-R” with and without DYT, from MC simulation.

Figure 4.14 shows the peak width and the RMS of the relative dimuon invariant mass residual distribution, comparing “Tune-P” and “Tune-R” versions of the “Cocktail” algorithm. A reduction of the tails together with a reduction of the gaussian cores are visible for the “Tune-R+DYT” (magenta lines) at high masses, confirming the impact of the DYT candidate in the improvement of the “Cocktail” algorithm. The effect of the further tunings is mainly visible considering the TB misalignment scenario.

Muon Alignment Position Errors

The performance of muon momentum reconstruction at high- p_T , as said in Section 4.1.4, is crucially dependent on the detector alignment, and in particular

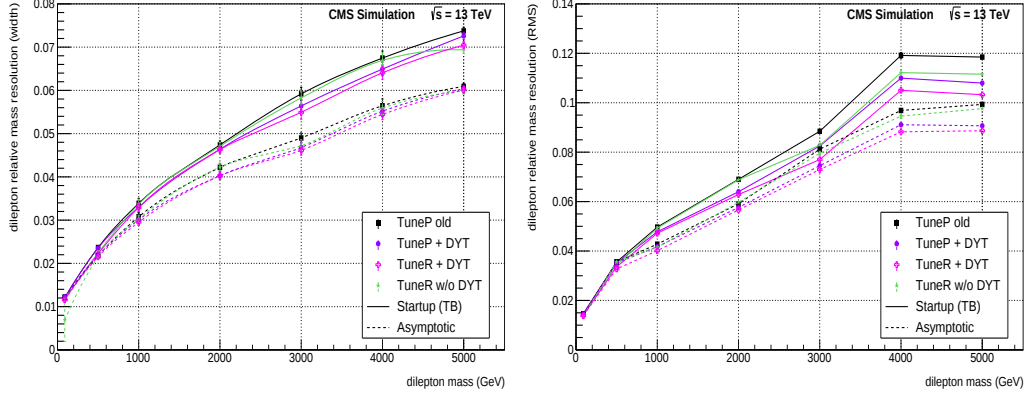


Figure 4.14: Core width (left) and RMS (right) of the relative mass residual distribution for simulated Z' events as a function of the dilepton mass for the various “Cocktail” versions: the old and new “Tune-P” and the “Tune-R” with or without DYT. Both the TB scenario (solid lines) and the asymptotic scenario (dashed lines) are shown.

on the alignment of the muon chambers relative to each other and of the muon system with respect to the inner tracking detector. Momentum reconstruction at intermediate p_T values is instead affected only by the alignment of the inner tracker.

For any given alignment scenario the best performance at high- p_T is obtained by the correct relative weighting of the tracker and muon hits. Ideally this would be achieved by having the Alignment Position Errors (APEs) added in quadrature to the uncertainties of both the tracker and the muon hits used in the global trajectory fit. Currently only the Tracker APEs are used, the muon APEs are set to zero in the standard configuration.

Including the muon APEs in the global reconstruction, improvements are expected on the efficiency to reconstruct hits coming from a muon trajectory, on the track quality variables (like the normalized χ^2) and on the resolution and pull of track coordinates.

The relative p_T resolution as a function of muon p_T is shown in Figure 4.15 separately for the barrel and endcap regions. Here the “Picky”-muon performance is shown in different startup scenarios, including both the first muon scenario (representing the HB alignment, labeled as **startup** in the figure) and the TB misalignment scenario (labeled as **TB-Sep2015**), in comparison with the default asymptotic scenario. The performance of the tracker-only fit is also shown as a reference. There is an evident improvement of the TB misalignment scenario with respect to the previous HB misalignment scenario, particularly in the endcaps: here the first HB misalignment scenario resulted in “Picky”-

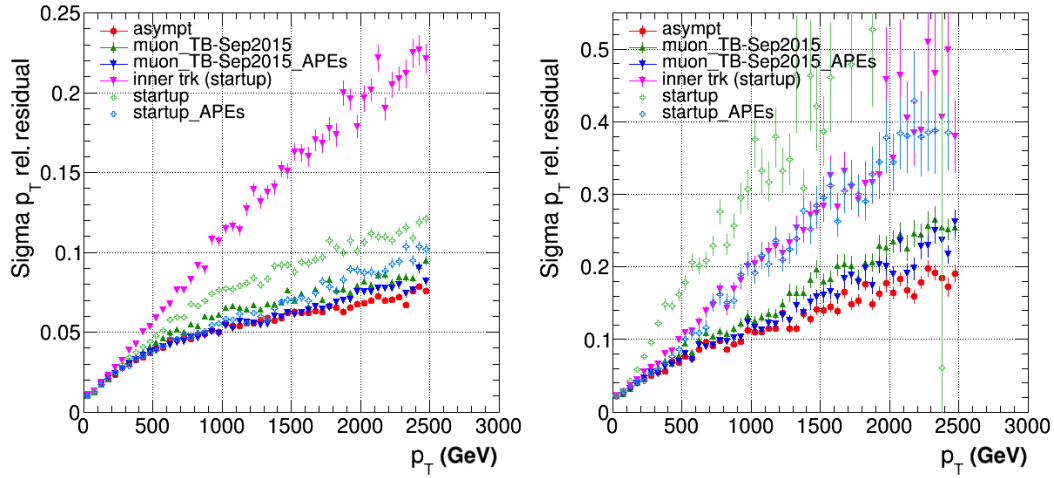


Figure 4.15: Relative p_T resolution as a function of muon p_T shown separately for the barrel (left) and endcap (right) regions, from MC simulation. The plotted values are obtained with a Gaussian fit to the relative residual distribution. The “Picky” fit performance is shown for various alignment scenarios: the asymptotic scenario (without muon APEs), the HB misalignment scenario (labeled as **startup**) and the TB misalignment scenario (labeled as **TB-Sep2015**) both with and without muon APEs. For comparison the tracker-only performance is also shown.

muon resolution largely worse than that of the tracker-only fit. The new TB misalignment scenario recovers the natural hierarchy, with tracker+muon fit better than the tracker-only. The application of muon APEs provides relevant improvements in both the startup scenarios. With reference to the anomalously bad performance in the endcaps for the first HB misalignment scenario, it is quite impressive to see the impact of muon APEs which are able to bring back the performance to the level of the tracker-only or slightly better than it. In the new TB misalignment scenario the application of muon APEs recovers the performance of the default asymptotic scenario up to ~ 1.7 TeV in the barrel and ~ 1 TeV in the endcaps.

Figure 4.16 shows the relative mass resolution achievable on the reconstruction of a dimuon state from simulated Z' decays in the different misalignment scenarios. The “Picky” muon and the PF performances are shown: they are found quite similar. As observed from the previous results, the new TB misalignment scenario gives a big improvement in comparison to the first HB misalignment scenario. In both scenarios the application of muon APEs brings significant improvements.

However, a significant impact of muon APEs is expected on track-quality

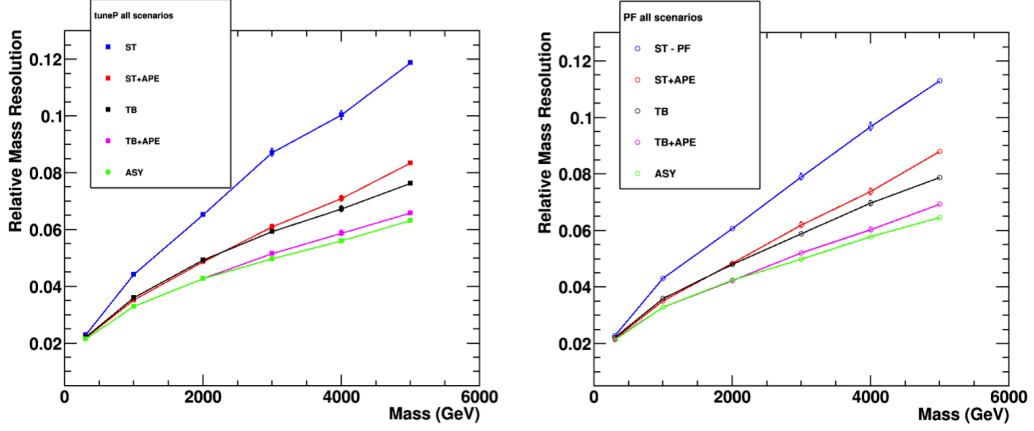


Figure 4.16: Relative mass resolution as a function of dimuon mass for (left) the new “Tune-P” and (right) the Particle-Flow algorithm, from Z' MC simulation. The plotted values are obtained with a Gaussian fit to the core of the resolution and include: the asymptotic scenario (without muon APEs), the HB misalignment scenario (labeled as ST in the plots) and the TB misalignment scenario, both with and without muon APEs.

variables as the normalized χ^2 of the global track or the $\sigma(p_T)/p_T$, even at intermediate p_T values for all the misalignment scenarios. Moreover the muon APEs would reduce the tails of the momentum resolution at high- p_T , which affect also the observed E_T^{miss} . Therefore the global event description, as obtained by the PF algorithm, would be improved as well.

Since the current muon reconstruction still uses APEs equal to zero, the best relative weighting of tracker and muon hits is dealt with by the “Cocktail” algorithms (“Tune-P”, “Tune-R”), described in Section 4.1.3, which in general need tuning specific to any given misalignment scenario.

Chapter 5

Search for new physics in dimuon events

In this Chapter is described the search for new heavy narrow spin-one resonances, using the invariant mass spectrum of selected dimuons from pp collisions at a center-of-mass energy $\sqrt{s} = 13$ TeV with the CMS detector. As already discussed in Chapter 1, there exist many models beyond the SM that predict new heavy resonances at the TeV scale. The analysis presented here is not designed for a specific model, but to be as general as possible, so that the results can be interpreted in the context of many different models that predict spin-one particles. Common models have been chosen to act as benchmark interpretations: the Z'_{SSM} , from the sequential standard model (SSM) with SM-like couplings [11], and the Z'_Ψ from grand unified theories with the E_6 gauge group [12, 13]. In the following the new resonance is denoted by a generic Z' particle.

The signal event topology have a muon and an antimuon in the final state, which lead to a very clean signature in the detector. Furthermore, as there are no neutrinos involved that lead to missing energy, the invariant mass of a muon-antimuon pair would peak at the new resonance mass value, giving a clear signal over the background, smoothly falling in the high-mass region above the Z peak.

The event selection is described in Section 5.1, the measurement of the muon momentum scale factor is explained in Section 5.2 and the high-mass resolution estimation in Section 5.3. The relevant background sources and the methods to estimate them are introduced in Section 5.4. In Section 5.5 the invariant mass spectra are shown, while the statistical interpretation is presented in Section 5.6.

5.1 Event selection

Events with heavy resonances decaying into a muon pair are characterised by a final state with two high-energy muons. Thus, the selection of the muon candidates must be optimised for high energies. Muons from the Z boson decay are also interesting for the normalisation of the background samples at the Z peak. It is also desirable to extend the energy range of the selected muon candidates to low values. Since the expected signal is a narrow peak over a rapidly falling, continuous background, already a few events are enough to discover new physics. Thus, the philosophy of the event selection is to have a very high efficiency of the trigger and the muon candidate selection, in order not to lose events, while keeping a good purity at the same time. As the priority of the selection lies on the efficiency, it is essential that the background processes are well understood.

The candidate muon pairs selection have been inherited from the Run-1 analysis [2], although the tuning of few cuts has been performed.

5.1.1 Data and Monte Carlo samples

Datasets and run selection

The data recorded by CMS are stored in several different datasets. All events that are accepted by a specific set of high level triggers enter one specific dataset, so that the choice of a trigger for the analysis defines which dataset has to be used. During 2015, as mentioned in Section 2.1, there have been four running periods labeled from B to D. The datasets used in this analysis are the `/SingleMuon` primary datasets listed in Table 5.1.

Data set	Run range
<code>/SingleMuon/Run2015B-16Oct2015-v1/AOD</code>	251162–251883
<code>/SingleMuon/Run2015C-PromptReco-v1/AOD</code>	253888–254914
<code>/SingleMuon/Run2015D-PromptReco-v3/AOD</code>	256629–258158
<code>/SingleMuon/Run2015D-PromptReco-v4/AOD</code>	258159–260627

Table 5.1: Data sets used in this analysis.

All Run2015B runs are taken with 50 ns bunch spacing, while for Run2015C and Run2015D all runs are taken with 25 ns bunch spacing, but run 254833 which was at 50 ns.

Only runs that satisfy the data quality criteria were used in the analysis. These runs are listed in a file in the JSON format. The “MuonPhys” official JSON files for data collected with 3.8 T magnetic field are used. For these

specific data selection the subsystems not directly used in our studies, such as ECAL and HCAL, do not have to be marked as good. This yields a dataset corresponding to 2.8 fb^{-1} of integrated luminosity (~ 3 G events). In studies where electrons or other objects that use the calorimeters are used, we revert to using the all-good (“Golden”) JSON files, which yields a data set corresponding to 2.1 fb^{-1} of integrated luminosity. A special JSON file, called “Silver” JSON and corresponding to an integrated luminosity of 2.6 fb^{-1} , has been produced to include data declared as bad only in the HF.

Monte Carlo samples

Several MC simulation samples were used for the background and signal estimations in pp collisions at $\sqrt{s} = 13 \text{ TeV}$. The $Z/\gamma^* \rightarrow \mu\mu$ MC samples use POWHEG 2.0 [64, 65] using the NNPDF3.0 parton distribution functions [66] with the hadronisation based on PYTHIA 8 [67, 68]. The $t\bar{t}$ and tW processes are generated using POWHEG 2.0 [69, 70]. The WW, WZ, ZZ, QCD and Z’ signal processes are generated using PYTHIA 8. The W+jet simulated sample is generated using the MADGRAPH 5 aMC@NLO generator [71].

The particles that are generated by the event generators are then propagated through the detector with the GEANT 4 [72, 73] program, which simulates the detector response to these particles. Using a detailed model of the CMS detector including the geometries and materials, GEANT 4 generates the hits and particle showers that would happen in the subdetectors and subsequently simulates the response of the detector electronics to these signals.

After the simulation by GEANT 4, the data format of a simulated event is the same as for the data, so that, from this point onward, the same software can be used for the reconstruction of data and simulation. Pileup is included in the samples by mixing randomly chosen minimum bias events with the simulated events to achieve the expected PU distribution, shown in Figure 2.4.

In Table 5.2 the list of samples, their correspondent cross section and the details about the generation parameters are reported, while the names of the datasets are listed in Table 5.3. The **Asympt25ns**, and **Startup25ns** tags in the names of the datasets refer respectively to the asymptotic and track-based misalignment scenarios discussed in Section 4.1.4.

For the DY samples the respective next-to-next-to-leading-order (NNLO) cross sections corrections, calculated with FEWZ [77], are used.

In order to use the whole available statistic of the Drell-Yan, the samples generated in the mass intervals listed in Tab. 5.2 have been combined.

Process	Program	Generation parameters	σ (pb)	Events
$Z' \rightarrow \mu^+ \mu^-$	PYTHIA	$M = 5000$ GeV	5.2E-5 (LO)	99320
$Z/\gamma^* \rightarrow \mu^+ \mu^-$	POWHEG	$50 < M_{\mu\mu} < 120$ GeV	1975 (NLO)	2848076
		$120 < M_{\mu\mu} < 200$ GeV	1.93E+1 (NLO)	100000
		$200 < M_{\mu\mu} < 400$ GeV	2.73 (NLO)	100000
		$400 < M_{\mu\mu} < 800$ GeV	2.41E-1 (NLO)	100000
		$800 < M_{\mu\mu} < 1400$ GeV	1.68E-2 (NLO)	100000
		$1400 < M_{\mu\mu} < 2300$ GeV	1.39E-3 (NLO)	99600
		$2300 < M_{\mu\mu} < 3500$ GeV	1.65E-4 (NLO)	100000
		$3500 < M_{\mu\mu} < 4500$ GeV	7.58E-6 (NLO)	100000
		$4500 < M_{\mu\mu} < 6000$ GeV	4.56E-7 (NLO)	100000
		$M_{\mu\mu} > 6000$ GeV	2.06E-8(NLO)	100000
$t\bar{t}$	POWHEG	—	8.15E+2 (NNLO)	19699896
tW	POWHEG	—	3.56E+1 (NNLO)	998400
$\bar{t}W$	POWHEG	—	3.56E+1 (NNLO)	1000000
WW	PYTHIA	—	1.18E+2 (NLO)	994416
WZ	PYTHIA	—	6.61E+1 (NLO)	996920
ZZ	PYTHIA	—	1.54E+1 (NLO)	998848
$W + jets \rightarrow \mu\nu$	MADGRAPH	—	6.15E+4 (NLO)	16430759
Inclusive- μ QCD	PYTHIA	$p_T > 20$ GeV,	8.67E+8 (NLO)	4767935
		$50 < p_T < 80$ GeV	1.92E+7 (LO)	4983675
		$80 < p_T < 120$ GeV	7.76E+6 (LO)	3459761
		$120 < p_T < 170$ GeV	4.71E+5 (LO)	3458385
		$170 < p_T < 300$ GeV	1.17E+5 (LO)	3364368
		$300 < p_T < 470$ GeV	7.82E+3 (LO)	2935633
		$470 < p_T < 600$ GeV	6.48E+2 (LO)	1937537
		$600 < p_T < 800$ GeV	1.87E+2 (LO)	1964128
		$800 < p_T < 1000$ GeV	3.23E+1 (LO)	1937216
		$1000 < p_T < 1400$ GeV	9.42 (LO)	1487136
		$1400 < p_T < 1800$ GeV	8.42E-1 (LO)	197959
		$1800 < p_T < 2400$ GeV	1.15E-1 (LO)	193608
		$2400 < p_T < 3200$ GeV	6.82E-3 (LO)	194456
		$p_T > 3200$ GeV	1.65E-4 (LO)	192944

Table 5.2: Summary of simulated signal and background process samples.

Process	Dataset path
$Z \rightarrow \mu\mu, \tilde{Z}_\phi$	/ZprimeToMuMu_M-5000_TuneCUETP8M1_13TeV_pythia8/RunIISpring15DR74-Asympt25ns_MCRUN2_74_V9-v1 /ZprimeToMuMu_M-5000_TuneCUETP8M1_13TeV_pythia8/RunIISpring15DR74-Startup25ns_EXORereco_74X_Spring15_mcRun2_startup25ns_v0-v1
$DY \rightarrow \mu^+ \mu^-$	/ZToMuMu_NNPDF30_13TeV_powheg_M_50_120/RunIISpring15DR74-Asympt25ns_MCRUN2_74_V9-v1 /ZToMuMu_NNPDF30_13TeV_powheg_M_120_200/RunIISpring15DR74-Asympt25ns_MCRUN2_74_V9-v1 /ZToMuMu_NNPDF30_13TeV_powheg_M_200_400/RunIISpring15DR74-Asympt25ns_MCRUN2_74_V9-v1 /ZToMuMu_NNPDF30_13TeV_powheg_M_400_800/RunIISpring15DR74-Asympt25ns_MCRUN2_74_V9-v1 /ZToMuMu_NNPDF30_13TeV_powheg_M_800_1400/RunIISpring15DR74-Asympt25ns_MCRUN2_74_V9-v1 /ZToMuMu_NNPDF30_13TeV_powheg_M_1400_2300/RunIISpring15DR74-Asympt25ns_MCRUN2_74_V9-v1 /ZToMuMu_NNPDF30_13TeV_powheg_M_2300_3500/RunIISpring15DR74-Asympt25ns_MCRUN2_74_V9-v2 /ZToMuMu_NNPDF30_13TeV_powheg_M_3500_4500/RunIISpring15DR74-Asympt25ns_MCRUN2_74_V9-v1 /ZToMuMu_NNPDF30_13TeV_powheg_M_4500_6000/RunIISpring15DR74-Asympt25ns_MCRUN2_74_V9-v1 /ZToMuMu_NNPDF30_13TeV_powheg_M_6000_Inf/RunIISpring15DR74-Asympt25ns_MCRUN2_74_V9-v1 /ZToMuMu_NNPDF30_13TeV_powheg_M_50_120/RunIISpring15DR74-Startup25ns_EXORereco_74X_Spring15_mcRun2_startup25ns_v0-v1 /ZToMuMu_NNPDF30_13TeV_powheg_M_120_200/RunIISpring15DR74-Startup25ns_EXORereco_74X_Spring15_mcRun2_startup25ns_v0-v1 /ZToMuMu_NNPDF30_13TeV_powheg_M_200_400/RunIISpring15DR74-Startup25ns_EXORereco_74X_Spring15_mcRun2_startup25ns_v0-v1 /ZToMuMu_NNPDF30_13TeV_powheg_M_400_800/RunIISpring15DR74-Startup25ns_EXORereco_74X_Spring15_mcRun2_startup25ns_v0-v1 /ZToMuMu_NNPDF30_13TeV_powheg_M_800_1400/RunIISpring15DR74-Startup25ns_EXORereco_74X_Spring15_mcRun2_startup25ns_v0-v1 /ZToMuMu_NNPDF30_13TeV_powheg_M_1400_2300/RunIISpring15DR74-Startup25ns_EXORereco_74X_Spring15_mcRun2_startup25ns_v0-v1 /ZToMuMu_NNPDF30_13TeV_powheg_M_2300_3500/RunIISpring15DR74-Startup25ns_EXORereco_74X_Spring15_mcRun2_startup25ns_v0-v1 /ZToMuMu_NNPDF30_13TeV_powheg_M_3500_4500/RunIISpring15DR74-Startup25ns_EXORereco_74X_Spring15_mcRun2_startup25ns_v0-v1 /ZToMuMu_NNPDF30_13TeV_powheg_M_4500_6000/RunIISpring15DR74-Startup25ns_EXORereco_74X_Spring15_mcRun2_startup25ns_v0-v1 /ZToMuMu_NNPDF30_13TeV_powheg_M_6000_Inf/RunIISpring15DR74-Startup25ns_EXORereco_74X_Spring15_mcRun2_startup25ns_v0-v1
$t\bar{t}$	/TT_TuneCUETP8M1_13TeV_powheg_pythia8/RunIISpring15DR74-Asympt25ns_MCRUN2_74_V9-v2 /TT_TuneCUETP8M1_13TeV_powheg_pythia8/RunIISpring15DR74-Startup25ns_EXORereco_74X_Spring15_mcRun2_startup25ns_v0-v1 /ST_tW_top_5f_inclusiveDecays_13TeV_powheg_pythia8_TuneCUETP8M1/RunIISpring15DR74-Asympt25ns_MCRUN2_74_V9-v1 /ST_tW_antitop_5f_inclusiveDecays_13TeV_powheg_pythia8_TuneCUETP8M1/RunIISpring15DR74-Startup25ns_EXORereco_74X_Spring15_mcRun2_startup25ns_v0-v1 /ST_tW_antitop_5f_inclusiveDecays_13TeV_powheg_pythia8_TuneCUETP8M1/RunIISpring15DR74-Startup25ns_EXORereco_74X_Spring15_mcRun2_startup25ns_v0-v1 /WW_TuneCUETP8M1_13TeV_pythia8/RunIISpring15DR74-Asympt25ns_MCRUN2_74_V9-v1 /WW_TuneCUETP8M1_13TeV_pythia8/RunIISpring15DR74-Startup25ns_EXORereco_74X_Spring15_mcRun2_startup25ns_v0-v1 /WZ_TuneCUETP8M1_13TeV_pythia8/RunIISpring15DR74-Asympt25ns_MCRUN2_74_V9-v1 /WZ_TuneCUETP8M1_13TeV_pythia8/RunIISpring15DR74-Startup25ns_EXORereco_74X_Spring15_mcRun2_startup25ns_v0-v1 /ZZ_TuneCUETP8M1_13TeV_pythia8/RunIISpring15DR74-Asympt25ns_MCRUN2_74_V9-v3 /ZZ_TuneCUETP8M1_13TeV_pythia8/RunIISpring15DR74-Startup25ns_EXORereco_74X_Spring15_mcRun2_startup25ns_v0-v1 /WJetsToLNu_TuneCUETP8M1_13TeV-uncatnloFxFX_pythia8/RunIISpring15DR74-Asympt25ns_MCRUN2_74_V9-v1
$W + jets \rightarrow \mu\nu$	/QCD_Pt_20toInf_MuEnrichedPt15_TuneCUETP8M1_13TeV_pythia8/RunIISpring15DR74-Asympt25ns_MCRUN2_74_V9-v1 /QCD_Pt_50to80_TuneCUETP8M1_13TeV_pythia8/RunIISpring15DR74-Asympt25ns_MCRUN2_74_V9-v2 /QCD_Pt_80to120_TuneCUETP8M1_13TeV_pythia8/RunIISpring15DR74-Asympt25ns_MCRUN2_74_V9-v1 /QCD_Pt_120to170_TuneCUETP8M1_13TeV_pythia8/RunIISpring15DR74-Asympt25ns_MCRUN2_74_V9-v1 /QCD_Pt_170to300_TuneCUETP8M1_13TeV_pythia8/RunIISpring15DR74-Asympt25ns_MCRUN2_74_V9-v2 /QCD_Pt_300to470_TuneCUETP8M1_13TeV_pythia8/RunIISpring15DR74-Asympt25ns_MCRUN2_74_V9-v1 /QCD_Pt_470to600_TuneCUETP8M1_13TeV_pythia8/RunIISpring15DR74-Asympt25ns_MCRUN2_74_V9-v2 /QCD_Pt_600to800_TuneCUETP8M1_13TeV_pythia8/RunIISpring15DR74-Asympt25ns_MCRUN2_74_V9-v3 /QCD_Pt_800to1000_TuneCUETP8M1_13TeV_pythia8/RunIISpring15DR74-Asympt25ns_MCRUN2_74_V9-v2 /QCD_Pt_1000to1400_TuneCUETP8M1_13TeV_pythia8/RunIISpring15DR74-Asympt25ns_MCRUN2_74_V9-v1 /QCD_Pt_1400to1800_TuneCUETP8M1_13TeV_pythia8/RunIISpring15DR74-Asympt25ns_MCRUN2_74_V9-v1 /QCD_Pt_1800to2400_TuneCUETP8M1_13TeV_pythia8/RunIISpring15DR74-Asympt25ns_MCRUN2_74_V9-v1 /QCD_Pt_2400to3200_TuneCUETP8M1_13TeV_pythia8/RunIISpring15DR74-Asympt25ns_MCRUN2_74_V9-v1 /QCD_Pt_3200toInf_TuneCUETP8M1_13TeV_pythia8/RunIISpring15DR74-Asympt25ns_MCRUN2_74_V9-v1
Inclusive- μ QCD	

Table 5.3: Names of the datasets for the simulated samples listed in Table 5.2.

5.1.2 Trigger

The HLT used to select the events for this analysis, as mentioned in Section 2.2.5, is the unprescaled single-muon trigger with the lowest p_T threshold that does not include muon isolation requirements and pseudorapidity restrictions. Although muons produced by the decay of a high-mass Z' tend to be isolated, their high momentum enhances the production of electromagnetic showers, that can mimic a non-isolated muon candidate. This choice, already employed in the analysis performed at 7 and 8 TeV centre-of-mass energies, ensures high efficiency for signal events, which are characterized by high p_T muons, and simplifies the analysis compared to a dimuon trigger.

The HLT path used is HLT_Mu50, that selects single muons with $p_T > 50$ GeV in the pseudorapidity range of the muon detector acceptance, $|\eta| < 2.4$.

A comparison with the path HLT_Mu45_eta2p1, which represents a possible alternative for the single-muon HLT path for this analysis, has been performed. Figure 5.1 shows the trigger efficiency for the trigger paths HLT_Mu50 and HLT_Mu45_eta2p1, as a function of p_T (left) and η (right) of the muon candidate.

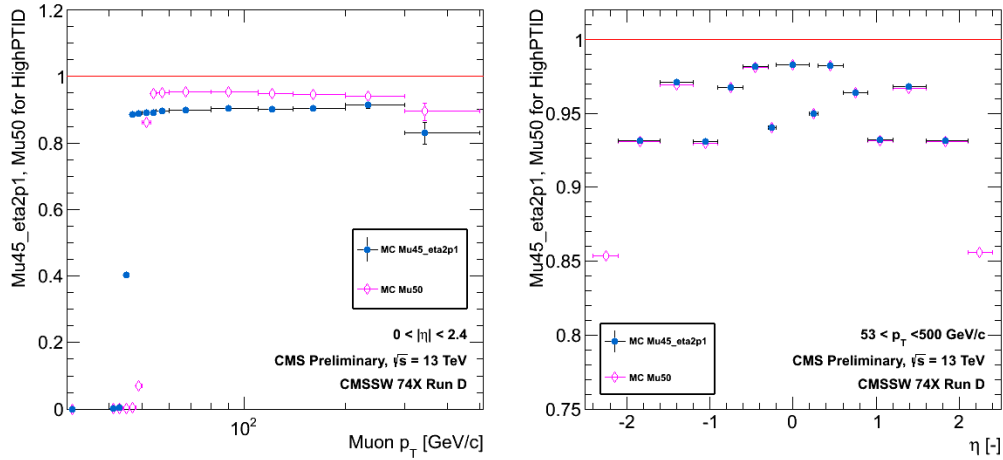


Figure 5.1: Trigger efficiency as a function of the muon p_T (left) and η (right) for the two trigger paths HLT_Mu50 and HLT_Mu45_eta2p1. When computing the efficiency as a function of η , the muon candidates are required to have a minimum p_T value 3 GeV higher than the corresponding HLT threshold. In both cases the efficiency is computed on a sample of simulated DY events reweighted according to the pile-up content of the 2015D dataset.

The efficiency is determined with the tag-and-probe method from simulated DY events, reweighted to match the pile-up conditions observed in data of Run

2015D. The results show that the efficiency reaches the maximum value about 3 GeV above the p_T threshold. The higher efficiency of the path HLT_Mu50 is due to the wider angular acceptance of this trigger selection. Indeed, the efficiency is identical in the common angular region. Since muons from the decay of a Z' of several TeV mass are characterized by very large p_T , well above the trigger threshold, the 5 GeV higher threshold of HLT_Mu50 does not introduce any significant efficiency loss for the signal compared to HLT_Mu45_eta2p1. The pattern of the trigger efficiency as a function of η is related to the acceptance of the muon detector and the presence of small non instrumented regions between the barrel wheels.

The efficiencies reported in Figure 5.1 refer to single muons, and therefore the total efficiency to trigger a Z' candidate, where two high- p_T muons are present and two chances to trigger, is close to unity.

High- p_T trigger performance

For High- p_T muon performance, the tag-and-probe (TnP) method, described in Section 3.2.6, is used in two different ways: the standard TnP “fit method”, and the “count method” described below.

In the “fit method”, a maximum-likelihood fit is performed on the invariant mass peak between 70 and 130 GeV of the TnP pair, to calculate the total number of probe muons and those that pass the HLT_Mu50 trigger selection.

In the “count method”, a simple counting is performed to calculate the total number of probe muons satisfying the trigger path for which the efficiency is measured. Contrary to the “fit method”, the invariant mass range of the TnP muon, [70, 130] GeV, can be relaxed, to allow pairs with higher invariant mass to contribute to the efficiency measurement. This provides a better statistical precision in the determination of the efficiency and allows the trigger efficiency to be better tested in the more relevant high- p_T region. For these reasons it is used to provide the scale factors for the muon-trigger efficiency for this analysis.

The efficiency ϵ is computed separately for data and MC, and the resulting data to MC ratio represents the scale factor to be applied to the simulated events to correct them as a function of p_T and η of the triggered muon.

Figure. 5.2 shows the trigger efficiency obtained with the TnP method as a function of the η of the probe muon (left), and the number of vertices in the event (right), for data and MC, and the data to MC ratio, for the running period 2015D. The efficiency is independent of the number of primary vertices. Figure. 5.3 shows the trigger efficiency obtained with the TnP method as a function of the p_T of the probe muon in the event, for data and MC, and the data to MC ratio, for the running period 2015D.

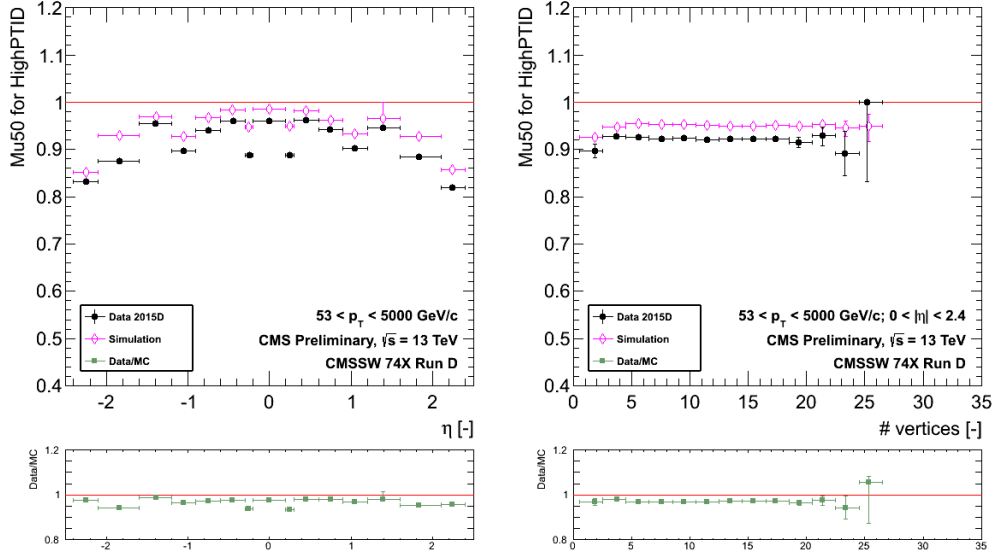


Figure 5.2: Trigger efficiency as a function of the probe muon η (left), and the number of vertices in the event (right), determined using the TnP “count method”. Results for data and simulation, and the data to simulation ratio, are shown for datasets 2015D.

The single muon and dimuon trigger efficiencies measured from data and the data/MC scale factors are reported in Table 5.4

Single muon trigger efficiency		
$0 < \eta < 2.4$	ϵ_{data}	data/MC
$53 < p_T < 140 \text{ GeV}$	0.9452 ± 0.00079	0.9657 ± 0.00068
$p_T > 140 \text{ GeV}$	0.9192 ± 0.0054	0.989 ± 0.007
Dimuon muon trigger efficiency		
$0 < \eta < 2.4$	ϵ_{data}	data/MC
$53 < p_T < 140 \text{ GeV}$	0.9933 ± 0.0001	0.9958 ± 0.0001
$p_T > 140 \text{ GeV}$	0.9935 ± 0.0008	0.9985 ± 0.001

Table 5.4: Single muon and dimuon trigger efficiencies measured from data and the data/MC ratios.

Prescaled Trigger for dimuons at the Z peak

The primary single muon trigger used in this analysis, HLT_Mu50, has a too high threshold that reduces the $Z \rightarrow \mu^+\mu^-$ signal and could lead to different

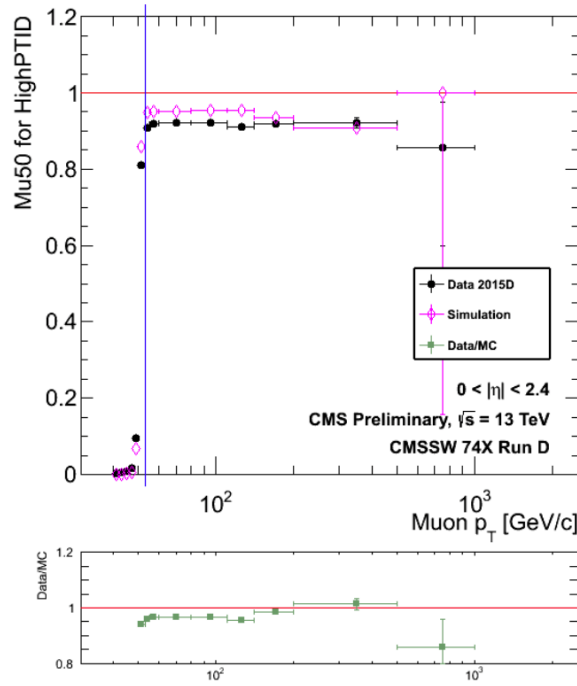


Figure 5.3: Trigger efficiency as a function of the probe muon p_T , determined using the ThP “count method”. Results for data and simulation, and the data to simulation ratio, are shown for datasets 2015D.

kinematics than the original Z production. A large number of $Z \rightarrow \mu^+\mu^-$ candidates is needed in order to obtain a more accurate model of the background around the Z resonance.

Therefore, for a more accurate study of events at the Z peak, a prescaled trigger `HLT_Mu27` and a correspondingly reduced value of 30 GeV for the p_T cut for the offline muon are used. Using a prescaled trigger also avoid the systematic uncertainty on the efficiency caused by having the turn-on curve of the trigger efficiency in the middle of the Z peak.

The amount of prescaling changes with different instantaneous luminosity periods and this leads to different values of prescale factors at different runs and luminosity sections during the data taking. In order to enlarge the statistics at the Z peak the whole dataset was divided into sub-datasets with different prescale factors and different integrated luminosity, as reported in Table 5.5. The mean `HLT_Mu27` prescale rate in the data is $1/73.737$.

Prescale factor	Integrated luminosity [pb ⁻¹]
3	0.34
25	33.60
35	83.21
70	1727
120	724.64
180	39.21
500	13.30
17	7.81
33	22.01
50	20.80
250	0.07

Table 5.5: Integrated luminosities for different prescale factors of HLT_Mu27.

5.1.3 Muon selection

In this analysis the high- p_T muon identification (High p_T ID), described in Section 3.2.4, is used to select muon candidates. The main goal of the High p_T ID is to maintain a high efficiency for the muon candidate selection over a wide energy range, while remaining independent of the number of primary vertices.

The High p_T ID selection criteria are listed in detail in the following and are unchanged with respect to the Run-1 analysis, except for the trigger path and the offline p_T cut:

- the muon must be reconstructed as a “global” muon and a “tracker” muon;
- the relative p_T error $\delta p_T/p_T$ is required to be smaller than 0.3, to suppress grossly misreconstructed muons;
- the muon’s transverse impact parameter with respect to the primary vertex, as measured by the tracker-only fit, must be less than 0.2 cm;
- the global muon track must have at least six tracker layers with hits in the fit;
- the global muon track fit must include at least one hit from each of the pixel detector and the muon system;
- the tracker muon must be matched to segments in at least two muon stations.

The selected muons are required to pass the following additional criteria:

- the offline muon p_T must be at least 53 GeV, so as to be in the plateau of the single-muon HLT_Mu27 trigger efficiency;
- the muon must pass a relative tracker-only isolation cut: the scalar sum of the p_T of all other tracks in a cone of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.3$ around but not including the muon's tracker track must be less than 10% of the muon's p_T , also as measured by the tracker. To be used in the calculation of the tracker isolation, tracks have to be within $\Delta z = 0.2$ cm of the primary vertex with which the muon candidate is associated.

Muon ID and isolation efficiencies

The efficiencies of the muon selection requirements and isolation described above are measured with the TnP “fit method”. The muon ID efficiency is shown in Figure. 5.4 as a function of the η of the probe muon (left), and the number of vertices in the event (right) and in Figure. 5.5 as a function of the p_T of the probe muon. Efficiencies are estimated from data, for periods 2015 C and D, and MC. The data to MC ratio is also reported. Muons with offline $p_T > 30$ GeV are considered. The efficiency is independent of the number of primary vertices.

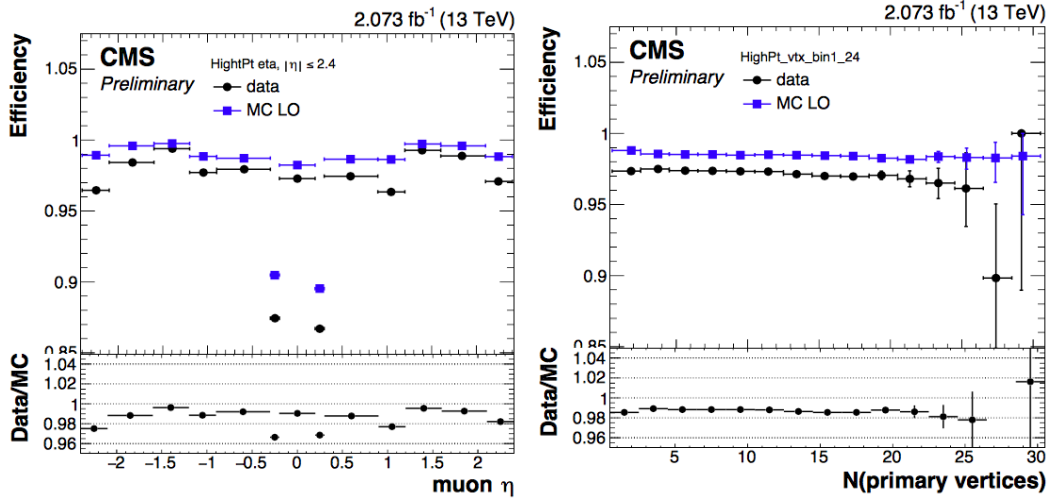


Figure 5.4: High p_T ID efficiency as a function of the probe muon η (left), and the number of vertices in the event (right), determined using the TnP “fit method”. Results for data and simulation, and the data to simulation ratio, are shown for datasets 2015 C and D. Muons with offline $p_T > 30$ GeV are considered.

The single muon High p_T ID efficiency measured from data, for muons with $p_T > 30$ GeV and $0 < |\eta| < 2.4$, is $\epsilon_{data} = 0.9730 \pm 0.0002$ and the data/MC

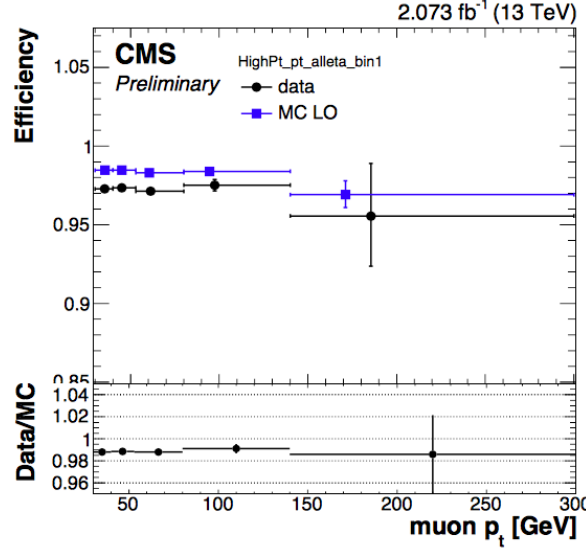


Figure 5.5: High p_T ID efficiency as a function of the probe muon p_T , determined using the TnP “fit method”. Results for data and simulation, and the data to simulation ratio, are shown for datasets 2015 C and D. Muons with offline $p_T > 30$ GeV are considered.

ratio is 0.9879 ± 0.0003 .

The tracker isolation efficiency obtained is shown in Figure. 5.6 as a function of the η of the probe muon (left), and the number of vertices in the event (right) and in Figure. 5.7 as a function of the p_T of the probe muon. Efficiencies are estimated from data, for periods 2015 C and D, and MC. The data to MC ratio is also reported. Muons with offline $p_T > 30$ GeV are considered. The efficiency is independent of the number of primary vertices.

The single muon tracker isolation efficiency measured from data, for muons with $p_T > 30$ GeV and $0 < |\eta| < 2.4$, is $\epsilon_{data} = 0.9838 \pm 0.0001$ and the data/MC ratio is 1.0 ± 0.0002 .

Effect of pile-up on muon isolation

Our selection requires the muons to be isolated in order to reject background from hadrons misidentified as muons, or non-prompt muons coming from jets. The way to perform the isolation calculation, in particular choosing tracks only instead of PF candidates, is based on two considerations:

- at high momentum (above 200 GeV), the muon can radiate photons via Bremsstrahlung process. The photon energy should not be considered when summing the energy inside the isolation cone. These photons are

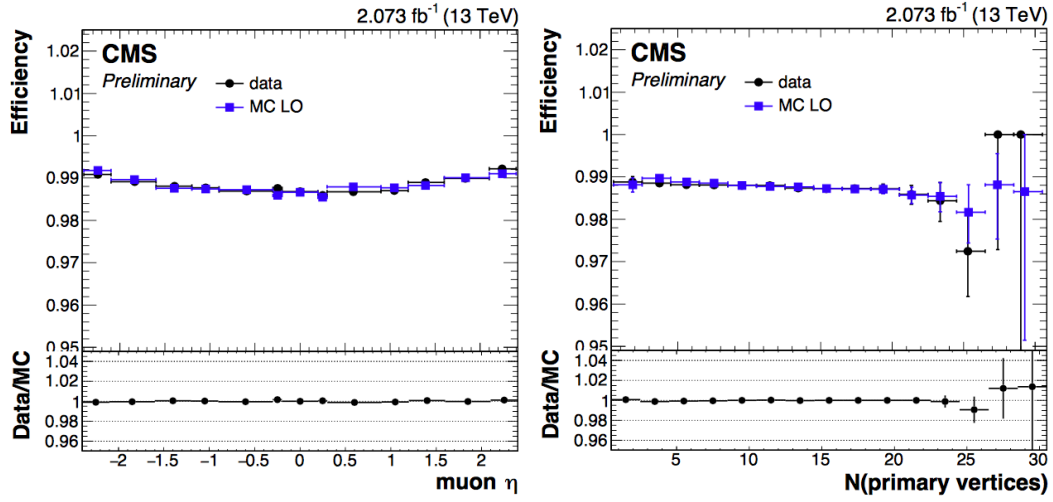


Figure 5.6: Tracker isolation efficiency as a function of the probe muon η (left), and the number of vertices in the event (right), determined using the TnP “fit method”. Results for data and simulation, and the data to simulation ratio, are shown for datasets 2015 C and D. Muons with offline $p_T > 30$ GeV are considered.

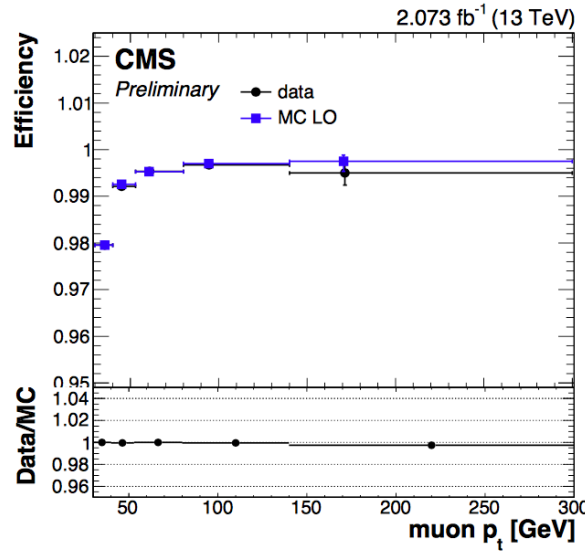


Figure 5.7: Tracker isolation efficiency as a function of the probe muon p_T , determined using the TnP “fit method”. Results for data and simulation, and the data to simulation ratio, are shown for datasets 2015 C and D. Muons with offline $p_T > 30$ GeV are considered.

necessarily included within the PF candidates collection;

- the isolation needs to be independent of pileup otherwise its efficiency will decrease. The dependence of the tracker isolation on pile-up is reduced by including in the calculation of the p_T sum only those tracks that originated within $\Delta z = 0.2$ cm of the primary vertex with which the muon candidate is associated (as for Run1 analysis). Calorimeter data can not be traced back to a primary vertex easily.

The distributions of the relative tracker-only and PF isolation as a function of the number of reconstructed primary vertices are displayed in Fig. 5.8. As seen in the TnP efficiency, the tracker-only isolation is independent of the pileup. The particle flow isolation has been tuned by the DB correction in order to be less affected by pileup and is seen to be flat as a function of the number of vertices. Still, the fraction of events rejected by the PF isolation cut on Z signal is 30 % higher.

According to the tracker-only isolation distribution and its tag-and-probe efficiency as a function of the number of vertices, we do not need to apply the reweighting of the pileup distribution in the simulation.

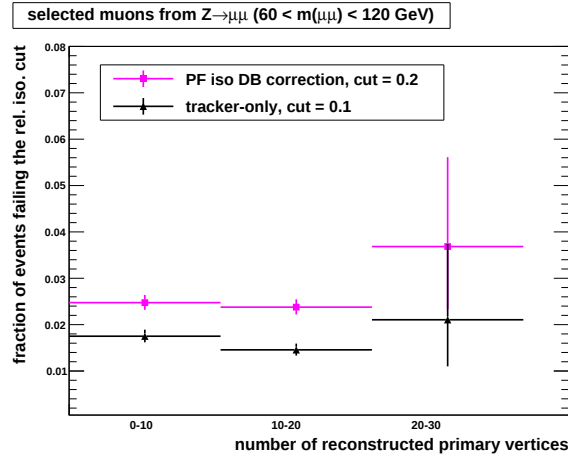


Figure 5.8: The fraction of muons selected using the analysis cuts that fail the tracker-only and PF relative isolation at 0.1 and 0.2, respectively, as a function of reconstructed primary vertices, for dimuons in the Z peak ($60 < M_{\mu\mu} < 120$) in data. The thresholds correspond to the standard loose muon selection in CMS.

5.1.4 Dimuon event selection

To search for high-mass resonances in the dimuon decay channel, events with two High p_T ID muons are selected. The event must have a “good” offline-reconstructed primary vertex (PV), as defined by the CMS standard selection:

at least four tracks must be associated to the vertex and the vertex must be located within $|r| < 2$ cm and $|z| < 24$ cm of the nominal interaction point (IP). This cut has been established to ensure the quality of the hadronic collisions and is particularly useful in rejecting cosmic ray muons triggering in empty bunch-crossings, which can produce fake dimuons when traversing the detector near the IP.

The event must be triggered requiring that one of the muons be matched within $\Delta R < 0.2$ to the HLT muon candidate that fired the single-muon path HLT_Mu50. To form a dimuon, two muons of opposite charge are considered. In events with more than one opposite-sign dimuon, the two muons with highest p_T are selected.

A fit to a common vertex (using the Kalman filter formulation as implemented in the CMS offline SoftWare framework (CMSSW) [74]) is performed to compute the kinematics of the dimuon system, particularly its invariant mass. This also serves to ensure that the two muons originate from the same vertex, as a guard against pile-up and as a check on reconstruction quality. A cut on the goodness of the fit is explicitly required and only vertex fit with $\chi^2/\text{d.o.f.} < 20$ are considered. This threshold has been increased with respect to the value used during Run-1 to recover a lost in efficiency of this cut due to changes in the muon reconstruction, as described in Section 3.2.6.

To reduce the background from cosmic ray muons that are in-time with a collision event and pass the primary vertex and impact parameter cuts, the three-dimensional angle between the two muons' momenta is required to be less than $\pi - 0.02$ rad. This cut is 99% efficient at rejecting cosmic ray muons and this background is then reduced to a negligible level.

Overall acceptance times efficiency

The product of geometrical acceptance and detection efficiency is estimated from simulations as a function of the generated dimuon invariant mass. Figure 5.9 shows, as a function of dimuon invariant mass, the combined reconstruction and selection efficiency for dimuons passing the above cuts with respect to triggered events in the acceptance (defined as both muons in $-2.4 < \eta < 2.4$ and $p_T > 53$ GeV, red circles), with respect to all events in the acceptance (green squares), and the total acceptance times efficiency (blue triangle). The study is performed on simulated DY events from 50 to 6000 GeV. The same behavior is expected for all spin-one particles. The fit of the acceptance times efficiency is used to parametrise the Z' efficiency and is one of the inputs to the final limit setting that will be discussed in Section 5.6.

The efficiency of the first invariant mass bin is lower by several percents because of the high muon p_T cut which selects mainly boosted Z events. The

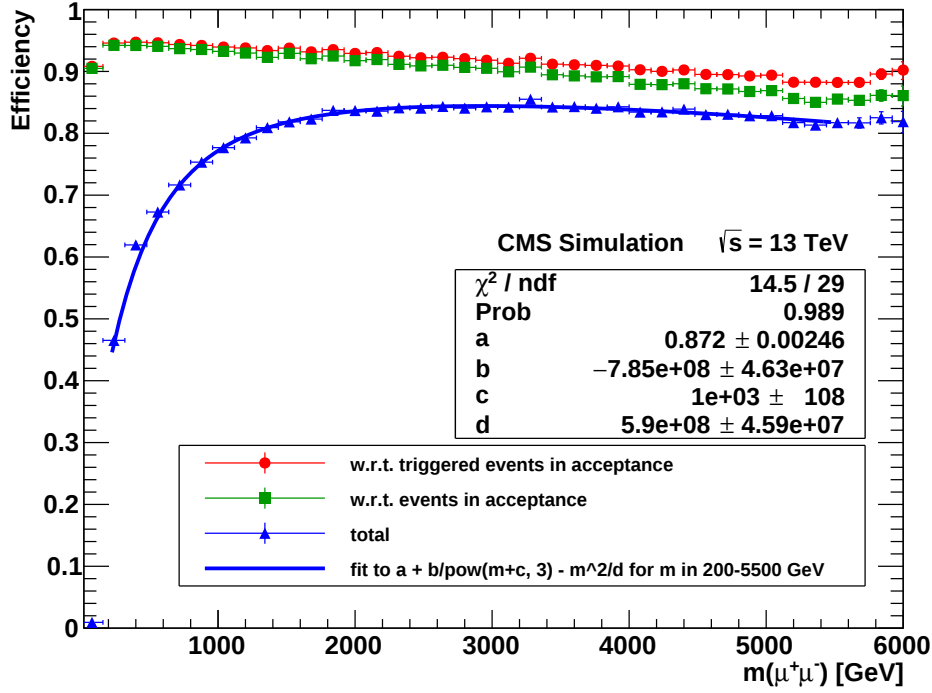


Figure 5.9: The combined reconstruction and selection efficiency, as a function of the invariant mass, for dimuons passing our selection with respect to triggered events in acceptance (red circles), with respect to all events in acceptance (green squares), and the total acceptance times efficiency (blue triangle), as evaluated on simulated Drell-Yan events.

acceptance in this specific invariant mass bin is also very low since muons coming from boosted Z are pushed out of the pseudorapidity range. Above the Z peak most of the total inefficiency at dimuon invariant masses below 1 TeV is due to the geometrical acceptance.

The combined reconstruction and selection efficiency for triggered events in acceptance is about 94% at $M_{\mu\mu} = 200$ GeV and decreases by only 4 % in the range of $M_{\mu\mu} = 200 - 6000$ GeV. As a comparison, for Run-1 analysis, the efficiency for triggered events was about 90 % at $M_{\mu\mu} = 200$ GeV and decreases by 3 % in the range of $M_{\mu\mu} = 200 - 3000$ GeV. The difference can be mainly explained due to the new muon reconstruction which is now much more efficient (close to 98 % for single muon having a very tight matching to their generated candidate, $\Delta R = 0.25$).

In order to get a better idea of the effect of each cut applied in this analysis, Figure 5.10 shows the ratio of the number of events that pass all selection cuts to the number of events passing all cuts but the one indicated. These N-1 efficiencies are performed in two mass regions, $60 < M_{\mu\mu} < 120$ GeV and

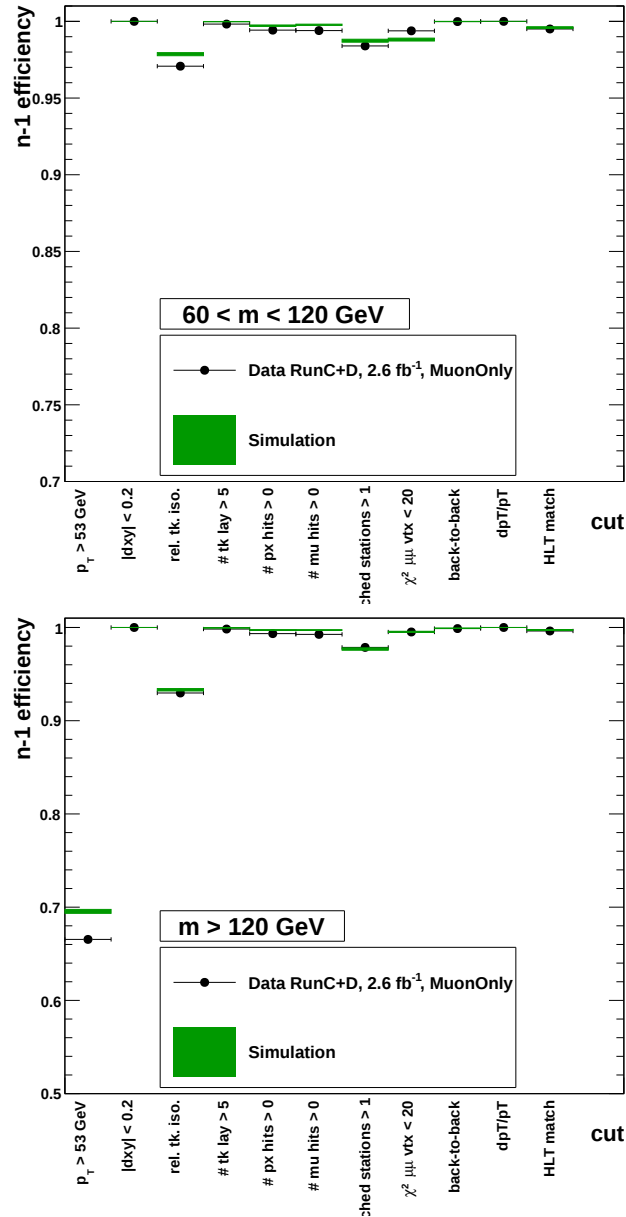


Figure 5.10: The ratio of the number of events in the region $60 < M_{\mu\mu} < 120$ (top) and $M_{\mu\mu} > 120$ (bottom), that pass all selection cuts to the number of events passing all cuts but the one indicated. Here simulation includes all the backgrounds.

for $M_{\mu\mu} > 120$ GeV. The data are compared to simulation where simulation includes all the possible electroweak backgrounds: Drell-Yan, diboson, $t\bar{t}$, etc., and QCD. Data and MC show very good agreement. The MC statistical uncertainties are calculated by taking into account the full number of generated

events in each of the available samples.

5.2 High- p_T muon momentum scale measurement

A precise measurement of the muon momentum scale is related to the uncertainty in measuring the transverse curvature (κ), defined as $\kappa = q/p_T$. Beside those related to physics, there are a number of effects originating from the intrinsic limits of the apparatus used for the measurement, which can bias the measurement of the muon curvature and thus of its transverse momentum. For the high p_T muons the consequences due to a non perfect alignment or a systematic distortion of the muon system chambers (internally or with respect to the tracker) have the major effect in biasing the measurement.

The approach to this problem consists in parametrizing any detector-related bias affecting the measurement of the curvature and to quote a systematics on the measurement of the muon transverse momentum. A constant bias in the transverse curvature means a non-constant shift in the measured p_T . A method, called hereafter “generalized endpoint”, already in usage during LHC Run-1 [75, 76], has been developed and re-adapted in order to be run on the data collected by CMS experiment during 2015.

As input, the method exploits the muon curvature distributions of Drell-Yan events decaying into two muons. The principle behind consists to bring the distributions of the positive and negative muon curvatures to be symmetric, as it would be expected by the decays of Z^*/γ^* intermediate states into positive and negative charged muons. In order to reach this, a constant bias, which would best symmetrize the q/p_T distribution between the positive and the negative charged muons, is extracted for tracks above a chosen cut-off momentum.

Technically, this is done by injecting different sizes of bias ($\Delta\kappa$) for each entry of the positive and negative curvature distributions, with the target of modifying the shapes until the two distributions resemble. The criteria used is a χ^2 goodness-of-fit test applied to the two distributions at each injection of $\Delta\kappa$. The granularity of the injected bias has been chosen to be smaller than the bin size of the curvature histograms, otherwise a larger one would only lead to a constant shift of the two distributions. The degree of freedom of each χ^2 test is defined by the number of non-empty bins of the histograms used in the test, at each value of the injected $\Delta\kappa$.

Figure 5.11 shows the closure test for an injected null bias of $\Delta\kappa = 0.0/\text{TeV}$ and for a non-null $\Delta\kappa = 0.5/\text{TeV}$ on a simulated MC sample. The minimum in the χ^2 curve defines the best estimate for the parameter $\Delta\kappa$, while the uncertainty on the parameter is defined by the values corresponding to a $\Delta\chi^2 = 1$,

after interpolating the trend with a parabolic shape. The aperture of the parabola is directly connected to the statistical uncertainty on the minimum, as it varies according to the number of entries in the curvature histograms used for the χ^2 test.

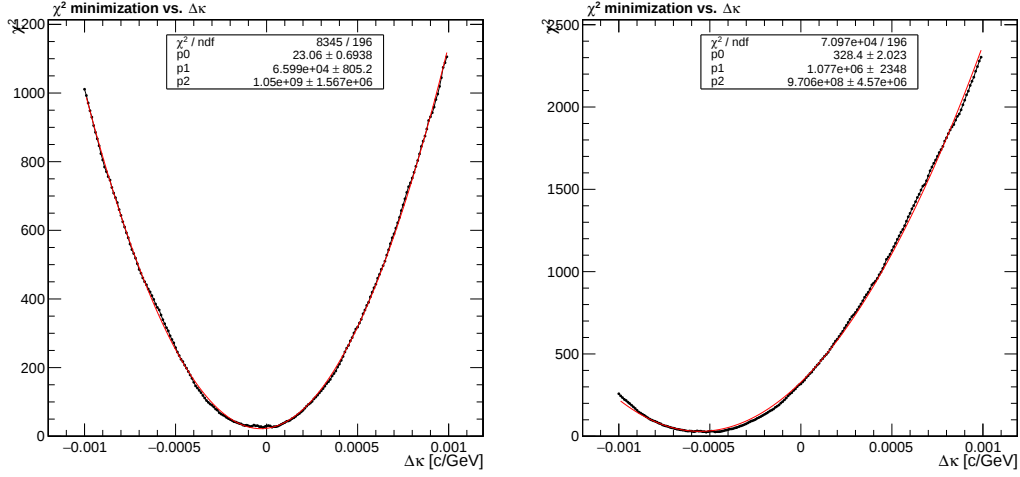


Figure 5.11: Closure test for an injected bias of $\Delta\kappa = 0.0/\text{TeV}$ on a MC simulated sample (left). Closure test for an injected bias of $\Delta\kappa = 0.5/\text{TeV}$ on a MC simulated sample (right), using a statistics of 30k events as input. Parabolic shape (pol2) is used to fit the trend.

For the data collected during 2015 and corresponding to an integrated luminosity of 2.6 fb^{-1} , using the SingleMu primary dataset, results are reported for two chosen cut-off momentum on the leading muon $p_T > 50 \text{ GeV}$ and $p_T > 200 \text{ GeV}$. The positive and the negative curvature distributions for the leading muon of the pair in the range $|\eta| < 2.4$ (Figure 5.12) are taken as an input to the χ^2 goodness-of-fit test and the results are reported in Figure 5.13. The positive and negative distributions are normalized to the same number of events for purposes of comparison, in order to cancel any asymmetric charge effect. The net action of the “generalized endpoint” method procedure is essentially to modify only the shape of the two curvature distributions. The TuneP algorithm is used to determine the p_T of the muons entering the histograms used in the minimization. It might be noticed as the results for the $p_T > 50 \text{ GeV}$ case are driven by the misalignment of the tracker, given in this regime the choice of the muon TuneP algorithm would be, in the vast majority of the cases, the tracker-only fit. For the $p_T > 200 \text{ GeV}$ case instead the extended lever-arm provided by the muon detector can contribute to add

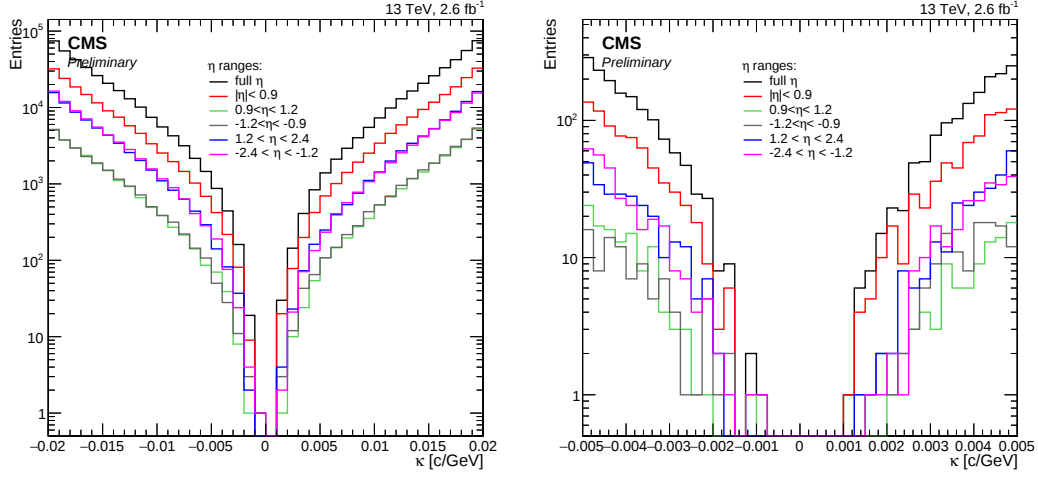


Figure 5.12: Overview of the curvature distributions in output from TuneP (in logarithmic scale) for different pseudorapidity regions, used as input for the “generalized endpoint” method, corresponding to the leading muon cut-off $p_T > 50$ GeV and $p_T > 200$ GeV (right) from the 2015 dataset (2.0 fb^{-1}).

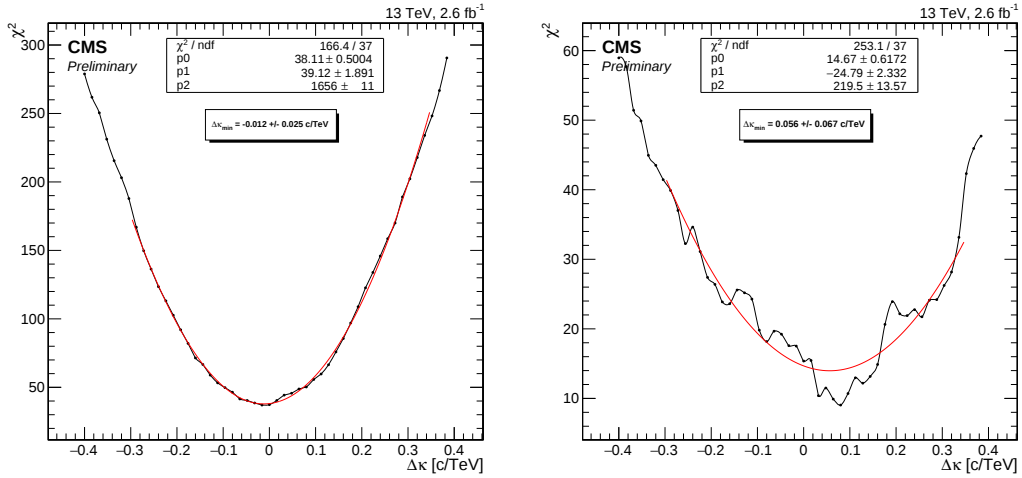


Figure 5.13: Results from the “generalized endpoint” method corresponding to the leading muon cut-off $p_T > 50$ GeV (left) and $p_T > 200$ GeV (right) from the 2015 dataset (2.6 fb^{-1}) using TuneP reconstruction.

bias to the momentum assignment, in combination with the ones affecting the tracker-only.

From the outcome of the “generalized endpoint” method, a conservative estimate of the bias affecting the high p_T muons (namely $p_T > 200$ GeV) can be quoted, being of the order of $\Delta\kappa = 0.06 \pm 0.07/\text{TeV}$, over the full eta and phi region. Given the large statistical uncertainty (2700 events) affecting this measurement, the bias is still compatible with zero.

A more interesting option is to derive the bias according to the pseudorapidity of the muons, and therefore probing separately the barrel ($|\eta| < 0.9$), the forward ($0.9 < \eta < 2.4$), and the backward ($-2.4 < \eta < -0.9$) endcap regions. A drawback of this approach would be the low statistics in each pseudorapidity bin, in particular for the endcaps, since the high p_T muons are preferably emitted in the barrel region. The bias measured for the barrel region is found to be $\Delta\kappa = 0.02 \pm 0.05/\text{TeV}$, using as input about 16k events. For the endcaps the global minimum can not be precisely defined as there are still oscillations in the χ^2 and more statistics would be needed for deriving a more precise measurement for the bias. However, with about 8k events as input for each endcap, the values found for the bias are $\Delta\kappa = -0.03 \pm 0.08/\text{TeV}$ for the positive endcap ($0.9 < \eta < 2.4$), and $\Delta\kappa = 0.06 \pm 0.10/\text{TeV}$ for the negative endcap ($-2.4 < \eta < -0.9$). The results quite differ between the positive and the negative endcap because of the effect of a weak mode induced in the tracker negative endcap, known to affect the geometry in prompt reconstruction.

In order to account for the still large uncertainty in the derivation of the bias in particular for the endcap, it has been decided to quote a more conservative value of $\Delta\kappa = 0.1/\text{TeV}$ for the barrel region and of $\Delta\kappa = 0.2/\text{TeV}$ for the endcap regions. In particular for the very negative endcap region ($-2.4 < \eta < -2.0$), where a huge bias from a tracker weak mode is expected, the value has been safely inflated to $\Delta\kappa = 0.9/\text{TeV}$. This quantifies how much the curvature is expected to change, by re-recoiling with a weak-mode-free tracker geometry, one of the selected high mass events having one of the muon sampling this particular detector region.

Consistent results are also obtained from the endpoint method by using as input cosmic muons instead of muon tracks from collisions. The principle is the same as described above, aiming at symmetrizing the distributions of the positive and negative muon curvatures observed in data. The advantage of the cosmics is that the tails of the curvature distributions contains more high energetic muons than those from collisions, but it has the limitation of being sensitive to potential biases localized in the barrel region only, due to the topology of the cosmic tracks crossing CMS detector.

5.3 High-mass resolution

The dimuon mass resolution as a function of mass has been parameterized after the full selection, also including the event trigger and matching of one of the two muons to the triggering object. The reconstructed invariant mass of each dimuon passing our selection criteria is compared to the true mass. Figure 5.14 (left) shows the overall performance of the new Tune-P considering the asymptotic misalignment scenario. The corresponding results for the TB startup misalignment scenario are shown in Figure 5.14 (right). The distribution is fitted to a polynomial function, and the result of the fit is also shown in the figure.

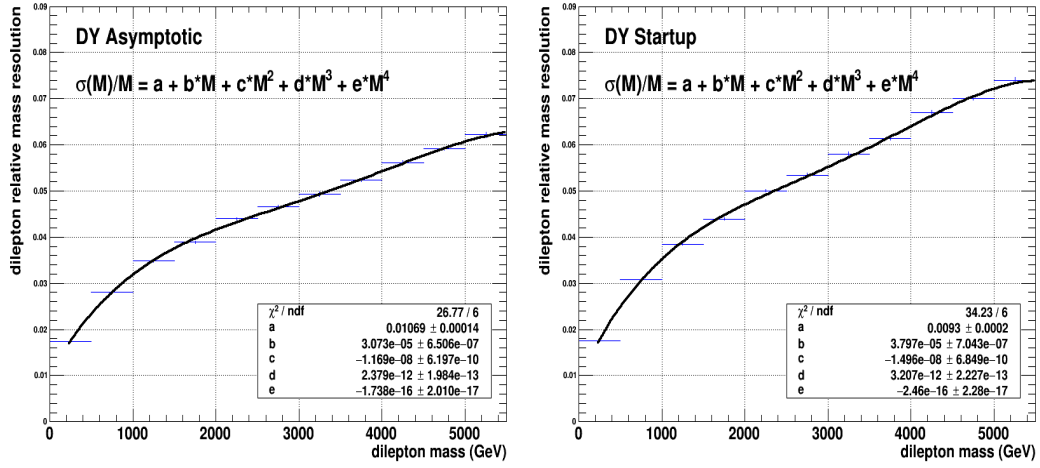


Figure 5.14: Relative invariant mass resolution $\sigma(m)/m$ as a function of dimuon invariant mass for TuneP p_T assignment and asymptotic misalignment scenarios (left), startup misalignment scenarios (right). The fit of the resolution curve to a fourth-order polynomial is overlaid.

The relative mass resolutions have been performed in different pseudorapidity regions. Separate panels in Figures 5.15 and 5.16 show the relative mass resolutions as a function of invariant mass, extracted at the end of the selection for events with both muons reconstructed in $|\eta| < 0.9$ or when at least one muon has $|\eta| > 0.9$ (top, left and right respectively) and, similarly, for events with both muons reconstructed in $|\eta| < 1.2$ or when at least one muon has $|\eta| > 1.2$ (bottom, left and right respectively). In Figure 5.15 the asymptotic misalignment scenarios has been considered and Figure 5.16 shows results for the TB startup misalignment scenario. Even though the resolutions appear degraded in the endcaps, the statistical analysis is performed without η categorization.

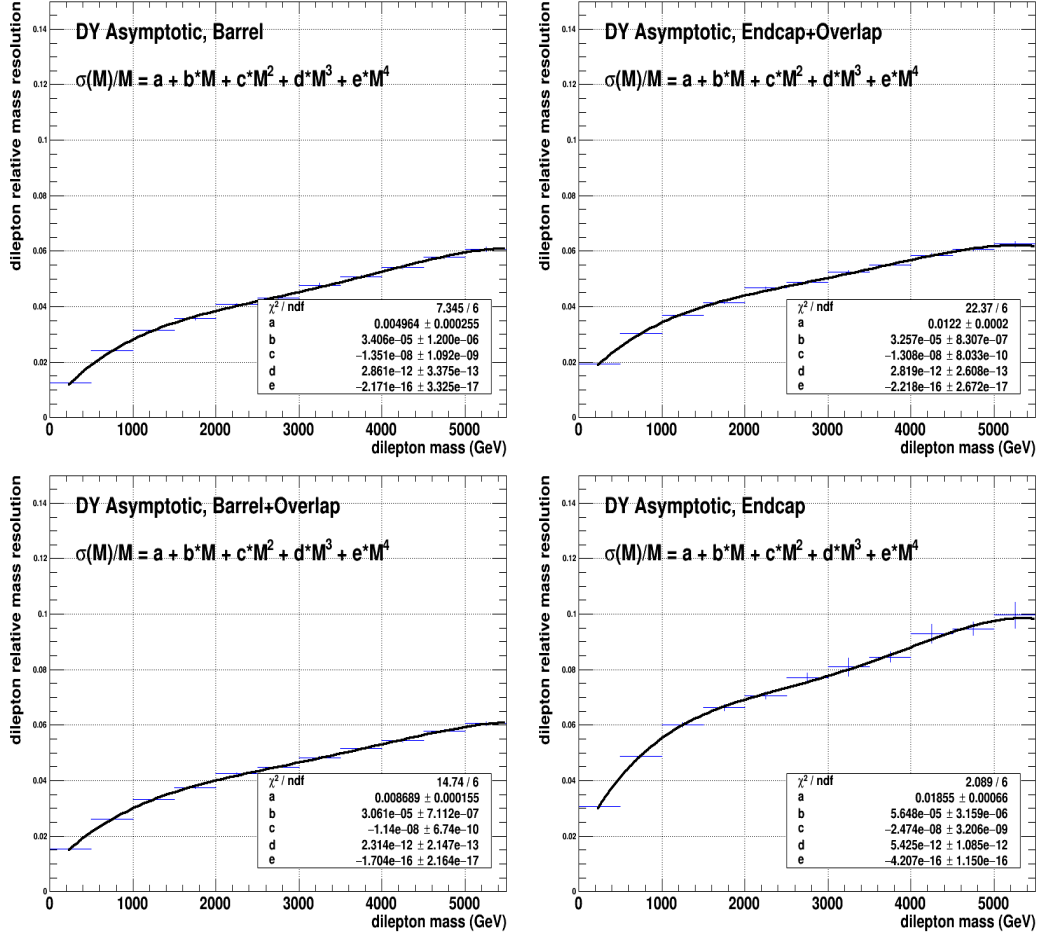


Figure 5.15: Relative invariant mass resolution $\sigma(m)/m$ as a function of dimuon invariant mass for TuneP p_T assignment and asymptotic misalignment scenarios. Events where both muons are reconstructed in the barrel ($|\eta| < 0.9$) or in the barrel and the overlap regions ($|\eta| < 1.2$) are reported on the left side (top, bottom respectively). Events where at least one muon falls in the endcaps and the overlap regions ($|\eta| > 0.9$) or in the endcaps only ($|\eta| > 1.2$) are reported on the right side (top, bottom respectively). The fit of the resolution curve is overlaid.

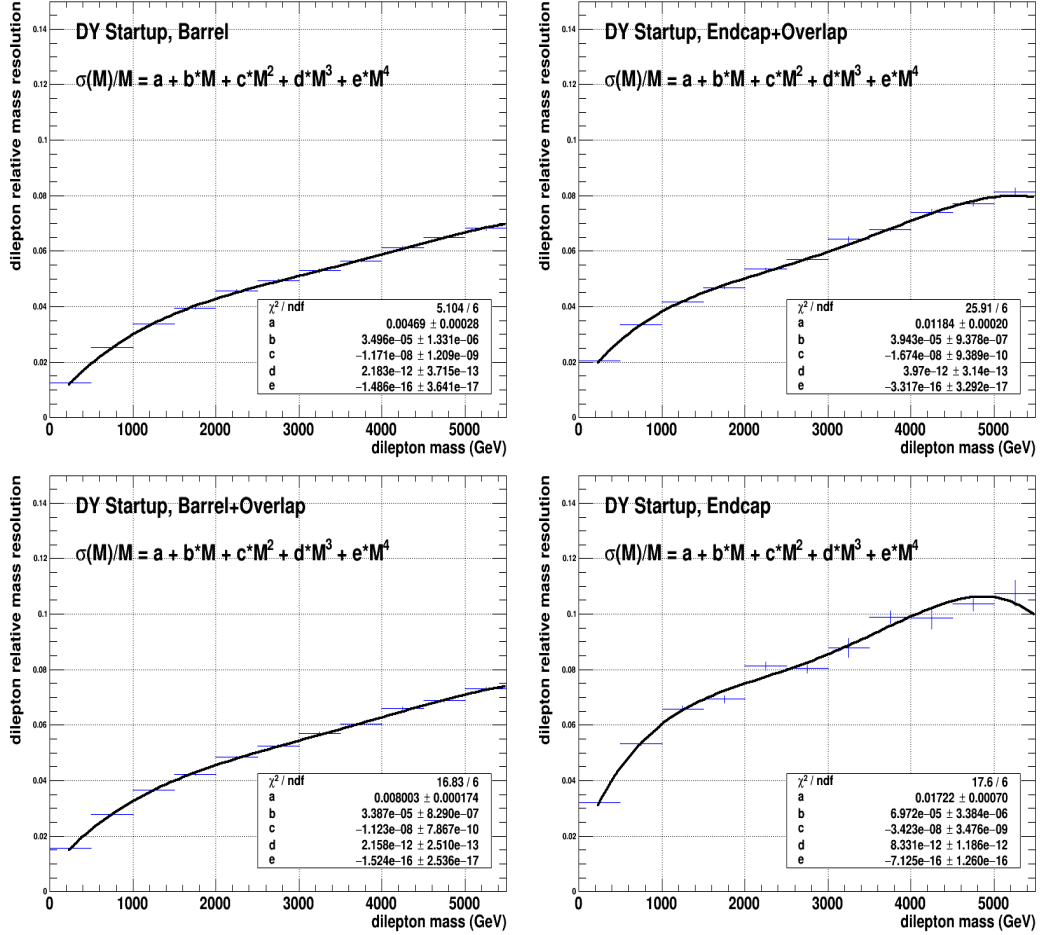


Figure 5.16: Relative invariant mass resolution $\sigma(m)/m$ as a function of dimuon invariant mass for TuneP p_T assignment and startup misalignment scenarios. Events where both muons are reconstructed in the barrel ($|\eta| < 0.9$) or in the barrel and the overlap regions ($|\eta| < 1.2$) are reported on the left side (top, bottom respectively). Events where at least one muon falls in the endcaps and the overlap regions ($|\eta| > 0.9$) or in the endcaps only ($|\eta| > 1.2$) are reported on the right side (top, bottom respectively). The fit of the resolution curve is overlaid.

5.4 Background estimation

The SM backgrounds to a Z' boson decaying into a muon pair can be divided into four categories. First, the most important background comes from the Drell-Yan process. This background has the same final state as the signal and is, thus, irreducible.

The second category contains those processes which produce real prompt muons where the two prompt muons are from different particles, usually W bosons. The dominant processes here are $t\bar{t}$, tW and WW processes. WZ and ZZ processes are also included in this category as they can only produce a significant background when both of the muons are not from the same Z boson.

The third category is the background arising from non-prompt and misidentified muons. This occurs when one or more of the muons is wrongly identified as a prompt muon. The muon may be a real lepton, for example due to a b -jet decay, or a jet misidentified as a muon. The dominant processes in this category are dijets, where both jets give rise to a misidentified prompt muon, W +jets, where there is a real muon from the W decay and a jet which gives rise to a misidentified prompt muon.

The final category of background consists of cosmic rays hitting the detector in time with collision events. This is highly suppressed by requiring a reconstructed vertex in the event and applying cuts on the muons impact parameters as well as on the 3D angle between the muons. These cuts reduce the cosmic ray background to negligible levels.

More details about the estimation of Drell-Yan, $t\bar{t}$ like and jet backgrounds are described respectively in Sections 5.4.1, 5.4.2, and 5.4.3.

5.4.1 Drell-Yan background

Drell-Yan events are the largest irreducible source of background in this analysis, $\sim 70\%$ of the total background rate for dimuon masses above 200 GeV, and are simulated using the POWHEG event generator interfaced to PYTHIA 8, as said in Section 5.1.1. The values of the Drell-Yan NLO cross section in POWHEG in different mass intervals are listed in Table 5.2. In order to take into account the next-to-next-to-leading order (NNLO) QCD corrections, these values are scaled to NNLO by using a K -factor equal to 1.006 computed as ratio of the standard model FEWZ [77] cross section for $M > 50$ GeV [78] to the POWHEG cross section.

The expected event rates at dimuon masses above the Z peak are obtained

by the following formula:

$$N_{\text{DY}}^{\text{Exp}}(M_{\mu\mu} \gg m_Z) = N_{\text{DY}}^{\text{Obs}}(M_{\mu\mu} \gg m_Z) \times \frac{N_{\text{DY}}^{\text{Exp}}(60 < M_{\mu\mu} < 120 \text{ GeV})}{N_{\text{DY}}^{\text{Obs}}(60 < M_{\mu\mu} < 120 \text{ GeV})} \quad (5.1)$$

where $N_{\text{DY}}^{\text{Exp}}(60 < M_{\mu\mu} < 120 \text{ GeV})$ is the number of expected events under the Z peak, $N_{\text{DY}}^{\text{Obs}}(M_{\mu\mu} \gg m_Z)$ and $N_{\text{DY}}^{\text{Obs}}(60 < M_{\mu\mu} < 120 \text{ GeV})$ are the number of observed events at higher masses and under the Z peak, respectively.

By taking the ratio of observed events at higher masses to events in the normalization region, the dependence on experimental acceptance, trigger and offline efficiencies is eliminated to first order, leaving only a residual dependence on the variation of these quantities with invariant mass.

The number of events expected from Drell-Yan processes, with an integrated luminosity of 2.8 fb^{-1} , are reported in Table 5.6. The uncertainties quoted are statistical only.

Mass region (GeV)	Z/γ^* (MC)
120–200	12717 ± 28
200–400	3983 ± 16
> 400	446 ± 5

Table 5.6: Number of events expected from Drell-Yan processes with an integrated luminosity of 2.8 fb^{-1} . The uncertainties quoted are statistical only.

5.4.2 Background from $t\bar{t}$ and other sources of prompt leptons

The largest background after the Drell-Yan contribution, $\sim 29\%$ of the total background rate for dimuon masses above 200 GeV, comes from $t\bar{t}$ and $t\bar{t}$ like decays. Most of the $t\bar{t}$ decays which end in our selection are events in which both W bosons decayed leptonically.

These backgrounds are again estimated from Monte Carlo simulated processes and the prediction from the Monte Carlo simulation is validated using $e\mu$ events as these processes should produce twice as many $e\mu$ events compared to $\mu\mu$ events.

The number of dimuon background events is estimated from the $e\mu$ spectrum:

$$N_{\mu^+\mu^-}^{\text{exp}} = SF_{\text{MC}} \times N_{e^\pm\mu^\mp}^{\text{obs}} \quad (5.2)$$

where $N_{e^\pm\mu^\mp}^{obs}$ is the number of dileptons found in data, while SF_{MC} is derived from simulation.

To estimate the contribution to the dimuon spectrum from $t\bar{t}$ and other sources of prompt leptons, 2.1 fb^{-1} of data from the lumisections in which all subdetectors are certified as good have been used.

In each $e\mu$ pair, the muon is required to pass the full selection as given in Sec. 5.1.3. For electron identification, the official selection provided by the high-energy electron pairs (HEEP) group is applied. An electron veto is also applied to filter out all of those electrons produced by muon bremsstrahlung. For the $e\mu$, a fit to a common vertex to calculate the invariant mass is not performed.

Figure 5.17 shows the observed $e^\pm\mu^\mp$ dilepton invariant mass spectrum overlaid with the prediction from simulation. The prediction from simulation is normalized to the luminosity estimate. Good agreement is seen in the $e\mu$ channel between the observed data and the predicted background that suggests we can rely on MC simulations to derive the scale factors to be used on data.

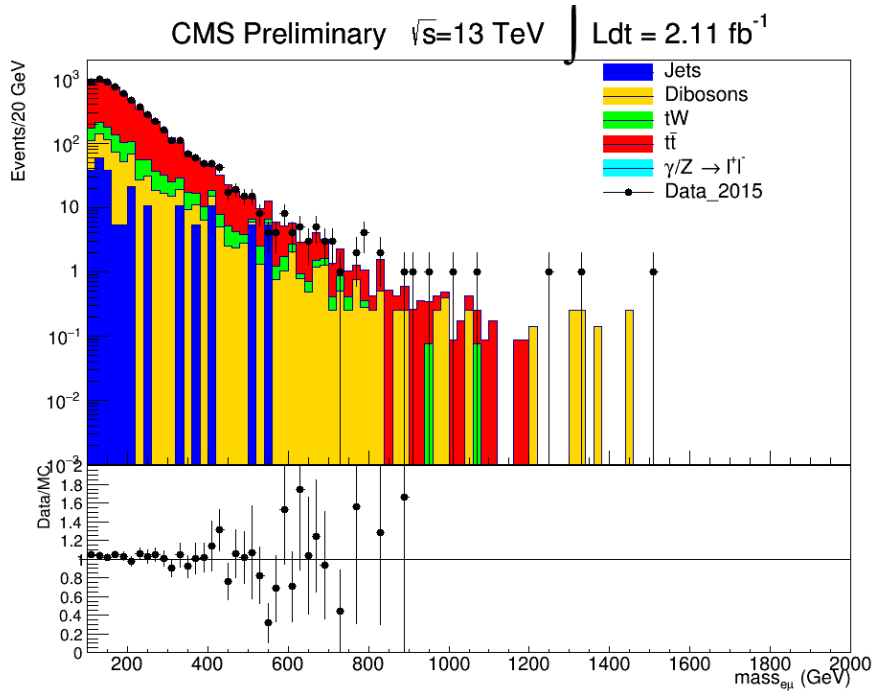


Figure 5.17: Invariant mass spectrum for opposite–sign $e\mu$ events in data (black dots) and simulation (stacked histogram). The simulated distribution has been normalized to the data luminosity of 2.1 fb^{-1} . The ratio between data and simulation shows a good agreement.

There are several decay processes that originate this dimuon background, among which the dominant one is the $t\bar{t}$ ($\sim 75\%$ of all simulated processes in the $e\mu$ mass spectra). This is the main reason to derive the scale factors (SF) from $t\bar{t}$ simulation without worrying about the different contamination rates from the various smaller contribution from other processes. Figure 5.18 (left) shown the number of simulated $t\bar{t}$ events used to derive the $\mu\mu/e\mu$ scale factors, plotted in Figure 5.18 (right). Furthermore the scale factors for the

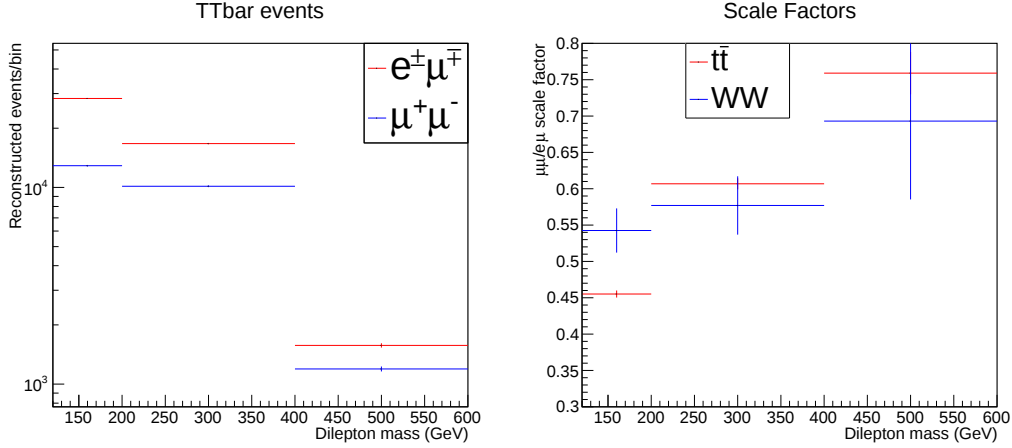


Figure 5.18: Number of simulated $t\bar{t}$ events used to derive the $\mu\mu/e\mu$ scale factors, with the binning representing the considered dilepton mass ranges (left). The $\mu\mu/e\mu$ scale factors derived separately from $t\bar{t}$ and WW simulated samples (right).

next largest contribution, WW ($\sim 10\%$ of all simulated processes in the $e\mu$ mass spectra), are quite close to those from $t\bar{t}$, as shown by the blue histogram and error bars in Figure 5.18 (right).

The number of expected dimuons has been estimated in three mass bins: $120 < m < 200$ GeV, $200 < m < 400$ GeV, and $m > 400$ GeV, and consequently the $t\bar{t}$ scale factors has been derived in each reconstructed mass bin according to:

$$SF_{MC} = \frac{N_{MC \rightarrow \mu^+ \mu^-}}{N_{MC \rightarrow e^\pm \mu^\mp}} \quad (5.3)$$

Table 5.7 lists values of scale factors and numbers of observed $e^\pm \mu^\mp$ in data and expected $\mu^+ \mu^-$ in data and simulation. We highlight the result that overlaps more with the range of masses in which we are searching for a resonance signal, namely for $m > 400$ GeV: the $e\mu$ method predicts 168 ± 12 dimuon events from these processes, while the simulation predicts 165 ± 8

events (the first uncertainty is the combination of the statistical and systematic uncertainties; the latter includes only the dominant which is the luminosity uncertainty of 4.6%).

Mass range	$N(e^\pm\mu^\mp)$ observed	$\mu\mu/e\mu$ scale factor	$N(\mu^+\mu^-)$, data prediction	$N(\mu^+\mu^-)$, sim. prediction
120–200 GeV	3223	0.455 ± 0.005	1467 ± 27	14775 ± 68
200–400 GeV	1857	0.607 ± 0.008	1127 ± 28	1160 ± 53
> 400 GeV	221	0.759 ± 0.029	168 ± 12	165 ± 8

Table 5.7: Comparison of numbers of dimuon events predicted using the $e\mu$ method with data to the values from simulation of the relevant processes, scaled to the integrated luminosity of 2.1 fb^{-1} . Estimates have been calculated in three different invariant-mass ranges. The quoted errors are the combination of the statistical and systematic uncertainties as described in the text.

5.4.3 Jet background

The contribution to the total background due to objects falsely identified as prompt muons, or “fake” muons is lower than 1% above a mass of 200 GeV. The main source of such background is the misidentification of jets as muons. This background is estimated using the “fake rate” (FR) technique by first measuring the probability for a misidentified prompt lepton passing a loose selection, presented in Table 5.8, to then pass the full selection (High p_T ID and isolation).

variable	cut value
$ dz $	< 1.0
$ dxy $	< 0.2
Nb. of Tracker Layers with Measurement	> 5
Nb. of Valid Pixel Hits	> 0

Table 5.8: The selection requirements to define the control region for the fake rate calculation.

The FR is derived first by using both QCD MC samples and data. Events are selected between those passing the trigger requirements. The loose-selection pointed above define a control region enriched in QCD events with a non-negligible contamination from W +jets, DY +jets, $t\bar{t}$, which are large at low

$M_{\mu\mu}$ and gets smaller as the p_T increases. The contamination in data coming from different electroweak processes was evaluated using simulation, and the relative contribution was subtracted from data.

The resulting fake rate from data and the best fit function, as a function of muons transverse momentum, are shown in Figure 5.19 for muons reconstructed in the barrel (left) and in the endcaps with $50 < p_T < 110$ GeV (middle), and $p_T > 110$ GeV (right). The functional form using the best fit

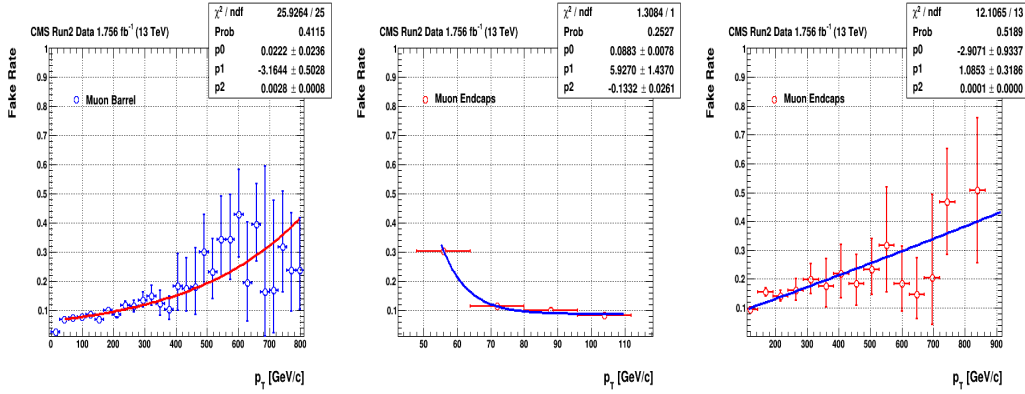


Figure 5.19: Best fit of the fake rate vs transverse momentum of muons in the muon barrel and in the endcap; the functional forms are reported in Table 5.9 for the barrel (left) and for the endcaps in the range $p_T < 110$ GeV (middle) and in the range $p_T > 110$ GeV (right).

parameters is reported in Table 5.9. The fake rate in the endcap is higher than in the Barrel by at least 10%.

Eta region	p_T range [GeV]	functional form
Barrel	$p_T > 50$	$2.22 \times 10^{-2} + \exp(-3.16 + 2.80 \times 10^{-2} \times p_T)$
Endcap	$p_T < 110$	$8.83 \times 10^{-3} + \exp(5.93 - 1.33 \times 10^{-1} p_T)$
Endcap	$p_T > 110$	$-2.91 + \exp(1.08 + 1.32 \times 10^{-4} \times p_T)$

Table 5.9: Functional forms of the measured fake rate in barrel and endcap parts of the muon detector.

The dijet background contribution in the signal region can be estimated by applying the measured FR probability to events from data and simulated QCD, $t\bar{t}$, $DY \rightarrow \mu\mu$, ZZ and WZ processes, with two muons failing the High p_T ID and the isolation requirements, while passing the loose selection and the matching with HLT objects. Each event is weighted by $FR/(1 - FR)$ twice.

The estimate of the W+jets background in the signal region is derived by applying the measured FR probability to MC simulated events in which one muon passes the full selection and the other fails the identification and isolation requirements, while passing the loose selection. Each MC event is then weighted by $FR/(1 - FR)$ once.

The non-negligible contamination from Drell–Yan and $t\bar{t}$ events, which is large at low mass and gets smaller as the mass increases, is evaluated using simulation and subtracted from data.

The opposite-sign and same-sign dimuon background spectra derived with the fake rate method by using data and MC are shown in Figure 5.20, with an integrated luminosity of 2.6 fb^{-1} . A good agreement between the prediction of dimuon spectrum from MC and data is observed.

Different sources of systematic uncertainty need to be taken into account in the calculation of the fake rate. The first source is the difference in jet kinematic spectra between fake enriched control region and the signal region, that may lead to a different source of fake muon candidates. The second one, that affects only W+jets, is the different quark content in W+jets processes (dominant source of prompt-fake events) and QCD one (source of fake-fake events). A safe 50% uncertainty is assigned for dijet yield, while a maximum deviation of 25% is assigned for W+jets yield.

The number of events for dijet as estimated from MC simulation and from data using the FR method, after subtracting the electroweak contamination, is reported in Tables 5.10. The prediction for W+jets background in the signal region, obtained by applying the fake rate method to simulation, is reported in Table 5.11. The large statistics of events in the control region ensures a small statistical error compared to the systematic uncertainty.

The method confirms that the contribution from jet-related backgrounds to the selected sample of opposite-sign dimuon events is negligible compared to other SM backgrounds in all mass regions.

Mass region (GeV)	dijet OS (data)	dijet OS (MC)	dijet SS (data)	dijet SS (MC)
120–200	$29.7 \pm 6.9 \pm 14.9$	$33.9 \pm 0.6 \pm 17.0$	$19.6 \pm 1.4 \pm 9.8$	$13.0 \pm 0.4 \pm 6.5$
200–400	$14.4 \pm 4.8 \pm 7.2$	$10.8 \pm 0.3 \pm 5.4$	$11.4 \pm 1.1 \pm 5.7$	$14.2 \pm 0.4 \pm 7.1$
> 400	$1.0 \pm 1.3 \pm 0.5$	$3.3 \pm 0.2 \pm 1.7$	$1.4 \pm 0.4 \pm 0.7$	$4.0 \pm 0.2 \pm 2.0$

Table 5.10: Data-driven prediction of the dimuon background from dijet events, for both opposite-sign (OS) and same-sign (SS) events. The quoted uncertainties are statistical (first) and systematic (last). Numbers are estimated for an integrated luminosity of 2.6 fb^{-1} .

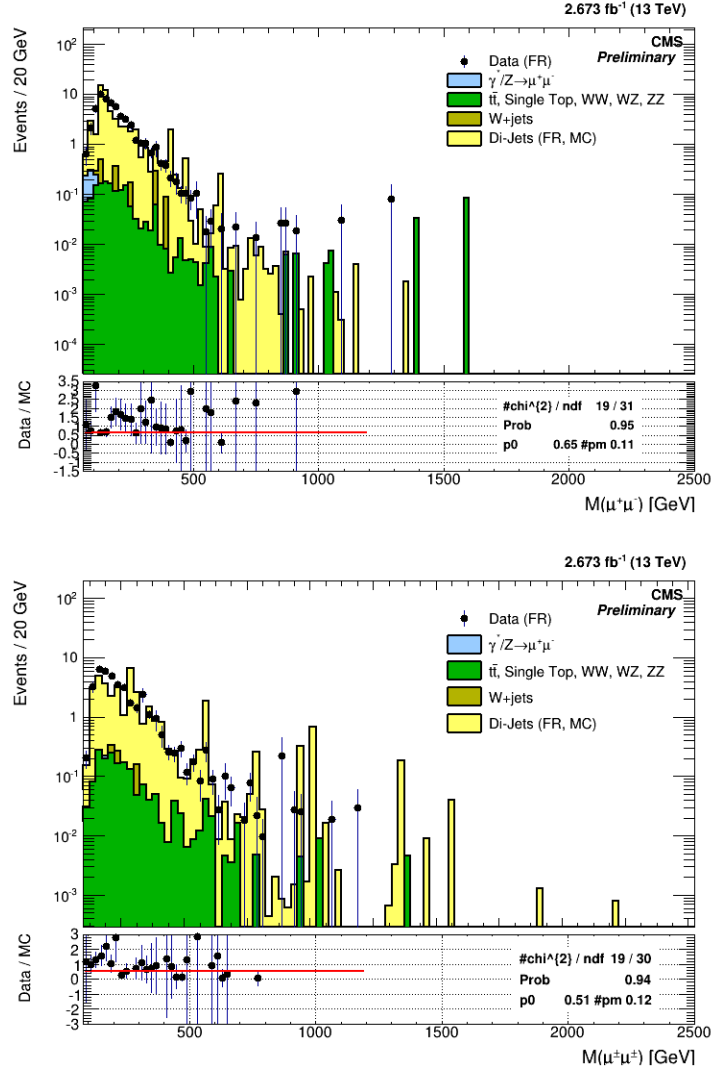


Figure 5.20: The dijet estimated backgrounds for events with two muons passing the loose selection and failing the High p_T ID and isolation, using data and MC simulated events. The opposite-sign di-jet (left) and same-sign (right) predictions are reported after the subtraction of other backgrounds contributing via MC.

Mass region (GeV)	W+jets OS (MC)	W+jets SS (MC)
120–200	$40.3 \pm 1.9 \pm 10.1$	$21.8 \pm 1.5 \pm 5.5$
200–400	$42.7 \pm 2.0 \pm 10.7$	$18.4 \pm 1.3 \pm 4.6$
> 400	$3.8 \pm 0.6 \pm 1.0$	$2.2 \pm 0.5 \pm 0.5$

Table 5.11: Data-driven prediction of the dimuon background from W+jets events, for both opposite-sign (OS) and same-sign (SS) events. The uncertainties are statistical and systematic. Numbers are estimated for an integrated luminosity of 2.6 fb^{-1} .

5.5 Invariant mass spectrum

The observed mass spectra together with the predicted SM backgrounds, for dimuon events selected as described in Section 5.1, are shown in Figure 5.21. The SM background estimations are obtained from simulations and from data, following the methods explained in Section 5.4. The MC samples of the background processes are listed in Tables 5.2 and 5.3. Data correspond to an integrated luminosity of 2.8 fb^{-1} . The distribution from each simulated sample is scaled by weights derived from the information presented in Table 5.2.

The MC simulated events for all processes are normalised such that the total background prediction agrees with the data in the mass region from 60 to 120 GeV. The default cuts described in Section 5.1.3, in particular, the trigger and the offline p_T cut requests, cut heavily into the Z peak in this region. For the final counting of events at the Z peak a prescaled trigger HLT_Mu27 and a correspondingly reduced value of 30 GeV for the p_T cut for the offline muon is used. As described in Section 5.1.2, the whole dataset has been divided into sub-datasets with different prescale factors (reported in Table 5.5), and for each sub-dataset the ratio between observed events from data and MC predictions at the Z peak has been computed. An average overall factor of 1.024 is obtained.

Figure 5.22 shows cumulated versions of the invariant mass spectra, with each bin containing the number of events with an invariant mass greater or equal to the bin mass.

The observed mass spectrum agrees well with that of the predicted SM background. Event counts for both the data and simulation are listed in Table 5.12.

The event with the highest invariant mass selected has $m(\mu\mu) = 2396 \text{ GeV}$ and an event display is shown in Figure 5.23.

To further compare the measurement with the theory prediction, a Z cross section measurement is performed in the region from $60 < M < 120 \text{ GeV}$ using

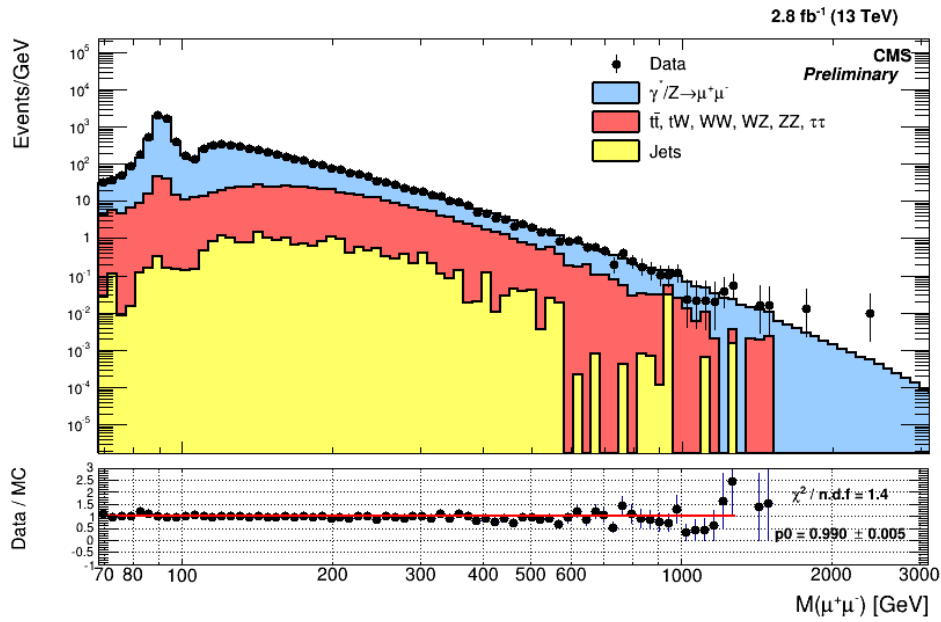


Figure 5.21: Invariant mass spectrum of dimuon events. The points with error bars represent the data. The histograms represent the expectations from standard model processes: Z/γ^* , $t\bar{t}$ and other sources of prompt muons (tW , diboson production, $Z \rightarrow \tau\tau$), and the multijet backgrounds. Multijet backgrounds contain at least one jet that has been misreconstructed as a muon. The Monte Carlo simulated backgrounds are normalised to the data in the region of $60 < M < 120$ GeV, using events collected using a prescaled lower threshold trigger for this purpose.

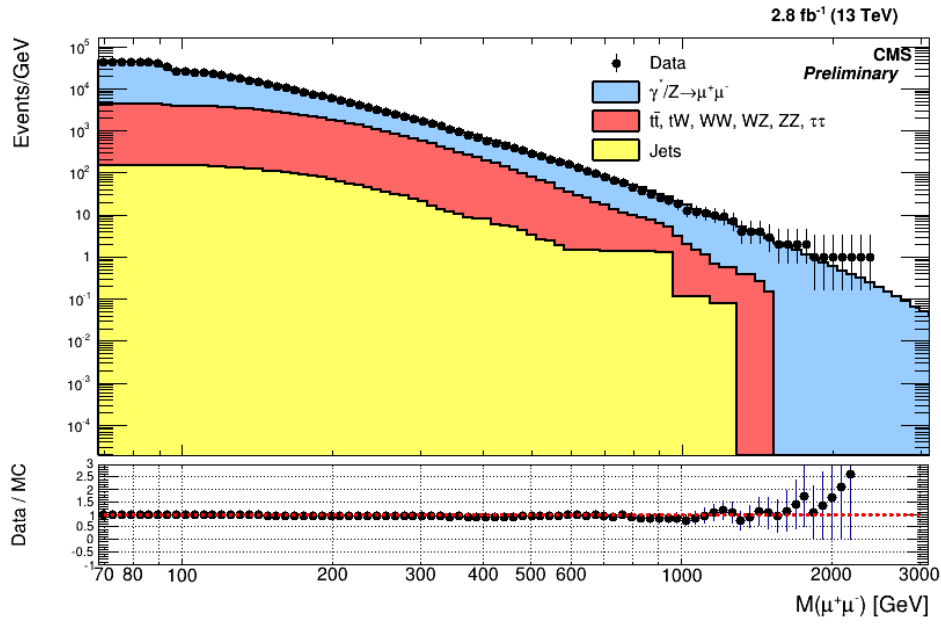


Figure 5.22: Number of opposite-sign dimuons with invariant mass greater than the given value Cumulative invariant mass spectrum of dimuon events. The points with error bars represent the data. The histograms represent the expectations from standard model processes: Z/γ^* , $t\bar{t}$ and other sources of prompt muons (tW , diboson production, $Z \rightarrow \tau\tau$), and the multijet backgrounds. Multijet backgrounds contain at least one jet that has been misreconstructed as a muon. The Monte Carlo simulated backgrounds are normalised to the data in the region of $60 < M < 120$ GeV, using events collected using a prescaled lower threshold trigger for this purpose.

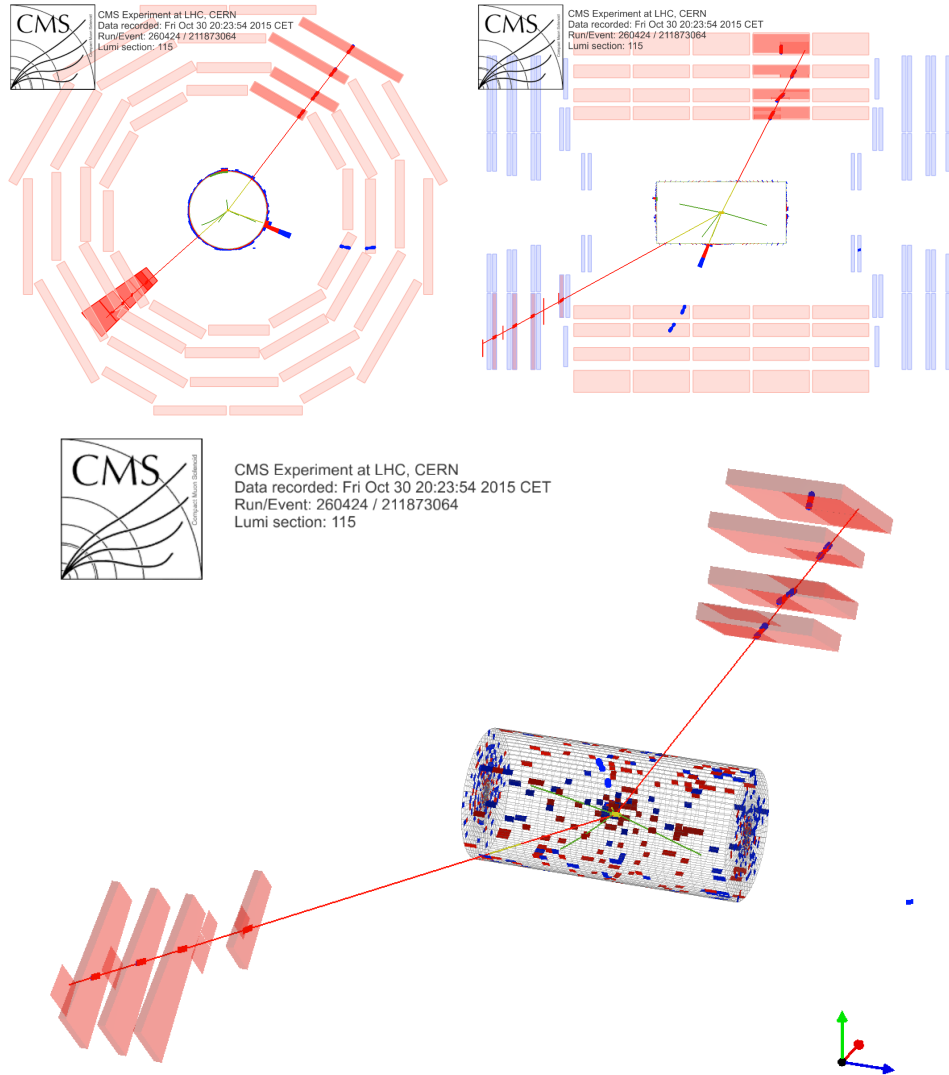


Figure 5.23: Event displays of the highest invariant mass $\mu^+\mu^-$ events selected, with a mass of 2396 GeV. The top left plot shows the event in the $\rho - \phi$ plane of the detector and the top right plot shows the $\rho - z$ plane. The red tracks indicate the muons. The bottom plot shows magnified a 3D view of the event.)

	Number of events		
	120–200 GeV	>200 GeV	>400 GeV
	Data		
	14514	5461	567
Source	Background		
Total	14598 ± 497	5639 ± 185	631 ± 38
Z/γ^*	12710 ± 487	3980 ± 161	445 ± 34
$t\bar{t}$	1452 ± 101	1292 ± 91	135 ± 15
Other prompt leptons	368 ± 19	319 ± 17	45 ± 7
Multi-jet events	68 ± 13	48 ± 12	6 ± 2

Table 5.12: Number of dimuon events with invariant mass in the control region 120–200 GeV and in the search regions $m > 200$ GeV and > 400 GeV. The total background is the sum of the SM processes listed. The MC yields are normalized to the expected cross sections. Uncertainties include both statistical and systematic components added in quadrature.

the following formula:

$$\sigma_Z = \frac{N_Z}{A \times \epsilon \cdot SF_\epsilon \cdot \mathcal{L}} \quad (5.4)$$

where $N_Z = N_{data} - N_{bkg}$ is the pure Z event yield evaluated as the difference between the event yields for data N_{data} and the non-DY backgrounds N_{bkg} , $A \times \epsilon$ is the acceptance times efficiency at the Z mass, SF_ϵ is the selection efficiency scale factor for dimuons and $\mathcal{L}$ is the integrated luminosity.

Using the prescaled trigger HLT_Mu27, as described in Section 5.1.2, 20189 events have been found in the data and, after subtracting background ($t\bar{t}$, dibosons, single top, $\tau\tau$), the estimate number of events in data coming from Drell-Yan (N_Z) contribution is 20064 events. The acceptance times efficiency of both trigger and offline reconstruction, estimated by simulations, corresponds to $A \times \epsilon = 0.3006$ and the overall offline scale factor to $SF_\epsilon = 0.9759$ (per event) from tag-and-probe studies for efficiencies of high- p_T identification and relative tracker-based isolation. According to the recommendations for systematic uncertainties issued by the Muon POG, additional 1% systematic uncertainties are assigned for both identification and isolation scale factors and, adding them in quadrature, a systematic uncertainty of 2.8% per event is obtained.

The measured value for the Z production cross section at $\sqrt{s} = 13$ TeV is: $\sigma(Z) \times \text{Br}(Z \rightarrow \mu^+\mu^-) = 1887 \pm 53 \pm 226$ pb. It agrees well with the result published by CMS using 43 pb⁻¹: $\sigma(pp \rightarrow ZX) \times \text{Br}(Z \rightarrow \mu^+\mu^-) = 1910 \pm 10$ (stat) ± 40 (syst) ± 90 (lumi) pb [79].

No excesses over the SM expectation are seen in the invariant mass spectra

that would indicate new physics.

5.6 Statistical interpretation

The analysis follows the approach of a shape-based search for a resonance in the dimuon mass spectrum [2]. Existence (or lack) of a signal is established by performing a Bayesian unbinned maximum likelihood fits to the observed dimuon mass spectrum. In the absence of an excesses over the SM expectation, 95% confidence level upper limits on the ratio of cross sections R_σ of a new resonance to the Z resonance are calculated. Such ratio is defined as:

$$\begin{aligned} R_\sigma &= \frac{\sigma(pp \rightarrow Z' + X \rightarrow \mu^+ \mu^- + X)}{\sigma(pp \rightarrow Z + X \rightarrow \mu^+ \mu^- + X)} \\ &= \frac{N(Z' \rightarrow \mu^+ \mu^-)}{N(Z \rightarrow \mu^+ \mu^-)} \times \frac{A(Z \rightarrow \mu^+ \mu^-)}{A(Z' \rightarrow \mu^+ \mu^-)} \times \frac{\epsilon(Z \rightarrow \mu^+ \mu^-)}{\epsilon(Z' \rightarrow \mu^+ \mu^-)}, \end{aligned} \quad (5.5)$$

where N is the number of events, A is the detector acceptance, and ϵ is the total selection efficiency.

5.6.1 Modelling of signal and background shapes

The probability density function (pdf) is modeled as the sum of a resonant signal pdf f_{sig} and a steeply falling background pdf f_{bkg} .

The pdf for the signal, $f_{sig}(m | \Gamma, M, w)$, is modeled as the convolution of a nonrelativistic Breit–Wigner of width Γ and mass M with a Gaussian of width w , where the Breit-Wigner models the resonance and the Gaussian models the detector resolution. The width of the resonance in the models considered are 3% for Z'_{SSM} and 0.6% for Z'_Ψ .

The detector mass resolution $\sigma_{\mu^+\mu^-}(m)$ is calculated from a fit to Drell–Yan Monte Carlo with tracker-based (startup) alignment, as shown in Figure 5.14. It is parametrised as

$$\sigma_{\mu^+\mu^-}(m) = e^{a+b \cdot m+c \cdot m^2+d \cdot m^3+e \cdot m^4}, \quad (5.6)$$

where $a = 0.0093 \pm 0.0002$, $b = 3.797 \pm 0.070 \times 10^{-5}$, $-1.496 \pm 0.068 \times 10^{-8}$, $d = 3.207 \pm 0.223 \times 10^{-12}$, and $e = -2.46 \pm 0.23 \times 10^{-16}$. The detector resolution is the dominant contribution to the total signal width.

The background pdf shape is parameterised fitting the simulated dimuon mass spectrum from Figure 5.21 representing a weighted sum of all backgrounds generated with the track-based (startup) alignment. The fit, per-

formed in the mass range 200–5500 GeV, is shown in Figure 5.24. The functional form obtained is:

$$f_{bkg}(m | a, b, c, d, e) = e^{a+b\cdot m+c\cdot m^2+d\cdot m^3} m^e, \quad (5.7)$$

and the parameter values extracted from the fits are $a = 25.2457$, $b = -0.00239286$, $c = 3.19923 \times 10^{-07}$, $d = -3.38796 \times 10^{-11}$, and $e = -3.3634$.

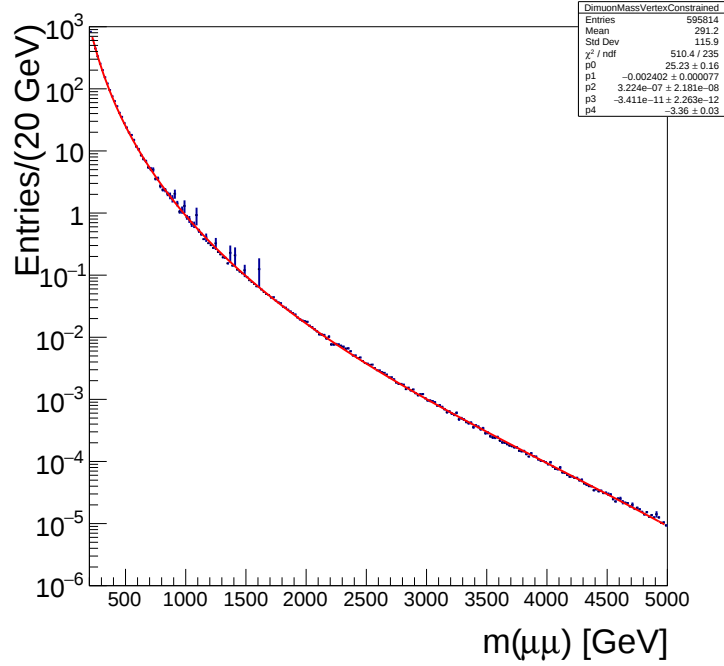


Figure 5.24: The fit to background Monte Carlo dimuon spectrum.

5.6.2 Limit setting procedure

The extended unbinned signal-plus-background likelihood function used is the following:

$$\mathcal{L}(\mathbf{m}|R_\sigma, \boldsymbol{\nu}) = \frac{\mu(R_\sigma, \boldsymbol{\nu})^N e^{-\mu(R_\sigma, \boldsymbol{\nu})}}{N!} \cdot \prod_{i=1}^N \left(\frac{\mu_{sig}(R_\sigma, \boldsymbol{\nu})}{\mu(R_\sigma, \boldsymbol{\nu})} f_{sig}(m_i|\boldsymbol{\nu}) + \frac{\mu_{bkg}(\boldsymbol{\nu})}{\mu(R_\sigma, \boldsymbol{\nu})} f_{bkg}(m_i|\boldsymbol{\nu}) \right), \quad (5.8)$$

where the product is taken over all N events observed above 200 GeV (events in the dataset $\mathbf{m}$), $\boldsymbol{\nu}$ is the vector of the nuisance parameters, and $\mu(R_\sigma, \boldsymbol{\nu}) =$

$\mu_{sig}(R_\sigma, \boldsymbol{\nu}) + \mu_{bkg}(\boldsymbol{\nu})$ is the sum of the Poisson mean of the signal and background event yields (total number of events expected).

The expected signal yield μ_{sig} is a function of the parameter of interest R_σ , defined in Equation (5.5), via the formula

$$\mu_{sig} = R_\sigma \frac{(A \times \epsilon)_{Z'}}{(A \times \epsilon)_Z} N_Z, \quad (5.9)$$

where $(A \times \epsilon)_{Z'}$ and $(A \times \epsilon)_Z$ are, respectively, the acceptance times efficiency of the Z' and the Z , and N_Z is the number of selected events at the Z peak. The product of the selection efficiency and the detector acceptance ϵ , parametrized as a function of the mass, has been shown in Figure 5.9.

Starting from Equation 5.8, confidence intervals are computed using Bayesian approach, multiplying $\mathcal{L}$ by prior pdfs for the parameters of the model, thus obtaining a posterior pdf in them.

$$f(R_\sigma | \mathbf{m}, \boldsymbol{\nu}) \cdot p(\mathbf{m}) = \mathcal{L}(\mathbf{m} | R_\sigma, \boldsymbol{\nu}) \cdot p(R_\sigma, \boldsymbol{\nu}), \quad (5.10)$$

where $p(R_\sigma, \boldsymbol{\nu})$ is the prior pdf for the parameters in the model. After integrating over the nuisance parameters $\boldsymbol{\nu}$

$$p(R_\sigma | \mathbf{m}) \cdot p(\mathbf{m}) = \mathcal{L}(\mathbf{m} | R_\sigma) \cdot p(R_\sigma), \quad (5.11)$$

that links the posterior pdf $p(R_\sigma | \mathbf{m})$ to the prior pdf $p(R_\sigma)$ using the likelihood function. A positive, flat prior is used for the signal cross section (which yields good frequentist coverage properties, since μ_{sig} is Poisson mean), and log-normal priors for the systematic uncertainties.

For the posterior pdf, it follows that

$$p(R_\sigma | \mathbf{m}) = \frac{\mathcal{L}(\mathbf{m} | R_\sigma) \cdot p(R_\sigma)}{p(\mathbf{m})} = \frac{\mathcal{L}(\mathbf{m} | R_\sigma) \cdot p(R_\sigma)}{\int \mathcal{L}(\mathbf{m} | R_\sigma) \cdot p(R_\sigma) dR_\sigma}. \quad (5.12)$$

Only events in a window of ± 6 times the mass resolution around the probed signal mass are considered in the likelihood fit. At high masses, the edges of the window are symmetrical adjusted so that there is a minimum of 400 events in the window (corresponding to 5% statistical uncertainty in the estimation of the local mean background μ_{bkg} , chosen to dominate expected systematic uncertainties in the background shape at high mass). The prior for μ_{bkg} is a broad 20% log-normal (chosen slowly varying over the range where the likelihood function is not-negligible, several times wider than the statistical uncertainty on the measurement of μ_{bkg}) that results in a posterior pdf for μ_{bkg} dominated by the likelihood.

Given the posterior pdf for the parameter of interest R_σ , the 95% C.L. upper limit R_σ^{95} is defined by the following condition:

$$\int_0^{R_\sigma^{95}} p(R_\sigma|\mathbf{m})dR_\sigma = 0.95. \quad (5.13)$$

Two different methods can be used for the posterior pdf integration providing a cross check in the limit setting. The Metropolis-Hastings algorithm [80], a Markov Chain Monte Carlo (MCMC) method, is used as the primary method for integration. Alternatively, an asymptotic method can be used for the integration, implemented in a different code. Having the two methods for generating the limits provides a cross check.

The limits are set assuming a narrow resonance, specifically this means the observed limit is a limit on the on-shell cross section only and does not include contributions from interference or PDF effects. This is also referred to in the literature as the cross section calculated in the narrow width approximation. The cross-sections are corrected for next-to-leading order effects by applying a flat k-factor of 1.3.

Expected limits

We compare the observed upper limits on the cross section ratio R_σ with an expectation, given the model and the background-only hypothesis. Under the assumption that there is no signal, pseudo-data are generated following the background shape. The 95% C.L. limit for this pseudo-data is then estimated using the same procedure used for the observed limits. The expected limit is then obtained as the median of the set of limits computed using an ensemble of randomly drawn pseudo-datasets. In addition to the expected limits, bands defining the $\pm 1\sigma$ and $\pm 2\sigma$ uncertainty on the expected limit are also calculated from the distribution of the 95% C.L. limits of the pseudo-datasets.

5.6.3 Systematic uncertainties

Our analysis technique explores only the difference in shape (and not in absolute levels) between the mass spectra of the signal and that of background. Since the limits are set on the ratio R_σ of $\sigma \times Br$ for high-mass resonances to that for the Z boson, a number of experimental and theoretical uncertainties have a negligible or small impact on the results. All p_T independent effects (both known and unknown) cancel out, one example is the uncertainty on the integrated luminosity. It follows that only the mass dependence of the uncertainty in the muon reconstruction efficiency needs to be taken into account,

not the absolute uncertainty. The same is true for the trigger efficiency and the uncertainty in the mass scale.

The following sources of uncertainties have been studied and their impacts on the background and signal shape are presented below for the most relevant ones:

- mass-dependent uncertainty in the triggering and reconstruction efficiency is taken from the difference between data and simulation (DY) efficiencies, and is set at 15% to be conservative;
- momentum resolution and alignment effects, as explained in Section 4.2.1, are estimated, in the barrel, from comparison between data (cosmic) and MC (DY) in the highest p_T bin available (500 GeV-2 TeV) and comparing Z resolution in data and MC in the endcaps. An extra smearing of 4% on $1/p_T$ resolution, per muon, is needed to correct resolutions obtained from simulations. This extra smearing corresponds to 80% of the muon momentum resolution obtained in MC and is then depending on the muon p_T .

Propagating this extra smearing to the invariant mass for all MC samples and looking at the effects on the background shape, an uncertainty of 10% on the background yield over the full range (1-4 TeV) is evaluated;

- the scale bias on the muon p_T , as explained in Section 5.2, is found to be $\Delta k = 0.1$ c/TeV for muon in barrel. This number has been established using endpoints method using cosmic. Generalized endpoint method with DY events in collisions found compatible number and estimated the endcaps bias to 0.2 c/TeV. Each muon, according to its position, and to its charge, is shifted by $\pm \Delta k$ in order to increase (decrease) $\mu^+(\mu^-)$ momentum or decrease (increase) $\mu^+(\mu^-)$ momentum.

Propagating the effect of the momentum scale to the invariant mass for all MC samples and looking at the effects on the background shape, an uncertainty on the background yield of 5% (1-2 TeV) up to 15% (3-4 TeV) is obtained;

- the impact of PDF uncertainties on the cross section of the dominant Drell–Yan background is evaluated using the program FEWZ version 3.1b2 [82], following the recommendations from the PDF4LHC group [83]. The estimates are based on the MSTW2008 [84], CTEQ12 [85], and NNPDF23 [86] NLO PDF sets available from the LHAPDF library [87], using the reweighting technique [88]. The calculations are performed inside the CMS acceptance used for this analysis. The overall uncertainty

from the three PDF sets combined varies from 2% at $M_{\mu\mu} = 1$ TeV to about 12% at $M_{\mu\mu} = 4$ TeV, as shown in Figure 5.25.

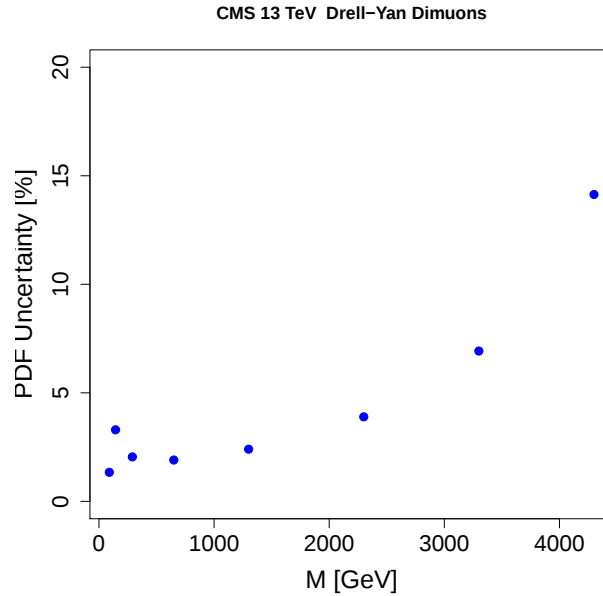


Figure 5.25: PDF uncertainties at 13 TeV, calculated with FEWZ in the CMS acceptance.

Systematic uncertainties explicitly modelled in the limit calculations correspond to the uncertainty on the signal strength (which consists on the uncertainty on the acceptance time efficiency ratio, estimated to be 15%), and uncertainty on the mass scale (3%, for combination with the electron channel).

The overall maximum systematic uncertainty on the background shape, combining all the different sources of systematic uncertainty in quadrature (efficiency, p_T scale bias, p_T resolution smearing and PDFs) corresponds to 26% at 3.5 TeV. The statistical procedure to estimate final limits is designed in a way to minimize the sensitivity of results to the uncertainties in the background shape. Thanks to the relatively narrow fit region, the statistical uncertainty dominates and the limits becomes robust against the variation of the functional form used to describe the background.

A systematic on the resolution parametrisation has been considered including the effects of the p_T scale and p_T resolution smearing in the Gaussian

component of the signal pdf and on the mass window used for the posterior integration.

New mass resolution parametrizations, as a function of the mass, have been evaluated (in DY MC) propagating the p_T scale corrections or the p_T smearing on the invariant mass. An increasing of the 14% at 1 TeV and 24% at 3.5 TeV is observed with respect to the values in Figure 5.14 (right). For the final limit the worse mass resolution is considered.

5.6.4 Results on the limit calculation

With the methods described above the observed and expected 95% C.L. upper limits on the ratio of the cross section of a new resonance to the cross section of the Z resonance can be calculated for resonances with spin-one. The 5% C.L. lower limits on the resonance mass of a specific model, Z'_Ψ and Z'_{SSM} in this thesis, assuming a narrow resonance hypothesis, are estimated by finding an intersection of the observed limit line and the line with the theoretical prediction. Only the on-shell cross section of the model has to be taken into account in the narrow width approximation, not including the low mass tails of resonances produced at the kinematic limit.

The inputs used to the limit setting tool is provided in Table 5.13. For the Z' -to-Z normalization, the Z cross section of 1928 pb is considered. N_{data} and N_{bkg} are, respectively, the number of events found in data and the estimated background event count in the specified mass range. The uncertainty in the background yield is discussed in Section 5.6.3. The parameterization of Z' acceptance times efficiency as a function of the dimuon invariant mass is taken from the fit in Figure 5.9 of Section 5.1.4. The invariant mass resolution parametrization is obtained from simulation as described in Section 5.3. Results reported in Figure 5.14 (right) are increased taking into account the effects of the muon momentum extra smearing and scale, as described in Section 5.6.3. Finally, the background shape parametrization is reported in Section 5.6.1, with the fit illustrated in Figure 5.24.

Figure 5.26 shows the observed and expected 95% C.L. upper limits on the ratio R_σ of the Z' production cross section times branching fraction relative to that of the Z boson for Breit-Wigner widths of 0%, 0.6% and 3%. Also shown in the plot are the predicted on-shell cross section times branching fraction ratios for the Z'_Ψ and Z'_{SSM} models reweighted with a constant NNLO to LO K-factor of 1.3. The limits exclude at 95% C.L. a Z'_Ψ with a mass lighter than 2.40 TeV and a Z'_{SSM} with a mass lighter than 3 TeV.

Figure 5.27 shows the observed and expected upper limits for an input width of 0.6%. Shaded green and yellow bands correspond to the 68% and 95% quantiles for the expected limits. The observed limit agrees with the

Input	Value
N_Z in 60–120 GeV from prescaled trigger (background subtracted)	20064
Z cross section (pb)	1928
N_{data} in $m > 200\text{GeV}$	5461
N_{bkg} in $m > 200\text{GeV}$	5639
Z' acc.×eff. fit	$\exp(0.872 - 7.85 \times 10^8 / (1 \times 10^3 + m)^3 - (m^2)/5.9 \times 10^8)$
Z' acc×eff uncertainty	15%
Mass resolution fit	$\exp(0.0093 + 3.797 \times 10^{-5}m - 1.496 \times 10^{-8}m^2 + 3.207 \times 10^{-12}m^3 - 2.46 \times 10^{-16}m^4)$
Background shape	$\exp(25.2457 - 0.00239286 \times m + 3.19923 \times 10^{-07} \times m^2 - 3.38796 \times 10^{-11} \times m^3)m^{-3.3634}$

Table 5.13: The input parameters to the limit setting code. Masses m are in GeV.

expected limits within 2σ .

The observed limits have been found robust and do not significantly change for reasonable variations of the limit setting procedure, such as varying the window of events being included in the likelihood, and changes in the background normalization and shape.

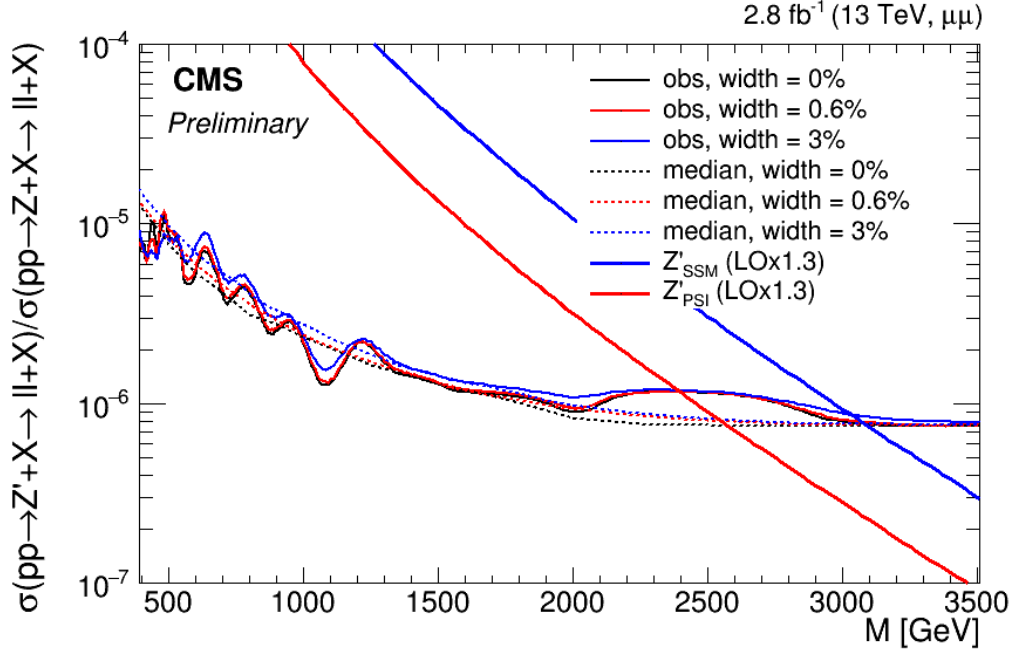


Figure 5.26: The observed and expected upper limits as a function of the resonance mass M on the ratio $R\sigma$ of the Z' production cross section time branching fraction into muon pairs relative to that of the Z boson. Breit-Wigner widths of 0%, 0.6% and 3% are considered. The median expected limit is shown as the dashed lines and the observed limit is shown as the solid lines. Also plotted are the predicted cross section times branching fraction ratios for the Z'_Ψ and Z'_{SSM} models.

Combination with the dielectron resonance search

A similar search for new resonance has been performed using the dielectron invariant mass spectrum [4]. The sensitivity of the two searches is comparable and they are combined, with the assumption that the branching ratio to dielectrons and dimuons is the same.

The highest mass event observed in the electron channel has a mass of 2.9 TeV. To put this into context, in the electron channel 0.31 ± 0.05 events are expected above 2 TeV, 0.080 ± 0.016 events are expected above 2.5 TeV and 0.036 ± 0.009 events are expected above 2.8 TeV. The local p-value for

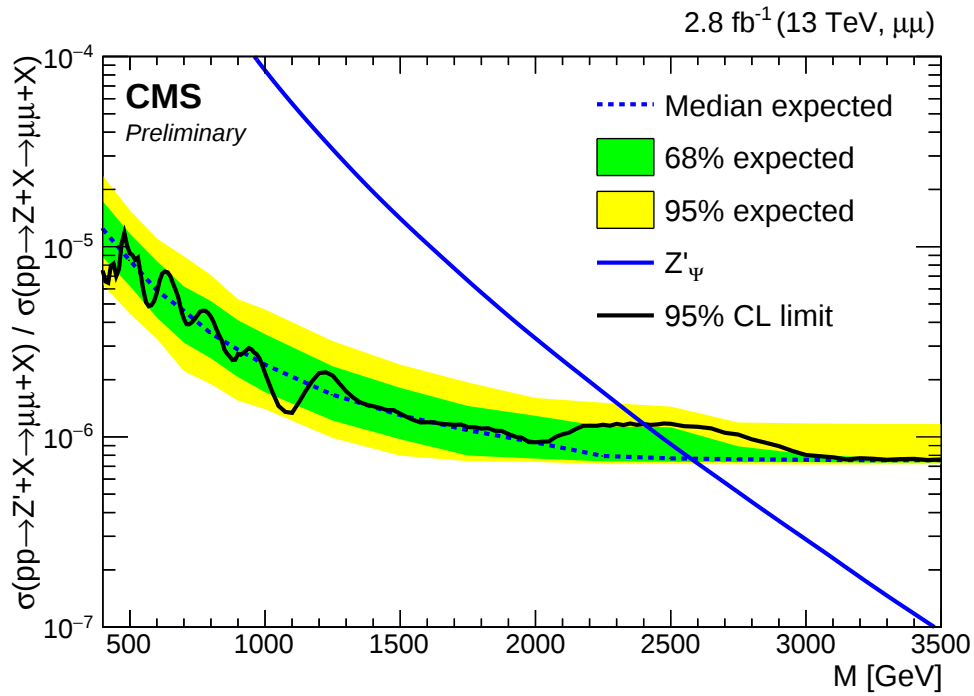


Figure 5.27: The observed and expected upper limits as a function of the resonance mass M on the ratio $R\sigma$ of the Z' production cross section time branching fraction into muon pairs relative to that of the Z boson, for a Breit-Wigner function with width 0.6%. The median expected limit is shown as the dashed blue line, with green and yellow bands representing ± 1 and ± 2 standard deviations from this limit respectively. The observed limit is shown as the black line. Also plotted is the predicted cross section times branching fraction ratios for the Z'_ψ model.

the null-hypothesis calculated as the Poisson probability to observe at least one event in the electron channel above 2.8 TeV is 0.036.

Figure 5.28 shows the observed and expected 95% C.L. upper limits on the ratio R_σ of the Z' production cross section time branching fraction relative to that of the Z boson for Breit-Wigner widths of 0%, 0.6% and 3%. The limits exclude at 95% C.L. a Z'_{SSM} with a mass less than 3.15 TeV and Z'_Ψ and with a mass less than 2.60 TeV. This surpasses the current best published limits of 2.90 TeV and 2.57 TeV respectively [2].

Figure 5.29 shows the observed and expected upper limits for an input width of 0.6%. Shaded green and yellow bands correspond to the 68% and 95% quantiles for the expected limits. The observed limit agrees with the expected limits within 2σ .

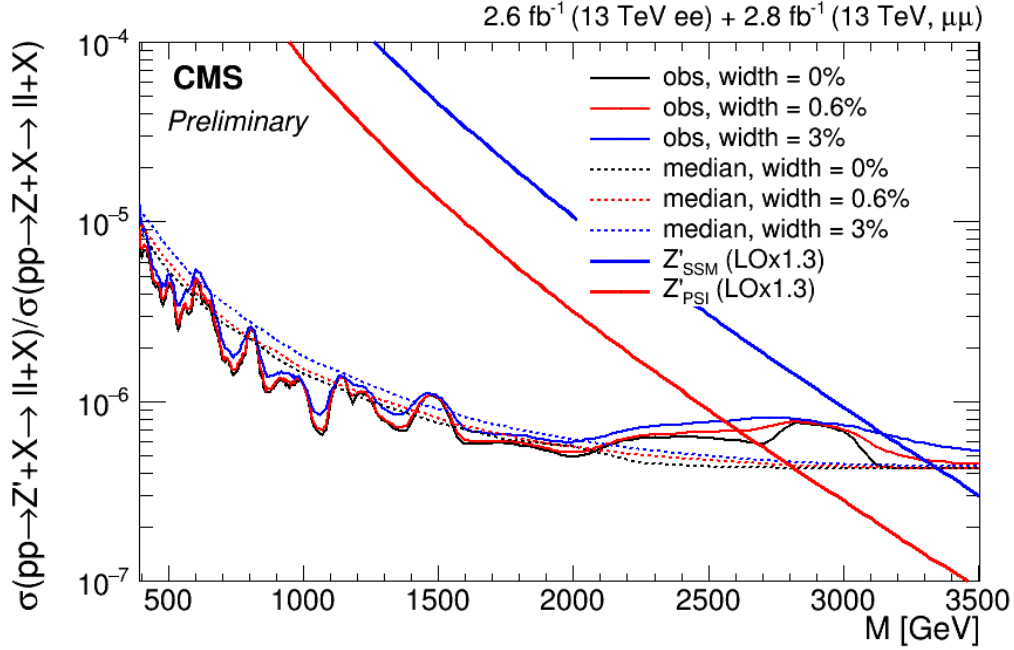


Figure 5.28: The observed and expected upper limits as a function of the resonance mass M on the ratio R_σ of the Z' production cross section time branching fraction for the muon and electron channels combined relative to that of the Z boson. Breit-Wigner widths of 0%, 0.6% and 3% are considered. The median expected limit is shown as the dashed lines and the observed limit is shown as the solid lines. Also plotted are the predicted cross section times branching fraction ratios for the Z'_Ψ and Z'_{SSM} models.

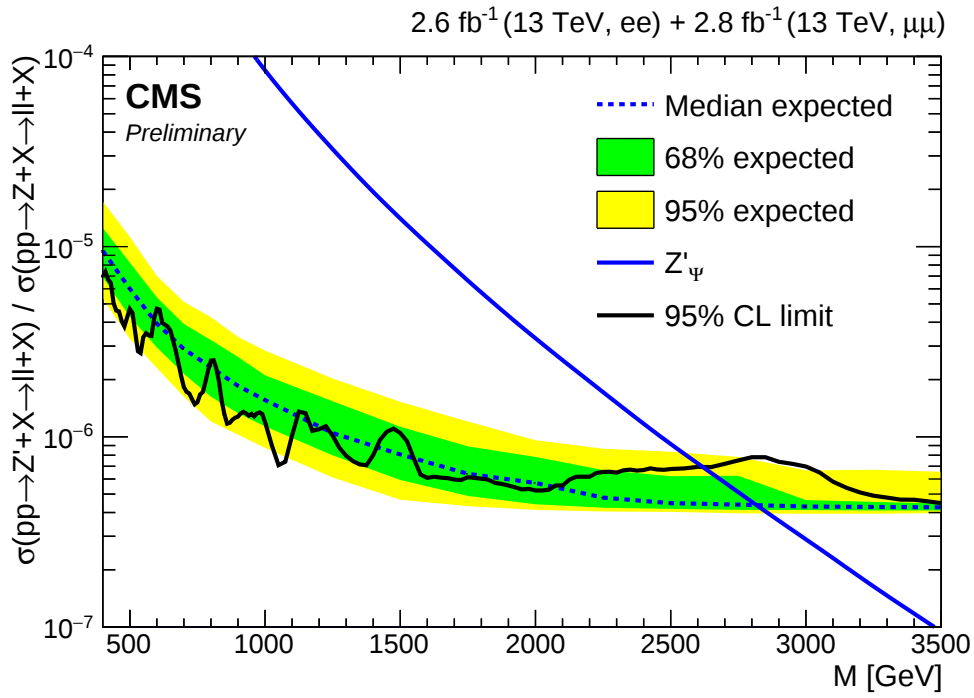


Figure 5.29: The observed and expected upper limits as a function of the resonance mass M on the ratio $R\sigma$ of the Z' production cross section time branching fraction for the muon and electron channels combined relative to that of the Z boson, for a Breit-Wigner function with width 0.6%. The median expected limit is shown as the dashed blue line, with green and yellow bands representing ± 1 and ± 2 standard deviations from this limit respectively. The observed limit is shown as the black line. Also plotted is the predicted cross section times branching fraction ratios for the Z'_ψ model.

Conclusions

A search for dimuon decays of heavy neutral resonances has been performed using proton-proton collision data collected at $\sqrt{s}=13$ TeV by the CMS experiment at the LHC in 2015. The data set corresponds to an integrated luminosity of 2.8 fb^{-1} .

This analysis represents an important search channel for new physics. It is considered of high priority within the CMS collaboration and benefits from the never before achieved center-of-mass energy of the proton-proton collisions at the LHC.

The muon reconstruction plays a crucial role since the muon performance at high momentum is strongly affected by radiative processes (electromagnetic showers or hard bremsstrahlung) and by the muon detector alignment. Specialized algorithms for high-energy muon reconstruction, known as “TeV-muon” refits, have been developed in CMS and the final momentum assignment is performed by the so called “Cocktail” algorithm which chooses the best muon track candidate. These algorithms have been updated and re-tuned to optimize the performance in collisions at 13 TeV.

The analysis uses a muon reconstruction and selection that was optimized for high efficiency at high energies. The most important background for the search comes from the Drell-Yan process, which accounts for about 83% of the events in the search region. The DY background estimation was taken from simulations. Other backgrounds with prompt leptons in the final state include $t\bar{t}$ and WW production, and were also taken from simulations. A data driven verification of the simulation for these processes was performed, using the electron-muon invariant mass spectrum. The jet background, contributing to the dimuon mass spectrum, was estimated from data and correspond to less than 1% of the total background.

The dimuon mass distribution is consistent with Standard Model predictions. An upper limit on the ratio of the cross section times branching fraction of new bosons, normalized to the cross section times branching fraction of the Z boson, is set at the 95% confidence level. Using the ratio as a parameter of interest cancels all the p_T independent systematic uncertainties. Notably, the

uncertainty on the measured integrated luminosity does not have an impact on the result.

With the measured 95% C.L. upper limit on the cross section ratio, lower limits on the resonance masses, for particles predicted by various models, could be set. The limits exclude at 95% C.L. a Z'_ψ with a mass lighter than 2.40 TeV and a Z'_{SSM} with a mass lighter than 3 TeV with the dimuon channel alone.

When combined with the analysis in the dielectron channel, masses below 3.15 TeV and 2.60 TeV are excluded at 95% C.L. for the Z'_{SSM} and the Z'_ψ , respectively. This surpasses the current best published limits of 2.90 TeV and 2.57 TeV respectively [2].

A further increase to a center-of-mass energy of 14 TeV is planned until the end of this LHC run. With the full dataset of an integrated luminosity of about 300 fb^{-1} , that is expected to be collected until the next long shutdown of the LHC, the discovery potential can reach resonance masses beyond 4.5 TeV [89].

The analysis has been approved and results have been presented at CERN Jamboree (December 15th 2015) by the CMS collaboration. The results of the analysis are part of a public CMS Physics Analysis Summary (PAS) [4], and are going to be published as a paper of the CMS collaboration in Spring 2016.

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