

Search for Top Quark Pair Resonances with the CMS Detector at the LHC

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Abstract

The Standard Model of particle physics is not the final theory. It breaks at larger (TeV) scales and thus can not explain the hierarchy problem, the unification of couplings and some physical phenomena. Several physical models, referred to as Beyond the Standard Model, have been proposed to account for the phenomena which are not explained by the Standard Model, and to answer to some of these open questions.

As the top quark has as an enormous mass of about 173.3 GeV, it plays an essential role in searches for new physics. Various models beyond the Standard Model predict the existence of heavy particles decaying into top quark pairs. These particles manifest themselves as resonant structures in the invariant mass spectrum of the top quark pairs.

In this thesis, a model-independent search has been performed for top quark pair resonances in the mass range close to the top quark pair production threshold. The Topcolor Z' model is considered as a reference model. The presented search focuses on top quark pair events selected from data samples corresponding to 1.09 fb^{-1} of integrated luminosity collected with the CMS detector in the 2011 run period at a center-of-mass energy of $\sqrt{s} = 7 \text{ TeV}$ at the large hadron collider (LHC). A cut based selection is implemented to identify top quark pair candidates decaying in the muon+jets channel, by requiring one isolated muon, missing transverse energy and at least four jets. The identified final state objects are used to reconstruct the invariant top quark pair mass spectrum. No excess is observed in the CMS data over the expectation of the standard model processes, namely no considerable evidence of new physics was found. Therefore, a limit is set on the topcolor Z' boson production cross section as a function of the Z' mass. Leptophobic topcolor Z' bosons with narrow (wide) width 1.2% (10%) are excluded at 95% confidence level for masses below 710 (1145) GeV.

Zusammenfassung

Das Standard Modell der Teilchenphysik ist keine endgültige Theorie, es hat keine Erklärung für Hierarchie Problem und die Unifikation von Kopplungen. Bei größeren (TeV) Skalen bricht es und es zeigen sich möglicherweise neue physikalische Phänomene. Mehrere physikalische Modelle, die jenseits des Standard Modells vorgeschlagen wurden, geben möglicherweise Antworten auf diese offenen Fragen.

Wegen der enormen Masse von etwa 173.3 GeV, spielt das Top Quark eine wesentliche Rolle bei der Suche nach neuer Physik. Verschiedene Modelle jenseits des Standard Modells sagen die Existenz von schweren Teilchen voraus, die in Top-Quark-Paare zerfallen. Diese Teilchen manifestieren sich als resonante Strukturen im invarianten Massenspektrum der Top-Quark-Paare. In dieser Arbeit wird eine unabhängige Suche nach Top-Quark-Paar Resonanzen in der Nähe der Produktionsschwelle durchgeführt. Das Topcolor Z' Modell wird als Referenzmodell betrachtet. Die vorgestellte Suche konzentriert sich auf Top Quark Paar Ereignisse aus Daten, entsprechend 1.09 fb^{-1} integrierter Luminosität mit dem CMS Detektor in 2011 bei einer Schwerpunktsenergie von $\sqrt{s} = 7 \text{ TeV}$ am LHC Collider. Eine Selektion wird implementiert um Top Quark Kandidaten im Myon+Jets Kanal durch die Forderung nach einem isolierten Myon, fehlender transversaler Energie und mindestens vier Jets zu identifizieren. Der Endzustand der identifizierten Objekte wird verwendet, um das invariante Top Quark Paar Massenspektrum zu rekonstruieren.

Kein Signal wird in den CMS Daten beobachtet. Es wurden keine nennenswerten Hinweise auf neue Physik gefunden. Daher wird ein Limit auf den Topcolor Z' Bosonen Wirkungsquerschnitt in Abhängigkeit von der Z' Masse gesetzt. Leptophobic topcolor Z' Bosonen mit schmalen (breiten) Breite 1.2 % (10%) werden bei 95% Konfidenzniveau für Massen unter 710 (1145) GeV ausgeschlossen.

Chapter 1

Overview

In this chapter we introduce the Standard Model (SM), then we will focus on a single particle of the SM (the top quark). The Beyond the Standard Model (BSM) phenomenology will be discussed and particularly the Topcolor Assisted Technicolor model.

1.1 Introduction

The attempts to understand physics has made great progress in the last centuries. So that the fundamental constituents of matter and the interactions among them have been united into one model called the Standard Model (SM) of Particle Physics. In this model the particles can be classified, depending on their characteristics, into different groups. These groups are leptons and quarks, which interact as point-like, spin-1/2 particles (fermions). They interact via three SM fundamental interactions: electromagnetic, weak and strong interaction and non-SM interaction which is the gravitation.

- The electromagnetic force is important for all charged objects, mainly known from the interactions between atoms.
- The weak force scale is about 1/1000 of the scale of a nucleus or atom, most commonly known in radioactive decays.
- The strong force keeps the nucleus and even its components, the nucleons, bound by gluing the quarks together.

- The gravitational force is the vital one on large scales, as in astrophysics.

The weak and the electromagnetic forces have been unified in an electroweak force. It is believed that this force can be unified in a Grand Unified Theory (GUT) [1] with the strong force at the GUT-(energy)-scale. The GUT could offer a more elegant understanding of the universe.

Remark

In elementary particle physics it is standard to use natural units. This analysis uses natural units ($\hbar = c = 1$). Thus, the units of common observables in this convention like energy, momentum, mass time and length can be expressed in terms of electron-volt (eV). $[\text{Energy}] = [\text{Momentum}] = [\text{Mass}] = [\text{Time}]^{-1} = [\text{Length}]^{-1} = \text{eV}$.

1.2 The Standard Model of Particle Physics (SM)

The Standard Model (SM) [2, 3, 4, 5] is the quantum field theory which includes descriptions of the electromagnetic, weak and strong interactions. Within the SM, the matter is described by spin-1/2 fermions, while the interactions are mediated by the exchange of spin-1 gauge bosons in this model. The fermions are split into three generations of particles. These generations are identical with respect to their quantum numbers and vary with respect to their masses. Each generation consists of one charged lepton and the corresponding neutrino, which partake in the electroweak interaction, and one up-type and one down-type quark which partake in the electroweak and strong interactions.

There are six quarks known as quark flavours: up, down, charm, strange, top, bottom, and six leptons: electron, electron neutrino, muon, muon neutrino, tau, tau neutrino. The first generation particles build all stable matter.

Fermions	I	II	III	$Q[e]$	T_3	Y
Quarks	$\begin{pmatrix} u \\ d \end{pmatrix}$	$\begin{pmatrix} c \\ s \end{pmatrix}$	$\begin{pmatrix} t \\ b \end{pmatrix}$	$\begin{pmatrix} 2/3 \\ -1/3 \end{pmatrix}$	$\begin{pmatrix} 1/2 \\ -1/2 \end{pmatrix}$	$\begin{pmatrix} 1/3 \\ 1/3 \end{pmatrix}$
Leptons	$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}$	$\begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}$	$\begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}$	$\begin{pmatrix} 0 \\ -1 \end{pmatrix}$	$\begin{pmatrix} 1/2 \\ -1/2 \end{pmatrix}$	$\begin{pmatrix} -1 \\ -1 \end{pmatrix}$

Table 1.1: The three generations of quarks and leptons and their quantum numbers within the SM: the electrical charge Q , the third component of the weak isospin T_3 , and the hypercharge Y [6].

Bosons	Interaction	Range[m]	Spin[$\hbar$]	Q[e]	Mass[GeV/c ²]
8 Gluons g	strong	10^{-15}	1	0	0
$W^\pm/Z^0$	weak	$\ll 10^{-16}$	1	$\pm 1/0$	$\approx 80.4/91.2$
Photon γ	electromagnetic	∞	1	0	0
Graviton G	gravitational	∞	2	0	0

Table 1.2: The forces and their mediating fundamental gauge bosons in the SM. The Graviton as the mediator of Gravity is included to complete the four fundamental interactions [6].

The second and third generation charged particles have only be observed in high energy interactions and they decay into first generation particles in short times due to their higher masses. Neutrinos of all generations do not decay and rarely interact with matter, therefore its detection is difficult. Quarks, except the top quark, are bound in combinations of quarks and antiquarks called hadrons, which are always color neutral. Hadrons built of three quarks are called baryons. Hadrons built of a quark-antiquark pair are called mesons. In addition to fermions, there are 12 bosons in the SM carrying the electromagnetic, weak and strong forces:

- The photon (γ) mediates the electromagnetic interaction.
- The $W^\pm$ and Z bosons mediate the weak interactions.
- The gluon (g) mediates the strong interaction.

Thus, the SM does not describe the gravitational force which is supposed to be mediated by the not yet found graviton. At large energy scales the gravitation can be neglected since its strength is around 43 orders of magnitude smaller than the strong interaction. The SM has provided a novel success in its agreement with the experiment measurements. Thus, the SM is not a complete fundamental theory and new theories which extend beyond the SM could play an important role in our understanding of the nature of the universe. Table 1.1 lists the quarks and the leptons and some of their quantum numbers. The gauge bosons are listed in table 1.2.

The Higgs boson is the last particle to complete the SM list of particles. It is the consequence of introducing a Higgs field in the SM theory in order to explain the mass of the W and Z bosons and fermions.

1.3 The Top Quark

The existence of the top quark as a weak-isospin partner of the bottom quark was predicted by the SM. It was experimentally discovered in 1995 by CDF and DØ experiments at the Tevatron [7, 8] and completed the table of quarks. It has a high mass as high as a tungsten atom. The latest measurement of its mass, from the combination of the CDF and DØ results, gives $M_t = 173.2 \pm 0.9$ GeV [9]. The CMS combined measurements for top mass at the LHC at center-of-mass energy of $\sqrt{s} = 7$ TeV gives $M_t = 173.36 \pm 0.38(\text{stat.}) \pm 0.91(\text{syst.})$ GeV [10]. The top quark decays via weak interaction, its lifetime (5×10^{-25} s) is much smaller than the time needed for typical hadronization processes, which is about 3×10^{-24} s. The top quark therefore decays before it can hadronize. The study of top quark properties allows to test the SM predictions. More details about the top quark physics can be found in [11, 12].

1.3.1 Top Quark Pair Production

The center-of-mass energy of a particle collider should be at least twice as large as the top quark mass in order to produce top quark pairs ($t\bar{t}$). This is possible at the Tevatron ($\sqrt{s} = 1.96$ TeV) and the The Large Hadron Collider ($\sqrt{s} = 7$ TeV until the end of 2011). The top quark can be produced either as top quark pairs ($t\bar{t}$) via the strong interaction or as single top quarks via the electroweak interaction.

The dominant top quark production mechanism at hadron colliders is via the strong interaction. At the LHC top quark pairs ($t\bar{t}$) can be produced via gluon gluon (gg) fusion (80%) or by quark-antiquark ($q\bar{q}$) annihilation (20%) [13]. Figure 1.1 shows the leading order Feynman diagrams for these processes. The production cross section for top quark pairs at hadron colliders in the QCD-improved parton model is calculated using the factorization theorem as a convolution of the parton distribution functions (PDF) for the protons and the partonic cross section ($\hat{\sigma}$):

$$\sigma_{pp \rightarrow t\bar{t}}(s, m_t) = \sum_{i,j=q,\bar{q},g} \int dx_i dx_j f_i(x_i, \mu_f^2) f_j(x_j, \mu_f^2) \cdot \hat{\sigma}_{ij \rightarrow t\bar{t}}(\hat{s}, m_t, \mu_r, \alpha_s), \quad (1.1)$$

where s is the center-of-mass energy of the collider and m_t is top quark mass. Each parton i carries a fraction x_i of the proton momenta. $f_i(x_i, \mu_f^2)$ is the PDF of the proton, $\mu_{f(r)}$ are the factorization and renormalization scales. $\hat{\sigma}_{ij \rightarrow t\bar{t}}(\hat{s}, m_t, \mu_f, \alpha_s)$ is the partonic cross section, α_s is the strong

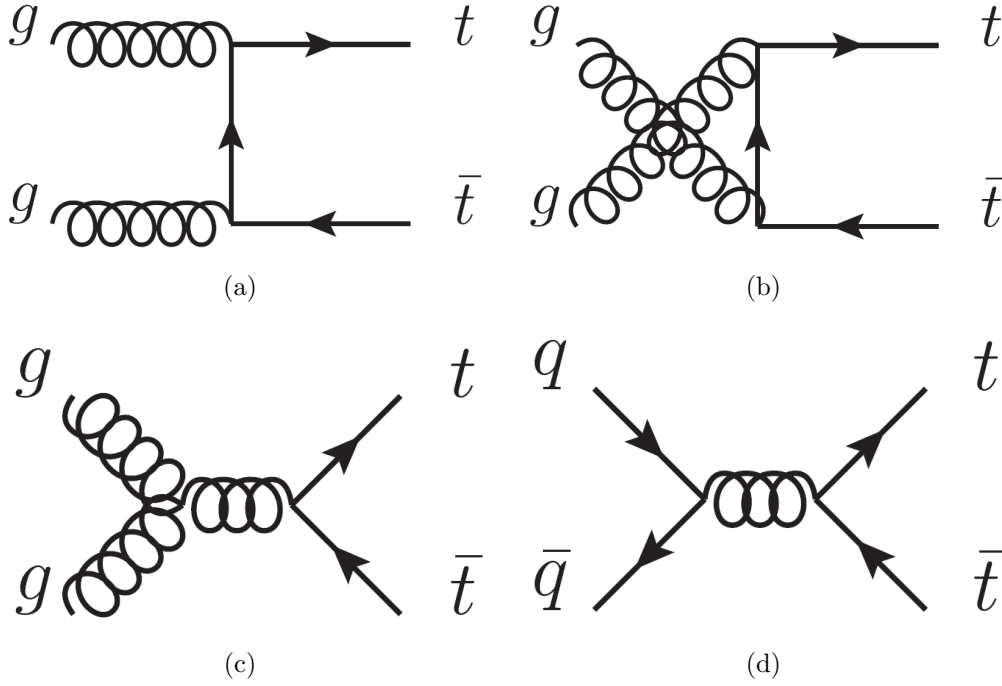


Figure 1.1: The leading order Feynman diagram for top quark pair production at the Tevatron and the LHC, the production is through (a, b, c) gluon-gluon fusion and (d) quark-antiquark annihilation [13].

coupling and $\hat{s}$ is the partonic center-of-mass energy. The cross sections for specific physics processes are shown in Figure 1.2, the dashed lines marking the LHC center-of-mass energy of 7, 14 TeV and the solid line shows the current LHC center-of-mass energy of 8 TeV.

As the top quark pair is the main background source for this analysis, it is important to measure the $t\bar{t}$ cross section. The theoretical prediction of the $t\bar{t}$ cross section at the LHC from the next-to-leading order (NLO) approximation at $\sqrt{s} = 7\text{TeV}$ [15, 16], assuming a top quark mass of $m_t = 172.5\text{ GeV}$, is:

$$\sigma_{t\bar{t}} = 157.5 \pm 24 \text{ pb}. \quad (1.2)$$

The $t\bar{t}$ cross section measurement from the combination of the measurements performed in various top quark decay channels for the CMS experiments at $\sqrt{s} = 7\text{ TeV}$ [17] is:

$$\sigma_{t\bar{t}} = 165.8 \pm 2.2 \text{ (stat.)} \pm 10.6 \text{ (syst.)} \pm 7.8 \text{ (lum.) pb}. \quad (1.3)$$

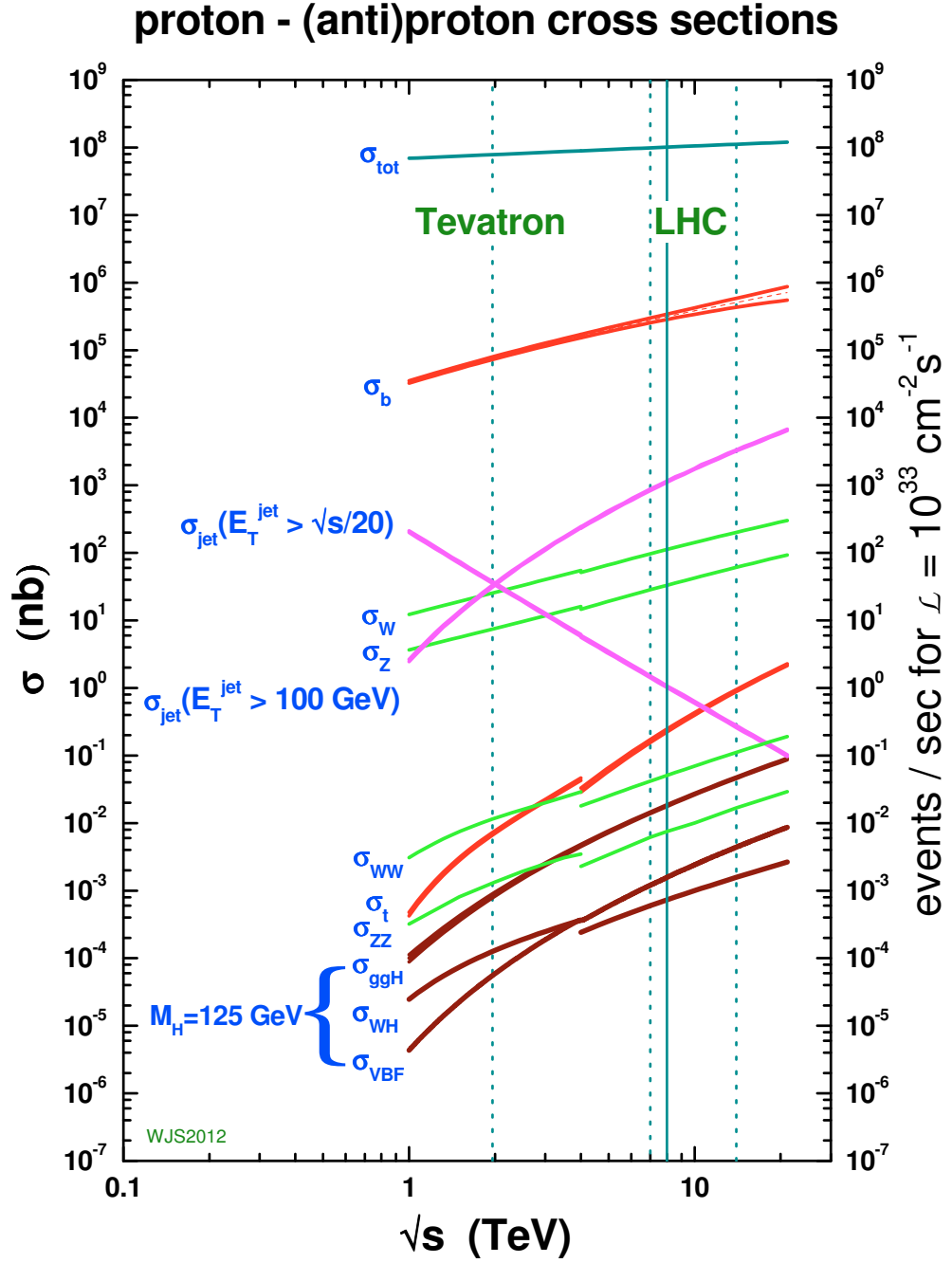


Figure 1.2: SM production cross section in NLO using the MSTW Model for Parton Distribution Functions (PDF). The dotted lines show the energies of the LHC at $\sqrt{s} = 7$ and 14 TeV, the solid line shows the current LHC energy of $\sqrt{s} = 8$ TeV [14].

1.3.2 Top Quark Decay Channels

The SM predicts that top quarks decay mostly via the weak interaction into a W boson and a b quark ($t \rightarrow Wb$). Therefore, the decay of the top quark is classified by the decay of the W boson. The decay rate of a top quark to a b quark is proportional to the the Cabibbo- Kobayashi-Maskawa (CKM) matrix element $|V_{tb}|$. In the SM with three generations of fermions, the CKM matrix element V_{tb} is measured by CMS in dilepton channel and has a value of $|V_{tb}| = 0.98 \pm 0.04$ [18], thus the decay mode $t \rightarrow Wb$ has almost 100 percent branching fractions. The decay width of the top quark in the SM at NLO using $m_t = 172.5$ GeV is $\Gamma_{t \rightarrow Wb} = 1.33$ GeV [13]. The W boson decays into a lepton (electron, muon, tau) and a corresponding neutrino or into a quark-antiquark pair which leads to different decay signatures of the top quark pair ($t\bar{t}$). Thus, the decay of top quark pair ($t\bar{t}$) can be classified into three possible decay channels: Full-hadronic channel, dilepton channel and lepton+jets channel as shown in Figure 1.3.

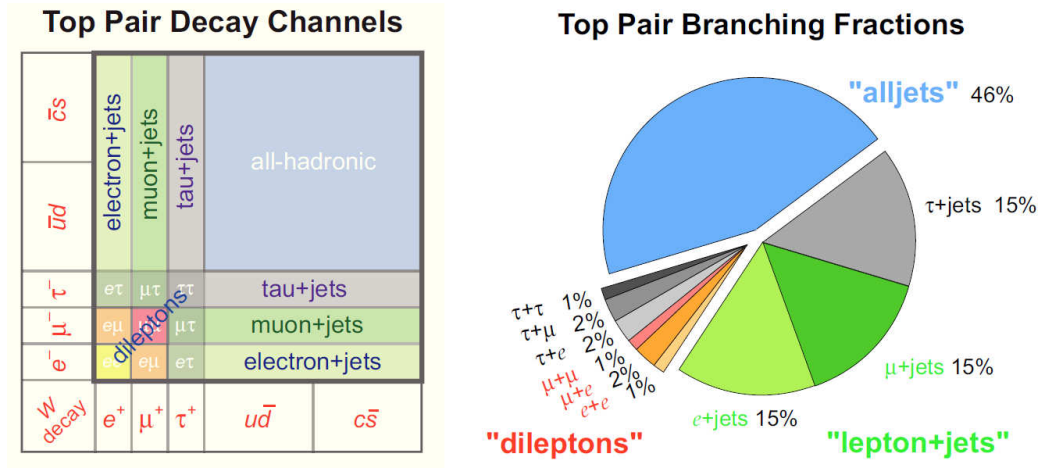


Figure 1.3: Top quark pair decay channels: the full-hadronic channel, the dileptonic channel and the lepton+jets channel (left), and their corresponding branching fractions (right) [19].

Full-hadronic channel:

In this channel both of the W bosons decay into quark-antiquark pairs giving a signature with six jets in the final state (two b -jets and four light-quark jets), $t\bar{t} \rightarrow W^+bW^-\bar{b} \rightarrow q\bar{q}'bq''\bar{q}'''\bar{b}$. This channel has the largest branching fraction of 46.2%. All final state objects can be detected but it is difficult to separate the signal from the large QCD multijet background. A large multiplicity of jet combinations and the jet energy uncertainty make precision measurements of top properties in this decay channel challenging.

Dilepton channel:

Both W bosons decay into a charged lepton and the corresponding neutrino $t\bar{t} \rightarrow W^+bW^-\bar{b} \rightarrow \bar{l}\nu_l b l' \bar{\nu}_{l'} \bar{b}$. This channel has very clean signature with two hard leptons. It has a low branching fraction of 10.3%, by considering only decays to muons and electrons the branching fraction is decrease to 6.45%. The event reconstruction is very difficult due to two unmeasured neutrinos.

Lepton+jets channel:

In this channel one W boson decays into quark-antiquark pair and the other decays into a charged lepton and neutrino $t\bar{t} \rightarrow W^+bW^-\bar{b} \rightarrow q\bar{q}'bl\bar{\nu}_l\bar{b}$. This channel has a good separation from the background. It has a high branching fraction of 43.5%. Usually only the decay into electron and muon are considered due to the pure topology. The decay into tau is not considered because tau has a very short lifetime of $2.9 \cdot 10^{-13}$ s, such that it decays before reaching the detector. Tau is investigated indirectly via hadronic or leptonic decay, thus the tau+jets channel a challenging one due to large backgrounds.

In order to avoid additional systematic uncertainties this analysis only focuses on the muon+jets channel, since CMS is dedicated to have an excellent muon reconstruction performance. For the muon +jets channel the corresponding branching fraction is 14.5%. The event kinematic reconstruction is affected by the ambiguities due to unmeasured neutrino.

1.4 Top Quark Pair Resonances

The existence of top quark pair resonances is not expected in the SM. The resonant production of top quark pairs in the SM is only possible via the decay of a heavy Higgs boson with a mass of more than twice of top mass ($m_H \geq 350$ GeV). This production mechanism is unlikely because a candidate for the Higgs boson was found at a mass of about 125 GeV by the CMS and ATLAS experiments. The results of CMS and ATLAS were presented on July 4th, 2012 and can be found in [20, 21].

The high mass of the top quark which is very close to the electroweak symmetry breaking (EWSB) scale (ν), $m_t \approx \nu/\sqrt{2}$. This will enable it to play a central role in the Higgs sector and in several theories Beyond the Standard Model (BSM) [22]. This analysis is searching for any sign of new physics in a model-independent way. Some BSM theories consider concepts of generating boson and fermion masses. These theories are predicting new heavy particles, that decay into top quark pairs like Topcolor [23, 24], top see-saw [25, 26], Kaluza-Klein (KK) excitations of the gluon [27], RandallSundrum model of

Spin	color	parity ($1, \gamma_5$)	some examples
0	0	(1,0)	SM/MSSM/2HDM, Ref. [51, 52, 53]
0	0	(0,1)	MSSM/2HDM, Ref. [52, 53]
0	8	(1,0)	Ref. [54, 55]
0	8	(0,1)	Ref. [54, 55]
1	0	(SM,SM)	Z'
1	0	(1,0)	vector
1	0	(0,1)	axial vector
1	0	(1,1)	vector-left
1	0	(1,-1)	vector-right
1	8	(1,0)	coloron/KK gluon, Ref. [56, 57, 58]
1	8	(0,1)	axigluon, Ref. [57]
2	0	-	graviton, Ref. [17, 18]

Table 1.3: Some benchmark Beyond Standard Models of top quark pair resonance and their properties: the spin ,the color and the parity [22].

gravitons [28, 29], axigluons [30, 31], coloron [32] and models with extra dimensions [33]. The predicted new particles couple predominantly to top quark pairs. These particles could be realized in many different ways and can be classified according to their spin, color and CP parity. The supposed new particles could have a spin of 0, 1 or 2 and can be scalar or pseudo-scalar, color singlet or color octet, vector or axialvector particle [22]. Some benchmark models and their parameters are listed in Table 1.3. In this search, the Topcolor Assisted Technicolor Z' model is considered as a reference model. It is discussed in the next section.

1.4.1 Topcolor Assisted Technicolor Z'

The Technicolor models (TC) [34, 35, 36] are one of the theories BSM which offer a possible explanation for the hierarchy problem. Thus, instead of introducing Higgs bosons to break the electroweak symmetry, technicolor models introduce a new force, analogous to the strong force, called “technicolor” and additional massless fermions called “technifermions”. The technicolor becomes strong at a scale in the vicinity of a few hundred GeV ($\Lambda_{TC} \approx 500$ GeV) leading to the formation of technifermions condensates. The electroweak symmetry breaking takes place when the technifermions condensates are formed at the technicolor scale of $\Lambda_{TC} \approx 1$ TeV. The chiral symmetry of the massless technifermions is broken in these models too, when the technifer-

mions condensates are formed. Thus, the technifermions get a dynamical mass and massless Goldstone bosons are formed. The combination of three of these goldstone bosons give masses for the W and Z bosons. The quarks and leptons constructed in the technicolor models are massless. In order to produce quark and lepton masses, technicolor models have to be extended by additional gauge interactions. A new model is the Extended Technicolor (ETC) model and the new interactions called extended technicolor forces [37, 38], which couple SM fermions to technifermions. The energy scale of ETC is very high compared to that for TC, which is about 0.1 - 1 TeV. The ETC scale (Λ_{ETC}) is given by:

$$\Lambda_{ETC} = 14 \sqrt{\frac{1\text{GeV}}{m_q N^{3/2}}} \text{ TeV}, \quad (1.4)$$

where N is the number of techni-doublets and m_q the mass of the quark.

Quarks and leptons get masses if the ETC symmetry is broken at a scale M_{ETC} larger than Λ_{TC} . The flavor changing neutral currents (FCNC) measurements impose strong bounds on M_{ETC} of the order of 100 TeV. Therefore, the ETC can generate only the masses for the first fermions generation (light fermion masses) and can not explain the larger masses of the second and third generations. The addressing of the heavy top quark requires new dynamical mechanisms such as Topcolor. The Topcolor model produces the large top quark mass by introducing a new strong gauge interaction, which is called topcolor [24]. This involves a dynamical $t\bar{t}$ condensate at a scale, Λ_t , generated by the topcolor force. The topcolor force couples strongly to the third generation and weakly to the first and second generation. Thus, the topcolor could explain the top quark mass but if the condensates were required to account for all of the electroweak symmetry breaking, then the fermion masses would be large of about 600 GeV.

In order to describe the mechanism for electroweak symmetry breaking and the large top mass in one model, a new model called Topcolor assisted Technicolor (TC2) is assumed [23]. This model combines the extended technicolor model (ETC) and the Topcolor model. In the TC2 model the technicolor interactions cause electroweak symmetry breaking and the combination of ETC model with the Topcolor model can generate the masses of all fermions including the top quark. The topcolor interactions form a $t\bar{t}$ condensate which gives the large top quark mass. The TC2 model predicts the existence of massive gauge bosons which couples preferentially to the third generation quarks: a color octet gauge boson called “coloron” and a color singlet gauge

bosons called “ Z' ”.

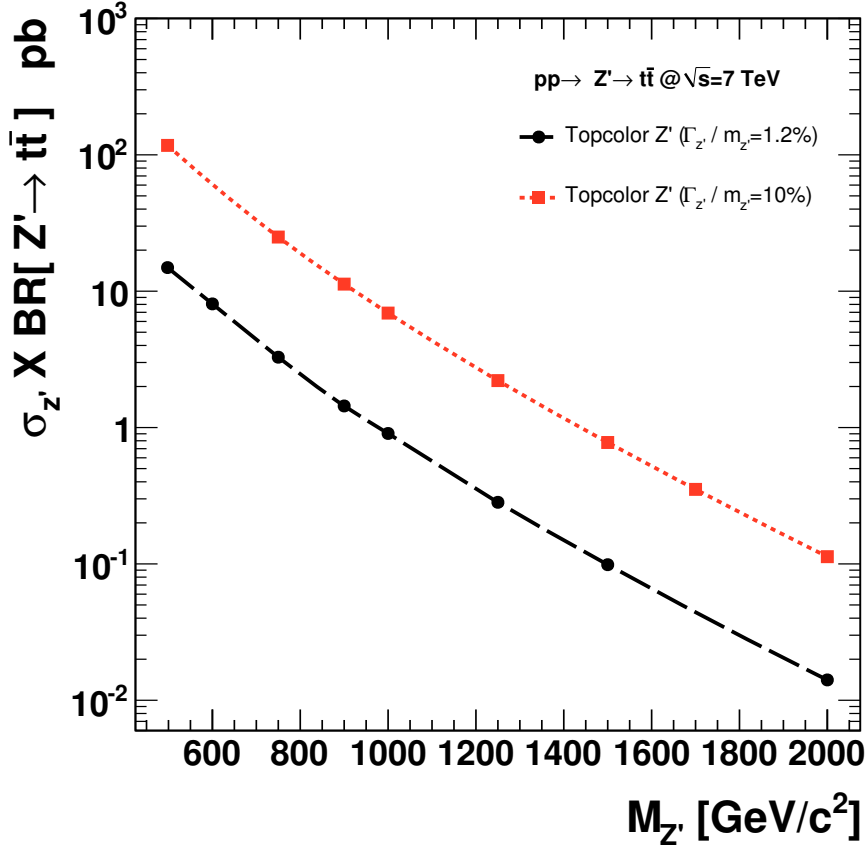


Figure 1.4: Cross sections for leptophobic topcolor $Z' \rightarrow t\bar{t}$ at $\sqrt{s}=7$ TeV, with two different widths 1.2% and 10% of the resonance mass [39].

The Z' gauge bosons is predicted by the topcolor assisted technicolor (TC2) model. This model is referred as to the Leptophobic Topcolor Z' , in which Z' couples weakly to the first and second generations and strongly to the third generation of quarks (preferentially to top quark pairs) and has no significant couplings to the leptons. Thus, it is leptophobic. Therefore, Z' in this model has predicted cross sections large enough to be experimentally accessible at the Tevatron and the Large Hadron Collider (LHC). In order to ensure the top quark is heavy and the b quark is light, a tilting mechanism is required. This mechanism blocks the formation of the $b\bar{b}$ condensate and enhances the formation of $t\bar{t}$ condensate. In this analysis, the leptophobic topcolor Z' is considered as a benchmark model for searches for top quark pair resonances. The calculation of the predicted production cross section for Z'

decaying into top quark pairs in proton-proton collisions $pp \rightarrow Z' \rightarrow t\bar{t}$ can be found in [39]. The cross sections for this model at the LHC at center-of-mass energy of $\sqrt{s} = 7$ TeV for the CTEQ6L PDFs [40] and for widths 1.2% and 10% of the resonance mass are shown in Figure 1.4 [39].

Chapter 2

The CMS Detector at the LHC

CERN is the European Organization for Nuclear Research. A provisional body founded in 1952 with the mandate of establishing a world-class fundamental physics research organization in Europe. At that time, pure physics research concentrated on understanding the inside of the atom, hence the word “nuclear”.

Today, our understanding of matter goes much deeper than the nucleus, and CERN’s main focus of research is particle physics, the study of the fundamental constituents of matter and the forces acting between them. Because of this, the laboratory operated by CERN is commonly referred to as the European Laboratory for Particle Physics.

2.1 The Large Hadron Collider

The Large Hadron Collider (LHC) is a two ring superconducting hadron accelerator and collider [41] for the exploration of physics at the TeV scale. The LHC is installed in the Large Electron-Positron Collider (LEP) tunnel with a circumference of 26.7 km and 40-170 m below the ground. The LHC is located between the Jura mountain range in France and Lake Geneva in Switzerland. It is designed to produce head-on collisions between two beams of protons (lead ions) with a design center-of-mass energy of $\sqrt{s} = 14$ TeV ($\sqrt{s} = 5.5$ TeV) and a design luminosity of $\mathcal{L} = 10^{34} \text{cm}^{-2} \text{s}^{-1}$ leads to around 1 billion proton-proton interactions per second.

The differential luminosity $\mathcal{L}$ is defined by the ratio of the rate dN/dt of

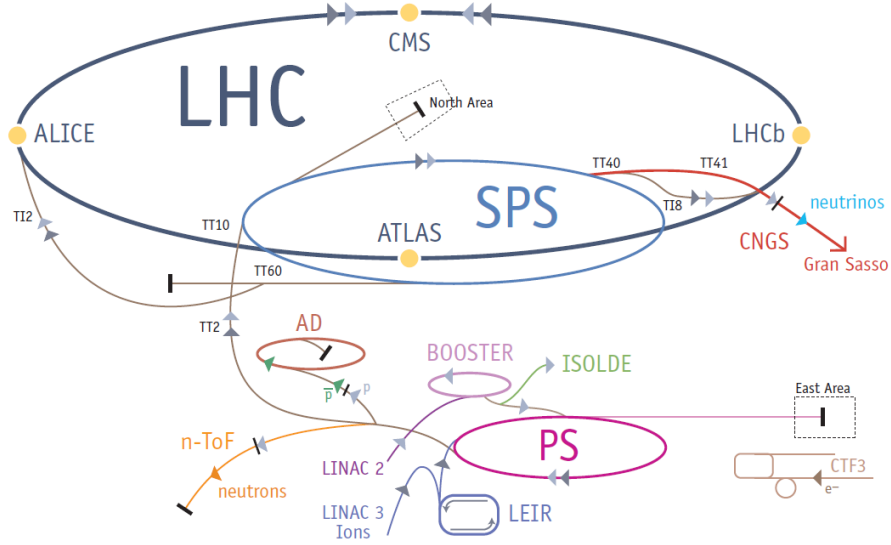


Figure 2.1: Schematic overview shows CERN accelerator complex and LHC injection system [42].

a process and its cross section σ :

$$\frac{dN}{dt} = \sigma \mathcal{L}. \quad (2.1)$$

Time integration yields, the integrated luminosity:

$$L = \int \mathcal{L} dt = \frac{N}{\sigma}. \quad (2.2)$$

From the technical point of view the luminosity can be written as

$$\mathcal{L} = \frac{\gamma f k_B N_P^2}{4\pi \epsilon_n \beta^*} F, \quad (2.3)$$

where γ is the Lorentz factor, f is the revolution frequency, k_B is the number of bunches, N_P is the number of protons per bunch, ϵ_n is the normalized transverse emittance, β^* is the betatron function at the interaction point and F is the reduction factor due to the crossing angle.

Each proton beam at design intensity will consist of 2808 bunches per beam and each bunch will contain 1.15×10^{11} protons per bunch at the start of a nominal fill.

The LHC is supplied with protons from the injector chain, which consists of: Linear Accelerator (Linac2), Proton Synchrotron Booster (PS Booster), Proton Synchrotron (PS) and Super Proton Synchrotron (SPS) as shown in Figure 2.1.

In November 2009 the LHC has operated, and provided collisions at $\sqrt{s} = 2.36$ TeV. Since March 2010 the energy is increased and the first longer run period in 2010 was performed at 3.5 TeV energy per beam corresponding to a center-of-mass energy of $\sqrt{s} = 7$ TeV. In 2012 the center-of-mass energy has been increased to $\sqrt{s} = 8$ TeV. This was done for safety reasons, especially to avoid magnet quenches, which could damage the machine. Attempts to achieve the nominal energy are planned to be made after a longer maintenance and upgrade shutdown in 2013.

The integrated luminosity is increased throughout the data taking periods. Figure 2.2 shows the integrated luminosity delivered by LHC and recorded by CMS for the year 2010 and 2011.

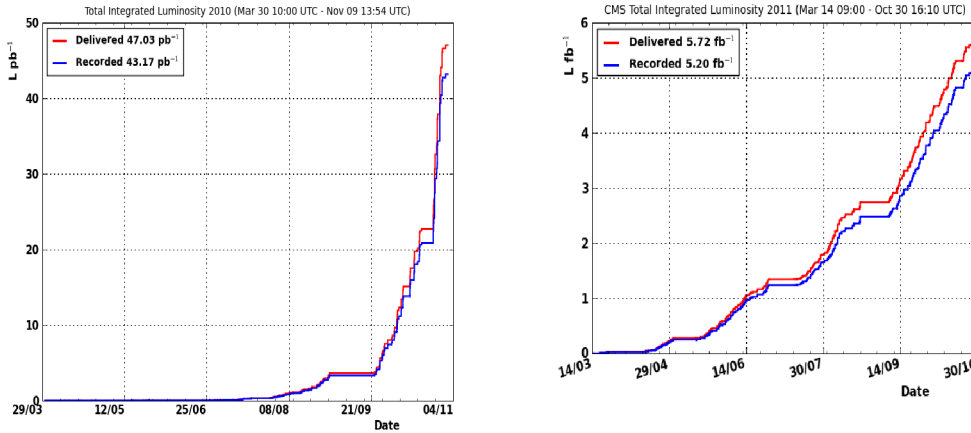


Figure 2.2: The total integrated luminosity for data taking periods 2010 and 2011, the upper line indicates the luminosity delivered by LHC and the lower line indicates the luminosity recorded by CMS [43].

The beams inside the LHC collide at four locations around the accelerator ring, corresponding to the positions of the particle detectors. The four major experiments [44, 45, 46, 47] installed on the ring in the determined positions are shown in Figure 2.3. The two large-size experiments, ATLAS (**A** Toroidal **L**H**C** **A**pparatus) and CMS (**C**ompact **M**uon **S**olenoid), are general-purpose

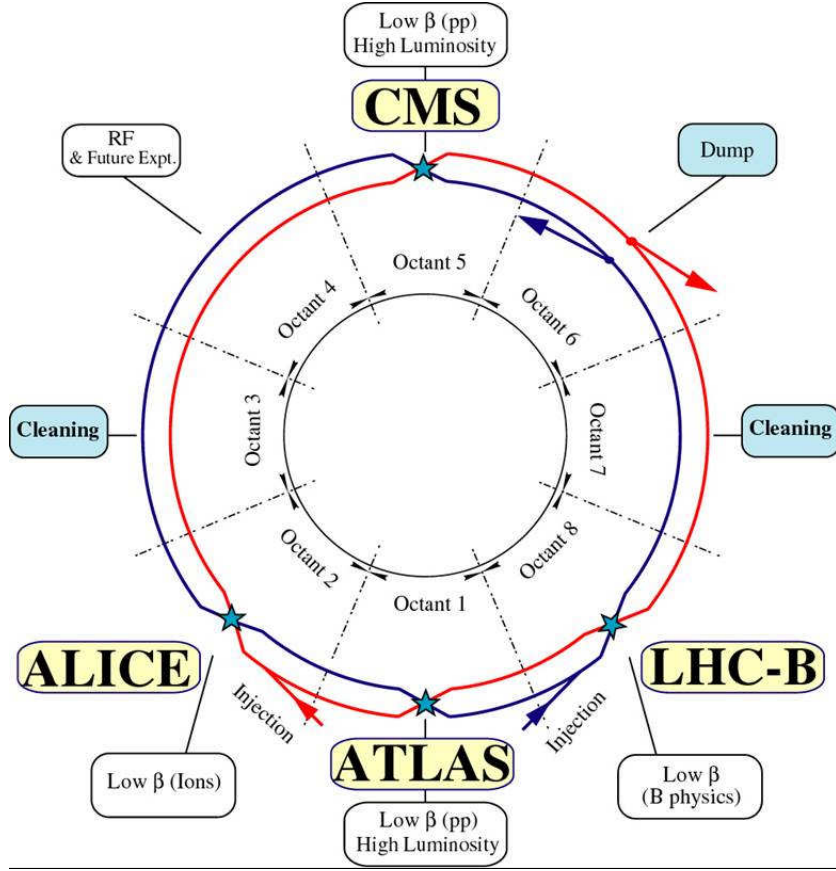


Figure 2.3: Schematic layout shows the four main experiments (CMS, ATLAS, ALICE and LHC-B) and the two ring structure of the Large Hadron Collider [48].

detectors to analyze the huge number of particles produced by the collisions in the accelerator. They are designed to investigate a wide range of physics especially physics beyond the Standard Model and Higgs physics.

Two medium-size experiments, ALICE (**A** **L**arge **I**on **C**ollider **E**xperiment) and LHCb (The **LHC** beauty experiment), have specialized detectors for analyzing the LHC collisions. The LHCb experiment will investigate B-physics and ALICE is dedicated for the heavy ion (lead-lead) collisions.

Two experiments, TOTEM and LHCf, are much smaller in size. They are designed to focus on forward particles (protons or heavy ions). These are particles that just graze past each other as the beams collide, rather than meeting head-on.

2.2 The CMS Detector

The Compact Muon Solenoid (CMS) detector [49, 50, 51] is a general purpose apparatus whose main goal is to explore physics at the TeV scale. The design foresees to study proton-proton collision, and it has already operated for heavy ion (lead-lead) collisions in 2011. The CMS detector is located about 100 meters underground near the French village of Cessy, between Lake Geneva and the Jura mountains.

The overall layout of CMS is shown in Figure 2.4. Its dimensions are a length of 21.6 m, a diameter of 14.6 m and a total weight of 12500 tons. It is “compact ” when compared to the ATLAS detector, which has about twice the volume and half the weight of CMS [44]. As a general-purpose

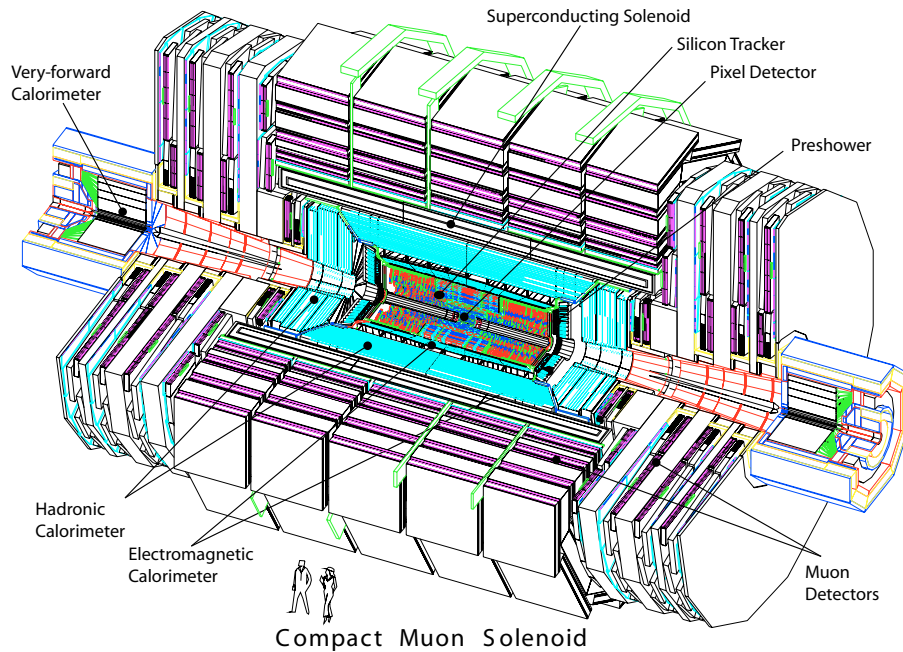


Figure 2.4: An exploded view of the CMS detector at the LHC and its different sub-detectors [52]

detector, a high angular coverage is important in order to identify and measure a large phase space of final state particles escaping the interaction point. In order to achieve that, CMS consists of a cylindrical barrel built of five slices, whose symmetry axis is the beam pipe, and its terminations are closed with four endcap wheels. It contains sub-systems which are

designed to measure the energy and momentum of photons, electrons, muons, and hadrons. The innermost layer is a silicon-based tracker. Surrounding it, a scintillating crystal electromagnetic calorimeter (ECAL) is installed, which is itself surrounded with a sampling calorimeter for hadrons (HCAL). The tracker and the calorimetry are compact enough to fit inside the CMS solenoid which generates a very homogeneous powerful magnetic field of 3.8 T. Outside the magnet the large muon detectors (Muon System) are installed, which are inside the return yoke of the magnet. More details can be found in [45, 53, 54, 55, 56, 57].

2.2.1 The CMS Requirements

The CMS detector requirements to suit the LHC physics goals are defined as follows:

- Good muon identification and momentum resolution over a wide range of momenta and angles, good dimuon mass resolution ($\approx 1\%$ at 100 GeV), and capability to determine the muons charge with $p < 1$ TeV.
- Good reconstruction efficiency and momentum resolution for charged-particles in the inner tracker, with particular attention to an efficient triggering and offline tagging of b-jets, requiring a pixel detector near to the interaction point.
- Good electromagnetic energy resolution, good di-photon and di-electron mass resolution ($\approx 1\%$ at 100 GeV), with high angular coverage and efficient photon and lepton isolation at high luminosities.
- Good missing-transverse-energy and dijet-mass resolution, requiring hadron calorimeters with a large hermetic geometric coverage and with fine lateral segmentation.

These requirements are implemented by the previously mentioned different specialized sub-detectors. Before going into the details of these sub-detectors, the interactions of various high-energy particles passing through the CMS sub-detectors are reviewed as shown in Figure 2.5 which shows a cross-sectional view of the CMS detector and the particles passing its sub-detectors.

Generally, the various high-energy particles (charged, neutral), incident on the CMS detector, interact with the material of the CMS sub-detectors in different ways:

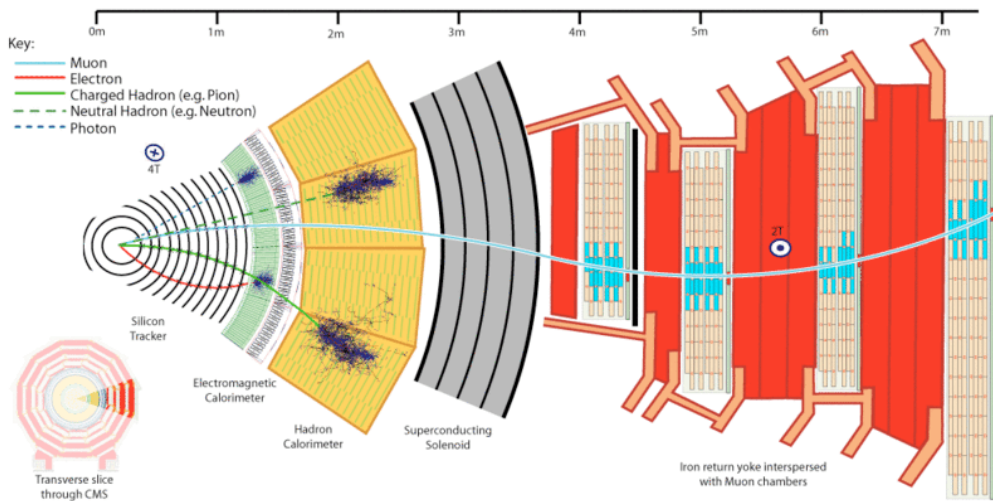


Figure 2.5: Transverse slice through CMS showing particles incident on the different sub-detectors [52]: Charged particles leave a track in the inner silicon tracker, electrons and photons stop in the electromagnetic calorimeter and hadrons in the hadron calorimeter, muons are the only type of particles reaching the muon system.

- Electrons leave a track in the inner tracker. In the electromagnetic calorimeter (ECAL) they interact mainly by radiating high-energy photons (bremsstrahlung) which in turn produce electron-positron pairs. This leads to a cascade of secondary particles (an electromagnetic shower).
- Photons, which are neutral, do not leave any track in the inner tracker. They form similar cascade compared to electrons in the ECAL.
- Charged hadrons (mainly pions, kaons and protons from jets) leave a track in the inner tracker and produce a shower in the electromagnetic and hadron calorimeters. Most of the energy is deposited in the hadron calorimeter, because hadronic showers have a longer interaction length compared to electromagnetic showers.
- Neutral hadrons (mainly neutrons, pions and kaons from jets) leave no track in the inner tracker. They produce a hadronic shower mainly in the hadron calorimeter.
- Muons leave a track in the inner tracker. The energy loss due to bremsstrahlung is much lower as for electrons due to their mass. Thus,

they lose very little energy in the calorimeters. Therefore, muons reach the muon system which is used to identify them.

- Neutrinos do not interact with any sub-detector. Therefore, they can be identified indirectly by using momentum conservation in the transverse plane assuming an event to be balanced out at least in the (x-y) plane.

2.2.2 The CMS Coordinates

The coordinate system adopted by CMS is defined as follows: the y-axis pointing vertically upward, the x-axis points radially inward toward the center of LHC, and the z-axis is along the beam axis at the interaction point (the direction is toward the Jura mountains).

The polar angle θ is measured from the z-axis ($0 \leq \theta \leq \pi$), while the azimuthal angle ϕ is measured from the x-axis in the x-y plane ($0 \leq \phi \leq 2\pi$) and the radial coordinate in this plane is denoted by r . Instead of the angle θ , the preferred parameter is the pseudorapidity, which is defined as:

$$\eta = -\ln\left(\tan\frac{\theta}{2}\right). \quad (2.4)$$

For large energies $m/E \rightarrow 0$, η approaches the rapidity (y) of a particle,

$$y = \tanh^{-1} \beta = \frac{1}{2} \ln \frac{1 + \beta}{1 - \beta} = \frac{1}{2} \ln \frac{E + p_z}{E - p_z} \approx \eta. \quad (2.5)$$

For a longitudinal Lorentz boost along the z axis to a reference frame with velocity β , $y \rightarrow y + \tanh^{-1} \beta$. Therefore, not only transverse quantities but differences in η (y) are invariant under the boost. As a consequence, a solid angle ΔR in (η, ϕ) space is also invariant.

$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}. \quad (2.6)$$

Since the total boost along the z-axis is null, the transverse momentum p_T and the transverse energy E_T , are computed from the x and y components. The missing transverse energy $\cancel{E}_T$ is defined as the imbalance of energy measured in the transverse plane.

2.2.3 The CMS Inner Tracking System

Starting from the interaction point, the emerging particles from the LHC collision pass firstly through the CMS inner tracker, which will provide an accurate measurement of the trajectories of the charged particles and the reconstruction of secondary vertices. The CMS inner tracking system is designed to reconstruct high p_T muons, isolated electrons and hadrons with high momentum.

There are various requirements that have been taken into account for the CMS inner tracker. It has to have a fast response and high granularity because of the high frequency of bunch crossing (40 MHz) and high track multiplicities which are about 1000 particles per bunch crossing at the LHC design luminosity. For this reason, the inner tracker is constructed from silicon detectors technology.

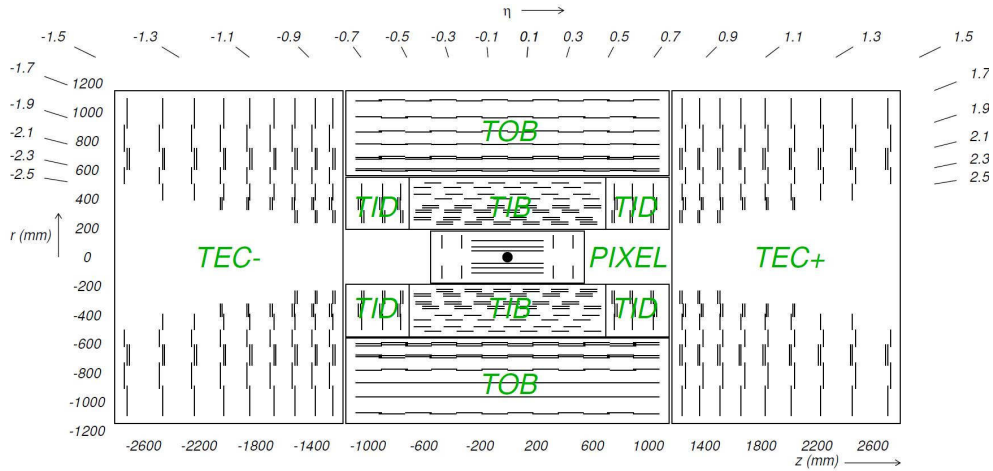


Figure 2.6: Transverse schematic through the CMS tracker [45]. Single line represents a detector module, double lines indicate back-to-back modules.

The CMS inner tracker is located around the LHC beam pipe and it is covered by a homogeneous magnetic field of 3.8 T provided by the CMS solenoid. It has a length of 5.8 m and has a diameter of 2.5 m. It consists of a pixel detector with three barrel layers surrounding the interaction point and a silicon strip tracker with 10 barrel layers around the pixel detector. Each of these tracking detectors contain endcaps. The endcaps consist of 2 disks for the pixel detector and 3 plus 9 disks for the silicon strip tracker

on each side of the barrel as shown in Figure 2.6. The spatial trajectory resolution is in the order of $25\ \mu\text{m}$, which allows for a relative momentum resolution $\sigma(p)/p$ from 1 to 5% in the momentum range from 1 GeV to 1TeV. The tracker system covers a pseudorapidity range of $|\eta| < 2.4$. More details about the performance of tracking and primary vertex reconstruction, the measurement of momentum scale and resolution can be found in [58, 59, 60].

2.2.4 The Electromagnetic Calorimeter

The Electromagnetic Calorimeter (ECAL) [55] as shown in Figure 2.7 is designed to identify and measure with high accuracy the deposited energy and direction of high energy electrons and photons. It is also important for measuring the missing transverse energy $\cancel{E}_T$. The ECAL is a homogeneous calorimeter made of 75848 lead tungstate (PbWO_4) scintillating crystals, 61200 in the barrel and 7234 in each of the two endcaps. It covers a pseudorapidity range up to $|\eta| < 3$.

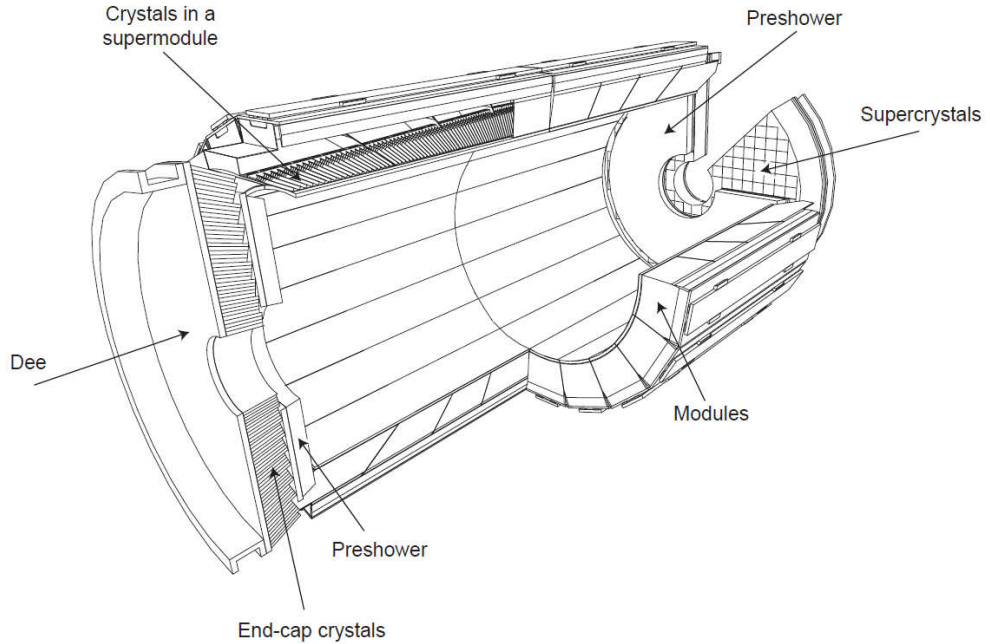


Figure 2.7: A 3-D view of the CMS electromagnetic calorimeter shows the barrel, the endcaps and the preshower in front cms.

The ECAL lead tungstate crystal (PbWO_4) has a short radiation length ($X_0 = 0.89\ \text{cm}$) and a small Molière radius of 2.2 cm due to its high density

(8.28 g/cm^3). It is a fast scintillator (80% of the light is emitted within 25 ns). The crystals emit blue-green scintillation light, low light yield of 30 photons per MeV, which is collected by photodetectors attached to the crystals. The ECAL system forms a layer between the inner tracker and the HCAL and consists of three main parts: ECAL Barrel (EB), ECAL Endcaps (EE), and Preshower Detector (ES). Figure 2.8 shows a quarter of the ECAL in the r-z-view.

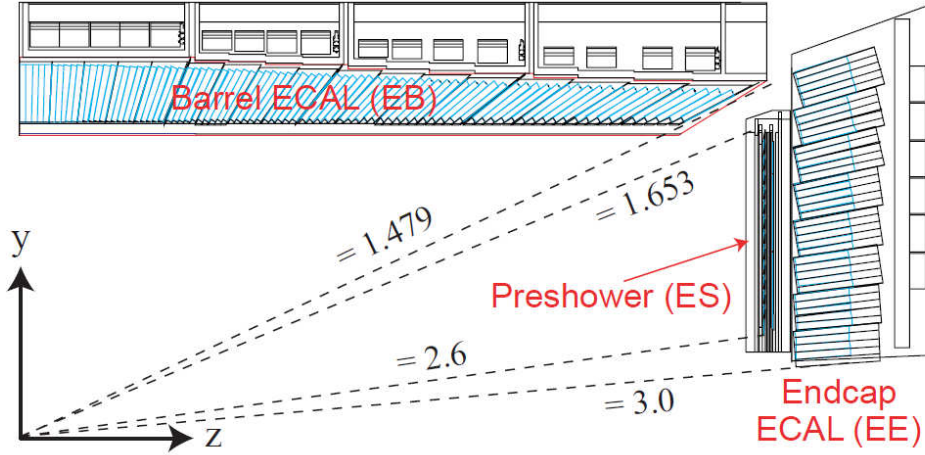


Figure 2.8: A quarter of the CMS electromagnetic calorimeter in the r-z view shows its three part and their pseudorapidity coverage [50].

The ECAL barrel (EB) has an outer radius of 180 cm, an inner radius of 129 cm and a length of about 6 m. The barrel crystals are formed into 36 supermodules and covers the pseudorapidity range of $|\eta| < 1.479$. The crystal length is 23 cm which corresponds to $25.8X_0$ with a granularity correspond to $\Delta\eta \times \Delta\phi = 0.0175 \times 0.0175$. The ECAL trigger towers are grouped to 5×5 crystals in the barrel to match the HCAL tower granularity.

The ECAL endcaps (EE) are located at a distance of ± 3.15 m from the vertex along the z-direction and have a length of 0.7 m. Their design provides precision energy measurement to $|\eta| = 2.6$. Each endcap is divided into two desks and cover the pseudorapidity range of $1.479 < |\eta| < 3$. The endcap crystal length is 22 cm which corresponds to $24.7X_0$ with a granularity correspond to $\Delta\eta \times \Delta\phi = 0.05 \times 0.05$. Crystals are assembled into units of 5×5 crystals called (supercrystals), the crystal and supercrystal are arranged in a rectangular x-y grid.

For extra spatial precision, the ECAL also contains Preshower detectors which is located in front of the endcaps at 3.05 m along z-direction. These

allow CMS to identify neutral pions, help to distinguish between electrons and minimum ionizing particles and improve position resolution of electrons and photons. The preshower is a sampling calorimeter consists of a lead/silicon layer. The combining of the information from the preshower with the crystal calorimeter information, give the ability to measure the photon angle to an accuracy of $45 \text{ of } mrad/\sqrt{E}$ at high luminosity.

The energy resolution of an ECAL as a function of the deposited particle energy measured in electron test beam is given by:

$$\frac{\sigma(E)}{E} = \frac{2.8\%}{\sqrt{E(\text{GeV})}} \oplus \frac{12\%}{E(\text{GeV})} \oplus 0.3\%. \quad (2.7)$$

The first contribution is a stochastic term, which is due to shower containment, photostatistics and fluctuation in preshower absorber with respect to the measured energy. The second contribution is a noise term, which is due to electronics, digitization or pileup. The third contribution is a constant term, caused by nonuniformity of the longitudinal light collection, intercalibration errors and leakage of the back of the crystal [61].

2.2.5 The Hadronic Calorimeter

The Hadronic Calorimeter (HCAL) is a sampling calorimeter [56], it is optimized to measure the energy and position of charged and neutral hadron energies (protons, neutrons, pions and kaons) and for measuring the missing transverse energy $\cancel{E}_T$, due to neutrinos or exotic particles. It is important for hadrons identification. In conjunction, with the ECAL and the muon system the HCAL is important for electron, photon and muon identification. It covers the pseudorapidity range $|\eta| \leq 3$.

The HCAL is located between the ECAL and the magnet coil, it consists of the barrel (HB), the endcaps (HE), the outer barrel (HO), and the forward calorimeters (HF), Figure 2.9 shows the HCAL constituents and their position.

The hadron calorimeter barrel (HB) part consists of 36 identical wedges (two half-barrels) and covers the pseudorapidity range $|\eta| < 1.3$. The wedges are constructed of flat brass absorber plates aligned parallel to the beam axis, each wedge is segmented into four azimuthal sectors and contains 15 brass plates plus 2 external stainless steel plates. The plastic scintillator tiles are installed between these absorber layers and are divided into 16 η sectors,

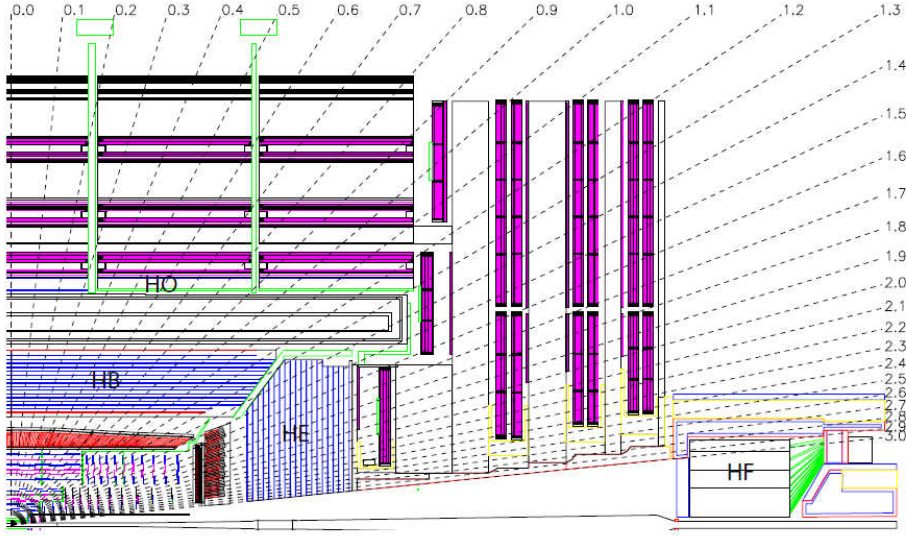


Figure 2.9: Longitudinal view of the CMS Hadronic Calorimeter showing the locations of the HCAL parts, the hadron barrel (HB), the endcap (HE), the outer (HO) and forward (HF) calorimeters [45].

resulting in a segmentation of $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$. The fiber cables lead the scintillation light to be detected by hybrid photodiodes.

The HCAL endcaps (HE) part consists of brass absorber plates (module) in an 18-fold ϕ -geometry matching that of the barrel calorimeter and covers the pseudorapidity range $1.3 < |\eta| < 3$. Each module is made up of 19 layers of brass and scintillator. The HE granularity is $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$ for $\eta < 1.6$ and $\Delta\eta \times \Delta\phi = 0.17 \times 0.17$ for $\eta \geq 1.6$.

The ECAL barrel (EB) and the HCAL barrel (HB) inside the solenoid is relatively thin, this mean the stopping power of ECAL and HCAL is not sufficient. Therefore for $|\eta| < 1.3$ the hadron calorimeter is extended outside the solenoid by installing the HCAL outer calorimeter (HO) which identify and measure the late showers. The HO is composed of five 2.5 m wide rings along the z-axis (-2, -1, 0, +1, +2). At the central ring (ring 0) HB has the smallest absorber depth. Therefore, two additional scintillator layers are installed on either side of this ring. Thus, the HO extends the minimum effective absorber thickness to $11.8 \lambda_I$ except at the barrel-endcap boundary region.

The energy resolution of the complete calorimeter system is measured by combining the ECAL and HCAL information in the pseudorapidity region

and energy. The hadronic energy resolution of the combined barrel HCAL and ECAL is given by:

$$\frac{\sigma(E)}{E} = \frac{0.847}{\sqrt{E(\text{GeV})}} \oplus 0.074. \quad (2.8)$$

The energy resolution in the endcaps is similar to that in the barrel. The first contribution is a stochastic term, and the second is a constant term [62].

2.2.6 The Superconducting Magnet

CMS has a large superconducting solenoid, which in part gives CMS its name. This allows the calculation of the momentum of incident charged particles by measuring the curvature of the particle trajectory caused by the magnetic field. The CMS magnet [45] consists of a solenoid, a magnet yoke, a vacuum tank, cryogenic plant and ancillaries, power supplies and process controls. The flux return yoke and the muon detector are located outside the magnet.

The CMS solenoid is designed to provide a maximum field of 4 T, at present the magnet is running at 3.8 T instead of the full design strength in order to maximize life time.

2.2.7 The Muon System

The detection of muons from a few GeV to a few TeV is one of the most important tasks of the CMS detector. The muon system [57] provides an excellent muon detection and efficient triggering in the pseudorapidity range $0 < \eta < 2.4$.

The muon detection system is composed of three different gaseous subdetectors. These use different detection technologies as shown in Figure 2.10.

- The drift tube chambers (DT) in the barrel region, which cover the pseudorapidity region $|\eta| < 1.2$.
- The cathode strip chambers (CSC) in the endcap region, which cover the pseudorapidity region $0.9 < |\eta| < 2.4$.
- The resistive plate chambers (RPC) in both the barrel and the endcap regions, which cover the pseudorapidity region $|\eta| < 1.6$.

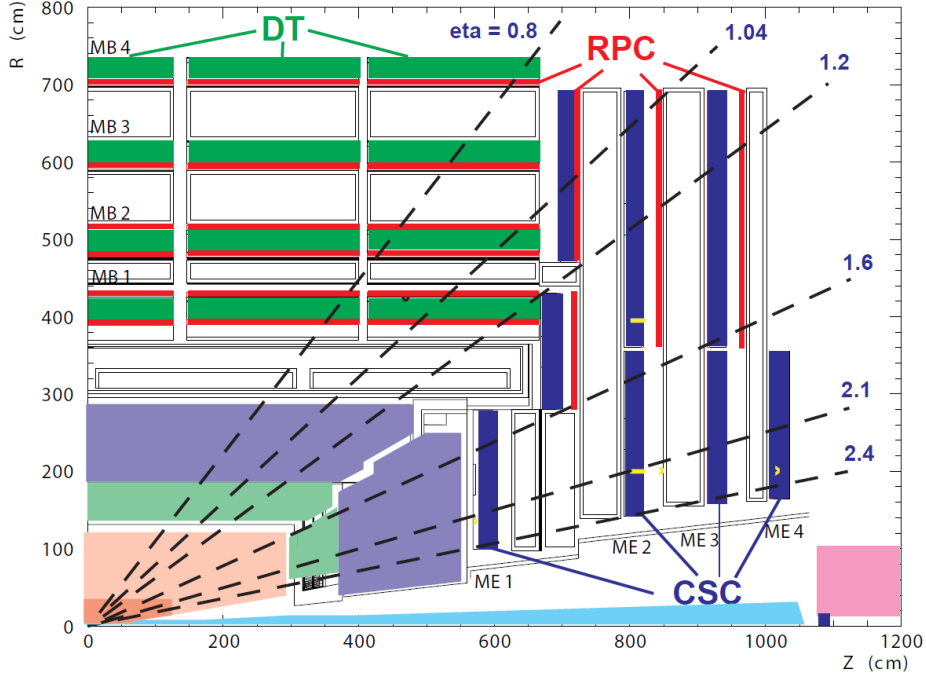


Figure 2.10: A quarter of the CMS muon system showing the different subdetectors: Drift Tubes Chambers (DT), Cathode Strip Chambers (CSC) and Resistive Plate Chambers (RPC) [63].

The Drift Tube Chambers:

Drift Tube Chambers (DT) are gaseous ionization detectors, filled with a mixture of 85% Ar and 15% CO₂ as quenching gas. They can be used for low muon rate at low neutron induced background rate. The barrel muon detector consists of 4 stations of DTs, these stations are located inside the magnet return yoke (5 wheel). The typical DT chamber spatial resolution is about 100 μm and the angular resolution in ϕ is about 1 mrad.

The Cathode Strip Chambers:

Cathode Strip Chambers (CSC) are multi-wire proportional chambers working in avalanche mode. They are filled with gas mixture of 30% Ar, 20% CF₄ and 50% CO₂. They can be used for high muon rate at high neutron induced background rate. The CMS endcap muon detector consists of 468 CSCs, each of the two endcap has four stations of CSCs. The typical CSC spatial resolution is about 200 μm , while the angular resolution in ϕ is about 10 mrad.

The Resistive Plate Chambers:

Resistive Plate Chambers (RPC) are fast gaseous detectors which are used as complementary trigger detectors. RPCs combine the spatial resolution with then time resolution and have a time resolution shorter than the LHC bunch crossing time (25 ns) while their spatial resolution is worse compared to DTs and CSCs. RPCs are installed in the barrel and the endcaps regions. The RPCs are attached to DTs in the barrel region, while they are attached to CSCs in the endcaps region.

Momentum Resolution:

The momentum resolution of the muon system only (standalone muon) is better than 10% for muon with $p_T \approx 100$ GeV. By combining the information from the muon system with that from the inner tracker (global muon), the momentum resolution can be improved from 1% to 6% depending on pseudorapidity for muons with p_T below 100 GeV and about 10% for muons with p_T up to 1 TeV muon [64].

2.2.8 The Trigger System

The LHC is designed to produce about 25 collisions per bunch crossing with a frequency of 40 MHz. The processing and storing all produced data is impossible. For this reason, the CMS trigger system [65, 66] is used to reduce the data rate in order to be stored. In CMS the rate is reduced in two steps, the Level-1 Trigger (L1) which is implemented in hardware and the High Level Trigger (HLT) which is implemented in software. The rate reduction capability will be a factor of 10^6 for the combined Level-1 and HLT Trigger.

The Level-1 trigger consists of programmable electronics (hardware) and uses coarse local data from the calorimeter and the muon systems to provide electron (photon) triggers, jet triggers, and muon triggers. The latency between a bunch crossing and the trigger decision is about $3 \mu s$, during the latency of the Level-1 trigger the event data is stored in the detector front-end electronics modules. The Level-1 trigger output rate is about 100 kHz. The Level-1 triggered data is passed to the HLT which is a software based system, it runs on a computer farm of about one thousand processors using software code that is similar to the offline software code. Each processor runs the HLT software code, so that the Level-1 output rate of 100 kHz is reduced to 100 Hz which is the final output rate of the HLT. Figure 2.11 represents the trigger performance for a single muon trigger from 2011 and 2012 data-taking, to illustrate typically the performance of the trigger system.

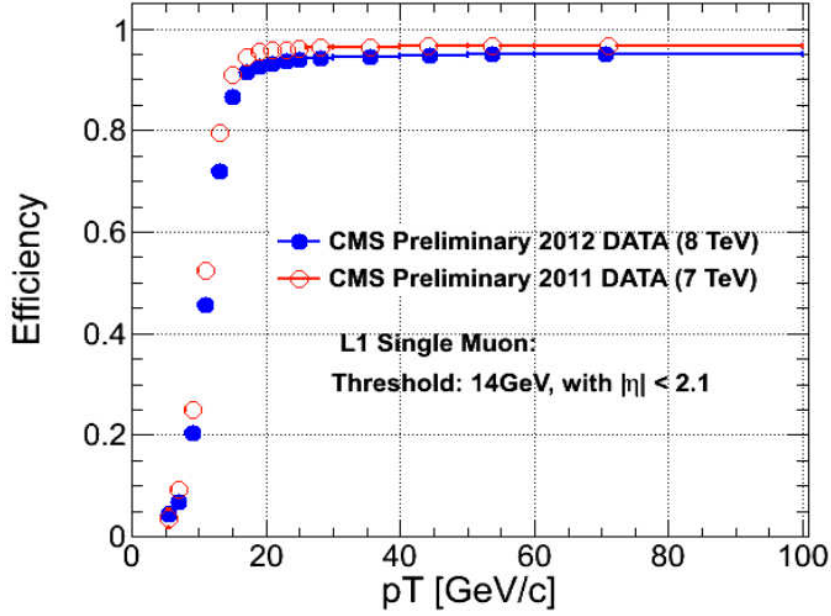


Figure 2.11: Level-1 trigger efficiency for a single muon trigger [67].

In order to trigger events it is generally preferred to use a simple and stable trigger. For this analysis, top quark pair events are triggered via a single muon trigger which is called *HLT_IsoMu24*, this trigger is unrescaled over the considered run period and the turn-on curve sharply saturates at 97%. The single muon trigger *HLT_IsoMu24* requires an isolated muon with a transverse momentum p_T greater than 24 GeV and the isolation criterion is a maximum deposit of energy in a cone around the muon. This trigger ensures, that the events containing at least one muon are selected. The use of a single muon trigger avoids the use of cross-triggers which are complex and would enhance the effects of systematic uncertainties. The used HLT muon trigger will be discussed in more details in section 4.4.1.

Chapter 3

Object Identification and Reconstruction

In the previous chapter, the CMS detector and its sub-detectors are discussed. In this chapter, the reconstruction and identification of the physics objects is described. The construction of the physics objects from the raw data collected in the experiment is called reconstruction.

After a collision has taken place in the CMS detector a large amount of information is recorded for every event that passes the final level of the CMS triggering system. Each sub-detector of CMS records data in hundreds or thousands of channels. Thus, all channels containing data must be analyzed to reconstruct the momenta and identity of particles that pass through the detector.

Complex algorithms (Kalman Filter) are used at the reconstruction level to combine information from the multiple layers of sub-detectors. Tracks and primary vertices are reconstructed using data obtained from the tracker combined with other sub-detectors, if possible. The data obtained from the calorimeters (HCAL, ECAL) is used to reconstruct hadronic jets, or showers of particles arising from hadrons in the calorimeters. The calorimeter data is also used to reconstruct missing transverse energy ($\cancel{E}_T$). The reconstruction of electrons uses the combined information from the tracker and the electromagnetic calorimeter. The muon system, the tracker and the calorimeters are used to reconstruct muon tracks and to identify good muons from physics events.

3.1 Reconstruction of Tracks

When charged particles traverse the inner detector material, they lose energy through ionization and therefore deposit small amounts of energy along their trajectory. Measurements of these energy deposits by the inner detector are called hits. The reconstructed particle trajectory from the hits caused by a charged particle is called a track.

The track reconstruction in the CMS tracker is a challenging phase of the event reconstruction. Two track finders are used in CMS, the Combinatorial Track Finder (CTF) and the Road Search (RS) [68, 69]. The default track reconstruction at CMS is performed by the CTF track finder, which uses a Kalman Filter [70] for the trajectory building and for the estimation of the track parameters (track finding and fitting). Thus, the track can be reconstructed by combining measured hits to a trajectory using pattern recognition algorithms. The tracking sequence is an iterative approach in which CTF is run multiple times, and the used hits in an iteration process are considered in the next one. The track reconstruction process is divided into 5 steps, it starts with the local reconstruction of digis and ends producing tracks :

1. Local reconstruction
2. Seed finding
3. Pattern recognition (trajectory building)
4. Final fit
5. Track cleaning and quality

Local reconstruction:

The local reconstruction transforms the digitized hits from the tracker into reconstructed hits in the local coordinate system of the silicon sensors. This is performed in two subsequent steps: the clustering (grouping together neighboring, gain corrected digis) and the reconstructed hit conversion. Thus, clusters of adjacent pixels or strips above a certain threshold are formed. The formed clusters are then translated into possible hit measurements in the hit conversion using a cluster parameter estimator algorithm. The hit positions and a corresponding uncertainties are estimated in the local coordinate system of the silicon sensors. These two steps are performed separately for pixel

and strip detector, and by gathering them a local reconstruction for the whole tracker can be performed giving reconstructed hits. The resulted reconstructed hits are then needed as input for the track reconstruction.

Seed finding:

The starting point for the pattern recognition (trajectory) in the tracker is a trajectory seed. The seed should contain five parameters which are needed to start the trajectory building and the uncertainties. At least three hits in the inner layers, or two hits in the inner layers and a beam constraint, are necessary for each estimate. The starting parameters of the trajectory are calculated making a helix which pass through the three points.

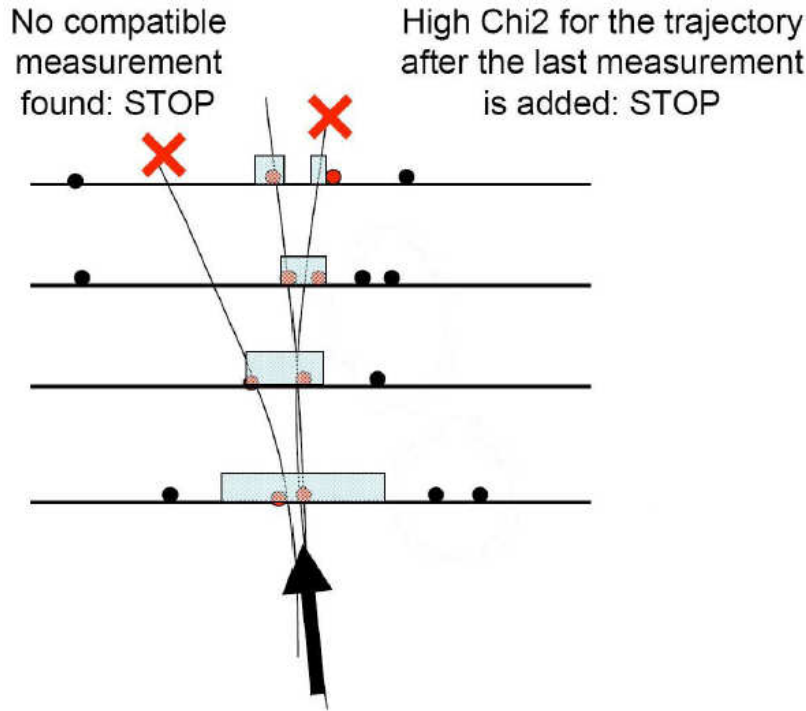


Figure 3.1: The Kalman Filter based CTF track pattern recognition [68].

Pattern recognition (trajectory building):

The trajectory building is based on a combinatorial Kalman Filter (CTF) method, which starts from the estimate of the track parameters provided by the seed. The trajectory is built iteratively by extrapolating the trajectory to the next layer, accounting for multiple scattering and energy loss in the

material.

Several new trajectory candidates, one per hit, are created in a new layer that is compatible with the predicted trajectory. When a hit is found in the expected position it is added to the candidate trajectory and the track parameters are updated using the new hit information with a Kalman Filter. If no measured hit is compatible with the track in the predicted position the trajectory is rejected as a fake and is not propagated anymore and the extrapolation continues to the next layer. Figure 3.1 shows the procedure of the Kalman Filter based CTF pattern recognition, so that only the five best candidates are kept for further propagation. To avoid biases and exponential growth of track candidates, all resulting trajectory candidates are then grown in turn to the next compatible layer, and the procedure is repeated until the outermost layer of the tracker is reached or no more compatible hits can be found. The algorithm can be tuned to limit CPU time consumption. For example, no track candidates with invalid hits in two consecutive layers are considered. Also, during HLT, pattern recognition stops after five hits, even if there are much more.

Final fit:

Hits selected during the pattern recognition are fitted in order to find the best estimate of track parameters and errors. The used Kalman Filter for the track fit is a “dynamic” Least Squares Method [70]. The trajectory state is a vector $\vec{P}$ on each detector surface, this vector is defined as:

$$\vec{P} = \left(\frac{q}{p}, \lambda, \phi, x_t, y_t \right). \quad (3.1)$$

The vector components are: the inverse track’s signed momentum, the dip-angle $\tan\lambda = p_z/p_t$, the ϕ angle $\tan\phi = p_y/p_x$ and the hit coordinates (x_t, y_t) on a local frame called tangent frame. The Kalman Filter proceeds in an iterative way through all hits of the track candidates and estimates the track parameters. The starting point of the fit is the estimated track parameters from the pattern recognition, hits are added to them iteratively. Thus, the state vector on the new surface is calculated for every iteration process, this leads that the state vector accuracy is improved from the first to last surface. The final precision is obtained only for the last surface, this procedure called the forward fit. A second fit called backward fit is applied in the opposite direction in order to recover the same degree of precision. The forward and backward fit information are combined to give the best estimate of the state vector on each surface. This procedure yields optimal estimates of the parameters at the surface associated with each hit.

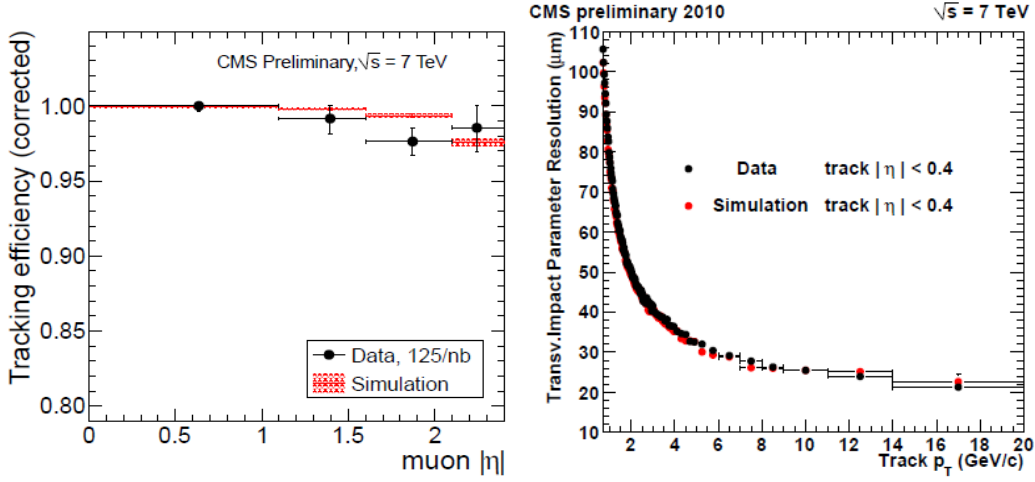


Figure 3.2: Corrected tracking efficiency as a function of η for muons (left) and measured resolution of the track transverse impact parameter as a function of the track p_T (right) [60, 58].

Track cleaning and quality:

Once the track final fits, the CFT track collection is cleaned (filtered) in order to reduce ambiguities arising from double counting of tracks. This is performed by keeping only the best track which is the one with the smallest χ^2 . In fact, the track finder (CTF) yields a significant fraction of fake reconstructed tracks. Thus, in addition to the track cleaning, quality cuts are applied on the tracks that pass the cleaning in order to reduce the fake rate. The way to reduce the fake rate can be found in [69].

Figure 3.2 shows the muon tracking efficiency as a function of the muon η and the transverse impact parameter resolution as a function of the track p_T . More details about the performance of the track reconstruction can be found in [60, 58].

3.2 Reconstruction of Primary Vertices

The identification of vertices plays an important role in event reconstruction. The primary-vertex (PV) is the position where the pp collision has taken place. Usually multiple primary vertices are reconstructed because there is more than one pp collision per bunch crossing. Vertices coming from decays of long-lived particles like heavy flavor hadrons (e.g., B hadrons) and tau

leptons are called secondary vertices (SV).

Vertex reconstruction is explained in detail in [71, 72] and can be done after the reconstruction of tracks. The vertex reconstruction at CMS is done in two steps:

- Vertex finding: which is the task of identifying vertices within a given set of tracks.
- Vertex fitting: which is the determination of the vertex position and parameters assuming it is formed by a given set of tracks.

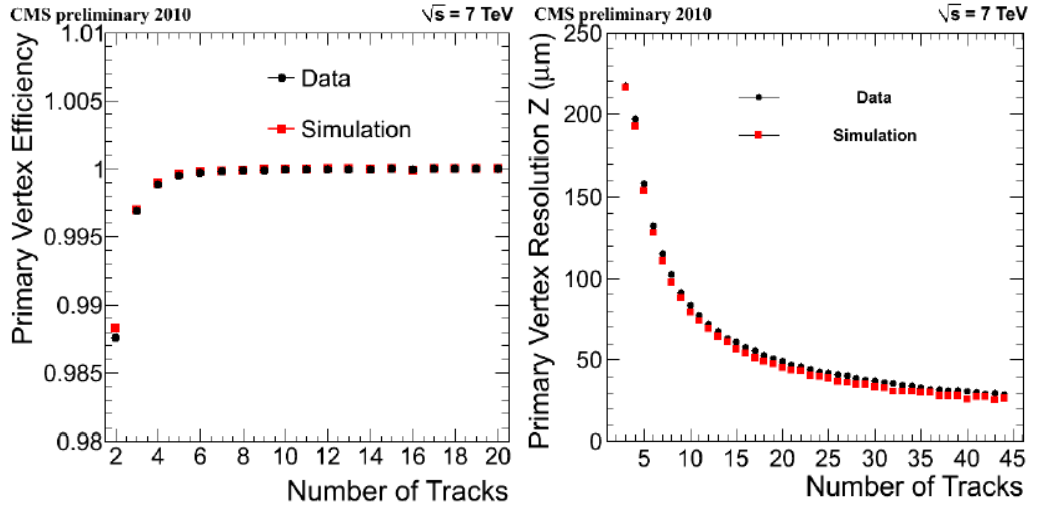


Figure 3.3: Primary vertex efficiency as a function of the tracks number (left) and primary vertex resolution in z as a function of the tracks number used in the fitted vertex (right) [58].

A Kalman Filter provides the best possible vertex estimate. CMS has used two primary-vertex finding algorithms: The histogramming algorithm which merges adjacent tracks (tracklet) to each other in z_{IP} to form primary-vertex candidates. The second algorithm is the divisive algorithm which looks for large z_{IP} intervals without tracks to divide the z axis in several regions. The primary-vertex finding, provides a primary-vertex position measurement to the HLT. There are several vertex fitters available for CMS like the Adaptive Vertex Fitter, the Trimmed Vertex Fitter, the Gaussian Sum Fitter, the Kalman Vertex Fitter and the Adaptive Gaussian Sum Vertex Fitter [73]. The most often used algorithms for vertex fitting are the Trimmed Vertex Fitter and the Adaptive Vertex Fitter which are explained in [71, 74]. The

primary vertex reconstruction starts from a given set of reconstructed tracks which are selected to be compatible with beam line. The selected tracks are then clustered according to their z coordinates. These clustered tracks are then used to form the primary vertex candidates. Figure 3.3 shows the primary-vertex efficiency as a function of the tracks number and the primary-vertex resolution as a function of the tracks number using an Adaptive Vertex Fitter. More details about the performance of the vertex reconstruction can be found in [58].

3.3 Reconstruction and Identification of Muons

3.3.1 Reconstruction of Muons

The muon reconstruction and identification is explained in [50, 75, 63, 64] is performed using both the muon system and the silicon tracker. It uses the concept of regional reconstruction in order to allow its use in both the offline reconstruction and the HLT online event selection.

Track reconstruction is only performed in the part of the tracker which can possibly be involved in the reconstruction of a charged particle track compatible with the hits in the muon chambers. This method depends strongly on the identification of a good *seed*, which provides initial values of the five trajectory parameters and their errors, that can start the reconstruction with high efficiency and reliability. A seed-generation algorithm has been developed for offline reconstruction. The algorithm performs local reconstruction in the entire muon system and uses patterns of segments reconstructed in the CSC and/or DT chambers as initial seeds.

The reconstruction of muons is performed in three stages:

- local reconstruction (local-pattern recognition): produces a track segment for each DT and CSC chamber.
- standalone reconstruction: uses only information from the muon system.
- global reconstruction: uses information from the muon system and the silicon tracker.

Standalone muon reconstruction:

Standalone muon reconstruction uses information from the muon system (DT, CSC and RPC). Tracks are reconstructed in a manner similar to the track reconstruction in the inner tracker. The track-reconstruction algorithm, which is based on a Kalman Filter technique, consists of the following steps: trajectory building (pattern recognition), trajectory cleaning (resolution of ambiguities) and trajectory smoothing (final track fit). The standalone muon reconstruction and identification chain starts with the *local reconstruction*, so that the positions of hits in the DT, CSC and RPC subsystems are reconstructed. The hits within each DT and CSC chamber are matched forming segments (track stubs). The seeds are constructed by matching and combining the segments. The seeds contain a position, direction and estimated p_T . These seeds are used as a starting point for the track fit of DT, CSC and RPC hits. Track parameters and the corresponding errors are updated at each step. Finally the Kalman Filter is applied backwards and the track is extrapolated to the interaction region.

Global muon reconstruction (outside-in):

The concept of a global muon is to combine information from multiple sub-detectors in order to obtain a more accurate description of the muon. Therefore, it uses and combine the information from the inner tracker (tracker muon), and the muon system (standalone muon). The reconstruction of global muon is performed in two steps:

- **Matching Tracks reconstructed in the silicon tracker to Standalone Muon Tracks:** The track matching is the process of choosing tracks reconstructed in the silicon tracker to combine with standalone muon tracks. It proceeds in two steps. The first step is to define a region of interest, this region is rectangular in $\eta - \phi$ space, and to select a subset of tracker tracks that are in the region of interest. The second step is to iterate over the subset of tracker tracks, and choose the best track to combine with the standalone muon. In order to match the standalone muon track to tracker track, the two tracks are propagated to a common reference point or surface where the track parameters are compared. The surface is chosen differently for low and high p_T muons. Possible choices are the outer surface of the tracker, the inner surface of the muon system or somewhere in between. After propagation to a common surface, a comparison of the track parameters is made using the tracks position and momentum. Comparing the momentum parameters provides the best match for low- p_T tracks, while the spatial

coordinates gives the best match to the high- p_T candidate.

- **Global fit of Silicon Hits and Muon Hits:** After matching of the tracks to the standalone muon track, a global fit of the hits in the tracker and the muon system is performed. If there is more than one global muon track, the global muon track with the best χ^2 is chosen. Thus, there is only one reconstructed global muon for each reconstructed standalone muon. The global fit improves the momentum resolution for high-momentum muons with $p_T \geq 200$ GeV compared to the tracks reconstructed only from silicon tracker.

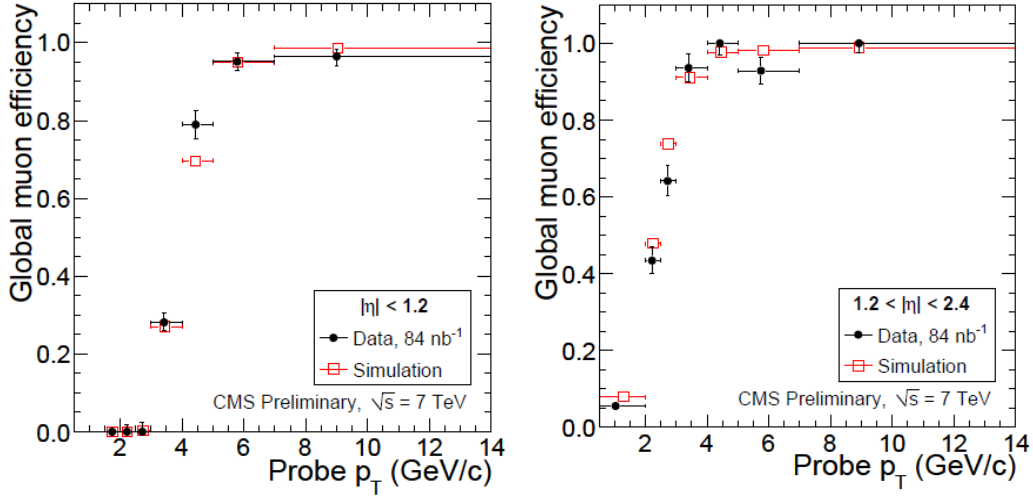


Figure 3.4: The muon reconstruction efficiency as a function of muon p_T for Tag-and-probe method in data compared to the Monte Carlo. The plots show the efficiency for Global Muons in the barrel (left) and endcaps (right) [76].

Tracker muon reconstruction (inside-out):

The muon track reconstruction algorithms presented so far start from the muon system. To identify muons with a low number of hits (low p_T) in the muon system, a complementary approach has been performed which considers all inner tracks and identifies them as muons by looking for compatible signatures in the calorimeters and in the muon system. These muons are called *Tracker Muons*. Tracker muons are reconstructed starting from a reconstructed inner track that is extrapolated to the muon system. The energy deposition in the calorimeter can also be used for muon identification. All tracks with $p_T > 0.5$ GeV and total momentum $p > 2.5$ GeV are treated

as potential muon candidates for this algorithm [64]. The extrapolation takes into account the expected energy loss in the material between the tracker and the muon system as well as the uncertainty due to multiple scattering. If the extrapolated track can be matched to at least one track segment in one DT or CSC chamber within the uncertainty, it is considered as a tracker muon. There is a list of criteria used in order to improve the identification of muons. More details can be found in [77, 76, 64].

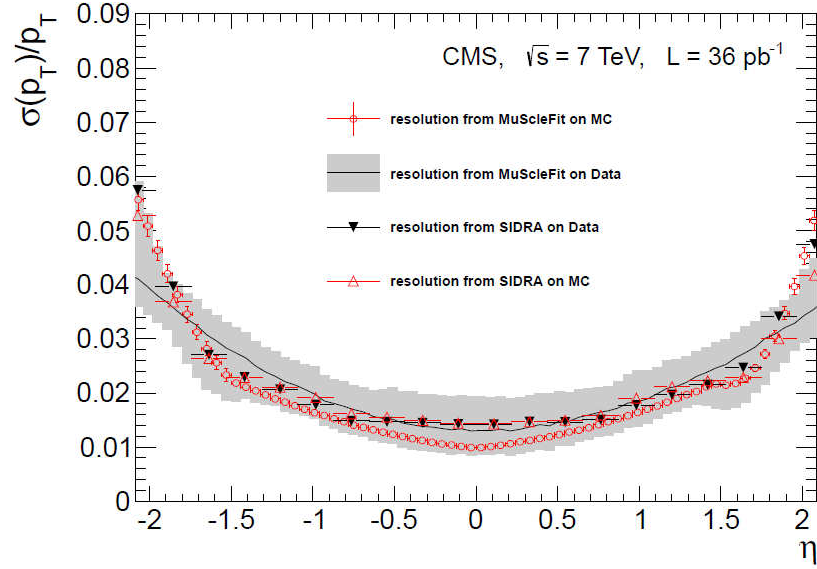


Figure 3.5: Relative transverse momentum resolution for muons as a function of muon η , for data (black line) compared to the Monte Carlo for the MuSclFit (red circles) method and SIDRA (red triangle) method. The gray band represents the statistical and systematic 1σ uncertainty of the measurement [64].

Figure 3.4 shows the muon reconstruction efficiency as a function of the muon p_T for a Tag-and-probe method [76]. The tagged muon is defined as a Global Muon that passed a single muon trigger, and the probe muon is a tracker track with minimum-ionizing particle (MIP) signature. The relative muon transverse momentum resolution as a function of the muon η is shown in Figure 3.5.

3.4 Reconstruction of Electrons

When a high energetic electron traverses through matter, it initiates an electromagnetic shower via bremsstrahlung and photon conversion. The reconstruction of electrons in CMS is based on the information from the pixel detector, the silicon strip tracker and the electromagnetic calorimeter.

The reconstruction of electrons has three major steps [50, 78], which are the electron clustering, electron track reconstruction and final matching between cluster and track.

Electron clustering:

Because of the strong magnetic field (3.8 T) an electron shower deposits its energy in several ECAL crystals distributed in ϕ . About 35% of all electrons deposit more than 70% of their initial energy via bremsstrahlung in the tracker before reaching the ECAL, in 10% of the cases, more than 95% of the initial energy is deposited.

The spread energy is clustered by building a cluster of crystal clusters, called supercluster, which is extended in ϕ . The building of superclusters is done by collecting the shower energy, in particular by recovering the energy spread in ϕ due to secondary bremsstrahlung emission and photon conversions in the material, in front of the ECAL. These algorithms must also avoid collecting in the same supercluster energy deposits due to different particles, and to minimize the effects of noise fluctuation. The CMS standard algorithms are the Hybrid algorithm in the ECAL barrel region and the Island algorithm for the endcap. These two algorithms start from seed crystals and collect energy deposits to form clusters and finally superclusters. The ECAL superclusters are used for the finding of pixel seeds for the primary electron tracks.

Electron Track Reconstruction:

The track reconstruction process is the analogous to that of the muons. It starts with the seed generator which looks for initial tracks. The trajectory builder builds the track from the seed. Then the trajectory cleaner will clean the ambiguities among all possible tracks and maximum number of tracks are kept. The last step is so-called trajectory smoother which uses all collected hits and re-evaluates the track parameters through a backward fit.

Two algorithms are used to reconstruct electrons at the track seeding stage, tracker driven seeding and ECAL driven seeding. The first one is suitable for low p_T electrons which may not reach the ECAL or the electrons

inside jets and thus is not important for electrons from top-pair decays in this analysis. The ECAL driven seeds start from ECAL superclusters with $E_T > 4$ GeV. It is optimized for isolated electrons in the p_T range relevant for Z and W decays and down to approximately $p_T \approx 5$ GeV.

The track seeds (triplets of hits or pairs of hits compatible with a given beam spot) are created in the pixel detector. The ECAL driven seeding requires the matching of the seed with a supercluster. The electron tracks suffer from non-Gaussian fluctuations due to bremsstrahlung. Starting from the seed, a trajectory is created. Compatible hits on the next silicon layers are first searched for. Then an extrapolation is performed, using a Bethe Heitler modeling of the electron losses and a Gaussian Sum Filter (GSF) [79] in the forward fit. The process iterates and stops when the final tracker layer is reached or no hit is found in two subsequent layers. Finally, a minimum of five hits is required to create a track.

Track-cluster matching: Due to the bremsstrahlung emission, the matching between the track and the supercluster is done using the track parameters at vertex. There are two possibilities for the matching between the track and the supercluster: The first one is to match the initial track with the energy weighted average impact point calculated from the supercluster taking into account that the track parameters are known with good precision at the initial vertex from the outer-to-inner track fit. The second possibility is to use the track parameters at the outermost state to perform the matching. The track parameters at the outermost state means that the track parameters can be estimated at ECAL entrance. This leads to improve the matching between the tracker and the calorimeter, and gives the possibility to estimate the bremsstrahlung radiated by the track using the tracker information only.

There is a list of criteria used for the matching in order to improve the identification and classification of electrons. For more details see [80].

3.5 Reconstruction of Jets

Due to the huge QCD cross section the jets will dominate high- p_T physics at the LHC. Jets will not only provide a benchmark for understanding the detector, but will play an important role in the search for physics beyond the Standard Model. Event signatures for new gauge bosons like Z' , SUSY, Higgs boson production, compositeness, and other new physics processes require accurate reconstruction and measurement of jets coming from high- p_T quarks and gluons [50].

In the particle accelerators (e.g. LHC) the produced quarks and gluons cannot be observed singularly due to color confinement in Quantum Chromodynamics (QCD). Thus, they fragment into final state particles through spontaneous creation of quark-antiquark pairs, which is referred to as fragmentation, resulting in bunches of hadrons called jets that are collimated in the direction of the initial partons. These jets are reconstructed using jet reconstruction algorithms.

3.5.1 Jet Algorithms

Various algorithms are used at CMS for the jets reconstruction. These algorithms can be run on several reconstructed input objects like calorimeter towers, particle candidates or tracks. Two non-trivial desired requirements for jet algorithms are: Infrared safety and collinear safety.

- Infrared safety: means that the jets have to be insensitive to addition of soft particles.
- Collinear safety: means stability of the jet finding if a hard particle is split into two or more particles.

Another performance criterion, especially on trigger level, is the speed of the algorithm [81]. The iterative cone algorithm is used on trigger level because of its fast and predictable runtime.

Jet algorithms can be classified in two classes:

- Cone algorithms: like the Midpoint Cone [82], the SISCone (Seedless Infrared Safe Cone) [83] and Iterative Cone [84], which try to maximize the energy flow within a cone with a given radius R in (η, ϕ) space [85].
- Clustering algorithms: like the Inclusive kT jet algorithm [86, 87], Cambridge-Aachen Algorithm [88] and the Anti kt Jet Clustering Algorithm [88] which combines sequentially entities based on their distances to each other. A distance d_{ij} between two entities (particles, pseudojets) and a distance d_{iB} between entity i and the beam (B) are defined for these algorithms. The algorithm searches the smallest of these distances and if it is a d_{ij} the two entities i and j are recombined. If d_{iB} is the smallest distance, i is called a jet and removed from the list of entities. The distances are recalculated and the procedure repeated until no entities are left.

The most important difference between the clustering algorithms is the defining way of the distances d_{ij} and d_{iB} . The definition:

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2}, \quad (3.2)$$

$$d_{iB} = k_{ti}^{2p}, \quad (3.3)$$

where $\Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$ and k_{ti}, y_i and i are the transverse momentum, rapidity and azimuth of particle i respectively. R and p are free parameters of the algorithm. The parameter R is a size parameter to weight the distances d_{ij} . The behavior of the algorithm strongly depends on the value of p that sets the power of the momentum scale.

The most important cases are the case of $p = 1$ which is called the inclusive kt algorithm, the case of $p = 0$ is special and it corresponds to the inclusive Cambridge/Aachen algorithm and the case of $p = -1$. Because of the negative power, the last one is called the anti-kT jet-clustering algorithm. These algorithms fulfill the requirements of infrared and collinear safety and produce jets with boundaries which are flexible with respect to soft radiation. Out of these algorithms, the anti-kT algorithm is the default algorithm for most physics analyses at CMS [88].

All jets algorithms can run on several input quantities. They can be directly applied on generated particles in the simulation to produce generator jets. Reconstructed jets (detector jets) belong to four types, depending on the way the individual contributions from subdetectors are combined: Calorimeter jets, Jet-Plus-Track jets, Particle-Flow jets and Track jets [89].

Calorimeter jets (CALO jets):

They are reconstructed from energy deposits in the calorimeter towers. A calorimeter tower consists of one or more HCAL cells and the geometrically corresponding ECAL crystals. As the HCAL has a much coarser segmentation than the ECAL, corresponding ECAL cells are added to match the HCAL geometry. This yields 4176 calorimeter towers which are used as input for the jet algorithm. The resulting jets are called CALO jets.

Jet-Plus-Track jets (JPT jets):

As the energy resolution of the calorimeters, especially of the HCAL, is not sufficient for most analysis purposes, the energy response and resolution can be improved, according to the Jet-Plus-Track algorithm [90]. In this

method tracks are added by matching them to the CALO jets and making use of the excellent momentum resolution of the tracking detector. These track corrected CALO jets are called Jet-Plus-Track jets (JPT jets).

The Particle-Flow jets (PF jets):

Particle flow means that all stable particles, namely muons, electrons, photons, charged hadrons, and neutral hadrons, in the event are reconstructed. The particle-flow algorithm [91, 92] combines the information from all CMS sub-detectors to identify and reconstruct all particle-flow candidates in the event. In the first step of the particle flow algorithm, fundamental elements like tracks and calo clusters are reconstructed. These are then linked to each other in blocks based on their position in (η, ϕ) space. In the last step, particles are reconstructed from these blocks. For example, charged hadrons, electrons and muons are reconstructed from tracks in the tracker. Neutral hadrons and photons are reconstructed from energy clusters separated from the extrapolated positions of tracks in ECAL and HCAL, respectively. A neutral particle overlapping with charged particles in the calorimeters is identified as a calorimeter energy excess with respect to the sum of the associated track momenta. Particle flow jets are reconstructed afterwards with the algorithms described above running on the list of PF particles as input. The PF jet momentum and spatial resolutions are improved with respect to calorimeter jets, as the use of the tracking detectors and of the high granularity of ECAL allows resolution and measurement of charged hadrons and photons inside a jet, which together comprise 85% of the jet energy. In this analysis, we use anti-kT PF jet algorithm with a cone size of $\Delta R = 0.5$.

The Track jet:

The track jet algorithm uses only the tracks from the silicon tracking detector as input. These jets are used at CMS only as cross check to compare with other jet types since the systematic uncertainties of their energy scale is complementary to those of the CALO jets.

The Monte Carlo particle jets (Gen jets):

They are reconstructed by clustering the four-momentum vectors of all stable particles generated in the simulation, those jets are called "Gen jets". In particular, there are two types of MC particle jets:

- In the first type, the neutrinos are excluded from the clustering. These MC particle jets are used for the study of the PF and JPT jet response in the simulation.

- In the second type, both the neutrinos and the muons are excluded from the clustering. These MC particle jets are used for the study of the CALO jet response (because muons are minimum ionizing particles and therefore do not contribute appreciably to the CALO jet reconstruction).

3.5.2 Jet Energy Corrections

The raw energy of a reconstructed jet is given by the sum of energies deposited in the calorimeter cells within the jet cone and is affected by calorimeter response, noise, showering effects, underlying event and pileup event. Therefore, after the reconstruction of jets it is important to correct the jet energy to match the energy measured for the measured jet to the energy of the corresponding true particle jet, where true particle jet means from the clustering of all stable particles originating from the fragmenting parton, as well as of the particles from the underlying event activity. Thus, the measured energy of the reconstructed jets is corrected in several steps in order to bring it in accordance with the energy of the true particle [93].



Figure 3.6: Schematic picture of the multi-level jet correction, in which corrections to the reconstructed jet are applied in sequence to obtain the final calibrated jet [94]

The multi-level jet correction, shown schematically in Figure 3.6, is applied in the following fixed sequence:

- Level1 or offset correction:**

It is the first step of the correction chain. The goal of the offset correction is to estimate and remove the energy coming from pileup events and electronical noise. Alternative correction called "Level1 Fast jet" correction can be applied too.

- Level2 or Relative Jet Correction:**

The goal of this correction is to make the jet response flat with respect to η . Essentially, it is used to measure the response of a jet at any η relative to the jet energy response in the central region $|\eta| < 1.3$. The derivation of the Relative correction is done either by using MC truth or by employing a data driven method.

3. Level3 or Absolute Jet Correction:

It is used to make the jet response flat with respect to p_T . Once a jet has been corrected for η dependence (Level2 correction), it is corrected back to particle level (the corrected CALO jet p_T is equal on average to the Gen jet p_T). The derivation of the absolute correction is done either by using MC truth information or by employing data driven techniques.

4. Level4 or EMF (electromagnetic energy fraction) Jet Correction:

It is optional. It is used to make the jet response uniform versus the electromagnetic energy fraction (EMF).

5. Level5 or Jet Flavor Correction:

The goal of this optional jet correction is to correct for the jet flavor dependence. It is applied on top of the default Level2+Level3 jet corrections and corrects back to the particle level. If corrections back to the parton level are required, for example when reconstructing the Z or W mass in their hadronic decays, the Level2+Level3+Level5 corrections can be combined with the Level7 correction.

6. Level6 or Underlying Event Correction:

It is optional correction for underlying event energy due to soft interactions involving spectator partons.

7. Level7 or Parton Jet Correction:

This optional parton correction is applied on the default Level2+Level3 jet corrections and corrects back to the parton level, which means that the corrected CALO jet p_T is equal on average to the originating parton p_T of the hard process.

The corrections used for this analysis are fast jet correction, relative jet correction, absolute jet correction, jet flavor correction and parton jet correction.

Measurements of the jet transverse momentum resolution for data sample corresponding to an integrated luminosity of 36 pb^{-1} , for three types of jets are shown in Figure 3.7. The solid red line shows the corrected generator level MC (MC truth) resolution and the yellow band is its total systematic uncertainty. The uncorrected generator level MC resolution is shown as a red-dashed line. The black dots are the bias-corrected data measurements [95].

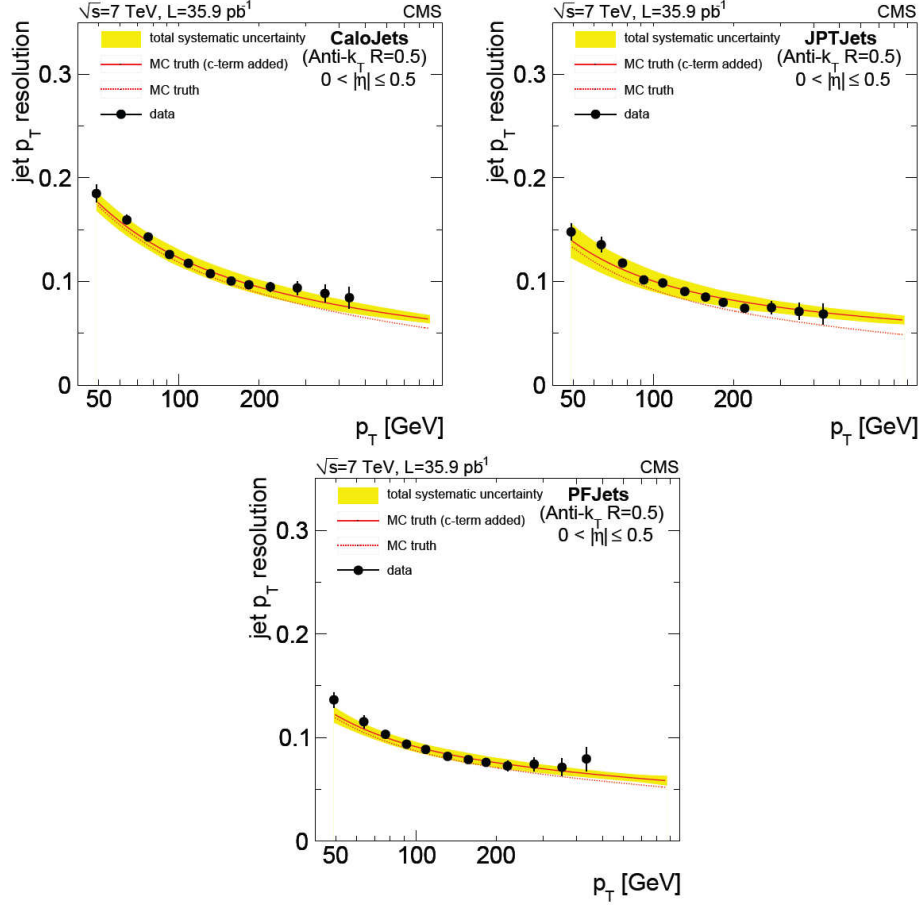


Figure 3.7: Jet transverse momentum resolution of Bias-corrected data measurements (black dots), corrected MC truth (solid red line) and uncorrected MC truth (red-dashed line). For CALO jet (top left), JPT jet (top right), and PF jets (bottom) in $\eta < 0.5$. [95].

3.6 Missing Transverse Energy ($\cancel{E}_T$)

Missing transverse energy $\cancel{E}_T$ is an important variable for electroweak measurements and for searches for new physics with the CMS detector. The direct observation of neutrinos in the CMS detector is impossible since they only interact through the weak interaction, and therefore they escape the detector without being measured directly. Therefore, neutrinos have to be identified as an imbalance in transverse momentum and thus appear as missing transverse energy ($\cancel{E}_T$). The measurement of $\cancel{E}_T$ in the CMS detector benefits from excellent cell segmentation, hermeticity, and good forward coverage. The

reconstruction of $\vec{\cancel{E}}_T$ vector is calculated from the vector sum over uncorrected transverse energy deposits in projective calorimeter towers, which have an energy E_n , polar angle θ_n and azimuthal angle ϕ_n :

$$\vec{\cancel{E}}_T = - \sum_n \left(E_n \sin \theta_n \cos \phi_n \hat{i} + E_n \sin \theta_n \sin \phi_n \hat{j} \right) = \cancel{E}_x \hat{i} + \cancel{E}_y \hat{j}, \quad (3.4)$$

where the index n runs over all calorimeter input objects.

Corresponding to the different types of jets described in the previous subsection, the $\cancel{E}_T$ can be reconstructed using either the energy deposits in the calorimeters, the tracks, or the particle flow candidates. The $\cancel{E}_T$ used for this analysis is reconstructed using particle flow objects. The missing transverse energy is reconstructed by simply calculating the vectorial sum of the transverse momenta of all PF candidates in the event and taking the negative value as $\cancel{E}_T$ [91, 95].

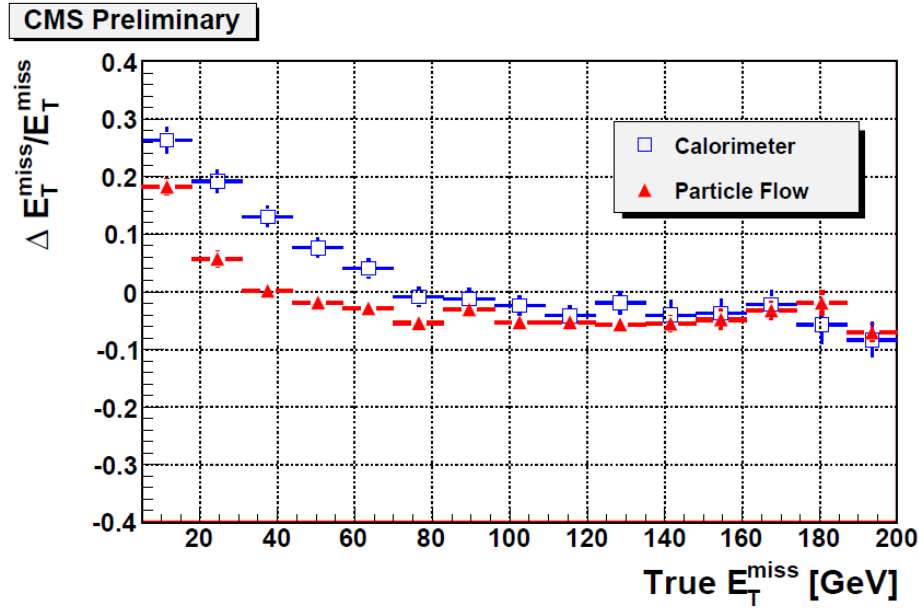


Figure 3.8: Missing transverse energy response as a function of the true $\cancel{E}_T$ for inclusive $t\bar{t}$ sample, for particle flow reconstruction (solid triangles) and for calorimeter reconstruction (open squares) [91, 95].

This reconstruction has in fact large uncertainty. This uncertainty is for

instance due to the presence of pileup collisions or the bending of tracks in the 3.8 T magnetic field, but mainly comes from the calorimeter energy resolution. The $\cancel{E}_T$ resolution in CMS is expected to be dominated by calorimeter resolution. The jet energy corrections are used to calibrate the measured $\cancel{E}_T$, so that the vector sum of absolute corrections on jet p_T is subtracted from the measured raw $\cancel{E}_T$ in order to obtain calibrated $\cancel{E}_T$. The muons, deposit very small fraction of their energy in the calorimeter, and hence mimic $\cancel{E}_T$. Thus $\cancel{E}_T$ has to be corrected for the energy deposited by the muon in the calorimeter. Correction are also needed for the tau lepton decays which yield jets that differ substantially from those of gluon or quark jets. This is why the measured tau energy is replaced by the energy measured by the Particle Flow (PF) algorithm which provides rather precise tau measurement. This correction improves $\cancel{E}_T$ resolution significantly [81]. In order to study the real case of missing transverse energy, a $t\bar{t}$ event sample is used. Figure 3.8 shows the missing transverse energy response, defined as the relative average difference between the reconstructed and the true $\cancel{E}_T$.

Chapter 4

Data Samples and Event Selection

In the previous chapter, we discussed the reconstruction and identification of the physics objects. In this chapter, we introduce the used datasets for the present analysis and apply a standard reference selection for $t\bar{t}$ events in the muon+jets channel in the mass range close to the $t\bar{t}$ production threshold.

4.1 Data Samples

The data sample used in this analysis was collected with the CMS detector at a center-of-mass energy of 7 TeV during the first half of 2011. The data samples spans the run range 160404-167993, which correspond to a total integrated luminosity of $L = 1092 \text{ pb}^{-1}$ with an uncertainty of 4.5% [96].

4.2 Monte Carlo Samples

Simulated events are needed to validate the expectation and to estimate the CMS potential to discover $t\bar{t}$ resonances. Samples of different physics processes are generated to model signal and backgrounds. The signal and background events are generated at the center-of-mass energy of 7 TeV. Simulated events are weighted according to the number of pileup collisions observed in data.

4.2.1 Resonant $t\bar{t}$ Processes

The resonant signal is simulated with MadGraph [97] to investigate the reconstruction performance of generic high mass $t\bar{t}$ resonances. The leptophobic topcolor Z' model in which the Z' has the same fermionic coupling as the Standard Model Z is used as a benchmark as discussed in section 1.4.1. The production and decay of the Z' boson is shown in Figure 4.1. Signal samples

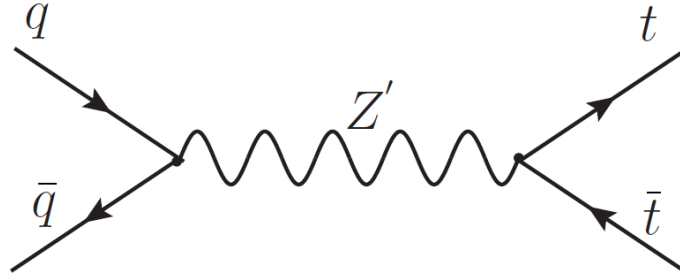


Figure 4.1: The leading order Feynman diagram for the Z' boson, it shows the Z' production and decay to top quark pair.

are produced with different mass assumptions and widths. Samples with $M_{Z'} = 500, 750, 1000, 1250$ and 1500 GeV with width of $\Gamma_{Z'} = 0.012M_{Z'}$ are produced using $m_t = 172.5$ GeV, in order to be coherent with the simulated SM $t\bar{t}$ sample. The width of the resonance is set by hand to $\Gamma_{Z'} = 0.012M_{Z'}$, which is smaller than the expected experimental resolution. Additional Z' samples are produced with $M_{Z'} = 500, 1000$ and 1500 GeV with width of $\Gamma_{Z'} = 0.10M_{Z'}$. The resonant particle is forced to decay to $t\bar{t}$, all possible $t\bar{t}$ decay channels are allowed: lepton+jets channel, full-hadronic channel and dilepton channel.

4.2.2 Modelling Background Processes

There are several Standard Model processes which can fake the signal in the muon+jets channel. These are referred to as background processes. The main irreducible background source are SM $t\bar{t}$. Other sources of background are W and Z boson in association with jets (W +jets, Z/γ +jets), QCD multijet, single top and dibosons (WW , ZZ and WZ) processes. All background samples are processed with the full detector simulation using Geant4 [98]. They are generated using the CTEQ6L Parton Distribution Functions (PDF) [40] and modeled using the MADGRAPH+PYTHIA and POWHEG+PYTHIA

generators [97, 99, 100, 101]. In the following, a detailed description of investigated Monte Carlo background samples is given.

4.2.2.1 Top Quark Pair Backgrounds

Non-resonant SM $t\bar{t}$ production is the main background source. Figure 4.2 shows the Feynman diagram for $t\bar{t}$ events in the muon+jets channel. Top

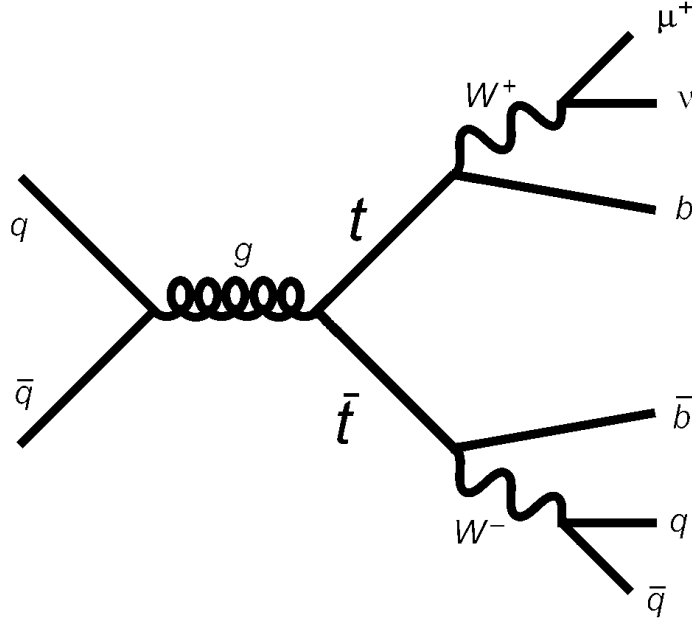


Figure 4.2: The leading order Feynman diagram for the top quark pair event in the muon+jets channel [19].

quark pairs is described with MadGraph which includes spin correlation in the top decay. The top quark pair production is accompanied by up to four additional hard jets. The hard parton configurations are matched to parton showers from PYTHIA using the MLM matching prescription [102]. All possible top quark decay modes are allowed and the default top quark mass is set to $m_t = 172.5$ GeV. The W mass is set to $m_W = 80.4$ GeV. The $t\bar{t}$ cross section, from the CMS measurements at $\sqrt{s} = 7$ TeV, is $\sigma_{t\bar{t}} = 165.8 \pm 2.2$ (stat.) ± 10.6 (syst.) ± 7.8 (lum.) pb [17].

4.2.2.2 W+jets and Z+jets Events

Other sources of backgrounds which can fake a $t\bar{t}$ signature are processes with a muon in the final state in addition to other object from the hard processes. These background processes include $W \rightarrow l\nu$ and $Z \rightarrow ll$ bosons or γ plus additional jets (up to four jets).

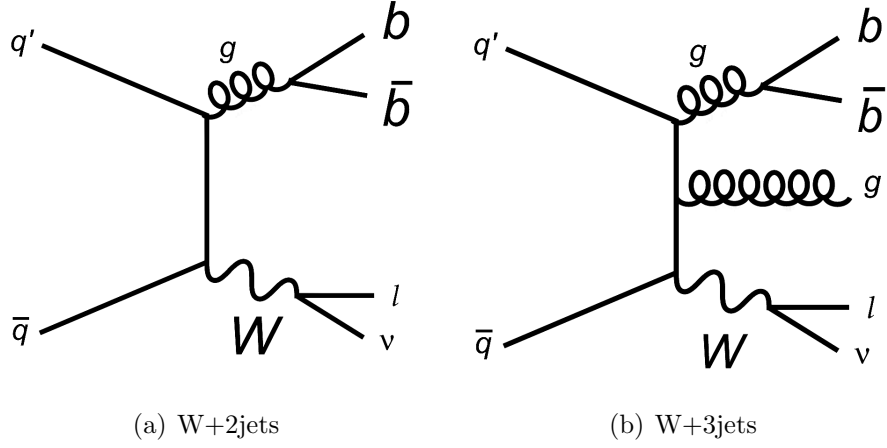


Figure 4.3: Some Feynman diagrams for W boson with additional jets [19].

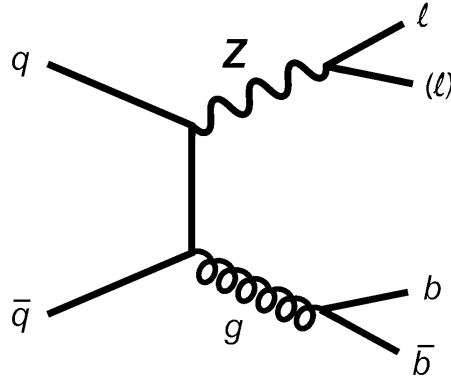


Figure 4.4: The leading order Feynman diagram for the Z boson with additional two jets [19].

Figure 4.3 shows two Feynman diagrams for the W +jets background with two and three additional jets, while a typical Z +jets background with two

additional jets is shown in Figure 4.4.

For the W +jets and Z +jets events the W boson mass is set to $m_W = 80.4$ GeV and the Z boson mass is set to $m_Z = 90.2$ GeV. The cross section for the W +jets sample at the next to next to leading order (NNLO) is $\sigma_W = 31314 \pm 1558$ pb, while for the Z +jets at NNLO the cross section is $\sigma_Z = 3048 \pm 132$ pb [103, 104].

4.2.2.3 QCD Background

Another background process is QCD multijet events. The QCD multijet background arises mainly from decays-in-flight of short lived hadrons into muons. It can be suppressed by requiring a high energetic isolated muon.

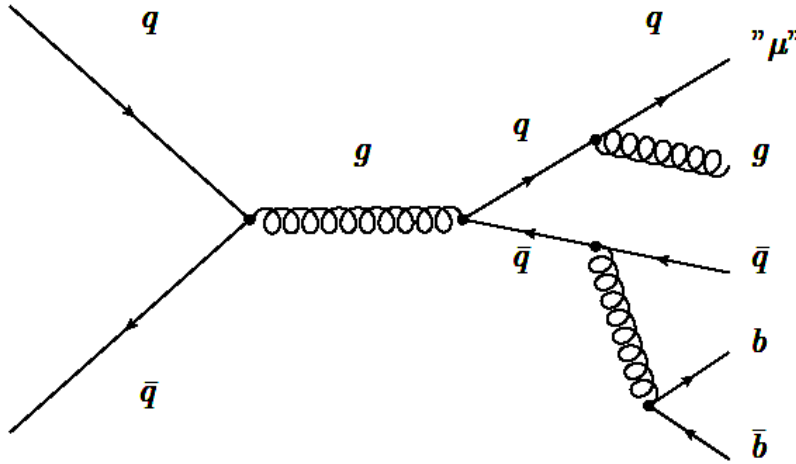


Figure 4.5: Example of Feynman diagram for QCD event [19].

An example for a QCD event is shown in Figure 4.5. In this event two quarks decay into jets. One of these jets is misidentified as a muon, which can be considered as an isolated muon if it has a high momentum. The *PYTHIA* generator is used to generate QCD events. Cuts on generator level are applied. There is a requirement of at least one generated muon with $p_T(\mu) > 15$ GeV and only events with $\hat{p}_T > 20$ GeV are taken into account. The enormous QCD cross section at (LO) of $\sigma_{QCD} = 84679.3$ pb [97], leads to non-negligible numbers of the signal like events. They are efficiently suppressed by the single muon trigger *HLT_IsoMu24*.

4.2.2.4 Single Top Backgrounds

Single top events are produced in three channels, s-channel, t-channel and tW-channel as shown in Figure 4.6.

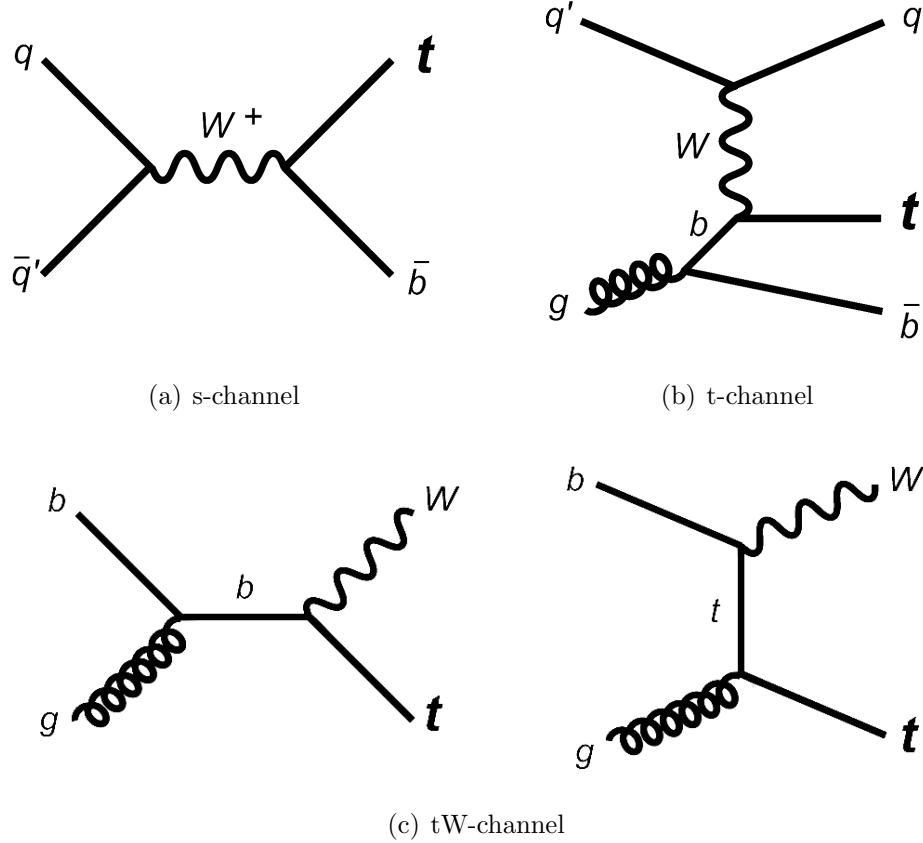


Figure 4.6: The leading order Feynman diagram for the Single top production [19].

The single top production for the three channels s-, t- and tW-channel is simulated using POWHEG. Only leptonic W boson decays are considered ($W \rightarrow l\nu$). The approximate NNLO cross section for the generated single top events is $\sigma_{s-channel}^{s.t.} = 2.72 \pm 0.1$ pb and $\sigma_{s-channel}^{s.\bar{t}.} = 1.49 \pm 0.1$ pb for the s-channel [105]. For the t-channel the corresponding NNLO value is $\sigma_{t-channel}^{s.t.} = 42.6 \pm 2.4$ and $\sigma_{t-channel}^{s.\bar{t}.} = 22 \pm 0.1$ [106] pb. The NNLO cross section value for the tW-channel is $\sigma_{tW-channel}^{s.t(\bar{t})} = 7.9 \pm 0.6$ pb for the tW-channel [107].

4.2.3 Other Backgrounds

Additional background processes are also considered which are Diboson (WW , ZZ and WZ). Dibosons processes have been generated using MADGRAPH, Figure 4.7 shows the Feynman diagrams for the dibosons production. The NLO cross sections for these samples are: 9.5 ± 0.36 pb for $WW \rightarrow 2l2q$ +jets production, 3.46 ± 0.13 pb for $WZ \rightarrow 2l2q$ +jets production, and 1.52 ± 0.05 pb for $ZZ \rightarrow 2l2q$ +jets production [108, 109].

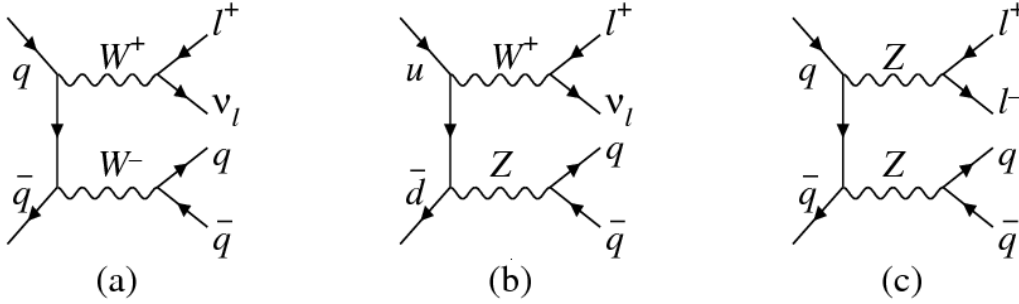


Figure 4.7: Feynman diagrams for diboson production (WW , WZ , ZZ), for lepton+jets channel [110].

4.3 Event Topology

The standard top quark pair reconstruction algorithms assume that the decay products of the top quark pair are well separated. The expected event signature for the muon+jets decays assume one high energetic isolated muon, missing transverse energy and four jets. Two of them are expected to be associated with a b-quark and the other two jets coming from light quarks. Additional jets can contribute which come from QCD interactions. This topology is dominant if the top quarks are produced with a small boost in the detector frame. This is referred to as the low mass scenario. In the high mass scenario the top quarks are highly boosted. The decay products of the individual top quarks will be more collimated and merged partially or entirely. Figure 4.8 shows that the angular distance between the partons of hadronically decaying top quark in the low mass scenario is bigger than jet clustering distance parameter ($R = 0.5$). For the high mass scenario above 1 TeV the angular distance between the partons is smaller than the jet clustering distance parameter. The hadronic top decay products thus may be

reconstructed as one or two jets, and the muon may be not isolated. For more details about the angular distance between the light quark and the b-quark, the two light quarks, and between the muon and b-quark see Appendix.

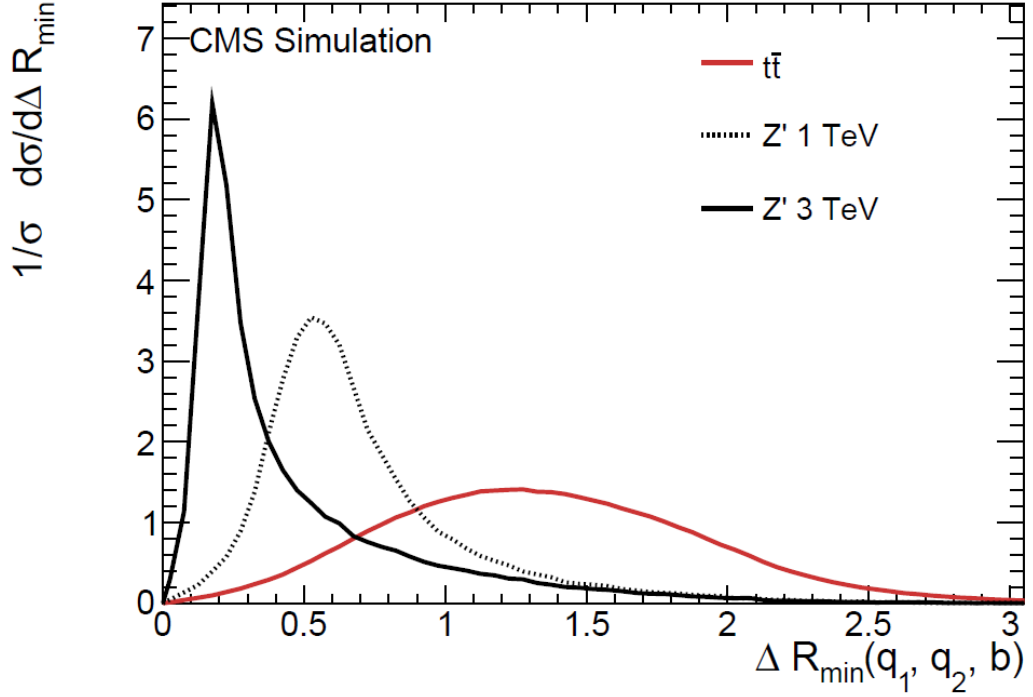


Figure 4.8: The minimum DR distribution between the three quarks (q_1, q_2, b) of the hadronic top quark decay for SM $t\bar{t}$ events and Z' events with two different masses. Jets merge for events with ΔR_{min} smaller than the jet clustering parameter $R = 0.5$ [111].

4.4 Event Selection

The purpose of the event selection, is to find an event candidate with the final event signature of the $t\bar{t}$ signal and reject background events. The event selection applied in this analysis is based on the CMS top reference selection [112]. The selected events are required to fulfill the following requirements:

4.4.1 Trigger

We expect a muon with high p_T in the muon+jets decay. Thus a muon trigger is used to obtain a clean signature of muon candidates. For this analysis top quark pair events are triggered via the unscaled muon trigger IsoMu24 with threshold of $p_T > 24$ GeV. The trigger efficiency is about 85.3 % for data and 86.3% for simulated events [113], as shown in Figure 4.9.

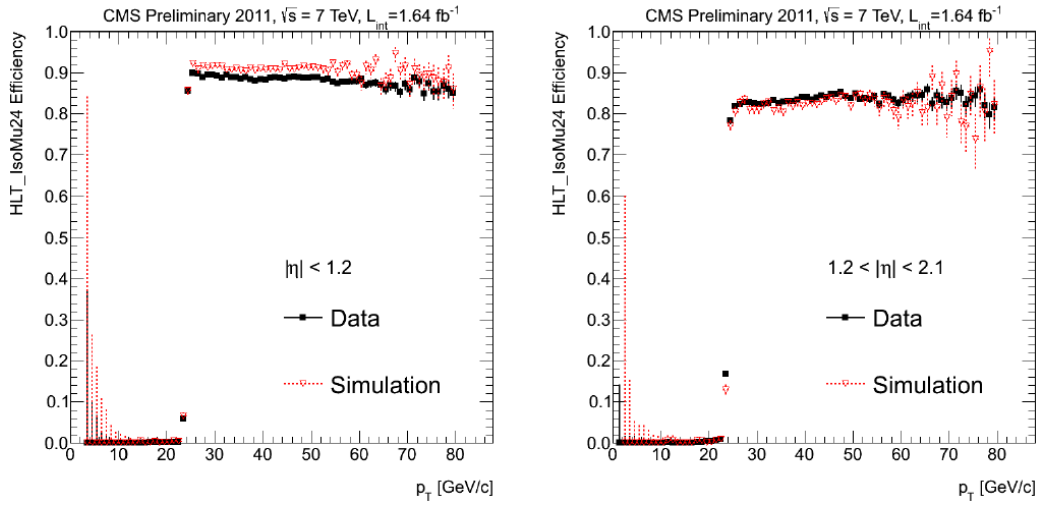


Figure 4.9: The IsoMu24 trigger efficiency as a function to the muon transverse momentum p_T for MC and data [113].

4.4.2 Primary Vertex

We require that the events should have at least one good identified primary vertex. This primary vertex requires more than four tracks ($ndof > 4$) and should be reconstructed in the central detector region ($|z| < 24$ cm) around the nominal interaction point. It should have a transverse distance of less than 2 cm to the center of the beamline ($\rho < 2$ cm). All charged objects connected to pileup vertices are rejected during additional reconstruction steps.

4.4.3 Muons

The events are required to have exactly one isolated high quality muon candidate using the information from the silicon tracker and the muon system. These muons are referred to as global muons. The muon is required to have a pseudorapidity of $|\eta| < 2.1$ and a momentum of $p_T > 26$ GeV above the trigger thresholds and in the plateau of the trigger turn on curve. Tracks are selected by requiring at least one hit in the muon system and at least 11 hits in the inner tracker. The muon candidate is required to be isolated to ensure that it does not originate from a jet. The isolation is defined as:

$$relIso = \frac{I_{charged} + I_{neutral} + I_{photon}}{p_T} < 0.05,$$

where p_T is the transverse momentum of the muon, and $I_{charged}$, $I_{neutral}$, and I_{photon} are the sums of the transverse energies of the charged and neutral hadrons and the photons reconstructed in a cone of $\Delta R < 0.4$ around the muon direction. Furthermore, the muon must be well separated from the next jet with a distance of $\Delta R(\mu, jet) > 0.3$.

4.4.4 Muon Veto

Events with an additional loose muon are rejected in order to suppress background, e.g. Z boson decays. The loose muon is defined by requiring all global muon with $p_T > 10$ GeV and pseudorapidity $|\eta| < 2.5$ and an isolation value of $relIso < 0.2$.

4.4.5 Electron Veto

In addition to the loose muon veto events containing electrons are rejected in order to suppress background. e.g. from dileptonic top quark pair events and W or Z boson decay. The loose electron is defined by requiring any electron candidate with $E_T > 15$ GeV and pseudorapidity $|\eta| < 2.5$ and an isolation value $relIso < 0.2$. The isolation for the electrons is defined in a similar way as for muons:

$$relIso = \frac{I_{charged} + I_{neutral} + I_{photon}}{E_T}.$$

The difference is that the isolation for electrons is calculated relative to the E_T of the electron.

4.4.6 Jets

For this analysis the events are required to have at least four jets. These jets originate from the hadronization of the bottom and light quarks. The jets are reconstructed by the particle-flow algorithm and with an anti-Kt jet algorithm with a cone of size $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} = 0.5$ [91, 88] as discussed in section 3.5.1. Several jet energy corrections, discussed and explained in section 3.5.2, are applied to account for the dependence of the jet response on p_T and η . These corrections are the Level Fast jet correction, Relative jet correction, Absolute jet correction, Jet Flavor correction and Parton jet correction. The jet candidates are required to have a transverse momentum of $p_T > 30$ GeV within the pseudorapidity range of $|\eta| < 2.4$.

4.4.7 Expected and observed event yields

The event yields after applying the event selection are given in table 4.1. The total number for background events is 16878 and 14031 events for data.

Process	Expected events	Efficiency
$t\bar{t}$	6889	$3.81 \cdot 10^{-2}$
W + Jets	8452	$2.48 \cdot 10^{-4}$
Z + Jets	840	$2.53 \cdot 10^{-4}$
single-Top	474	$5.51 \cdot 10^{-3}$
Diboson	34	$2.58 \cdot 10^{-3}$
QCD	154	$1.67 \cdot 10^{-6}$
Total background	16878	$1.41 \cdot 10^{-3}$
Data	14031	$3.76 \cdot 10^{-4}$

Table 4.1: Number of expected and observed events and selection efficiency for $L = 1.09 \text{ fb}^{-1}$ after applying the event selection.

The expected and observed event yields for every step of the selection is shown in section A.3 (see Appendix). The effect of the individual event selection steps for simulated samples and data as percentage is shown in Tables 4.2, 4.3, 4.4 and 4.5. The individual rows show the following selection steps:

- Muon trigger: Requirement of an isolated muon (24 GeV).
- Muon: Selection of an isolated muon (26 GeV).

- Muon veto: Veto of loose isolated muon.
- Electron veto: Veto of loose isolated electron.
- 1 jet: Events with at least 1 jet (30 GeV).
- 2 jets: Events with at least 2 jets (30 GeV).
- 3 jets: Events with at least 3 jets (30 GeV).
- 4 jets: Events with at least 4 jets (30 GeV).

Yield [%]	Data	$t\bar{t}$	W + Jets	Z + Jets	QCD
Muon trigger	2.1	13.0	14.8	22.6	0.75
Muon	0.8	9.7	10.5	11.1	0.06
Muon veto	2.0	12.1	14.8	8.0	0.75
Electron veto	2.0	11.5	14.7	22.4	0.74
≥ 1 Jet	1.9	12.9	4.6	9.7	0.67
≥ 2 Jet	1.2	12.4	1.0	2.6	0.35
≥ 3 Jet	0.45	10.2	0.25	0.7	0.07
≥ 4 Jet	0.13	6.2	0.06	0.17	0.02

Table 4.2: Fraction of selected events at several stages of the muon+jets selection for data and simulated samples.

Yield [%]	ST-(s)	ST-(t)	ST-(tW)	WW	WZ	ZZ
Muon trigger	6.1	6.4	13.4	34.3	21.3	28.9
Muon	4.6	4.9	10.3	24.3	11.8	16.1
Muon veto	6.1	6.4	12.4	26.9	7.4	9.2
Electron veto	6.0	6.3	11.8	23.5	20.9	28.3
≥ 1 Jet	5.8	5.9	13.1	22.2	19.0	26.8
≥ 2 Jet	4.2	3.6	11.3	8.8	12.9	18.5
≥ 3 Jet	1.7	1.3	7.2	2.8	5.7	7.3
≥ 4 Jet	0.5	0.35	3.1	0.8	1.7	1.9

Table 4.3: Fraction of selected events at several stages of the muon+jets selection for simulated samples.

Yield [%]	Z' 500 $\Gamma=1.2\%$	Z' 750 $\Gamma=1.2\%$	Z' 1000 $\Gamma=1.2\%$	Z' 1250 $\Gamma=1.2\%$	Z' 1500 $\Gamma=1.2\%$
Muon trigger	12.0	12.5	12.3	11.7	10.6
Muon	8.9	9.7	9.4	8.8	7.7
Muon veto	11.1	11.6	11.4	10.9	9.9
Electron veto	10.7	11.0	10.8	10.3	9.4
≥ 1 Jet	11.9	12.5	12.2	11.7	10.6
≥ 2 Jet	11.3	12.1	12.0	11.5	10.4
≥ 3 Jet	9.0	10.3	10.5	10.0	8.8
≥ 4 Jet	5.0	6.5	7.0	6.7	5.6

Table 4.4: Fraction of selected events at several stages of the muon+jets selection for benchmark Z' (1.2% width of mass) simulated samples.

Yield [%]	Z' 500 $\Gamma=10\%$	Z' 1000 $\Gamma=10\%$	Z' 1500 $\Gamma=10\%$
Muon trigger	11.9	12.3	11.3
Muon	8.8	9.5	8.3
Muon veto	11.0	11.5	10.5
Electron veto	10.6	10.8	9.9
≥ 1 Jet	11.8	12.3	11.2
≥ 2 Jet	11.3	12.1	11.0
≥ 3 Jet	9.1	10.5	9.3
≥ 4 Jet	5.2	7.0	5.9

Table 4.5: Fraction of selected events at several stages of the muon+jets selection for benchmark Z' (10% width of mass) simulated samples.

Chapter 5

The $t\bar{t}$ Invariant Mass

In the previous chapter, we discussed the event selection for the muon+jets channel. In this chapter, we probe the top quark pair invariant mass ($m_{t\bar{t}}$) distribution from the reconstructed physics objects, and try to extract a signal (Z') signature or reject this hypothesis. The reconstruction of $m_{t\bar{t}}$ has been developed to deal with the topology of events produced in the mass range close to the $t\bar{t}$ production threshold (low mass scenario), where the signal and background events may have a similar decay topology.

5.1 Pileup Reweighting

Pileup are multiple interactions in a single bunch crossing for different proton-proton collisions. Thus, more than one primary vertex in the event can exist when more than two protons of the colliding bunches interact with each other. This phenomenon can occur in two types: In-time pileup, due to additional inelastic proton-proton collisions within the same bunch crossing, and out-of-time pileup from different bunch crossings. Pileup has to be considered when comparing MC simulation with the real data. Pileup reweighting is performed by assigning weights to a simulated event such that the distribution of the number of primary vertices in simulated samples matches the one in the data sample. In this analysis, the MC samples have been simulated to follow a certain distribution for the number of pileup interactions. A flat distribution up to ten interactions is combined with a poisson tail for higher numbers (Flat10+Tail). This does not reflect the real number of pileup interactions in data. Thus a pileup weight is assigned to simulated events. The recommendation of CMS is to perform a three dimensional

(3D) reweighting method [114]. This method works as follows: the input distribution is sampled for data and simulated events separately, yielding a distribution of instantaneous luminosities. This distribution describes the number of in- and out-of-time interactions. The input luminosity will generate three poisson distributions stored in three dimensional (3D) matrices. The distributions are normalized and then the MC histogram is divided by the data histogram generating the weight (Weight3D) matrix, in addition to the MC and Data matrices. Figure 5.1 shows the number of reconstructed vertices before and after pileup reweighting for the selected data set.

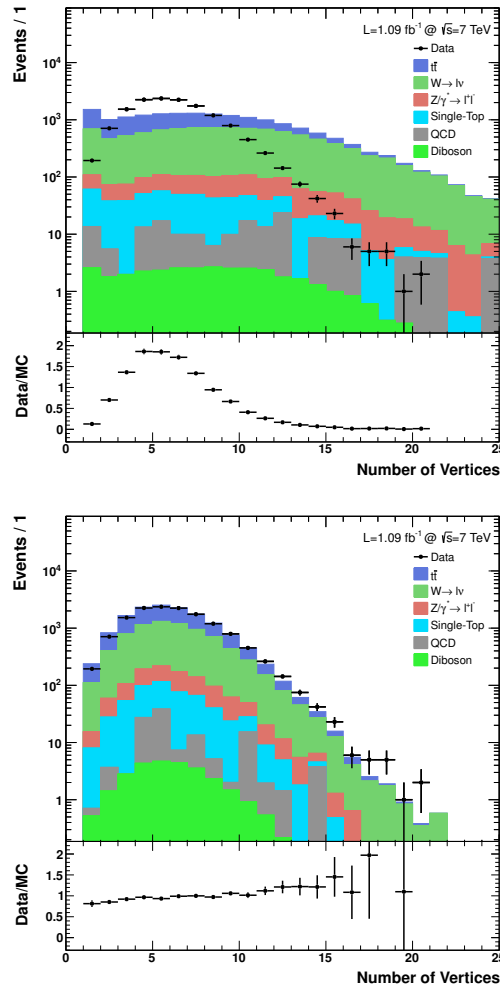


Figure 5.1: Number of reconstructed vertices per event without pileup reweighting (top) and with pileup reweighting (bottom) using the 3D pileup reweighting method.

5.2 Reconstruction of the $t\bar{t}$ Events

In all decay channels, both top quarks decay to $W + b$, where each b quark produces a hadronic jet. In the muon+jets channel, one of the W 's decays leptonically to a muon and a neutrino, while the other W decays hadronically and produces two jets. Therefore, an event in the muon+jets channel will have a high energetic muon, missing transverse energy due to the neutrino and four jets. The reconstruction and identification of the muon and jets has been discussed in chapter 3 and chapter 4. The reconstruction and identification of the neutrino will be discussed in this section.

5.2.1 Neutrino Reconstruction and Identification

All physics objects (jets, leptons), except the neutrino can be fully reconstructed in the detector. The neutrino momentum can only be calculated from the missing transverse energy $\cancel{E}_T$, which lacks the longitudinal component of the neutrino (z component). To solve this problem, the longitudinal component of the neutrino momentum is calculated using a W mass constraint ($m_W = 80.4$ GeV) based on the fact that the neutrino originates from the W decay which in turn originates from the top decay ($t \rightarrow Wb$, $W \rightarrow \mu\nu$). This approach assumes that the $t\bar{t}$ system is balanced in the transverse plane. The component of the missing transverse energy $\cancel{E}_T$ are the transverse components of the neutrino momentum.

$$p_{\nu,x} = \cancel{E}_x \quad p_{\nu,y} = \cancel{E}_y. \quad (5.1)$$

The sum of the four-vectors of the muon P_μ and the neutrino P_ν is equal to the four-vector of the W boson P_W :

$$m_W^2 = (P_\mu + P_\nu)^2 = m_\mu^2 + 2P_\mu P_\nu. \quad (5.2)$$

This equation can be written as follows:

$$m_W^2 = m_\mu^2 + 2(E_\mu \sqrt{p_{\nu,x}^2 + p_{\nu,y}^2 + p_{\nu,z}^2} - p_{\mu,x}p_{\nu,x} - p_{\mu,y}p_{\nu,y} - p_{\mu,z}p_{\nu,z}). \quad (5.3)$$

This equation yield a quadratic equation for the unknown longitudinal component of the neutrino momentum ($p_{\nu,z}$). Thus, the $p_{\nu,z}$ is calculated by

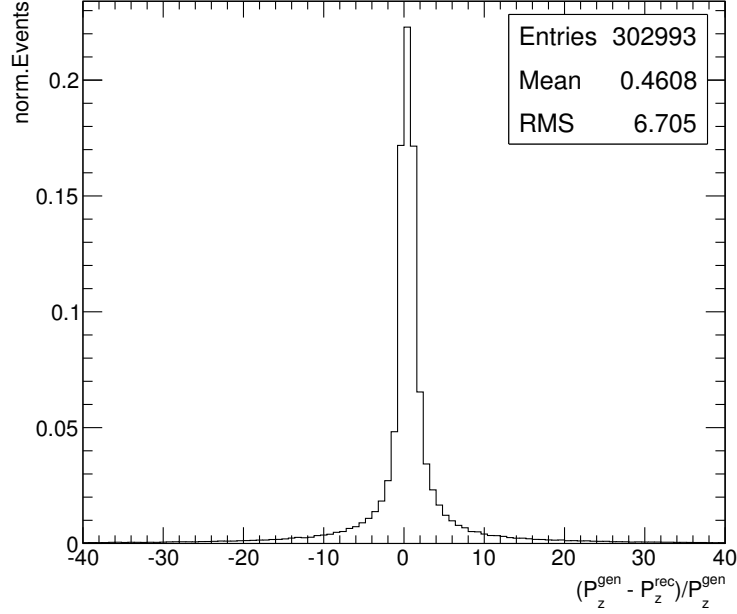


Figure 5.2: The resolution of the longitudinal component of the neutrino momentum ($p_{\nu,z}$).

solving this equation:

$$p_{\nu,z} = \frac{1}{2} \frac{A \pm E_\mu \sqrt{B}}{E_\mu^2 - p_{\mu,z}^2}, \quad (5.4)$$

where A and B are defined as follows:

$$A = 2p_{\nu,y}p_{\mu,y}p_{\mu,z} + 2p_{\nu,x}p_{\mu,x}p_{\mu,z} - p_{\mu,z}m_\mu^2 + p_{\mu,z}m_W^2. \quad (5.5)$$

$$\begin{aligned} B = & -4p_{\nu,x}^2E_\mu^2 - 4p_{\nu,y}^2E_\mu^2 - 4p_{\nu,x}p_{\mu,x}m_\mu^2 + 4p_{\nu,x}p_{\mu,x}m_W^2 - 4p_{\nu,y}p_{\mu,y}m_\mu^2 \\ & + 4p_{\nu,y}p_{\mu,y}m_W^2 - 2m_\mu^2m_W^2 + 4p_{\nu,x}^2p_{\mu,x}^2 + 4p_{\nu,y}^2p_{\mu,y}^2 + 4p_{\nu,x}^2p_{\mu,z}^2 \\ & + 4p_{\nu,y}^2p_{\mu,z}^2 + m_\mu^2 + m_W^2 + 8p_{\nu,x}p_{\mu,x}p_{\nu,y}p_{\mu,y}. \end{aligned} \quad (5.6)$$

Equation (5.4) has either zero, one or two real solutions. In case of zero solution the events are rejected. If there are two solutions, the top mass constraint is used to solve the ambiguity. The $p_{\nu,z}$ solution is selected so that it gives an invariant mass of the muon, neutrino, and the highest p_T jet

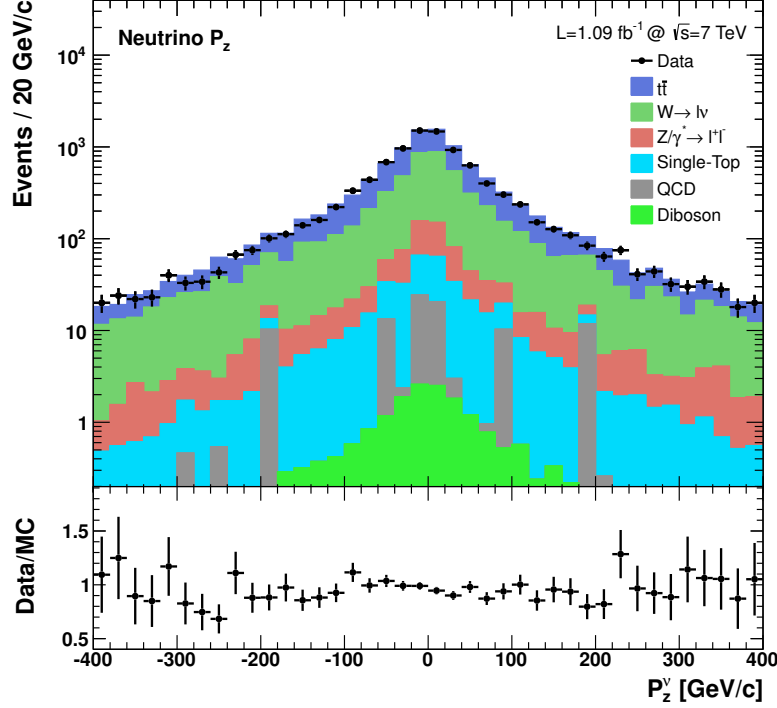


Figure 5.3: The reconstructed $p_{\nu,z}$ distribution for MC and data.

(which is associated to the leptonic side as b-jet) close to the top mass.

$$\min \left\{ |(P_b + P_\mu + P_\nu)^2 - m_t^2| \right\}. \quad (5.7)$$

The correct solution is achieved in 80% of the cases. The resolution of the longitudinal component ($p_{\nu,z}$) of the neutrino momentum is shown in Figure 5.2. The distribution of the reconstructed $p_{\nu,z}$ for MC and data samples is shown in Figure 5.3.

5.3 Reconstruction of the $t\bar{t}$ Invariant Mass

The reconstruction of the invariant mass of the top quark pair ($m_{t\bar{t}}$) close to the $t\bar{t}$ production threshold requires the reconstruction of the four-vectors of the top quark pair from the final state products. The four leading jets in every event are associated to the partons (two b quark, two light quark)

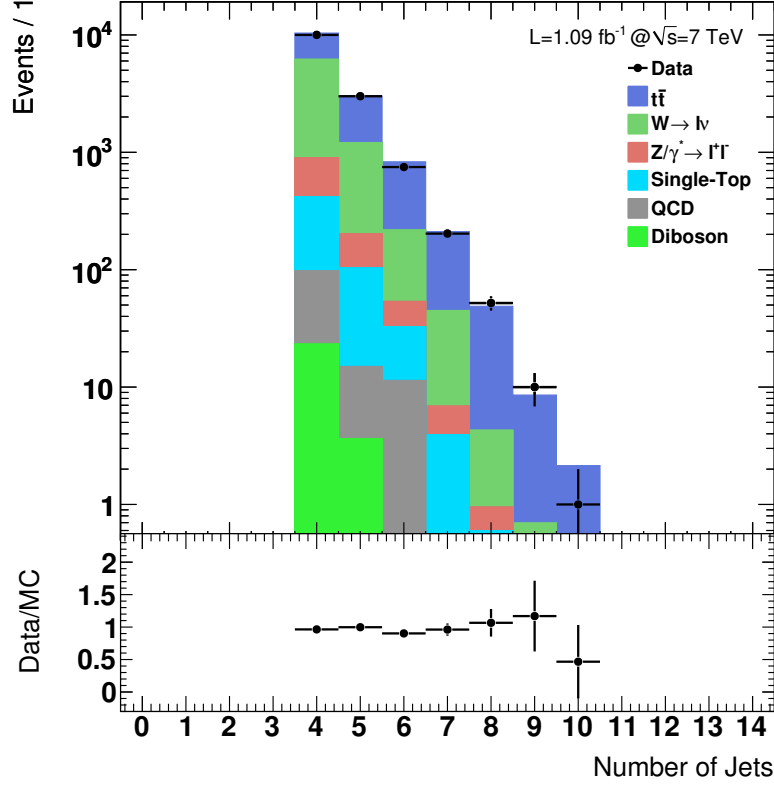


Figure 5.4: MC-Data comparison of jet multiplicities of the high quality jets.

coming from the top quark pair decay. No requirement of b-tagging is used.

Figure 5.4 shows the jet multiplicity for MC and Data events. There is an overall good agreement between MC and Data.

The invariant mass is reconstructed by summing up the four momenta of the following reconstructed objects: muon, neutrino and jets. The invariant mass of the $t\bar{t}$ system is calculated as following:

$$\begin{aligned}
 m_{t\bar{t}}^2 &= (P_t + P_{\bar{t}})^2 \\
 &= (P_b + P_\mu + P_\nu + P_{\bar{b}} + P_{\bar{q}} + P_{q'})^2.
 \end{aligned} \tag{5.8}$$

The reconstructed $t\bar{t}$ invariant mass for MC and data is shown in Figure 5.5. The cross section for signal samples was set to 50 pb for illustration purposes.

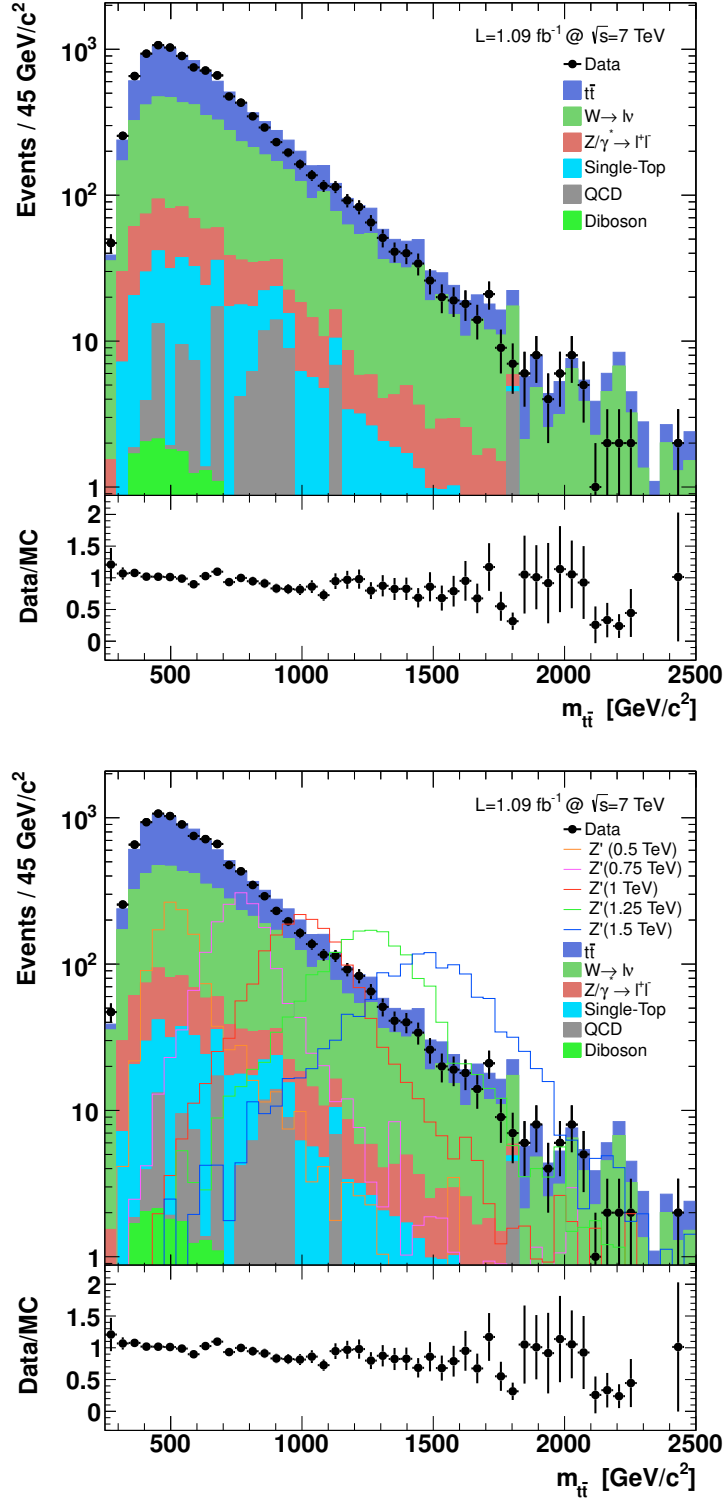


Figure 5.5: The reconstructed invariant mass of the $t\bar{t}$ system for the MC backgrounds and data (top), for both MC backgrounds and Z' boson with different masses and data (bottom), the cross section for signal samples was set to 50 pb for illustration purposes.

5.3.1 Mass Resolution

The invariant mass of top quark pair system ($t\bar{t}$) is a sensitive variable for searching for top quark pair resonances. The better mass resolution the higher sensitivity to resonances, especially for narrow resonances. The mass resolution of Z' boson is determined as follows:

$$\frac{\sigma(M)}{M} = \frac{M_{gen} - M_{rec}}{M_{gen}}. \quad (5.9)$$

where M_{gen} is the generated mass and M_{rec} is the reconstructed mass of the Z' boson (SM $t\bar{t}$).

The mass resolution for a SM $t\bar{t}$ sample is about 65 GeV. The mass resolution for different Z' boson samples with different masses are listed in 5.1. The table shows the width of the generated Z' boson and the mass resolution in GeV and percentage of the mass. The mass resolution is $12.5 \pm 1.7\%$, larger than the generated width. The width of the Z' boson is unmeasurable by the detector and can be neglected as systematic effect.

$M_{Z'}$ [GeV]	Width [GeV]	Mass Resolution [GeV]	Mass Resolution [%]
500	6.0	69.0	13.8
750	9.0	94.5	12.6
1000	12.0	132.0	13.2
1250	15.0	150.0	12.0
1500	18.0	166.5	11.1

Table 5.1: The mass resolution of the Z' bosons given in GeV and in % of the rest mass. The Z' boson width of 1.2% of the rest mass is smaller than the detector mass resolution in all cases.

Figure 5.6 shows the mass resolution for Z' boson samples as a function of Z' boson mass, it shows also the mean and the mass resolution as a function of mass. For more details, the pull distributions for Z' boson and for SM $t\bar{t}$ are shown in Figure A.9 (see Appendix).

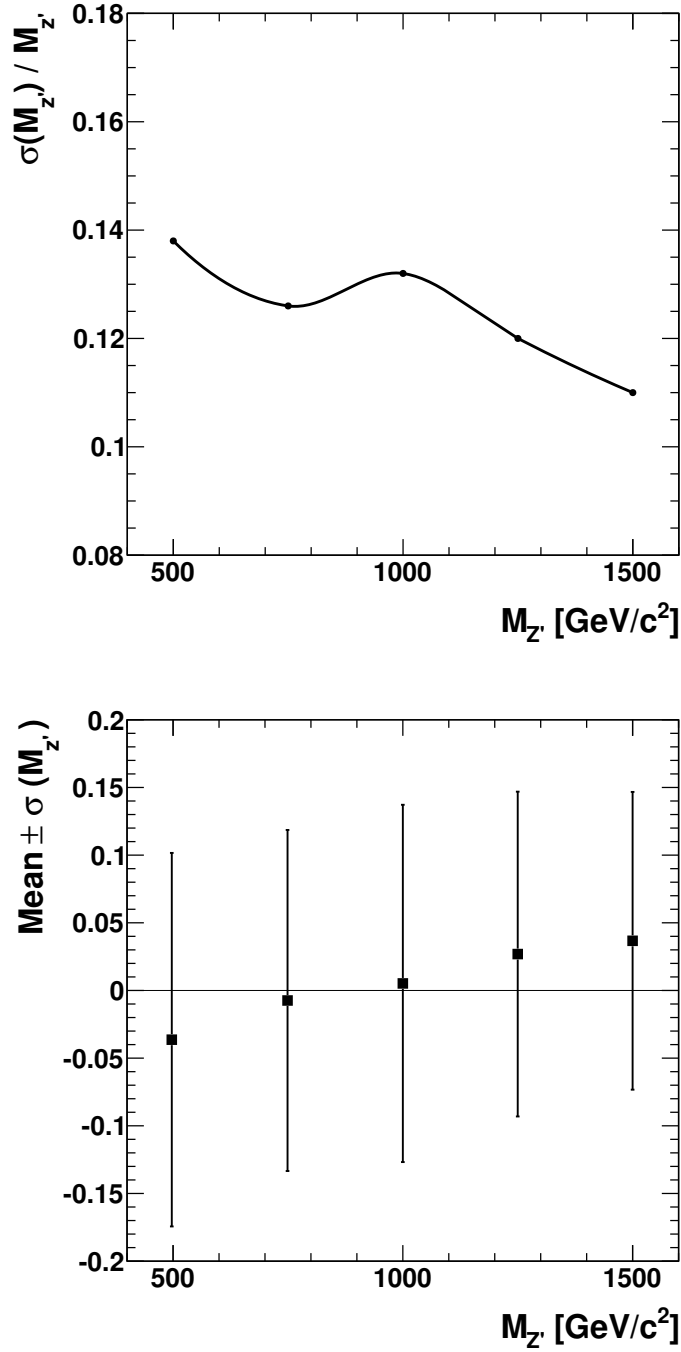


Figure 5.6: The mass resolution of the Z' boson samples with different masses (500, 750, 1000, 1250 and 1500 GeV) as a function of mass Z' boson (top) and the mean $\pm$ resolution as a function of Z' boson (bottom).

5.4 Systematic Uncertainty Studies

The following section focuses on the discussion of systematic uncertainties and their impact on the discovery potential of top quark pair resonances.

5.4.1 Sources of Systematic Uncertainties

In this analysis, several sources of systematic uncertainties are considered. These uncertainties can affect the shape of the $m_{t\bar{t}}$ distribution and the overall normalization. The following sources of systematic uncertainties have been investigated and are included in the statistical evaluation.

Luminosity:

The uncertainty of the measured integrated luminosity can only affect the normalization of the $t\bar{t}$ invariant mass distributions. An uncertainty of $\pm 4.5\%$ was taken into account [96], this means that normalization of the $m_{t\bar{t}}$ distribution will shift up and down around the nominal distribution. Figure 5.7 shows the $m_{t\bar{t}}$ shapes of the nominal and altered distributions for background events and signal events from a Z' boson with mass of $m_{Z'} = 1000$ GeV.

Jet Energy Scale (JES):

The uncertainty on the jet energy scale (JES) affects the shape and the normalization of the $m_{t\bar{t}}$ distribution. To determine the impact of this uncertainty, the energy of all selected jets have been scaled up and down by 10%. Missing transverse energy ($\cancel{E}_T$) is calculated from the total energy balance of the event. Thus, the variation in jet energies is propagated to $\cancel{E}_T$. Figure 5.8 shows the influence of the jet energy scale variation on the $m_{t\bar{t}}$ distribution for signal events and for background events.

Pileup Modeling:

The uncertainties on the total inelastic cross section and the measured luminosity influence the pileup modeling and is used to estimate the corresponding systematics. The pileup uncertainties is expected to affect the shape and the normalization of the $t\bar{t}$ invariant mass distributions. A variation of 8% of the mean number of interactions is used to cover the uncertainties due to pileup modeling [115].

Top Quark Mass:

The top quark mass influences the kinematic properties of its decay products. Thus, it affects the shape and the normalization of the $m_{t\bar{t}}$ distribution. The uncertainty due to the top quark mass uncertainty is estimated by modifying m_t in the simulation of the dominating $t\bar{t}$ background. Dedicated samples with $m_t = 169$ GeV and $m_t = 175$ GeV are used to estimate the corresponding uncertainties. Figure 5.9 (left) shows the $m_{t\bar{t}}$ shapes of the nominal and altered distributions for background events.

Radiation Modeling:

The transition scale between jet production on matrix element level and via parton showering (matching scale) is varied to study the effect of additional jet production. The matching scale uncertainties affect the shape and the normalization of the $m_{t\bar{t}}$ distribution. To investigate this effect dedicated samples are produced for W+jets, Z+jets and $t\bar{t}$ +jets, so that the jet threshold for the matching algorithm [116] is varied with a factor 0.5 and 2 from its default value. The $m_{t\bar{t}}$ shapes of the nominal and altered distributions are shown in Figure 5.9 (right).

Renormalization and Factorization Scale (Q^2): The uncertainty on the modelling of the hard interaction process is investigated by varying the factorization and renormalization Q^2 scale up and down. The Q^2 scale uncertainties affect the shape and the normalization of the $m_{t\bar{t}}$ distribution. This effect is estimated by using dedicated samples which have been produced for the $t\bar{t}$ +jets, W+jets and Z+jets background processes. Figure 5.10 shows the $m_{t\bar{t}}$ shapes of the nominal and altered distributions.

Background Contribution:

The uncertainties on the cross section of background events will be taken into account by varying them within their theoretical uncertainties. Top pair cross section including PDF and top mass dependence have a theoretical uncertainty of 15%. Theoretical uncertainties of 30% on the cross section are considered for single top, W+jets, Z+jets and Diboson. For QCD multijet a 50% theoretical uncertainty on the cross section are considered [112, 111]. The influence of the cross sections uncertainties is shown in Figure 5.11.

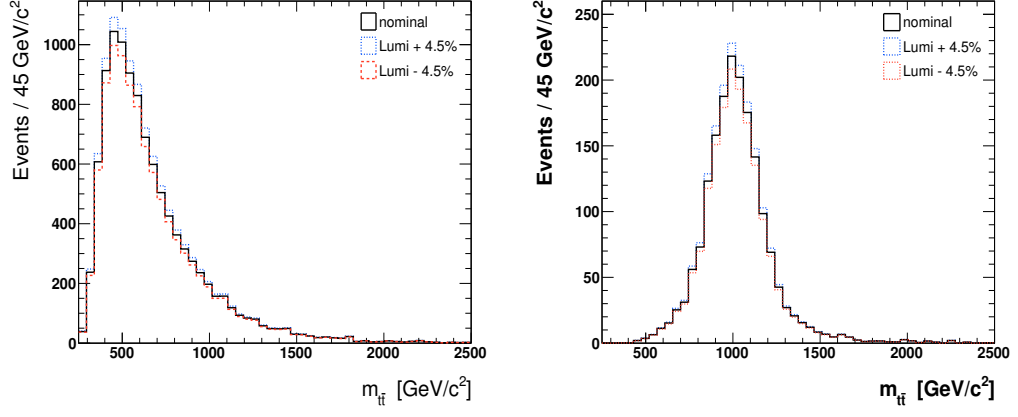


Figure 5.7: The influence of uncertainties of the integrated luminosity on the invariant mass spectrum for MC background (left) and for Z' boson with $m_{Z'} = 1000$ GeV (right).

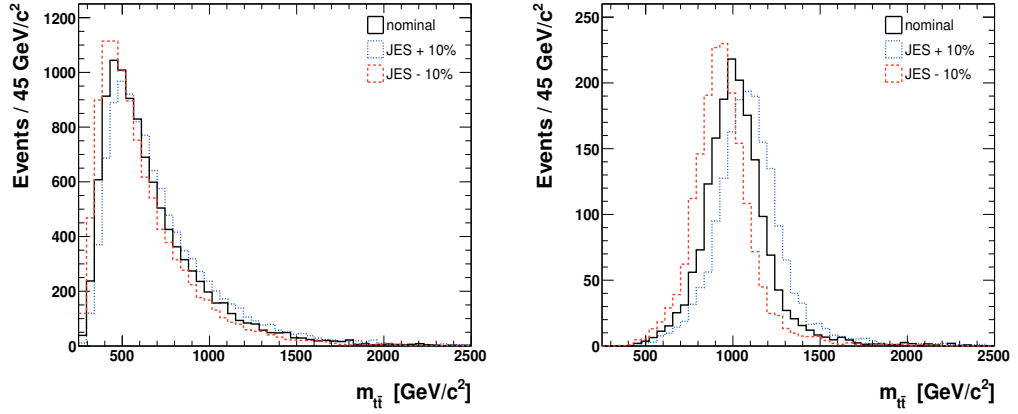


Figure 5.8: The influence of uncertainties of the Jet energy scale for MC background (left) and for Z' boson with $m_{Z'} = 1000$ GeV (right).

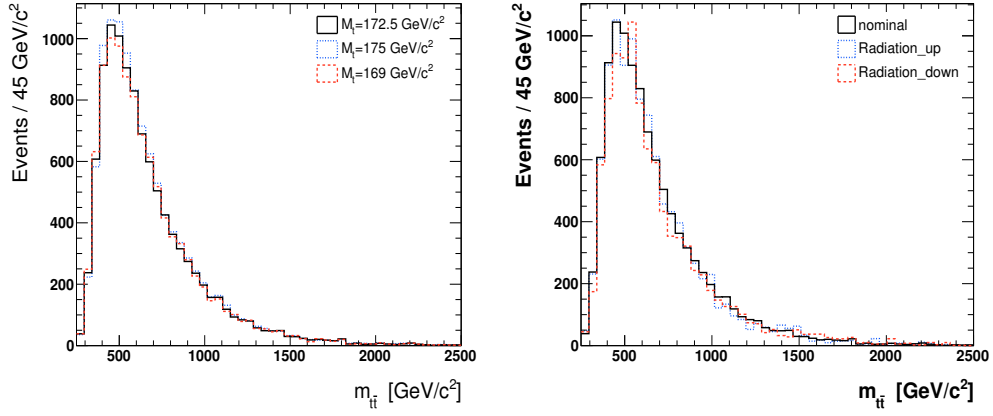


Figure 5.9: The influence of uncertainties of the top mass (left) and the Radiation modeling (right) on the invariant mass spectrum for MC background.

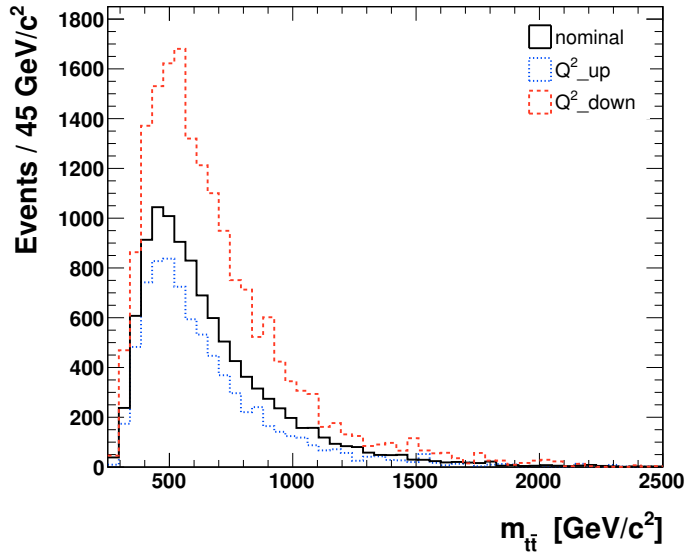


Figure 5.10: The influence of uncertainties of the Q^2 scale on the invariant mass spectrum for MC background.

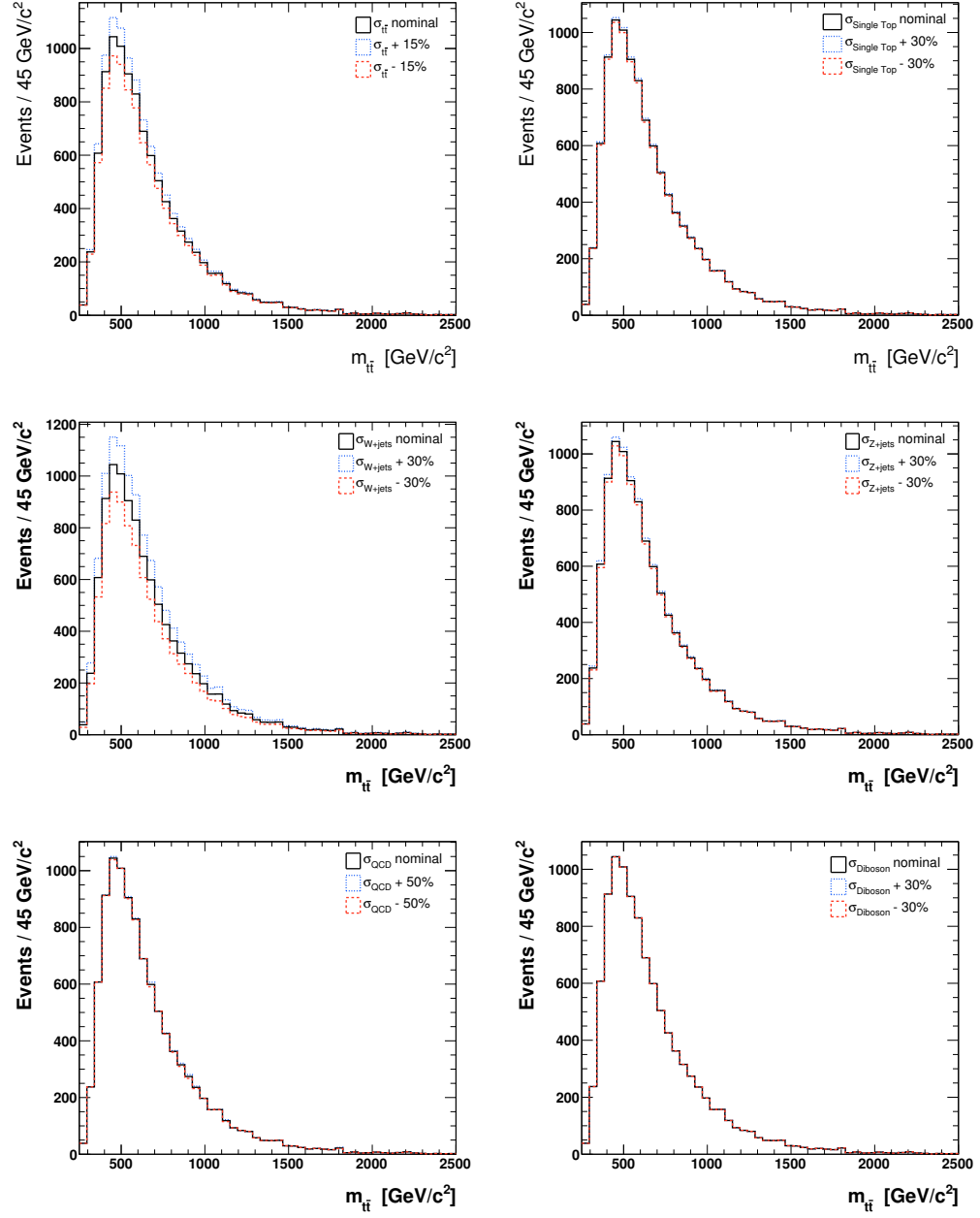


Figure 5.11: Background cross section systematics for the $t\bar{t}$ +jets, Single Top, W+jets, Z+jets, QCD and diboson background samples (from top left to bottom right) respectively.

Chapter 6

Search for $t\bar{t}$ Resonances

In the previous chapter, we discussed the reconstruction of the $t\bar{t}$ mass distribution and the mass resolution as well as the investigation of systematics uncertainties. In this chapter, we introduce the search for $t\bar{t}$ resonances and the statistical methods which have been used to extract the Z' production cross section limits from the reconstructed $t\bar{t}$ mass spectrum.

6.1 Statistical Interpretation

No significant excess can be seen in the measured $t\bar{t}$ invariant mass distribution as discussed in chapter 5. Therefore, upper limits on the production cross section $\sigma_{Z'} \times B(Z' \rightarrow t\bar{t})$ for a Z' model can be set. The combination of theoretical predictions from Z' models with the experimental limits allows to constrain these models.

In this analysis, two methods are applied to calculate upper limits on the Z' production cross section $\sigma_{Z'} \times B(Z' \rightarrow t\bar{t})$ at 95% confidence level (CL), for several different Z' masses. The first method is the Bayesian Method and the second one is the CLs Method. Both of them are described below. The limits are then interpreted in the Z' model.

6.1.1 The Bayesian Method

To extract limits on the production cross section for Z' with Bayesian statistics, a binned likelihood fit is applied to the $t\bar{t}$ mass distribution of the signal

and background expectations and compared to data [117, 118, 119]. The backgrounds, including SM $t\bar{t}$ production, are normalized to the predictions. The binned likelihood uses three distributions in $t\bar{t}$ mass: data, background, and signal.

- **D**: the measured number of events from data.
- **b**: the expected number of events from the background sources.
- **s**: the expected number of events from signal for a given cross section and branching ratio.

The probability to observe D events, when μ events are predicted is given by the poisson probability distribution:

$$P(D|\mu) = \frac{\mu^D e^{-\mu}}{D!}. \quad (6.1)$$

The mean μ is defined as the sum of the predicted contributions from the signal **s** and N background sources **b**. It is given by:

$$\mu = s + b = a \sigma + \sum_i^N b_i, \quad (6.2)$$

The variable σ is the signal cross section times the branching ratio $B(Z' \rightarrow t\bar{t})$. The variable a is the signal acceptance, which is defined as:

$$a = \epsilon \mathcal{L}, \quad (6.3)$$

where ϵ is the signal selection efficiency and $\mathcal{L}$ is the integrated luminosity.

A binned likelihood fit of the signal and background expectations can be performed for the case of more than one counting experiment. Thus, the likelihood to obtain an observed distribution D for given M bins, is the product of the poisson probability distribution over all bins in the mass spectrum:

$$L(D|\mu) = L(D|\sigma, a, b) = \prod_{i=1}^M P(D_i|\sigma, a_i, b_i), \quad (6.4)$$

The posterior probability density function for the parameter σ is obtained from Bayes' theorem:

$$P(\sigma|D) = \frac{1}{N} \int \int L(D|\sigma, a, b) \pi(\sigma, a, b) da db. \quad (6.5)$$

The parameter N is the overall normalization which is obtained using $\int_0^{\sigma_{max}} P(\sigma|D) d\sigma = 1$, where σ_{max} is a sufficient upper bound on the signal cross section where the value of the posterior is practically zero. For this analysis the value of σ_{max} is set to $\sigma_{max} = 100$. The prior density $\pi(\sigma, a, b)$ describes prior knowledge of the parameters σ , a and b , assuming no correlation between these parameters. Thus, the prior density is independent of the signal cross section:

$$\pi(\sigma, a, b) = \pi(a, b) \pi(\sigma). \quad (6.6)$$

The prior $\pi(\sigma)$ is a multivariate Gaussian where the systematic uncertainties are taken into account. The posterior probability density can be written as:

$$P(\sigma|D) = \frac{L(D|\sigma)\pi(\sigma)d\sigma}{\int L(D|\sigma)\pi(\sigma)d\sigma}, \quad (6.7)$$

To obtain the Bayesian upper limit of the signal production cross section at 95% confidence level (CL), the posterior probability density function is integrated, dependent on σ of the signal only, up to the point where its integral reaches 0.95. Thus, the upper limit is the solution of

$$\int_0^{\sigma^{95}} P(\sigma|D) d\sigma = 0.95. \quad (6.8)$$

To estimate the expected upper limit of the signal production cross section, pseudo-experiments with Gaussian distributed random events were generated according to the expected MC distribution in the background only hypothesis. The median of the upper limit distribution is used as the central value (50% quantile), a $\pm 34\%$ ($\pm 47.5\%$) deviation from the median is used as an estimate of the $\pm 1\sigma$ ($\pm 2\sigma$) sigma bands of the expected limit. An example of the posterior probability density function including only statistical uncertainties is shown in Figure 6.1.

The posterior probability density in the presence of systematics is determined by convoluting this posterior with the systematic uncertainty as a

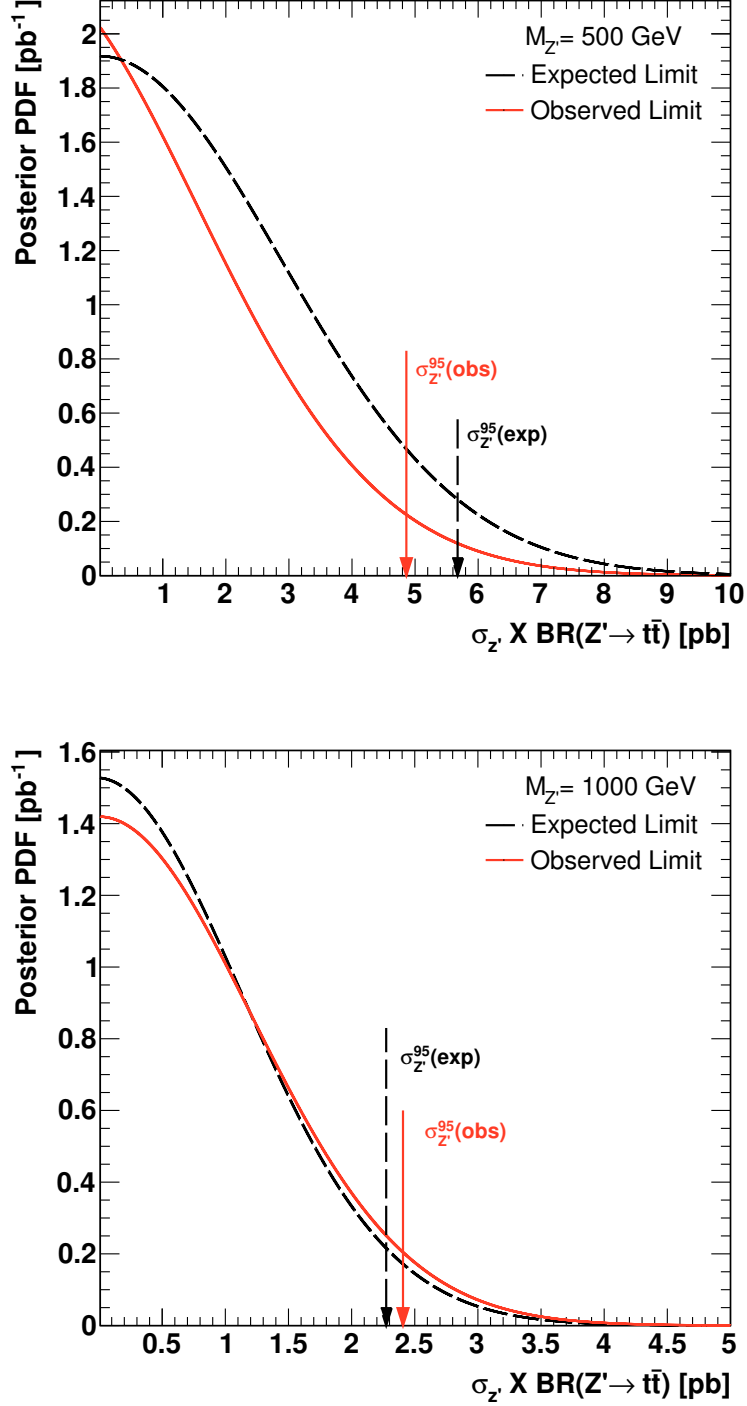


Figure 6.1: The Bayesian posterior probability density function for observing a Z' signal of mass 500 GeV (top) and 1000 GeV (bottom) in a 1.09 fb^{-1} data sample. The upper limit including only statistical uncertainties on the signal production cross section is calculated at 95% confidence level, the red solid line indicates the observed limit and the dashed black line indicates the expected limit.

function of signal cross section. The shifts are summed in quadrature:

$$\sigma_{tot} = \sqrt{\sigma_{JES}^2 + \sigma_{Back}^2 + \sigma_{Lumi}^2 + \sigma_{PU}^2 + \sigma_{Radiation}^2 + \sigma_{scale}^2 + \sigma_{m_{top}}^2}. \quad (6.9)$$

The posterior probability density are convoluted with a Gaussian for each resonance mass. The equation of convolution is:

$$P(\sigma) = \int_0^\infty P(\sigma') G(\sigma, \sigma') d\sigma', \quad (6.10)$$

where

$$G(\sigma, \sigma') = \frac{1}{\sqrt{2\pi}\sigma_{uncer}} e^{\frac{-(\sigma' - \sigma)^2}{2\sigma_{uncer}^2}}. \quad (6.11)$$

$P(\sigma')$ is the posterior probability density at signal cross section σ' . The Gaussian width σ_{uncer} is the absolute uncertainty on the cross section, it is given by:

$$\sigma_{uncer} = \sigma_{tot} \sigma_{95\%}. \quad (6.12)$$

This procedure is repeated for each resonance mass values.

6.1.2 The CLs Method

The modified frequentist construction CLs (Cls method) [120, 121, 122] is used to derive 95% confidence level (CL) upper limits on the Z' production cross section. In this method, the estimated events from signal, background, and the mesured events from data are used in the calculation of confidence levels. If we suppose that:

- **n**: is the number of data events.
- **b**: is the expected background events.
- **s**: is the expected signal events.

Then, the signal and background events can be defined as:

$$s = \epsilon \sigma \mathcal{L} \quad , \quad b = \left(\sum_k^{background} \epsilon_k \sigma_k \right) \mathcal{L}, \quad (6.13)$$

where ϵ and σ are the selection efficiency and the cross section for the signal and these with the index k are for the background. $\mathcal{L}$ is the integrated luminosity.

A test statistic has to be defined, in order to test the signal plus background and the background only hypotheses with the data in an optimal statistical precision. The test statistic summarizes the results of the experiment with expectations of the signal plus background and the background only hypotheses. The likelihood function for the poisson distributed $m_{t\bar{t}}$ spectrum, which will be used in constructing the test statistic, is defined as:

$$L(n|\mu) = \frac{\mu^n e^{-\mu}}{n!}, \quad (6.14)$$

where L is the probability to observe n events in an experiment, when μ events are predicted. Confidence levels (CL) are computed by comparing the observed data configuration to the expectations for two hypotheses:

- **The background only hypothesis:** in this hypothesis only the SM background processes contribute to the accepted event rate ($\mu = b$), the corresponding likelihood function for all bins i , is given by:

$$L(data|background) = \prod_{i=1}^{n_{bins}} \frac{(b_i)^{n_i} e^{-b_i}}{n_i!}. \quad (6.15)$$

- **The signal plus background hypothesis:** in this hypothesis the signal is added to the background ($\mu = s + b$), the corresponding likelihood function in each bin i , is given by:

$$L(data|signal + background) = \prod_{i=1}^{n_{bins}} \frac{(s_i + b_i)^{n_i} e^{-(s_i + b_i)}}{n_i!}. \quad (6.16)$$

The two likelihood functions for the background only hypothesis and the signal plus background hypothesis can be used to construct a test statistic Q for the significance of the signal, this variable is defined as the likelihood ratio of poisson probabilities and given by:

$$Q = \frac{L(data|signal + background)}{L(data|background)}. \quad (6.17)$$

One can calculate the likelihood ratio Q_i for n_{bins} in each bin i , for n_i data events and predictions for signal s_i and background b_i . The product of the likelihood ratio combines all bins.

$$Q = \prod_{i=1}^{n_{bins}} Q_i. \quad (6.18)$$

Instead of using the test statistic Q it is more convenient to be expressed in the logarithmic form, a simple calculation using the equations (6.8), (6.9) and (6.10) leads to:

$$-2 \ln Q = -2 \sum_{i=1}^{n_{bins}} \left[n_i \ln \left(1 + \frac{s_i}{b_i} \right) - s_i \right] = 2 \sum_{i=1}^{n_{bins}} s_i - 2 \sum_{i=1}^{n_{bins}} n_i \ln \left(1 + \frac{s_i}{b_i} \right). \quad (6.19)$$

This formula makes it possible to interpret the likelihood ratio as the sum of the observed events n_i , which are weighted with the weight $w = \ln(1 + \frac{s_i}{b_i})$. This sum is shifted by the sum of the signal events $\sum_{i=1}^{n_{bins}} s_i$. Bins with a signal to background ratio less than 5% are neglected for the calculation of the $-2 \ln Q$ distribution. To determine the signal significance, pseudo-experiments for signal and background were generated with enough statistics. The test statistic $-2 \ln Q$ distribution is constructed from the formula (6.19) for each pseudo-experiment. Figure 6.2 shows a typical example [122] of the distribution of the test statistic $-2 \ln Q$ for two different signals.

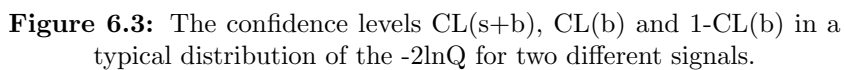
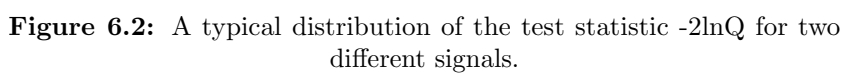
The determination of the confidence levels (CL) for the background only hypothesis and the signal plus background hypothesis, can be used to test the consistency of the data with each hypothesis.

For the background only hypothesis, the agreement of the data with this hypothesis is tested by defining the confidence level CL_b :

$$CL_b = P(Q \leq Q_{obs} | background), \quad (6.20)$$

For the signal plus background hypothesis, the confidence level CL_{s+b} is defined to test the agreement of the data with this hypothesis, it is given by:

$$CL_{s+b} = P(Q \leq Q_{obs} | signal + background), \quad (6.21)$$



The confidence levels CL_{s+b} , CL_b and $1 - CL_b$ are shown in Figure 6.3.

By convention a discovery is defined as an excess in data of at least five standard deviation 5σ . This leads to:

$$1 - CL_b < 5.7 \cdot 10^{-7}. \quad (6.22)$$

If no significant excess can be seen, an exclusion limit can be set. A signal plus background hypothesis is excluded at the 95% confidence level (CL) if

$$CL_{s+b} < 0.05. \quad (6.23)$$

If the background has downward fluctuations, the data will have low statistic which means that the data is inconsistent with the background. Thus, the signal plus background hypothesis can be excluded even if the signal is very small. In order to avoid this effect, the confidence level CL_{s+b} is normalized to CL_b giving the confidence level CL_s :

$$CL_s = \frac{CL_{s+b}}{CL_b}. \quad (6.24)$$

Then, the exclusion at 95% confidence level (CL) for the signal hypothesis is given by:

$$CL_s < 0.05. \quad (6.25)$$

Systematic uncertainties are accounted for using the Bayesian procedure of integrating the likelihood weighted by a prior density.

6.2 Limits on Z' Production Cross Section

To determine the sensitivity to discover a possible $t\bar{t}$ resonances, the statistical methods described in the previous section 6.1 has been applied to the reconstructed $m_{t\bar{t}}$ distribution. No signal is seen, an upper limit on the signal production cross section at 95% confidence level is calculated. The inputs for the limit calculation is the $m_{t\bar{t}}$ distributions for the measured data, the signal Monte Carlo and for the all sources of background.

The observed limits are calculated using the measured data as input and

$M_{Z'}$ [GeV] $\Gamma/M_{Z'}=1.2\%$	Expected Limit [pb] Stat. Uncertainty		Observed Limit [pb] Stat. Uncertainty	
	Bayesian method	CLs method	Bayesian method	CLs method
500	5.73	5.89	4.83	4.95
750	3.04	3.07	2.95	3.03
1000	2.28	2.23	2.32	2.29
1250	1.78	1.73	1.74	1.70
1500	1.68	1.61	1.59	1.53

Table 6.1: Expected and observed limits on the $\sigma_{Z'} \times B(Z' \rightarrow t\bar{t})$ at 95% confidence level (CL) including only statistical uncertainties.

$M_{Z'}$ [GeV] $\Gamma/M_{Z'}=1.2\%$	Expected Limit [pb] Stat. & Syst. Uncertainty		Observed Limit [pb] Stat. & Syst. Uncertainty		$\sigma_{Z'}^{TopColor}$ [pb] $\Gamma/M_{Z'}=1.2\%$
	Bayesian method	CLs method	Bayesian method	CLs method	
500	7.92	8.04	6.59	6.77	14.61
750	3.80	3.83	3.71	3.81	3.28
1000	3.05	2.88	3.12	2.93	0.905
1250	2.41	2.37	2.36	2.25	0.2830
1500	2.34	2.24	2.18	2.02	0.0987

Table 6.2: Expected and observed limits on the $\sigma_{Z'} \times B(Z' \rightarrow t\bar{t})$ at 95% confidence level (CL) including all considered systematic uncertainties. The last column indicates the predicted production cross section for a leptophobic topcolor Z' with width of ($\Gamma/M_{Z'} = 1.2\%$).

$M_{Z'}$ [GeV] $\Gamma/M_{Z'}=10\%$	Expected Limit [pb] Stat. Uncertainty		Observed Limit [pb] Stat. Uncertainty	
	Bayesian method	CLs method	Bayesian method	CLs method
500	6.23	6.81	5.41	5.92
1000	2.95	2.84	2.88	2.98
1500	1.96	1.85	1.89	1.72

Table 6.3: Expected and observed limits on the $\sigma_{Z'} \times B(Z' \rightarrow t\bar{t})$ at 95% confidence level (CL) including only statistical uncertainties.

describe the real limits. While, the expected limits are calculated using the SM expectation as input and describe the expected limits. The expected and the observed limits on the $\sigma_{Z'} \times B(Z' \rightarrow t\bar{t})$ are obtained at the 95% confidence level including the statistical uncertainties and the systematic uncertainties. They are calculated for different Z' masses with two different widths 1.2% and 10% of mass.

The list of calculated 95% confidence level upper limits on the $\sigma_{Z'} \times B(Z' \rightarrow t\bar{t})$, using the CLs method and Bayesian method, as a function of $M_{Z'}$ are given in Table 6.1 and Table 6.3 with statistical uncertainties only, and in Table 6.2 and Table 6.4 when including statistical and systematic uncertainties. The limits are displayed in Figure 6.4 for a leptophobic topcolor Z' with a width of ($\Gamma/M_{Z'} = 1.2\%$), for a leptophobic topcolor Z' with a width of ($\Gamma/M_{Z'} = 10\%$) the figures shows only the calculated limits using the CLs method which is considered as the reference method. The tables and figures also include the predicted $\sigma_{Z'} \times B(Z' \rightarrow t\bar{t})$ for a leptophobic topcolor Z' with width of $\Gamma/M_{Z'} = 1.2\%$ and $\Gamma/M_{Z'} = 10\%$, which are calculated using the CTEQ6L parton distribution function for leading order calculation [39].

The observed limits are displayed by a solid red line, while the expected limits are displayed by a solid black line. The expected limits with the $\pm 1\sigma$ band are displayed as the yellow area, while the green area displays the $\pm 2\sigma$ band of the expected limits. The plots are shown in normal scale (upper plot) and in logarithmic scale (lower plot).

Using as a reference model the leptophobic topcolor Z' model. In Figure 6.4, the observed upper limits at 95% confidence level range from 6.77

$M_{Z'}$ [GeV]	Expected Limit [pb] Stat. & Syst. Uncertainty		Observed Limit [pb] Stat. & Syst. Uncertainty		$\sigma_{Z'}^{TopColor}$ [pb] $\Gamma/M_{Z'}=10\%$
	Bayesian method	CLs method	Bayesian method	CLs method	
500	9.81	10.32	7.68	8.78	115.29
1000	4.21	4.14	4.31	4.40	6.91
1500	2.76	2.58	2.61	2.30	0.777

Table 6.4: Expected and observed limits on the $\sigma_{Z'} \times B(Z' \rightarrow t\bar{t})$ at 95% confidence level (CL) including all considered systematic uncertainties. The last column indicates the predicted production cross section for a leptophobic topcolor Z' with width of ($\Gamma/M_{Z'} = 10\%$).

pb at 500 GeV to 2.02 pb at 1.5 TeV. These limits are below the predicted production cross section of a topcolor Z' with width of $\Gamma/M_{Z'} = 1.2\%$ at a mass of about $M_{Z'} \approx 710$ GeV. Therefore, this model can be excluded for masses $M_{Z'} < 710$ GeV.

In Table 6.4, due to the higher width of the topcolor Z' model ($\Gamma/M_{Z'} = 10\%$), the expected and observed limits are higher than for the narrow width topcolor Z' model ($\Gamma/M_{Z'} = 1.2\%$) which corresponds to the theoretical prediction for the topcolor Z' . In Figure 6.4, the observed upper limits at 95% confidence level range from 8.78 pb at 500 GeV to 2.30 pb at 1.5 TeV. These limits are below the predicted production cross section of a topcolor Z' with width of $\Gamma/M_{Z'} = 10\%$ at a mass of about $M_{Z'} \approx 1145$ GeV. Therefore, this model can be excluded for masses $M_{Z'} < 1145$ GeV.

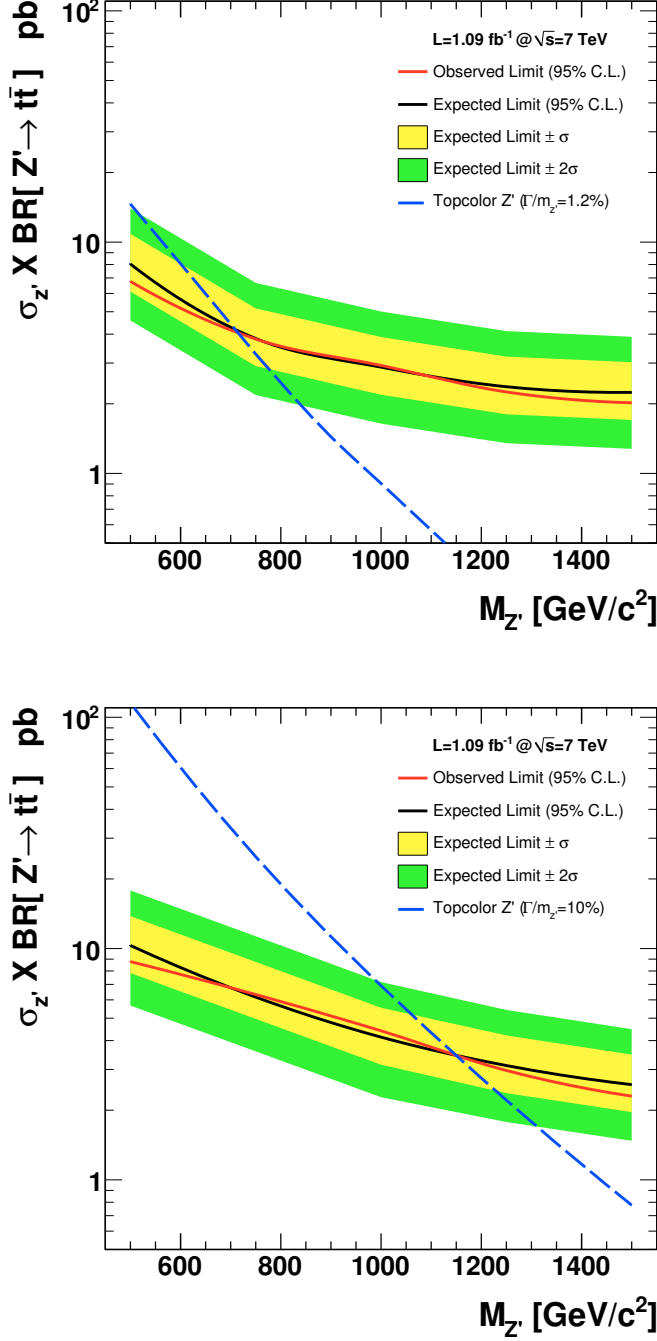


Figure 6.4: Expected and observed limits from CLs on the $\sigma_{Z'} \times B(Z' \rightarrow t\bar{t})$ at 95% confidence level (CL) as a function of Z' mass using Z' model with width of $\Gamma/M_{Z'} = 1.2\%$ (top) and $\Gamma/M_{Z'} = 10\%$ (bottom), including all considered systematic uncertainties. The yellow band indicates the $\pm 1\sigma$ band of the expected limits, and the green band the $\pm 2\sigma$ band of expected limits.

6.3 Comparison with other Analyses

Both experiments CMS and ATLAS performed a search for top quark pair resonances. The analysis performed by CMS [111] on $4.4\text{--}5.0\text{ fb}^{-1}$ of 2011 data used different events reconstruction as in this analysis. It used a kinematic fit to reconstruct the top quark pair invariant mass in the lepton+jets channel in both the boosted and threshold scenarios. It found no evidence for a top quark pair resonance and could exclude a topcolor Z' with a width of 1.2 (10)% of the Z' mass for masses below 1.49 (2.04) TeV. The ATLAS analysis [123] performed on 2.05 fb^{-1} of 2011 data also used different event reconstructions for the lepton+jets channel and the boosted scenario. It found no evidence for a top quark pair resonance and could exclude a topcolor Z' with a width of 1.2 % of the Z' mass for masses below 880 GeV.

Chapter 7

Conclusion

This analysis presents a measurement of the top quark pair invariant mass distribution and a search for top quark pair resonances close to the production threshold. The analysis uses the muon+jets final state. It has been performed using data corresponding to an integrated luminosity of about 1.09 fb^{-1} at a center-of-mass energy of 7 TeV, collected with the CMS detector during the first half of 2011. A cut based selection is implemented to identify top quark pair candidates decaying in the muon+jets channel, by requiring one isolated muon, missing transverse energy and at least four jets. The identified final state objects are used to reconstruct the invariant top quark pair mass distribution. The reconstructed top quark pair invariant mass distributions agree with the Standard Model prediction and no statistically significant deviation indicating a top quark pair resonance could be observed. Therefore, no evidence for new physics can be claimed.

By analyzing the reconstructed top quark pair invariant mass distribution and using a CLs method. Upper limits at 95% confidence level on the production cross section $\sigma_{Z'} \times B(Z' \rightarrow t\bar{t})$ have been obtained for different Z' boson masses and for two widths 1.2% (10%).

These limits range from 6.77 pb at 500 GeV to 2.02 pb at 1.5 TeV for a Z' boson with width $\Gamma/M_{Z'}=1.2\%$, and from 8.78 pb at 500 GeV to 2.30 pb at 1.5 TeV for Z' boson with width $\Gamma/M_{Z'}=10\%$.

The existence of a leptophobic topcolor Z' bosons is excluded at 95% confidence level for masses of $M_{Z'} < 710 \text{ GeV}$ for width $\Gamma/M_{Z'}=1.2\%$ and $M_{Z'} < 1145 \text{ GeV}$ for width $\Gamma/M_{Z'}=10\%$.

Appendix A

Additional Information

A.1 Datasets

The used datasets for this analysis are listed in tables A.1 and A.2.

A.2 Additional Event Topology Plots

The partons, coming from W bosons most probably, may merge in one jet. For highly boosted top quarks, the isolation criterion for muons may be not fulfilled any more. The behaviour of the b-quark and one of the light quarks for SM top quark pairs and different Z' boson events is shown in Figure A.1 and the behaviour of the other b-quark and muon is shown in Figure A.2. It is obvious from the Figure A.1, that the angular distance between the b-quark and one of the light quark decreasing with increasing invariant mass of the $t\bar{t}$ system. The same behaviour is noticed for the angular distance between the muon, which comes from W decays, and the b-quark as shown in Figure A.2. The other combination of the angular distance between the other light quark and the b-quark and between the two light quarks also have a similar behaviour as show in Figure A.3 and Figure A.4.

Process	Dataset name	
Dataset	Data 2011	L[pb ⁻¹] / Run Range
SingleMu	SingleMu/Run2011A-May10ReReco-v1	205 / (Runs 160404-163869)
SingleMu	SingleMu/Run2011A-PromptReco-v4	887 / (Runs 163870-167993)
Signal datasets	Summer11 production	
Z'(M=500 GeV)	/Zprime_M500GeV_M5GeV-madgraph/	
Z'(M=500 GeV)	/Zprime_M500GeV_W50GeV-madgraph/	
Z'(M=750 GeV)	/Zprime_M750GeV_W7500MeV-madgraph/	
Z'(M=1000 GeV)	/Zprime_M1000GeV_W10GeV-madgraph/	
Z'(M=1000 GeV)	/Zprime_M1000GeV_W100GeV-madgraph/	
Z'(M=1250 GeV)	/Zprime_M1250GeV_W1250MeV-madgraph/	
Z'(M=1500 GeV)	/Zprime_M1500GeV_W15GeV-madgraph/	
Z'(M=1500 GeV)	/Zprime_M1500GeV_W150GeV-madgraph/	
Z'(M=2000 GeV)	/Zprime_M2000GeV_W20GeV-madgraph/	
Z'(M=2000 GeV)	/Zprime_M2000GeV_W200GeV-madgraph/	
Background datasets	Summer11 production	cross section [pb]
$t\bar{t}$ + jets	/TTJets_TuneZ2_7TeV-madgraph-tauola/	165.8
$W(\rightarrow l\nu) + \text{jets}$	/WJetsToLNu_TuneZ2_7TeV-madgraph-tauola/	31314 (NNLO)
$Z/\gamma^*(\rightarrow l^+l^-) + \text{jets}$	/DYJetsToLL_TuneZ2_M-50_7TeV-madgraph-tauola/	3048 (NNLO)
QCD μ enriched	/QCD_Pt-20_MuEnrichedPt-15_TuneZ2_7TeV-pythia6/	84679.3 (LO)
Single top s ($W \rightarrow l\nu$)	/T_TuneZ2_s-channel_7_TeV-powheg-tauola/	2.72 (NNLO)
Single top s ($W \rightarrow l\nu$)	/Tbar_TuneZ2_s-channel_7_TeV-powheg-tauola/	1.49 (NNLO)
Single top t ($W \rightarrow l\nu$)	/T_TuneZ2_t-channel_7_TeV-powheg-tauola/	42.6 (NNLO)
Single top t ($W \rightarrow l\nu$)	/Tbar_TuneZ2_t-channel_7_TeV-powheg-tauola/	22 (NNLO)
Single top tW ($W \rightarrow l\nu$)	/T_TuneZ2_tW-channel-DR_7TeV-powheg-tauola/	7.9 (NNLO)
Single top tW ($W \rightarrow l\nu$)	/Tbar_TuneZ2_tW-channel_7_TeV-powheg-tauola/	7.9 (NNLO)
$WW(\rightarrow 2l2q) + \text{jets}$	/WWJetsTo2L2q_TuneZ2_7TeV-madgraph-tauola/	9.5 (NLO)
$ZZ(\rightarrow 2l2q) + \text{jets}$	/ZZJetsTo2L2q_TuneZ2_7TeV-madgraph-tauola/	3.46 (NLO)
$WZ(\rightarrow 2l2q) + \text{jets}$	/WZJetsTo2L2q_TuneZ2_7TeV-madgraph-tauola/	1.52 (NLO)

Table A.1: Signal and Background Monte Carlo datasets used for this analysis.

Process	Dataset name
Systematic datasets	Summer11 production
Top mass 169 GeV	/TTJets_TuneZ2_mass169_5_7TeV-madgraph-tauola/
Top mass 175 GeV	/TTJets_TuneZ2_mass175_5_7TeV-madgraph-tauola/
$t\bar{t}$ + jets matching up	/TTjets_TuneZ2_matchingup_7TeV-madgraph-tauola/
$t\bar{t}$ + jets matching down	/TTjets_TuneZ2_matchingdown_7TeV-madgraph-tauola/
$t\bar{t}$ + jets scale up	/TTjets_TuneZ2_scaleup_7TeV-madgraph-tauola/
$t\bar{t}$ + jets scale down	/TTjets_TuneZ2_scaledown_7TeV-madgraph-tauola/
$W (\rightarrow l\nu)$ + jets matching up	/WJetsToLNu_TuneZ2_matchingup_7TeV-madgraph-tauola/
$W (\rightarrow l\nu)$ + jets matching down	/WJetsToLNu_TuneZ2_matchingdown_7TeV-madgraph-tauola/
$W (\rightarrow l\nu)$ + jets scale up	/WJetsToLNu_TuneZ2_scaleup_7TeV-madgraph-tauola/
$W (\rightarrow l\nu)$ + jets scale down	/WJetsToLNu_TuneZ2_scaledown_7TeV-madgraph-tauola/
$Z/\gamma^* (\rightarrow l^+l^-)$ + jets matching up	/ZJetsToLL_TuneZ2_matchingup_7TeV-madgraph-tauola/
$Z/\gamma^* (\rightarrow l^+l^-)$ + jets matching down	/ZJetsToLL_TuneZ2_matchingdown_7TeV-madgraph-tauola/
$Z/\gamma^* (\rightarrow l^+l^-)$ + jets scale up	/ZJetsToLL_TuneZ2_scaleup_7TeV-madgraph-tauola/
$Z/\gamma^* (\rightarrow l^+l^-)$ + jets scale down	/ZJetsToLL_TuneZ2_scaledown_7TeV-madgraph-tauola/
Single top s scale up	/T_TuneZ2_scaleup_s-channel_7TeV-powheg-tauola/
Single top s scale down	/T_TuneZ2_scaledown_s-channel_7TeV-powheg-tauola/
Single top s scale up	/Tbar_TuneZ2_scaleup_s-channel_7TeV-powheg-tauola/
Single top s scale down	/Tbar_TuneZ2_scaledown_s-channel_7TeV-powheg-tauola/
Single top t scale up	/Tbar_TuneZ2_scaleup_t-channel_7TeV-powheg-tauola/
Single top t scale down	/Tbar_TuneZ2_scaledown_t-channel_7TeV-powheg-tauola/
Single top tW scale up	/T_TuneZ2_scaleup_tW-channel-DR_7TeV-powheg-tauola/
Single top tW scale down	/T_TuneZ2_scaledown_tW-channel-DR_7TeV-powheg-tauola/
Single top tW scale up	/Tbar_TuneZ2_scaleup_tW-channel-DR_7TeV-powheg-tauola/
Single top tW scale down	/Tbar_TuneZ2_scaledown_tW-channel-DR_7TeV-powheg-tauola/

Table A.2: Systematic Monte Carlo datasets used for this analysis.

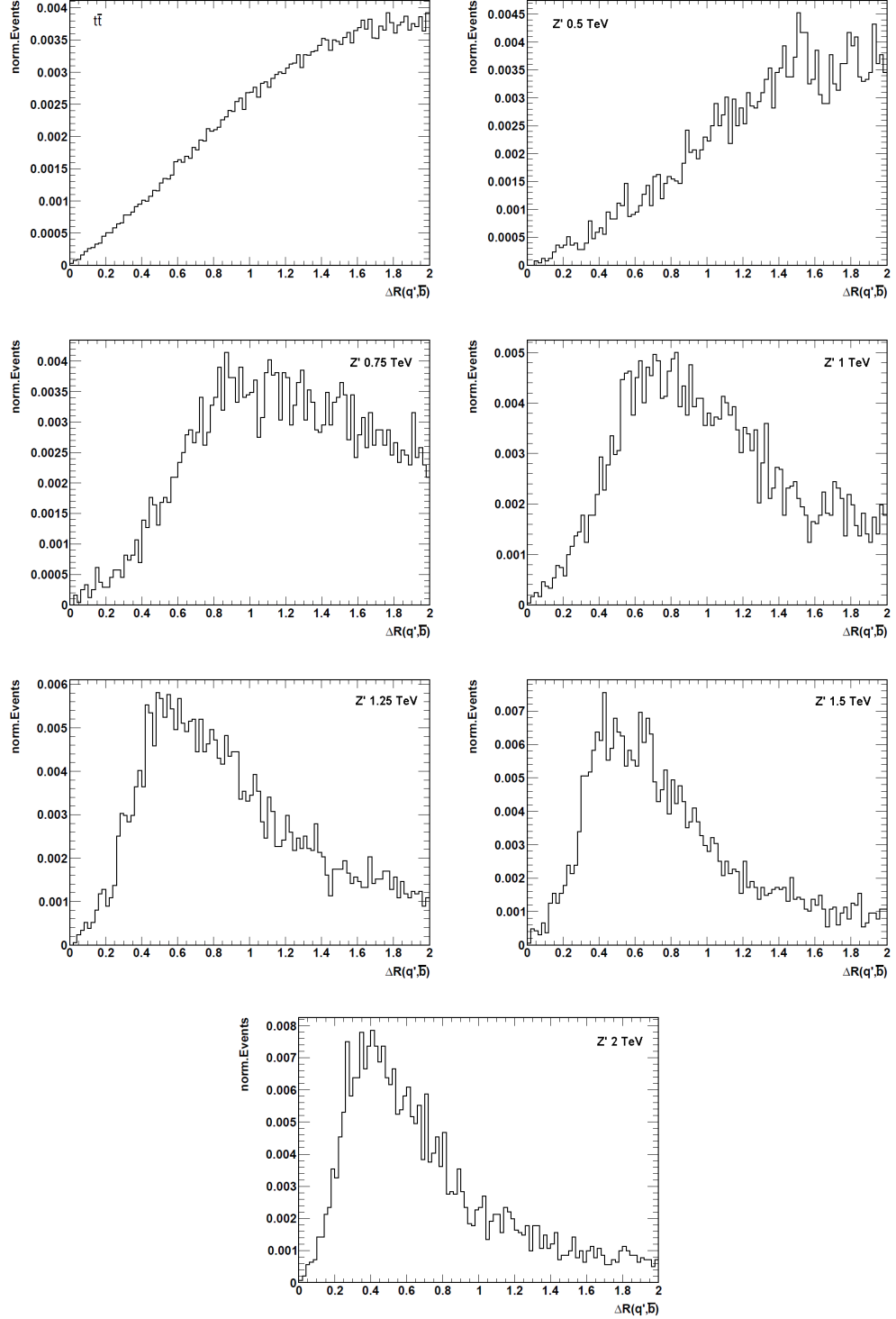


Figure A.1: ΔR distribution of b-quark and one light-quark for SM top quark pair and for different Z' masses, 500 GeV, 750 GeV, 1000 GeV, 1250 GeV, 1500 GeV and 2000 GeV (from top left to bottom right) respectively.

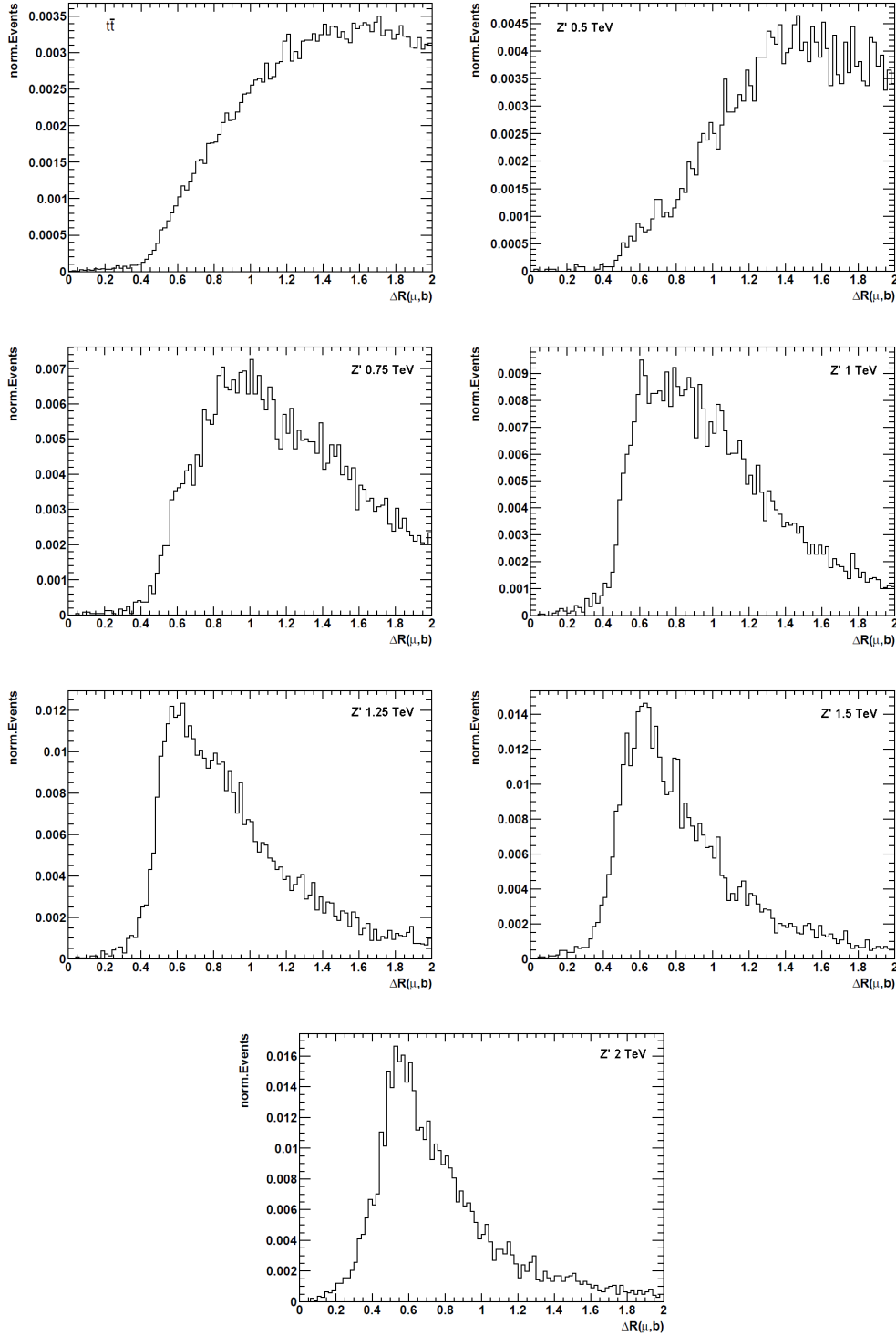


Figure A.2: ΔR distribution of b-quark and muon for SM top quark pair and for different Z' masses, 500 GeV, 750 GeV, 1000 GeV, 1250 GeV, 1500 GeV and 2000 GeV (from top left to bottom right) respectively.

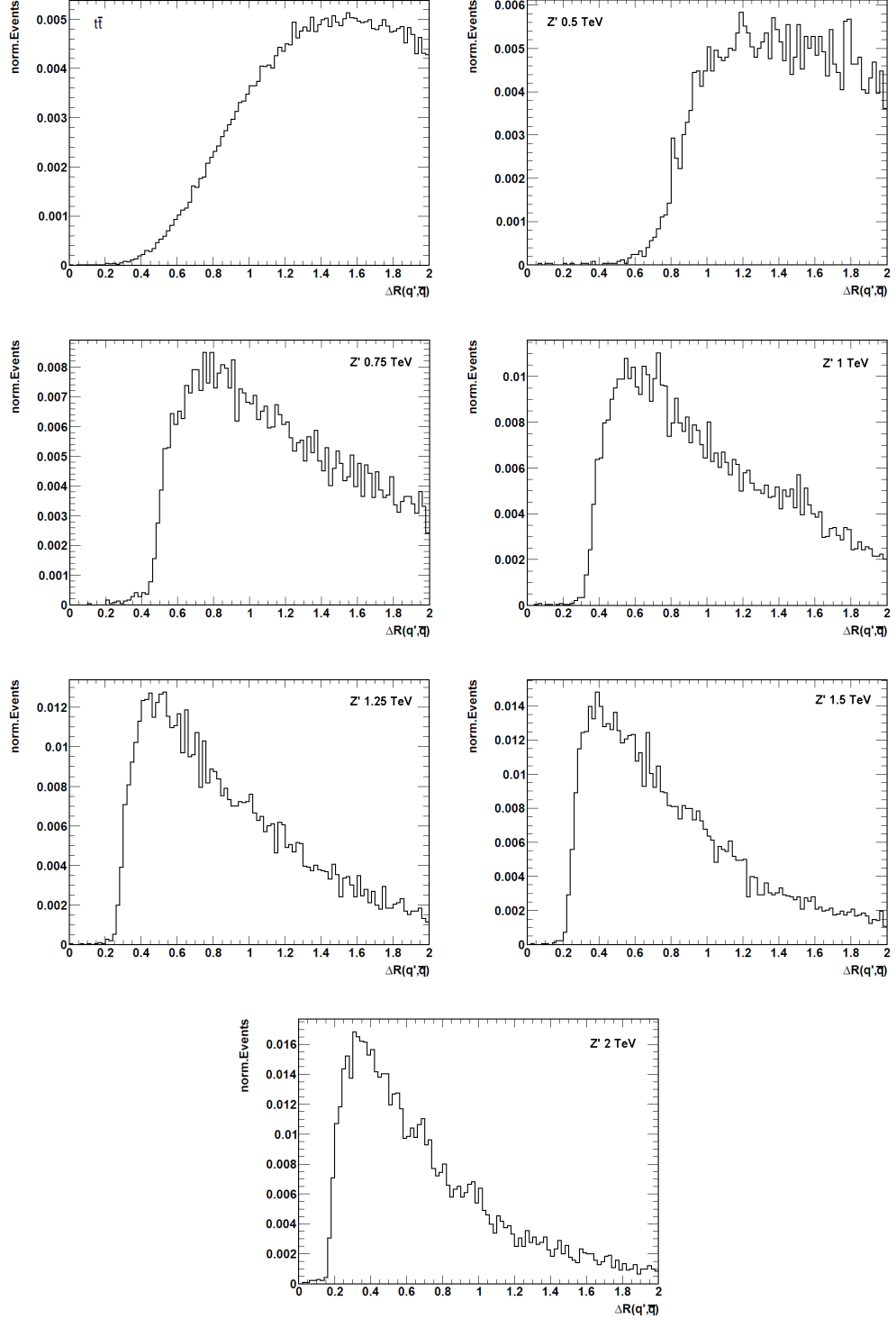


Figure A.3: ΔR distribution of the light quarks for SM top quark pair and for different Z' masses, 500 GeV, 750 GeV, 1000 GeV, 1250 GeV, 1500 GeV, 2000 GeV (from top left to bottom right) respectively.

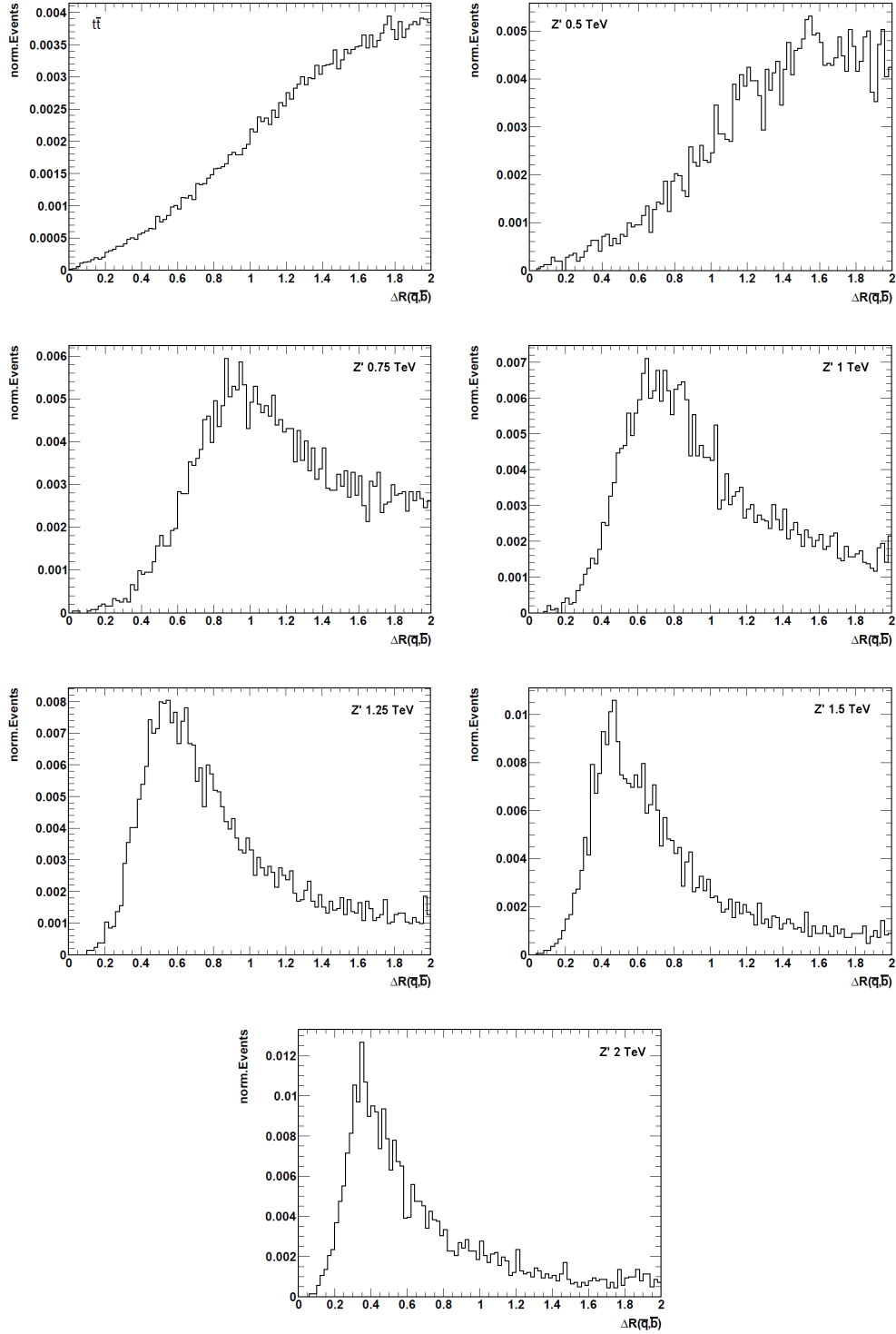


Figure A.4: ΔR distribution of b-quark and light quark for SM top-pair and for different Z' masses, 500 GeV, 750 GeV, 1000 GeV, 1250 GeV, 1500 GeV, 2000 GeV (from top left to bottom right) respectively.

A.3 Event Yields at Several Selection Stages

The expected and observed event yields at several stages of the selection are shown in the form of event selection tables.

Cut/ Sample [GeV]	Z' 500	Z' 750	Z' 1000	Z' 1250	Z' 1500
Generated Events	232074	206525	209447	191559	170783
Trigger	27767	25880	25695	22489	18143
Muon	20656	20002	19653	16805	13189
Muon veto	19568	19045	18752	15971	12530
Electron veto	17324	16696	16311	13951	11035
≥ 1 Jet	17263	16670	16299	13938	11027
≥ 2 Jet	16498	16252	16046	13719	10839
≥ 3 Jet	13230	14009	14144	11989	9198
≥ 4 Jet	7109	8815	9485	7943	5850

Table A.3: Event yields at several stages of the selection for signal samples.

Cut/Sample [GeV]	Z' 500	Z' 1000	Z' 1500
Generated Events	224460	230471	197523
Trigger	26620	28463	22235
Muon	19782	21847	16383
Muon veto	18809	20808	15545
Electron veto	16630	18191	13630
≥ 1 Jet	16590	18168	13619
≥ 2 Jet	15942	17849	13353
≥ 3 Jet	12887	15743	11253
≥ 4 Jet	7214	10438	6992

Table A.4: Event yields at several stages of the selection for signal sample.

Cut/Sample	Data	$t\bar{t}$	W + Jets	Z + Jets
Generated Events	37317271	3701947	81176311	36277961
Trigger	791727	481911	12007883	8202176
Muon	291460	358004	8522298	4028789
Muon veto	271384	340112	8521644	1876442
Electron veto	264541	297179	8506769	1842742
≥ 1 Jet	233951	296316	1638358	603565
≥ 2 Jet	120781	285097	388109	146985
≥ 3 Jet	43728	235292	88198	37170
≥ 4 Jet	14031	148416	20094	9181
Norm to $1.09fb^{-1}$	14031	6889	8452	840

Cut/Sample	QCD	Single-top(s)	Single-top(t)	Single-top(tW)
Generated Events	25080241	397951	5844997	1624374
Muon trigger	188509	24363	372480	217083
Muon	14881	18242	287140	166729
Muon veto	14871	18205	286605	159140
Electron veto	14677	18076	283935	139466
≥ 1 Jet	7705	17028	262205	137203
≥ 2 Jet	1268	11918	146309	119830
≥ 3 Jet	245	4028	44618	76640
≥ 4 Jet	42	1046	10870	31398
Norm to $1.09fb^{-1}$	154	13	131	330

Table A.5: Event yields at several stages of the selection for background samples.

Cut/Sample	WW	WZ	ZZ
Generated Events	1197558	952332	1013369
Muon trigger	410524	203247	292998
Muon	290567	112896	163083
Muon veto	247308	50301	68039
Electron veto	147367	48692	65930
≥ 1 Jet	74816	42583	60207
≥ 2 Jet	25570	27852	40518
≥ 3 Jet	7595	11217	14577
≥ 4 Jet	2045	2882	3246
Norm to $1.09fb^{-1}$	17	5	12

Table A.6: Event yields at several stages of the selection for background samples.

A.4 Generated and Reconstructed Z' Mass

The generated and reconstructed Z' invariant mass for different mass assumptions and widths (1.2% and 10%).

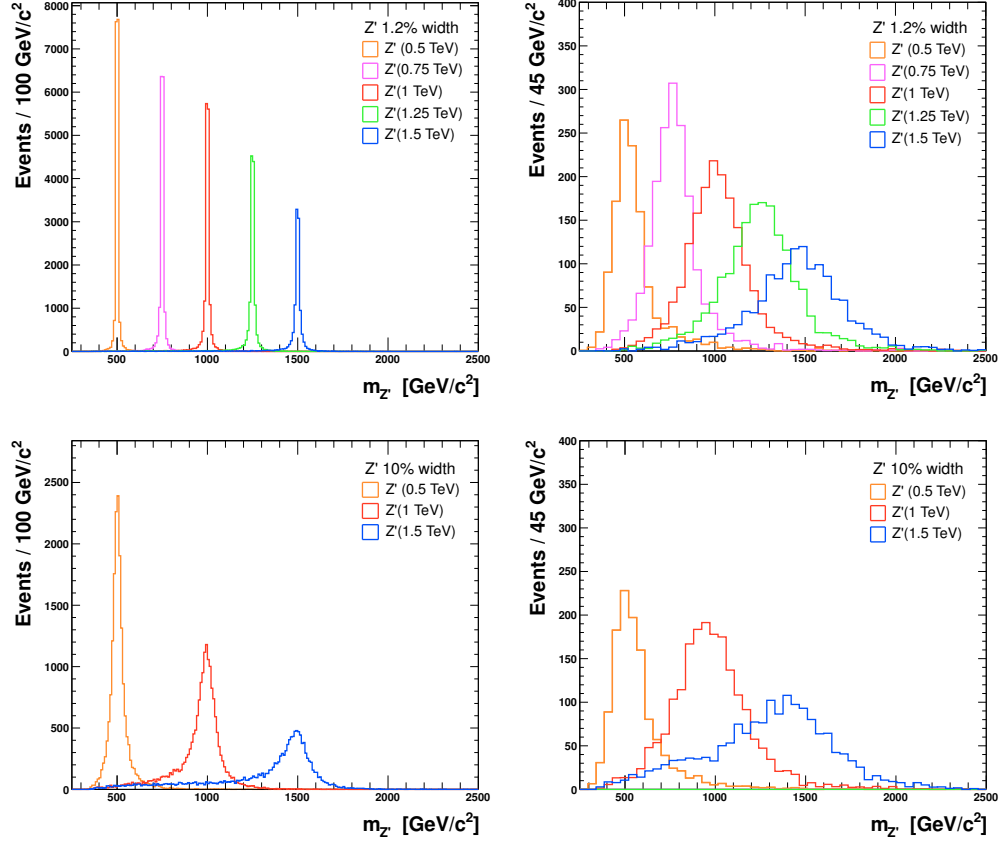


Figure A.5: Z' mass at generated level (left) and reconstructed level (right) for different masses and two widths 1.2% (top) and 10% (bottom).

A.5 Data-MC Control Plots

This section shows comparisons of kinematic distributions in MC simulation and in data. In general, the agreement of data and simulation is good as shown in the next figures.

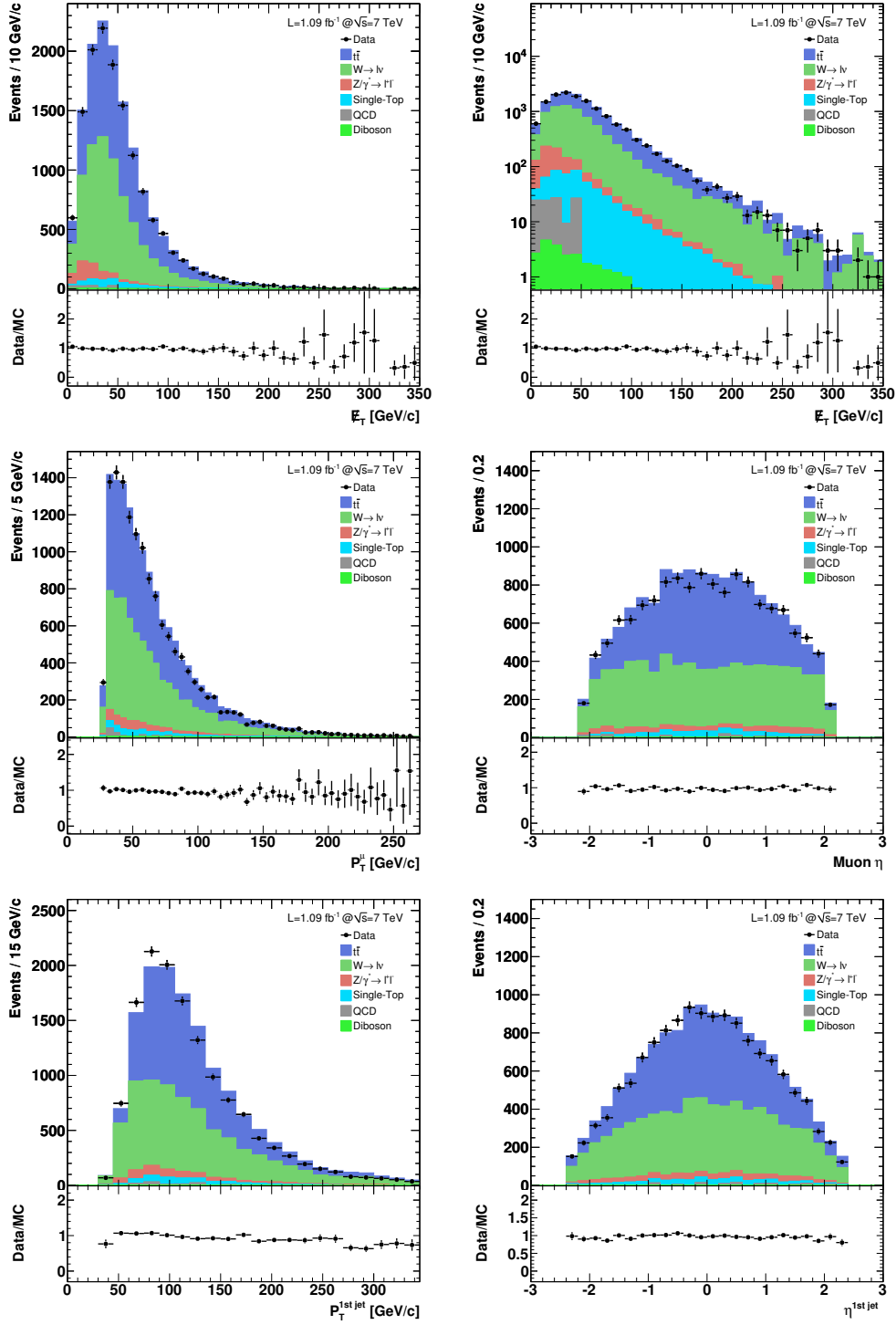


Figure A.6: Data-MC control plots for $\cancel{E}_T$ and muon and first leading jet.

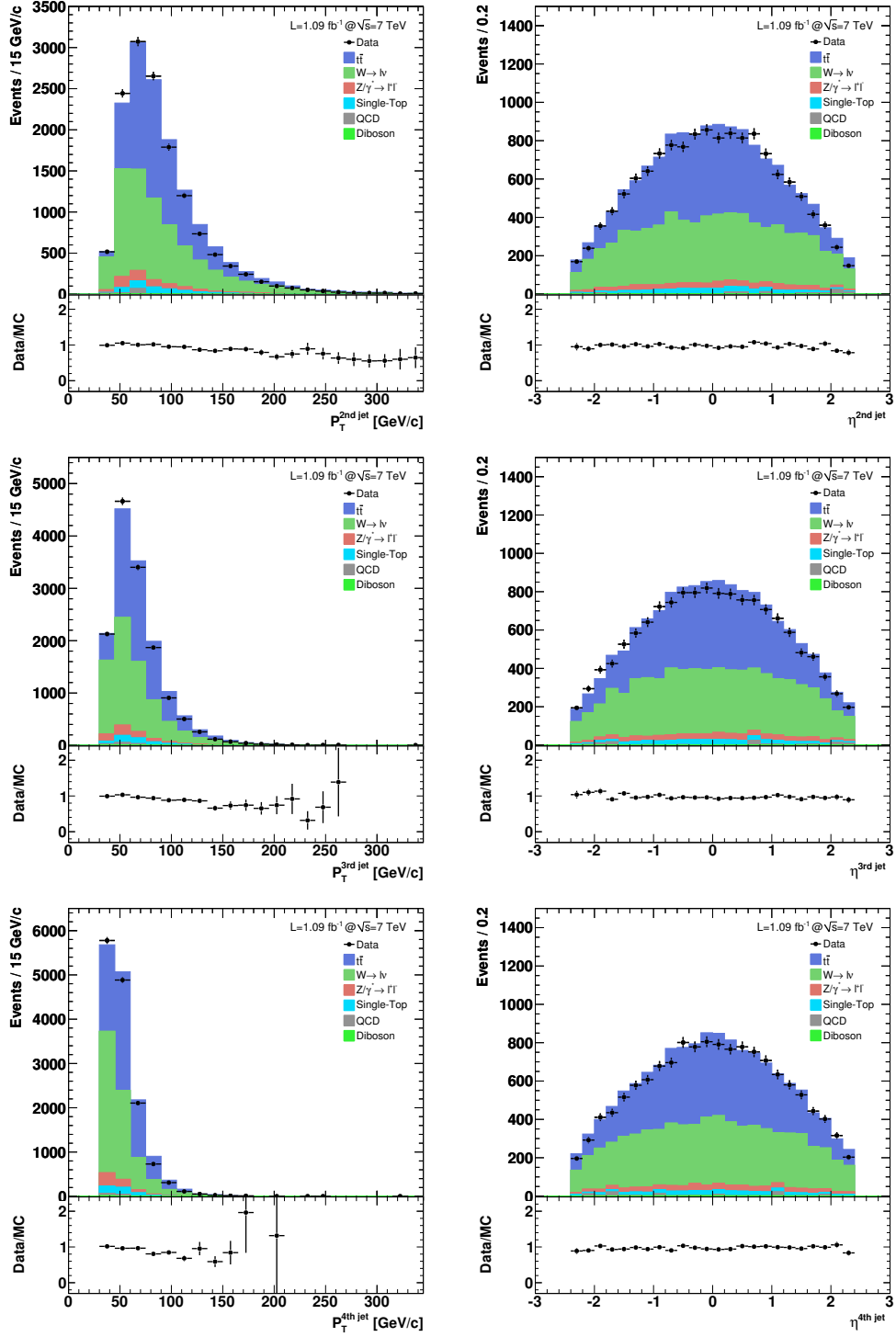


Figure A.7: Data-MC control plots for second, third and fourth leading jet.

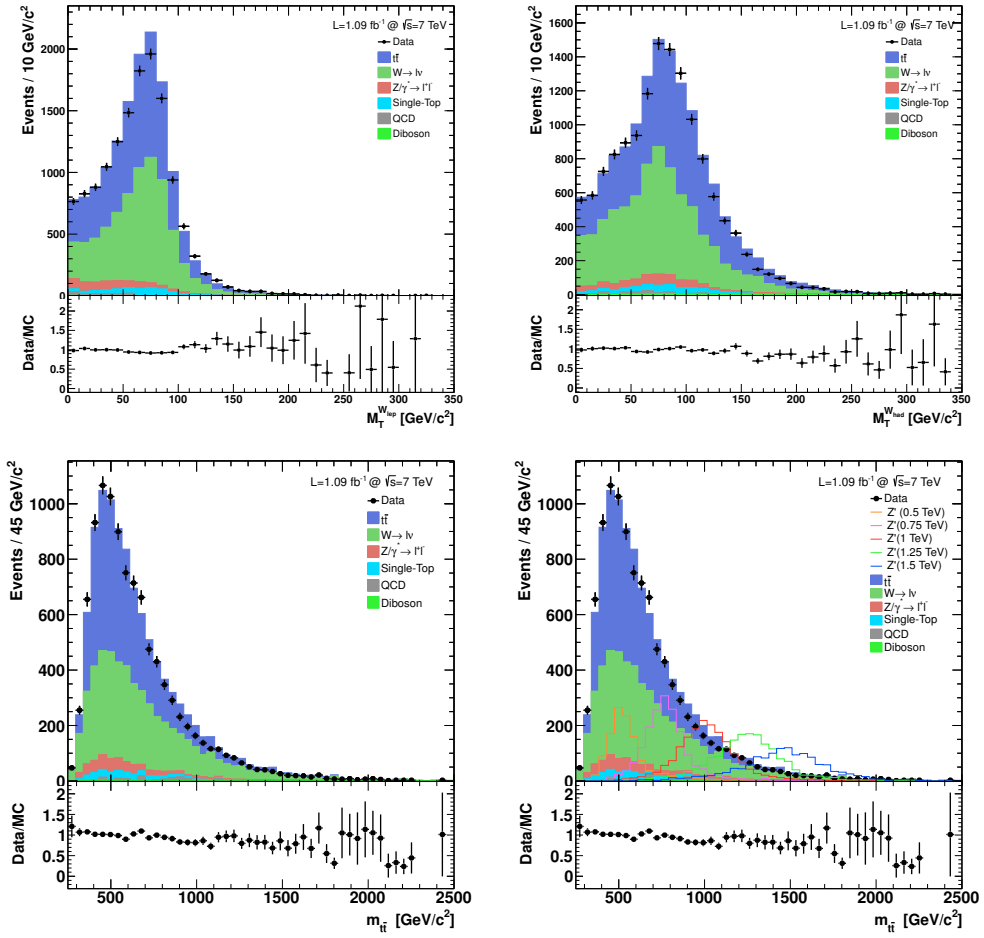


Figure A.8: Data-MC control plots for transverse W mass (top) and $t\bar{t}$ invariant mass for MC, data and signal (bottom).

A.6 Mass Resolution

The pull distributions for $m_{Z'} = 500, 750, 1000, 1250, 1500 \text{ GeV}/c^2$ and for SM $t\bar{t}$ are shown in Figure A.9. The mean of the pull is shifted from the negative to the positive values for SM $t\bar{t}$ and Z' boson of masses $m_{Z'} = 500, 750, 1000, 1250, 1500 \text{ GeV}/c^2$. This means that the mass peak of the residual ($M_{gen} - M_{rec}$) is shifted to the positive values for all samples. The reason for the shift is the gluon radiation of the partons coming from the top quark decay. The radiated parton can be reconstructed as an additional jet, if the radiation is strong. The resulted jet is not taken into account for the invariant mass calculation, hence the reconstructed invariant mass is underestimated. The probability to radiate gluons increases by the increasing of the quark energy, thus the shift will rise and become larger for the higher Z' boson masses. The pull distributions are asymmetric, especially for the SM $t\bar{t}$ and Z' boson masses below $1000 \text{ GeV}/c^2$ and become more symmetric with the increasing of the Z' mass. The tails are due to wrong reconstruction of jets.

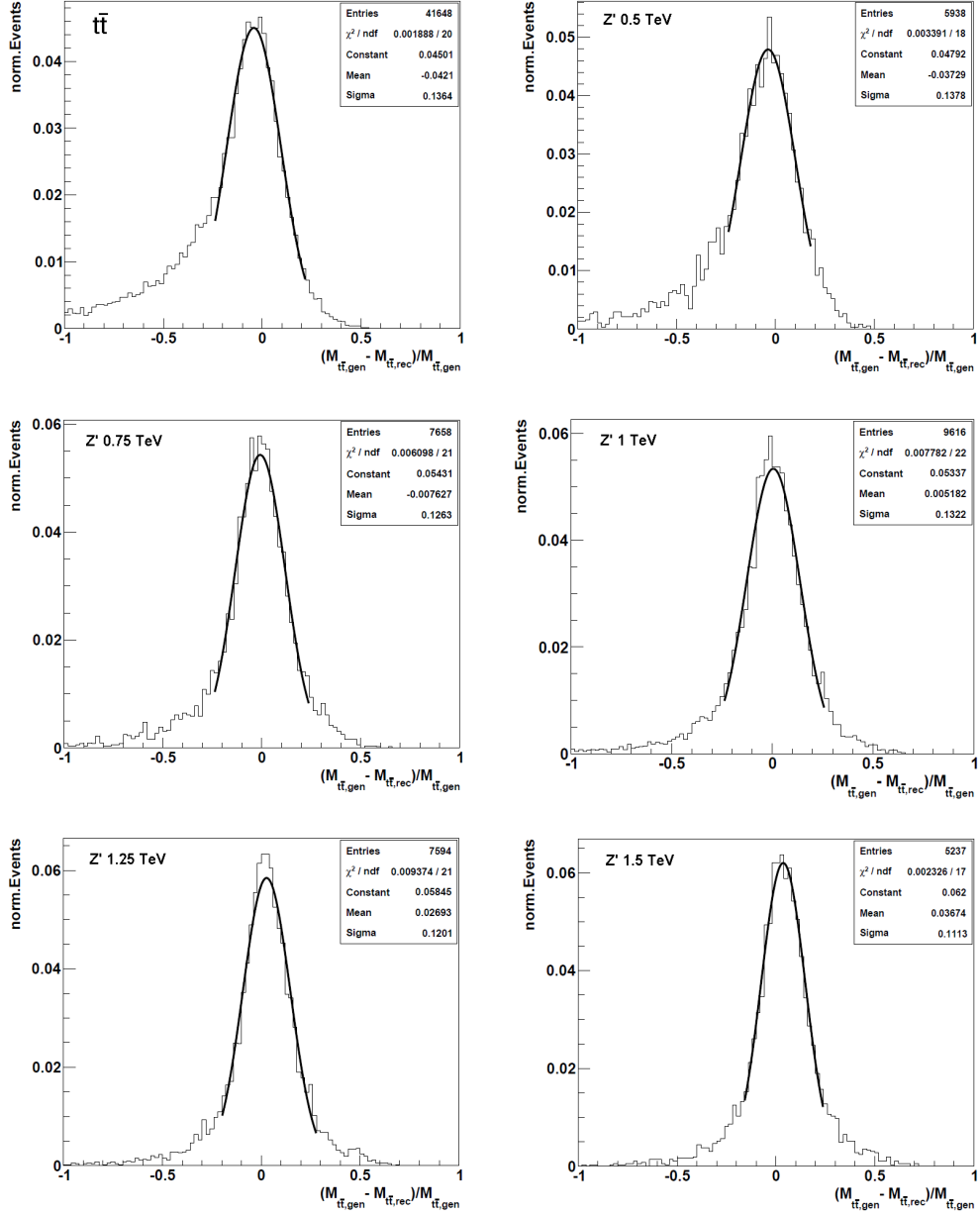


Figure A.9: The mass resolution of the $t\bar{t}$ system for SM top quark pair and for Z' samples with different masses, 500 GeV, 750 GeV, 1000 GeV, 1250 GeV and 1500 GeV (from top left to bottom right) respectively.

A.7 Limits on Z' Production Cross Section

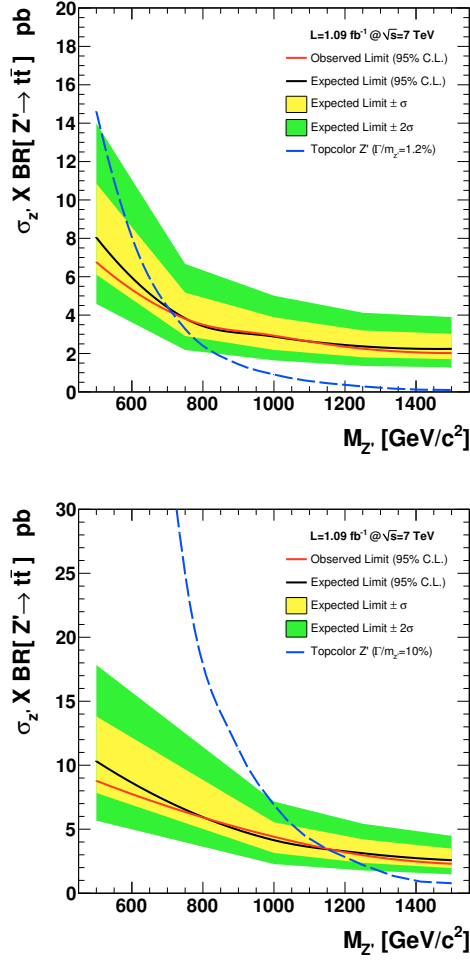


Figure A.10: Upper limits from CLs method on the $\sigma_{Z'} \times B(Z' \rightarrow t\bar{t})$ at 95% confidence level (CL) as a function of Z' mass using Z' model with width of $\Gamma/M_{Z'} = 1.2\%$ (top) and $\Gamma/M_{Z'} = 10\%$ (bottom), including all considered systematic uncertainties. The yellow band indicates the $\pm 1\sigma$ band and the green band the $\pm 2\sigma$ band of expected limits.

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Statement of Authorship

I declare that I wrote this thesis myself. All information derived from the work of others has been acknowledged in the text and a list of references is given. This work has not been submitted for any other degree or professional qualification except as specified.

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