

Thesis for the Degree of Doctor of Science

Searches for Supersymmetric Partners of Top and Bottom Quarks
in Proton-Proton Collisions at $\sqrt{s} = 7$ TeV

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Abstract

Supersymmetry (SUSY) is one of the most compelling theories to describe physics beyond the Standard Model (SM). In the framework of R -parity conserving minimal extension of the SM, supersymmetric particles are produced in pairs and the lightest supersymmetric particle (LSP) is stable. Due to the mixing of the right-handed and left-handed supersymmetric quarks, and the strong Yukawa coupling, the stops and the sbottoms (supersymmetric partners of top and bottom quarks) are lighter than the other supersymmetric quarks. Moreover, considering the “naturalness” of the Higgs mass, the stop mass is expected to be order of several hundreds GeV even if other colored supersymmetric particles are much heavier. If kinematically allowed, they could be produced via direct pair production or from the decay of gluinos (supersymmetric partner of gluons). This result in complex final states consisting of the missing transverse momentum (from the LSP) and bottom-jets (from the decay of stops or sbottoms).

In this thesis, searches for the stop and the sbottom will be presented focusing on the most probable models using the proton-proton collisions at $\sqrt{s} = 7$ TeV recorded by the ATLAS detector. The data with the integrated luminosity of about 2 fb^{-1} are used. Searches in four kinds of topologies have been performed; no-lepton multi-jet selection, one-lepton multi-jet selection, no-lepton di-jet selection, and two-lepton multi-jet selection optimized for each targeted SUSY model. None of them shows the significant excess from the SM predictions. These results are used to set limits on the several SUSY models. For the representative models, the following limits are set especially on the lightest stop mass at 95 % confidence level;

- $m_{\tilde{t}_1} > 640$ GeV in the mSUGRA model with $\tan\beta = 40$, $A_0 = -500$ GeV and $\mu > 0$,
- $m_{\tilde{t}_1} > 400$ GeV with the $\tilde{\chi}_1^0$ LSP of $m_{\tilde{\chi}_1^0} = 0$ GeV and $m_{\tilde{t}_1} > 350$ GeV with $m_{\tilde{\chi}_1^0} = 120$ GeV from the stop pair production with $\tilde{t}_1 \rightarrow b + \tilde{\chi}_1^+$, $\tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^0 + f + f'$, but $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$ are degenerated.
- $m_{\tilde{t}_1} > 320$ GeV with the next-to-LSP $\tilde{\chi}_1^0$ of $m_{\tilde{\chi}_1^0} = 180$ GeV and $m_{\tilde{t}_1} > 230$ GeV with $m_{\tilde{\chi}_1^0} > 91$ GeV from the stop pair production in the light-gravitino light-higgsino model with $\tilde{t}_1 \rightarrow b + \tilde{\chi}_1^+$, $\tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^0 + f + f'$, and $\tilde{\chi}_1^0 \rightarrow Z/h + \tilde{G}$, $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$ are degenerated.

They are the most stringent limits obtained by the collider experiments and lead to the strong limits on the naturalness of the Higgs mass in the supersymmetric models.

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Chapter 1

Standard Model and Supersymmetry

1.1 Introduction

The Standard Model (SM) of particle physics describes well the known phenomena below an energy scale of the order of 100 GeV. However, if we consider higher energies up to the Grand Unified Theory (GUT) ($\Lambda_{\text{GUT}} \approx 10^{16}$ GeV) or Planck scale (1.22×10^{19} GeV), we encounter a number of problems.

One problem is why the electroweak energy scale and the GUT or the Planck scales are so different. It is called hierarchy problem. This causes the problem on the Higgs mass. Without any cancellation mechanisms, the Higgs mass can easily diverge by the one-loop diagram contributions. It is also a problem that there is no appropriate candidate of dark matter in the SM. Moreover, unification of gravity in the framework of quantum field theory is not achieved in the SM.

Supersymmetry is one of the solutions which aim to solve these problems. In Chapter 1, motivations to introduce supersymmetry will be explained. If supersymmetry exists, supersymmetric partner particles of the SM particles exist. If supersymmetry is not broken, they have the same masses and the same quantum numbers as the SM partner particles. However, no such particles have been discovered. Therefore supersymmetry must be broken by a certain mechanism. One of the features of supersymmetry is that it predicts light supersymmetric partners of the top and bottom quarks. In R -parity conserving supersymmetry, the production of supersymmetric partners of the top and bottom quarks results in a final state with b -jets and the missing momentum in an event. In Chapter 2 the expected topologies from the production of supersymmetric particles will be described.

Searches for the supersymmetric partners of the top and bottom quarks have been performed using proton-proton collisions at $\sqrt{s} = 7$ TeV recorded by the ATLAS detector installed at the LHC machine. In Chapter 3, outlines of the LHC and the ATLAS detector are introduced. The collected data is compared with the Monte Carlo simulation. The detector is reproduced in simulations and proton-proton collision events are simulated for the SM processes and SUSY signals. In Chapter 4, the data

1.2.1 Electroweak model and spontaneous symmetry breaking

The electromagnetic interaction and the weak interaction are unified under an $SU(2) \times U(1)$ gauge group and referred to the electroweak interaction. The corresponding gauge bosons are the three W^i bosons ($i = 1, 2, 3$) of weak isospin from $SU(2)$ where the i -th W boson couples to Pauli matrices τ_i , and the B boson of weak hypercharge from $U(1)$. The corresponding gauge coupling constants are given by g and g' , respectively. The left-handed fermion fields transform as doublets under $SU(2)$ and the right-handed fields are $SU(2)$ singlets. These bosons and fermions are massless before symmetry breaking. The Higgs field is a complex spinor of the group $SU(2)$.

After spontaneous symmetry breaking, the W bosons acquire mass. The mass of the charged W bosons $W^\pm \equiv (W^1 \pm iW^2)/\sqrt{2}$ is expressed by

$$m_W = \frac{1}{2}vg, \quad (1.1)$$

where $v = 246$ GeV is called the vacuum expectation value (VEV). The neutral weak boson W^3 and B boson states are mixed and form the massless photon field A and the massive Z boson field,

$$A = B \cos \theta_W + W^3 \sin \theta_W, \quad (1.2)$$

$$Z = -B \sin \theta_W + W^3 \cos \theta_W \quad (1.3)$$

where $\theta_W \equiv \arctan(g'/g)$ is the electroweak mixing angle also known as the Weinberg angle. The mass of the Z boson is given by

$$m_Z = \frac{1}{2}v\sqrt{g^2 + g'^2}. \quad (1.4)$$

The fermions also acquire mass from their coupling to the Higgs doublet by the equation

$$m_f = \frac{G_f v}{\sqrt{2}}. \quad (1.5)$$

However, since G_f cannot be predicted from the theory, these values need to be determined from measurements for each particle.

After spontaneous symmetry breaking, only one physical neutral Higgs scalar field remains.

1.2.2 Quantum chromodynamics

The strong interaction is formulated as Quantum Chromodynamics (QCD), which is defined by the $SU(3)$ gauge group. The strong interaction acts on the quarks and gluons only. In QCD, there are three kinds of charge, called “color”. There are eight types of gluons because QCD is $SU(3)$ gauge group.

QCD has two distinct features:

- Confinement

Although analytically unproven, it is widely believed that confinement of quarks occurs in QCD. This is because free quarks have not been observed yet. They are observed only in the composite states called hadrons. This can be possible if the strong interaction between quarks does not diminish as they are separated unlike the electromagnetic interaction.

When two quarks become separated, it is more energetically favorable for a new quark-antiquark pair to spontaneously appear, than to allow them to be further separated. As a result, when quarks are produced in particle accelerators, instead of seeing the individual quarks, “jets” of many color-neutral particles are observed. This process is called hadronization or fragmentation.

- Asymptotic freedom

In very high-energy reactions, the strong interaction becomes weak. This can be derived by calculating the beta-functions describing the variation of the theory’s coupling constant under the renormalization group. Calculation of the beta-function involves the evaluation of Feynman diagrams contributing to the interaction of a quark emitting or absorbing a gluon. In non-abelian gauge theories, the existence of asymptotic freedom depends on the gauge group and the number of flavors of interacting “quark”-like particles. To lowest nontrivial order, the beta-function in $SU(N)$ gauge theory with n_{gen} kinds of generations is

$$\beta_1(\alpha) = \frac{\alpha^2}{2\pi} \left(-\frac{11N}{3} + \frac{n_{\text{gen}}}{3} \right) \quad (1.6)$$

where α is the theory’s equivalent of the fine-structure constant, equals to $g^2/(4\pi)$. If this function is negative, the theory is asymptotically free. For the strong interaction, $N = 3$ and $n_{\text{gen}} = 3$, therefore $\beta_1 < 0$.

1.3 Problems of the Standard Model

1.3.1 Grand unification

It is known that if we extrapolate the running of the coupling constants of the three forces ($U(1)_Y$, $SU(2)_L$, $SU(3)_C$) to higher energy scales, no grand unification occurs. It can be formulated as follows [2].

Define the three fine-structure constants, α_1 , α_2 and α_3 for the gauge groups $U(1)_Y$, $SU(2)_L$ and $SU(3)_C$, respectively by

$$\alpha_1 = \frac{5}{3} \frac{g'^2}{4\pi} = \frac{5\alpha}{3} \cos^2 \theta_W, \quad (1.7)$$

$$\alpha_2 = \frac{g^2}{4\pi} = \frac{\alpha}{\sin^2 \theta_W}, \quad (1.8)$$

$$\alpha_3 = \frac{g_s^2}{4\pi} \quad (1.9)$$

where α is the fine-structure constant for the electromagnetic interaction. To first order, the reciprocals of the fine-structure constants are proportional to $\ln(q^2)$ where q is energy at which the couplings are evaluated,

$$\alpha_i^{-1}(q^2) = \frac{b_i}{4\pi} \ln \left(\frac{q^2}{\mu_0^2} \right) + \alpha_i^{-1}(\mu_0^2). \quad (1.10)$$

The coefficients b_i are given as follows in the SM,

$$b_i^{\text{SM}} = \begin{pmatrix} b_1 \\ b_2 \\ b_3 \end{pmatrix} = \begin{pmatrix} 0 \\ -\frac{22}{3} \\ -11 \end{pmatrix} + n_{\text{gen}} \begin{pmatrix} \frac{4}{3} \\ \frac{4}{3} \\ \frac{4}{3} \end{pmatrix} + n_{\text{Higgs}} \begin{pmatrix} \frac{1}{10} \\ \frac{1}{6} \\ 0 \end{pmatrix}. \quad (1.11)$$

where n_{gen} is the number of generations and n_{Higgs} is the number of Higgs doublets. In the SM, $n_f = 3$ and $n_{\text{Higgs}} = 1$. Using the current knowledge on the SM parameters, the extrapolation to the higher energy scale can be calculated as shown in Figure 1.2 (left). There are no points where the three forces intersect.

On the other hand, in the *Minimal Supersymmetric Standard Model* (MSSM), which will be described later, the coefficients b_i change and are given by

$$b_i^{\text{MSSM}} = \begin{pmatrix} b_1 \\ b_2 \\ b_3 \end{pmatrix} = \begin{pmatrix} 0 \\ -6 \\ -9 \end{pmatrix} + n_{\text{gen}} \begin{pmatrix} 2 \\ 2 \\ 2 \end{pmatrix} + n_{\text{Higgs}} \begin{pmatrix} \frac{3}{10} \\ \frac{1}{2} \\ 0 \end{pmatrix}. \quad (1.12)$$

In the MSSM, the number of the Higgs fields is two as shown later. If we assume the existence of SUSY particles around mass scale of 1 TeV, the three fine-structure constants cross around 10^{16} GeV and the grand unification occurs as shown in Figure 1.2 (right). This is one of the strong motivations for supersymmetry.

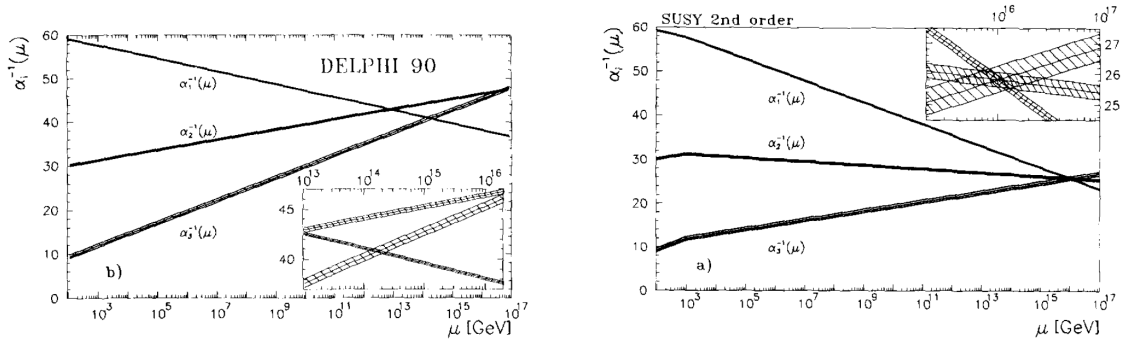


Figure 1.2: First order evolution of the three coupling constants in the Standard Model using M_Z and $\alpha_s(M_Z)$ from DELPHI data (left) and second order evolution of the three coupling constants in the minimal SUSY model assuming mass scale of SUSY particles M_{SUSY} of around 1 TeV (right) [2].

1.3.2 Hierarchy problem

The Planck scale is about $M_{\text{Pl}} = G_{\text{N}}^{-1/2} \approx 10^{19}$ GeV where quantum gravity is not negligible anymore (G_{N} is the gravitational constant). On the other hand, all the SM particles have masses on the order of 100 GeV. Why are these two energy scale so different?

This problem is also related to the stability of the Higgs mass [3]. The electrically neutral part of the Standard Model Higgs field is a complex scalar H with a classical potential

$$V = m_h^2 |H|^2 + \lambda |H|^4. \quad (1.13)$$

The SM requires a non-vanishing vacuum expectation value (VEV) for H at the minimum of the potential. This becomes $\langle H \rangle = \sqrt{-m_h^2/2\lambda} \approx 174$ GeV. Therefore m_h^2 must be the order of $-(100 \text{ GeV})^2$.

However, the one-loop diagram containing a Dirac fermion f with mass m_f , shown in Figure 1.3 (left) can correct m_h^2 . If the Higgs field couples to f with a term in the Lagrangian $-\lambda_f H \bar{f} f$, then the Feynman diagram in Figure 1.3 (left) yields a correction

$$\Delta m_h^2 = -\frac{|\lambda_f|^2}{8\pi^2} \Lambda_{\text{UV}}^2 + \dots \quad (1.14)$$

where Λ_{UV} is an ultraviolet momentum cutoff used to regulate the loop integral: the cutoff can be interpreted as the energy scale up to which the SM is valid. If there is no new physics beyond the SM up to the Planck scale, then the Higgs mass quadratically diverges.

If there exists a heavy complex scalar particle S with mass m_S that couples to the Higgs with a Lagrangian term $-\lambda_S |H|^2 |S|^2$, the Feynman diagram in Figure 1.3 (right) gives a correction

$$\Delta m_h^2 = \frac{\lambda_S}{16\pi^2} [\Lambda_{\text{UV}}^2 - 2m_S^2 \ln(\Lambda_{\text{UV}}/m_S) + \dots]. \quad (1.15)$$

As shown later, in supersymmetry, two scalar particles are newly introduced per a SM fermion. Therefore if these scalar particles have the coupling constants satisfying $\lambda_S = |\lambda_f|^2$ the first terms of Equation 1.14 and 1.15 can be canceled. This is the strong motivation to introduce scalar particles by supersymmetry.

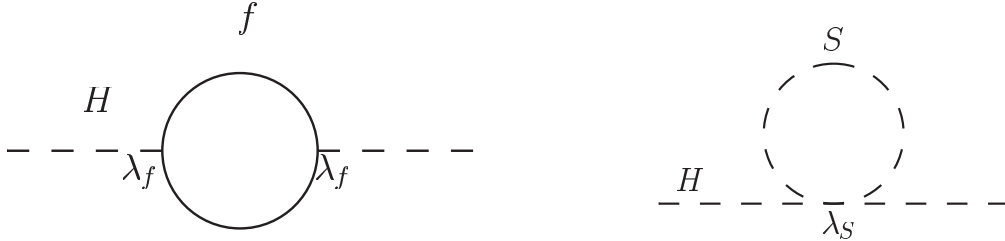


Figure 1.3: One-loop quantum corrections to the Higgs squared mass parameter m_h^2 , due to a Dirac fermion f (left) and a scalar S (right).

1.3.3 Dark matter

Dark matter candidates have been categorized into *cold*, *warm* and *hot* by its velocity in the early universe.

- Cold dark matter are the objects moving at classical velocities.
- Warm dark matter are the objects moving relativistically, that is, at velocities ranging typically from 0.1 to 0.95 of the speed of the light.
- Hot dark matter matter are objects moving at velocities over 0.95 of the speed of the light.

Since warm and hot dark matter move too quickly, they cannot explain how individual galaxies formed from the Big Bang. Therefore, they are not regarded as the main composition of dark matter, and the existence of cold dark matter is now well established [4].

In the past, one candidate for cold dark matter was baryonic matter such as Massive Astrophysical Compact Halo Objects (MACHOs) [5, 6] or cold molecular gas clouds [7]. However, according to the latest measurements of the anisotropy of the cosmic microwave background (CMB) and of the spatial distribution of galaxies [4], the density of cold, non-baryonic matter is

$$\Omega_{\text{nbm}}h^2 = 0.110 \pm 0.006 \quad (1.16)$$

where h is the Hubble constant in units of 100 km/(s·Mpc) while the baryonic matter density is

$$\Omega_{\text{b}}h^2 = 0.0227 \pm 0.0006. \quad (1.17)$$

That is, the baryonic matter explains only 17 % of dark matter. Thus nonbaryonic dark matter must possess features that:

- It is stable on the cosmological time scale.
- It interacts very weakly with electromagnetic radiation.
- It has the right relic density.

There are no particles in the SM satisfying these conditions.

Considering physics beyond the SM, one of the candidates is the axion [8] which was first postulated to solve the strong CP problem of QCD, but it has not been discovered yet. Another candidate is the Weakly Interacting Massive Particles (WIMPs), which have mass roughly between 10 GeV and a few TeV, and an interaction cross-sections of approximately weak strength. As shown later, in the so-called R -parity conserving supersymmetry models, the lightest supersymmetry particle (LSP) cannot decay further and becomes the good dark matter candidate satisfying the above requirements.

1.3.4 Gravity

Gravity, which is the attractive force between physical objects with a strength of proportional to the masses of two objects, is described by the general theory of relativity as the curvature of space-time. It is one of the four fundamental interactions of nature. If we try to describe gravity in the framework of quantum field theory like the other three fundamental forces, such that the attractive force of gravity arises due to the exchange of a *graviton*, general relativity is reproduced in the classical limit. However, this approach fails at a short distance of the order of the Planck length. Therefore, a more complete theory of quantum gravity is required.

In *supergravity*, which is one of the supersymmetric models, gravity is naturally introduced producing graviton and its supersymmetric partner, *gravitino*. This is also a good motivation to introduce supersymmetry.

1.4 Supersymmetry

As described in the previous section, the Standard Model is not a complete theory and there must be some new physics beyond the SM. There are many theories to solve these problems and supersymmetry is one of the most promising theories.

Supersymmetry is a symmetry of exchanging fermions and bosons. In an unbroken supersymmetric theory, there exist supersymmetric partners corresponding to all Standard Model particles with the same mass and internal quantum numbers. However, since no such particles have not been discovered, hence supersymmetry must be broken and supersymmetric particles must be heavier than SM particles.

In a broken supersymmetric model, the masses of SUSY particles can take any values but to solve the problems in the SM, they need to be at the TeV energy scale.

1.4.1 Minimal Supersymmetric Standard Model

A general approach to the phenomenological study of SUSY is to assume the minimal possible particle content and to parametrize the SUSY-breaking Lagrangian as the sum of all the terms which do not reintroduce quadratic divergences into the theory. This minimal extension of the Standard Model is called the *Minimal Supersymmetric Standard Model* (MSSM). In the MSSM, the following new particles are introduced.

- Squarks

The squarks or the scalar quarks are the superpartners of the quarks. They have the same quantum numbers of the corresponding quarks except for the spin and the mass. Their spins are zero. Their names are formed by taking the name of the corresponding quark and appending an “s” (which stands for scalar) in front, e.g. sbottom, stop and so on. They are also called scalar quarks. The symbol for the supersymmetric particles is a tilde $\tilde{}$.

The superpartners of left-handed and right-handed quarks are called left- and right-handed squarks and are written by $\tilde{q}_L$ and $\tilde{q}_R$ but since they are spin 0, this

handedness does not refer to their helicities. The gauge interaction is the same as the SM, and only the left-handed squarks can couple to the W boson.

- Sleptons

The sleptons or the scalar leptons are the superpartners of the leptons. As in the quark sector, these superparticles also have the same quantum numbers as their SM partners except for the spin and the mass. Their spins are also zero. They are named selectron, smuon, stau and sneutrino or “scalar electron” and so forth.

- Gluinos

The superpartners of the gluon is called gluino. Since supersymmetry relates the particles with different spin by a half unit, the gluino spins are one half. They are Majorana fermions. The mass of gluinos is given by M_3 .

In case of the supersymmetric fermions, they are named by taking the name of their SM partners and adding 'ino' at the end.

- Winos and bino

The superpartners of electroweak gauge bosons are called wino and bino (together they are referred to electroweak gauginos). They have spin one half. The masses of the winos and bino are given by M_2 and M_1 , respectively.

- Higgses and higgsinos

In the SM, the Higgs field is a two-dimensional complex field. Its degrees of freedom are absorbed into the W and Z boson masses and there is only one physical Higgs boson. If supersymmetry exists, one Higgs doublet field is not enough because the electroweak gauge symmetry suffers a gauge anomaly [3]. Therefore, a Higgs field must be a weak isodoublet with weak hypercharge $Y = 1/2$, which gives masses to up-type quarks (up, charm, top), or $Y = -1/2$, which gives masses to down-type quarks (down, strange, bottom) and to the charged leptons. They are denoted by H_u and H_d respectively, and consist of electrically charged and neutral fields,

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}, \quad H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}. \quad (1.18)$$

The vacuum expectation values of H_u^0 and H_d^0 are written as

$$v_u = \langle H_u^0 \rangle, \quad v_d = \langle H_d^0 \rangle. \quad (1.19)$$

These VEVs are related to the SM parameters:

$$v_u^2 + v_d^2 = v^2 = \frac{2m_Z^2}{g^2 + g'^2}. \quad (1.20)$$

The ratio of the VEVs is traditionally written as

$$\tan \beta \equiv \frac{v_u}{v_d}. \quad (1.21)$$

When the electroweak symmetry is broken, three of the Higgs scalar fields are the Nambu-Goldstone bosons and become the longitudinal modes of the Z^0 and $W^\pm$ bosons. The remaining five Higgs scalar mass eigenstates consist of two CP-even neutral scalars h^0 and H^0 , one CP-odd neutral scalar A^0 , and charged scalars $H^\pm$.

The superpartners of the Higgs bosons are called higgsinos, denoted by $\tilde{H}_u$ and $\tilde{H}_d$ for the $SU(2)_L$ -doublet left-handed spinor fields, with weak isospin components $(\tilde{H}_u^+, \tilde{H}_u^0)$ and $(\tilde{H}_d^0, \tilde{H}_d^-)$. The mass of higgsinos is given by μ .

- Neutralinos and charginos

The higgsinos and electroweak gauginos mix with each other because of the effects of electroweak symmetry breaking. The neutral higgsinos ($\tilde{H}_u$ and $\tilde{H}_d$) and the neutral gauginos ($\tilde{B}$ and $\tilde{W}^0$) combine to form four mass eigenstates called *neutralinos*. The charged higgsinos ($\tilde{H}_u^+$ and $\tilde{H}_d^-$) and winos ($\tilde{W}^+$ and $\tilde{W}^-$) mix to form two mass eigenstates with charge ± 1 called *charginos*. These neutralino and chargino mass eigenstates are denoted by $\tilde{\chi}_i$ ($i = 1, 2, 3, 4$) and $\tilde{\chi}_i^\pm$ ($i = 1, 2$), respectively. They are ordered by their masses from the smallest to the largest. The neutralinos are Majorana fermions.

If the gaugino masses M_1, M_2 are much smaller than the higgsino mass μ , the lightest neutralino and the lightest chargino are “gaugino-like” whose eigenstates are gaugino dominant. On the other hand, if $\mu \ll M_1, M_2$, then the lightest neutralino and the lightest chargino are “higgsino-like” and have degenerated mass close to the higgsino mass μ .

- goldstino and gravitino

In the MSSM, supersymmetry breaking is accomplished by including the most general renormalizable soft-supersymmetry-breaking terms consistent with the $SU(3) \times SU(2) \times U(1)$ gauge symmetry. If supersymmetry breaking occurs spontaneously, then a massless Goldstone fermion called the *goldstino* must exist. However, the goldstino degrees of freedom are physical only in models of spontaneously-broken global supersymmetry.

In *supergravity* models [9, 10], it is assumed that global supersymmetry is broken but supersymmetry is a local symmetry taking into account gravity. The graviton whose spin is two has a spin 3/2 fermion superpartner called the gravitino ($\tilde{G}$). The gravitino absorb the goldstino and acquire a mass, $m_{3/2}$. This is analogous to the ordinary Higgs mechanism in the SM, and called super-Higgs mechanism.

Usually, the gravitino mass is assumed to be comparable to the other SUSY particles. Since its interaction will be of gravitation strength, the gravitino will not play an important role in collider experiments, as long as the gravitino is not the LSP.

Figure 1.4 shows the SM particles and the corresponding supersymmetric particles in the MSSM.

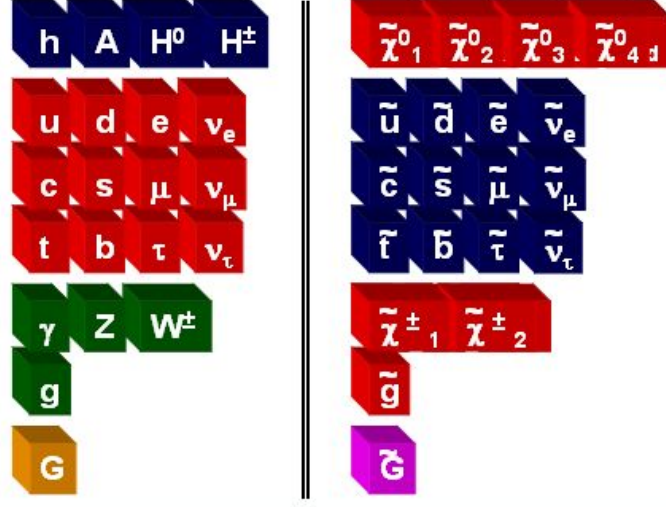


Figure 1.4: The list of Standard Model particles and corresponding supersymmetric particles

The Lagrangian in the MSSM can be written as [3]:

$$\begin{aligned}
\mathcal{L}_{\text{soft}}^{\text{MSSM}} = & \frac{1}{2} \left(M_3 \tilde{g} \tilde{g} + M_2 \tilde{W} \tilde{W} + M_1 \tilde{B} \tilde{B} + \text{c.c.} \right) \\
& - \left(\tilde{u} \mathbf{a}_u \tilde{Q} H_u - \tilde{d} \mathbf{a}_d \tilde{Q} H_d - \tilde{e} \mathbf{a}_e \tilde{L} H_d + \text{c.c.} \right) \\
& - \tilde{Q}^\dagger \mathbf{m}_Q^2 \tilde{Q} - \tilde{L}^\dagger \mathbf{m}_L^2 \tilde{L} - \tilde{u} \mathbf{m}_u^2 \tilde{u}^\dagger - \tilde{d} \mathbf{m}_d^2 \tilde{d}^\dagger - \tilde{e} \mathbf{m}_e^2 \tilde{e}^\dagger \\
& - m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - (b H_u H_d + \text{c.c.}).
\end{aligned} \tag{1.22}$$

The $\mathbf{a}_u$, $\mathbf{a}_d$ and $\mathbf{a}_e$ terms in the second line are complex 3×3 matrix in family space, with dimensions of mass. They correspond to the trilinear couplings.

In the MSSM, supersymmetry breaking is assumed to be universal to flavors to avoid dangerous flavor-changing and CP-violating effects. Then the mass matrix is proportional to the 3×3 identity matrix in family space:

$$\begin{aligned}
\mathbf{m}_Q^2 &= m_Q^2 \mathbf{1}, & \mathbf{m}_u^2 &= m_u^2 \mathbf{1}, & \mathbf{m}_d^2 &= m_d^2 \mathbf{1}, \\
\mathbf{m}_L^2 &= m_L^2 \mathbf{1}, & \mathbf{m}_e^2 &= m_e^2 \mathbf{1}.
\end{aligned} \tag{1.23}$$

Then all squark and slepton mixing angles are trivial because squarks and sleptons with the same electroweak quantum numbers will be degenerated in mass. Further assumption is applied on the trilinear scalar coupling constant matrices, $\mathbf{a}_u, \mathbf{a}_d, \mathbf{a}_e$ in

the MSSM. They are proportional to the corresponding Yukawa coupling constants,

$$\begin{aligned} \mathbf{a}_u &= \begin{pmatrix} A_u y_u & 0 & 0 \\ 0 & A_c y_c & 0 \\ 0 & 0 & A_t y_t \end{pmatrix}, & \mathbf{a}_d &= \begin{pmatrix} A_d y_d & 0 & 0 \\ 0 & A_s y_s & 0 \\ 0 & 0 & A_b y_b \end{pmatrix}, \\ \mathbf{a}_e &= \begin{pmatrix} A_e y_e & 0 & 0 \\ 0 & A_\mu y_\mu & 0 \\ 0 & 0 & A_\tau y_\tau \end{pmatrix}. \end{aligned} \quad (1.24)$$

where y_f are the Yukawa coupling constants ($f = u, d, c, s, t, b, e, \mu, \tau$). A_f are called the trilinear coupling constants.

The third line of Equation 1.22 consists of squark and slepton mass terms. The fourth line of Equation 1.22 consists of the supersymmetry-breaking contributions to the Higgs potential; the first two terms are diagonal components and the remaining two are off-diagonal components.

1.4.2 R -parity

In the MSSM, one needs to introduce a new symmetry in order not to violate the conservation of the baryon number and the lepton number. It is called R -parity, which is 1 for the SM particles and -1 for the SUSY partners. Models that violate R -parity are also possible but in this thesis, only the models which conserve R -parity are considered.

As a result of R -parity conservation, SUSY particles must be produced in pairs and they decay to the Lightest SUSY Particle (LSP) which must be stable. In order to be consistent with cosmological constraints, a stable LSP must be electrically and color neutral. As far as collider experiments are concerned, an LSP will behave like a heavy neutrino and escape collider detectors without being directly observed. Therefore if SUSY particles are produced, the LSP causes a momentum imbalance in events. Searches for the SUSY particles described in this thesis rely on this momentum imbalance.

1.4.3 Supersymmetry breaking models

Since it is almost impossible to construct a realistic model of spontaneous supersymmetry breaking from the interaction between the particles of MSSM, a *hidden* sector is introduced, which is consisting of particles that are completely neutral with respect to the SM gauge group.

Supersymmetry breaking is assumed to originate in the hidden sector, and its effects are transmitted to the MSSM by some mechanism. The MSSM is characterized by a large number of parameters (about 100), implying that a 100-dimensional space must be considered. To reduce the number of parameters and search for the most probable models, we need to adopt specific assumptions for the SUSY breaking mechanism. Here, major models which are considered in this thesis are introduced.

Supergravity and mSUGRA

In models of gravity-mediated supersymmetry breaking, which is a natural outcome of supergravity, gravity is the messenger of supersymmetry breaking. In this scenario, the gravitino mass is of order that electroweak symmetry breaking scale, while its couplings are roughly gravitational in strength. Therefore the gravitino does not play an important role in supergravity.

One important case is that when we apply plausible assumptions to reduce the parameters in MSSM. In the minimal supergravity (mSUGRA) models, the numbers of parameters are reduced to four plus one sign parameter.

- m_0 : universal scalar mass at GUT scale

Assume all scalar particles have the same mass at the GUT scale ($\approx 10^{16}$ GeV).

- $m_{1/2}$: universal gaugino mass

Assume all gauginos are unified at GUT scale and they have the same mass. Then the masses of the gauginos are give by the following equation,

$$\frac{M_1}{\frac{5}{3}g'^2} = \frac{M_2}{g^2} = \frac{M_3}{g_s^2} = m_{1/2}. \quad (1.25)$$

At the electroweak energy scale, they are related by

$$M_1 : M_2 : M_3 \approx 1 : 2 : 6. \quad (1.26)$$

- A_0 : universal trilinear coupling

Assume all trilinear coupling constants are the same value.

- B_0 : Higgs mixing term

Assume Higgs mixing term b in Equation 1.22 is given by $B_0\mu$ where B_0 is a real scalar.

From Equation 1.20, the relations between m_Z , $\tan \beta$, B_0 and μ can be written as follows;

$$m_{H_u}^2 + |\mu|^2 - B_0\mu \cot \beta - \frac{m_Z^2}{2} \cos(2\beta) = 0, \quad (1.27)$$

$$m_{H_d}^2 + |\mu|^2 - B_0\mu \tan \beta - \frac{m_Z^2}{2} \cos(2\beta) = 0. \quad (1.28)$$

Usually, instead of B_0 and μ , the use of $\tan \beta$ and m_Z are favored as parameters (but the sign of μ cannot be fixed from these equations). Therefore m_0 , $m_{1/2}$, A_0 , $\tan \beta$ and sign of μ are the free parameters in the mSUGRA model.

In mSUGRA, the LSP is the lightest neutralino in most of the parameter spaces; otherwise stau becomes the LSP. Since the LSP can be dark matter, if the stau is the LSP, it will violates the cosmological constraints that dark matter must be electrically neutral. The lightest neutralino is a promising candidate for dark matter.

Gauge-mediated supersymmetry breaking

In Gauge-Mediated Supersymmetry Breaking (GMSB) models [11, 12], the ordinary gauge interactions, rather than gravity, are responsible for the appearance of soft supersymmetry breaking in the MSSM.

GMSB models predict the gravitino is much lighter than the other MSSM sparticles (order of keV). Therefore, the gravitino is the LSP in most cases. The gravity is too weak but since the goldstino has been absorbed, the couplings between the gravitino and the other particles can be strong enough so that in collider experiments, they will decay quickly.

It is different from the WIMP dark matter scenario but gravitino dark matter scenario is also allowed [13]. The gravitino is sometimes called a super-WIMP as dark matter because its interaction strength is much weaker than that of other supersymmetric dark matter candidates.

1.4.4 Naturalness

In Section 1.3.2 (Hierarchy problem), it was discussed that the quadratic divergence of the Higgs mass can be canceled by introducing supersymmetry. However, one problem arises. Even if the quadratic Λ_{UV} term is canceled, the term proportional to $m_S^2 \cdot \ln(\Lambda_{UV}/m_S)$ cannot be eliminated without the physically unjustifiable tuning of a counter-term. This is called “naturalness” problem. The theory to be natural, certain limits on the masses of scalar particles are required. The tightest limit is the one on the stop mass because of its strong coupling to the Higgs boson. The following discussion is based on Reference [14].

Generally in electroweak symmetry breaking via the Higgs mechanism, there is a relation between the Higgs boson mass (m_h) and the quadratic term in the potential (the negative mass squared), m^2 ,

$$\frac{m_h^2}{2} = -m^2. \quad (1.29)$$

In the MSSM, the Higgs mass is 130 GeV at most. For a moderately large value of $\tan\beta$ ($\gtrsim 10$), electroweak symmetry breaking is mainly due to the vacuum expectation value of the up-type Higgs field, H_u . In this case, the m^2 can be written as

$$m^2 = \mu^2 + m_{H_u}^2|_{\text{tree}} + m_{H_u}^2|_{\text{rad}} \quad (1.30)$$

where $m_{H_u}^2|_{\text{tree}}$ and $m_{H_u}^2|_{\text{rad}}$ represent the tree-level and radiative contributions. The Higgs mass is the result of a cancellation between these terms. If the absolute values of these terms are much larger than $m_h^2/2$, it looks un-“natural”. Defining the tuning parameter by $\Delta^{-1} = m_h^2/2\mu^2$, and taking $\Delta^{-1} > 10\%$, one obtains

$$|\mu| \lesssim 290 \text{ GeV} \left(\frac{m_h}{130 \text{ GeV}} \right) \left(\frac{\Delta^{-1}}{10\%} \right). \quad (1.31)$$

Another important contribution is from the stop-top loop diagrams to the $m_{H_u}^2$ parameters. There are two kinds of interactions in the diagrams; one with the top

Yukawa interaction ($-y_t \bar{q}_3 u_3 H_u$) and another through the three-point stop-stop-Higgs interaction ($A_t y_t \tilde{q}_3 \tilde{u}_3 H_u$). The three-point interaction also provides an important contribution to the Higgs boson mass, m_h . The dominant contribution to $m_{H_u}^2|_{\text{rad}}$ arises from top-stop loop:

$$m_{H_u}^2|_{\text{rad}} \approx -\frac{3y_t^2}{8\pi^2}(m_{Q_3}^2 + m_{U_3}^2 + |A_t|^2) \ln \left(\frac{M_{\text{mess}}}{m_{\tilde{t}}} \right) \quad (1.32)$$

where M_{mess} represents the scale at which squark and slepton masses are generated.

By setting $m_{Q_3}^2 \simeq m_{U_3}^2 \simeq m_{\tilde{t}}^2$ for simplicity and defining $\Delta'^{-1} \equiv m_h^2/2m_{H_u}^2|_{\text{rad}}$ and $x \equiv |A_t|/m_{\tilde{t}}$, the stop mass is given by

$$m_{\tilde{t}}^2 \simeq \frac{2\pi^2}{3y_t^2} \frac{m_h^2}{\left(1 + \frac{x^2}{2}\right) \Delta'^{-1} \ln \frac{M_{\text{mess}}}{m_{\tilde{t}}}} \quad (1.33)$$

$$\simeq (500 \text{ GeV})^2 \frac{\frac{3}{2}}{1 + \frac{x^2}{2}} \left(\frac{10 \text{ \%}}{\Delta'^{-1}} \right) \left(\frac{3}{\ln \frac{M_{\text{mess}}}{m_{\tilde{t}}}} \right) \left(\frac{m_h}{130 \text{ GeV}} \right)^2. \quad (1.34)$$

By assuming a small logarithm ($M_{\text{mess}} \sim 10 \text{ TeV}$, which is possible in GMSB), we obtain upper and lower bounds on the stop mass parameter from the naturalness and the Higgs boson mass bound, respectively. Requiring $\Delta'^{-1} > 10 \text{ \%}$ and $m_h > 114.4 \text{ GeV}$, the bounds for $|A_t| \sim m_{\tilde{t}}$ are

$$500 \text{ GeV} \lesssim m_{\tilde{t}} \lesssim 500 \text{ GeV} \quad (1.35)$$

and for $|A_t| \sim 2m_{\tilde{t}}$

$$250 \text{ GeV} \lesssim m_{\tilde{t}} \lesssim 360 \text{ GeV}. \quad (1.36)$$

There is no allowed region for $|A_t| \lesssim m_{\tilde{t}}$ or $|A_t| \gtrsim 2.5m_{\tilde{t}}$. For $A_t = 0$, we obtain $\Delta'^{-1} \lesssim 2 \text{ \%}$. The maximum value of Δ'^{-1} is about 20 % which can be achieved when $|A_t| \sim 2m_{\tilde{t}}$. The naturalness upper bound on the lighter stop mass is then,

$$m_{\tilde{t}_1} \lesssim 400 \text{ GeV} \quad (|A_t| \sim m_{\tilde{t}}), \quad (1.37)$$

$$m_{\tilde{t}_1} \lesssim 200 \text{ GeV} \quad (|A_t| \sim 2m_{\tilde{t}}) \quad (1.38)$$

for $\Delta'^{-1} > 10 \text{ \%}$. This kind of constraint is not required on the other superparticles. Therefore, the minimal requirements for natural SUSY are light stops and light higgsinos.

For a higher logarithm (e.g. $M_{\text{mess}} \approx M_{\text{Pl}}$), the requirement on Δ'^{-1} need to be tightened by a factor of $10 \approx \ln(M_{\text{Pl}}/m_{\tilde{t}})/\ln(10 \text{ TeV}/m_{\tilde{t}})$.

1.4.5 Third generation supersymmetry particles

In principle, any scalars with the same electric charge, R -parity, and color quantum number can mix with each other; however, off-diagonal components of the mass matrix

of SUSY particles of the first- and second-generations are negligibly small. Thus their mass eigenstates can be written in terms of the gauge eigenstate as follows [3],

$$m_{\tilde{d}_L}^2 = m_0^2 + K_3 + K_2 + \frac{1}{36}K_1 + \Delta_{\tilde{d}_L}, \quad (1.39)$$

$$m_{\tilde{u}_L}^2 = m_0^2 + K_3 + K_2 + \frac{1}{36}K_1 + \Delta_{\tilde{u}_L}, \quad (1.40)$$

$$m_{\tilde{u}_R}^2 = m_0^2 + K_3 + \frac{4}{9}K_1 + \Delta_{\tilde{u}_R}, \quad (1.41)$$

$$m_{\tilde{d}_R}^2 = m_0^2 + K_3 + \frac{1}{9}K_1 + \Delta_{\tilde{d}_R} \quad (1.42)$$

where

$$K_1 \approx 0.15m_{1/2}^2, \quad K_2 \approx 0.5m_{1/2}^2, \quad K_3 \approx (4.5 \text{ to } 6.5)m_{1/2}^2 \quad (1.43)$$

and

$$\Delta_{\tilde{u}_L} = \left(\frac{1}{2} - \frac{2}{3} \sin^2 \theta_W \right) \cos(2\beta) m_Z^2, \quad (1.44)$$

$$\Delta_{\tilde{d}_L} = \left(-\frac{1}{2} + \frac{1}{3} \sin^2 \theta_W \right) \cos(2\beta) m_Z^2, \quad (1.45)$$

$$\Delta_{\tilde{u}_R} = \left(\frac{2}{3} \sin^2 \theta_W \right) \cos(2\beta) m_Z^2, \quad (1.46)$$

$$\Delta_{\tilde{d}_R} = \left(-\frac{1}{3} \sin^2 \theta_W \right) \cos(2\beta) m_Z^2. \quad (1.47)$$

Here m_0 and $m_{1/2}$ are the common scalar mass and gaugino mass at the unification scale.

On the other hand, in the case of SUSY particles of the third generation, due to the large Yukawa coupling, the gauge eigenstates can mix. For stop, the mass matrix is written as

$$\mathcal{L}_{\text{stop masses}} = -(\tilde{t}_L^* \tilde{t}_R^*) \mathbf{m}_{\tilde{t}}^2 \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix}, \quad (1.48)$$

$$\mathbf{m}_{\tilde{t}}^2 = \begin{pmatrix} m_{Q_3}^2 + m_t^2 + \Delta_{\tilde{u}_L} & v(a_t^* \sin \beta - \mu y_t \cos \beta) \\ v(a_t \sin \beta - \mu^* y_t \cos \beta) & m_{\tilde{u}_3}^2 + m_t^2 + \Delta_{\tilde{u}_R} \end{pmatrix}. \quad (1.49)$$

Here the Yukawa coupling at tree-level is given by,

$$y_t = \frac{m_t}{v \sin \beta}, \quad (1.50)$$

$$y_b = \frac{m_b}{v \cos \beta}. \quad (1.51)$$

This hermitian matrix can be diagonalized by a unitary matrix to give the mass eigenstates:

$$\begin{pmatrix} \tilde{t}_1 \\ \tilde{t}_2 \end{pmatrix} = \begin{pmatrix} c_{\tilde{t}} & -s_{\tilde{t}}^* \\ s_{\tilde{t}} & c_{\tilde{t}} \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix}. \quad (1.52)$$

Here $m_{\tilde{t}_1}^2 < m_{\tilde{t}_2}^2$ are the eigenvalues of Equation 1.49, and $|c_t|^2 + |s_t|^2 = 1$. Due to the off-diagonal components, $\tilde{t}_1$ tend to be lighter than $\tilde{t}_L, \tilde{t}_R$. Moreover, $m_{\tilde{u}_3}$ and m_{Q_3} are generally smaller than the masses of the first and second family squarks because of the larger Yukawa coupling. Therefore the lighter stop often has the lightest mass of all squarks.

A similar equation holds for the sbottoms. For the gauge-eigenstate of $(\tilde{b}_L, \tilde{b}_R)$, the squared mass matrix is given by

$$\mathbf{m}_{\tilde{b}}^2 = \begin{pmatrix} m_{Q_3}^2 + \Delta_{\tilde{d}_L} & v(a_b^* \cos \beta - \mu y_b \sin \beta) \\ v(a_b \cos \beta - \mu^* y_b \sin \beta) & m_{\tilde{d}_3}^2 + \Delta_{\tilde{d}_R} \end{pmatrix}. \quad (1.53)$$

This can be diagonalized to give the mass eigenstates $\tilde{b}_1, \tilde{b}_2$ where $m_{\tilde{b}_1} \leq m_{\tilde{b}_2}$. For the sbottoms, the mixing of off-diagonal components is significant if the value of $\tan \beta$ is large. In fact, there are good theoretical motivations for considering models with large $\tan \beta$ [15, 16]. Therefore, the sbottom is also expected to be lighter than the other light-flavor squarks.

Chapter 2

Stop and Sbottom Signatures

As described in the previous chapter, third generation squarks (the stop and the sbottom) are expected to be lighter than the other squarks, and as a result, their production can be dominant. In this chapter, the expected topologies from stop and sbottom production are described.

2.1 Production processes

If the stop or the sbottom are relatively light, there are mainly two types of production processes. One is via the decay from gluinos and the other is via direct pair production. If the gluino is not much heavier than the stop, the direct production of gluinos dominates over direct stop (or sbottom) production as shown in Figure 2.1. However, as described in Section 1.4.4, if we consider the naturalness of Higgs mass, it is possible that the stop is only light (i.e. mass on the order of several hundreds GeV) colored SUSY particle and the other squarks and the gluinos are heavier than a few TeV. In this case, only direct stop pair production would be observed

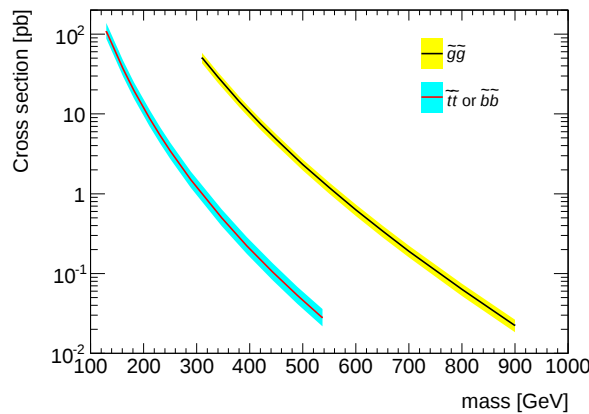


Figure 2.1: Cross-sections for the pair production of gluinos, stops and sbottoms as a function of their masses calculated to NLO using PROSPINO [17, 18].

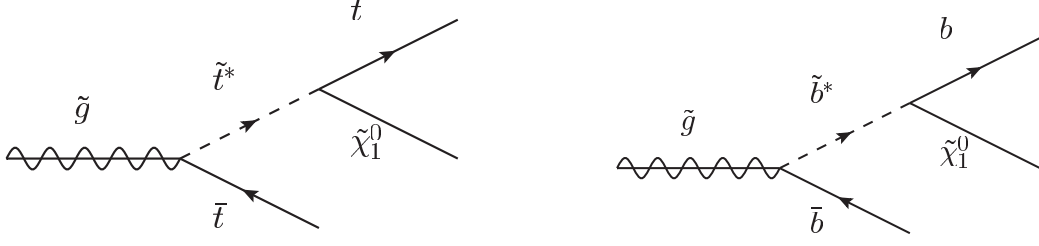


Figure 2.2: The Feynman diagrams for the gluino three-body decay to top quark pair (left) and bottom quark pair (right).

Gluino pair is produced at first, when $m_{\tilde{g}} > m_{\tilde{t}_1} + m_t$ or $m_{\tilde{g}} > m_{\tilde{b}_1} + m_b$, the gluino can decay via

$$\tilde{g} \rightarrow \tilde{t}_1 + t, \quad (2.1)$$

$$\tilde{g} \rightarrow \tilde{b}_1 + b. \quad (2.2)$$

When these two-body decays are forbidden, gluinos decay via three-body or four-body decay modes. One important case is that even if the stop (or the sbottom) is heavier than the gluino, the decay modes of gluinos to a top quark pair (or a bottom quark pair, or top-bottom quark pair) can be enhanced if the stop (or sbottom) is lighter than the other squarks;

$$\tilde{g} \rightarrow t + \bar{t} + \tilde{\chi}_1^0, \quad (2.3)$$

$$\tilde{g} \rightarrow b + \bar{b} + \tilde{\chi}_1^0. \quad (2.4)$$

When gluinos decay via the three-body mode, a virtual squark is emitted as shown in Figure 2.2. This propagator is proportional to $1/(m_{\tilde{q}^*})^4$. Therefore even a small mass difference between the stop (or the sbottom) and the other squarks is enhanced by the fourth power. Moreover, if the lightest neutralino is higgsino-like, the couplings to the squarks of the third generation are much larger than the first and the second generations. From these reasons, the branching ratio of the gluino to the top (or bottom) quark pairs becomes large.

2.2 Decay modes

The decay modes of the stop and the sbottom depend highly on the SUSY particle mass spectrum. For simplicity, only the lightest stop, the lightest chargino and the lightest neutralino are considered as the active SUSY particles; the other SUSY particles are assumed to be heavy enough (masses on the order of TeV) such that they decouple. The decay modes of the sbottom can be inferred by the analogy to the stop.

2.2.1 Two-body decay

A1) If $m_{\tilde{t}_1} > m_t + m_{\tilde{\chi}_1^0}$, the stop can decay via

$$\tilde{t}_1 \rightarrow t + \tilde{\chi}_1^0. \quad (2.5)$$

If the lightest neutralino is the LSP, $\tilde{\chi}_1^0$ cannot decay anymore but the top quark will decay further. The final state therefore consists of multi-jets including b -jets, leptons and E_T^{miss} .

A2) If $m_{\tilde{t}_1} > m_b + m_{\tilde{\chi}_1^+}$, the stop can decay via

$$\tilde{t}_1 \rightarrow b + \tilde{\chi}_1^+. \quad (2.6)$$

Since the lightest chargino is in general heavier than the lightest neutralino, the lightest chargino can decay further via $\tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^0 + f + f'$, where f and f' are any SM fermions. The branching ratios to fermion flavors depend on the corresponding scalar fermion masses.

A3) If the above two decay modes and the three-body decay modes shown below are all suppressed, the stop can decay via

$$\tilde{t}_1 \rightarrow c + \tilde{\chi}_1^0, \quad (2.7)$$

if $m_{\tilde{t}_1} > m_c + m_{\tilde{\chi}_1^0}$ via the one-loop diagram such as shown in Figure 2.3. However, this topology is only possible in a limited parameter space, and therefore it will not be considered in this thesis.

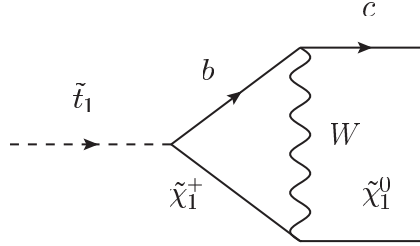


Figure 2.3: One of the $\tilde{t}_1 \rightarrow c + \tilde{\chi}_1^0$ decay diagram in one-loop.

2.2.2 Three-body decay

The branching ratios for three-body decays are much smaller than those of two-body decays. If the two-body decay modes (A1 and A2) are forbidden, however, three-body decays can be dominant. Here it is assumed that all other squarks are much heavier than the stop.

B1) If the sleptons are lighter than the stop, the stop can decay via

$$\tilde{t}_1 \rightarrow b + \nu + \tilde{l}. \quad (2.8)$$

Since a charged LSP is forbidden from the cosmological constraints, none of the sleptons can be the LSP and therefore they will decay further. This results in the final states with b -jets, leptons and E_T^{miss} .

B2) If the sneutrinos are lighter than the stop, the stop can decay via

$$\tilde{t}_1 \rightarrow b + l + \tilde{\nu}. \quad (2.9)$$

Regardless of whether one of the sneutrinos is the LSP or not, the sneutrino or other LSP are not detected. This decay mode therefore also results in the final states with b -jets, leptons and E_T^{miss} .

These decay processes are different from two-body decays but the final states are the same as one of the decay modes described in Section 2.2.1. Therefore by searching for two-body decay modes, these three-body decay modes are naturally covered.

2.2.3 Four-body decay

If all two-body decay modes (A1 and A2) and three-body decay modes (B1 and B2) are forbidden, the branching ratio of the stop decay via four-body decay modes can be dominant.

C1) In this case, the stop can decay via

$$\tilde{t}_1 \rightarrow b + f + f' + \tilde{\chi}_1^0 \quad (2.10)$$

where f and f' are any SM fermions. Figures 2.4 show some examples of tree-level Feynman diagrams of this decay mode. Since this mode has the same order in perturbation theory as the loop-induced A3 decay ($\mathcal{O}(\alpha^3)$), its branching ratio is competitive to that of the A3 mode. For example, it can be enhanced if the charginos have masses not much larger than their present experimental bounds, or if the sfermions are light [19].

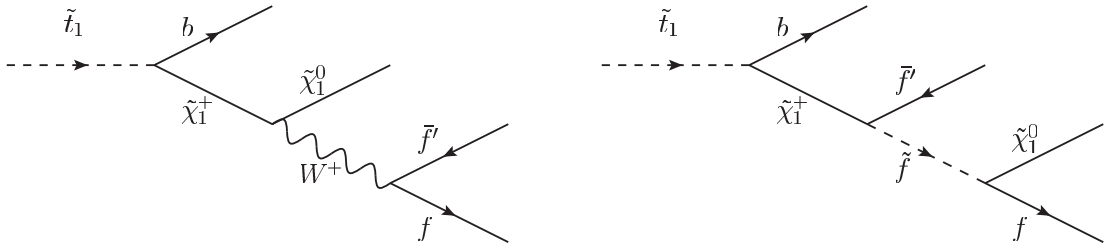


Figure 2.4: The tree-level Feynman diagrams for $\tilde{t}_1 \rightarrow b + f + f' + \tilde{\chi}_1^0$.

Although this is a different decay process from the two-body decay, the final states are nevertheless b -jets, multi-jets (or leptons) and E_T^{miss} , and these modes are naturally covered by the two-body decay searches.

2.2.4 Light gravitino models

In light gravitino scenario such as GMSB models in which the gravitino mass is expected to be $\mathcal{O}(\text{keV})$, a different topology is possible. Most of the topologies can be interpreted by replacing the gravitino by the massless neutralino but there are some different topologies.

One is the lightest neutralino decay mode of

$$\tilde{\chi}_1^0 \rightarrow \gamma + \tilde{G}. \quad (2.11)$$

The bino and the neutral wino couple with the photon but generally, the lightest neutralino is the LSP and it cannot decay further. Therefore this topology is seen only when the lightest neutralino is not the LSP. Since the SUSY particles are always produced in pair, the final states have two photons.

The other decay mode is as follows. If $m_{\tilde{\chi}_1^0} > m_Z$, the lightest neutralino can decay via

$$\tilde{\chi}_1^0 \rightarrow Z + \tilde{G}. \quad (2.12)$$

This decay mode is possible whether the lightest neutralino is gaugino-like or higgsino-like.

If $m_{\tilde{\chi}_1^0} > m_h$, the lightest neutralino can decay via

$$\tilde{\chi}_1^0 \rightarrow h + \tilde{G}. \quad (2.13)$$

The Higgs boson is not yet discovered but it is expected to be heavier than the Z boson. Therefore, the branching ratio of Equation 2.12 dominates that of Equation 2.13 in most cases.

2.2.5 Categorization

Figure 2.5 summarizes the decay modes of the stop for two types of chargino and neutralino mass relations and dependence on whether or not the gravitino. If the lightest chargino and neutralino are higgsino-like, their masses are very close ($m_{\tilde{\chi}_1^\pm} \simeq m_{\tilde{\chi}_1^0}$). On the other hand, if they are gaugino-like, their mass can be differ. The case of $m_{\tilde{\chi}_1^\pm} = 2m_{\tilde{\chi}_1^0}$ is considered here as a representative model.

The decay process can be different depending on the mass relations between $\tilde{t}_1$, $\tilde{\chi}_1^0$ and $\tilde{\chi}_1^\pm$, but the final state is the same as A1) $\tilde{t}_1 \rightarrow t + \chi_1^0$ except for some special cases.

2.3 Expected Topologies

2.3.1 Multi-jets including b -jet and E_T^{miss}

Gluino production results in final states with multi-jets and E_T^{miss} . If the gluino decays to stop, final states always include b -jets. This topology also covers the case that gluino decays to sbottom. The search for this topology is described in Section 6.2.

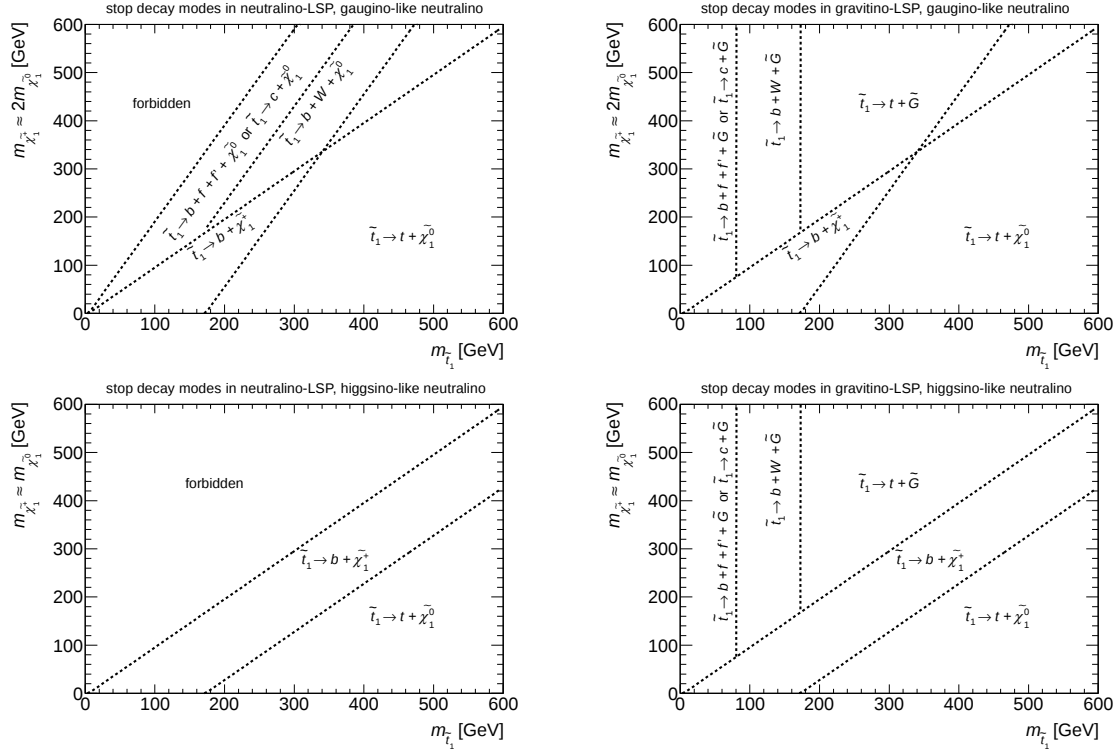


Figure 2.5: Decay modes of the stop in the neutralino-LSP model (left) and gravitino-LSP model (right) with the two cases: $m_{\tilde{\chi}_1^\pm} \approx 2m_{\tilde{\chi}_1^0}$ (top) and $m_{\tilde{\chi}_1^\pm} \approx m_{\tilde{\chi}_1^0}$ (bottom).

2.3.2 Multi-jets including b -jet, one lepton and E_T^{miss}

This topology is almost the same as the above, but if stops are produced, the possibility that the final states have at least one lepton is high. Therefore this topology is more sensitive to stop signature than to sbottom. The search for this topology is described in Section 6.3.

2.3.3 Two b -jets and E_T^{miss}

One of the topologies that is not covered by the above multi-jet analyses is the following.

Suppose that a stop pair is produced directly and they each decay to a chargino and a bottom quark. The chargino decays to a neutralino and SM fermion pair;

$$\tilde{t}_1 \rightarrow b + \tilde{\chi}_1^+, \quad (2.14)$$

$$\tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^0 + f + f'. \quad (2.15)$$

If charginos and neutralinos degenerate in mass, which is possible when they are higgsino-like, the fermion pairs from the chargino decay cannot be detected in the collider experiment. In this case the final state has only two b -jet and E_T^{miss} . This topology is also possible when a sbottom pair is produced and each sbottom decays to the lightest neutralino only

$$\tilde{b}_1 \rightarrow b + \tilde{\chi}_1^0. \quad (2.16)$$

The search for this topology is described in Section 6.4

2.3.4 b -jets, two leptons and E_T^{miss}

Another topology which is not covered by the above analyses is the one which is possible in the light-gravitino models in which the lightest neutralino can decay further. In particular, when the lightest neutralino decays to the Z boson plus gravitino, the sensitivity to the signal can be highly enhanced by identifying the decay products of the Z boson.

The decay chain is the same as Equation 2.14 and Equation 2.15, but in this case the neutralino decays further by Equation 2.12. If $m_{\tilde{\chi}_1^0} > m_h$, the decay of Equation 2.13 is also possible. Since the decay to the Z boson usually dominates, the decay to the Higgs boson is not targeted here. Thus the the final state has the decay products from the Z (or Higgs) boson, two b -jets and E_T^{miss} . Two leptons from the Z boson can be detected with the high efficiency while providing high rejection of the background process. The search for this topology is described in Section 6.5.

2.3.5 b -jets, two photons and E_T^{miss}

Similar to the case of Section 2.3.4, the topology of the lightest neutralino decaying to a photon plus a gravitino is also not covered by the above analyses. However, the final state with two photons are already sought in ATLAS without requiring b -jets and the strong exclusion limits have been set [20]. Figure 2.6 shows the expected and observed

exclusion limits at 95 % CL for the stop pair production in the light-gravitino model with light higgsinos in the final state of two-photon plus E_T^{miss} . The signals are obtained by the ATLAS fast simulation [21] (called Atlfast-I). The method for exclusion limit calculation will be shown in Chapter 7. The signal productions are normalized to the integrated luminosity of 36 pb^{-1} . From this result, a stop mass of 395 GeV is already excluded.

Therefore, the search for this topology is not described in this thesis.

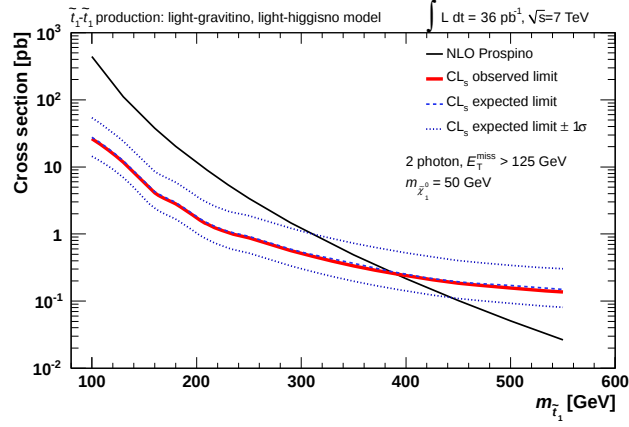


Figure 2.6: The expected and observed exclusion limits at 95 % confidence level for the stop pair production in the light-gravitino model with light higgsinos using the final state of two-photon plus E_T^{miss} .

Chapter 3

LHC and ATLAS Detector

3.1 Large hadron collider

The Large Hadron Collider (LHC) [22] at CERN was constructed to collide proton beams with an unprecedented center-of-mass energy of 14 TeV and a luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ aiming at the investigation of electroweak symmetry breaking and the search for the Higgs boson as well as the search for physics beyond the Standard Model. At the end of the year 2011, the accelerator was operating at a center-of-mass energy of 7 TeV with the peak luminosity of $3.65 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$. Table 3.1 shows the proton beam parameters of the LHC.

Table 3.1: LHC proton beam parameters.

	Design	Recorded ²
Proton energy [GeV]	7000	3500
Number of particles per bunch	1.15×10^{11}	$\sim 1.45 \times 10^{11}$
Number of bunches	2808	1380
Number of colliding bunches ³		1331
Peak luminosity [$\text{cm}^{-2}\text{sec}^{-1}$]	1.0×10^{34}	3.65×10^{33}
Bunch spacing	25 ns	50 ns

The LHC can also collide heavy (lead) ions with an energy of 2.8 TeV per nucleon and a peak luminosity of $5.1 \times 10^{27} \text{ cm}^{-2}\text{s}^{-1}$.

Figure 3.1 shows an overall view of the LHC experiments. The LHC was installed in the existing 26.7 km tunnel that was originally constructed for the LEP machine[23]. The tunnel lies between 45 m and 170 m below the surface on a plane inclined at a slope of 1.4 %. The LHC uses superconducting magnets to bend the beams and the nominal field is 8.33 T, corresponding to an energy of 7 TeV.

²recorded at the ATLAS detector up to the end of year 2011

³at the ATLAS detector

There are four main experiments going on at the LHC. ATLAS (described in the next section) and CMS [24] are general-purpose detectors for studying mainly proton-proton collisions of the LHC at the highest luminosity and at the maximum center-of-mass energy. The LHCb [25] experiment is for B-physics in proton-proton collisions and requires a lower luminosity of $L = 10^{32} \text{ cm}^{-2}\text{s}^{-1}$. ALICE [26] is the dedicated experiment for heavy ion collisions.

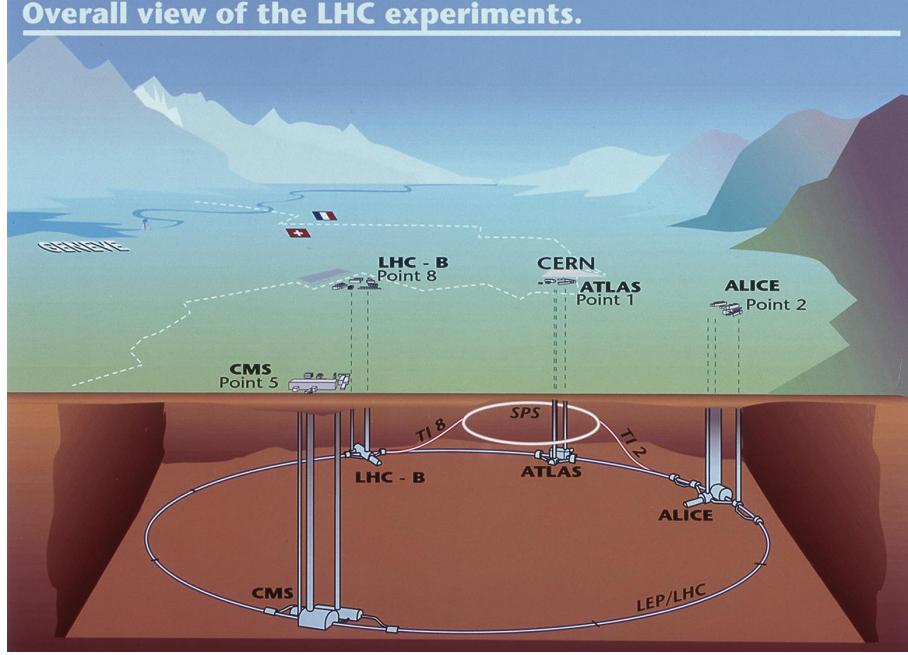


Figure 3.1: The overall view of LHC experiments.

3.2 ATLAS detector

The ATLAS (acronym of A Toroidal LHC ApparatuS) experiment [27, 28, 29] is a general-purpose detector at the LHC. It was designed by the needs to accommodate a wide spectrum of possible physics signatures.

3.2.1 Coordinate system

The coordinate system used in this thesis is summarized here.

The beam direction defines the z -axis and the x - y plane is transverse to the beam direction. The positive x -axis is defined as pointing from the interaction point to the center of the LHC ring and the positive y -axis is defined as pointing upwards. Side-A of the detector is defined as that with positive z and side-C is that with negative z . The azimuthal angle ϕ is measured around the beam axis, and the polar angle θ is the

angle from the beam axis. The pseudorapidity is defined as

$$\eta = -\ln \tan \left(\frac{\theta}{2} \right). \quad (3.1)$$

In case of massive objects such as jets, the rapidity y ,

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

is used. The transverse momentum p_T , the transverse energy E_T , and the missing transverse energy (or momentum) E_T^{miss} are defined in the x - y plane unless stated otherwise. The distance ΔR in the pseudorapidity-azimuthal angle space is defined as

$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}. \quad (3.3)$$

These are shown in Figure 3.2.

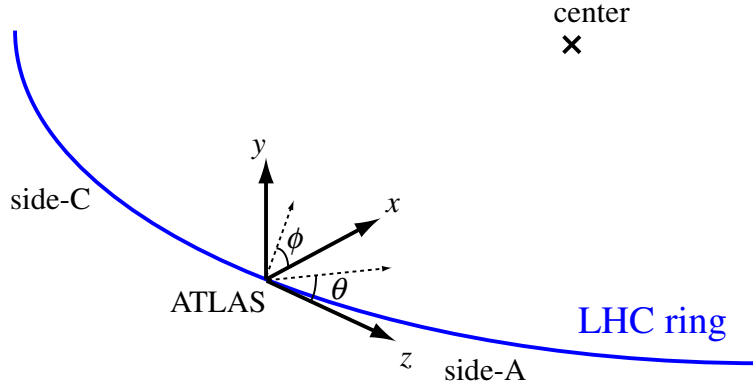


Figure 3.2: The coordinate system of the ATLAS detector

3.2.2 Magnet system

The ATLAS magnet system consists of four superconducting magnets. One is a solenoid and the other three are toroids (one in barrel and two in end-caps).

A solenoid is aligned on the beam axis and provides a 2 T axial magnetic field for the inner detector. The layout of the solenoid magnet is designed to keep the material thickness in front of the calorimeter as low as possible for better calorimeter performance. For this requirement, the solenoid windings and LAr calorimeter share a common vacuum vessel to eliminate two vacuum walls. The single-layer coil is wound with a high-strength Al-stabilized NbTi conductor to achieve a high field while optimizing thickness. The inner and outer diameters of the solenoid are 2.46 m and 2.56 m and its axial length is 5.8 m. The flux is returned by the steel of the ATLAS hadronic calorimeter and its girder structure as shown in Figure 3.3. The solenoid assembly contributes a total of ~ 0.66 radiation length at normal incidence [30].

A barrel toroid and two end-cap toroids produce a toroidal magnetic field of approximately 0.5 T and 1 T for the muon detectors in the central and end-cap regions, respectively. Figure 3.3 shows the layout. The barrel toroid consists of eight coils encased in individual racetrack-shaped, stainless-steel vacuum vessels. The coil assembly is supported by eight inner and outer rings of struts. The overall size of the barrel toroid system is 25.3 m in length, with inner and outer diameters of 9.4 m and 20.1 m, respectively. Each end-cap toroid consists of a single cold mass built up from eight flat, square coil units and eight keystone wedges, bolted and glued together into a rigid structure. The conductor and coil-winding technology is the same in the barrel and end-cap toroids. It is based on winding a pure Al-stabilized Nb/Ti/Cu conductor into pancake-shaped coils [31], followed by vacuum impregnation.

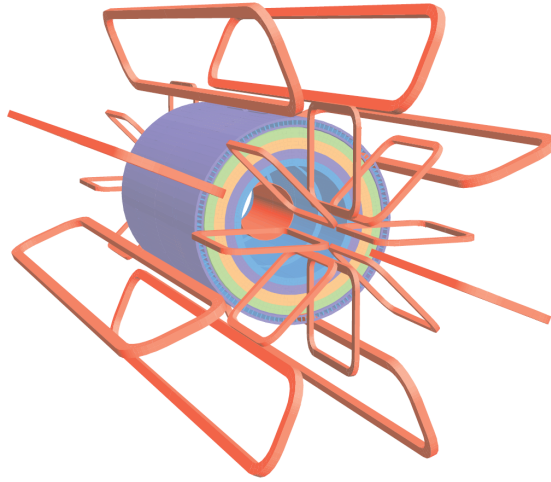


Figure 3.3: Geometry of magnet windings and tile calorimeter steel of the ATLAS detector [29]. The eight barrel toroid cells, with the end-cap coils interleaved are visible. The solenoid windings lie inside the calorimeter volume. The tile calorimeter consists of four layers with different magnetic properties, plus an outside return yoke.

3.2.3 Tracking system

For the precise measurement of tracks of charged particle tracks, three types of detectors are used: pixel and silicon micro-strip trackers (or SemiConductor Tracker:SCT), and the straw tubes of the Transition Radiation Tracker (TRT). The layout of these Inner Detectors (IDs) are illustrated in Figure 3.4.

The IDs are immersed in a 2 T magnetic field generated by the central solenoid. The precision tracking detectors (pixels and SCT) cover the region $|\eta| < 2.5$. In the barrel region, they are arranged in concentric cylinders around the beam axis while in the end-cap regions they are located on disks perpendicular to the beam axis.

The pixel detector is located in the innermost layer just 5 cm from the nominal beam axis. It consists of 1744 silicon pixel modules. All pixel sensors are identical and

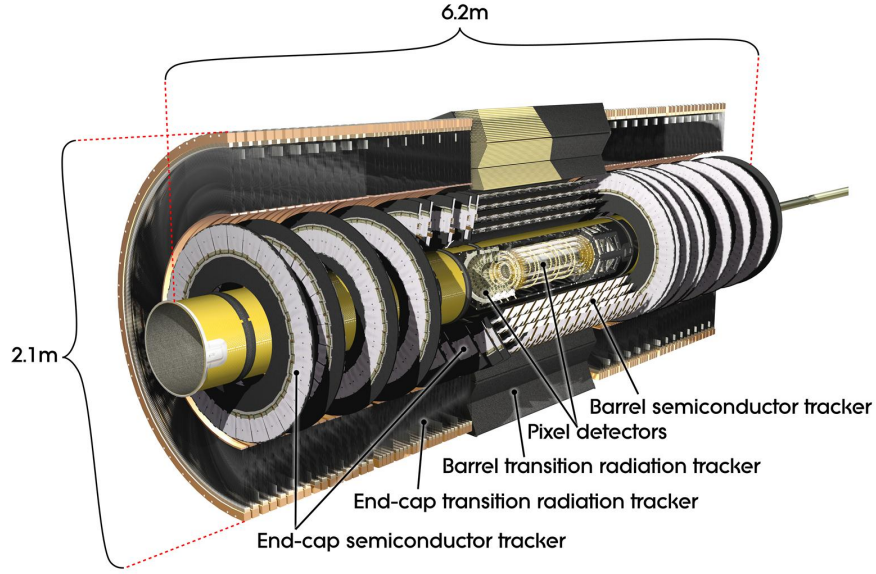


Figure 3.4: Cut-away view of the ATLAS inner detector [29].

have a minimum pixel size of $50 \times 400 \mu\text{m}^2$. The intrinsic resolution in the barrel are $10 \mu\text{m}$ (r - ϕ) and $115 \mu\text{m}$ (z) and in the end-cap disks are $10 \mu\text{m}$ (r - ϕ) and $115 \mu\text{m}$ (r).

The SCT modules are built from two pairs of single-sided silicon micro-strip sensors. Each side of a detector module consists of two 6.4 cm long, daisy-chained sensors with a mean strip pitch of $80 \mu\text{m}$. Two layers of sensors are rotated by $\pm 20 \text{ mrad}$ around the geometrical center as seen in Figure 3.5. This layout enables the measurement of two-dimensional coordinates. In the barrel, one set of strips in each layer is set to parallel to the beam direction, measuring the r - ϕ coordinate. In the end-cap region, the detectors have a set of strips running radially. The intrinsic resolutions per module in the barrel are $17 \mu\text{m}$ (r - ϕ) and $580 \mu\text{m}$ (z) and in the end-cap disks are $17 \mu\text{m}$ (r - ϕ) and $580 \mu\text{m}$ (r).

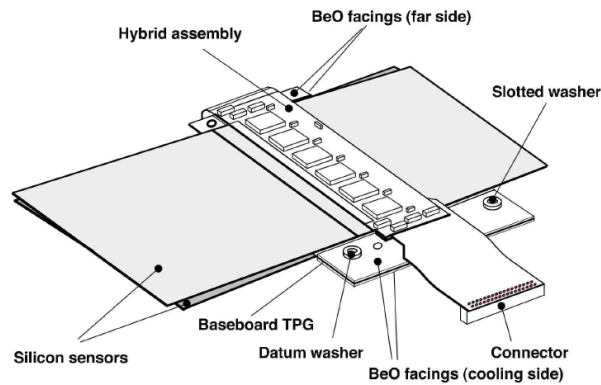


Figure 3.5: Drawing of a SCT module in the barrel, showing its components [29].

The TRT is the outermost and largest of the ID subdetectors. The TRT consists of 4 mm diameter straw tubes which cover up to $|\eta| = 2.0$ and provides r - ϕ information only. Its intrinsic accuracy is 130 μm per straw.

Table 3.2 shows the main parameters of the inner detectors.

Table 3.2: Summary of the main parameters of the three ATLAS inner detectors.

	Radius [cm]	Element size	Resolution	Hits/track in the barrel	Readout channels
Pixel	5 - 12	$50\ \mu\text{m} \times 400\ \mu\text{m}$	$10\ \mu\text{m} \times 115\ \mu\text{m}$	3	80×10^6
SCT	30 - 52	$80\ \mu\text{m}$	$17\ \mu\text{m}$	8	6×10^6
TRT	56 - 107	4 mm	$130\ \mu\text{m}$	30	3.5×10^5

Figures 3.6 show the material distribution measured by the radiation length (X_0) and the nuclear interaction length (λ) at the exit of the inner detector envelope.

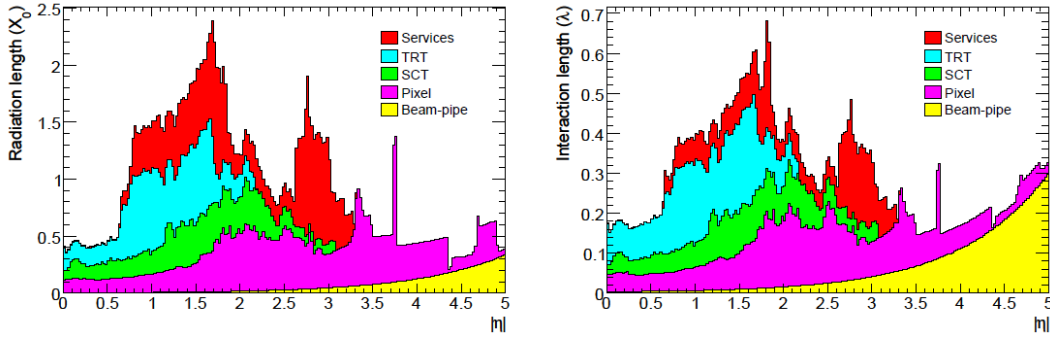


Figure 3.6: The material distributions measured by the radiation length (left) and the nuclear interaction length (right) at the exit of the inner detector envelope, including the services and thermal enclosures [29]. The distribution is shown as a function of $|\eta|$ and averaged over ϕ .

3.2.4 Calorimeter system

The ATLAS calorimeters cover the range $|\eta| < 4.9$. The electromagnetic (EM) calorimeter with fine granularity is used for the precise measurement of electrons and photons. The hadron calorimeter with coarser granularity is sufficient for jet reconstruction and $E_{\text{T}}^{\text{miss}}$ measurement. Figure 3.7 shows the ATLAS calorimeter system.

EM calorimeter

The EM calorimeter is divided into a barrel part ($|\eta| < 1.475$) and two end-cap parts ($1.375 < |\eta| < 3.2$). The EM calorimeter is lead-LAr detector with accordion-shaped

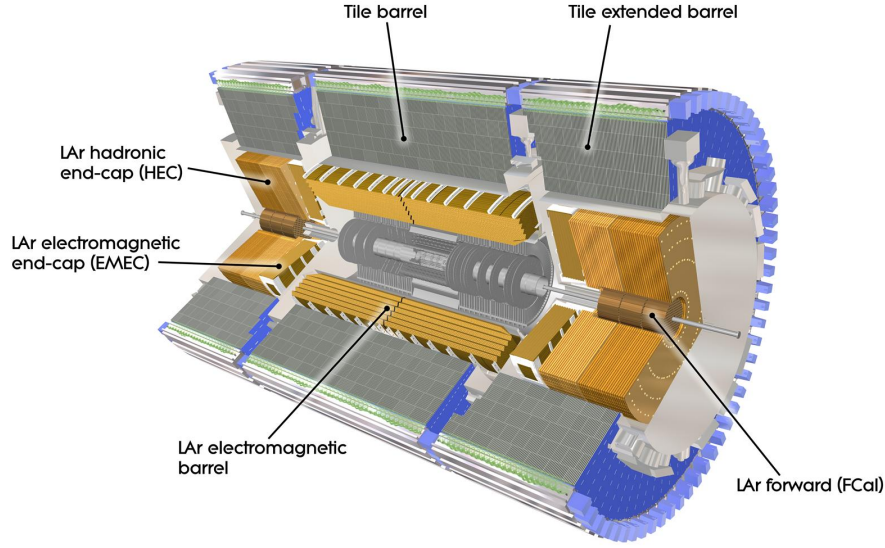


Figure 3.7: Cut-away view of the ATLAS calorimeter system [29].

kapton electrodes and lead absorber plates over its full coverage. Due to the accordion-shape, it provides complete azimuthal coverage without cracks. Figure 3.8 shows a sketch of the EM calorimeter in the barrel region. In the barrel, the accordion waves are axial and run in ϕ , and the folding angles of waves varying with radius to keep the liquid-argon gap constant. In the end-gaps, the waves are parallel to the radial direction and run axially.

As seen in Figure 3.8, the EM calorimeter is constructed from three layers in the radial direction (in most of η range). The first layer is finely segmented along η . The second layer has coarser granularity but it collects the largest fraction of the energy of the electromagnetic shower. The third layer collects only the tails of the electromagnetic shower and is therefore less segmented in η . Table 3.3 summarizes the parameters of the EM calorimeter.

In the region $|\eta| < 1.8$ a presampler detector is placed, consisting of an active LAr layer of thickness 1.1 cm (0.5 cm) in the barrel (end-cap) region. It corrects the energy lost by electrons and photons upstream of the calorimeter.

Figures 3.9 show the cumulative amounts of material in units of radiation length X_0 and as a function of $|\eta|$, in front of and in the electromagnetic calorimeters.

Hadronic calorimeter

The ATLAS hadronic calorimeter consists of three types of detectors described in the following. They cover different η ranges and have granularity suited to each of the regions. The granularity and covered ranges for the hadronic calorimeters are shown in Table 3.3.

Figure 3.10 shows the cumulative amount of material in units of interaction length,

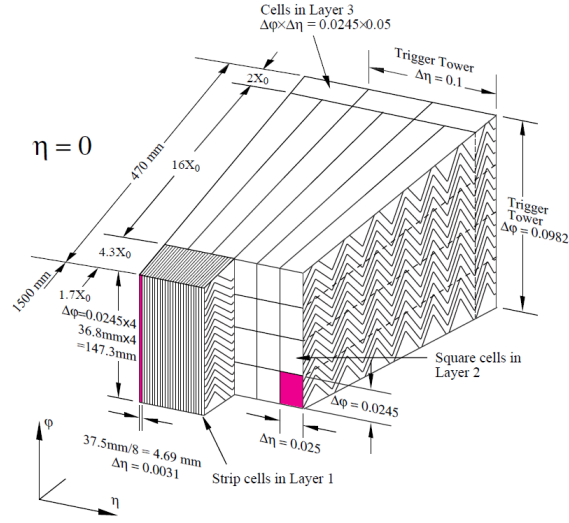


Figure 3.8: Sketch of a barrel module of the LAr EM calorimeter where the different layers are visible with the ganging of electrodes in ϕ [29].

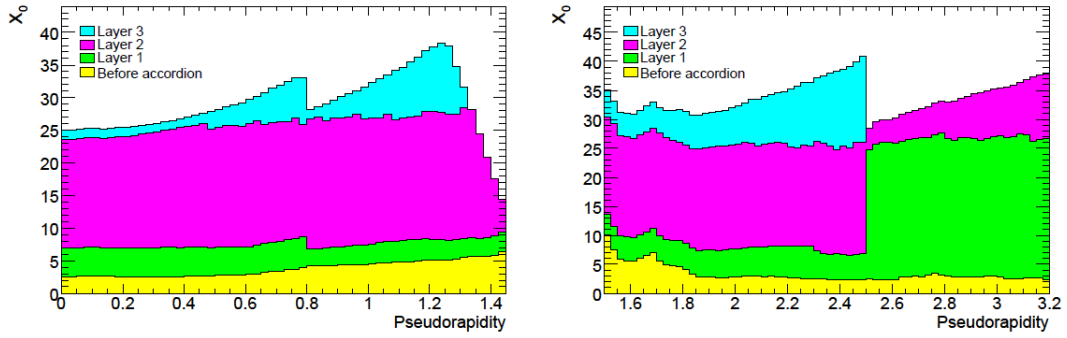


Figure 3.9: Cumulative mounts of material in units of radiation length X_0 and as a function of $|\eta|$, in front of and in the electromagnetic calorimeters [29]. The left figure shows the barrel and the right figure shows the end-cap.

Table 3.3: The main parameters of the ATLAS calorimeter system [29].

	Barrel			End-cap	
	Number of layers and $ \eta $ coverage				
EM presampler	1	$ \eta < 1.52$	1	$1.5 < \eta < 1.8$	
EM calorimeter	3	$ \eta < 1.35$	2	$1.375 < \eta < 1.5$	
	2	$1.35 < \eta < 1.475$	3	$1.5 < \eta < 2.5$	
			2	$2.5 < \eta < 3.2$	
LAr hadronic end-cap calorimeter			4	$1.5 < \eta < 3.2$	
LAr forward calorimeter			3	$3.1 < \eta < 4.9$	
Tile calorimeter	3	$ \eta < 1.0$	3	$0.8 < \eta < 1.7$	
	Granularity $\Delta\eta \times \Delta\phi$ in η range				
EM presampler	0.025×0.1	$ \eta < 1.52$	0.025×0.1	$1.5 < \eta < 1.8$	
EM calorimeter 1st layer	$0.025/8 \times 0.1$	$ \eta < 1.40$	0.050×0.1	$1.375 < \eta < 1.425$	
	0.025×0.025	$1.40 < \eta < 1.475$	0.025×0.1	$1.425 < \eta < 1.5$	
			$0.025/8 \times 0.1$	$1.5 < \eta < 1.8$	
			$0.025/6 \times 0.1$	$1.8 < \eta < 2.0$	
			$0.025/4 \times 0.1$	$2.0 < \eta < 2.4$	
			0.025×0.1	$2.4 < \eta < 2.5$	
			0.1×0.1	$2.5 < \eta < 3.2$	
EM calorimeter 2nd layer	0.025×0.025	$ \eta < 1.40$	0.050×0.025	$1.375 < \eta < 1.425$	
	0.075×0.025	$1.40 < \eta < 1.475$	0.025×0.025	$1.425 < \eta < 2.5$	
			0.1×0.1	$2.5 < \eta < 3.2$	
EM calorimeter 3rd layer	0.050×0.025	$ \eta < 1.35$	0.050×0.025	$1.5 < \eta < 2.5$	
LAr hadronic end-cap calorimeter			0.1×0.1	$1.5 < \eta < 2.5$	
			0.2×0.2	$2.5 < \eta < 3.2$	
LAr forward calorimeter 1st layer			3.0×2.6	$3.15 < \eta < 4.30$	
			0.75×0.65	$3.10 < \eta < 3.15$	
			0.75×0.65	$4.30 < \eta < 4.83$	
LAr forward calorimeter 2nd layer			3.3×4.2	$3.24 < \eta < 4.50$	
			0.825×1.05	$3.20 < \eta < 3.24$	
			0.825×1.05	$4.50 < \eta < 4.81$	
LAr forward calorimeter 3rd layer			5.4×4.7	$3.32 < \eta < 4.60$	
			1.35×1.175	$3.29 < \eta < 3.32$	
			1.35×1.175	$4.60 < \eta < 4.75$	
Tile calorimeter 1st, 2nd layer	0.1×0.1	$ \eta < 1.0$	0.1×0.1	$0.8 < \eta < 1.7$	
Tile calorimeter 3rd layer	0.2×0.1	$ \eta < 1.0$	0.2×0.1	$0.8 < \eta < 1.7$	

as a function of $|\eta|$, in front of the electromagnetic calorimeters, in the electromagnetic calorimeters themselves, in each hadronic calorimeter.

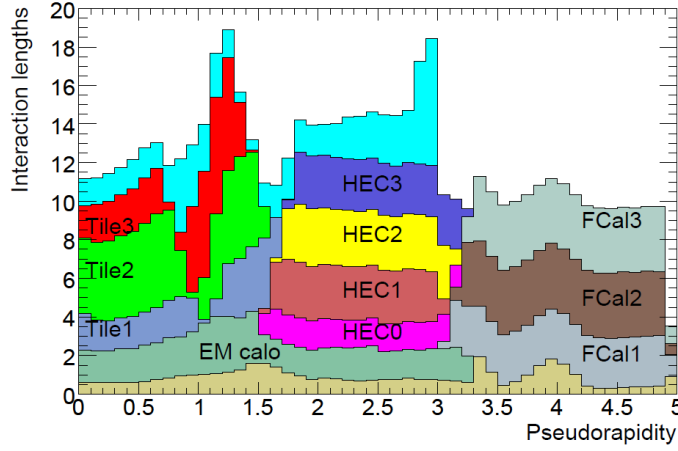


Figure 3.10: The cumulative amount of material in units of interaction length, as a function of $|\eta|$, in front of the electromagnetic calorimeters, in the electromagnetic calorimeters themselves, in each hadronic calorimeter [29]. The total amount of material in front of the first active layer of the muon spectrometer up to $|\eta| < 3.0$ is also shown by light-blue filled area.

Tile calorimeter The tile calorimeter is placed directly outside of the EM calorimeter in the central barrel region. The central barrel part covers the region $|\eta| < 1.0$ and two extended barrels cover $0.8 < |\eta| < 1.7$. This is a sampling calorimeter using 14 mm thick steel plates as the absorber and 3 mm thick scintillating tiles as the active material in one period. It is longitudinally segmented in three layers approximately 1.5, 4.1 and 1.8 interaction length thick for the barrel and 1.5, 2.6 and 3.3 interaction length for the extended barrel. Two sides of the scintillating tiles are read out by wavelength shifting fibers into two separate photomultiplier tubes.

LAr hadronic end-cap calorimeter The hadronic end-cap calorimeter (HEC) consists of two independent wheels in each end-cap, located behind the end-cap EM calorimeters. To reduce the drop in material density in the transition between the end-cap and the forward calorimeter around $|\eta| = 3.1$, the HEC extends out to $|\eta| = 3.2$. Also the HEC covers up to $|\eta| = 1.5$ in the barrel region and slightly overlaps with the barrel tile calorimeter which covers $|\eta| < 1.7$. Each wheel has four layers. The innermost layer is built from 25 mm parallel copper plates, while the outer layers use 50 mm copper plates, interleaved with 8.5 mm LAr gaps as the active medium for this sampling calorimeter.

LAr forward calorimeter The forward calorimeter (FCal) is integrated into the end-cap cryostats covering the range of $3.1 < |\eta| < 4.9$. The FCal is approximately

ten interaction lengths deep and consists of three modules in each end-cap. The first is made of copper optimized for electromagnetic measurements. The other two are made of tungsten for hadronic interaction measurements. The Liquid argon is also used as the sensitive medium. In order to reduce the amount of neutrons reflected into the inner detector cavity, the front face of the FCal is recessed by about 1.2 m with respect to the EM calorimeter front face. To compensate it, the density of the detector is raised.

3.2.5 Muon system

The ATLAS muon system measures the muon momentum using the magnetic deflection of muon tracks in the superconducting air-core toroid magnets. Over the range $|\eta| < 1.4$, magnetic bending is provided by the barrel toroid. For $1.6 < |\eta| < 2.7$, muon tracks are bent by the two end-cap magnets inserted into both ends of the barrel toroid. Between these regions, $1.4 < |\eta| < 1.6$, the magnetic field is provided by a combination of barrel and end-cap magnets.

For the measurement of muon hit positions, four types of muon chambers are used. Figure 3.11 shows the layout of the muon system.

Monitored Drift Tubes (MDT's) measure the track coordinates precisely in the range $|\eta| < 2.7$ except for the innermost plane ($|\eta| < 2.0$ in the innermost plane). These chambers consist of three to eight layers of drift tubes, which achieve an average resolution of $80 \mu\text{m}$ per tube, or about $35 \mu\text{m}$ per chamber. In the center of the detector ($|\eta| \approx 0$), a gap in chamber coverage has been left open to allow the gap varies from sector to sector depending on the service necessities.

Cathode Strip Chambers (CSC's), which are multiwire proportional chambers with cathodes segmented into strips, are used in the innermost plane $2.0 < |\eta| < 2.7$ for additional precise coordinate measurement. The resolution of chamber is $40 \mu\text{m}$ in the bending plane and about 5 mm in the transverse plane. The difference in resolution is due to the different readout pitch.

The muon trigger system consists of Resistive Plate Chambers (RPC's) and Thin Gap Chambers (TGC's) covering $|\eta| < 1.0$ and $1.05 < |\eta| < 2.4$ respectively.

RPC's consist of three concentric cylindrical layers around the beam axis, referred to as the three trigger stations. The large lever arm between inner and outer stations permits the trigger to select high momentum tracks in the range of $p_T = 9\text{-}35 \text{ GeV}$, while the two inner chambers provide the low- p_T trigger in the range $6\text{-}9 \text{ GeV}$. Each station further consists of two independent detector layers, each measuring η and ϕ .

TGC's are multi-wire proportional chambers with the wire-to-wire distance of 1.8 mm. TGC's are also used to determine azimuthal coordinate to complement the measurement of the MDT's in the bending direction.

3.2.6 Trigger system

The ATLAS experiment is designed to receive data at a rate of around 40 MHz but the data acquisition system can only commit data to permanent storage at the rate of a few hundred Hz. To select 'interesting' data from the large number of incoming

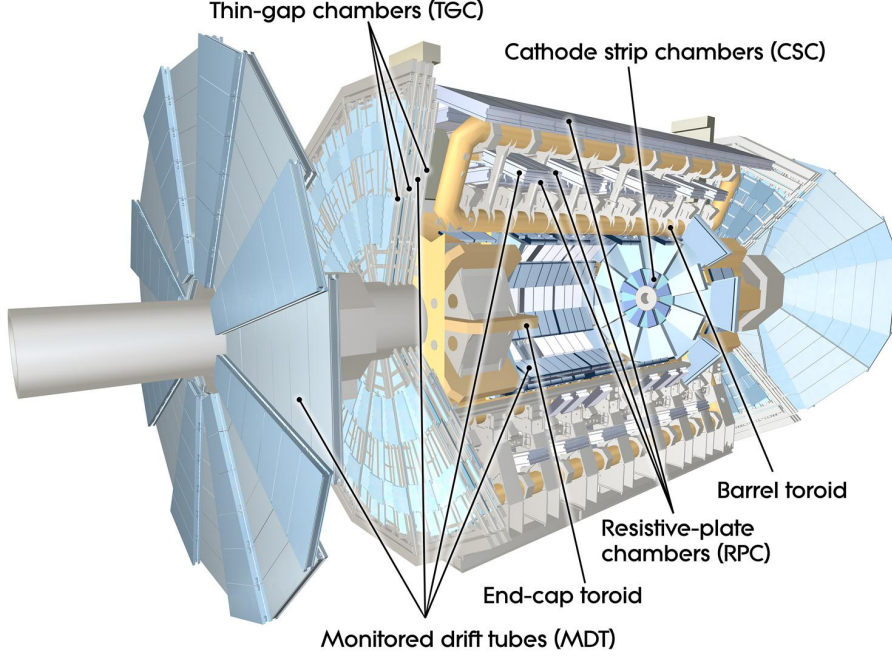


Figure 3.11: Cut-away view of the ATLAS muon system [29].

events, the ATLAS trigger system is divided into three levels, Level 1 (L1), Level 2 (L2) and the event filter (EF).

The L1 trigger searches for high transverse-momentum muons, electrons, photons, jets, τ -leptons decaying into hadrons, large missing and total transverse energy. In each event, the L1 trigger defines one or more Regions-of-Interest (RoI) which is the geographical coordinate in η and ϕ where the detector identified interesting features. The maximum L1 accept rate which the detector readout systems can handle is 75 kHz and the L1 decision must reach the front-end electronics within $2.5 \mu\text{s}$ after the bunch-crossing with which it is associated.

The L2 trigger is seeded by the RoI information provided by the L1 trigger to limit the amount of data which must be transferred from the detector readout. The L2 is designed to reduce the trigger rate to approximately 3.5 kHz within an event processing time of about 40 ms on average.

The final stage of the event selection, the EF trigger reduces the event rate to roughly 200 Hz. Its selections are implemented using offline analysis software.

Prescale

For the physics analysis, the events collected by the raw trigger rates are used. With the increase of the luminosity, to keep the trigger rates the same, the thresholds of kinematics need to be raised. However, for studies of physics objects or triggers, soft events with high rates must also be collected. To trigger on such events given the limited trigger bandwidth, only a fraction of such events can be collected by the

triggers. The reciprocal of this fraction is called the *prescale*.

The whole trigger system can operate with prescales and each individual trigger chain can be scaled to match the desired content of the final data sample. Trigger for which no prescale is applied as referred to as an *unprescaled* trigger.

3.2.7 Luminosity detectors

Two primary detectors are used to measure bunch-by-bunch luminosity.

The LUCID (Luminosity measurement using a Cerenkov Integrating Detectors) are located on the each side of the interaction point (IP) at a distance of 17 m, covering the pseudorapidity range $5.6 < |\eta| < 6.0$. The LUCID are made of aluminum tubes filled with C_4F_{10} gas and surrounds the beampipe as shown in Figure 3.12 (left). It can measure the integrated luminosity and provide online monitoring of the instantaneous luminosity and beam conditions.

The Beam Conditions Monitor (BCM) consists of four small diamond sensors on each side of the ATLAS IP arranged around the beampipe in a cross pattern. It is located at $z = \pm 184$ cm and $r = 5.5$ cm, which corresponds to a $|\eta| = 4.2$. Figure 3.12 (right) shows the installed BCM. The BCM is a fast device primarily designed to monitor background levels and issue a beam-abort request in case beam losses start to risk damage to ATLAS detectors.

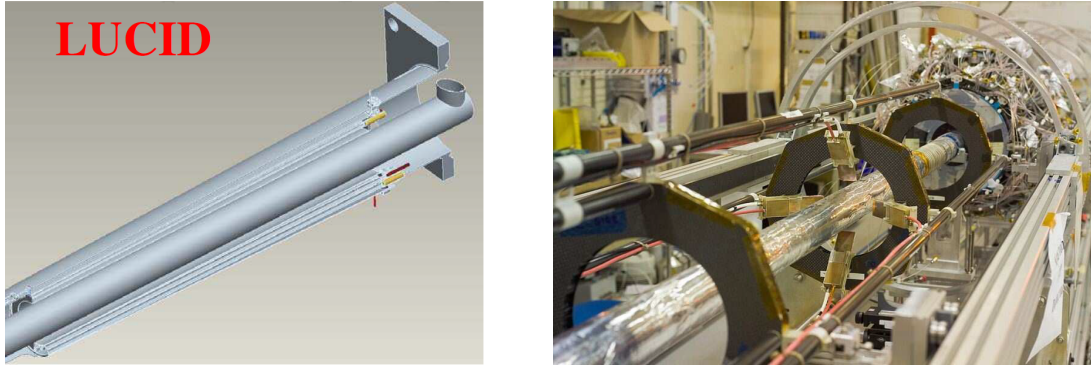


Figure 3.12: The cut-away view of the LUCID detector (left) and close-up view of one BCM station installed at 184 cm from the center of the pixel detector.

Chapter 4

Data and Monte Carlo Simulation

4.1 Data samples

With the ATLAS detector, 5.25 fb^{-1} of proton-proton collisions at $\sqrt{s} = 7 \text{ TeV}$ were recorded in 2011. Figure 4.1 shows the cumulative luminosity versus day/month. The analysis presented in this thesis is based on a sample of proton-proton collisions at $\sqrt{s} = 7 \text{ TeV}$ delivered by the LHC and collected by the ATLAS experiment between 22 March and 22 August 2011. Only data collected during stable beam periods in which all sub-detectors were fully operational are used. The total integrated luminosity is about 2.05 fb^{-1} .

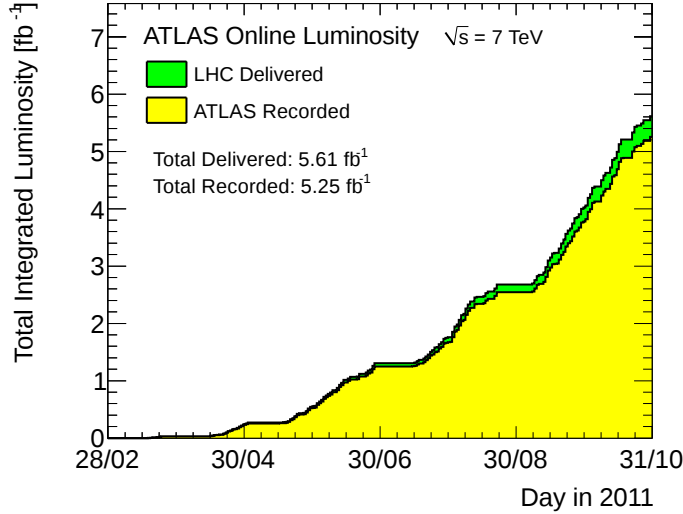


Figure 4.1: Cumulative luminosity versus day/month delivered to (green) and recorded by the ATLAS detector (yellow) during stable beams of p - p collisions at the center-of-mass energy of 7 TeV in 2011 [32].

4.1.1 Luminosity measurement

The general method for calibrating the ATLAS luminosity scale is based on *van der Meer* (*vdM*) scans (also called *beam-separation* or *luminosity* scans) [33].

The luminosity of p - p collider can be expressed as

$$\mathcal{L} = \frac{\mu n_b f_r}{\sigma_{\text{inel}}} \quad (4.1)$$

where μ is the average number of inelastic interactions per bunch crossing, n_b is the number of colliding bunch pairs, f_r is the machine revolution frequency, and σ_{inel} is the p - p inelastic cross-section.

ATLAS monitors the delivered luminosity by measuring the observed interaction rate per crossing μ_{vis} independently with a variety of detectors and using several different algorithms. The total luminosity can be written as

$$\mathcal{L} = \frac{\mu_{\text{vis}} n_b f_r}{\sigma_{\text{vis}}} \quad (4.2)$$

where $\sigma_{\text{vis}} = \epsilon \sigma_{\text{inel}}$ is the total inelastic cross-section multiplied by the efficiency ϵ of a particular detector and algorithm.

The calibration of σ_{vis} is performed using dedicated *vdM* scans where the absolute luminosity can be inferred from direct measurements of machine parameters. The delivered luminosity can be written as

$$\mathcal{L} = \frac{n_b f_r n_1 n_2}{2\pi \Sigma_x \Sigma_y} \quad (4.3)$$

where n_1 and n_2 are the bunch populations (protons per bunch) in beam 1 and beam 2 respectively, and Σ_x and Σ_y characterize the horizontal and vertical profiles of the colliding beams. In a *vdM* scan, the beams are separated by steps of a known distance which allows a direct measurement of Σ_x and Σ_y . Combining this with an external measurement of the bunch charge product $n_1 n_2$ provides a direct determination of the luminosity when the beams are unseparated. By comparing this peak luminosity to the peak interaction rate $\mu_{\text{vis}}^{\text{MAX}}$ observed by a given detector and algorithm during the *vdM* scan, a determination of σ_{vis} can be made according to

$$\sigma_{\text{vis}} = \mu_{\text{vis}}^{\text{MAX}} \frac{2\pi \Sigma_x \Sigma_y}{n_1 n_2}. \quad (4.4)$$

Two *vdM* scans have been performed to derive calibrations for the LUCID and BCM detectors. The total relative uncertainty on the luminosity measurement of ATLAS in the 2011 data sample is measured to be 3.7 % [34]. The dominant systematic uncertainty on the luminosity calibration is the determination of the bunch charge product, which is represented by $n_1 n_2$ in Equation 4.4. This uncertainty is measured to be 3.1 % [35].

4.2 Monte Carlo simulation

In this section Monte Carlo (MC) samples used in this thesis are described. The MC samples are produced using the ATLAS MC10b parameter tune [36, 37] and a GEANT4 [38] based detector simulation.

The energy deposited by particles in the active detector material is converted into detector signals in the same format as the detector read-out. The MC generated events are processed through the trigger simulation package of the experiment and are reconstructed with the same software as for the real data.

4.2.1 Standard Model process

Table 4.1 shows the SM process with cross-sections in the proton-proton collision at the center-of-mass energy of 7 TeV. The detail of each process will be shown in this section.

Table 4.1: The Standard Model processes with cross-sections times branching ratio. Generators mainly used for each process are also shown.

Production process	$\sigma \times \text{BR}$ (perturbative order)	Generator
QCD di-jet ($\hat{p}_T > 8$ GeV)	11 mb (LO)	PYTHIA
$W(\rightarrow l\nu)+\text{jets}$	31.5 nb (NNLO)	ALPGEN with HERWIG+JIMMY
$Z(\rightarrow \nu\bar{\nu})+\text{jets}$	5.92 nb (NNLO)	ALPGEN with HERWIG+JIMMY
$Z/\gamma^*(\rightarrow l^+l^-)+\text{jets}$ ($M_{ll} > 10$ GeV)	12.0 nb (NNLO)	ALPGEN with HERWIG+JIMMY
Di-boson (WW, WZ, ZZ)	104 pb (NLO)	HERWIG
$t\bar{t}$	164.6 pb (NLO+NLL)	MC@NLO with HERWIG+JIMMY
single t	85.0 pb (NLO+NLL)	MC@NLO with HERWIG+JIMMY
$t\bar{t} + b\bar{b}$	0.9 pb (LO)	ALPGEN with HERWIG+JIMMY
$t\bar{t} + W/Z$	0.4 pb (LO)	MADGRAPH with PYTHIA

QCD di-jet

QCD di-jet events are generated with PYTHIA 6.4.21 [39]. MRST2007LO* modified leading-order (LO) PDFs [40] are used. PYTHIA simulates non-diffractive collisions in $2 \rightarrow 2$ scattering processes using a matrix-element (ME) plus parton shower model in a leading log approximation. Hadronization, fragmentation and underlying event are also modeled and simulated with PYTHIA.

Top pair and single top

Productions of top quark pair and single top quark are simulated with MC@NLO [41, 42] in which a top quark mass of 172.5 GeV and the next-to-leading order (NLO) PDF CTEQ6.6 [43] are used. Figures 4.2 show Feynman diagrams of single-top quark

production processes. Fragmentation and hadronization are performed with HERWIG [44, 45] using JIMMY [46] for the underlying event.

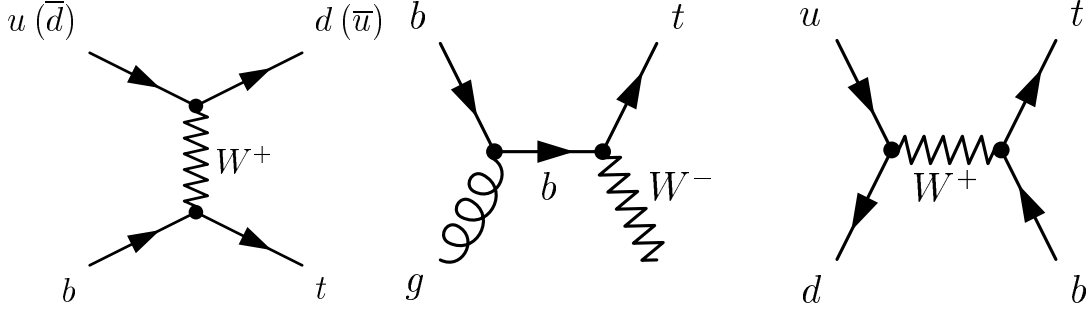


Figure 4.2: Feynman diagrams of single-top quark production process. The left shows t -channel production, the center shows associated Wt production and the right shows s -channel production.

The total cross-section of top pair production is normalized to $164.6^{+11.4}_{-15.7}$ pb which is calculated at approximately NNLO precision and the scale uncertainty (the renormalization and the factorization scales) and the PDF uncertainty are considered [47, 48]. The cross-sections of single top quark production processes are given in Table 4.2

Table 4.2: Cross-sections of single top quark production processes, shown with the uncertainty [49, 50, 51].

process	cross-section [pb]
t -channel	$64.57^{+2.71}_{-2.01}$
$W + t$	$15.74^{+1.06}_{-1.08}$
s -channel	$4.63^{+0.19}_{-0.17}$

W and Z/γ^*

Samples of W and Z/γ^* production with accompanying jets are produced with ALPGEN [52]. HERWIG plus JIMMY is applied for fragmentation and hadronization. These samples are generated with different numbers of partons exclusively from zero to four and inclusively from five and above. The MLM [53] matching scheme which is implemented in ALPGEN is used to remove overlap between the the n and $n + 1$ parton samples from the matrix element (ME) and the parton shower.

Cross sections are normalized to NNLO calculations, following the strategy described in [54]. A theoretical uncertainty of 4 % is assigned to the inclusive W and Z +jets cross sections.

The systematic uncertainty on the MLM matching is studied in Reference [55] where it is found that the variations of the renormalization scale by a factor of $1/2$

downward and a factor of 2 upward from the default value change the cross-section ratios of $(n+1)/n$ inclusive jet rate for ALPGEN samples. For this uncertainty, 24 % is added in quadrature per parton. For an n parton process, the uncertainty is therefore becomes $\sqrt{N} \times 24$ %.

For W +jets production, associated production with b - and c -quarks are generated differently, by giving masses to b - and c -quarks. For Z +jets production, only associated production with b -quarks is generated differently. Overlap between heavy-flavor quarks that originate from ME production and those that originate from the parton shower is removed. For W +heavy-flavor jet production, a theoretical uncertainty of 17 % is assigned following Reference [56]. For Z +heavy-flavor jet production, a theoretical uncertainty of 15 % is assigned [57].

Di-boson

Samples of di-boson (WW , WZ , ZZ) production are produced with HERWIG. Their total cross sections are normalized to the NLO QCD prediction from the MCFM programs following Reference [54]. A 5 % uncertainty is assigned to the theoretical values of the cross-sections.

$t\bar{t} + b\bar{b}$

The process $t\bar{t}$ accompanying $b\bar{b}$ is produced by ALPGEN with HERWIG plus JIMMY. Its cross section is calculated at leading order only. Since no dedicated study has yet been performed for this process, an uncertainty of ± 100 % is assigned as the theoretical systematic uncertainty. The downward uncertainty -100 % is the most conservative value and the upward uncertainty $+100$ % is expected to be conservative enough because the ratio of the NLO to the LO cross-sections will not exceed 2 considering the calculation of the other SM processes.

$t\bar{t} + W, Z$

The process $t\bar{t}$ accompanying W or Z is produced by MADGRAPH [58] interfaced with PYTHIA. The cross-sections are calculated at leading order. Again, since no dedicated study has been performed for these processes, an uncertainty of ± 100 % is assigned as the theoretical systematic uncertainty for the conservative estimate.

4.2.2 SUSY signals

SUSY signals are generated as follows.

1. Generate mass spectrum using ISAJET v7.80 [59] or SUSYHIT [60].
2. Pass the spectrum to HERWIG++ [61] v2.4.2 and generate the event. LO PDF set MRST2007LO* is used.
3. Signal cross-sections are obtained in next-to-leading (NLO) order calculations using PROSPINO [18, 17] v2.1.

SUSY signal yield uncertainty

As theoretical uncertainties on the SUSY signal cross sections, the following sources are considered.

- Renormalization and factorization scale : Since the calculated cross sections depend on the choice of renormalization and factorization scales μ_R and μ_F , the variations of them become the systematic uncertainty.

The central value of the cross-section is obtained by setting the scales equal to the average of the produced supersymmetric particle masses, $\mu_R = \mu_F = \mu$. The variation of cross section by varying μ downward $\mu/2$ and upward 2μ is considered to be the systematic uncertainty.

- Parton Distribution Function (PDF) : CTEQ6.6M PDF sets [43] are used to estimate the uncertainty of the parton distribution functions of the five lightest quarks/anti-quarks and the gluons. The PDF sets come with 44 error sets (22 eigenvectors times up and down variations). The uncertainty due to the PDFs are calculated by the so-called symmetric Hessian method. Let $\sigma_{\text{PDF},i+/-}$ ($i = 1, \dots, N$) be cross-sections for the i -th PDF, + for the up and - for the down variations. The PDF uncertainty on the cross-section $\Delta\sigma_{\text{PDF}}$ is then given by

$$\Delta\sigma_{\text{PDF}} = \frac{0.5}{1.645} \sqrt{\sum_{i=1}^N (\sigma_{\text{PDF},i+} - \sigma_{\text{PDF},i-})^2}. \quad (4.5)$$

The denominator of 1.645 is to give a 68 % CL uncertainty instead of 90 % CL.

These uncertainties are summed in quadrature to give the total theoretical uncertainty,

$$\Delta\sigma_{\text{total}} = \sqrt{\Delta\sigma_{R/F}^2 + \Delta\sigma_{\text{PDF}}^2}, \quad (4.6)$$

where $\Delta\sigma_{R/F}$ is the uncertainty of renormalization/factorization scale.

4.3 Fast calorimeter simulation

For the simulation of the physics processes, a detailed description of the detector geometry and the simulation of particle interactions in the detector material with GEANT4 is essential. The drawback of such detailed simulation is a CPU time requirement of several minutes per event. This CPU time requirement is a challenge for the production of sufficiently large amount of Monte Carlo samples. Hence an accurate but fast detector simulation is useful.

Most of the CPU time more than 90 % is spent inside the calorimeter systems. The FastCaloSim [62] package provides a parametrized simulation of the particle energy response and of the energy distribution in the ATLAS calorimeter and reduce the calorimeter simulation time to a few seconds per event. The parametrization is based

on the GEANT4 simulations of single photons, electrons and charged pions in a fine grid of simulated particle energies and directions.

The combination of the FastCaloSim package and the full GEANT4 simulation of the inner detector and the muon system is called Atlfast-II.

4.3.1 Simplifications

For the fast simulation, the following simplifications are taken:

- The calorimeter cells are approximated by cuboids in η , ϕ and the depth of the calorimeter with larger size (forward calorimeter cells are cuboids in x , y and z).
- The simulation of the development of particle showers in the calorimeter is replaced by parametrizations. The fast simulation model reproduces the longitudinal shower properties, including fluctuations and correlations.
- Only three types of particles are parametrized and used for the simulation: photons, electrons and charged pions. The charged pions parametrization is used for all hadrons (neutral and charged).

4.3.2 Application

Usually, hundreds of signal points are required for a new physics model search as shown in Figure 7.8, 7.11 and so on. At the same time, large number of Monte Carlo simulated samples are needed for each point with the increase of the integrated luminosity at the LHC. The preparation of these signals with the full GEANT4 simulation are demanding. Fortunately, the discrepancy between the full GEANT4 simulation and the fast simulation is negligibly small compared to theoretical uncertainties on new physics model. Figures 4.3 show the distributions of the leading jet p_T and E_T^{miss} for the mSUGRA model with $m_0 = 1320$ GeV, $m_{1/2} = 340$ GeV, $\tan \beta = 40$, $A_0 = -500$ GeV and $\mu > 0$ comparing the full GEANT4 simulation and the fast calorimeter simulation. The fast calorimeter simulation reproduces well the distribution of full GEANT4 simulation.

Therefore, this fast simulation is widely used for the production of new physics models. The Monte Carlo simulation of supersymmetric models treated in this thesis are also produced with the fast simulation.

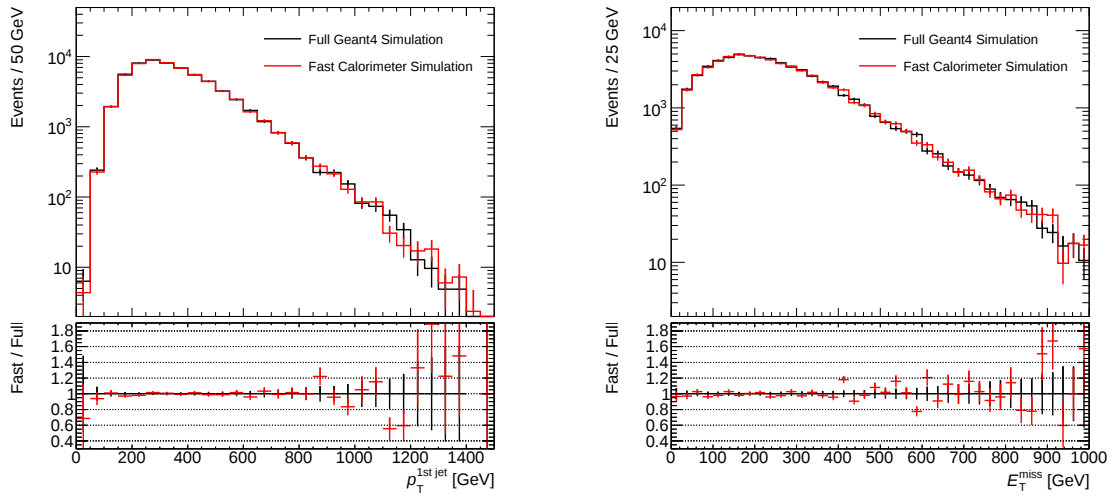


Figure 4.3: Comparison of the full GEANT4 simulation and fast calorimeter simulation with the leading jet p_T (left) and E_T^{miss} using the mSUGRA model with $m_0 = 1320$ GeV, $m_{1/2} = 340$ GeV, $\tan \beta = 40$, $A_0 = -500$ GeV and $\mu > 0$. The statistical error bars are shown. The ratio fast simulation/full simulation is shown at the bottom of the plots.

Chapter 5

Object Reconstruction and Definition

In this chapter, definition and methods of reconstruction for the physics objects used in the analyses are introduced.

5.1 Track

Track reconstruction in the ATLAS inner detector is performed in the following steps [63]. Charged particle tracks with $p_T > 0.4$ GeV and $|\eta| < 2.5$ are reconstructed from this algorithm.

1. Pre-processing stage

The raw data from the pixel and SCT detectors are converted into clusters and the TRT raw timing information is translated into calibrated drift circles. The SCT clusters are transformed into space-points, using a combination of the cluster information from back-to-back of a SCT module.

2. Track-finding stage

The default tracking uses the high granularity of the pixel and SCT detectors to find prompt tracks originating from the interaction region, following an “inside-out” pattern recognition algorithm. First, track seeds are formed from a combination of space-points in the three pixel layers and the first SCT layer. These seeds are then extended through the SCT to form track candidates.

Next, these candidates are fitted, the clusters with bad quality of the fit (called *outlier*) are removed, ambiguities in the cluster-to-track association are resolved, and fake tracks are rejected. Here, quality of refitted tracks

The selected tracks are then extended into the TRT to associate drift-circle information in a road around the extrapolation and to resolve the left-right ambiguities.

Finally, the extended tracks are refitted with the full information of all three detectors. The quality of the refitted tracks is compared to the silicon-only track candidates and hits on track extensions resulting in bad fits are labeled as outliers.

3. Post-processing stage

A dedicated vertex finder is used to reconstruct primary vertex candidates. This is followed by algorithms dedicated to the reconstruction of photon conversions and of secondary vertices.

5.2 Jet

5.2.1 Reconstruction

Jets (in a narrower sense, called calorimeter jets) are reconstructed in the following steps.

1. Clustering of calorimeter cells to build inputs for jets.
2. Running a jet finding algorithm with a full four-momentum recombination scheme, using the clusters of calorimeter cells.
3. Calibrating the reconstructed jets to the hadronic energy scale.

The details of each step are described in the following sections.

For the analyses described in this thesis, jets with $p_T > 20$ GeV (in the hadronic energy scale) and $|\eta| < 2.8$ are preselected.

5.2.2 Clustering of calorimeter cells

Clusters are built starting from seed calorimeter cells with a signal at least four times higher than the root-mean-square (RMS) of the noise distribution. Cells neighboring the seed which have a signal-to-RMS-noise ratio of two are then iteratively added. Finally, all nearest neighbor cells are added to the cluster without any energy threshold. These form three-dimensional topological clusters (*topo-clusters*). The cluster position is calculated using the energy weighted cell positions.

5.2.3 Jet finding algorithm

Jets are reconstructed using topo-clusters as an input to the jet finding algorithm anti- k_t [64] with a distance parameter of $R = 0.4$ using the FastJet software [65].

In the algorithm, one defines distances d_{ij} between entities i and j and d_{iB} between entity i and the beam (B). The clustering proceeds by identifying the smallest of the distances and if it is a d_{ij} recombining entities i and j , while if it is d_{iB} , calling entity i a jet and removing it from the list of entities. The distances are recalculated and the procedure is repeated until no entities are left.

These distances are defined as follows:

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2}, \quad (5.1)$$

$$d_{iB} = k_{ti}^{2p} \quad (5.2)$$

where $\Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$ and k_{ti} , y_i and ϕ_i are the transverse momentum, rapidity and azimuthal angle of entity i , respectively. R is a distance parameter and p is a parameter to govern the relative power of the energy versus geometrical (Δ_{ij}) scales. In the anti- k_t algorithm, $p = -1$ is adopted, therefore it is referred as the “anti- k_t ” jet clustering algorithm.

There are other jet finding algorithms which use different p parameters. The k_t algorithm [66, 67] uses $p = 1$ and the Cambridge/Aachen algorithm [68, 69] uses $p = 0$. Since the anti- k_t algorithm has several advantages over these algorithms [64], it is adopted as the default jet reconstruction in ATLAS.

5.2.4 Calibration

Jets are reconstructed using calorimeter clusters at the electromagnetic (EM) scale. This EM energy scale is calibrated based on the energy deposit in the calorimeter by electromagnetic showers. This energy scale is established using test-beam measurements for electrons in the barrel and end-cap calorimeters [70, 71].

The final jet energy is obtained by applying corrections for hadronic energy scale as well as energy losses in the dead material. The correction is derived from Monte Carlo simulations that restore the calorimeter response of the reconstructed jet to the true jet response [72].

For this purpose, *truth jets* (or particle jets) are defined in MC simulations. They are built from stable particles produced by the fragmentation model in the physics generator. In ATLAS, stable particles are defined as those with the lifetime of 10 picoseconds or more in the laboratory frame. Typically they include electrons, muons, photons, charged pions, charged and neutral kaons, protons, neutrons, neutrinos and their corresponding antiparticles. Neutrinos and muons are excluded from the truth-jet reconstruction, since they are almost invisible in the calorimeter. The same jet finding algorithm is applied for interacting stable particles to reconstruct truth jets.

The uncertainty for the jet energy scale (JES) is determined from the measurements of calorimeter response to single hadrons and from the comparison of the jet response of the ATLAS detector in Monte Carlo simulation samples with systematic variations. Figures 5.1 show the overall jet energy scale uncertainty for anti- k_t jets with a distance parameter of $R = 0.6$ as a function of jet p_T . The size of the JES uncertainty for anti- k_t jets with a distance parameter $R = 0.4$ is similar to that of jets shown in Figures 5.1.

The jet energy calibration was tested in-situ, using a well calibrated object as a reference and comparing data to the PYTHIA Monte Carlo simulation: direct transverse momentum balance between a jet and a photon [73], photon balance using the missing transverse momentum projection [73], balance between a high- p_T jet recoiling against one or more lower- p_T jets [74], and finally by comparison of jet calorimeter energy to

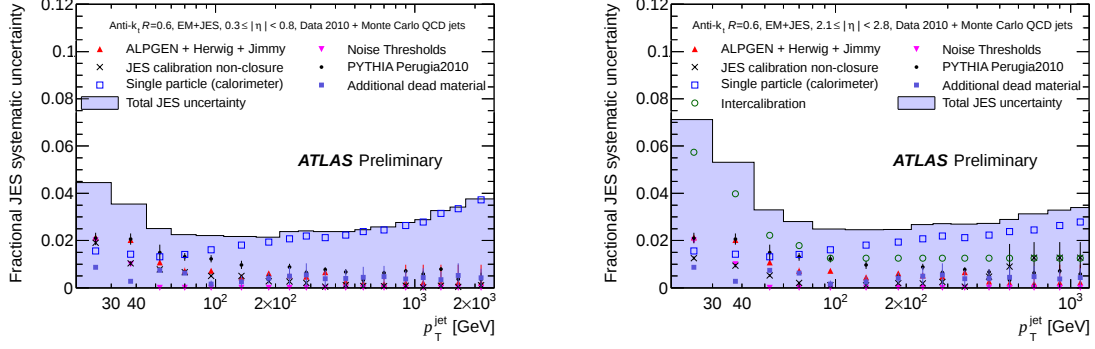


Figure 5.1: Relative jet energy scale systematic uncertainty as a function of jet p_T for jets in the region $0.3 < |\eta| < 0.8$ in the calorimeter barrel (left) and in the region $2.1 < |\eta| < 2.8$ in the end-cap calorimeter (right) [72]. The total uncertainty is shown as the solid light blue area. The individual sources are also shown, with statistical uncertainties when applicable.

the momentum carried by tracks associated to a jet [75]. Figure 5.2 shows the comparison of data to MC simulation for these in-situ measurements together with the JES uncertainty. These results support the estimate of the default jet energy calibration.

Close-by jet effects

In the JES calibration, *isolated* jets are used. Jets are classified as isolated if they fulfill the requirement of $R_{\min} > 2.5 \times R$ where $R_{\min} \equiv \sqrt{\Delta\eta_{\min}^2 + \Delta\phi_{\min}^2}$ is the distance from the jet to the closest jet in η and ϕ with $p_T > 7$ GeV at the EM energy scale, and R is the distance parameter used in the anti- k_t algorithm.

In this analysis, all jets are used, including non-isolated jets. Therefore the impact on the non-isolated jet energy scale due to close-by jets is evaluated as a function of $R_{\min}$ in Reference [76].

This evaluation uses the fact that the track-jet response is stable against the presence of close-by jets and has a much weaker $R_{\min}$ dependence than the calorimeter-jet response. Here, track-jets are reconstructed with the same jet algorithm as calorimeter-jets, but using tracks as an input. Track-jets are defined in detail in Reference [77]. This is because tracks have a better position and angular resolution than calorimeter clusters. This lead to a smaller energy transfer between two close jets when jets are reconstructed. Figures 5.3 show the calorimeter-jet response relative to the matched truth-jet and the track-jet response relative to the matched truth-jet as a function of truth-jet p_T .

The jet energy scale uncertainty for non-isolated jets is evaluated by the p_T ratio of the calorimeter-jet response relative to the matched track-jet $r = p_T^{\text{cal}}/p_T^{\text{track}}$. The relative difference of non-isolated jets ($R_{\min}$) with respect to that of isolated jets ($1.4 < R_{\min} < 1.5$) $r_{\text{non-iso}}/r_{\text{iso}}$ is then compared between data and MC simulations:

$$A_{\text{close-by}} = \frac{[r_{\text{non-iso}}/r_{\text{iso}}]_{\text{data}}}{[r_{\text{non-iso}}/r_{\text{iso}}]_{\text{MC}}}. \quad (5.3)$$

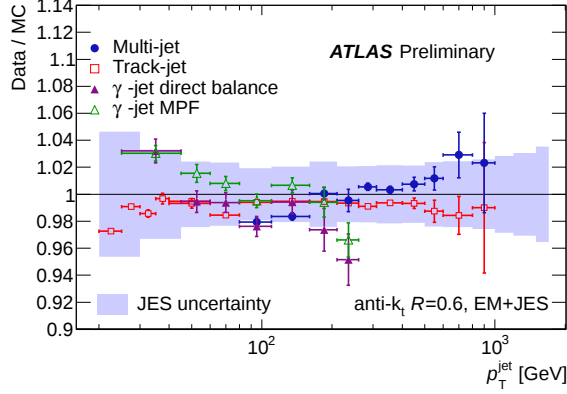


Figure 5.2: Jet energy scale uncertainty as a function of jet p_T for jets with $0 \leq |\eta| < 1.2$, showing the ratio of data to Monte Carlo simulation for several in-situ techniques that test the jet energy scale, exploiting photon jet balance (direct balance or using the missing transverse momentum projection technique), the balance of a leading jet with a recoil system of two or more jets at lower transverse momentum (multi-jet) or using the momentum measurement of tracks in jets [72].

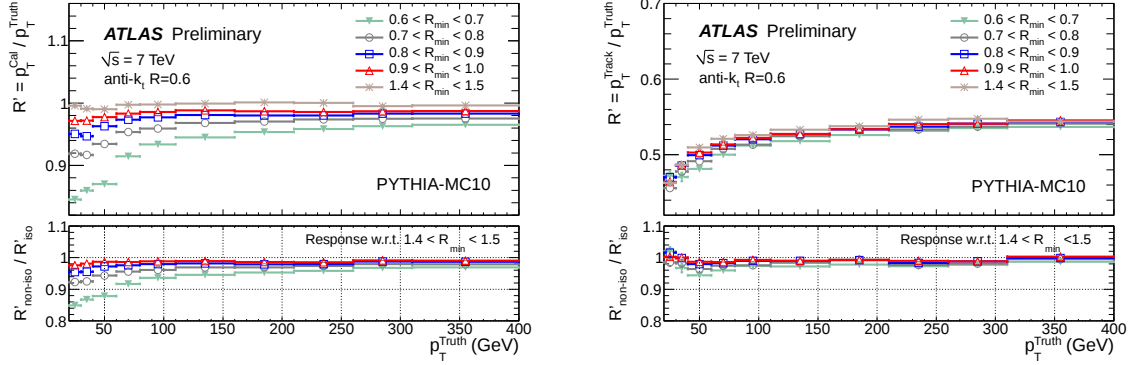


Figure 5.3: Ratio of calorimeter-jet p_T (left) and of track-jet p_T (right) to the matched truth-jet p_T as a function of truth-jet p_T for anti- k_t jets with $R = 0.6$ for different $R_{\min}$ values of jets [76]. The bottom part of the figures show the relative response of non-isolated jets with respect to that of isolated jets, obtained as the calorimeter- or track-jet response for $R_{\min} < 1.0$ divided by the jet response for $1.4 < R_{\min} < 1.5$.

Figure 5.4 shows $A_{\text{close-by}}$ as a function of calorimeter-jet p_T for anti- k_t jets with the distance parameter $R = 0.4$. $A_{\text{close-by}}$ differs from one by at most $\sim 3\%$ within the statistical uncertainty depending on the R_{min} value in the range of $R < R_{\text{min}} < R + 0.3$, and shows no significant jet p_T dependence over the measured p_T range. Table 5.1 shows a summary of the systematic uncertainty of JES assigned for non-isolated jets. These values are added in quadrature to the JES uncertainty obtained for isolated jets.

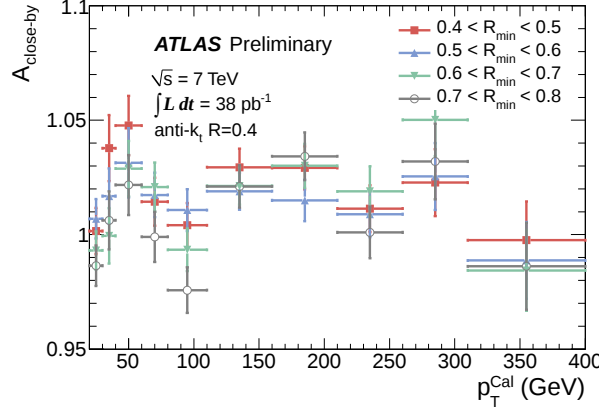


Figure 5.4: Data to MC ratio of the relative response of non-isolated jets with respect to that of isolated jets for anti- k_t jets with the distance parameter of $R = 0.4$ [76].

Table 5.1: Summary of jet energy scale systematic uncertainty assigned for non-isolated jets accompanied by a close-by jet within the denoted R_{min} ranges [76].

R_{min} range	20-30 GeV	> 30 GeV
$0.4 < R_{\text{min}} < 0.5$	2.7 %	2.8 %
$0.5 < R_{\text{min}} < 0.6$	1.7 %	2.3 %
$0.6 < R_{\text{min}} < 0.7$	2.5 %	2.7 %
$0.7 < R_{\text{min}}$	0 %	

Pile-up

The above measurements were performed using 2010 data but in 2011 the pile-up condition has been changed significantly. In the present jet reconstruction, the bias to the jet energy from the pile-up is not applied and it is considered as a systematic uncertainty in the JES. This bias was measured using MC simulations and the result is confirmed by the comparison of the gamma-jet data in 2010 and 2011 for the central region and by a di-jet balance analysis for the forward region. The systematic uncertainty of the JES from the pile-up is determined as shown in Table 5.2 and it is added in quadrature to the other uncertainties on the jet energy scale.

Table 5.2: Additional uncertainty to the jet energy scale due to pile-up conditions in 2011 data

	$0 \leq \eta^{\text{jet}} < 2.1$	$2.1 \leq \eta^{\text{jet}} < 4.5$
$20 \text{ GeV} < p_{\text{T}}^{\text{jet}} \leq 50 \text{ GeV}$	5 %	7 %
$50 \text{ GeV} < p_{\text{T}}^{\text{jet}} \leq 100 \text{ GeV}$	2 %	3 %
$100 \text{ GeV} < p_{\text{T}}^{\text{jet}}$	0 %	

Gluon-, light-flavor-quark jet uncertainty

The jet energy scale determination is based on the QCD di-jet samples, which are expected to consist mostly of gluon-initiated jets at low p_{T} and central rapidity. However, in some conditions, quark-initiated jets can dominate. Therefore the difference of the calorimeter response to gluon- and (light-)quark jets can be a systematic uncertainty to the jet energy scale. This uncertainty is studied in Reference [78]. The difference between the heavy-flavor-quark jets are described in the next section.

Jets in the MC simulation are identified as gluon-jets or quark-jets using the partons in the generator event record. The highest energy parton that points to the jet ($\Delta R < 0.4$ for the jet with the distance parameter of $R = 0.4$) determines the flavor of the jet.

The jets identified as gluon-jets tend to have more particles, and those particles tend to be softer than in the case of quark-jets. Additionally, the gluon-jets tend to be wider (i.e. with lower energy density in the core of jet) before interacting with the detector. The magnetic field of the inner detector amplifies the broadness of gluon-jets, since their low- p_{T} charged particles tend to bend more than the higher- p_{T} particles in quark-jets. The harder particles in quark-jets additionally tend to penetrate further into the calorimeter. These differences lead to overestimate of the energy of light-flavor-quark jets comparing with the energy of gluon-jets. Figures 5.5 show the difference in calorimeter response between gluon-jets and quark-jets for jets with distance parameter $R = 0.4$ and separately for jets in the barrel ($|\eta| < 0.8$) and end-cap ($2.1 \leq |\eta| \leq 2.8$) calorimeters. In all cases, the difference is larger at low- p_{T} (up to 6 %) and falls to several percent at high- p_{T} . In Reference [78], the composition of jet flavors in the samples used for the jet energy scale determination is validated; data and MC simulation agree within the systematic uncertainties.

Since a variety of signal models is treated in this thesis, the jet flavor composition is not the same. Therefore, the difference of the jet energy scale between gluon-jets and quark-jets is taken as a systematic uncertainty, taking conservative values.

Heavy-flavor-quark jet uncertainty

To account for the leptonic decay of heavy-flavor hadrons in a jet, an additional uncertainty is assigned to b -tagged jets; (b -tagging is described in Section 5.7). Figure 5.6 shows the ratio of reconstructed calorimeter-jet p_{T} to the truth-jet p_{T} for b -tagged and non- b -tagged jets as a function of truth-jet p_{T} in the Monte Carlo simulation. The

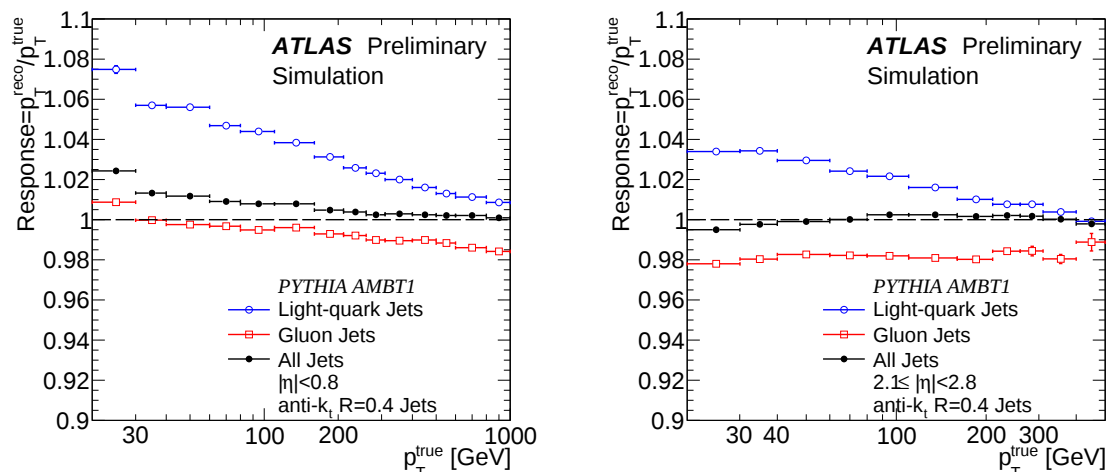


Figure 5.5: Response as a function of truth-jet p_T for all jets in the di-jet sample (black solid circles), gluon-jets (red open squares), and light-flavor-quark jets (blue open circles) falling in the barrel (left) and in the end-cap (right) in MC simulation. Jets are reconstructed with the anti- k_t algorithm with the distance parameter $R = 0.4$ and calibrated with the EM+JES calibration scheme.

b -tagged jets tend to have smaller energy than non- b -tagged jets because of the loss of energy by the leptonic decay of heavy-flavor hadrons. The difference is smaller than 2 % for all p_T ranges. For the systematic uncertainty of the JES for heavy-flavor-quark jets, 2.5 % is added in quadrature for the b -tagged jets as a conservative estimate.

5.3 Electron

Electron reconstruction [79] starts from the clustering of cells in the electromagnetic calorimeter, which are then associated to reconstructed tracks of charged particles in the inner detector. The details are described in the following.

5.3.1 Cluster reconstruction

Seed clusters to be used for electron reconstruction are formed with energies above 2.5 GeV by a sliding window algorithm [80]. Here the seed clusters are 3×5 in η/ϕ middle layer cell units (0.025×0.025). After an energy comparison, duplicate clusters are removed from nearby seed clusters.

5.3.2 Inner detector tracks

Inner detector tracks are reconstructed as described in Section 5.1. In the region covered by tracking detectors ($|\eta| < 2.5$), an electron is defined by the existence of one or more reconstructed tracks matched to a seed cluster.

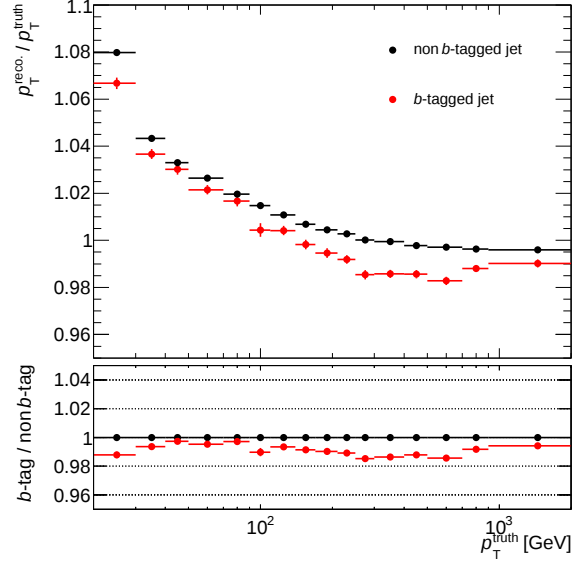


Figure 5.6: The ratio of reconstructed calorimeter-jet p_T to truth-jet p_T for b -tagged and non- b -tagged jets as a function of the truth-jet p_T .

5.3.3 Track-to-cluster matching

Reconstructed tracks are matched to seed clusters by extrapolating them from their last measurement point to the second layer of the calorimeter. The impact point η and ϕ coordinates are then compared to the corresponding seed cluster η and ϕ in that layer. If their difference is below a certain threshold then the track is considered matched to the cluster. To account for Bremsstrahlung losses, the sign-corrected $\Delta\phi$ window is larger on the side where the extrapolated track bends as it traverses the tracker magnetic field.

If several tracks are matched to the same cluster, tracks with SCT hits are preferred and the one with the smallest ΔR distance to the seed cluster is chosen.

Finally the electron four-momentum is computed using in addition the track information from the best track matched to the original seed cluster. The energy is computed as a weighted average between the cluster energy and the track momentum if the track satisfies the following conditions.

- $N_{\text{Hits}} > 3 \parallel p_{T,\text{track}} > 2 \text{ GeV}$, where N_{Hits} is the sum of the number of hits in the pixel detector and the SCT for the track, $p_{T,\text{track}}$ is the transverse momentum of the track.
- $\sigma = \sqrt{\frac{E_{\text{clus}} - p_{\text{track}}}{\sigma_{E_{\text{clus}}}^2 + \sigma_{p_{\text{track}}}^2}} \leq 3$ where E_{clus} and $\sigma_{E_{\text{clus}}}$ are the energy of the cluster and its uncertainty, p_{track} and $\sigma_{p_{\text{track}}}$ are the momentum of the track and its uncertainty.

When the conditions are not satisfied, the cluster energy is used.

The ϕ and η directions are taken from the corresponding track parameters unless

N_{Hits} defined above is less than three, in which case η is provided by the cluster η -pointing.

5.3.4 Further optimization of identification

The baseline electron identification in ATLAS relies on cuts using variables that provide good separation between isolated electrons and jets (faking electrons). These variables include calorimeter, tracker and combined calorimeter/tracker information. They are given as an input to a multi-variate analysis program (TMVA [81]) in order to perform a cut optimization in 10 bins of cluster η (defined by calorimeter geometry, detector acceptances and regions of increasing material in the inner detector) and 11 bins of cluster E_T (from 5 to 80 GeV). This allows for a proper handling of corrections between variables assuring the highest possible electron efficiency for a given jet rejection.

The following describes the details of the variables used.

- The hadronic leakage defined as the ratio of E_T in the first layer of the hadronic calorimeter to E_T of the EM cluster and the ratio of E_T in the hadronic calorimeter to E_T of the EM cluster using the range of $|\eta| < 0.8$ and $|\eta| > 1.37$.
- The lateral width of the shower in the second layer of the EM calorimeter
- The ratio in η of cell energies in 3×7 versus 7×7 cells in the second layer of the EM calorimeter.
- The total shower width in the first layer of the EM calorimeter.
- The ratio of the energy difference associated with the largest and the second largest energy deposit over the sum of these energies in the first layer of the EM calorimeter.
- The cuts on the number of pixel-layer hits and on total number of SCT hits are set to ≥ 1 and ≥ 7 respectively. These values have shown to provide high efficiency with good rejection while being at the same time quite robust.
- Following a similar argument, the cut on the $\Delta\eta$ matching between the extrapolated track and the cluster $\Delta\eta_1 = |\eta_{\text{calo}}^{\text{1st layer}} - \eta_{\text{track}}|$ is set to ≤ 0.01 .
- The cut on the electron transverse impact parameter d_0 measured at the perigee with respect to the beam spot is set to ≤ 5 mm.

5.3.5 Identification criteria

Electrons are preselected using the above criteria and are required to have $p_T > 20$ GeV and $|\eta^{\text{cl}}| < 2.47$, where η^{cl} is the electromagnetic cluster associated with the electron. These criteria for electrons are defined as *loose* in this thesis.

For higher rejection of fake electrons, *tight* criteria in this thesis are defined as follows.

- The number of hits in the innermost layer of the pixel detector is greater than one.
- $\Delta\phi$ between the cluster position in the second layer of the calorimeter and the extrapolated track is required to be less than 0.02.
- Cluster energy over track momentum (E/p) cut is optimized for each η and E_T range.
- The difference of the total number of TRT hits between the measured and the expected is required to be within 15.
- Fraction of high threshold TRT hits is optimized for each η and E_T range.
- Electrons matching reconstructed conversion photons are rejected. Details on how photon conversions reconstructed are given in [82].
- More stringent cuts on $\Delta\eta$ (< 0.005) and the impact parameter cut (< 1.0 mm) than the baseline selection.
- The total transverse momentum of the tracks in a cone of $\Delta R = 0.2$ from a electron (except for the tracks matched to the electron) divided by the electron transverse momentum is smaller than 0.1.

5.3.6 Performance

To correct for the differences of energy scale and resolution between data and MC simulation, energy resolution of electrons in MC samples are smeared and the energy scale of electrons in data is rescaled according to the measurements described in [83]. The measurements were performed for $Z \rightarrow e^+e^-$, $W \rightarrow e\nu$ and $J/\psi \rightarrow e^+e^-$ events and these results are combined. Figures 5.7 show the energy-scale correction factor α as a function of the electron energy for the barrel and the end-cap regions. The energy-scale correction factor is defined by

$$\alpha \equiv \frac{E^{\text{meas}} - E^{\text{true}}}{E^{\text{true}}} \quad (5.4)$$

where E^{meas} is the energy measured by the calorimeter after the MC-based energy-scale correction and E^{true} is the true electron energy.

Moreover, scale factors that take into account the discrepancies between data and MC simulation in the electron reconstruction and identification efficiencies are applied to MC events. For example, Figure 5.8 shows the reconstruction efficiencies as a function of electron E_T and Figures 5.9 show the identification efficiencies for *tight* selection as a function of electron E_T and η .

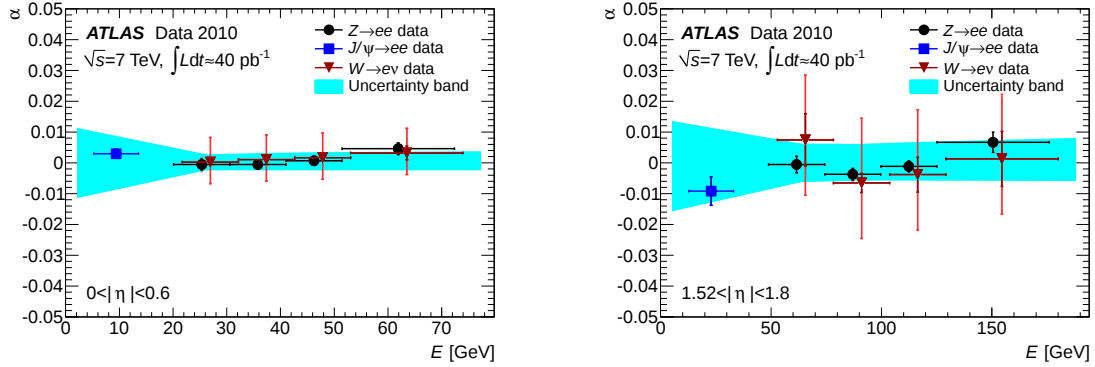


Figure 5.7: The energy-scale correction factor as a function of the electron energy for $|\eta| < 0.6$ (left) and $1.52 < |\eta| < 1.8$ (right) using $Z \rightarrow e^+e^-$ (black filled circles), $J/\psi \rightarrow e^+e^-$ (blue filled squares) and $W \rightarrow e\nu$ decays (brown filled triangles) [83].

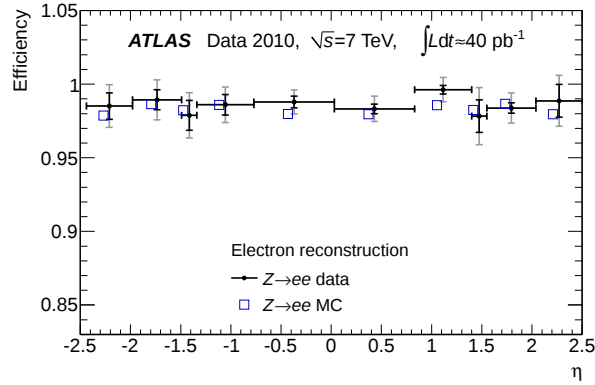


Figure 5.8: Reconstruction efficiencies of electron measured from $Z \rightarrow e^+e^-$ events and predicted by MC as a function of the cluster η integrated over the range $20 \text{ GeV} < E_T < 50 \text{ GeV}$ [83]. The results for the data (black filled circle) are shown with their statistical uncertainties (inner error bars) and total uncertainties (outer error bars). The statistical error on the MC efficiencies plotted as blue open squares is negligible.

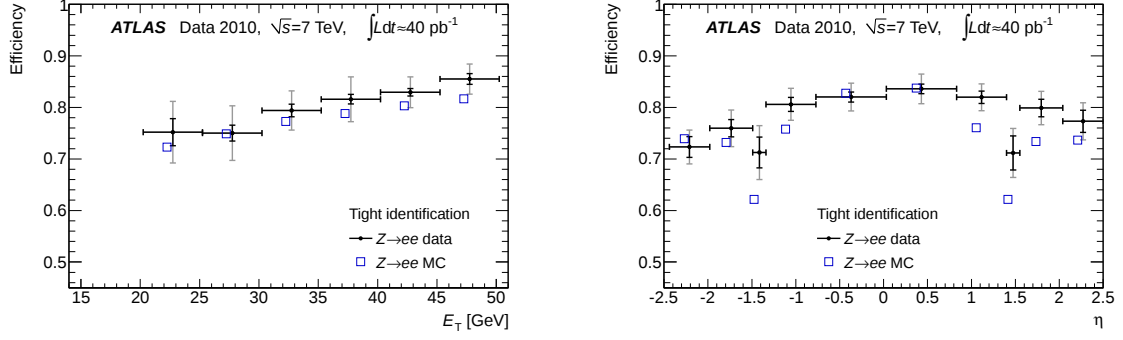


Figure 5.9: The identification efficiencies measured from $Z \rightarrow e^+e^-$ events and predicted by MC for *tight* identification as a function of E_T integrated over $|\eta| < 2.47$ excluding the transition region $1.37 < |\eta| < 1.52$ (left) and η integrated over $20 \text{ GeV} < E_T < 50 \text{ GeV}$ [83]. The results for the data (black filled circles) are shown with their statistical uncertainties (inner error bars) and total uncertainties (outer error bars). The statistical error on the MC efficiencies plotted as blue open squares is negligible.

5.4 Muon

Muons are selected by the STACO algorithm [84], which matches a standalone muon to a nearby inner detector track and then combines the two into one muon object. The details of the algorithm are as follows.

5.4.1 Standalone muons

The standalone algorithm first builds track segments in each of the three muon stations and then links the segments to form tracks. In STACO-family algorithms, an algorithm called Muonboy [85] is used to find the spectrometer tracks and extrapolate them to the beam line. The extrapolation accounts for both multiple scattering and energy loss in the calorimeter. In Muonboy, energy loss is assigned based on the material crossed in the calorimeter.

5.4.2 Inner detector muons

For the inner detector muon candidates, tracks reconstructed by the standard ATLAS software are used as described in Section 5.1.

5.4.3 Combined muons

The match chi-square defined as the difference between the standalone muon track and the inner detector track vectors weighted by their combined covariance matrix:

$$\chi_{\text{match}}^2 = (\mathbf{T}_{\text{MS}} - \mathbf{T}_{\text{ID}})^T (\mathbf{C}_{\text{ID}} + \mathbf{C}_{\text{MS}})^{-1} (\mathbf{T}_{\text{MS}} - \mathbf{T}_{\text{ID}}) \quad (5.5)$$

is used to determine which pair of them should be retained. Here $\mathbf{T}$ denotes a vector of five track parameters, which are expressed at the point of closest approach to the beam line, and $\mathbf{C}$ is the covariance matrix. The subscript ID refers to the inner detector and MS to the muon spectrometer.

Then the combined muon track vector is given by

$$\mathbf{T} = (\mathbf{C}_{\text{ID}}^{-1} + \mathbf{C}_{\text{MS}}^{-1})^{-1}(\mathbf{C}_{\text{ID}}^{-1}\mathbf{T}_{\text{ID}} + \mathbf{C}_{\text{MS}}^{-1}\mathbf{T}_{\text{MS}}). \quad (5.6)$$

The ID dominates the measurement up to $p_{\text{T}} \sim 80$ GeV in the barrel and $p_{\text{T}} \sim 20$ GeV in the end-cap. For higher $p_{\text{T}} \lesssim 100$ GeV the ID and MS measurements have similar weight while the MS dominates at $p_{\text{T}} \gtrsim 100$ GeV.

5.4.4 Further selection

Muons are considered for the analysis only if $p_{\text{T}} > 10$ GeV and $|\eta| < 2.4$.

Furthermore, the following quality cuts on the tracks are applied.

- One hit in the innermost layer of the pixel detector if a hit is expected.
- At least one hit in any pixel layers.
- At least six SCT hits.
- A successful TRT-extension where it is expected. This requirement can be written as follows.

Define N_{TRT} as the number of hits in the TRT associated to the track, and $N_{\text{TRT}}^{\text{outliers}}$ as the number of TRT outliers on the muon track, where outliers is a set of nearby TRT hits when the track fit quality is bad. For $|\eta| < 1.9$ muons are required to have $N_{\text{TRT}} = N_{\text{TRT}}^{\text{hits}} + N_{\text{TRT}}^{\text{outliers}} > 5$. Tracks with $N_{\text{TRT}} > 5$ should satisfy $N_{\text{TRT}}^{\text{outliers}} < 0.9 * N_{\text{TRT}}$

5.4.5 Performance

The muon reconstruction efficiencies have been measured from the experimental data using a tag-and-probe method with the di-muon decay of the Z boson as described in Reference [86]. The measurement has been performed for the data taken in 2011 also and MC simulations are scaled to data. The results are consistent with the measurements of 2010 data. Figures 5.10 show the measured efficiencies for combined muons from the experimental data and Monte Carlo simulation as a function of muon p_{T} and η .

At $\eta \sim 0$ the MS is only partially equipped with muon chambers to provide space for services of the ID and the calorimeters. This causes an efficiency drop in this region. The efficiency drop in the transition region ($|\eta| \sim 1.2$) is due to the limited accuracy of the magnetic field map used in the reconstruction of the ATLAS data in this region.

To correct the imperfect muon p_{T} resolution and energy scale predicted by the MC simulation with respect to the data, the di-muon invariant mass distribution at the Z

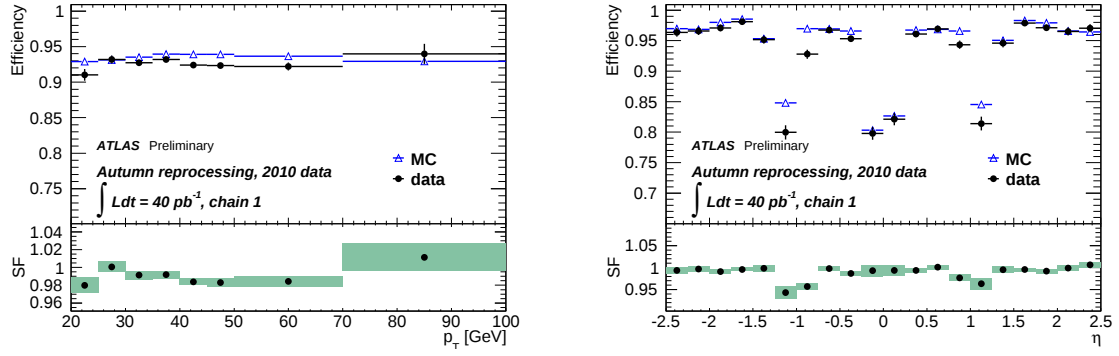


Figure 5.10: Reconstruction efficiencies and scale factors for the combined muons obtained from data (black filled circles) and Monte Carlo simulation (blue open triangles) are shown in the upper part of each figure. The corresponding scale factors are shown in the lower part [86].

pole [87]. This measurement is performed for 2011 data and an additional smearing and rescaling of the muon p_T is applied to MC simulations for MS and ID respectively. Figures 5.11 show di-muon mass resolutions of the inner detector track and the muon spectrometer as a function of muon η comparing data and MC simulation. An overall discrepancy between measured and simulated resolution is observed in all η regions. It is partially understood as a result of the limited accuracy with which the calibration and alignment constants. For the MS, inaccuracies in the description of the detector material and the magnetic field can also contribute to a poorer resolution at low momentum.

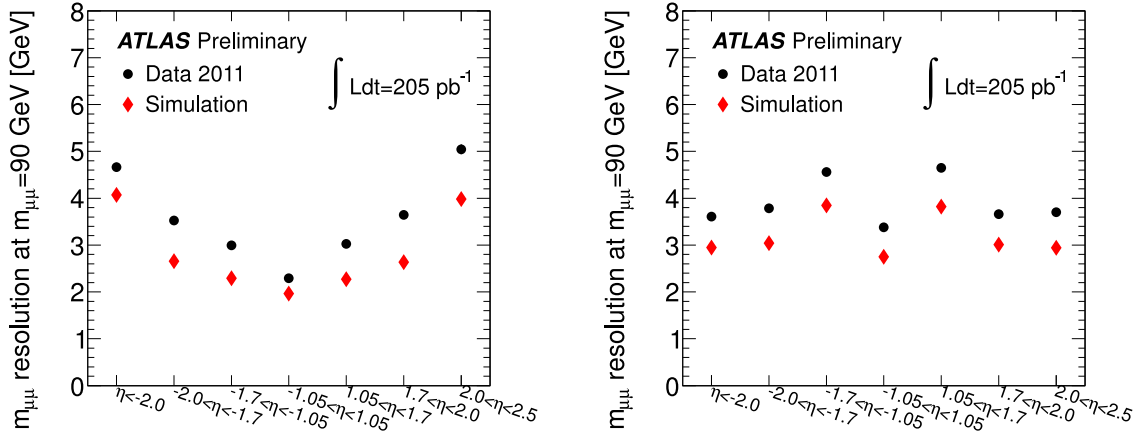


Figure 5.11: Di-muon mass resolutions of the inner detector (left) and the muon spectrometer (right) in different η region. The experimental resolution (black filled circles) is compared to Monte Carlo prediction using PYTHIA generated $Z \rightarrow \mu^+ \mu^-$ events (red filled diamonds) [88].

5.4.6 Identification criteria

The above requirements are applied as *loose* criteria for muons in this thesis.

For *tight* criteria, the total transverse momentum of tracks reconstructed in a cone of $\Delta R = 0.2$ around the muon is required to be less than 1.8 GeV to reduce muons from the leptonic decay of heavy-flavor hadrons.

5.5 Missing transverse momentum

The E_T^{miss} is reconstructed by object-based algorithm described below. For electrons, *loose* selection criteria described in Section 5.3 are applied. For jets, the same criteria and energy calibration are applied as in the standard jet selection for this thesis, except that the η range is extended to $|\eta| < 4.5$. Remaining calorimeter clusters not belonging to high p_T objects are included in the *CellOut* term. The E_T^{miss} is corrected by muons identified by *loose* criteria described in Section 5.4. Then the final E_T^{miss} is given by

$$E_{x(y)}^{\text{miss}} = - \sum_{\text{electron}} p_{x(y)}^{\text{electron}} - \sum_{\text{jet}} p_{x(y)}^{\text{jet}} - \sum_{\text{muon}} p_{x(y)}^{\text{muon}} - \sum_{\text{CellOut}} p_{x(y)}^{\text{CellOut}} \quad (5.7)$$

$$E_T^{\text{miss}} = \sqrt{(E_x^{\text{miss}})^2 + (E_y^{\text{miss}})^2}. \quad (5.8)$$

and the azimuthal position of the E_T^{miss} vector is given by

$$\phi^{\text{miss}} = \arctan(E_y^{\text{miss}}/E_x^{\text{miss}}). \quad (5.9)$$

The energy scale uncertainties of jets, electrons and muons are propagated to the E_T^{miss} calculation and it is taken as the uncertainty of the E_T^{miss} . The uncertainty on the *CellOut* term is evaluated in Reference [89] and was found to be about 13 % on $\sum_{\text{CellOut}} p_{x(y)}^{\text{CellOut}}$. Since the contribution from the *CellOut* E_T^{miss} term is much smaller than E_T^{miss} after requiring several jets, its systematic uncertainty on E_T^{miss} is negligibly small.

5.6 Pile-up reweighting

Monte Carlo simulated samples are usually produced before or during the data taking period. In this case, only a best-guess of pile-up conditions in data can be put into the simulation. To solve this situation, a method to reweight the MC simulated samples according to the pile-up conditions was developed.

If the bunch separation of the LHC is large, the number of reconstructed vertices is a good measure of pile-up. It is directly connected to the so-called “in-time” pile-up, which is the number of interactions in the same bunch crossings. However, in the 2011 data taking period, the LHC is running with the bunch trains with an in-train bunch separation of 50 ns. In this condition, the “out-of-time” pile-up, which are the additional interactions in preceding bunch crossings and which distort the signal shape, is significant and the number of vertices in a given event is not a good

measure. Instead, the average number of pile-up interactions (computed from the beam parameters) denoted as $\langle\mu\rangle$ in the following is used.

MC simulated samples are produced with a wide range of $\langle\mu\rangle$ (from 0 to 20) to cover future data period. Figure 5.12 (left) shows the $\langle\mu\rangle$ distributions for the default MC samples and data. The $\langle\mu\rangle$ of data was measured using the online luminosity monitors. When the MC simulation is compared to data, MC simulated samples are reweighted according to each $\langle\mu\rangle$ value to reproduce the data distribution as shown in Figure 5.12 (right).

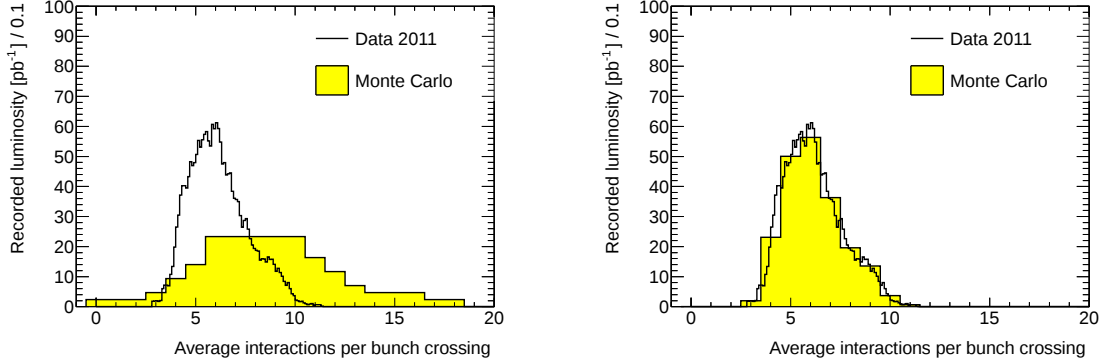


Figure 5.12: Average number of interactions per bunch crossing measured in data samples and produced for Monte Carlo simulation samples (left). Monte Carlo simulation after reweighting (right).

5.7 b -tagging

In ATLAS, various algorithms are used to tag b -jets. The most powerful are the spatial algorithms built on tracks and subsequently vertices. In this section, the algorithms relevant for this thesis will be described.

5.7.1 Tagging algorithm

Impact parameter-based algorithms

For the tagging, the impact parameters of tracks are computed at the point of closest approach with respect to the primary vertex.

As an impact parameter-based tagging algorithm, the *IP3D* which utilizes a likelihood ratio technique, is used. Input variables are compared to predefined smoothed and normalized distributions for both the b - and light-flavor-quark jet hypotheses obtained from Monte Carlo simulation. The two-dimensional histograms of the signed transverse impact parameter significance d_0/σ_{d_0} and longitudinal impact parameter significance z_0/σ_{z_0} of tracks are used as inputs taking advantage of the correlations between them.

The transverse impact parameter d_0 is the distance of closest approach of the track to the primary vertex point in the $r\phi$ projection. The z coordinate of the track at this point of closest approach is referred to as the longitudinal impact parameter z_0 . The impact parameters are signed to discriminate the tracks coming from b -hadron decays from tracks originating from the primary vertex. The sign is positive if the track extrapolation crosses the jet direction in front of the primary vertex, and negative otherwise. Therefore, tracks from b/c hadron decays tend to have a positive sign. The errors on d_0 and z_0 are the values returned by the track fit. Figures 5.13 show the distributions of d_0/σ_{d_0} and z_0/σ_{z_0} for b -tagging quality tracks in selected jets, for data and simulation. In case of d_0/σ_{d_0} , the distribution is moderately underestimated in the simulation. This discrepancy seems to come from the mismodeling of high-momentum tracks [90]. In case of z_0/σ_{z_0} , the resolution in data is better than in simulation. However, in both cases, the size of disagreements between data and the simulation are within 10 % for the most of region and will be absorbed by the calibration procedures described in later section.

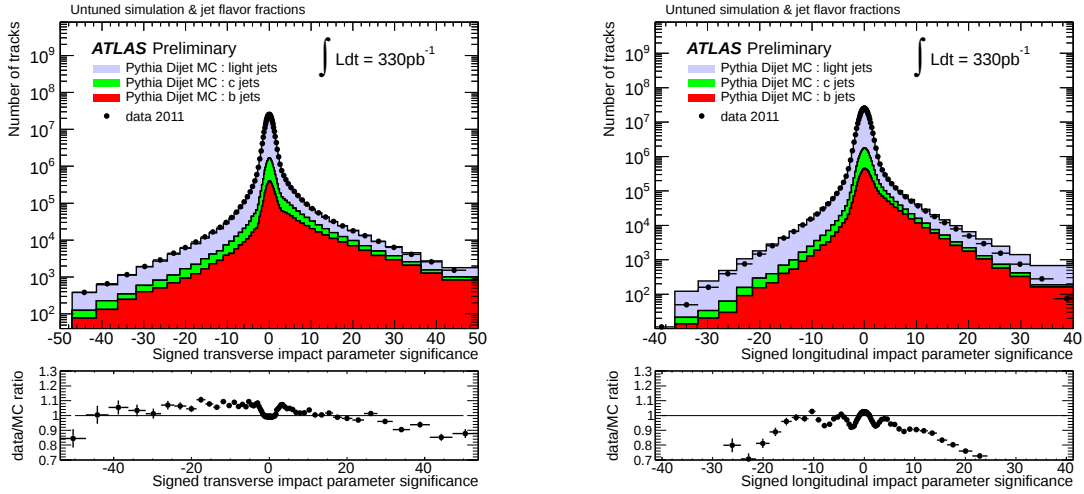


Figure 5.13: Distributions of the signed significance of the transverse impact parameter d_0/σ_{d_0} and the longitudinal impact parameter z_0/σ_{z_0} with respect to the primary vertex for tracks of b -tagging quality associated to jets for data (black filled circle) and for simulation (filled histograms for the various colors) [90]. The ratio data/simulation is shown at the bottom of the plots.

Secondary vertex-based algorithm

The tagging algorithm which exploits the topology of weak b - and c -hadron decays inside a jet is called *JetFitter* [29, 91]. A Kalman filter is used to find a common line on which the primary vertex and the b - and c -vertices lie, as well as their position on this line, giving an approximate flight path for the b -hadron. The discrimination between b -, c - and light-flavor-quark (including gluon) jets is based on a likelihood using variables such as the following:

- The decay length significance $L_{3D}/\sigma_{L_{3D}}$ measured in three-dimensions and signed with respect to the jet direction.
- The invariant mass of all tracks associated to the vertex.
- The ratio of the sum of the energies of the tracks in the vertex to the sum of the energies of all tracks in the jet.
- The number of two-track vertices.
- The flight length significances of the vertices.

Combinations of algorithms

The impact parameter tagging algorithm IP3D and the secondary vertex tagging algorithm JetFitter are combined based on artificial neural network techniques with Monte Carlo simulated training samples and additional variables describing the topology of the decay chain. Figure 5.14 shows the output of combination of JetFitter and IP3D for jets with $p_T > 20$ GeV and $|\eta| < 2.5$. The shape in experimental data is closely reproduced by the simulation, except in both ends of the distribution (> 4.0 and < -4.0).

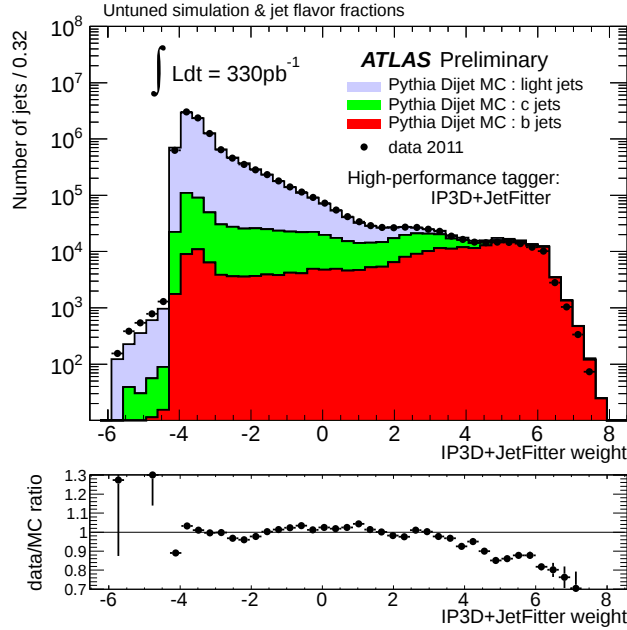


Figure 5.14: The distribution of the output of the IP3D+JetFitter tagging algorithm for experimental data (solid black points) and for simulated data (filled histograms for the various flavors) [90]. Jets are from the inclusive leading jet sample with $p_T > 20$ GeV and $|\eta| < 2.5$. The ratio data/simulation is shown at the bottom of the plot.

Expected performance and operation point

For the study of jets with heavy-flavor hadrons, jet flavor is categorized into light-flavor, c , b and τ in MC simulation. If a b -quark is found with $\Delta R < 0.3$ of the jet direction, the jet is labeled as a b -jet. If no b -quark is found and a c -quark is found with $\Delta R < 0.3$ of the jet, the jet is labeled as c -jet. If no b -quark nor c -quark is found and a τ is found, the jet is labeled as τ -jet. Finally, if the jet is not labeled as any of the above, it is labeled as a light-flavor jet.

Figure 5.15 shows the expectation for the light-flavor jet rejection as a function of the b -jet tagging efficiency (ε_b) for the various ATLAS b -tagging algorithms. It is obtained by varying continuously the operating point of each tagger (that is the cut on its output discriminating variable) using simulated $t\bar{t}$ events with the jet $p_T > 20$ GeV and $|\eta| < 2.5$. The tagging efficiency is the fraction of jets labeled as b -jets that are properly tagged, while the rejection is the reciprocal of the fraction of jets that are labeled as light jets that are mistakenly tagged as b -jets. The combination of IP3D and JetFitter is shown as “IP3D+JetFitter” in the figure and shows the largest light-jet rejection when comparing with other tagging algorithms at the same b -jet efficiency for $\varepsilon_b > 55$ %.

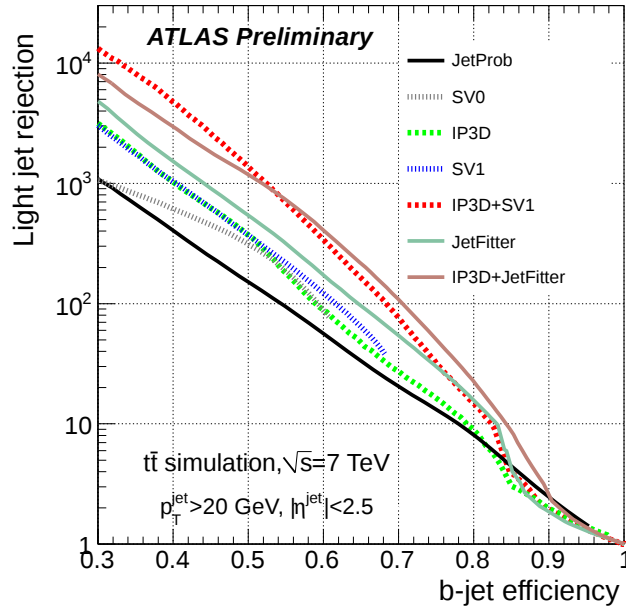


Figure 5.15: Light-jet rejection as a function of the b -jet tagging efficiency for the tagging algorithm used in ATLAS, based on simulated $t\bar{t}$ events [90].

In the analyses described in this thesis, the operating point with a b -tagging efficiency of 60 % point for $t\bar{t}$ events is chosen; this point has enough light-jet rejection (~ 400) with an adequate efficiency. Figure 5.16 shows the b -tagging efficiency (left) and mistag rate (right) as a function of jet p_T and $|\eta|$ for simulated $t\bar{t}$ events.

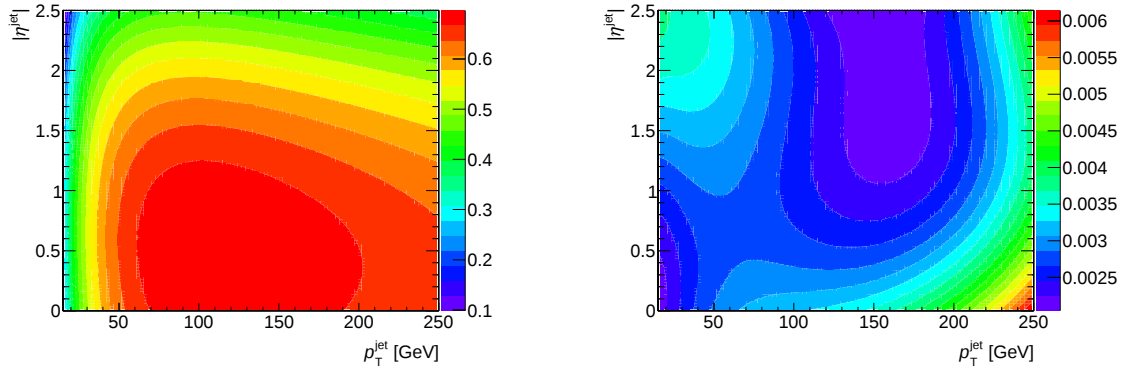


Figure 5.16: b -tagging efficiency (left) and mistag rate (right) as a function of jet p_T and $|\eta|$ for simulated $t\bar{t}$ events at the operating point with an average b -tagging efficiency of 60 %.

5.7.2 Calibration

The efficiency of the b -tagging algorithm for a jet originating from a b -quark needs to be measured using b -jet enriched data. Similarly the probability of mistakenly tagging a jet originating from a light-flavor (u -, d -, s -quark or gluon) jet as a b -jet, which is referred to as the mistag rate, also needs to be measured.

The measured results are presented as scale factors on the ratio of the b -tagging efficiency or mistag rate in data and Monte Carlo simulation:

$$\kappa_{\varepsilon_b}^{\text{data/MC}} = \frac{\varepsilon_b^{\text{data}}}{\varepsilon_b^{\text{MC}}}, \quad \kappa_{\varepsilon_l}^{\text{data/MC}} = \frac{\varepsilon_l^{\text{data}}}{\varepsilon_l^{\text{MC}}}. \quad (5.10)$$

where $\varepsilon_b^{\text{MC(data)}}$ and $\varepsilon_l^{\text{MC(data)}}$ are the fractions of b - and light-flavor jets which are tagged in simulated events (or data), with the jet flavor defined by matching to the generator-level parton. The b -tag efficiency and mistag rate depend on not only on jet p_T and η but also on other quantities such as the fraction of jets in the sample originating from gluons. But the calibration results in the form of scale factors between data and Monte Carlo simulation are likely to be valid. These scale factors are applied to the analysis in the way described in Section 6.1.8.

Several methods are developed to measure the scale factors. Here the main methods used in ATLAS will be explained, based on Reference [92].

b -tagging efficiency

The main method to calibrate the b -tagging efficiency is called the p_T^{rel} method. First, to collect b -jet enriched samples, jets with a reconstructed muon within its cone ($\Delta R < 0.4$) are selected. Then p_T^{rel} is defined by the momentum of the muon transverse to the axis defined by the combined muon plus jet. Muons originating from b -hadron decays have a harder p_T^{rel} spectrum than muons in c - and light-flavor jets due to the b -quark mass.

Templates of p_T^{rel} are constructed for b - and c - and light-flavor jets separately. Then by fitting the obtained p_T^{rel} spectrum to these templates, the fraction of each component can be obtained. It is confirmed that the p_T^{rel} distributions agree within uncertainty between before and after b -tagging using MC simulation.

By performing the fit before and after b -tagging, the tagging efficiency for b -jets is calculated,

$$\varepsilon_b = \frac{N_{b\text{-jet}}^{\text{after}}}{N_{b\text{-jet}}^{\text{before}}}. \quad (5.11)$$

The tagging efficiency for c -jets also needs to be measured but due to the difficulty to select c -jet samples, a dedicated measurement has not been performed. For now the same scale factors measured for b -jet are used, but doubling the systematic uncertainties.

Jet energy correction The energy of the reconstructed jet with an associated muon is corrected for the energy of the muon and the neutrino that is undetected in the calorimeters. The correction is implemented by parametrizing the corrected jet p_T as a function of measured jet p_T and muon p_T in MC simulation. Figure 5.17 shows the ratio of corrected jet p_T over the measured jet p_T .

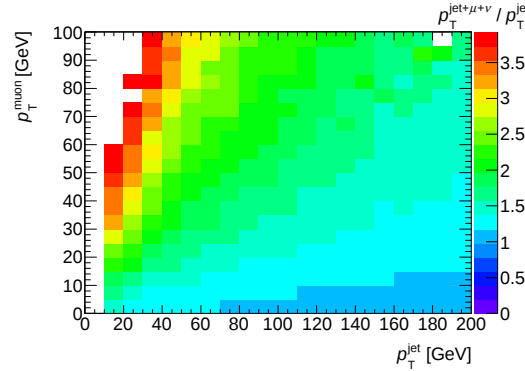


Figure 5.17: The ratio of the corrected jet p_T over the measured jet p_T where the correction takes into account the momenta of the muons and neutrinos within a cone of the jet. Results are obtained from MC simulation (left).

p_T^{rel} template The templates for b - and c -jets are derived from the simulated QCD di-jet sample mentioned in Section 4.2.1 (QCD di-jet). The p_T^{rel} template for light-quark jets is derived from muons in jets in a light-flavor dominated data sample. The sample is constructed by requiring that no jet in the event is b -tagged by the IP3D+JetFitter tagging algorithm using an operating point that yields a b -tag efficiency of approximately 80 % in simulated $t\bar{t}$ events. Even after this selection, heavy-flavor components are included in the light-flavor template. This contamination is subtracted according to the MC simulation.

The templates are prepared for the corrected jet p_T ranges of $20 \text{ GeV} < p_T < 30 \text{ GeV}$, $30 \text{ GeV} < p_T < 60 \text{ GeV}$, $60 \text{ GeV} < p_T < 90 \text{ GeV}$ and $90 \text{ GeV} < p_T < 140 \text{ GeV}$. Figure 5.18 shows the p_T^{rel} templates in each jet p_T range. The c - and light-flavor templates have peaks at smaller p_T^{rel} while the b -templates has broader shape and a peak at larger p_T^{rel} . However, in the higher jet p_T range, the difference between the templates becomes small. Therefore the template fits are regarded as unreliable for jet p_T higher than around 140 GeV. For the higher jet p_T range than 140 GeV, the scale factor is taken from the highest calibrated jet p_T range (90-140 GeV), and assigning twice the uncertainty.

The p_T^{rel} value is affected by how well the b -hadron direction and calorimeter jet axis are modeled in the simulation. To study this, the difference between the track-jet and calorimeter-jet axis, $\Delta R(\text{calo}, \text{track})$, was derived in both data and simulation. $\Delta R(\text{calo}, \text{track})$ is slightly larger in data than in simulation, and smearing based on a Gaussian distribution with a width of 0.01 was found to give good agreement between data and simulation in all ranges of jet p_T . The p_T^{rel} templates for b - and c -jets were derived from this smeared sample.

Template fit To enhance the b -jet fraction in data, the template fit is performed to events that have at least one jet is b -tagged by IP3D+JetFitter at the operating point with 60 % b -tag efficiency in simulated $t\bar{t}$ events. In order not to bias the calibration, this b -tagged jet is required not to have muons.

The obtained p_T^{rel} distributions are fitted by the templates using a binned maximum likelihood technique in which each bin is treated as an independent Poisson variable in the range $p_T < 2.5 \text{ GeV}$. Figure 5.19 shows the result of the p_T^{rel} template fit.

Systematic uncertainties The following sources of systematic uncertainties are the dominant for the p_T^{rel} considered in Reference [92].

- Statistics of data sample
- p_T^{rel} template statics

The p_T^{rel} templates are varied according to a Gaussian distribution within its statistical uncertainty and pseudo-experiments were carried out 1000 times. The RMS of the variations is taken as the systematic uncertainty.

- b -hadron direction

For a conservative estimate, the correction for the $\Delta R(\text{calo}, \text{track})$ distribution was varied by 100 % relatively and the resulting variation of the b -tagging efficiency from this is taken as the systematic uncertainty.

- Modeling of heavy-flavor quark production

In the case of the heavy-flavor quark production from gluon splitting, the angle between two quarks can be so small that both of them end up within the same reconstructed jet. Such heavy-flavor jets have a larger probability of being b -tagged than those containing just one heavy-flavor quark.

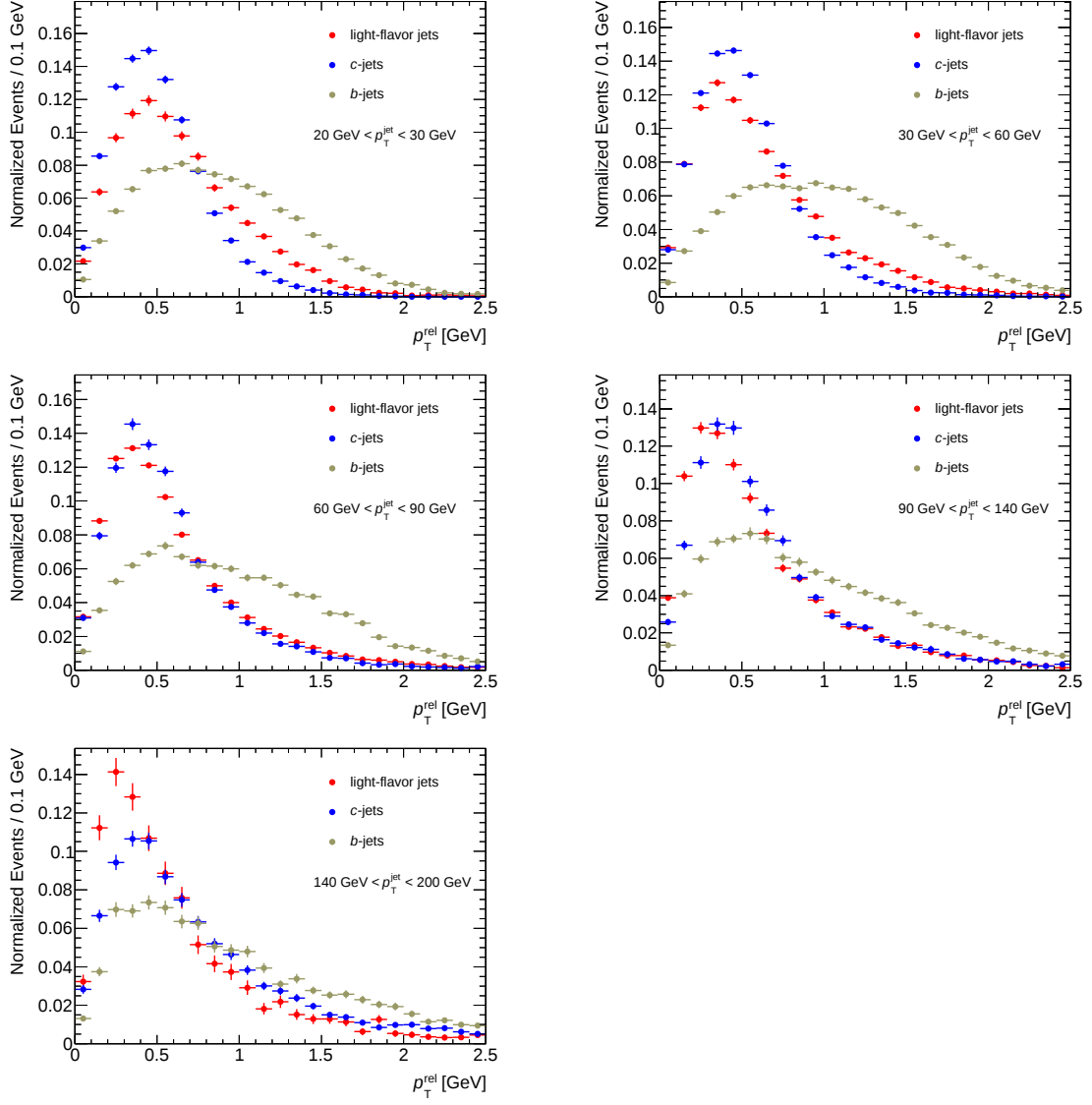


Figure 5.18: The p_T^{rel} templates for light-flavor, c -, b -jets in different jet p_T (corrected) ranges.

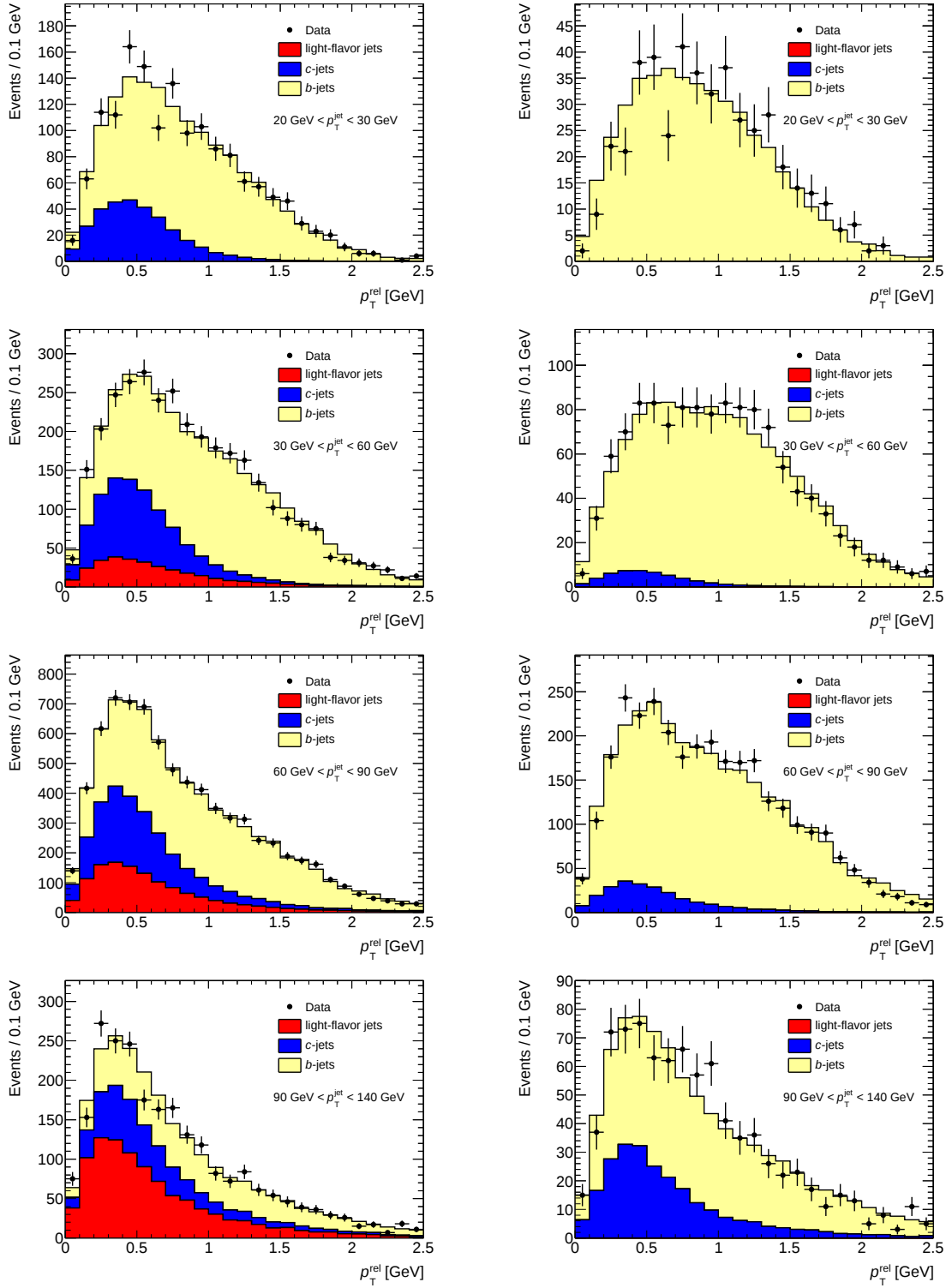


Figure 5.19: The results of the p_T^{rel} template fit before (left) and after (right) the b -tagging.

The systematic uncertainty associated with this heavy-flavor quark production is estimated by varying the ratio of double-heavy-flavor-quark jets to single-heavy-flavor-quark jets in simulation. This ratio is set to zero or twice from the default value and the effect on the b -tagging efficiency was taken as a systematic uncertainty.

- Jet energy scale

The p_T^{rel} templates obtained from MC simulations are varied within the systematic uncertainty for the JES described in Section 5.2.4.

- Scale factor for inclusive b -jets

Since the p_T^{rel} method is applied to b -jets with a semi-leptonic b -hadron decay, the bias to b -jets with a hadronic b -hadron decay is considered. For this, the distribution of the number of tracks, significantly displaced from the primary vertex, was obtained for jets with muons and for all jets in both data and MC simulation. The b -tagging efficiency in semi-leptonic and inclusive jets in simulation was also binned in this variable. The ratio of the weighted averages of the b -tagging efficiency for semi-leptonic and inclusive jets are given as follows:

$$\text{SF}_{\text{data}}^{\mu \rightarrow \text{incl}} = \frac{\sum_i N_i^{\text{incl,data}} \cdot \varepsilon_i^{\text{incl,sim}} / \sum_i N_i^{\text{incl,data}}}{\sum_i N_i^{\mu,\text{data}} \cdot \varepsilon_i^{\mu,\text{sim}} / \sum_i N_i^{\mu,\text{data}}} \quad (5.12)$$

$$\text{SF}_{\text{sim}}^{\mu \rightarrow \text{incl}} = \frac{\sum_i N_i^{\text{incl,sim}} \cdot \varepsilon_i^{\text{incl,sim}} / \sum_i N_i^{\text{incl,sim}}}{\sum_i N_i^{\mu,\text{sim}} \cdot \varepsilon_i^{\mu,\text{sim}} / \sum_i N_i^{\mu,\text{sim}}} \quad (5.13)$$

where $N_i^{\mu,\text{data}}$, $N_i^{\mu,\text{sim}}$, $N_i^{\text{incl,data}}$ and $N_i^{\text{incl,sim}}$ are the number of semi-leptonic (μ in the superscripts) or inclusive (incl in the superscripts) jets with a given number of displaced tracks in data and simulation, and $\varepsilon_i^{\mu,\text{sim}}$ and $\varepsilon_i^{\text{incl,sim}}$ are the b -tagging efficiencies in simulation for semi-leptonic and inclusive jets with a given number of displaced tracks. The deviation of the double-ratio $\text{SF}_{\text{data}}^{\mu \rightarrow \text{incl}} / \text{SF}_{\text{sim}}^{\mu \rightarrow \text{incl}}$ from one was taken as a systematic uncertainty.

Summary Figure 5.20 shows the result of the b -tagging efficiency calibration as a function of jet p_T . Since no significant dependence on the jet η is seen, the b -tagging efficiency scale factors are only parametrized by jet p_T .

Mistag rate

The main approach used in the mistag rate measurement is called the negative tag. Light-flavor jets are mistakenly tagged as b -jets mainly because the finite resolution of the inner detector and the presence of tracks stemming from displaced vertices from long-lived particles or material interactions. In the case of detector resolution, the impact parameter and the secondary vertex position used in the lifetime taggers are expected to be symmetric with respect to zero. Therefore by inverting these parameters, light-flavor mistag rate can be determined. However, two corrections have to be applied.

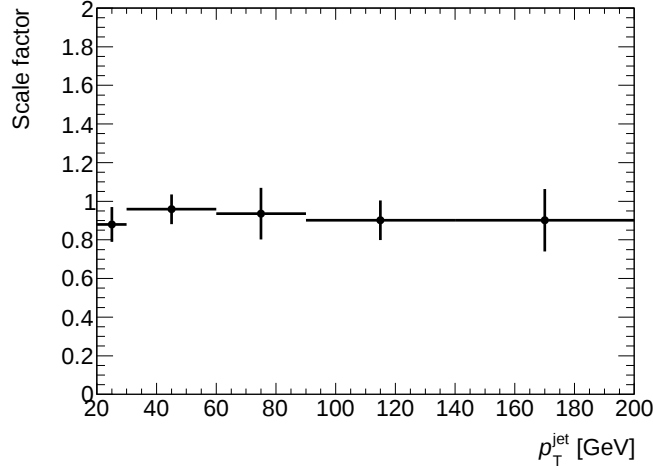


Figure 5.20: The scale factors of b -tagging efficiency between data and MC simulation as a function of jet p_T with systematic uncertainties.

One is the contribution of heavy-flavor jets. The negative tag rate for b - and c -jets differs from the negative tag rate for light-flavor jets because they have the measurable lifetimes of b - and c -hadron decays. The correction factor $k_{\text{hf}} = \varepsilon_l^{\text{neg}} / \varepsilon_{\text{inc}}^{\text{neg}}$ is defined to account for this effect where $\varepsilon_l^{\text{neg}}$ is the negative tag efficiency for light-jets and $\varepsilon_{\text{inc}}^{\text{neg}}$ is the negative tag efficiency for inclusive jets.

The other is the contribution of light-flavor long-lived particles (K_s^0 , Λ^0 and so on) and material interaction (hadronic interactions and photon conversions). These will show up mainly at positive decay length or impact parameter significances and thus cause an asymmetry for the positive versus negative tag rate for light-flavor jets. The correction factor $k_{ll} = \varepsilon_l / \varepsilon_l^{\text{neg}}$ is defined to account for this effect where ε_l is the positive tag efficiency for light-flavor jets and $\varepsilon_l^{\text{neg}}$ is the negative tag efficiency for light-flavor jets.

These correction factors are derived from simulation. The mistag rate is computed from the inclusive negative tag rate:

$$\varepsilon_l = \varepsilon_{\text{inc}}^{\text{neg}} k_{\text{hf}} k_{ll}. \quad (5.14)$$

The dominant uncertainties to the negative tag calibration are the following.

- Statistical uncertainty on k_{hf} and k_{ll} .
- Uncertainties on heavy-flavor tagging efficiencies:

The tagging efficiencies for b - and c -jets affect the calibration through the correction factor k_{hf} . The b - and c -tag efficiencies as obtained from simulation have been varied by the systematic uncertainties obtained in the p_T^{rel} method.

- Uncertainty on track impact parameter:

As seen in Figures 5.13, track impact parameters in the simulation are slightly better than those in data. Therefore, track impact parameters in the simulation have been smeared in order to bring data and simulation into better agreement. After having applied this smearing, the effect on k_U and k_{hf} has been propagated through the full negative tag analysis.

Figure 5.21 shows the result of the mistag rate calibration as a function of jet p_T and η . Error bars shown are the sum in quadrature of all uncertainties.

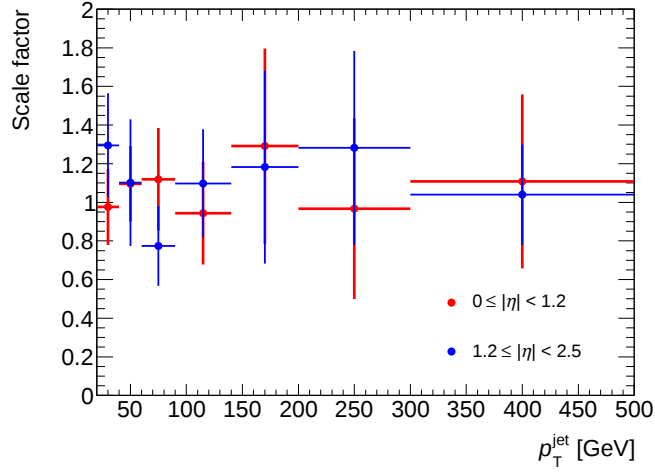


Figure 5.21: The scale factors of mistag rate between data and MC simulation as a function of p_T and $|\eta|$ of jet.

Chapter 6

Event Selection and Background Estimation

In this chapter, event selection and the background estimation for the searches of SUSY signals are described.

6.1 Common Event Selection

In this section, the event selection commonly used in all searches as far as this thesis is concerned are described.

6.1.1 Primary vertex selection

Among the primary vertex candidates reconstructed by the ATLAS inner detector, the vertex with the largest value of a scalar sum of the track particle p_T is examined; if this vertex has more than four tracks, the event is kept.

6.1.2 Overlap removal and isolation

Since the objects explained in Chapter 5 are reconstructed independently of each other, their overlap needs to be removed to avoid double counting. Moreover, objects expected to be derived from other objects are removed. Overlap removal is performed in the following way.

1. First, remove a jet which overlaps with an electron. If a jet is reconstructed within $\Delta R < 0.2$ of an electron, they are considered to be seeded by the same object and in this case, the object is regarded as an electron.
2. After the above overlap removal, search for an electron with $\Delta R < 0.4$ around a jet and the found electrons are removed. Since jets are reconstructed with the distance parameter of $\Delta R = 0.4$, that electron is accounted in the original jet.
3. Similarly, a muon with $\Delta R < 0.4$ with respect to a jet is removed. Unlike the electron case, even if a muon is close to a jet, the muon deposits only a small

amount of energy in the calorimeter. The removed muon is not counted as an isolated muon candidate but its momentum is included in the missing momentum calculation.

6.1.3 Event Cleaning

Fake jets can arise from non-collision background (which is mainly beam halo mimicking collision events) or cosmic-ray events with a catastrophic muon energy loss in the calorimeters or from fake signals in the calorimeter, arising either from noise bursts in the HEC or the presence of coherent noise in the LAr EM calorimeter. A set of cuts has been designed to have a high rejection against fake jets while keeping an inefficiency of about 0.1 % for real jets [93]. The selection criteria are based on the timing of the calorimeter signal with respect to that of the bunch crossing, on the quality factor of the pulse shape of the calorimeter signal, on the fraction of jet energy deposited in specific calorimeter layers and on the amount of jet charged energy fraction (as measured in the ID). Events are rejected if any jet with $p_T > 20$ GeV after the overlap removal between objects described above satisfies the bad jet definition.

A further selection is applied to the jets in the all hadronic channels in order to reject spurious jet signals. If any of the selected jets is central ($|\eta| < 2.0$) and the ratio of the jet charge track particle p_T to the jet calorimeter p_T is smaller than 5 %, the event is rejected.

6.1.4 Cosmic ray muon veto

To reject cosmic-ray muons, events with muons which have large impact parameters with respect to the primary vertex are not used for the analysis. The impact parameters are measured in the transverse to the beam (d_0) and the beam direction (z_0). If a muon has $|d_0| > 0.2$ mm or $|z_0| > 1.0$ mm, that event is rejected.

6.1.5 Trigger

The ATLAS trigger and data-acquisition systems are based on three levels of online event selection. Each trigger level refines the decisions made at the previous level as explained in Section 3.2.6.

The ATLAS data taking periods are grouped per different trigger menus based on the evolution of the peak luminosity. Table 6.1 shows the data sample used in this thesis and corresponding lowest threshold triggers.

Jet plus E_T^{miss} trigger

In the all hadronic channels, a combination of a single-jet trigger and a E_T^{miss} trigger, `EF_j75_a4(tc)_EFFS_xe45_loose_noMu` is used. The meaning of this trigger is that at the Event Filter, the trigger scans for all jets (not for RoI) reconstructed from topological clusters in the calorimeter using an anti- k_t algorithm with a distant parameter $\Delta R = 0.4$. At least one such jet with a transverse momentum greater than 75 GeV is

Table 6.1: Data periods and triggers

Period	Integrated luminosity [pb ⁻¹]
B	11.4
D	154
E	42.6
F	123
G	464
H	240
I	305
J	212
K	500
Total	2052

Period	Trigger name
Jet plus E_T^{miss}	
B	EF_j75_a4_EFFS_xe45_loose_noMu
D-K	EF_j75_a4tc_EFFS_xe45_loose_noMu
Single electron	
B,D-J	EF_e20_medium
K	EF_e22_medium
Single muon (plus jet)	
B,D-I	EF_mu18 EF_mu40_MSonly_barrel
J,K	EF_mu18_L1J10 EF_mu40_MSonly_barrel_medium

required; in addition, $E_T^{\text{miss}} > 45$ GeV is required without considering the contribution of muons to E_T^{miss} calculation. To avoid the systematic uncertainty from the trigger efficiency in the turn-on region, tight jet p_T and E_T^{miss} are required in offline analysis.

Figure 6.1 (left) shows the trigger efficiency as a function of E_T^{miss} using data samples collected by the single-jet trigger `EF_j75_a4(tc)_EFFS`; this trigger runs exactly the same algorithm as the jet part of `EF_j75_a4(tc)_EFFS_xe45_loose_noMu` and therefore any bias on E_T^{miss} from the jet trigger part is included in this measurement. The trigger efficiency for the MC simulated $t\bar{t}$ samples, which is the dominant SM background in all analyses described in this thesis, is also shown as a reference. The turn-on efficiency curves look different between data and $t\bar{t}$ MC simulation because in data fake E_T^{miss} events coming from the QCD multi-jet process are included. For the E_T^{miss} calculation of the trigger, a muon contribution is not considered. Muons from QCD multi-jet process are removed due to overlap with jets and not considered in the offline E_T^{miss} calculation. On the other hand, isolated muons coming from such as a decay of W boson, are considered in the offline E_T^{miss} calculation.

Nevertheless, the trigger is fully efficient for events with $E_T^{\text{miss}} > 130$ GeV for both data and MC simulation.

Figure 6.1 (right) shows the trigger efficiency as a function of the leading jet p_T using data samples collected by the single-muon trigger `EF_mu18` so as to not bias the samples. Moreover, $E_T^{\text{miss}} > 130$ GeV is required to study only jet p_T dependence. In events containing a leading jet $p_T > 130$ GeV, the trigger is fully efficient.

Table 6.2 shows the trigger efficiency measured with the single-jet trigger and with the single-muon trigger for both data and $t\bar{t}$ MC simulation after requiring $E_T^{\text{miss}} > 130$ GeV and the leading jet $p_T > 130$ GeV. The two measurements agree within the statistical uncertainty.

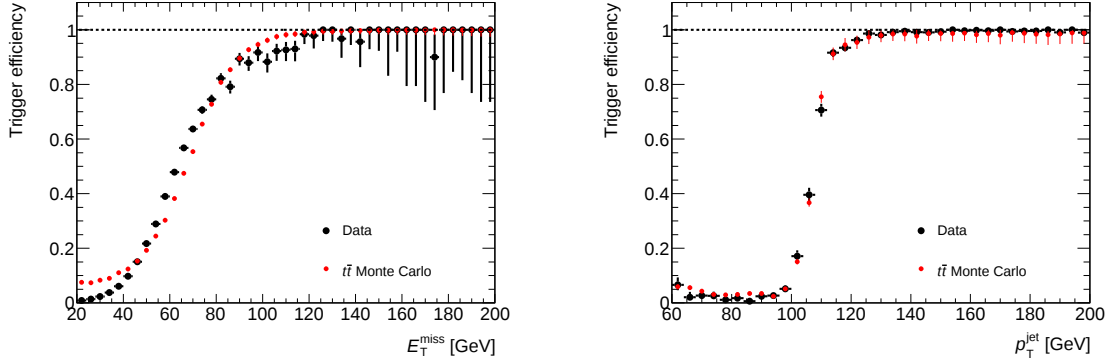


Figure 6.1: Trigger efficiency of `EF_j75_a4tc_EFFS_xe45_loose_noMu` as a function of the offline E_T^{miss} (left) and the leading jet p_T (right) comparing data (black filled circles) and $t\bar{t}$ Monte Carlo simulation (red filled circles).

Electron trigger

In the channel which requires electrons, a single-electron trigger `EF_e20_medium` is used; this trigger requires an electron $p_T > 20$ GeV which passes *medium* criteria defined in

Table 6.2: The trigger efficiency of EF_j75_a4tc_EFFS_xe45_loose_noMu after requiring $E_T^{\text{miss}} > 130$ GeV and the leading jet $p_T > 130$ GeV, shown for data and $t\bar{t}$ MC simulation. Only statistical uncertainties are shown.

	data	$t\bar{t}$ MC
after EF_j75_a4(tc)_EFFS	$99.0^{+1.0}_{-8.0} \%$	$99.8^{+0.2}_{-0.5} \%$
after EF_mu18	$99.5^{+0.5}_{-1.0} \%$	$98.6 \pm 0.8 \%$

Reference [79]. To measure the trigger efficiency, data collected by single-muon trigger EF_mu18 is used. Figure 6.2 (left) shows the efficiency of EF_e20_medium as a function of the electron p_T for *tight* electrons. The efficiency reaches close to its plateau value for $p_T > 25$ GeV. Small differences between data and MC samples are corrected using correction factors obtained from an in-situ measurement using the process $Z \rightarrow e^+e^-$ in the way described in Reference [83]. Figure 6.2 (right) shows the trigger efficiency as a function of electron η after $p_T^{\text{electron}} > 25$ GeV is required. Except for the transition region between the barrel and end-cap calorimeters ($1.37 < \eta < 1.52$) and the ends of the ID volume ($\eta = 2.5$), the trigger efficiency exceeds 90 %.

In the later run (period K), the lowest unprescaled single-electron trigger was EF_e22_medium which triggers on a *medium* electron with $p_T > 22$ GeV; after the requirement of electron $p_T > 25$ GeV, the integrated efficiency of the trigger is the same as EF_e20_medium.

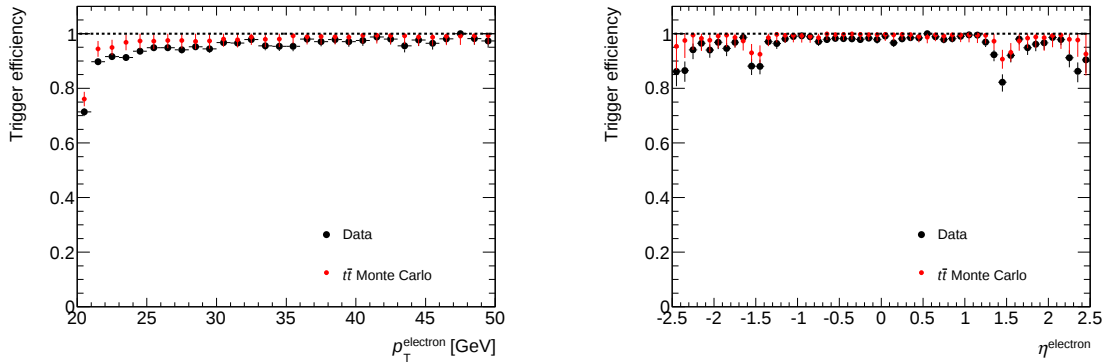


Figure 6.2: Trigger efficiency of EF_e20_medium as a function of electron p_T (left) and η (right) for offline *tight* electron comparing data (black filled circle) and $t\bar{t}$ Monte Carlo simulation (red filled circle). In the right figure, electron $p_T > 25$ GeV is required.

Muon Trigger

The single-muon trigger `EF_mu18` is used mainly to trigger on events containing a combined muon (see Section 5.4) with $p_T > 18$ GeV⁴. To measure the efficiency of this trigger, data samples collected by the single-electron trigger `EF_e20_medium` is used. Figure 6.3 (left) shows the trigger efficiency of `EF_mu18` as a function of muon p_T for *tight* offline muons. In events with $p_T > 20$ GeV, the trigger is fully efficient. Worse trigger efficiency in the barrel ($|\eta| < 1.0$) than in the end-cap is due to the geometrical losses. In the region of $-2.3 \leq \phi \leq 1.7$ and $-1.4 \leq \phi \leq 0.9$, the magnet support structures causes the inefficiency of muon triggers. In the barrel, the region of $\eta \sim 0$ is not covered by RPCs and smaller inefficiency occurs due to magnetic ribs.

Small differences between data and MC simulations are corrected with correction factors obtained from in-situ measurements of the process $Z \rightarrow \mu^+\mu^-$.

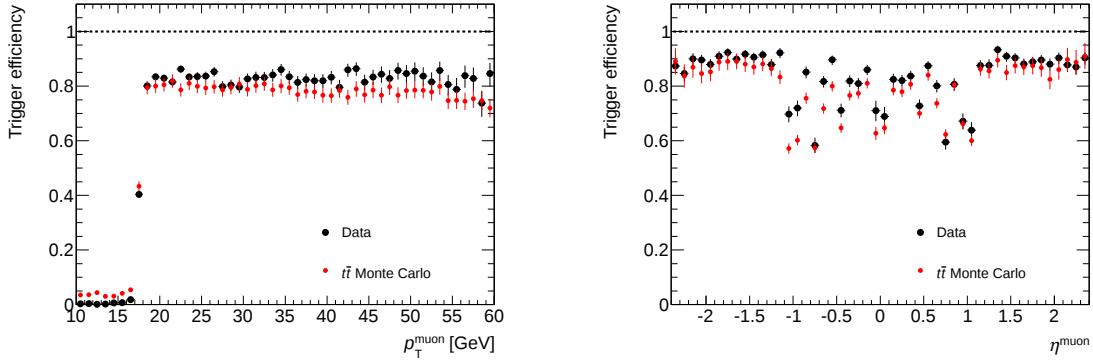


Figure 6.3: Trigger efficiency of `EF_mu18` as a function of muon p_T for *tight* muons (left) comparing data (black filled circle) and $t\bar{t}$ MC simulation. Samples were collected by the single-electron trigger `EF_e20_medium`. The right figure shows the dependence of the trigger efficiency on muon η for *tight* muons after $p_T^{\text{muon}} > 20$ GeV has been required.

Due to the increase of the luminosity, this trigger is prescaled from period J onwards. For these periods, therefore, the `EF_mu18_L1J10` is used instead; this trigger requires one additional jet to be present in the event. The muon p_T threshold is the same as `EF_mu18`. Figure 6.4 shows the trigger efficiency of `EF_mu18_L1J10` as a function of the leading jet p_T after requiring a muon with $p_T > 20$ GeV. The trigger is fully efficient for events with jet $p_T > 60$ GeV.

6.1.6 Jet selection

After the application of the pile-up reweighting, described in Section 5.6, Monte Carlo simulation provides a good description of the pile-up condition. Figure 6.5 shows the

⁴Because of the bug in the trigger algorithm for MC simulation, trigger inefficiency occurred to the trigger `EF_mu18` for muons in the central ($|\eta| < 1.0$) and higher p_T range ($\gtrsim 40$ GeV). To compensate it, the other single-muon trigger `EF_mu40_Monly_barrel` is also used. It triggers a muon $p_T > 40$ GeV in the barrel region ($|\eta| < 1.05$) using the muon spectrometers only.

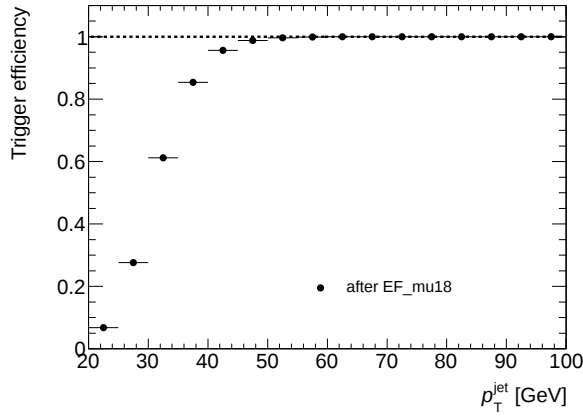


Figure 6.4: Trigger efficiency of EF_mu18_L1J10 as a function of the leading jet p_T . Data samples were collected by EF_mu18.

number of reconstructed vertices which have at least five tracks after requiring one electron in the event. The data and MC simulation agree well.

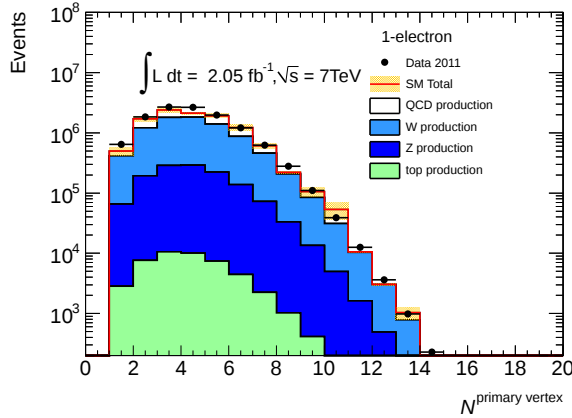


Figure 6.5: The number of reconstructed vertices which have at least five track particles, shown after requiring one electron in the event.

Since jets can arise from pile-up from inelastic proton-proton collisions during the hard collision, the jet multiplicity tends to be larger under conditions of higher pile-up. To reduce the bias due to the different pile-up conditions or mismodeling of soft collisions in simulation, jet p_T threshold of 50 GeV is applied for all jets required in this analysis. Figure 6.6 shows the jet multiplicity distributions for the jet p_T threshold of 30 GeV and 50 GeV, shown for the different conditions on the number of the reconstructed vertices. If the jet p_T threshold is 30 GeV, the distribution of the number of jets is highly affected by the number of reconstructed vertices. If four jets with $p_T > 30$ GeV are required, a 70 % variation can be seen in the number of events as a function of the number of the reconstructed vertices. However, if the jet p_T threshold is 50 GeV, the

jet multiplicity distributions are within 20 % of each other (except for outliers due to small statistics).

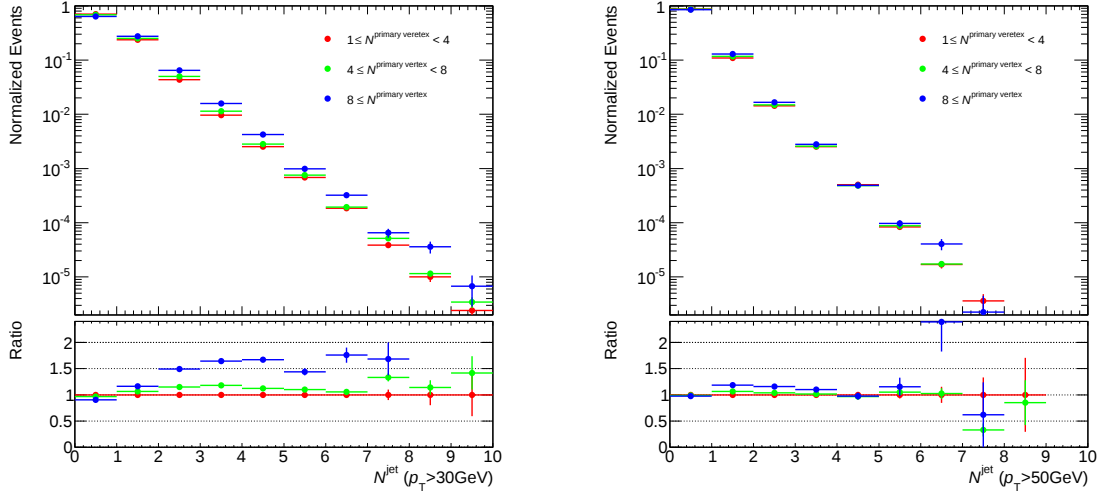


Figure 6.6: The jet multiplicity distributions shown for varying numbers of reconstructed vertices. The left figure is the number of jet with $p_T > 30$ GeV and the right is the number of jets with $p_T > 50$ GeV.

6.1.7 LAr EM calorimeter trouble

On 30 April 2011, a problem arose in the Liquid Argon EM calorimeter. The readout failed on six front-end boards, covering a rectangular region in η - ϕ space, $0.0 < \eta < 1.45$ and $-0.788 < \phi < -0.592$ in the second and the third layers of the calorimeter. During the technical stop in summer of 2011, the dead controllers for the second layer (comprising four of the six problematic boards) were replaced and the calorimeter performance was almost recovered. However, the data taken before the fix, corresponding to an integrated luminosity of 877 pb^{-1} , was affected by this problem.

The electron reconstruction is affected most by this problem. Figure 6.7 shows the number of reconstructed electrons with $p_T > 20$ GeV in η - ϕ space. A clear drop in the reconstruction efficiency can be seen in the dead detector region. This dead calorimeter region is not reproduced in the MC simulations; in order to treat both data and MC samples consistently, if an electron falls in this dead detector region, the electron is removed from analysis in all data and MC samples.

The effect of LAr EM calorimeter trouble on the jet reconstruction is smaller than to the electron reconstruction but there is still a mismeasurement of the jet energy which in turn causes fake missing energy. Figure 6.8 (left) shows a comparison of the E_T^{miss} distribution of the events triggered by jet plus E_T^{miss} trigger, EF_j75_a4(tc)_EFFS_xe45_loose_noMu before and after the trouble. The number of events is normalized by the corresponding integrated luminosity. This figure indicates the increase in the rate of events triggered by jet plus E_T^{miss} trigger. Similarly, Figure

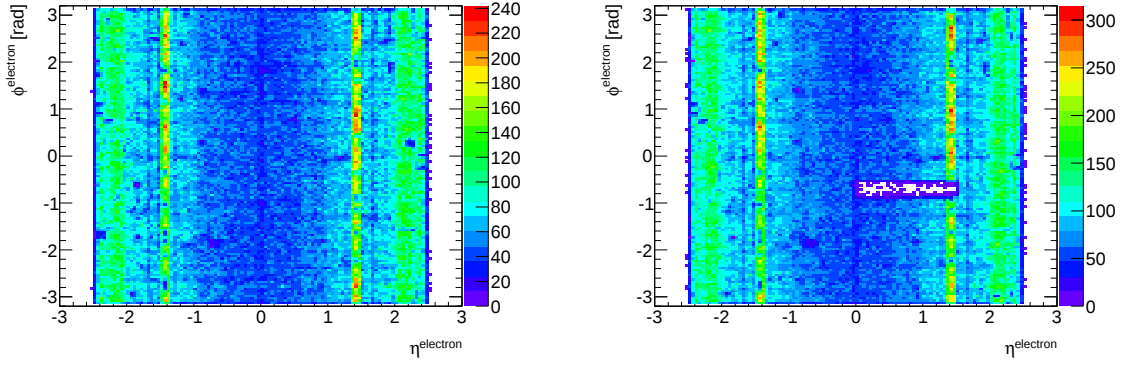


Figure 6.7: η - ϕ distributions of the reconstructed electrons which pass baseline selection before (left) and after (right) the LAr EM calorimeter trouble.

6.8 (right) shows the ϕ of the E_T^{miss} with $E_T^{\text{miss}} > 130$ GeV. The increase in the rate of triggered events can be seen in the dead detector region ($-1.0 \lesssim \phi^{\text{miss}} \lesssim -0.5$).

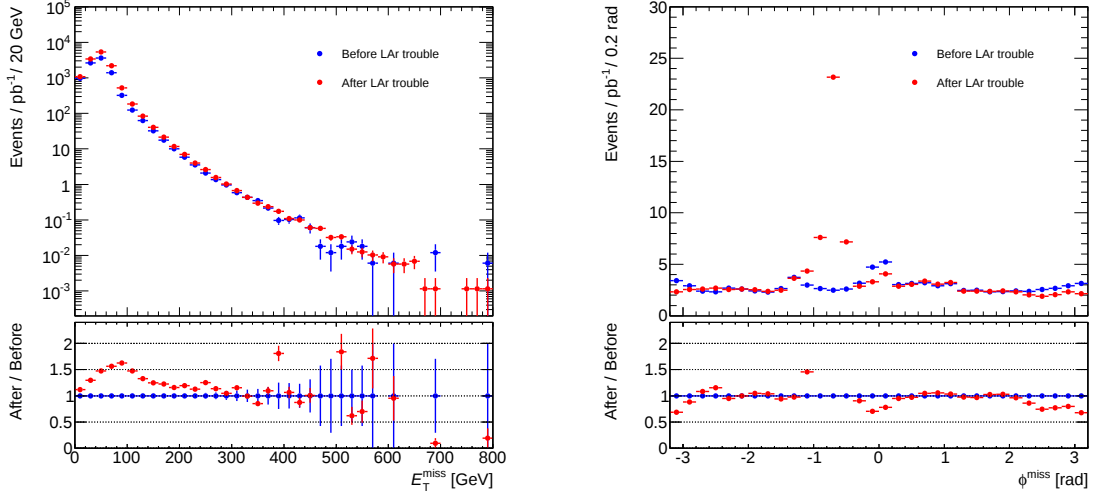


Figure 6.8: The distributions of E_T^{miss} and ϕ^{miss} for events triggered by jet plus E_T^{miss} trigger before (blue filled circles) and after (red filled circles) the LAr calorimeter problem.

To reduce this effect, events containing a jet with $p_T > 50$ GeV in the region of $-0.1 < \eta < 1.5$ and $-0.9 < \phi < -0.5$ are rejected. Considering the jet size (distance parameter of $\Delta R = 0.4$), the region removed is broader than the actual dead region. In MC simulations, events are rejected simply if there are jets with $p_T > 50$ GeV in the dead region. In real data, due to lack of measurements in this dead calorimeter region, the measured jet energy is not correct. To compensate for this, the following variables are used.

- $B_{\text{jet}}^{\text{corr}}$: Fractional energy correction to account for bad cells, derived from jet profiles.

Assuming the jet profile, which gives the energy deposit distribution around the center of the jet, the energy expected to be in the dead calorimeter region is calculated. The profile is obtained from the MC simulation and parametrized as a function of jet p_T , jet η , calorimeter types and layers. This variable is not used in the default jet reconstruction.

- $B_{\text{cell}}^{\text{corr}}$: Fractional energy which is assigned to the bad calorimeter cells estimated from neighboring cells.

Using two-dimensional information of neighboring cells, the average energy density is calculated. The missing energy in the bad cell is estimated by extrapolating the energy density. In the default jet reconstruction, this estimation is applied using the hadronic tile calorimeters only.

Figures 6.9 (right) show the map of the tile calorimeter cells in bad status. As a reference, the map of LAr calorimeter cells in bad status is also shown in the left. The top and bottom figures are for the runs before and after the LAr EM calorimeter trouble respectively. The red squares are masked cells, whose information is totally missing and the black squares are cells in other bad status (noisy and so on), whose information is partially used. Generally the bad tile calorimeter cells are smaller than the dead region of LAr EM calorimeter.

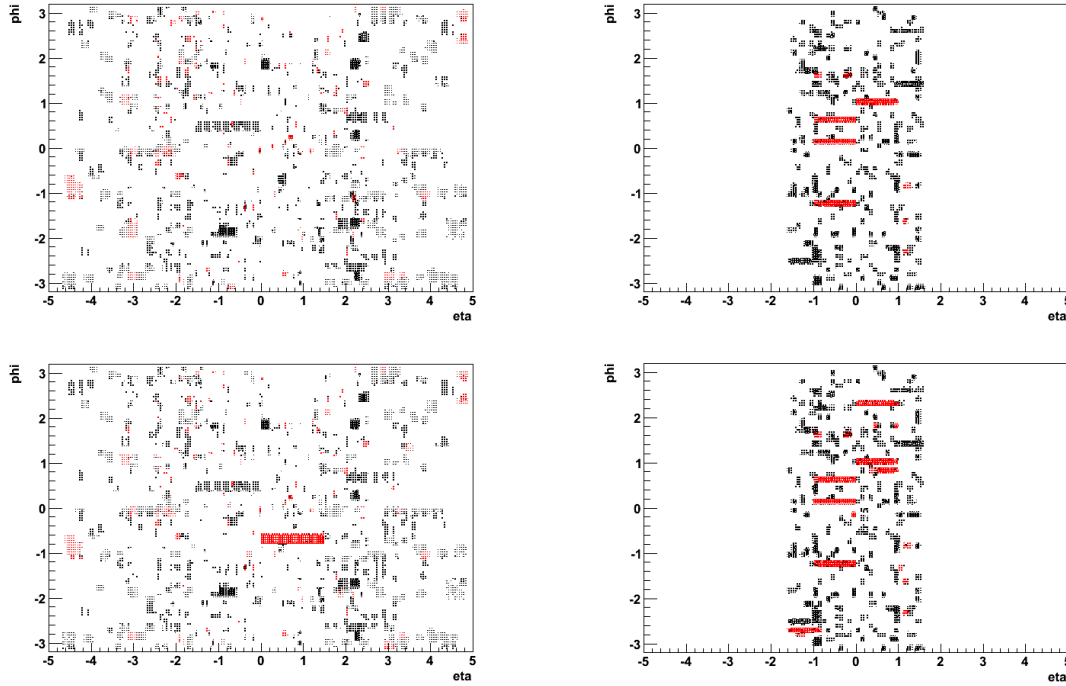


Figure 6.9: The maps of the LAr calorimeter cells (left) and the tile calorimeter cells (right) in bad status. The red squares are masked cells and the black squares are cells in any other bad status (noisy and so on). The top figures are for the run before the LAr EM calorimeter trouble and the bottom figures are for the run after the trouble.

$B_{\text{jet}}^{\text{corr}}$ is not used in the default jet reconstruction but is useful for correcting the missing energy due to the dead LAr EM calorimeter. Since the correction by $B_{\text{cell}}^{\text{corr}}$ is applied in the default jet reconstruction, the energy in dead tile calorimeter cells has usually already been included by default in the η - ϕ region corresponding to the dead region of the LAr EM detector; $B_{\text{cell}}^{\text{corr}}$ therefore needs to be subtracted in order to avoid double counting of the missing energy. The corrected jet p_T in the dead region is calculated by

$$p_T^{\text{corr}} = p_T \frac{1 - B_{\text{cell}}^{\text{corr}}}{1 - B_{\text{jet}}^{\text{corr}}}. \quad (6.1)$$

For data, events are rejected if there are jets with $p_T^{\text{corr}} > 50$ GeV in the dead LAr EM calorimeter region.

Figures 6.10 show the distributions of E_T^{miss} and ϕ^{miss} for events triggered by the jet plus E_T^{miss} trigger after the event veto by jets in the dead region. Used data samples are the same as those used in Figure 6.8. In the region $E_T^{\text{miss}} > 130$ GeV, the E_T^{miss} distributions before and after the trouble agree within the statistical uncertainty.

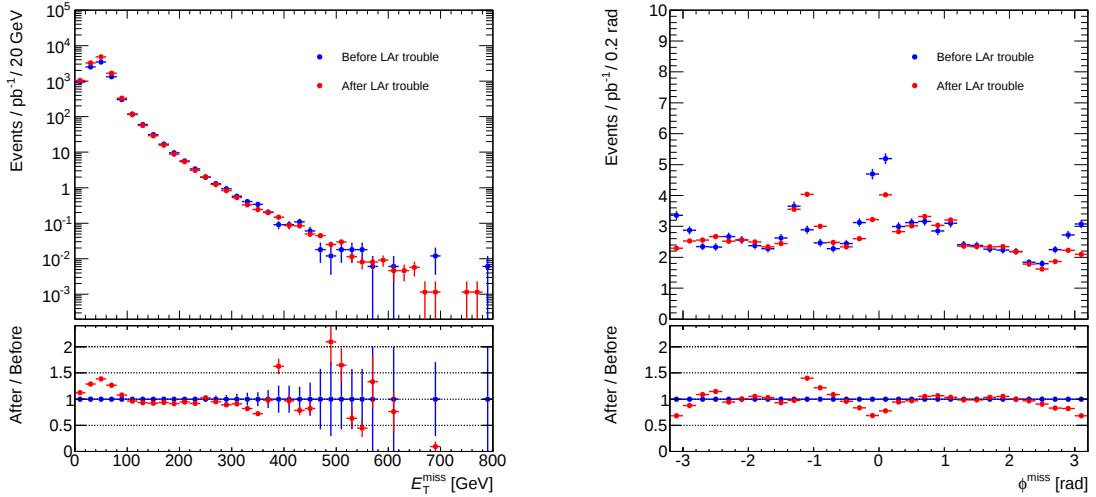


Figure 6.10: The distributions of E_T^{miss} and ϕ^{miss} for events triggered by jet plus E_T^{miss} trigger before (blue filled circles) and after (red filled circles) the LAr calorimeter problem, shown after application of the veto in the problematic LAr calorimeter region.

6.1.8 b -tagging scale factor

To apply the b -tagging scale factor obtained in the section 5.7 to Monte Carlo simulated samples, each MC event is reweighted in the following way as described in Reference [94].

If a jet is b -tagged, a weight is assigned to that jet by the scale factor of the b -tagging efficiency itself.

$$w_{\text{jet}} = \kappa_{\varepsilon}^{\text{data/MC}} = \frac{\varepsilon^{\text{data}}}{\varepsilon^{\text{MC}}}. \quad (6.2)$$

If a jet is not b -tagged, the weight is given by

$$w_{\text{jet}} = \frac{1 - \varepsilon^{\text{data}}}{1 - \varepsilon^{\text{MC}}} = \frac{1 - \kappa_{\varepsilon}^{\text{data/MC}} \varepsilon^{\text{MC}}}{1 - \varepsilon^{\text{MC}}}. \quad (6.3)$$

The weight for an event is obtained by the product of the weights of all the jets in that event.

$$w_{\text{event}} = \prod_{\text{jet}} w_{\text{jet}} \quad (6.4)$$

6.2 No-lepton multi-jet channel

As described in Chapter 2, events with multi-jets including b -jets and with E_T^{miss} are expected for stops or sbottoms from gluino decays. In this section, events without leptons are studied.

6.2.1 Benchmark signals

As a benchmark, the mSUGRA model with $\tan\beta = 40$, $A_0 = -500$ GeV and $\mu > 0$ is considered here. Because of the selection of relatively large $\tan\beta$ and $|A_0|$, the stop and the sbottom are lighter than the other squarks in this model. Figures 6.11 show the gluino masses (top left), the average of light-flavor squark masses (top right), the lightest stop masses (bottom left) and the lightest sbottom masses (bottom right) as a function of m_0 and $m_{1/2}$.

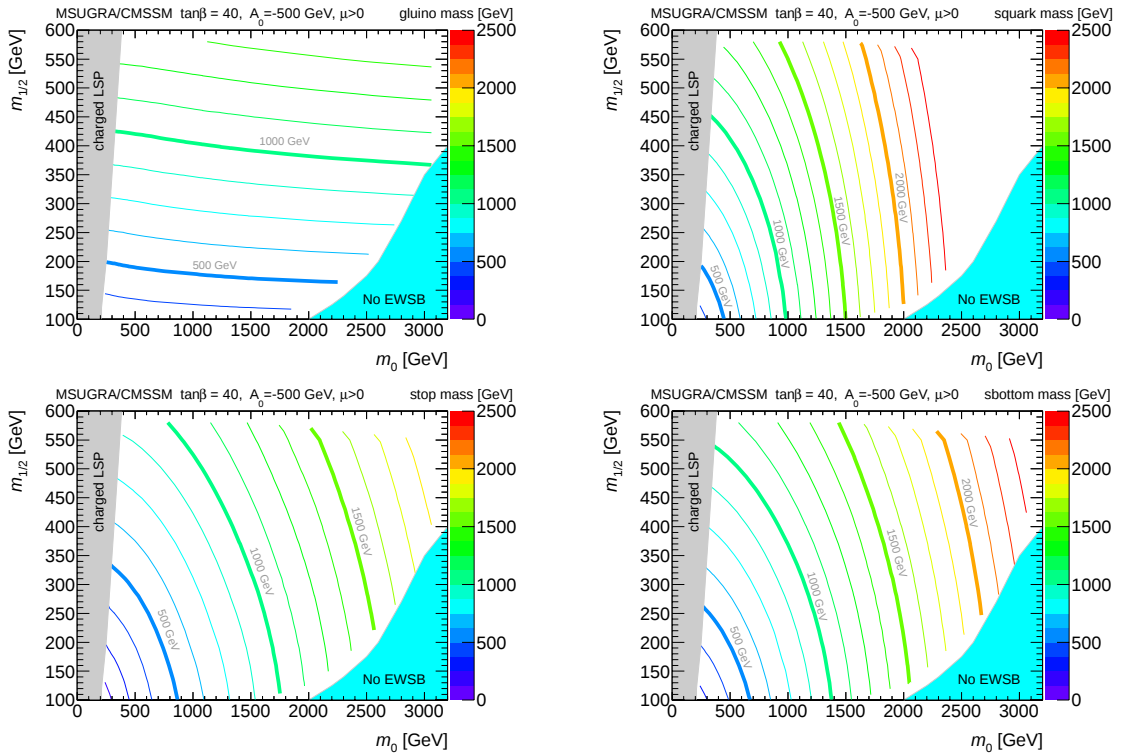


Figure 6.11: The gluino masses (top left), the average of light-flavor squark masses (top right), the lightest stop $\tilde{t}_1$ masses (bottom left) and the lightest sbottom $\tilde{b}_1$ masses (bottom right) in the mSUGRA model with $\tan\beta = 40$, $A_0 = -500$ GeV and $\mu > 0$ as a function of m_0 and $m_{1/2}$.

In large m_0 region, the gluino is lighter than the squarks and the gluino pair production is the dominant colored SUSY particle production process. With the increase of $m_{1/2}$, the squark masses get closer to the gluino mass and the contribution of the gluino and the light-flavor squark associate production gets larger. Table 6.3 shows

the cross-sections of each production process for some representative points. Figure 6.12 shows total cross-sections of colored SUSY particle productions in this model. Cross-sections of signals are calculated to NLO accuracy using PROSPINO [17, 18].

Table 6.3: The masses of colored SUSY particles and cross-sections of the various production processes of colored SUSY particles in the mSUGRA model with $\tan\beta = 40$, $A_0 = -500$ GeV and $\mu > 0$. For squark productions (denoted by $\tilde{q}$), sbottoms and stops are not included. In the cases of sbottom pair and stop pair production, both mass eigenstates ($\tilde{b}_1, \tilde{b}_2$) and ($\tilde{t}_1, \tilde{t}_2$) are included, respectively.

	low mass	large $m_{1/2}$	large m_0
$(m_0[\text{GeV}], m_{1/2}[\text{GeV}])$	(520, 220)	(560, 400)	(1240, 220)
$m_{\tilde{g}}$ [GeV]	587	960	607
$m_{\tilde{q}}$ [GeV]	708	1010	1314
$m_{\tilde{b}_1}$ [GeV]	546	835	981
$m_{\tilde{t}_1}$ [GeV]	418	680	782
$\tilde{g}\tilde{g}$	0.718 pb	7.92 fb	500 fb
$\tilde{g}\tilde{q}$	1.48 pb	43.3 fb	87 fb
$\tilde{q}\tilde{q}$	0.569 pb	40.2 fb	3 fb
$\tilde{b}\tilde{b}$	0.025 pb	0.85 fb	0.2 fb
$\tilde{t}\tilde{t}$	0.153 pb	4.70 fb	1.4 fb

Although the stop and the sbottom are lighter than the other squarks as seen in Figure 6.11, cross-sections of their direct pair productions are much smaller than those of the other colored particle productions. Therefore the main production process of the heavy-flavor squarks is the decay of gluinos. Table 6.4 shows the branching ratios for the gluino decay in the representative points. Even if the mass difference between the gluino and the stop or the sbottom is small (or the gluino is lighter than the stop or the sbottom) and the gluino cannot decay to them directly (it occurs in large m_0 region), decays of the gluino to top quark pair or bottom quark pair via three-body decay are enhanced as explained in Section 2.1. Consequently, events with b -jets in the final state can be expected in most of the $(m_0, m_{1/2})$ parameter space.

6.2.2 Optimization of event selection

To search for SUSY signals without leptons in the final state, events which do not have isolated leptons (electron or muons) are selected. Hadronically-decaying taus are not positively identified. This cut reduces electroweak SM processes such as $W \rightarrow l\nu$.

To select energetic SUSY signal events, large leading jet p_T and high E_T^{miss} are required. This condition is also required to trigger events. As explained in Section 6.1.5, to make the jet plus E_T^{miss} trigger fully efficient, leading jet $p_T > 130$ GeV and $E_T^{\text{miss}} > 130$ GeV are required.

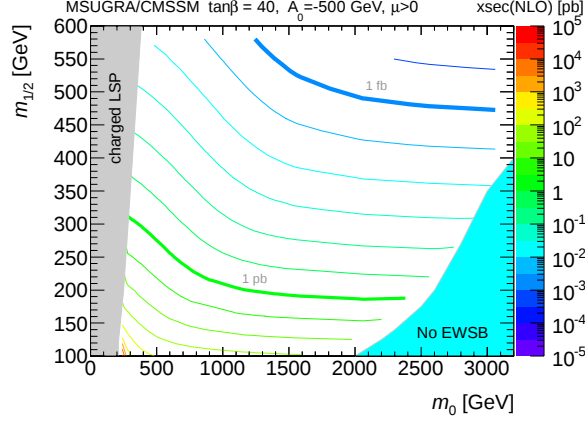


Figure 6.12: Total cross-sections calculated to NLO accuracy of colored SUSY particle productions in the mSUGRA model with $\tan\beta = 40$, $A_0 = -500$ GeV and $\mu > 0$ model as a function of m_0 and $m_{1/2}$.

Table 6.4: The branching ratios for the gluino decay in the mSUGRA model with $\tan\beta = 40$, $A_0 = -500$ GeV and $\mu > 0$. In the table, q and $\bar{q}$ stand for light-flavor quarks and squarks, respectively. Charge conjugations are not explicitly written.

	low mass	large $m_{1/2}$	large m_{10}
$(m_0 \text{ [GeV]}, m_{1/2} \text{ [GeV]})$	(520, 220)	(560, 400)	(1240, 220)
$\tilde{g} \rightarrow \tilde{b}_1 + \bar{b}$	0.793	0.340	0
$\tilde{g} \rightarrow \tilde{b}_2 + \bar{b}$	0	0.066	0
$\tilde{g} \rightarrow \tilde{t}_1 + \bar{t}$	0	0.572	0
$\tilde{g} \rightarrow \tilde{\chi}_1^0 + q + \bar{q}$	0.025	0.003	0.076
$\tilde{g} \rightarrow \tilde{\chi}_1^0 + b + \bar{b}$	0	0	0.033
$\tilde{g} \rightarrow \tilde{\chi}_1^0 + t + \bar{t}$	0	0	0.040
$\tilde{g} \rightarrow \tilde{\chi}_2^0 + q + \bar{q}$	0.044	0.005	0.141
$\tilde{g} \rightarrow \tilde{\chi}_2^0 + b + \bar{b}$	0.019	0	0.155
$\tilde{g} \rightarrow \tilde{\chi}_3^0 + b + \bar{b}$	0	0	0.020
$\tilde{g} \rightarrow \tilde{\chi}_4^0 + b + \bar{b}$	0	0	0.016
$\tilde{g} \rightarrow \tilde{\chi}_1^+ + q + \bar{q}'$	0.088	0.010	0.282
$\tilde{g} \rightarrow \tilde{\chi}_1^+ + b + \bar{t}$	0.021	0.003	0.175
$\tilde{g} \rightarrow \tilde{\chi}_2^+ + b + \bar{t}$	0	0	0.008
others	0.011	0.002	0.054

SUSY signals considered here have the hard multi-jet final state. Figures 6.13 show the distributions of the number of jets for $p_T^{\text{jet}} > 50$ GeV (left) and $p_T^{\text{jet}} > 80$ GeV (right) shown for SM backgrounds estimated by MC simulations and SUSY reference points of $(m_0, m_{1/2}) = (1240 \text{ GeV}, 220 \text{ GeV})$, $(560 \text{ GeV}, 400 \text{ GeV})$ in the mSUGRA model. Comparing the distributions for a fixed number of jets, the enhancement of SUSY signals is higher for jet $p_T > 80$ GeV than for jet $p_T > 50$ GeV. At the same time, with the increase in the number of jets, the systematic uncertainty from the jet reconstruction becomes larger. Therefore a smaller number of jets above the high p_T threshold is required. To keep high acceptance for the signal and high rejection for the SM backgrounds, four jets with $p_T > 80$ GeV are required.

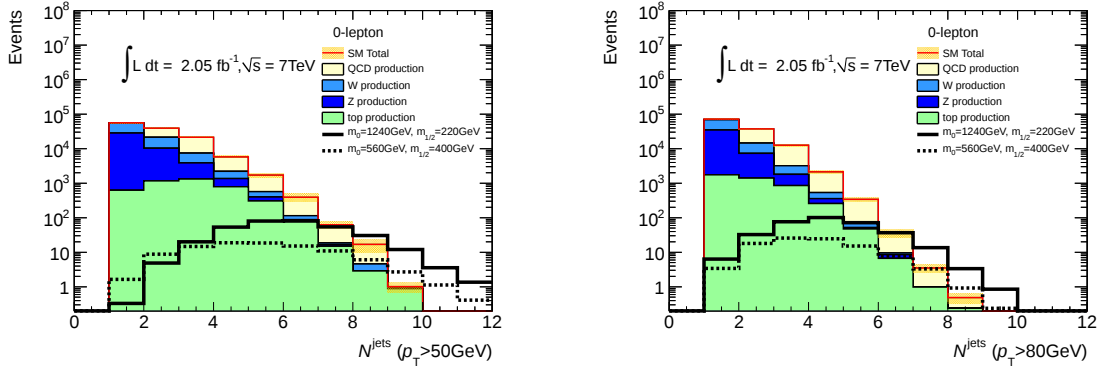


Figure 6.13: The distributions of the number of jets for $p_T > 50$ GeV (left) and $p_T > 80$ GeV after requiring the leading jet $p_T > 130$ GeV and $E_T^{\text{miss}} > 130$ GeV in the no-lepton channel. The sum of the SM prediction is shown by the red lines with the orange error bands showing the statistical uncertainty of the MC simulations. The MC simulated SUSY signals are shown by the black solid ($m_0 = 1240 \text{ GeV}$, $m_{1/2} = 220 \text{ GeV}$) and broken ($m_0 = 560 \text{ GeV}$, $m_{1/2} = 400 \text{ GeV}$) lines.

Since leptons are not required in this selection, the QCD multi-jet is the dominant background process. This background is reduced by a cut on the $\min \Delta\phi_{1,2,3}$ defined by the minimum of $\Delta\phi$ between three leading jets and the E_T^{miss} vector,

$$\min \Delta\phi_{1,2,3} = \min_{i=1}^3 |\phi_i^{\text{jet}} - \phi^{\text{miss}}|. \quad (6.5)$$

Since the missing energy in the QCD multi-jet events arise from the mismeasurement of a jet or the leptonic decay of heavy-flavor hadrons in a jet, the missing energy direction tends to point in the same direction as one of the hard jets. Figure 6.14 (left) shows this distribution with the reference SUSY signals. If the events have true missing energy sources like SUSY signals and $W \rightarrow l\nu$ process, this distribution becomes flat. On the other hand, QCD multi-jet events tend to have small $\min \Delta\phi_{1,2,3}$. By selecting the events with $\min \Delta\phi_{1,2,3} > 0.4$ rad, the QCD background is effectively reduced.

Most of the QCD multi-jet events are removed by the above cut, but fourth leading jet can be still the source of the missing energy although the probability is low compared

to the leading three jets. Therefore a looser cut, $\Delta\phi_4 \equiv |\phi_4^{\text{jet}} - \phi^{\text{miss}}| > 0.2$ rad is used for the fourth leading jet.

QCD multi-jet events, where the missing energy is derived from several jets or where the missing energy points in the direction opposite to the mismeasured jet, are not removed by the above cut. Even in this case, the missing energy in QCD multi-jet events is not significantly large compared to the sum of all calorimeter activity. To reduce QCD events using this mechanism, the effective mass defined by the following equation is used.

$$m_{\text{eff}} = E_T^{\text{miss}} + \sum_{i=1}^4 \left(p_T^{\text{jet}} \right)_i \quad (6.6)$$

Taking the ratio $E_T^{\text{miss}}/m_{\text{eff}}$, QCD multi-jet events have smaller values compared to the other SM backgrounds and SUSY signals as shown in Figure 6.14 (right).

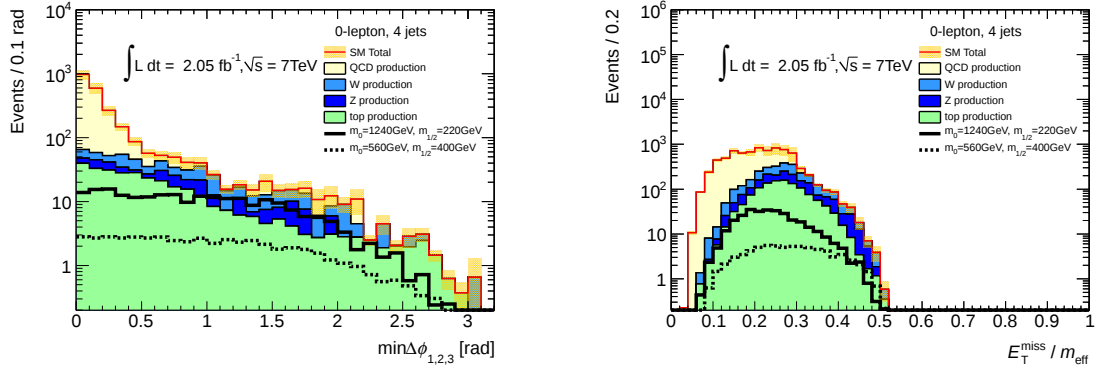


Figure 6.14: The distributions of $\min\Delta\phi_{1,2,3}$ (left) and $E_T^{\text{miss}}/m_{\text{eff}}$ after requiring the leading jet $p_T > 130$ GeV, four jets with $p_T > 80$ GeV and $E_T^{\text{miss}} > 130$ GeV selection in the no-lepton channel.

As explained earlier, since the branching ratios for the gluino decay to the stop or the sbottom are higher in the model under consideration here, the final states contains b -jets. Figure 6.15 (left) shows the distribution of the multiplicity of b -tagged jets after the four-jet cut. By requiring at least one b -tagged jet, most W/Z +jets events are removed.

Finally to enhance the hard SUSY signals, the effective mass m_{eff} defined above is used. The effective mass is expected to reflect the total masses of initially produced particles. Therefore high-mass SUSY signals have larger m_{eff} . Since the optimum m_{eff} cut depends on the masses of SUSY particles, the optimum cut is chosen for each signal point. Figure 6.15 shows the m_{eff} distribution after all other cuts.

These event selection criteria are summarized as follows.

- lepton veto (for electrons $p_T > 20$ GeV and for muons $p_T > 10$ GeV)
- leading jet $p_T > 130$ GeV
- $E_T^{\text{miss}} > 130$ GeV

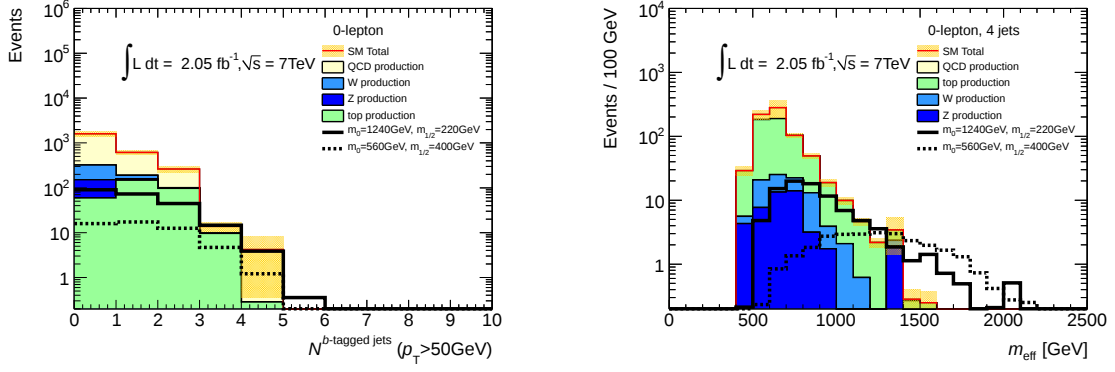


Figure 6.15: The multiplicity of b -tagged jet distribution after requiring four jets with $p_T > 80$ GeV (left). The effective mass m_{eff} after all other selection cuts (right).

- 4th leading jet $p_T > 80$ GeV
- $\min \Delta\phi_{1,2,3} > 0.4$ rad
- $\Delta\phi(4\text{th jet} - E_T^{\text{miss}}) > 0.2$ rad
- $E_T^{\text{miss}}/m_{\text{eff}} > 0.2$
- at least one b -tagged jet with $p_T > 50$ GeV
- optimum m_{eff} cut as follows.

To determine the best m_{eff} cut, the cut which gives the largest signal significance is selected for each signal point. The significance is defined as follows [95],

$$\mathcal{S} = \sqrt{2[(s+b)\ln(1+s/b) - s]} \quad (6.7)$$

Here s and b are the number of events of SUSY signal and SM backgrounds after the event selection. Figure 6.16 shows the best m_{eff} cut for each signal point. Since the best signal region depends on the practical background estimation and the systematic uncertainties, it will be determined after those numbers are fixed. To cover all the signal points, three m_{eff} signal regions, $m > 500$ GeV, $m > 750$ GeV, $m_{\text{eff}} > 1000$ GeV are defined.

6.2.3 SM background estimation

Top estimation

The most dominant SM background in this channel is the $t\bar{t}$ process. The main decay mode is that one of the top quarks decays to a tau lepton and the tau decays hadronically, and the other top quark decays hadronically. The neutrinos lead the missing

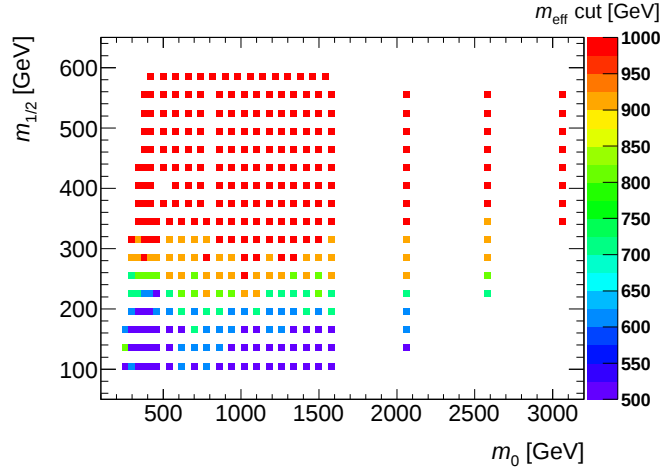


Figure 6.16: The best m_{eff} cut for each mSUGRA signal point in the no-lepton multi-jet channel.

energy and the jet multiplicity tends to be large. Also if one top quark decays leptonically but this lepton (electron or muon) is missed or misidentified as a jet, the event enters the no-lepton sample.

If the $t\bar{t}$ is estimated from Monte Carlo simulation only, systematic uncertainties tend to be large due to the stiff cuts on the event kinematics. Table 6.6 (top) is the summary of the dominant systematic uncertainties to the $t\bar{t}$ Monte Carlo simulation.

Since single-top productions (after the selection, the main contribution is from the $t + W$ process) are similar processes to the $t\bar{t}$ production, the systematic uncertainties obtained for the $t\bar{t}$ process are also applied. The expected numbers of events shown in Table 6.6 are the sum of the $t\bar{t}$ and single-top processes.

The systematic uncertainties considered here are as follows.

Jet energy scale uncertainty For the jet energy scale (JES) uncertainty, the numbers described in Section 5.2.4 are used. The variation of jet energy scale is also propagated to the $E_{\text{T}}^{\text{miss}}$ calculation. The effect of JES variation on the m_{eff} distribution and acceptance is shown in Figure 6.17 (left); the m_{eff} distributions is shown after all other cuts have been applied. The JES uncertainty changes the acceptance since it in effect changes the thresholds of jet p_{T} and $E_{\text{T}}^{\text{miss}}$. At higher m_{eff} range, the relative shifts by the JES uncertainty is larger than the lower m_{eff} range.

b -tagging uncertainty The systematic uncertainty from b -tagging is investigated by shifting the scale factors between data and simulations for b -tagging efficiency and mistag rate by 1σ of their uncertainties. The effect of b -tagging variation to the m_{eff} distribution and acceptance is shown in Figure 6.17 (right). The b -tagging uncertainty affects mainly the cut on the number of b -tagged jet; the distribution of other variables are not much affected.

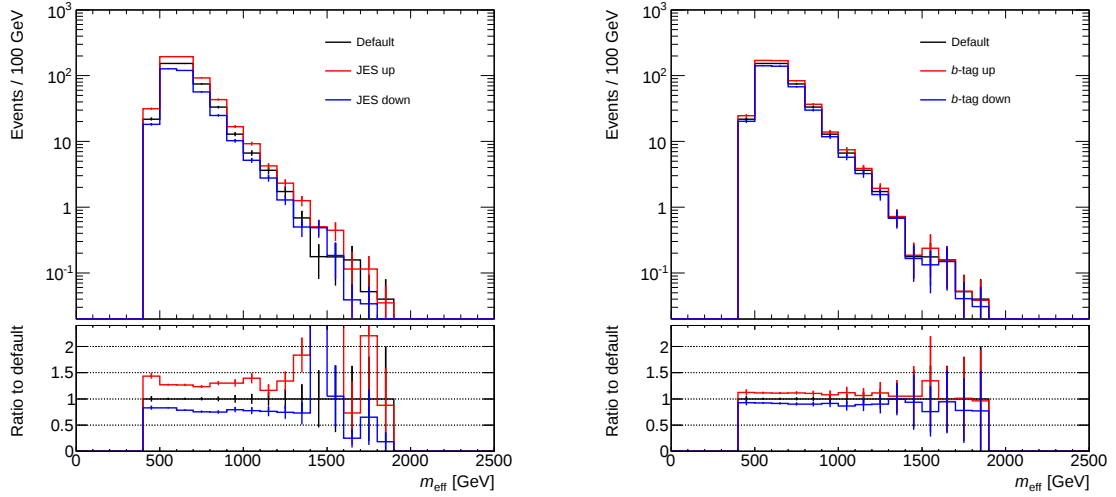


Figure 6.17: The effects of the jet energy scale variation (left) and the b -tagging efficiency variation (right) within their systematic uncertainty on the $t\bar{t}$ Monte Carlo simulation in no-lepton multi-jet channel.

Luminosity uncertainty For the systematic uncertainty on the integrated luminosity, 3.7 % is assigned as described in Section 4.1.1.

ISR/FSR To study the effect of the initial state radiation (ISR) and the final state radiation (FSR) on $t\bar{t}$ process, the ACERMC [96] generator interface to the PYTHIA shower model is used. The parameters controlling ISR and FSR are varied within a range consistent with the experimental data as in Reference [97]. Half of the relative difference between the maximum and the minimum variations is assigned to the nominal background estimated by MC@NLO as this systematic uncertainty. Table 6.5 summarizes the ISR/FSR parameters that were varied. The meaning of each parameters is as follows.

- Q^2 : the Q^2 scale of the $2 \rightarrow 2$ hard scattering
- $k_{\perp}^2$: the squared transverse momentum evolution scale in the space-like parton-shower evolution
- Λ_{time} : Λ value used in running α_s for time-like parton showers except for showers in the decay of a resonance.
- m_{min} : invariant mass cut-off of parton showers, below which partons are not assumed to radiate.

Figure 6.18 (left) shows the effect of the ISR/FSR parameter variations on the m_{eff} distributions. The envelope of the distributions is taken as the systematic uncertainty.

Table 6.5: The variation of the parameters controlling ISR and FSR for $t\bar{t}$ MC simulation. Each parameter is scaled from the default value by the factor shown in the table.

	Q^2	$k_{\perp}^2$	Λ_{time}	m_{min}
ISR down (0)	0.5	4.0	1.0	1.0
ISR down (1)	1.0	3.0	1.0	1.0
ISR down (2)	2.0	2.0	1.0	1.0
ISR up (0)	6.0	0.3	1.0	1.0
ISR up (1)	5.0	0.5	1.0	1.0
ISR up (2)	4.5	0.75	1.0	1.0
FSR down (0)	1.0	1.0	0.5	2.0
FSR down (1)	1.0	1.0	0.75	2.0
FSR up (0)	1.0	1.0	2.0	0.5
FSR up (1)	1.0	1.0	1.2	0.5
ISR down, FSR down	0.5	4.0	0.5	2.0
ISR up , FSR up	6.0	0.3	2.0	0.5

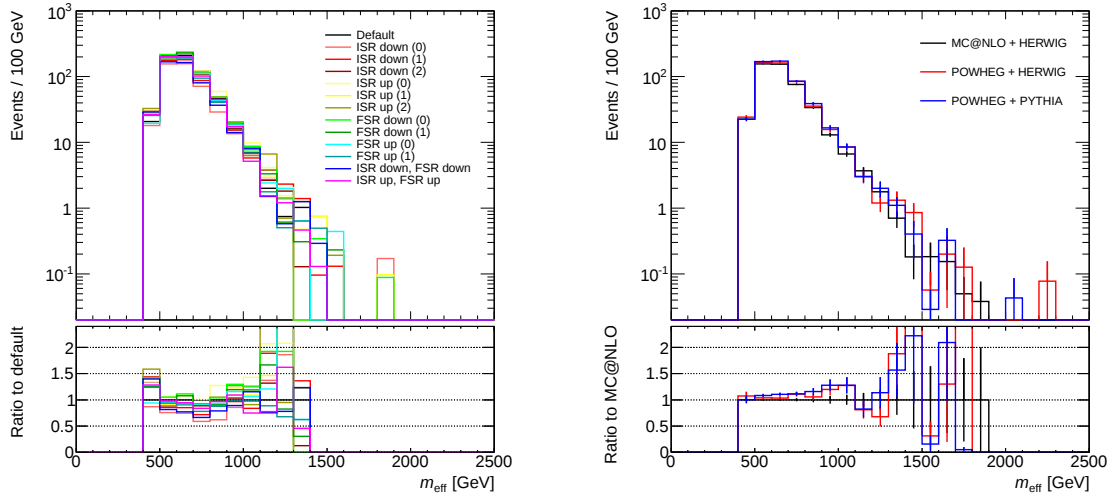


Figure 6.18: The effects of the ISR/FSR variations (left) and the generator/shower modeling difference (right) to the m_{eff} distribution of $t\bar{t}$ MC simulation in no-lepton multi-jet channel.

Generator The generator dependence is checked by using POWHEG [98] instead of MC@NLO. Both generators are interfaced with fragmentation and hadronization model using HERWIG-JIMMY as same as the nominal MC@NLO simulation. Half of the difference between them is assigned as the systematic uncertainty. Figure 6.18 (right) shows the effect of the generator difference to the m_{eff} distribution. POWHEG simulates harder m_{eff} .

Shower modeling The systematic uncertainty from the shower modeling is studied by changing interface for POWHEG. One is HERWIG and the other is PYTHIA. Again, half of the relative difference between the two cases is taken as the systematic uncertainty. Figure 6.18 shows the effect of the shower modeling difference for POWHEG $t\bar{t}$ MC simulation. The effect is found to be much smaller than the generator difference.

The systematic uncertainties are reduced by considering a control region with similar event selection criteria, but where one lepton is required. Then Monte Carlo simulation of the top productions ($t\bar{t}$ and single top) are normalized to data, after subtracting the contamination from other SM processes using MC simulations. The normalization factor obtained in this control region is applied to the top events in no-lepton signal regions. That is, the top events in the signal regions (SR), $N_{\text{SR}}^{\text{top}}$ is estimated by

$$N_{\text{top}}^{\text{SR}} = \frac{N_{\text{data}}^{\text{CR}} - N_{\text{non-top,MC}}^{\text{CR}}}{N_{\text{top,MC}}^{\text{CR}}} N_{\text{top,MC}}^{\text{SR}} \quad (6.8)$$

where $N_{\text{data}}^{\text{CR}}$, $N_{\text{non-top,MC}}^{\text{CR}}$ and $N_{\text{top,MC}}^{\text{CR}}$ are the number of events in the control regions (CR) for data, non-top MC simulation and top MC simulation, respectively, and $N_{\text{top,MC}}^{\text{SR}}$ is the number of events in the signal regions from the top MC simulation. Since the dominant background process in the one-lepton control region is also top pair with semi-leptonic decay, the kinematics is similar to that of the no-lepton signal regions.

The event selection is as follows.

- exactly one *tight* lepton ($p_{\text{T}} > 25$ GeV for an electron and $p_{\text{T}} > 20$ GeV for a muon) and no additional leptons with the *loose* criteria
- $40 \text{ GeV} < m_{\text{T}} < 100 \text{ GeV}$ (m_{T} defined by Equation 6.17)
- $E_{\text{T}}^{\text{miss}} > 80 \text{ GeV}$
- leading jet $p_{\text{T}} > 60 \text{ GeV}$
- 4th leading jet $p_{\text{T}} > 50 \text{ GeV}$
- at least one *b*-tagged jet with $p_{\text{T}} > 50 \text{ GeV}$

Use of one-lepton control region will introduce other systematic uncertainties related to lepton identifications but as they are smaller than the other systematic uncertainties described in Table 6.6, the total uncertainty is reduced by normalizing the MC simulated sample to data in the control region. SUSY signals with smaller mass can contribute even in the background enhanced control region. Therefore its contribution to the control region is assigned as an additional systematic uncertainty and if the total systematic uncertainty with the MC-normalized estimation is smaller than MC-only estimation, MC-normalized estimation is used. Figure 6.19 shows the ratio of SUSY signals to the top events from the MC simulations in the one-lepton control region to see the signal contamination.

Figure 6.20 shows distributions of E_T^{miss} , m_{eff} and the leading jet p_T in the one-lepton control region comparing data and default MC simulations. The error bands shown are the sum in quadrature of the JES uncertainty and the b -tagging efficiency uncertainty. The MC simulation reproduces the shape of data within the systematic uncertainty. Other variables used in event selection are also agree between data and MC simulation within the systematic uncertainty. The purity of top events in the control regions is 89 % and the top normalization factor obtained is 1.03 ± 0.04 (stat.).

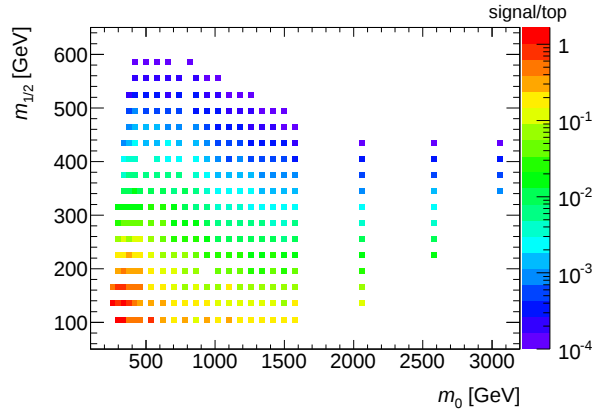


Figure 6.19: The ratio of SUSY signal in the mSUGRA model to the top background in the one-lepton low- m_T control region.

W +jets estimation

The second largest SM background is $W + b\bar{b}$ process. Here again a control region is prepared to determine the normalization of MC simulation. For cases where the signal contribution to the control region is small, the W +jets background can be estimated by the equation

$$N_W^{\text{SR}} = \frac{N_{\text{data}}^{\text{CR}} - N_{\text{non-}W}^{\text{CR}}}{N_{W,\text{MC}}^{\text{CR}}} N_{W,\text{MC}}^{\text{SR}}. \quad (6.9)$$

When the MC samples are normalized to data, the signal contribution to the W +jets control region is taken as an additional systematic uncertainty. On the other hand,

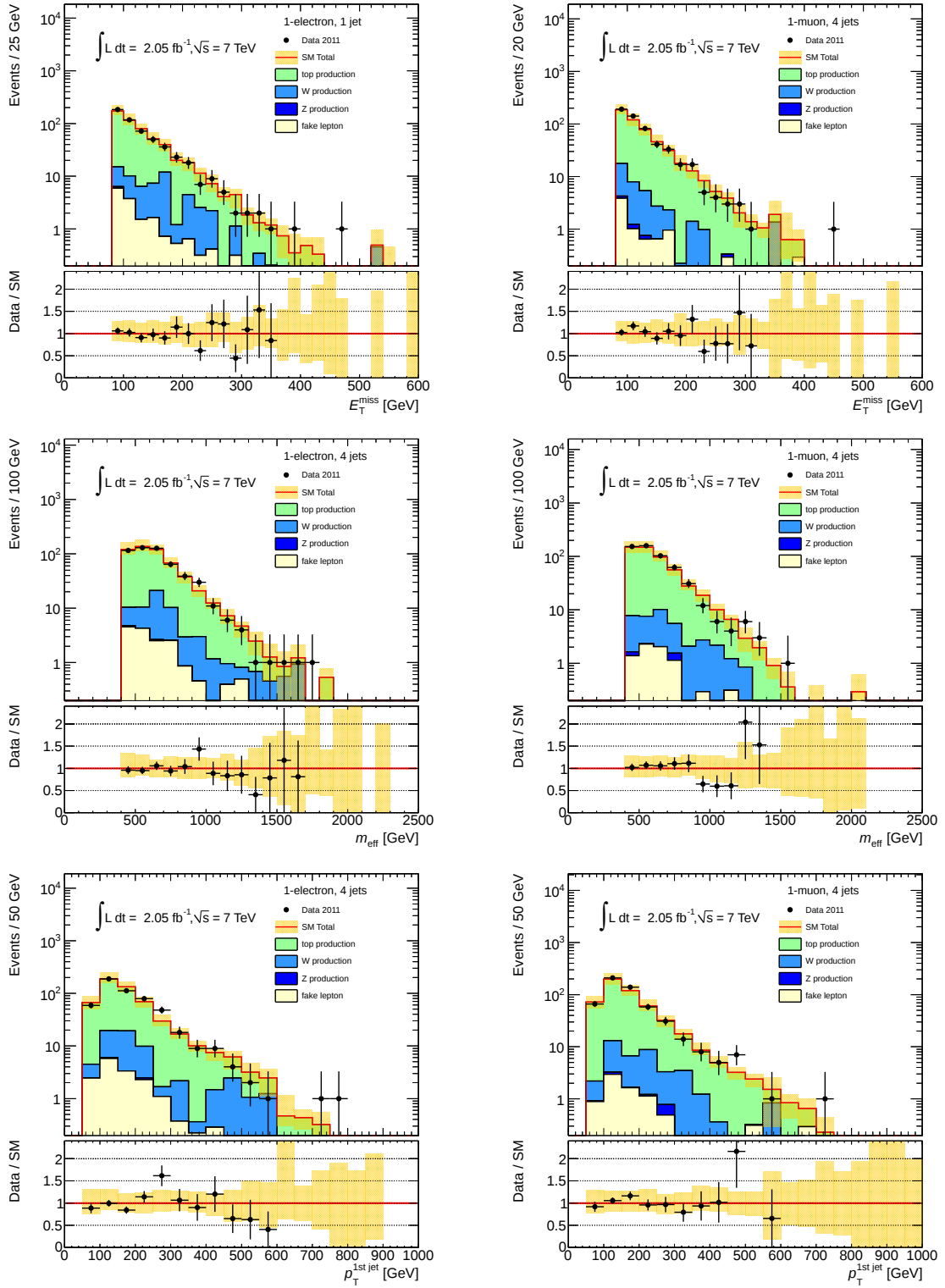


Figure 6.20: The distributions of E_T^{miss} (top), m_{eff} (middle) and leading jet p_T (bottom) in the one-lepton control region defined by $40 \text{ GeV} < m_T < 100 \text{ GeV}$ for the estimation of top events. The left figures are for the electron channel and the right are for the muon channel.

Table 6.6: The estimated number of top events in the no-lepton multi-jet signal regions and the associated systematic uncertainties. The top table is without normalizing the MC samples to data and the bottom are with the normalization.

without MC normalization			
	$m_{\text{eff}} > 500 \text{ GeV}$	$m_{\text{eff}} > 750 \text{ GeV}$	$m_{\text{eff}} > 1000 \text{ GeV}$
events	94	40	7.4
Jet energy scale	$^{+29}_{-24} \%$	$^{+35}_{-23} \%$	$^{+46}_{-27} \%$
b -tagging efficiency	$\pm 10 \%$	$^{+9.1}_{-10} \%$	$^{+9.8}_{-12} \%$
Luminosity	$\pm 3.7 \%$	$\pm 3.7 \%$	$\pm 3.7 \%$
ISR/FSR	$\pm 28 \%$	$\pm 33 \%$	$\pm 39 \%$
Generator	$\pm 7 \%$	$\pm 13 \%$	$\pm 14 \%$
Shower modeling	$\pm 0.6 \%$	$\pm 2.5 \%$	$\pm 6.4 \%$
Cross section	$^{+6.9}_{-9.5} \%$	$^{+6.9}_{-9.5} \%$	$^{+6.9}_{-9.6} \%$
Uncertainty sum	$^{+43}_{-40} \%$	$^{+51}_{-44} \%$	$^{+62}_{-51} \%$
with MC normalization			
	$m_{\text{eff}} > 500 \text{ GeV}$	$m_{\text{eff}} > 750 \text{ GeV}$	$m_{\text{eff}} > 1000 \text{ GeV}$
events	97	41	7.6
Jet energy scale	$^{+0}_{-3.5} \%$	$^{+0}_{-7.3} \%$	$^{+7.1}_{-4.7} \%$
b -tagging efficiency	$^{+0}_{-2.6} \%$	$^{+0}_{-3.6} \%$	$^{+0}_{-3.0} \%$
ISR/FSR	$\pm 13 \%$	$\pm 16 \%$	$\pm 29 \%$
Generator	$\pm 3.5 \%$	$\pm 15 \%$	$\pm 16 \%$
Shower modeling	$\pm 1.2 \%$	$\pm 2.9 \%$	$\pm 5.0 \%$
Statics	$\pm 3.7 \%$	$\pm 3.7 \%$	$\pm 3.7 \%$
Electron trigger	$\pm 0.2 \%$	$\pm 0.2 \%$	$\pm 0.2 \%$
Electron reconstruction	$\pm 0.8 \%$	$\pm 0.8 \%$	$\pm 0.8 \%$
Muon trigger	$\pm 0.5 \%$	$\pm 0.5 \%$	$\pm 0.5 \%$
Muon reconstruction	$\pm 0.3 \%$	$\pm 0.3 \%$	$\pm 0.3 \%$
Uncertainty sum	$^{+14}_{-15} \%$	$\pm 20 \%$	$\pm 38 \%$

when the signal contribution in the control region is too large, the background can be estimated purely from the MC simulation. In practice, both methods are tried and the method that gives the smaller total uncertainty is used to estimate the background.

Since $t\bar{t}$ events are dominant after four-jet selection, one-jet exclusive region is used for W +jets control region. The event selection is as follows.

- exactly one *tight* lepton ($p_T > 25$ GeV for an electron and $p_T > 20$ GeV for a muon) and no additional leptons with *loose* criteria
- $40 \text{ GeV} < m_T < 100 \text{ GeV}$ (m_T defined by Equation 6.17)
- $E_T^{\text{miss}} > 30 \text{ GeV}$
- leading jet $p_T > 60 \text{ GeV}$
- 2nd leading jet $p_T \leq 50 \text{ GeV}$
- leading jet is b -tagged

Figures 6.21 show the distributions of E_T^{miss} and leading jet p_T (b -tagged) in the electron and muon channels before the normalization of MC simulated samples to data. The error bands shown are the sum of the JES uncertainty and b -tagging efficiency uncertainty. The distributions of data and MC simulation agree within the systematic uncertainty. The purity of W +jets events in the control regions is 61 % and the normalization factor obtained is 1.02 ± 0.03 (stat.). Table 6.7 shows the estimated number of W +jets events with and without normalization. The JES and b -tagging systematic uncertainties are assigned in the same way. For the cross-section uncertainty, 4 % and 17 % are assigned to the associated production of light-flavor and heavy-flavor jets, respectively. An additional uncertainty of 24 % per parton (added in quadrature) is assigned to take into account the MLM matching used in the production of the ALPGEN samples.

QCD multi-jet estimation

The QCD multi-jet events which pass large E_T^{miss} cut are due to mismeasurement of the jet energy or to the leptonic decay of heavy-flavor hadrons in jets. Monte Carlo simulation cannot describe well such events for a number of reasons. The first is that that a large number of events is required to simulate such rare events. The second is that it is difficult to validate such a rare event. Therefore this background needs to be estimated in a data-driven way.

The method used in this estimation is called *jet smearing method* [99]. The method proceeds as follows.

1. Collect low E_T^{miss} significance (defined by Equation 6.10) events from the data; these events are dominated by the QCD multi-jet process.
2. Prepare jet energy smearing functions from the Monte Carlo simulation. The differences between data and MC are corrected by in-situ measurements.

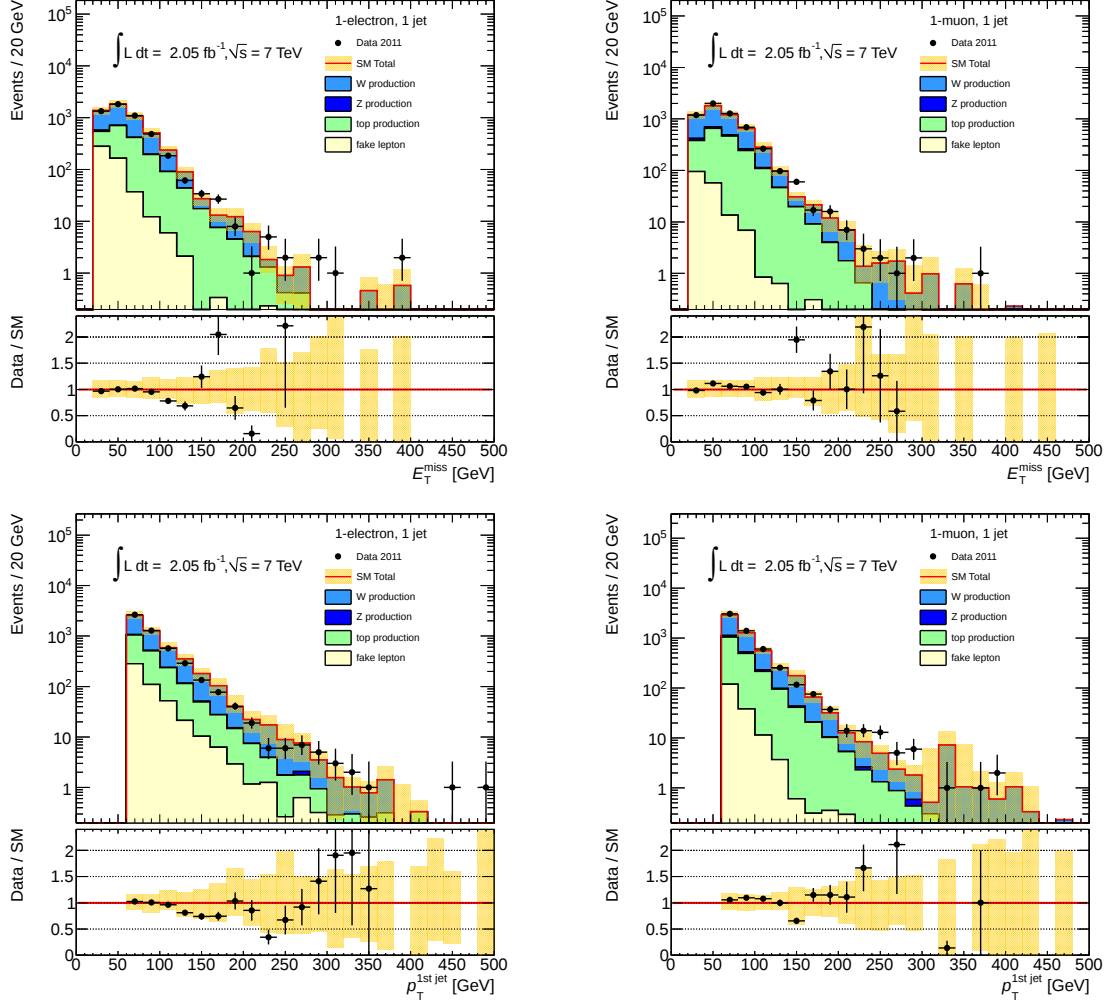


Figure 6.21: The distributions of E_T^{miss} (top) and the leading jet p_T (bottom) in the one-lepton $W + b\bar{b}$ control region. The left figures show the electron channel and the right the muon channel.

Table 6.7: The estimated number of W +jets events in the no-lepton multi-jet channel with and without the normalization of MC samples to data in the one-lepton control region. The systematic uncertainties are also shown.

without MC normalization			
	$m_{\text{eff}} > 500 \text{ GeV}$	$m_{\text{eff}} > 750 \text{ GeV}$	$m_{\text{eff}} > 1000 \text{ GeV}$
events	10.9	7.7	1.8
Jet energy scale	$^{+15}_{-28} \%$	$^{+21}_{-28} \%$	$^{+68}_{-62} \%$
b -tagging efficiency	$^{+15}_{-20} \%$	$^{+19}_{-26} \%$	$^{+28}_{-26} \%$
Luminosity	$\pm 3.7 \%$	$\pm 3.7 \%$	± 3.7
Cross section	$\pm 8 \%$	$\pm 7 \%$	$\pm 8 \%$
Number of parton	$\pm 49 \%$	$\pm 49 \%$	$\pm 49 \%$
Uncertainty sum	$^{+54}_{-60} \%$	$^{+57}_{-63} \%$	$^{+89}_{-83} \%$
with MC normalization			
	$m_{\text{eff}} > 500 \text{ GeV}$	$m_{\text{eff}} > 750 \text{ GeV}$	$m_{\text{eff}} > 1000 \text{ GeV}$
events	11.2	7.9	1.9
Jet energy scale	$^{+12}_{-21} \%$	$^{+18}_{-21} \%$	$^{+64}_{-58} \%$
b -tagging efficiency	$^{+7.2}_{-15} \%$	$^{+0}_{-12} \%$	$^{+0}_{-5.1} \%$
Number of parton	$^{+26}_{-37} \%$	$^{+26}_{-38} \%$	$^{+25}_{-37} \%$
Statistics	$\pm 3.2 \%$	$\pm 3.2 \%$	$\pm 3.2 \%$
Electron trigger	$\pm 0.2 \%$	$\pm 0.2 \%$	$\pm 0.2 \%$
Electron reconstruction	$\pm 0.8 \%$	$\pm 0.8 \%$	$\pm 0.8 \%$
Muon trigger	$\pm 0.5 \%$	$\pm 0.5 \%$	$\pm 0.5 \%$
Muon reconstruction	$\pm 0.3 \%$	$\pm 0.3 \%$	$\pm 0.3 \%$
Uncertainty sum	$^{+29}_{-45} \%$	$^{+32}_{-45} \%$	$^{+69}_{-69} \%$

3. Smear the jet p_T in the data samples which have low E_T^{miss} significance, using the jet smearing function obtained in the above. Repeat this procedure many times (in this analysis 10000 times) for one event and generate enough jet p_T smeared samples.
4. Apply the same signal selection to the smeared samples. The number of QCD multi-jet events in the signal region can be estimated by normalizing these samples to data in a QCD multi-jet dominant region. In the case of a signal whose contribution in the QCD control region is large, the smeared samples are normalized to the MC simulation of the QCD di-jet process.

In the following, the detail of these procedures are described.

Seed event selection The seed events are collected from data samples using the single-jet triggers with different p_T thresholds as shown in Table 6.8. Since the lower p_T threshold triggers are highly prescaled, the appropriate trigger is chosen to collect the required leading jet p_T range from these triggers. The triggers are not fully efficient just above the p_T thresholds; higher p_T ranges than the thresholds are used for the analysis.

To select events with small jet energy fluctuation, the region of small E_T^{miss} significance is used. E_T^{miss} significance, S is defined as follows,

$$S = \frac{E_T^{\text{miss}}}{\sqrt{\Sigma E_T}}. \quad (6.10)$$

Here the sum over E_T is for all reconstructed objects and also the clusters not belonging to any selected objects. Figure 6.22 shows the distribution of S collected by the single-jet triggers. The events with $S < 0.8$ [$\text{GeV}^{1/2}$] are used as seed events for the jet smearing method.

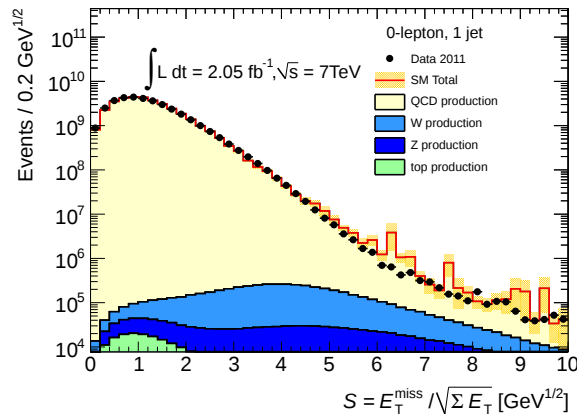


Figure 6.22: The distribution of E_T^{miss} significance after the several single-jet triggers. The SM contributions shown are from Monte Carlo simulation.

Table 6.8: The single-jet triggers used to collect the seed events for the jet smearing method. The threshold of each trigger and the corresponding leading jet p_T range used in the analysis are also shown.

trigger name	trigger threshold	used range
EF_j30_a4(tc)_EFTS	$p_T > 30 \text{ GeV}$	$p_T^{\text{1st jet}} < 90 \text{ GeV}$
EF_j40_a4(tc)_EFTS	$p_T > 40 \text{ GeV}$	$90 \text{ GeV} \leq p_T^{\text{1st jet}} < 110 \text{ GeV}$
EF_j55_a4(tc)_EFTS	$p_T > 55 \text{ GeV}$	$110 \text{ GeV} \leq p_T^{\text{1st jet}} < 140 \text{ GeV}$
EF_j75_a4(tc)_EFTS	$p_T > 75 \text{ GeV}$	$140 \text{ GeV} \leq p_T^{\text{1st jet}} < 180 \text{ GeV}$
EF_j100_a4(tc)_EFTS	$p_T > 100 \text{ GeV}$	$180 \text{ GeV} \leq p_T^{\text{1st jet}} < 230 \text{ GeV}$
EF_j135_a4(tc)_EFTS	$p_T > 135 \text{ GeV}$	$230 \text{ GeV} \leq p_T^{\text{1st jet}} < 300 \text{ GeV}$
EF_j180_a4(tc)_EFTS	$p_T > 180 \text{ GeV}$	$300 \text{ GeV} \leq p_T^{\text{1st jet}} < 400 \text{ GeV}$
EF_j240_a4(tc)_EFTS	$p_T > 240 \text{ GeV}$	$400 \text{ GeV} \leq p_T^{\text{1st jet}}$

Smearing function The jet smearing functions are obtained from PYTHIA QCD di-jet samples mentioned in Section 4.2.1 (QCD di-jet). Smearing functions are obtained from the ratio of the reconstructed jet p_T to the truth jet p_T ,

$$R = \frac{p_T^{\text{reco.}}}{p_T^{\text{truth}}}. \quad (6.11)$$

To account for the leptonic decay of heavy-flavor hadrons in a jet, momentums of muons and neutrinos within the cone size of the jet ($\Delta R = 0.4$) are added to the truth jet momentum.

Smearing functions are parametrized by truth jet p_T . The performance of the smearing changes around jet $|\eta| = 1.8$ as seen in Figure 6.23 (left). Smearing functions are prepared for $0 \leq |\eta^{\text{jet}}| < 1.8$ and $1.8 \leq |\eta^{\text{jet}}| < 2.8$ regions separately.

Also, due to the leptonic decay of heavy-flavor hadrons in a jet, the smearing functions behave differently between light-flavor and heavy-flavor jets. In practice, jet flavor is not obtained for data. Therefore, different smearing functions are prepared for b -tagged and non b -tagged jets. Figure 6.23 (right) shows the smearing functions for b -tagged and non b -tagged jets. The fluctuations to the lower side is greater for b -tagged jets than for non b -tagged jets while the upper fluctuation is similar for both flavor of jets.

Correction of smearing function The Gaussian response of the jet smearing function just obtained from MC simulation is adjusted to data and validated in the following way.

- Jet asymmetry

Events are selected by requiring two jets with $p_T > 20 \text{ GeV}$ and third leading jet $p_T \leq 20 \text{ GeV}$ (if it exists) on the data samples collected by the single-jet triggers

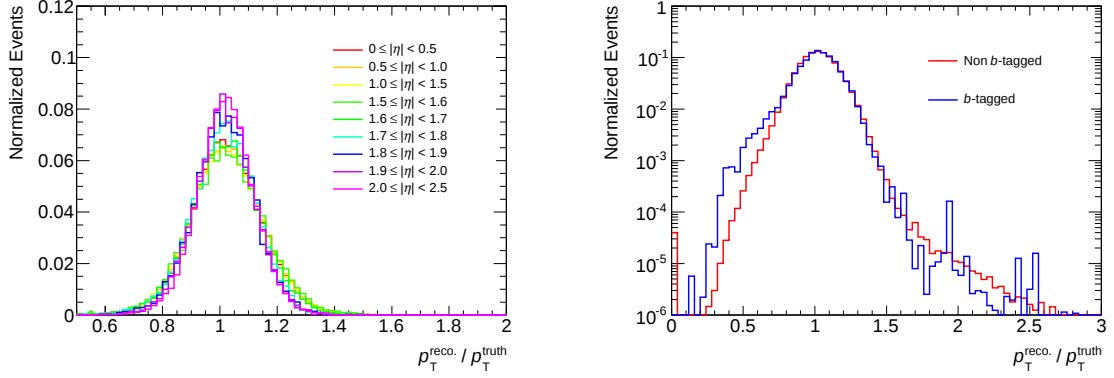


Figure 6.23: η dependence of smearing functions for $p_T > 50$ GeV (left). The right figure is smearing functions of b -tagged (blue line) and non b -tagged jets (red line) with $p_T > 50$ GeV.

shown in Table 6.8 and the jet smeared samples. To reduce real E_T^{miss} events like $Z(\rightarrow \nu\bar{\nu}) + \text{jets}$, two leading jets are required to be back-to-back ($\Delta\phi_{jj} > 2.8$ rad). Then the jet asymmetry A defined by the following equation is used.

$$A = \frac{p_T^{\text{1st jet}} - p_T^{\text{2nd jet}}}{p_T^{\text{1st jet}} + p_T^{\text{2nd jet}}}, \quad (6.12)$$

where $p_T^{\text{1st jet}}$ and $p_T^{\text{2nd jet}}$ are the leading jet p_T and the second leading jet p_T by p_T ordering. This distribution is sensitive to the Gaussian response of the jets. By fitting this distribution to the Gaussian function, σ_A is obtained. Assuming that two jets have the same Gaussian σ_{p_T} , their relation can be given by:

$$\sigma_A = \frac{\sqrt{\sigma(p_T^{\text{1st jet}})^2 + \sigma(p_T^{\text{2nd jet}})^2}}{\langle p_T^{\text{1st jet}} + p_T^{\text{2nd jet}} \rangle} \simeq \frac{\sigma_{p_T}}{\sqrt{2}p_T}, \quad (6.13)$$

where transverse momenta are expected to be balanced, i.e. $\langle p_T^{\text{1st jet}} \rangle = \langle p_T^{\text{2nd jet}} \rangle \equiv p_T$.

Figures 6.24 show the jet asymmetry distributions for data, for samples smeared with initially obtained jet smearing functions and for samples smeared with the corrected jet smearing functions (explained below) for different ranges in jet p_T . Before the correction, jet p_T resolutions in smeared samples are narrower than in the data. By fitting these distributions to a Gaussian function, the difference in Gaussian response of the smearing is obtained. The default smeared samples are further smeared by this Gaussian function to reduce the difference between the data and the smeared samples.

Figure 6.25 shows the comparison of fitted Gaussian σ_A as a function of the average jet p_T , comparing data and the smeared samples. After the correction, the agreement in the jet p_T resolution becomes within 10 % in all ranges of jet p_T .

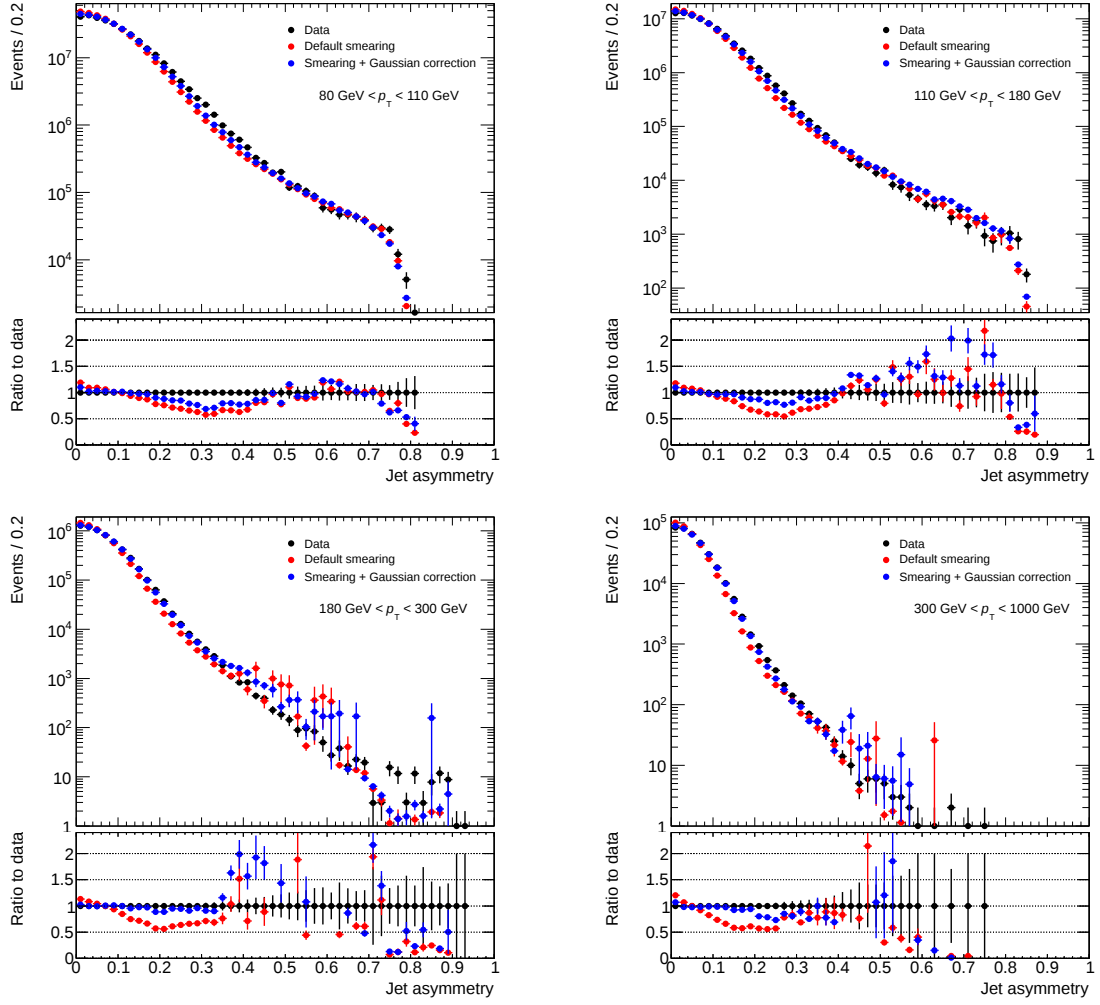


Figure 6.24: Jet asymmetry distributions for data, for default smeared samples and for the smeared samples with correction for different ranges in jet p_T .

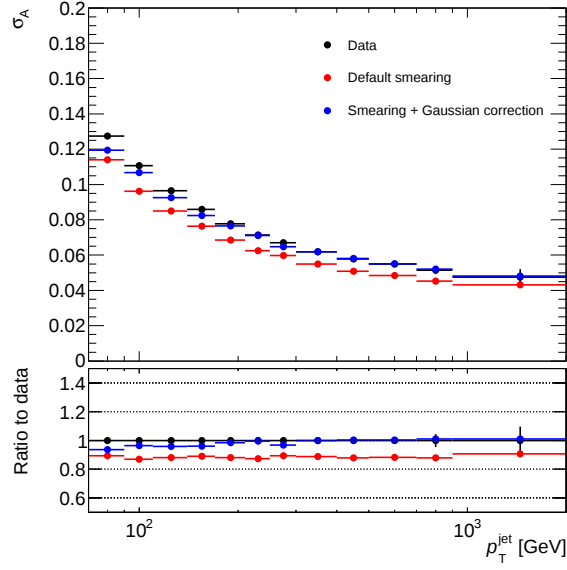


Figure 6.25: Fitted Gaussian σ of jet asymmetry, A as a function of jet p_T for data, for smeared data and for smeared data after the correction of the difference.

- Mercedes events

In case of the di-jet asymmetry, upper and lower fluctuations of jet p_T cannot be distinguished. The analysis of the so-called 'Mercedes' events allows for an examination of both the up-side and low-side response tails of jets. The selection criteria for Mercedes events are shown in Table 6.9, where j^i ($i = 1, \dots, N$) stands for jets with $p_T > 50$ GeV sorted by the distance in azimuthal angle to the E_T^{miss} vector. Events containing only one jet parallel or antiparallel to the E_T^{miss} vector as in Figure 6.26 are selected. Such events are called *Mercedes* events because of their resemblance to the Mercedes logo.

Table 6.9: Event selection criteria for Mercedes events.

Parallel	Antiparallel
at least three jet with $p_T > 50$ GeV $E_T^{\text{miss}} > 15$ GeV	
$ \Delta\phi(j^1, E_T^{\text{miss}}) < \pi - \Delta\phi(j^N, E_T^{\text{miss}}) $	$\pi - \Delta\phi(j^N, E_T^{\text{miss}}) < \Delta\phi(j^1, E_T^{\text{miss}}) $
$ \Delta\phi(j^1, E_T^{\text{miss}}) < 0.1$ rad	$\pi - \Delta\phi(j^N, E_T^{\text{miss}}) < 0.1$ rad
$ \Delta\phi(j^2, E_T^{\text{miss}}) > 1.0$ rad	$\pi - \Delta\phi(j^{N-1}, E_T^{\text{miss}}) > 1.0$ rad
$\pi - \Delta\phi(j^N, E_T^{\text{miss}}) > 0.25$ rad	$ \Delta\phi(j^1, E_T^{\text{miss}}) > 0.25$ rad

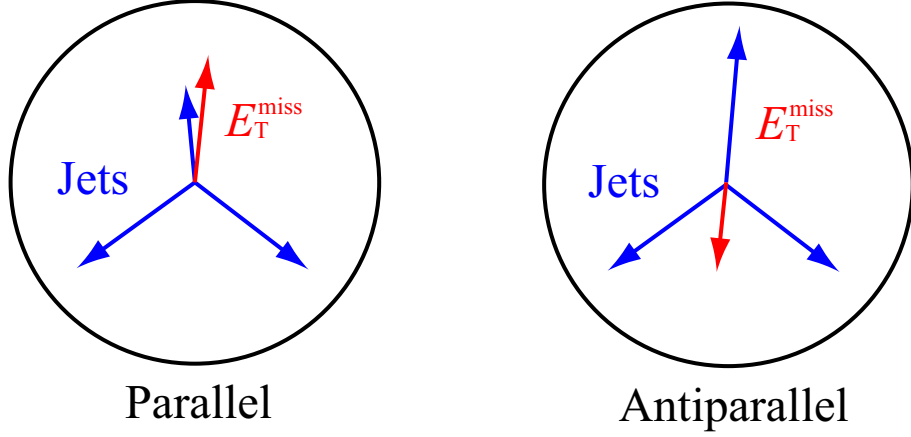


Figure 6.26: The schematic diagrams of the Mercedes events. The E_T^{miss} vector is either parallel (left) or antiparallel (right) to one jet.

The jet response R_2 is defined in analogy to Equation 6.11,

$$R_2 = \frac{\vec{p}_T^{\text{jet}} \cdot (\vec{p}_T^{\text{jet}} + \vec{E}_T^{\text{miss}})}{|\vec{p}_T^{\text{jet}} + \vec{E}_T^{\text{miss}}|^2}, \quad (6.14)$$

where $\vec{p}_T^{\text{jet}}$ is the transverse momentum of the jet which is parallel or antiparallel to the $\vec{E}_T^{\text{miss}}$ vector. This follows the facts that for Mercedes events, $\vec{p}_T^{\text{jet}} + \vec{E}_T^{\text{miss}}$ is expected to be close to the transverse momentum of truth jets; R_2 therefore corresponds to the jet smearing function. Figures 6.27 and 6.28 show the R_2 distributions for non b -tagged and b -tagged jets. After the correction, data and smeared samples agree within the sum of statistical uncertainties of data and the smeared samples in both directions of fluctuation in most ranges. In higher- p_T range for non- b -tagged jets, there are slightly larger discrepancy can be seen between data and the smeared samples. The excess of the smeared samples comes from the events triggered by the lower- p_T jet triggers.

Normalization Finally the smeared events are normalized to data in the region $\min \Delta\phi_{1,2,3} < 0.4$ rad after requiring

- leading jet $p_T > 130$ GeV
- 4th leading jet $p_T > 80$ GeV
- $E_T^{\text{miss}} > 130$ GeV
- at least one b -tagged jet ($p_T > 50$ GeV)

assuming the signal contribution is negligible. When normalizing smeared samples, non-QCD SM process are subtracted from data using MC simulation,

$$N_{\text{QCD}}^{\text{SR}} = \frac{N_{\text{data}}^{\text{CR}} - N_{\text{non-QCD,MC}}^{\text{CR}}}{N_{\text{QCD,smeared}}^{\text{CR}}} N_{\text{QCD,smeared}}^{\text{SR}}. \quad (6.15)$$

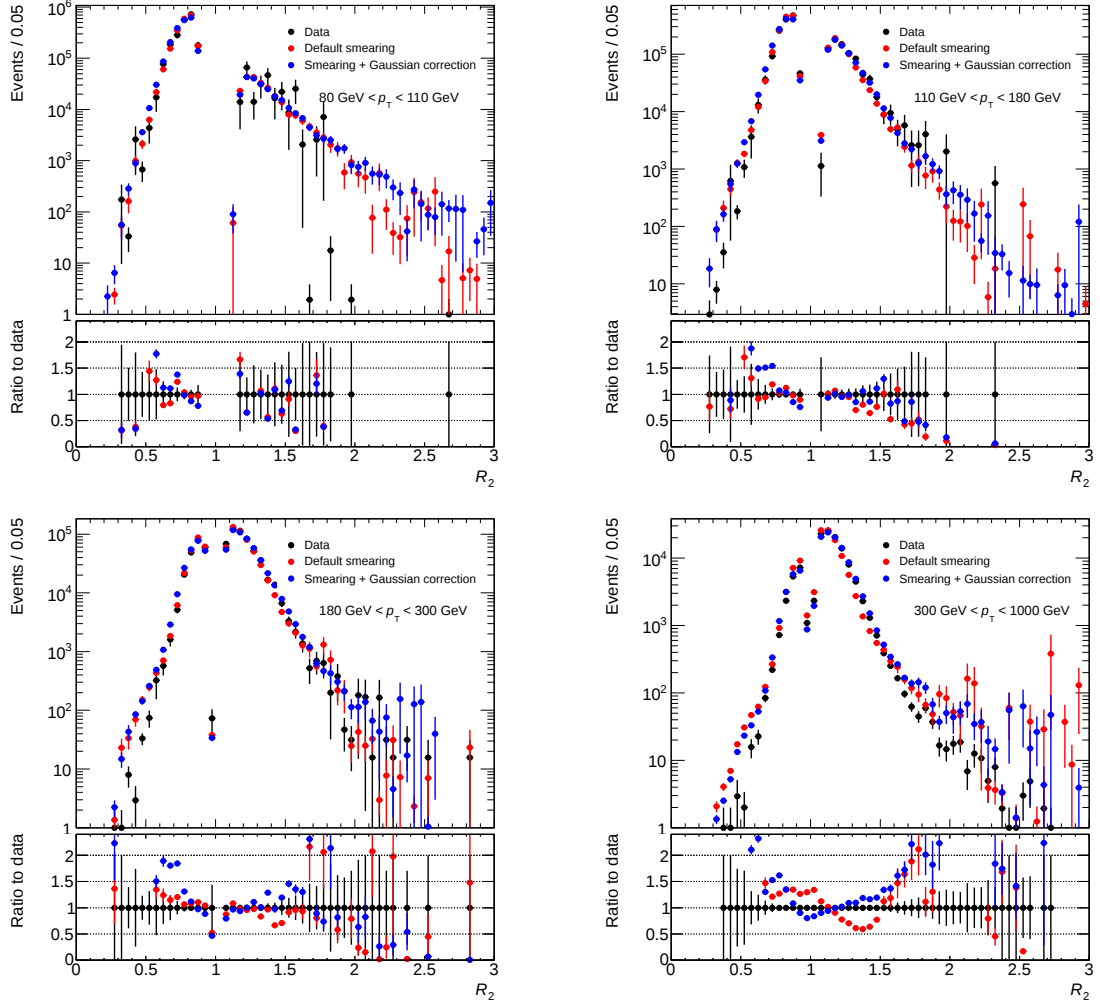


Figure 6.27: The R_2 distributions for data, for default smeared samples and for smeared samples with corrections for different ranges in jet p_T . The jet which is parallel or antiparallel to the E_T^{miss} vector is not b -tagged.

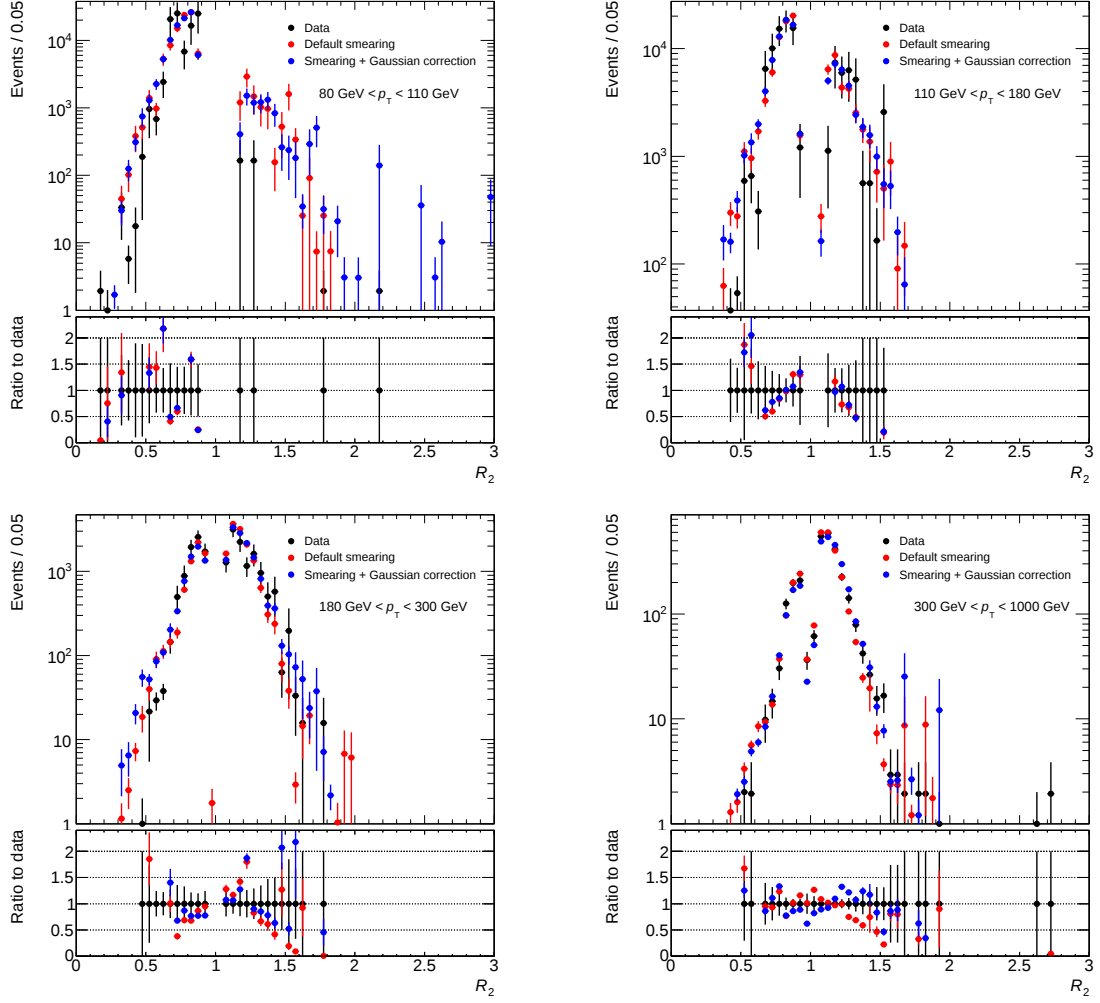


Figure 6.28: The R_2 distributions for data, for default smeared samples and for smeared samples with corrections for different ranges in jet p_T . The jet which is parallel or antiparallel to the E_T^{miss} vector is b -tagged.

If the signal contribution to the control region is not negligible, the smeared samples can be normalized to the MC simulation of QCD di-jet sample after the same event selection,

$$N_{\text{QCD}}^{\text{SR}} = \frac{N_{\text{QCD,MC}}^{\text{CR}}}{N_{\text{QCD,smeared}}^{\text{CR}}} N_{\text{QCD,smeared}}^{\text{SR}}. \quad (6.16)$$

In practice, the signal contribution to the QCD control region is assigned as the additional systematic uncertainty. If the total uncertainty when the smeared samples are normalized to data is smaller than the total uncertainty when the smeared samples are normalized to MC simulation, the estimation by normalization to data is used.

Figure 6.29 (top left) shows the $\min\Delta\phi_{1,2,3}$ distribution in this control region and the rest of Figures 6.29 are other variables in $\min\Delta\phi_{1,2,3} < 0.4$ rad region after normalizing the smeared samples to data. The error bars shown are for the statistical uncertainty only. Good agreement with data is seen within uncertainties.

Systematic uncertainties When the smeared samples are normalized to data, the JES uncertainty changes both the non-QCD background estimation in the control region and the smearing functions. The b -tagging efficiency uncertainty affects the non-QCD MC simulation only. For the systematic uncertainty related to the correction of the smearing functions, the variations when the correcting Gaussian sigma is changed by ± 50 % are assigned.

When the smeared samples are normalized to the MC simulation, additionally to the other systematic uncertainties, 100 % systematic uncertainty is assigned for the theory since the MC is normalized to LO cross-section and heavy-flavor fraction is not well known in the theory. To check the QCD MC simulation, the distributions of the leading jet p_{T} , number of jets, $\min\Delta\phi_{1,2,3}$ and the number of b -tagged jets are compared with data after requiring $p_{\text{T}} > 130$ GeV and $E_{\text{T}}^{\text{miss}} > 130$ GeV; the results are shown in Figure 6.30. The error bars show the JES and b -tagging uncertainties only. The number of events observed in data is larger than the estimation from the MC simulated QCD process. This discrepancy, however, within 50 % and smaller than the systematic uncertainty considered here.

The estimated numbers of QCD events in the signal regions are summarized in the Table 6.13.

Z +jets estimation

The contribution of the Z +jets process is expected to be smaller than the backgrounds described earlier and is estimated by MC simulation only. Table 6.11 shows the estimated number of Z +jets events with associated systematic uncertainties. The uncertainties are calculated in the same way as for the W +jets production.

Estimation of other SM backgrounds

Other Standard Model backgrounds are estimated purely by Monte Carlo simulation. The JES and b -tagging systematic uncertainties are calculated in the same way as described earlier. For the theoretical uncertainty, 100 % is assigned to each process

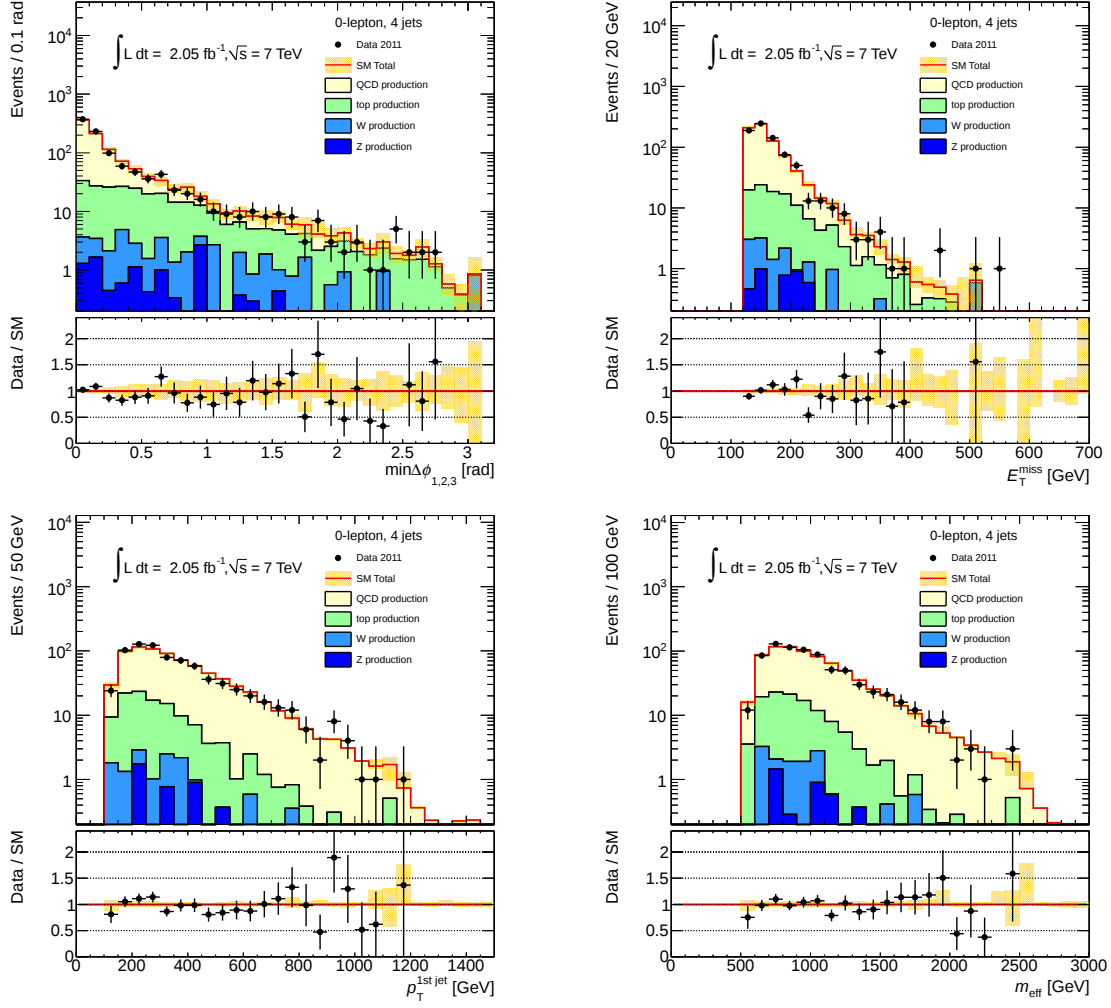


Figure 6.29: The $\min\Delta\phi_{1,2,3}$ distribution in the QCD control region (top left). The rest of figures are distributions of E_T^{miss} (top right), leading jet p_T (bottom left) and m_{eff} (bottom right) in the region defined by $\min\Delta\phi_{1,2,3} < 0.4 \text{ rad}$.

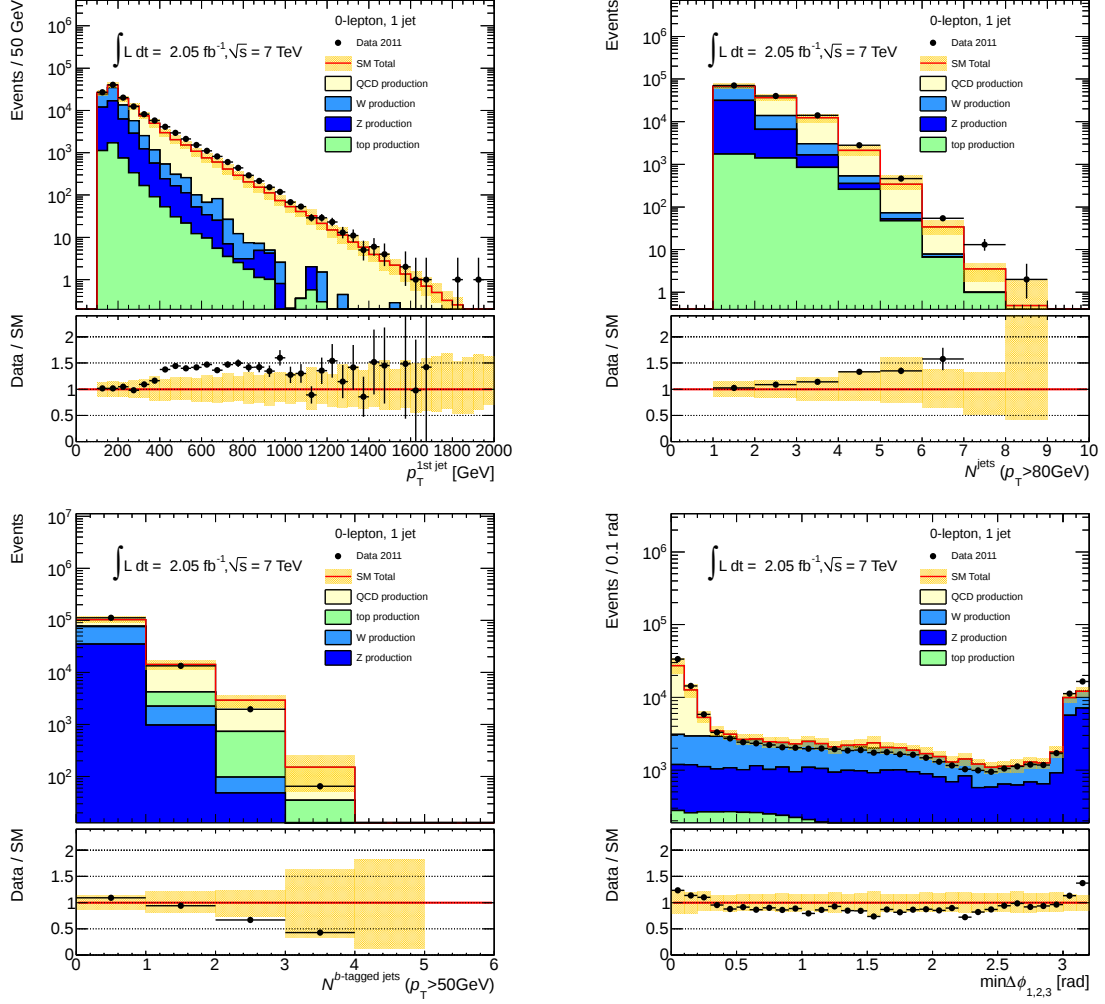


Figure 6.30: The distributions of the leading jet p_T (top left), the number of jets (top right), the number of b -tagged jets (bottom left) and $\min\Delta\phi_{1,2,3}$ (bottom right) after requiring leading jet $p_T > 130$ GeV and $E_T^{\text{miss}} > 130$ GeV comparing data and MC simulations.

Table 6.10: The estimated number of QCD multi-jet events in the no-lepton multi-jet channel, shown together with the associated systematic uncertainties.

normalized to MC			
	$m_{\text{eff}} > 500 \text{ GeV}$	$m_{\text{eff}} > 750 \text{ GeV}$	$m_{\text{eff}} > 1000 \text{ GeV}$
events	17	5.9	1.3
Jet energy scale	$+31_{-25} \%$	$+67_{-5} \%$	$+40_{-42} \%$
b -tagging efficiency	$+16_{-22} \%$	$+16_{-22} \%$	$+16_{-22} \%$
Luminosity	$\pm 3.7 \%$	$\pm 3.7 \%$	$\pm 3.7 \%$
Gaussian correction	$+0_{-18} \%$	$+18_{-2} \%$	$+0_{-18} \%$
Theory	$\pm 100 \%$	$\pm 100 \%$	$\pm 100 \%$
Statistics	$\pm 14 \%$	$\pm 16 \%$	$\pm 15 \%$
Uncertainty sum	$+109_{-100} \%$	$+123_{-100} \%$	$+111_{-100} \%$
normalized to data			
	$m_{\text{eff}} > 500 \text{ GeV}$	$m_{\text{eff}} > 750 \text{ GeV}$	$m_{\text{eff}} > 1000 \text{ GeV}$
events	22	7.9	1.7
Jet energy scale	$+0_{-21} \%$	$+16_{-0} \%$	$+0_{-29} \%$
b -tagging efficiency	$\pm 2 \%$	$\pm 2 \%$	$\pm 2 \%$
Gaussian correction	$+0_{-18} \%$	$+18_{-2} \%$	$+0_{-18} \%$
Statistics	$\pm 14 \%$	$\pm 16 \%$	$\pm 15 \%$
Uncertainty sum	$+14_{-31} \%$	$+29_{-16} \%$	$+15_{-37} \%$

Table 6.11: The estimated number of Z +jets events in the no-lepton multi-jet channel with the associated systematic uncertainties.

	$m_{\text{eff}} > 500 \text{ GeV}$	$m_{\text{eff}} > 750 \text{ GeV}$	$m_{\text{eff}} > 1000 \text{ GeV}$
events	4.2	1.9	0.2
Jet energy scale	$+8.7_{-40} \%$	$+0_{-9.9} \%$	$+102_{-12} \%$
b -tagging efficiency	$+20_{-15} \%$	$+29_{-17} \%$	$+12_{-9.6} \%$
Luminosity	$\pm 3.7 \%$	$\pm 3.7 \%$	$\pm 3.7 \%$
Cross section	$\pm 9.8 \%$	$\pm 12 \%$	$\pm 15 \%$
Number of parton	$\pm 39 \%$	$\pm 32 \%$	$\pm 42 \%$
Uncertainty sum	$+46_{-59} \%$	$+45_{-39} \%$	$+112_{-48} \%$

as a conservative estimate. For the $t\bar{t} + W/Z$ and $t\bar{t} + b\bar{b}$ processes, only the LO cross-sections are available and no dedicated study on these MC simulations have been performed. Table 6.12 shows the contributions of the remaining SM backgrounds to the signal regions of the no-lepton multi-jet channel.

Table 6.12: The estimated number of events of the remaining SM backgrounds in the no-lepton multi-jet signal regions.

	$m_{\text{eff}} > 500 \text{ GeV}$	$m_{\text{eff}} > 750 \text{ GeV}$	$m_{\text{eff}} > 1000 \text{ GeV}$
WW, WZ, ZZ	0.1	0.1	0
$t\bar{t} + b\bar{b}$	0.9	0.3	0.04
$t\bar{t} + W \text{ or } Z$	2.5	1.3	0.3

6.2.4 Summary

Table 6.13 shows the expected and the observed number of events in the signal regions. Observations agree with expectations within the uncertainties and no significant excess beyond the SM prediction is not seen. Figures 6.31 show the distributions of $E_{\text{T}}^{\text{miss}}$, the leading jet p_{T} and m_{eff} for data and the SM prediction before the m_{eff} cuts. The SM predictions have not been normalized to data in the control region. The error bands shown are the sum in quadrature of the JES uncertainty and b -tagging uncertainty. In Chapter 7, the exclusion limits on the mSUGRA model and the other SUSY models are computed.

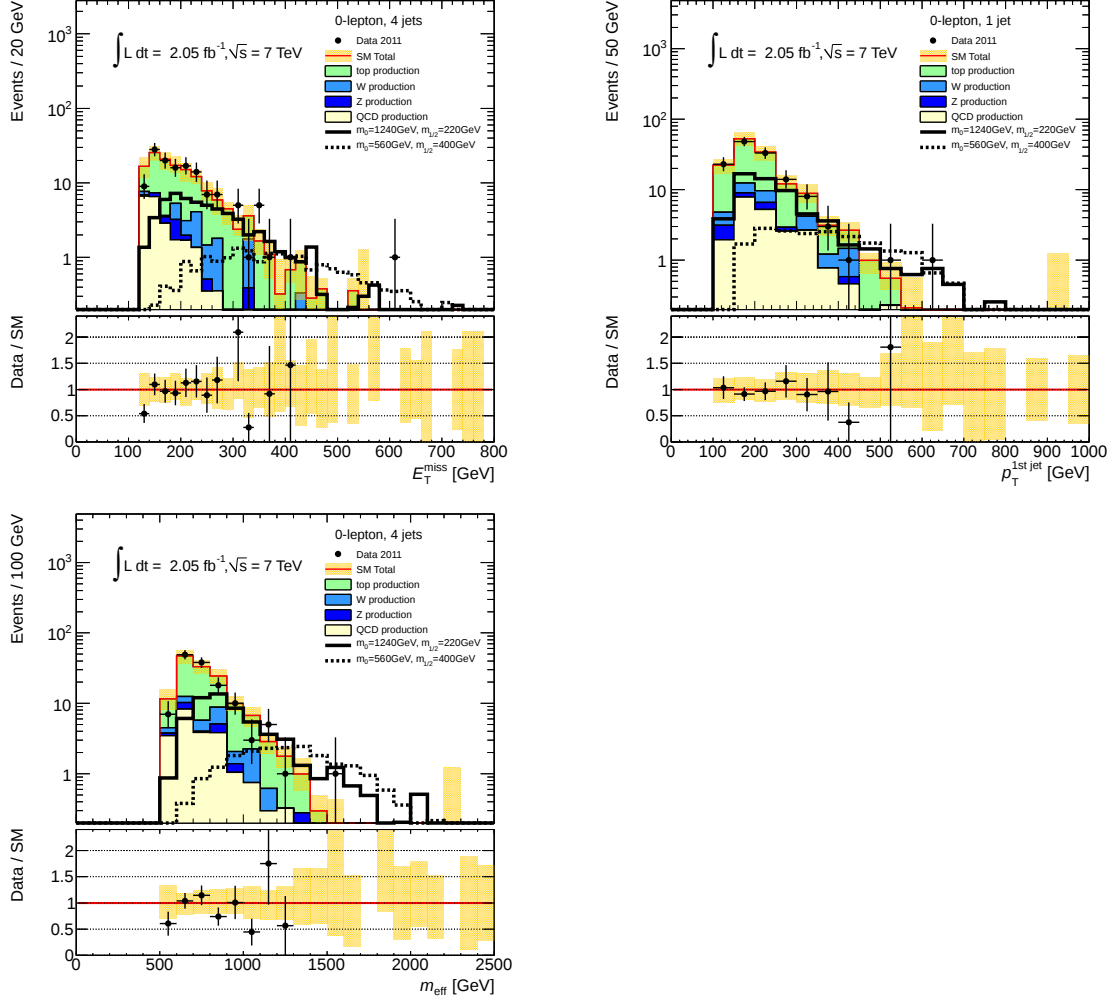


Figure 6.31: The distributions of E_T^{miss} (top left), leading jet p_T (top right) and m_{eff} (bottom left) in the no-lepton multi-jet signal region before m_{eff} cut. The SM predictions are not normalized to data.

Table 6.13: The expected and observed number of events in the no-lepton multi-jet signal regions. In the table, sim. means the estimation with MC simulation only (for QCD, smeared samples are normalized to MC simulation) and norm. means the estimation with MC simulation normalized to data in the control region (for QCD, smeared samples are normalized to data).

	$m_{\text{eff}} > 500 \text{ GeV}$	$m_{\text{eff}} > 750 \text{ GeV}$	$m_{\text{eff}} > 1000 \text{ GeV}$
Data (2.05 fb^{-1})	132	57	10
SM (sim.)	129^{+51}_{-50}	57^{+26}_{-22}	$11.0^{+6.4}_{-5.3}$
SM (norm.)	138^{+14}_{-18}	$60.3^{+8.7}_{-9.1}$	$11.6^{+3.3}_{-3.5}$
top (sim.)	94^{+41}_{-37}	40^{+20}_{-18}	$7.4^{+4.5}_{-3.7}$
top (norm.)	97 ± 14	$40.9^{+8.2}_{-8.4}$	$7.6^{+2.9}_{-2.8}$
W +jets (sim.)	$10.9^{+5.9}_{-6.6}$	$7.7^{+4.4}_{-4.9}$	$1.8^{+1.6}_{-1.5}$
W +jets (norm.)	$11.2^{+3.3}_{-5.1}$	$7.9^{+2.5}_{-3.6}$	1.9 ± 1.3
QCD (sim.)	17^{+18}_{-17}	$5.9^{+7.3}_{-5.9}$	$1.3^{+1.4}_{-1.3}$
QCD (norm.)	$22.1^{+3.2}_{-7.0}$	$7.9^{+2.3}_{-1.3}$	$1.7^{+0.3}_{-0.6}$
Z +jets	$4.2^{+1.9}_{-2.5}$	$1.9^{+0.8}_{-0.7}$	$0.2^{+0.2}_{-0.1}$
Others	3.5 ± 2.2	$1.7^{+1.1}_{-1.2}$	0.4 ± 0.3

6.3 One-lepton multi-jet channel

If gluinos are pair-produced and decay to a stop or a sbottom and its SM partners followed by their decay to a chargino, b -jets and leptons can be observed in the final state. In this section, the analysis for the final state consisting of multi-jets including b -jets, $E_{\text{T}}^{\text{miss}}$ and a lepton is described.

6.3.1 Benchmark signals

As in the previous section, the mSUGRA model with $\tan \beta = 40$, $A_0 = -500 \text{ GeV}$ and $\mu > 0$ model is used as a benchmark SUSY signal.

6.3.2 Optimization of event selection

First, events are selected by the single-electron trigger `EF_e20_medium` and the single-muon trigger `EF_mu18` (and `EF_mu18_L1J10`) with exactly one lepton (electron or muon) satisfying the *tight* criteria described in Section 5.3 and 5.4. To satisfy the single-lepton trigger requirements described in Section 6.1.5, an electron with $p_{\text{T}} > 25 \text{ GeV}$ or a muon with $p_{\text{T}} > 20 \text{ GeV}$ are selected. If there are other leptons in the event satisfying *loose* criteria, the event is rejected.

In the later data-taking periods, the single-muon trigger required one jet with $p_{\text{T}} > 60 \text{ GeV}$ in addition to the muon, a leading offline jet with $p_{\text{T}} > 60 \text{ GeV}$ is required throughout all data periods for consistency in both electron and muon channels.

Figure 6.32 (left) shows the distribution in MC simulation of the number of jets, after requiring one electron. As references, two SUSY signal points, $(m_0, m_{1/2}) = (1240 \text{ GeV}, 220 \text{ GeV})$, $(560 \text{ GeV}, 400 \text{ GeV})$ are overlaid. By requiring at least four jets with $p_T > 50 \text{ GeV}$, SM backgrounds are greatly reduced while keeping high signal acceptance.

Figure 6.32 (right) is the E_T^{miss} distribution again after requiring one electron. $E_T^{\text{miss}} > 80 \text{ GeV}$ is chosen to reduce SM backgrounds while keeping high signal acceptance.

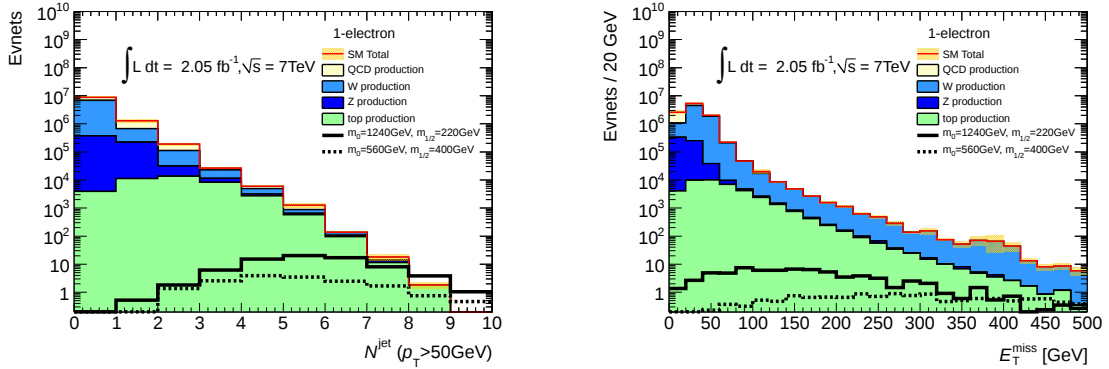


Figure 6.32: The distributions of the number of jets (left) and the E_T^{miss} (right) after requiring one electron.

Because of the enhancement of the gluino decay to the stop and the sbottom in the mSUGRA model with large $\tan \beta$, SUSY signals have b -jets in the final state. Figure 6.33 shows the distribution of the number of b -tagged jets after the requirement of one electron. By requiring at least one b -tagged jets, most of the W/Z -jets processes are removed.

To further reduce SM backgrounds, a cut is placed on the transverse mass between the lepton and the E_T^{miss} , defined as follows,

$$m_T = \sqrt{2 \left(p_T^{\text{lepton}} E_T^{\text{miss}} - \vec{p}_T^{\text{lepton}} \cdot \vec{E}_T^{\text{miss}} \right)}. \quad (6.17)$$

If one neutrino which is a decay product of the W boson is the only source of missing energy, this m_T corresponds to the transverse mass of the W . However, if there are other sources of the missing energy, m_T distributions is distorted. Figure 6.33 (left) shows the m_T distribution after requiring four jets with $p_T > 50 \text{ GeV}$ and $E_T^{\text{miss}} > 80 \text{ GeV}$. Above $m_T = 100 \text{ GeV}$, SM backgrounds decrease sharply but SUSY signals have flatter distributions. By requiring $m_T > 100 \text{ GeV}$, SUSY signals are enhanced.

Finally, to enhance the SUSY signals further, the effective mass m_{eff} defined by

$$m_{\text{eff}} = E_T^{\text{miss}} + \sum_{i=1}^4 (p_T^{\text{jet}})_i + p_T^{\text{lepton}} \quad (6.18)$$

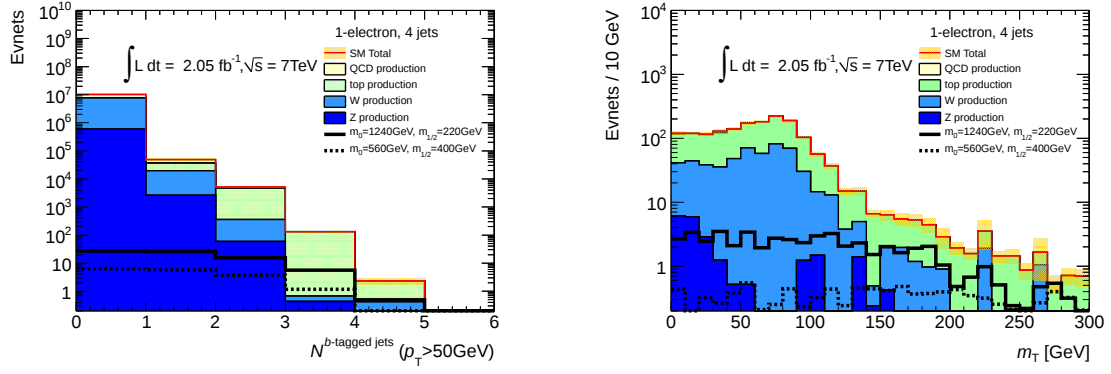


Figure 6.33: The distributions of the number of b -tagged jets after requiring one electron (left). The transverse mass m_T distribution after requiring four jets and $E_T^{\text{miss}} > 80$ GeV (right).

is used. The effective mass is expected to reflect the total masses of the initially produced particles. Since the optimum m_{eff} cut depends on the masses of SUSY particles, the optimum cut is chosen for each signal point. Figure 6.34 is the m_{eff} distribution after all other cuts.

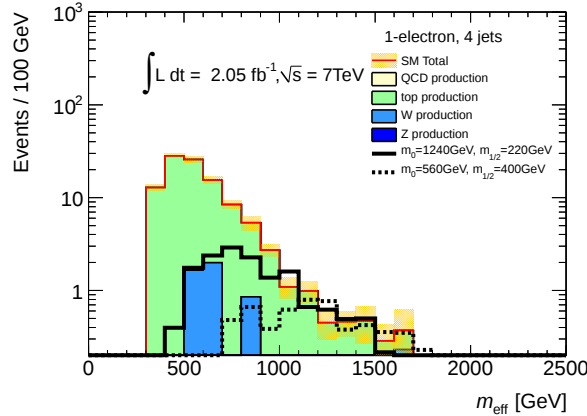


Figure 6.34: The effective mass m_{eff} distribution after all other event selection for one electron channel.

The event selection is summarized as follows.

- exactly one *tight* lepton ($p_T > 25$ GeV for an electron and $p_T > 20$ GeV for a muon) and no additional leptons satisfying *loose* criteria.
- leading jet $p_T > 60$ GeV
- at least four jets with $p_T > 50$ GeV
- $E_T^{\text{miss}} > 80$ GeV

- $m_T > 100$ GeV
- at least one b -tagged jet with $p_T > 50$ GeV
- optimum m_{eff} cut as follows.

The optimum m_{eff} cut is determined to give the highest signal significance as defined by Equation 6.7. Figure 6.35 is the best m_{eff} cut for each SUSY signal point. To cover the whole range, three signal regions, $m_{\text{eff}} > 400$ GeV, $m_{\text{eff}} > 700$ GeV $m_{\text{eff}} > 1000$ GeV are prepared. The actual signal region for each signal point is determined after fixing the background estimation and associated uncertainties.

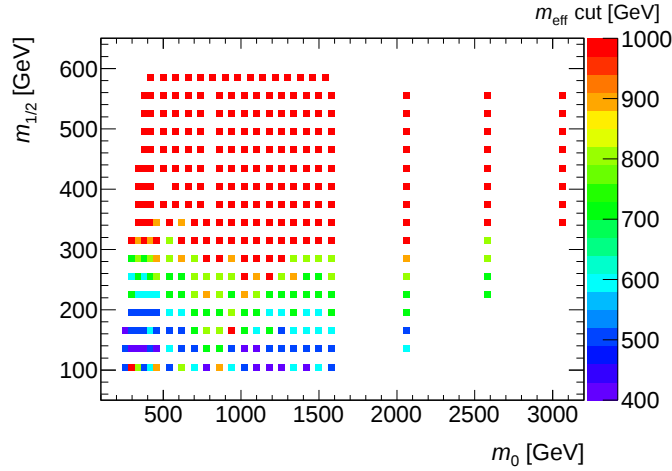


Figure 6.35: The best m_{eff} cut for each mSUGRA signal point in the one-lepton multi-jet channel.

6.3.3 SM background estimation

QCD multi-jet estimation

QCD events can mimic the signal signature in the one-lepton channel if a non-prompt lepton arising from the leptonic decay of heavy-flavor hadrons in a jet or a γ conversion or a misidentified jet satisfies the lepton criteria. This category of leptons will be referred to as fake leptons while leptons from W or Z boson decay will be referred to as real leptons. Since it is difficult to describe the fake leptons in simulation, the so-called *matrix method* is used, which estimates the QCD background from data [100].

For this method, two selection criteria for leptons, *loose* and *tight* are prepared. These criteria are defined in Section 5.3 and 5.4. The *tight* criteria corresponds to the signal selection of leptons which is dominated by real leptons. The *loose* criteria corresponds to the preselection of lepton which is dominated by fake leptons.

The number of events in the two samples, N^{loose} and N^{tight} can be expressed in terms of the number of events with real leptons and fake leptons, $N_{\text{real}}^{\text{loose}}$ and $N_{\text{fake}}^{\text{tight}}$, and

the probability for a real (fake) lepton which passes the loose selection to also satisfy the tight selection: $\varepsilon_{\text{real(fake)}} = N_{\text{real(fake)}}^{\text{tight}} / N_{\text{real(fake)}}^{\text{loose}}$.

$$\begin{aligned} N^{\text{loose}} &= N_{\text{real}}^{\text{loose}} + N_{\text{fake}}^{\text{loose}} \\ N^{\text{tight}} &= \varepsilon_{\text{real}} N_{\text{real}}^{\text{loose}} + \varepsilon_{\text{fake}} N_{\text{fake}}^{\text{loose}} \end{aligned} \quad (6.19)$$

$$\begin{pmatrix} N^{\text{loose}} \\ N^{\text{tight}} \end{pmatrix} = \begin{pmatrix} 1 & 1 \\ \varepsilon_{\text{real}} & \varepsilon_{\text{fake}} \end{pmatrix} \begin{pmatrix} N_{\text{real}}^{\text{loose}} \\ N_{\text{fake}}^{\text{loose}} \end{pmatrix} \quad (6.20)$$

Since N^{loose} and N^{tight} are obtained from data, if $\varepsilon_{\text{real}}$ and $\varepsilon_{\text{fake}}$ are known, the number of fake-lepton events which pass the *tight* selection $N_{\text{fake}}^{\text{tight}}$ can be obtained as follows.

$$\begin{pmatrix} N_{\text{real}}^{\text{loose}} \\ N_{\text{fake}}^{\text{loose}} \end{pmatrix} = \frac{1}{\varepsilon_{\text{fake}} - \varepsilon_{\text{real}}} \begin{pmatrix} \varepsilon_{\text{fake}} & -1 \\ -\varepsilon_{\text{real}} & 1 \end{pmatrix} \begin{pmatrix} N^{\text{loose}} \\ N^{\text{tight}} \end{pmatrix} \quad (6.21)$$

$$N_{\text{fake}}^{\text{tight}} = \varepsilon_{\text{fake}} N_{\text{fake}}^{\text{loose}} = \frac{\varepsilon_{\text{fake}}}{\varepsilon_{\text{real}} - \varepsilon_{\text{fake}}} (\varepsilon_{\text{real}} N^{\text{loose}} - N^{\text{tight}}). \quad (6.22)$$

The efficiency $\varepsilon_{\text{real}}$ and $\varepsilon_{\text{fake}}$ can be estimated from data in the control regions enriched by either real or fake leptons.

Measurement of $\varepsilon_{\text{fake}}$ To measure $\varepsilon_{\text{fake}}$ in the region similar to the signal region, at least one *b*-tagged jet is required. To enhance fake lepton events, a region with low $E_{\text{T}}^{\text{miss}}$ and low m_{T} is used:

- at least one *b*-tagged jet with $p_{\text{T}} > 50$ GeV
- $E_{\text{T}}^{\text{miss}} < 30$ GeV
- $m_{\text{T}} < 40$ GeV

Real-lepton events estimated by Monte Carlo simulation are subtracted from data. The systematic uncertainties associated to these MC simulations are assigned as the systematic uncertainties on $\varepsilon_{\text{fake}}$. The fake rate does not show a dependence on the number of reconstructed vertices and the number of *b*-tagged jets (as long as at least one *b*-tagged jet is required) but a dependence on the number of jets can be seen due to the QCD multi-jet topology. Figure 6.36 is the inclusive fake rate dependence on the number of jets. The standard deviation of this variation is assigned as the systematic uncertainty of the fake rate.

Figures 6.37 show $\varepsilon_{\text{fake}}$ as a function of lepton p_{T} . The fake rate is also parametrized as a function of the lepton η . For electrons, the transition region between barrel and end-cap calorimeters ($1.37 < |\eta| < 1.52$) has a performance that is different compared to the neighboring ranges. The binning in η takes this dependence into account. For p_{T} values larger than those shown in these figures ($p_{\text{T}} > 50$ GeV for electrons and $p_{\text{T}} > 40$ GeV for muons), the measurement of $\varepsilon_{\text{fake}}$ is difficult due to the small number of fake-lepton events compared to real-lepton events. In those regions, the values of the fake rate from the highest p_{T} bin that is measured are used, taking twice the uncertainty.

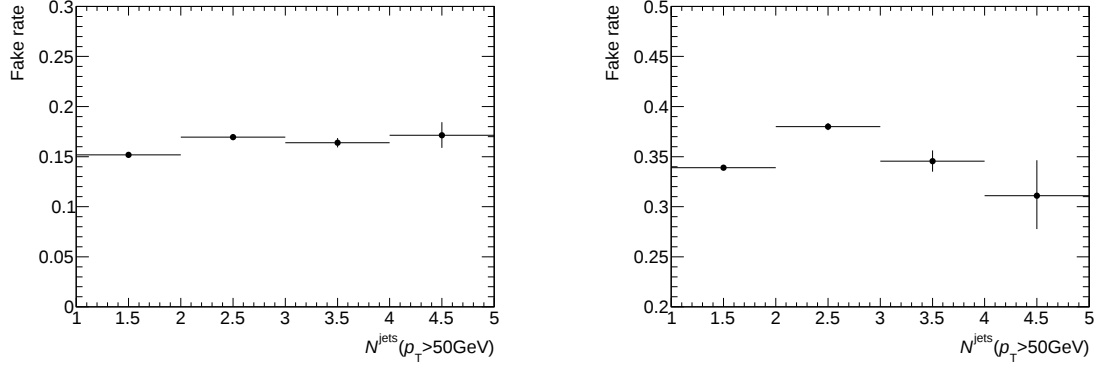


Figure 6.36: The fake rates as a function of the number of jets for an electron (left) and a muon (right).

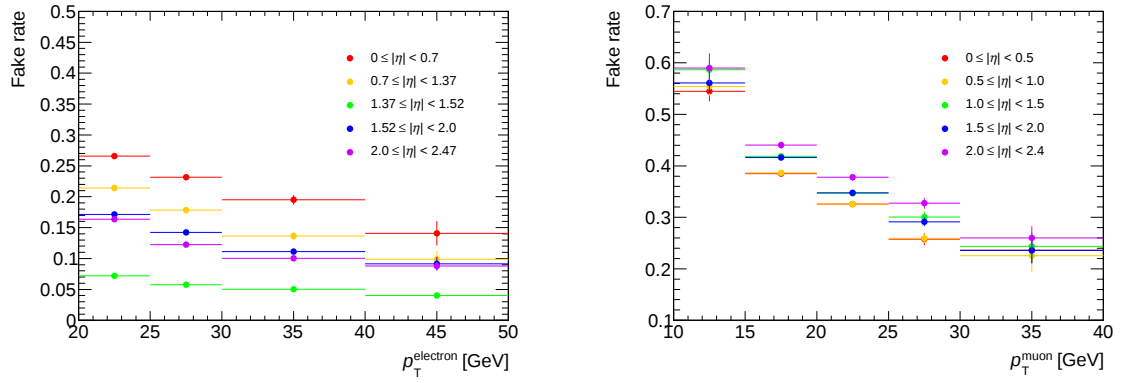


Figure 6.37: $\varepsilon_{\text{fake}}$ as a function of lepton p_T and η . The left is for electrons and the right is for muons.

Measurement of $\varepsilon_{\text{real}}$ To measure $\varepsilon_{\text{real}}$, the $Z \rightarrow l^+l^-$ process is used (where l denotes either an electron or a muon). To select this process, the following conditions are required on the samples collected by the single-electron trigger EF_e20_medium or the single-muon trigger EF_mu18.

- exactly two same flavor *loose* leptons which have opposite charge
- invariant mass of two leptons, M_{ll} satisfies $81 \text{ GeV} < M_{ll} < 101 \text{ GeV}$

To remove backgrounds to this process, one of the lepton is required to satisfy the *tight* criteria; the other lepton in the event is then used to measure $\varepsilon_{\text{real}}$. The contamination from fake-lepton events is negligible after imposing these criteria.

To evaluate the systematic uncertainties on these values, the dependence on the number of jets and on the number of reconstructed vertices were checked, but no significant difference was observed.

Figures 6.38 show $\varepsilon_{\text{real}}$ as a function of lepton p_T in different bins of η . For p_T values larger than those shown in Figures 6.38 ($p_T > 200 \text{ GeV}$), the values of the real rate from the highest p_T bin that is measured are used, taking twice the uncertainty.

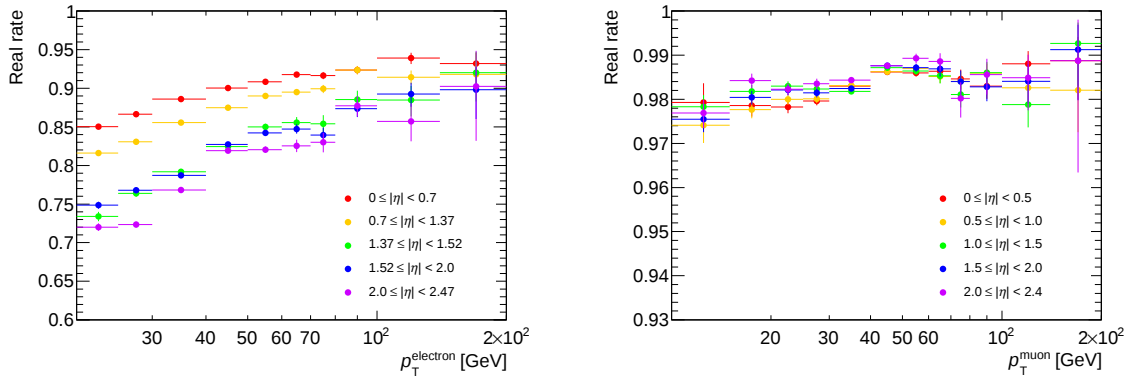


Figure 6.38: $\varepsilon_{\text{real}}$ as a function of lepton p_T and η for electrons (left) and for muons (right).

To validate the method, the distributions of p_T^{lepton} , m_T and E_T^{miss} are checked after requiring one lepton and one b -tagged jet (Figure 6.39). All distributions of data are well reproduced by the estimated QCD production. The estimated number of fake-lepton events and distributions in the signal regions are shown in Table 6.18 and Figure 6.40.

Top estimation

The dominant SM background is the $t\bar{t}$ production whose contribution to the signal regions are first estimated purely by Monte Carlo simulation. Since the single-top production also has a similar topology, it is estimated inclusively with the $t\bar{t}$ production. Table 6.14 shows the estimated number of events in the signal regions together with the associated systematic uncertainties.

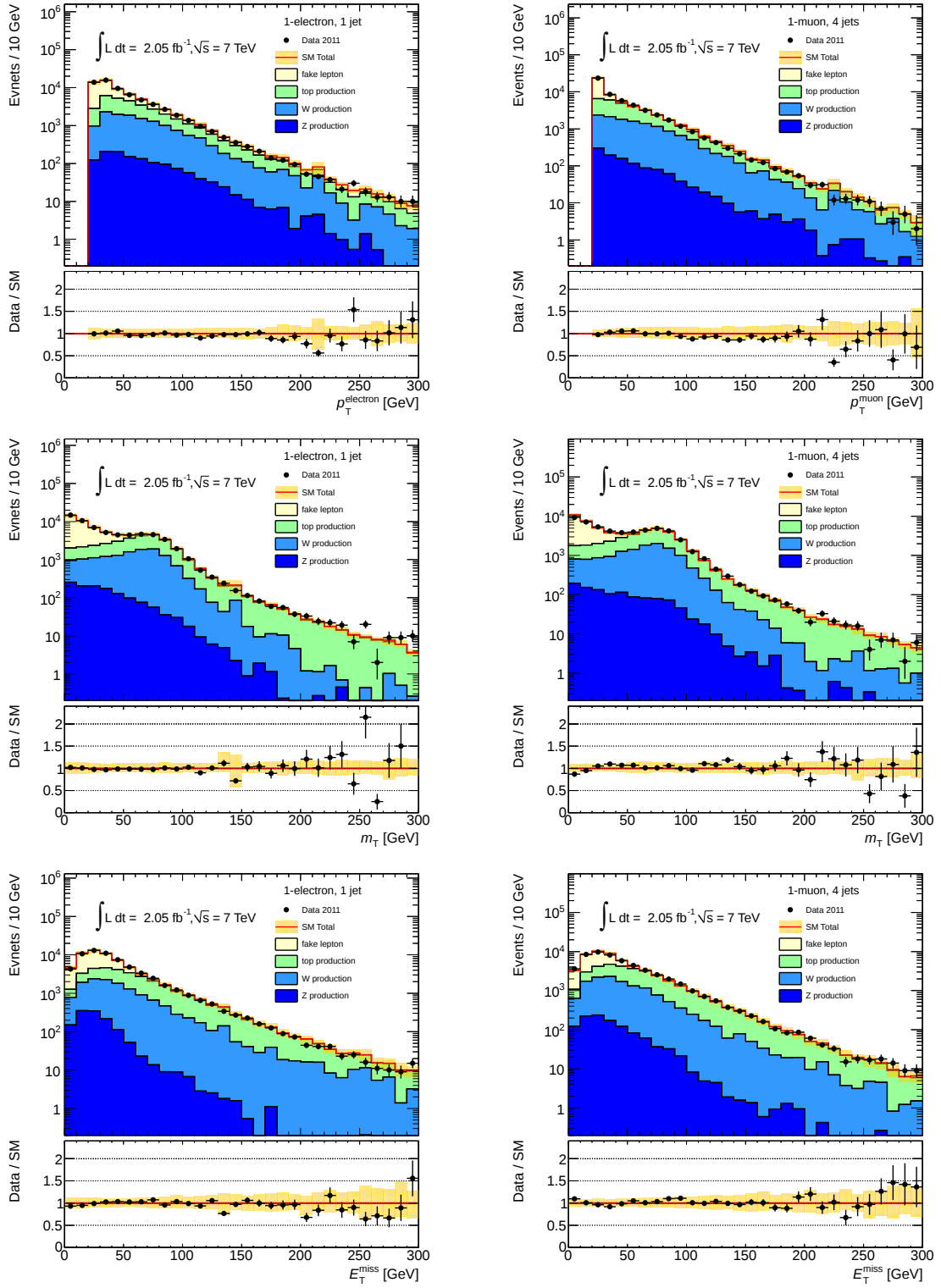


Figure 6.39: The distributions of p_T^{lepton} (top), m_T (middle) and E_T^{miss} (bottom) after requiring one lepton and one b -tagged jet, showing the validation of the QCD estimation by the matrix method. The left figures show the electron channel and the right figures the muon channel.

Table 6.14: The estimated number of events of top backgrounds in the one-lepton signal regions without normalizing the MC simulated samples to data in the control region.

electron channel			
	$m_{\text{eff}} > 400 \text{ GeV}$	$m_{\text{eff}} > 700 \text{ GeV}$	$m_{\text{eff}} > 1000 \text{ GeV}$
events	87.2	24.9	5.4
Jet energy scale	$^{+32}_{-20} \%$	$^{+30}_{-18} \%$	$^{+16}_{-27} \%$
b -tagging efficiency	$^{+10.1}_{-8.1} \%$	$^{+8.9}_{-9.4} \%$	$^{+6.1}_{-7.3} \%$
Luminosity	$\pm 3.7 \%$	$\pm 3.7 \%$	$\pm 3.7 \%$
ISR/FSR	$\pm 28 \%$	$\pm 31 \%$	$\pm 56 \%$
Generator	$\pm 10 \%$	$\pm 16 \%$	$\pm 18 \%$
Shower modeling	$\pm 0.1 \%$	$\pm 3.7 \%$	$\pm 1.6 \%$
Cross section	$^{+6.9}_{-9.5} \%$	$^{+6.9}_{-9.5} \%$	$^{+6.9}_{-9.5} \%$
Electron trigger	$\pm 0.4 \%$	$\pm 0.4 \%$	$\pm 0.4 \%$
Electron reconstruction	$\pm 1.6 \%$	$\pm 1.6 \%$	$\pm 1.6 \%$
Uncertainty sum	$^{+46}_{-37} \%$	$^{+47}_{-41} \%$	$^{+61}_{-65} \%$

muon channel			
	$m_{\text{eff}} > 400 \text{ GeV}$	$m_{\text{eff}} > 700 \text{ GeV}$	$m_{\text{eff}} > 1000 \text{ GeV}$
events	102	27.5	5.5
Jet energy scale	$^{+30}_{-20} \%$	$^{+26}_{-18} \%$	$^{+33}_{-14} \%$
b -tagging efficiency	$^{+10.8}_{-8.3} \%$	$^{+9.4}_{-10.4} \%$	$^{+6.3}_{-11.4} \%$
Luminosity	$\pm 3.7 \%$	$\pm 3.7 \%$	$\pm 3.7 \%$
ISR/FSR	$\pm 33 \%$	$\pm 35 \%$	$\pm 61 \%$
Generator	$\pm 11 \%$	$\pm 14 \%$	$\pm 11 \%$
Shower modeling	$\pm 1.5 \%$	$\pm 3.3 \%$	$\pm 19 \%$
Cross section	$^{+6.9}_{-9.5} \%$	$^{+6.9}_{-9.5} \%$	$^{+6.9}_{-9.5} \%$
Muon trigger	$\pm 1 \%$	$\pm 1 \%$	$\pm 1 \%$
Muon reconstruction	$\pm 0.7 \%$	$\pm 0.7 \%$	$\pm 0.7 \%$
Uncertainty sum	$^{+48}_{-42} \%$	$^{+47}_{-44} \%$	$^{+73}_{-67} \%$

To reduce the systematic uncertainty, the number of events from simulated samples is normalized in the background dominant control region defined by

- $40 \text{ GeV} < m_T < 100 \text{ GeV}$
- $m_{\text{eff}} > 400 \text{ GeV}$

which is also used in the previous section for top estimation. The number of top events in the signal regions can then be estimated by Equation 6.8. Low-mass SUSY signal can contribute to this control region. Therefore the signal contribution to the control region is taken as an additional systematic uncertainty. If the total systematic uncertainty is smaller than the one based purely on MC simulation, the estimation with MC normalization is used.

Figures 6.20 show the distributions of E_T^{miss} , m_{eff} and leading jet p_T in the control region $40 \text{ GeV} < m_T < 100 \text{ GeV}$. The error bands shown are the sum of JES and b -tagging systematic uncertainties before normalizing to data. Table 6.15 shows the expected number of top events in the one-lepton signal regions with MC normalization in the control region.

W +jets estimation

$W + b\bar{b}$ is the second largest background but its contribution is much smaller than the top backgrounds and it is difficult to find an appropriate control region. Therefore it is estimated by purely MC simulation. Table 6.16 shows the estimated number of W +jets events in the signal regions.

Estimation of other SM backgrounds

Contributions from other SM backgrounds are much smaller than the backgrounds already described. They are estimated by Monte Carlo simulation with the cross-section calculated by the theory. A conservative 100 % uncertainty is assigned to each process. Table 6.17 shows the expectation for these backgrounds.

6.3.4 Summary

Table 6.18 summarizes the expected and observed number of events in the one-lepton multi-jet signal regions. Figure 6.40 shows the distributions of E_T^{miss} , m_T and m_{eff} after requiring $m_{\text{eff}} > 400 \text{ GeV}$. In all regions, the data and SM prediction agree within the uncertainties and no significant excess is seen. In Chapter 7, the limits on SUSY models are calculated using this result.

Table 6.15: The expected number of top events in the one-lepton signal regions, normalizing MC simulated samples to data in the control regions. The systematic uncertainties are also shown.

electron channel			
	$m_{\text{eff}} > 400 \text{ GeV}$	$m_{\text{eff}} > 700 \text{ GeV}$	$m_{\text{eff}} > 1000 \text{ GeV}$
events	87.7	25.0	5.3
Jet energy scale	$+1.8 \%$ -1.1%	$+4.2 \%$ -2.6%	$+0 \%$ -14%
b -tagging efficiency	$+2.3 \%$ -3.0%	$+0.9 \%$ -4.1%	$+3.2 \%$ -6.6%
ISR/FSR	$\pm 15 \%$	$\pm 23 \%$	$\pm 47 \%$
Generator	$\pm 11 \%$	$\pm 25 \%$	$\pm 30 \%$
Shower modeling	$\pm 0.9 \%$	$\pm 4.4 \%$	$\pm 0.9 \%$
Statistics	$\pm 5.4 \%$	$\pm 5.4 \%$	$\pm 5.4 \%$
Uncertainty sum	$\pm 29 \%$	$\pm 35 \%$	$+56 \%$ -58%

muon channel			
	$m_{\text{eff}} > 400 \text{ GeV}$	$m_{\text{eff}} > 700 \text{ GeV}$	$m_{\text{eff}} > 1000 \text{ GeV}$
events	107	28.8	5.7
Jet energy scale	$+1.0 \%$ -2.1%	$+3.5 \%$ -5.7%	$+8.9 \%$ -0%
b -tagging efficiency	$+1.0 \%$ -1.7%	$+0 \%$ -2.9%	$+0 \%$ -5.7%
ISR/FSR	$\pm 20 \%$	$\pm 22 \%$	$\pm 58 \%$
Generator	$\pm 15 \%$	$\pm 23 \%$	$\pm 15 \%$
Shower modeling	$\pm 5.4 \%$	$\pm 6.1 \%$	$\pm 15 \%$
Statistics	$\pm 5.0 \%$	$\pm 5.0 \%$	$\pm 5.0 \%$
Uncertainty sum	$\pm 25 \%$	$\pm 33 \%$	$\pm 63 \%$

Table 6.16: The estimated number of W +jets events in the one-lepton signal regions purely using MC simulation.

electron channel			
	$m_{\text{eff}} > 400 \text{ GeV}$	$m_{\text{eff}} > 700 \text{ GeV}$	$m_{\text{eff}} > 1000 \text{ GeV}$
events	4.6	2.6	0.2
Jet energy scale	$^{+31}_{-0.8} \%$	$^{+42}_{-0} \%$	$^{+360}_{-0} \%$
b -tagging efficiency	$^{+31}_{-28} \%$	$^{+44}_{-41} \%$	$^{+27}_{-46} \%$
Number of partons	$\pm 44 \%$	$\pm 41 \%$	$\pm 42 \%$
Cross section	$\pm 11 \%$	$\pm 17 \%$	$\pm 17 \%$
Electron trigger	$\pm 0.4 \%$	$\pm 0.4 \%$	$\pm 0.4 \%$
Electron reconstruction	$\pm 1.6 \%$	$\pm 1.6 \%$	$\pm 1.6 \%$
Uncertainty sum	$^{+63}_{-54} \%$	$^{+75}_{-61} \%$	$^{+361}_{-64} \%$

muon channel			
	$m_{\text{eff}} > 400 \text{ GeV}$	$m_{\text{eff}} > 700 \text{ GeV}$	$m_{\text{eff}} > 1000 \text{ GeV}$
events	4.5	3.2	1.1
Jet energy scale	$^{+53}_{-15} \%$	$^{+2}_{-13} \%$	$^{+68}_{-0} \%$
b -tagging efficiency	$^{+21}_{-16} \%$	$^{+26}_{-20} \%$	$^{+24}_{-20} \%$
Number of partons	$\pm 40 \%$	$\pm 40 \%$	$\pm 39 \%$
Cross section	$\pm 17 \%$	$\pm 17 \%$	$\pm 16 \%$
Muon trigger	$\pm 1 \%$	$\pm 1 \%$	$\pm 1 \%$
Muon reconstruction	$\pm 0.7 \%$	$\pm 0.7 \%$	$\pm 0.7 \%$
Uncertainty sum	$^{+72}_{-49} \%$	$^{+51}_{-50} \%$	$^{+48}_{-82} \%$

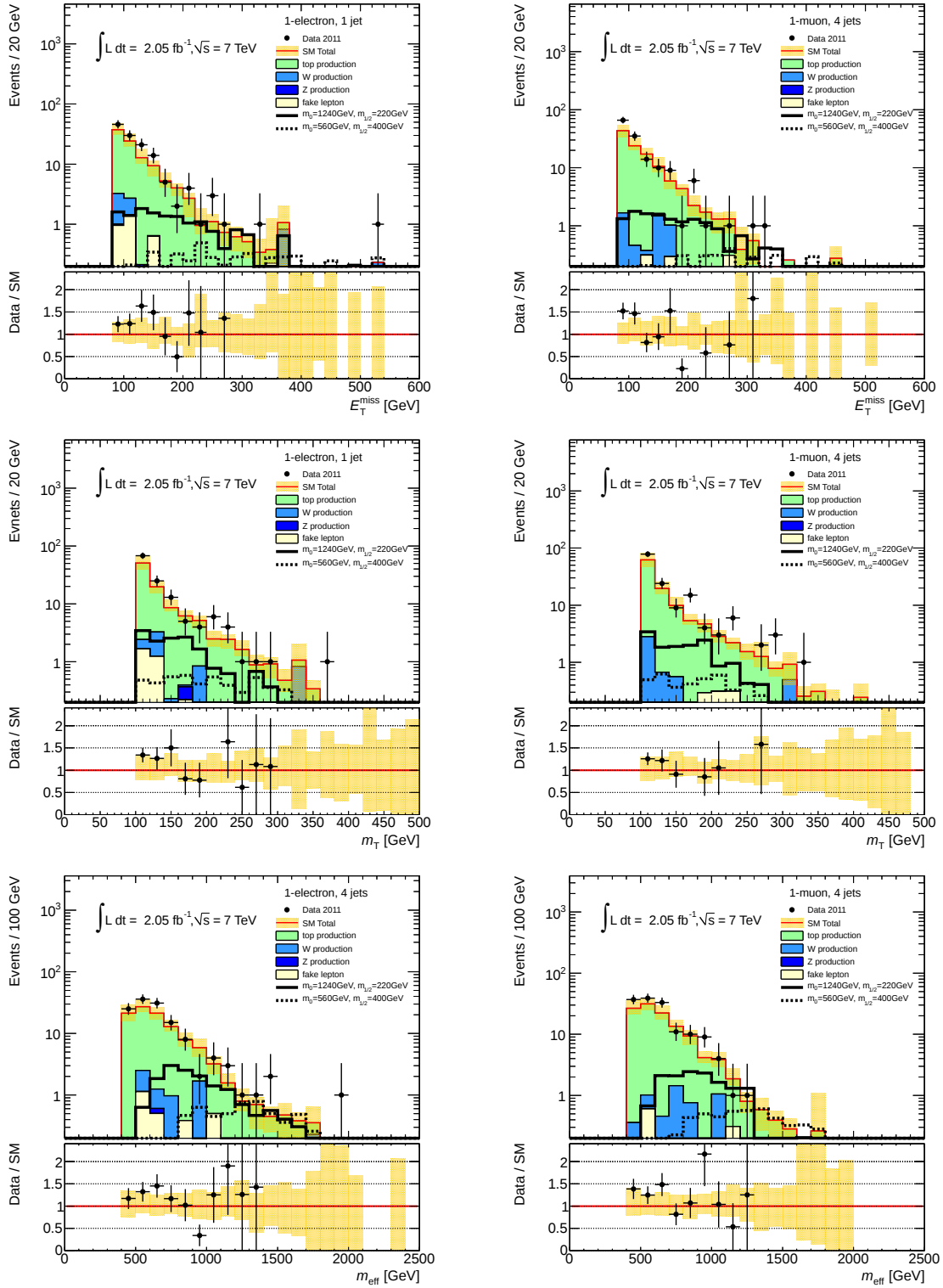


Figure 6.40: The distributions of E_T^{miss} , m_T and m_{eff} in the one-lepton multi-jet signal regions for $m_{\text{eff}} > 400$ GeV. The left figures show the electron channel and the right figures the muon channel.

Table 6.17: The expected SM backgrounds in the one-lepton signal regions, excluding backgrounds from top, W +jets and fake lepton events.

electron channel			
	$m_{\text{eff}} > 400 \text{ GeV}$	$m_{\text{eff}} > 700 \text{ GeV}$	$m_{\text{eff}} > 1000 \text{ GeV}$
Z +jets	0.1	0.04	0
Di-boson	0	0	0
$t\bar{t}+b\bar{b}$	1.3	0.4	0.03
$t\bar{t}+W$	1.1	0.5	0.2
$t\bar{t}+Z$	1.1	0.4	0.09

muon channel			
	$m_{\text{eff}} > 400 \text{ GeV}$	$m_{\text{eff}} > 700 \text{ GeV}$	$m_{\text{eff}} > 1000 \text{ GeV}$
Z +jets	0.08	0.08	0
Diboson	0	0	0
$t\bar{t}+b\bar{b}$	1.3	0.2	0
$t\bar{t}+W$	1.0	0.4	0.08
$t\bar{t}+Z$	1.2	0.5	0.1

6.4 No-lepton di-jet channel

As described in Section , if stops or sbottoms are directly pair-produced and directly decay to the LSP or decay such that only soft particles are produced other than b -jets, the final state becomes two b -jets and E_T^{miss} . In this section, the search in this topology is described.

6.4.1 Benchmark signals

As a benchmark signal, sbottom pair production decaying to $b + \tilde{\chi}_1^0$ with a branching ratio of 100 % are used. The LSP is $\tilde{\chi}_1^0$. Cross-sections are only a function of the sbottom mass as shown in Figure 6.41 (left).

Signals are generated in the $(m_{\tilde{b}_1}, m_{\tilde{\chi}_1^0})$ plane as shown in Figure 6.41 (right).

6.4.2 Optimization of event selection

Since the signal does not produce any isolated leptons in the decay, the no-lepton selection is applied. The jet plus E_T^{miss} trigger, EF_j75_a4tc_EFFS_xe45_loose_noMu is used to collect data samples. Hence a leading jet with $p_T > 130 \text{ GeV}$ and $E_T^{\text{miss}} > 130 \text{ GeV}$ are required in the offline analysis.

Figure 6.42 shows the distributions of the number of jets and the number of b -tagged jets after the jet plus E_T^{miss} trigger. As expected, sbottom signals have at least two jets. If the b -jet candidates are constrained to be the two leading jets, signals are

Table 6.18: Summary of the expected and observed number of events in the one-lepton signal regions. In the table, top sim. means the top estimated purely from MC simulation and top norm. means the top estimation after normalizing the MC samples to data.

electron channel			
	$m_{\text{eff}} > 400 \text{ GeV}$	$m_{\text{eff}} > 700 \text{ GeV}$	$m_{\text{eff}} > 1000 \text{ GeV}$
Data (2.05 fb ⁻¹)	127	37	12
SM (top sim.)	99 ⁺⁴³ ₋₃₅	32 ⁺¹³ ₋₁₁	8.8 ^{+3.7} _{-3.6}
SM (top norm.)	100±18	32.4±8.9	8.8±3.0
top (sim.)	87 ⁺⁴⁰ ₋₃₃	25 ⁺¹² ₋₁₀	5.3 ^{+3.2} _{-3.4}
top (norm.)	88±17	25±8.8	5.3 ^{+3.0} _{-3.1}
W + jets	4.6 ^{+2.9} _{-2.5}	2.6 ^{+1.9} _{-1.6}	0.2 ^{+0.8} _{-0.1}
QCD	3.2±1.0	1.6±0.6	1.0±0.5
Others	3.7±3.7	1.4±1.4	0.3±0.3

muon channel			
	$m_{\text{eff}} > 400 \text{ GeV}$	$m_{\text{eff}} > 700 \text{ GeV}$	$m_{\text{eff}} > 1000 \text{ GeV}$
Data (2.05 fb ⁻¹)	132	31	4
SM (top sim.)	111 ⁺⁵³ ₋₄₅	32 ⁺¹⁴ ₋₁₃	7.1 ^{+4.1} _{-3.7}
SM (top norm.)	116±26	33.5 ^{+9.2} _{-9.4}	7.3 ^{+3.7} _{-3.5}
top (sim.)	102 ⁺⁴⁹ ₋₄₄	28 ⁺¹³ ₋₁₂	5.5 ^{+4.0} _{-3.7}
top (norm.)	107±27	28.8 ^{+9.5} _{-9.6}	5.7±3.6
W+jets	4.5 ^{+3.2} _{-2.2}	3.2 ^{+1.6} _{-1.6}	1.1 ^{+0.5} _{-0.9}
QCD	0.9±0.6	0.3±0.3	0.3±0.3
Others	3.5±3.5	1.2±1.2	0.2±0.2

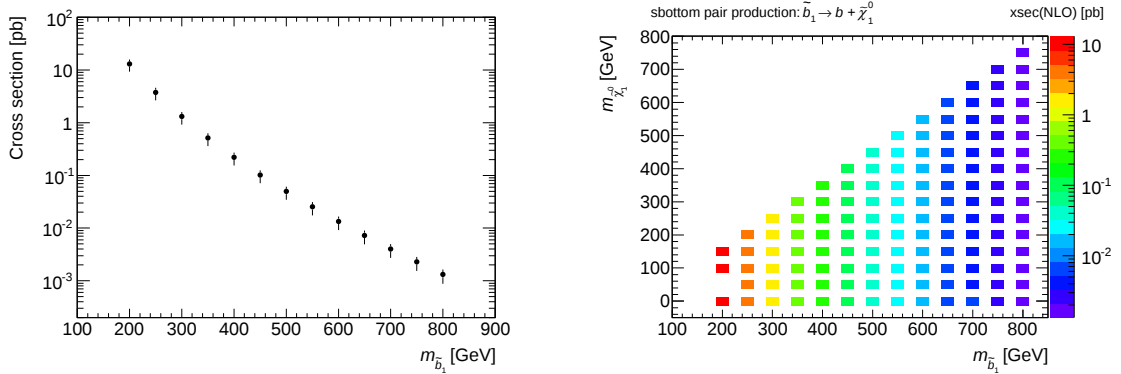


Figure 6.41: Cross-sections of sbottom pair production calculated to NLO accuracy (left) and generated sbottom pair production samples in the $(m_{\tilde{b}_1}, m_{\tilde{\chi}_1^0})$ plane (right).

highly enhanced by requiring two b -tagged jets. To reduce SM backgrounds (mainly for the $t\bar{t}$ process), if there is a third jet with $p_T > 50$ GeV, the event is rejected. To allow for ISR jets which are possible in sbottom signals, the third jet threshold is set relatively high.

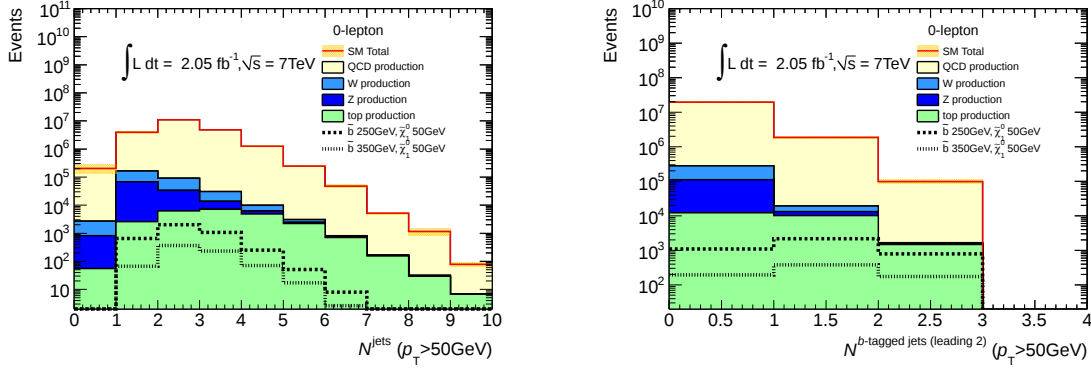


Figure 6.42: The distributions of the number of jets (left) and the number of b -tagged jets from the two leading jets (right) after requiring the jet plus E_T^{miss} trigger in the no-lepton channel.

To reduce the QCD di-jet background, selections are made on the $\min\Delta\phi_{1,2}$ defined by

$$\min\Delta\phi_{1,2} = \min_{i=1}^2 \left| \phi_i^{\text{jet}} - \phi^{\text{miss}} \right|. \quad (6.23)$$

To further reduce the QCD di-jet events remaining after this cut, $\Delta\phi$ between the third leading jet and E_T^{miss} is also used if there is a third leading jet with $p_T > 30$ GeV. Figure 6.43 (left) shows the $\min\Delta\phi_{1,2}$ distribution after the requirements on two jets and E_T^{miss} .

Another cut to reduce QCD background uses the effective mass, defined by the two leading jets and E_T^{miss} as follows,

$$m_{\text{eff}} = E_T^{\text{miss}} + \sum_{i=1}^2 \left(p_T^{\text{jet}} \right)_i. \quad (6.24)$$

A cut is applied on the quantity $E_T^{\text{miss}}/m_{\text{eff}} > 0.25$. Figure 6.43 (right) shows the $E_T^{\text{miss}}/m_{\text{eff}}$ distribution after the requirements on two jets and E_T^{miss} .

Finally, to enhance the SUSY signal from the SM backgrounds (mainly the $t\bar{t}$ process at this stage), the contranverse mass, m_{CT} [101] is used. The contranverse mass can be used to measure the masses of pair-produced semi-invisibly decaying heavy particles. It is defined using the two visible particle v_1 and v_2 ,

$$m_{\text{CT}}(v_1, v_2)^2 = [E_T(v_1) + E_T(v_2)]^2 - [\vec{p}_T(v_1) - \vec{p}_T(v_2)]^2. \quad (6.25)$$

where $E_T(v)$ is the transverse energy defined by

$$E_T(v) = \sqrt{p_T(v)^2 + m(v)^2}. \quad (6.26)$$

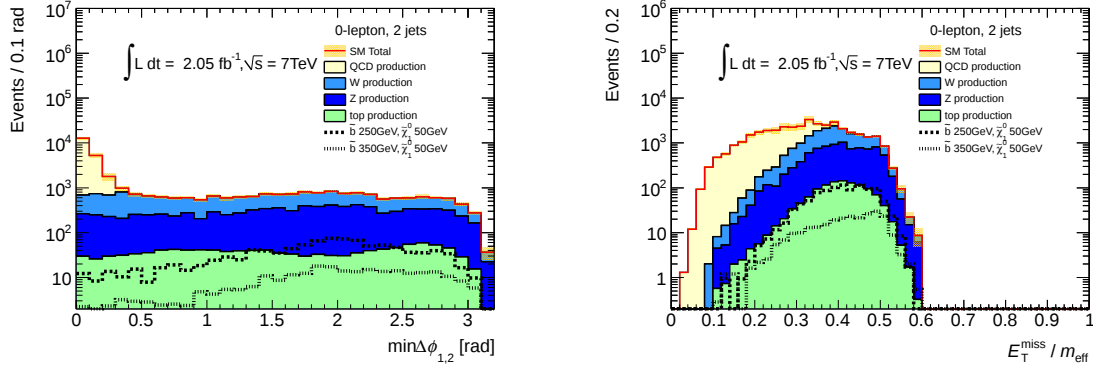


Figure 6.43: The distributions of $\min\Delta\phi_{1,2}$ (left) and $E_T^{\text{miss}}/m_{\text{eff}}$ (right) after the requirements on two jets and E_T^{miss} in the no-lepton channel.

Suppose that heavy particles δ_i ($i=1,2$) are pair-produced and they decay to v_i and the invisible particle α_i . Here, assume each pair δ_i , α_i , v_i consists of the same particle such that

$$m(\delta) = m(\delta_1) = m(\delta_2), \quad (6.27)$$

$$m(\alpha) = m(\alpha_1) = m(\alpha_2), \quad (6.28)$$

$$m(v) = m(v_1) = m(v_2). \quad (6.29)$$

The m_{CT} has an end-point at

$$m_{\text{CT}}^{\text{max}}(v_1, v_2) = \frac{m(v)^2 + m(\delta)^2 - m(\alpha)^2}{m(\delta)}. \quad (6.30)$$

This feature can be used to separate SUSY signal from SM backgrounds. In this analysis the two leading b -tagged jets are used for the m_{CT} calculation. Figure 6.44 shows the m_{CT} distribution after all other selection cuts.

In the case of sbottom pair production, δ , α , v correspond to sbottom, lightest neutralino, b -quark, respectively. The end-point of m_{CT} is therefore

$$m_{\text{CT}}^{\text{max}}(b, b) = \frac{m_b^2 + m_{\tilde{b}_1}^2 - m_{\tilde{\chi}_1^0}^2}{m_{\tilde{b}_1}}. \quad (6.31)$$

For the signal $(m_{\tilde{b}_1}, m_{\tilde{\chi}_1^0}) = (250 \text{ GeV}, 50 \text{ GeV})$, $m_{\text{CT}}^{\text{max}}$ is 240 GeV and for the signal $(m_{\tilde{b}_1}, m_{\tilde{\chi}_1^0}) = (350 \text{ GeV}, 50 \text{ GeV})$, $m_{\text{CT}}^{\text{max}}$ is 343 GeV.

Applying this calculation to the $t\bar{t}$ pair process, δ , α , v correspond to top, W , b -quark, respectively, and the end-point of m_{CT} then becomes

$$m_{\text{CT}}^{\text{max}}(b, b) = \frac{m_b^2 + m_t^2 - m_W^2}{m_t} = 135 \text{ GeV}. \quad (6.32)$$

Therefore, the $t\bar{t}$ background is reduced sharply at 135 GeV.

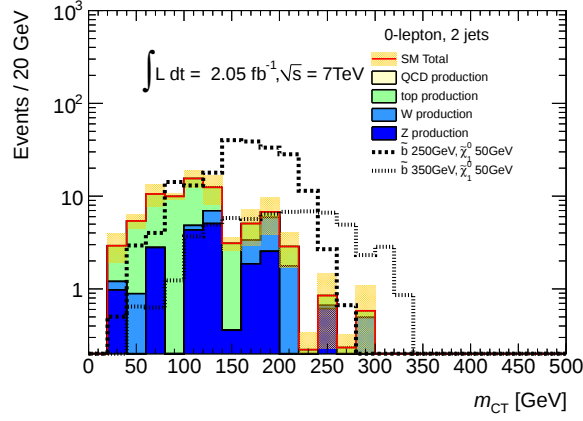


Figure 6.44: The m_{CT} distribution after all other selection cuts for the no-lepton di-jet channel

If the $\delta_1\delta_2$ center-of-mass (CoM) frame is boosted in the laboratory transverse plane, the $m_{CT}^{\max}$ is not Lorentz invariant. Therefore, following Reference [102], a correction is applied in order to give a conservative value for m_{CT} which is smaller than the m_{CT} value in the $\delta_1\delta_2$ CoM frame.

The event selection is summarized below.

- lepton veto ($p_T > 20$ GeV for electrons and $p_T > 10$ GeV for muons)
- leading jet $p_T > 130$ GeV
- $E_T^{\text{miss}} > 130$ GeV
- 2nd leading jet $p_T > 50$ GeV
- 3rd leading jet $p_T \leq 50$ GeV (if 3rd jet exists)
- $\min\Delta\phi_{1,2} > 0.4$ rad
- $\Delta\phi(3\text{rd jet} - E_T^{\text{miss}}) > 0.2$ rad (if 3rd jet with $p_T > 30$ GeV exists)
- $E_T^{\text{miss}}/m_{\text{eff}} > 0.25$
- two leading jets are b -tagged
- optimum m_{CT} cut.

To determine the optimum m_{CT} cut, the discovery significance, defined by Equation 6.7, is scanned as a function of the m_{CT} cut. Figure 6.45 shows the best m_{CT} cut for sbottom pair production signals estimated from purely MC simulations. To cover the grid of signal points, three signal regions, $m_{CT} > 100$ GeV, $m_{CT} > 150$ GeV and $m_{CT} > 200$ GeV are prepared. The actual cut used in the final analysis is determined after the completion of the background estimation including uncertainties.

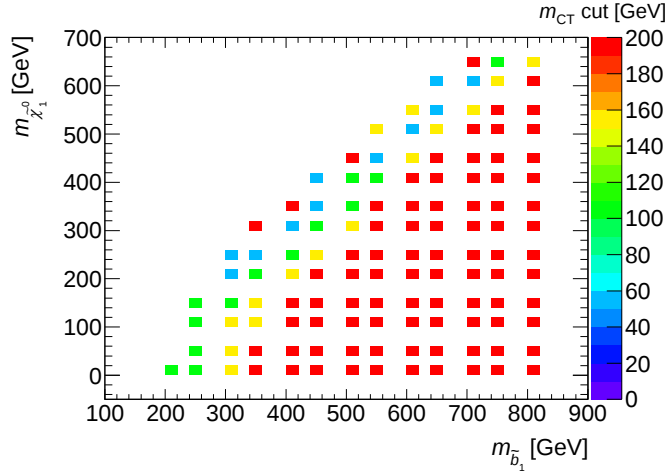


Figure 6.45: The best m_{CT} cut for sbottom signals in the no-lepton di-jet channel.

6.4.3 SM background estimation

QCD di-jet estimation

Although several cuts are employed to reduce the background from QCD di-jet events, this background might still contribute to the signal regions. To estimate this contribution, the same technique described in Section 6.2.3 (QCD multi-jet estimation) is used. The normalization of the smeared samples is obtained in the region defined by $\min\Delta\phi_{1,2} < 0.4$ rad. Figure 6.46 (top left) shows the $\min\Delta\phi_{1,2}$ distribution, normalizing the smeared samples to data. Other plots in Figures 6.46 are the distributions of E_T^{miss} , m_{CT} and leading jet p_T in the region $\min\Delta\phi_{1,2} < 0.4$ rad. The errors shown are statistical only. Some distribution show the deviations exceeding the statistical uncertainty but all of them are within relative difference of 50 %.

Since low-mass signal can contribute to this control region, the size of the contribution is treated as an additional systematic uncertainty. Table 6.19 shows the estimated number of QCD events in the signal regions along with their systematic uncertainties.

Top estimation

The largest SM background just before the m_{CT} cut is the $t\bar{t}$ production where one top quark decays to a tau-lepton with the tau decaying hadronically and where the other top quark decays hadronically. This background is estimated by Monte Carlo simulation. To reduce the systematic uncertainty in this estimation, the Monte Carlo simulated samples are normalized to data in the one-lepton channel because semi-leptonic $t\bar{t}$ decays have similar kinematics to the decays contributing to the no-lepton signal region. The number of events in the signal regions is then estimated by Equation 6.8. Since the SUSY signals considered here do not produce isolated leptons, no signal contamination is expected in this one-lepton region. Single-top production (mainly $W + t$ after the selection) which has a topology similar to the $t\bar{t}$ production is also

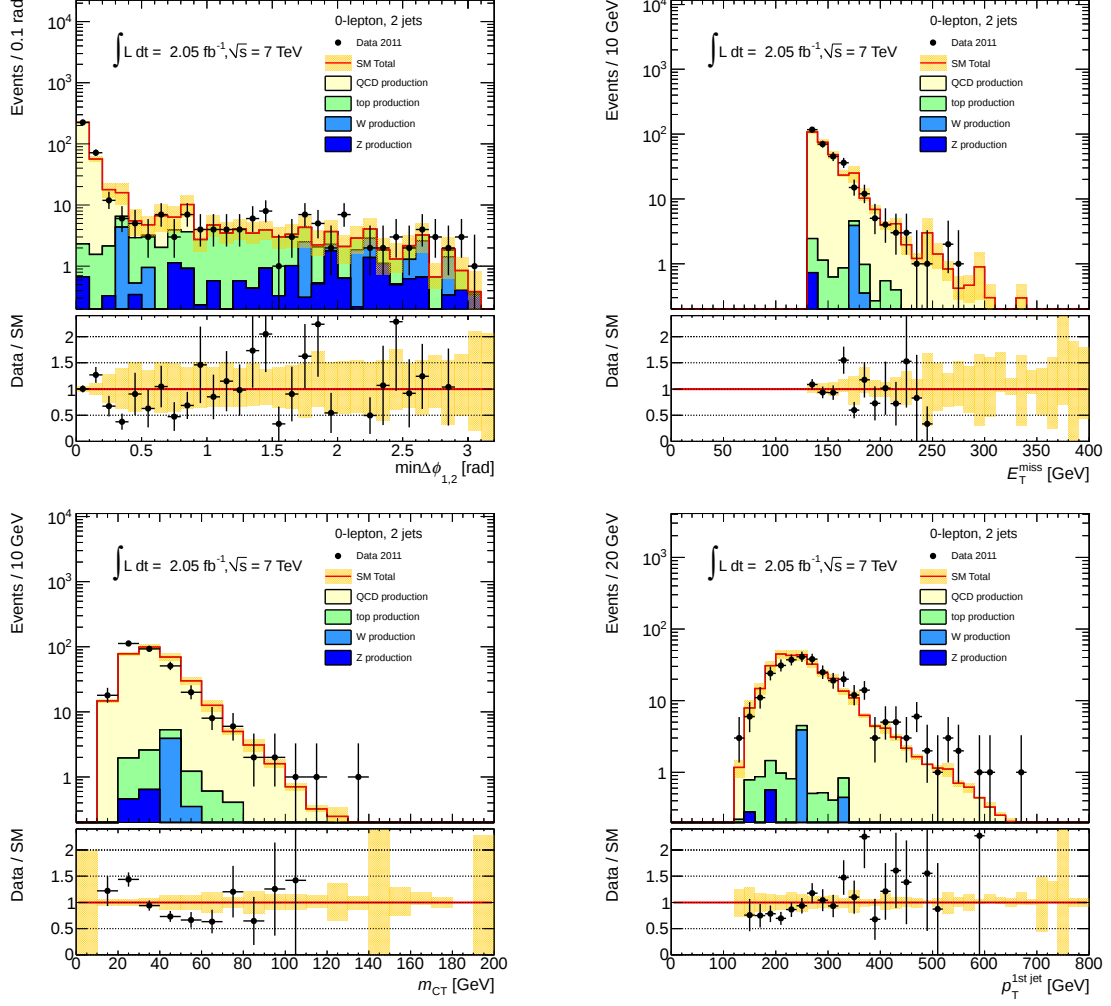


Figure 6.46: The $\min\Delta\phi_{1,2}$ distribution after requiring two b -tagged jets (top left). The distributions of E_T^{miss} (top right), m_{CT} (bottom left), leading jet p_T (bottom right) in the region $\min\Delta\phi_{1,2} < 0.4$ rad.

Table 6.19: The expected number of QCD di-jet events in the no-lepton two-jet signal regions estimated by the jet smearing method.

	$m_{\text{CT}} > 100 \text{ GeV}$	$m_{\text{CT}} > 150 \text{ GeV}$	$m_{\text{CT}} > 200 \text{ GeV}$
events	0.1	0.1	0.01
Jet energy scale	$^{+100}_{-0} \%$	$^{+100}_{-0} \%$	$^{+61}_{-19} \%$
b -tagging efficiency	$^{+1.6}_{-2.2} \%$	$^{+1.6}_{-2.2} \%$	$^{+1.6}_{-2.2} \%$
Gaussian correction	$^{+10}_{-9} \%$	$^{+6}_{-13} \%$	$^{+12}_{-13} \%$
Statistics	$\pm 61 \%$	$\pm 61 \%$	$\pm 63 \%$
Uncertainty sum	$^{+118}_{-62} \%$	$^{+128}_{-63} \%$	$^{+89}_{-67} \%$

normalized using this control region.

The event selection for the control region is as follows.

- exactly one *tight* lepton ($p_{\text{T}} > 25 \text{ GeV}$ for an electron and $p_{\text{T}} > 20 \text{ GeV}$ for a muon)
- $40 \text{ GeV} < m_{\text{T}} < 100 \text{ GeV}$ (m_{T} defined by Equation 6.17)
- leading jet $p_{\text{T}} > 60 \text{ GeV}$
- 2nd leading jet $p_{\text{T}} > 50 \text{ GeV}$
- 3rd leading jet $p_{\text{T}} \leq 50 \text{ GeV}$
- $E_{\text{T}}^{\text{miss}} > 50 \text{ GeV}$
- leading two jets are b -tagged.

Figure 6.47 shows the distributions of $E_{\text{T}}^{\text{miss}}$ and m_{CT} in this control region before simulated top sample is normalized to data. The errors shown are the sum in quadrature of the JES and b -tagging uncertainties. The expected purity of top events in the control region, estimated from MC simulation, is 87 % and the normalization factor obtained for top events is 1.23 ± 0.04 (stat.) which clearly differs from the unity. This difference is thought to come from the exclusive requirement of two b -tagged jets in the two leading jets. Since the $t\bar{t}$ process tends to be multi-jet final state, this selection cut is highly biased by the modeling of the QCD in simulation. Table 6.20 shows the estimated number of top events in the no-lepton di-jet signal regions. The larger systematic uncertainties can be seen in the JES uncertainty and the ISR/FSR uncertainty.

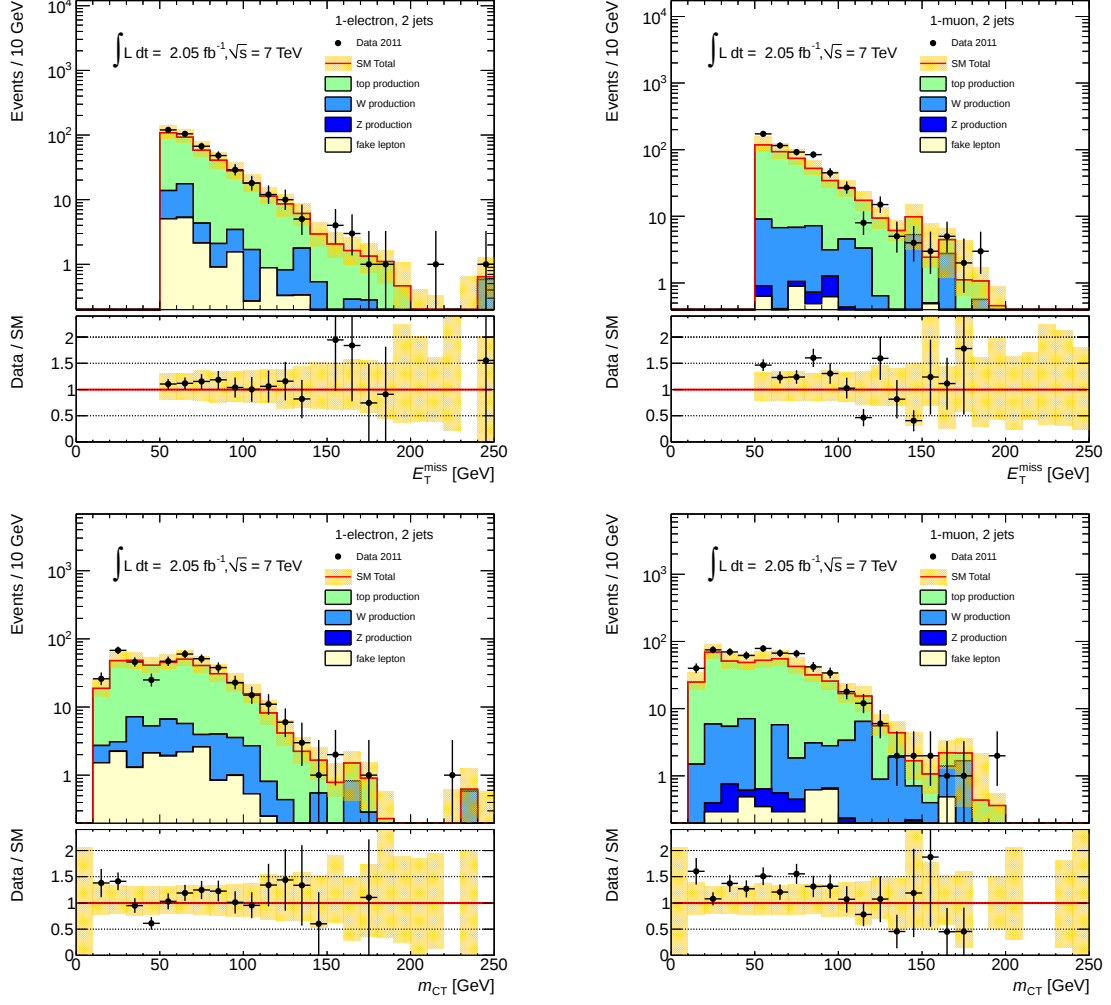


Figure 6.47: The distributions of E_T^{miss} (top) and m_{CT} (bottom) in the one-lepton di-jet control region. The left figures are for the electron channel and the right are for the muon channel.

Table 6.20: The estimated number of top events in the no-lepton di-jet signal regions after normalizing MC simulated samples to data in the one-lepton control region.

	$m_{\text{CT}} > 100 \text{ GeV}$	$m_{\text{CT}} > 150 \text{ GeV}$	$m_{\text{CT}} > 200 \text{ GeV}$
events	27.9	6.2	2.2
Jet energy scale	$\pm 17 \%$	$^{+20}_{-12} \%$	$^{+0}_{-20} \%$
b -tagging efficiency	$^{+1.1}_{-8.0} \%$	$^{+4.2}_{-14} \%$	$^{+7.3}_{-20} \%$
ISR/FSR	$\pm 20 \%$	$\pm 35 \%$	$\pm 55 \%$
Generator	$\pm 1.8 \%$	$\pm 3.3 \%$	$\pm 2.8 \%$
Shower modeling	$\pm 5.3 \%$	$\pm 13 \%$	$\pm 50 \%$
Statistics	$\pm 3.8 \%$	$\pm 3.8 \%$	$\pm 3.8 \%$
Electron trigger	$\pm 0.2 \%$	$\pm 0.2 \%$	$\pm 0.2 \%$
Electron reconstruction	$\pm 1.6 \%$	$\pm 1.6 \%$	$\pm 1.6 \%$
Muon trigger	$\pm 0.5 \%$	$\pm 0.5 \%$	$\pm 0.5 \%$
Muon reconstruction	$\pm 0.7 \%$	$\pm 0.7 \%$	$\pm 0.7 \%$
Uncertainty sum	$^{+27}_{-28} \%$	$^{+43}_{-42} \%$	$^{+75}_{-80} \%$

W +jets estimation

The background from the $W + b\bar{b}$ process is also estimated by normalizing the Monte Carlo simulation to data in a control region. The control region is defined by the same selection as used in Section 6.2.3 (W +jets estimation) for the estimation of the W +jets background. The distributions in this control region are shown in Figure 6.21. Table 6.21 shows the expected number of events of W +jets process in the signal regions from the W +jets process.

Z +jets estimation

$Z(\rightarrow \nu\bar{\nu}) + b\bar{b}$ also contribute to the signal regions. It is also estimated by normalizing Monte Carlo simulated samples to data, using $Z(\rightarrow l^+l^-) + b\bar{b}$ process in the two-lepton control region defined as follows.

- exactly two same flavor, *tight* leptons (opposite charged) with $p_{\text{T}} > 20 \text{ GeV}$ for electrons and $p_{\text{T}} > 10 \text{ GeV}$ for muons, at least one lepton required to have $p_{\text{T}} > 25 \text{ GeV}$ for electrons, $p_{\text{T}} > 20 \text{ GeV}$ for muons
- two-lepton invariant mass M_{ll} satisfies $81 \text{ GeV} < M_{ll} < 101 \text{ GeV}$
- leading jet $p_{\text{T}} > 80 \text{ GeV}$
- 2nd leading jet $p_{\text{T}} > 50 \text{ GeV}$
- $E_{\text{T},l}^{\text{miss}} > 50 \text{ GeV}$ (defined by Equation 6.33)

Table 6.21: The expected number of events of W +jets in no-lepton di-jet signal regions. The systematic uncertainties are also shown.

	$m_{\text{CT}} > 100 \text{ GeV}$	$m_{\text{CT}} > 150 \text{ GeV}$	$m_{\text{CT}} > 200 \text{ GeV}$
events	9.7	7.3	2.4
Jet energy scale	$+7.5 \%$ -6.2%	$+17 \%$ -2.6%	$+85 \%$ -65%
b -tagging efficiency	$+6.2 \%$ -8.8%	$+6.4 \%$ -6.9%	$+4.8 \%$ -9.4%
Number of partons	$+1.6 \%$ -1.1%	$+3.1 \%$ -2.1%	$+16 \%$ -11%
Statistics	$\pm 3.2 \%$	$\pm 3.2 \%$	$\pm 3.2 \%$
Electron trigger	$\pm 0.2 \%$	$\pm 0.2 \%$	$\pm 0.2 \%$
Electron reconstruction	$\pm 0.8 \%$	$\pm 0.8 \%$	$\pm 0.8 \%$
Muon trigger	$\pm 0.5 \%$	$\pm 0.5 \%$	$\pm 0.5 \%$
Muon reconstruction	$\pm 0.3 \%$	$\pm 0.3 \%$	$\pm 0.3 \%$
Uncertainty sum	$+12 \%$ -9.5%	$+20 \%$ -8.0%	$+86 \%$ -67%

- leading two jets are b -tagged.

To mimic the $Z \rightarrow \nu\bar{\nu}$ process, the two identified leptons are added to $E_{\text{T}}^{\text{miss}}$. This corrected $E_{\text{T}}^{\text{miss}}$ is calculated by

$$E_{\text{T},l}^{\text{miss}} = \sqrt{\left| \vec{E}_{\text{T}}^{\text{miss}} + \sum_{i=1}^2 \left(\vec{p}_{\text{T}}^{\text{lep}} \right)_i \right|^2}. \quad (6.33)$$

The number of Z +jets events in the signal regions is then estimated by

$$N_Z^{\text{SR}} = \frac{N_{\text{data}}^{\text{CR}} - N_{\text{non-Z}}^{\text{CR}}}{N_{Z,\text{MC}}^{\text{CR}}} N_{Z,\text{MC}}^{\text{SR}} \quad (6.34)$$

In this control region, the contribution of $t\bar{t}$ is also large and the purity of Z +jets is only 50 % according to the MC simulations while $t\bar{t}$ contribution is 45 %. To reduce the systematic uncertainties related to the $t\bar{t}$ process, the $t\bar{t}$ MC simulation is normalized to data in a region defined by inverting M_{ll} cut ($41 \text{ GeV} < M_{ll} < 81 \text{ GeV}$, $101 \text{ GeV} < M_{ll} < 141 \text{ GeV}$); in this control region, the purity of the $t\bar{t}$ is high (90 %). The normalization factor obtained for the $t\bar{t}$ MC simulation is 1.17 ± 0.14 (stat.).

Other SM backgrounds contributing to the Z +jets control region are estimated using MC simulation, except for the fake-lepton events which are estimated in a data-driven way as described in Section 6.5.3 (Fake lepton event estimation). The normalization factor finally obtained for Z +jets events is 1.41 ± 0.37 (stat.). Table 6.22 shows the expected number of Z +jets events in the no-lepton di-jet signal regions. Figures 6.48 show the distributions of m_{CT} and $E_{\text{T},l}^{\text{miss}}$ in the two-lepton control region.

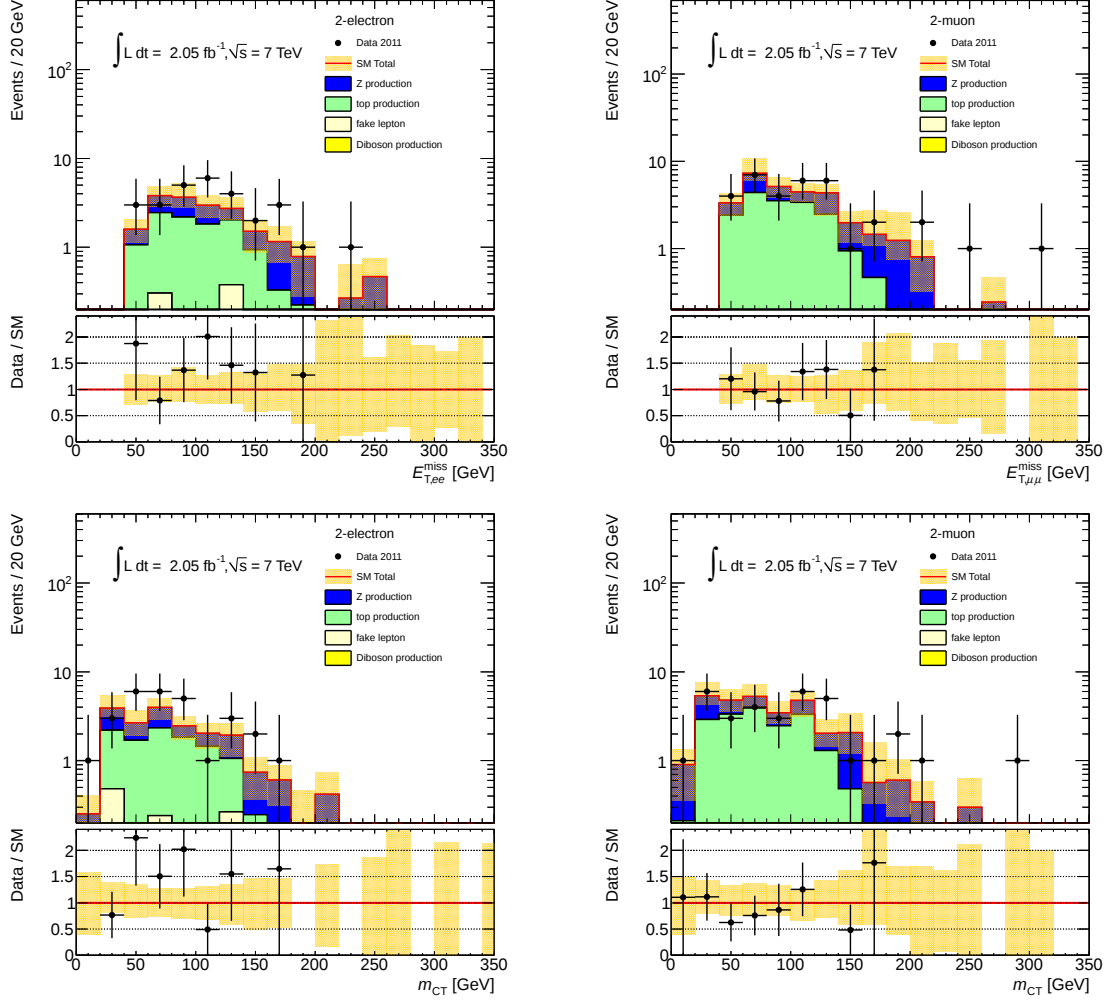


Figure 6.48: The distributions of $E_{T, \ell\ell}^{\text{miss}}$ (top) and m_{CT} (bottom) in the two -lepton Z +jets control regions. The left figures shows the e - e channel and the right shows the μ - μ channel.

Table 6.22: The expected number of Z +jets events in the no-lepton di-jet signal regions, obtained by normalizing MC simulation to data in the two-lepton control regions.

	$m_{\text{CT}} > 100 \text{ GeV}$	$m_{\text{CT}} > 150 \text{ GeV}$	$m_{\text{CT}} > 200 \text{ GeV}$
events	23	12	3.9
Jet energy scale	$^{+33}_{-0} \%$	$^{+8.8}_{-2.5} \%$	$^{+3.2}_{-1.0} \%$
b -tagging efficiency	$^{+4.5}_{-6.5} \%$	$^{+5.7}_{-8.2} \%$	$^{+7.9}_{-11} \%$
Number of partons	$^{+13}_{-11} \%$	$^{+12}_{-11} \%$	$^{+14}_{-2} \%$
Cross section	$^{+4.6}_{-5.6} \%$	$^{+4.6}_{-5.6} \%$	$^{+4.6}_{-5.6} \%$
Statistics	$\pm 33 \%$	$\pm 36 \%$	$\pm 39 \%$
Electron trigger	$\pm 0.2 \%$	$\pm 0.2 \%$	$\pm 0.2 \%$
Electron reconstruction	$\pm 1.6 \%$	$\pm 1.6 \%$	$\pm 1.6 \%$
Muon trigger	$\pm 0.5 \%$	$\pm 0.5 \%$	$\pm 0.5 \%$
Muon reconstruction	$\pm 0.7 \%$	$\pm 0.7 \%$	$\pm 0.7 \%$
Uncertainty sum	$^{+48}_{-36} \%$	$^{+40}_{-39} \%$	$^{+43}_{-41} \%$

Estimation of other SM backgrounds

The contributions from other SM backgrounds to the no-lepton di-jet signal regions are small compared to the backgrounds estimated above. They are estimated purely by Monte Carlo simulation assigning a conservative systematic uncertainty of 100 %. Table 6.23 shows the expected numbers of events of these other SM backgrounds.

Table 6.23: The expected number of events from other SM backgrounds in the no-lepton di-jet signal regions.

	$m_{\text{CT}} > 100 \text{ GeV}$	$m_{\text{CT}} > 150 \text{ GeV}$	$m_{\text{CT}} > 200 \text{ GeV}$
WW	0	0	0
WZ	0.5	0.5	0.3
ZZ	0.8	0.8	0.6
$t\bar{t} + b\bar{b}$	0.1	0.02	0.002
$t\bar{t} + W$	0.04	0.01	0.003
$t\bar{t} + Z$	0.09	0.03	0.01

6.4.4 Summary

Table 6.24 shows the expected and observed number of events in the no-lepton di-jet channel signal regions. Figures 6.49 show the distributions for m_{CT} and $E_{\text{T}}^{\text{miss}}$ just

before m_{CT} cuts. Since no significant excess can be seen from the SM prediction, the exclusion limits on the SUSY models are calculated in Chapter 7.

Table 6.24: The expected and observed number of events in the no-lepton di-jet signal regions.

	$m_{CT} > 100$ GeV	$m_{CT} > 150$ GeV	$m_{CT} > 200$ GeV
Data (2.05 fb ⁻¹)	56	28	10
SM	62^{+17}_{-12}	$26.9^{+6.6}_{-5.9}$	9.3 ± 3.2
top	$27.9^{+7.6}_{-7.9}$	$6.2^{+2.6}_{-2.6}$	$2.2^{+1.6}_{-1.7}$
W+jets	$9.7^{+1.2}_{-0.9}$	$7.3^{+1.4}_{-0.6}$	$2.4^{+2.0}_{-1.6}$
Z+jets	23^{+11}_{-8}	$12^{+4.8}_{-4.7}$	$3.9^{+1.7}_{-1.6}$
QCD	0.1 ± 0.1	0.1 ± 0.1	0.01 ± 0.01
Others	1.5 ± 1.5	1.3 ± 1.3	0.9 ± 0.9

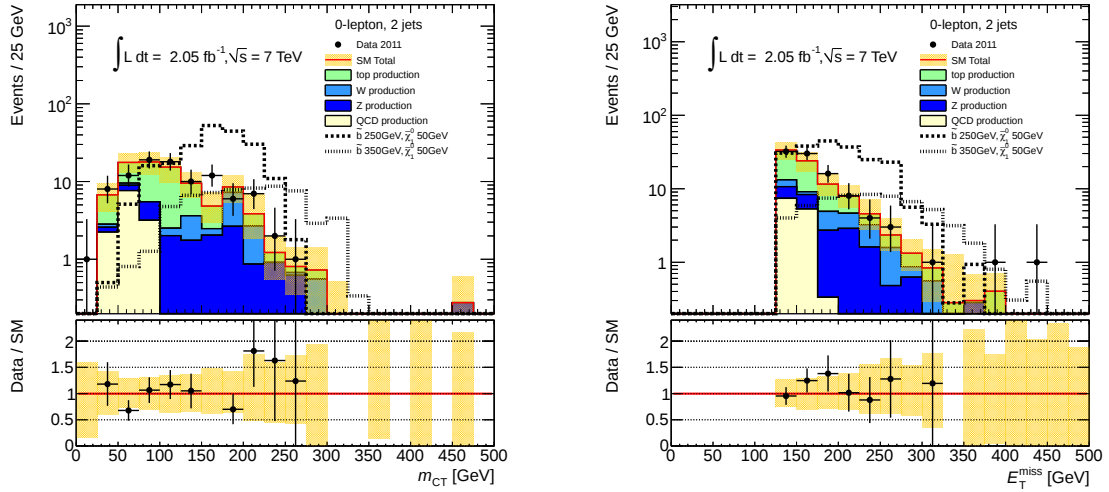


Figure 6.49: The distributions of m_{CT} (left) and E_T^{miss} (right) in the no-lepton di-jet channel, shown before the m_{CT} cuts.

6.5 Two-lepton multi-jet channel

As shown in Section 2.2.4, the two-lepton selection is sensitive to the stop pair production signals in the light-gravitino, light-higgsino scenario if $m_{\tilde{\chi}_1^0} > m_Z$.

6.5.1 Benchmark signals

To search for direct stop pair production in the light-gravitino (GMSB-like), light-higgsino models, benchmark signals are generated following the Natural SUSY scenario in Reference [14]⁵. Parameters for the stop sector are as follows.

$$m_{\tilde{q}_3} = m_{\tilde{u}_3} = -\frac{A_t}{2} \quad (6.35)$$

$$\tan \beta = 10 \quad (6.36)$$

The parameters, $m_{\tilde{q}_3}$ and μ are scanned to give the desired stop and higgsino masses. Masses of all other superparticles are set high enough (2 TeV) so that their production can be ignored.

Figure 6.50 (right) shows the signal points generated in the $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0})$ plane with these parameters. The cross-section for the stop pair production depends only on the stop mass as shown in Figure 6.50 (left) and is calculated to NLO accuracy using PROSPINO [18].

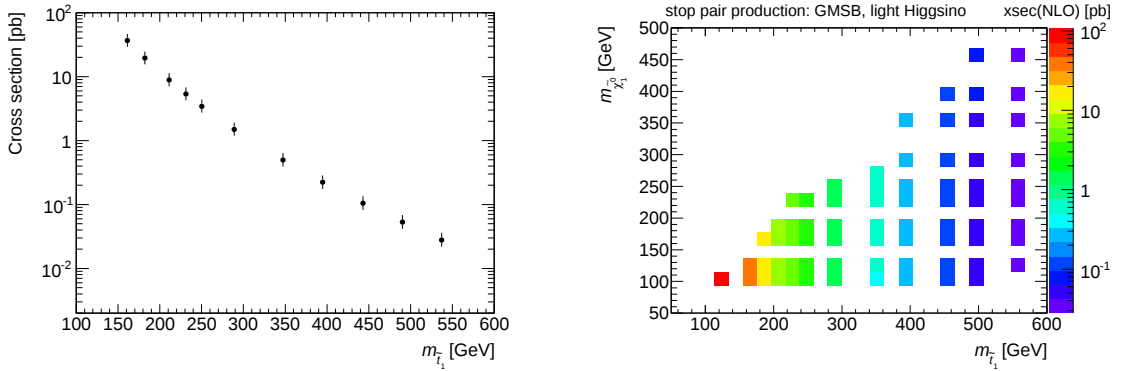


Figure 6.50: Cross-sections for the stop pair production at NLO accuracy (left). The stop pair production samples generated for this analysis in the Natural SUSY model (right).

6.5.2 Optimization of event selection

Event selection is optimized for the above signals as follows.

⁵This model requires some additional mechanisms which generate an appropriate A -term along with the gauge mediation mechanism to obtain the mass parameters in Equation 6.35 and 6.36.

First, events are selected by the single-electron trigger `EF_e20_medium` and the single-muon trigger `EF_mu18` (and `EF_mu18_L1J10`) with two leptons (electrons or muons) with same flavor and opposite charge are selected. The leptons are required to pass *tight* identification criteria and have $p_T > 20$ GeV for electrons and $p_T > 10$ GeV for muons. For the trigger requirements, at least one lepton must satisfy $p_T > 25$ GeV for electrons and $p_T > 20$ GeV for muons.

Since the two leptons in the signal events come from the decay of the Z boson, their invariant mass, M_{ll} peaks around Z mass. By selecting the invariant mass in the range $86 \text{ GeV} < M_{ll} < 96 \text{ GeV}$, the $t\bar{t}$ background is reduced. Figure 6.51 (left) shows the M_{ll} distribution after two opposite charged electrons are selected (the situation is the same for two-muon selection).

Most Z +light-flavor jet events are rejected by requiring at least one b -tagged jet. Figure 6.51 (right) shows the distribution of the number of b -tagged jets after two electrons have been selected.

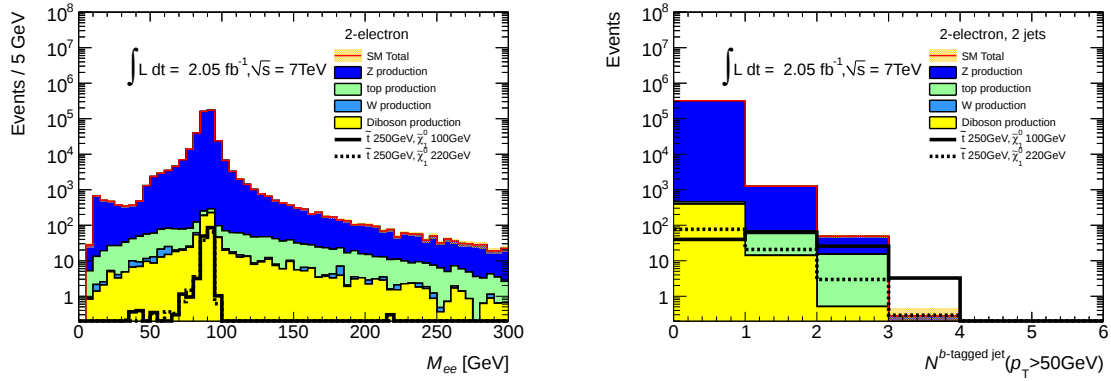


Figure 6.51: Monte Carlo simulation of the M_{ee} distribution after an electron-positron pair is selected (left). The distribution of the number of b -tagged jets after $86 \text{ GeV} < M_{ee} < 96 \text{ GeV}$ (right).

Since the Z or Higgs boson appearing in the decay of the lightest neutralino has a large branching ratio to two quarks, stop events will tend to contain multiple jets in the final state, composed of two b -jets and two additional jets. On the other hand, the hard process of the $t\bar{t}$ di-leptonic decay produce only two (b -)quarks. Hence a cut requiring higher jet multiplicity enhances the stop signal. However, if the mass difference between the stop and the NLSP is small, b -jets from stop decays become softer and they cannot exceed the p_T threshold. Therefore jet multiplicity cut must be changed depending on the mass spectrum of the signal. Figure 6.52 (left) shows the distribution of jet multiplicity for jet $p_T > 50$ GeV for the representative stop signals and the SM prediction from MC simulation. The signal of $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0}) = (250 \text{ GeV}, 100 \text{ GeV})$ which has the larger mass difference has a peak in the number of jets at two to three. On the other hand, the signal of $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0}) = (250 \text{ GeV}, 220 \text{ GeV})$ which has the smaller mass difference has a peak in the number of jets at one. As a baseline selection, at least two jets are required and for higher jet multiplicity signals, the

Table 6.25: Summary of two leptons channel selection

Baseline	Large missing E_T	High jet multiplicity
same flavor, opposite charged two leptons (electron or muon)		
$86 \text{ GeV} < M_{ll} < 96 \text{ GeV}$		
leading jet $p_T > 60 \text{ GeV}$		
at least one b -tagged jet with $p_T > 50 \text{ GeV}$		
$N^{\text{jet}}(p_T > 50 \text{ GeV}) \geq 2$	$N^{\text{jet}}(p_T > 50 \text{ GeV}) \geq 2$	$N^{\text{jet}}(p_T > 50 \text{ GeV}) \geq 3$
$E_T^{\text{miss}} > 50 \text{ GeV}$	$E_T^{\text{miss}} > 80 \text{ GeV}$	$E_T^{\text{miss}} > 50 \text{ GeV}$

selection criteria of three jets is prepared.

To reduce the Z +jets background, a cut requiring $E_T^{\text{miss}} > 50 \text{ GeV}$ is applied. For the signals with a smaller mass difference between $\tilde{t}_1$ and $\tilde{\chi}_1^0$, a higher E_T^{miss} cut is favored. Therefore an additional signal region with $E_T^{\text{miss}} > 80 \text{ GeV}$ is prepared. Figure 6.52 shows the E_T^{miss} distribution after a cut on the two-lepton invariant mass.

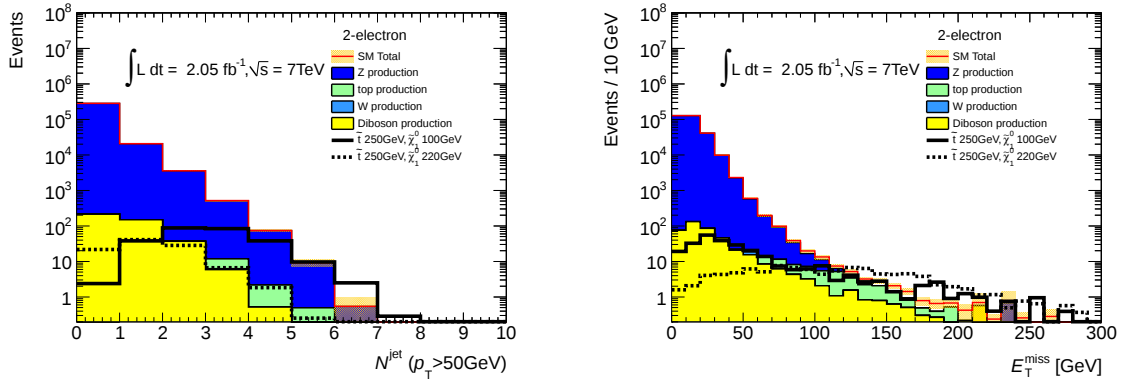


Figure 6.52: The distribution of the number of jets (left) and of E_T^{miss} (right) after the cut requiring $86 \text{ GeV} < M_{ee} < 96 \text{ GeV}$.

In Table 6.25 the above selections are summarized. To cover the broad signal parameter space, three signal regions are prepared; for each signal point, the signal significance defined by Equation 6.7 is calculated for an integrated luminosity of 2 fb^{-1} . Figure 6.53 shows the best signal region giving the largest significance for each signal point. The actual signal region used is determined after the SM background estimation with systematic uncertainties.

6.5.3 SM background estimation

Fake-lepton event estimation

One prompt lepton can be produced from the leptonic decay of the W and if an additional jet mimics a lepton, the event would pass the two-lepton selection. Furthermore,

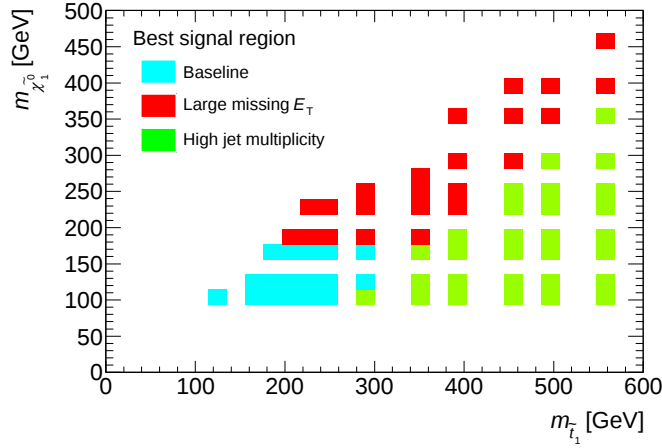


Figure 6.53: Choice of the two-lepton signal regions for the stop pair production in the light-gravitino, light-higgsino model, based on the signal significance for 2 fb^{-1} .

if two jets mimic leptons, QCD di-jet events can also pass the two-lepton selection. To estimate these backgrounds inclusively, a method similar to that described in Section 6.3.3 (QCD multi-jet estimation) is used.

The true composition of two-lepton events is categorized by N_{rr} , N_{rf} , N_{fr} and N_{ff} , where the subscripts indicate the true component (r:real, f:fake) of the leading (in p_{T}) and sub-leading leptons. Events are also categorized by the criteria for lepton as N^{ll} , N^{lt} , N^{tl} and N^{tt} where the superscripts indicate the criteria (*l:loose, t:tight*) satisfied by the leading and sub-leading leptons, respectively. The efficiency that a fake (real) lepton, which passed the *loose* selection, also passes the *tight* cuts is written as $\varepsilon_{\text{f(r)1}}$ for the leading lepton and $\varepsilon_{\text{f(r)2}}$ for the sub-leading lepton.

The relationship between these quantities can be written in four equations as follows,

$$\begin{aligned}
 N^{ll} &= N_{\text{rr}}^{ll} + N_{\text{rf}}^{ll} + N_{\text{fr}}^{ll} + N_{\text{ff}}^{ll} \\
 N^{lt} &= \varepsilon_{\text{r2}} N_{\text{rr}}^{ll} + \varepsilon_{\text{f2}} N_{\text{rf}}^{ll} + \varepsilon_{\text{r2}} N_{\text{fr}}^{ll} + \varepsilon_{\text{f2}} N_{\text{ff}}^{ll} \\
 N^{tl} &= \varepsilon_{\text{r1}} N_{\text{rr}}^{ll} + \varepsilon_{\text{r1}} N_{\text{rf}}^{ll} + \varepsilon_{\text{f1}} N_{\text{fr}}^{ll} + \varepsilon_{\text{f1}} N_{\text{ff}}^{ll} \\
 N^{tt} &= \varepsilon_{\text{r1}} \varepsilon_{\text{r2}} N_{\text{rr}}^{ll} + \varepsilon_{\text{r1}} \varepsilon_{\text{f2}} N_{\text{rf}}^{ll} + \varepsilon_{\text{f1}} \varepsilon_{\text{r2}} N_{\text{fr}}^{ll} + \varepsilon_{\text{f1}} \varepsilon_{\text{f2}} N_{\text{ff}}^{ll}
 \end{aligned} \tag{6.37}$$

In the matrix form, the equation can be expressed as

$$\begin{pmatrix} N^{ll} \\ N^{lt} \\ N^{tl} \\ N^{tt} \end{pmatrix} = \begin{pmatrix} 1 & 1 & 1 & 1 \\ \varepsilon_{\text{r2}} & \varepsilon_{\text{f2}} & \varepsilon_{\text{r2}} & \varepsilon_{\text{f2}} \\ \varepsilon_{\text{r1}} & \varepsilon_{\text{f1}} & \varepsilon_{\text{r1}} & \varepsilon_{\text{f1}} \\ \varepsilon_{\text{r1}} \varepsilon_{\text{r2}} & \varepsilon_{\text{r1}} \varepsilon_{\text{f2}} & \varepsilon_{\text{f1}} \varepsilon_{\text{r2}} & \varepsilon_{\text{f1}} \varepsilon_{\text{f2}} \end{pmatrix} \begin{pmatrix} N_{\text{rr}}^{ll} \\ N_{\text{rf}}^{ll} \\ N_{\text{fr}}^{ll} \\ N_{\text{ff}}^{ll} \end{pmatrix}. \tag{6.38}$$

By solving these equation for N_{rr}^{ll} , N_{rf}^{ll} , N_{fr}^{ll} and N_{ff}^{ll} , the true components of two-lepton events in the signal regions can be obtained. These equations are solved event

by event so that the distributions of each variable for fake-lepton events can be obtained. For the efficiencies ε_f , ε_r , the values obtained in Section 6.3.3 (QCD multi-jet estimation) are used. Table 6.26 shows the estimated number of fake-lepton events in the two-lepton signal regions.

Table 6.26: The estimated number of fake-lepton events in two lepton signal regions.

<i>e-e</i> channel			
	Baseline	Large missing E_T	High jet multiplicity
fake lepton sum	2.4 ± 0.9	1.1 ± 0.6	1.0 ± 0.5
fake-fake lepton	0.06 ± 0.04	0.03 ± 0.03	0.003 ± 0.009
fake-real lepton	2.4 ± 0.9	1.1 ± 0.6	1.0 ± 0.5
$\mu\text{-}\mu$ channel			
	Baseline	Large missing E_T	High jet multiplicity
fake lepton sum	0.00 ± 0.08	0.00 ± 0.07	0.00 ± 0.04
fake-fake lepton	$(1.4 \pm 0.4) \times 10^{-3}$	$(0.8 \pm 0.2) \times 10^{-3}$	$(0.3 \pm 0.1) \times 10^{-3}$
fake-real lepton	0 ± 0.08	0 ± 0.07	0 ± 0.04

Top estimation

The number of top events in the signal regions are obtained by normalizing MC simulated samples to data in a control region defined by inverting the M_{ll} cut ($|M_{ll} - M(Z)| > 10$ GeV). Most of the systematic uncertainties associated to MC simulation can be canceled. When normalizing the $t\bar{t}$ Monte Carlo to data, the contamination from other SM backgrounds which peaks at the Z mass in the two-lepton invariant mass (Z +jets, WZ , ZZ) are subtracted using MC simulation. Fake-lepton events as described in the previous section are also subtracted.

The contamination from the Z +jets and signal in this control region are found to be negligible. The low invariant mass region ($M_{ll} < 15$ GeV) is removed from the $t\bar{t}$ control region because the Drell/Yan process is simulated only for $M_{ll} > 10$ GeV in truth level and furthermore the QCD di-jet background contribution in this region is expected to be large.

Other process with two real leptons which do not have a M_{ll} peak around Z mass are also normalized inclusively using this control region. These are single top (main component is $t + W$), $t\bar{t} + b\bar{b}$, $t\bar{t} + W$ and WW .

Figures 6.54 show this $t\bar{t}$ control region for three selections (Baseline, Large missing E_T , High jet multiplicity regions) in the $e\text{-}e$ and the $\mu\text{-}\mu$ channels. The normalization factors obtained in these control regions are shown in Table 6.27. They are all close to unity.

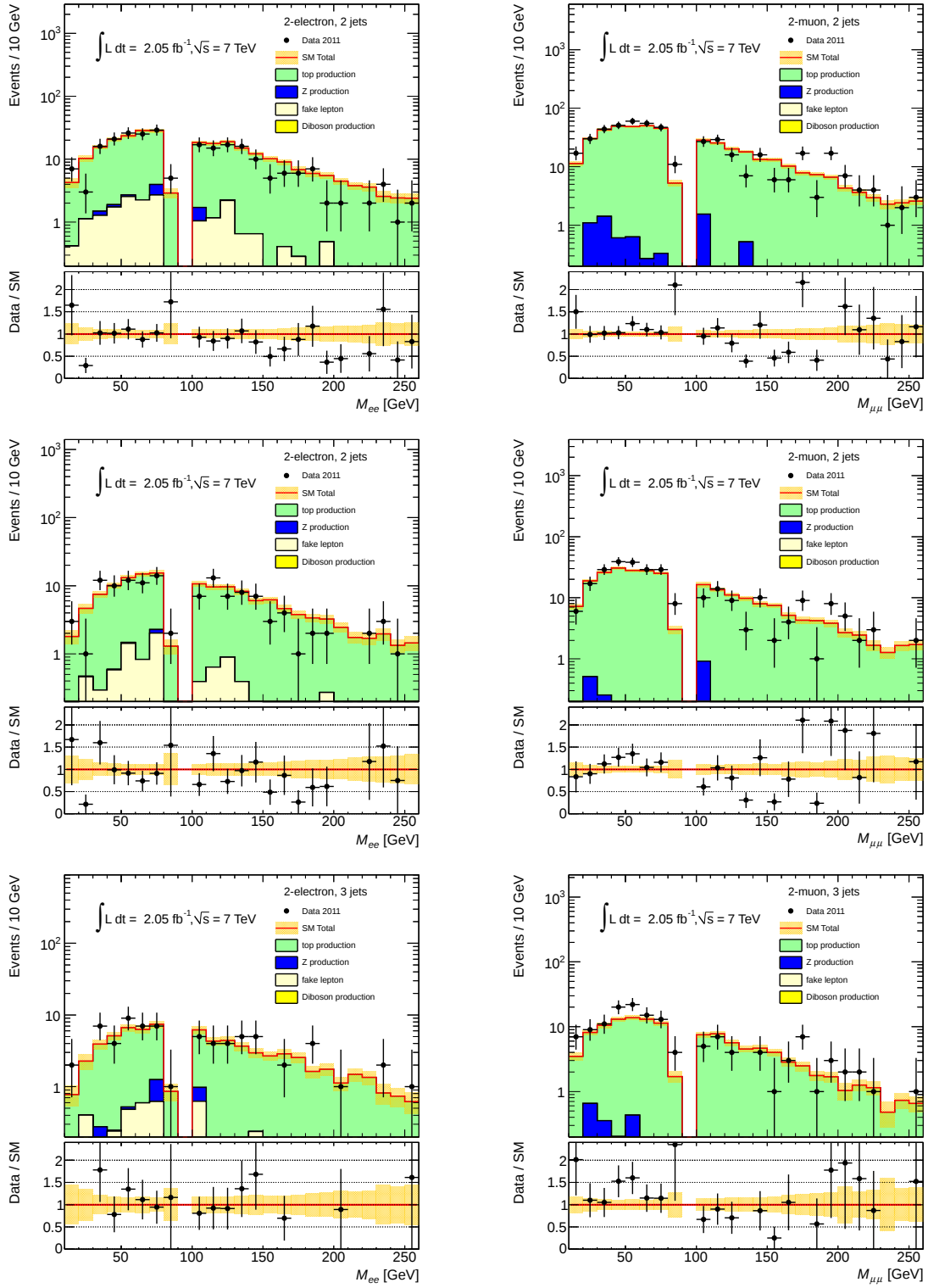


Figure 6.54: M_{ll} distributions in the top background control region ($15 \text{ GeV} < M_{ll} < 81 \text{ GeV}$, $101 \text{ GeV} < M_{ll}$) for “Baseline”, “Large missing E_T^{miss} ”, “High jet multiplicity” selections from the top to the bottom. The left figures are for the e - e channel and the right are for the μ - μ channel. The error bars shown are the sum of the JES uncertainty and the b -tagging efficiency uncertainty.

Table 6.27: The normalization factors for top MC samples in the M_{ll} cut reversed region with the statistical errors.

	Baseline	Large missing E_T^{miss}	High jet multiplicity
e - e channel	0.98 ± 0.07	0.95 ± 0.09	1.01 ± 0.13
μ - μ channel	0.97 ± 0.05	0.98 ± 0.06	1.18 ± 0.10

Table 6.28 shows the estimated top backgrounds in the signal regions together with their systematic uncertainties.

Z +jets estimation

The $Z + b\bar{b}$ process is the second largest background, but due to the similar topology to the signal, it is difficult to separate this background from the lower stop mass signals. Therefore the background is estimated purely by Monte Carlo simulation. To validate the E_T^{miss} distribution of Z +jets Monte Carlo simulation, a region with no b -tagged jets is checked. Figures 6.55 show the E_T^{miss} distributions requiring the number of b -tagged jet to be zero, while keeping other selections the same. The MC simulated Z +jet events reproduce the distribution of data within the systematic uncertainty.

Table 6.29 shows the estimated number of Z +jets events in the signal regions and the associated systematic uncertainties. Since the theoretical uncertainty cannot be constrained from the measurement due to the similarity to the signal process, an uncertainty of ± 100 % is assigned as the theoretical systematic uncertainty for the conservative estimate. With the increase of the number of associated partons, 24 % uncertainty is added in quadrature to the theoretical cross section.

Estimation of other SM backgrounds

Other processes with two real leptons which are not included in the above are ZZ , WZ and $t\bar{t} + Z$. After all the selection cuts, these contributions are negligibly small compared to the main backgrounds and are therefore estimated purely by Monte Carlo simulation with an conservative uncertainty of 100 %.

6.5.4 Summary

The expected SM background events and observed events in the signal regions are summarized in Table 6.31. In all signal regions, the expectation and observation agree within errors. The correlated errors are added linearly and the uncorrelated errors are added in quadrature. Figures 6.56 show the distributions of E_T^{miss} and the number of jets in the signal regions.

This result is used to set limits on stop production in the light-gravitino, light-higgsino model in Chapter 7.

Table 6.28: The estimated number of top events in the signal regions and the associated systematic and statistical uncertainties.

$e\text{-}e$ channel			
	Baseline	Large missing E_T	High jet multiplicity
events	23.9	11.9	6.9
Jet energy scale	$^{+0}_{-6.2}$ %	$^{+0}_{-8.2}$ %	$^{+0}_{-5.1}$ %
b -tagging	$^{+0.5}_{-0.3}$ %	$^{+2.3}_{-1.5}$ %	$^{+2.8}_{-2.7}$ %
Generator	± 0.6 %	± 2 %	± 3.3 %
ISR/FSR	± 18 %	± 18 %	± 31 %
Shower modeling	± 1.5 %	± 5.4 %	± 8.2 %
Statistics	± 8.7 %	± 12 %	± 16 %
Uncertainty sum	$^{+20}_{-21}$ %	$^{+23}_{-24}$ %	± 37 %
$\mu\text{-}\mu$ channel			
	Baseline	Large missing E_T	High jet multiplicity
events	40.4	22.9	11.2
Jet energy scale	$^{+0.3}_{-1.3}$ %	$^{+0.4}_{-1.4}$ %	$^{+8.5}_{-0}$ %
b -tagging	$^{+0}_{-0.3}$ %	$^{+0.5}_{-0.3}$ %	$^{+1.1}_{-2.1}$ %
Generator	± 4.4 %	± 4.1 %	± 10.6 %
ISR/FSR	± 13 %	± 16 %	± 19 %
Shower modeling	± 4.9 %	± 1.6 %	± 14 %
Statistics	± 6.0 %	± 7.8 %	± 12 %
Uncertainty sum	± 15 %	± 19 %	$^{+30}_{-29}$ %

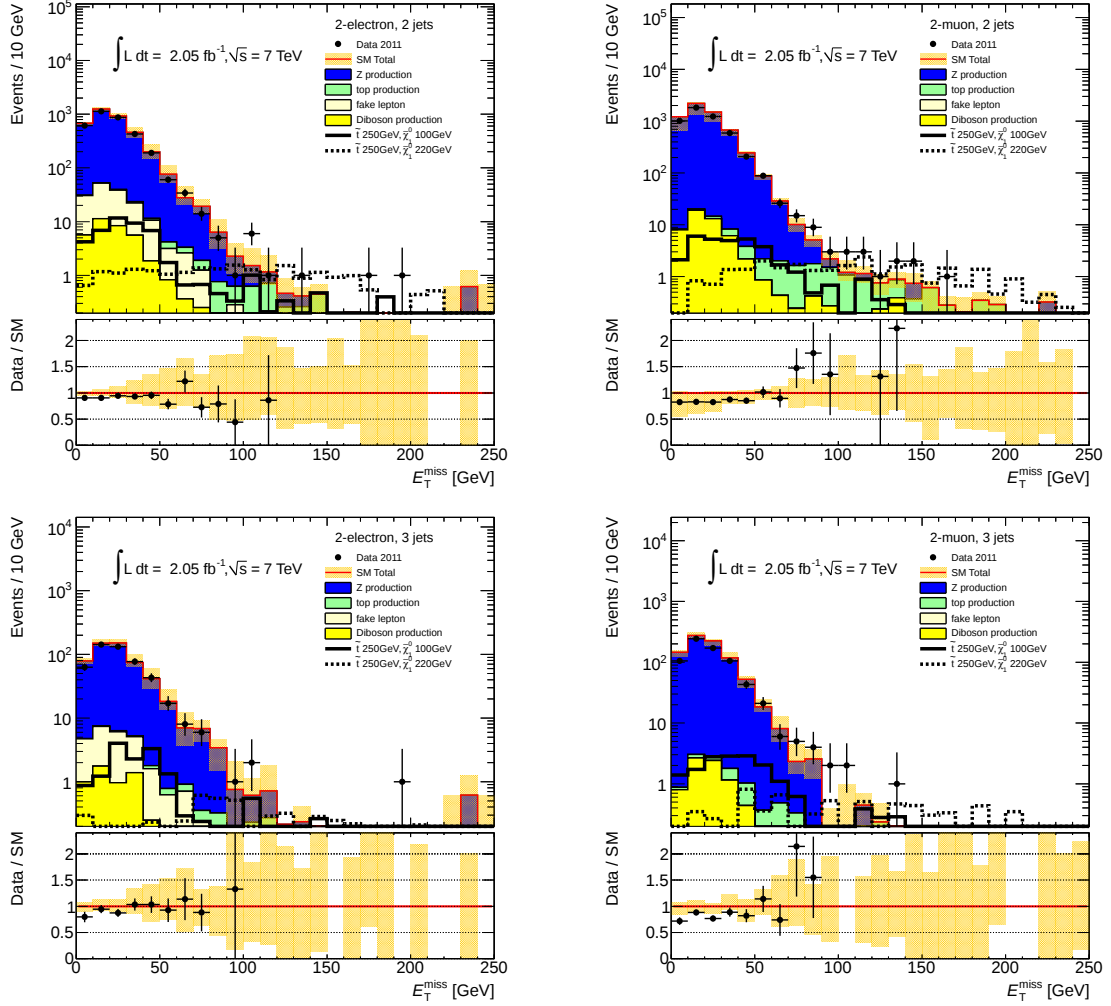


Figure 6.55: The E_T^{miss} distributions in the two-lepton channel, requiring no b -tagged jets. The top figures show the two-jet selection and the bottom show the three-jet selection. The left figures are for the e - e channel and the right are for the μ - μ channel. The Z +jets background is not normalized to data. Error bars shown are the sum of the JES uncertainty and the b -tagging efficiency uncertainty.

Table 6.29: The estimated number of Z +jets events in the signal regions and the associated systematic and statistical uncertainties.

$e\text{-}e$ channel			
	Baseline	Large missing E_T	High jet multiplicity
events	9.0	0.9	4.0
Jet energy scale	$^{+28}_{-7}$ %	$^{+102}_{-21}$ %	$^{+25}_{-33}$ %
b -tagging	$^{+18}_{-14}$ %	$^{+15}_{-5}$ %	$^{+21}_{-18}$ %
Luminosity	± 3.7 %	± 3.7 %	± 3.7 %
Electron trigger	± 0.4 %	± 0.4 %	± 0.4 %
Electron reconstruction	± 1.6 %	± 1.6 %	± 1.6 %
Theory	± 100 %	± 100 %	± 100 %
Number of partons	± 38 %	± 16 %	± 44 %
Uncertainty sum	$^{+112}_{-100}$ %	$^{+145}_{-100}$ %	$^{+114}_{-100}$ %
$\mu\text{-}\mu$ channel			
	Baseline	Large missing E_T	High jet multiplicity
events	13.2	3.0	5.0
Jet energy scale	$^{+21}_{-2}$ %	$^{+7.5}_{-2.8}$ %	$^{+47}_{-13}$ %
b -tagging	$^{+20}_{-16}$ %	$^{+29}_{-22}$ %	$^{+27}_{-19}$ %
Luminosity	± 2.2 %	± 2.0 %	± 1.6 %
Muon trigger	± 1 %	± 1 %	± 1 %
Muon reconstruction	± 0.7 %	± 0.7 %	± 0.7 %
Theory	± 100 %	± 100 %	± 100 %
Number of partons	± 34 %	± 38 %	± 40 %
Uncertainty sum	$^{+110}_{-100}$ %	$^{+111}_{-100}$ %	$^{+121}_{-100}$ %

Table 6.30: Expectations for the remaining SM backgrounds in the two-lepton signal regions.

$e\text{-}e$ channel			
	Baseline	Large missing E_T	High jet multiplicity
ZZ	0.04	0.04	0.03
WZ	0.008	0.008	0
$t\bar{t} + Z$	0.4	0.2	0.4

$\mu\text{-}\mu$ channel			
	Baseline	Large missing E_T	High jet multiplicity
ZZ	0.1	0	0.06
WZ	0	0	0
$t\bar{t} + Z$	0.6	0.3	0.5

Table 6.31: The number of observed and expected events in the two-lepton signal regions

$e\text{-}e$ channel			
	Baseline	Large missing E_T	High jet multiplicity
Data (2.05 fb ⁻¹)	39	20	8
SM	35.8 ⁺¹² ₋₁₁	14.1 ^{+2.5} _{-2.7}	12.2 ± 5.1
top	23.8 ^{+4.7} _{-4.9}	11.9 ^{+2.7} _{-2.9}	6.8 ^{+2.5} _{-2.6}
Z +jets	9.4 ^{+10.6} _{-9.4}	0.9 ^{+1.3} _{-0.9}	4.2 ^{+4.7} _{-4.2}
fake lepton	2.4 ± 0.9	1.1 ± 0.6	1.0 ± 0.5
Others	0.5 ± 0.5	0.2 ± 0.2	0.4 ± 0.4

$\mu\text{-}\mu$ channel			
	Baseline	Large missing E_T	High jet multiplicity
Data (2.05 fb ⁻¹)	47	23	10
SM	55 ⁺¹⁷ ₋₁₆	26.6 ^{+4.5} _{-4.4}	17.3 ^{+7.6} _{-6.7}
top	40.4 ± 6.1	22.9 ± 4.1	11.2 ± 2.5
Z +jets	14 ⁺¹⁶ ₋₁₄	3.3 ^{+3.7} _{-3.3}	5.6 ^{+6.7} _{-5.6}
fake lepton	0.00 ± 0.08	0.00 ± 0.07	0.00 ± 0.04
Others	0.7 ± 0.7	0.3 ± 0.3	0.5 ± 0.5

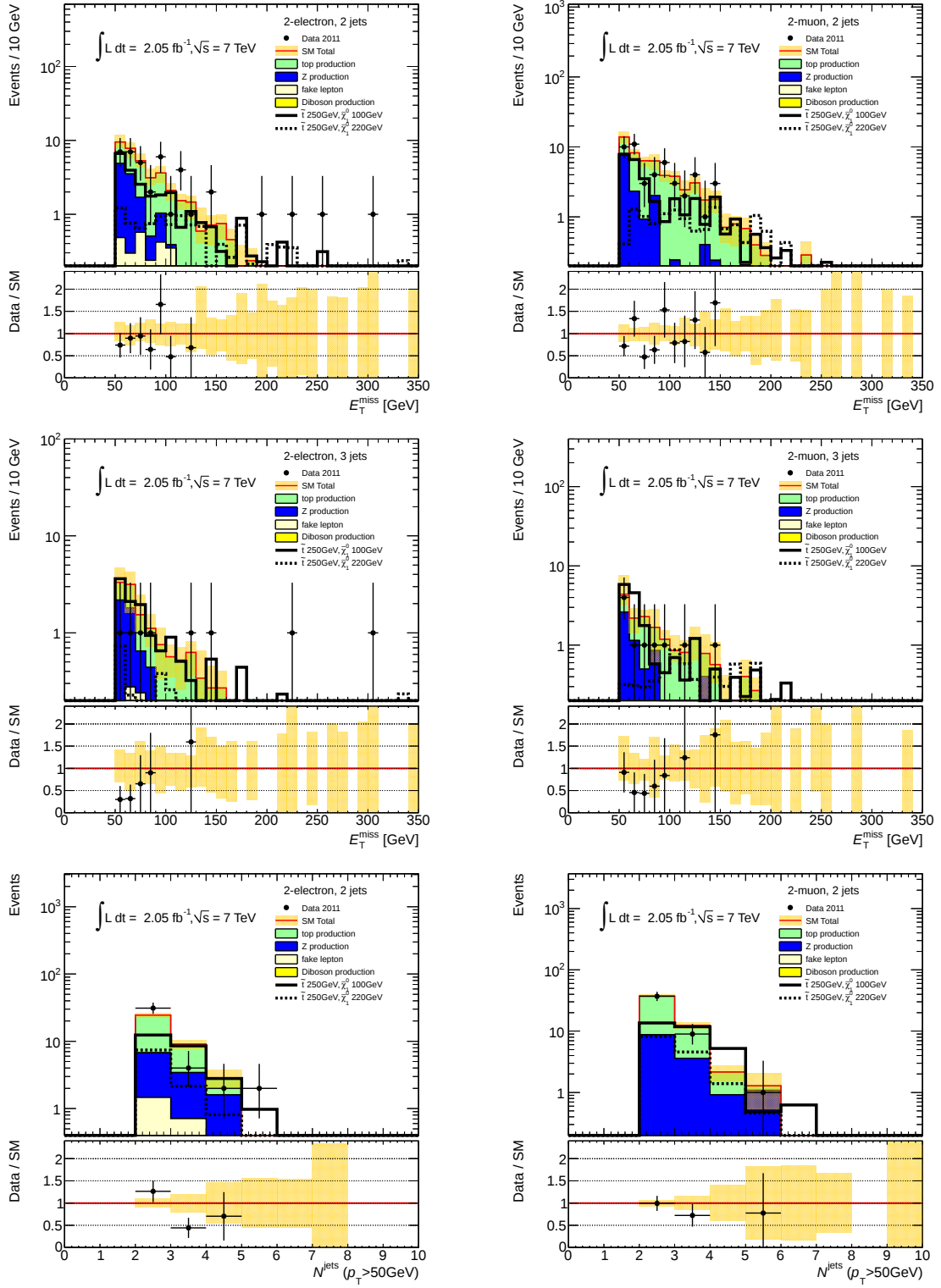


Figure 6.56: The distributions of E_T^{miss} for the two-jet (top) and for the three-jet (middle) selection. The distribution of the number of jets after requiring $E_T^{\text{miss}} > 50$ GeV (bottom). The left figures are for the $e-e$ channel and the right are for the $\mu-\mu$ channel.

Chapter 7

Interpretations and Discussions

In Chapter 6, various searches for stops and sbottoms have been presented. None of the searches show a significant excess beyond the SM predictions.

Using these results, exclusion limits on the SUSY models are calculated.

7.1 Limit calculation

To set limits on the signal models, a statistical method commonly used in the ATLAS Collaboration is followed [103].

A frequentist approach is adopted, formulated as follows. The expected number of events n is

$$E[n] = \mu s + b_{\text{tot}} \quad (7.1)$$

where s and b_{tot} are the expectations for the number of signal and background events. The signal contribution is given by the product of intensity parameter μ multiplied by s . For discovery, we test the background-only hypothesis $\mu = 0$. If there is no significant evidence against such hypothesis, we set an upper limit on the magnitude of the intensity parameter.

Suppose that b_{tot} consists of N components:

$$b_{\text{tot}} = \sum_{i=1}^N b_i. \quad (7.2)$$

To estimate the expected number of events from background component i , we construct N control regions, where we make subsidiary measurement m_i modeled as following a Poisson distribution with expectation value

$$E[m_i] = \tau_i b_i. \quad (7.3)$$

Here τ_i is a scale factor that relates the mean number of events that contribute to n to that of i -th subsidiary measurement.

The likelihood function for the parameters μ and $\mathbf{b} = (b_1, \dots, b_N)$ is the product of Poisson probabilities:

$$L(\mu, \mathbf{b}) = \frac{(\mu s + b_{\text{tot}})^n}{n!} e^{-(\mu s + b_{\text{tot}})} \prod_{i=1}^N \frac{\tau_i b_i^{m_i}}{m_i!} e^{-\tau_i b_i}. \quad (7.4)$$

To test a hypothesized value of μ , one computes the profile likelihood ratio

$$\lambda(\mu) = \frac{L(\mu, \hat{\mathbf{b}})}{L(\hat{\mu}, \hat{\mathbf{b}})} \quad (7.5)$$

where the double-hat notation refers to the conditional maximum-likelihood estimators (MLEs) for the given value of μ , and the single hats denote the unconditional MLEs.

For purpose of establishing a one-sided upper limit, we define the test statistic

$$q_\mu = \begin{cases} -2 \ln \lambda(\mu) & \hat{\mu} \leq \mu, \\ 0 & \hat{\mu} > \mu, \end{cases} \quad (7.6)$$

The ratio $\lambda(\mu)$ is expected to be close to unity (i.e., q_μ is near zero) if the data are in good agreement with the hypothesized value of μ .

Suppose the data results in a value of $q_\mu = q_{\text{obs}}$, then the level of agreement between the data and hypothesized μ is given by the p -value,

$$p = \int_{q_{\text{obs}}}^{\infty} f(q_\mu | \mu) dq_\mu, \quad (7.7)$$

where $f(q_\mu | \mu)$ is the sampling distribution of q_μ under the assumption of μ .

One can define the significance corresponding to a given p -value as the number of standard deviation Z at which a Gaussian random variable of zero mean would give a one-sided tail area equal to p . That is, the significance Z is related to the p -value by

$$p = \int_Z^{\infty} \frac{1}{\sqrt{2\pi}} e^{-x^2/2} dx = 1 - \Phi(Z) \quad (7.8)$$

where Φ is the cumulative distribution for the standard (zero mean, unit variance) Gaussian. The relation between the p -value and the observed q_μ and also with the significance Z are illustrated in Figure 7.1.

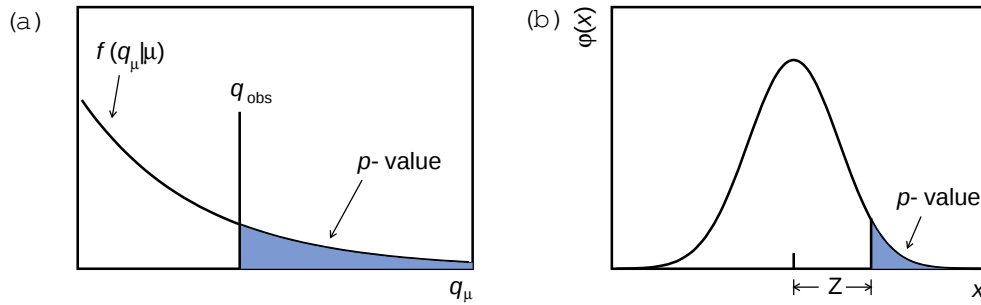


Figure 7.1: (a) Illustration of the relation between the p -value obtained from an observed value of the test statistic q_μ . (b) The standard normal distribution $\phi(x) = (1/\sqrt{2\pi}) \exp(-x^2/2)$ showing the relation between the significance Z and the p -value.

7.1.1 CL_s method

When excluding signals, the null hypothesis H_0 is signal plus background while the alternative hypothesis H_1 is the background only. One may then decide to reject the hypothesis if the p -value is lower than some threshold. In the classical approach (what is called the “ CL_{s+b} ” method), one carries out a standard statistical test of the signal plus background hypothesis based on its p -value, p_{s+b} . The signal model is regarded as excluded at a confidence level (CL) of $1 - \alpha$ if one finds

$$p_{s+b} < \alpha. \quad (7.9)$$

However, in this approach, one may exclude any signal and even the background itself if too few candidates are observed to account for the estimated background. To solve this problem, the CL_s method [104, 105] is commonly used. In the CL_s method, the signal plus background hypothesis is rejected if

$$\text{CL}_s \equiv \frac{p_{s+b}}{1 - p_b} \leq \alpha, \quad (7.10)$$

where p_b is the p -value based on the background-only hypothesis. A value of 95 % CL is commonly used to set an exclusion limit on signal models; this convention is also followed in this thesis. A threshold p -value of 0.05 (i.e., 95 % confidence level) corresponds to $Z = 1.64$.

7.1.2 Asymptotic formula

Consider a test of the strength parameter μ and suppose the data are distributed according to a strength parameter μ' . In the large sample, $\lambda(\mu)$ can be given as follows according to Reference [106],

$$-2 \ln \lambda(\mu) = \frac{(\mu - \hat{\mu})^2}{\sigma^2} + \mathcal{O}(1/\sqrt{N}) \quad (7.11)$$

for the case of a single parameter of interest. Here $\hat{\mu}$ follows a Gaussian distribution with a mean μ' and standard deviation σ , and N represents the data sample size.

If we neglect the $\mathcal{O}(1/\sqrt{N})$, we can write the test statistic for upper limits, Equation 7.6 as

$$q_\mu = \begin{cases} \frac{(\mu - \hat{\mu})^2}{\sigma^2} & \hat{\mu} < \mu, \\ 0 & \hat{\mu} > \mu. \end{cases} \quad (7.12)$$

The p -value of the hypothesized μ is

$$p_\mu = 1 - \Phi(\sqrt{q_\mu}) \quad (7.13)$$

and therefore the corresponding significance is

$$Z_\mu = \Phi^{-1}(1 - p_\mu) = \sqrt{q_\mu}. \quad (7.14)$$

As discussed in Reference [95], this approximation is sufficiently accurate for $b_{\text{tot}} \gtrsim 10$ and is used in all analyses described in this thesis.

7.2 mSUGRA

Using the result of the no- and one-lepton multi-jet analyses, the exclusion limit on the mSUGRA model will be calculated.

7.2.1 No-lepton multi-jet channel

First, the exclusion limit is set on the mSUGRA model with $\tan\beta = 40$, $A_0 = -500$ GeV and $\mu > 0$ from the result of no-lepton multi-jet analysis described in Section 6.2. Figures 7.2 show the signal significance calculated from the expected CL_s of each signal point in the no-lepton multi-jet signal regions including uncertainties on the SM backgrounds and each SUSY signal point. From this distribution, the best signal region is selected for each signal point.

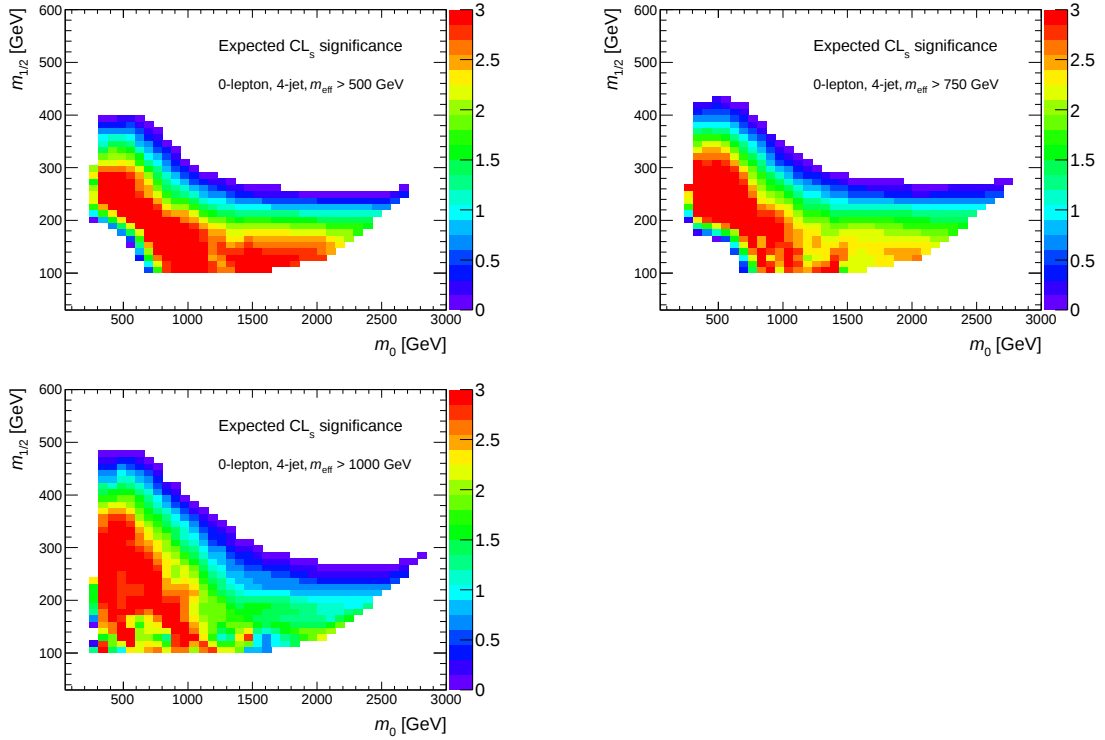


Figure 7.2: The signal significance calculated from the expected CL_s for the signal points of the mSUGRA model with $\tan\beta = 40$, $A_0 = -500$ GeV and $\mu > 0$ in the no-lepton multi-jet channel.

Figures 7.3 show the expected and the observed exclusion limits at 95 % CL for the mSUGRA model. The exclusion limit by LEP searching for the lightest chargino [107] and the exclusion limit by ATLAS using 35 pb^{-1} data [108] are also shown. In this analysis, gluino masses of 600 GeV are excluded in all regions and a gluino mass of 990 GeV can be excluded in the best case. Stop masses of 640 GeV are excluded in all regions.

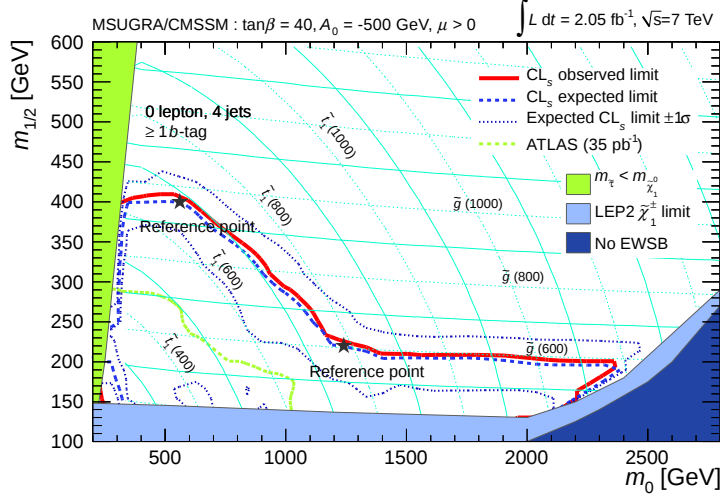


Figure 7.3: The expected and the observed exclusion limits at 95 % CL for the mSUGRA model with $\tan\beta = 40$, $A_0 = -500$ GeV and $\mu > 0$ using the no-lepton multi-jet analysis.

7.2.2 One-lepton multi-jet channel

The mSUGRA model with $\tan\beta = 40$, $A_0 = -500$ GeV, $\mu > 0$ is also used to interpret the results from the one-lepton multi-jet analysis described in Section 6.3. Figures 7.4 show the signal significance calculated from the expected CL_s of each signal point in the one-lepton multi-jet signal regions including all uncertainties on the SM backgrounds and each SUSY signal point. From this, the best signal region is selected for each signal point.

Figure 7.5 shows the expected and observed exclusion limits at 95 % CL for the mSUGRA model in the one-lepton multi-jet analysis. Compared to the no-lepton multi-jet analysis, the one-lepton multi-jet analysis is not as sensitive in the large m_0 region. A gluino mass up to 950 GeV with a stop mass of 640 GeV is excluded in the best case. In almost all regions, a stop mass of 600 GeV is excluded.

7.2.3 Combination of the no- and one-lepton multi-jet channels

The exclusion limit for the mSUGRA model from the no-lepton with multi-jet analysis and the one-lepton multi-jet analysis are combined. Figure 7.6 shows the expected and observed exclusion limits with these combination. Since the exclusion limits by the no-lepton channel is much higher than the one-lepton channel, the contribution of the one-lepton channel is small.

The result is almost the same as the no-lepton multi-jet channel. Sbottom masses of 750 GeV, stop masses of 640 GeV and gluino masses of 600 GeV are excluded in all regions. A gluino mass of 990 GeV is excluded in the best case.

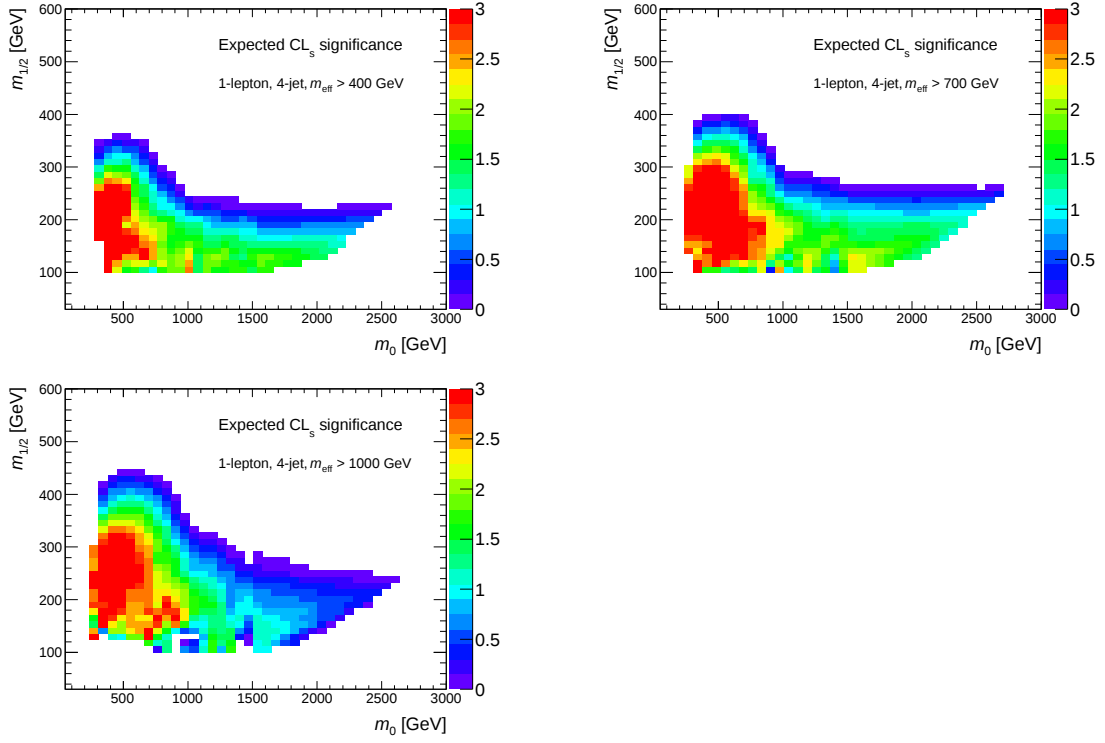


Figure 7.4: The signal significance calculated from the expected CL_s for the signal point in the mSUGRA model with $\tan\beta = 40$, $A_0 = -500$ GeV and $\mu > 0$ in the one-lepton multi-jet analysis.

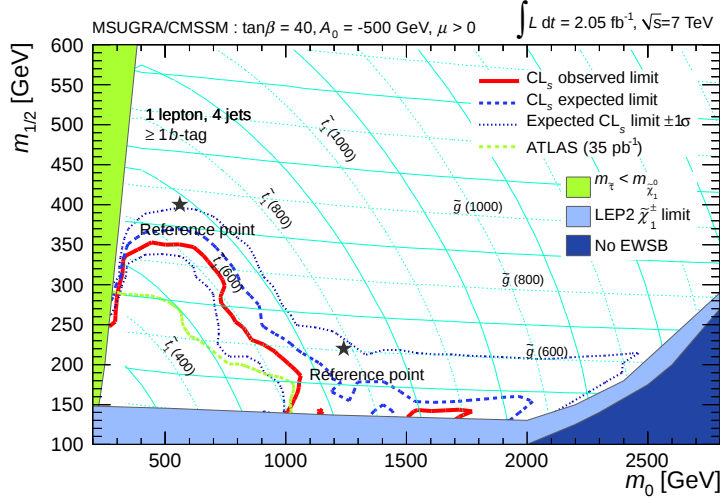


Figure 7.5: The expected and observed exclusion limits at 95 % CL for the mSUGRA model with $\tan\beta = 40$, $A_0 = -500$ GeV and $\mu > 0$ using the one-lepton multi-jet analysis.

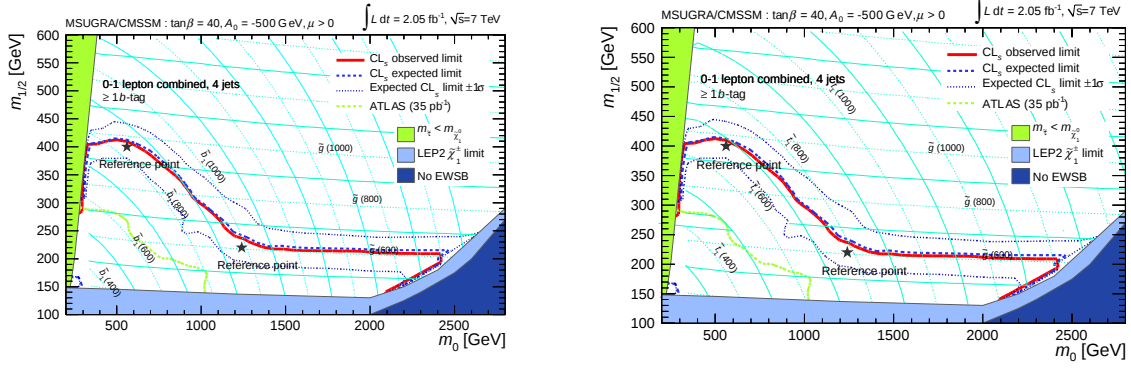


Figure 7.6: The expected and observed exclusion limits at 95 % CL for the mSUGRA model with $\tan\beta = 40$, $A_0 = -500$ GeV and $\mu > 0$ using the combined no-lepton and one-lepton multi-jet channels. The left figure is with the sbottom mass contours and the right figure is with the stop mass contours.

From this result, the limits on the naturalness are also calculated. Figure 7.7 shows the expected and observed exclusion limits for the mSUGRA model with the contours of tune parameters $\Delta^{-1} = m_h^2/2\mu^2$ and $\Delta'^{-1} = m_h^2/2m_{H_u}^2|_{\text{rad}}$. $m_{H_u}^2|_{\text{rad}}$ is calculated assuming $M_{\text{mess}} = M_{\text{Pl}}$.

A tune parameter $\Delta^{-1} > 2\%$ is excluded at the best case in low m_0 region but in larger m_0 region, still large tune parameter regions remain. However, $\Delta'^{-1} \gtrsim 0.3\%$ is excluded in all $(m_0, m_{1/2})$ spaces in this model. Therefore, it is difficult to achieve the naturalness of the Higgs mass considering the current exclusion limits on such mSUGRA models.

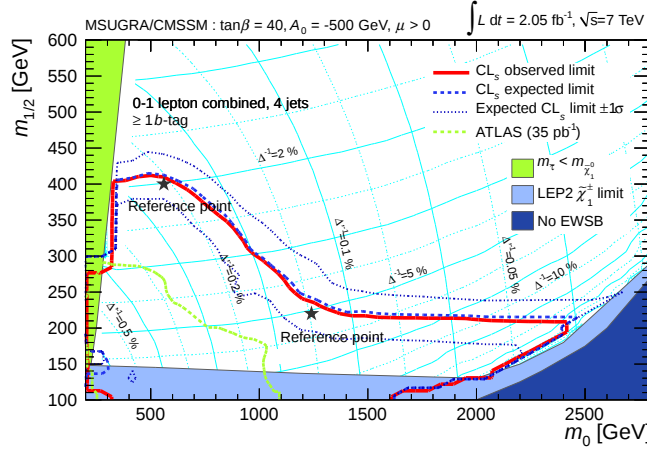


Figure 7.7: The expected and observed exclusion limits at 95 % CL for the mSUGRA model with $\tan\beta = 40$, $A_0 = -500$ GeV and $\mu > 0$ using the combined no-lepton and one-lepton multi-jet channels with the contours of tune parameters $\Delta^{-1} = m_h^2/2\mu^2$ and $\Delta'^{-1} = m_h^2/2m_{H_u}^2|_{\text{rad}}$.

7.3 Phenomenological $\tilde{g} \rightarrow \tilde{b}_1 b$ decay model

The results of the no-lepton multi-jet analysis is used to set limits on the phenomenological $\tilde{g} \rightarrow \tilde{b}_1 + b$ decay model. In this model, the gluinos are pair-produced and decay to the lightest sbottom and bottom quark pair. The decay mode of the sbottom is fixed to

$$\tilde{b}_1 \rightarrow \tilde{\chi}_1^0 + b. \quad (7.15)$$

The lightest neutralino is the LSP, denoted by $\tilde{\chi}_1^0$, whose mass is fixed to 60 GeV. Sbottom pair production is also included but its contribution to the signal regions is negligible. This scenario is possible in the MSSM. Figures 7.8 show the generated signal points and the corresponding cross-sections.

Figures 7.9 show the signal significance calculated from the expected CL_s of this signal in the no-lepton multi-jet signal regions. From this, the best signal region is selected for each signal point.

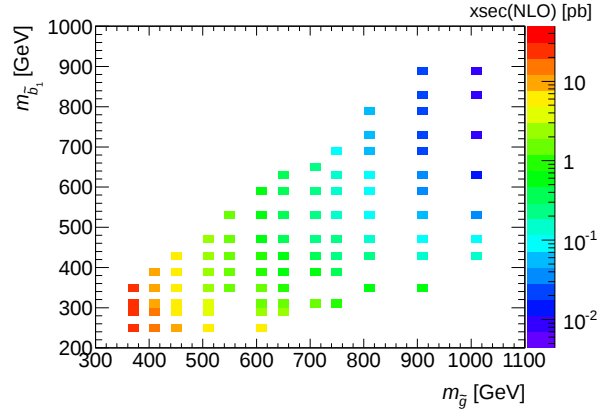


Figure 7.8: The cross-sections for gluino pair and sbottom pair production

Figure 7.10 shows the expected and the observed exclusion limits at 95 % CL for this signal. The exclusion limit by CDF for the same signal [109], the exclusion limits by CDF [110] and by D0 [111] for sbottom-pair production are also shown. Gluino masses of 900 GeV are excluded for sbottom masses up to 700 GeV.

7.4 Phenomenological $\tilde{g} \rightarrow b\bar{b}\tilde{\chi}_1^0$ model

The result of the no-lepton multi-jet analysis is also used to set limits on a model in which the gluino is lighter than the sbottom. Assuming the sbottom is lightest squark, the gluino decays to bottom quark pair exclusively.

$$\tilde{g} \rightarrow b + \bar{b} + \tilde{\chi}_1^0 \quad (7.16)$$

The lightest neutralino is the LSP and the signals are scanned in $(m_{\tilde{g}}, m_{\tilde{\chi}_1^0})$ space. This scenario is also possible in the MSSM. Figure 7.11 shows the generated signal points with their cross-sections.

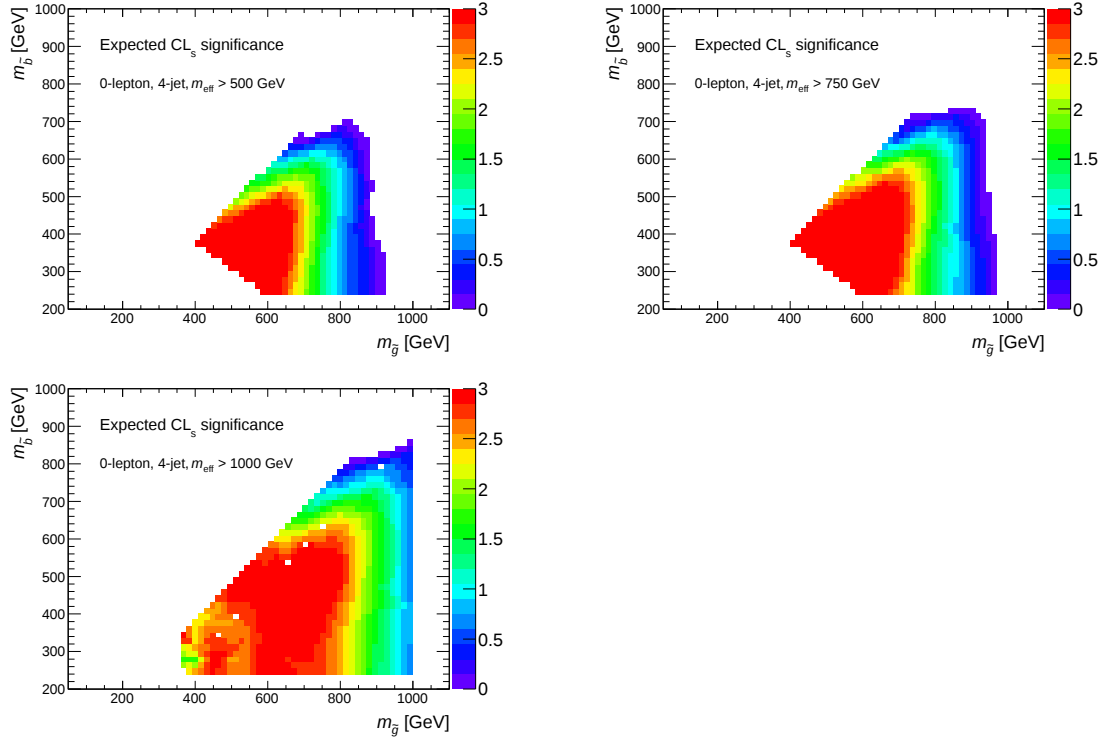


Figure 7.9: The signal significance calculated from the expected CL_s of the phenomenological $\tilde{g} \rightarrow \tilde{b}_1 b$ model in the no-lepton multi-jet signal regions.

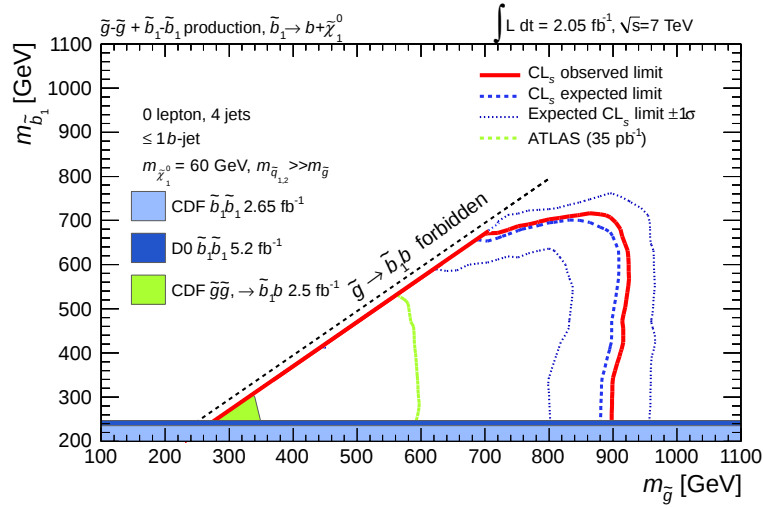


Figure 7.10: The expected and observed exclusion limits at 95 % CL of the phenomenological $\tilde{g} \rightarrow \tilde{b}_1 b$ model in the no-lepton multi-jet signal regions.

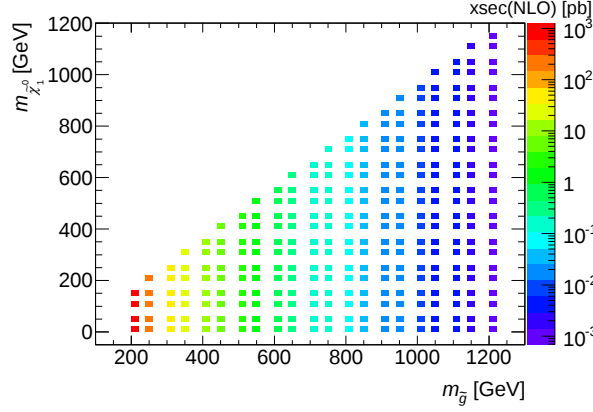


Figure 7.11: The generated signal points for the phenomenological $\tilde{g} \rightarrow b\bar{b}\tilde{\chi}_1^0$ model, shown with the associated each cross-section.

Figures 7.12 show the expect signal significances in the no-lepton multi-jet signal regions for $\tilde{g} \rightarrow b\bar{b}\tilde{\chi}_1^0$ signals. The signal region which gives the largest significance is used to set a limit on each signal point.

Figure 7.13 shows the expected and observed exclusion limits at 95 % CL for the $\tilde{g} \rightarrow b\bar{b}\tilde{\chi}_1^0$ scenario in the no-lepton multi-jet channel. A gluino mass of 900 GeV is excluded with the lightest neutralino mass of 0 GeV. A neutralino mass of 300 GeV is excluded with the gluino mass of $500 \text{ GeV} < m_{\tilde{g}} < 800 \text{ GeV}$.

7.5 Phenomenological $\tilde{g} \rightarrow \tilde{t}t$ decay model

The result of the one-lepton multi-jet analysis is used to set limits on the phenomenological $\tilde{g} \rightarrow \tilde{t}t$ decay model. In this model, gluinos are pair-produced and each gluino decays to stop and top quark. The decay modes of the gluino daughters are fixed to

$$\tilde{t}_1 \rightarrow \tilde{\chi}_1^+ + b \quad (7.17)$$

$$\tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^0 + W^{+*}. \quad (7.18)$$

The W^* boson decays according to the SM background ratio and $\tilde{\chi}_1^0$ is the LSP. The masses of $\tilde{\chi}^\pm$ and $\tilde{\chi}_1^0$ are fixed to 120 GeV and 60 GeV respectively. Stop pair production is also included. The cross-sections for gluino pair and stop pair productions are shown in Figure 2.1. The production of gluino-stop pair is negligibly small. Figure 7.14 shows the generated signal points with their total cross-sections.

To determine the best signal region for each signal point, the signal significance is calculated from the expected CL_s using the estimated SM backgrounds and each SUSY signal point including all systematic uncertainties on them. Figure 7.15 shows this signal significance for each signal region.

Figure 7.16 shows the expected and observed exclusion limits at 95 % CL for this model using the one-lepton multi-jet results. This result exceeds the ATLAS exclusion

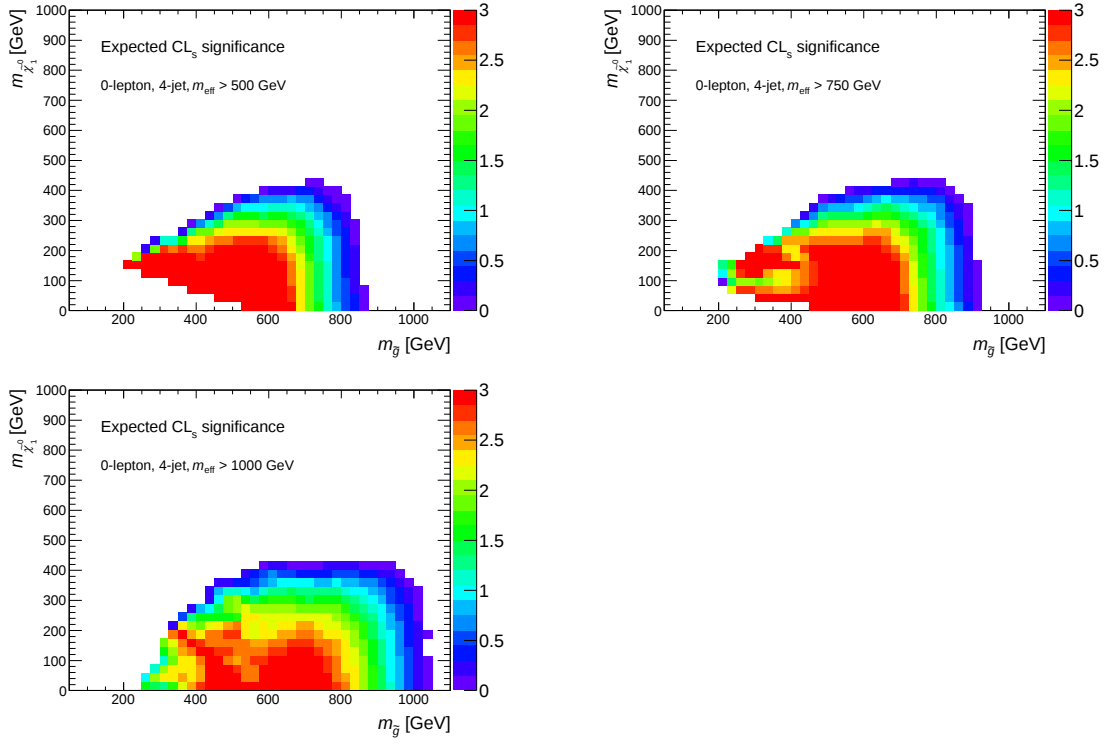


Figure 7.12: The signal significance calculated from the expected CL_s for the signal points of $\tilde{g} \rightarrow b\bar{b}\chi_1^0$ model in the no-lepton multi-jet signal regions.

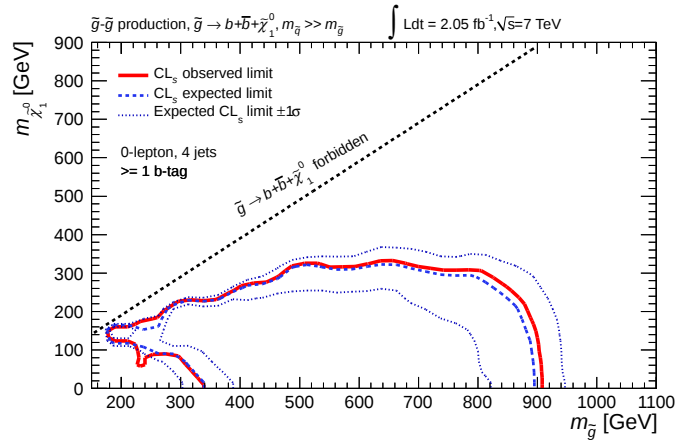


Figure 7.13: The expected and observed exclusion limit for phenomenological $\tilde{g} \rightarrow b + \bar{b} + \tilde{\chi}_1^0$ model using the no-lepton multi-jet analysis.

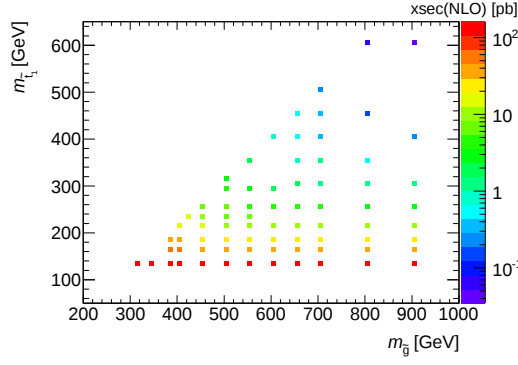


Figure 7.14: The cross-sections for gluino pair and stop pair production

limit from 35 pb^{-1} of data [108] and excludes a gluino mass up to 630 GeV at maximum with the lighter stop mass of 420 GeV.

7.5.1 Phenomenological $\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$ model

The result of the one-lepton multi-jet analysis is used to set limits on the phenomenological $\tilde{g} \rightarrow t + \bar{t} + \tilde{\chi}_1^0$ model. Here assume the stop is heavy and the gluino cannot decay via $\tilde{g} \rightarrow \tilde{t}_1 + t$ mode but the stop is the lightest squark. Therefore the gluino decays exclusively to a top quark pair exclusively. Figure 7.17 shows the signal significance calculated from the expected CL_s of this model in the one-lepton with multi-jet signal regions including all uncertainties on the SM backgrounds and each SUSY signal point.

Figure 7.18 shows the expected and observed exclusion limits on this model at 95 % CL using the best signal region for each point. A gluino mass of 660 GeV is excluded at $\tilde{\chi}_1^0 = 0$ GeV and a gluino mass of 600 GeV is excluded at $\tilde{\chi}_1^0 = 100$ GeV. Since the stop mass is assumed to be larger than $m_{\tilde{g}} - m_t$, a stop mass of 488 GeV is excluded indirectly at $\tilde{\chi}_1^0 = 0$ GeV and 428 GeV at $\tilde{\chi}_1^0 = 100$ GeV in this model.

7.6 Phenomenological sbottom pair production

As described in Section 6.4.1, one of the interpretation of the no lepton with two b -jets and E_T^{miss} topology is the sbottom pair production with $\tilde{b}_1 \rightarrow b + \tilde{\chi}_1^0$ decay. We will set the exclusion limit on this model.

Figure 7.19 shows the signal significance calculated from the expected CL_s in this model in the no-lepton di-jet channel. The signal region which gives the best significance is used to set the exclusion limit for each signal point.

Figure 7.20 shows the expected and the observed exclusion limits at 95 % CL for the sbottom pair production signals. The exclusion limits for the same signals by D0 [111] and CDF [110] are also shown. A sbottom mass of 400 GeV is excluded with the lightest neutralino mass of 0 GeV and 350 GeV is excluded with the lightest neutralino mass of 120 GeV.

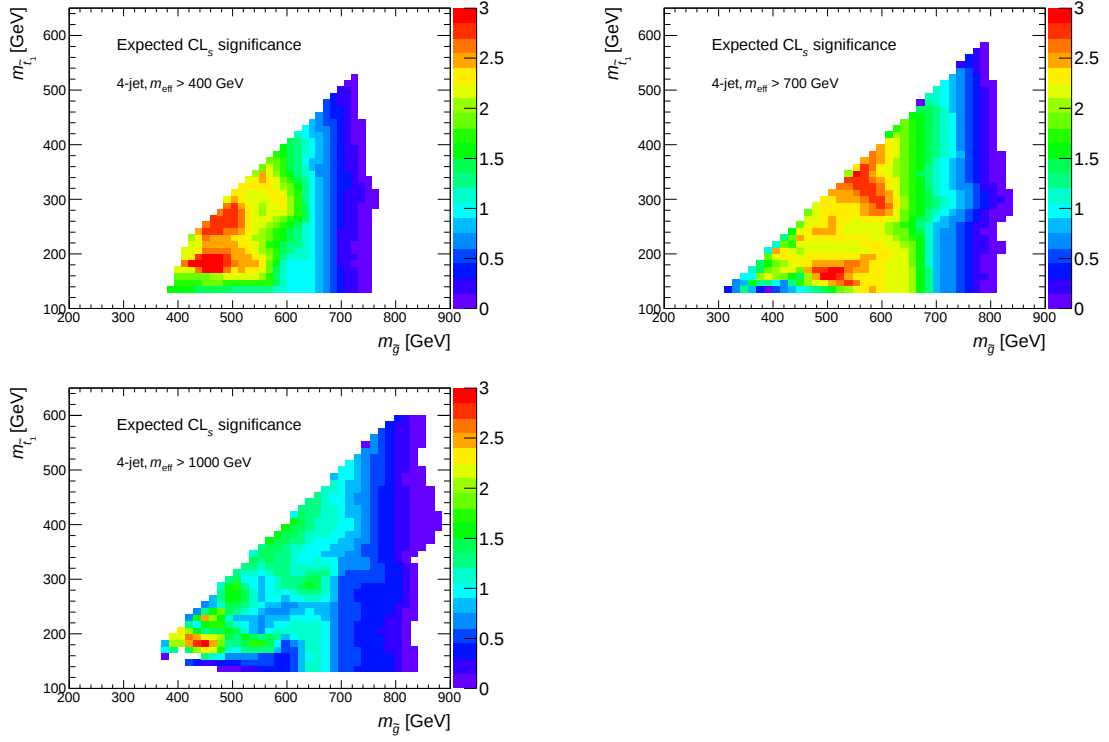


Figure 7.15: The signal significances calculated from the expected CL_s for the one-lepton multi-jet signal regions for the phenomenological $\tilde{g} \rightarrow \tilde{t}_1 + t$ model.

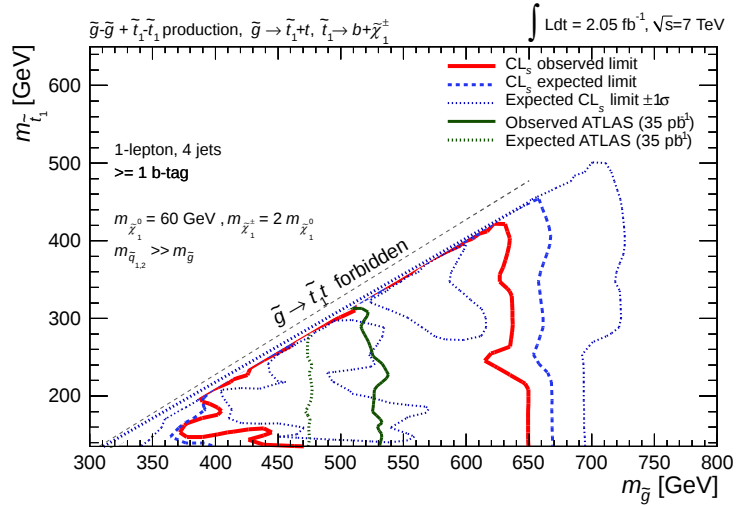


Figure 7.16: The expected and observed exclusion limit for phenomenological $\tilde{g} \rightarrow \tilde{t}_1 + t$ model using the one-lepton multi-jet analysis. Exclusion limit by ATLAS at 35 pb^{-1} data is also shown.

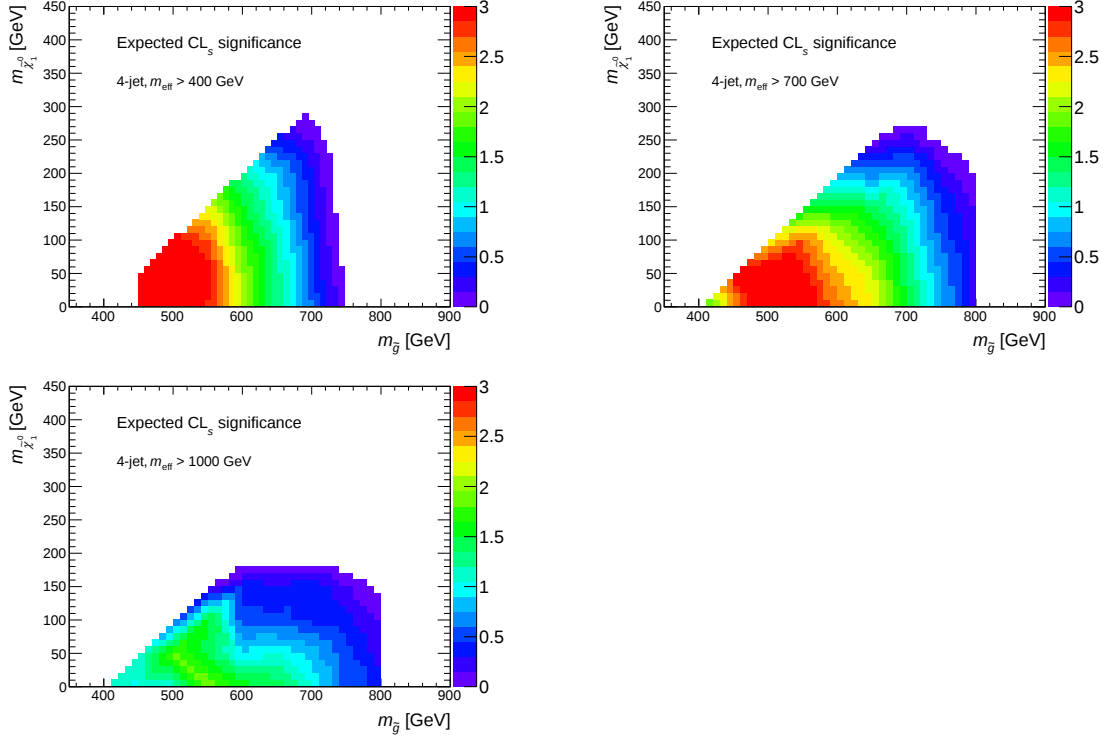


Figure 7.17: The expected CL_s of phenomenological $\tilde{g} \rightarrow t + \bar{t} + \tilde{\chi}_1^0$ model in the one-lepton multi-jet signal regions.

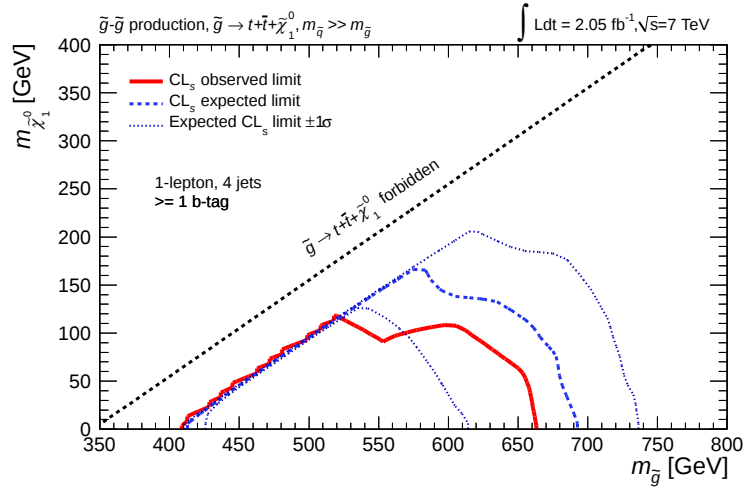


Figure 7.18: The exclusion limits on the phenomenological $\tilde{g} \rightarrow t + \bar{t} + \tilde{\chi}_1^0$ model at 95 % CL in the one-lepton multi-jet signal regions.

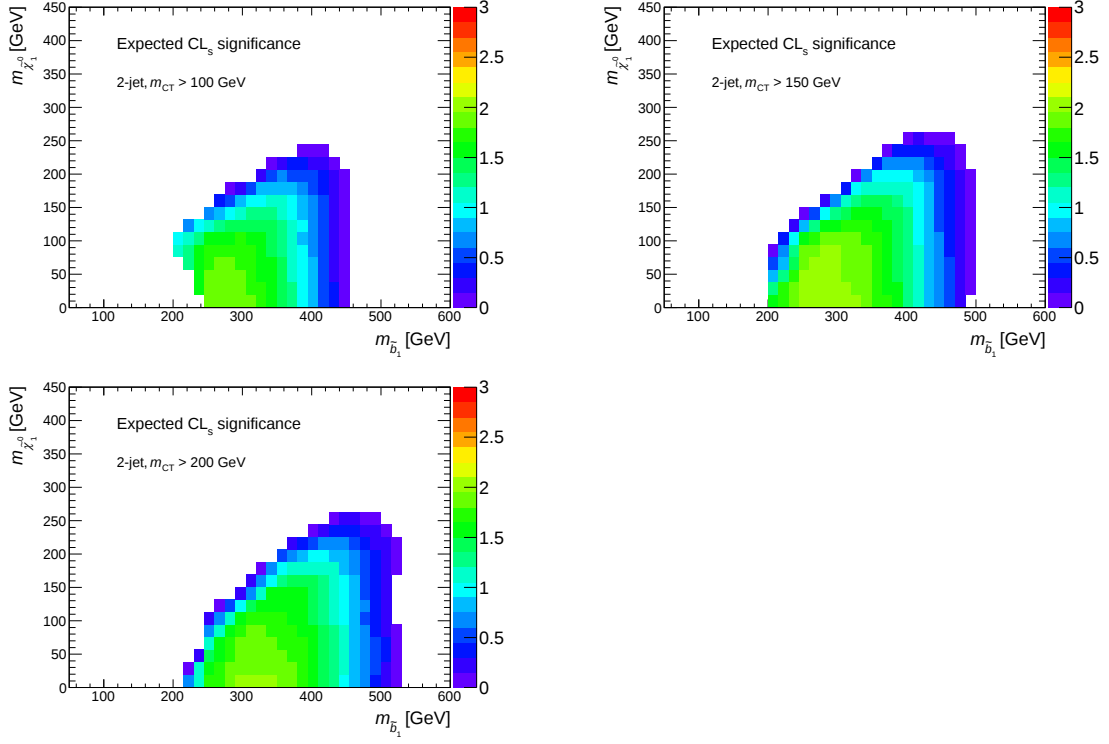


Figure 7.19: The signal significance calculated from the expected CL_s for the sbottom pair production signals in the no-lepton di-jet channel.

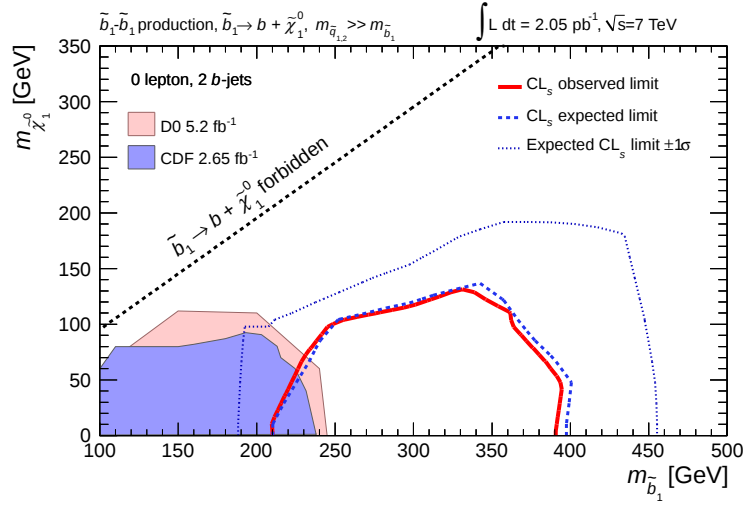


Figure 7.20: The expected and the observed exclusion limits at 95 % CL for sbottom pair production signals in the no-lepton di-jet channel.

7.6.1 Stop pair production in higgsino LSP model

If the stop is light and the other colored SUSY particles are much heavier, the stop pair production becomes dominant. If the lightest chargino and the lightest neutralino are higgsino-like, their masses are close. The dominant stop decay process then becomes

$$\tilde{t}_1 \rightarrow b + \tilde{\chi}_1^+. \quad (7.19)$$

The $\tilde{\chi}_1^+$ decay via

$$\tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^0 + f + f' \quad (7.20)$$

but if f and f' are too soft, they cannot be detected. If $\tilde{\chi}_1^0$ is the LSP, it becomes the missing energy. The resulting topology is two b -jets and $E_{\text{T}}^{\text{miss}}$. This is exactly as same as the sbottom pair production considered above.

Figure 7.21 show the exclusion limits on the two tune parameters $\Delta^{-1} \equiv m_h^2/2\mu^2$ and $\Delta'^{-1} \equiv m_h^2/2m_{H_u}^2|_{\text{rad}}$ when this result is interpreted for the stop and the higgsino masses, assuming $M_{\text{mess}} = 10$ TeV. The current limits on Δ^{-1} are not significant. The limits on Δ'^{-1} are > 8 % for $A_t = -m_{\tilde{t}}$ and > 3.5 % for $A_t = -2m_{\tilde{t}}$ in the best case, respectively. If $M_{\text{mess}} = M_{\text{Pl}}$, the limits on Δ'^{-1} are tightened by a factor of ≈ 10 .

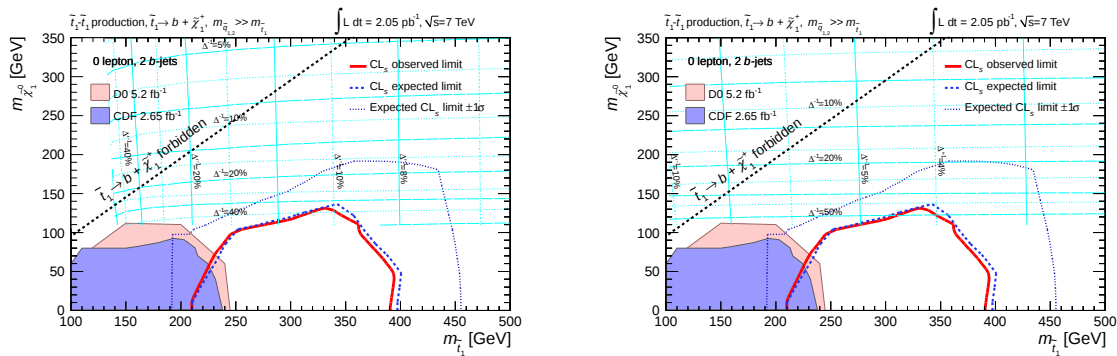


Figure 7.21: The exclusion limits for stop pair production signals in light higgsino model with the contours for tuning parameters Δ^{-1} and Δ'^{-1} . The left figure is for $A_t = -m_{\tilde{t}}$ and the right figure is for $A_t = -2m_{\tilde{t}}$.

7.7 Stop pair production in light-gravitino and light-higgsino model

From the result of the two-lepton multi-jet analysis described in Section 6.5, exclusion limits on the stop are calculated in the light-gravitino and light-higgsino model expected in the Natural SUSY scenario. There have been no dedicated analysis on this type of signals. Figures 7.22 show the signal significance calculated from the expected CL_s for the stop signals in the different signal regions. The signal region which gives the best CL_s is used for limit setting.

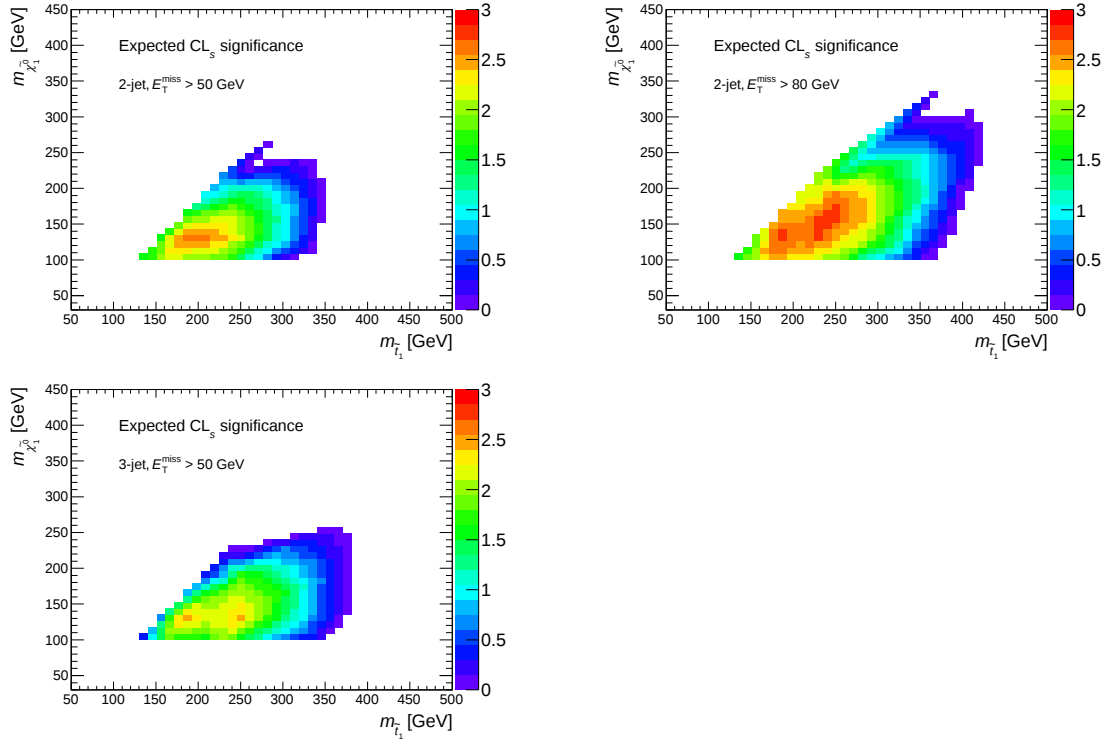


Figure 7.22: The expected CL_s for the stop pair production in the light-gravitino, light-higgsino model, shown in different signal regions of the two-lepton channel

Figure 7.23 shows the expected and observed exclusion limits for this model at 95 % CL. If the lightest neutralino is lighter than the Z boson, it dominantly decays to $\gamma + \tilde{G}$. Moreover, if $m_{\tilde{t}_1} < m_b + m_{\tilde{\chi}_1^0}$, the stop cannot decay via this mode. Therefore these parameter spaces are not considered here.

Figure 7.23 shows the expected and observed exclusion limits at 95 % CL on stop pair production in the light-gravitino, light-higgsino model using the best signal regions in the two-lepton channel. A stop mass up to 320 GeV is excluded with the lightest neutralino mass of 180 GeV; a stop mass < 230 GeV is excluded for the region of $m_Z < \tilde{\chi}_1^0 < 220$ GeV.

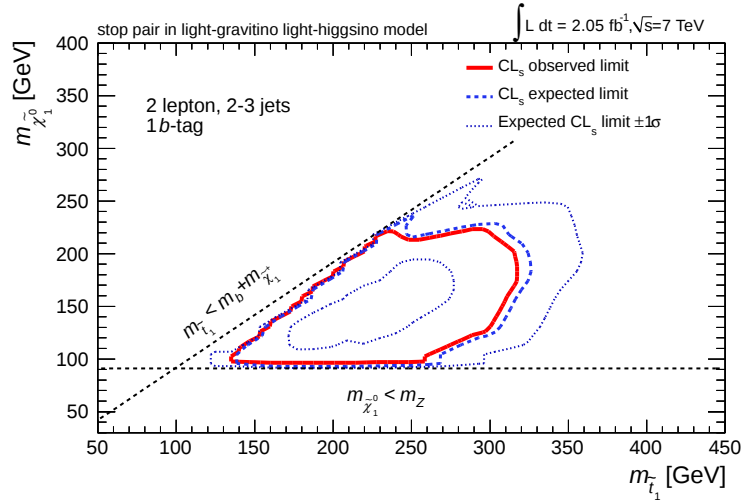


Figure 7.23: The expected and observed exclusion limits for stop pair production in the GMSB model with a light higgsino.

This result can be interpreted in the naturalness of the Higgs mass. Figures 7.24 show the exclusion limits with the contours of the two tuning parameters $\Delta^{-1} \equiv m_h^2/2\mu^2$ and $\Delta'^{-1} \equiv m_h^2/2m_{H_u}^2|_{\text{rad}}$. The left figure is for $A_t = -m_{\tilde{t}}$ and the right figure is for $A_t = -2m_{\tilde{t}}$. The messenger mass M_{mess} is assumed to be 10 TeV. The tuning for $\Delta^{-1} \lesssim 15$ % is excluded with the stop mass of $m_{\tilde{t}_1} < 250$ GeV. For $A_t = -m_{\tilde{t}}$, $\Delta'^{-1} > 11$ % is excluded and for $A_t = -2m_{\tilde{t}}$, $\Delta'^{-1} > 4.5$ % is excluded in the best case, respectively. If $M_{\text{mess}} = M_{\text{Pl}}$, the limits on Δ'^{-1} are tightened by a factor of ≈ 10 .

7.8 Signal candidate events

In this section, interesting signal candidate events are selected from each channel. They are likely to be SUSY signals but so far no significant excess is seen in all channels. Therefore, these events are interpreted in terms of the SM processes.

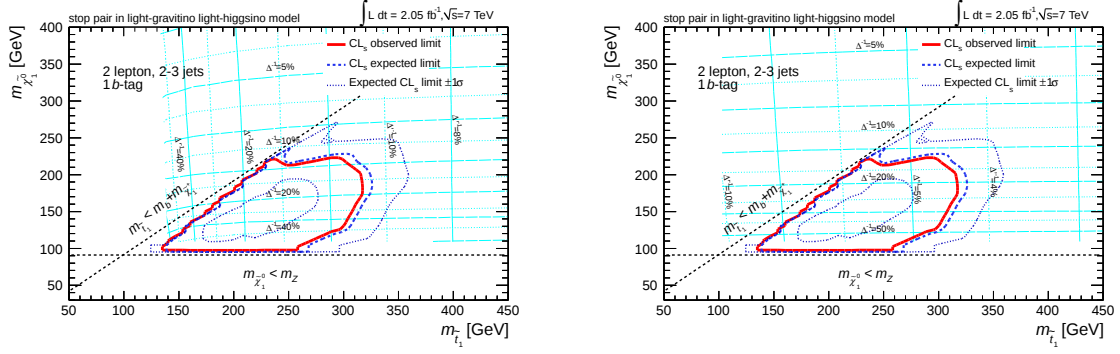


Figure 7.24: The exclusion limits for stop pair production in the light-gravitino light-higgsino model shown with the contours of the tuning parameters Δ^{-1} and Δ'^{-1} . The left figure is for $A_t = -m_{\tilde{t}}$ and the right figure is for $A_t = -2m_{\tilde{t}}$.

7.8.1 No-lepton multi-jet channel

Figure 7.29 shows the highest m_{eff} event in the no-lepton multi-jet channel. Figure 7.25 shows the m_{eff} distribution in the no-lepton multi-jet channel encircling this event by the orange circle.

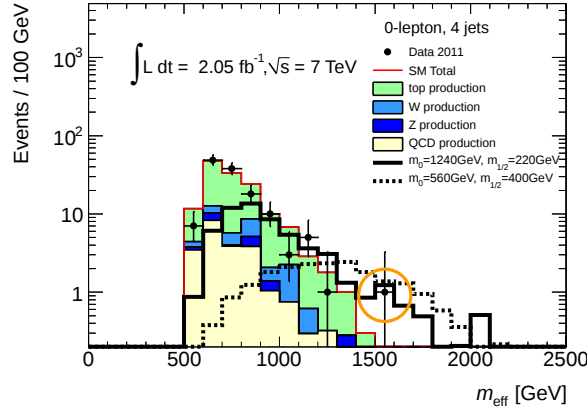


Figure 7.25: The m_{eff} distribution in the no-lepton multi-jet signal region before m_{eff} cut. The highest m_{eff} event in data is encircled by the orange circle.

In this event, there are six jets with $p_T > 50$ GeV and very high m_{eff} is due to the leading jet and E_T^{miss} . If we interpret this event in terms of the SM processes, there is only one b -tagged jet satisfying a softer p_T ; therefore the event is unlikely to be from the $t\bar{t}$ process. The fourth leading jet failed the electron identification but it deposited a large fraction of energy in the EM calorimeter and it has $m_T = 74$ GeV (the transverse mass calculated with E_T^{miss} by Equation 6.17) in EM scale which is consistent with the W boson mass. The other jets in the event do not have these features. Hence this event is interpreted as the $W(\rightarrow e\nu) + b\bar{b}$ process.

7.8.2 One-lepton multi-jet channel

Figure 7.30 and 7.31 show the highest m_{eff} events in the electron and the muon channels. Figures 7.26 show m_{eff} distributions in the one-lepton multi-jet signal region encircling these events by the orange circles.

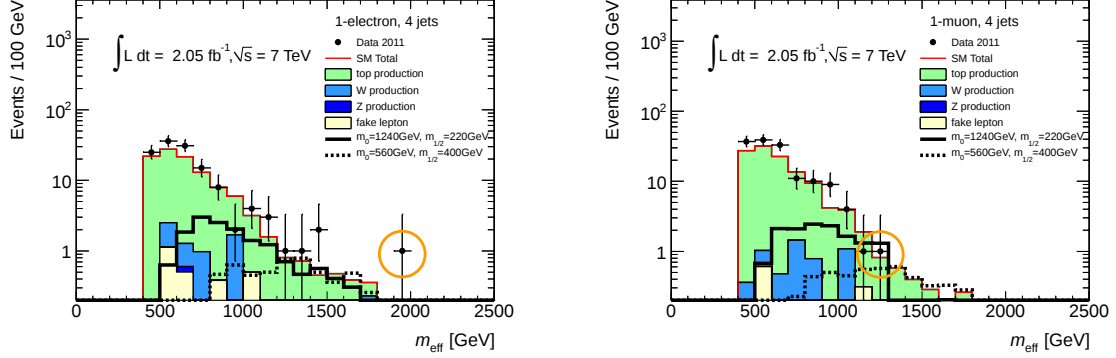


Figure 7.26: The m_{eff} distributions in the one-lepton multi-jet channel. The left figure shows the electron channel and the right figure shows the muon channel. The highest m_{eff} events in each channel are encircled by the orange circles.

In both events, m_T exceeds 100 GeV, hence it is most likely to be di-leptonic decay of the $t\bar{t}$ production. In the analyses described in this thesis, τ -jets are not positively identified. No jet passed *tight* criteria for the τ -jet [112] in the highest m_{eff} event in the electron channel (Figure 7.30). However, the efficiency to identify τ -jets correctly with this criteria is about 30 % at most. Therefore it is possible that a τ -jet is missed and that event is from the $t\bar{t} \rightarrow b\bar{b}e^+\nu_e\tau^-\bar{\nu}_\tau$. Also m_{CT} calculated from the two b -tagged jet is 120 GeV, which is consistent with the $t\bar{t}$ interpretation.

In the highest m_{eff} event in the muon channel (Figure 7.31), there are no other isolated electron or muon candidates. Moreover, there is only one b -tagged jet. This event does not look like it comes from the $t\bar{t}$ process. However, looking at the calorimeter cells, we notice that the reconstructed leading and sub-leading jets seem to be actually two jets respectively. Since all of them deposit energy in both EM and hadronic calorimeters, they are not likely to be an electron. Also they did not pass the τ identification but if each of these jets were properly reconstructed as separate objects, they might have passed the τ criteria. Therefore one possibility is that this event is $t\bar{t} \rightarrow b\bar{b}\mu^-\nu_\mu\tau^+\bar{\nu}_\tau$.

7.8.3 No-lepton di-jet channel

Figure 7.32 shows the highest $m_{CT}(b, b)$ event in the no-lepton di-jet channel. Figure 7.27 shows the m_{CT} distribution in the no-lepton di-jet channel with the highest m_{CT} event encircled by the orange circle.

If we interpret this event in terms of the SM processes, since m_{CT} exceeds the 136 GeV, it is unlikely to be from the $t\bar{t}$ process. There are no lepton candidates. Hence

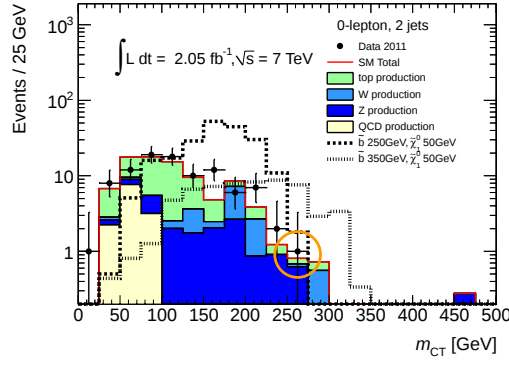


Figure 7.27: The m_{CT} distribution in the no-lepton di-jet channel. The highest m_{CT} event is encircled by the orange circle.

this event can be interpreted as coming from the $Z(\rightarrow \nu\bar{\nu}) + b\bar{b}$ process.

7.8.4 Two-lepton multi-jet channel

The event displays of the SUSY signal candidates in the two-lepton multi-jet channel are shown in Figure 7.33 and 7.34. Figures 7.28 show the E_T^{miss} distributions in the two-lepton multi-jet channel, with the highest E_T^{miss} events encircled by the orange circle.

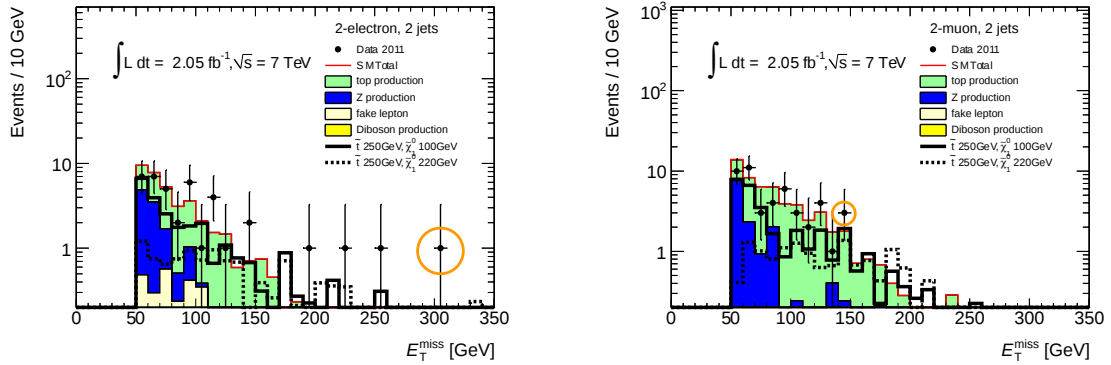


Figure 7.28: The E_T^{miss} distributions in the two-lepton multi-jet signal region. The left figure shows the electron channel and the right figure shows the muon channel. The highest E_T^{miss} events in data for each channel are encircled by the orange circles.

These are the highest E_T^{miss} events in the e - e and μ - μ channels respectively. Both events have the two-lepton invariant mass which is consistent with the Z boson mass. However, there are two b -tagged jets and they form m_{CT} which is consistent with the $t\bar{t}$ process. Since E_T^{miss} is too large for a Z +jets event, these events can be interpreted as coming from the di-leptonic decay of $t\bar{t}$ process.

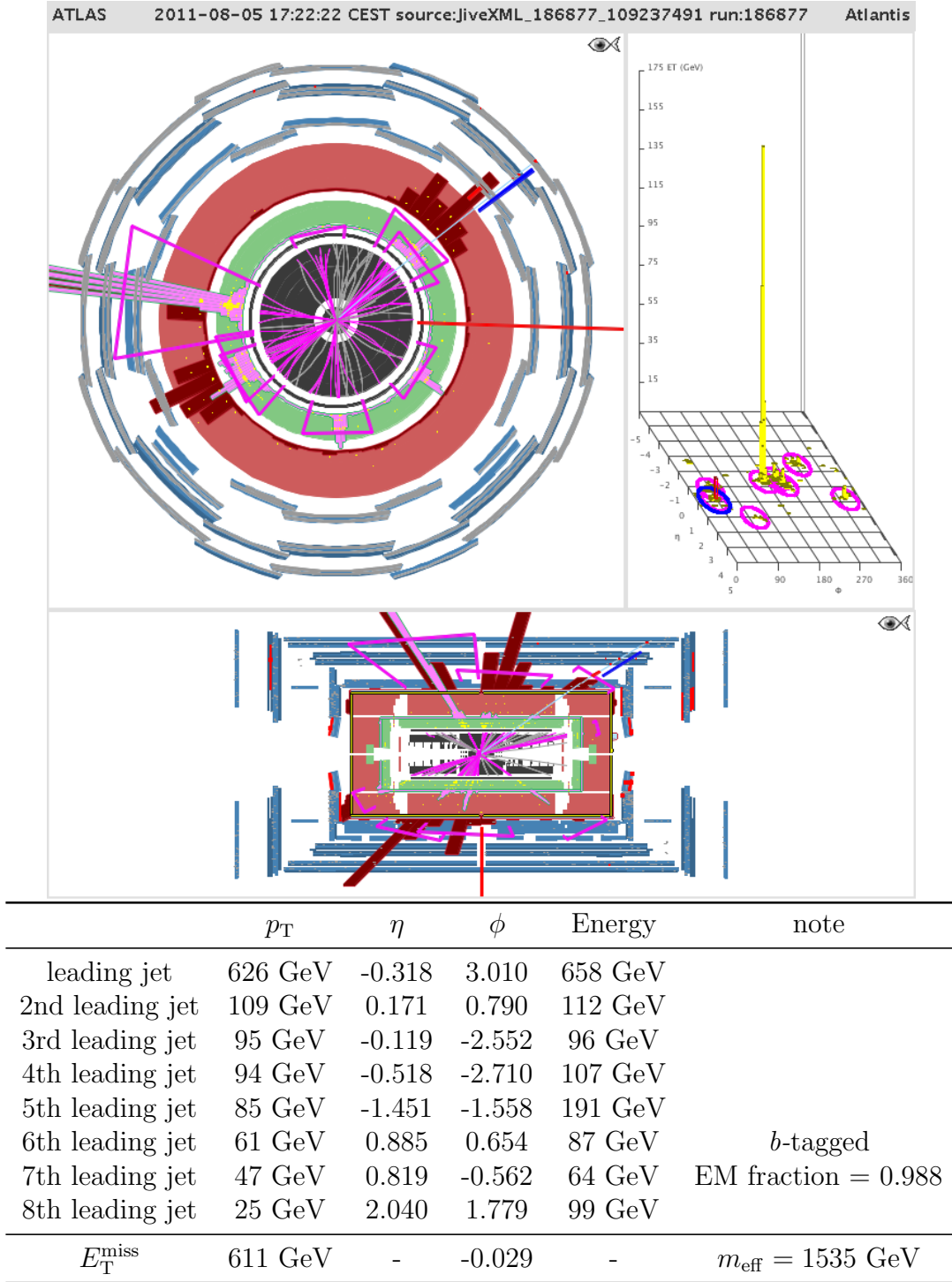


Figure 7.29: The highest m_{eff} event in the no-lepton multi-jet channel.

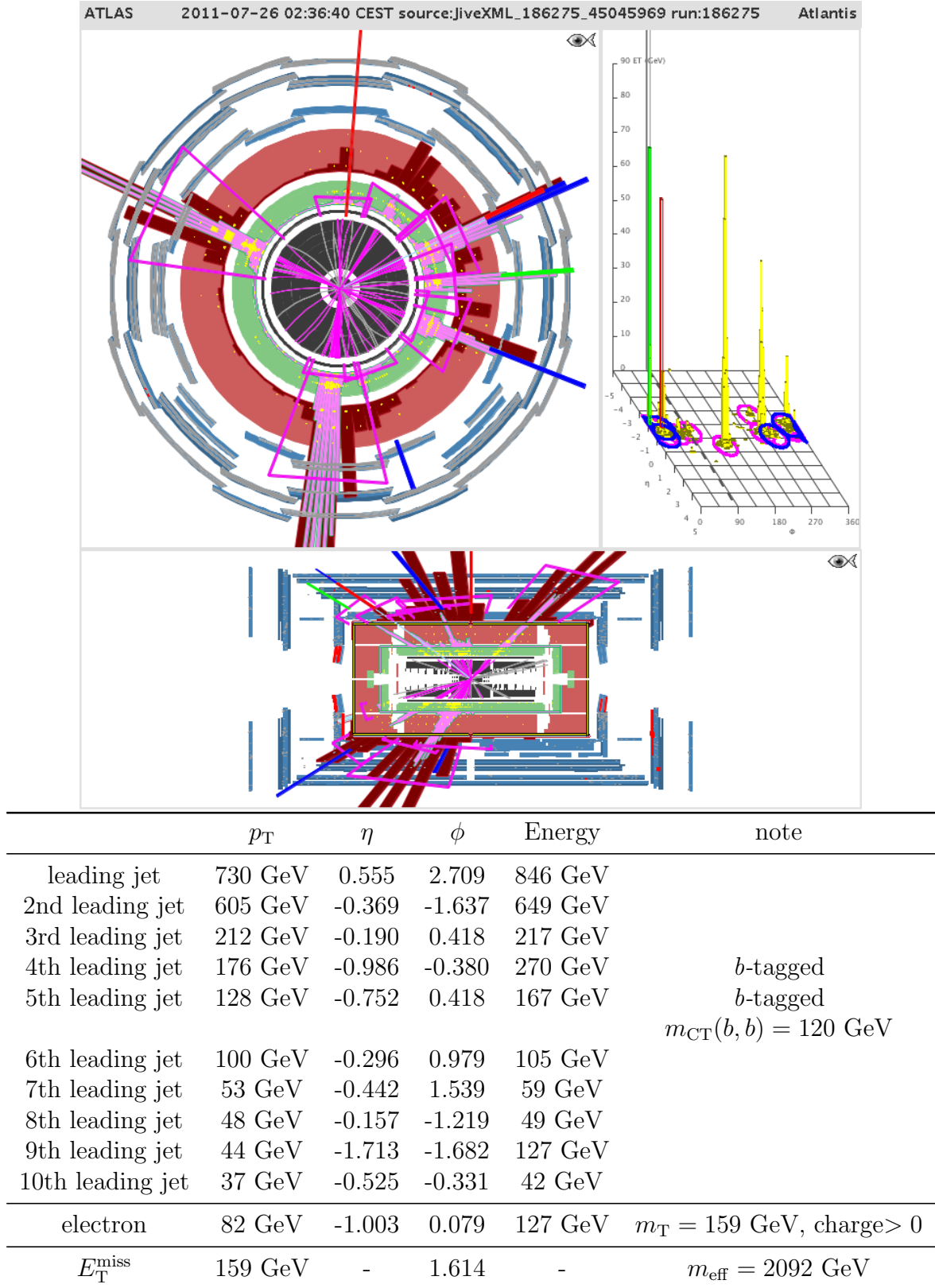


Figure 7.30: The highest m_{eff} event in the one-electron multi-jet channel.

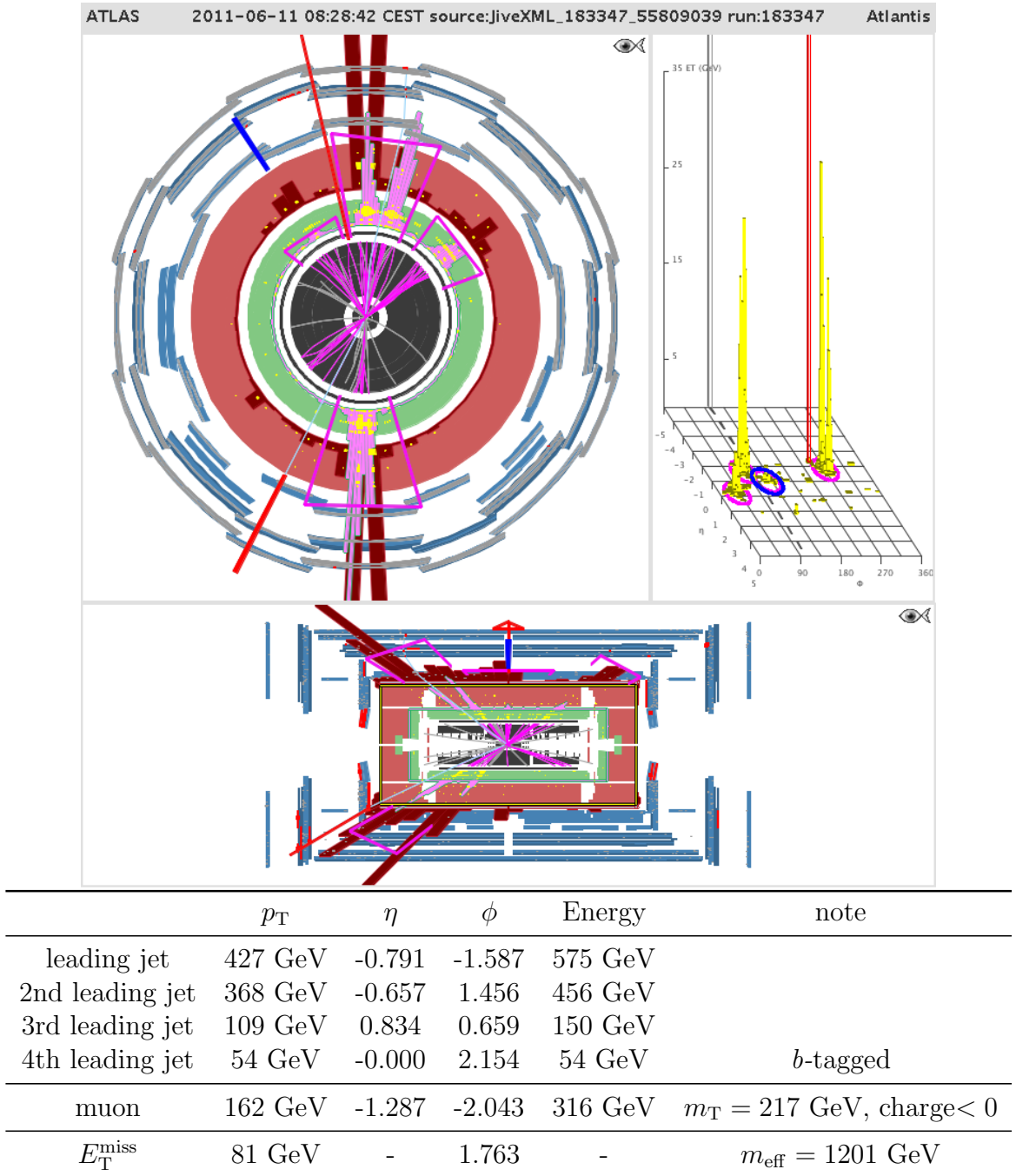


Figure 7.31: The highest m_{eff} event in the one-muon multi-jet channel.

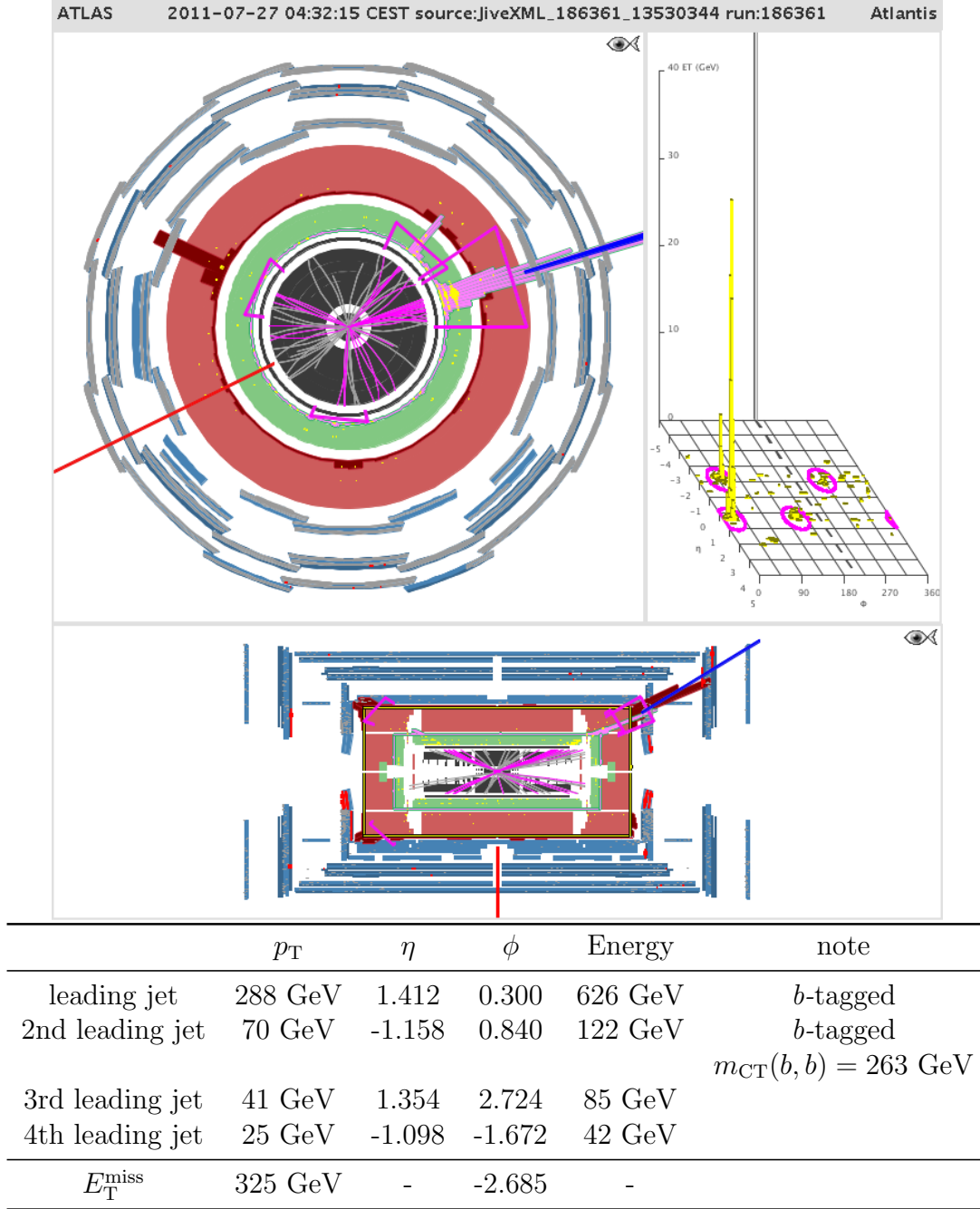


Figure 7.32: The highest $m_{CT}(b, b)$ event in the no-lepton di-jet channel

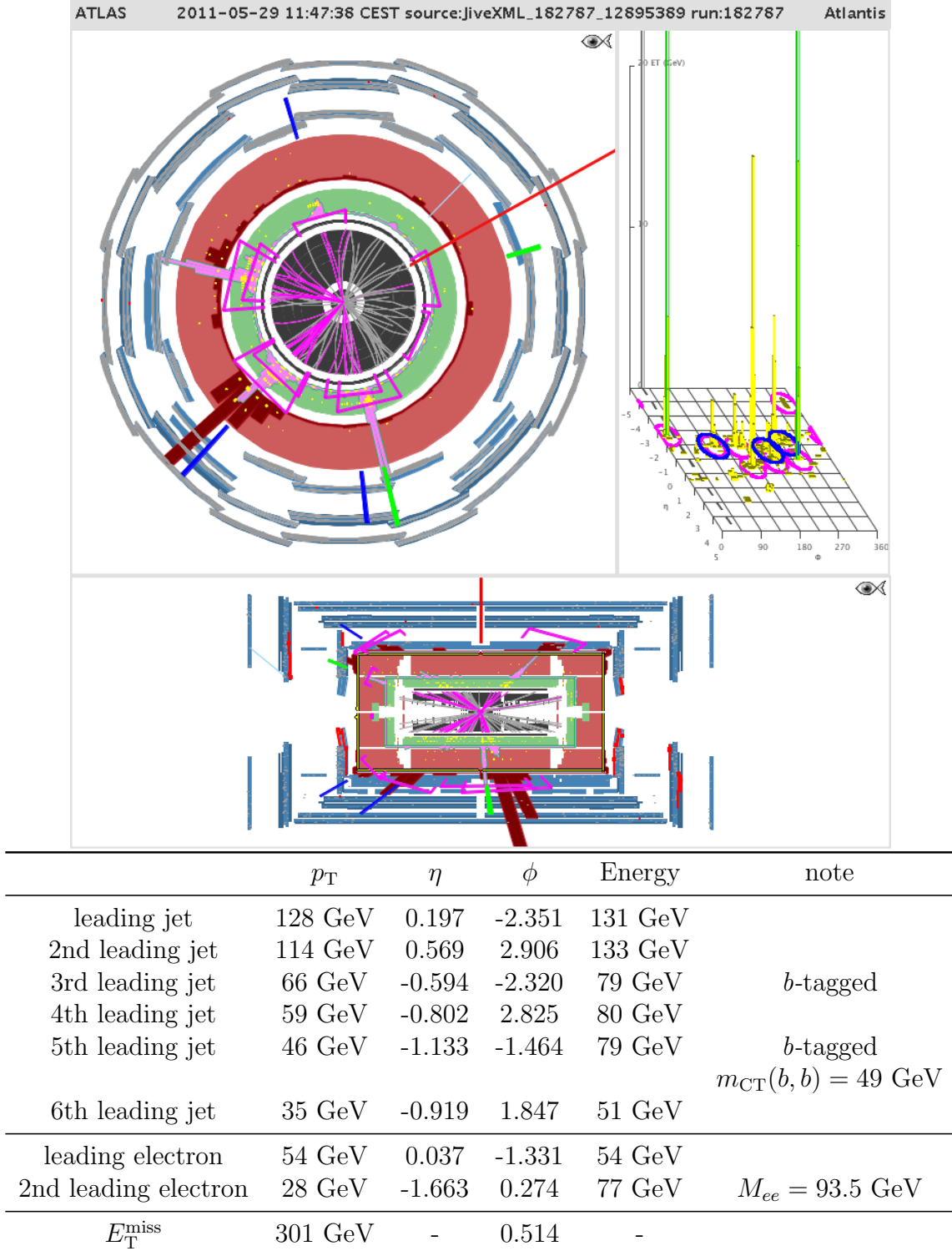


Figure 7.33: The highest E_T^{miss} event in the e - e channel

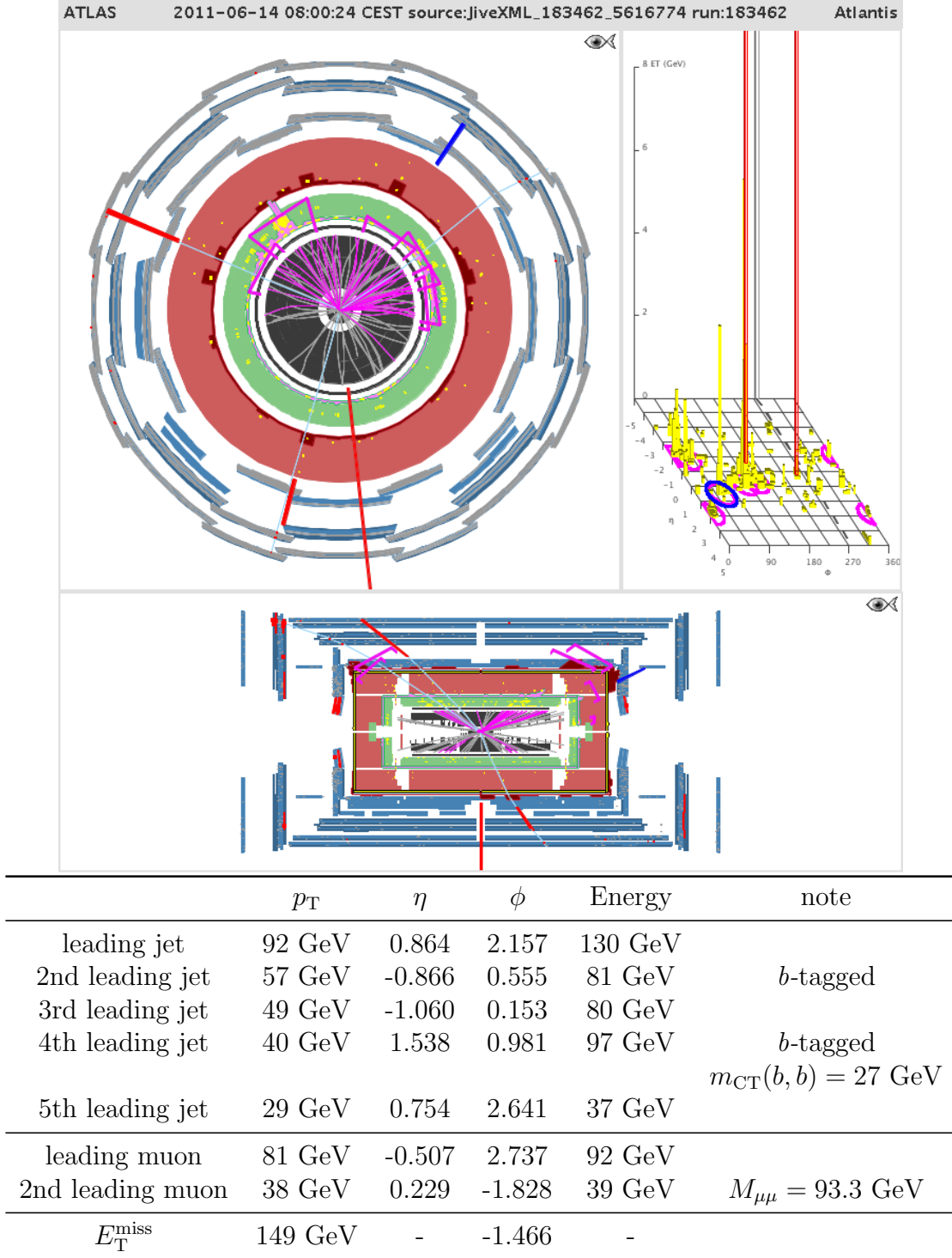


Figure 7.34: The highest E_T^{miss} event in the $\mu\text{-}\mu$ channel

Chapter 8

Conclusion

Searches for the stop and sbottom (supersymmetric partners of the top and bottom quarks) in proton-proton collisions at $\sqrt{s} = 7$ TeV are presented using data with the integrated luminosity of 2 fb^{-1} recorded by the ATLAS detector. Generally, the stop and the sbottom are expected to be lighter than the other colored SUSY particles due to the large Yukawa coupling. The stop is also required to be light for the naturalness of the Higgs mass. Four searches described in this thesis are as follows;

- 0-lepton, 1st jet $p_T > 130$ GeV, 4th jet $p_T > 80$ GeV, at least one b -tagged jets, $E_T^{\text{miss}} > 130$ GeV and optimum m_{eff} cuts,
- 1-lepton, 1st jet $p_T > 60$ GeV, 4th jet $p_T > 50$ GeV, at least one b -tagged jets, $E_T^{\text{miss}} > 80$ GeV and optimum m_{eff} cuts,
- 0-lepton, 1st jet $p_T > 130$ GeV, 2nd jet $p_T > 50$ GeV, 3rd jet $p_T \leq 50$ GeV, two b -tagged jets, $E_T^{\text{miss}} > 130$ GeV and optimum m_{CT} cuts,
- 2-lepton, 1st jet $p_T > 60$ GeV, 2nd (3rd) jet $p_T > 50$ GeV, $E_T^{\text{miss}} > 50(80)$ GeV and at least one b -tagged jet.

No significant excess is seen in all searches and the observed numbers of events after the selection were consistent with the SM prediction. Exclusion limits on the stop and sbottom masses in the SUSY models were obtained as follows from these results.

- In the mSUGRA model with $\tan\beta = 40$, $A_0 = -500$ GeV and $\mu > 0$, a stop mass of 640 GeV is excluded in all $(m_0, m_{1/2})$ spaces at 95 % CL.
- In the phenomenological $\tilde{g} \rightarrow \tilde{b}_1 b$ decay model, a sbottom mass of 650 GeV is excluded at 95 % CL as long as a gluino mass is less than 900 GeV.
- In the phenomenological $\tilde{g} \rightarrow \tilde{t}_1 t$ decay model, a stop mass of 420 GeV is excluded at 95 % CL as long as a gluino mass is less than 640 GeV.
- In the sbottom pair production $\tilde{b}_1 \rightarrow b + \tilde{\chi}_1^0$ decay model, a sbottom mass of 400 GeV is excluded with $m_{\tilde{\chi}_1^0} = 0$ GeV and the sbottom mass of 350 GeV is excluded with $m_{\tilde{\chi}_1^0} = 120$ GeV.

This result is also interpreted as the stop pair production with $\tilde{t}_1 \rightarrow b + \tilde{\chi}_1^+$ and $\tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^0 + f + f'$ but the lightest chargino and neutralino are degenerated.

- In the stop pair production in the light-gravitino, light-higgsino model, a stop mass of 230 GeV is excluded as long as $m_Z < m_{\tilde{\chi}_1^0} < 220$ GeV and a stop mass of 320 GeV is excluded at $m_{\tilde{\chi}_1^0} = 180$ GeV.

If we define the tuning parameter by $\Delta'^{-1} \equiv m_h^2/2m_{H_u}^2|_{\text{rad}}$, the allowed stop mass regions by $\Delta'^{-1} > 10\%$ is $m_{\tilde{t}_1} \lesssim 400$ GeV for $|A_t| \sim m_{\tilde{t}}$ and $M_{\text{mess}} = 10$ TeV. Therefore in the models with the stop production from gluino decays, the naturalness of 10 % is almost excluded within the accessible gluino masses. In the models with stop pair production, there is still allowed region for the stop mass but the stringent limits have been set on the naturalness.

Appendix A

Acronyms

Acronyms used in this thesis.

ATLAS	A Troidal LHC ApparatuS
BR	Branching Ratio
CL	Confidence Level
CMB	Cosmic Microwave Background
CoM	Center-of-Mass
CR	Control Region
CSC	Cathode Strip Chamber
EF	Event Filter
EM	Electro-Magnetic
GMSB	Gauge Mediated Supersymmery Breaking
GUT	Grand Unified Theory
HEC	Hadronic End-cap Calorimeter
ID	Inner Detector
ISR	Initial State Radiation
L1	Level 1
L2	Level 2
LAr	Liquid Argon
LHC	Large Hadron Collider
LO	Leading Order
LSP	Lightest Supersymmetric Particle
MACHO	Massive Astrophysical Compact Halo Object
MC	Monte Carlo
MDT	Monitored Drift Tube
ME	Matrix Element
mSUGRA	minimal SUper Gravity
MSSM	Minimal Supersymmetric Standard Model

NLL	Next-to-leading Log
NLO	Next-to-leading Order
NLSP	Next-to-Lightest Supersymmetric Particle
PDF	Parton Distribution Function
RoI	Region-of-Interest
RMS	Root-Mean-Square
RPC	Resistive Plate Chamber
QCD	Quantum Chromodynamics
SCT	Semiconductor Tracker
SM	Standard Model
SR	Signal Region
SUGRA	SUPERGRAvity
SUSY	SUPERSYmmetry
TGC	Thin Gap Chamber
TRT	Transition Radiation Tracker
VEV	Vacuum Expectation Value
WIMP	Weakly Interacting Massive Particle

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