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Data-driven Background Estimation for the One-lepton SUSY Search Mode in ATLAS

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Abstract

In this thesis a search strategy for Supersymmetry within $\int \mathcal{L} dt = 1 \text{ fb}^{-1}$ of ATLAS data is described. The focus is on inclusive signatures with multiple high- p_T jets, missing transverse energy and one isolated lepton in the final states. The discovery potential is evaluated for several benchmark points in minimal Supergravity parameter space using Monte-Carlo simulations with next-to-leading order cross-section corrections.

Further, extensive studies of data-driven methods for the estimation of the Standard Model backgrounds in this particular search channel are carried out. The performance of a two-dimensional sideband-based approach is evaluated and found to be dominated by systematic effects. A new, analytical data-driven background estimation technique ('4-tiles'-method) is introduced and tested extensively using toy Monte-Carlo simulations. Stable and accurate results are obtained. The discovery potential for all studied benchmark points using this method is re-evaluated, including a full treatment of systematic uncertainties.

Zusammenfassung

Gegenstand der vorliegenden Arbeit ist eine mögliche Strategie für die Suche nach Supersymmetrie mit dem ATLAS Experiment, wie sie mit einem Datenvolumen von $\int \mathcal{L} dt = 1 \text{ fb}^{-1}$ durchgeführt werden könnte. Den Schwerpunkt bilden inklusive Signaturen mit mehreren hochenergetischen Jets, fehlender transversaler Energie, und einem isoliert rekonstruierten Lepton in den Endzuständen. Das Entdeckungspotential für mehrere charakteristische Modelle im Parameterraum der minimalen Supergravitation (mSUGRA) wird mit Hilfe von Monte-Carlo Simulationen, deren Wirkungsquerschnitte zu nächstführender Ordnung korrigiert sind, bestimmt.

Des Weiteren werden umfangreiche Studien zur Daten-basierten Abschätzung des Untergrundes von Standard-Modell Prozessen in diesem speziellen Suchkanal durchgeführt. Die Untersuchung eines Verfahrens, das auf der Extrapolation von zweidimensionalen Seitenbändern der Datenverteilungen beruht, ergibt zunächst eine starke Dominanz von systematischen Effekten. Ein neuer, analytischer Ansatz ('4-tiles'-Methode) wird daraufhin vorgestellt und umfangreichen Tests mit vereinfachten 'toy' Monte-Carlo Simulationen unterzogen. Die Methode zeichnet sich durch eine hohe Stabilität und Genauigkeit der Abschätzungen aus. Das Entdeckungspotential für alle untersuchten mSUGRA Modelle wird unter Benutzung dieser Methode und unter Berücksichtigung möglicher systematischer Fehlerquellen erneut bestimmt.

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Chapter 1

Introduction

In high energy physics, particle collisions are used to explore the elementary constituents of matter and their interactions. Over the past decades, enormous experimental and theoretical efforts have led to a consistent and remarkably accurate theoretical description of the physical observations - the *Standard Model of particle physics*. Therein, 12 point-like fermions and their corresponding antiparticles constitute the basic building blocks of matter. The interactions between them are mediated by 12 gauge bosons which account for the weak, electromagnetic and strong forces. The last important prediction of the Standard Model yet to be confirmed by experiments, is the concept of electro-weak symmetry breaking and the associated existence of the Higgs-particle.

Despite the outstanding success of the Standard Model at the currently accessible energy scale, it is not expected to be the ultimate theory of particle physics. Reasons for this are, amongst many others, the failure of the Standard Model's formalism to incorporate the gravitational interactions, the lack of an explanation for dark matter which makes up $\sim 23\%$ of our universe, and the non-unification of the electro-weak and strong coupling constants when extrapolated to high energies.

One candidate theory beyond the Standard Model, that provides convenient solutions to many of these problems, is Supersymmetry (SUSY). SUSY is a fundamental symmetry between fermions and bosons, that postulates a set of new partner particles to the known Standard Model particles. While no SUSY particles have yet been observed by experiment, many theoretically motivated arguments favour their existence at the electro-weak energy scale.

With the start-up of the Large Hadron Collider (LHC) at the European Laboratory for particle physics (CERN¹), this energy regime will become experimentally accessible for the very first time. Once fully operational, the LHC will reach a center-of-mass energy of 14 TeV in proton-proton collisions at a design luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ and thus provide excellent conditions to search for physical phenomena beyond the Standard Model.

One of four large-scale experiments at the LHC that will record first collisions in the near future is the ATLAS detector. A major design goal of ATLAS is the search for Supersymmetry. In order to exploit its full discovery potential, a wide range of experimental signatures and analysis strategies must be investigated. Furthermore, for an observation of an excess of hypothetical SUSY events in a realistic data analysis, the expected Standard Model backgrounds must be well understood. As Monte-Carlo simulations are associated with large uncertainties, dedicated techniques to extract the Standard Model backgrounds directly from the experimental data are necessary.

Subject of this thesis are comprehensive studies of the discovery potential of minimal Supergravity² scenarios within 1 fb^{-1} of ATLAS data, using data-driven background estimation techniques. An introduction to the theoretical foundations of Supersymmetry and minimal Supergravity will be given in

¹Conseil Européen pour la Recherche Nucléaire.

²Minimal Supergravity is one possible manifestation of Supersymmetry.

Chapter 2. Chapter 3 constitutes a brief outline of the LHC, the ATLAS detector components and related technical aspects. In Chapter 4, the offline reconstruction algorithms of the objects and quantities relevant for the subsequent analysis will be reviewed and their performance will be tested in Monte-Carlo simulations of hypothetical SUSY events. A detailed description of an inclusive search strategy for a variety of characteristic benchmark points in minimal Supergravity parameter space will follow in Chapter 5. In Chapter 6 the performance of an existing data-driven background estimation method for SUSY searches is studied and a new approach is introduced, including a full treatment of systematic uncertainties. Finally, Chapter 7 will summarize the results of this thesis.

Chapter 2

Theoretical Background

2.1 The Standard Model of Particle Physics

Today's experimentally verified knowledge of the fundamental particles and their interactions is summarized in the Standard Model of particle physics. In this section we briefly outline the main features of the Standard Model and then concentrate on a detailed introduction to Supersymmetry. Further information about the Standard Model can be found in numerous textbooks, e.g. [1].

Within the Standard Model, the elementary constituents of matter are 12 spin-1/2 fermions and their respective antiparticles. They can be further classified according to their interactions into quarks and leptons, for each of which three generations of particle pairs exist. For both fermion species the second and third generations are heavy copies of the first generation with identical quantum numbers. A summary of the Standard Model fermions is shown in Table 2.1.

Quarks participate in the strong, weak and electromagnetic interactions and therefore carry color, electric charge and weak isospin. For each generation there is one up-type quark with electric charge $+2/3$ ("up", "charm", "top") and one down-type quark with $-1/3$ ("down", "strange", "bottom"). The lepton doublets consist of one electron-type lepton ("electron", "muon", "tau") with electric charge -1 and a neutral almost massless lepton-neutrino. Whereas electron-type leptons are charged and participate in electromagnetic and weak interactions, neutrinos can only interact weakly due to their lack of electric charge.

The interactions between the matter particles are mediated by integer spin gauge bosons. Their existence arises from invariance of the respective interaction Lagrangians under local symmetry transformations. The underlying mathematical structure is the direct product of the internal symmetry groups $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$, where $SU(3)_C$ describes the strong force mediated by eight gluons and $SU(2)_L \otimes U(1)_Y$ the unified electro-weak force with $W^\pm$, Z bosons and the photon γ . Gravitational interactions are not incorporated into the Standard Model.

The unification of the weak and electromagnetic forces happens by virtue of the so-called GSW mechanism [2][3][4], in which a local gauge transformation of the left-handed weak isospin doublets $SU(2)_L$ and the $U(1)_Y$ multiplets and singlets with respect to hypercharge Y takes place. The invariance of the Lagrangian under these transformations necessitates the introduction of new massless vector fields $W^{1,2,3}$ and B , of which the physically observed $W^\pm$, Z and γ bosons are linear combinations. The mass eigentstates of the latter two bosons are additionally rotated by a so-called Weinberg-angle θ_W .

The Standard Model particles acquire their masses through interaction with a scalar Higgs background field, which spontaneously breaks the electro-weak symmetry. The introduction of this breaking mechanism is necessary since gauge invariance requires massless gauge bosons, which contradicts experimental results. The existence of the scalar Higgs particle, however, has not yet been experimentally verified.

Name	1 st Generation	2 nd Generation	3 rd Generation	$SU(3)_C, SU(2)_L, U(1)_Y$
Quarks	(u_L, d_L)	(c_L, s_L)	(t_L, b_L)	$(3, 2, \frac{1}{3})$
	u_R	c_R	t_R	$(3, 1, \frac{4}{3})$
	d_R	s_R	b_R	$(3, 1, -\frac{2}{3})$
Leptons	(ν_e, e_L)	(ν_μ, μ_L)	(ν_τ, τ_L)	$(1, 2, -1)$
	e_R	μ_R	τ_R	$(1, 1, -2)$

Table 2.1: *Summary of the matter fermions of the Standard Model, grouped into left-handed weak isospin doublets and right handed singlets. Neutrino masses are neglected. The last column indicates the dimensions of the $SU(3)_C$, $SU(2)_L$, and $U(1)_Y$ representations. The hypercharge Y of a multiplet is given by $Y = 2(Q - T_3)$, where Q is electric charge and T_3 the third isospin component.*

2.2 Supersymmetry

2.2.1 Introduction

The Standard Model of particle physics has been very successful in describing the fundamental particles and their interactions at the currently accessible energy scales in high energy physics. It is expected, however, that more comprehensive theories are necessary to explain the physical phenomena in higher energy regimes. Such theories originate from the Standard Model's inability to clarify important theoretical questions, such as the arbitrariness of gauge couplings, mixing angles and particle masses, the lack of an explanation for gauge symmetry, quantum numbers and generations, the Higgs-mass fine-tuning problem and eventually the incorporation of gravity into a unified theory. In addition significant cosmological observations, such as cold dark matter, dark energy, the observed matter-antimatter asymmetry as well as results from neutrino physics are not addressed within the Standard Model.

The ultimate goal of particle physics is to consistently explain and integrate all these phenomena into a single Theory of Everything (ToE) valid up to the Planck energy scale¹ $M_P \approx 10^{19} \text{ GeV}$, including quantum gravitational effects. Superstring models [5] are currently the most promising candidates on the way to such a ToE, but they are not yet entirely understood and experimental validation is in most cases far beyond technical possibilities.

An essential requirement for most String models is Supersymmetry (SUSY). SUSY is a fundamental symmetry between fermions and bosons introducing a set of new partner particles with opposite spin statistics for each Standard Model particle. The possible implications of SUSY on the electroweak scale make it one of the best-motivated theories beyond the Standard Model. As we shall see in the following, Supersymmetry suggests very elegant solutions to many open questions of the Standard Model. Moreover there is good reason to believe that measurable SUSY effects will be within reach of the Large Hadron Collider.

The Hierarchy Problem. A strong argument for Supersymmetry at the electroweak scale is the so-called Hierarchy Problem [6]. It describes the unnatural discrepancy between the energy scale of the renormalized Higgs-boson mass and that of its bare mass at the lowest order of perturbation theory. This tremendous difference is caused by large quantum corrections to Higgs-boson processes, such as fermion loops as illustrated in Fig. 2.1a. These contributions result in quadratically divergent correction terms to the physical Higgs mass:

$$m_H^2 = m_0^2 - \frac{|\lambda_f|^2}{8\pi^2} \Lambda^2 + \mathcal{O}(\ln \frac{\Lambda^2}{m_f^2}) \quad (2.1)$$

Here m_0 is the bare mass of the Higgs-boson at Born-level, λ_f is the Yukawa coupling of the process

¹The Planck scale is defined as the energy scale at which the known physical concepts of space and time cease to be valid.

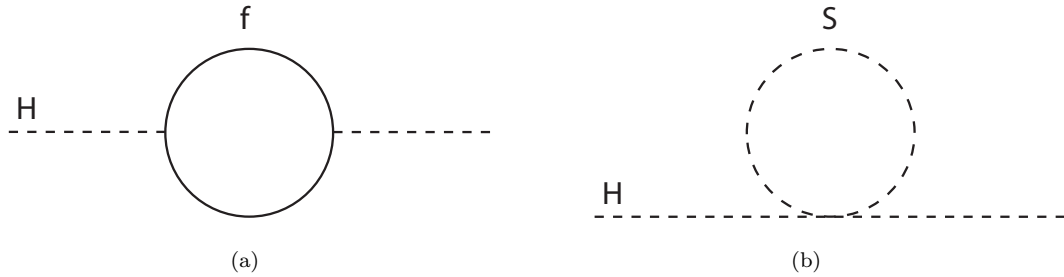


Figure 2.1: *One-loop quantum correction to the physical Higgs mass from (a) fermion loop and (b) scalar loop diagrams.*

of interest, m_f the mass of the involved fermion, and Λ the cut-off parameter used to regulate the loop integral. The latter parameter can be interpreted as the upper validity limit of the theory and is usually identified with the GUT scale at $\Lambda_{GUT} \approx 10^{16} GeV$.

In contrast, the mass of the Higgs Boson m_H is expected to be at the order of 100 GeV, as predicted by measurements from LEP II and Tevatron experiments [7] [8] [9] and required by electroweak symmetry breaking. It follows then from equation 2.1 that m_0^2 must be known up to a precision of ~ 24 significant digits to yield the correct value of m_H . From a theoretical point of view it is unlikely that such a fine-tuning of parameters in every order of perturbation theory is realized in nature.

A more elegant solution to this problem is provided by Supersymmetry, where the supersymmetric partner particles contribute with opposite sign loop corrections to those of the Standard Model. In this way fermion loop processes cancel with loop diagrams from scalar SUSY particles as shown in Fig 2.1b. Likewise Standard Model boson contributions are absorbed by their respective Spin-1/2 superpartners.

For the case of a scalar particle S with mass m_S the corrections can be written as

$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2} (\Lambda^2 - 2m_S^2 \ln \frac{\Lambda}{m_S} + \dots). \quad (2.2)$$

A comparison between equations 2.1 and 2.2 shows that the quadratic divergences can be absorbed, if there are two scalar contributions and $\lambda_S = |\lambda_f|^2$ holds between the couplings. In fact this relation is an intrinsic property of Supersymmetry as we will see in the following sections. Now the remaining one loop correction can be approximated as

$$\Delta m_H^2 \approx \mathcal{O}\left(\frac{\alpha}{\pi}\right)(m_S^2 - m_f^2), \quad (2.3)$$

where α measures the effect of a typical coupling constant. Hence, if Supersymmetry is softly broken, the masses of the fermions and their supersymmetric partners must lie close together to allow for a natural value of m_H without artificial fine tuning:

$$|m_S^2 - m_f^2| \lesssim 1 TeV^2 \quad (2.4)$$

This is one of the strongest motivations to expect Supersymmetry at the electroweak scale.

Grand Unification. Motivated by the evolution of the Standard Model coupling constants with energy, Grand Unified Theories (GUTs) aim to provide a unified description of the electroweak and strong interactions at high energies. The underlying idea is to embed the Standard Model's gauge groups $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ into a universal symmetry group G_{GUT} , representing a single interaction with one coupling constant at a unification scale M_{GUT} .

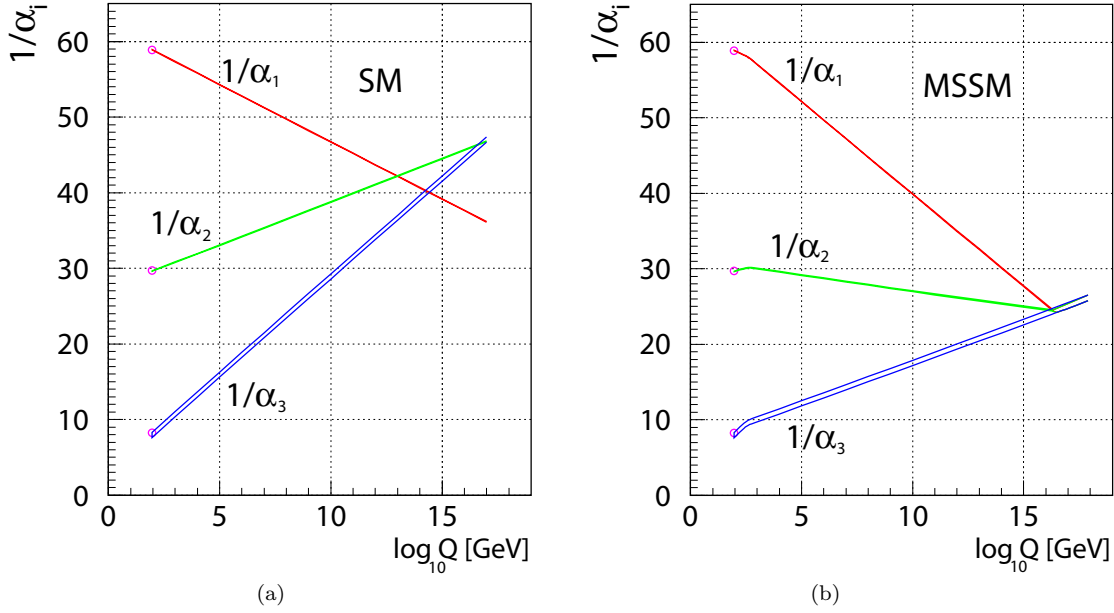


Figure 2.2: Evolution of the inverse coupling constants with energy. Within the Standard Model (left) a unification is not natural, whereas for minimal supersymmetric models (right) the coupling constants intersect at $M_{GUT} \approx 10^{16} \text{ GeV}$ [10]. The thickness of the lines indicates the error on the coupling constants. The plots are taken from [11].

This requires the three coupling constants of the SM, usually defined as

$$\begin{aligned}\alpha_1 &= (5/3)g'^2/(4\pi) = 5\alpha/(3\cos^2\theta_W), \\ \alpha_2 &= g^2/(4\pi) = \alpha/\sin^2\theta_W, \\ \alpha_3 &= g_s^2/(4\pi),\end{aligned}\tag{2.5}$$

where g' , g and g_s are the respective $U(1)_Y$, $SU(2)_L$ and $SU(3)_C$ coupling constants², to intersect at M_{GUT} .

The energy dependence of the parameters α_i is provided by the renormalization formalism. Using a specific renormalization scheme³, the contributions of vacuum polarization processes to the boson propagators are taken into account. The corresponding renormalization group equations at one-loop level are given by [14]

$$\frac{d\alpha_i}{dt} = \frac{b_i}{2\pi}\alpha_i^2, \quad i = 1, 2, 3,\tag{2.6}$$

with $t = \ln(Q^2/\mu^2)$, where Q^2 stands for the energy of the interaction and μ^2 is the renormalization scale. The analytical solution of equation (2.6),

$$\frac{1}{\alpha_i(Q^2)} = \frac{1}{\alpha_i(\mu^2)} - \frac{b_i}{2\pi} \ln\left(\frac{Q^2}{\mu^2}\right),\tag{2.7}$$

²The factor $\frac{5}{3}$ for α_1 in equations (2.5) is used for correct normalization of the generators [12].

³Here the so-called modified minimal subtraction scheme $\overline{MS}$ is used [13].

describes the so-called 'running' of the coupling constants as a function of energy. The coefficients b_i carry intrinsic information about the particle content of the underlying model. In the case of the Standard Model they have been determined to [15]

$$b_i = \begin{pmatrix} b_1 \\ b_2 \\ b_3 \end{pmatrix} = \begin{pmatrix} 0 \\ -22/3 \\ -11 \end{pmatrix} + N_{Fam} \begin{pmatrix} 4/3 \\ 4/3 \\ 4/3 \end{pmatrix} + N_{Higgs} \begin{pmatrix} 1/10 \\ 1/6 \\ 0 \end{pmatrix}, \quad (2.8)$$

where $N_{Fam} = 3$ stands for the number of generations and $N_{Higgs} = 1$ is the number of Higgs doublets.

Using equations (2.7), (2.8) and the experimentally measured values for the couplings, one can extrapolate to high energies to examine a possible unification [10]. The result of this extrapolation is shown in Fig. 2.2a, which clearly indicates that a unification in a single point is not natural. In fact it is ruled out by more than 7 standard deviations [10] and so is a minimal GUT based on the Standard Model.

To maintain the idea of a Grand Unified Theory, new physics must exist between the electroweak and Planck scale to alter the behaviour of the α_i . This is where Supersymmetry enters the picture. Assuming a minimal supersymmetric model as described in section 2.3, the extended particle content changes the coefficients b_i to [15]

$$b_i = \begin{pmatrix} b_1 \\ b_2 \\ b_3 \end{pmatrix} = \begin{pmatrix} 0 \\ -6 \\ -9 \end{pmatrix} + N_{Fam} \begin{pmatrix} 2 \\ 2 \\ 2 \end{pmatrix} + N_{Higgs} \begin{pmatrix} 3/10 \\ 1/2 \\ 0 \end{pmatrix}, \quad (2.9)$$

where $N_{Fam} = 3$ remains and an additional Higgs doublet is introduced $N_{Higgs} = 2$. It turns out, with these parameters a unification becomes possible at around $10^{16} GeV$ as illustrated in Fig. 2.2b. Furthermore the most perfect intersection of the coupling constants can be obtained if the SUSY masses lie around 1 TeV [10]. This provides yet another very strong motivation for low energy Supersymmetry.

Dark Matter. A third reason to believe in Supersymmetry is its possible explanation for dark matter. Dark matter is a hypothetical form of matter that cannot be observed directly, but whose existence can be inferred from gravitational effects on visible matter, such as the rotation of galaxies. Latest cosmological results, e.g. from WMAP-data [16], suggest that the cold dark matter content makes up about 23% of the energy density of the universe.

Candidate particles for dark matter include the so-called weakly-interacting massive particles (WIMPs). These hypothetical neutral particles only participate in the gravitational and weak interactions and thus are extremely difficult to detect. Within the Standard Model there are no known particles that exhibit all features of WIMPs.

Supersymmetry, however, assumes the existence of a lightest supersymmetric particle (LSP), which is stable for R-Parity conserving SUSY models (see section 2.3) and also neutral in many scenarios. It therefore has all properties of a WIMP and constitutes a promising candidate for dark matter.

Gravity. As a last important point the connection between Supersymmetry and Gravity is briefly mentioned. As will be further explained in section 2.4.2, by making Supersymmetry a local symmetry the principles of both theories can be unified into a single concept, called Supergravity.

Supergravity is non-renormalizable and therefore not a candidate for a Theory of Everything, but it can be understood as an effective description of physical phenomena including gravity at energies below the Planck scale [17]. This is certainly a very attractive implication of Supersymmetry.

In conclusion, a variety of reasons point to Supersymmetry as the theory for physics beyond the Standard Model. In the following sections of this chapter the mathematical formalism of Supersymmetry will be introduced step-by-step.

2.2.2 Supersymmetry Algebra

In this section we examine more closely the group-theoretical foundations of Supersymmetry. As a starting point we consider the so-called Poincaré group, one of the most fundamental symmetry groups in physics. It contains the full symmetry of special relativity, including the four translations in Minkowski space, plus the three rotations and boosts of the Lorentz group. The known elementary particles are irreducible representations of the Poincaré group.

To obtain a unified theory of all interactions, it is desirable to combine the internal gauge symmetries of the Standard Model, represented by the Lie groups $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$, with the structure of space-time provided by the Poincaré group. Unfortunately, the existence of such a group is ruled out for any but the trivial case, as was shown by Coleman and Mandula [18] in 1967. However, after Wess and Zumino found the first supersymmetric model in 1974 [19], this theorem had to be significantly generalized. In fact it was shown by Haag, Lopuszanski, and Sohnius [20] a year later that under weaker boundary conditions a non-trivial extension to the Poincaré symmetry is possible, namely *Supersymmetry*.

Thus Supersymmetry is a space-time symmetry. Its generators transform bosonic states into fermionic states and vice-versa:

$$Q|Boson\rangle = |Fermion\rangle, \quad Q|Fermion\rangle = |Boson\rangle \quad (2.10)$$

It follows that Q and its hermitian conjugate $Q^\dagger$ must have fermionic character and carry spin angular momentum 1/2. Within the easiest supersymmetric extension of the Poincaré group, the above mentioned Wess-Zumino model, the generators are required to satisfy the following algebra,

$$\{Q_\alpha, Q_\beta^\dagger\} = 2\sigma_{\alpha\dot{\alpha}}^\mu P_\mu \quad (2.11)$$

$$\{Q_\alpha, Q_\beta\} = \{Q_\alpha^\dagger, Q_\beta^\dagger\} = 0 \quad (2.12)$$

$$[Q_\alpha, P^\mu] = [Q_\alpha^\dagger, P^\mu] = 0, \quad (2.13)$$

where P^μ denotes the four-momentum in space-time, σ^μ are the Pauli matrices and α and β spinorial indices. Note that equations 2.11-2.13 contain both anticommutation and commutation relations, which constitutes the generalization necessary to combine internal symmetries and the Poincaré group.⁴

Direct implications of this supersymmetric algebra are the following:

- The bosonic or fermionic states and their respective superpartners with opposite spin statistics are ordered in supersymmetric multiplets, so-called *supermultiplets*. The supermultiplets are the irreducible representations of the supersymmetric algebra.
- Superpartners must have equal mass, since the squared mass operator $-P^2$ commutes with both Q and $Q^\dagger$ as well as all generators of the Poincaré group.
- Superpartners must have equal gauge quantum numbers, such as charge, isospin and color, since Q and $Q^\dagger$ commute with all generators of the internal gauge symmetry groups.
- A concatenation of two supersymmetric transformations leads to a translation in space-time, since the square of the generator Q is equal to P_μ . For local supersymmetric transformations this implies a connection between Supersymmetry and General Relativity as we shall see later on.
- The bosonic and fermionic degrees of freedom of each supermultiplet are related as $n_B = n_F$.

⁴Mathematically speaking the boundary conditions of the Coleman-Mandula theorem are loosened by introducing a Z_2 -grading into the Lie algebra.

The latter statement needs a short explanation: As we know the fermionic generators of Supersymmetry Q and $Q^\dagger$ map the bosonic subspace B onto a fermionic subspace F and vice-versa. It is also known that for a linear mapping $f : X \rightarrow Y$ the relation $\dim(Y) \leq \dim(X)$ holds. Thus, for a two-fold supersymmetric transformation $B \rightarrow F \rightarrow B$, the equation $\dim(F) = \dim(B)$ must apply, since the concatenation of two SUSY transformations maps the bosonic subspace onto itself. The same argument holds for the fermionic subspace and thus the bosonic and fermionic degrees of freedom in each supermultiplet must be equal.

Following this rule we examine the possible constellations of supermultiplets. The easiest example is the so-called *chiral supermultiplet*. Each chiral supermultiplet consists of one fermion with two spin degrees of freedom $n_F = 2$ and two real scalar fields with $n_B = 1$ each. The two real components are equivalent to one complex scalar field. Per naming convention, the supersymmetric scalar particle states receive an "s"-prefix to their name ("s-fermion"), to distinguish them from the original particle.

Next are the *gauge supermultiplets*. They contain massless spin-1 vector bosons with two helicity states and again a spin-1/2 fermion with $n_F = 2$ as superpartner. Here the superparticles are indicated by an "ino"-suffix to the name of the corresponding gauge boson ("gaugino").

Depending on the underlying supersymmetric model there are also other possible constellations. We will return to an explicit discussion of supermultiplets and their particle content in section 2.3 for the case of the Minimal Supersymmetric Standard Model.

2.2.3 Supersymmetric Lagrangians

In this section we derive the Lagrangian formalism of Supersymmetry. The goal is to obtain a general formulation of the supersymmetric field theory with its particle masses and interactions. Following the approach in [6], we introduce step-by-step the Lagrangians of the chiral and gauge supermultiplets and their respective field interactions.

The chiral Supermultiplet

We begin with the simplest possible SUSY model, containing a single left-handed two component Weyl fermion ψ and a complex scalar field ϕ as its superpartner. This is equivalent to a theory with only one chiral supermultiplet, also referred to as the massless non-interacting Wess-Zumino model [19]. The Lagrangian density of this model reads

$$\mathcal{L}_{chiral, free} = \mathcal{L}_{scalar} + \mathcal{L}_{fermion} = -\partial^\mu \phi^* \partial_\mu \phi - i\psi^\dagger \bar{\sigma}^\mu \partial_\mu \psi, \quad (2.14)$$

where we have two kinetic terms from the scalar and fermionic states.

We now introduce the minimal supersymmetric transformations of the scalar fields

$$\delta\phi = \epsilon\psi \quad \text{and} \quad \delta\phi^* = \epsilon^\dagger\psi^\dagger, \quad (2.15)$$

where ϵ is an infinitesimal fermion-like parameter. The scalar part of the Lagrangian transforms under these equations as

$$\delta\mathcal{L}_{scalar} = -\epsilon\partial^\mu\psi\partial_\mu\phi^* - \epsilon^\dagger\partial^\mu\psi^\dagger\partial_\mu\phi. \quad (2.16)$$

We recall that according to Hamilton's principle the Action

$$S = \int d^4x \mathcal{L}, \quad (2.17)$$

must stay invariant under any symmetry transformations. Therefore the Lagrangians before and after the transformation must be equivalent up to a total derivative $\mathcal{L}' = \mathcal{L} + \partial_\mu \Lambda^\mu$. This implies the following transformations of the fermion fields:

$$\delta\psi_\alpha = i(\sigma^\mu \epsilon^\dagger)_\alpha \partial_\mu \phi \quad \text{and} \quad \delta\psi^\dagger_{\dot{\alpha}} = -i(\epsilon\sigma^\mu)_{\dot{\alpha}} \partial_\mu \phi^* \quad (2.18)$$

Using Pauli matrix identities and commutation relations for partial derivatives one obtains

$$\delta\mathcal{L}_{fermion} = \epsilon\partial^\mu\psi\partial_\mu\phi^* + \epsilon^\dagger\partial^\mu\psi^\dagger\partial_\mu\phi - \partial_\mu(\epsilon\sigma^\nu\bar{\sigma}^\mu\psi\partial_\nu\phi^* + \epsilon\psi\partial^\mu\phi^* + \epsilon^\dagger\psi^\dagger\partial^\mu\phi). \quad (2.19)$$

Comparing 2.16 and 2.19 we see that the two contributions cancel up to a total derivative and thus leave the action invariant as required.

However, for the SUSY algebra to be valid off-shell, we need to generalize this formalism and introduce an auxiliary field F . F has no kinematic term and its Lagrangian density is given by

$$\mathcal{L}_{auxiliary} = F^*F. \quad (2.20)$$

The auxiliary fields transform as

$$\delta F = i\epsilon^\dagger\bar{\sigma}^\mu\partial_\mu\psi \quad \text{and} \quad \delta F^* = -i\partial_\mu\psi^\dagger\bar{\sigma}^\mu\epsilon, \quad (2.21)$$

and to keep the action invariant we are forced to modify equations 2.18 with additional F -terms

$$\delta\psi_\alpha = i(\sigma^\mu\epsilon^\dagger)_\alpha\partial_\mu\phi + \epsilon_\alpha F \quad \text{and} \quad \delta\psi^\dagger_{\dot{\alpha}} = -i(\epsilon\sigma^\mu)_{\dot{\alpha}}\partial_\mu\phi^* + \epsilon^\dagger_{\dot{\alpha}}F^*. \quad (2.22)$$

The need for the auxiliary field F becomes apparent, if one compares the scalar and fermionic degrees of freedom on- and off-shell. In the on-shell case, the complex scalar field ϕ has two real components corresponding to the two helicity states of the fermion field ψ . Going off-shell, however, ψ becomes a two-dimensional complex object with four real degrees of freedom. To balance out this inequality the complex field F with two additional degrees of freedom must be introduced.

The final Lagrangian of the free chiral supermultiplet can now be written as

$$\boxed{\mathcal{L}_{chiral,free} = -\partial^\mu\phi^{*i}\partial_\mu\phi_i - i\psi^{\dagger i}\bar{\sigma}^\mu\partial_\mu\psi_i + F^{*i}F_i}, \quad (2.23)$$

where i is the index over all flavour and gauge degrees of freedom.

Interactions. We now consider interactions between the scalar and fermion fields inside the supermultiplets. It can be shown [6] that the most general renormalizable form of the interaction Lagrangian is given by

$$\mathcal{L}_{chiral,int} = \left(-\frac{1}{2}W^{ij}\psi_i\psi_j + W^iF_i\right) + c.c. , \quad (2.24)$$

where W^{ij} and W^i are functions of the scalar fields participating in the interaction. The invariance of $\mathcal{L}_{chiral,int}$ under SUSY transformations implies the following form of the W^{ij} and W^i [6]

$$W^{ij} = \frac{\partial^2}{\partial\phi_i\partial\phi_j}W = \frac{1}{2}M^{ij} + \frac{1}{6}y^{ijk}\phi_k, \quad (2.25)$$

$$W^i = \frac{\partial W}{\partial\phi_i} = \frac{1}{2}M^{ij}\phi_j + \frac{1}{6}y^{ijk}\phi_j\phi_k, \quad (2.26)$$

where W is the *superpotential*

$$W = \frac{1}{2}M^{ij}\phi_i\phi_j + \frac{1}{6}y^{ijk}\phi_i\phi_j\phi_k. \quad (2.27)$$

Here M^{ij} is the symmetric mass matrix for the fermion fields and y^{ijk} the Yukawa coupling of two fermion fields with one scalar. We see that the superpotential contains only bilinear and trilinear scalar coupling terms and no fermionic contributions.

The auxiliary field terms of Lagrangians 2.23 and 2.24 are $F_i F^{i*} + W^i F_i + W_i^* F^{i*}$. They can be reformulated in terms of the superpotential by applying the Euler-Lagrange equations of motions leading to

$$F_i = -W_i^* \quad \text{and} \quad F^{i*} = -W^i. \quad (2.28)$$

With this we obtain an auxiliary-free representation of the total Lagrangian of the interacting chiral supermultiplet:

$$\mathcal{L}_{chiral} = -\partial^\mu \phi^{i*} \partial_\mu \phi_i - V(\phi, \phi^*) - i\psi^{i\dagger} \bar{\sigma}^\mu \partial_\mu \psi_i - \frac{1}{2} M^{ij} \psi_i \psi_j - \frac{1}{2} M_{ij}^* \psi^{i\dagger} \psi^{j\dagger} - \frac{1}{2} y^{ijk} \phi_i \psi_j \psi_k - \frac{1}{2} y_{ijk}^* \phi^{i*} \psi^{j\dagger} \psi^{k\dagger} \quad (2.29)$$

Here V is referred to as the *scalar potential*

$$V(\phi, \phi^*) = W^k W_k^* = F^{*k} F_k = M_{ik}^* M^{kj} \phi^{i*} \phi_j + \frac{1}{2} M^{in} y_{jkn}^* \phi_i \phi^{j*} \phi^{k*} + \frac{1}{2} M_{in}^* y^{jkn} \phi^{i*} \phi_j \phi_k + \frac{1}{4} y^{ijn} y_{kln}^* \phi_i \phi_j \phi^{k*} \phi^{l*}. \quad (2.30)$$

We note that the scalar potential contains cubic and quartic scalar coupling terms as well as a mass term with the same mass matrix as the fermionic part in equation 2.29. This leads to the expected mass-degenerate partner states inside each supermultiplet.

Equation 2.29 also demonstrates that the coupling strength of a scalar particle with two fermion fields is of the order y^{ijk} , whereas equation 2.30 implies $(y^{ijk})^2$ for a quartic scalar process. This is equivalent to the relation $\lambda_S = \lambda_f^2$ we postulated in section 2.2.1 for the solution of the hierarchy problem.

The Gauge Supermultiplet

The gauge supermultiplets consist of massless gauge bosons A_μ^a and their gaugino superpartners λ_a

$$\begin{pmatrix} A_\mu^a \\ \lambda_a \end{pmatrix}, \quad (2.31)$$

where a is the index over the group representations, e.g. $a = 1, \dots, 8$ for $SU(3)_C$. The corresponding supersymmetric transformations are given by

$$\delta_{gauge} A_\mu^a = \partial_\mu \Lambda^a + g f^{abc} A_\mu^b \Lambda^c \quad (2.32)$$

$$\delta_{gauge} \lambda^a = g f^{abc} \lambda^b \Lambda^c. \quad (2.33)$$

Here Λ denotes an infinitesimal gauge transformation parameter, g is the coupling strength of the interaction and f^{abc} the structure constant in the case of a non-abelian theory. The total Lagrangian density of the gauge supermultiplets must again leave the action invariant under equations 2.32 and 2.33. It is given by:

$$\mathcal{L}_{gauge} = -\frac{1}{4} F_{\mu\nu}^a F^{a\mu\nu} - i\lambda^{a\dagger} \bar{\sigma}^\mu D_\mu \lambda^a + \frac{1}{2} D^a D^a \quad (2.34)$$

The first term describes the kinetic energy with the gauge field tensor

$$F_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + g f^{abc} A_\mu^b A_\nu^c, \quad (2.35)$$

where the A_μ are the respective gauge field components of the interaction. The second term expresses the kinetic energy of the gaugino fields and includes a covariant derivative

$$D_\mu \lambda^a = \partial_\mu \lambda^a + g f^{abc} A_\mu^b \lambda^c, \quad (2.36)$$

which contains the interactions between the gauge and gaugino fields. With the third term again an auxiliary field D is introduced to account for the inequality of degrees of freedom within the supermultiplets on- and off-shell. In this case only one additional degree of freedom is necessary and thus D has one real component. As in the case of the chiral Lagrangian this field vanishes when going on-shell.

The Combined Supersymmetric Lagrangian

Now the results for the Lagrangian of the chiral and gauge supermultiplets can be combined. First, the derivatives of the scalar and fermion fields need to be replaced by the respective covariant derivative to preserve gauge invariance:

$$\partial_\mu \psi \rightarrow D_\mu \psi = \partial_\mu \psi + ig A_\mu^a T^a \psi \quad (2.37)$$

$$\partial_\mu \phi \rightarrow D_\mu \phi = \partial_\mu \phi + ig A_\mu^a T^a \phi \quad (2.38)$$

Here T^a stands for the generators of the gauge groups, and one can see that equations 2.37 and 2.38 yield the couplings between the gauge bosons and the scalar and fermion fields of the chiral supermultiplet.

There are also possible couplings between the gaugino fields λ^a and the D auxiliary fields. It can be shown [6] that possible renormalizable couplings of this sort contribute with terms:

$$-\sqrt{2}g(\phi^* T^a \psi) \lambda^a - \sqrt{2}g \lambda^{\dagger a} (\phi^\dagger T^a \phi) + g(\psi^* T^a \phi) D^a \quad (2.39)$$

The D -term in equation 2.34 and the last term in 2.39 combine to the equation of motion

$$D^a = -g(\phi^* T^a \phi). \quad (2.40)$$

Since 2.40 contains only scalar fields it is then usually written with the scalar potential

$$V(\phi, \phi^*) = W_i^* W^i + \frac{1}{2} g^2 (\phi^* T \phi)^2. \quad (2.41)$$

The results of this chapter can now be summarized in the total Lagrangian density for Supersymmetry:

$$\mathcal{L}_{SUSY} = \underbrace{-D^\mu \phi^* D_\mu \phi}_{\text{scalars}} \underbrace{-i\psi^\dagger \bar{\sigma}^\mu D_\mu \psi}_{\text{fermions}} \underbrace{-\frac{1}{2}(W^{ij} \psi_i \psi_j + W^{ij*} \psi_i^\dagger \psi_j^\dagger)}_{\text{fermion mass term and Yukawa coupling}} \quad (2.42)$$

$$\underbrace{-W^i W_i^* - \frac{1}{2} g^2 (\phi^* T \phi)^2}_{\text{scalar potential}} \underbrace{-\frac{1}{4} F_{\mu\nu}^a F^{a\mu\nu}}_{\text{gauge bosons}} \underbrace{-i\lambda^{\dagger a} \bar{\sigma}^\mu D_\mu \lambda^a}_{\text{gauginos}}$$

$$\underbrace{-\sqrt{2}g(\phi^* T^a \psi) \lambda^a - \sqrt{2}g \lambda^{\dagger a} (\psi^\dagger T^a \phi)}_{\text{additional couplings}} \underbrace{+\mathcal{L}_{soft}}_{\text{soft breaking term}}$$

We recapitulate: The first two terms are the kinetic terms of the scalar and fermionic fields in the chiral supermultiplet. They are followed by the fermion mass terms and the Yukawa coupling of scalar and fermion fields, written in terms of the superpotential 2.27. The mass terms of the scalar fields and their associated interactions are contained in the scalar potential. The next three terms account for the kinetic energy and interactions of the gauge bosons and their gaugino superpartners plus additional couplings as discussed above. For completeness we also include the SUSY breaking term $\mathcal{L}_{soft}$ which will be explained in section 2.4.

2.3 The Minimal Supersymmetric Standard Model

In the previous section of this chapter the general theoretical features of Supersymmetry have been discussed. We now want to specifically examine the Minimal Supersymmetric Standard Model (MSSM), which represents the simplest possible supersymmetric extension to the Standard Model.

The MSSM contains the minimal number of couplings and fields. The field content is described in terms of:

- Chiral supermultiplets with SM leptons and quarks and their associated scalar superpartners ("s-quarks" and "s-leptons").
- Gauge supermultiplets with SM gauge bosons and associated superpartners ("gauginos"), based on the $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ internal symmetry.

A summary of all MSSM multiplets can be found in Tables 2.2 and 2.3. For the chiral supermultiplets, each SM fermion has two helicity states, which transform differently under gauge symmetry. Therefore they must both have their own scalar superpartner. This is illustrated in Table 2.2, e.g. for the left- and right-handed electrons e_L and e_R and their corresponding scalar particles $\tilde{e}_L$ and $\tilde{e}_R$.⁵ The latter two scalar fields are of course completely independent and the index refers only to the handedness of the associated SM particles. For reasons of mathematical convenience, all fermions in the chiral supermultiplets are defined in terms of left-handed Weyl-spinors. Conjugations are therefore applied to the right-handed fields of Table 2.2.

We now take a look at the supersymmetric Higgs-sector. Higgs-fields are scalar and therefore also accommodated in the chiral supermultiplets along with their "Higgsino" superpartners (see Table 2.2). However, within the MSSM one Higgs-doublet is not sufficient. In particular, gauge anomalies from triangle diagrams, as we know them from the SM, do not cancel within the MSSM unless a second doublet is introduced. Two Higgs-doublets are also required to give mass to all matter fermions by means of electro-weak symmetry breaking. The doublets are of the form

$$\begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix} \quad \text{and} \quad \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}, \quad (2.43)$$

with weak Isospin $Y = \pm 1/2$ to induce the necessary Yukawa couplings to all up- and down-like quarks. As can be seen from 2.43 there are 4 complex or 8 real degrees of freedom in the Higgs doublets. As in the Standard Model three phases are absorbed by Goldstone bosons⁶ leaving us with 5 physical Higgs eigenstates:

- h , a light neutral scalar Higgs particle.
- H , a heavy neutral scalar Higgs Particle.

⁵The tilde symbol is used to denote supersymmetric partners of SM particles.

⁶Goldstone bosons are hypothetical massless particles that occur in the context of spontaneous symmetry breaking.

Name		Scalar ϕ (S=0)	Fermion ψ (S=1/2)	$SU(3)_C, SU(2)_L, U(1)_Y$
Squarks, Quarks (3 Generations)	Q_1	$(\tilde{u}_L, \tilde{d}_L)$	(u_L, d_L)	$(3, 2, \frac{1}{3})$
	$\bar{U}_1$	$\tilde{u}_R^*$	$u_R^\dagger$	$(\bar{3}, 1, -\frac{4}{3})$
	$\bar{D}_1$	$\tilde{d}_R^*$	$d_R^\dagger$	$(\bar{3}, 1, \frac{2}{3})$
Sleptons, Leptons (3 Generations)	L_1	$(\tilde{\nu}_e, \tilde{e}_L)$	(ν_e, e_L)	$(1, 2, -1)$
	$\bar{E}_1$	$\tilde{e}_R^*$	$e_R^\dagger$	$(1, 1, 2)$
Higgs, Higgsino	H_u	(H_u^+, H_u^0)	$(\tilde{H}_u^+, \tilde{H}_u^0)$	$(1, 2, 1)$
	H_d	(H_d^0, H_d^-)	$(\tilde{H}_d^0, \tilde{H}_d^-)$	$(1, 2, -1)$

Table 2.2: Content of the chiral supermultiplets in the Minimal Supersymmetric Standard Model. The symbols Q_i and L_i stand for the supermultiplets containing $SU(2)_L$ doublets, while $\bar{U}_i$, $\bar{D}_i$, and $\bar{E}_i$ contain the corresponding conjugate right-handed singlet states [6].

- A , a neutral CP-odd pseudoscalar Higgs particle.
- $H^\pm$, two charged scalar Higgs particles.

The gauge supermultiplets are shown in Table 2.3. They contain the mediators of the SM interactions and their spin-1/2 superpartners. These are 8 gluons and gluinos in the case of $SU(3)_C$ for QCD and $W^\pm, W^0, B^0$ with superpartners for $SU(2)_L \otimes U(1)_Y$. After electroweak symmetry breaking the latter four mix to the mass eigenstates Z^0 and γ and the respective gaugino combinations "Zino" $\tilde{Z}^0$ and "Photino" $\tilde{\gamma}$.

Electroweak gauginos also form new mass eigenstates with the Higgsinos of same charge. In the neutral sector $\tilde{W}^0, \tilde{B}^0, \tilde{H}_u^0, \tilde{H}_d^0$ mix to four "Neutralinos" $\tilde{\chi}_{1,2,3,4}^0$, whereas the charged $\tilde{W}^\pm, \tilde{H}_u^\pm$ and $\tilde{H}_d^\pm$ form the "Charginos" $\tilde{\chi}_{1,2}^\pm$ and $\tilde{\chi}_{1,2}^\mp$. The mixing is possible because the participating states have identical quantum numbers as can be inferred from Table 2.3. A typical example of the spectrum of MSSM mass eigenstates can be found in Fig. 2.5.

It should be noted here that if Supergravity (see section 2.4.2) is to be included into the theory, we must also introduce an additional type of supermultiplet containing the spin-2 graviton and its spin-3/2 superpartner ("gravitino").

An important quantum number in the MSSM is *R-Parity*. Whereas in the Standard Model baryon- and lepton-numbers are automatically conserved, the MSSM theoretically allows interaction terms that violate this symmetry. To avoid this undesired effect, the conservation of R-Parity

$$R = (-1)^{3(B-L)+2S} \quad (2.44)$$

is introduced. B and L are lepton and baryon numbers and S the spin of the participating particles in the process. All SM fields carry R-Parity $R = +1$, all superfields $R = -1$. In addition R-Parity is a multiplicative quantum number. It follows that in this case supersymmetric particles can only be produced in pairs by SM particles due to

$$R_{total} = R_1^{SM} \cdot R_2^{SM} = 1^2 = R_1^{SUSY} R_2^{SUSY} = (-1)^2 = 1. \quad (2.45)$$

Another consequence of R-Parity conservation is the stability of the lightest supersymmetric particle. Due to $R = -1$ it cannot decay into SM matter and due to its mass not into any other supersymmetric particle. It is therefore considered a candidate for dark matter.

We are now ready to look at the interactions of the MSSM. The generic superpotential of equation 2.27 is to be replaced by [6]

$$W_{MSSM} = y_u \bar{U} Q H_U - y_d \bar{D} Q H_d - y_e \bar{E} L H_d + \mu H_u H_d, \quad (2.46)$$

Name	Boson A^μ (S=1)	Fermion λ (S=1/2)	$SU(3)_C, SU(2)_L, U(1)_Y$
Gluon, Gluino	g	$\tilde{g}$	$(8, 1, 0)$
W-Bosons, Winos	$W^\pm, W^0$	$\tilde{W}^\pm, \tilde{W}^0$	$(1, 3, 0)$
B-Boson, Binos	B^0	$\tilde{B}^0$	$(1, 1, 0)$

Table 2.3: Content of the gauge supermultiplets in the Minimal Supersymmetric Standard Model [6].

where $Q, L, \bar{U}, \bar{D}, \bar{E}, H_u$, and H_d stand for the superfields of the respective multiplets shown in table 2.2. The indices for each generation of quarks and leptons are suppressed in this vector notation. The 3×3 matrices y_u, y_d and y_e are the corresponding Yukawa couplings and determine the CKM mixing angles and masses after electroweak symmetry breaking. The last term is the supersymmetric Higgs term with mass parameter μ . In the following we examine the various interactions resulting from 2.46.

Yukawa Interactions. Compared to other supersymmetric interactions Yukawa couplings are expected to be relatively small. Since the coupling strengths are directly related to the masses of the participating fermions, one can make the approximation as suggested in [6] that only the heavy third generation of quark and lepton fields contribute to the interactions:

$$y_u \approx \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_t \end{pmatrix}, \quad y_d \approx \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_b \end{pmatrix}, \quad y_e \approx \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_\tau \end{pmatrix} \quad (2.47)$$

With this and the weak isospin doublets and singlets according to Table 2.2, one can rewrite equation 2.46 approximatively as

$$W_{MSSM} \approx y_t(\bar{t}tH_u^0 - \bar{t}bH_u^+) - y_b(\bar{b}tH_d^- - \bar{b}bH_d^0) - y_\tau(\bar{\tau}\nu_\tau H_d^- - \bar{\tau}\tau H_d^0) + \mu(H_u^+ H_d^- - H_u^0 H_d^0). \quad (2.48)$$

From the first term of equation 2.48 for example, we can infer couplings of a left-handed top quark to a neutral up-type Higgs field and a right-handed anti-top. In supersymmetric field theories the Yukawa couplings y^{ijk} must be totally symmetric under index interchange. Therefore we must also have similar processes with supersymmetric particles such as Higgsino-slepton-lepton and Higgsino-squark-quark. For the latter case possible combinations are illustrated in Fig. 2.3a. They all have the same couplings strength y_t .

In addition there are quartic scalar couplings due to the form of the scalar potential $W^i W_i^*$ with an associated coupling strength of y_t^2 (see equation 2.30 in the previous section). According to the definition of W^i in equation 2.26 we determine the total derivative of W_{MSSM} :

$$W_{MSSM}^i \approx y_t(\bar{t}t - \bar{t}H_u^0 + tH_u^0 - \bar{t}b - \bar{t}H_u^+ - bH_u^+) + \dots \quad (2.49)$$

We consider here only the first term of equation 2.48, which is sufficient for our purposes. The allowed quartic couplings of the scalar potential $W^i W_i^*$ are then

$$y_t^2(\bar{t}t\bar{t}t - \bar{t}H_u^0\bar{t}H_u^0 + \bar{t}H_u^+\bar{t}H_u^+), \quad (2.50)$$

plus the respective couplings of the down-type, leptonic and Higgs-sectors. A sample of the possible quartic interactions is shown in Fig. 2.3b. The following constellations are possible: (Squark)⁴, (Slepton)⁴, (Squark)²(Slepton)², and (Squark)²(Higgs)². The general form of the scalar potential 2.30 also implies additional cubic scalar couplings.

Gaugino Interactions. The coupling of SM gauge bosons to supersymmetric particles is governed by the kinetic terms of the SUSY Lagrangian. We can again obtain the MSSM gauge interactions by

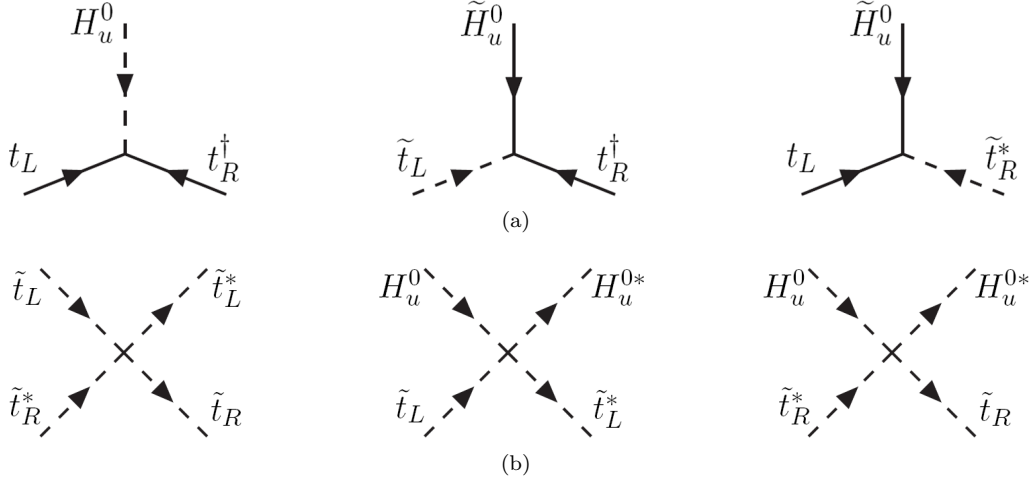


Figure 2.3: (a) A Standard Model Higgs-quark-quark coupling and corresponding supersymmetric interactions with coupling strength y_t . They can be obtained through interchange of any two participating SM particles into their superpartners. (b) Sample of quartic scalar interactions in the MSSM with coupling strength y_t^2 [6].

interchanging any two of the three participating particles in a SM gauge interaction by their respective superpartners.

This rule of thumb also gives us gaugino-sfermion-fermion interactions, which are possible through the additional renormalizable couplings, corresponding to the first two terms in equation 2.39. Some representative processes are shown in Fig. 2.4.

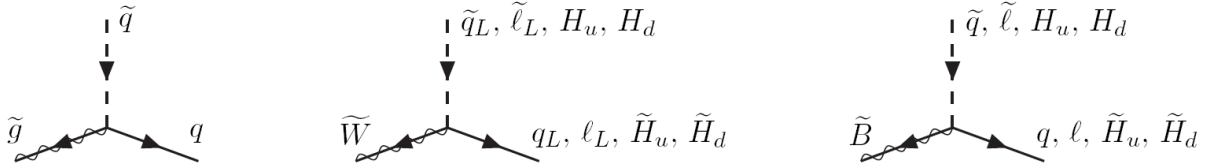


Figure 2.4: Sample of gaugino interactions in the MSSM. $\tilde{W}$ and $\tilde{B}$ are interaction and not mass eigenstates [6].

2.4 SUSY-breaking

If Supersymmetry exists it must be spontaneously broken, since no mass-degenerate superpartners of the SM particles have been found. The breaking mechanism should preserve the renormalizability of the theory as well as the cancelation of quadratic divergences to maintain the hierarchy of the energy scales as discussed in the introduction. A symmetry breaking with these basic SUSY properties can be introduced into the theory by adding a so-called "soft-breaking" term in the Lagrangian density. The general form of this term is [6]

$$\mathcal{L}_{soft} = -\left(\frac{1}{2}M_a\lambda^a\lambda^a + \frac{1}{6}a^{ijk}\phi_i\phi_j\phi_k + \frac{1}{2}b^{ij}\phi_i\phi_j\right) + c.c. - (m^2)_j^i\phi_j^*\phi_i, \quad (2.51)$$

with squared scalar mass terms $(m^2)_j^i$ and b^{ij} , cubic scalar couplings a^{ijk} , and gaugino mass terms M_a

for each gauge group. As we can see, 2.51 contains only scalar and gaugino terms and thus breaks the symmetry by giving masses to the associated particles. A phenomenological explanation of this breaking mechanism will follow in the next section. In the case of the MSSM the soft breaking term specializes to [6]

$$\begin{aligned} \mathcal{L}_{soft}^{MSSM} = & -\frac{1}{2}(M_3\tilde{g}\tilde{g} + M_2\tilde{W}\tilde{W} + M_1\tilde{B}\tilde{B} + c.c.) \\ & -(\bar{U}a_UQH_u - \bar{D}a_DQH_d - \bar{E}a_ELH_d + c.c.) \\ & -Q^\dagger m_Q^2 Q - L^\dagger m_L^2 L - \bar{U}m_{\bar{U}}^2 \bar{U}^\dagger - \bar{D}m_{\bar{D}}^2 \bar{D}^\dagger - \bar{E}m_{\bar{E}}^2 \bar{E}^\dagger \\ & -m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - (bH_u H_d + c.c.). \end{aligned} \quad (2.52)$$

The first line represents the mass terms of winos, gluinos and binos, and the third line those of the squarks and sleptons with hermitian 3×3 mass matrices. Here the tildes on the scalar superfields $Q, \bar{U}, \bar{D}, L, \bar{E}$ are again suppressed for readability. The second line contains the cubic scalar couplings of equation 2.51 with the matrices a_U, a_D, a_E , where again all three generations contribute. Finally, in the last line we have soft breaking contributions from the squared Higgs-mass terms $m_{H_u}^2$ and $m_{H_d}^2$ plus one b^{ij} -type term.

Equation 2.52 demonstrates the complexity of the spontaneously broken MSSM. In total 105 new parameters are introduced: 21 masses, 36 mixing angles, 40 CP-violating phases in the squark and slepton sector and 5 real and 3 CP-violating parameters in the Higgs-sector. However, not all of these parameters are independent. In particular flavour and CP-conserving relations reduce the number of degrees of freedom significantly.

2.4.1 SUSY-breaking Models

With equation 2.51 we introduced a parameterized ad-hoc Ansatz for soft Supersymmetry breaking. In this section the associated breaking mechanisms are discussed.

The most common framework for SUSY breaking models is based on a so-called "hidden sector", in which the symmetry is spontaneously broken [21] [22]. The introduction of this hidden sector is necessary, since none of the MSSM fields, which are referred to as the "visible sector", can have a non-zero vacuum expectation value in order to not violate gauge invariance⁷. Therefore the underlying idea of the hidden sector is, that the spontaneous SUSY breaking is communicated down to the observable MSSM sector via hypothetical flavour-blind messenger fields. This mediation mechanism, however, is highly dependent on the model framework assumed.

The most common scenarios are:

- Gauge Mediated Supersymmetry Breaking (GMSB)
- Anomaly Mediated Supersymmetry Breaking (AMSB)
- Gravity Mediated Supersymmetry Breaking (mSUGRA)

In GMSB the SUSY breaking is invoked by the minimal gauge group interactions $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$, where the associated gauge bosons couple to the messenger fields to make the breaking observable. AMSB is a special case of gravity-mediated SUSY breaking, where there are no direct tree-level couplings between the sectors and the masses of the sparticles are generated with higher order loop corrections. We will not discuss these scenarios here in more detail but instead concentrate on standard supergravity scenarios, in particular mSUGRA, which is the focus of this thesis.

⁷Spontaneous breaking of global Supersymmetry would require non-zero vacuum expectation values of either the F or D auxiliary fields (see section 2.2.3).

2.4.2 Minimal Supergravity

The principles of Supergravity were already briefly mentioned in the introduction of section 2.2. The underlying idea is that supersymmetry, when made a local symmetry, gives us both, an effective field theory for energies below the Planck scale and an elegant mechanism for SUSY breaking. In this way Supergravity, as any local gauge theory, necessitate the introduction of new gauge fields, the spin-2 graviton and its spin-3/2 gravitino superpartner. In an unbroken theory the masses of both particles are zero. The couplings, however, still scale with the dimensionful Newton's constant and are thus proportional to $\sim 1/M_{Planck}$. Therefore the associated terms in the Lagrangian are non-renormalizable and so is the concept of Supergravity, which hence does not represent a full theory of quantum gravity.

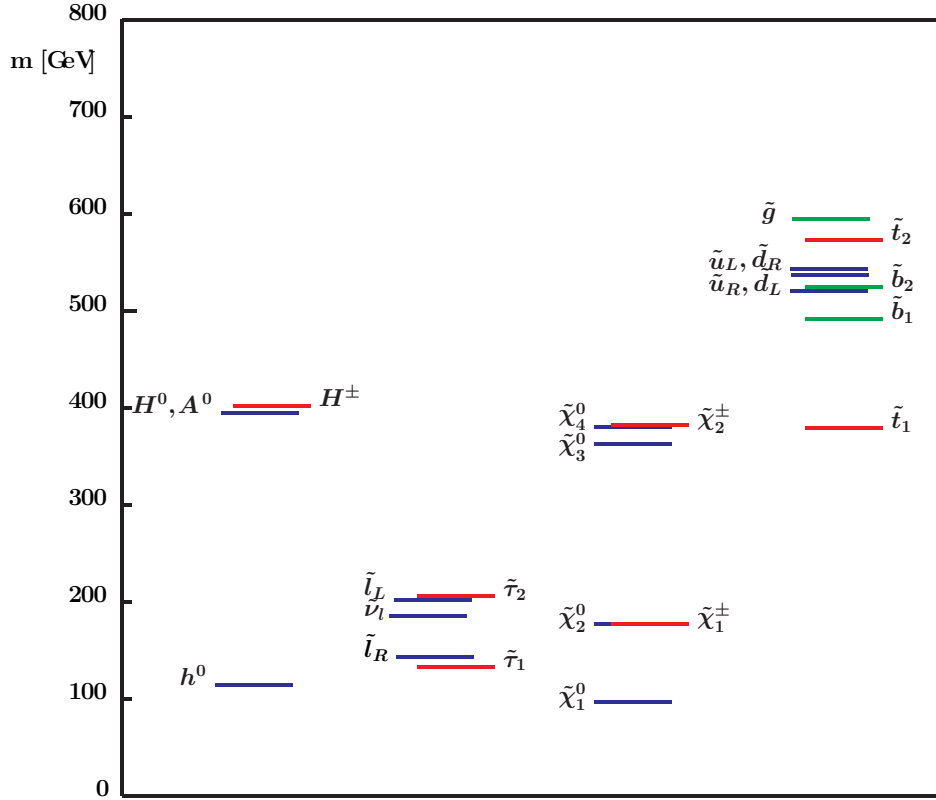


Figure 2.5: *Mass spectrum of a typical mSUGRA scenario with $m_0 = 100$ GeV, $m_{1/2} = 250$ GeV, $A_0 = -100$ GeV, $\tan \beta = 10$, $\text{sign } \mu = +$ generated with ISAJET 7.58 [23].*

The breaking mechanism of Supergravity, also referred to as super-Higgs-mechanism, takes place in two steps: First the spontaneous breaking of *global* Supersymmetry yields a massless Weyl fermion called Goldstino. This Goldstino has two degrees of freedom which are subsequently absorbed through the spontaneous breaking of *local* Supersymmetry to give mass to the gravitino. The SM graviton, however, is still massless and thus the degeneracy in the gravitational supermultiplet is broken.

The breaking happens in the hidden sector with a vacuum expectation value $\langle F \rangle$ and a non-renormalizable coupling to the visible sector of strength $\sim 1/M_{Planck}$ as mentioned above. In the case of vanishing gravitational interactions $M_{Planck} \rightarrow \infty$ and vacuum expectation value $\langle F \rangle \rightarrow 0$, the soft breaking mass terms m_{soft} must also vanish. This leads to the following approximative formula

$$m_{soft} \sim \frac{\langle F \rangle}{M_{Planck}}, \quad (2.53)$$

which implies for $m_{soft} \lesssim 1 \text{ TeV}$ a scale of $\sqrt{\langle F \rangle} \approx 10^{11} \text{ GeV}$ for the hidden sector. The F-Field here refers to the auxiliary field of section 2.2.3, which is related to the superpotential as in equation 2.26.

An attractive, but quite constrained scenario, is that of minimal Supergravity (mSUGRA). It implies universal soft breaking terms and thereby reduces greatly the number MSSM parameters at the unification scale to:

- m_0 , the universal scalar mass,
- $m_{1/2}$, the universal gaugino mass,
- A_0 , the universal trilinear Higgs-sfermion-sfermion couplings,
- $\tan\beta$, the ratio of the vacuum expectation values of the two Higgs-doublets,
- $\text{sign } \mu$, the sign of the Higgsino mass parameter.

All parameters of the MSSM at the electroweak scale can be obtained from these 5 GUT scale parameters by application of the renormalization group equations. The mass spectrum of a given mSUGRA model depends of course highly on the chosen parameters. Fig. 2.5 shows a typical scenario. In most cases the lightest supersymmetric particle is the lightest neutralino $\tilde{\chi}_1^0$.

2.5 mSUGRA Parameter Space

Minimal Supergravity is one of the most studied SUSY breaking scenarios in high energy physics. Experimental efforts as well as theoretical considerations have significantly contributed to the understanding of allowed and forbidden regions of mSUGRA parameter space. In this final section of the chapter the current limits are reviewed and a prospect is given for the reach at the Large Hadron Collider.

Fig. 2.6 shows the m_0 - $m_{1/2}$ plane of mSUGRA parameter space with $A_0 = 0$ in four possible constellations of the remaining parameters $\tan\beta$ and $\text{sign } \mu$. Large parts of this parameter space are ruled out for theoretical reasons, such as the dark shaded areas at high $m_{1/2}$, corresponding to models with a charged LSP. Also the high m_0 regions are theoretically restricted, due to incompatibility with electro-weak symmetry breaking (barely visible on the scale of Fig. 2.6). Besides this, there are numerous experimental constraints, which are now discussed in more detail:

Cosmological constraints. It has previously been mentioned that in R-Parity conserving SUSY models, the lightest supersymmetric particle (LSP) exhibits all features of a weakly interacting massive particle (WIMP), which in turn constitutes a candidate for cold dark matter. For mSUGRA scenarios this LSP with WIMP-features is the lightest neutralino $\tilde{\chi}_1^0$.

According to cosmological models, WIMPs were created in the early universe, when the energy density was high enough for the production processes. Thereafter they remained in thermal equilibrium until temperatures dropped below $m_{\tilde{\chi}_1^0}$ and production was suppressed. At the same time increasing distances between the particles reduced annihilation rates until the today's "freeze-out" relic density $\Omega_{\tilde{\chi}_1^0}$ at a temperature of $\sim 2.7 \text{ K}$ was reached.

Precise measurements of this relic density have been performed by the WMAP satellite [25]. The results can be translated into constraints of mSUGRA parameter space by the following mechanism:

The relic density is proportional to the inverse expectation value of the thermally averaged inclusive annihilation and co-annihilation cross section of the LSP pair times its relative velocity $\Omega_{\tilde{\chi}_1^0} \propto 1/\langle \sigma v \rangle$ [26]. σ depends highly on the particular supersymmetric model and its associated masses and couplings. To find the allowed regions of parameter space for a model with universal parameters at the GUT scale like mSUGRA, one first needs to evaluate the renormalization group equations to obtain the MSSM

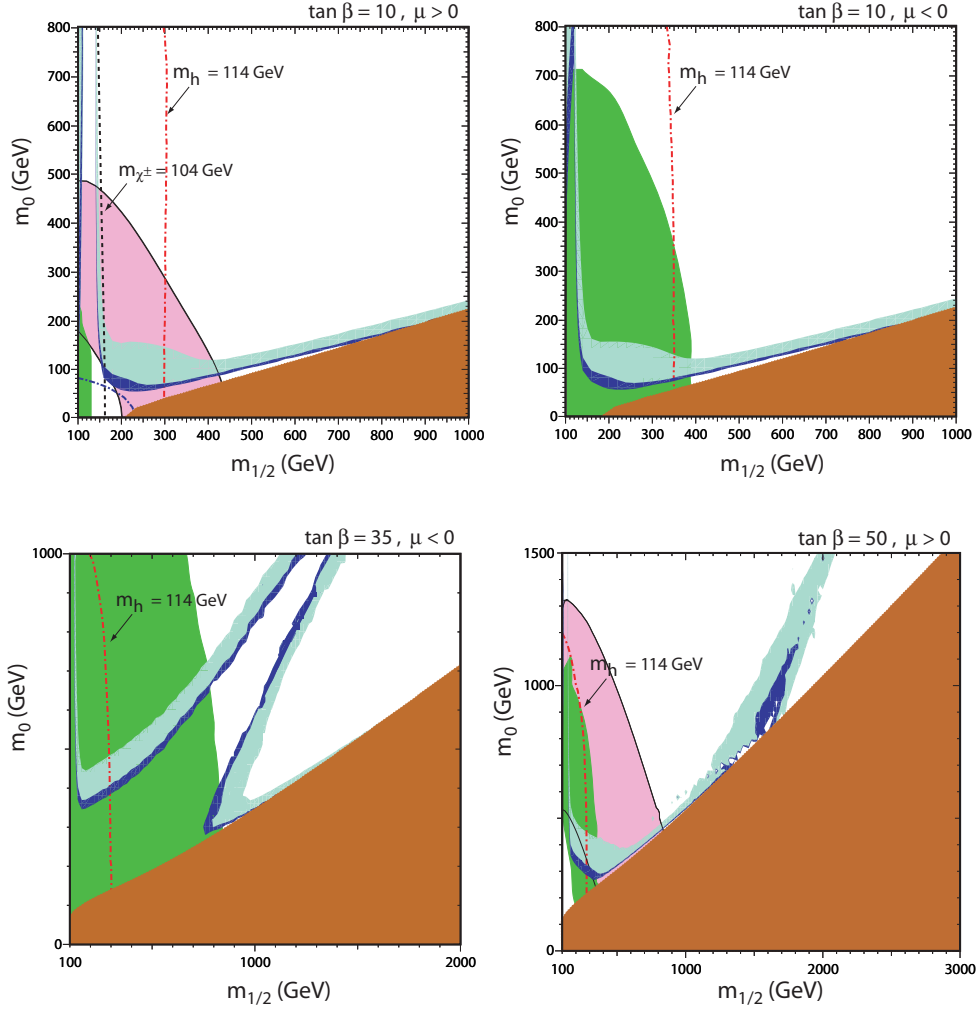


Figure 2.6: *Parameter space of minimal Supergravity in the m_0 - $m_{1/2}$ planes with trilinear coupling constant $A_0 = 0$ for four constellations of the remaining parameters $\tan\beta$ and sign μ as indicated. The large brown-shaded zones imply a charged LSP and are therefore excluded. The green areas are disallowed by measurements of $b \rightarrow s\gamma$. Regions favoured by the determination of $(g-2)$ of the muon at the 2σ level are denoted in pink. Cosmologically allowed regions according to WMAP measurements of the relic density (equation 2.54) are marked in dark blue and supersede the previous constraints in grey. The limits on chargino and Higgs masses corresponds to the areas left of the indicated lines [24].*

parameters in the weak regime. Then a SUSY-spectrum generator can be used to determine higher-order contributions to masses and couplings. These are then fed into calculations of the annihilation inclusive cross section σ to yield the corresponding neutralino density.

The constraints of WMAP on the neutralino relic density are [25]

$$0.094 \leq \Omega_{\tilde{\chi}_1^0} h^2 \leq 0.129, \quad (2.54)$$

which corresponds to the blue-shaded areas Fig. 2.6.

Constraints from $b \rightarrow s\gamma$. Another restriction on the parameter space results from measurements of the flavour-changing process $b \rightarrow s\gamma$. In the SM this decay involves loops containing W-bosons and

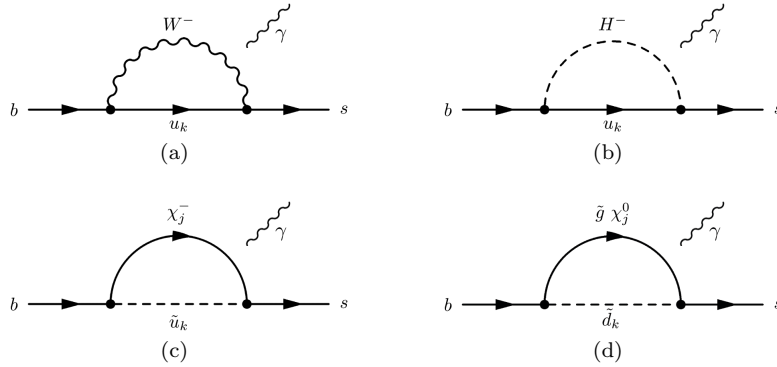


Figure 2.7: Possible $b \rightarrow s\gamma$ processes in (a) the Standard Model and (a)-(d) supersymmetric models. The photon line may be attached in all possible ways. [17]

up-type quarks as shown in Fig. 2.7a. In the MSSM additional diagrams with SUSY contributions are possible (see Fig. 2.7b-d).

Measurements of the corresponding inclusive branching ratio, e.g. $BR(b \rightarrow X_s\gamma) = (3.27 \pm 0.18) \cdot 10^{-4}$ by the BABAR Collaboration [27], put constraints on the kinematically allowed regions of parameter space, when compared with precise SM calculations. The green shaded areas in Fig. 2.6 show these regions, where the branching ratio is allowed to vary within a 2σ range.

The muon anomalous magnetic moment. The magnetic moment of the muon

$$\mu = \frac{eg}{2mc}\mathbf{S}, \quad (2.55)$$

with spin operator $\mathbf{S}$, contains a gyromagnetic factor g , which is expected to have a value of two, plus small higher-order corrections. Deviations from this value, expressed in terms of $a = (g-2)/2$, have been determined to high precision by the E821-experiment at Brookhaven [28]:

$$a_\mu = 11659208(6) \cdot 10^{-10} \quad (2.56)$$

Comparing this value to SM expectancies, we find a deviation of up to 2.7σ . This discrepancy can be interpreted as a SUSY contribution, mainly through additional neutralino-smuon and chargino-sneutrino loops. The implications on mSUGRA parameter space are again shown in Fig. 2.6, where the favoured regions at 2σ level are denoted in pink. It can be seen clearly that a positive sign of the Higgsino mass parameter μ is the preferred choice of this measurement.

LEP and Tevatron constraints. Important upper limits on SUSY masses come from the direct searches in high energy physics experiments. The most obvious constraint is the non-observation of the lightest chargino in the process $e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^-$ at LEP II [29], which gives an approximate bound on the chargino mass of $m_{\tilde{\chi}_1^\pm} \gtrsim 104 \text{ GeV}$. The region left of the indicated dotted line in Fig. 2.6 denotes the corresponding excluded region in parameter space. This region is again derived from the experimental results via the renormalization group equations.

Other constraints come from searches for the light MSSM Higgs boson h . The lower bound for the SM Higgs has been determined by LEP II to $M_{H^0} \gtrsim 113.5 \text{ GeV}$ at the 95% confidence level in the process $e^+e^- \rightarrow ZH^0$. The translation of this constraint into a limit in the supersymmetric Higgs sector is valid if the coupling of the lightest SUSY Higgs h to the Z boson is SM-like. The area left of the dot-dashed line in Fig. 2.6 denotes the corresponding limits on h in mSUGRA parameter space.

There are also new mSUGRA constraints from Tevatron data. In a recent publication of the DØ collaboration [30], the absolute lower limits for squark and gluino masses are quoted as 379 GeV and 308 GeV respectively. The corresponding limits at the GUT scale in mSUGRA parameter space are

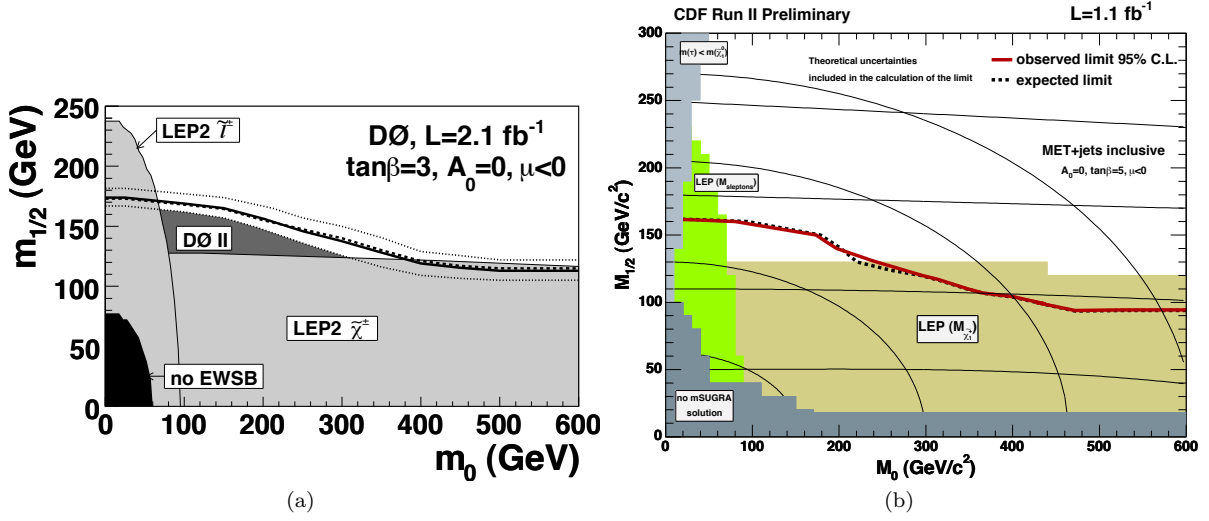


Figure 2.8: Upper bounds on $mSUGRA$ parameter space in the m_0 - $m_{1/2}$ plane from the (a) DØ and (b) CDF experiments in events with jets and missing transverse energy with a 95% confidence level. The parameter configurations are only slightly different as indicated in the plots. [30] [31]

visualized in Fig. 2.8a for $A_0 = 0$, $\tan\beta = 3$ and negative sign of μ . One can infer that lower bounds of LEP II on the chargino masses are pushed up to 300 GeV in some regions. The LEP Higgs search limits, however, are still more restrictive. Similar results have been published by the CDF experiment [31]. The respective bounds are shown in Fig. 2.8b for an inclusive jet plus missing transverse energy analysis. The parameter set-up is with $\tan\beta = 5$ only slightly different to the corresponding DØ graph.

Experimental prospects. The Large Hadron Collider (LHC) with a center of mass energy of 14 TeV in p-p collisions is expected to bring a major breakthrough in the further exploration of $mSUGRA$ -scenarios. We finish this chapter with a short outlook on the projected reach at the upcoming experiments, illustrated in Figures 2.9a and 2.9b for various inclusive analyses in events with missing transverse energy, jets and leptons in the ATLAS detector (see Chapter 3).

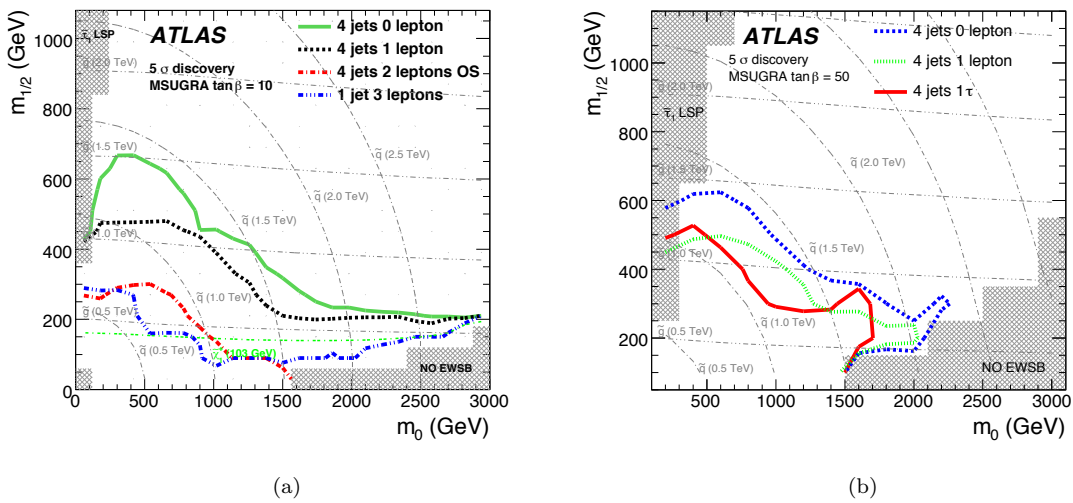


Figure 2.9: Expected 5σ reach contours for 1 fb^{-1} of ATLAS data in analyses with missing transverse energy and various jet and lepton requirements as indicated. The parameter set-up is (a) $\tan\beta = 10$ and (b) $\tan\beta = 50$ with all remaining parameters identical. [32]

Chapter 3

The ATLAS Experiment at the Large Hadron Collider

3.1 The Large Hadron Collider

The Large Hadron Collider (LHC) [33] is currently being completed at the European laboratory for particle physics (CERN). Once fully operational, the LHC will collide counter-propagating proton beams at a center of mass energy of 14 TeV. The main acceleration facility is located 50-175 m underground in a circular tunnel of 27 km circumference. Bunches of protons from the Super Proton Synchrotron (SPS) are injected into this ring at 450 GeV, where they are further boosted to the nominal energy of 7 TeV by eight radio-frequency cavities per beam. The particles are maintained on their circular path with 1232 superconducting NbTi dipole magnets, inducing a magnetic field of $B = 8.33$ T. They operate at 1.9 K and are cooled with superfluid helium. In addition approximately 7000 quadrupole and correction magnets are used to focus the beams in the vertical plane.

The LHC hosts four large-scale experiments, which are located at interaction points along the ring:

- **ATLAS** (**A** Toroidal LHC Apparatu**S**) and **CMS** (**C**ompact Muon Solenoid), two general-purpose experiments for precision measurements and discovery physics.
- **LHC-B**, a specialized B-physics experiment.
- **ALICE** (**A** Large Ion Collider Experiment), a heavy ion physics experiment.

The instantaneous luminosity at the interaction points depends purely on the beam parameters and can be written as [33]

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

where N_b is the number of protons per bunch, n_b the number of bunches per beam, f_r the revolution frequency, γ the relativistic Lorentz factor, ϵ_n the transverse beam emittance¹, β^* the amplitude of the betatron function at the collision point², and F a geometry factor accounting for the beam crossing angle. At the LHC, the nominal values of these parameters are $1.15 \cdot 10^{11}$ protons per bunch, a bunch crossing rate of 40 MHz, a relativistic γ of 7461, a normalized transverse beam emittance of $3.75 \mu\text{m rad}$, a

¹The normalized transverse beam emittance is defined as $\epsilon_n = \sigma_x \sigma_y \gamma / \beta$, with the relativistic γ and β factors and the gaussian transverse bunch widths σ_x and σ_y .

²Due to restoring forces of the focussing magnets the proton bunches perform a so-called betatron oscillation with amplitude β^* around their nominal path.

betatron amplitude of $\beta^* = 0.55$ m and an angular reduction factor of $F = 0.836$, resulting in a peak luminosity of $\sim 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ [33].

This value, however, will only be reached in advanced stages of operation. For the immediate future a 10 TeV run is foreseen until the end of 2008. Thereafter the superconducting magnets will be commissioned and trained to full current to allow for a low luminosity running phase at 14 TeV with up to $10^{33} \text{ cm}^{-2}\text{s}^{-1}$. The full design luminosity will be reached in later stages of the experiment providing an approximate annual data volume of 100 fb^{-1} and thus laying the basis for detailed studies of rare physics processes at unprecedented energies.

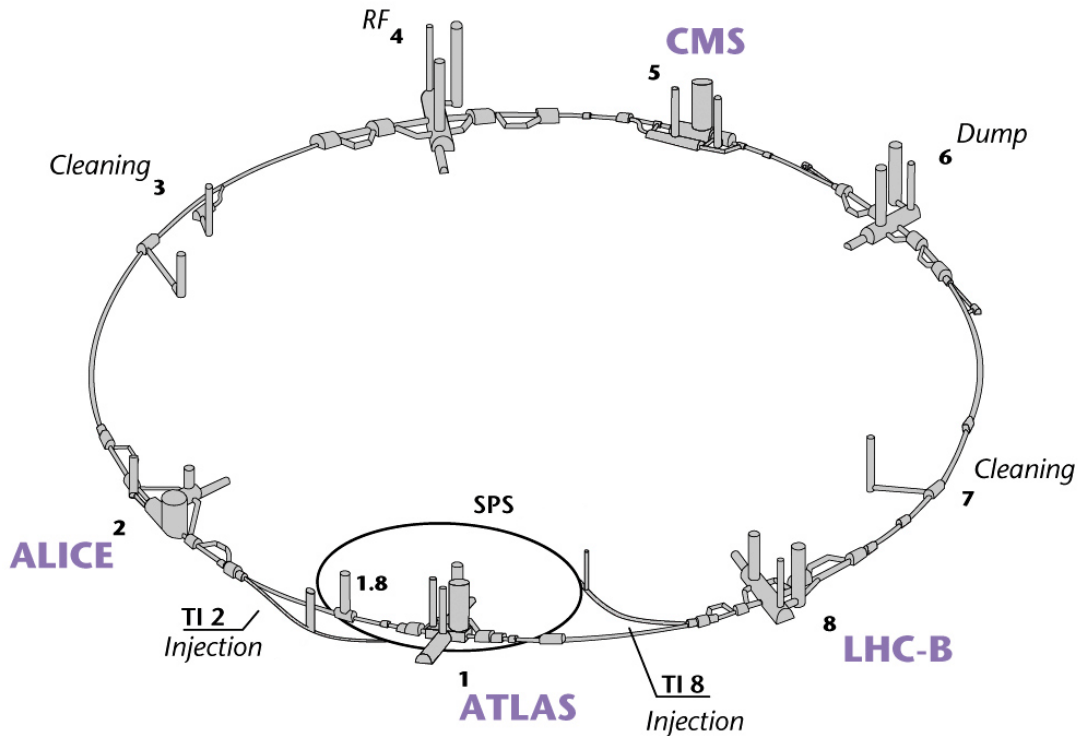


Figure 3.1: Schematic view of the main LHC ring, including the Super Proton Synchrotron (SPS) and the location of the four experiments ATLAS, CMS, ALICE, and LHC-B.

3.2 The ATLAS Detector

The ATLAS (A Toroidal LHC ApparatuS) detector [34] is a general-purpose experiment designed to exploit the full discovery potential of the LHC, while at the same time enabling high precision measurements of known physical phenomena. The technical requirements for a successful realization of these goals are enormous.

The high interaction rates and large cross sections at the LHC require extremely radiation resistant detector components and fast read-out mechanisms. A fine granularity throughout all devices is necessary to distinguish the large number of particles per event as well as the pile-up of several independent hard-scattering processes within the same bunch crossing. Furthermore a coverage in regions of high pseudorapidity is desirable to identify interesting physics processes close to beam direction and to measure

the complete transverse energy balance of each event. Excellent position and momentum resolution of charged particles in the inner detector is needed for high reconstruction efficiencies. The calorimeter system must deliver precise measurements of electrons, photons, jets and missing transverse energy. Eventually a robust identification of muons is a vital ingredient for most discovery searches.

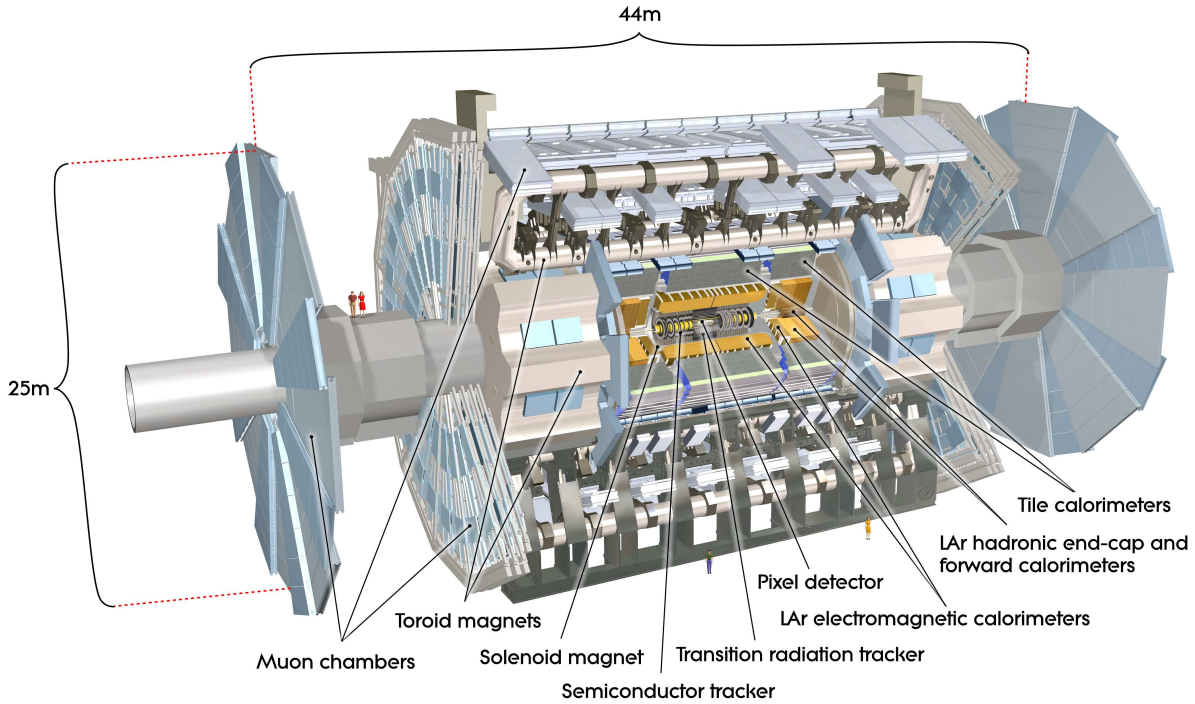


Figure 3.2: Schematic view of the ATLAS detector [34].

The layout of the ATLAS detector is illustrated in Fig. 3.2. The dimensions are 44 m in length, 25 m in height and the overall weight is approximately 7000 tons. As in most high energy physics experiments, the various detector components are aligned in layers around the interaction point. The innermost part consists of the pixel detector, the semiconductor tracker (SCT) and the transition radiation tracker (TRT), which are enclosed in a solenoid magnetic field. They are followed by the electromagnetic and hadronic calorimeter systems. The outer layer consists of muon spectrometers, immersed into the field of large superconducting air-toroid magnets. Each of the ATLAS detector components will be described in detail in the following sections.

3.3 Inner Detector

The main task of the inner detector (ID) is to provide pattern recognition, precise momentum and position measurements of charged particle tracks, as well as primary and secondary vertex reconstruction within a coverage region of $|\eta| < 2.5$. As mentioned above, the main three components are the silicon pixel detectors, the SCT, and the TRT, which are enclosed into a solenoid magnetic field of 2 T. A schematic layout is shown in Fig. 3.3. The complete ID is contained in a cylindrical volume of 7 m length and 1.15 m radius. The overall tracking resolution is $\sigma_{p_T}/p_T = 0.05 \% p_T \oplus 1\%$, where the latter term accounts for systematic effects.

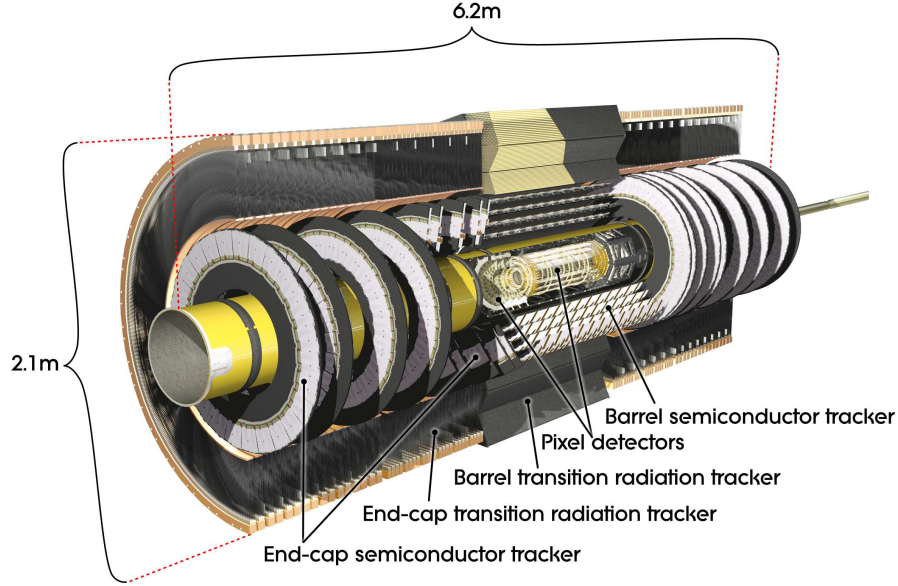


Figure 3.3: *Schematic view of the Inner Detector [34].*

3.3.1 The Pixel Detector

The pixel detector [34] [35] [36] is the first element of the ID and lays the basis for a precise reconstruction of tracks and in particular the identification of short-lived particles like τ -leptons and b-hadrons. It is located in immediate proximity of the beam pipe and consists of 1744 modules providing a total of 80.4 million rectangular-shaped silicon pixels with a minimum size of $50 \times 500 \mu\text{m}^2$.

The functioning principle of the pixel detectors as well as the SCT is based on reversely-biased semiconductors. When a particle traverses the depletion zone ionization processes create so-called electron-hole pairs which drift to the electrodes and produce a signal proportional to the energy of the particle.

In case of the pixel detectors, the signal from the active medium is read out by 16 bump-bonded front-end electronic chips per module, each of which provides 2880 channels. The modules are aligned in three barrel layers at radii of 5.05 cm, 8.85 cm, and 12.25 cm and three endcap disks on each side at $z = 49.5$ cm, 58.0 cm, and 65.0 cm from the nominal interaction point. This setup translates into an $|\eta|$ -coverage of 2.5 with at least three space-points for each track as can be inferred from Fig. 3.4. While all pixel sensors are designed to tolerate large radiation doses, the inner-most layer of modules, also referred to as B-layer, suffers particularly strong impact and must be replaced after approximately 3 years of running at full luminosity. To reduce noise from radiation damage and other sources the pixel detector is cooled to -7°C .

3.3.2 The Semiconductor Tracker

The semiconductor tracker (SCT) [34] [35] [36] consists of 4088 modules, which are aligned in 4 barrel layers and 9 end-cap disks on each side providing a total of 4 space-points per track within the nominal $|\eta|$ -region. Each barrel module is made of four sensors, which consist of 6.4 cm long and $80 \mu\text{m}$ wide daisy-chained silicon strips. The sensors are arranged in double-layers rotated by ± 20 mrad with respect to the axial direction to allow position measurements in both coordinates. The end-cap modules are similar in design, with radially aligned stereo silicon strips and the same relative rotation angle.

The intrinsic accuracies of the modules are $\sim 17 \mu\text{m}$ (R- ϕ) and $\sim 580 \mu\text{m}$ (z) in the barrels and $\sim 17 \mu\text{m}$

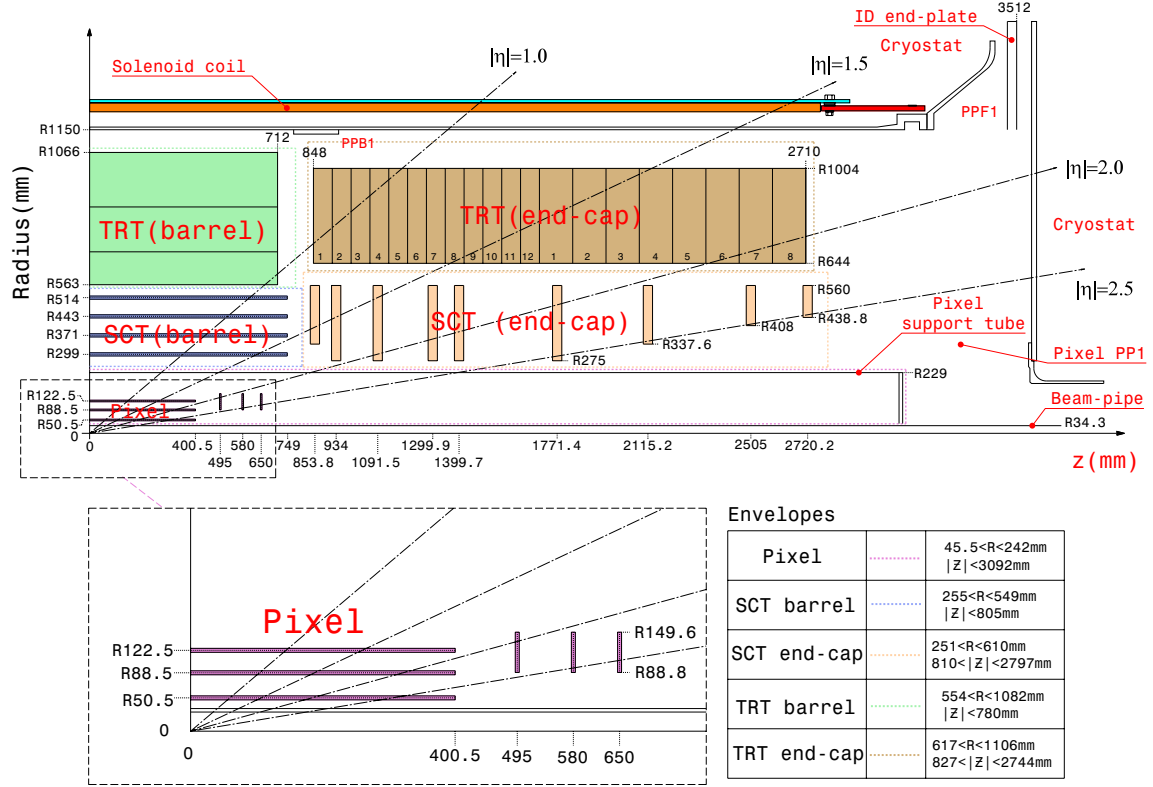


Figure 3.4: Longitudinal cut through a quarter section of the ID, showing pixel detectors, SCT, and TRT and associated components [34].

($R-\phi$) and $\sim 580 \mu\text{m}$ (R) in the end-caps. As for the pixels, the SCT is cooled to -7°C . The sensors will initially run at a 150 V bias, which will have to be increased up to 450 V for sufficient charge collection after severe radiation ageing.

3.3.3 Transition Radiation Tracker

The transition radiation tracker (TRT) [34] [35] [36] is a multi-wire proportional chamber in combination with transition radiation detection and constitutes the outermost part of the ID. It consists of about 351000 straw tubes of 4 mm diameter, filled with a xenon gas mixture (70% Xe, 27% CO_2 , 3% O_2) and a $31 \mu\text{m}$ gold-plated tungsten anode wire. The tube layers are interleaved with passive material, which causes traversing particles (mostly electrons) to induce transition radiation due to different refractive indices. Thus the energy deposition in the TRT is the sum of two effects, the ionization losses of charged particles in the active medium, and the absorption of transition radiation photons. The latter mechanism is significantly stronger than the ionization and thus the TRT is a particular powerful instrument for the identification of low-energy electrons.

In the barrel section of the TRT approximately 52000 straw tubes of 1.44 m length are aligned in parallel to the beam axis between radii of 56.3 cm and 1.07 m. The roughly 300000 endcap straws are located in radial direction between 64.4 cm and 1.00 m up to a distance of 2.7 m from the interaction point resulting in an $|\eta|$ -coverage below 2.5. The straw structure provides information only in the ($R-\phi$)-plane where it has a single wire accuracy of $150 \mu\text{m}$. Due to its fine granularity the TRT provides in general a large number of space-points (typically 36).

3.4 Calorimeter System

Calorimeters are blocks of instrumented material measuring the energy and position of neutral and charged high energy particles. In the process of measurement the particles are fully absorbed in the detector, generating a cascade of secondary particles with progressively degraded energies. At a certain threshold ionization and excitation processes produce a signal in the form of charge or light which is detectable by readout media. By integrating over the energy loss signals the total energy of the initial particle can be reconstructed. The underlying principle is a proportionality between total measured shower energy of the charged particles in the active material and the initial particle energy.

The ATLAS detector features several electromagnetic and hadronic calorimeter components with different granularity and coverage, predominantly for the reconstruction and measurement of electrons, photons, jets and missing transverse energy. All calorimeters have a sampling geometry, where energy deposition and signal detection are separated in alternating layers of high Z absorbing passive material and a sensitive low density active medium. Sampling calorimeters offer the advantage of being relatively compact devices, as the passive layers can be used exclusively for energy dissipation. The possibility of fine segmentation in the longitudinal and lateral directions results in a better position resolution. A drawback is the lack of precision in the energy measurement, which is due to fluctuations caused by the sampling structure.

A sketch of the ATLAS calorimeter system is shown in Fig. 3.5. The further specifications are described in the following subsections.

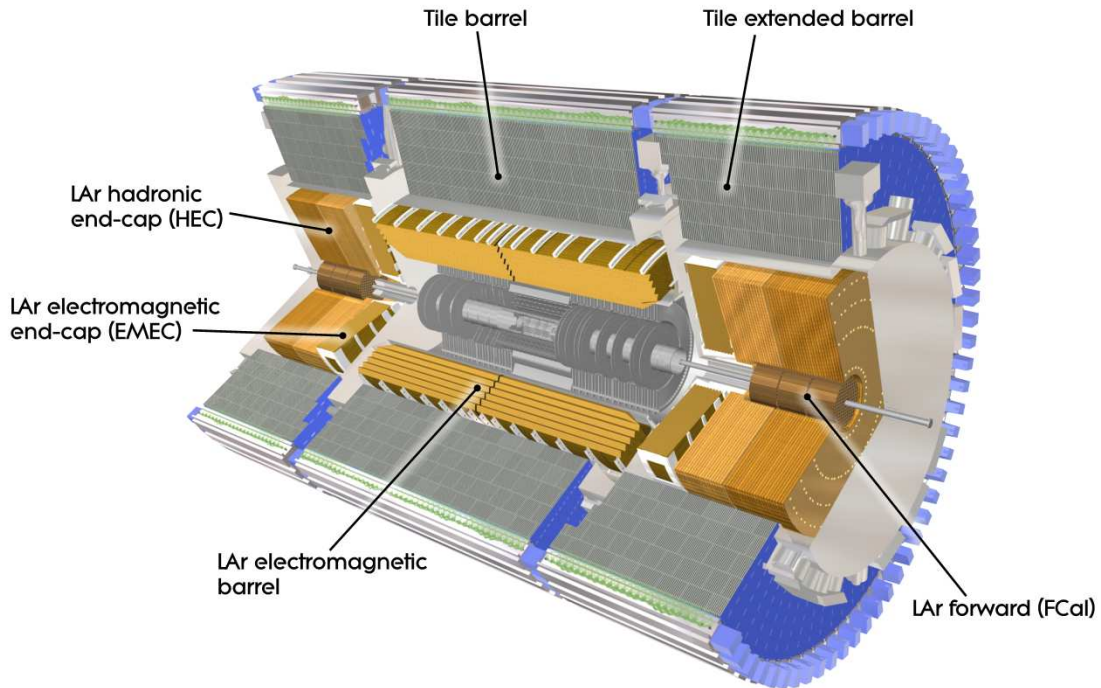


Figure 3.5: *Schematic view of the ATLAS calorimeter system [34].*

The electromagnetic calorimeter (ECAL) [34] [37] consists of a barrel component in regions $|\eta| < 1.475$ and two end-caps with an inner and outer wheel covering $1.375 < |\eta| < 2.5$ and $1.375 < |\eta| < 3.2$ respectively. The thickness of the ECAL is equivalent to ~ 22 radiation lengths³ (X_0) in the barrel and $24 X_0$ in the end-caps. Due to its inherent radiation hardness and intrinsic linear behavior with energy the noble gas liquid argon (LAr) has been chosen as active medium. The LAr layers are interleaved with passive lead absorber material in an accordion-like geometry as shown in Fig. 3.6. This ensures full coverage in ϕ without azimuthal cracks and facilitates fast read-out of signal at both ends of the electrodes.

The ID-, solenoid- and cryostat-material in front of the ECAL is equivalent to about $2.3 X_0$ in the central barrel and increases with $|\eta|$. To correct for the energy loss of electrons and photons in this region a pre-sampler is used in the barrel ($|\eta| < 1.52$) and on the end-caps ($1.5 < |\eta| < 1.8$) consisting of a single layer of $\Delta\eta \times \Delta\phi = 0.025 \times 0.1$ segments with 1.1 cm and 0.5 cm thickness respectively. The region $1.37 < |\eta| < 1.52$ close to the crack between barrel and end-caps is particularly affected by dead material from the solenoid and cryostat walls. It is therefore usually exempted from precision measurements.

Diagram illustrating the geometry of the detector cells and the Trigger Tower. The diagram shows a 3D view of the detector structure, with dimensions and parameters labeled.

Key parameters and dimensions:

- $\eta = 0$
- 1500 mm
- 470 mm
- 16 X_0
- 2 X_0
- Trigger Tower $\Delta\eta = 0.1$
- Trigger Tower $\Delta\phi = 0.0982$
- 4.3 X_0
- 1.7 X_0
- $\Delta\phi = 0.0245 \times 4$
36.8 mm $\times$ 4
 ≈ 147.3 mm
- 37.5 mm / 8 = 4.69 mm
 $\Delta\eta = 0.0031$
- Strip cells in Layer 1
- Square cells in Layer 2
- $\Delta\phi = 0.0245$
- $\Delta\eta = 0.025$
- Cells in Layer 3
 $\Delta\phi \times \Delta\eta = 0.0245 \times 0.05$

³A radiation length X_0 is a material characteristic, indicating the mean distance over which a high-energy electron loses the fraction $1/e$ of its original energy by bremsstrahlung processes (e here denotes Euler's constant).

3.4.2 Hadronic Calorimeter

As shown in Fig. 3.5, the hadronic ATLAS calorimeter system (HCAL) [34] [37] consists of a tile calorimeter, a LAr hadronic end-cap calorimeter, and a LAr forward calorimeter. The tile calorimeter is composed of a barrel component and a so-called extended barrel component covering regions $|\eta| < 1.0$ and $0.8 < |\eta| < 1.7$ respectively. Both elements are situated directly outside the EMC in the radial range $2.28 < R < 4.25$ m. They use steel as absorber material and scintillating tiles as active medium and have a total material thickness of 7.4 interaction lengths⁴.

The hadronic end-caps (HEC) consist of two wheels on each side with 25 mm thick copper plate absorbers on the inner wheel and 50 mm plates on the outer wheel. Due to the radiation-intensive environment around the beam-pipe liquid argon technology is used instead of scintillators. The HEC covers a regions between $1.5 < |\eta| < 3.2$.

The forward calorimeter (FCAL) is located inside the hadronic end-caps and therefore further extends the $|\eta|$ -coverage to 4.9. It consists of three modules in the longitudinal direction. The innermost module is optimized for the measurement of electromagnetic objects and uses copper plates as the absorbing material. The other two compartments use tungsten absorbers to obtain good containment of hadronic showers and limit punch-throughs into the muon system. To handle the high particle fluxes close to the beam-pipe all modules feature very fine LAr gaps for fast signal read-out.

The intrinsic resolution of the barrel and endcap hadronic calorimeters is $\sigma_e/E = 50\%/\sqrt{E} \oplus 3\%$ and for the FCAL $\sigma_e/E = 100\%/\sqrt{E} \oplus 10\%$.

3.5 Muon Spectrometers

Muons are minimally ionizing particles and traverse all detector layers without significant energy dissipation. Therefore the ATLAS muon system [34] [39] represents the largest and outermost part of the detector. It consists of a variety of high-precision tracking and trigger chambers, immersed in the field of three large super-conducting air-toroid magnets for momentum reconstruction. A schematic view is shown in Fig. 3.7. The field coverage is $|\eta| < 1.4$ for the barrel toroid and $1.6 < |\eta| < 2.7$ for the two end-cap magnets. The transition region in between $1.4 < |\eta| < 1.6$ is dominated by residual effects.

The spectrometer modules are arranged in three cylindrical layers in the barrel region, at radii of approximately 5 m, 7.5 m, and 10 m and in four large end-cap wheels, at distances of 7.4 m, 10.8 m, 14 m, and 21.5 m from the interaction point. Four main types of muon detectors are used:

- Monitored Drift Tube Chambers (MDT)
- Cathode Strip Chambers (CSC)
- Resistive Plate Chambers (RPC)
- Thin Gap Chambers (TGC)

A total of 1088 MDTs are installed in the initial spectrometer configuration, covering a surface area of 5500 m^2 at $|\eta| < 2.7$. MDTs consists of three to eight layers of pressurized drift tubes with a diameter of 29.97 mm filled with a Ar/CO₂ gas mixture and a central tungsten-rhenium wire of 50 μm biased with 3080 V. The intrinsic resolution is $\sim 35 \mu\text{m}$ per chamber.

The MDTs are complemented by 32 Cathode Strip Chambers (CSC), which are placed into the first layer of the forward direction between $2.0 < |\eta| < 2.7$. Due to their higher spatial resolution and faster response times they are able to handle the high particles fluxes and track densities in immediate proximity

⁴The interaction length λ is defined as the mean free path of a high-energy particle in a material before undergoing an inelastic scattering.

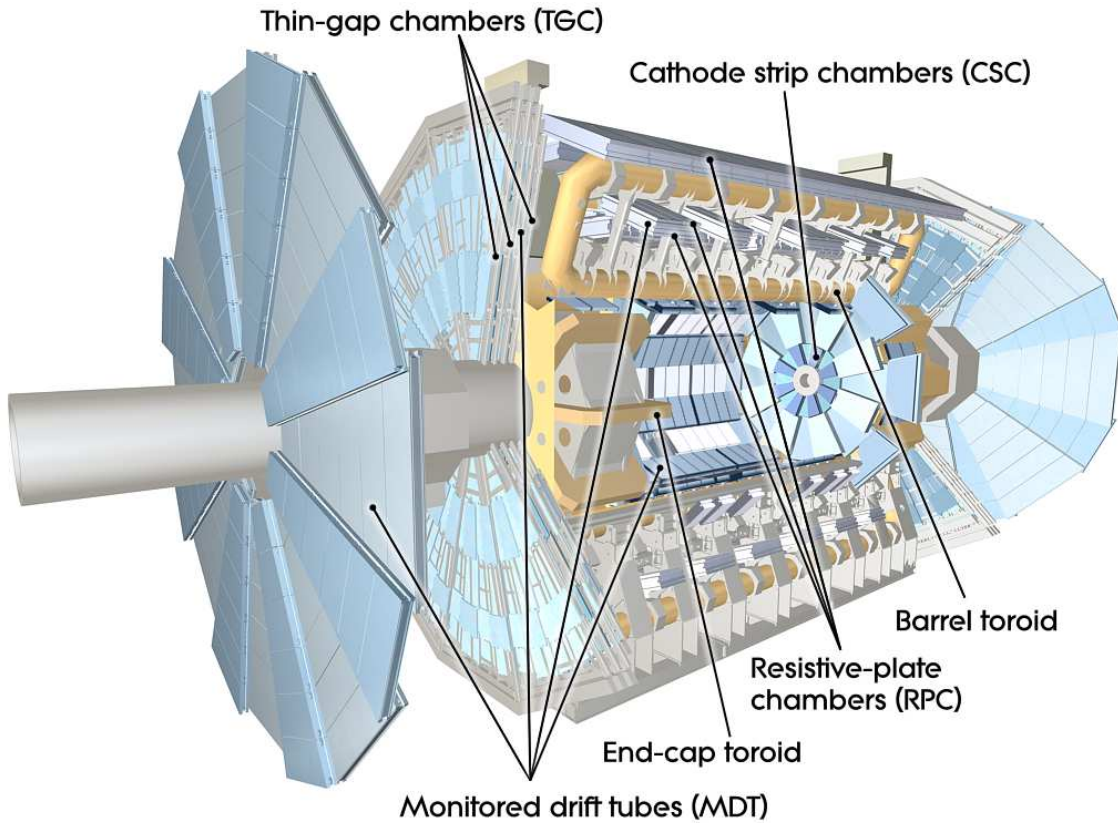


Figure 3.7: *Schematic view of the ATLAS Muon Spectrometer [34].*

of the beam-line. The CSCs are multi-wire proportional chambers with both cathodes divided into strips perpendicular and parallel to the anode wire allowing precise position measurements in the transverse (accuracy $40 \mu\text{m}$) and the bending plane (accuracy 5 mm). A high-resolution optical alignment system of the MDT and CSC tracking chambers in combination with track-based alignment algorithms is in place to obtain the required position and momentum accuracy.

The MDT and CSC tracking chambers are complemented by fast read-out trigger chambers providing track information within nanosecond time-intervals to facilitate the trigger decision. The systems cover regions of $|\eta| < 2.4$ and consists of Resistive Plate Chambers (RPC) in the barrel region and Thin Gap Chambers (TGC) on the end-caps. The RPCs are located in three cylindrical layers around the beam axis next to the MDT units. Each RPC module consists of two independent layers measuring η and ϕ . The principle of operation is based on two parallel resistive electrode plates with a pitch of 2 mm . The area in between is filled with gas and an electric field of 4.9 kV/mm induces avalanches along the ionizing trajectory of traversing particles. The TGC's are located in the end-cap wheels and provide fast trigger information as well as the azimuthal track coordinate to complement the MDT measurements in the bending direction. They are multi-wire proportional chambers with a cathode pitch of 2.8 mm , a distance of 1.8 mm between neighbouring anode wires, and filled with a $\text{CO}_2/\text{n-pentane}$ gas mixture at a potential of 3.1 kV for short drift times.

The overall resolution of the muon system is $\sigma_{p_T}/p_T = 10\%$ at a transverse momentum of 1 TeV .

3.6 Trigger System

At design luminosity the LHC will have a bunch crossing interval of 25 nanoseconds with an interaction rate of ~ 1 GHz. The task of the trigger and data acquisition (T/DAQ) systems [34] is to select and record a small fraction of interesting high- p_T physics signatures and reject the bulk of soft QCD events. The DAQ can handle average bandwidths up to $\mathcal{O}(200 \text{ Hz})$, which requires the trigger system to reduce the number of events by a factor of 10^7 per second while maintaining high efficiencies for the rare processes of interest.

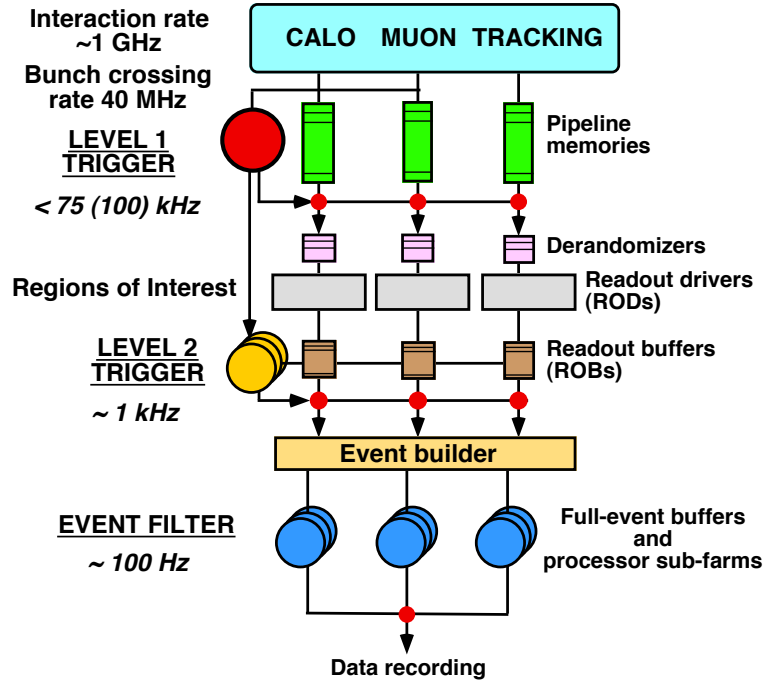


Figure 3.8: Illustration of the architecture of the ATLAS trigger system [40].

The architecture of the ATLAS trigger system is illustrated in Fig. 3.8. It consists of three levels of online event processing. The first level (LVL1) trigger decision is based on a subset of detector components, namely the RPC and TGC muon chambers and reduced granularity information from the electromagnetic and hadronic calorimeters, so-called trigger towers. No tracking information is used. The data is processed in very fast custom-made hardware processors and searches for potential electron, photon, muon, jet and hadronically decaying τ -lepton candidates above a certain p_T -threshold as well as large amounts of missing and total transverse energy. The final LVL1 decision, made by the Central Trigger Processor (CTP), is based on coincidence and veto of these objects and has a latency time of $2.5 \mu\text{s}$ during which the complete event information is conserved in pipeline buffers. Upon selection of the LVL1 trigger the event data is moved via detector specific Readout Drivers (ROD's) to Readout Buffers (ROB's) to be processed by the subsequent trigger steps. The LVL1 trigger reduces the number of potentially interesting events from 1 GHz to the order of 100 kHz.

The software-based LVL2 algorithms are seeded by Regions of Interest (RoI) from LVL1, which contain the type, as well as position and energy threshold information of LVL1 objects. Within the RoIs, LVL2 makes use of the full detector information and therefore comes to a locally well informed decision while using only a fraction of the total event data. This principle allows fast processing times with a maximum latency of $\mathcal{O}(100 \text{ ms})$. The LVL2 trigger significantly refines the decision of LVL1 not only by using

full calorimeter granularity but also by applying isolation requirements, performing track-matches with the inner detector and reading out precision muon chamber information to sharpen p_T -thresholds. The output event rate of LVL2 is of the order of 1 kHz.

The final event selection is performed by the Event Filter (EF), the third step of online processing in the ATLAS trigger system. The EF accesses the complete event information from all detector systems to full granularity and precision and runs complex offline-like reconstruction algorithms to further reduce the output rate to the order of 100 Hz. The results are written to mass storage for physics analyses.

3.7 ATLAS Computing

For data processing, simulation, reconstruction and physics analysis the fully object-oriented ATHENA framework [41] has been developed. It is an ATLAS-specific implementation of the Gaudi architecture [42], a framework for high energy physics experiments originally designed for LHC-b. Athena is based on the programming language C++ in combination with the joboptions concept⁵, which allows simple steering of ATHENA jobs without source code recompilation. The ATLAS software is subject to ongoing development. This thesis is based on releases 13.0.30 (Chapter 4) and 12.0.7.2 (Chapters 5 and 6).

3.7.1 Simulation and Reconstruction with ATHENA

One important functionality of the ATHENA software is the production of simulated data, which allows to prepare and develop extensive detector performance and physics studies. The production cycle of data samples in ATHENA consists a sequence of steps which are summarized below:

- **Generation.** The initial position and momentum four vectors of the particles produced by specified physics processes in the proton-proton collisions are generated by Monte-Carlo programs. The Monte-Carlo generators used for this thesis will be specified in the Chapter 5.
- **Simulation.** The generation step is followed by simulation of the passage of the generated particles through the detector material using the GEANT4 toolkit [44] interfaced to ATHENA. GEANT4 models the full geometry of the ATLAS detector including the magnetic field and simulates all interaction processes with matter, such as multiple scattering, photon conversions, ionization and further decays of unstable particles. GEANT4 produces as output-format so-called "hit"-objects, i.e. a record of where an interaction with active detector material occurred and how much energy was deposited. The simulation step is usually highly CPU-time intensive, due to the complex development of electromagnetic and hadronic showers.
- **Digitization.** The digitization step transforms the GEANT4 hits into detector read-out signals such as drift-times and voltages from the individual detector components. The output-format is equivalent to the raw data output as it would come from the real detector.
- **Reconstruction.** In this final step the raw data from the digitization step is interpreted with complex reconstruction algorithms to identify particles, tracks and related quantities. The output-format is termed Event Summary Data (ESD) and is further compactified to Analysis Object Data (AOD) for physics analyses.

Large-scale productions of Monte-Carlo data-samples using the above described full chain of steps from generation to reconstruction are extremely CPU-time intensive and may at LHC energies quickly become prohibitive. A possible alternative to full simulation is the ATHENA package ATLFAST [45], which bypasses the costly simulation and reconstruction steps by smearing out and parameterizing the generator level four vectors with resolutions measured in full simulation studies.

⁵The scripting language Python [43] is used for joboptions files.

3.7.2 Physics Analyses

The actual physics or Monte-Carlo analyses can be performed in multiple ways in- and outside the ATHENA framework. Two methods relevant in the context of this thesis are outlined below.

- One possibility is the transformation of the AOD-files to ROOT⁶ ntuples using dedicated PhysicsView packages within the EventView analysis framework [47]. This method has been chosen for the analysis in Chapter 5. The advantage is that EventView provides a number of functionalities, such as overlap removal tools and user variable calculation. In addition the processing speed of flat ROOT ntuples is higher than that on ATHENA pool data.
- Currently the development goes towards further light-weight AOD-based data formats, so-called DPDs (Derived Physics Data), which exist in several incarnations and contain only the essential information for specific physics studies. As of release 13, direct AOD- and DPD-analyses can be performed interactively using AthenaROOTAccess (ARA) [48], a stand-alone ATHENA package allowing direct access to ATHENA pool data in ROOT. This approach has been chosen for the offline reconstruction performance studies in Chapter 4.

⁶Root is the standard data analysis framework used by ATLAS and many other high energy physics experiments [46].

Chapter 4

Offline Reconstruction and Performance in SUSY Events

Relevant physics objects and quantities for the SUSY search studies of thesis are electrons, muons, jets, and missing transverse energy. In this chapter the corresponding reconstruction algorithms are reviewed and their performance on events with typical SUSY signatures is studied.

4.1 Electrons

4.1.1 The eGAMMA Algorithm

The analysis of Chapter 5 uses the cluster-based **eGAMMA** algorithm for the reconstruction of electrons. The information summarized in the following is taken from [34][49][50].

In the initial phase, the **eGAMMA** algorithm searches for electromagnetic clusters in the ECAL as a seed for further reconstruction. This is done using the sliding window algorithm, which proceeds in three steps: First the electromagnetic calorimeters within the range $|\eta| < 2.5$ are divided into segments of granularity $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$ (see Fig. 3.6) and the energy in each cell is integrated longitudinally forming so-called calorimeter towers. In a second step, this η - ϕ -space is scanned with a sliding window of the size of 5×5 tower units. Whenever the total transverse energy in the window is above the threshold of 3 GeV a pre-cluster is formed. Overlaps between neighbouring pre-clusters are removed by giving priority to the one with highest energy. After identification of the pre-cluster positions the electromagnetic clusters are filled by including all calorimeter cells located inside a rectangle centered at the seed position.

Each cluster identified by the sliding window algorithm with an energy above 5 GeV is matched to a track from the Inner Detector if the following conditions are satisfied:

- The agreement between the position of the origin of the track and the cluster is $\Delta\eta < 0.05$, $\Delta\phi < 0.1$, and the ratio of the cluster energy to track momentum is smaller than 10.
- The position of the extrapolated track to the calorimeter position for each compartment is within $\Delta\eta < 0.025$ and $\Delta\phi < 0.05$ of the electromagnetic cluster.

The subsequent identification of the electromagnetic clusters as isolated electrons and the associated rejection of non-electron objects or background electrons such as photon conversions, neutral pion-, Dalitz-, and u/d/s-hadron decays is based on the following discriminating variables in the various samplings of the ECAL and in the Inner Detector.

- **Hadronic Leakage.** The hadronic leakage is defined as the ratio of transverse energy in the first sampling of the hadronic calorimeter behind the electromagnetic cluster and the transverse energy of the electromagnetic cluster.
- **Variables in the 2nd ECAL compartment.** The following variables are used in the second sampling of the electromagnetic calorimeter, where the bulk of the shower energy is deposited:
 - *Lateral Shower Shape.* The lateral shower shape variable (R_{η}^{shape}) is given by the ratio of the uncalibrated energy in a 3×7 rectangle and that of a 7×7 rectangle ($\eta \times \phi$ in cell units) around the shower. For electrons this value should be close to one, due to the compact nature of electromagnetic showers.
 - *Lateral Shower Width.* The lateral shower width $w_{\eta 2}$ is calculated within a window of 3×5 cells, in which the energy weighted sum over all cells depending on the particle impact point inside the cell defined as:

$$w_{\eta 2} = \sqrt{\frac{\sum_i E_i \eta_i^2}{\sum_i E_i} - \left(\frac{\sum_i E_i \eta_i}{\sum_i E_i} \right)^2} \quad (4.1)$$

- **Variables in the 1st ECAL compartment.** The first sampling of the ECAL is mainly used for the rejection of pions faking electrons. The finely segmented structure can resolve small substructures and thus allows efficient separation with the following variables:
 - The first two variables exploit the fact that jets with π^0 -decays often show two maxima. If this is the case within a window of $\Delta\eta \times \Delta\phi = 0.125 \times 0.2$ two variables are used: The difference

$$\Delta E = E_{max2} - E_{min}, \quad (4.2)$$

between the energy of the second highest energy maximum E_{max2} and the energy in the strip with the minimal value between the first and second maximum E_{min} , and as second variable

$$R_{max2} = \frac{E_{max2}}{(1 + 9(5) \times 10^{-3} E_T)}, \quad (4.3)$$

where E_T is the total transverse energy of the cluster in the electromagnetic calorimeter and the value $9(5)$ refers to low (high) luminosity. The value of E_{max2} has to be higher than a threshold value to be insensitive to fluctuations.

- *Total Shower Width.* The total shower width is determined within a window of $\Delta\eta \times \Delta\phi = 0.0625 \times 0.2$ as

$$w_{tot1} = \sqrt{\frac{\sum_i E_i (i - i_{max})^2}{\sum_i E_i}}, \quad (4.4)$$

where i is the strip number and i_{max} the number of the most energetic strip.

- For the study of very fine and narrow showers the following two variables are used:

$$F_{side} = \frac{E(\pm 3) - E(\pm 1)}{E(\pm 1)}, \quad (4.5)$$

where $E(\pm n)$ is the energy in $\pm n$ strips around the strip with the highest energy, and the shower width

$$w_{3strips} = \sqrt{\frac{\sum_i E_i (i - i_{max})^2}{\sum_i E_i}}, \quad (4.6)$$

using only three strips around the one with maximal energy deposition.

- **Variables from the Inner Detector.** The calorimeter cuts are very powerful in the rejection of charged hadrons. The remaining non-electron objects are photon conversions and low-multiplicity jets containing high- p_T neutral pions, which can be reduced with ID track and track-calorimeter matching requirements.

- *Track quality cuts.* A set of track quality cuts is required consisting of a) at least nine precision hits in the Pixel detectors and SCT b) at least two hits in the pixel layers including one hit in the first so-called B-layer and c) a transverse impact parameter below 0.1 cm.
- *ID/Calorimeter spatial matching.* The position of the electromagnetic clusters and their associated tracks are checked for consistency. The difference $\Delta\eta_1$ between the η -position of the cluster in the first sampling and the η of the track extrapolated to the first sampling is calculated as well as the difference $\Delta\phi_2$ between the ϕ -position of the cluster in the second sampling and the ϕ of the track extrapolated to the second sampling.
- *ID/Calorimeter energy matching.* The energies of the electromagnetic clusters and the momenta of associated tracks are checked for consistency by calculating the ratio of the two variables, E/p . The value should be close to one for electrons.
- *TRT information.* Further rejection of non-electron objects is possible by requiring a high fraction of high-threshold TRT hits N_{TR} , as electrons are expected to have large transition radiation energy deposition in the TRT. The variable used is N_{TR}/N_{straw} , where N_{straw} is the total number of TRT hits.

The cut-values of the above described variables depend strongly on the $|\eta|$ -region, the transverse momentum, as well as the luminosity scenario and are also subject to minor changes between releases. The most recent version can be found in [50] and web-references therein. The number and type of cuts passed by an electron-candidate are summarized in the so-called `isEM()` bit-word, in which a bit is set if a cut is not passed. According to the resulting `isEM()` pattern electron objects are classified into one of the following three categories:

- **Loose Electrons.** Loose electrons are located in an $|\eta|$ -range < 2.47 and satisfy the requirements on hadronic leakage, lateral shower shape and lateral shower width in the second sampling of the calorimeter providing high identification efficiency but low background rejection. The corresponding bit pattern is `(isEM() & 0x7) == 0`.
- **Medium Electrons.** Medium electrons must additionally fulfill all requirements in the first sampling of the EM calorimeter and the track quality cuts. The medium selections reduce the identification efficiency by $\sim 10\%$ with respect to loose electrons, while the background rejection increases by a factor of ~ 4 . The corresponding bit pattern is `(isEM() & 0x3FF) == 0`.
- **Tight Electrons.** The tight selection requires all possible cuts to be fulfilled. This includes in particular the tight track-cluster-matching criteria in position and energy as well as a minimal number of high threshold TRT hits. The corresponding bit pattern is `isEM() == 0`.

4.1.2 eGamma Reconstruction Performance in SUSY Events

The performance of the reconstruction and identification procedures for electrons described above has been evaluated for one of the Monte-Carlo SUSY samples with high- p_T electrons to be used later in the analysis. The sample is labeled "SU3", which corresponds to a concrete benchmark point in mSUGRA parameter space. A detailed description of the parameter configuration as well as the Monte-Carlo generator specifications will be given in Chapter 5. The sample has been reconstructed with ATLAS software release 13.0.30 and the analysis is performed directly at AOD-level using AthenaROOTAccess (see section 3.7.2). The reconstruction efficiencies are obtained by comparison with Monte-Carlo truth information. In a first step, the data sample is filtered for Monte-Carlo truth electrons above a transverse energy threshold of 5 GeV. Additionally they are required to be direct decay products of the hypothetical SUSY particles or known heavy SM particles, such as W- and Z-bosons. Subsequently the selected electrons are matched to reconstructed electrons within a distance of $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.02$. The reconstruction efficiency is then defined as the number of truth electrons matched with reconstructed electrons, divided by the total number of selected truth electrons within a region of $|\eta| < 2.5$. The resulting efficiencies as a function of transverse momentum p_T , η , and ϕ for loose, medium, and tight

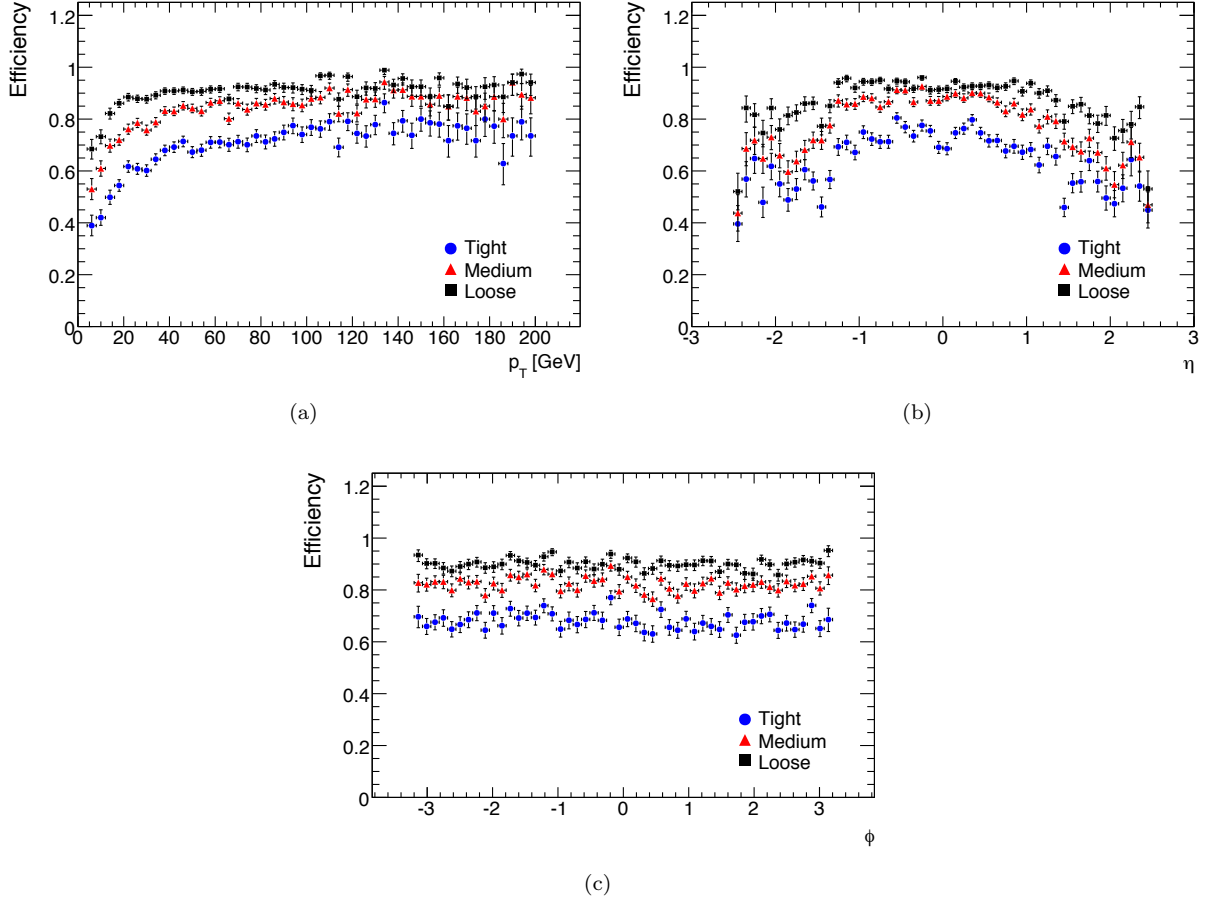


Figure 4.1: *Reconstruction and identification efficiencies for offline electrons with loose, medium, and tight cuts as functions of p_T , η , and ϕ .*

cuts are shown in Fig. 4.1. As expected the p_T -distribution shows a strong increase in the low energy regime until a plateau value characteristic to each set of cuts is reached. In the η -graph the detector geometry effects are clearly visible, with the best performance in the barrel region, significant drops in the crack to the end-cap calorimeters at around $|\eta| \approx 1.4$, and lower efficiencies in the end-caps themselves. At $\eta = 0$ the transition region between the two half-barrels is reflected in a localized efficiency drop.

4.2 Muons

4.2.1 The STACO Algorithm

The reconstruction of muons in the subsequent analysis is performed with the **STACO** (**ST**Atistical **CO**mposition) [40] algorithm. **STACO** is a combined tracking algorithm that makes use of independently reconstructed tracks in the ID and the muon system. These stand-alone tracks are defined by their track-fit parameter vectors $\mathbf{P}_1$ and $\mathbf{P}_2$ and the corresponding covariance matrices $\mathbf{C}_1$ and $\mathbf{C}_2$. If there is a reasonable agreement in η and ϕ between the two tracks the parameter vector $\mathbf{P}$ of the combined track is calculated as solution of the equation

$$\mathbf{C}^{-1} \times \mathbf{P} = \mathbf{C}_1^{-1} \times \mathbf{P}_1 + \mathbf{C}_2^{-1} \times \mathbf{P}_2, \quad (4.7)$$

where $\mathbf{C} = (\mathbf{C}_1^{-1} + \mathbf{C}_2^{-1})^{-1}$ is the combined covariance matrix. The χ^2 of the track can be evaluated as

$$\chi^2 = (\mathbf{P} - \mathbf{P}_1)^T \times \mathbf{C}_1^{-1} \times (\mathbf{P} - \mathbf{P}_1) + (\mathbf{P} - \mathbf{P}_2)^T \times \mathbf{C}_2^{-1} \times (\mathbf{P} - \mathbf{P}_2). \quad (4.8)$$

The two stand-alone track reconstruction algorithms used are **Muonboy** [51] for the muon spectrometers and **xKalman++** [52] [53] for the inner detector. **Muonboy** operates in four main steps: First, so-called regions of activity (ROA) seeded by the RPC and TGC trigger chambers are identified. This information is then used by pattern recognition algorithms to reconstruct local straight track segments inside each muon station. At this stage some sanity checks are performed such as the requirement that tracks point roughly in the direction of the interaction point. In the next step the individual track segments of the muon stations are connected to form track candidates. Finally a global fit through the full system is performed using the hits from the best-matching track segments. A successfully identified track is then defined by a vector of the resulting track-fit parameters and the associated covariance matrix. A correction for energy loss of muons in the calorimeter system is applied.

The **xKalman++** package for the inner detector track identification starts with initial track seeds in one of the ID subsystems. From there, global pattern recognition algorithms compute all possible particle trajectories. The track candidates are then successively propagated through the ID components searching for matching hits. After each match the track fit parameters and associated covariance matrices are updated and an extrapolation to the most likely position for the next measurement is calculated. The best matching tracks of this procedure are kept.

4.2.2 STACO Performance in SUSY Events

As for the case of electrons, the performance of the **STACO** algorithm has been evaluated in SUSY events. In order to obtain the corresponding efficiencies the data sample was first filtered for Monte-Carlo truth muons above a p_T threshold of 5 GeV. Additionally they were again required to be direct decay products of the postulated SUSY particles or heavy SM particles, such as W- and Z-Bosons.

Reconstructed **STACO** muons within $|\eta| < 2.5$ were selected, if the χ^2 value of the track-match (equation 4.8) was smaller than 100, which corresponds to loosely matching tracks between ID and muon system. Further selections were not considered for this simplified study. The matching requirement between truth and reconstructed particles is again a distance $\Delta R = 0.2$.

The resulting efficiencies are shown in Fig. 4.2 as a function of p_T , η , and ϕ respectively. While the first plot shows a good reconstruction efficiency over almost the whole p_T -range above the 5 GeV threshold, the η distribution reflects detector non-uniformities such as the central gap for services at $\eta = 0$, the barrel end-cap transition between $1.1 < |\eta| < 1.3$, where the middle layer muon stations will be missing in the initial detector configuration, and the lower efficiency above $|\eta| > 2.0$, where the momentum resolution of the inner-detector decreases due to the lack of TRT measurements. In the ϕ -distribution a significant drop of efficiency can be seen at the location of the detector support structure ('feet') at $\phi \approx -1$ and -2 , as well as smaller magnetic field non-uniformity effects over the whole range.

4.3 Jets

4.3.1 towerCone4 Jets

For the subsequent study **towerCone4** [34] [54] jets are used. The reconstruction procedure starts with the combination of active calorimeter cells into so-called projective calorimeter signal towers, longitudinally integrated segments in η and ϕ from a grid of $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ elements over the whole acceptance

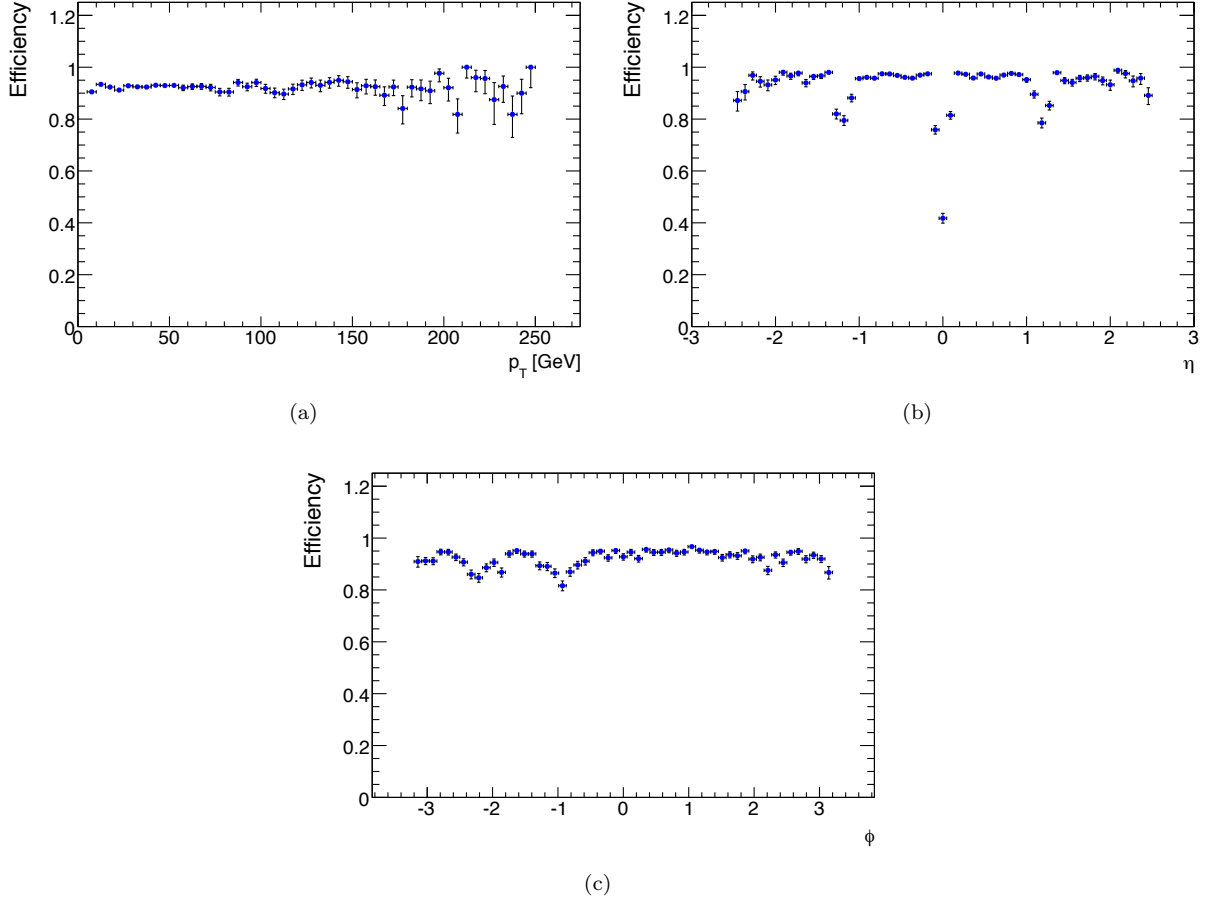


Figure 4.2: *Reconstruction efficiencies of STACO-muons as functions of p_T , η , and ϕ .*

region of the calorimeters. Calorimeter cells which do not entirely fit into this scheme contribute the corresponding averaged fraction of their energy. Negative towers, which may originate in electronics or pile-up noise fluctuations are compensated with close-by positive cells to not bias the overall reconstructed jet four-momenta. The resulting objects are input to the jet finding algorithm, which uses as seeds towers above an energy threshold of $p_T > 1$ GeV. Around identified seeds the algorithm searches within a cone of $R_{Cone} = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.4$ for the next-closest tower and then combines the two constituents to a common object with combined four-momentum. In an iterative procedure a cone is again built around the new object to search for and merge further tower contributions until the jet direction has stabilized and the next seed can be processed. Jets that share more than a certain fraction of constituents are merged, while in the opposite case jet splitting procedures are in place.

The next step is the calorimeter-level calibration of reconstructed jets to account for non-linearities in the energy measurement due to the non-compensating structure of the ATLAS calorimeters. The underlying idea is to give each calorimeter cell an energy weighting according to the nature of the signal. Whereas electromagnetic showers are characterized by relatively compact high density energy deposition and therefore do not need further energy corrections, the broad and low density hadronic showers loose more energy in the absorber material and therefore must be weighted accordingly. The correction factor for each cell is a function of the cell location $\vec{X}_i$ and the energy density $\rho_i = E_i/V_i$, with energy E_i and volume V_i . The calibrated jet four-momentum is then recalculated from the individual cell four-momenta $(E_i, \vec{p}_i)$ as

$$(E_{calo}, \vec{p}_{calo}) = \left(\sum_i w(\rho_i, \vec{X}_i) E_i, \sum_i w(\rho_i, \vec{X}_i) \vec{p}_i \right). \quad (4.9)$$

The weighting function w is derived from Monte-Carlo simulations validated with test-beam data. For energies at the electromagnetic shower scale w is around one, whereas low density hadronic signals are upscaled by up to 50 %. Further detector-level calibrations are applied to account for cracks and dead material, longitudinal leakage, magnetic field deflection effects and algorithm effects, such as out-of-cone particle contributions. A detailed description can be found in [55]. The resulting jets are calibrated to what is referred to as 'particle level'.

On data, a further refinement to 'parton level' requires in-situ calibrations, that correct for physics effects such as clustering, fragmentation, underlying event, and initial and final state radiation.

4.3.2 towerCone4 Performance in SUSY Events

The reconstruction performance of **towerCone4** jets is evaluated by comparison with truth particle jets built from stable particles produced by the fragmentation model in the Monte-Carlo generator. The efficiency is defined as the number of truth particle jets within $|\eta| < 2.5$ matched within $\Delta R < 0.02$ to reconstructed **towerCone4** jets calibrated with the above described weighting scheme, divided by all truth particle jets within $|\eta| < 2.5$. The results are shown in Fig. 4.3, where an increase to a plateau region in p_T from around 50 GeV can be seen. The plots in η and ϕ are normalized with respect to a cut in p_T at 50 GeV and show good uniformity for this energy range. The corresponding distributions without this selection are shown in Appendix A.1.

4.4 Missing Transverse Energy

A precise and reliable reconstruction of missing transverse energy is a crucial ingredient to Supersymmetry searches. At the interaction rates and particle fluxes of the LHC, it is also a task of unprecedented difficulty, as it requires $\sim 200\,000$ relevant read-out channels to be combined to a precise global measurement.

For the studies in the following chapters missing transverse energy has been reconstructed with the refined cell-based algorithm described in [56]. Prior to the actual reconstruction, a calorimeter noise suppression procedure using cell or topocluster¹ thresholds is applied to optimize the resolution.

The residual cells as well as the signal from other detector components are combined to form the quantity

$$\vec{E}_T^{RefFinal} = \vec{E}_T^{e,\gamma} + \vec{E}_T^{\mu} + \vec{E}_T^{jet} + \vec{E}_T^{out} + \vec{E}_T^{cryo}. \quad (4.10)$$

The first term corresponds to the negative sum over the transverse energy vectors of the cells of identified electron and photon objects (**IsEM()==0**). The second term builds the respective negative vector sum of combined **STACO** muons in an $|\eta|$ -coverage of 2.5 and stand-alone **Muonboy** muons between $2.5 < |\eta| < 2.7$. Calorimeter energy loss corrections are not applied to avoid double-counting. $\vec{E}_T^{jet}$ is the missing transverse energy contribution from cells inside jets, which are calibrated to the hadronic scale with the weighting scheme introduced in section 4.3.1. The remaining calibrated contribution from topocluster cells outside identified objects, is summarized in $\vec{E}_T^{out}$. Finally, the last term represents a correction for the jet energy lost in the cryostat walls between the last layer of the ECAL and the first layer of the HCAL. It is the negative vector sum over the jet corrections of all reconstructed jets with absolute value

¹Topological calorimeter clusters or short topoclusters are three dimensional clusters of active calorimeter cells built around a seed above a certain energy threshold.

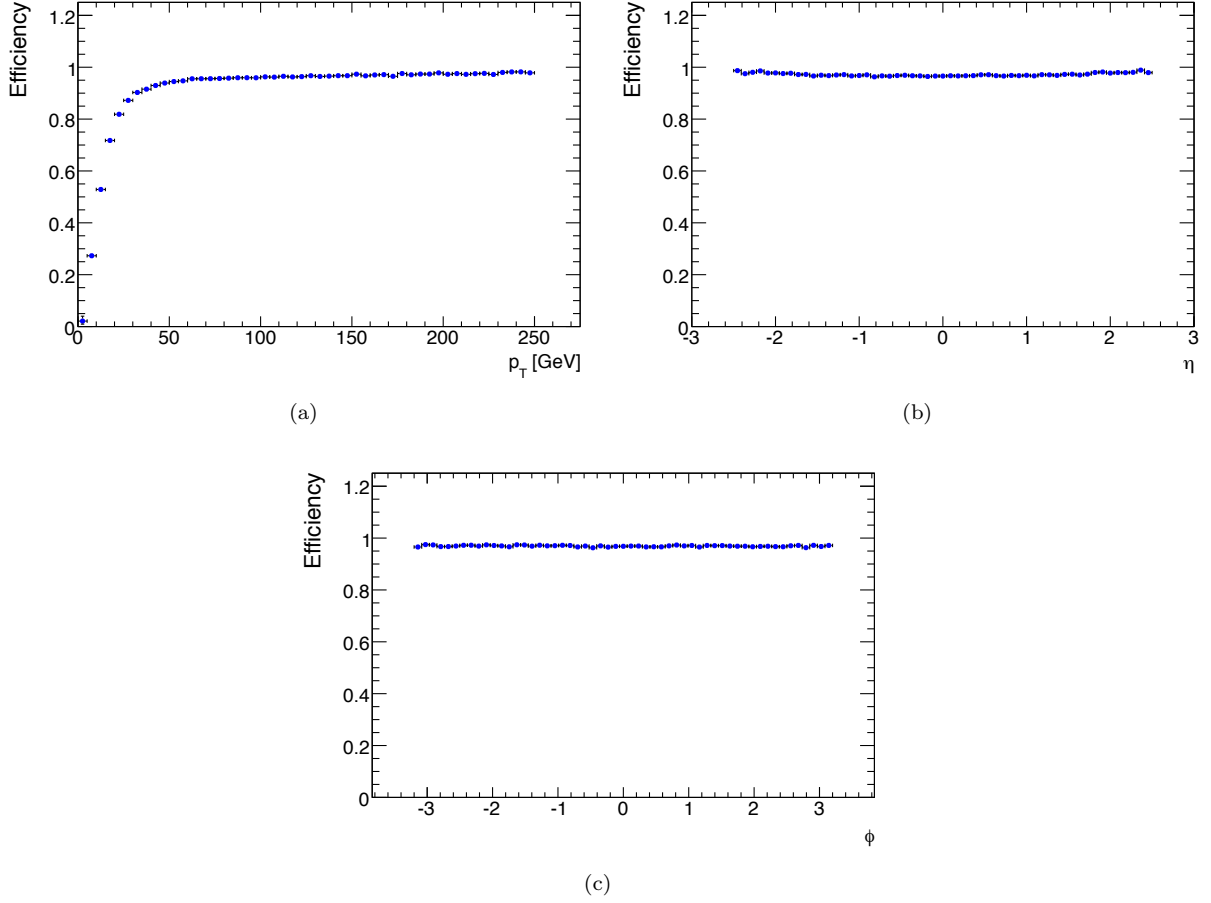


Figure 4.3: Reconstruction efficiencies for *towerCone4*-jets as functions of p_T , η , and ϕ . The latter two plots are normalized with respect to a cut at 50 GeV.

$$E_T^{jet,Cryo} = w^{Cryo} \sqrt{E_{EM3} \times E_{HAD1}} \quad (4.11)$$

each, where w^{Cryo} is a calibration weight and E_{EM3} and E_{HAD1} are the energies in the third ECAL and the first HCAL sampling respectively.

The performance of $\cancel{E}_T^{RefFinal}$ has not been explicitly studied within this thesis. The results from [56] are adopted, where the missing transverse energy resolution is estimated by performing a gaussian fit to the width of the $\cancel{E}_T^{RefFinal} - \cancel{E}_T^{Truth}$ distribution in intervals of the scalar sum of the total transverse energy. The corresponding distributions can be seen in Fig. 4.4 for low to medium values of total transverse energy and a variety of different physics processes as indicated. The resolution can be quantified with a parameter a , which results from a fit with the function $\sigma = a\sqrt{\sum E_T}$ as indicated in Fig. 4.4. The values of parameter a range between 0.53 and 0.57 in the low and medium $\sum E_T$ regime.

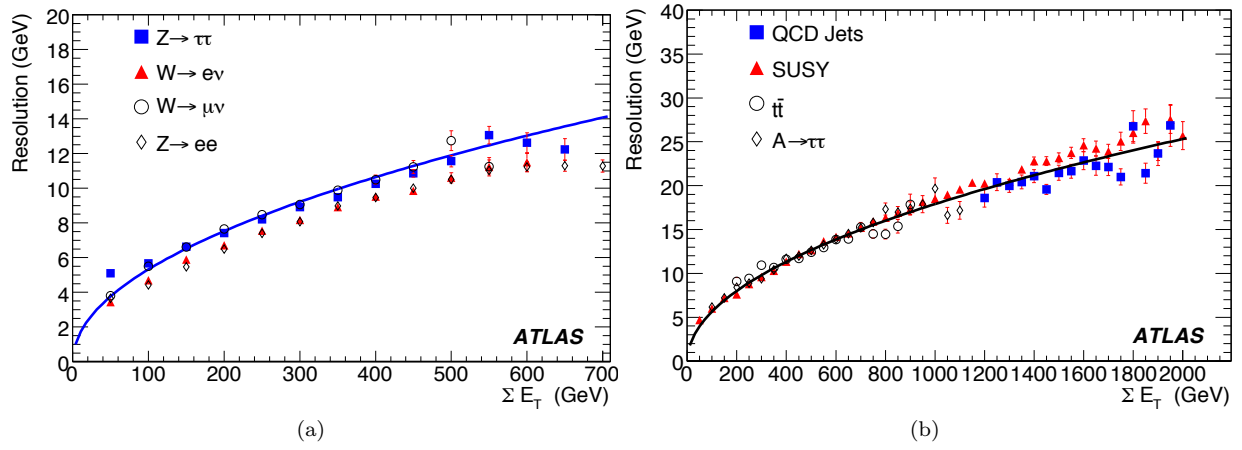


Figure 4.4: Resolution of $\cancel{E}_T^{RefFinal}$ from various physics processes as a function of the total transverse energy ΣE_T for (a) low and (b) medium values [56].

Chapter 5

Inclusive SUSY Searches with One Lepton

In this chapter a generic search strategy for mSUGRA SUSY scenarios is described. Based on Monte-Carlo simulations the discovery potential for signatures with missing transverse energy, high- p_T jets and one isolated lepton is evaluated for 1 fb^{-1} of understood and well calibrated ATLAS data. This particular channel is one of the most promising for a discovery of Supersymmetry in ATLAS, as many QCD background processes are effectively rejected. The exact specifications of the analysis, such as used data-sets, object definitions and selections are given in the following.

5.1 Introduction

If supersymmetric particles exist at LHC energies, their production will be dominated by the strong interactions. The corresponding QCD processes will lead from gg , gq and qq initial states via various production channels to pairs of final state super-particles¹, such as $\tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$, and $\tilde{q}\tilde{q}$. Some of these processes with gg initial states are shown in Fig. 5.1. Depending on the underlying SUSY model the respective cross sections can be of the order of several picobarns (see section 5.2.1).

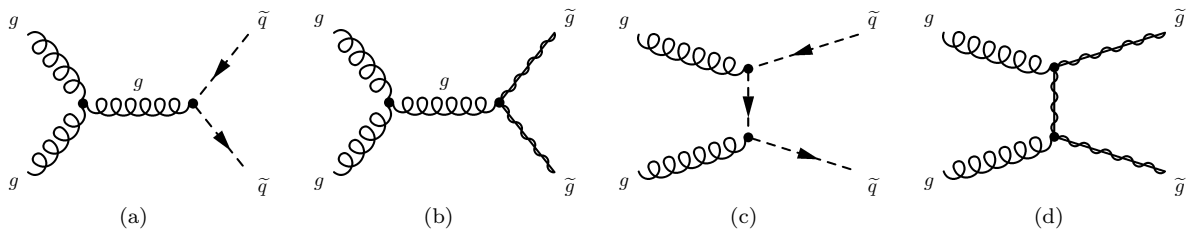


Figure 5.1: *Sample production mechanisms of SUSY particles at the LHC with gluon initial states.*

As squarks and gluinos are relatively heavy in most mSUGRA scenarios (see Fig. 2.5), they successively decay into lighter supersymmetric particles down to the stable LSP. An example is shown in Fig. 5.2a. The typical experimental signature of such SUSY cascades consists of many high- p_T jets from squark and gluino decays, missing transverse energy from the undetected LSP, and possibly a number of isolated hard leptons from neutralino, chargino or slepton processes. As this characteristic event topology is common

¹As shown in section 2.3, in R-parity conserving models supersymmetric particles can only be produced in pairs from SM particles.

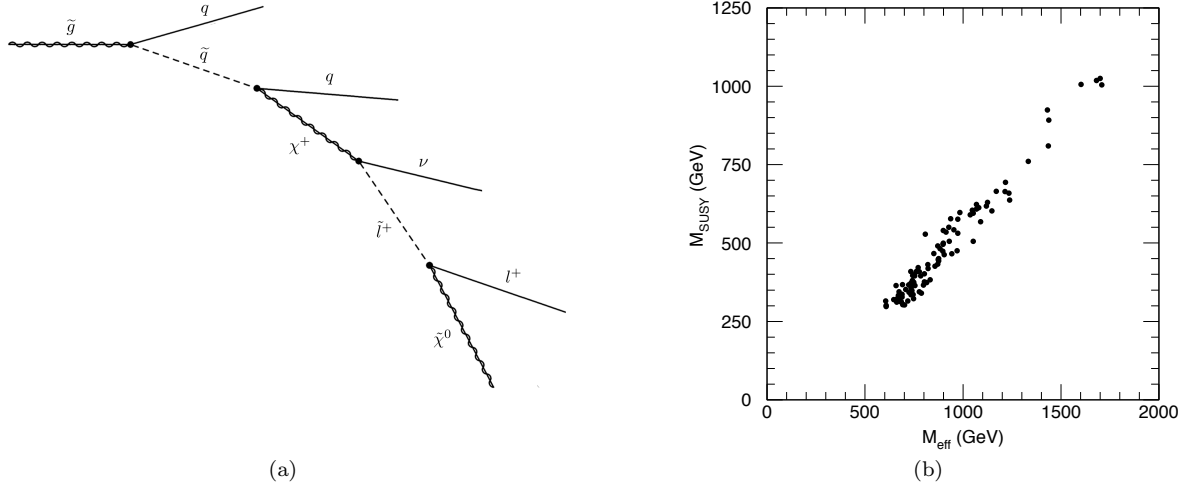


Figure 5.2: (a) Typical SUSY cascade with one-lepton signature. (b) Correlation between the effective mass M_{eff} (equation 5.1) and the mass scale of supersymmetric particles M_{SUSY} for 50 different mSUGRA models [57].

to most decay modes and also holds for wide ranges of R-Parity conserving mSUGRA parameter space an inclusive search strategy is the preferred choice.

To differentiate signal from background, variables that are sensitive with the above described SUSY signatures have to be determined. In this analysis *missing transverse energy* $\cancel{E}_T$ and the *effective mass* M_{eff} are used. The latter is defined as $\cancel{E}_T$ plus the scalar sum of the transverse momenta of the four hardest jets²

$$M_{\text{eff}} = \cancel{E}_T + p_{T,1} + p_{T,2} + p_{T,3} + p_{T,4} (+ \sum_{\text{leptons}} p_T). \quad (5.1)$$

Where applicable, the transverse momenta of the isolated leptons are added. M_{eff} can be interpreted as a measure of the SUSY mass scale, which is defined as the minimum of the squark and gluino masses [57]

$$M_{\text{SUSY}} = \min(m_{\tilde{g}}, m_{\tilde{u}_R}). \quad (5.2)$$

This is illustrated by the approximately linear relationship of Fig. 5.2b, which shows the correlation between the maximum of the M_{eff} distribution and M_{SUSY} for a variety of mSUGRA models.

Within the inclusive event signatures one can put additional requirements on the number of isolated leptons in the event. The most commonly studied channels are the 0-lepton, 1-lepton, 2-lepton (same-sign and opposite-sign), and 3-lepton modes. Thereafter the branching ratios are usually too small to provide statistically significant results.

In most scenarios the fully hadronic channel has the largest fraction of events, but is also strongly contaminated by QCD background processes. These can quickly become the limiting factor in discovery searches, as they suffer from large systematic Monte Carlo and detector performance uncertainties. A more promising alternative is the one-lepton mode, where QCD backgrounds are significantly reduced due to the lepton requirement and branching fractions are still at a sufficient level for further study. In the following sections of this chapter a search for mSUGRA scenarios in this particular channel is described.

²Events with less than four jets are not considered.

5.2 Datasets

For this study reconstructed data from full and fast simulation have been used from the official production for the SUSY CSC notes³. Each data-set has a unique CSC production ID as can be inferred from the tables below. The data-sets are available as Analysis Object Data (AOD), the reconstructed data format from the full chain of steps from generation to data reconstruction within the Athena framework (see section 3.7.1). Different Monte Carlo generators have been chosen for the various signal and background processes. The main features of each of these generators will be outlined below. For the final analysis the AOD files are converted to ROOT [46] ntuples using SUSYVIEW, a PhysicsView package within the EventView analysis framework [47] (see section 3.7.2).

5.2.1 Signal Samples

Despite the relatively low number of parameters in minimal Supergravity, full simulation scans of the parameter space are too CPU-time intensive to be performed on a large scale. Instead one has to resort to concrete benchmark points which exhibit characteristic features of each region. A list of the studied points and their corresponding parameter configurations are given in Table 5.1. The names SUx , $x = 1, \dots, 8$, are internal ATLAS labels.

Benchmark Point	Region	m_0 [GeV]	$m_{1/2}$ [GeV]	A_0	$\tan \beta$	$\text{sgn } \mu$
SU1	co-annihilation	70	350	0	10	+
SU2	focus point	3350	300	0	10	+
SU3	bulk	100	300	-300	6	+
SU4	low mass	200	160	-400	10	+
SU6	funnel	320	375	0	50	+
SU8	co-annihilation	210	360	0	40	+

Table 5.1: *Parameter configurations of the studied mSUGRA SUx benchmark points.*

Points SU1 and SU8 lie in the co-annihilation region, which is a small corridor at low m_0 close to the border where the LSP is charged (compare Fig. 2.6). The focus point SU2 has large values of m_0 and is located near the area of incompatibility with electro-weak symmetry breaking. SU3 inhabits the so-called bulk region at low m_0 and $m_{1/2}$. Here neutralino annihilation in the early universe (see section 2.5), occurred via t-channel slepton exchange and the mass of the LSP is below 200 GeV. SU4 is labeled low mass point as it lies relatively close to the Tevatron bound and SU6 has large values of $\tan \beta$ and is situated in a funnel-like region where $2m_{\tilde{\chi}_1^0} = 2m_A$.

Sample ID	Process	σ_{LO} [pb]	σ_{NLO} [pb]	k-factor	MC events	$\int \mathcal{L} dt [fb^{-1}]$
5401	SU1	7.43	10.7	1.46	196350	18.1
5402	SU2	4.18	7.18	1.72	49700	6.92
5403	SU3	18.6	27.7	1.49	492150	17.8
6400	SU4	262	402	1.54	194850	0.485
5404	SU6	4.48	6.07	1.36	29950	4.93
5406	SU8	6.44	8.70	1.35	47750	5.49

Table 5.2: *List of signal samples with leading and next-to-leading-order cross sections, k-factors, number of Monte Carlo events and corresponding integrated luminosities. The samples were produced with ISAJET [58], HERWIG [59] and Jimmy [60] [61] as indicated in the text. Next-to-leading order cross sections have been calculated with Prospino 2.0.6 [62].*

³In a recent effort a set of notes has been produced by the ATLAS physics and combined performance groups using data made for the Computing Systems Commissioning (CSC). The data samples are reconstructed with ATLAS software release 12.

The sparticle masses, mixings and branching fractions of the benchmark points described above are calculated with the ISASUSY component of ISAJET [58], which is then interfaced to HERWIG [59] for event generation. HERWIG is used in conjunction with a Jimmy plug-in [60] [61] to account for ‘underlying event’, i.e. additional proton-proton interactions which do not contribute to the high- p_T scattering process of interest. K-factors are applied to normalize the leading order generator cross sections to next-to-leading order. They are calculated with Prospino 2.0.6 [62]. The samples are summarized in Table 5.2.

5.2.2 Background Samples

Relevant Standard Model backgrounds to the SUSY signatures above described are $W + \text{jets}$, $Z + \text{jets}$, $t\bar{t}$, QCD and di-boson production. A list of the corresponding physics processes and Monte-Carlo generators used is given in the following.

$W + \text{jets}$ and $Z + \text{jets}$ backgrounds. A major background for inclusive SUSY studies are $W + \text{jets}$ and $Z + \text{jets}$ processes. Two corresponding diagrams are shown in Figures 5.4a and 5.4b, where interaction of two quarks leads to W and Z production and initial state QCD radiation gives rise to additional jets. Processes like these with up to six additional partons can be calculated at leading order by the generator AlpGen 2.05 [63], which has been utilized for this study. The computation of the leading order matrix elements, however, is only feasible for hard scattering processes, where partons are well separated. In the soft and collinear regime, AlpGen interfaces HERWIG 6.510 [59] for the generation of partonic cascades and the subsequent transformation into hadrons, also referred to as parton showering. Underlying event is taken care of by Jimmy.

To avoid double counting of jets from the matrix element calculation and parton showering, the so-called MLM matching procedure [65] is applied. The MLM algorithm decides for each event, which domain of the jet phase space should be generated by which of the two mechanisms. Events with duplicate objects are discarded.

The data samples used are summarized in Table 5.3. They are separated into exclusive samples with different parton numbers. The quoted cross sections include generator level cuts and MLM matching efficiencies. For next-to-leading order corrections these samples are merged and normalized with k-factors determined by MCFM [64].

Top backgrounds. The production of top quark pairs at LHC happens via QCD processes, such as gluon-gluon fusion and scattering or quark-antiquark initial states. Corresponding diagrams are shown in Fig. 5.3. The generator MC@NLO [66] is capable of calculating full next-to-leading order matrix elements for these processes. However, no sufficiently large data-sets for the analyses performed in chapter 6 were available at the time of writing. We therefore resort to AlpGen samples at leading order, which are tuned to match MC@NLO distributions by k-factor normalization. The samples are separated into fully hadronic, fully leptonic and semi-leptonic channels as can be seen from Table 5.4. They contain relatively hard cuts at generator level, such as

- missing transverse energy $\cancel{E}_T > 50\text{GeV}$,
- a minimum of 4 jets with transverse momentum $p_T > 40\text{GeV}$,
- a leading jet with transverse momentum $p_T > 80\text{GeV}$,

and therefore scale to the high integrated luminosities. The samples are produced with ATLFAST, where the full simulation step is bypassed as described in section 3.7.1.

QCD Multijets. Another major background are QCD multijet processes. An example is shown in Fig. 5.4c. The samples relevant for this study have been produced with Pythia [67], a multi-purpose generator which calculates matrix elements to leading order and takes care of parton showering, hadronization and underlying event. Extensive documentation can be found here [67]. The samples are sliced into intervals

Sample ID	Process	σ_{LO} [pb]	σ_{NLO} [pb]	k-factor	MC events	$\int \mathcal{L} dt [fb^{-1}]$
5223	$W \rightarrow e\nu + 2 \text{ jets}$	0.668	0.768	1.15	750	0.977
5224	$W \rightarrow e\nu + 3 \text{ jets}$	3.39	3.90	1.15	14750	3.78
5225	$W \rightarrow e\nu + 4 \text{ jets}$	2.02	2.32	1.15	8900	3.83
5226	$W \rightarrow e\nu + 5 \text{ jets}$	0.596	0.685	1.15	2950	4.31
8203	$W \rightarrow \mu\nu + 3 \text{ jets}$	0.695	0.799	1.15	4000	5.01
8204	$W \rightarrow \mu\nu + 4 \text{ jets}$	1.85	2.13	1.15	7750	3.64
8205	$W \rightarrow \mu\nu + 5 \text{ jets}$	0.609	0.700	1.15	4000	5.71
8208	$W \rightarrow \tau\nu + 2 \text{ jets}$	0.535	0.615	1.15	2750	4.47
8209	$W \rightarrow \tau\nu + 3 \text{ jets}$	2.84	3.26	1.15	1750	0.536
8210	$W \rightarrow \tau\nu + 4 \text{ jets}$	2.66	3.08	1.15	14000	4.58
8211	$W \rightarrow \tau\nu + 5 \text{ jets}$	0.813	0.935	1.15	4700	5.03
5161	$Z \rightarrow ee + 1 \text{ jets}$	0.316	0.401	1.27	1500	3.74
5162	$Z \rightarrow ee + 2 \text{ jets}$	3.27	4.15	1.27	6000	1.45
5163	$Z \rightarrow ee + 3 \text{ jets}$	2.17	2.76	1.27	21850	7.96
5164	$Z \rightarrow ee + 4 \text{ jets}$	0.547	0.695	1.27	6000	8.63
5165	$Z \rightarrow ee + 5 \text{ jets}$	0.139	0.177	1.27	2000	11.2
8109	$Z \rightarrow \mu\mu + 3 \text{ jets}$	0.189	0.240	1.27	2000	8.34
8110	$Z \rightarrow \mu\mu + 4 \text{ jets}$	0.415	0.527	1.27	3450	6.55
8111	$Z \rightarrow \mu\mu + 5 \text{ jets}$	0.134	0.170	1.27	1750	10.29
8120	$Z \rightarrow \tau\tau + 2 \text{ jets}$	0.170	0.215	1.27	3750	22.1
8121	$Z \rightarrow \tau\tau + 3 \text{ jets}$	0.324	0.411	1.27	7000	17.0
8122	$Z \rightarrow \tau\tau + 4 \text{ jets}$	0.163	0.207	1.27	4000	19.3
8123	$Z \rightarrow \tau\tau + 5 \text{ jets}$	0.0486	0.0617	1.27	1000	16.2
5124	$Z \rightarrow \nu\nu + 3 \text{ jets}$	0.841	1.07	1.27	11500	10.7
5125	$Z \rightarrow \nu\nu + 4 \text{ jets}$	2.41	3.06	1.27	26000	8.50
5126	$Z \rightarrow \nu\nu + 5 \text{ jets}$	0.746	0.947	1.27	11500	12.1

Table 5.3: List of $W + \text{jets}$ and $Z + \text{jets}$ background samples, associated physics processes, leading and next-to-leading order cross sections, k-factors, number of simulated MC events and corresponding integrated luminosities. The generator AlpGen 2.05 [63] has been used in conjunction with HERWIG 6.510 [59] and Jimmy [60] [61] for underlying event. The next-to-leading order cross section have been calculated with MCFM [64].

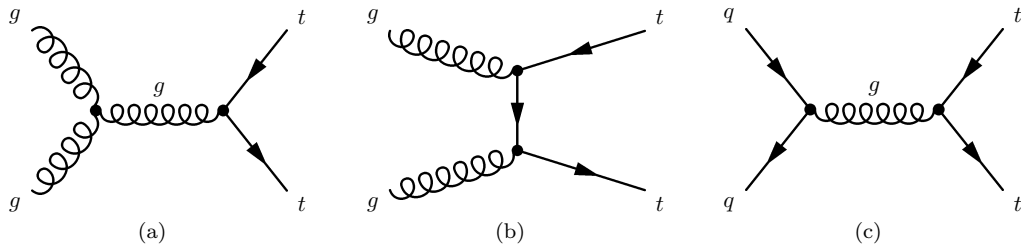


Figure 5.3: Leading order $t\bar{t}$ production mechanisms at the LHC. Gluon-fusion (a), gluon-scattering (b), and quark-scattering (c). The further decay of top quarks leads to fully leptonic, semi-leptonic, and fully hadronic final states.

of transverse momentum of the initial state partons. As can be seen in Table 5.5, the corresponding integrated luminosities are in most cases far below the envisaged 1 fb^{-1} of this study. This is because the simulation of the numerous QCD interactions is extremely CPU-time intensive. Therefore, where necessary, the available samples have been scaled up to 1 fb^{-1} . The resulting bias, especially in the low p_T regime, is expected to be small due to the restrictive selections of this study.

Sample ID	Process	σ_{LO} [pb]	σ_{NLO} [pb]	k-factor	MC events	$\int \mathcal{L} dt [fb^{-1}]$
5530	$tt \rightarrow l\nu qq$	17.0	34.4	2.02	1495869	43.5
5531	$tt \rightarrow l\nu qq + 1 \text{ jet}$	20.9	42.1	2.02	1294400	30.7
5532	$tt \rightarrow l\nu qq + 2 \text{ jets}$	10.5	21.2	2.02	762269	36.0
5533	$tt \rightarrow l\nu qq + 3 \text{ jets}$	4.33	8.75	2.02	321559	36.7
5535	$tt \rightarrow l\nu l\nu$	2.67	5.39	2.02	569497	106
5536	$tt \rightarrow l\nu l\nu + 1 \text{ jet}$	4.34	8.77	2.02	443282	50.6
5537	$tt \rightarrow l\nu l\nu + 2 \text{ jets}$	2.77	5.60	2.02	322015	57.5
5538	$tt \rightarrow l\nu l\nu + 3 \text{ jets}$	1.28	2.59	2.02	145861	56.3
5540	$tt \rightarrow qq qq$	0.87	1.76	2.02	77604	44.1
5541	$tt \rightarrow qq qq + 1 \text{ jet}$	0.92	1.89	2.02	56663	30.0
5542	$tt \rightarrow qq qq + 2 \text{ jets}$	0.50	1.01	2.02	36690	36.3
5543	$tt \rightarrow qq qq + 3 \text{ jets}$	0.260	0.525	2.02	19246	37.0

Table 5.4: List of $t\bar{t}$ background samples, associated physics processes, leading and next-to-leading order cross sections, k-factors, number of simulated Monte Carlo events and corresponding integrated luminosities. The generator AlpGen 2.05 [63] in conjunction with HERWIG [59] and Jimmy [60] [61] has been used. Next-to-leading order cross sections are obtained by comparison with MC@NLO [66]. Full detector simulation has been bypassed with ATLFAST.

Sample ID	Process	σ_{LO} [pb]	MC events	$\int \mathcal{L} dt [fb^{-1}]$
8090	J4 ($140 < p_T < 280$)	916	24500	0.0267
8091	J5 ($280 < p_T < 560$)	356	51650	0.145
8092	J6 ($560 < p_T < 1120$)	67.4	12750	0.189
8093	J7 ($1120 < p_T < 2240$)	5.30	3500	0.660
8094	J8 ($p_T > 2240$)	0.0221	4250	192

Table 5.5: List of QCD background samples with leading order cross sections, number of simulated Monte Carlo events and corresponding integrated luminosities. The samples are sliced into intervals of transverse momentum of the initial state partons. The generator Pythia [67] has been used.

Di-boson production. Di-boson processes are also considered a possible background to SUSY events. They include WW, WZ, and ZZ production. An example diagram is shown in Fig. 5.4d. The samples have been generated with Herwig 6.510 [59] and are summarized in Table 5.6.

Sample ID	Process	σ_{LO} [pb]	σ_{NLO} [pb]	k-factor	MC events	$\int \mathcal{L} dt [fb^{-1}]$
5985	WW	24.5	39.1	1.59	49000	1.25
5986	ZZ	2.10	2.84	1.35	67100	23.6
5987	WZ	7.80	14.1	1.80	48900	3.47

Table 5.6: List of di-boson production samples, leading and next-to-leading order cross sections, k-factors, number of simulated Monte-Carlo events and corresponding integrated luminosities. The generator HERWIG 6.510 [59] has been used in conjunction with Jimmy [60] [61].

5.3 Object Definitions and Overlap Removal

In this section the definitions of objects and quantities relevant to the subsequent analysis are described. These include the reconstruction and identification prescriptions of electrons, muons, jets, and the calculation of missing transverse energy. In addition, the applied overlap removal procedures between reconstructed objects are specified. All requirements quoted here are standard ATLAS definitions as they have been used for the CSC notes.

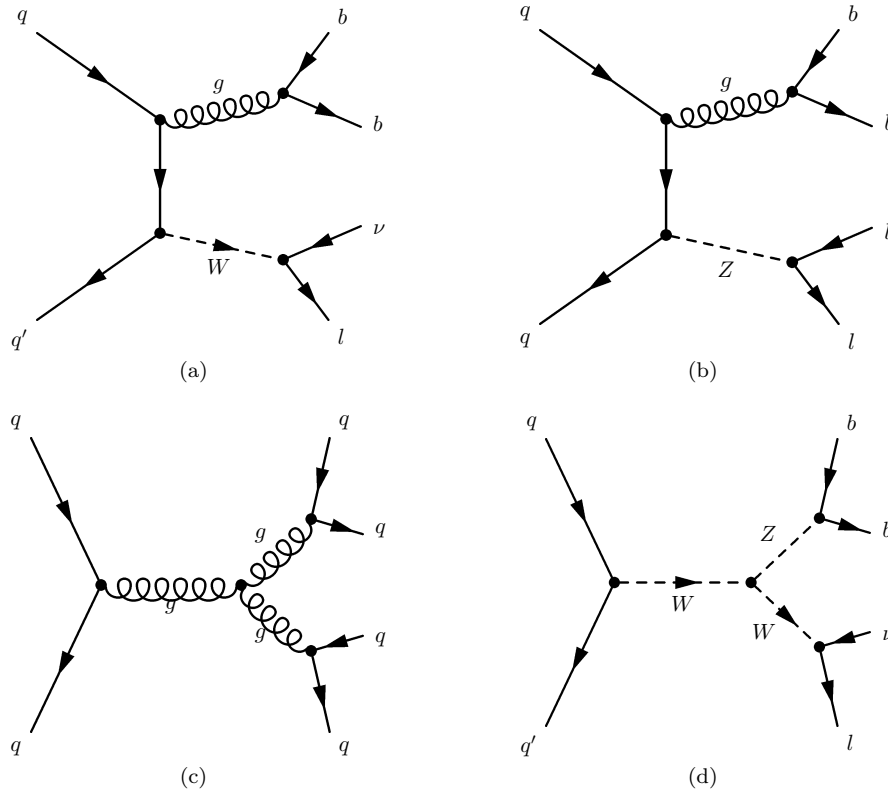


Figure 5.4: Sample background processes for $W + \text{jets}$ (a), $Z + \text{jets}$ (b), QCD (c), and $\text{di-boson production}$ (d). For reasons of simplicity (a) and (b) contain only 1 or 2 additional jets. The processes relevant for the subsequent studies are subject to stronger initial state radiation than shown in these simplified graphs.

5.3.1 Electrons

For the reconstruction of electrons the calorimeter-seeded **eGamma** algorithm as described in Section 4.1.1 is used. Each object reconstructed with this algorithm contains a set of cut parameters, which correspond to different selection criteria, such as hadronic leakage or shower shape requirements in the calorimeter. If one of these cuts is not passed, a bit is set in the so-called `isEM()` flag. According to the resulting `isEM()` bit pattern, electrons can be classified as "loose", "medium" or "tight" (see section 4.1.1). For this analysis "medium" electrons (corresponding to `(isEM() & 0x3FF) == 0`) as defined for release 12 are selected. They satisfy most criteria, except tight track matching and TRT requirements and therefore guarantee sufficient rejection of jets with only moderate loss of reconstruction efficiency.

Furthermore calorimeter isolation is required, where the additional transverse energy within a cone of half-opening angle of 0.2 rad around an electron candidate must be less than 10 GeV. To obtain a good momentum measurement of electrons in the inner tracking detector $|\eta| < 2.5$ is required. Events with electron candidates in the crack regions of the calorimeter $1.37 < |\eta| < 1.52$ are vetoed, as the calorimeter isolation cannot be calculated in these areas. The transverse momentum threshold for electrons is set to 20 GeV.

5.3.2 Muons

The **STACO**-algorithm, as described in section 4.2.1, is used for the reconstruction of muons. It combines track segments from the Inner Detector and the muon spectrometers. For this study only muons with matching tracks in both detector components are considered. The corresponding χ^2 value of the match is required to be smaller than 100. This is relatively loose and therefore does not significantly reduce the overall efficiency. As for the case of electrons, calorimeter isolation is applied to muons with a maximum excess of 10 GeV of transverse energy within a cone of half opening angle 0.2 rad. The kinematic cuts are $\eta < 2.5$, excluding the crack regions, and transverse momentum $p_T > 20 \text{ GeV}$.

5.3.3 Jets

Jets are reconstructed with the seeded cone algorithm **towerCone4** as described in section 4.3.1. For good identification and to avoid initial state radiation effects, jets are selected in the range $|\eta| < 2.5$ with a reconstructed p_T -threshold of $p_T > 20 \text{ GeV}$.

5.3.4 Missing Transverse Energy

For the reconstruction and calculation of missing transverse energy the cell-based algorithm, described in section 4.4, is used. The $\cancel{E}_T$ -variable for the subsequent analysis is calculated as

$$\cancel{E}_T^{RefFinal} = \cancel{E}_T^{e,\gamma} + \cancel{E}_T^\mu + \cancel{E}_T^{jet} + \cancel{E}_T^{out} + \cancel{E}_T^{cryo}, \quad (5.3)$$

where $\cancel{E}_T^{e,\gamma}$ is the contribution of calorimeter cells in electron and photon clusters, $\cancel{E}_T^{jet}$ the cell contributions from jets, and $\cancel{E}_T^\mu$ of muons. $\cancel{E}_T^{out}$ is calculated from cells of the residual topoclusters, which do not belong to reconstructed objects. $\cancel{E}_T^{cryo}$ is a correction applied for the loss of energy in the dead material of the cryostat between electromagnetic and hadronic calorimeter.

5.3.5 Overlap Removal

The reconstruction of the objects defined above is not mutually exclusive. A particular signature may fulfill the selection criteria of two or more different reconstruction algorithms. To avoid double counting the following overlap removal procedure are in place:

Jets that match an electron within $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.2$ are removed. The subsequent separation of the electron to the closest jet must be $\Delta R > 0.4$. Muons matching a remaining jet within a cone of 0.4 are also removed.

5.4 Selections

The study presented here consists of several analysis cycles. In a first step the above described object definitions are applied to the chosen data-sets. In addition only events with one isolated lepton according to 5.3.1 and 5.3.2 are kept. In the subsequent steps the selection variables are calculated and eventually the cuts are applied on these variables to differentiate signal from background.

Within the scope of this study, the baseline selections of the ATLAS Technical Design Report [40] are used. It is obvious, however, that these do not represent the optimal selection criteria and that in particular multivariate techniques may provide a better differentiation between signal and background events.

- **Lepton Selections** As mentioned above only SUSY signatures with one isolated lepton are considered in this study. This lepton must be an electron or muon and satisfy the corresponding criteria in 5.3.1 or 5.3.2.
- **Jet Selections.** As described in the introduction of this chapter, characteristic SUSY events contain several high- p_T jets. This feature can be exploited to reject background events. In this analysis at least four jets according to definition 5.3.3 with transverse momentum $p_T > 50$ GeV are required for each event. Additionally the hardest jet must have a minimum transverse momentum of 100 GeV.
- **Missing Transverse Energy.** Significant transverse energy of the lightest supersymmetric particle will escape the experiment undetected. To distinguish the resulting missing transverse energy from Standard Model electro-weak processes a cut is applied at the maximum of $\cancel{E}_T = 100$ GeV and the fraction $\cancel{E}_T = 0.2 M_{eff}$ of the effective mass as defined in equation 5.1. The performance of this cut can be seen in Fig. 5.6a for the SU3 benchmark point.
- **Transverse Mass.** The transverse mass of the isolated lepton and missing transverse energy has proven to be very effective in the rejection of Standard Model backgrounds. It is defined as

$$M_T = \sqrt{2p_t^\ell \cdot \cancel{E}_T(1 - \cos \varphi_{p_t^\ell, \cancel{E}_T})}, \quad (5.4)$$

where p_t^ℓ is the transverse momentum of the hardest lepton and $\varphi_{p_t^\ell, \cancel{E}_T}$ its angle to the direction of the missing transverse energy vector. A transverse mass of at least 100 GeV is required. This is a very powerful cut as can be seen in Fig. 5.6c, where a clear edge in the transverse mass distribution at around 100 GeV is visible. In particular the processes with W decays such, as W + jets, or semi- and fully-leptonic $t\bar{t}$ are effectively suppressed.

- **Transverse Sphericity.** Transverse sphericity is an event shape variable and measures the isotropy of an event. It is defined as $S_T = 2\lambda_2/(\lambda_1 + \lambda_2)$ with λ_1 and λ_2 being the eigenvalues of the 2x2 sphericity tensor $S_{ij} = \sum_k p_{ki}p_{kj}$, obtained by summing over the transverse momenta of all leptons and jets with $|\eta| < 2.5$ and $p_T > 20$ GeV. Values for S_T range between 0 and 1, where $S_T = 1$ corresponds to a fully isotropic event. As the assumed SUSY signatures contain many high- p_T objects, they are expected to be more spherical than Standard Model events. From a theoretical point of view it is therefore sensible to favour events with a minimum level of isotropy. However, in this particular channel, where $S_T > 0.2$ has been chosen, the cut has only marginal effects as will be shown below.

5.5 Results

The effects of the selections on the signal and background data-sets for 1 fb^{-1} of integrated luminosity are shown in Fig. 5.5 for the SU3 benchmark point. The cuts are applied successively in the order described above. Fig. 5.6 shows the separation between the signal and background distributions for various cut variables with the corresponding selections indicated by the dotted line. Whereas M_T in particular has a distinctive mass edge at ~ 100 GeV and therefore is very powerful in background rejection the cut on transverse sphericity has only a limited impact.

As can be seen from Fig. 5.7, a localized excess of signal over background events is expected for all benchmark points in the M_{eff} - and $\cancel{E}_T$ -distributions. The corresponding cut-flow of events is listed in Table 5.7. The most dominant backgrounds by far are $t\bar{t}$ processes, followed by W + jets and Z + jets. QCD multijets and di-boson production are effectively suppressed. Systematic uncertainties of the background distributions are included in all Figures. They are derived from comparison between different Monte-Carlo generators and data-driven background estimation techniques. The exact numbers are adopted from [32], where 50 % uncertainty has been estimated for QCD multijet backgrounds and

Sample	Original	Lepton Cuts	Jet Cuts	$\cancel{E}_T$ Cuts	S_T Cut	M_T Cut	S/B
SU1	10860	2294.0	767.10	571.68	422.95	259.90	1.43
SU2	7180	940.33	192.57	86.97	75.41	45.51	0.251
SU3	27680	3998.2	1492.2	996.29	767.83	450.39	2.48
SU4	402190	67094	18451	7523.7	6260.4	2974.4	16.4
SU6	6070	985.99	462.70	342.31	250.91	161.93	0.893
SU8	8700	1064.6	414.32	296.44	214.45	151.41	0.835
$t\bar{t}$	133870	48096	9284	1991.0	1531.8	165.59	-
W + jets	19198	5910.8	1206.4	422.74	316.15	13.776	-
Z + jets	15094	3440.5	472.02	22.092	15.889	1.2583	-
QCD	1345390	3391.1	782.18	0.00	0.00	0.00	-
Diboson	55947	29336	31.350	6.8470	4.6390	0.79701	-
SM Total	1569500	90174	11776	2442.2	1868.5	181.42	-

Table 5.7: *Cut-flow of the number of events for all SM and SUSY benchmark point samples normalized to 1 fb^{-1} of integrated luminosity including the final signal over background ratio.*

20 % for $t\bar{t}$, W + jets, Z + jets and diboson production. The uncertainties are applied independently of selections and added per bin in quadrature with the statistical uncertainty.

The discovery potential for each model is evaluated by convoluting the Poissonian probability that the expected number of signal events results from background fluctuations, with a gaussian probability density function around the expected number of background events with a width equivalent to the quadratic sum of statistical and systematic uncertainties [68]. For the calculation of this p-value and the statistical significance $\mathcal{S}$ in terms of standard deviations the **StatTools** package [69] has been used.

As suggested in [32], the signal to background ratios can be further increased by cutting on M_{eff} . Selections are applied at 400, 800, and 1200 GeV as shown in Table 5.8. It can be seen that all benchmark points except SU2⁴ reach above the nominal 5σ significance level for a discovery within 1 fb^{-1} of integrated luminosity.

Sample	$M_{eff} > 0.4 \text{ TeV}$		$M_{eff} > 0.8 \text{ TeV}$		$M_{eff} > 1.2 \text{ TeV}$	
	Events	$\mathcal{S}$	Events	$\mathcal{S}$	Events	$\mathcal{S}$
SU1	259.90	6.72	232.41	15.3	113.83	17.8
SU2	45.51	1.25	39.01	3.33	14.88	3.75
SU3	450.39	11.1	363.39	21.7	110.07	17.4
SU4	2974.4	32.1	895.82	31.3	99.08	16.2
SU6	161.93	4.30	147.95	10.7	76.41	13.4
SU8	151.41	4.03	136.29	9.95	66.32	12.1
SM Total	181.42	-	48.93	-	8.72	-

Table 5.8: *Cut-flow of event numbers for all benchmark points and Standard Model backgrounds normalized to 1 fb^{-1} for selections in M_{eff} as indicated. The corresponding significances $\mathcal{S}$ in units of standard deviations are shown after each selection.*

⁴As described in section 5.2.1, the focus point SU2 is located at high m_0 , where different production mechanisms dominate. This leads to different event signatures for which the analysis described here is not optimized.

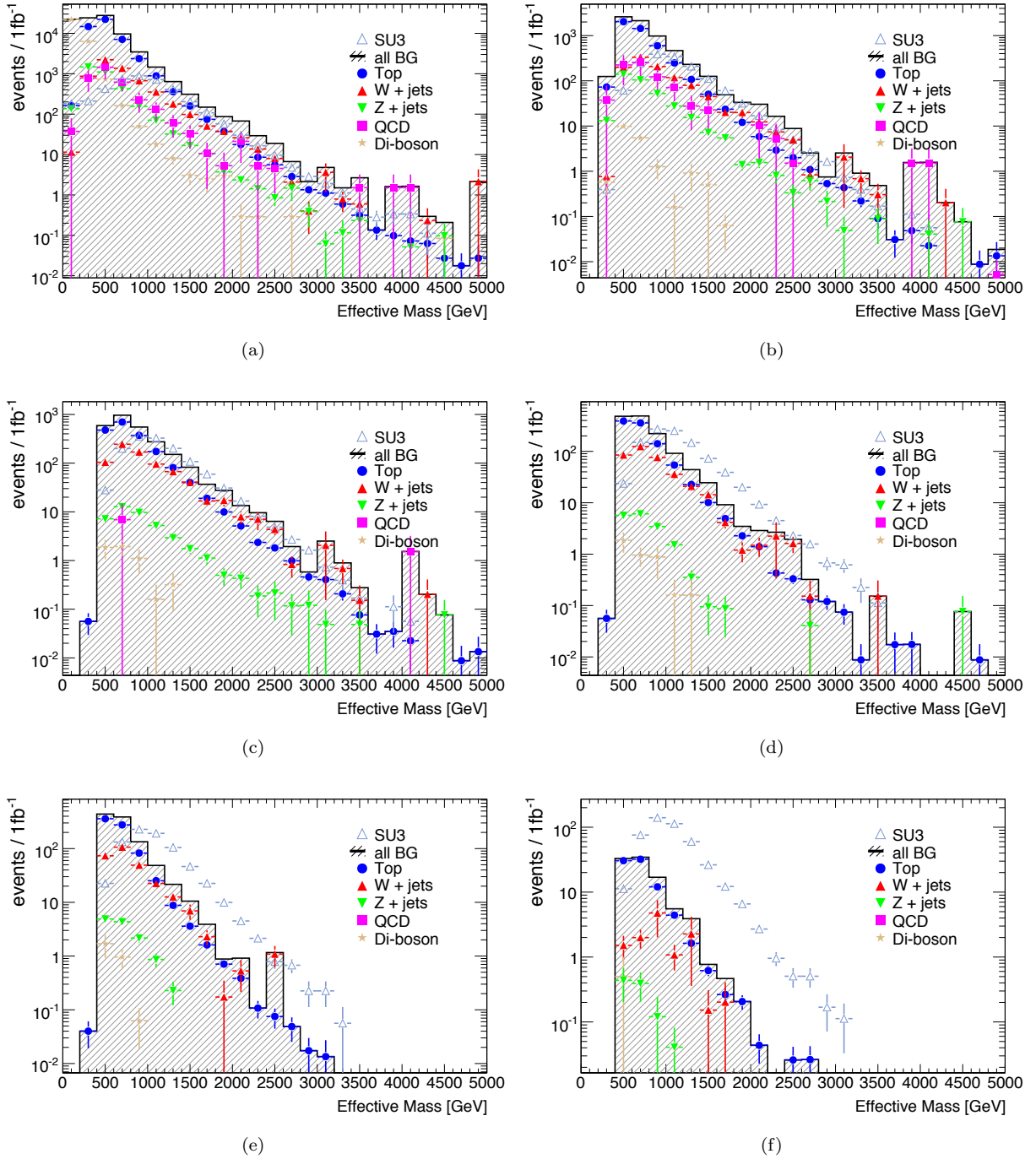


Figure 5.5: *Evolution of the signal and background distributions after successive application of (a) lepton selections, (b) jet selections, (c) $\cancel{E}_T > 100\text{GeV}$, (d) $\cancel{E}_T > 0.2M_{eff}$, (e) $S_T > 0.2$, and (f) $M_T > 100\text{GeV}$.*

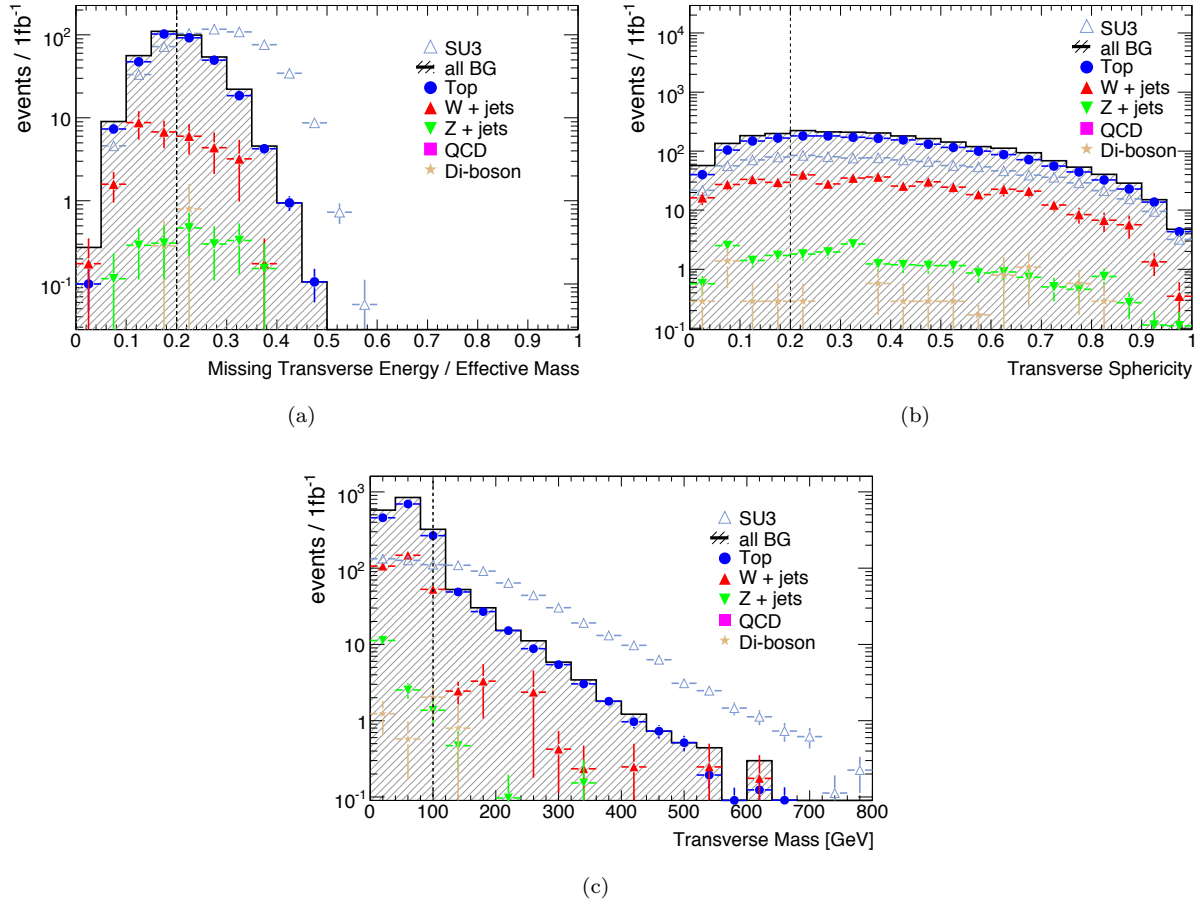


Figure 5.6: (a)-(c) Distributions of $\cancel{E}_T/M_{eff}$, transverse sphericity, and transverse mass after application of all preceding cuts. The dashed line indicates the corresponding selection.

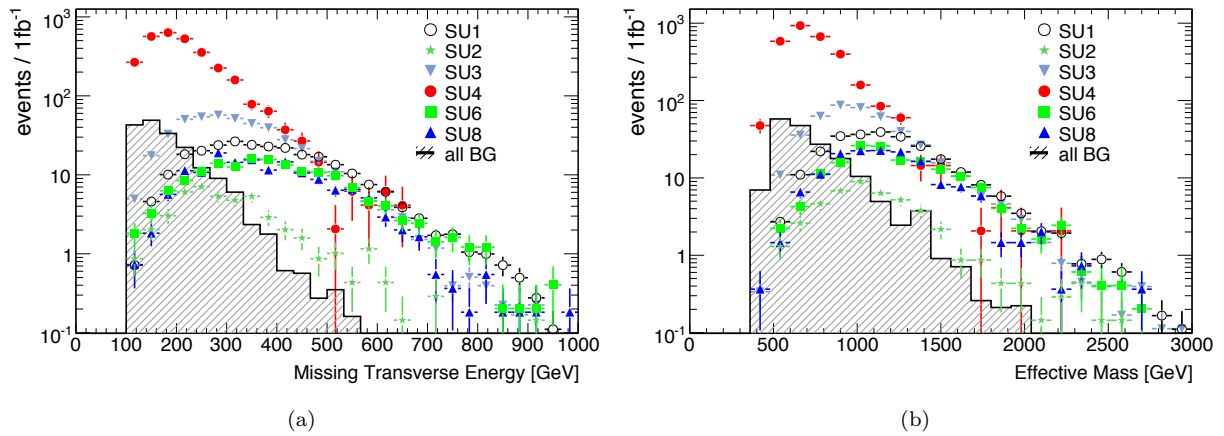


Figure 5.7: Missing transverse energy (a) and effective mass distributions (b) for all studied benchmark points with all selections applied.

Chapter 6

Data-driven Background Estimation

To discover a significant excess of hypothetical SUSY signal events in a realistic analysis, the expected Standard Model backgrounds in data must be well understood. However, while Monte-Carlo simulations may represent a coarse approximation of the true background distributions, the associated uncertainties are too large to provide a sufficient and reliable estimate on their own. Therefore the backgrounds must be extracted from the experimental data itself, where necessary in combination with Monte-Carlo information.

The goal of this final chapter is to describe the successive development and testing of a stable and accurate data-driven background estimation method for the SUSY search strategy described in Chapter 5. This is done in several steps. In the first section the performance of a simple, almost entirely data-driven approach, with only small dependence on Monte-Carlo simulations, is investigated. The results of this study are then used as a starting point for the development of a more sophisticated technique, including a full treatment of method- and detector-related systematic uncertainties. Finally, the performance of this method is evaluated using the combined Monte-Carlo signal and background samples of the preceding chapter as test-‘data’ to determine the discovery potential for all SUx benchmark points.

6.1 Two-dimensional Sidebands

One of the most commonly used data-driven background estimation techniques is based on the extrapolation of background-enhanced two-dimensional side-band distributions into regions where an excess of signal events is expected. The simplest form of this method will be explained and tested in this section. To facilitate later systematic studies and subsequent improvements, a toy Monte-Carlo approach is chosen initially. The technique is then extended to the SUSY analysis of the preceding chapter.

6.1.1 Toy Monte-Carlo Studies

The classical sideband method is based on two ideally uncorrelated variables which exhibit clear signal- and background-enhanced regions. This situation is modeled here in a simplified way with two uncorrelated two-dimensional gaussian Monte-Carlo toy distributions representing signal and background as illustrated in Fig. 6.1a. According to the signal- and background-enhancement in regions of variable one and two, Fig. 6.1a can be subdivided into four quadrants A, B, C, and D. If the separation power is high enough and the cut values are chosen carefully, quadrants A, B, and C are almost entirely dominated by background, whereas D shows an excess of signal events. The knowledge of where to set these selections is an assumption that is put into the method. On real data, this information may be taken from previous measurements in which the signal has been excluded up to a certain value.

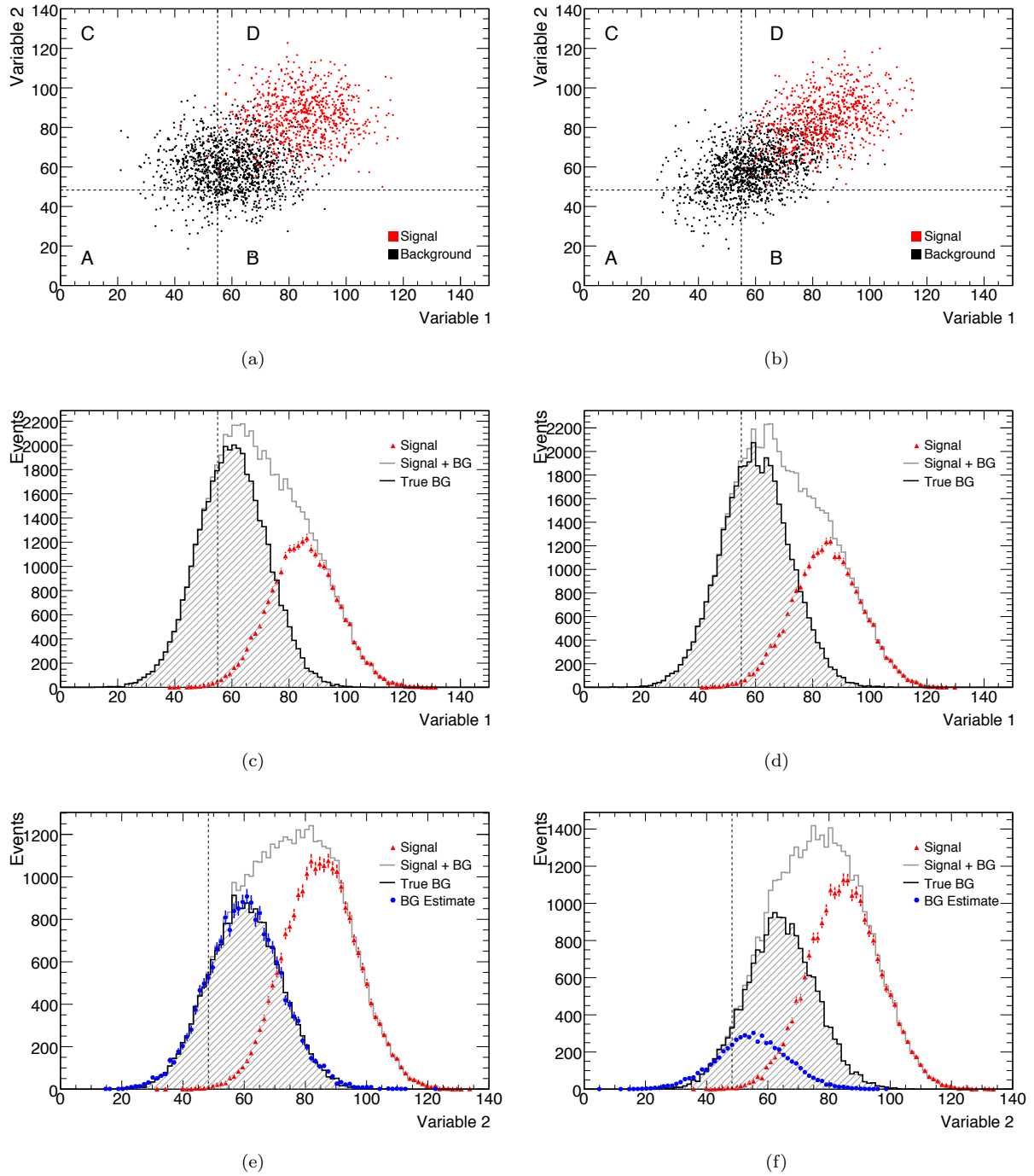


Figure 6.1: Two-dimensional toy Monte-Carlo distributions for signal and background events without correlations (left set of plots) and with strong linear correlations (right set of plots). The middle plots show the projections in variable one along with the control sample selections left of the dotted lines. The bottom two figures indicate the corresponding projections in variable two with the normalization regions left of the dotted line and the resulting background estimates. Figures (a) and (b) are for illustrative purposes and do not scale to the number of events in the plots below.

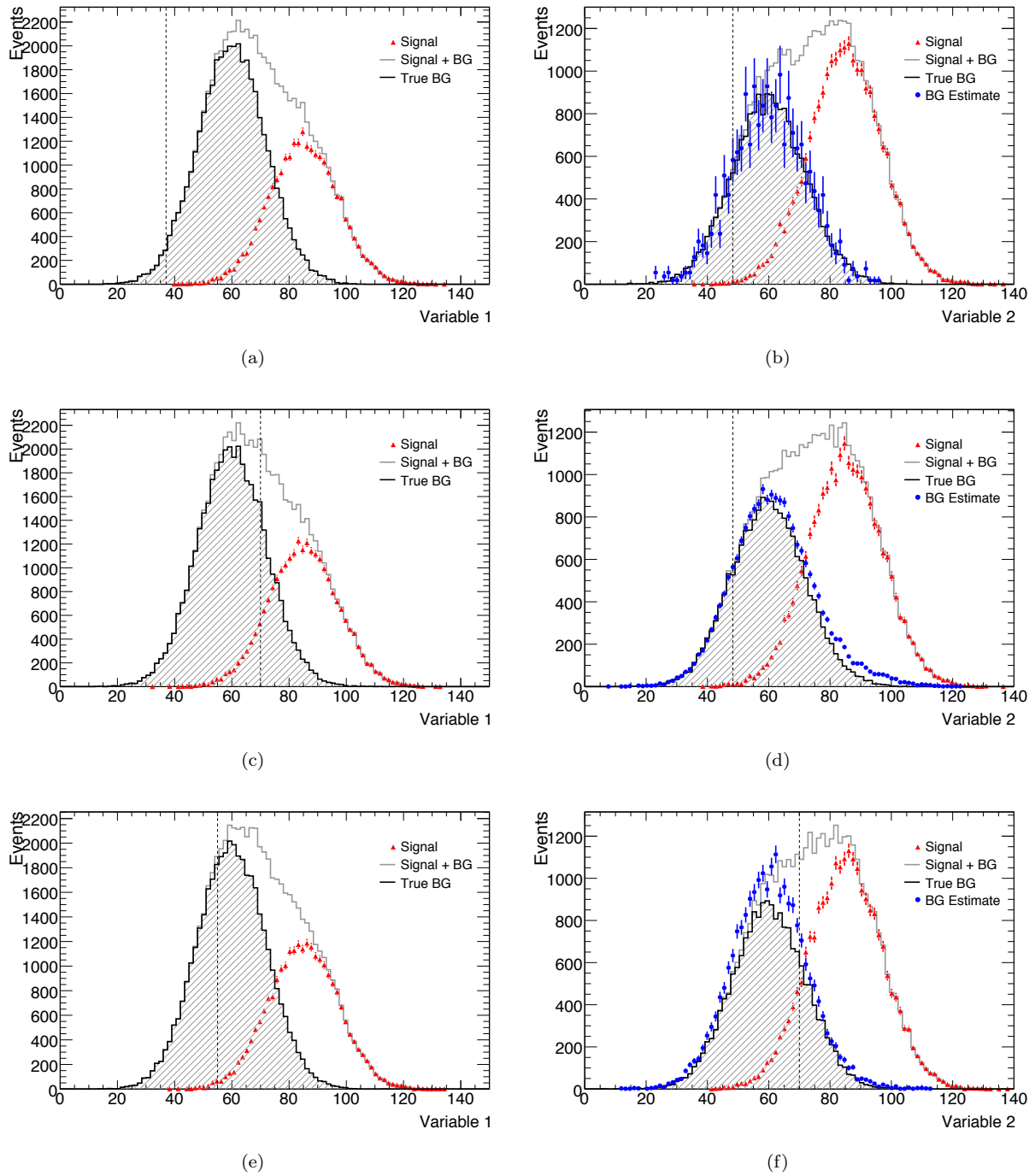


Figure 6.2: Toy Monte-Carlo distributions for signal and background events in variables one and two, illustrating potential biases of the background estimate from signal contamination. Top: Large statistical fluctuations due to narrow control sample band. Middle: Overestimation for high values of variable two, due to strong signal contamination in the control sample. Bottom: Overestimation of the normalization factor due to large normalization region. The control and normalization regions correspond to the areas left the dotted lines.

In the next step, the background-enhanced region in the first variable is used to define a 'control sample', corresponding to quadrants A and C. The corresponding selection is shown in Fig. 6.1c left of the dotted line. The control sample quadrants A and C are then projected into the second variable yielding within statistical fluctuations a distribution of identical shape to the background distribution in this variable. To obtain the correct normalization, the control sample distribution is then scaled to the background-enhanced region of variable two in quadrant B with a normalization factor N_B/N_A , where N_X denotes the number of events per quadrant. In Fig. 6.1e the area left of the dotted line is used for normalization. The resulting background estimate is denoted by the blue circles and shows good agreement with the true background distribution.

While the results in this idealized toy model look very promising, realistic scenarios have to cope with the following difficulties:

Signal Contamination. The quality of the background estimate strongly depends on the separation between signal and background and the chosen control- and normalization regions. A contribution of signal events in the control sample will introduce a bias to the shape of the estimated distribution, whereas signal contamination in the normalization region will lead to an overestimation of background events.

Therefore the selections must be chosen in such a way, that the statistical uncertainties on control sample and normalization factor, and the systematic effects from signal contamination are minimized. The resulting uncertainties are always a trade-off between both effects. For instance, a narrow control sample band, will limit the systematic inclusion of signal events but may suffer from strong statistical errors as illustrated in Figs. 6.2a-b. The contrary case with strong signal contamination is shown in Figs. 6.2c-d, and leads to an overestimation of background events in the high range of variable two. Signal contamination in the normalization region and the resulting systematic overestimation is illustrated in Figs. 6.2e-f.

Correlations. An additional difficulty results from correlations between the discriminating variables, which lead to a distortion of the expected shape and thus may cause significant over- or underestimation of the backgrounds in the signal region. This is illustrated in the right set of plots in Fig. 6.1, where a strong linear correlation with a correlation factor of 40 % for signal and background distributions is introduced. While the projected distributions in variable one and two are almost identical and the same cuts are chosen, the background estimate clearly lacks accuracy.

6.1.2 The M_T -Method

The above described background estimation technique is now applied to the SUSY search studies of the preceding chapter. The total Standard Model background is estimated inclusively in 'Missing Transverse Energy' using the discriminating variable 'Transverse Mass'. The control sample is defined by reversing the M_T -cut of section 5.4 at 100 GeV and for normalization a region between 100-140 GeV in $\cancel{E}_T$ is chosen. The two-dimensional signal and background distributions as well as the applied cuts are illustrated in Fig. 6.3 for the benchmark point SU3. The method is referred to as ' M_T -method' and has been studied previously in a dedicated data-driven background estimation CSC note [70]. In this section the performance of the M_T -method is evaluated and it is used as a starting point for further developments.

Study of separation. As can be inferred from Fig. 5.6c and Fig. 5.7a, the signal and background distributions for both variables, missing transverse energy, $\cancel{E}_T$, and transverse mass, M_T , are well separated for most benchmark points. To quantify this statement the separation power $\langle S \rangle$ can be calculated according to

$$\langle S \rangle = \frac{1}{2} \int_{-\infty}^{\infty} \frac{(f(x) - g(x))^2}{f(x) + g(x)}, \quad (6.1)$$

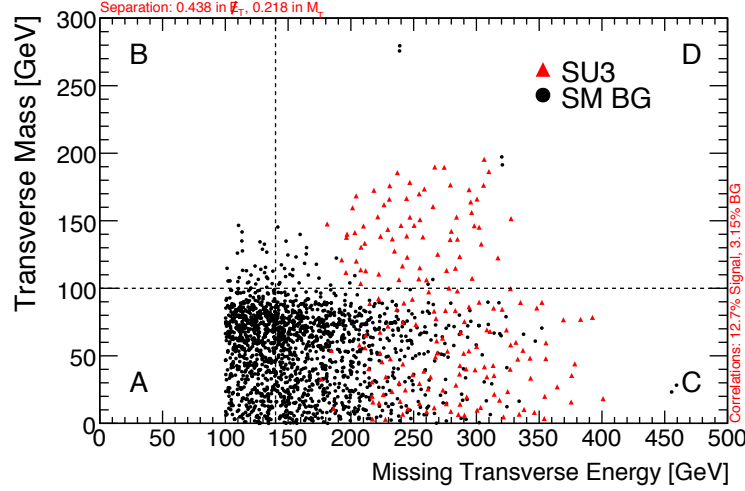


Figure 6.3: Scatter plot of the distributions of Standard Model background and $SU3$ signal events in M_T - $\cancel{E}_T$ -space. The dashed lines indicate the selections in the two variables.

where f and g are the signal and background distributions normalized to unity and x is the discriminating variable. $\langle S \rangle = 1$ corresponds to entirely separated distributions with no overlap, whereas for identical and completely overlapping shapes of signal and background this value is zero. The separation power between all benchmark points and the SM backgrounds is listed in Table 6.1 for $\cancel{E}_T$ after all selections as described in section 5.4, and for M_T with all selections except the transverse mass cut applied.

Sample	$\langle S \rangle$ in M_T	$\langle S \rangle$ in $\cancel{E}_T$
SU1	0.242	0.577
SU2	0.232	0.407
SU3	0.218	0.438
SU4	0.125	0.076
SU6	0.279	0.579
SU8	0.335	0.582

Table 6.1: Separation power between all SUx benchmark points and SM backgrounds in transverse mass and missing transverse energy.

While in most cases the separation is high enough to identify clear signal- and background enhanced regions in both variables, the low mass scenario SU4 has a large overlap with the Standard Model background. It is therefore difficult to obtain an accurate estimate for this model as will be shown later in this section.

Using the above described separation properties, the control sample of the M_T -method is defined by reversing the M_T -cut of chapter 5 and thus selecting all events with $M_T < 100$ GeV. This takes advantage of the sharp SM mass edge at ~ 100 GeV (see Fig. 5.6c), which is due to W-processes from the two dominating background contributions, $t\bar{t}$ (semi- and fully-leptonic¹) and W + jets. To limit the statistical uncertainty of the control sample, large ATLFASST top samples as described in section 5.2.2 are used for this study.

The absolute normalization of the control sample in $\cancel{E}_T$ is obtained in the low $\cancel{E}_T$ -region between 100-140 GeV, which is background-enhanced for all models except SU4 (see Fig. 5.7).

Study of correlations. By definition missing transverse energy and transverse mass are correlated (see

¹Fully-leptonic $t\bar{t}$ -processes may contribute if one of the isolated leptons is misidentified.

equation 5.4). To obtain an accurate background estimate, the extent of correlation and the impact on the shape of the control sample must be understood. This is a somewhat difficult task, since the true distributions for comparison are unknown. The approach adopted in [70] is to assess correlation effects from the Monte-Carlo signal- and background-distributions, assuming their correlations are modeled qualitatively correctly.

In Table 6.2 the linear correlation coefficients for all signal benchmark points, the Standard Model background, and signal + background combined are summarized for the control sample region (quadrants A and C) and for the full range of the distributions (quadrants A, B, C and D).

Sample	Control Region (AC)			Control & Signal Region (ABCD)		
	Sig.	BG	Sig. + BG	Sig.	BG	Sig. + BG
SU1	-9.45 %	-8.42 %	-8.26 %	9.73 %	3.15 %	35.2 %
SU2	-9.49 %	-8.42 %	-8.26 %	20.1 %	3.15 %	14.4 %
SU3	-4.31 %	-8.42 %	-8.77 %	12.7 %	3.15 %	33.7 %
SU4	-11.8 %	-8.42 %	-11.4 %	27.5 %	3.15 %	26.9 %
SU6	-6.97 %	-8.42 %	-8.41 %	14.6 %	3.15 %	34.4 %
SU8	-7.71 %	-8.42 %	-8.09 %	11.9 %	3.15 %	34.4 %

Table 6.2: *Linear correlation factors in the control region and over the whole M_T - E_T -range for all SUx benchmark points, the Standard Model background, and signal + background combined.*

It can be seen that the correlations of the background distributions are relatively low. Over the full M_T - E_T -range they are of the order 3 %, whereas in the control region values are slightly higher and of opposite sign due to the additional M_T -selection. The signal correlations over the whole range are significantly higher. Due to the lower number of signal events in the control region, this effect on the combined signal + background samples is rather low. Therefore the corresponding correlation coefficients may give a first idea on the background correlations from data. However, this approach is not viable over the whole range, where signal and background events will be of the same order of magnitude and thus bias the overall results. This is reflected in the high 'signal + background' correlation coefficients shown in the right column of Table 6.2.

While the linear background correlations derived from Monte-Carlo prove to be relatively low, the numbers quoted above do not allow a direct conclusion on the quality of the resulting background estimate, since non-linear higher order correlation effects may also significantly alter the shape of the control sample distributions.

To study the direct effect of the correlations on the shape of the background estimate, the true control sample and background distributions can be compared as suggested in [70]. This is shown in Fig. 6.4, where both distributions are normalized to unity. Despite some visible deviations it can be seen that the shapes are largely compatible, which allows us to use the control sample shape as a coarse approximation of the background distribution in the signal region.

Results. The resulting background estimates without further corrections for systematic effects due to correlations or signal contamination are shown in Fig. 6.5 for the benchmark point SU3 in missing transverse energy and effective mass. The figures for all scenarios can be found in Appendix A.2. The expected number of background events for each model is listed in Table 6.3. The statistical errors therein are obtained by gaussian error propagation from the corresponding statistical uncertainty of the total number of events in the control sample and the uncertainty on the normalization factor.

It can be seen that most estimates differ significantly from the true number of background events. While correlation effects are expected to have smaller impact, signal contamination represents the main source of systematic error. The fraction of signal events in the control sample is generally of the order of 10-20 % and about 60 % for the problematic low mass point SU4, leading to a bias in the expected background shape and the absolute normalization.

As expected earlier, the estimate for the SU4 point is particular poor, due to the low separation power

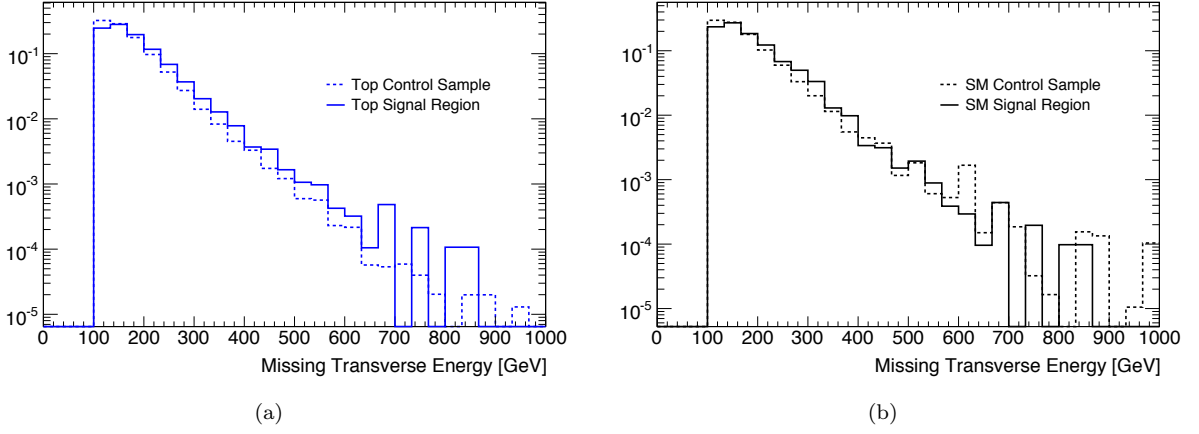


Figure 6.4: Comparison of the true control sample shape ($M_T < 100$ GeV) and true signal region shape ($M_T > 100$ GeV) of (a) top backgrounds exclusively and (b) all Standard Model backgrounds as a function of missing transverse energy. The plots are normalized to unity.

to the Standard Model backgrounds and the subsequent large signal contamination effects. However, as indicated in Chapter 5, the SU4 cross section at LHC energies is high enough for a discovery even with large systematic errors on the backgrounds attached.

While the presented estimates are dominated by systematic effects of the method itself, further detector-related systematic uncertainties e.g. on the jet energy scale may be investigated. However, we do not further pursue a treatment of systematic uncertainties here and instead concentrate on a more sophisticated background estimation approach in the following section.

In conclusion it should be noted, that despite the poor overall performance of the M_T -method, it represents an almost completely data-driven approach with only weak dependence on Monte-Carlo simulations.

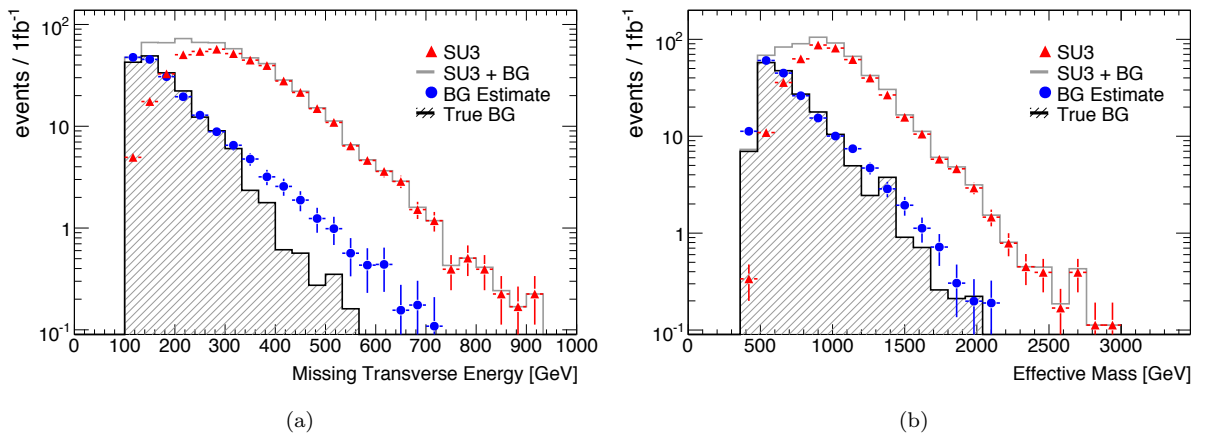


Figure 6.5: Missing transverse energy and effective mass distributions for true Standard Model background, the SU3 signal, combined signal and Standard Model background, and the resulting background estimate.

Sample	Estimated BG	True BG
SU1	159 $\pm$ 4	181 $\pm$ 4
SU2	149 $\pm$ 4	181 $\pm$ 4
SU3	188 $\pm$ 4	181 $\pm$ 4
SU4	1377 $\pm$ 20	181 $\pm$ 4
SU6	157 $\pm$ 4	181 $\pm$ 4
SU8	188 $\pm$ 4	181 $\pm$ 4

Table 6.3: Number of estimated background events using the M_T -method and true Standard Model background events for comparison.

6.2 The '4-tiles'-Method

In order to obtain more accurate background estimates, the above described sideband method must be refined to correct for correlations and in particular for strong signal contamination effects. Often this is achieved by making explicit assumptions about the form of the hypothetical signal from Monte-Carlo simulations, which introduces a major systematic uncertainty.

In this section a new, more sophisticated two-dimensional sideband method (hereafter referred to as '4-tiles'-method) is presented, which corrects for signal contamination as well as correlation effects by using information from MC background distributions only. After a brief introduction to the method, the performance will again be tested on toy simulations and then applied to the analysis of chapter 5, including a treatment of systematic uncertainties.

Introduction. As for the previously described method, the refined sideband or '4-tiles' method is again based on selections in two discriminating variables, which define four quadrants or 'tiles' A, B, C, D with signal- and background-enhancement. The total number of events in each quadrant is given by

$$\begin{aligned}
N_A &= \epsilon_A^{Bkg} (N^{tot} - N^{Sig}) + \epsilon_1^{Sig} \epsilon_2^{Sig} N^{Sig}, \\
N_B &= \epsilon_B^{Bkg} (N^{tot} - N^{Sig}) + \epsilon_1^{Sig} (1 - \epsilon_2^{Sig}) N^{Sig}, \\
N_C &= \epsilon_C^{Bkg} (N^{tot} - N^{Sig}) + (1 - \epsilon_1^{Sig}) \epsilon_2^{Sig} N^{Sig}, \\
N_D &= \epsilon_D^{Bkg} (N^{tot} - N^{Sig}) + (1 - \epsilon_1^{Sig}) (1 - \epsilon_2^{Sig}) N^{Sig},
\end{aligned} \tag{6.2}$$

where N^{tot} is the total number of events integrated over all quadrants, N^{Sig} the total number of signal events, $\epsilon_{1,2}^{Sig}$ the efficiencies of the cuts in variable one and two on the signal distribution, and $\epsilon_{A,B,C,D}^{Bkg}$ the efficiencies of each individual quadrant for the background distribution. This system of linear equations can be solved for the number of signal events, yielding in its simplest form the signal-independent solution

$$\begin{aligned}
N^{Sig} = \frac{1}{2 (\epsilon_A \epsilon_D - \epsilon_B \epsilon_C)} & \left(-2 \epsilon_B \epsilon_C N_A + \epsilon_A \epsilon_D N_A - \epsilon_B \epsilon_D N_A - \epsilon_C \epsilon_D N_A - \epsilon_D^2 N_A \right. \\
& + \epsilon_A \epsilon_C N_B - \epsilon_B \epsilon_C N_B + \epsilon_C^2 N_B + 2 \epsilon_A \epsilon_D N_B + \epsilon_C \epsilon_D N_B + \epsilon_A \epsilon_B N_C + \epsilon_B^2 N_C \\
& - \epsilon_B \epsilon_C N_C + 2 \epsilon_A \epsilon_D N_C + \epsilon_B \epsilon_D N_C - \epsilon_A^2 N_D - \epsilon_A \epsilon_B N_D - \epsilon_A \epsilon_C N_D - 2 \epsilon_B \epsilon_C N_D \\
& + \epsilon_A \epsilon_D N_D \cdot \left[(\epsilon_D N_A)^2 + (\epsilon_C N_B)^2 + (\epsilon_B N_C - \epsilon_A N_D)^2 - 2 \epsilon_D (\epsilon_C N_A N_B + \epsilon_B N_A N_C \right. \\
& \left. \left. - 2 \epsilon_A N_B N_C + \epsilon_A N_A N_D) - 2 \epsilon_C (\epsilon_B N_B N_C - 2 \epsilon_B N_A N_D + \epsilon_A N_B N_D) \right]^{1/2} \right).
\end{aligned} \tag{6.3}$$

Alternatively, equations 6.2 can also be reformulated in terms of $N^{Bkg} = N^{tot} - N^{Sig}$ to obtain the following equivalent estimator for the number of background events

$$\begin{aligned}
N^{Bkg} = & \frac{1}{2(\epsilon_B\epsilon_C - \epsilon_A\epsilon_D)} \left(-\epsilon_D N_A + \epsilon_C N_B + \epsilon_B N_C - \epsilon_A N_D + \left[-\epsilon_D N_A \right. \right. \\
& - \epsilon_C(2N_A + N_B) + 2\epsilon_A N_C + \epsilon_B N_C + \epsilon_A N_D \left. \right]^2 - 4(\epsilon_C N_A - \epsilon_A N_C) \\
& \left. \cdot [(\epsilon_C + \epsilon_D)(N_A + N_B) - (\epsilon_A + \epsilon_B)(N_C + N_D)] \right)^{\frac{1}{2}}. \tag{6.4}
\end{aligned}$$

In both equations the upper indices on the background efficiencies have not been written out for better readability. The estimators N^{Sig} and N^{Bkg} are functions of the total number of events in each quadrant $N_{A,B,C,D}$ and the background efficiencies $\epsilon_{A,B,C,D}^{Bkg}$. Whereas $N_{A,B,C,D}$ can be retrieved directly from data, the background efficiencies must be obtained from Monte-Carlo simulations. The systematic effects of incorrect efficiencies from inaccurate Monte-Carlo simulations on the estimate will be studied later in this chapter.

As the exact background efficiencies are used for each quadrant, background correlations will not affect the estimate. Signal correlations, however, can bias the results since the approximation $\epsilon_A^{Sig} = \epsilon_1^{Sig} \epsilon_2^{Sig}$, and like-wise for quadrants B,C, and D, holds only for uncorrelated signal distributions. A study of the systematic effects of signal correlations will be performed section 6.2.3.

The statistical uncertainties of both estimators N^{Sig} and N^{Bkg} can be derived from equations 6.3 and 6.4, where the quantities $N_{A,B,C,D}$ have an associated Poissonian error of $\sigma_{N_{A,B,C,D}} = \sqrt{N_{A,B,C,D}}$, while the efficiencies $\epsilon_{A,B,C,D}^{Bkg}$ are assumed to be taken from the corresponding probability density function of the Monte Carlo background distribution with no statistical error attached. Gaussian error propagation yields for the error on $N^{Sig/Bkg}$

$$\begin{aligned}
\sigma_{N^{Sig/Bkg}} = & \left[\left(\frac{\partial N^{Sig/Bkg}}{\partial N_A} \sigma_{N_A} \right)^2 + \left(\frac{\partial N^{Sig/Bkg}}{\partial N_B} \sigma_{N_B} \right)^2 + \left(\frac{\partial N^{Sig/Bkg}}{\partial N_C} \sigma_{N_C} \right)^2 + \left(\frac{\partial N^{Sig/Bkg}}{\partial N_D} \sigma_{N_D} \right)^2 \right]^{\frac{1}{2}} \\
= & \left[\left(N^{Sig/Bkg}(N_A, N_B, N_C, N_D) - N^{Sig/Bkg}(N_A + \sqrt{N_A}, N_B, N_C, N_D) \right)^2 \right. \\
& + \left(N^{Sig/Bkg}(N_A, N_B, N_C, N_D) - N^{Sig/Bkg}(N_A, N_B + \sqrt{N_B}, N_C, N_D) \right)^2 \\
& + \left(N^{Sig/Bkg}(N_A, N_B, N_C, N_D) - N^{Sig/Bkg}(N_A, N_B, N_C + \sqrt{N_C}, N_D) \right)^2 \\
& \left. + \left(N^{Sig/Bkg}(N_A, N_B, N_C, N_D) - N^{Sig/Bkg}(N_A, N_B, N_C, N_D + \sqrt{N_D}) \right)^2 \right]^{\frac{1}{2}}. \tag{6.5}
\end{aligned}$$

In the second step the partial derivatives have been approximated due to the complex structure of equations 6.3 and 6.4. Results from this formula have been compared with the width of the estimated N^{Sig} - and N^{Bkg} -distributions from toy simulations (see sections 6.2.1 and 6.2.3) and agreed within a few percent.

6.2.1 Toy Monte-Carlo Studies

To evaluate the performance of the N^{Sig} - and N^{Bkg} -estimators, 10000 gaussian two-dimensional uncorrelated toy Monte-Carlo signal- and background-distributions similar to section 6.1.1 were generated to determine the error on the number of signal and background events for various degrees of signal and background separation. The background efficiencies for all toy simulations were taken from the corresponding gaussian probability density functions. The number of signal and background events for each toy was determined from a Poisson distribution with mean of $N_{true}^{Sig} = 500$ and $N_{true}^{Bkg} = 1500$ events. The projection into one of the discriminating variables for one sample toy is shown in the left column of Fig. 6.6 to illustrate the separation, which was chosen to be identical in the second variable. The right column of Fig. 6.6 shows the corresponding distribution of the estimated number of signal events using equation 6.3 for the full 10000 toy samples, indicating the estimated mean $\langle N^{Sig} \rangle$, with its associated

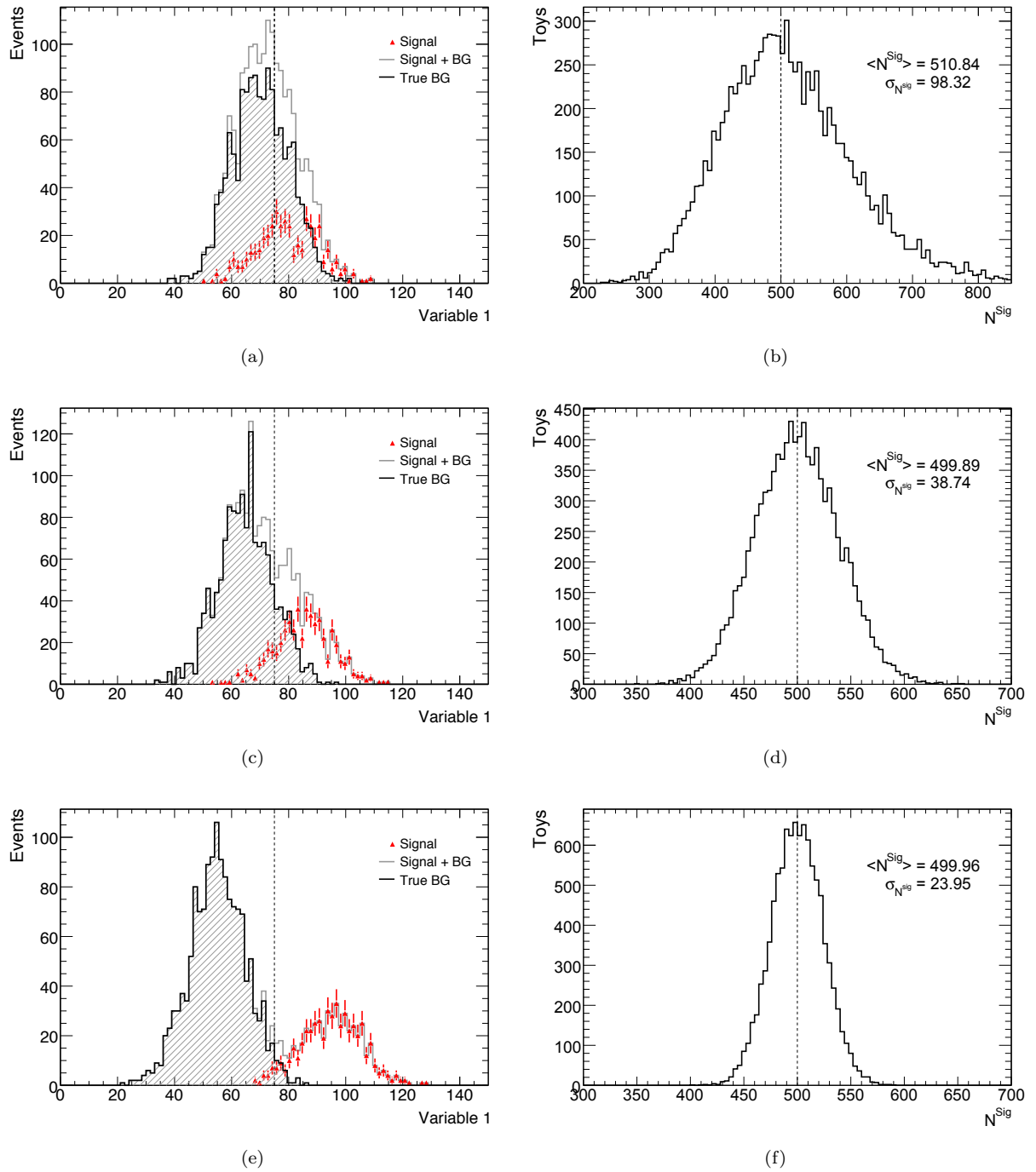


Figure 6.6: Left set of plots: Separation between signal and background distributions projected into one of the discriminating variables for one sample MC toy simulation. The dotted line indicates the cut in variable one. Right set of plots: Distribution of the estimated number of signal events for 1000 toy simulations corresponding to the separation indicated on the left. The dotted line here represents the true number of signal events.

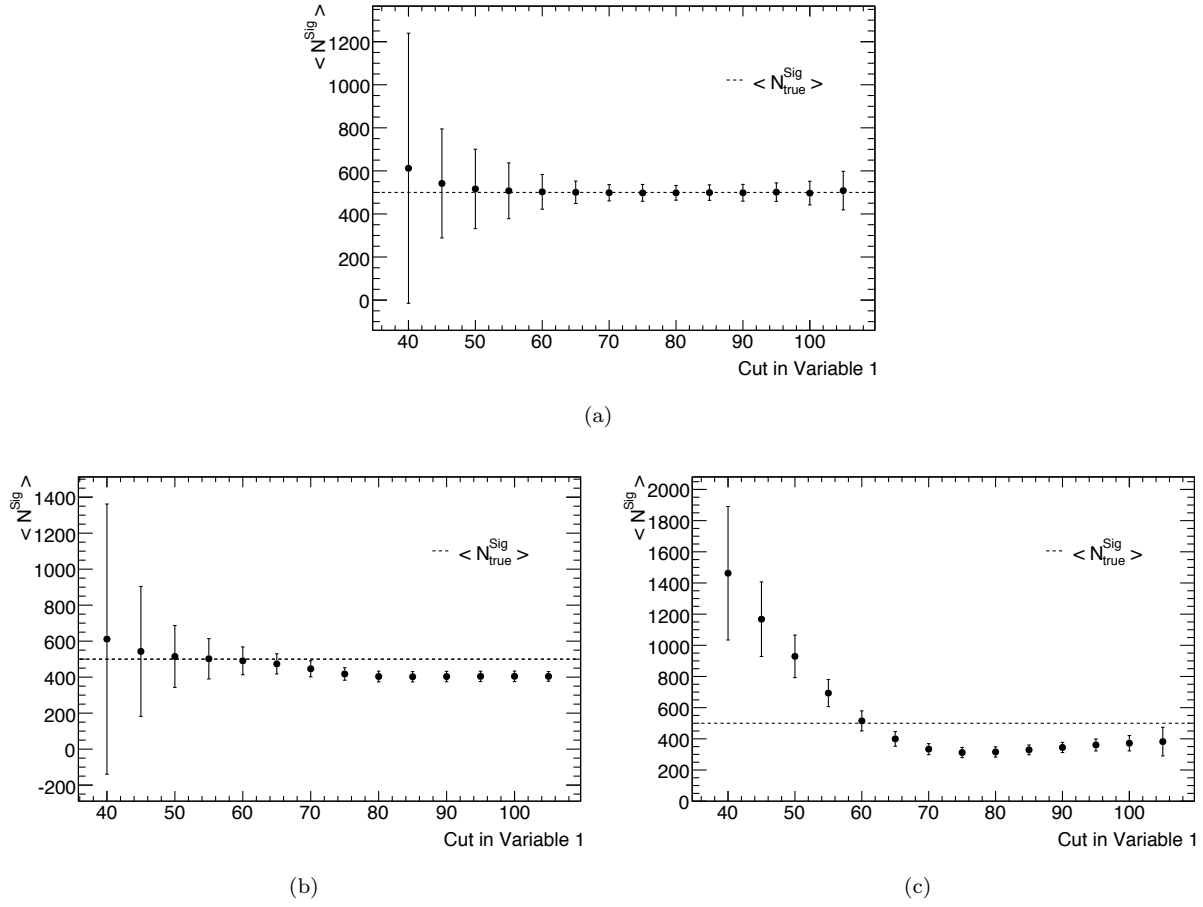


Figure 6.7: Estimated number of signal events as a function of a cut in one of the discriminating variables indicating the goodness of the estimate with (a) no signal correlations and correct background efficiencies, (b) strong linear signal correlations, and (c) incorrect background efficiencies.

gaussian uncertainty $\sigma_{N_{Sig}} = (\langle N_{Sig}^2 \rangle - \langle N_{Sig} \rangle^2)^{1/2}$. It can be seen that for high separation powers the width approaches the nominal error of $\sigma_{N_{Sig}} = \langle N_{Sig} \rangle^{1/2}$, whereas for large overlap between signal and background the associated errors become larger.

Statistical uncertainties. The estimate of $N_{Sig/Bkg}^{Sig/Bkg}$, and in particular the associated errors, depend strongly on the selections in variables one and two which define the quadrants A, B, C, D. This is illustrated in Fig. 6.7a for the estimated number of signal events, where the cuts in variable one are propagated through in intervals, using the correct background efficiencies. The widths and the statistical errors are again obtained from 10000 toy simulations. One can see that the estimate has large statistical uncertainties at the fringes of the distributions, while the errors are small in the intermediate region, where the cut well separates signal and background. The asymmetric structure of the errors in Fig. 6.7a is due to the different number of signal and background events. For all cuts the estimator yields an accurate result.

Systematic effects. The method-specific systematic biases on toy-MC level are correlations in the signal distributions and incorrect background efficiencies. The effects on the scan through the discriminating variables are illustrated in the bottom two plots of Fig. 6.7. In Fig. 6.7b strong linear correlations (90%) have been introduced in the signal distribution leading to a significant underestimation for cuts in the signal dominated region at high values of variable one. Fig. 6.7c shows how incorrect background efficiencies, which in this case have been taken from a gaussian probability density function with different

width, can significantly impact the quality of the estimate. In a realistic analysis the magnitude of both effect needs to be assessed and treated as a systematic uncertainty of the method. A detailed study will be performed in section 6.2.3.

Goodness-of-estimate. It is important to note that a scan through the discriminating variables as shown in Fig. 6.7 represents a powerful test of the goodness of the estimate. If there is no shift in the estimated $\langle N^{Sig} \rangle$ or $\langle N^{Bkg} \rangle$ for a series of consecutive cuts throughout the entire distributions in both variables the method is not significantly biased by systematic effects, such as signal correlations or incorrect background efficiencies, and the true value lies within the statistical errors of the estimate.

6.2.2 Performance in SUSY Searches

The above described '4-tiles'-method is now applied to the SUSY search studies of Chapter 5. Contrary to the preceding toy studies we are now predominantly investigating the estimated number of background events (equation 6.4), which turns out to be more convenient for the significance calculations of section 6.3.

The discriminating variables of the method are defined to be effective mass M_{eff} and transverse mass M_T due to their good separation properties. The performance for all SUx models is evaluated by scanning through cuts in M_{eff} over the full range of the distribution. The transverse mass selection remains at 100 GeV as in section 6.1.2 and the knowledge of correct background efficiencies is assumed. The resulting goodness-of-estimate tests are shown in Fig. 6.8 for the N^{Bkg} estimator and in A.4 for N^{Sig} . With the exception of SU4 it can be seen that all estimates agree within the statistical uncertainty of the method with the true values over the full M_{eff} -range. For some models small systematic shifts within these errors due to signal correlations can be observed. As for the toy studies shown in Figures 6.6 and 6.7, the estimate is best and the associated error smallest if the cut in M_{eff} well separates the signal and background distributions. In the case of the low mass point SU4, strong correlations as well as SM-like M_T - and M_{eff} -distributions with low separation power (see Fig. 5.7) significantly bias the result.

For each benchmark point the best-discriminating M_{eff} -cut was chosen to determine the estimated number of background events N_{Bkg} . The results are summarized in Table 6.4 .

Sample	SU1	SU2	SU3	SU4	SU6	SU8
M_{eff} -cut	1200 GeV	1200 GeV	800 GeV	500 GeV	1200 GeV	1200 GeV
N^{Bkg}	1865 ± 59.5	1870 ± 59.0	1880 ± 61.4	3128 ± 244.6	1870 ± 55.2	1865 ± 54.3

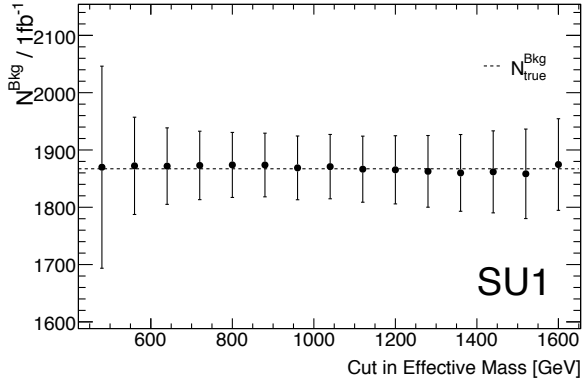
Table 6.4: M_{eff} -selection and resulting estimated number of background events including statistical errors for all SUx benchmark points.

6.2.3 Treatment of Systematic Uncertainties

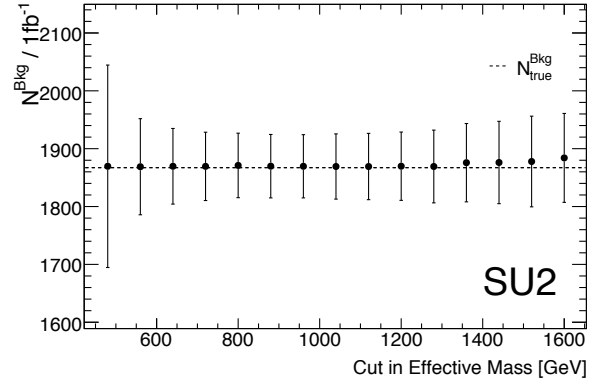
To evaluate the discovery potential for the SUx benchmark points with the estimates of N^{Bkg} obtained above, detailed studies of the method- and detector-related systematic uncertainties are necessary. The effects of correlations have been studied explicitly within the scope of this thesis and the remaining effects are summarized from [71].

Signal Correlations

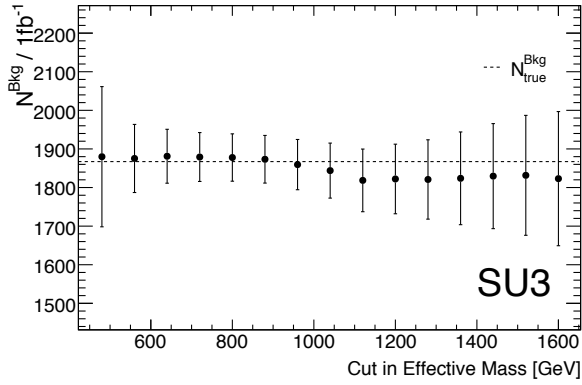
To quantify and study the effect of signal correlations, 'realistic' toy samples were produced from a two-dimensional probability density function of the Monte-Carlo SM backgrounds and all SUx benchmark points in M_T - M_{eff} -space. The probability density functions were created with the RooFit toolkit for data modeling [72], which allows to perform two-dimensional fits to arbitrary input datasets as a superposition of Gaussian kernels for each data point. A detailed description of the general algorithm can be found in



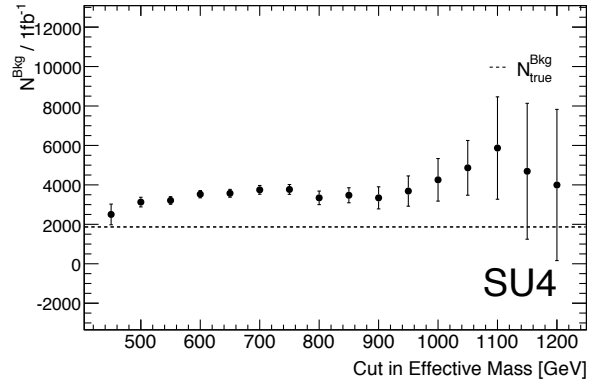
(a)



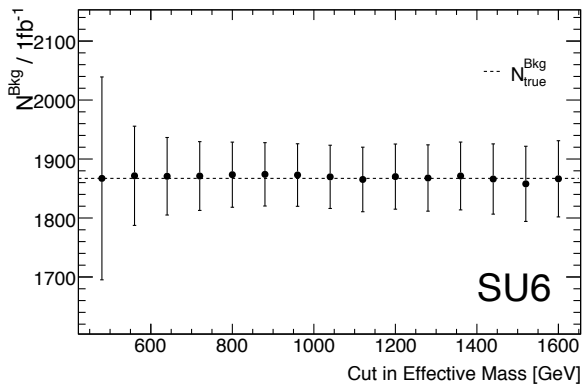
(b)



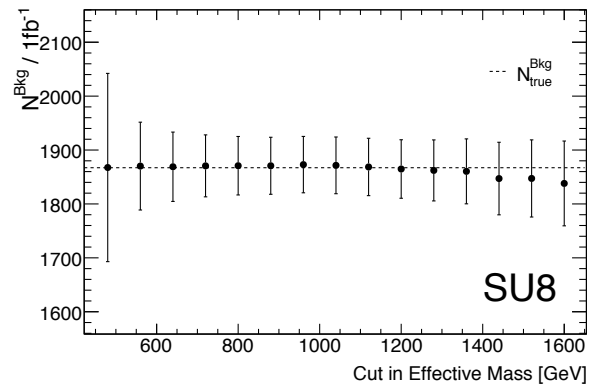
(c)



(d)



(e)



(f)

Figure 6.8: Estimated number of background events as a function of a cut in M_{eff} (goodness-of-estimate test) for all SUx benchmark points.

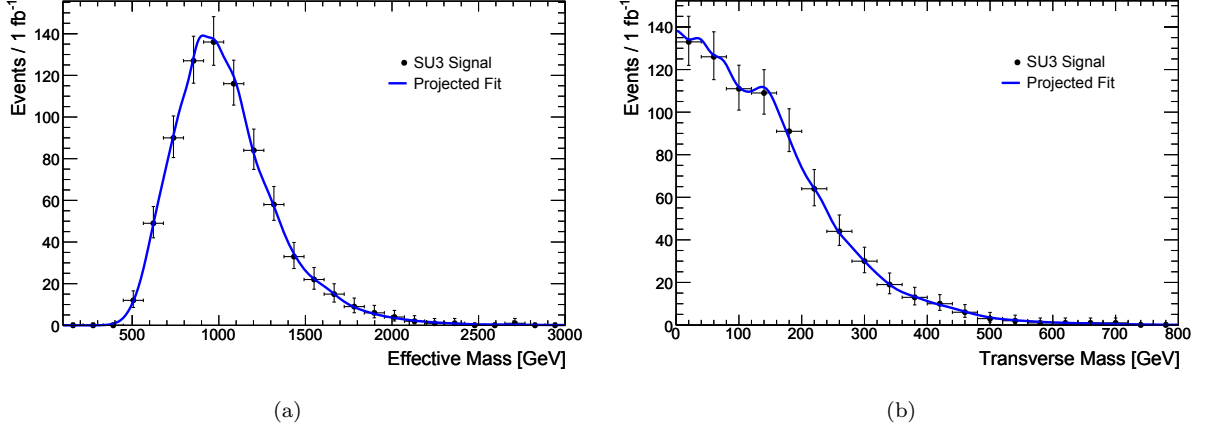


Figure 6.9: *Projections of the two-dimensional fit of the SU3 signal distribution in M_{eff} and M_T using Gaussian kernel estimation.*

[73]. An example of the quality of the fit is shown in Fig. 6.9 for the SU3 signal distribution projected into M_{eff} and M_T . From the fitted signal and background probability density functions 1000 toy Monte-Carlo samples were generated using the 'accept-reject' method². As the two-dimensional fit allows to model correlations correctly, one can now investigate the systematic shift of the estimated number of signal and background events. In Fig. 6.10a, the effect is shown for SU3 signal denoted by the black histogram, using 1000 toy simulations and a cut at $M_{eff} = 800$ GeV. As one can see the central value of the estimated number of background events differs from the true value. For comparison the same SU3 signal sample can be artificially decorrelated by interchanging the values of one variable from one event with the corresponding values of the next event. The resulting distribution is denoted by the red histogram, which is centered around the true value as expected. The magnitude of the shift between the two distributions is the systematic error of the method due to correlations.

In addition to the study of correlations, the toy Monte-Carlo simulations are a powerful tool to further validate the '4-tiles' background estimation method on more 'realistic' data samples. Fig. 6.10b for example shows the 'pull' of the estimated number of background events, which is defined as $(N^{Bkg} - N_{true}^{Bkg}) / \sigma_{N^{Bkg}}$ evaluated for each toy, where $\sigma_{N^{Bkg}}$ is obtained from the error approximation 6.5. As one can see, the width of the distributions is compatible with one, which confirms the correctness of (6.5) within a few percent.

In A.5 the remaining 'pull'-distributions are shown for all SUx benchmark points and the expected systematic shifts on the number of background events due to correlations are summarized in Table 6.5. As expected the effect is rather small for most models except SU4, where a strong deviation from the true value is observed (see Fig. A.5d).

Sample	SU1	SU2	SU3	SU4	SU6	SU8
Deviation	0.241 %	0.137 %	0.621 %	67.5 %	0.107 %	0.229%

Table 6.5: *Systematic bias on the background estimate due to signal correlations.*

²The 'accept-reject'-method is a statistical technique to generate sampling values from an arbitrary probability density function [74].

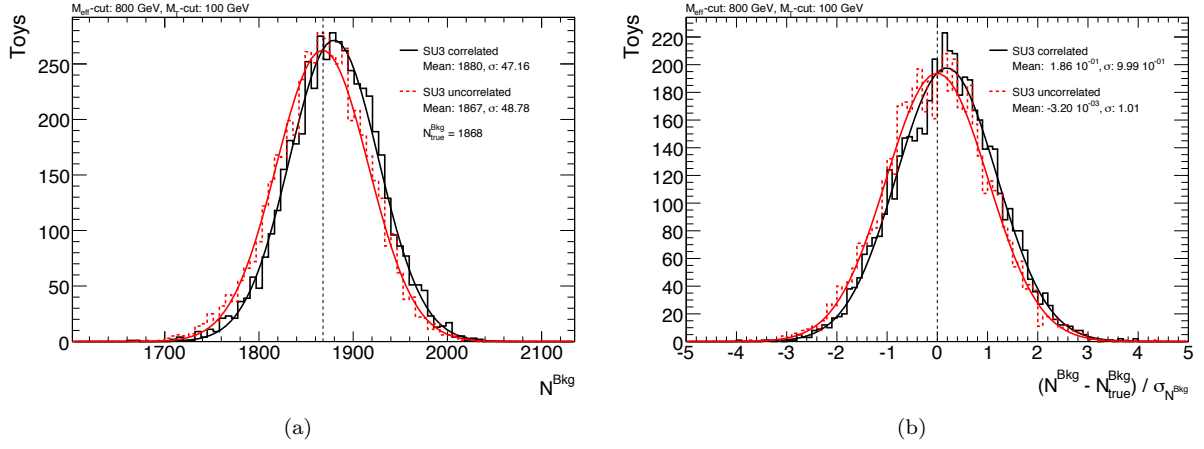


Figure 6.10: Illustrations of the systematic shift of the estimated number of background events due to signal correlations using SU3 signal for 1000 'realistic' toy-MC simulations. Left: Absolute number of estimated background events. Right: Relative deviation from the true value divided by the statistical uncertainty of the estimate. The true values are denoted by the dashed vertical line.

MC cross sections

The '4-tiles' method uses background efficiencies determined from Monte-Carlo simulations that may not describe the true Standard Model distributions in data correctly. In particular the cross sections of the constituent background contributions may be associated with different uncertainties leading to a variation of the shape of the total background distribution and thus different background efficiencies. In [71] this bias has been investigated by rescaling the two dominating background contributions $W + \text{Jets}$, and $t\bar{t}$ by $\pm 5\%$, which reflects the expected uncertainties on the corresponding cross section as quoted by the ATLAS Standard Model and Top Physics working groups [75] [76]. Additionally the leptonic and semi-leptonic components of the $t\bar{t}$ background sample have been varied by $\pm 1\%$ to account for uncertainties in the lepton identification efficiency.

The incorrect background efficiencies from the above described variations have been fed into the N^{Bkg} -estimator to determine the systematic shift. The results are summarized in Table 6.6.

Sample	SU1	SU2	SU3	SU4	SU6	SU8
$\sigma_W + 5\%$, $\sigma_{t\bar{t}} - 5\%$	0.05 %	0.18 %	0.22 %	0.73 %	0.04 %	0.07%
$\sigma_W - 5\%$, $\sigma_{t\bar{t}} + 5\%$	-0.04 %	-0.13 %	-0.20 %	-0.67 %	-0.03 %	-0.06%
$\sigma_{t\bar{t}(l\nu qq)} + 1\%$, $\sigma_{t\bar{t}(l\nu l\nu)} - 1\%$	0.23 %	0.25 %	0.25 %	0.25 %	0.21 %	0.20%
$\sigma_{t\bar{t}(l\nu qq)} - 1\%$, $\sigma_{t\bar{t}(l\nu l\nu)} + 1\%$	-0.23 %	-0.25 %	-0.25 %	-0.25 %	-0.21 %	-0.19%

Table 6.6: Systematic errors on the background estimate due to cross section uncertainties [71].

Jet Energy Scale

To incorporate the uncertainty on the jet energy scale, the jet energies of the background Monte-Carlo samples are varied by $\pm 10\%$ prior to the application of any analysis selections. Subsequently all jet-dependent quantities such as missing transverse energy are recalculated and the resulting background efficiencies are derived. The systematic biases in the estimated number of background events are summarized in Table 6.7 [71].

Sample	SU1	SU2	SU3	SU4	SU6	SU8
JES +10 %	0.31 %	0.81 %	2.77 %	14.23 %	0.29 %	0.80%
JES -10 %	1.23 %	1.49 %	-0.56 %	-12.14 %	1.14 %	0.59%

Table 6.7: *Systematic bias of the background estimate due to the jet energy scale uncertainty [71].* **$\cancel{E}_T$ resolution**

In addition to the bias of jet energy scale variations on missing transverse energy, the effect of decreased resolution in the $\cancel{E}_T$ measurement has been studied by adding a Gaussian smearing 100 % to the measured values. The effects on the background estimates are summarized in Table 6.8 [71].

Sample	SU1	SU2	SU3	SU4	SU6	SU8
$\cancel{E}_T$ resolution	3.65 %	4.01 %	3.72 %	5.62 %	3.36 %	2.67%

Table 6.8: *Systematic bias of the background estimate due to decreased $\cancel{E}_T$ -resolution [71].***6.3 Determination of the Discovery Potential**

The estimated number of background events and the associated statistical and systematic uncertainties are now used to evaluate the discovery potential for the SUx benchmark points. The significance is calculated in the signal-dominated D-quadrant from the number of observed data events N_D^{Data} and the estimated number of background events $N_D^{Bkg} = \epsilon_D^{Bkg} N^{Bkg}$. The above listed statistical and systematic uncertainties are propagated into the D-region accordingly, as shown in Table 6.9. For a conservative background estimate the following errors have been applied globally for all benchmark points except SU4

$$\sigma_{N_D^{Bkg}} = \sigma_{stat}(4\%) \oplus \sigma_{corr}(1\%) \oplus \sigma_{MC}(2\%) \oplus \sigma_{JES}(22\%) \oplus \sigma_{\cancel{E}_T}(11\%). \quad (6.6)$$

In the case of SU4 the uncertainties have been taken as quoted in Table 6.9. The p-values and the corresponding significance $\mathcal{S}$ in terms of standard deviations have been determined as described in Chapter 5 using the **StatTools** package [69].

All results are summarized in Table 6.9. One can see that the expected significance levels in 1 fb^{-1} of integrated luminosity using the '4-tiles' background estimation method are only slightly reduced with respect to the values obtained directly from Monte-Carlo simulations (see Table 5.8). An exception is again the low mass point SU4, which is dominated by systematic effects. However, as mentioned in the previous sections and confirmed by the results presented here, the hypothetical cross section of SU4 at LHC energies is high enough to observe a significant excess of signal events despite the large uncertainties on the background estimate.

Sample	SU1	SU2	SU3	SU4	SU6	SU8
$M_{eff}\text{-cut [GeV]}$	1200	1200	800	500	1200	1200
N_D^{Bkg}	7.93	7.95	48.0	278	7.95	7.92
N_D^{Data}	113	21.8	402	3039	76.4	68.2
σ_{stat}	3.2 %	3.2 %	3.3 %	7.8 %	3.0 %	2.9 %
Correlations	0.24 %	0.14 %	0.62 %	67.5 %	0.11 %	0.23 %
$\sigma_W + 5 \text{ \%}, \sigma_{t\bar{t}} - 5 \text{ \%}$	-1.4 %	-1.5 %	-0.3 %	0.2 %	-1.4 %	1.9%
$\sigma_W - 5 \text{ \%}, \sigma_{t\bar{t}} + 5 \text{ \%}$	1.5 %	1.7 %	0.4 %	-0.2 %	1.5 %	-1.7%
$\sigma_{t\bar{t}(l\nu q\bar{q})} + 1 \text{ \%}, \sigma_{t\bar{t}(l\nu l\nu)} - 1 \text{ \%}$	1.2 %	1.3 %	1.4 %	1.3 %	1.2 %	1.2%
$\sigma_{t\bar{t}(l\nu q\bar{q})} - 1 \text{ \%}, \sigma_{t\bar{t}(l\nu l\nu)} + 1 \text{ \%}$	-1.2 %	-1.2 %	-1.3 %	-1.3 %	-1.2 %	-1.2%
JES +10 %	1.9 %	1.7 %	-0.4 %	11.3 %	1.2 %	2.1%
JES -10 %	-21.3 %	-21.0 %	5.4 %	-4.7 %	-21.3 %	-17.6%
$\cancel{E}_T$ resolution	8.6 %	9.0 %	10.7 %	24.2 %	8.3 %	9.6%
Significance $\mathcal{S}$	15.4	3.24	17.8	13.6	11.4	10.4

Table 6.9: Summary of the estimated number of background events N_D^{Bkg} , applied M_{eff} -selections, number of observed data events N_D^{Data} , systematic uncertainties, and resulting significances in units of standard deviations for all SUx benchmark points. All numbers apply to the signal-dominated D -quadrant.

Chapter 7

Summary

The ATLAS experiment at the Large Hadron Collider is currently starting operation. One of its main design goals is the search for new physics beyond the Standard Model. Supersymmetry (SUSY) is one of the most attractive possible extensions to the standard model answering many open questions in the field of particle physics. If SUSY really exists at the electroweak energy scale it is likely to be found at the LHC.

Within this thesis extensive studies of the discovery potential for mSUGRA SUSY scenarios within 1 fb^{-1} of ATLAS data corresponding to $\mathcal{O}(200)$ days of LHC operation at $\mathcal{L} = 10^{32} \text{ cm}^{-2}\text{s}^{-1}$ were carried out. The focus of this work was on signatures with multiple high- p_T jets, missing transverse energy and one isolated lepton in the final states. The reconstruction performance of these objects and quantities in hypothetical SUSY events was investigated. Based on Monte-Carlo simulations with next-to-leading order cross section corrections, an inclusive search strategy was described and tested for a variety of characteristic mSUGRA benchmark points and the relevant background processes. The effective mass M_{eff} and missing transverse energy $\cancel{E}_T$ were chosen as discriminating variables and selections were applied as suggested in [32] and [40]. Systematic uncertainties on the Monte-Carlo background distributions were included in the analysis. For all benchmark points except the focus point 'SU2', a significant excess of signal over background events above the nominal 5σ threshold for a discovery could be observed (see Table 5.8). As shown by earlier studies [32][40], these results confirm that the one-lepton search mode constitutes a promising channel for a potential discovery of mSUGRA-like SUSY scenarios.

To put the results of this analysis into a more realistic context, methods to determine the Standard Model backgrounds from data were investigated. Initially, toy Monte-Carlo simulations were used to systematically study a simple sideband-based approach, which extrapolates a background-enhanced control sample distribution into regions where an excess of signal events is expected. This well-known technique was then extended to the mSUGRA search studies using the discriminating variables transverse mass M_T and missing transverse energy $\cancel{E}_T$ as suggested in [70]. The performance was evaluated for all constituent background processes inclusively by using the combined Monte-Carlo signal and background distributions as test-'data'. It was found that the method yields severe deviations from the true number of background events and is strongly dominated by systematic effects, such as control sample signal contamination and to a smaller extend correlations between the discriminating variables.

In order to improve on these results, a new data-driven background estimation approach, referred to as '4-tiles'-method, was introduced. Therein an analytical estimator is derived for the number of signal and background events by introducing a partial, but systematically controllable dependence on Monte-Carlo information. The method is based on four ideally signal- or background enhanced quadrants or 'tiles', resulting from selections in two discriminating variables. Extensive studies and tests with toy Monte-Carlo samples showed stable and very accurate results. Subsequently the performance of the '4-tiles'-method was evaluated on the Monte-Carlo test-'data' of Chapter 5 using the discriminating variables

transverse mass M_T and effective mass M_{eff} , including a full treatment of method- and detector-related systematic uncertainties. For all benchmark points except the problematic low mass point 'SU4', the obtained discovery potential was only slightly reduced compared to the results directly obtained from Monte-Carlo simulations (see Table 6.9). In the case of 'SU4', the large fraction of signal events, strong signal correlations and the low separation power to Standard Model background led to a major increase of systematic uncertainties. However, due to the large cross section the statistical significance of 'SU4' was found to still be well above the 5σ threshold.

In summary, the '4-tiles'-method appears to be a promising data-driven approach to estimate the Standard Model backgrounds to inclusive SUSY searches. Further developments and a generalization to 'n-tiles' using a likelihood-based approach are currently under investigation and will be reported in [71].

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Appendix A

Additional Figures

A.1 Jet reconstruction efficiencies without p_T -selection

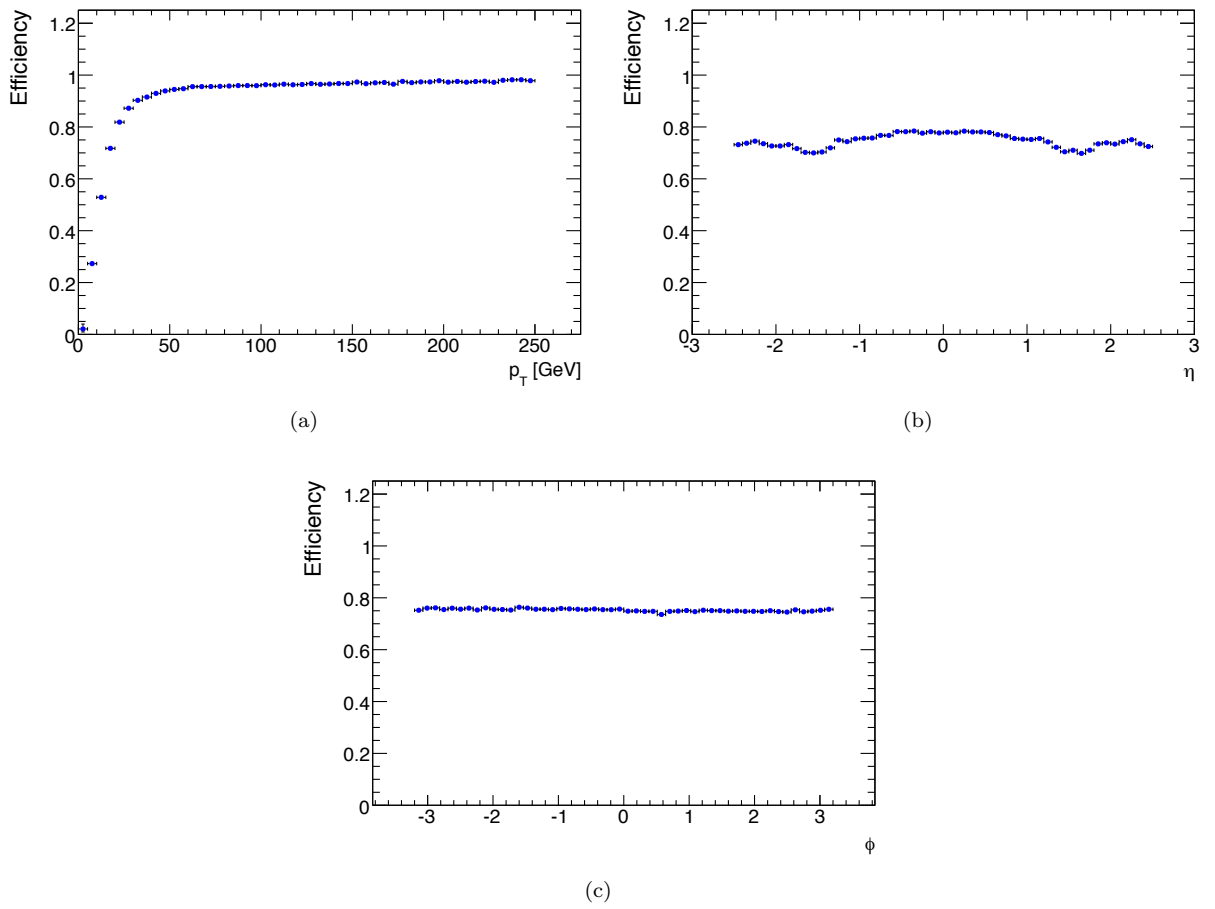


Figure A.1: *Reconstruction efficiencies for *towerCone4*-jets as functions of p_T , η , and ϕ without cut at $p_T = 50\text{GeV}$.*

A.2 M_T -method background estimates in $\cancel{E}_T$ and M_{eff} for all benchmark points

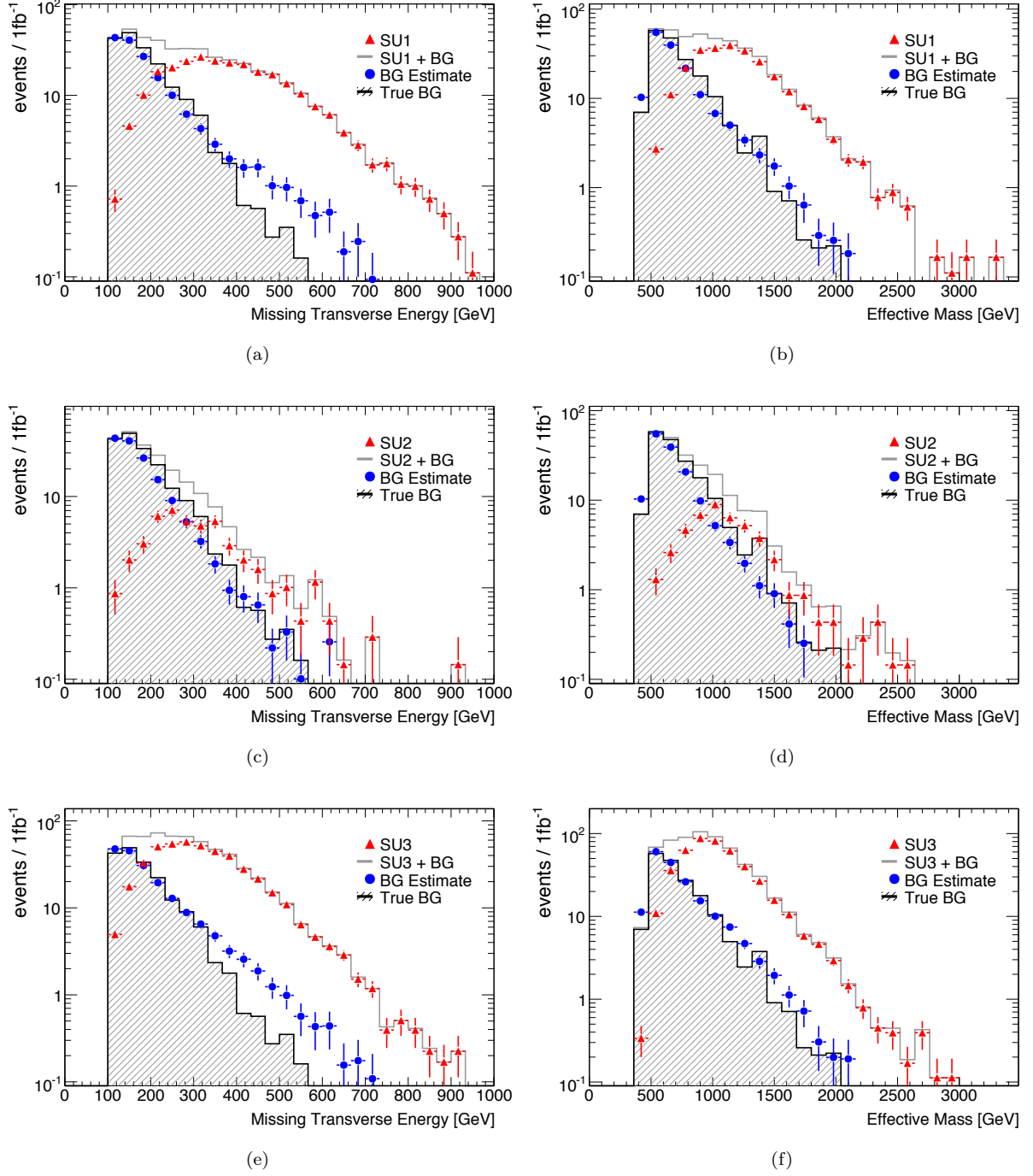


Figure A.2: Missing transverse energy and effective mass distributions for true Standard Model background, the SUSY signal, combined signal and Standard Model background, and the resulting background estimate for the SU1, SU2, and SU3 benchmark points.

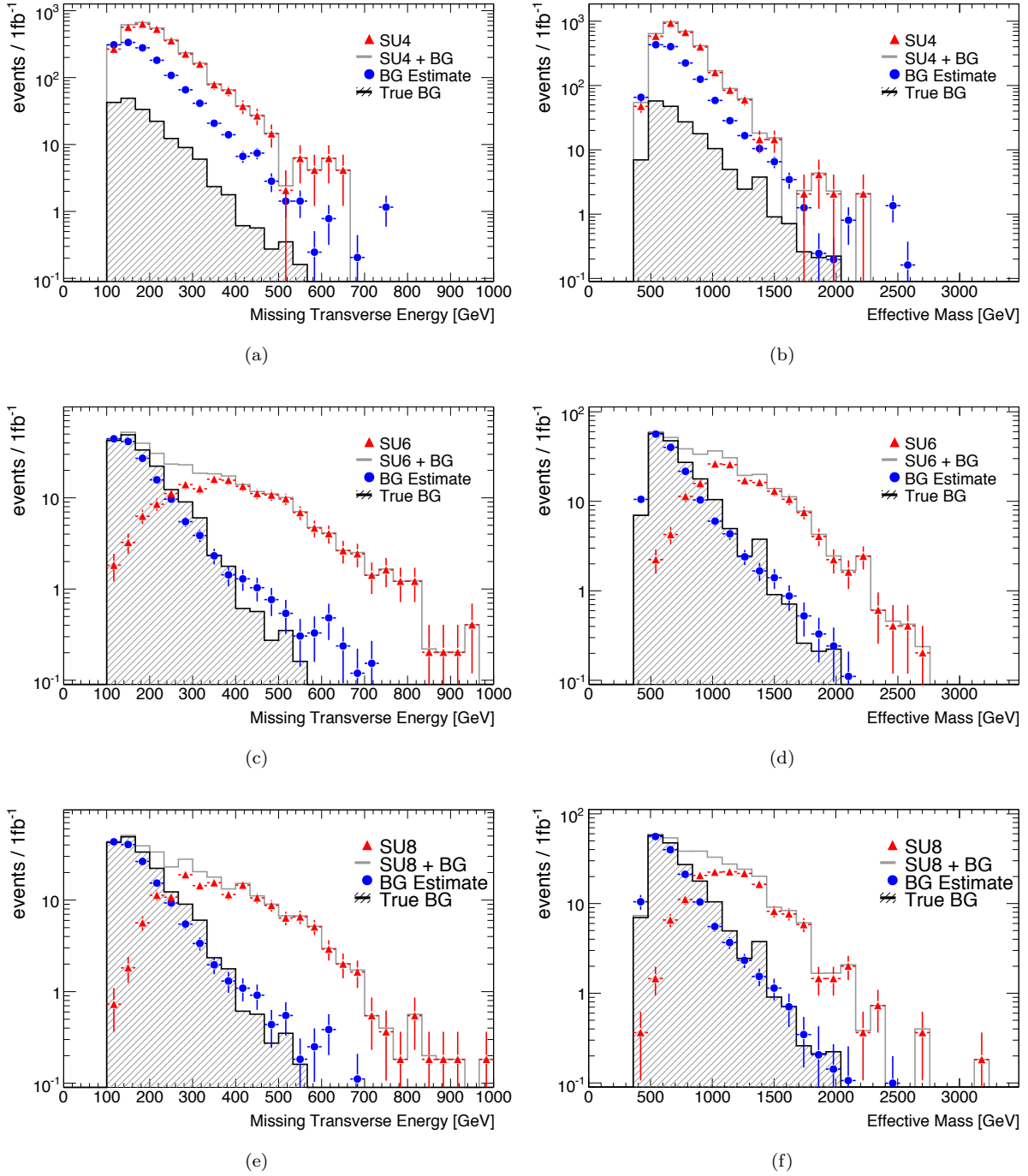


Figure A.3: Missing transverse energy and effective mass distributions for true Standard Model background, the SUSY signal, combined signal and Standard Model background, and the resulting background estimate for the SU4, SU6, and SU8 benchmark points..

A.3 '4-tiles'-method signal estimates for all benchmark points

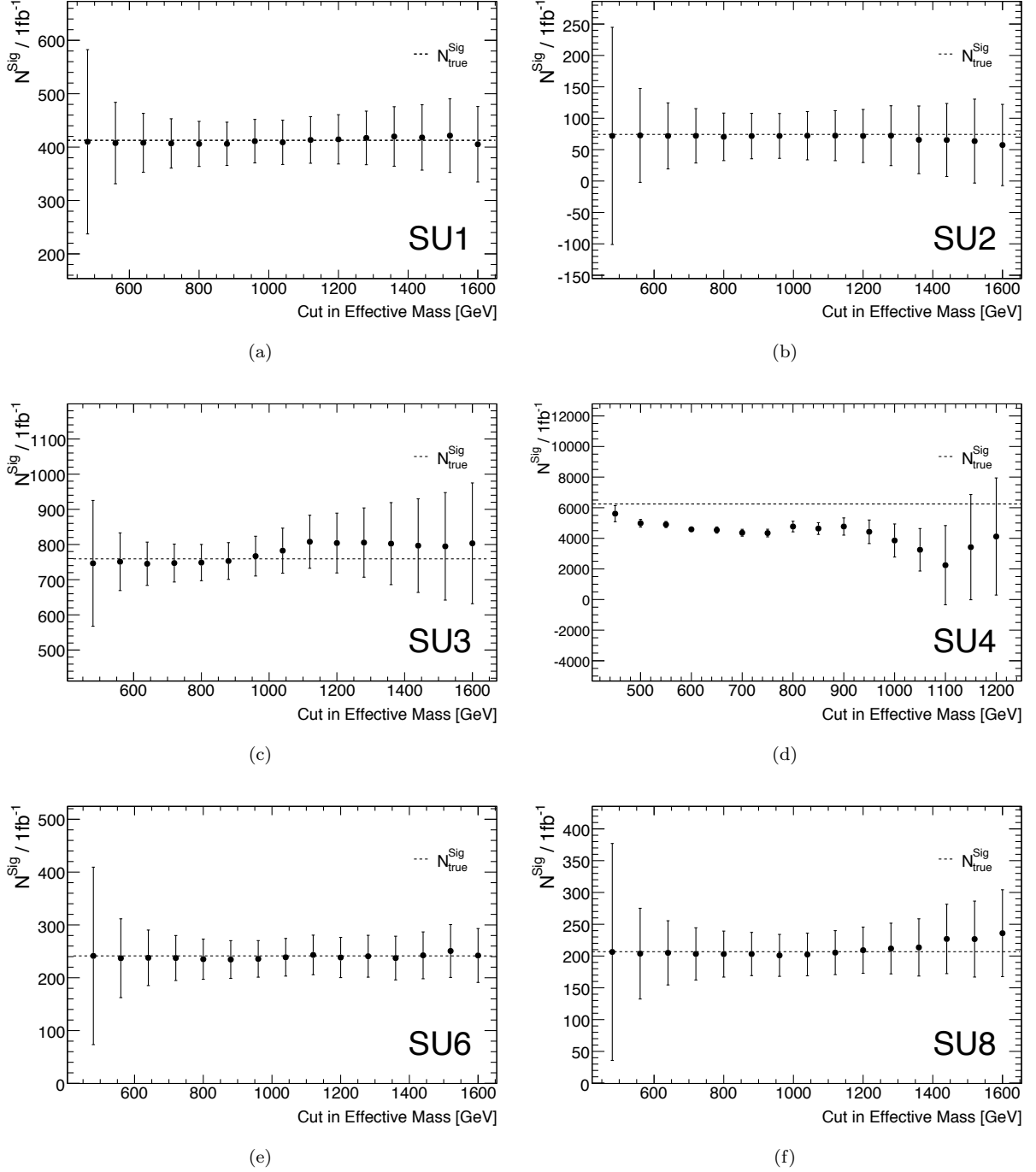


Figure A.4: *Estimated number of signal events as a function of a cut in M_{eff} (goodness-of-estimate test) for all SU_x benchmark points.*

A.4 'Pull'-distributions for all benchmark points

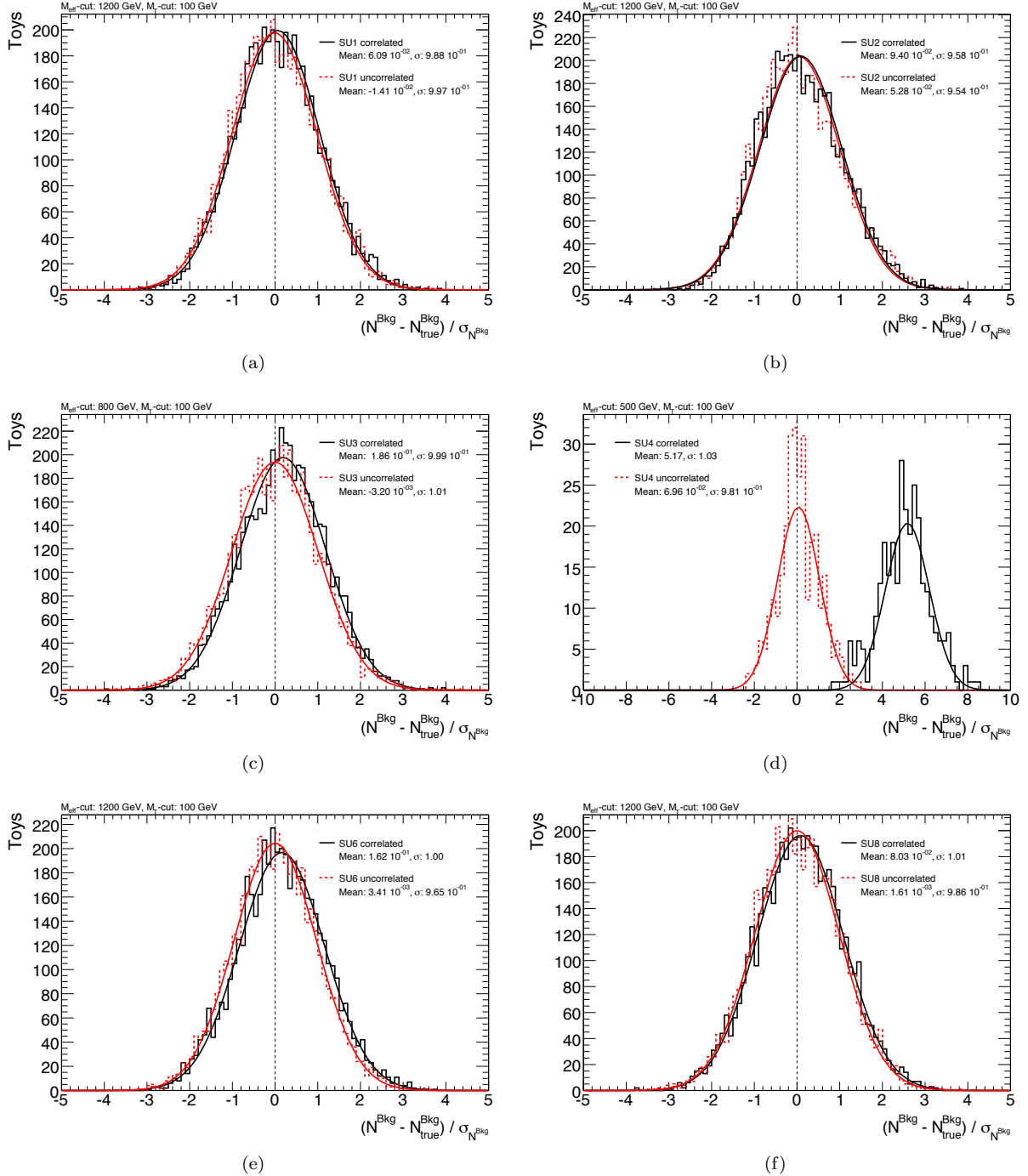


Figure A.5: Illustration of the systematic shift of the estimated number of background events due to signal correlations for all SUx benchmark points using 'realistic' toy-MC simulations. The graphs show the relative deviation from the true value divided by the statistical uncertainty of the estimate.

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Erklärung

Ich versichere, dass ich diese Diplomarbeit selbständig angefertigt, nicht anderweitig für Prüfungszwecke vorgelegt, alle benutzten Quellen und Hilfsmittel angegeben, sowie wörtliche und sinngemäße Zitate gekennzeichnet habe.

Ich bin damit einverstanden, dass meine Diplomarbeit öffentlich einsehbar ist (Bibliothek) und der wissenschaftlichen Forschung zur Verfügung steht.

Hamburg, den 15. September 2008

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