Search for Supersymmetry Signatures at the LHC

N. Öztürk, for the ATLAS and CMS Collaborations

Department of Physics, University of Texas at Arlington, Arlington, TX, 76019, USA

Supersymmetry (SUSY) is one of the most interesting and comprehensively studied models for new physics beyond the Standard Model. If SUSY exists in nature the Large Hadron Collider will provide excellent opportunities to search for SUSY. SUSY discovery strategies of the ATLAS and CMS experiments are presented with a focus on early data. SUSY mass measurement techniques and determination of SUSY model parameters are also demonstrated.

1. Introduction

Supersymmetry is a theoretically attractive model for extension of the Standard Model (SM) [1]. It proposes that all the SM particles have SUSY partners with a spin difference of ±1/2. Among its motivations; SUSY solves the fine-tuning problem (Higgs mass stabilization against loop corrections), SUSY modifies running of the SM gauge couplings just enough to give the grand unification at a single scale and SUSY also offers a candidate for dark matter through R-parity conservation. Since SUSY partners of the SM particles have not been observed at the same mass scale SUSY must be a broken symmetry at low energy. The Minimal Supersymmetric Standard Model (MSSM) brings more than a hundred free parameters into the theory, thus searching for SUSY is a very challenging task.

One of the main objectives for building the Large Hadron Collider (LHC) is to discover SUSY. The ATLAS (A Toroidal LHC ApparatuS) and CMS (Compact Muon Solenoid) are two general purpose detectors at the LHC designed to search for SUSY particles (and for the Higgs boson). Both experiments have successfully seen the first beam events in September 2008 and have been commissioning with the cosmic rays since then. The LHC is scheduled to start up in November 2009.

The ATLAS and CMS experiments put enormous efforts recently to get ready for the analysis of the first LHC data. ATLAS has written a collection of notes published as a CERN book [2] based on the results from the Computer System Commissioning (CSC) exercise. CMS has written a Technical Design Report II [3]. Both have dedicated chapters to SUSY covering a broad spectrum in SUSY analyses with 14 TeV center of mass energy. Post-CSC studies in ATLAS [4, 5, 6, 7, 8] and post-TDR studies in CMS [9, 10, 11, 12, 13] have followed for both 14 TeV and 10 TeV center of mass energies resulting in a variety of public notes. This review article is based on these recent studies. A brief mention of the SUSY search strategies at the LHC, examples of the data-driven methods will be given for estimating the SM backgrounds to SUSY searches. Then searches with the inclusive missing transverse energy (\(E_T^{\text{miss}}\)) signatures and an exclusive search without explicit use of \(E_T^{\text{miss}}\) will be summarized. Examples from special SUSY signatures of the non-standard SUSY models will be presented together with the discovery reach of some SUSY models. The article will conclude after a discussion on the SUSY mass measurements and determination of SUSY model parameters upon a possible SUSY discovery.

2. SUSY Search Strategies at the LHC

The SUSY breaking mechanism determines the phenomenology and search strategy in the collider experiments. Many possible mechanisms have been proposed; mSUGRA [14], GMSB [15], AMSB [16], SO(10) SUSY GUTs [17], Split-SUSY [18] and others. The search strategies can be discussed in two classes of models:

1. Standard SUSY models with R-parity conservation. In this class SUSY is searched for as an evidence of excess above the SM background in the following channels; 0, 1, 2 leptons+≥ 2, 3, 4 jets+\(E_T^{\text{miss}}\), \(\gamma+jets+E_T^{\text{miss}}\), τ or b-jets+\(E_T^{\text{miss}}\), multi-leptons, multi-jets without \(E_T^{\text{miss}}\) and others.

2. Non-standard SUSY models with special signatures; displaced vertices, stopped gluinos in the calorimeter, non-pointing photons, long-lived stable massive particles and others.

Understanding the SM backgrounds play an essential role in SUSY searches. Main sources of the SM backgrounds come from the following processes; \(t\bar{t}+jets\), \(W^{+}+jets\), \(Z^{+}+jets\), QCD jets and diboson (ZZ, WW, WZ) production. The data-driven estimation of the SM backgrounds, will be an emphasis of early analyses. Understanding the fake \(E_T^{\text{miss}}\) distributions as well as the reconstruction of the non-standard signatures will be a critical task in the search for SUSY.
3. Estimation of the Standard Model Backgrounds to SUSY Searches

Several Monte Carlo-driven and data-driven estimation techniques have been developed to estimate the SM backgrounds. Some of the data-driven estimation techniques are listed as:

- $Z \rightarrow \nu\bar{\nu}$ background in 0-lepton mode \cite{13}.
- QCD background in 0-lepton mode SUSY search using the jet smearing method \cite{2}.
- QCD background in 1-lepton mode SUSY search using the lepton isolation method \cite{2}.
- $t\bar{t}$ background in 0-lepton mode using the replacement technique \cite{6}.
- $t\bar{t}$ background in 1-lepton mode SUSY search using the Topbox method \cite{2}.
- Combined background in 1-lepton mode SUSY search using $m_T$ method \cite{2} (further development with combined fit) and Tiles method \cite{2}.
- Others.

As an example two of the data-driven approaches are summarized below.

3.1. Data-driven estimation of the QCD background in the hadronic channel

The biggest background estimation challenge for SUSY searches in the jets+$E_T^{\text{miss}}$ channels will be estimation of the QCD jet background. This background involves two sources of $E_T^{\text{miss}}$:

1. Fake $E_T^{\text{miss}}$: non-Gaussian tails to the detector jet response function arising from the dead material, jet punch-through, pile-up and other effects. It can be suppressed by applying the jet-$E_T^{\text{miss}}$ azimuthal angle cuts, calorimeter and tracking cuts and cosmic background rejection cuts.

2. Real $E_T^{\text{miss}}$: resulting from the non-interacting particles such as neutrinos or the Lighest Supersymmetric Particle (LSP).

Two approaches are taken to estimate the remaining QCD jet backgrounds; Monte Carlo-driven estimates and data-driven estimates. The Monte Carlo based estimates are subject to large systematics effects arising from the proton parton distributions, underlying event uncertainties, jet energy scale uncertainty and an uncertainty in modeling the QCD jet physics with Monte Carlo generators (PYTHIA versus ALPGEN). There will also be an uncertainty from the luminosity measurement. In addition, the detector simulation uncertainties (imperfect description of the response of the detector to jets) and the statistical uncertainties (large QCD cross section rendering production of full simulation samples unfeasible) will contribute. As for the data-driven estimates they will be crucial in early phase of data taking as they are less prone to input systematics.

A method from an ATLAS study \cite{2} is described here for estimating the QCD jet background in the 0-lepton mode SUSY search. The method makes use of smearing the jet transverse momenta in low $E_T^{\text{miss}}$ QCD jet data with a data measured jet response function $R$ (ratio of the measured jet $p_T$ to the true jet $p_T$). The Gaussian part of the jet response function is measured with the balance of the $\gamma$+jet events. The non-Gaussian part of the jet response function is measured from the 'Mercedes' type of configuration ($E_T^{\text{miss}}$ is parallel or anti-parallel to the $p_T$ of one of the three jets selected in the event).

The jet response function is then used to smear the jet $p_T$ in multijet events with low $E_T^{\text{miss}}$ in order to estimate the $E_T^{\text{miss}}$ distribution of QCD multijet events. Figure 1 shows the $E_T^{\text{miss}}$ distribution of the

![Figure 1: The $E_T^{\text{miss}}$ distribution of signal and background for an integrated luminosity of 23.8 pb$^{-1}$ at 14 TeV. The QCD background is estimated from the jet smearing method in 0-lepton SUSY search as explained in the text. The signal point is the ATLAS mSUGRA benchmark point SU3.](image-url)
estimate is then 60% for 23.8 pb\(^{-1}\). The same uncertainty is assumed for 1 fb\(^{-1}\) of data. Given the difficulty of obtaining accurate estimates of the QCD background, results from a number of independent techniques should be compared to obtain a robust QCD background estimate.

### 3.2. Data-driven background estimates for SUSY diphoton search

The GMSB model with two high \(p_T\) photons and large \(E_T^{\text{miss}}\) in the final state is among the promising models for early SUSY searches. A method from a CMS study [11] is described here to predict the \(E_T^{\text{miss}}\) distribution in a diphoton sample from the SM processes. Seeing an excess of events at high \(E_T^{\text{miss}}\) would indicate a signal for new physics. The physics background is small and comes from the \(Z\gamma\to\nu\nu\gamma\) and \(W\gamma\to\nu\nu\gamma\) SM processes. The instrumental background comes from three major sources:

1. QCD background; results from \(\gamma\)-jet misidentification in QCD events with no real \(E_T^{\text{miss}}\) such as photon plus jets and multijet production.
2. Electroweak background; results from \(\gamma\)-\(e\) misidentification in events with real \(E_T^{\text{miss}}\) from \(W\gamma\) and \(W\,\gamma\)-jet production.
3. Non-beam background; results from high energy muons from cosmic rays or beam-halo.

It has been demonstrated that the QCD and electroweak backgrounds are under control, and the techniques explored will effectively eliminate the non-beam background. A CMS benchmark point, GM1C, is used in this study with parameters \(\Lambda = 100\) TeV, \(M_0 = 200\) TeV, \(N_5 = 1\), \(C_Q = 1\), \(\tan(\beta) = 15\), \(\text{sgn}(\mu) = +\). Figure 2 shows the \(E_T^{\text{miss}}\) distribution from the background closure test (using \(Z \rightarrow e^+e^-\) events to describe the QCD background) in absence of SUSY signal for an integrated luminosity of 100 pb\(^{-1}\) at 10 TeV. As for comparison with the Monte Carlo truth, event counts yield \((2.78 \pm 0.24)\) for the Monte Carlo \(\gamma\gamma\) data and \((2.69 \pm 0.66)\) for the estimated background in absence of SUSY signal, and \((17.5 \pm 0.26)\) and \((2.99 \pm 0.68)\) respectively in presence of SUSY signal. A good agreement is seen between the data-driven estimated and the predicted background. The data-driven strategy demonstrated in this study can be used at the start-up of the LHC.

### 4. SUSY Searches with Inclusive \(E_T^{\text{miss}}\) Signatures

SUSY phenomenology varies significantly through the SUSY parameter space, therefore SUSY is searched inclusively based on very general signatures. It is expected that gluinos and squarks (heaviest SUSY particles) will be produced in the initial proton-proton interaction at the LHC and then their cascade decays will result in events with high \(p_T\) jets and leptons in the final state. In addition, if the R-parity is conserved the LSP would be stable and undetected leading to events with large \(E_T^{\text{miss}}\). Thus typical inclusive SUSY searches cover a broad range of search modes depending on the presence of leptons (electron/muon), \(\tau\) lepton or \(b\) quarks in the final state: the 0-lepton mode, 1-lepton mode, 2-lepton mode, 3-lepton mode, tau-mode and \(b\)-jet mode and others. Examples of these search modes are given in the following. A review of the SUSY searches with inclusive \(E_T^{\text{miss}}\) signatures from an ATLAS study can be found in more detail in this volume [19].

#### 4.1. The 0-lepton and 1-lepton modes

The 0-lepton mode (\(\text{jets}+E_T^{\text{miss}}\)) provides the least model dependent search. Events with at least four jets or three jets or two jets can be chosen. The main background in this mode is the QCD multi-jet background \(E_T^{\text{miss}}\) is produced either by fluctuations in jet energy measurement or by \(B\) hadron decays to real neutrino). A strong event selection cuts (requirement of high multiplicity jets, high \(p_T\) cuts on jets and a cut on the azimuthal angle between each of the first three jets and the \(E_T^{\text{miss}}\)) reduces this background significantly. The remaining background comes from \(t\tilde{t}+\text{jets}, W+\text{jets}, Z+\text{jets}\) and diboson production. The global event variable, \(M_{\text{eff}}\), is used in discriminating SUSY from the SM events. \(M_{\text{eff}}\) is defined as the scalar sum of the \(p_T\) of the leading jets and the \(E_T^{\text{miss}}\) and the \(p_T\) of the leptons (if present) considered in the analysis. \(M_{\text{eff}}\) is also used to quantify the SUSY mass scale. From an ATLAS study [\ref{19}],...
the $M_{\text{eff}}$ distribution of the signal (ATLAS mSUGRA benchmark point, SU4, with parameters $m_0 = 200$ GeV, $m_{1/2} = 160$ GeV, $A_0 = -400$, $\tan(\beta) = 10$, $\text{sgn}(\mu) = +$) and the total background are shown in Figure 3 for an integrated luminosity of 200 pb$^{-1}$ at 10 TeV. An excess of events is clearly observed in this mode.

The 1-lepton mode (jets+one lepton+$E_T^{\text{miss}}$) is often considered to be the golden mode for early SUSY searches. Requirement of the additional lepton (electron or muon) strongly reduces the QCD multijet background. The event selection cuts are similar to that of the zero-lepton mode but includes a cut on the transverse mass of the lepton and the $E_T^{\text{miss}}$ to suppress the $t\bar{t}+$jets and $W+$jets backgrounds. Figure 4 shows the $E_T^{\text{miss}}$ distribution for the same ATLAS study as in Figure 3. Although the statistics is reduced, the background is dominated by $t\bar{t}+$jets and $W+$jets which are expected to be better understood than the QCD background. Thus 1-lepton mode is more robust against uncertainties in the background estimations.

### 4.2. The 2-lepton and 3-lepton modes

The 2-lepton mode with jets+two leptons (opposite-sign or same-sign)+$E_T^{\text{miss}}$ in the final state can have high discovery potential in early SUSY searches. The opposite-sign (OS) dileptons arising from the SUSY decays ($X_0^0 \rightarrow \tilde{\chi}_1^0 \tilde{\nu} \gamma$) have the same-flavor to avoid $\mu \rightarrow e\gamma$ decay. The dileptons coming from different decay chains (SUSY combinatorial and the SM backgrounds) can be of the same-flavor (SF) or opposite-flavor (OF) with the same probability. Thus observing an excess of OSSF dilepton events over OSOF events would indicate a clear evidence for new physics. Figure 5 shows the invariant mass of OSSF dileptons from a CMS study for an integrated luminosity of 200 pb$^{-1}$ at 10 TeV. The CMS mSUGRA benchmark point, LMO ($m_0 = 200$ GeV, $m_{1/2} = 160$ GeV, $A_0 = -400$, $\tan(\beta) = 10$, $\text{sgn}(\mu) = +$) is considered. The red histogram shows the contribution from SUSY events. The dominant background is found to be $t\bar{t}+$jets. A significant excess of OSSF dileptons events over OSOF events (shown by the black solid line) is seen with the first 200 pb$^{-1}$ of the LHC data. The same-sign dileptons could provide an almost background free channel for SUSY searches. Events with two prompt, isolated and same-sign dileptons are rare...
in the SM while in SUSY the gluino is a Majorana particle so events with same-sign dileptons can be common. Though the event rates will be very small (from 10 to 100 events/fb$^{-1}$) a recent ATLAS study [8] discusses that gluinos and squarks with masses up to 500 GeV can be discovered with a 3$\sigma$ signal significance for an integrated luminosity of 200 pb$^{-1}$ at 10 TeV.

The 3-lepton mode (three leptons+$E_T^{\text{miss}}$) to search for signals from direct gaugino (such as $\tilde{\chi}_1^0$ and $\tilde{\chi}_1^0$) pair production has perhaps been a best search mode at the Tevatron [20]. The trilepton signal can come from leptonic decay of pairs of heavy gauginos (produced directly or in the decay of heavier partner particles) through real or virtual $W^\pm$, $Z^0$ or $t$ to leptons and a pair of LSPs. A general approach has been to consider two analyses; first with the selection of the 3-leptons+jet events (no cut on $E_T^{\text{miss}}$) and second with the selection of the 3-leptons+$E_T^{\text{miss}}$ events. In an ATLAS study [2], the 3-leptons+jet analysis is found to be more sensitive than the 3-leptons + $E_T^{\text{miss}}$ one for the mSUGRA benchmark points studied for an integrated luminosity of 1 fb$^{-1}$ at 14 TeV.

4.3. The tau- and b-jet modes

As for the tau- and b-jet modes, they can be dominant in SUSY models with large $\tan(\beta)$, thus they can help determining the underlying model parameters. The requirement of a reconstructed $\tau$ in the final state eliminates the QCD background and the remaining background is dominated by $t\bar{t}$+jets and $W$+jets. Though the lower efficiency and purity in $\tau$ reconstruction, $\tau$ decays provide complimentary info on the nature of new physics: $\tau$ LSP, $e/\mu/\tau$ universality.

In mSUGRA models with large $\tan(\beta)$ the $\tilde{b}$ and $\tilde{t}$ are lighter than the first and second generation squarks. In this case $\tilde{b}$ production is enhanced leading to decays with b-jets in the final state. A similar analysis is performed as in the 0-lepton mode with the additional selection of at least two or three b-jets. The b-tagging performance at high $p_T$ is an important issue for identifying b-jets. A recent ATLAS study [4] uses a b-tagging efficiency of $\sim 60\%$ and a rejection of $\sim 100$ ($\sim 10$) against light quark (c-quark) jets and shows that requiring b-jets reduces the QCD multijets, $W$+jets and $Z$+jets backgrounds leaving the almost only background from $t\bar{t}$+jets. Figure 5 shows the $M_{\text{eff}}$ distribution of the mSUGRA signal point SU6 ($m_0 = 320$ GeV, $m_{1/2} = 375$ GeV, $A_0 = 0$, $\tan(\beta) = 50$, $\text{sgn}(\mu) = +$) together with the SM backgrounds for an integrated luminosity of 1 fb$^{-1}$ at 14 TeV. A clear excess is seen for the signal events above the SM backgrounds.

![Figure 6: The $M_{\text{eff}}$ distribution of the b-jet mode (two b-jets analysis) SUSY search for an integrated luminosity of 1 fb$^{-1}$ at 14 TeV. The signal point is the ATLAS mSUGRA benchmark point SU6. The contributions from the signal and the SM backgrounds are indicated in the legend.](image)

5. An Exclusive Search without $E_T^{\text{miss}}$

A new approach to SUSY searches with dijet events has recently been proposed [21]. It focuses on a SUSY parameter space where squarks are pair produced and both decay directly to a quark and the lightest neutralino, leading to dijet events with $E_T^{\text{miss}}$ in the final state. It exploits powerful discriminating variables to separate signal and background without making explicit use of the $E_T^{\text{miss}}$ measurement, thus providing a very promising channel for early SUSY searches. A CMS study [9] based on this approach is summarized in this section. The study has been carried out in the context of the mSUGRA model for an integrated luminosity of 100 pb$^{-1}$ at 10 TeV.

The main backgrounds to the event topology are the QCD dijet events ($E_T^{\text{miss}}$ is introduced through jet energy mismeasurements) and $Z$+jets events with $Z$ decaying into two neutrinos. A kinematic variable, $\alpha_T = E_T^{\text{miss}}/M_T$, is defined as the ratio of the transverse energy of the second jet and the transverse mass of the two jets. It exploits the requirement of back-to-back jets of equal magnitude for QCD events, thus $\alpha_T$ is exactly 0.5 for well measured QCD dijet events. Figure 6 shows the $\alpha_T$ distribution for dijet events for signal and background. The mSUGRA benchmark points are labelled as LMO ($m_0 = 200$ GeV, $m_{1/2} = 160$ GeV, $A_0 = -400$, $\tan(\beta) = 10$, $\text{sgn}(\mu) = +$) and LM1 ($m_0 = 60$ GeV, $m_{1/2} = 250$ GeV, $A_0 = 0$, $\tan(\beta) = 10$, $\text{sgn}(\mu) = +$). Events are selected with $\alpha_T > 0.55$ cut which removes almost all QCD background. The remaining small background is from $t\bar{t}$+jets, $W$+jets and $Z \rightarrow \nu\bar{\nu}$+jets events. This study also extends the dijet analysis to higher jet multiplicities where $n$ jets ($n = 2...6$) are considered. It
is found that the discriminating power of $\alpha_T$ against QCD background provides signal over background ratios of 4 to 8 for favorable SUSY benchmark points. The results are shown to be robust against systematic uncertainties from the jet energy scale and jet direction. A data-driven approach has been taken to estimate both the QCD background and the remaining backgrounds. Even though the above Monte Carlo study suggests that the QCD background is negligible (after the $\alpha_T$ cut), it has been verified by the data-driven estimates that it is indeed the case. The details of this study can be found in this volume [22].

![Figure 7: The $\alpha_T$ integrated luminosity of 100 pb$^{-1}$ at 10 TeV. The labels LMO and LM1 represent the CMS mSUGRA benchmark points as their parameters given in the text. The SM backgrounds are also indicated in the legend.](image)

6. Special SUSY Signatures

A number of SUSY models predict specific signatures that may not be observed by the above traditional SUSY searches, such as long-lived massive particles or high $p_T$ photons. For these specific signatures the SM backgrounds are often small thus their detection could provide unique constraints on the SUSY breaking mechanisms. A list of SUSY models giving rise to stable massive particles can be found in [23]. Examples are MSSM, GMSB, AMSB and Split-SUSY models.

These particles live long enough to pass through the detector or decay in it. Such a particle can be a slepton ($\tilde{\tau}_1$, $\tilde{\ell}_R$, $\tilde{\mu}_R$ in GMSB model), a gluino (in Split-SUSY model), a stop (gravitino LSP scenario of SUGRA models [24]) or a lightest neutralino (in GMSB model). Their signatures will be different at the detector. If it is a stable charged slepton, its interaction with the detector will only be ionizations, its observed track will look like a muon, except for its higher energy deposition and longer time of flight than a muon. If it is a gluino or a stop, it is meta-stable, it will form bound states, so-called R-hadrons. Their signatures will be similar to that of the stable slepton together with the appearance of high $p_T$ tracks in the muon system with no matching track in the inner detector or the electric charge flipping between the inner detector and the muon system. If it is a long lived neutralino, it can travel a significant distance before decaying into a photon and a gravitino. Such photons will not point back to the beam interaction point called as non-pointing photons. If the neutralino’s lifetime is not too long, events with two high $p_T$ photons (prompt photons, originate close to the beam interaction point) plus large $E_T^{miss}$ (from gravitinos) are expected.

As an example one study on the detection of the long lived gluinos is summarized in what follows. The Split-SUSY model suggests a large mass splitting between the new scalars and new fermions, then gluinos can only decay through a highly virtual squark if R-parity is conserved. Gluinos can thus be long-lived and may well be stable on the typical experimental timescales. When produced these gluinos will hadronize into bound states (R-hadrons), $\tilde{g}, \tilde{g}'$. A recent CMS study [12] discusses a search strategy to detect the decays of such R-hadrons. The charged R-hadrons will lose energy via ionization as they traverse the detector, this energy loss may be sufficient to stop a significant fraction of the particles inside the detector volume. These stopped R-hadrons may decay at times when there are no collisions (beam gaps) or no beam (interfill period) in the LHC. Observing such decays would immediately indicate a new physics signal.

A custom Monte Carlo simulation has been developed to estimate the signal efficiency and a novel triggering strategy has been implemented to improve the signal sensitivity. The only physics background is from cosmic rays. There is also an instrumental background. The uncertainties on the background determination are statistical and they are found to be small. However, the search sensitivity to a particular model (Split-SUSY) involves some significant systematic uncertainties; theoretical uncertainties in the NLO calculation of the gluino-gluino production cross section, uncertainty on the stopping efficiency from the Monte Carlo simulation, uncertainty on modeling the exponential decay of the instantaneous luminosity. Figure 8 shows the signal significance that can be achieved after 30 days of running with an instantaneous luminosity of $10^{31}$ cm$^{-2}$ at 10 TeV as a function of the gluino mass from a counting experiment. A 5$\sigma$ discovery should be possible in a matter of days for the models with large cross sections (~1 nb).
7. SUSY Discovery Reach

In the previous sections examples of SUSY search strategies have been given based on the analyses of SUSY benchmark points with R-parity conservation. These points can not be representative of all possible SUSY models to be found at the LHC. They have been chosen with the aim of studying a variety of signatures and developing analysis techniques that can be applied to much of the SUSY parameters space accessible with early LHC data. In order to map the 5σ discovery reach of a SUSY model, a scan over its parameters is performed.

A recent ATLAS study focuses on scanning the parameter space of mSUGRA, pMSSM (phenomenological MSSM with 19 free soft SUSY breaking parameters) and UED (Universal Extra Dimensions) models considering an integrated luminosity of 200 pb⁻¹ at 10 TeV. Figure 9 shows the 5σ discovery reach of a SUSY model, a scan over its parameters is performed.

The reaches for the 2-lepton modes are less than the reaches for the 0-lepton and 1-lepton modes. As for the 5σ discovery potential of the tau-mode, it is found to be slightly worse than the 0-lepton and 1-lepton modes due to the lower efficiency and purity in τ reconstruction which is studied in for 1 fb⁻¹ at 14 TeV.

The 5σ discovery potential of the b-jet mode is found to be comparable to that of the 1-lepton mode from a recent ATLAS study for 1 fb⁻¹ at 14 TeV. It is a competitive search mode specially at higher m₀ values.

Scans in the NUHM (Non Universal Higgs Model) and GMSB SUSY parameter space have also been performed in an ATLAS study for 1 fb⁻¹ at 14 TeV. The discovery reach of the NUHM model is found to be virtually identical to that of mSUGRA in the 0-lepton and 1-lepton modes. The 5σ discovery reach of the GMSB model as a function of tan(β) can be seen in Figure 10 with other parameters set to $M_m=500$ TeV, $N_5=5$, $C_G=1$ and sgn($\mu$) = +. The reach for the 3-lepton analysis is significantly better than that of the 2-lepton analysis.
The searches strategies to establish SUSY discovery have been outlined in the previous sections. As soon as a SUSY discovery can be made by these searches, the emphasis will move on to confirming that it is really SUSY. The masses and spins of the newly discovered particles should be measured and the underlying model parameters should be determined. Since it is not possible to cover all of the allowed SUSY models, mSUGRA model is taken as an example to develop the mass measurement techniques that can be applicable to large variety of SUSY and SUSY-like models. The study presented here is based on an ATLAS study performed for integrated luminosity of 1 fb$^{-1}$ at 14 TeV.

The mass measurement strategy is to exploit kinematics of the long decay chains. In the R-parity conserving mSUGRA models SUSY particles are pair produced and their cascade decays typically have high $p_T$ jets, leptons and large $E_T^{\text{miss}}$ (due to two invisible LSPs in every SUSY event) in the final states. No mass peaks can be reconstructed, however kinematic endpoints in the invariant mass distributions of dilepton, dijet, leptons+jets and ditau can be measured. These measurements are then used in deriving relations between SUSY masses. The theoretical positions of the endpoints are well known from the analytical expressions $^{28}$.

8. SUSY Mass Measurements

As an example from the decay chain:

$$q \bar{l}_L \rightarrow q_X \bar{\chi}^0_{1L} \rightarrow q_X^{\prime0} l^\mp \bar{l}$$

the masses of $q_L$, $\bar{l}_R$, $\chi^0_2$ and $\chi^0_1$ can be measured. This is the first decay chain likely to be reconstructed as it has the advantage of having charged leptons, $E_T^{\text{miss}}$ and hadronic jets in the final state which ensures a large signal to background ratio. Also, the technique known as flavor subtraction allows to determine both the SUSY combinatorial and the SM background from the data itself with high accuracy. This technique exploits the fact that the signal contains two opposite-sign same-flavor (OSSF) leptons, while the background is due to pair of leptons coming from different decay chains, which can be of the same-flavor (SF) or opposite-flavor (OF) with the same probability. Thus the background cancels in the subtraction $N(e^+e^-)/\beta + \beta N(\mu^+\mu^-) - N(e^\pm\mu^\mp)$ where $N$ indicates the respective number of events and $\beta$ is the ratio of the electron and muon reconstruction efficiencies ($\beta=0.86$ for this study).

8.1. Kinematic endpoints

Starting with the two leptons (electron or muon) in the final state, the invariant mass distribution of dilepton exhibits a triangular shape with an endpoint at:

$$m_{\ell\ell}^{\text{edge}} = m_{\chi^0_{1L}} \left[ 1 - \left( \frac{m_{\chi^0_{1L}}}{m_{\chi^0_{2}}} \right)^2 \right]^{1/2} \left[ 1 - \left( \frac{m_{\chi^0_{1L}}}{m_{\ell R}} \right)^2 \right]^{1/2}$$

In Figure 11 the dilepton invariant mass distribution is shown after flavor subtraction applied for the ATLAS benchmark point SU3. The line histogram shows the small SM background contribution (dominated by t$^\pm$+jets), while the points are the sum of SM and SUSY contributions. A clear excess is seen together with a clear edge structure. The distribution is fitted with a triangle smeared with a Gaussian which is superimposed in the plot. Also, the expected (truth) position of the endpoint is indicated by a vertical dashed line. The fitted endpoint is $(99.7 \pm 1.4 \pm 0.3)$ GeV where the first error is statistical and the second is the systematic error on the lepton energy scale and the $\beta$ parameter ($10\%$). Compared to its truth value of 100.2 GeV (calculated from Eq. 2) the endpoint can be measured with a precision of a few percent already with 1 fb$^{-1}$ of integrated luminosity at 14 TeV for the model chosen.

In order to determine the masses of all the SUSY particles involved in the decay chain, further kinematic endpoints need to be measured from the mass distributions involving a jet: $m_{\ell\ell}^{\text{edge}}$, $m_{\ell\ell}^{\text{thr}}$, $m_{\ell\ell}^{\text{edge} \text{(low)}}$, $m_{\ell\ell}^{\text{edge} \text{(high)}}$. The label thr indicates lower endpoint of the distribution (a non-zero threshold value) whereas low/high indicate minimum/maximum of the two masses $m_{\ell^+q}$ and $m_{l^-q}$. Only the two leading jets are considered in event selection as it is not possible.
to identify the quark from the \( \tilde{q}_{L} \) decay. Therefore it is assumed that it hadronizes into one of the two highest \( p_{T} \) jets in the event. The fitted endpoints together with their truth values can be seen in Table I. The first error is statistical, the second and third are the lepton energy scale uncertainty and the jet energy scale uncertainty, respectively. While the measured values are compatible with their truth values, there are large uncertainties on the measured values. This is due to not having clear edge structure (combinatorics from choosing the wrong jet in a true SUSY event) and thus trying to fit the tails (beyond the endpoint) with straight lines.

Table I Measured endpoint values for the ATLAS mSUGRA benchmark point SU3 with an integrated luminosity of 1 fb\(^{-1} \) at 14 TeV. The truth values are also listed.

| Endpoint | SU3 Measured (GeV) | SU3 Truth (GeV) |
|----------|-------------------|-----------------|
| \( m_{\text{\(\tau\)q\(\tau\)}}^{\text{edge}} \) | 517 ± 30 ± 10 ± 13 | 501 |
| \( m_{\text{\(\tau\)q\(\tau\)}}^{\text{th}} \) | 265 ± 17 ± 15 ± 7 | 249 |
| \( m_{\text{\(\tau\)q\(\tau\)}}^{\text{edge(low)}} \) | 333 ± 6 ± 6 ± 8 | 325 |
| \( m_{\text{\(\tau\)q\(\tau\)}}^{\text{edge(high)}} \) | 445 ± 11 ± 11 ± 11 | 418 |

In a similar way, the endpoint of the invariant mass distribution of ditau, \( m_{\text{\(\tau\)q\(\tau\)}}^{\text{edge}} \), can be measured from the decay \( \chi_{2}^{0} \rightarrow \tau_{1} \tau_{1} \rightarrow \chi_{1}^{0} \tau \tau \). The fitted endpoint is \((102 \pm 17_{\text{stat}} \pm 5.5_{\text{syst}} \pm 7_{\text{pol}}) \) GeV for the ATLAS benchmark point SU3. The first error is statistical, the second is the systematic uncertainty dominated by the fitting procedure and the third is the uncertainty from the polarization effects. Its truth value is 98.3 GeV.

Also, from the decay \( \tilde{q}_{R} \rightarrow \chi_{1}^{0} q \) the mass of the right-handed squark can be measured from the endpoint of the transverse mass distribution by assuming that the mass of \( \chi_{1}^{0} \) is known from the dilepton and leptons+jets endpoint measurements. The fitted endpoint is \( 590 \pm 9_{\text{stat}}^{+13}_{-11} \) (syst) for the ATLAS benchmark point SU3. The systematic uncertainty accounts for the choice of the fit limits and the jet energy scale variations. It agrees well with its truth value of 611 GeV.

8.2. Extraction of SUSY masses from endpoint measurements

From a combination of experimentally measured endpoints as above the SUSY particle masses can be extracted. By using the five endpoint measurements, \( m_{\text{\(\tau\)q\(\tau\)}}^{\text{edge}}, m_{\text{\(\tau\)q\(\tau\)}}^{\text{th}}, m_{\text{\(\tau\)q\(\tau\)}}^{\text{thr}}, m_{\text{\(\tau\)q\(\tau\)}}^{\text{edge(low)}}, m_{\text{\(\tau\)q\(\tau\)}}^{\text{edge(high)}} \), the four unknown SUSY particle masses involved in the decay, \( \tilde{q}_{L}, \tilde{\ell}_{R}, \chi_{0}^{2}, \chi_{1}^{0} \) can be solved. A numerical \( \chi^{2} \) minimization based on the MINUIT package is performed. The masses resulting from the \( \chi^{2} \) fit can be seen in Table II for the SU3 point. The first error is statistical, the second accounts for the jet energy scale uncertainty. An anticorrelation with the jet energy scale variation is indicated by \( \mp \) sign. The reconstructed masses are found to be highly correlated with \( \chi_{1}^{0} \) which is not well determined by the endpoint techniques. Therefore the precision on the absolute mass values is rather moderate. However, the mass differences are better measured than the absolute masses as expected.

Table II Reconstructed SUSY particle masses and mass differences together with their truth values for the SU3 benchmark point with 1 fb\(^{-1} \) at 14 TeV.

| Observable | SU3 Reconstructed (GeV) | SU3 Truth (GeV) |
|------------|-------------------------|-----------------|
| \( m_{\chi_{1}^{0}} \) | 88 ± 60 ± 2 | 118 |
| \( m_{\chi_{2}^{0}} \) | 189 ± 60 ± 2 | 219 |
| \( m_{\chi_{L}} \) | 614 ± 91 ± 11 | 634 |
| \( m_{\ell_{L}} \) | 122 ± 61 ± 2 | 155 |
| \( m_{\chi_{2}^{0}} - m_{\chi_{1}^{0}} \) | 100.6 ± 1.9 ± 0.0 | 100.7 |
| \( m_{\chi_{L}} - m_{\chi_{1}^{0}} \) | 526 ± 34 ± 13 | 516.0 |
| \( m_{\ell_{L}} - m_{\chi_{1}^{0}} \) | 34.2 ± 3.8 ± 0.1 | 37.6 |

9. Determination SUSY Model Parameters

The ultimate goal is to pin down the SUSY model parameters. The SUSY parameter-fitting package Fitino [30] has been used to perform the calculations...
of the model parameters from all the endpoints measured; \( m_{\ell\ell q}^{\text{edge}}, m_{\ell\ell q}^{\text{th}}, m_{\ell\ell q}^{\text{edge}}, m_{\ell\ell q}^{\text{edge}}(\text{low}), m_{\ell\ell q}^{\text{edge}}(\text{high}), m_{T2}(\tilde{g}_R) \). The fitted mSUGRA parameters can be seen in Table III for the SU3 point. Already with 1 fb\(^{-1}\) of data \( m_0 \) and \( m_{1/2} \) parameters can be derived reliably, however determination of \( \tan(\beta) \) and \( A_0 \) is more problematic since no information from the Higgs sector is available at low luminosity.

Table III Fitted mSUGRA parameters for the SU3 point with 1 fb\(^{-1}\) at 14 TeV, \( \text{sgn}(\mu) = + \).

| Parameter | SU3 Fitted | SU3 Truth |
|-----------|------------|-----------|
| \( \tan(\beta) \) | 7.4 ± 4.6 | 6         |
| \( m_0 \) (GeV) | 98.5 ± 9.3 | 100       |
| \( m_{1/2} \) (GeV) | 317.7 ± 6.9 | 300       |
| \( A_0 \) (GeV) | 445 ± 408 | -300      |

10. Conclusions

If SUSY particles exist in nature at sub-TeV mass range the ATLAS and CMS experiments will open up a discovery window for new physics beyond the Standard Model. Search strategies have been developed to cover a broad range of signatures expected from SUSY models. Understanding the detector performance and controlling the SM backgrounds via data-driven methods are important tasks for early SUSY analyses. Once a signature consistent with SUSY has been established then various measurements will have to be combined to reconstruct the SUSY mass spectrum and to understand the SUSY breaking mechanism. Early SUSY searches with 100/200 pb\(^{-1}\) integrated luminosity at 10 TeV center of mass energy suggest that we are already sensitive to an unexplored area in less than a year running. Exciting times are ahead with the upcoming start-up of the LHC.

References

[1] See e.g. S. P. Martin, “A Supersymmetry Primer,” hep-ph/9709356 (1997).
[2] G. Aad et al., The ATLAS Collaboration, “Expected Performance of the ATLAS Experiment - Detector, Trigger and Physics,” arXiv:0901.0512 [hep-ex], pp. 1617-1642 (2009).
[3] The CMS Collaboration, “CMS Physics Technical Design Report, Volume II: Physics Performance,” J. Phys. G: Nucl. Part. Phys. 34 995-1579 (2007).
[4] ATLAS note, “Discovery Potential for Supersymmetry with b-jet Final States with the ATLAS detector,” ATL-PHYS-PUB-2009-075.
[5] ATLAS note, “Background Estimation for Inclusive SUSY Searches - The Tiles Method,” ATL-PHYS-PUB-2009-077.
[6] ATLAS note, Data-Driven Determination of \( t\bar{t} \) Background to Supersymmetry Searches in ATLAS,” ATL-PHYS-PUB-2009-083.
[7] ATLAS note, “Prospects for Supersymmetry and Universal Extra Dimensions discovery based on inclusive searches at a 10 TeV centre-of-mass energy with the ATLAS detector,” ATL-PHYS-PUB-2009-084.
[8] ATLAS note, “Searching for Supersymmetry with two same-sign leptons, multi-jets plus missing transverse energy in ATLAS at \( \sqrt{s} = 10 \) TeV,” ATL-PHYS-PUB-2009-085.
[9] CMS note, “Search strategy for exclusive multi-jet events from supersymmetry,” CMS PAS SUS-09-001.
[10] CMS note, “Discovery potential and measurement of a dilepton mass edge in SUSY events at 10 TeV,” CMS PAS SUS-09-002.
[11] CMS note, “Data-Driven Background Estimates for SUSY Di-Photon Searches,” CMS PAS SUS-09-004.
[12] CMS note, “Searching for Stopped Gluinos during Beam-off Periods,” CMS PAS EXO-09-001.
[13] CMS note, “Data driven estimation of the Z → invisible background for the early SUSY searches,” CMS PAS SUS-08-002.
[14] See e.g. P. Nath, hep-ph/0307123 (2003).
[15] See e.g. M. Dine et al., Phys. Rev. D53 2658 (1996).
[16] See e.g. A. J. Barr et al., JHEP 03 045 (2003).
[17] See e.g. H. Baer et al., JHEP 0810 079 (2008).
[18] See e.g. N. Arkani-Hamed and S. Dimopoulos, JHEP 06, 073 (2005).
[19] T. Sarangi, “Inclusive search for Supersymmetry with missing transverse energy signatures in ATLAS,” in this volume.
[20] CDF Collaboration, CDF/PUB/EXOTIC, PUB-LIC/9176. D0 Collaboration, D0 Note 5348-Conf. 101118703 (2008).
[21] L. Randall and D. Tucker-Smith, Phys. Rev. Lett. 101, 221803 (2008).
[22] G. Lungu, “Search for supersymmetry at the CMS in all-hadronic final state,” in this volume.
[23] M. Fairbairn et al., Phys. Rept. 438, 1 (2007).
[24] J. L. Diaz-Cruz et al., JHEP 05, 003 (2007).
[25] C. F. Berger et al., JHEP 0902, 023 (2009).
[26] T. Appelquist et al., Phys. Rev. D64, 035002 (2001).
[27] See e.g. J. Ellis et al., Nucl. Phys. B652, 259 (2003).
[28] See e.g. C. G. Lester et al., JHEP 0710, 0051 (2007).
[29] A. J. Barr et al., J. Phys. G 29, 2343 (2003).
[30] K. Desch and P. Wiemann, Comput. Phys. Commun., 174, 47 (2006).