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Searching for Supersymmetry with two same-sign leptons, multi-jets plus missing transverse energy in ATLAS at $\sqrt{s} = 10$ TeV

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Abstract

A search for R-parity conserving supersymmetry using the ATLAS detector is described. The final state under study includes two same-charge leptons, two jets, and missing transverse energy. A data-driven method to estimate the number of Standard Model background events is proposed, and its discovery potential is assessed assuming an integrated luminosity of 200 pb^{-1} and a center of mass energy of 10 TeV.

1 Introduction

Supersymmetry is one of the prime theories [1] for physics beyond the Standard Model (SM). It predicts a super partner for every known elementary particle in the SM. The super partners are commonly known as *sparticles* and differ by a half unit of spin from their SM partners. A new discrete symmetry called R-parity is defined as $R_p = (-1)^{2s+3B+L}$, where s is the spin, B is the baryon number and L is the lepton number of the particle. Under R_p, all the SM particles carry even parity while their super partners carry odd parity due to the $(-1)^{2s}$ factor. In our study, we have considered an R_p conserving scenario in which the lightest supersymmetric particle (LSP) is stable. Here, the LSP is a neutral particle which is produced at the end of the cascade decays of other massive supersymmetric particles and escapes detection, causing large missing transverse energy in the event. Thus a requirement of large missing transverse energy in the event along with other final state particles such as leptons and jets has potential to discover R_p conserving supersymmetry at the LHC.

The primary production of sparticles comes from cascade decays of pair-produced squarks ($\tilde{q}$) and gluinos ($\tilde{g}$). In minimal supergravity (mSUGRA) the gluinos and squarks will eventually decay into final state leptons, jets and the LSP ($\tilde{\chi}_1^0$) via other sparticles such as sleptons ($\tilde{l}$), charginos ($\tilde{\chi}_1^{\pm}$,$\tilde{\chi}_2^{\pm}$), and heavier neutralinos ($\tilde{\chi}_{2,3,4}^0$).

The production of two leptons with same charge ("hereafter, called same-sign leptons") at the LHC can be enhanced by events where two gluinos are produced and both subsequently decay to same-sign charginos which decay leptonically. An example of such a gluino decay is given in Figure 1. Searches

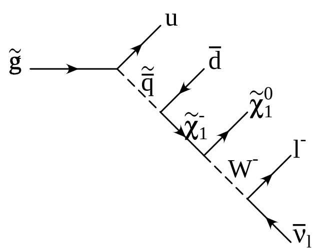

Figure 1: The decay of one of the gluinos in a $\tilde{g}\tilde{g}$ pair production.

for supersymmetry in the same-sign dilepton channel have been performed at Tevatron; details on the limits obtained in these searches can be found in Ref. [2, 3]. It has been shown that same-sign dilepton production can be an important discovery channel for supersymmetry at the LHC as well [4–6]; this note evaluates the performance of this channel with the ATLAS detector and introduces a data-driven procedure to estimate the SM backgrounds in such a search. One important feature of the method presented here is that it performs well for a broad range of points in the SUSY parameter space. To demonstrate this, we present results based on several SUSY points with strongly differing kinematic properties.

2 Standard Model processes

The present analysis looks for a pair of high p_T same-sign leptons ($l^{\pm}l^{\pm}; l = e, \mu$), accompanied by at least two jets and missing transverse energy in the final state. The possible SM processes that can mimic these final states are the production of top-quark pair ($t\bar{t}$), W, Z, Wbb, WZ, WW, ZZ, $W\gamma$, $Z\gamma$, $b\bar{b}$ along with light-quark jets and missing energy. All these processes are modeled using a full (GEANT4) MC simulation of ATLAS detector.

The dominant background in this analysis is $t\bar{t}$ production. Here, one lepton originates from a W decay, whereas the other originates from a semi-leptonic b decay. $t\bar{t}$ production implies high jet multiplicities and missing transverse energy from the semi-leptonic W and b decays. Therefore, it is difficult to suppress this background without losing the signal. It is of the utmost importance to measure the contribution of this background to the signal selection from the data; this will be discussed in a later section of this note. We have studied MC sample that corresponds to $\sim$9.0 fb^{-1} of integrated luminosity for the $t\bar{t}$ process.

The W+light-quark jets and Wbb+jets processes are among the major backgrounds in this analysis. In the case of W+jets, one lepton originates from W decay, while the other is a light jet faking a lepton. For Wbb+jets, one of the leptons originates from the W decay while the other originates from either of the two b quarks. These backgrounds can be suppressed by requiring isolated leptons and high p_T jets. We have studied MC samples that correspond to $\sim$0.1 fb^{-1} of integrated luminosity for $W \to l\nu$+(0,1) parton and $\sim$1.0 fb^{-1} of integrated luminosity for $W \to l\nu$+(2-5) parton processes.

The $b\bar{b}$ background is potentially dangerous for this analysis due to its high production cross-section. There are a few mechanisms for same-sign lepton production from a $b\bar{b}$ pair. In one case, one of the leptons originates from a semi-leptonic b decay and one of the jets is misidentified as a lepton. In a second case, both gluons in a gluon-gluon event may split into a $b\bar{b}$ pair, possibly leading to a pair of same-sign leptons in the final state. A few other cases *e.g.* $B^0 - \bar{B}^0$ mixing can also contribute to the final state with two same-sign leptons. The p_T spectrum of leptons coming from a semi-leptonic b decay drops off sharply at high p_T. Therefore, by requiring high p_T leptons, we can suppress the $b\bar{b}$ background by orders of magnitude. Since a lepton coming from a semi-leptonic b decay will typically be associated with hadronic depositions, tight isolation criteria will also help prevent these leptons from contributing to the signal selection. We have studied a MC sample that corresponds to $\sim$0.5 fb^{-1} of integrated luminosity for the $b\bar{b}$ process.

The diboson backgrounds WZ and ZZ will produce three or more leptons; if one of the leptons is not reconstructed it is possible to have two same-sign leptons. Moreover, due to the W decay to a lepton and a neutrino, such events are likely to have significant missing transverse energy as well. In the case of WW production, there may be two same-sign leptons and at least two jets from a $W^{\pm}W^{\pm}$ pair, whereas due to charge misidentification a $W^{\mp}W^{\pm}$ pair can also produce two same-sign leptons. The inclusive cross-section for same-sign WW production is fairly small [7]. Since we do not have a simulated MC sample for this process, we made a rough estimation of the cross-section using Ref. [7]. Based on Figure 2 in that article, we estimate that the same-sign WW production cross-section multiplied by the leptonic branching ratio is approximately 0.03 pb. We expect that applying further kinematic cuts like requiring high p_T jets will reduce this contribution to negligible levels compared to other SM background processes. We have studied MC samples that correspond to $\sim$1.6, $\sim$2.0, $\sim$7.0 fb^{-1} of integrated luminosity for the $W^{\pm}W^{\mp}$, WZ and ZZ processes, respectively.

The $W\gamma$ and $Z\gamma$ backgrounds typically originate from events where the photon converts to an e+e- pair, with another lepton from a W or Z decay. This kind of background can be suppressed by requiring high p_T leptons and imposing a cut on the invariant mass of the dilepton system. We have studied MC samples that correspond to $\sim$1.1 and $\sim$13.4 fb^{-1} of integrated luminosity for the $W\gamma$ and $Z\gamma$ processes, respectively.

3 Signal Model

For the signal, we have chosen the mSUGRA model as a potential signal for this analysis. The mSUGRA parameter space is governed by 5 parameters: the scalar particle mass (m_0), the gaugino mass ($m_{1/2}$), the ratio of vacuum expectation values of the two Higgs fields giving mass to up-quarks and down-quarks ($\tan\beta$), the trilinear coupling A_0, and the SUSY conserving Higgs mass parameter μ. The mSUGRA model predicts SUSY mass scales within the LHC reach [8–10].

Events are generated with the ISAJET event generator [11], using HERWIG [12] for fragmentation and hadronization. Generated events are passed through the full GEANT4 simulation of the ATLAS detector. The configurations and cross-sections for some of the mSUGRA benchmark points [5] are given in Table 1.

Process	m_0(GeV)	$m_{1/2}$(GeV)	$\tan\beta$	A_0	NLO σ (pb)
SU1	70	350	10	0	3.6
SU3	100	300	6	-300	8.1
SU4	200	160	10	-400	164.6
SU6	320	375	50	0	1.8

Table 1: Parameters for the various mSUGRA benchmark points considered, and their NLO cross sections.

In our analysis, we have considered SU4 as a reference signal point due to its high cross-section (large enough for an early discovery at the LHC), but we also mention the results for the other signal points described above.

4 Event Selection

The analysis consists of a set of basic cuts to select events with electrons, muons, jets and mising transverse energy, a set of loose "preselection" cuts, and finally a data-driven background estimation technique discussed in Section 5. The object selection is described in brief in this note, since it follows a wide range of criteria that are already mentioned in Ref. [5]. We have studied various trigger menu items and found that there are several trigger menu items that are suitable for this analysis with trigger efficiencies more than 90%. We have designed the analysis to remain sensitive to any excess of events beyond the SM.

4.1 Electrons

The following criteria are used to select a good electron candidate:

- Use the *'medium'* category of electron identification cuts described in Ref. [5].
- The p_T of the electrons must be greater than 10 GeV.
- The pseudorapidity, η, of the electrons must be between $+2.5$ and -2.5. In addition, we do not consider the electrons that fall into $1.37 < |\eta| < 1.52$, since the reconstruction of these electrons may not be efficient due to the transition between barrel and endcap calorimeter in the ATLAS detector. We remove the entire event if it contains one or more electrons within this η range.
- To select isolated electrons, we apply a cut of less than 10 GeV on the sum of the calorimeter energy within a distance ΔR=0.2 around the electron candidate where $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$.
- Electrons that are found inside jets may not be very useful for the analysis. We remove any electron candidate that is found within a distance 0.2 $<\Delta R<$ 0.4 from a good jet candidate (See Section:4.3 for the definition of a good jet candidate.)

4.2 Muons

We use the following criteria to select a good muon candidate for this analysis:

- We use a combined reconstruction algorithm which uses both muon spectrometer and inner detector information to reconstruct a muon candidate [5].
- The p_T of the muons is required to be greater than 10 GeV.
- Muons must lie within the pseudorapidity range $|\eta| < 2.5$.
- The muon combination algorithms pair muon-spectrometer tracks with inner-detector tracks to identify combined muons. The match chi-square is defined as the difference between outer and inner track vectors weighted by their combined covariance matrix. We require the χ^2 to be smaller than 100.
- We use isolated muons for the analysis by requiring the sum of the calorimeter energy within a distance of ΔR=0.2 around a muon to be less than 10 GeV.
- A muon candidate is removed if it is found within a distance ΔR=0.4 from a good jet candidate (See Section:4.3).

4.3 Jets

Jets are reconstructed with a seeded fixed-size cone algorithm [5]; we use a cone radius of ΔR= 0.4. The algorithm operates on energy depositions in towers in the calorimeters. The following selection criteria are made to select a good jet candidate for the analysis:

- Jets are required to have p_T greater than 20 GeV and $|\eta|$ less than 2.5.
- Since electrons are likely to be reconstructed also as jets, we remove any jet candidate that falls within a distance ΔR=0.2 of a good electron candidate.

4.4 Missing Transverse Energy, $\not{E}_T$

This analysis depends on the accurate measurement of missing transverse energy in the events. The missing transverse energy in an event is calculated using calorimeter cell energy and the momentum of the reconstructed muons in the muon spectrometer. More detail about the missing energy resolution, fake $\not{E}_T$ and performance can be found in [5].

4.5 Event preselection

After the selection of electrons, muons, jets and $\not{E}_T$ in the event, the event preselection consists of the following cuts:

- Exactly one pair of leptons with the same charge is required, where the leading lepton should have a $p_T > 20$ GeV and sub-leading lepton should have $p_T > 10$ GeV. We veto any event with a third lepton having $p_T > 10$ GeV.
- A requirement on the invariant mass (M_{ll}) of the dilepton system is imposed. M_{ll} >5 GeV is required to suppress the background that might arise due to reconstruction inefficiencies when two calorimeter clusters point to the same track inside the inner detector and count the same lepton twice in the reconstruction.
- We require at least two jets with $p_T > 40$ GeV in the event. This reduces the contribution from SM background processes which may have high lepton multiplicities but low jet multiplicities.

- $\not\!\!E_T$ is required to be greater than 50 GeV for all events. This cut is very effective against QCD di-jet events and Z+jets events.

- We use the transverse mass, M_T, of the leading lepton and $\not\!\!E_T$ in an event to study the dominant background process. It is defined as $M_T = \sqrt{2\,(p_{T,l1}\ \not\!\!E_T\ \ (1-\cos\Delta\phi(l1,\not\!\!E_T)))}$. Later in the analysis we impose a cut on this variable ($M_T >$ 50 GeV) to discriminate signal against background events.

5 Data-driven background estimation method

After the event preselection cuts, the contributions from the $t\bar{t}$ and W+jets processes are the dominant ones among all of the SM background processes. In order to estimate the SM background in situ, we classify the events that survive the preselection into four different categories. We rely on four different variables that have power to discriminate between signal and background for the categorization. These variables are:

- $\not\!\!E_T$ in the event. R-parity conserving SUSY signal events are more likely to have higher $\not\!\!E_T$ than the SM events.

- p_T of the second leading jet in the event. SUSY signal events are more likely to have high p_T jets in the event produced from cascade decays of squarks and gluinos. We consider low p_T values of the second leading jet distribution as a control region along with other variables.

- p_T of the second leading lepton in the event. Keeping in mind the two dominant background processes, the sub-leading lepton in the event will be coming from a semi-leptonic b decay (in case of $t\bar{t}$) or a fake lepton from a misidentified jet. In most of these cases, the sub-leading lepton in the event will be of a reasonably low p_T and will be non-isolated compared to the leading lepton that comes from a $W \to l\nu$ decay. Rather than cutting on a very high value of p_T for these sub-leading leptons, we use the lower p_T region as a sideband to estimate the background in the high p_T region with the help of other variables described below.

- M_T of the leading lepton and $\not\!\!E_T$ system in the event. In the dominant background processes, the leading lepton will usually be from a $W \to l\nu$ decay and will be well isolated. Therefore, the transverse mass for these background events will accumulate in the vicinity of the W boson mass and provide a handle to distinguish between signal events and dominant SM events.

We define a signal-like region SR and a sideband region SB as follows: SR is defined by $\not\!\!E_T > 80$ GeV and $p_{T,j2} >$80 GeV, whereas for SB we require $50 < \not\!\!E_T < 80$ GeV and $40 < p_{T,j2} < 80$ GeV. Each of these two regions is subdivided in a region A and B, as follows: A: $p_{T,l2} > 20$ GeV and $M_T >$ 80 GeV; B: $10 < p_{T,l2} < 20$ GeV and $50 < M_T < 80$ GeV.

A_{SR}, i.e. the signal-like portion of Region A, is the actual SUSY signal region, and it is in this region that we want to estimate the SM background. The three other regions, B_{SR}, A_{SB} and B_{SB} serve as control regions. If the correlation between the variables can be neglected, the following expression holds:

$$\frac{A_{SB}}{B_{SB}} \simeq \frac{A_{SR}}{B_{SR}} \tag{1}$$

$$\Longrightarrow A'_{SR} \simeq \left(\frac{A_{SB}}{B_{SB}}\right) \times B_{SR} \tag{2}$$

Here, A'_{SR} is the estimated SM event rate in the signal region and A_{SR} is the expected MC event rate in the signal region. In the ideal case, if the extrapolation method works, then A'_{SR} will yield the same number of events as A_{SR}. Since in this note the study is done on MC, we will be able to compare the estimated SM event rate in the signal region against the MC expectation. In real data we will not have a number for A_{SR} but just the estimated number A'_{SR}.

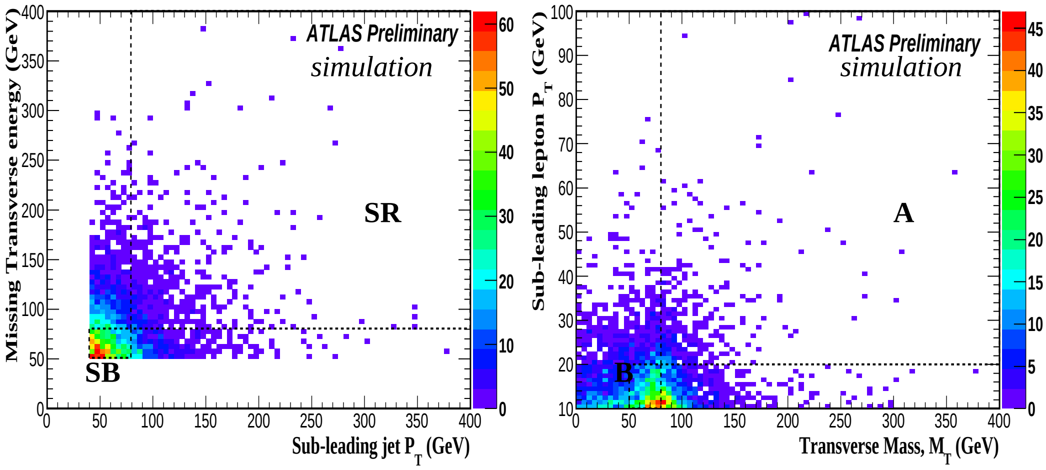

Figure 2: Left: 2-D distribution between $p_{T,j2}$ and $\not{E}_T$ for the $t\bar{t}$ events. The small box that refers to lower values of these two variables is called the Side-Band (SB) and the bigger box called the Signal-like region (SR). Right: 2-D distribution between M_T and $p_{T,l2}$. The small box that refers to lower values is called Region B and the higher values of these variables are called Region A.

As shown in Figure 2, the correlation between the variables used for the selection of control regions is indeed small and measured to be within 15%. The number of events in different regions are given in Table 2 for different signal and SM processes. The Table shows that $t\bar{t}$ has the largest contribution in the total SM processes in all four regions. The background estimation method relies on the assumption that the signal contributions to the control regions are small, especially to the B_{SR} region, and in the case where substantial signal present in this region, the SM background events in A_{SR} will be overestimated. For the background estimation, we consider two different scenarios. In the *No SUSY scenario*, we consider the case where a SUSY signal is absent and only SM events populate the four regions. In the *SUSY scenario*, we consider, in turn, the case that nature has chosen each of the SUx models, and add the proper number of events to each region. The results given in Table 3 show that the extrapolation method is able to estimate the number of SM background events in A_{SR} region properly for the *No SUSY scenario*, and generally also for the *SUSY scenario*. For the low mass, high cross section, SUSY point SU4, however, the method overestimates the number of SM events to some extent. Nevertheless, for low mass SUSY signals, the signal cross section is sufficiently high that a discovery sensitivity above 5 *sigma* is maintained for an integrated luminosity of 200 pb^{-1} at a 10 TeV CM energy.

Process	A_{SR}	B_{SR}	A_{SB}	B_{SB}
W	-	0.7±0.4	0.9±0.5	2.2±0.7
Z	-	-	0.1±0.1	0.1±0.1
Wbb	-	-	-	0.4±0.2
Wt single top	-	0.3±0.3	-	-
t-chan single top	-	-	0.9±0.6	1.1±0.6
$t\bar{t}$	1.3±0.2	3.0±0.3	3.8±0.3	10.3±0.5
Total SM events	1.3±0.2	4.0±0.6	5.7±0.8	14.0±1.1
SU1	2.4±0.4	0.1±0.1	0.1±0.1	-
SU3	2.7±0.7	-	-	-
SU4	40.2±4.4	8.0±1.9	2.8±1.2	2.4±1.1
SU6	1.1±0.2	0.2±0.1	-	-

Table 2: The expected number of events in 200 pb^{-1} for different SM and signal processes. $t\bar{t}$ is the dominant SM process in this analysis. SU4 signals have a very high production cross-section and consequently a sizable number of events survives in the signal region. Only the processes where at least one MC event survived the cuts are shown. The uncertainties on the expected number of events shown in the table arise only from finite Monte Carlo statistics.

Data Content	Expected Signal Events in A_{SR}	Expected Signal+SM events in A_{SR}	Estimated SM events in A'_{SR}
No SUSY(only SM)	-	1.3±0.2	1.6±1.1
SM+SUSY SU1	2.4±0.4	3.7±0.5	1.6±1.2
SM+SUSY SU3	2.7±0.7	4.0±0.7	1.6±1.1
SM+SUSY SU4	40.2±4.4	41.5±4.4	6.2±3.2
SM+SUSY SU6	1.1±0.2	2.4±0.3	1.6±1.2

Table 3: The expected and the estimated number of SM events in the signal region A_{SR}. The fourth column shows the estimated number of SM events as a result of the extrapolation method. A comparison is made with the expected number of SM events in the signal region for both the *No SUSY scenario* and the *SUSY scenario*. All the numbers are shown for 200 pb^{-1} of integrated luminosity with a 10 TeV CM energy. Errors in the second and third columns are statistical errors from MC. In the fourth column, the error is from the uncertainty due to finite statistics in the control regions in 200 pb^{-1} of data. The expected number of SM background events for different scenarios is always same and it is given in the third column of the first row. This should be compared with the estimated number of SM events given in the fourth column.

5.1 Sources of systematic uncertainty

We define $R_{\tt sm}$ as the ratio between the expected and the estimated number of SM background events in region A_{SR}, and estimate systematic uncertainties on $R_{\tt sm}$, both for the *No SUSY scenario*, and the *SUSY* SU4 *scenario* in the A_{SR} region. The values of $R_{\tt sm}$ are 0.81±0.25 and 0.21±0.06 for the *No SUSY scenario* and the *SUSY* SU4 *scenario*, respectively.

Major systematic errors in this method can come from the following sources; we quote the more conservative values between the two scenarios.

- Jet energy scale: We vary the energy of each reconstructed jet by ±10%. The $\not{E}_T$, M_T and other variables related to the jet energy scale are recomputed. Then the whole estimation procedure is repeated and ratios for both scenarios are calculated. The difference with the nominal ratio values are quoted as systematic errors. The resulting systematic error to the background estimation method due to the jet energy scale variation is ∼10%.

- Jet energy resolution: The energy for each of the reconstructed jets is smeared by a Gaussian resolution, where the σ=0.45 $\times\sqrt{E_{jet}}$, which approximately adds in qudrature with the nominal MC jet energy resolution of 60%. The $\not{E}_T$ in each event is corrected after the change in the jet energy resolution for each jet in the event. The systematic errors for this category are calculated in the same way as in the jet energy scale case. The resulting systematic error to the background estimation method due to the jet energy resolution is ∼12%.

- Generator dependency: Since $t\bar{t}$ is the dominant background in this channel in both the control and signal regions, we use $t\bar{t}$ datasets produced by three different generators to probe any bias due to MC generators. We use $t\bar{t}$ events from the MC@NLO [13], AcerMC [14] and Alpgen [15] generators. We repeat the estimation method for each of these generator events along with other SM background events. The values of the ratio $R_{\mathtt{sm}}$ as predicted by several different Monte Carlo generators agree within statistical errors. The dominant source of uncertainty arises from the finite size of the Monte Carlo samples used to determine the ratio $R_{\mathtt{sm}}$; the resulting uncertainty is 30%.

6 Discovery potential

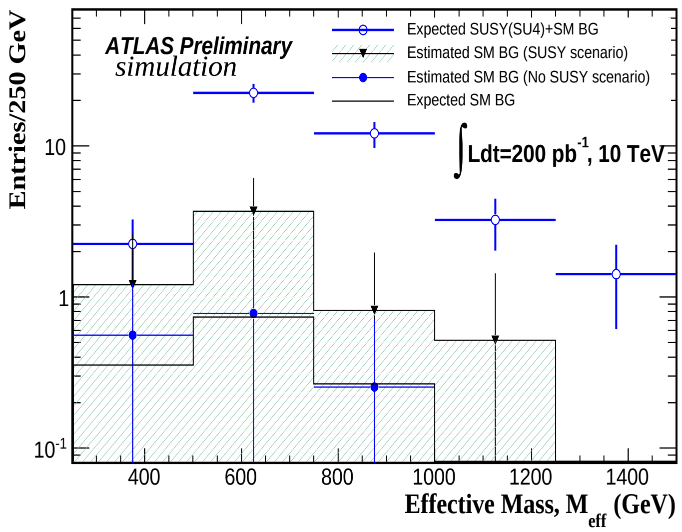

Figure 3: Effective mass distribution for same-sign dileptons in the inclusive two-jet and missing-energy final state. The events are for 200 pb^{-1} integrated luminosity at 10 TeV CM energy. SU4 SUSY signal events are considered for this figure.

From Table 3, we conclude that if nature has chosen an SU4-like SUSY signal in data, we will be able to observe a clear signature with an integrated luminosity of 200 pb^{-1} at 10 TeV. Figure 3 shows the effective mass ($M_{\rm eff}$) distribution for signal and background, defined as $M_{\rm eff} = p_T^{lep} + \not{E}_T + \sum_{jets} p_T^j$ where the sum runs over the leading n($\leq$4) jets with $p_T > 20$ GeV in the event.

Similarly, we have also analyzed other mSUGRA signal samples and repeated the whole SM background estimation method. Since the mSUGRA signal samples use MC events from a fast simulation of the ATLAS detector, and since the SM background events use a full simulation of the ATLAS detector, we do not use the number of background events from the background estimation method for the significance calculation of different mSUGRA signals instead, we just use the expected background events in the signal region A_{SR}. For the signal significance we have used a number counting method Z_N [5]. We require the effective mass, $M_{\rm eff}$, to be greater than 550 GeV in the significance calculation. The method Z_N uses a convolution of a Poisson and a Gaussian term to account for a systematic error. We use a 50% systematic uncertainty on the expected SM background to calculate the signal significance for each mSUGRA signal processes. Figure 4 shows the discovery reach for various luminosity scenarios in one of the mSUGRA parameter planes.

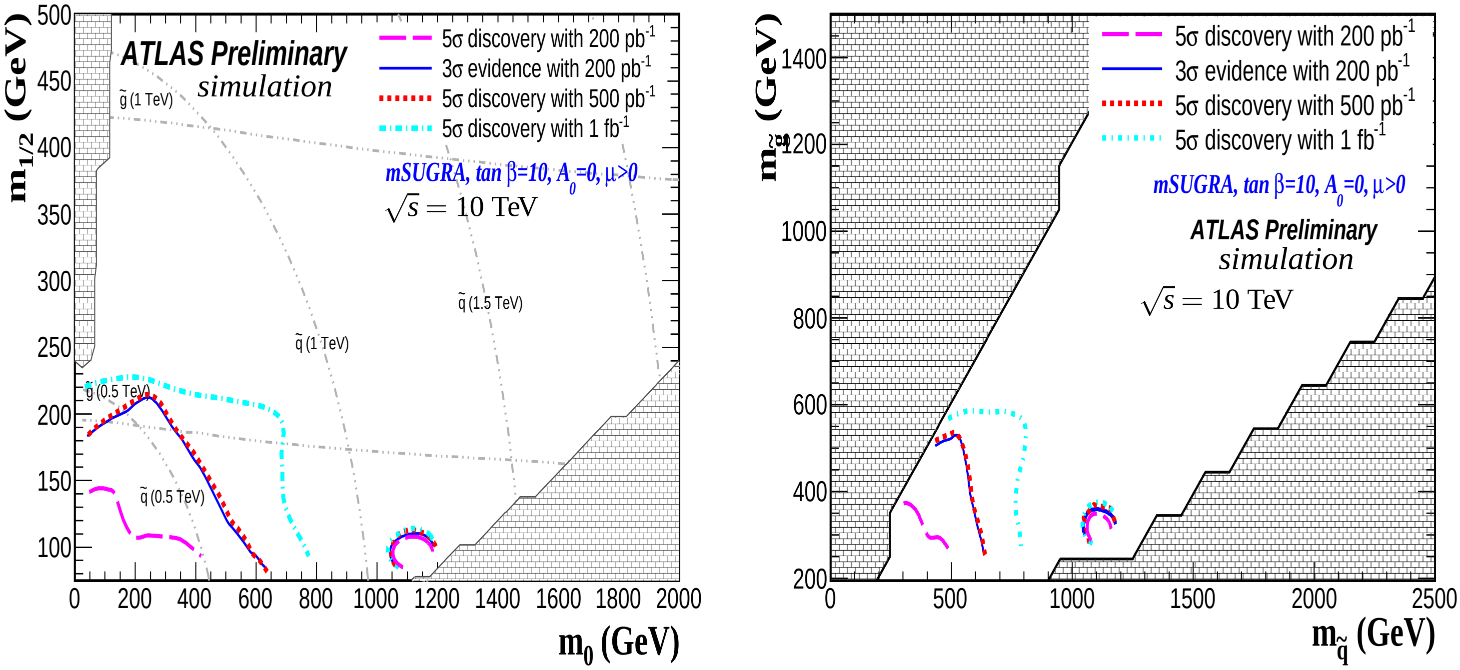

Figure 4: Left: Discovery reach in the mSUGRA m_0 and $m_{1/2}$ plane with the $\tan\beta$=10, $A_0 = 0$ and $\mu > 0$ configuration. Right: Discovery reach in the squark and gluino masses. Curves are shown for different luminosity scenario. The hatched regions at smaller m_0 values are excluded by the requirement that $\tilde{\chi}_1^0$ be the LSP. The hatched regions at larger m_0 values correspond to cases where no mSUGRA solution is found by ISAJET. Significance curves include statistical and systematic errors to the estimated background events. The curves in the plots correspond to a CM energy of 10 TeV.

7 Conclusion

Same-sign dilepton production along with jets and missing transverse energy is an important channel to discover supersymmetry in the early LHC data. Events with such signatures are scarcely produced in SM processes, providing an almost background-free and powerful channel for discovery of beyond the Standard Model signals. It is shown that we will be able to find evidence of gluinos and squarks of masses up to 500 GeV with a 3σ significance with as little as 200 pb^{-1} of integrated luminosity and a center of mass energy of 10 TeV.

In this note we have shown that low mass SUSY signals have a chance of 5σ discovery with LHC data in the same-sign dilepton final state. We have also developed a data-driven method to estimate the SM contribution into the signal region. The data-driven estimation method of SM events in the signal region is a necessity and plays a vital role in claiming an excess of events in physics beyond the Standard Model in the early data.

We have also made a more model-independent assessment of the sensitivity of the analysis by considering a wide range of mSUGRA parameter space for the signal production. We have computed the discovery potential for each of these points in the mSUGRA parameter space.

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