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Searches for supersymmetry at the Large Hadron Collider

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ABSTRACT: The potential for the general purpose detectors at the LHC, ATLAS and CMS, to discover supersymmetric particles is reviewed. Signals are considered from scenarios based on supergravity and gauge mediated supersymmetry breaking models, as well as from models in which R-parity is not conserved. In most cases, supersymmetric particles can be detected if the SUSY mass scale is in the LHC energy range, and the parameters of the underlying model can be determined.

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KEYWORDS: Supersymmetry, LHC, ATLAS.

Contents

1. Supersymmetric models

The addition of supersymmetry (SUSY) to the Standard Model (SM) offers a theoretically appealing way to solve the hierarchy problem, and to stabilise the Higgs mass at the electroweak scale. This requires that the SUSY scale be of order 1 TeV or less, giving a rich spectrum of SUSY particles in the mass range to be explored by the LHC. The SUSY signal is easy to find, and generally any SM backgrounds are easy to control. Therefore, in most cases, the ATLAS and CMS experiments have similar discovery potential for these particles. The main problem is to disentangle the underlying model using the observations. Full details of the ATLAS studies can be found in [1]. An overview of the CMS studies can be found in [2].

In the Minimal SUSY Standard Model (MSSM), R-parity conservation is assumed, and SUSY is broken by adding all possible mass terms and trilinear A terms to the Lagrangian, giving 105 parameters in addition to the 19 in the Standard Model. Since SUSY cannot be broken with the MSSM fields alone, a hidden sector, communicating to the normal sector by a messenger interaction, is used. In supergravity (SUGRA) models, the messenger interaction is gravity, while in Gauge Mediated Symmetry Breaking (GMSB) the SU(3)×SU(2)×U(1) fields are used at a low scale, perhaps as low as the electroweak scale. If R-parity is conserved, the lightest SUSY particle (LSP) is stable. Since it must also be weakly interacting (to satisfy cosmological constraints), SUSY particle production gives rise to an inclusive missing E_T signature. In R-parity violating models (RPV), the LSP can decay, making its complete reconstruction possible. Each of these models has different phenomenology and needs to be considered separately for experimental signatures.

2. Minimal SUGRA models

In Minimal SUGRA models, at the grand unified (GUT) scale, all scalars have mass m_0, all gauginos and higgsinos have mass $m_{1/2}$, and all trilinear terms have a common value A_0. The values of the bilinear couplings (B) and the higgsino mass parameter (μ^2) are derived from the mass of the Z and the ratio of the vacuum expectation values of the higgs doublets β, giving only 5 undetermined parameters: m_0, $m_{1/2}$, A_0, $tan(\beta)$ and sgn(μ). Points in this parameter space are chosen to study the various possible signatures which might face the experiments. The points used by ATLAS are shown in Table 1.

	m_0 (GeV)	$m_{1/2}$ (GeV)	A_0 (GeV)	$tan(\beta)$	sgn(μ)
1	400	400	0	2	+
2	400	400	0	10	+
3	200	100	0	2	-
4	800	200	0	10	+
5	100	300	0	2.1	+
6	200	200	300	45	-

Table 1: Points in SUGRA parameter space analysed by ATLAS.

An inclusive signature for SUSY can easily be detected in SUGRA models in channels with more than 2 jets, up to 3 leptons and large missing E_T, coming from the escaping LSP. A convenient measure of the SUSY mass scale can be obtained from the peak value of M_{eff}, the scalar sum of the transverse momenta of the four hardest jets and the missing E_T. At large M_{eff} the SUSY signal is an order of magnitude higher than the SM background, and squarks and gluinos with masses up to 2 TeV can be detected.

Once the SUSY signal is detected, a variety of precision measurements are possible. An example is the decay chain $\tilde{q}_L \to \tilde{\chi}_2^0 q \to \tilde{l}_R^{\pm} l^{\mp} q \to \tilde{\chi}_1^0 l^+ l^- q$ which occurs at point 5. The endpoint of the dilepton mass spectrum provides a measurement of the $\tilde{\chi}_2^0 - \tilde{\chi}_1^0$ mass difference with a precision of 0.5 GeV. The endpoint of the $l^{\pm} q$ mass spectrum and the threshold and endpoint of the $l^+ l^- q$ mass spectrum can also be measured. Together with information from the decay chain $\tilde{q}_L \to \tilde{\chi}_2^0 q \to \tilde{\chi}_1^0 h q \to \tilde{\chi}_1^0 b\bar{b} q$ these measurements allow all the masses in the chain to be determined in a model independent way. Precisions of 3%, 6%, 9% and 12% respectively can be attained after one year of running (10 fb^{-1}) on the $\tilde{q}_L$, $\tilde{\chi}_2^0$, $\tilde{l}_R^{\pm}$ and $\tilde{\chi}_1^0$ masses respectively. It should be noted that the masses obtained are highly correlated.

By fitting a set of such measurements, the underlying model parameters can be extracted. The results obtained by ATLAS at point 5 are given in Table 2.

Similar analyses are possible at other phase-space points, and in all cases the underlying model parameters can be determined.

Fitted value		
m_0	$m_{1/2}$	$tan(\beta)$
$100^{+4.1}_{-2.2}$ GeV	300 ± 2.7GeV	2.00 ± 0.10

Table 2: Model parameters extracted by ATLAS for SUGRA point 5, assuming 30fb^{-1} of data.

3. GMSB Models

GMSB models are characterised by 6 fundamental parameters: N_5, $\mathrm{C_{grav}}$, $tan(\beta)$, sgn(μ), M_m (the scale of the messenger interactions), and Λ (the ratio of the SUSY breaking scale to the messenger scale). The LSP is a gravitino with mass $\ll$ 1 GeV. The next-to-lightest SUSY particle (NLSP) is either a $\tilde{\chi}^0_1$ decaying via $\tilde{\chi}^0_1 \to \tilde{G}\gamma$, or a $\tilde{l}_R$ decaying via $\tilde{l}_R \to \tilde{G}l$, depending on the number of messenger multiplets (N_5) communicating between the MSSM and the hidden sectors. The lifetime of the NLSP is controlled by the parameter $\mathrm{C_{grav}}$. For large $\mathrm{C_{grav}}$ the NLSP decays produce new signatures inside the detector volume.

In the case that the NLSP is the $\tilde{\chi}^0_1$, production of $\tilde{\chi}^0_2$ pairs followed by the decay chain $\tilde{\chi}^0_2 \to \tilde{l}^{\pm}_R l^{\mp} \to \tilde{\chi}^0_1 l^+ l^- \to \tilde{G} l^+ l^- \gamma$ provides a clear two photon signature. Measurements of the final state kinematics allow all the SUSY masses in the chain to be determined, assuming that the $\tilde{G}$ mass is small. In addition, the $\tilde{\chi}^0_1$ decay length ($c\tau_{\tilde{\chi}^0_1}$) can be measured from Dalitz decays. This gives important information on SUSY breaking in all the hidden sectors, not just the messenger sector.

If $\mathrm{C_{grav}}$ is increased to 10^3, $c\tau_{\tilde{\chi}^0_1}$ would be over 1km. However, those decays which do occur inside the detector volume can still be detected as high energy photons which fail to point to the primary interaction vertex.

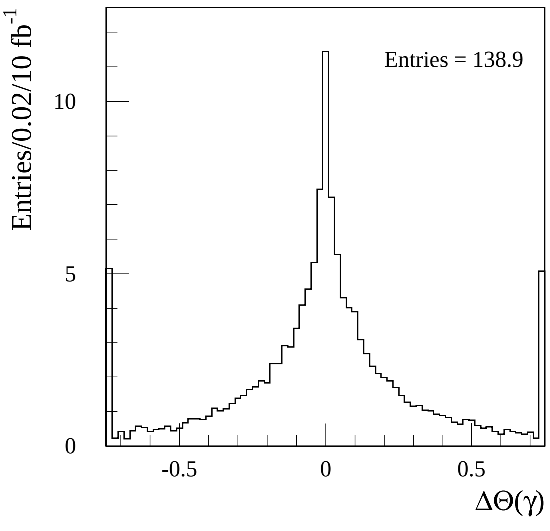

Figure 1: Simulation of the non-pointing angle $\Delta\Theta$ for photons from $\tilde{\chi}^0_1 \to \tilde{G}\gamma$ in the ATLAS calorimeter

Figure 1 shows the non-pointing angle of such photons simulated in the ATLAS electromagnetic calorimeter. The angular precision allows photons with $p_T > 20$ GeV from this signal to be detected with an overall signal efficiency of 52%, by selecting photons which miss the primary vertex by more than 5σ. With 30fb^{-1} of integrated luminosity, $c\tau_{\tilde{\chi}^0_1}$ as high as 100km can be detected, giving a 95% confidence limit of $\mathrm{C_{grav}} > 10^8$.

The CMS muon system consists of planes of drift tubes embedded in an absorber, and can thus function as an electromagnetic calorimeter for photons created inside it. The sensitivity of the system to the GMSB signals has been studied in [3].

ATLAS has also studied models with $N_5 > 1$, $C_{grav} = 1$, in which SUSY particles are produced with large cross sections (23pb), and the decays $\tilde{\chi}_i^0 \to \tilde{l}_R l \to \tilde{G}ll$ give rise to many signatures with final state leptons and missing energy. The discovery of SUSY is simple in these cases, and many mass measurements are possible, including the $\tilde{q}_R$, $\tilde{l}_R$ and $\tilde{\chi}_1^0$ in cases where the decay chains are favourable.

Figure 2 shows two edges in the dilepton distribution from decays of the $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$. Backgrounds from Standard Model processes and independent decays of charginos are removed by subtracting the opposite flavour pairs. The positions of the edges are determined by the differences between the $\tilde{l}_R$ and $\tilde{\chi}_i^0$ masses.

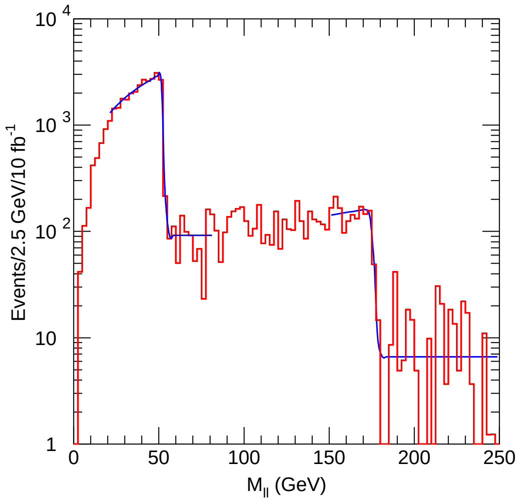

Figure 2: $e^+e^- + \mu^+\mu^- - e^\pm\mu^\mp$ dilepton mass distribution in GMSB.

Finally, the case where $N_5 > 1$ and $C_{grav} = 5 \times 10^3$ has been considered. The NLSP is the $\tilde{\tau}_1$ which has a decay length of 1km. The $\tilde{e}_R$ and $\tilde{\mu}_R$ are also long-lived, decaying to gravitinos with similar lifetimes. The signature is therefore a pair of quasi-stable heavy particles, which resemble muons in the detector, but have low velocity ($\beta < 1$) and high ionisation. The slepton masses can be determined by using their time-of-flight to the muon system [1, 3]. The decays $\tilde{\chi}_i^0 \to \tilde{l}_R l$ can then be fully reconstructed. Once the $\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$ masses have been determined, the decay $\tilde{q}_R \to \tilde{\chi}_i^0 q$ can be used to determine the $\tilde{q}_R$ mass.

Table 3 shows the fits to the GMSB parameters obtained by ATLAS for each of the four cases above.

In three of the cases, all the model parameters are reasonably determined, and the sign of μ is also unambiguous. In case b), Λ and N_5 are not well fit separately, and sgn(μ) is ambiguous.

4. R-parity violating models

If R-parity is broken, SUSY particles may decay to SM particles, and may be produced singly. So far, only models based on SUGRA with a small level of R-parity violation (RPV) have been considered, in which the only effect is to allow the LSP to decay with a short lifetime. Studies concentrate on reconstructing the LSP decay.

	Fitted value			
	Λ TeV	N_5	M_m TeV	$tan(\beta)$
a)	90.0 ±1.7	1.000 ±0.014	500 ±170	5.0 ±1.3
b)	$\Lambda N_5 =$	90.0 ±0.88	$< 7 \times 10^5$	5.0 $^{+2.7}_{-1.8}$
c)	30.0 ±0.54	3.00 ±0.05	250 ±60	5.0 ±1.0
d)	30.0 ±0.25	3.00 ±0.02	250 ±32	5.0 ±0.3

Table 3: Model parameters extracted by ATLAS for GMSB models, assuming 30fb^{-1} of data. a) $N_5 = 1$, $\text{C}_{\text{grav}} = 1$, b) $N_5 = 1$, $\text{C}_{\text{grav}} = 10^3$, c) $N_5 = 3$, $\text{C}_{\text{grav}} = 1$, d) $N_5 = 3$, $\text{C}_{\text{grav}} = 5 \times 10^3$. In case b), Λ and N_5 are not well-determined separately.

R-parity can be broken by three distinct interaction terms, with strengths λ, λ', and λ''. For $\lambda \neq 0$, lepton number is violated in the decay $\tilde{\chi}_1^0 \to l^+l^-\nu$. For $\lambda' \neq 0$, lepton number is violated in the decays $\tilde{\chi}_1^0 \to q\bar{q}\nu$ and $q\bar{q}l$. For $\lambda'' \neq 0$, baryon number is violated in the decay $\tilde{\chi}_1^0 \to qqq$.

The baryon number violating scenario ($\lambda'' \neq 0$) is the most challenging experimentally, since decays such as $\tilde{\chi}_1^0 \to cds$ do not give rise to a missing energy signature, and have no special lepton or quark flavour tags. In order to reduce the SM background to acceptable levels, it is necessary to seek a dilepton signature from the decay chain $\tilde{\chi}_2^0 \to \tilde{l}_R l \to \tilde{\chi}_1^0 l^+l^-$. The second SUSY decay chain will also end in a $\tilde{\chi}_1^0$, and each will decay to 3 jets. The signature therefore requires a minimum of 6 jets in the final state, in addition to two leptons. Since the SUSY production cross section is dominated by cascades from squarks and gluinos, typical final states contain around 12 jets.

The $\tilde{\chi}_1^0$ signature can be extracted from these jets by forming all combinations of 3 jet systems, and requiring that two combinations in an event give the same mass within 20 GeV. Combinations which fail to match can be used to measure the shape of the combinatoric background. The $\tilde{\chi}_1^0$ mass can be reconstructed to around 3 GeV. Once this is achieved, full reconstruction of the other particles in the decay chain is possible.

The lepton number violating decay $\tilde{\chi}_1^0 \to \nu ll$ ($\lambda \neq 0$) gives rise to a signature with ≥ 4 leptons which is easy to detect. The mass distribution of opposite-sign different-flavour leptons is shown in Figure 3. A clear kinematic endpoint is seen at the $\tilde{\chi}_1^0$ mass, which can be measured to a precision of 180 MeV.

Events at the kinematic edge have small missing energy due to the final state neutrino, and so can be used to reconstruct other masses in the decay chain. For example, combining $\tilde{\chi}_1^0$ candidates at the edge with events in the $h \to b\bar{b}$ peak allows the $\tilde{\chi}_2^0$ mass to be measured with a precision of 4.8 GeV.

The lepton number violating scenario with $\lambda' \neq 0$ provides two possible signatures. The $\tilde{\chi}_1^0 \to q\bar{q}l$ decay mode gives a fully reconstructable final state with a clear dilepton signature. The $\tilde{\chi}_1^0 \to q\bar{q}\nu$ final state is more difficult, as the missing energy signature is reduced compared to SUGRA models. However the presence of extra leptons from cascade decays, and high jet multiplicity make this scenario detectable.

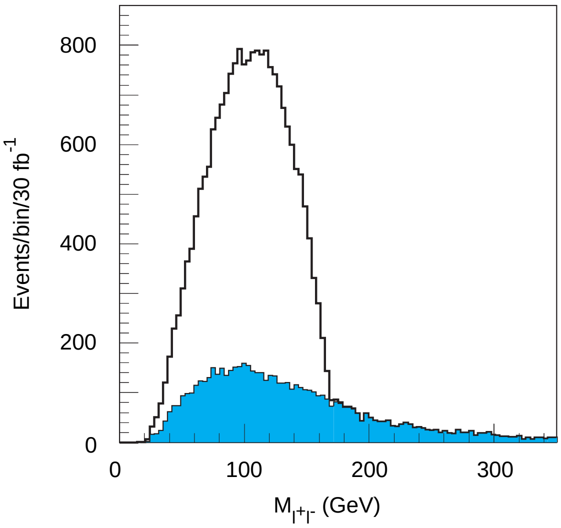

Figure 3: Oppsite-sign, different flavour dilepton mass distribution in a lepton number violating RPV model.

5. Conclusions

Signals for SUSY will be easy to detect at the LHC for all of the models studied to date. The main background to particular SUSY processes comes from other SUSY processes, not the Standard Model, and so the main challenge is to unravel the complex decay chains and extract the parameters of the underlying model. A range of possible models has been studied by ATLAS and CMS, including non-Univeral Supergravity, Gauge Mediated SUSY Breaking, and R-parity violation. In all cases a wide range of precise measurements are possible, and the model parameters can generally be extracted accurately.

Should SUSY be realised at the TeV scale, the LHC should not only discover it, but also pin down the mass spectrum and the SUSY breaking mechanism.

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