SUSY AT THE LHC

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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.

1 Supersymmetric models

Supersymmetric extension of the Standard Model (SM), with SUSY scales around 1 TeV, give a rich spectrum of SUSY particles in the mass range to be explored by the LHC. The SUSY signal is easy to find, with small SM backgrounds. Therefore, 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 past ATLAS studies can be found in [1], and a recent study of anomaly mediated SUSY breaking can be found in [2]. An overview of the CMS studies can be found in [3].

In the Minimal SUSY Standard Model (MSSM), R-parity conservation is assumed. 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. If R-parity is conserved, the lightest SUSY particle (LSP) is stable, weakly interacting (to satisfy cosmological constraints), and gives an inclusive E_T^{miss} signature. In R-parity violating models (RPV), the LSP can decay, making its complete reconstruction possible. Each of these models needs to be considered separately for experimental signatures.

2 Minimal SUGRA models

Minimal SUGRA models, have only 5 undetermined parameters: a scalar mass, m_0, gaugino and higgsino masses, $m_{1/2}$, trilinear couplings, A_0, the ratio of the vacuum expectation values of the higgs doublets, $\tan\beta$ and the sign of the higgsino mass parameter, $\mathrm{sgn}(\mu)$. Points in this parameter space are chosen to study the various possible signatures which might face the experiments.

An inclusive signature for SUSY can easily be detected in SUGRA models in channels with $\geq$ 2 jets, up to 3 leptons and large E_T^{miss}. 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 one of the points studied by ATLAS: $m_0 = 100$ GeV, $m_{1/2} =$ 300 GeV, $A_0 = 0$ GeV, $\tan\beta = 2.1$, $\mu > 0$. 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.

By fitting a set of such measurements, the underlying model parameters can be extracted. The results obtained by ATLAS at this point are $m_0 = 100^{+4.1}_{-2.2}$ GeV, $m_{1/2} = 300 \pm 2.7$ GeV, $\tan\beta = 2.00 \pm 0.10$. Similar analyses are possible at other phase-space points, and in most cases the underlying model parameters can be well determined.

3 GMSB Models

GMSB models have 6 fundamental parameters: N_5 (the number of messenger multiplets), 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 $\tilde{\chi}_1^0$ decaying via $\tilde{\chi}_1^0 \to \tilde{G}\gamma$, or a $\tilde{l}_R$ decaying via $\tilde{l}_R \to \tilde{G} l$, depending on N_5. C_{grav} sets the NLSP lifetime, and for large C_{grav} the NLSP decays produce new signatures inside the detector volume.

In the case that the NLSP is the $\tilde{\chi}_1^0$, production of $\tilde{\chi}_2^0$ pairs followed by the decay chain $\tilde{\chi}_2^0 \to \tilde{l}_R^{\pm} l^{\mp} \to \tilde{\chi}_1^0 l^+ l^- \to \tilde{G} l^+ l^- \gamma$ 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 $\tilde{\chi}_1^0$ decay length ($c\tau_{\tilde{\chi}_1^0}$) can be measured from Dalitz decays. This gives important information on SUSY breaking in all the hidden sectors, not just the messenger sector.

If C_{grav} is increased to 10^3, $c\tau_{\tilde{\chi}_1^0}$ 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.

The non-pointing angle of such photons has been simulated in the ATLAS calorimeter system. The angular precision allows photons with $p_T > 20$ GeV from this signal to be detected with an overall signal efficiency of 52%. With 30fb^{-1} of integrated luminosity, $c\tau_{\tilde{\chi}_1^0}$ as high as 100km can be detected, giving a 95% confidence limit of $C_{grav} > 10^8$. The CMS muon system can also function as an electromagnetic calorimeter for photons created inside it. The sensitivity of the system to the GMSB signals has been studied in [4].

ATLAS has also studied models with $N_5 > 1$, $C_{grav} = 1$, which have large SUSY cross sections (23pb). The decays $\tilde{\chi}_i^0 \rightarrow \tilde{l}_R l \rightarrow \tilde{G} l l$ give rise to many signatures with final state leptons and missing energy. 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. For example, two clear edges are seen 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.

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 [1,4]. The decays $\tilde{\chi}_i^0 \rightarrow \tilde{l}_R l$ can then be fully reconstructed. Once the $\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$ masses have been determined, the decay $\tilde{q}_R \rightarrow \tilde{\chi}_i^0 q$ can be used to determine the $\tilde{q}_R$ mass.

Fits to the GMSB parameters have been performed by ATLAS for each of the four cases above. In three of the cases, all the model parameters are reasonably determined, with typical precisions of $< 2\%$ for Λ and N_5, 10-40% for M_m and $\tan\beta$. The sign of μ is also unambiguous. In the case $N_5 = 1$, $C_{grav} = 10^3$, Λ and N_5 are not well fit separately, and $\text{sgn}(\mu)$ is ambiguous.

4 R-parity violating models

If R-parity violation allows SUSY particles to decay to SM particles. So far, only decays of the LSP have been considered. 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 scenario with $\lambda'' \neq 0$ 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 ≥ 6 jets in the final state, and ≥ 2 leptons. Typical final states contain around 12 jets.

The $\tilde{\chi}_1^0$ signature can be extracted 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 and reconstruction of the rest of the decay chain is then 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 shows a clear kinematic endpoint 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.

References

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