SUSY studies with ATLAS: hadronic signatures and focus point

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In this report recent studies made to understand the capability to discover and measure properties of SUSY particles with the ATLAS detector at LHC are presented. The first part of the report discusses the reconstruction of gluino, right-handed squarks and third generation squarks, whose decays give rise to complex hadronic signatures, for some mSUGRA benchmark points. In the second part, the potential of the ATLAS experiment is discussed for the Focus Point region of the mSUGRA parameter space.

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1 Introduction

One of the best motivated extensions of the Standard Model is Supersymmetry [1]. If Supersymmetry exists at the electroweak scale, it is likely to be discovered at LHC. Usually, the most abundant sparticles produced in the pp collisions are squarks and gluinos. In R-parity conserving models, they decay into the stable lightest supersymmetric particle (LSP), which escapes detection. This leads to an excess of events with large missing energy, multijet and multilepton final states over Standard Model expectations. The centre of mass energy of 14 TeV available at LHC extends the reach of searches for SUSY particles up to a squark/gluino mass of 2.5-3 TeV [2].

Determining the masses of supersymmetric particles is more difficult because each SUSY event contains two undetected particles, and there are not enough kinematic constraints to determine their momenta. Techniques to derive constraints on the masses from kinematic edges have been developed using a number of benchmark points in the SUSY parameter space [3,4]. At point SPS1a, for example, kinematic edges involving the leptons and jets from the decay chain (l is an electron or a muon) $\tilde{q} \to \tilde{\chi}_2^0 q \to \tilde{l}_R l q \to \tilde{\chi}_1^0 l l q$ allow to reconstruct the masses of all the supersymmetric particles involved [4,5]. In Section 2 of this report, it will be shown how the masses of additional particles (gluinos, third generation squarks and right-handed squarks) can be reconstructed using more complex signatures, involving combinations of these leptons with b-jets or purely hadronic final states.

The LSP is a natural candidate for Dark Matter. Once the parameters of a specific SUSY model have been chosen, it is possible to compute the expected relic density of LSPs in the present universe. Recent data from the WMAP experiment

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[6, 7] constrain the density of non-baryonic Dark Matter to be $\Omega h^2 = 0.1126^{+0.0161}_{-0.0181}$ (2σ interval). This is an upper bound to the LSP relic density, since there may be other contributions. Within the framework of mSUGRA, the best-studied class of SUSY models, most of the parameter choices result in a too large relic density of neutralinos [8–10]. The WMAP constraints can be respected if the SUSY mass scale is relatively light, which makes it easy to study Supersymmetry at the LHC, but there are some narrow strips of the parameters space which extends to high values of the SUSY mass scale. One of these strips is the Focus Point region [11–13] which is characterized by large values (in the multi-TeV range) of the scalar mass m_0 but relatively low values (a few hundred GeV) of the gaugino mass $m_{1/2}$. The lightest neutralino is a mixture of bino and higgsino (in contrast to most of the mSUGRA parameter space where it is mostly a bino) and the higgsino component gives rise to rapid s-channel neutralino annihilation in the early universe, so that the relic density is kept at acceptably low values. In this region the mass of squarks and sleptons is at the limit or beyond the LHC reach, and the SUSY production cross section will be dominated by gluinos, neutralinos and charginos. The ability of the ATLAS experiment to study the SUSY phenomenology in this scenario is the subject of Section 3.

2 Reconstruction of SUSY masses: hadronic signatures

In this section some techniques to reconstruct the mass of third generation squarks, right-handed squarks and gluinos will be presented. Unless otherwise specified, results will be presented for the mSUGRA reference point SPS1a, characterized by the parameters $m_0 = 100$ GeV, $m_{1/2} = 250$ GeV, $\tan\beta = 10$, $A = -100$ GeV and $\mu > 0$. However, the techniques that will be presented can be applied also in a variety of other scenarios. It will be assumed that the masses of the first two generation squarks, the two lightest neutralinos and the right-handed sleptons have already been measured as described in [5].

2.1 Gluino and sbottom reconstruction

This analysis [4] exploits the decay chain

$$\tilde{g} \to \tilde{b}b \to \tilde{\chi}_2^0 b \to \tilde{l}_R lb \to \tilde{\chi}_1^0 llb$$

and requires two tagged b-jets and two same-flavor and opposite-sign leptons (electrons or muons). The masses of the supersymmetric particles involved are m($\tilde{g}$)=611 GeV, m($\tilde{b}_1$)=515 GeV, m($\tilde{b}_2$)=539 GeV, m($\tilde{\chi}_2^0$)=177 GeV, m($\tilde{l}_R$)=143 GeV and m($\tilde{\chi}_1^0$)=96 GeV. Once the mass of the $\tilde{\chi}_1^0$ has been measured, it is possible to get the momentum of the $\tilde{\chi}_2^0$ via the approximate relation [3,4]

$$\vec{p}(\tilde{\chi}_2^0) = [1 - m(\tilde{\chi}_1^0)/m_{ll}]p_{ll}$$

where $\vec{p}_{ll}$ and m_{ll} are respectively the momentum and the invariant mass of the lepton pair. The relation holds reasonably well for the point under study as the $\tilde{\chi}_1^0$

momentum is close to zero in the $\tilde{\chi}_2^0$ rest frame when the lepton invariant mass is close to the maximum allowed value of 77 GeV. For situations in which the $\tilde{l}_R$ is close in mass to either the $\tilde{\chi}_1^0$ or the $\tilde{\chi}_2^0$ this assumption is not justified anymore. The analysis requires the lepton invariant mass to be between 65 GeV and 77 GeV.

Since the mass of $\tilde{\chi}_2^0$ is also known, it is possible to reconstruct the $\tilde{b}$ mass as $m(\tilde{\chi}_2^0 b)$ and the $\tilde{g}$ mass as $m(\tilde{\chi}_2^0 bb)$. The reconstructed masses are reported in the scatter plot of Fig. 1. Since there are two possible combinations for the sbottom mass, two well-separated regions appear in the plot. The upper region is the one with the correct pairing. In this case, a strong correlation is present between the sbottom and gluino reconstructed masses, because the dominant error on the $\tilde{\chi}_2^0$ momentum determination affects both.

The difference $m(\tilde{g}) - 0.99m(\tilde{\chi}_1^0)$ does not depend on the value assumed for $m(\tilde{\chi}_1^0)$ and can be measured with a statistical error of 2.5 GeV for an integrated luminosity of 300 fb^{-1}. Assuming a 1% uncertainty on the jet energy scale gives a systematic error of about 6 GeV.

Since the sbottom and gluino reconstructed masses are highly correlated, it is convenient to study their difference. This is shown in Fig.2 for an integrated luminosity of 300 fb^{-1}. The separation of the contribution from the two sbottom states will require a good understanding of the systematics in the detector response to b-jets. Under the assumption that two peaks do indeed exist the fit with two gaussians gives a statistical error of 1.5 GeV for $m(\tilde{g}) - m(\tilde{b}_1)$ and 2.5 GeV for $m(\tilde{g}) - m(\tilde{b}_2)$.

2.2 Right-handed squarks reconstruction

At point SPS1a the $\tilde{\chi}_1^0$ is essentially a bino, and the $\tilde{\chi}_2^0$ a wino. Therefore the $\tilde{q}_R$ which has zero SU(2) charge decays with almost 100% branching ratio into the corresponding quark and the $\tilde{\chi}_1^0$. The signature of events in which both gluinos decay into $\tilde{q}_R$ is thus the presence of two low p_T jets from the $\tilde{g} \to q\tilde{q}_R$ decay, two high p_T jets from the squark decay, and missing energy. These events are selected by requiring at most four jets with $p_T > 50$ GeV, at least one jet with $p_T > 300$ GeV, and no leptons, τ-jets or b-jets. The squark mass is estimated using the following variable [14]

$$M_{T2}^2 = \min_{p_1^{\text{miss}} + p_2^{\text{miss}} = p_T^{\text{miss}}} [\max\{m_T^2(p_T^{j_1}, p_1^{\text{miss}}), m_T^2(p_T^{j_2}, p_2^{\text{miss}})\}]$$

where p_1^{miss} and p_2^{miss} are the unknown transverse momenta of the neutralinos, m_T is the transverse mass, and $p_T^{j_1}$ and $p_T^{j_2}$ are the transverse momenta of the two leading jets. The maximum of the distribution of M_{T2} (Fig. 3) is a function of the mass difference between the decaying particle and the invisible particle. The position of the edge can be estimated with an uncertainty of about 10 GeV, dominated by the systematics on the background shape. A similar analysis can be performed to reconstruct the decay $\tilde{l}_L \to l\tilde{\chi}_1^0$ [4].

2.3 Stop reconstruction

The mass and mixing of the scalar top provide special informations on the SUSY breaking mechanism. In models with universal scalar mass at the GUT scale, the top squark can be significantly lighter than the first two generation squarks at the weak scale due to the Yukawa running effect. In addition, the left-right mixing is expected to be sizeable. The cascade decay $\tilde{g} \to t\tilde{t}_1$ or $b\tilde{b}_1 \to tb\tilde{\chi}_1^{\pm}$ has been studied [15] by reconstructing the tb final states where the top decays hadronically. The tb invariant mass has an edge structure providing a constraint on the mass of the supersymmetric particles involved in the decay. In addition to the usual cuts on jet and missing transverse momentum to reject the SM background, two b-jets and 4 to 6 non-b jets are required. The top decay is reconstructed by searching for jets with an invariant mass compatible with the $t \to Wb \to jjb$ decay. The combinatorial background is estimated and subtracted with the W sideband technique [3,15]. The analysis have been performed on several mSUGRA points (and a few non-mSUGRA points as well) [15]. The end point from a fit of the tb invariant mass distribution has been found to be within a few percent from the true weighted average of the parton-level end points from the two decay chains.

3 Focus Point

The measurements which can be performed at LHC in the Focus Point region of the mSUGRA parameter space were investigated for the point defined by the parameters $m_0 = 3000$ GeV, $m_{1/2} = 215$ GeV, $\tan\beta = 10$, $A = 0$ and $\mu > 0$, with a top quark mass of 175 GeV. The masses of supersymmetric particles were computed using ISASUGRA 7.69 [16]. The events at the LHC were generated with HERWIG 6.503 [17, 18] and passed through the fast detector simulation of the ATLAS experiment [19].

The mass spectrum of Supersymmetric particles for this point is reported in Fig. 4. The scalar quarks and leptons and the heavy Higgs states are very heavy, so their production at the LHC is suppressed. The gluino has a mass of 642 GeV, and gluino pair production at the LHC will occur with a cross section of 3.76 pb. Each gluino decays into a neutralino or chargino and two quarks or a gluon. These events are characterized by several hard jets and missing energy. In Fig. 5 the distribution of the effective mass $M_{\text{eff}} = \Sigma_{\text{jets}} p_T + E_T^{\text{miss}}$ is reported for the events passing the cuts $M_{\text{eff}} > 750$ GeV, $E_T^{\text{miss}} > 100$ GeV and at least one jet with $p_T > 100$ GeV. The contributions from gluino pair production (3.76 pb), $\tilde{\chi}\tilde{\chi}$ production (13.3 pb) and $\tilde{g}\tilde{q}$ production (23 fb) are shown. The Standard Model tt background is also reported. Already with 1 fb^{-1} of integrated luminosity, a clear excess of events over the Standard Model background would be observed. After the cuts to reject the Standard Model processes, most of the selected Supersymmetry events comes from gluino pair production. The $\tilde{\chi}\tilde{\chi}$ production cross section is larger, but these events are very difficult to isolate from the dominant Standard Model background, since they have a similar jet and missing energy distribution. The $\tilde{g}\tilde{q}$ production, while suppressed by the heavy squark mass, can be observed with enough integrated luminosity.

The flavor-subtracted $((e^+e^- + \mu^+\mu^-) - (\mu^+e^- + e^+\mu^-))$ dilepton invariant mass distribution is shown in Fig. 6 for an integrated luminosity of 30 fb^{-1}. It receives contributions from the direct three-body decays $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 ll$ and and $\tilde{\chi}_3^0 \rightarrow \tilde{\chi}_1^0 ll$. A Z peak is visible as well. The edges from the two neutralino decays are $m(\tilde{\chi}_2^0) - m(\tilde{\chi}_1^0) = 48.5$ GeV and $m(\tilde{\chi}_3^0) - m(\tilde{\chi}_1^0) = 81.6$ GeV respectively. The next step is the combination of leptons with jets to reconstruct the gluino mass, which is currently under study.

The tb invariant mass from the decay $\tilde{g} \rightarrow \tilde{\chi}^{\pm} tb$ is reconstructed as follows. In addition to the SUSY selection cuts described above, two b-jets with $p_T >$ 30 GeV are required. The top quark hadronic decay is reconstructed [3] and the candidate tops are combined with b-jets provided that the tb angular separation is $\Delta R(t, b) < 2$. The resulting invariant mass distribution is reported in Fig. 7 for an integrated luminosity of 30 fb^{-1}. The endpoint of the distribution allows to measure $m(\tilde{g}) - m(\tilde{\chi}_1^{\pm})$.

4 Conclusions

If SUSY exists at the electroweak scale, it is likely to be discovered in the first months of data taking at the LHC. The reconstruction of the mass spectrum and the decays of the new particles will be more challenging.

In this contribution it has been shown for a selected point in the mSUGRA parameter space (SPS1a) how the ATLAS detector will be able to measure the mass of some particles (gluinos, third generation squarks and right-handed squarks) which require the reconstruction of purely hadronic final states, b-jets identification or top quark reconstruction.

The first studies on the ability of the ATLAS experiment to study Supersymmetry in the Focus Point scenario, favoured by the constraints on the density of Dark Matter, have been presented. For the selected point in the parameter space, the gluino pair production cross section allows a fast discovery of the new physics. The reconstruction of three kinematic end points has been demonstrated, which allows to place constraints on the masses of gluinos, charginos and neutralinos. More work is in progress to evaluate the ATLAS capability to reconstruct the masses of supersymmetric particles in the Focus Point region.

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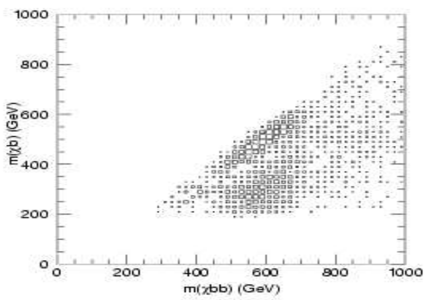

Fig. 1. Distribution of $m(\tilde{\chi}_2^0 b)$ versus $m(\tilde{\chi}_2^0 bb)$ for events passing the selections.

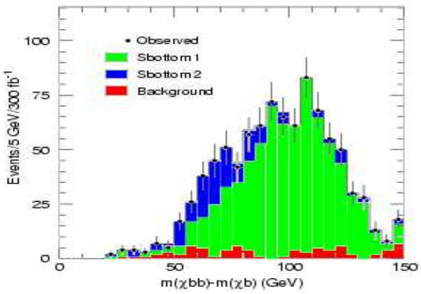

Fig. 2. Distribution of $m(\tilde{\chi}_2^0 bb) - m(\tilde{\chi}_2^0 b)$ for an integrated luminosity of 300 fb^{-1} (points with error bars). Superimposed are: $\tilde{g} \to \tilde{b}_1 b$ (green), $\tilde{g} \to \tilde{b}_2 b$ (blue), and background (red).

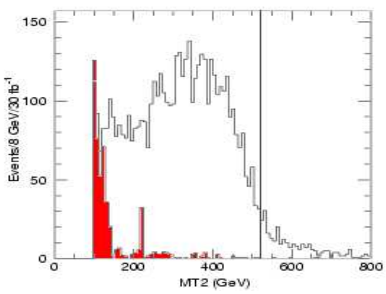

Fig. 3. Distribution of m_{T2} for the events passing the cuts. In red is shown the Standard Model background. The integrated statistic in the plot is 30 fb^{-1}.

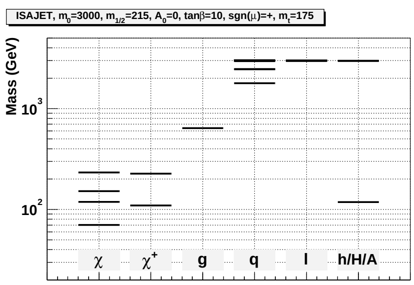

Fig. 4. Mass spectrum of Supersymmetric particles for the Focus Point model described in the text.

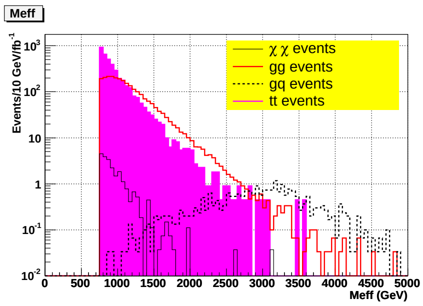

Fig. 5. Distribution of $M_{\text{eff}} = \Sigma_{\text{jets}} p_T + E_T^{\text{miss}}$ for the events passing the SUSY selection cuts. The contributions from the three dominant SUSY production processes and from the Standard Model tt background are shown.

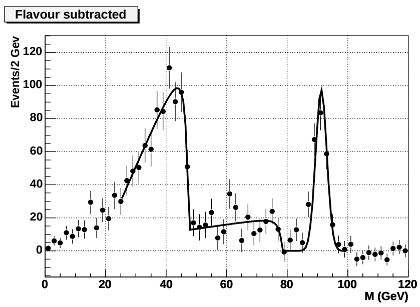

Fig. 6. Dilepton flavor-subtracted invariant mass distribution for the Focus Point scenario described in the text. The integrated luminosity is 30 fb^{-1}.

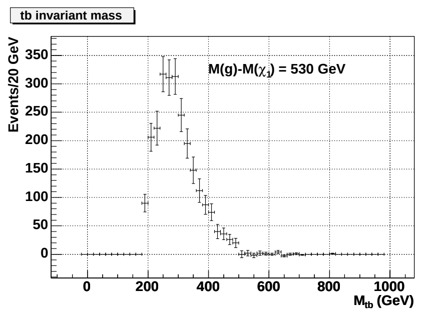

Fig. 7. tb invariant mass distribution for the Focus Point scenario described in the text. The integrated luminosity is 30 fb^{-1}.