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Study of supersymmetry at the LHC

If Supersymmetry exists at the electroweak scale, it could hardly escape detection at the LHC. In most R-parity conserving models, the production cross section is expected to be dominated by the pair production of coloured states (squarks and gluinos). These decay to lighter SUSY particles and ultimately to the LSP (Lightest Supersymmetric Particle). If this is stable and weakly interacting, as implied by R-parity conservation and cosmological arguments, it leaves the experimental apparatus undetected. The Supersimmetric events are thus expected to show up at the LHC as an excess over SM expectations of events with several hard hadronic jets and missing energy. The LHC center of mass of 14 TeV extends the search for SUSY particles up to squark and gluino masses of 2.5 to 3 TeV/c^2 [1,2].

If squarks and gluinos are lighter than 1 TeV, as implied by naturalness arguments, this signature would be observed with high statistical significance already during the first year of running at the initial LHC luminosity of 210^{33} cm^{-2}s^{-1} [3]. In practice, discovery would be achieved as soon as a good understanding of the systematics on Standard Model rates at the LHC is obtained.

A significant part of the efforts in preparation for the LHC startup is being spent in the simulations of the new physics potential. We give below a brief overview of these studies, dividing them in three categories: inclusive searches of the non-SM physics, measurement of SUSY particle masses, and measurements of other properties of SUSY particles, such as their spin or the flavour structure of their decays.

0.1 Inclusive searches

In these studies, the typical discovery strategy consists in searching for an excess of events with a given topology. A variety of final state signatures has been considered. Inclusive searches have mainly be carried out in the framework of mSUGRA, which has five independent parameters specified at high energy scale: the common gaugino mass $m_{1/2}$, the common scalar mass m_0, the common trilinear coupling A_0, the ratio of the vacuum expectations values of the two Higgs doublets $\tan\beta$ and the sign of the Higgsino mixing parameter μ. The masses and decay branching ratios of the SUSY particles are then computed at the electroweak scale using the renormalization group equations, and used as input to the LHC simulation codes.

For each point of a grid covering the mSUGRA parameter space, signal events are generated at parton level and handed over to the parametrized detector simulation. The main Standard Model background sources are simulated, where the most relevant are processes with an hard neutrino in the final state ($t\bar{t}$, W+jets, Z+jets). Multi-jet QCD is also relevant because its cross section is several orders of magnitude larger than SUSY. However it is strongly supressed by the requirement of large transverse missing energy and it gives a significant contribution only to the final state search channels without isolated leptons. The detailed detector simulation, much more demanding in terms of computing CPU power, validates the results with parametrized detector simulations for the Standard Model backgrounds and selected points in the mSUGRA parameter space.

Cuts on missing transverse energy, the transverse momentum of jets, and other disciminating variables are optimized to give the best statistical significance for the (simulated) observed excess of events. For each integrated luminosity the regions of the parameter space for which the statistical significance exceeds the conventional discovery value of 5σ are then displayed. An example is shown in Fig. 1 for the CMS experiment [4] with similar results for ATLAS [3]. A slice of the mSUGRA parameter space is shown, for fixed $\tan\beta = 10$, $A = 0$ and $\mu > 0$. The area of parameter space favoured by naturalness arguments can be explored with an integrated luminosity of only 1fb^{-1}.

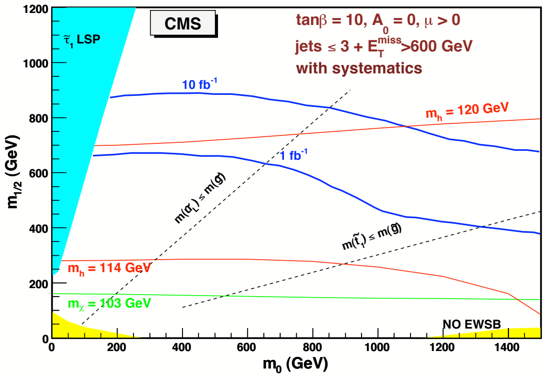

Fig. 1: CMS 5σ discovery potential using multi-jets and missing transverse energy final state [4].

Although these results were obtained in the context of mSUGRA, the overall SUSY reach in terms of squark and gluino masses is very similar for most of R-parity conserving models, provided that the LSP mass is much lower than the squark and gluino masses. This has been shown to be the case for GMSB and AMSB models [5] and even the MSSM [6].

0.2 Mass measurement

A first indication of the mass scale of the SUSY particles produced in the pp interaction will probably be obtained measuring the "effective mass", which is the scalar sum of transverse missing energy and the p_T of jets and leptons in the event. Such a distribution is expected to have a peak correlated with the SUSY mass scale. The correlation is strong in mSUGRA, and still usable in the more general MSSM [3].

The reconstruction of the mass spectrum of Supersymmetric particles will be more challenging. Since SUSY particles would be produced in pairs, there are two undetected LSP particles in the final state, which implies that mass peaks can not be reconstructed from invariant mass combinations, unless the mass of the LSP itself is already known.

The typical procedure consists in choosing a particular decay chain, measuring invariant mass combinations and looking for kinematical minima and maxima. Each kinematical endpoint is a function of the masses of the SUSY particles in the decay chain. If enough endpoints can be measured, the masses of all the SUSY particles involved in the decay chain can be obtained. Once the mass of the LSP is known, mass peaks can actually be reconstructed.

The main background for this kind of measurements usually comes from Supersymmetry events in which the desired decay chain is not present or was not identified correctly by the analysis. For this reason, these studies are made using data simulated for a specific point in SUSY parameter space, for which all Supersymmetric production processes are simulated.

The two body decay chain $\chi^0_2 \to \tilde{l}^{\pm} l^{\pm} \to l^{\pm} l^{\pm} \chi^0_1$ is particularly promising, as it leads to a very sharp edge in the distribution of the invariant mass of the two leptons, which measures:

$$M(\text{edge}) = m(\tilde{\chi}^0_2)\sqrt{1 - m^2(\tilde{l})/m^2(\tilde{\chi}^0_2)}\sqrt{1 - m^2(\tilde{\chi}^0_1)/m^2(\tilde{l})} \qquad (1)$$

The basic signature of this decay chain are two opposite-sign, same-flavour (OSSF) leptons; but two such leptons can also be produced by other processes. If the two leptons are independent of each other, one would expect equal amounts of OSSF leptons and OSOF leptons (i.e combinations $e^+\mu^-$, $e^-\mu^+$). Their distributions should also be identical, and this allows to remove the background contribution for OSSF by subtracting the OSOF events.

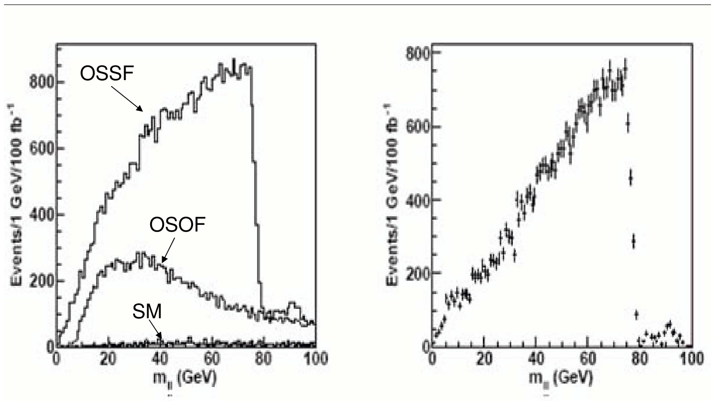

Fig. 2: Effect of subtracting background leptons, for the mSUGRA benchmark point SPS1a and an integrated luminosity of 100 fb^{-1}. In the left plot: the curves represent OSSF leptons, OSOF leptons and the SM contribution. In the right plot, the flavour subtraction OSSF-OSOF have been plotted: the triangular shape of the theoretical expectation is reproduced.

Fig. 2 shows the invariant mass of the two leptons obtained for SPS1A point [7] with 100 fb^{-1} of simulated ATLAS data [8]. The Standard Model background is clearly negligible. The real background consists of other SUSY processes, that are effectively removed by the OSOF subtraction.

Several other kinematical edges can be obtained using various invariant mass combinations involving jets and leptons. Two of such distributions are reported in Fig. 3 for the point SPS1a and 100 fb^{-1} of ATLAS simulated data [8]. Five endpoints, each providing a constraints on the mass of four particles, can be measured. The masses of the Supersimmetric particles present in the decay chain (the left-handed squark, the right-handed sleptons, and the two lightest neutralinos) can thus be measured with an error between 3% (for the squark) and 12% (for the lightest neutralino) for 100 fb^{-1}of integrated luminosity.

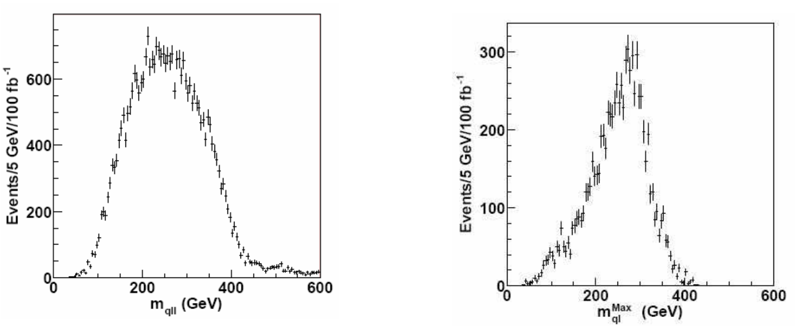

Fig. 3: Invariant mass distributions with kinematical endpoints, for an integrated luminosity of 100 fb^{-1}. In the left plot for qll combination, in the right plot for the maximum of ql combination.

For lepton pairs with an invariant mass near the kinematical endpoint, the relation

$$p_\mu(\tilde{\chi}_2^0) = (1 - m(\tilde{\chi}_1^0)/m(ll))p_\mu(ll) \tag{2}$$

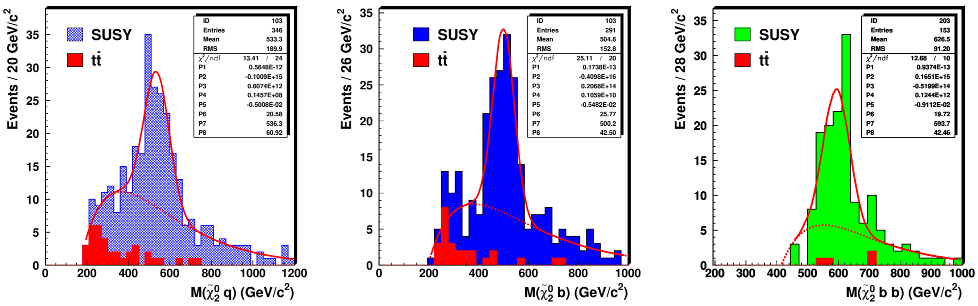

Fig. 4: Invariant mass peaks for squark (left), sbottom (middle) and gluino (right) at point B. The picture has been obtained using the parametrized simulation of the CMS detector. The integrated luminosity is 1 fb^{-1} for the squarks and 10 fb^{-1} for the other mass peaks.

can be used to get the four-momentum of the χ_2^0, provided that the mass of the lightest neutralino has already been measured. This four-vector can then be combined with that of hadronic jets to measure the gluino and squark masses. In Fig. 4 the gluino and squark mass peaks obtained with CMS parametrized simulation are reported for an other mSUGRA benchmark point, called point B [1] [9].

Several other techniques to reconstruct the masses of Supersymmetric particles have been investigated by the ATLAS and CMS collaborations. Here we will only mention a few other possibilities:

- At large $\tan\beta$ the decays into third generation leptons are dominant. The $\tau^+\tau^-$ kinematic endpoint is still measurable using the invariant mass of the tau visible decay products, but the expected precision is worse than that achievable with electrons and muons.SUSYintro3
- The right handed squark often decays directly in the LSP. $\tilde{q}_R\tilde{q}_R \rightarrow q\chi_1^0 q\chi_1^0$ events can be used to reconstruct the mass of this squark. A similar technique can be used to measure the mass of left-handed sleptons which decay directly into the LSP.

For the point SPS1a and an integrated luminosity of 300 fb^{-1} ATLAS expects to be able to measure at least 13 mass relations [8]. The constraints which can be put on the SUSY parameter space and on the relic density of neutralinos using these measurements are discussed in Ref. [10].

0.3 Flavour studies

Most studies by the LHC collaborations have focused on the discovery strategies and the measurement of the masses of SUSY particles. However, the possibility to measure other properties of the new particles, such as their spin or the branching ratios of flavour violating decays, has also been investigated.

The measurement of the spin is interesting because it allows to confirm the Supersimmetric nature of the new particles. This measurement was investigated in Ref. [11, 12] and it is also discussed later in this chapter.

In the hadronic sector, the experiments are not able to discriminate the flavour of quarks of the first two generations. Hence the only possibility for flavour studies relies on b-tagging techniques. In this report, the possibility to measure kinematical endpoints involving the scalar top is discussed. The scalar bottom masses may also be measured at the LHC.

[1] $m_0 = 100$ GeV, $m_{1/2} = 250$ GeV, A=0, $\mu > 0$, $\tan\beta = 10$

The leptonic sector is more favourable from the experimental point of view, as the flavour of the three charge leptons can be identified accurately by the detectors with relatively low backgrounds. This allows the possibility to test the presence of decays violating lepton flavour. This possibility was already discussed in early studies [13, 14] and it is investigated in a few contributions to this report.

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