SUSY searches at LHC and Dark Matter

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Supersymmetric models with R-parity conservation provide an excellent candidate for Dark Matter, the Lightest Supersymmetric Particle, which will be searched for with the ATLAS detector at the Large Hadron Collider (LHC). Based on recent simulation studies, we present the discovery potential for Supersymmetry (SUSY) with the first few fb^{-1} of ATLAS data, as well as studies of the techniques used to reconstruct decays of SUSY particles at the LHC. We further discuss how such measurements can be used to constrain the underlying Supersymmetric model and hence to extract information about the nature of Dark Matter.

Keywords:

1. Introduction

Several astronomical observations have hinted at the existence of non-baryonic matter in the Universe, the so-called *dark matter*. These observations tell us that dark matter constitutes about 90% of the matter density of the universe, where baryonic matter contributes only around 10%. Phenomena implying the presence of dark matter include the rotational speeds of galaxies and gravitational lensing of background objects by galaxy clusters and the behaviour of the Bullet cluster. The latter provides strong evidence that dark matter must be a Weakly Interacting Massive Particle (WIMP). Furthermore, precision measurements of the power spectrum fluctuations in the cosmic microwave background from WMAP,¹ strongly disfavour warm dark matter.

Despite these advancements, there are a lot of questions we still need to answer. Do fundamental particles comprise the bulk of the dark matter? If so, is there a symmetry from which these particles originate? How and when were these particles produced? There are many experiments that are attempting to answer these questions.

Astrophysical experiments attempt to detect dark matter by search-

ing for dark matter annihilation processes in the galaxy using land-based gamma ray telescopes or space-based satellites. Particle physics experiments aim to create and study dark matter in the laboratory. One of the latter is the Large Hadron Collider (LHC) at CERN, in Geneva, which will start taking data towards the end of 2009. The purpose of this proceeding is to describe how the LHC can help to understand the nature of dark matter.

The Standard Model (SM) of particle physics, while being a very successful description of the observed particles and their interactions, does not contain any particle that can explain dark matter. However, there are many extensions of the SM that can.

One popular extension of the SM is Supersymmetry (SUSY), in which a new symmetry between bosons and fermions is introduced. This symmetry leads to new particles, not yet observed. All existing particles of the SM would have partners called *sparticles*: each boson would have a fermionic partner and each fermion a bosonic one.

In SUSY there exists a new quantum number, R-parity, under which SM particles are even whilst SUSY particles are odd. In the following we consider the phenomenology of SUSY models where R-parity is conserved. This has two important phenomenological consequences. Firstly, sparticles can only be produced in pairs, and secondly, the lightest SUSY particle (LSP) is stable and escapes detection in high-energy physics detectors. Thus, the LSP is a natural WIMP candidate. Within SUSY there are several possibilities for WIMP candidates, depending on the SUSY model.

The most obvious feature of SUSY is that none of the superpartners have been discovered yet and hence SUSY must be a broken symmetry, with the masses of the superpartners being much larger than their SM counterparts. It is assumed that the spontaneous breaking of SUSY occurs in what is called the hidden sector. How this soft breaking is done defines the SUSY model and its phenomenology. We will focus on the assumption that supersymmetry exists in nature as the Minimal Supersymmetric Standard Model (MSSM). In this model, SUSY breaking is implemented by including explicit soft mass terms for the SUSY particles in the MSSM multiplets. These terms contain a vast number of free parameters that spoil the predictive power of this model. To reduce these, some specific assumptions for the SUSY breaking are adopted, giving models defined by a small number of parameters at the SUSY breaking scale. We will discuss here in detail the mSUGRA model, where SUSY breaking is mediated by gravitational interaction. In this model the LSP is the lightest neutralino.

Assuming the equality of various soft parameters at the pre-SUSY

breaking energy scale (universality), the MSSM phase space can be described by five soft SUSY breaking free parameters at the unification scale:² the Higgs field mixing, μ , the universal scalar mass m_0 , the universal gaugino mass $m_{1/2}$, the universal trilinear coupling A_0 and $\tan\beta = v_1/v_2$ the ratio between the vacuum expectation values of the two Higgs doublets. From these parameters, the mass spectrum of the superpartners, the cross-sections of their production as well as the branching ratios of their decays can be calculated. In these proceedings, we will use the MSSM as an example to show how measurements at the LHC can be used to calculate the relic density. Even within this reduced set of parameters, different regions of the MSSM parameter space have different LSP's, with possible options including the gluino, sneutrino, gravitino and the lightest neutralino. The last particle in this list is an admixture of the superpartners of the neutral SM gauge bosons, and is the subject of the majority of studies.

Supersymmetric extensions of the Standard Model, with scales around 1 TeV, give a rich spectrum of SUSY particles in the mass range to be explored by the LHC. At LHC energies mostly pairs of squarks or gluinos will be produced, which then subsequently decay via cascades into the LSP. Typical event topologies at the LHC are multi jet events with zero or more leptons and missing transverse energy due to the LSPs. This SUSY signal is relatively easy to find, with relatively small SM backgrounds. The main problem is to disentangle the underlying model using the observations.

2. Sparticle Production at the LHC

At the LHC, squarks and gluinos are produced via strong processes, hence their production will have a large cross section. For example, with 100 pb^{-1} of data, we expect about 100 events with squarks of 1 TeV mass. Direct production of charginos, neutralinos and sleptons occur via electroweak processes, hence the production cross sections are much smaller. They are produced much more abundantly in squark and gluino decays.

The strongly interacting sparticles (squarks, gluinos) which dominate the production are much heavier than the weakly interacting and SM particles, giving long decay chains to the LSP and large mass differences between SUSY states. Consequently, searches for Supersymmetry at the LHC concentrates on cascade decays, which will produce spectacular events with many jets, leptons and a lot of missing transverse energy, making it relatively easy to extract a SUSY signal from the SM background.

If the LHC discovers signatures that look like R-parity conserving SUSY signatures, the procedure to study their relation to Dark Matter is the

following:

- 1st Step: Look for deviations from the Standard Model, for example, in the multi-jet plus E_T^{miss} signature.
- 2st Step: Is it SUSY? If so, establish the SUSY mass scale using inclusive variables, e.g. effective mass distributions defined as:³
 $M_{eff} = \sum_{i=1}^n p_T^{\text{jet},i} + \sum_{i=1}^m p_T^{\text{lep},i} + E_T^{\text{miss}}$ where n and m are the number of jets and lepton in the events.

Relevance to Dark Matter:

- Inclusive studies: Verify if the discovered signal provides a possible Dark Matter candidate.
- Exclusive studies: Model-independent calculation of LSP mass and compare with direct searches.
- 3rd Step: Which SUSY flavour is it? Determine model parameters, selecting particular decay chains and use kinematics to determine mass combinations.

Relevance to Dark Matter:

- Model-dependent calculation of relic density.

In ATLAS the detailed SUSY analysis a set of benchmark points in the mSUGRA framework were chosen, with the aim of exploring sensitivity to a wide class of final-state signatures. In particular, the predicted cosmological relic density of neutralinos was chosen to be consistent with WMAP measurements.⁷ The points chosen are described in Reference 3.

2.1. Inclusive Searches

The chosen benchmark points provide a wide range of possible decay topologies. However, they share some common features, for example for all these points the gluino mass is less than 1 TeV and decay products of strongly interacting SUSY particles will contain two LSPs and a number of SM particles, in particular highly energetic quarks and gluons. Typical SUSY signatures are therefore based on large missing transverse energy and hard jets. Detailed studies have been carried out for a wide range of channels, including 0-, 1-, multi-lepton modes, as well as signatures involving τ - and b -jets. Selection criteria are discussed in Reference 3. After applying the selection criteria, SUSY production is evident in the distribution of the effective mass, defined as the scalar sum of E_T^{miss} and the transverse momentum of each of the requested particles. Figure 1 shows the effective mass

distribution for a set of benchmark scenarios and for the SM background in the 0-lepton and 1-jet channels. Channels with leptons will have smaller signal, but better signal to background conditions, providing a more robust discovery potential, specially in early data when the uncertainty on the backgrounds are large. In most cases, a noticeable excess of events is observable at high effective mass values with 1fb^{-1} of integrated luminosity, an amount of data that is expected to be collected within the first one or two years of LHC running.

The plot of Figure 2 shows the discovery contours for the same luminosity in the $(m_0, m_{1/2})$ parameter space of the Minimal Supergravity model for the 0-lepton and 1-lepton mode.³ The remaining parameters are fixed to $\tan\beta = 10$, $A_0 = 0\text{ GeV}$ and positive μ . Squark and gluino masses of the order of up to 1 TeV can be reached. The current limit from Tevatron is of the order of 400 GeV.

If the SUSY mass scale is in the sub-TeV range, early LHC data will likely be sufficient to claim a discovery of new physics, although new physics does not strictly mean SUSY as other new physics scenarios may have similar features and properties. To distinguish different scenarios and to determine the full set of model parameters within one scenario, as many measurements of the new observed phenomena as possible are needed. This includes the precise measurement of masses, spins and CP properties of the newly observed particles.

3. Mass Measurement and parameter determination

After the discovery of new physics beyond the SM, many measurements of the production process and particle properties are needed to pin-down the exact model of new physics. For example, the masses of the new particles can be used to distinguish between different SUSY models.

Due to the escaping LSPs in every SUSY event, no mass peaks can be reconstructed and masses must be measured by other means. The LHC strategy is to look for kinematic endpoints in the invariant mass distributions of visible decay products. For example, in mSUGRA models, the main source of mass information can be provided by $\tilde{\chi}_2^0$ decays. When kinematically accessible the $\tilde{\chi}_2^0$ can undergo sequential two-body decays to a $\tilde{\chi}_1^0$ via a right-handed slepton, $\tilde{\chi}_2^0 \rightarrow \tilde{\ell}^+ \ell^- \rightarrow \tilde{\chi}_1^0 \ell^+ \ell^-$, for example in the SU3 benchmark point ^a. Due to the scalar nature of the slepton, the invariant

^aSU3: $m_0 = 100\text{ GeV}$, $m_{1/2} = 300\text{ GeV}$, $A_0 = -300$, $\tan\beta = 6$, $\mu > 0$. Bulk region, the LSP annihilation happens through the exchange of light sleptons. .

Fig. 1. Effective mass distributions for the background processes and for an example SUSY benchmark point, SU3, in the 0-lepton mode (top) and 1-lepton mode (bottom) for an integrated luminosity of 1 fb⁻¹. The black circles show the SUSY signal. The black histogram shows the sum of all Standard Model backgrounds; also shown in different colours are the various components of the background.³

mass of the two leptons $m_{\ell\ell}$ from this decay chain exhibits a triangular shape with a sharp drop-off at a maximal value $m_{\ell\ell}^{max}$, Fig. 3(top). The position of this endpoint depends on the masses of the particles involved:

$$m_{\ell\ell}^{max} = m_{\chi_2^0} \sqrt{1 - \left(\frac{m_{\ell_R}}{m_{\chi_2^0}}\right)^2} \sqrt{1 - \left(\frac{m_{\chi_1^0}}{m_{\ell_R}}\right)^2}$$

The endpoint is measured from the di-lepton mass distribution.³ Combinatorial background from SM and other SUSY processes can be estimated from data and subtracted using the flavour-subtraction method. The

Fig. 2. The 1 fb^{-1} 5σ reach contours for the 1-lepton analyses with various jet requirements as a function of m_0 and $m_{1/2}$ for the $\tan\beta = 10$ mSUGRA scan. The horizontal and curved grey lines indicate the gluino and squark masses respectively in steps of 500 GeV.³

flavour subtraction method is based on the fact that the signal contains two opposite-sign same-flavour leptons, while the background leptons can be of the same flavour or of different flavour with the same probability.

In some SUSY parameter space region (co-annihilation region), the $\tilde{\chi}_2^0$ can decay to both left and right sleptons, for example in the SU1 benchmark point^b, giving a double dilepton invariant mass edge structure, Fig. 3(bottom), with the two edges about 50 GeV apart. The expected sensitivity for electrons and muons is listed in Table 1.

A similar analysis can be performed by replacing the electrons and muons with taus. Due to the additional neutrinos from the tau decay, the visible di-tau mass distribution is no longer triangular. This complicates measurements of the spectrum endpoint. A solution to this problem is to fit a suitable function to the trailing edge of the visible di-tau mass spectrum and use the inflection point as an endpoint sensitive observable, which can be related to the true endpoint using a simple MC based calibration procedure. Note that the third error is due to the SUSY-model dependent polarization of the two taus. On the other hand, the influence of the tau

^bSU1: $m_0 = 70 \text{ GeV}$, $m_{1/2} = 350 \text{ GeV}$, $A_0 = 0$, $\tan\beta = 10$, $\mu > 0$. Coannihilation region where $\tilde{\chi}_1^0$ annihilate with near-degenerate $\tilde{\ell}$.

Fig. 3. Distribution of invariant mass after flavour subtraction for various benchmark points with an integrated luminosity of 1 fb^{-1} . The line histogram is the Standard Model contribution while the points are the sum of Standard Model and SUSY contributions. The fitting function is superimposed and the expected position of the endpoint is indicated by a dashed line. Top: Two-body decay with $\tilde{\chi}_2^0$ decaying to right-sleptons for 1 fb^{-1} (SU3), bottom two-body decay with $\tilde{\chi}_2^0$ decaying to both left- and right-sleptons for 18 fb^{-1} (SU1).³

polarization on the di-tau mass distribution can be used to measure the tau polarization from the mass distribution and distinguish different SUSY models from each other.

In all cases the $m_{\ell\ell}$ endpoint can be measured without a bias although the required integrated luminosity is quite different. Furthermore, the fit function to extract the endpoint(s) needs to be adjusted to the underlying mass spectrum. The expected sensitivity is summarized in Table 1 including the assumed luminosity.

Reconstructed endpoint. The first error is statistical and the second is mainly due to the lepton energy scale and the ratio of the electron and muon reconstruction efficiency.

benchmark point	true $m_{\ell\ell}$ mass [GeV]	expected $m_{\ell\ell}$ mass [GeV]	luminosity [fb^{-1}]
SU1	56.1	$55.8 \pm 1.2 \pm 0.2$	18
SU1	97.9	$99.3 \pm 1.3 \pm 0.3$	18
SU3	100.2	$99.7 \pm 1.4 \pm 0.3$	1

By including the jet produced in association with the $\tilde{\chi}_2^0$ in the $\tilde{q}_L$ decay, several other endpoints of measurable mass combinations are possible. All these measured mass combinations can be used to extract the underlying high mass model parameters.

From the end point measurements we can derive the SUSY mass spectra and parameters. From the SUSY mass spectrum we can obtain the mSUGRA parameters and the unification scale. The procedure is described in Reference 3, where is discussed as an example, the mSUGRA benchmark points SU3 for a luminosity of 1 fb^{-1} . Here we will give only the results of a fit of the mSUGRA parameters for the SU3 point, which are listed in Table 2.

Results of a fit of the mSUGRA mass spectra for the the SU3 point for $\text{sig}(\mu) = +1$. The uncertainty due to theoretical uncertainties is also shown.

Parameter	true value	fitted value	uncertainty
$\tan\beta$	6	7.4	4.6
m_0	100 GeV	98.5 GeV	$\pm 9.3 \text{ GeV}$
$m_{1/2}$	300 GeV	317.7 GeV	$\pm 6.9 \text{ GeV}$
A_0	-300 GeV	445 GeV	$\pm 408 \text{ GeV}$

With 1 fb^{-1} the reconstruction of part of the SUSY mass spectrum will only be possible for favourable SUSY scenarios and with some assumptions about the decay chains involved.

4. Spin measurement

Measurements of the number of new particles and their masses will give us enough information to extract model parameters for one of the SUSY models. However, the mass information alone will not be enough to distinguish different new physics scenarios. For example Universal Extra Dimensions with Kaluza-Klein parity can have a mass spectrum very similar to the one of certain SUSY models. However, the spin of the new particles is different and can be used to discriminate between models.

One possibility is to use two-body slepton decay chain described above.

The charge asymmetry of lq pairs can be used to measure the spin of $\tilde{\chi}_2^0$, while the shape of dilepton invariant mass spectrum measures slepton spin.⁴ The first lepton in the decay chain is called the *near* lepton while the other is called the *far* lepton.

The invariant masses $m_{ql^{near}}$ charge asymmetry A is defined as:

$$A = \frac{s^+ - s^-}{s^+ + s^-}$$

where $s^\pm = d\sigma/dm_{ql^{near}(\pm)}$.

In general is not possible to distinguish between the near and the far lepton, but only $m_{\tilde{q}l^{near}}$ can be measured, diluting A . The expected asymmetry for SU3 is shown in Fig. 4 for a luminosity of 30 fb^{-1} .

Fig. 4. Expected charge asymmetry A for SU3 and 30 fb^{-1}

5. Determining Relic Density from LHC data

For neutralinos to account for the observed dark matter, their density at a certain time in the expansion of the early Universe would have had to become low enough to cease annihilation, leaving relic cold dark matter. Inflationary models of the universe along with astronomical data from experiments like WMAP and SDSS⁷ can be used to put limits on the rates of neutralino production and annihilation. There are four main mechanisms that can occur to cease annihilation:

- (1) Slepton exchange, which is suppressed unless the slepton masses are lighter than approximately 200 GeV.
- (2) Annihilation to vector bosons, that occurs when the neutralino LSP acquires a significant wino or higgsino component.
- (3) Co-annihilation with light sleptons, which happens when there are suitable mass degeneracies in the sparticle spectrum.
- (4) Annihilation to third-generation fermions that is enhanced when the heavy Higgs boson A is almost twice as massive as the LSP.

To reproduce the observed relic density, the model parameters must ensure efficient annihilation of the neutralinos in the early universe. In the mSUGRA scenario this is possible in restricted regions of the parameter space where annihilation is enhanced either by a significant higgsino components in the lightest neutralino or through mass relationships.

There are various strategies for determining the relic density; we will discuss here the one presented in Reference 6, where they target the weak scale parameters relevant to the relic density calculation. Endpoints are used to constrain sparticle masses, which are then used to constrain the neutralino mixing matrix, obtaining $\tan\beta$ dependent values of the mixing parameters. They then constrain the slepton sector using a ratio of branching fractions that is sensitive to the stau mixing parameters: $BR(\tilde{\chi}_2^0 \rightarrow \tilde{l}_R l)/BR(\tilde{\chi}_2^0 \rightarrow \tilde{\tau}_1 \tau)$. Finally, they consider constraints on the Higgs sector, even if their benchmark point is in a region in which the LHC is expected to produce only the lightest (SM-like) Higgs boson. They obtain a relic density distribution as a function of m_A , but show ways of improving their measurement by placing a lower limit of 300 GeV on m_A due to its non-observation in cascade decays. This assumption provides an improvement in their control over the relic density, and they obtain a final value of:

$$\Omega_\chi h^2 = 0.108 \pm 0.01(stat + sys)_{-0.002}^{+0.00} (m(A))_{-0.011}^{+0.001} (\tan\beta)_{-0.005}^{+0.002} (m(\tilde{\tau}_2))$$

In these proceedings we discussed some examples of a dark matter search at the LHC, however other measurements are possible ???. If the mass differences in cascade decays will be small, the measurement of the sparticle mass will be challenging. In such a case, one would hope to be able to constrain the SUSY Lagrangian from other measurements, but the LHC may prove insufficient to accomplish this.

6. Summary

We have reviewed recent work that explains how to use the LHC to learn about dark matter, using supersymmetry as an example. The LHC is an excellent discovery machine, with a wide search reach for observing SUSY WIMP candidates in inclusive channels. It has been shown that the LHC may be capable of determining the dark matter relic density with a precision of approximately 10% but that this is highly dependent on the underlying SUSY model.

However, there are questions that a collider can never address, for example how much of the observed astrophysical dark matter is comprised of WIMPS. Furthermore, we would know we have produced a WIMP candidate if we know its lifetime. For these reasons, direct and indirect experiments are complementary to the collider program.

7. Acknowledgments

8. References

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