1 Introduction

Several observations in the recent past have hinted at the existence of dark matter, starting with the observation of anomalies in galaxy rotational speeds, and culminating most recently in precision measurements of the power fluctuations in the cosmic microwave background (CMB). Indeed, the latter line of enquiry has proved fruitful in estimating the amount of dark matter present in the universe, and the WMAP experiment has recently extracted values for both the matter density and the baryon density of the universe. Assuming the difference is due to the presence of dark matter, one obtains the following $2\sigma$ range for the dark matter density:

$$0.093 < \Omega_m h^2 < 0.129 \quad (1)$$

Furthermore, in order to be consistent with the observed structure of the universe, WMAP favours cold dark matter, or matter comprised of particles that are non-relativistic when galaxy formation starts. This naturally leads one to conclude that some sort of weakly interacting massive particle, or WIMP, is providing this dark contribution to our universe, and it is here that exciting astrophysics suddenly evolves into challenging and captivating particle physics!

The Large Hadron Collider (LHC) at CERN in Geneva will start taking data next year and the purpose of this talk is to look at how much the LHC will be able to say about the dark matter problem, from the direct production and observation of WIMP candidates. Given the
impossibility of representing the state of the art in every potential scenario, the focus throughout will be on the reasonably well motivated theory of supersymmetry (SUSY). Even within supersymmetry, there are several possibilities for WIMP candidates, and a decision to focus on the lightest neutralino is made here, as is the assumption that supersymmetry exists in nature under the guise of the Minimal Supersymmetric Standard Model (MSSM). On the astrophysical side, specific attention is given to the measurement of WIMP relic density, as opposed to any other property of the dark matter.

In order to give as complete a picture of dark matter searches at the LHC as possible, I have chosen to address three important questions:

1. How does one reconstruct SUSY models at the LHC?
2. How does one obtain the dark matter relic density from these models?
3. What are the general prospects for the LHC in different regions of parameter space?

A comprehensive review of earlier work is given by Battaglia et al.², and the focus of this talk is on the major developments that have occurred during the last year.

2 Finding SUSY at the LHC

2.1 Supersymmetry

In SUSY theories, all existing particles of the standard model have partners with opposite spin statistics called sparticles. Furthermore, one can impose a symmetry called R-parity under which the standard model particles are even whilst the SUSY particles are odd. This has two important phenomenological consequences:

1. We will pair produce sparticles at the LHC.
2. The lightest sparticle (LSP) is absolutely stable.

Thus, the LSP is a natural WIMP candidate, and any consideration of SUSY models is highly relevant to the search for dark matter. It is noted that in different regions of the SUSY parameter space, one obtains 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 remains the subject of the majority of studies. Thus, it is the only SUSY candidate to be considered from now on.

2.2 Reconstructing SUSY Models at the LHC

The problem of finding SUSY at the LHC has occupied many researchers in recent years, and only the most recent results will be presented here. Any theory with as large a parameter space as the MSSM presents a considerable challenge to experimenters, and it is therefore useful to consider the problem in a stepwise fashion.

Step 1: Inclusive Searches

The first course of action is to perform inclusive searches that exploit generic features of SUSY events. For example, the presence of two invisible LSP’s in each event leads to large amounts of missing transverse energy, whilst squark and gluino decay ensure that jet multiplicity is high. Furthermore, many SUSY processes produce isolated leptons in conjunction with these other signatures. Hence, inclusive searches in relevant channels are, naively, an excellent way to discover R-parity conserving SUSY, even in the early days of data taking. The problem is
that the same could be said for other models such as UED, and hence one needs to measure some more details of the underlying model before a confident declaration of SUSY discovery can be made believable. Nevertheless, inclusive searches will provide the first key evidence that we have produced a WIMP candidate, and we see in figure 1 the search reach for the CMS detector, as calculated in the CMSSM. One can infer that the prospects for discovery of TeV-scale supersymmetry at the LHC are very good.

**Step 2: SUSY Parameter Extraction**

The second step in our search for SUSY involves the attempt to measure some of the weak scale SUSY parameters. In the past, it has been assumed that the isolation of specific decay processes (a process known as ‘exclusive’ measurement) will be used to perform this step, although more recent work has looked at combining exclusive and inclusive data to improve the results; both will be reviewed here.

Consider firstly the problem of measuring sparticle masses. This is non-trivial at the LHC for two reasons- all decay chains eventually produce LSP’s that leave the detector unseen and hence we do not see all of the decay products, and we also do not know the centre of mass frame at a hadron collider. However, one is always free to use clever tricks. Consider the sparticle decay chain shown in figure 2 which represents one side of an event in, for example, the ATLAS detector (remember that sparticles are produced in pairs). If one is in the rest frame of the squark, it is clear that the two decay products- in this case a $\tilde{\chi}^0_2$ and a quark- cannot have an invariant mass that exceeds the rest mass of the squark. The same applies to the decay products of the $\tilde{\chi}^0_2$ in its own rest frame. Ultimately, one will observe a jet and two leptons as the visible products of the decay, and each possible invariant mass that can be formed from these
decay products has a theoretical maximum which is given by a function of the four sparticle masses in the chain. Reconstructing the masses is therefore simply a case of plotting invariant mass distributions and looking for kinematic endpoints. The chain shown in figure 2 has the advantage that the standard model background is particularly small once one applies cuts to select events with large missing energy and opposite sign same flavour leptons.

An example of a kinematic endpoint taken from the ATLAS Physics TDR is shown in figure 3 and it is noted that further endpoints can be seen in invariant mass distributions featuring combinations of the jet and the leptons. Since each of the edge positions is a function of only four masses, enough distributions can be obtained to solve for the masses, and these can then be used to fit for the GUT scale SUSY parameters if one assumes that the SUSY breaking scenario is known.

Many studies have used this technique, though few of them have directly addressed the problems of the approach. Apart from the fact that the decay chain in figure 2 may not be open, there is a problem arising from the fact that the kinematic endpoint equations are sensitive to mass differences rather than absolute masses. Furthermore, the decay chain dealt with here will not be determined unambiguously by the selection cuts- one would observe the same visible decay products if the chain had other neutralinos in, or if the slepton was right-handed rather than left-handed for example. When trying to fit for GUT scale parameters, it is unclear whether a breaking scenario such as mSUGRA will prove sufficiently detailed- one must really try and fit in the general parameter space of the MSSM.

All of these problems are addressed in recent work performed by the Cambridge group, which combines inclusive and exclusive data in a Markov Chain Monte Carlo sampling of SUSY parameter space. The technique can easily be generalised to explore higher dimensional parameter spaces than mSUGRA, and can include the effects of ambiguities in decay chains (see figure 1). In addition, mass measurements are improved by the fact that the inclusive information is sensitive to the mass scale. The process described by the Cambridge group should be enough to determine properties of the SUSY Lagrangian, although it is noted that one ought to measure the spins of particles in order to make sure that we have observed SUSY rather than, for example, UED. This has been considered in more detail by Barr.

2.3 Determining the Dark Matter Relic Density From SUSY Measurements

In general, one finds that too many neutralinos are produced after the big bang, and we therefore require some kind of annihilation mechanism to bring the density down to within the limits set by astrophysical observation. There are four main mechanisms that can occur (at least within
Figure 3: Example of a dilepton invariant mass distribution, showing the standard model and SUSY backgrounds. The signal is generated at a point in parameter space where the decay shown in figure 2 is open.

Figure 4: A sampling of the mSUGRA parameter space using endpoint data in conjunction with a measurement of the cross-section of events passing a missing $p_T$ cut of 500 GeV, with the effects of decay chain ambiguity included. The plot represents the posterior probability distribution of the mSUGRA parameters based on the assumed experimental input. Two regions result from the scan, reflecting a lack of knowledge about which slepton is involved in the decay chain.
Figure 5: A schematic plot of the mSUGRA $m_0 - m_{1/2}$ plane showing the regions that are consistent with the WMAP relic density constraint, taken from Nojiri et al. The bulk region features annihilation through slepton exchange, the focus point region involves an enhanced annihilation to vector bosons, the funnel region involves enhanced annihilation to third-generation fermions, and the co-annihilation region is that in which mass degeneracies occur in the sparticle spectrum.

the mSUGRA framework):

1. Slepton exchange. This is suppressed unless the slepton masses are lighter than approximately 200 GeV.

2. Annihilation to vector bosons. This can occur if the neutralino LSP acquires a significant wino or higgsino component.

3. Co-annihilation with light sleptons. This occurs when there are suitable mass degeneracies in the sparticle spectrum.

4. Annihilation to third-generation fermions. This is enhanced when the heavy Higgs boson $A$ is almost twice as massive as the LSP.

Although these mechanisms can, and do, occur simultaneously in different regions of parameter space, imposing the WMAP constraint tends to give allowed regions in which one of these mechanisms is dominant (see figure 5). It is noted that more recent work examining the current state of the mSUGRA parameter space using astrophysical constraints along with other information has been performed by Allanach and Lester and, later still, Trotta et al, and that the effects of imposing the WMAP constraint on models more general than mSUGRA have been described by Belanger et al. We see that LHC experimenters will need to measure enough information to determine which region Nature has chosen and thus, naively, one must be able to determine the LSP mass, the masses of other light sparticles, the mass of the heavy Higgs
boson $m_A$, and the components of the neutralino mixing matrix:

$$
\mathcal{M} = \begin{pmatrix}
M_1 & 0 & -m_Z \cos \beta s_W & m_Z \sin \beta s_W \\
0 & M_2 & m_Z \cos \beta c_W & -m_Z \sin \beta c_W \\
-m_Z \cos \beta s_W & m_Z \cos \beta c_W & 0 & -\mu \\
m_Z \sin \beta s_W & -m_Z \sin \beta c_W & -\mu & 0
\end{pmatrix}
$$

(2)

where $M_1$ and $M_2$ are the U(1) and SU(2) gaugino masses, $\mu$ is the Higgsino mass parameter, $\tan \beta$ is the ratio of the vacuum expectation values of the two Higgs doublets and the other parameters are all from the standard model. Most significantly, we see that a complete knowledge of neutralino mixing requires some knowledge of the SUSY Higgs sector.

There are essentially two strategies for determining this long list of information; try and fit a GUT scale SUSY model or (more realistically) aggressively target the weak scale parameters relevant to the relic density calculation. An excellent example of the second approach is that recently published by Nojiri, Polesello and Tovey. They use an existing study of an mSUGRA benchmark point in the co-annihilation region (where the third mechanism in the previous list is the most significant), but perform an analysis within the framework of a general MSSM.

Their starting point is the exclusive analysis presented above- they use endpoint data to constrain sparticle masses (though they do not consider the problems tackled by Lester, Parker and White). They then use these mass values to constrain the neutralino mixing matrix, though they only obtain three (of four) neutralino masses and hence lack one parameter to constrain the matrix. They thus obtain only $\tan \beta$ dependent values of the mixing parameters but, nevertheless, manage to establish that the LSP is predominantly bino. Having established from the mass spectrum information that co-annihilations are likely to be important, they next set about trying to constrain the slepton sector using a ratio of branching fractions that is sensitive to the stau mixing parameters: $\text{BR}(\tilde{\chi}_2^0 \to \tilde{l}_R l)/\text{BR}(\tilde{\chi}_2^0 \to \tilde{\tau}_1 \tau)$. Again, their results are $\tan \beta$ dependent.

Finally, they consider constraints on the Higgs sector, although these are challenging due to the fact that their benchmark point is in a region in which ATLAS is not expected to observe anything other than the lightest (SM-like) Higgs boson. They obtain a relic density distribution as a function of $m_A$, shown in figure 6, but can improve their measurement by placing a lower limit of 300 GeV on $m_A$ due to its non-observation in cascade decays. This well-motivated assumption gives them a massive improvement in their control over the relic density, and they obtain a final value of:

$$
\Omega h^2 = 0.108 \pm 0.01(\text{stat} + \text{sys})^{+0.00}_{-0.002}(M(A))^{+0.001}_{-0.011}(\tan \beta)^{+0.002}_{-0.003}(m(\tilde{\tau}_2))
$$

(3)

2.4 General Prospects for Dark Matter Observation at the LHC

Having considered in detail one example of a dark matter search at the LHC, it is worth exploring whether the success encountered there is likely to be repeated in other regions of the parameter space, or whether it was specific to the chosen benchmark point. It is hard to be totally general here, but there are nevertheless some generic remarks that it is possible to make.

Firstly, we will always need to measure the masses of the lightest sparticles and the mixing parameters for the lightest neutralino. This ultimately leads one to conclude that the LHC will perform best in regions where light sparticles are copiously produced in cascade decays.

Secondly, it is noted that if co-annihilations are important, the mass differences in cascade decays will be small, and hence the visible (SM) decay products produced in such decays will have low transverse momentum and may be missed by the CMS and ATLAS detectors (which typically will only function well down to a $p_T$ of approximately 5 GeV). Thus the very mechanism
that allows SUSY to produce a consistent picture of dark matter may scupper our chances of measuring it! 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.

Finally, we have seen that $\tan\beta$ is an important quantity to know if we want to calculate the dark matter relic density, and this will always be difficult to measure at the LHC.

To put these points on a firmer footing, it is useful to refer to a recent study by Baltz et al.\textsuperscript{[10]} (reprising some themes considered earlier by Allanach et al.\textsuperscript{[11]}) that looks at points in different regions of the mSUGRA parameter space (though they are analysed in the framework of the MSSM), each of which has a dominant LSP annihilation mechanism that is one of the four introduced earlier. Their first point is similar to that studied by Nojiri et al, and they reach similar conclusions. It is therefore more interesting to consider their points LCC2 and LCC4.

LCC2 is in the ‘focus point region’ (where LSP annihilation occurs via enhanced annihilation to vector bosons). Their point has a large value of $m_0$, and the resulting squarks and sleptons are too heavy to be observed at the LHC. The result is that one does not obtain enough information to constrain the neutralino mixing matrix, and hence cannot constrain the relic density, shown clearly in figure 7 which plots the posterior probability distribution for $\Omega_\chi h^2$ obtained using a Markov Chain Monte Carlo sampling method. The same figure shows the improvement that results if one has access to the linear collider (running at both 500 and 1000 GeV).

A similar lack of constraint is observed in the funnel region, though for different reasons. Here, annihilation proceeds via a Higgs resonance (due to $m_A$ being roughly twice the LSP mass), and a knowledge of the $A$ decay width is needed to constrain the relic density. This cannot be done at the LHC, though it can be measured at a linear collider. It is worth noting that the study also examines the interplay between astrophysical direct/indirect search experiments and collider results, and it is hard to escape the conclusion that both sets of data will prove essential.
Figure 7: The posterior probability distribution of the dark matter relic density as determined from collider observables at the LHC and/or linear collider, calculated for a point in the focus point region.

if we are to develop a comprehensive understanding of the dark matter problem.

3 Summary

Physicists are currently entering one of the most exciting periods in the history of the subject. Not only do we believe that there is dark matter, but there is a wide array of experiments just around the corner that have the potential to explain what is currently a fascinating mystery of cosmic proportions.

I have briefly reviewed recent work that explains how to use the LHC to learn about dark matter, using supersymmetry as an example. It has been seen that the LHC is an excellent discovery machine, with a wide search reach for observing SUSY WIMP candidates in inclusive channels. Whilst it remains true that pinning down the precise nature of the SUSY model will prove harder, recent work allows one to make more model independent statements in this area than were previously possible.

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. There are indeed very specific reasons why the LHC might fail, and it is possible that the LHC will prove insufficient to completely constrain WIMP properties.

Finally, it is worth noting that there are questions which a collider can never address. Specifically, colliders alone will never determine how much of the observed astrophysical dark matter is comprised of WIMPS, nor reveal anything about the dark matter spatial and velocity distributions. It is also worth remembering that we would only know we have produced a WIMP candidate if we know its lifetime. For these reasons, direct and indirect experiments are entirely complementary to the collider programs at the LHC and/or linear collider.
Figure 8: The posterior probability distribution of the dark matter relic density as determined from collider observables at the LHC and/or linear collider, calculated for a point in the funnel region.

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