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SUSY AND DARK MATTER CONSTRAINTS FROM THE LHC

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The LHC will have much to say about the mysteries of dark matter, and this talk reviews this potential within the context of supersymmetry (SUSY). The SUSY search reach of CMS and ATLAS is presented, followed by a brief introduction to the methods of SUSY parameter measurement. A representative ATLAS study is then used to explain how the LHC can be used to obtain a measurement of the relic density of a neutralino WIMP candidate. Finally, the prospect of success is considered by looking at different points in the MSSM parameter space.

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1. Introduction

In the early 1930s, astronomers began to collect evidence for a form of matter that does not emit or reflect enough electromagnetic radiation to be observed directly. This imaginatively titled ‘dark matter’ was first hypothesized in the context of anomalies in galaxy rotational speeds, and has since been suggested by a range of observations, culminating most recently in precision measurements of the power fluctuations in the cosmic microwave background (CMB). Recent maps of the CMB obtained by the WMAP experiment have led to the extraction of values for both the the matter density and the baryon density of the universe. Assuming the difference is due to the presence of dark matter, one obtains the dark matter relic density.

The WMAP picture is consistent with the observed structure of the universe if the dark matter is ‘cold’, meaning that the particles comprising the matter 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, thus allowing an astrophysical problem to enter the domain of particle physics!

The Large Hadron Collider (LHC) at CERN in Geneva is in the final stages of commissioning, and the purpose of this talk is to look at how much the LHC will be able to say about the dark matter problem via 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.

The use of the LHC as a dark matter measurement device is explained here by first examining how one goes about reconstructing SUSY models at the LHC. The next step is to consider how to go from SUSY measurements to dark matter relic density measurements. Finally, it is worth looking at whether the LHC is likely to be successful in all regions of parameter space, or whether we might have to wait for a future machine for a definitive answer. The last part of this talk will provide some general ruminations on the prospects of success.

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 more recently.

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:

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

A light stable particle is, of course, a natural WIMP candidate, and hence any consideration of R-parity conserving SUSY models is highly relevant to the search for dark matter. Different regions of the SUSY parameter space have different mass spectra, and hence which particle is the lightest can be expected to vary. Possible options including the gluino, sneutrino, gravitino and the lightest neutralino, with the last particle in this list being an admixture of the superpartners of the neutral SM gauge bosons, and the subject of the majority of studies. For brevity, it is the only SUSY candidate to be considered from now on.

2.2. *Reconstructing SUSY Models at the LHC*

The LHC has two general purpose detectors designed to look for new physics- ATLAS and CMS. The methodology of SUSY searches is similar for both, and essentially revolves around trying to spot new physics processes above standard model backgrounds, and then analyzing the data in more detail to search for specific particle decays. 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.

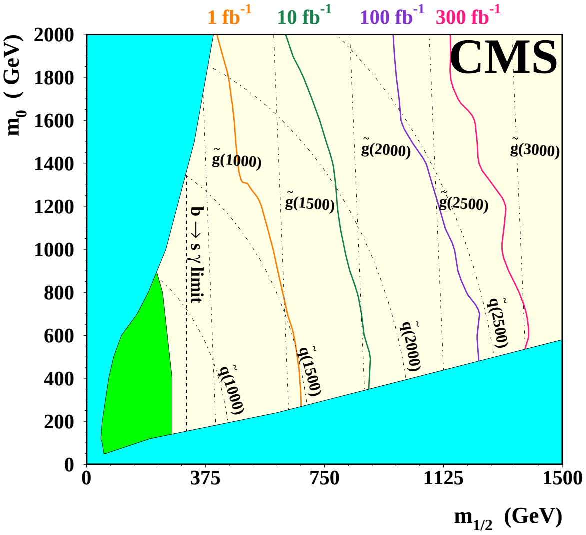

Fig. 1. Search reach of the *Jets* + E_T^{miss} channel to obtain a 5 σ discovery, as calculated in the framework of the CMSSM for the CMS detector, shown for different integrated luminosities. The dashed lines show fixed values of the squark and gluino masses.

2.2.1. *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. Many SUSY processes also 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 Fig. 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.

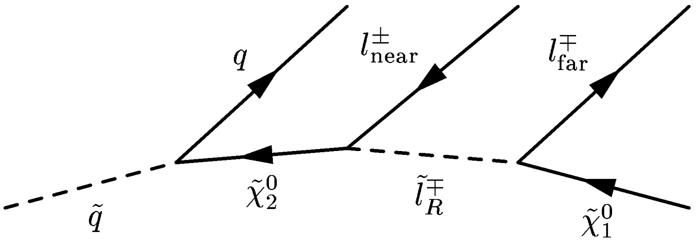

Fig. 2. A popular cascade decay chain for use in exclusive analysis.

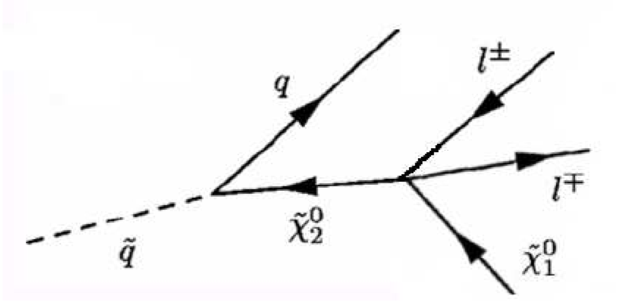

Fig. 3. An alternative decay process that may produce endpoints in an exclusive analysis.

2.2.2. *Step 2: SUSY Parameter Extraction*

The second step in our search for SUSY is much harder, and 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.

Firstly, consider 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

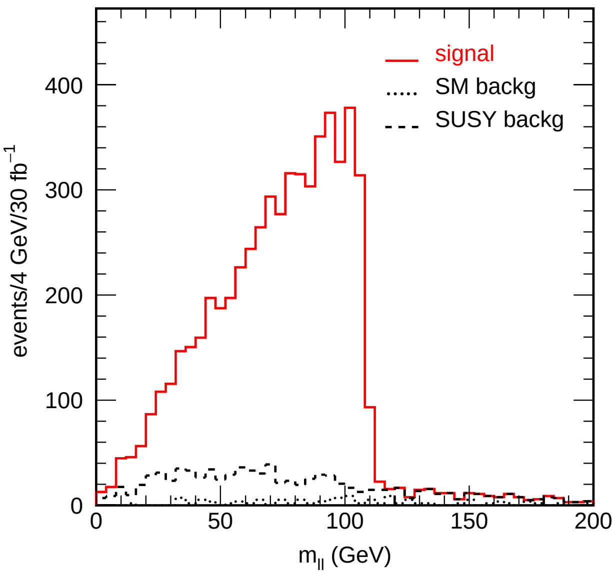

Fig. 4. Example of a dilepton invariant mass distribution, showing the standard model and SUSY backgrounds. The signal is generated at a point in parameter space where the decay shown in Fig. 2 is open.

do not know the center of mass frame at a hadron collider. It is still possible to measure masses, however, using a neat trick related to chains of particle decays. The sparticle decay chain shown in Fig. 2, represents one side of an event in, for example, the ATLAS detector. In the rest frame of the squark, it is clear that the two decay products- in this case a $\tilde{\chi}_2^0$ 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 $\tilde{\chi}_2^0$ 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. Thus one can reconstruct the masses by simply plotting invariant mass distributions and looking for kinematic endpoints. The chain shown in Fig. 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 flavor leptons.

An example of such a kinematic endpoint taken from the ATLAS Physics TDR[3] is shown in Fig. 4, 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, and yet things are not quite as simple as they first appear. Notwithstanding the fact that the decay chain in Fig. 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 cannot 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. Finally, fitting GUT scale parameters should really be done in the general parameter space of the MSSM, rather than in a restricted framework such as mSUGRA.

Extracting mass measurements from kinematic endpoints is further complicated by the fact that it may not be possible to tell the decay process shown in Fig. 2 from that shown in Fig. 3. The Cambridge group recently calculated the positions of the endpoints in lepton-jet invariant mass distributions for this process, and performed an analysis based on a fast simulation of the ATLAS detector[4]. The resulting distributions can look identical in shape to those produced by the 'two-body' process shown in Fig. 2. Furthermore, the fact that there is one less sparticle in the chain shown in Fig. 3 means that there may be insufficient constraints to measure all of the sparticle masses in the chain. At the very least, these facts indicate that one must not take for granted that the presence of endpoints implies a clean and rigorous isolation of a specific decay process.

All of these problems can be addressed by recent work performed in the Cambridge group[5], which combines inclusive and exclusive data in a Markov Chain Monte Carlo sampling of SUSY parameter space. The technique can easily be used to explore higher dimensional parameter spaces than mSUGRA, and can also include the effects of ambiguities in decay chains (see Fig. 5). In addition, the fact that the inclusive information is sensitive to the mass scale allows one to improve mass measurements.

The process described by the Cambridge group should be enough to determine the relevant properties of the SUSY Lagrangian for dark matter calculations, 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[6].

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 thus some kind of annihilation mechanism is required to bring the density down to

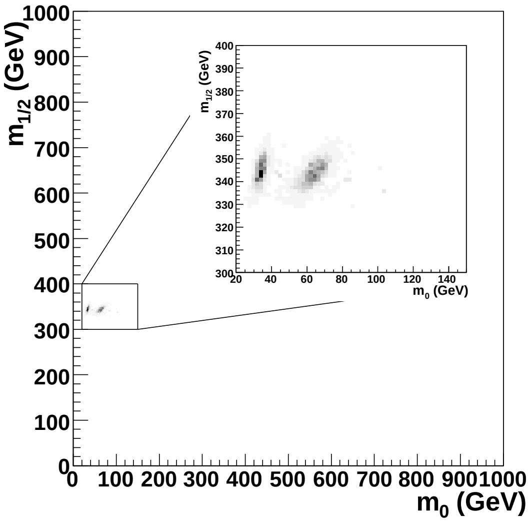

Fig. 5. A sampling of the mSUGRA parameter space using endpoint data in conjunction with a measurement of the cross-section of events passing a missing p_T cut of 500 GeV, with the effects of decay chain ambiguity included. The plot represents the posterior probability distribution of the mSUGRA parameters 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.

within the limits set by astrophysical observation. There are four main mechanisms that can occur (at least within the mSUGRA framework):

(i) Slepton exchange. This is suppressed unless the slepton masses are lighter than approximately 200 GeV.
(ii) Annihilation to vector bosons. This can occur if the neutralino LSP acquires a significant wino or higgsino component.
(iii) Co-annihilation with light sleptons. This occurs when there are suitable mass degeneracies in the sparticle spectrum.
(iv) Annihilation to third-generation fermions. This is enhanced when the heavy Higgs boson A is almost twice as massive as the LSP.

These mechanisms can, and do, occur simultaneously in different regions of parameter space, but imposing the WMAP constraint tends to give allowed regions in which one of these mechanisms is dominant (see Fig. 6). More recent work examining the current state of the mSUGRA parameter space using astrophysical constraints

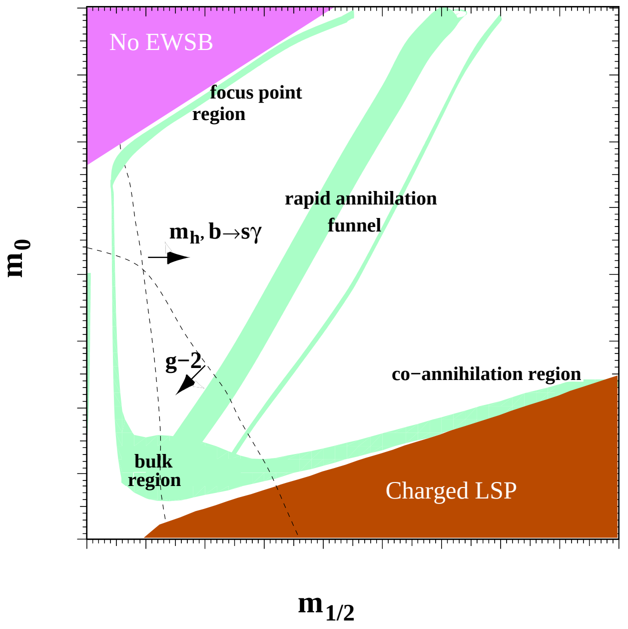

Fig. 6. A schematic plot of the mSUGRA $m_0 - m_{1/2}$ plane showing the regions that are consistent with the WMAP relic density constraint, taken from Nojiri et al. The bulk region features annihilation through slepton exchange, the focus point region involves an enhanced annihilation to vector bosons, 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.

along with other information has been performed by Allanach and Lester[7] and, later still, Trotta et al [8], and the effects of imposing the WMAP constraint on models more general than mSUGRA have been described by Belanger et al[9]. It is clear 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:

$$\mathcal{M} = \begin{pmatrix} M_1 & 0 & -m_Z\cos\beta s_W & m_Z\sin\beta s_W \\ 0 & M_2 & m_Z\cos\beta c_W & -m_Z\sin\beta c_W \\ -m_Z\cos\beta s_W & m_Z\cos\beta c_W & 0 & -\mu \\ m_Z\sin\beta s_W & -m_Z\sin\beta c_W & -\mu & 0 \end{pmatrix} \tag{1}$$

where M_1 and M_2 are the U(1) and SU(2) gaugino masses, μ is the Higgsino mass parameter, tanβ 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 two obvious strategies for determining this long list of information. One can either try and fit a GUT scale SUSY model or, more realistically, one can aggressively target the weak scale parameters relevant to the relic density calculation. An excellent example of the second approach is an ATLAS study published by Nojiri, Polesello and Tovey[10]. 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), and work through each of the steps required to calculate the relic density. In an important move toward a more rigorous analysis, they analyze their data within the framework of a more general MSSM rather than sticking with mSUGRA.

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[5]). These mass values can then be used to constrain the neutralino mixing matrix, although it transpires that they only obtain three (of four) neutralino masses and hence lack one parameter to constrain the matrix. This means that their values of the mixing parameters remain tanβ dependent but, nevertheless, they 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: $BR(\tilde{\chi}_2^0 \to \tilde{l}_R l)/BR(\tilde{\chi}_2^0 \to \tilde{\tau}_1 \tau)$. Again, their results are tanβ dependent.

Finally, they consider Higgs sector constraints, 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 Fig. 7, 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:

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

2.4. *General Prospects for Dark Matter Observation at the LHC*

Having walked though one example of a dark matter search at the LHC, it is worth asking how representative the study is in terms of the general SUSY parameter set. Is the success encountered there likely to be repeated in other regions of the parameter space, or is it specific to the chosen benchmark point? It is hard to be totally general here, but there are some generic remarks that it is possible to make.

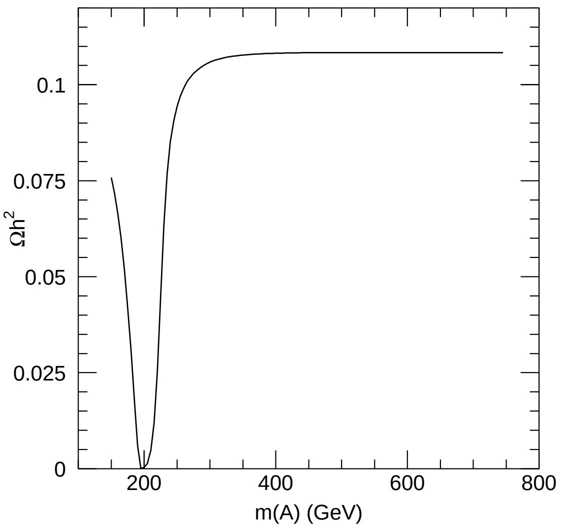

Fig. 7. The relic density of neutralino dark matter as a function of the pseudoscalar Higgs mass, as obtained by Nojiri et al.

Firstly, we will always need to measure the masses of the lightest sparticles and the mixing parameters for the lightest neutralino. The LHC will therefore perform best in regions where light sparticles are copiously produced in cascade decays.

Secondly, 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). This may be considered a classic application of 'Murphy's Law'- 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 (for example through use of the inclusive information described earlier), but the LHC may prove insufficient to accomplish this.

Finally, it has been shown that tanβ 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.

All of these points can be put on a firmer footing through reference to a recent study by Baltz et al[11] (reprising some themes considered earlier by Allanach et al[12]) that looks at points in different regions of the mSUGRA parameter space, each of which has a dominant LSP annihilation mechanism that is one of the four introduced earlier. As with the earlier study, the points are analyzed within the context of a more general MSSM, and hence the conclusions are not restricted to mSUGRA. 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. Since there are no golden cascade decays to observe (instead there are shorter chains of decays), it is not possible to measure enough masses to constrain the neutralino mixing matrix, and hence one cannot constrain the relic density. This is shown clearly in Fig. 8 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) which is able to measure more masses.

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.

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 make quantitative statements on the subject of dark matter, using supersymmetry as an example. We see 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, and an optimist would suggest that the facility of experimenters to devise even cleverer techniques during the lifetime of the experiment should not be underestimated.

Nevertheless, there are very specific reasons why the LHC might fail. 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

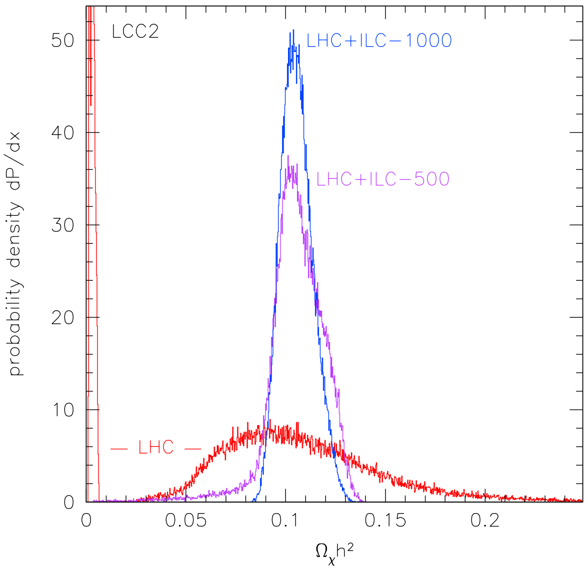

Fig. 8. The posterior probability distribution of the dark matter relic density as determined from collider observables at the LHC and/or linear collider, calculated for a point in the focus point region.

underlying SUSY model, and it is possible that the LHC will prove insufficient to completely constrain WIMP properties.

As a final note, it is worth pointing out 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, and a new generation of dark matter search experiments are due to run concurrently with the LHC. Add to this the improved measurements of the cosmic microwave background that will be obtained by the Planck experiment, and we see that particle astrophysics is on the threshold of an immensely exciting new era.

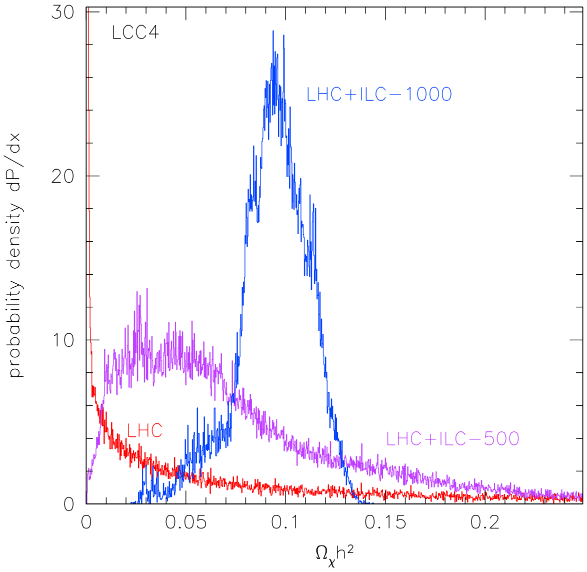

Fig. 9. The posterior probability distribution of the dark matter relic density as determined from collider observables at the LHC and/or linear collider, calculated for a point in the funnel region.

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