Abstract

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Presented at the XXXIXth Rencontres de Moriond, Electroweak Interaction and Unified Theories, La Thuile, Italy, March 21-28, 2004
DARK MATTER AND SPARTICLE RECONSTRUCTION AT THE LHC

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The present knowledge of the Dark Matter discovery and measurement potential of the LHC is reviewed, in the framework of Supersymmetry with R-parity conservation.

1 Introduction

Until now, the search for Dark Matter at accelerators (LEP, TeVatron) has been unsuccessful. Although unclear hints have been claimed for years by the DAMA experiment\(^1\) — and are being contradicted by other experiments\(^2\) — the vast majority of firm measurements regarding Dark Matter has come from Cosmology. The accuracy of the Cosmic Microwave Background (CMB) observations has recently improved very significantly with the contribution of WMAP\(^3\). The latter confirmed many earlier and less accurate determinations of the Cold Dark Matter (CDM) density, \(\Omega_m h^2\), in the Universe, which is now constrained to lie in the 95\% C.L. interval

\[
0.093 < \Omega_m h^2 < 0.129,
\]

in units of the critical density \(\rho_c = 1.86 \times 10^{-29} \text{ g/cm}^3\).

The most popular candidate for this Dark Matter, which complies with the electroweak precision measurements performed at LEP and SLC, appears in Supersymmetry (SUSY). With R-parity conservation, the lightest supersymmetric particle (LSP) is stable and its relic density may indeed lie in the above interval for suitable choices of SUSY parameters.

For the sake of definiteness and simplicity (and because most of the studies have yet been performed under these assumptions), the Minimal Supersymmetric extension of the Standard Model (MSSM) is chosen as the theoretical framework in this writeup. The LSP, which has to be neutral and colourless to be a reliable candidate for CDM, is assumed to be the lightest neutralino, \(\chi_1^0\). The mSugra-inspired SUSY-breaking mechanism is assumed throughout. Minimal Supergravity is described by only four parameters: the universal scalar mass \(m_0\), the universal
gaugino mass $m_{1/2}$, the ratio of the two Higgs-doublet vacuum expectation values $\tan \beta$, and the sign of the Higgs mixing parameter $\mu$. To simplify the picture, a fifth parameter, the trilinear SUSY-breaking parameter $A_0$, was fixed to zero.

This report is organized as follows. In Section 2, the constraints from the CMB measurements on the SUSY parameters are summarized and are then turned into a list of benchmark points (compatible with these measurements) for LHC to study. The LHC study of the most favourable of these benchmark points is presented in Section 3, in the simplified framework described above. More difficult situations, as well as the possible consequences of the simplifying theoretical assumptions are briefly discussed in Section 4.

## 2 Dark Matter: Cosmology and Supersymmetry

If the CDM density hinted at by the CMB measurements is solely made of the lightest neutralino $\chi_1^0$, it is equal to the product of the relic LSP density, $n_{\text{LSP}}$, and the LSP mass, $m_{\text{LSP}}$,

$$\rho_{\text{LSP}} = \Omega_0 h^2 = n_{\text{LSP}} \times m_{\text{LSP}}.$$  \hfill (2)

The measured $\Omega_0 h^2$ interval of Eq. 1 therefore allows this product to be constrained. This, as is shown below, constrains in turn the LSP mass to be rather small.

### 2.1 The annihilation bulk

The relic LSP density is expected to be inversely proportional to the cross section for the LSP annihilation in the early universe. In general, the latter is expected to be dominated by the annihilation into fermion pairs, $\chi_1^0 \chi_1^0 \rightarrow f \bar{f}$, through the $t$-channel exchange of the lightest sfermion $\tilde{f}$, the next-to-lightest supersymmetric particle (NLSP). This annihilation proceeds according to the graph of Fig. 1a, with a cross section proportional to $m_\chi^2/(m_\chi^2 + m_{\tilde{f}}^2)^2$. According to Eq. 2, the resulting CDM density is therefore proportional to $(m_\chi^2 + m_{\tilde{f}}^2)^2/m_\chi$, i.e., about proportional to $m_\chi^3$ if the NLSP and the LSP masses are of the same order. As a consequence, Eq. 1 allows lower and upper limits to be set on the LSP mass (or a combination of the LSP and the NLSP masses) or, equivalently, on a combination of $m_0$ and $m_{1/2}$.

The upper limits are, for the bulk of the parameter sets (called the *annihilation bulk*), of the order of 150 GeV/$c^2$ for $m_0$ and 300 GeV/$c^2$ for $m_{1/2}$, with the consequence that all sparticles are expected to be light — with an upper limit on the LSP mass of the order of 150 GeV/$c^2$ — hence to be produced copiously at the LHC.

### 2.2 The co-annihilation tail

This general picture is modified in a few corners of the parameter space, in which the total LSP-annihilation cross section can be made substantially larger than in the annihilation bulk.
Such exotic configurations happen when the LSP and the NLSP, i.e., the lighter \( \tilde{\tau} \) in mSugra, are almost degenerate. Indeed, if the mass difference \( m_{\tilde{\tau}} - m_{\chi_1^0} \) is smaller than the \( \tau \) mass, no direct decay of the \( \tilde{\tau} \) into \( \tau \chi_1^0 \) can take place. The \( \tilde{\tau} \) disappears slowly via the annihilation diagram of Fig. 1b, \( \tilde{\tau} \tilde{\tau} \rightarrow \tau \tau \), and the co-annihilation process of Fig. 1c, \( \tilde{\tau} \chi_1^0 \rightarrow \tau \gamma \) can proceed in parallel. The LSP relic density is reduced in turn, which allows larger values for the LSP mass and increases the upper limit on \( m_{1/2} \), typically of 1 TeV/\( c^2 \) or slightly more\(^4\).

2.3 The rapid annihilation funnels and the focus points

Neutralino annihilation may also proceed via the graph of Fig. 2 through an exchange of Higgs boson(s) in the \( s \) channel. This diagram becomes relevant in two situations, (i) at large \( \tan \beta \) and for \( m_0 \sim m_{1/2} \), in which case the LSP mass is about half the heavy Higgs boson (H and A) mass, and the on-shell \( s \)-channel annihilation is rapid enough to decrease the LSP relic density and to allow for larger LSP masses\(^5\); and (ii) at any large value of \( m_0 \), for which there is always a (large) value of \( \tan \beta \) yielding a small value of \( \mu \) through radiative electroweak symmetry breaking (focus points\(^6\)). In the latter configuration, the LSP gets a large Higgsino component, hence a large coupling to Higgs bosons. The large value of \( \tan \beta \) enhances the Higgs couplings to down-type fermion. This conspiracy of large couplings yields a large (off-shell) annihilation cross section.

The upper limits of \( m_0 \) and \( m_{1/2} \) can reach 1.5 TeV/\( c^2 \) if the rapid annihilation is open, and \( m_0 \) can increase to several TeV/\( c^2 \) in the parameter sets corresponding to the focus points.

2.4 A set of benchmark points

The annihilation bulk, the co-annihilation tail, the rapid annihilation funnels and the focus-point regions, qualitatively represented in the \( (m_{1/2}, m_0) \) plane in Fig. 2b, have been populated with different sets of benchmark points by various authors. The set of points, labelled from A to M and proposed in Ref.\(^7\), is displayed in Fig. 3a on top of the LHC reach\(^8\) in the \( (m_0, m_{1/2}) \) plane via the gluino and squark searches in the bread-and-butter “Jets + Missing \( E_T \)” final state.

It can be seen that the points in the annihilation bulk (A, B, C, D, J, L) would lead to a discovery of Supersymmetry with less than 1 fb\(^{-1}\). More luminosity may therefore allow detailed
measurements to be performed there. The co-annihilation tail points (J, H) need up to 10 fb$^{-1}$ for a discovery, which renders the subsequent measurements more demanding in integrated luminosity. Points in the rapid annihilation funnels (K, M) or focus points (E, F) require much more luminosity for a discovery, and may even not be visible at the LHC (F, M). It should be mentioned that the focus points of Ref. 7 were determined with a top quark mass of 171 GeV/$c^2$, and that $m_0$ and $m_{1/2}$ are rapidly-increasing functions of this mass. The recently revised value of $m_{\text{top}}$ from the TeVatron (about 178 ± 5 GeV/$c^2$) expels points E and F well beyond the reach of LHC.

3 A favourable example: Point B

Because it yields the smallest squark and gluino masses, the most favourable point for the LHC (as well as for any other collider) in the above set is point B. The $\tilde{g}$ and $\tilde{g}$ production cross section at this point is so large that it would be visible in the counting room by simply watching the Jet-Trigger rate. In addition, as all sparticles are expected to be light (from 100 to 800 GeV/$c^2$), long cascade decay chains are possible, e.g.,

$$\tilde{g} \rightarrow \tilde{b} \bar{b} \rightarrow \chi^0_2 \tilde{b} \bar{b} \rightarrow \ell^+ \ell^- \bar{b} \bar{b} \rightarrow \ell^+ \ell^- \bar{b} \bar{b} \chi^0_1$$

leading to spectacular final states with $b$ jets, missing energy and leptons, which are easy to separate from standard-model backgrounds.

3.1 End-point reconstruction

In addition to being spectacular, the final states of such a long decay chain are kinematically constrained by the masses of the numerous sparticles involved (here $\chi^0_1$, $\tilde{\ell}$, $\chi^0_2$, $\tilde{b}$ and $\tilde{g}$). For example, the invariant mass of the $\ell^+ \ell^-$ pair ($e^+e^-$ or $\mu^+\mu^-$) is bounded from above by

$$M_{\ell^+\ell^-}^{\text{max}} = \sqrt{(m^2_{\chi^0_1} - m^2_{\ell}) (m^2_{\ell} - m^2_{\chi^0_2})} / m_{\ell},$$
a value reached in the kinematical configuration in which the lepton from the $\tilde{\ell} \rightarrow \ell \chi^0_1$ decay is emitted back-to-back with the lepton from the $\chi^0_2 \rightarrow \ell\ell$ decay, in the $\chi^0_2$ rest frame. As can be seen from Fig. 3b, the distribution of the dilepton invariant mass obtained from events with jets, missing $E_T$ and same-flavour opposite-charge lepton pairs, allows this endpoint to be reconstructed with good accuracy and little background. This figure corresponds to an integrated luminosity of 1 fb$^{-1}$, i.e., about one month running at the design low luminosity value, 10$^{33}$ cm$^{-2}$s$^{-1}$. The latter can be determined, independently of any simulation, from the mass distribution obtained with opposite-flavour opposite-charge dilepton events.

Other distributions, such as those of the dilepton-jet and the lepton-jet invariant masses, do also have endpoints related to the masses of the sparticles involved. For example, the largest dilepton-jet mass among all the $\ell\ell$-jet combinations is expected to be bounded from above by

$$M_{\ell\ell q}^{\text{max}} = \sqrt{(m_{\chi^0_2}^2 - m_{\chi^0_1}^2)(m_{\tilde{q}}^2 - m_{\chi^0_2}^2)} / m_{\chi^0_2},$$

and the largest lepton-jet masses, for the first and the second leptons, by

$$M_{\ell q}^{\text{max}} = \sqrt{(m_{\chi^0_2}^2 - m_{\chi^0_1}^2)(m_{\tilde{q}}^2 - m_{\chi^0_2}^2)} / m_{\chi_2^0} \quad \text{and} \quad M_{\ell q}^{\text{max}} = \sqrt{(m_{\chi^0_2}^2 - m_{\chi^0_1}^2)(m_{\tilde{q}}^2 - m_{\chi^0_2}^2)} / m_{\tilde{\ell}}. \quad (6)$$

The corresponding distributions can be found in Ref. 11, and the various endpoints can be determined with an accuracy of the order of 5 GeV/c$^2$ with an integrated luminosity of 100 fb$^{-1}$ (i.e., one full year at the high-luminosity design value, 10$^{34}$ cm$^{-2}$s$^{-1}$). The same kind of measurements, but with correspondingly reduced statistics, can be repeated with b-tagged jets, which give access to mass combinations involving the two sbottom masses.

3.2 Sparticle mass evaluation

Owing to the length of the decay chain, the number of measurements (the distribution edges) turns out to be larger than the number of unknowns (the masses of the sparticles involved). It can therefore be expected that all sparticle masses can be determined by solving an over-constrained system of equations. Because the end-point values depend on mass differences rather than on the masses themselves, strong correlations between the masses take place. The resolution on the sparticle masses turns out to be worse by a factor 5 to 10 than that on the edges themselves. An example of such correlations is displayed in Fig. 4a for the LSP and the slepton mass determination with a large sample of gedanken experiments each representing 300 fb$^{-1}$ of data at the LHC. The vertical line in this figure exemplifies the ability of a 350 GeV $e^+e^-$ linear collider to determine the LSP mass for the same point B.

To go further with the LHC only, i.e., to improve the resolution on the sparticle masses and, ultimately, to evaluate the Dark Matter parameters, some additional input is needed. What is usually done is to inject some theoretical knowledge in the picture, e.g., the assumption that mSugra is indeed the proper description of Supersymmetry breaking, and to fit the mSugra predictions to the set of measured end-points. The same philosophy was adopted, for instance, at LEP to fit the measured Z-lineshape parameters to the Standard Model predictions.

3.3 Dark Matter evaluation in mSugra

The overall procedure for the evaluation of $\Omega \chi h^2$ is based on a Monte Carlo technique. Many gedanken experiments are generated, with all the end-point measurements and their expected uncertainties, for a specific value of the integrated luminosity, e.g., 100 fb$^{-1}$. For each gedanken
experiment, the best mSugra point is fitted by minimizing the overall $\chi^2$ of the end-point measurements. The fitted parameters allow the LSP mass and the expected LSP relic density to be computed, hence the value of $\Omega_\chi h^2$ to be determined. The distribution of $\Omega_\chi h^2$ for the whole sample of 100 fb$^{-1}$ gedanken experiments is displayed in Fig. 4b, for a parameter set yielding masses and cross sections similar to point B (but with a relic density of 0.19, i.e., outside the presently allowed interval). The long tail at low values disappears with 300 fb$^{-1}$, when the two sbottom masses may be disentangled, yielding an experimental accuracy of 2.5% on $\Omega_\chi h^2$, appropriate for a comparison with the CMB measurement.

To summarize, in the most favourable point of the annihilation bulk, the full LHC luminosity is needed to reach a level of accuracy deemed adequate for a sound Dark Matter evaluation, if mSugra is to be considered as the theory describing SUSY breaking.

### 3.4 A possible improvement: Full mass reconstruction

Because only events at the edges of mass distributions are considered, the end-point technique is affected by an important loss of statistics. In the decay chain of Eq. 3, each event can be optimally used in a set of five equations,

\begin{align}
    m_{\chi_1^0}^2 &= p_{\chi_1^0}^2, \\
    m_{\tilde{\ell}}^2 &= (p_{\chi_1^0} + p_{\ell_1})^2, \\
    m_{\chi_2^0}^2 &= (p_{\chi_1^0} + p_{\ell_1} + p_{\ell_2})^2, \\
    m_b^2 &= (p_{\chi_1^0} + p_{\ell_1} + p_{\ell_2} + p_{b_1})^2, \\
    m_{\tilde{g}}^2 &= (p_{\chi_1^0} + p_{\ell_1} + p_{\ell_2} + p_{b_1} + p_{b_2})^2,
\end{align}

for nine unknowns, namely the five sparticle masses, and the LSP four-momentum. (The four-momenta of the two leptons and the two b jets are measured.) These five equations therefore
yield, in principle, one relation between the five masses for each single event. Consequently, all masses can be determined with five events only.

Because all events can be used (not only the edge events), the statistics are expected to be a factor of about three higher than in the edge technique. This principle, however, has still to be tested with real simulations to properly evaluate its potential.

4 More difficult cases for LHC

The case described in Section 2 is valid for the most favourable point B, for which sparticle masses are small and branching ratios into $e^+e^-$ and $\mu^+\mu^-$ are large. For this point, the LHC full luminosity is just enough to come to a conclusion on Dark Matter, if a sufficient amount of theory is injected in the process.

The next-to-most favourable point (point G) already presents more difficulties because the leptonic branching fraction $\chi_2^0 \rightarrow \chi_1^0 \ell^+\ell^-$ is about ten times smaller than at point B. As a consequence, ten times more statistics (1 ab$^{-1}$) and the full mass reconstruction method of Section 3.4, are needed to say something relevant about Dark Matter. This integrated luminosity is beyond the current expectations for the LHC.

The next point (point I) is not an easier case because $\chi_2^0$ decays to $\chi_1^0 \tau^+\tau^-$ with a branching ratio close to 100%. The full mass reconstruction is therefore not possible, because the missing neutrinos prevent the four-momenta of the taus from being measured. The hope is that some end points may still be measurable in the $\tau \rightarrow a_1 \nu_\tau$ decay, and that other decay channels, such as $\chi_2^0 \rightarrow \chi_1^0 h \rightarrow \chi_1^0 b\bar{b}$ could be exploited as well. In both cases, more work is needed (and is being done) to come to a meaningful conclusion.

Some other points in the co-annihilation tail (D, J, L) have the same characteristics as point I. The small mass difference between the LSP and the stau, a general feature in the co-annihilation tail, does not help, as it tends to produce soft $\tau$'s. The larger sparticle masses further enhance the difficulty. Other points (A, C, H) are more similar to point B, but larger sparticle masses increase the luminosity needed for a sound Dark Matter measurement by factors from 10 to 100, i.e., well beyond the estimated capabilities of LHC.

As already mentioned, in most of the focus points and in the rapid annihilation funnels, the sparticles are too heavy to be seen at the LHC, especially with the recently revised top mass value from the TeVatron. In these points, only the lighter Higgs boson would be seen at the LHC. As pointed out at this conference$^{14}$, a sub-TeV $e^+e^-$ linear collider would very much help in point B (and in a few other points of the annihilation bulk and the co-annihilation tail) with an accurate determination of the LSP mass, thus alleviating the need of additional theoretical assumptions in the Dark Matter and sparticle mass fits.

5 Conclusions and Outlook

In the present state of the art, full sparticle reconstruction at LHC and confrontation with space measurements are possible in favourable parameter sets of the the so-called annihilation bulk. An integrated luminosity of 100 fb$^{-1}$ or more (i.e. the full design LHC luminosity) is needed for a sound comparison of LHC measurements with CMB. In the co-annihilation tail, more work is needed to include decays of the next-to-lightest neutralino to taus or to Higgs bosons. The full mass reconstruction method will undoubtedly help to best exploit the LHC-design integrated luminosity of 300 fb$^{-1}$. The focus points and the rapid annihilation funnels are essentially hopeless: there are no long decay chains available, and gluinos, squarks and sleptons are out of the reach of the LHC.

To conclude with a word of caution, it should be noted that existing studies are based on mSugra predictions, with R-parity conservation and in general use fast detector simulations. If
Supersymmetry breaking were to be described in the framework of a non-constrained MSSM (unlike mSugra), the situation would become really intricate. (The study of other SUSY breaking mechanisms, like Gauge-Mediated SUSY Breaking, is just starting, and no conclusions are yet available.) Of course, other/additional Dark Matter sources would change the picture significantly. Finally, the use of full detector simulations will certainly give rise to a series of additional systematic uncertainties (related, e.g., to b-tagging performance, missing transverse energy resolution, detector alignment and calibration) which are yet to be evaluated.

Dark Matter studies at the LHC will therefore be challenging, hence very interesting. Only data will tell what Dark Matter is made of. The data from the LHC will bring precious information, but the final word on the topic will probably require information from complementary colliders.

Acknowledgments

It is a real pleasure to thank J. Tran Thanh Van for his hospitality at the Rencontres de Moriond, and for his patience while waiting for my contribution to these proceedings. I am grateful to John Ellis, Fabiola Gianotti and Luc Pape for their help during the preparation of the talk. I am indebted to Nancy Marinelli, Luc Pape and Paris Sphicas for a careful reading of the manuscript.

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