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Accelerator Constraints on Dark Matter

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Abstract

The relic density of supersymmetric dark matter is calculable in terms of supersymmetric and Standard Model parameters. The discovery of supersymmetric particles and determination of their parameters could well happen at the next generation hadron collider LHC presently under construction at CERN. The accelerator constraints on the SUSY parameter space at the LHC are presented as well as the accuracy with which the density of supersymmetric cold dark matter could be predicted from collider measurements.

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1 Introduction

Data on the cosmic microwave background radiation (CMB), on high-redshift Type-Ia supernovae and on large-scale structure are in favour of a flat Universe with about 30 % of matter (mainly dark matter) and 70 % of dark (vacuum) energy. The sources of dark matter have not been identified so far, but a number of particle candidates exist. They range from particles with extremely small masses like axions or neutrinos (10^{-15} – 10^{-10} GeV/c²), to the lightest supersymmetric particle (LSP) with a mass of $\sim 10^{2-3}$ GeV/c², and even to superheavy metastable particles with masses of $\sim 10^{14\pm 5}$ GeV/c². The latter might have been produced in the very early Universe. Accelerator and non-accelerator measurements provide important constraints on the cosmological parameters and models. The Large Hadron Collider (LHC) at CERN has a good chance to discover supersymmetric particles and to measure their properties in detail. It will allow clarification of whether cold dark matter (CDM) consists of supersymmetric particles or whether supersymmetry (SUSY for short) provides only part of the measured CDM density.

The recent WMAP data in combination with either the HST key project measurement of the Hubble constant, the 2dFGRS measurements of the galaxy power spectrum *or* the Type Ia supernova measurements currently give the best precision for cold dark matter density, $\Omega_{\text{CDM}} h^2 = 0.113 \pm 0.009$ [Bennet et al. 2003]. The WMAP results are consistent with the Big Bang theory and inflation.

The LHC discovery potential is illustrated in this report with the two general-purpose detectors ATLAS [ATLAS 94] and the CMS [CMS 94] presently under construction at CERN, Geneva.

2 Search for supersymmetry at the LHC

2.1 SUSY particles as the dark matter candidate

The LEP, the SLC and the Tevatron colliders have done a good job of precisely measuring the Standard Model parameters. The shortcoming of the Standard Model is that it does not explain why most particles have mass, why their masses are so different and why the fundamental mass scale in physics (m_W) is so distant from the Planck mass. No physics beyond the Standard Model have been revealed yet. The SUSY is one of the most attractive candidates to extend the Standard Model. If the supersymmetry is associated with the origin of the scale of electroweak interactions, then the mass parameters introduced by the soft-supersymmetry-breaking terms must generally be in the order of 1 TeV or below. The argument for low-energy supersymmetry is supported by several indirect empirical evidences – the electroweak data are fitted well if the Higgs boson is relatively light, the experimental value of the Brookhaven experiment on the anomalous magnetic moment of the muon, $g_\mu - 2$, deviates significantly from the Standard Model prediction, the strengths of different gauge interactions measured at low energies are consistent with unification at high energies and finally the observed density for the cold dark matter in the Universe [Ellis 2003]. The supersymmetry predicts that for every known particle there is a superparticle partner equal in charge but different in spin by one half. The Minimal Supersymmetric extension of the Standard Model (MSSM) has five supersymmetric Higgs particles, two neutral scalar (h and H), one neutral pseudoscalar (A) and two charged Higgs bosons ($H^\pm$). It contains also the supersymmetric partners for the matter particles and for the intermediate bosons of the Standard Model, namely squarks, sleptons, gluinos, neutralinos and charginos (sparticles in short). Besides resolving the fundamental problems of elementary particle physics (the hierarchy problem in particular), SUSY provides a natural candidate for dark matter – the stable lightest supersymmetric particle (the lightest neutralino of the MSSM for example).

2.2 The LHC detectors

The Large Hadron Collider at CERN is being constructed for the purpose of exploring new physics in proton-proton collisions at 14 TeV – the highest energy ever achieved by an accelerator. The beam-crossing rate will be 40 MHz, resulting in about 20 superimposed minimum bias collisions every 25 ns at the peak luminosity of 10^{34} cm⁻² s⁻¹. The LHC will start collecting data in the year 2007.

The general purpose detectors at LHC have an onion structure where the innermost part comprises the high-precision tracker, then two types of high resolution and hermetic calorimeters – electromagnetic and hadron calorimeters – and finally a large acceptance muon spectrometer as the outermost detector. The layout of the CMS detector is shown in Fig. 1 as an illustration. The CMS detector [CMS 94] consists of silicon pixel and

silicon strip trackers followed by a lead tungstate electromagnetic calorimeter, a brass hadron calorimeter, a solenoid and finally a resistive plate, drift tube and cathode strip muon system. The tracking and calorimeter barrel systems are in a uniform 4 Tesla magnetic field.

2.3 SUSY at LHC

The MSSM possesses 124 truly independent parameters, 18 correspond to Standard Model parameters, one is the analog of the Standard Model Higgs boson mass and the remaining 105 are the new parameters of the model [Dimopoulos 1995]. This model provides no explanation for the origin of the supersymmetry-breaking parameters. Various theoretical prejudices exist to reduce the number of parameters of the MSSM, bringing it to the so called constrained MSSM (cMSSM). It is common to assume that all the spin-0 supersymmetric particles have the same universal mass m_0 at some GUT input scale, and similarly for the fermion masses $m_{1/2}$. Within a Minimal-Supergravity-inspired supersymmetry breaking scenario the MSSM spectrum and its interaction strengths are determined by only five parameters – $m_0, m_{1/2}, A_0, \tan\beta$ and the sign of μ , where A_0 is the trilinear coupling, μ is the higgsino mass mixing parameter and $\tan\beta$ is the ratio of the vacuum expectation values of the two Higgs doublets. In order to lighten the discussion of the physics reaches of different accelerators and detectors it is convenient to focus on a limited number of benchmark scenarios that illustrate the different supersymmetry possibilities [Battaglia 2001]. That is the approach adopted for the SUSY sensitivity estimates with the LHC detectors.

The SUSY searches at LHC exploit several features of the underlying cMSSM model. Assuming R-parity conservation, the sparticles are produced in pairs and the lightest supersymmetric particle is stable. The LSP is also neutral as follows from cosmological arguments. Interacting only weakly with ordinary matter, LSP escapes detection in the LHC detector. Thus the observation at the LHC of an excess of events containing large missing transverse energy could immediately tell that supersymmetry is present and the Universe should contain relic LSPs.

The LHC experiments ATLAS and CMS developed their own strategies for SUSY searches [ATLAS 99, CMS-SUSY] in a number of experimental signatures and topologies. The sparticles have striking experimental signatures due to cascade decays. The final state contains usually several isolated leptons, high- p_t jets and missing energy. In the case of high $\tan\beta$, the events also contain a number of b quarks and τ leptons. The squarks and gluinos dominate the SUSY production cross section. The LHC discovery potential for squarks and gluinos (usually the heaviest part of the SUSY spectrum) in several energy and luminosity scenarios is summarized in Fig. 2 [Gianotti 2002]. It shows expected 5σ discovery contours in the mSUGRA plane m_0 versus $m_{1/2}$ for $A_0 = 0$, $\tan\beta = 10$ and $\mu < 0$. The various curves show the potential of the CMS experiment at the standard LHC (for luminosities of 100 fb^{-1} and 200 fb^{-1}), at the Super LHC, (SLHC, for 1000 fb^{-1} and 2000 fb^{-1}), and at a machine with a centre-of-mass energy of 28 TeV (VLHC). The SLHC and the VLHC are considered as possible long-term luminosity and the energy upgrades of the LHC, correspondingly. Depending on the exact event selection criteria the mass reach for squarks and gluinos at LHC is at least $2.5 \text{ TeV}/c^2$.

The analysis of the currently allowed parameter space of the cMSSM in light of WMAP data has been performed in [Ellis 2003]. Figure 3 displays the strips of the $(m_{1/2}, m_0)$ plane allowed by the new cosmological constraint $0.094 < \Omega_{\text{CDM}} h^2 = \Omega_\chi h^2 < 0.129$ (Bennet et al. 2003) and the current accelerator constraints. The strips from the bottom to top correspond to the $\tan\beta$ increase from 5 to 55 in steps of $\Delta(\tan\beta) = 5$. The right (left) ends of the strips correspond to the maximal (minimal) allowed values of $m_{1/2}$ and hence m_χ . The lower bound on $m_{1/2}$ comes from the Higgs boson mass limit from LEP or the $b \rightarrow s\gamma$ constraint at high $\tan\beta$. In darker shading are restricted parts of the strips that are compatible with $g_\mu - 2$ measurement [Brown 2001, 2004] at 2σ level. For the allowed range of the LSP mass m_χ the authors find

$$m_\chi < 500 \text{ GeV}/c^2$$

for $\tan\beta < 45$ and $\mu > 0$, or $\tan\beta < 30$ and $\mu < 0$ and

$$m_\chi > 108 \text{ GeV}/c^2$$

for all values of $\tan\beta$. The strong upper limit means good prospects for measuring supersymmetry at the LHC.

In mSUGRA the decay products of SUSY particles always contain the LSP, assumed to be the lightest neutralino χ_1^0 . Kinematical endpoints for combinations of visible particles can be used to identify particular decay chains [Hinchliffe 1997]. The golden decay chain is $\chi_2^0 \rightarrow \chi_1^0 \ell^+ \ell^-$ where the dilepton mass distribution has an endpoint that measures the mass difference $m(\chi_2^0) - m(\chi_1^0)$. The LHC studies show that

for favourable model parameters such methods – under assumption of a known $m(\chi_1^0)$ – allow the masses of the sparticles to be measured with precisions of 10 % or better. This in turn provides constraints on the fundamental parameters of SUSY at the level of a few percent in minimal models like cMSSM. Using such measurements as input it should be possible to test the compatibility of the region of parameter space favoured by the LHC with that preferred by cold dark matter experiments. The following sparticle masses might be measurable with the indicated accuracies at the LHC at the point SPS1A (benchmark B) [Battaglia 2003]:

$$\begin{aligned} m_{\tilde{g}} &= 595.1(8.0), m_{\tilde{q}_L} = 540.3(8.8), m_{\tilde{q}_R} = 520.4(11.8), m_{\tilde{b}_1} = 491.9(7.5), m_{\tilde{b}_2} = 524.5(7.9), \\ m_{\tilde{l}_L} &= 202.3(5.0), m_{\tilde{l}_R} = 143.1(4.8), m_{\tilde{\tau}_1} = 132.5(6.3), \\ m_{\chi} &= 96.2(4.8), m_{\chi_2} = 176.9(4.7), m_{\chi_4} = 377.9(5.1) \text{ GeV}/c^2. \end{aligned}$$

These accuracies are translated into the following precision for m_0 , $m_{1/2}$ and $\tan\beta$

$$m_0 = 103 \pm 8 \text{ GeV}/c^2, m_{1/2} = 240 \pm 3 \text{ GeV}/c^2, \tan\beta = 10.8 \pm 2.$$

The estimated precisions for m_0 , $m_{1/2}$ and $\tan\beta$ in turn propagate to $\Omega_\chi h^2 = 0.111 \pm 0.018$ which is to be compared with the WMAP measurement $\Omega_{\text{CDM}} h^2 = 0.113 \pm 0.009$ [Bennet et al. 2003]. The quoted LHC uncertainty on the dark matter density $\Omega_\chi h^2$ already provides an interesting constraint, while being estimated for only one year of running the LHC at high luminosity (100 fb^{-1}). The precision depends strongly on the region of parameter space (and luminosity). For example ATLAS study of Point 5 [Tovey 2003] gives $\Omega_\chi h^2 = 0.2247 \pm 0.0035$ for luminosity of 300 fb^{-1} . For higher mass scale models (e.g. the focus point, coannihilation or rapid-annihilation regions of mSUGRA parameter space) the smaller number of mass constraints may lead to considerably increased uncertainties on SUSY parameters.

3 Conclusions

The accuracy with which it might be possible to predict the density of supersymmetric cold dark matter using collider measurements is comparable with that measured from observations in space. The LHC may therefore provide important constraints on the search for the origin of dark matter.

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Figure 1: The layout of the CMS detector.

Figure 2: The LHC discovery potential for squarks and gluinos. The bands of the standard LHC are in the bottom part of the picture, the estimate for Super LHC (SLHC) is in the middle, and at a machine with a centre-of-mass energy of 28 TeV (VLHC) is in the upper part.

Figure 3: The SUSY parameter space compatible with the all current accelerator measurements and the latest WMAP results on the dark matter density. The darker shading shows the parameter space preferred by the Muon $g-2$ experiment at Brookhaven. The strips from the bottom to top correspond to the $\tan\beta$ increase from 5 to 55 in steps of $\Delta(\tan\beta) = 5$ [Ellis 2003].

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