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Cosmology, dark matter and colliders

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Cosmological and astrophysical measurements indicate that the universe contains a large amount of dark matter. A number of weak scale dark matter candidates have been proposed in extensions of the standard model. The potential to discover the dark matter particle and determine its properties at future colliders is summarized.

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1. INTRODUCTION

There is strong evidence coming from various scales that dark matter (DM) dominates over luminous matter in the universe. First revealed in rotation curves of galaxies and galaxy clusters, the presence of DM is also required to amplify the small fluctuations in the Cosmic microwave Background (CMB) to form the large scale structure of the universe. In recent years the relic density of DM has been extracted with very good precision from measurements of small anisotropies in the CMB, $\Omega h^2 = 0.1099 \pm 0.0062$ [1]. This single measurement, although precise, is insufficient to elucidate the nature of DM as any new weakly interacting particle (WIMP) has roughly the right annihilation cross section to reproduce this value.

A variety of DM candidates in extensions of the standard model have been proposed [2]. The best motivated ones are those that arise in models constructed to solve the electroweak symmetry breaking problem. This includes: the Majorana neutralino in the minimal supersymmetric standard model (MSSM) or its extensions; the right-handed Dirac neutrino in models of warped extra dimensions [3]; the gauge boson or scalar photon in universal extra dimension models [4, 5]; the gauge boson of the little Higgs model [6]; the right-handed sneutrino of supersymmetric models [7]; the scalar in extensions of the standard model [8]. To this extensive list one should add candidates motivated by recent experimental results [10, 11] as well as those with super weak interactions such as the gravitino [12]. The latter have different signatures from the WIMP candidates, they will not be discussed here. All of these models can in some region of parameter space fit the measured value for the relic density. To unravel the nature of DM, searches for a new neutral stable particle are being pursued actively in astroparticle experiments as well as at colliders.

Direct detection experiments would unambiguously establish that a stable particle constitute the DM. For now the upper bounds on the elastic scattering cross section constrain the DM models [9] although some dependence on astroparticle quantities, such as the DM distribution are introduced. Indirect detection experiments that search for the products of DM annihilations have, in the last year, reported anomalous signals. In particular PAMELA [13] and Fermi [14] have seen excesses of positrons orG electrons. It is premature to claim DM discovery since astrophysical sources such as pulsars could also display a signal in these channels.

This leaves a double challenge for DM studies at colliders. The first goal is the search for the DM candidate and other new particles predicted in the framework of the various theoretical models. The second, if a signal is found, would be to determine the properties of the DM particle, its mass, spin and couplings. This information could then be used to infer the DM annihilation and elastic scattering cross sections. These could be compared to the value of the relic density extracted from cosmological observations as well as to the (in-)direct detection rates. The former would allow a test of the underlying cosmological model, for example the relic density can be reduced by orders of magnitude in non-standard scenarios with low reheat temperature and/or late entropy production [15, 16]. The latter would allow self-consistency checks and provide additional information on quantities such as the DM distribution, the propagation model, etc... How well the properties of DM can be determined strongly depend on the particle physics model. In this lecture we first review the main new results from DM searches before discussing the role of colliders in unravelling the nature of DM. At this point it will be more relevant to consider specific DM models such as the neutralino in supersymmetry and a little Higgs model.

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2. SEARCHES FOR DARK MATTER

The DM relic density is obtained after solving a Boltzmann equation and depends in particular on the effective DM annihilation cross section [18]. In the standard cosmological scenario, the measured value of $\Omega h^2 \approx 0.1$ implies that the annihilation cross section $\langle \sigma \mathrm{v} \rangle = 3 \times 10^{-26} \mathrm{cm}^2/\mathrm{sec}$ at the freeze-out temperature. Barring some strong velocity dependence a similar cross section is expected at the small velocities relevant for indirect detection.

Indirect detection of DM involves looking for the annihilation products of a pair of DM particles into standard particles. After hadronization their decay products can be observed. The search channels are positrons, antiprotons, photons and neutrinos. The rate of production, $Q(x,E)$, depends both on the details of the particle physiscs model through the annihilation cross section, $\langle \sigma \mathrm{v} \rangle$, as well as on astrophysical quantities such as the DM distribution, $\rho(x)$,

$$Q(x,E) = \frac{\sigma \mathrm{v}}{2} \left(\frac{\rho(x)}{m_\chi} \right)^2 \frac{dN}{dE} \tag{2.1}$$

here $\mathrm{v} = 0.001c$ is the velocity of the WIMP, m_χ its mass, and dN/dE the spectrum for a given particle production. dN/dE depends on the primary annihilation channel, for example large branching fractions into leptons will give a harder positron spectra than into gauge bosons. For charged particles the spectrum detected differs from the one at the source since cosmic rays are deflected by irregularities in the galactic magnetic field and suffer energy losses due to interactions with the interstellar medium. The computation of the spectrum from DM annihilation therefore involves solving a propagation equation. This can be done analytically or numerically [19]. The computation of the background from standard astrophysical sources of cosmic rays, necessary for extracting a signal from the data still suffers from large uncertainties [20]. Furthermore it has become customary to introduce an arbitrary boost factor B that could for example be due to DM clumping

PAMELA reported two results last year, first that the antiproton spectrum was in very good agreement with theoretical expectations and second that there was a large excess in the observed positron fraction in the energy range from 10-100GeV. Interpreting these results in term of DM annihilation implies rather peculiar DM characteristics. Most surprising is the fact that the annihilation cross-section needed to fit the data is much larger than the one expected from the relic density. The second unusual feature is that the excess is seen only in the positron channel. To explain this several ideas were proposed, a first solution is a leptophilic DM candidate of mass around 200 GeV which naturally preferentially annihilates into leptons. this solution has the advantage of requiring only a modest boost factor (less than 100). A second class of solutions postulates a much heavier DM candidate which could decay in any of the SM particles. Choosing its mass to be above 2TeV leads to important deviations in the positron spectrum without affecting much the antiproton spectrum. This is because the former is typically softer. The recent results of the Fermi/LAT telescope showing some excess in the $e^+ + e^-$ spectrum at energies of a few hundred GeV's favour the heavy DM candidate. This solution has the disadvantage of requiring an extremely large boost factor since $< \sigma \mathrm{v} >$ is inversely porportionnal to the mass. Furthermore a large $< \sigma \mathrm{v} >$ could impact the photon signals as photons could scatter on such high energies electrons [21]. At present there is no conclusive evidence that these signals are due to DM. Future results of Fermi, PAMELA, HESS and AMS in either the γ, e^+ or $\bar{p}$ channel should clarify the situation.

Finally direct searches for DM by measuring the recoil energy of nuclei in a large detector offer another sensitive probes of the underlying model. These experiments have improved their sensitivity in the last years to a point where they are now constraining a fraction of the parameter space of the MSSM with neutralino DM, Fig 1a. The expected reach of future experiments assuming an order of magnitude improvement over the present limit is displayed on Fig. 1.

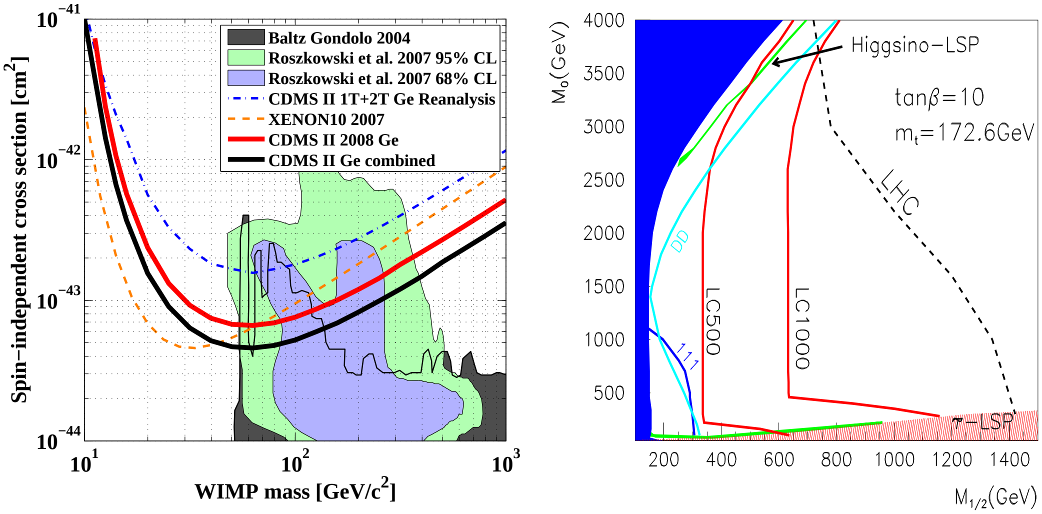

Figure 1: a) The direct detection limit as well as the expectations from the CMSSM, from [9]. b) Reach for SUSY in the CMSSM with $\tan\beta = 10$ for the LHC with 100 fb^{-1} [22] for the LC with $\sqrt{s} = 0.5, 1.$TeV and for direct detection with $\sigma_{\chi p} = 5. \times 10^{-9}$ pb. The region where $\Omega h^2 = 0.11 \pm 0.02$ (green) and the contour for $m_h > 111$ GeV are also displayed.

3. DARK MATTER AT COLLIDERS

The particle physics aspects of DM are best probed at colliders. The main questions to be addressed include: what are the prospects for new particles discovery? After discovery of physics beyond the standard model does this provide a solution to the DM problem? What are the properties of dark matter, its mass, spin, couplings? According to the theoretical argument that DM can be related to the new physics needed to solve the EWSB problem, it is natural to expect a DM candidate at the electroweak scale. However it is only after determining its properties that we will be able to make collider predictions of the DM observables such as the annihilation cross section and to check whether a self consistent picture emerge from cosmological measurements, detection rates and collider observables. Quantitative analyses of the collider potential to both search for and determine the property of DM were performed within specific models, we will illustrate these points by considering different scenarios.

3.1 Neutralino in supersymmetry

In supersymmetric models, DM candidates include the neutralino, the partner of the gauge and Higgs bosons, as well as the gravitino [12] and the axino [17]. We will here concentrate on the weakly interacting candidate, the neutralino, which has the richer collider phenomenology as well as good prospects for (in-)direct detection. The collider SUSY phenomenology was first analysed in the context of a constrained model with a small and manageable number of arbitrary parameters defined at the GUT scale, the CMSSM. The model parameters are the common scalar mass, m_0, the common gaugino mass, $m_{1/2}$, the trilinear coupling, A_0 and the ratio of the vevs of the two Higgs doublets $\tan\beta$ as well as the sign of μ. Even in this constrained model, combined fits to all collider and precision data do not allow to select a specific region of parameter space nor to determine the nature of the LSP [24, 25]. The LSP can be : 1) a bino LSP annihilating into light fermions through sfermion exchange at low $m_0 - m_{1/2}$ or coannihilating with another sfermion 2) a bino LSP annihilating through a light or heavy Higgs resonance, the latter takes place at large values of $\tan\beta$, 3) a bino/Higggsino LSP that is found at large values of m_0.

It has since been realised that the CMSSM might be a much too contrived scenario. Allowing additional parrameters in GUT scale model, for example non universality of the scalars or the gauginos, or even going to the full MSSM model with parameters defined at the weak scale will open up the possibilities for DM annihilation. thus expanding the range of possibilities for DM searches. The new DM scenarios include the bino/wino LSP which annihilates into gauge boson pairs [26] and the bino/Higgsino LSP associated with TeV scale sfermions.

At the LHC, a pp collider of 14TeV, the best channels to detect DM particles are via the production and decay of heavy coloured particles, squarks and gluinos, as direct DM production does not have a good signature. The cross sections for production of coloured particles are large, nevertheless finding efficient ways to cut the much larger SM background is a critical issue. Signatures of the DM candidate always produced in the decay chains involve observables such as $E_T^{\rm miss}$ accompanied by leptons and or jets. The combined reach of the LHC with a luminosity of $\mathscr{L} = 100$ fb^{-1} is displayed in Fig. 1b in the $m_0 - m_{1/2}$ plane of the CMSSM. The reach is almost 2TeV for gluinos in scenarios where squarks are very heavy (large m_0) and otherwise 3TeV for squarks [22]. In other models than the CMSSM, the LHC discovery potential in terms of squark and gluino masses should not be much affected if sparticle masses are not degenerate.

At the ILC the main issue is the available center of mass energy. Once above the threshold for pair production all sparticles are easily detectable. Furthermore heavy charginos and neutralinos can be produced in association with a lighter chargino or neutralino respectively. Finally photon radiation gives access to otherwise invisible final states such as the LSP or the sneutrino. The discovery potential of the ILC in the CMSSM is displayed in Fig. 1b. The discovery reach is basically set by the threshold for sleptons or chargino production. At a LC with 1TeV center-of-mass energy, all the cosmologically interesting region is covered. Furthermore because the light higgsinos can be produced the reach of LC1000 exceeeds that of the LHC in the region at large m_0 where only the gluino is available at the LHC. For a 3TeV LC, the full $m_0 - m_{1/2}$ parameter space displayed would be covered.

3.2 Determination of particle properties

For reconstructing the DM annihilation cross sections the quantities that need to be measured are the mass and couplings of the LSP, the mass of new particles (or lower limits) that contribute to DM (co-)annihilation and the mass of any resonance that can enter the LSP annihilation.

The difficulty in determining parameters of the DM model at the LHC is the large amount of missing energy that prevents the reconstruction of a mass peak. The standard method for mass determination relies rather on measuring end points in kinematic distributions [27] [1]. This gives information on the mass differences of the sparticles occurring in the decay chain, Case studies have shown that the precision achievable on the mass differences is typically at the few per-cent level [27] assuming that the particles in a decay chain are correctly identified. Combining this method with cross sections measurements can improve the parameter determination [28]. At a linear collider the precision expected on masses is much better, at per-cent or even per-mil level. This can be achieved either through threshold scans or through mass reconstruction. Furthermore precise measurements on cross sections further constrain the underlying model parameters.

The precision that could be achieved on a collider prediction of the relic abundance, $\Delta\Omega/\Omega$, was studied in a few generic scenario and benchmark analyses were performed for both the LHC and the ILC [33]. As a first example consider the CMSSM scenarios where the LSP is a light bino. In this case annihilation into fermion pairs through sfermion exchange dominate together with bino/stau coannihilation. The relevant parameters are the LSP mass, the LSP couplings and the slepton masses. It was shown that to have a 10% precision on a collider prediction of the relic abundance would require a precise measurement of the mass difference $\Delta(m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0})$ (at the % level) while other parameters of the neutralino sector $(M_1, \mu, \tan\beta)$ need to be measured at the 10% level, Fig. 2 [31]. For the LHC it seems difficult to achieve the required level of precision on the mass difference. Indeed a study of a benchmark point (SPS1a') which belongs to this class of scenario was performed by two groups. In [32] it was shown, using the endpoint methods that even with a high luminosity $\mathscr{L} = 300\mathrm{fb}^{-1}$ one could expect only $\Delta\Omega/\Omega \approx 20\%$. Similar results were obtained in [33]. Improving the determination of the neutralino and stau masses as well as the neutralino couplings as could be done at the ILC would drastically reduce the uncertainty in the Ωh^2 prediction to the few percent level [33]. For these scenarios the collider prediction for the elastic scattering cross section are expected to have almost an order of magnitude uncertainty.

A more challenging scenario is the one where the LSP is a mixture of bino and higgsino, in the CMSSM this means that scalars are very heavy. This is a natural MSSM scenario from the DM point of view as annihilation of the bino/higgsino into W pairs through chargino or boson exchange is efficient. The annihilation is governed by the higgsino fraction of the LSP which in turn depends strongly on M_1 and μ. It has been shown that an uncertainty of 1% on these two parameters induces an uncertainty of 10% in the prediction of the relic abundance [31]. Achieveing this level of precision is a real challenge for the LHC especially that in this scenario the gluinos are the only coloured particle that can be produced directly. An ATLAS benchmark study [34], showed that exploiting end point measurements the gluino mass as well as the mass difference between neutralinos and the LSP could be determined with only a 10% accuracy. At the ILC, the measurement of 3 neutralinos and a chargino mass allows to determine all parameters of the neutralino sector assuming that these states are kinematically accessible. Furthermore the cross sections $\sigma(e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_2^0, \tilde{\chi}_3^0)$ also constrain the higgsino fraction of the LSP. A case study has shown that one can expect a precision $\Delta\Omega/\Omega \approx 15\%$.

[1] New variables have been proposed for mass determination, see for example [29, 30].

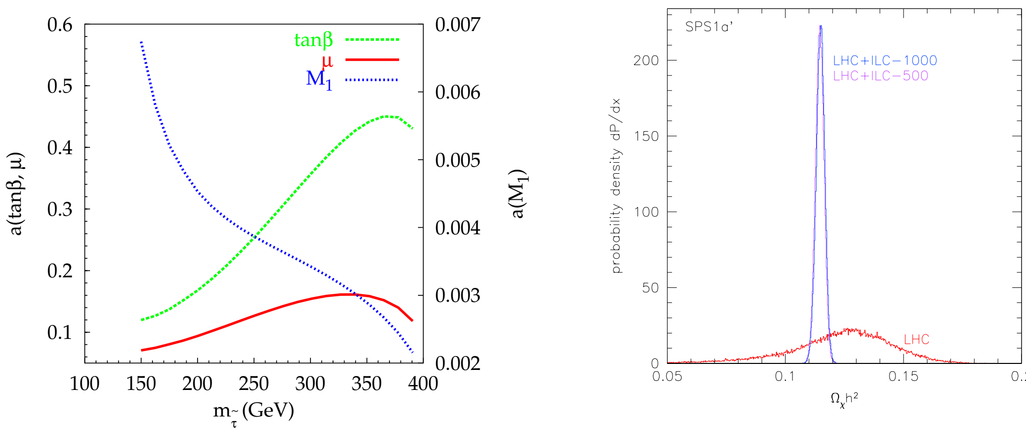

Figure 2: a) Required precision on $\tan\beta, \mu$ (left axis) and M_1 (right axis) for a 10% precision on the collider prediction of Ωh^2 in CMSSM bino scenarios, from [31] b) Collider prediction of Ωh^2 for benchmark Sps1A', from [33].

3.3 The little Higgs model

As a final example, consider the little Higgs model where the Higgs is a pseudo Goldstone boson originating from the spontaneous breaking of a global symmetry at a higher scale. The global symmetry protects the Higgs mass from large corrections. Strong constraints from electroweak precision observables can be avoided by imposing T-parity. The model contains new heavy gauge bosons as well as heavy top quarks (both T-odd, T_- and T-even, T_+). The DM candidate is the lightest T-odd particle, a new heavy neutral gauge boson A_H that annihilates preferentially through Higgs exchange into W pairs [6]. The minimal version of this model, called the littlest Higgs model has only 3 free parameters: the Higgs mass, the mass of the heavy photon and the mixing between standard and heavy quarks. Because of electroweak constraints the spectrum is rather light, with $m_{A_H} < 300$ GeV and $m_{T_+} < 1$TeV. The production of heavy quarks which further decay into top quarks and the heavy photon is therefore quite large at the LHC. A determination of the mass of the T_+ quark as well as some combination of the Higgs, heavy photon and T_- quark masses are sufficient to overconstrain the model and allow a "LHC prediction" of the DM relic abundance with a precision around 10%. At the ILC all new gauge bosons can be produced, $e^+e^- \to A_H Z_H, W_H^+ W_H^-$. The first process allows to measure the mass of the heavy photon while the second has a large cross section and gives a precise determination of the heavy SU(2) gauge boson, thus improving the precision on the determination of the model parameters. The uncertainty on the theoretical prediction of Ωh^2 is expected to go down to a few percent at a 1TeV LC [35].

4. CONCLUSION

Understanding the nature of dark matter is an exciting challenge for colliders. While the prospects for discovering physics beyond the standard model at the LHC are excellent, a precise determination of the properties of the DM particle, to the level where the theoretical predictions of DM observables reach the precision of the cosmological measurements is much more difficult and requires a precision machine such as the linear collider.

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