

LHC/ILC/cosmology interplay

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Abstract. There is a strong and growing interplay between particle physics and cosmology. In this talk, I discuss some aspects of this interplay concerning dark matter candidates put forth by theories beyond the standard model. In explaining the requirements for collider tests of such dark matter candidates, I focus in particular on the case of the lightest neutralino in the MSSM.

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1. Introduction

Cosmological data ranging from rotation curves of spiral galaxies to the cosmic microwave background tell us that most of the mass in the Universe is provided by non-luminous, ‘dark’ matter (DM); see [1–3] for reviews. To be concrete, recent measurements from WMAP [4,5] and SDSS [6] imply a (dominantly cold) dark matter density of $\Omega h^2 \simeq 0.1$ to an accuracy of about 10% at 1σ . The nature of this dark matter is one of the biggest puzzles of present-day physics. Although there are also other explanations, such as primordial black holes, many lines of reasoning suggest that the DM consists of a new weakly interacting massive particle, the so-called WIMP.

At the same time, we know that the Standard Model (SM) of particle physics, despite its tremendous success at energies up to ~ 100 GeV, is incomplete. For well-founded theoretical reasons, which I do not have to explain to this audience, we expect new physics beyond the standard model (BSM) to emerge at the TeV energy scale. This exciting new frontier will soon be probed by the LHC! In attempts to embed the SM in a more fundamental frame, theorists have come up with a wealth of BSM theories. These theories typically predict new particles, which may be discovered at the LHC. The lightest of these new particles is often stable by virtue of a new discrete symmetry and provides a natural DM candidate.

Such dark matter candidates put forth by particle physics are quite numerous [3] and contain, for example, the lightest supersymmetric particle (LSP) in supersymmetry (SUSY) with R -parity conservation; the lightest Kaluza–Klein (KK) excitation in models with extra dimensions and KK-parity; the lightest T-odd state

in little Higgs models with T -parity; etc. Note that all these possibilities are generally testable in collider experiments. This creates a very strong interplay between particle physics, at both theoretical and experimental levels, and cosmology.

In this talk, I discuss this interplay using the example of the minimal supersymmetric standard model (MSSM) with a neutralino LSP as the DM candidate. I focus in particular on the requirements for collider tests for determining whether the neutralino can be the DM in the Universe. I want to stress, however, that the general statements of this talk hold also for other, including non-SUSY, models.

2. Relic density of a WIMP

The standard assumption is that the dark matter particle, let us call it χ , is a thermal relic of the Big Bang as illustrated in figure 1. The argument goes as follows: When the early Universe was dense and hot, $T \gg m_\chi$, χ was in thermal equilibrium; annihilation of χ and $\bar{\chi}$ into lighter particles, $\chi\bar{\chi} \rightarrow \bar{l}l$, and the inverse process $\bar{l}l \rightarrow \chi\bar{\chi}$ proceeded with equal rates. As the Universe expanded and cooled to a temperature $T < m_\chi$, the number density of χ dropped exponentially, $n_\chi \sim e^{-m_\chi/T}$. Eventually the temperature became too low for the annihilation to keep up with the expansion rate and χ ‘froze out’ with the cosmological abundance observed today.

The time evolution of the number density $n_\chi(t)$ is described by the Boltzmann equation,

$$dn_\chi/dt + 3Hn_\chi = -\langle\sigma_A v\rangle [(n_\chi)^2 - (n_\chi^{\text{eq}})^2], \quad (1)$$

where H is the Hubble expansion rate, n_χ^{eq} is the equilibrium number density, and $\langle\sigma_A v\rangle$ is the thermally averaged annihilation cross-section summed over all contributing channels. It turns out that the relic density today is inversely proportional to the thermally averaged annihilation cross-section, $\Omega_\chi h^2 \sim 1/\langle\sigma_A v\rangle$. When the properties and interactions of the WIMP are known, its thermal relic abundance can be computed from particle physics’ principles and compared with cosmological data.

3. Collider tests of BSM DM candidates

As mentioned above, BSM scenarios with WIMP-DM candidates are testable at colliders. An important point in this regard is the following. Being electrically neutral and stable, the WIMP escapes the detector as missing energy and momentum. The preferred discovery channels therefore rely on the production of other new particles present in the theory and their subsequent decays into the DM candidate. By measuring the properties and decay kinematics of these new particles, one should then be able to determine the properties of the WIMP. If the measurements are precise enough, this allows to predict the annihilation cross-sections and hence the thermal relic density of the DM candidate, thus checking the consistency between a particular model of new physics and cosmology.

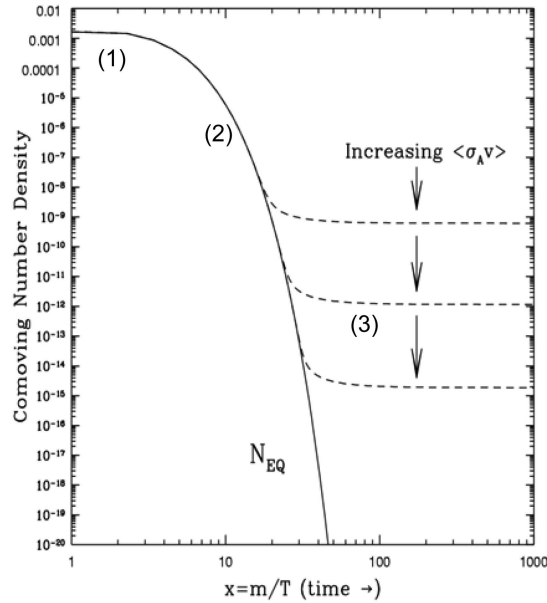


Figure 1. The cosmological evolution of a thermal relic’s comoving number density, from [1]. The full line is the equilibrium abundance; the dashed lines are the actual abundance after freeze-out. As the annihilation cross-section $\langle\sigma_A v\rangle$ is increased, the WIMP stays in equilibrium longer, leading to a smaller relic density.

At the LHC, the generic WIMP signature is jets (plus leptons) plus large missing transverse energy. This is often regarded as the golden SUSY signature, but it also holds for other models. This is great for discovery, but resolving the underlying theory and the nature of the DM candidate will not be trivial. For mass measurements, precisions of a few per cent can be expected. To decisively distinguish, for instance, SUSY from other BSM, spin measurements will be necessary. See [7] for first attempts along this line. In terms of predicting $\Omega_\chi h^2$, the precisions achievable at the LHC will, however, in general not be sufficient to match those of WMAP and other cosmological experiments. For this, precision measurements of masses, couplings and quantum numbers of the new states at a future international e^+e^- linear collider (ILC) will also be necessary. This will be described in more detail below.

4. Neutralino dark matter

4.1 Neutralino properties and annihilation channels

Let me now put the spotlight on a particular BSM DM candidate, the neutralino LSP of the minimal supersymmetric standard model. The neutralino mass matrix in the bino–wino–higgsino basis $\psi_j^0 = (-i\lambda', -i\lambda^3, \psi_{H_1}^0, \psi_{H_2}^0)$ is

$$\mathcal{M}_N = \begin{pmatrix} M_1 & 0 & -m_Z s_W c_\beta & m_Z s_W s_\beta \\ 0 & M_2 & m_Z c_W c_\beta & -m_Z c_W s_\beta \\ -m_Z s_W c_\beta & m_Z c_W c_\beta & 0 & -\mu \\ m_Z s_W s_\beta & -m_Z c_W s_\beta & -\mu & 0 \end{pmatrix} \quad (2)$$

with M_1 and M_2 the $U(1)$ and $SU(2)$ gaugino masses and μ the higgsino mass parameter. Furthermore, $s_W = \sin \theta_W$, $c_W = \cos \theta_W$, $s_\beta = \sin \beta$, $c_\beta = \cos \beta$ and $\tan \beta = v_2/v_1$ ($v_{1,2}$ being the vacuum expectation values of the two Higgs fields $H_{1,2}$). This matrix is diagonalized by a unitary mixing matrix N ,

$$N^* \mathcal{M}_N N^\dagger = \text{diag}(m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_3^0}, m_{\tilde{\chi}_4^0}), \quad (3)$$

where $m_{\tilde{\chi}_i^0}$, $i = 1, \dots, 4$, are the (non-negative) masses of the physical neutralino states with $m_{\tilde{\chi}_1^0} < \dots < m_{\tilde{\chi}_4^0}$. The lightest neutralino is then decomposed as

$$\tilde{\chi}_1^0 = N_{11} \tilde{B} + N_{12} \tilde{W} + N_{13} \tilde{H}_1 + N_{14} \tilde{H}_2. \quad (4)$$

It will hence be mostly bino, wino, or higgsino, according to the smallest mass parameter in eq. (2), M_1 , M_2 , or μ , respectively. If $\tilde{\chi}_1^0$ is the LSP and R -parity is conserved, this indeed provides an excellent cold dark matter candidate [8,9].

For its relic abundance to be in the right range, the neutralino LSP must annihilate efficiently enough. The relevant processes are (for a comprehensive discussion, see [10]): annihilation of a bino LSP into fermion pairs through t -channel sfermion exchange in case of very light sparticles; annihilation of a mixed bino–higgsino or bino–wino LSP into gauge boson pairs through t -channel chargino and neutralino exchange, and into top-quark pairs through s -channel Z exchange; and finally annihilation near a Higgs resonance (the so-called Higgs funnel). Furthermore, coannihilation processes with sparticles that are close in mass with the LSP may bring $\Omega_{\tilde{\chi}} h^2$ in the desired range. In particular, coannihilation with light sfermions can help to reduce the relic density of a bino-like LSP. The corresponding Feynman diagrams are depicted in figure 2. Note that coannihilation generically occurs when there is a small mass gap between the LSP and the next-to-lightest SUSY particle (NLSP). In scenarios with a higgsino or wino LSP, one has in fact a mass-degenerate triplet of higgsinos or winos, and coannihilations are so efficient that $\Omega_{\tilde{\chi}} h^2$ turns out much too small, unless the LSP has a mass of order TeV.

Requiring that the neutralino LSP provides all of the cold dark matter, i.e. $0.095 < \Omega_{\tilde{\chi}} h^2 < 0.129$ at 2σ , puts strong constraints on the parameter space of the general MSSM. It puts even tighter bounds on models which assume specific relations between the soft-breaking parameters, such as mSUGRA, CMSSM, AMSB, string-inspired models, etc.

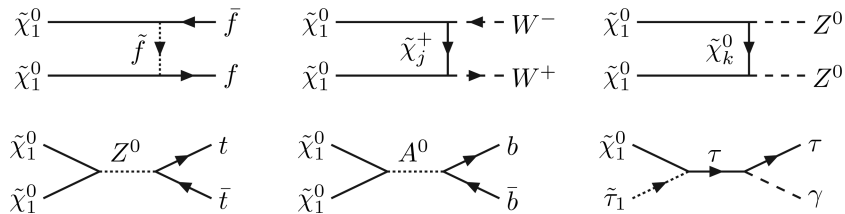


Figure 2. Examples of processes contributing to neutralino (co)annihilation.

4.2 What do we need to measure? With which precision?

From the above discussion it is clear that in order to predict the relic density of the LSP from collider experiments, we need to determine the properties of all sparticles potentially involved in the LSP (co)annihilation processes. That means not only determining the LSP mass but also the other neutralino, chargino, sfermion and Higgs masses (or at least lower limits on them to be sure that their contribution to $\langle\sigma v\rangle$ is negligible) as well as the relevant sparticle mixings. Naturally the question arises as to which precisions are necessary in order to infer $\Omega_{\tilde{\chi}}h^2$ with $\sim 10\%$ accuracy, compatible with the WMAP precision. This was studied in detail in ref. [11] for various cases of dominant (co)annihilation channels. Two examples, the stau coannihilation and the annihilation near the pseudoscalar Higgs resonance, are shown in figure 3.

Coannihilation with staus occurs for small neutralino–stau mass differences, typically $\Delta m_{\tilde{\chi}_1^0\tilde{\tau}_1} = m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0} \leq 10$ GeV. As can be seen in figure 3, this mass difference needs to be measured to better than 1 GeV. Obviously this will be very difficult at the LHC, where one relies on the measurement of the $\tau^+\tau^-$ invariant mass from cascade decays involving

$$\tilde{\chi}_2^0 \rightarrow \tau^\pm \tilde{\tau}_1^\mp \rightarrow \tau^+ \tau^- \tilde{\chi}_1^0. \quad (5)$$

The reason is that for small $\Delta m_{\tilde{\chi}_1^0\tilde{\tau}_1}$ the τ from the $\tilde{\tau}_1 \rightarrow \tau\tilde{\chi}_1^0$ decay is soft and can easily be missed. Moreover, even if both taus in (5) can be detected, one cannot tell whether the soft one comes from the $\tilde{\chi}_2^0 \rightarrow \tau\tilde{\tau}_1$ or the $\tilde{\tau} \rightarrow \tau\tilde{\chi}_1^0$ decay. Therefore one cannot tell whether it is $\Delta m_{\tilde{\chi}_1^0\tilde{\tau}_1}$ or $\Delta m_{\tilde{\chi}_2^0\tilde{\tau}_1}$ that is small. In addition to a precise determination of $\Delta m_{\tilde{\chi}_1^0\tilde{\tau}_1}$, one also needs to measure the absolute masses and the mixing angles with good accuracy (see figure 3). As shown in [12], this may be achieved in the clean experimental environment of the ILC; tunable beam energy and beam polarization are, however, essential for this aim.

The Higgs funnel and the higgsino-LSP scenarios are even more challenging. In the former, one needs precisions at the per cent or even permille level on $m_{\tilde{\chi}_1^0}$, m_A , the distance from the pole $m_A - 2m_{\tilde{\chi}_1^0}$, the pseudoscalar width Γ_A , and the higgsino mass parameter μ . In the latter, one needs to resolve the complete neutralino system with $\sim 1\%$ accuracy (see [11] for more details). The limitation of the ILC lies mostly in the kinematic reach: the heavy Higgs and neutralino/chargino states may simply be too heavy to be produced, in which case one has to rely on LHC measurements. See [13] for an example of SUSY parameter determination from combined LHC/ILC analysis.

It becomes clear that for a precise prediction of $\Omega_{\tilde{\chi}}h^2$ from colliders, we will need precision measurements of most of the MSSM spectrum. A combination of LHC and ILC analyses [14] may prove essential for this purpose.

4.3 What if CP is violated?

So far we have only considered the CP-conserving MSSM. In general, however, several parameters of the MSSM can be complex, thus introducing new sources

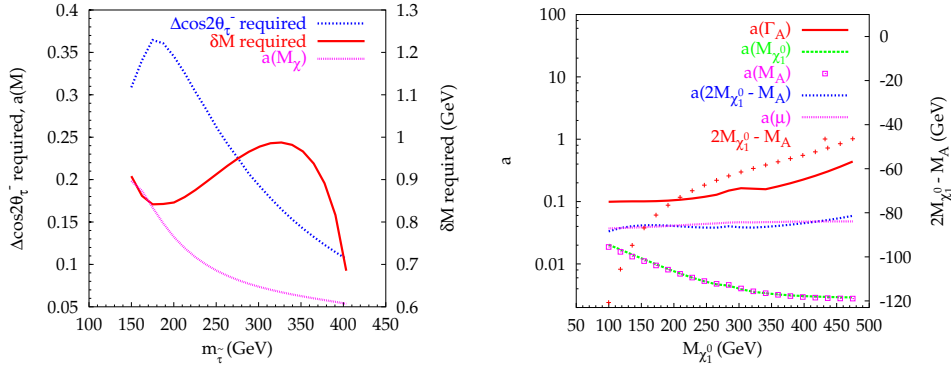


Figure 3. Fractional accuracies needed in the stau coannihilation (left) and Higgs funnel (right) scenarios (from [11]).

of CP violation (CPV) in the model. This is indeed a very interesting possibility since, given the Higgs mass bound of $m_h > 114$ GeV from LEP [15], the amount of CPV present in the SM is not sufficient to generate the correct baryon asymmetry in the Universe.

The parameters that can have CP phases are the gaugino and higgsino masses and the trilinear sfermion–Higgs couplings. Although constrained by electric dipole moments, non-zero phases can significantly influence the phenomenology of SUSY particles. They can also have a strong impact on the Higgs sector, inducing scalar–pseudoscalar mixing through loop effects [16]. This can in turn have a potentially dramatic effect on the relic-density prediction in the Higgs funnel region: neutralino annihilation through s -channel scalar exchange is p -wave suppressed; at small velocities it is dominated by pseudoscalar exchange. In the presence of phases, both heavy Higgs bosons can, for instance, acquire a pseudoscalar component and hence significantly contribute to neutralino annihilation, even at small velocities. Likewise, when only one of the resonances is accessible to the neutralino annihilation, large effects can be expected by changing the scalar/pseudoscalar content of this resonance.

CP phases however not only impact $\Omega_{\tilde{\chi}} h^2$ in the Higgs funnel region but they can also lead to important effects in almost any scenario of neutralino (co)annihilation. In ref. [17] we analysed in detail the influence of CP phases in the various scenarios of neutralino annihilation and coannihilation for which the LSP is a ‘good’ DM candidate. We found effects of up to an order of magnitude from modifications in the couplings due to non-zero CP phases (note that care has to be taken to disentangle phase effects in couplings and kinematics). As an example, figure 4 shows $\Omega_{\tilde{\chi}} h^2$ as a function of the phase of M_1 , $M_1 = |M_1| e^{i\phi_1}$, for a mixed bino–higgsino LSP, which dominantly annihilates into W^+W^- .

The largest effects are found, as expected, for annihilation through Higgs exchange, not only because of scalar–pseudoscalar Higgs mixing but also because a phase in the neutralino sector modifies the LSP’s couplings to scalar and pseudoscalar states [17]. Let me emphasize, however, that even in scenarios which feature a modest phase dependence, the variations in $\Omega_{\tilde{\chi}} h^2$ often exceed 10%. Therefore, when aiming at a precise prediction of the neutralino relic density from

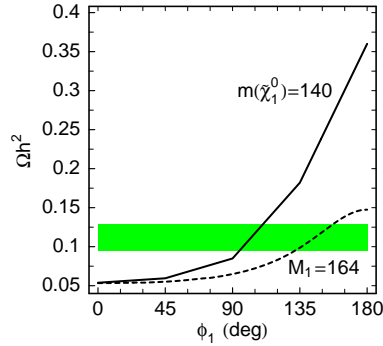


Figure 4. Ωh^2 as a function of ϕ_1 for a mixed bino–higgsino LSP scenario with $\mu = 200$ GeV and $\tan \beta = 10$; the dashed line is for fixed $M_1 = 164$ GeV, while for the full line M_1 is adjusted such that $m_{\tilde{\chi}_1^0} = 140$ GeV remains constant. The grey band shows the 2σ WMAP range (from [17]).

collider measurements, one needs not only precise sparticle spectroscopy as assumed in [18] – one also has to precisely determine the relevant couplings. This includes the determination of possible CP phases.

4.4 What if the inferred Ωh^2 is too high?

Suppose that we have discovered SUSY with a neutralino LSP and made precision measurements of all the relevant parameters, as pointed out above. It may turn out that $\Omega_{\tilde{\chi}} h^2$ of the neutralino thus inferred is below the cosmological dark matter density. We would be led to conclude that there exists yet another DM constituent, or else that there is some non-thermal mechanism contributing to the neutralino relic density.

However, what if the inferred $\Omega_{\tilde{\chi}} h^2$ is too high? There are several solutions to this problem.

- (a) $\tilde{\chi}_1^0$ may only appear to be the LSP but decay into an even lighter sparticle outside the detectors. In this case the $\tilde{\chi}_1^0$ would actually be the NLSP and the real LSP would be, for instance, a gravitino or axino. The thermal relic abundance would then roughly scale with $m_{\text{LSP}}/m_{\text{NLSP}}$. Strong constraints on this scenario come from BBN limits on late $\tilde{\chi}_1^0 \rightarrow Z\tilde{G}, h\tilde{G}$, etc., decays (for details, see [19]).
- (b) R -parity may be violated after all, but on long time-scales so that $\tilde{\chi}_1^0$ again appears stable in collider experiments. On cosmological scales, late decays of $\tilde{\chi}_1^0$ would have reduced its number density to zero, and the actual dark matter would be something else.
- (c) Our cosmological assumptions may be wrong. Our picture of dark matter as a thermal relic from the Big Bang may well be too simple. Note also that the exact value and uncertainty of Ωh^2 extracted from cosmological data depend

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on both the precise datasets used and the choice of parameters allowed to vary [20].

5. Conclusions

We expect new physics beyond the Standard Model at the TeV energy scale, and there is well-motivated hope that this new physics also provides the dark matter of the Universe. This creates a strong interplay between theoretical particle physics, collider experiments, and cosmology. Using the example of a neutralino LSP in the MSSM, I have argued that precision measurements at LHC and ILC will be necessary to pin down the nature and properties of the dark matter candidate.

Two more comments are in order. First, even if BSM with a WIMP DM candidate is discovered at future colliders, the properties of the WIMP are measured precisely and its Ωh^2 thus deduced matches the cosmological value, this is no proof that this WIMP is indeed the DM. Direct and/or indirect detection [2,3] will be indispensable in addition. Here, note that the rates for (in)direct detection can also be predicted once the properties of the WIMP are known. Second, the interplay between particle physics and cosmology is not limited to the dark matter question. Another example for this interplay is the baryon asymmetry of the Universe, where particle physics offers explanations through e.g. electroweak baryogenesis or leptogenesis [21].

To conclude, I think it is fair to say that these are exciting times for both particle physics and cosmology, with a steadily growing synergy between the two fields.

Acknowledgements

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