

Dark matter in the pre-LHC era

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Abstract. I highlight some main aspects of the present complementarity in looking for new physics beyond the Standard Model between accelerator physics and direct and indirect dark matter searches.

1. Introduction

The success of the standard model (SM) predictions is remarkably high and, indeed, to some extent, even beyond what one would have expected. As a matter of fact, a common view before LEP started operating was that some new physics (NP) related to the electroweak symmetry breaking should be present at the TeV scale. In that case, one could reasonably expect such new physics to show up when precisions at the percent level on some electroweak observable could be reached. As we know, on the contrary, even reaching sensitivities better than the percent has not given rise to any firm indication of departure from the SM predictions. To be fair, one has to recognize that in the almost four decades of existence of the SM we have witnessed a long series of "temporary diseases" of it, with effects exhibiting discrepancies from the SM reaching even more than four standard deviations. However, such diseases represented only "colds" of the SM, all following the same destiny: disappearance after some time (few months, a year) leaving the SM absolutely unscathed and, if possible, even stronger than before.

The fact that with the SM we have a knowledge of fundamental interactions up to energies of $O(100)GeV$ should not be underestimated: it represents a tremendous and astonishing success of our gauge theory approach in particle physics and it is clear that it represents one of the greatest achievements in a century of major conquests in physics. Having said that, we are now confronting ourselves with an embarrassing question: if the SM is so extraordinarily good, does it make sense to go beyond it? The answer, in my view, is certainly positive. This "yes" is not only motivated by what we could define "philosophical" reasons (for instance, the fact that we should not have a "big desert" with many orders of magnitude in energy scale without any new physics, etc), but there are specific motivations pushing us beyond the SM. I'd group them into two broad categories: theoretical and "observational" reasons.

On the former side, there are at least three important questions which do not find any satisfactory answer within the SM: the flavour problem (i.e., a rationale behind the large variety of fermion masses and mixings), the unification of the fundamental interactions and the gauge hierarchy problem (namely, why the tremendous gap between the electroweak and the Planck or GUT exists and how it can be preserved when radiative corrections to the Higgs mass are taken into account). Out of these three issues facing the SM, only the solution of the gauge hierarchy problem is clearly connected to the presence of NP *at the electroweak scale*.

Turning to the observational reasons calling for NP, it is remarkable that, apart from the evidence for neutrino oscillations and, hence, for neutrino masses, such reasons are to be found in what we could call “clashes” of the particle physics SM with the standard model of cosmology (i.e., the Hot Big Bang): baryogenesis, inflation and dark matter (DM). Undoubtedly, the demands for i) a dynamical generation of an adequate cosmic asymmetry between matter and antimatter and ii) an inflationary epoch in the primordial Universe seem to strongly point in favor of NP beyond the particle physics SM (new sources of CP violation, new scalar fields, etc.). However, the major hint for NP beyond the SM of particle physics has to be identified in the DM issue.

There exists an impressive evidence that not only most of the matter in the Universe is *dark*, i.e. it doesn't emit radiation, but what is really crucial for a particle physicist is that (almost all) such dark matter (DM) has to be provided by particles other than the usual baryons. Combining the WMAP data on the cosmic microwave background radiation (CMB) together with all the other evidences for DM on one side, and the relevant bounds on the amount of baryons present in the Universe from Big Bang nucleosynthesis and the CMB information on the other side, we obtain the astonishing result that, with the impressive significance of more than 10 standard deviations, *DM has to be of non-baryonic nature*. More quantitatively, the current “state-of-the-art” of dark matter studies faces an impressive progress in observational cosmology, which recently led to an unprecedented accurate determination of the amount of cold dark matter in the universe [1]:

$$\Omega_{\text{CDM}}h^2 = 0.1126^{+0.008}_{-0.009}, \quad (1)$$

where Ω_{CDM} represents the cold matter density of the universe and h parameterises the present Hubble rate, $H_0 = 100h \text{ Km sec}^{-1}\text{Mpc}^{-1}$, with $h = 0.72 \pm 0.08$. This has to be compared with the upper bound on the baryonic abundance as obtained from Big Bang nucleosynthesis, $\Omega_{\text{B}}h^2 < 0.023$, or the more recent joint analysis of the WMAP data together with other CMBR experiments, large-scale structure data, supernova data and the HST Key Project leading to:

$$\Omega_{\text{B}}h^2 = 0.024 \pm 0.009 \quad (2)$$

Since the SM does not provide any viable non-baryonic DM candidate, we conclude that together with the evidence for neutrino masses and oscillations, *DM represents the most impressive observational evidence we have so far for new physics beyond the SM*. Notice also that it has been repeatedly shown that massive neutrinos cannot account for such non-baryonic DM. Thus, the existence of a (large) amount of non-baryonic DM pushes us to introduce new particles in addition to those of the SM.

2. SUSY, LSP and DM

There exists an extension of the SM (and, to my knowledge, only one, so far) which succeeds to simultaneously cope with two of the above mentioned theoretical motivations for NP while providing a *natural* candidate for DM. This is *low-energy SUSY* [2] with its minimal (and most successful) implementation known as the Minimal Supersymmetric Standard Model (MSSM): it provides an ultraviolet completion of the SM at the *electroweak scale* effectively stabilizing the higgs mass at that scale and, thanks to the presence of the SUSY partners at that scale, it succeeds to modify the RG behavior of the gauge coupling constants ensuring an excellent unification of the electroweak and strong coupling constants at a grand unified scale of approximately 10^{16}GeV . These purely “particle physics” motivations nicely combine with a bonus of utmost relevance: the MSSM (where the theory is endowed with an additional discrete symmetry known as R parity to ensure matter stability) leads to a stable SUSY particle (LSP) which can be a (very) good candidate for DM [3].

This is going to be the decade where we should be able to establish whether low energy supersymmetry (SUSY) exists or not. We have three main roads to gain access to SUSY: (a) Direct SUSY searches at hadron colliders (b) Indirect SUSY searches in rare FCNC (Flavour Changing Neutral Currents) and/or CP violating processes (c) Direct and indirect SUSY Dark Matter (DM) searches. Given that low energy supersymmetry is rather a *framework* than a *predictive model*, one has to assume an explicit realisation of SUSY breaking in order to make predictions concerning the above mentioned three roads to SUSY. The Constrained Minimal SUSY Standard Model (CMSSM) represents the “prototype” of low energy supergravity having the minimal number of free parameters and being successful in not departing too violently from the Standard Model (SM) predictions. In view of the extraordinary agreement of the SM with all the experimental data on the above (a) and (b) points, it is of interest to consider models with features approaching those of the CMSSM.

In the CMSSM the lightest neutralino $\tilde{\chi}_1$ is the lightest supersymmetric particle (LSP) over a wide range of parameters, providing an ideal particle candidate for cold dark matter [4]. $\tilde{\chi}_1$ is practically always, to a high degree of purity, a *bino*, except for a thin strip close to the parameter space area where radiative electroweak supersymmetry breaking conditions are not fulfilled, named *focus point region* [5].

I require that neutralinos either totally or partly contribute to the inferred dark matter density. In most models of low energy SUSY it turns out that the computed amount of thermal relic neutralinos is typically larger than what indicated in Eq. (1) above¹. With this in mind, and allowing for the presence of extra DM components beside neutralinos, we will only consider as a constraint the 95% C.L. upper bound on the thermal relic abundance of neutralinos derived from Eq.(1):

$$\Omega_{\tilde{\chi}_1} h^2 < 0.129. \quad (3)$$

As regards prospects for direct and indirect detection of neutralino dark matter within the constrained MSSM, it has been shown that the most favorable parameter space points lie in the focus point-hyperbolic branch region. For instance, regarding the muon flux from neutralino pair-annihilation in the center of the Earth or of the Sun, one of the most promising indirect detection strategies, planned neutrino telescopes will probe, within the CMSSM, practically only regions at low neutralino masses and large higgsino content. On the other hand, it has been shown that direct detection spin-dependent searches have typical projected sensitivities lying orders of magnitude far from the expected signal. As regards, finally, direct detection through spin-independent interactions, once again promising signals are predicted only in the low neutralino masses and/or large higgsino fractions parameter space points of the CMSSM. To summarise, at present and future facilities, direct and indirect dark matter searches will compete with the LHC only in a very limited CMSSM parameter space region, in the focus point strip at moderate values of $M_{1/2}$, and therefore at low neutralino masses.

Combining all the constraints on the higgs and SUSY masses from LEP, the bounds on rare FCNC processes and the limits on the CDM abundance, three main regions survive in the CMSSM parameter space:

- *The Stau Coannihilation Regions:* If the lightest stau and the lightest neutralino are quasi degenerate in mass, efficient stau-stau as well as stau-neutralino (co-)annihilations

¹ It should be noted that in several examples, the presence of *extra components* in the Universe energy density at neutralino decoupling, for instance a scalar field in a Brans-Dicke-Jordan cosmology, a quintessential field [6, 7, 8], or the shear energy density associated to primordial anisotropies, only strongly *enhances* the predicted neutralino abundance: for instance, the presence of a quintessential scalar field may lead to enhancements in the neutralino relic density up to *six orders of magnitude* [8].

significantly contribute in suppressing the thermal χ_1 relic abundance. Similar mechanisms with the lightest stop are possible in regions with very large trilinear scalar couplings [9]. Most of these regions will be accessible to the LHC, at any value of $\tan\beta$, with the possible exception of very large values of $M_{1/2}$.

- *Funnel Regions:* In these regions, the bino-bino annihilation cross section is greatly enhanced through resonant s -channel exchange of the heavy neutral Higgses A and H . The conditions required for the resonant enhancement are a large value for $\tan\beta$ and $\mu < 0$, which are necessary to fulfill the relation $2m_{\chi_1^0} \approx m_A$. Here LHC might cover the parameter space corresponding, roughly, to $M_{1/2} \leq 1$ TeV.
- *Focus point or Hyperbolic Branch Regions:* These regions are narrow zones corresponding to large values of m_0 , yielding a *low* value for the μ parameter. The focus point region lies close to where radiative electroweak symmetry breaking (EWSB) is not valid, and is also relatively unstable numerically. The main feature is that a non-negligible higgsino fraction in the lightest neutralino is produced. The LHC reach of this region is pretty limited, owing to the large values of m_0 and $M_{1/2}$, yielding very heavy gluinos and squarks.

The ‘smallness’ of the surviving regions in the CMSSM is a result of the strict universality assumptions on the soft masses at the high scale within the CMSSM. It has been shown that, relaxing some assumptions about the Higgs or the sfermion soft SUSY breaking mass universality, other coannihilation partners may arise, such as the sneutrino or the bottom squark, leading to larger allowed regions in the parameter space compared to the present situation.

A thorough analysis of the CMSSM parameter space which survives after imposing the FCNC (in particular, those involved in the lepton flavor violation), the collider physics and the DM constraints is presented in ref. [10]

No matter how important the discussion of the CMSSM as a benchmark frame can be, it should be remembered that the CMSSM is only a *very particular SUSY realization* and most of its stringent implications arise from its very constrained nature (the CMSSM has only four parameters plus the sign of the μ parameter instead of the 124 parameters of an unconstrained MSSM). It is interesting to move to a generic MSSM case and, in particular, to envisage the possibility that at least part of the SUSY spectrum is not as light as we expected before the impressive bounds imposed on low-energy SUSY by the LEP results. An exhaustive analysis in this sense is conducted in our recent work with Profumo and Ullio [11]. While I refer the interested reader to that paper to get a more detailed discussion, here I want to emphasize at least one point of that analysis. Future DM direct detection experiments, DM indirect searches for antimatter and with gamma rays and neutrino telescopes, tests of the theory at future accelerators, such as the LHC and an NLC (Next Linear Collider) and, finally, rare processes (involving FCNC and/or CP violation) are truly complementary in our effort to uncover the structure of the NP which we (or, to be fair, most of us) think to be present at the electroweak scale. This is particularly true if such low-energy NP is represented by SUSY, for instance in regimes where the LSP instead of being the usual Bino of the CMSSM case is provided by some Wino-Higgsino mixing or arises from the Bino-Wino transition. Considering a generic SUSY setup with an MSSM possessing a rather heavy scalar sector, but allowing for a general fermionic sector, it is possible to see that there exist conspicuous slices of the SUSY parameter space which will not be within the reach of the LHC, while the interplay between direct and indirect DM detection searches will allow for a (full) coverage of such areas (this is what happens, for instance, going to values above 1 TeV for the M_1 , M_2 and μ SUSY parameters, when the region where the LSP is a gaugino-higgsino mixed state can be covered by DM direct searches - taking a next generation 1-ton Xenon detector as an example - while it would not be accessible even to a 1 TeV NLC).

On the other hand, once we give up the usual restrictions which are typical of the constrained

MSSM schemes, in particular the condition relating the different gaugino masses through a unification condition, we should keep in mind that even well-established bounds like the one referring to the mass of the lightest neutralino, can be removed with new, important variants in the approach for SUSY DM searches [12].

3. SuperWIMPS

In the previous section I considered the most common view that the LSP is the superpartner of a SM ordinary particle, for instance a neutralino. However, it may well be the case that the LSP is the *gravitino*, the spin 3/2 partner of the spin 2 graviton [13]. There exists the possibility that the superweakly-interacting massive particle (superWIMP) gravitino which would be produced from the decay of the next LSP (NLSP) is a DM candidate [14]. Alternatively, one can assume that the NLSP reaches its thermal relic density Ω_{NLSP}^{th} before decaying, and so $\Omega_{gravitino} = (m_{gravitino}/m_{NLSP})\Omega_{NLSP}^{th}$ [15]. In other words, one relaxes the constraint that gravitinos from NLSP decays account for all of dark matter. The thermal relic density assumption has consequences that differ markedly from the fixed gravitino relic density assumption with new allowed regions in the $(m_{gravitino}/m_{NLSP})$ parameter space (CMB and electromagnetic and hadronic BBN constraints have to be applied) [14].

The gravitino LSP scenario opens new prospects for DM searches at colliders. For instance, a common NLSP candidate can be a slepton, say a s-tau. At colliders, one can envisage the possibility of collecting the less energetic metastable NLSP sleptons in a detector and, then, one could monitor their decays (the decay lifetime can range from 10^4 to 10^8 seconds) [16]. Interestingly enough, if one could be able to measure the time distribution and the energy of the produced leptons, one could determine both the gravitino mass and the Planck scale in an independent way. This is a typical situation where the complementarity between accelerator physics and cosmology would have very far-reaching consequences.

4. A guaranteed rate for DM production at LHC?

The reasoning behind the hope to have a *guaranteed rate for DM production* at LHC or at ILC is rather straightforward: i) if stable WIMPs (or superWIMPs) exist, then they have to contribute to DM; ii) hence, given the mentioned observational upper bound on the DM energy density, this implies that such stable WIMPs or superWIMPs should have annihilated sufficiently fast at the time of their freeze-out; iii) the final step is that, if we are able to correlate the annihilation cross section of such WIMPs with their production cross section at colliders, we should be able to infer a minimum guaranteed rate for their production at our collider facilities. Since annihilation cross section and production cross sections are related by detailed balancing, one can hope to be come out with this relevant result: from the “known” cosmic abundance of WIMPs one could infer the WIMP production at colliders without specifying the particle physics model of WIMPs [17].

More quantitatively, we know that the measurement of the amount of present-day dark matter determines the size of the total annihilation cross-section σ_{an} of dark matter [17]: $\sigma_{an} \approx 0.85$ pb ($\sigma_{an} \approx 7$ pb) for dark matter particles annihilating in an *s*-wave (*p*-wave). This is just the ball-park range for the annihilation cross-section for WIMPs with a mass in the range between 100 to 1000 GeV ! As said above, this amazing coincidence is what made WIMPs so popular as DM candidates.

For simplicity. Let’s take the case when just a single WIMP particle, χ constitutes the entire DM and consider its annihilation into a pair of Standard Model particles

$$\chi + \chi \rightarrow X_i + \bar{X}_i, \quad (4)$$

where $X_i = l, q, g, \dots$ can be any Standard Model particle.

Following [17], using detailed balancing one finds the following expression for the production of non-relativistic χ pairs in $X_i\bar{X}_i$ collisions

$$\sigma(X_i\bar{X}_i \rightarrow 2\chi) = 2^{2(J_0-1)} \kappa_i \sigma_{\text{an}} \frac{(2S_\chi + 1)^2}{(2S_X + 1)^2} \left(1 - \frac{4M_\chi^2}{s}\right)^{1/2+J_0}, \quad (5)$$

where the initial state particles are assumed to be relativistic ($M_X \ll M_\chi$). J_0 takes the value 0 or 1 for s-wave or p-wave annihilation, respectively. κ_i denotes the fraction of the total annihilation cross section σ_{an} into the $X_i\bar{X}_i$ channel. Taking $X_i = q$ or g (or even W, Z) for a hadron collider or $X_i = e$ for an electron-positron machine, the above equation provides a prediction of the WIMP production rate [17]. In this way one can establish the reach for a collider machine for the discovery of WIMPs without making detailed assumptions on the nature of such WIMPs and the theory where they live in. For instance, for a 500 GeV unpolarized electron-positron collider (with an integrated luminosity of $500fb^{-1}$ it is possible to discover WIMPs (with p-annihilation) at the 3σ level for WIMP masses in the range $100GeV-200GeV$ for κ_e around 0.3-0.4 [17]. For further details, see also [18]

5. Conclusions

Here are a few main points that I hope emerged from the previous discussion, but, in any case, it's worthwhile recapitulating:

i) Together with neutrino physics, DM presently constitutes the major evidence we have for new physics beyond the SM;

ii) Although there exist several interesting DM candidates from the world of particle physics, in my view WIMPs look pretty *natural* candidates and in several SM extensions (SUSY, extra-dimensions, little higgs) the stability of the lightest new particle (to play the role of WIMP) does not require acrobatic realizations;

iii) Among the various WIMPs, the SUSY lightest superpartner looks promising and its search (both with direct and indirect searches) represents a highly complementary way to reveal and study the presence of low-energy supersymmetry. This is even more true if we consider the case when SUSY is not actually such a *low-energy* extension of the SM, but, at least part of its spectrum is relatively heavy;

iv) In addition to the WIMP scenarios, also the case of the LSP gravitino playing the role of SuperWIMP exhibits potentially interesting features from the point of view of the complementarity between cosmology and accelerator physics. The NLSP (for instance the scalar tau) could decay into the gravitino plus observable particles with lifetimes long enough to make it possible to collect the NLSP produced in the collisions at accelerators waiting for their subsequent (observable) decays.

v) If DM is provided by a WIMP (or a SuperWIMP), the implementation of the upper bound on the present DM energy density can be translated (under certain assumptions) into a lower bound on the production cross section for such DM candidate at colliders. Such an analysis does not require to specify the nature of the WIMP (and, hence, the model of new physics one has in mind), but, rather, it is based on the general correlation between WIMP annihilation cross section at freeze-out and WIMP production cross section in high energy experiments.

Just a final comment: if it is true, in my view, that the *only* way to get direct access to the new physics that most of us think (or at least hope) to exist is to perform experiments at high energy facilities (LHC, ILC, etc.), it remains true as well that flavor physics (FCNC and CP violation) on one side and DM searches on the other side are really complementary to accelerator physics in our tenacious effort to get evidence and understanding of such TeV new physics.

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