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Astroparticle physics view on supersymmetry

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Summary. — The particle physics interpretation of the missing-mass, or dark-matter, problem of cosmological and astrophysical nature is going to be posed under deep scrutiny in the next years. From the particle physics side, accelerator physics will deeply test theoretical ideas of new physics beyond the Standard Model, where a particle physics candidate to dark matter is often naturally obtained. From the astrophysical side, many probes are already providing a great deal of independent information on the signals which can be produced by the galactic or extra-galactic dark matter. The ultimate hope is in fact to be able to disentangle a dark matter signal from the various sources of backgrounds and to extract a coherent picture of new physics from the accelerator physics, astrophysics and cosmology side. A very ambitious and far-reaching project, indeed!

PACS 95.35.+d – Dark matter (stellar, interstellar, galactic, and cosmological).
PACS 11.30.Pb – Supersymmetry.
PACS 12.60.Jv – Supersymmetric models.
PACS 95.30.Cq – Elementary particle processes.

1. – Introduction

The presence of dark matter has been assessed on very different scales by a large number of experimental observations, ranging from dynamics of galaxy clusters, to the rotational curves of galaxies, weak lensing, the theory of structure formation and from the energy density budget of the Universe. Non-baryonic cold dark matter is needed, and this fact poses challenges to fundamental Physics since no viable Dark Matter (DM) candidate is present in the Standard Model. Extensions like Supersymmetry or theories of extra-dimensions typically accommodate succesful DM candidates, like neutralinos or sneutrinos in Supersymmetric (SUSY) theories, or Kaluza-Klein excitations in theories of extra-dimensions.

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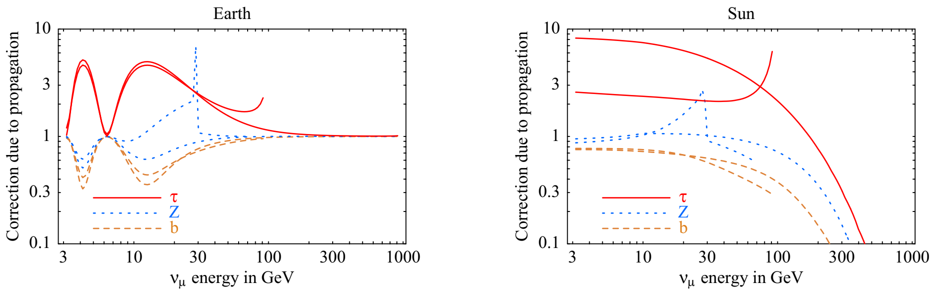

Fig. 1. – Modifications of neutrino fluxes from DM annihilation due to neutrino propagation [1]. The figures show the ratio of ν_μ fluxes "with" over "without" the effects of neutrino propagation (oscillations, absorptions, regeneration). The lines refer to neutrinos from DM annihilations into $\tau\bar{\tau}$ (continuous line), ZZ (dotted) and $b\bar{b}$ (dashed), for $m_{\rm DM} = 100$, 1000 GeV.

2. – Multichannel search of dark mater

Galactic DM may be sarched for in many ways: by looking at the recoil energy directly deposited in a low-background detector (direct detection) or by looking for annihilation products which are produced in the galactic environment (antimatter, gamma-rays) or in the Earth and Sun (neutrinos). In the following we will briefly report some recent results and give a comparative summary of the various searches.

3. – Neutrinos as dark matter messengers

DM captured and accumulated inside bodies like the Earth and the Sun may annihilate and produce a neurtino flux which can escape the body. Recent advances in the calculation of the theoretical fluxes have dealt with the effect induced by neutrino oscillation and by neutrino interactions with the medium (relevant for the Sun) [1, 2]. The relevance of the effect is shown in fig. 1 and summarized in table I in the case of the signal consisting of upgoing muons. *E.g.*, for $m_{\rm DM} = 1000$ GeV, the rate is unaffected if annihilation into W^+W^- occurs in the Earth, while it gets reduced to 0.04 of its value if annihilations occur in the Sun. The largest enhancement of the rate due to oscillations occurs in the $\tau\bar{\tau}$ channel. Other channels cause a reduction. At large values of $m_{\rm DM}$ oscillations have a smaller impact.

Table I. – *Ratios of through-going muon rates "with" over "without" the effects of neutrino propagation, for DM annihilations around the center of the Earth/Sun.*

DM mass m_χ	$\nu\bar{\nu}$	$b\bar{b}$	$\tau\bar{\tau}$	$c\bar{c}$	$q\bar{q}$	$t\bar{t}$	ZZ	W^+W^-
	DM annihilation channels in the Earth/Sun							
50 GeV	1/0.73	0.51/0.69	3.9/2.8	0.33/0.61	0.50/0.68	–/–	–/–	–/–
100 GeV	1/0.53	0.69/0.62	2.1/2.4	0.49/0.55	0.46/0.62	–/–	1.0/0.74	1.0/0.68
200 GeV	1/0.29	0.86/0.52	1.3/1.7	0.75/0.47	0.54/0.50	1.0/0.61	1.0/0.45	1.0/0.42
400 GeV	1/0.11	0.95/0.39	1.1/0.90	0.90/0.36	0.72/0.37	1.0/0.33	1.0/0.22	1.0/0.19
1000 GeV	1/0.02	0.99/0.16	1.0/0.23	0.98/0.19	0.92/0.19	1.0/0.09	1.0/0.05	1.0/0.04

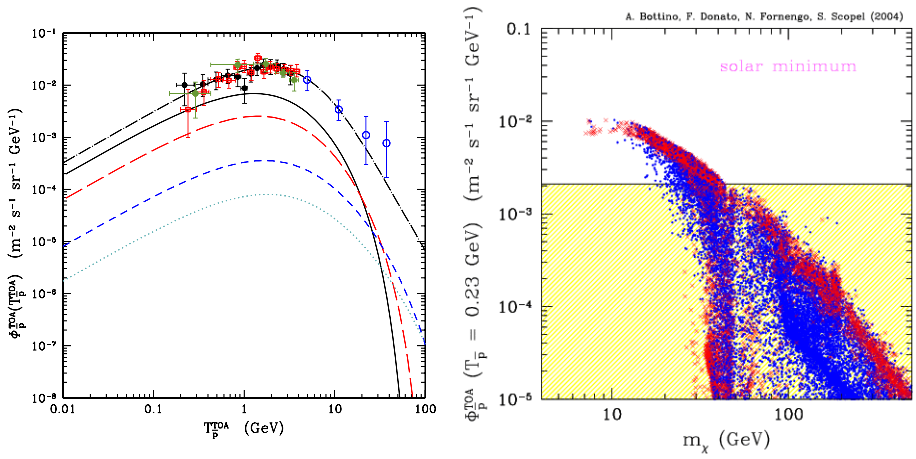

Fig. 2. – (Colour on-line) Left panel: Primary Top-Of-Atmosphere (TOA) antiproton fluxes as a function of the antiproton kinetic energy, for some representative spectra from neutralino annihilation [3]: the solid, long-dashed, short-dashed, dotted lines refer to $m_\chi = 60$, 100, 300, 500 GeV, respectively. The astrophysical parameters correspond to the median choice. Solar modulation is for minimal solar activity. The upper dot-dashed curve corresponds to the antiproton secondary flux [4, 5]. Full circles, open squares, stars and empty circles show the data from BESS 1995-97 [6], BESS 1998 [7], AMS [8] and CAPRICE [9]. Right panel: Antiproton flux at $T_{\bar{p}} = 0.23$ GeV *vs.* the neutralino mass, at solar minimum and for the best fit set for the astrophysical parameters [10]. A spherical isothermal DM density profile has been used. The scatter plots are derived by a full scan of the parameter space of non-universal gaugino models which predict low-mass neutralinos [11-13]. Crosses (red) and dots (blue) denote neutralino configurations with $0.095 \le \Omega_\chi h^2 \le 0.131$ and $\Omega_\chi h^2 < 0.095$, respectively. The shaded region denotes the amount of primary antiprotons which can be accommodated at $T_{\bar{p}} = 0.23$ GeV without entering in conflict with the experimental BESS data [6, 7] and secondary antiproton calculations [14].

4. – Antiprotons

Annihilation in the galactic environment may produce antimatter, adding an exotic contribution to cosmic rays. The case of antiprotons is shown in fig. 2, where predictions for the differential flux and for a scan of the SUSY parameter space of a low-energy realization of the Minimal Supersymmetric Standard Model (MSSM) where neutralino is the DM candidate are provided [3,15,10]. Theoretical uncertainties of astrophysical origin are sizeable [3]. *E.g.*, in the right panel of fig. 2 the scatter plot can be shifted upward or downward by about a factor of 6–10 [3], due to uncertainties in galactic propagation. Recently, PAMELA provided new reuslts on the $\bar{p}/p$ ratio [16]. Consequences have been derived in [17].

5. – Antideuterons

Antideuterons as a DM indirect signal have been proposed in ref. [23]. Recently a reanalysis has been developed, where also theoretical uncertainties have been quantified [18]. Some results are reported in fig. 3, where it is shown that the low-energy spectrum offers a unique opportunity to desentangle a signal from the background. The capability to probe the SUSY parameter space with a future experimental mission (GAPS)

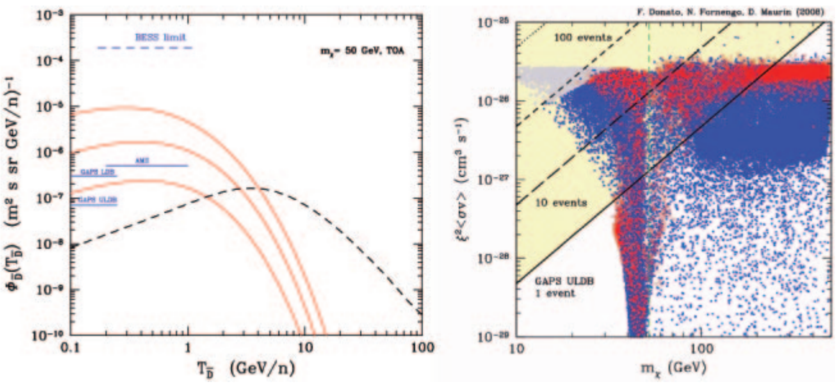

Fig. 3. – (Colour on-line) Left panel: TOA primary (solid lines) and secondary antideuteron fluxes, modulated at solar minimum, for a Weakly Interacting Massive Particle (WIMP) with $m_\chi = 50\,\mathrm{GeV}$ and for the three propagation models which encompass astrophysical uncertainties [18]. The secondary flux (dashed line) is shown for the median propagation model. The upper dashed horizontal line shows the current BESS upper limit on the search for cosmic antideuterons. The three horizontal solid (blue) lines are the estimated sensitivities for (from top to bottom): AMS-02 [19], GAPS on a long (LDB) and ultra-long (ULDB) duration balloon flights [20-22]. Right panel: GAPS ULDB reach compared to predictions for neutralino DM in low-energy supersymmetric models, shown in the plane-effective annihilation cross-section $\xi^2\langle\sigma_{\rm ann}v\rangle_0$ *vs.* neutralino mass m_χ [18]. The solid, long-dashed and short-dashed lines show the estimate of the capability of GAPS ULDB of measuring 1, 10 and 100 events, respectively, for the median propagation model. The scatter plot reports the quantity $\xi^2\langle\sigma_{\rm ann}v\rangle_0$ calculated in a low-energy MSSM (for masses above the vertical (green) dashed line) and in non-universal gaugino models which predict low-mass neutralinos [11-13]. Crosses (red) refer to cosmologically dominant neutralinos, while dots (blue) stand for subdominant neutralinos. Grey points are excluded by antiproton searches.

is shown in the rigth panel of the same figure. Neutralino consifurations with masses up to a few hundreds of GeV may be probed and rates as large as 100 events are possibile.

6. – Positrons

Positrons are currently the most interesting signal to look at, since recently PAMELA detector has released its first data on the positron fraction $e^+/(e^- + e^+)$ [33]. Novel theoretical analyses both for the signal component from DM annihilation in the Galaxy and for the astrophysical background have been recently derived [24, 32]. It has been shown that theoretical uncertainties are relevant also for the positron flux, and they are reported in fig. 4. The importance of the electron flux in comparing theoretical predictions of the positron fraction with the data has been raised in ref. [32]: this fact may have impact on the assessing of the presence of an excess in the PAMELA data and on the determination of the size of such an effect.

7. – Gamma-rays

Gamma-rays are another important tool in studying dark matter. The search for this signal will largely benefit from the FERMI/GLAST detector: a summary of its capabilities may be found in ref. [34].

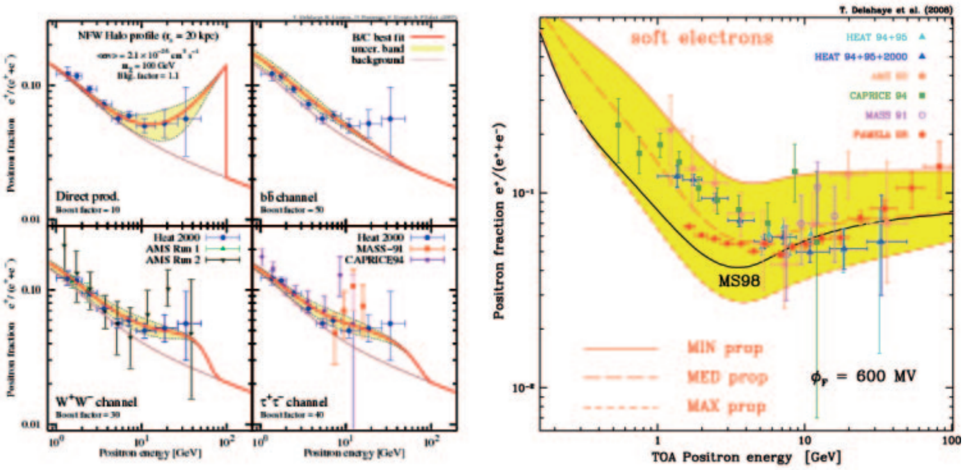

Fig. 4. – Left panel: Positron fraction $e^+/(e^-+e^+)$ *vs.* the positron detection energy E for a DM particle with a mass of 100 GeV and for a Navarro-Frenk-White (NFW) profile [24]. The four cases refer to different annihilation final states: direct e^+e^- production (top left), $b\bar{b}$ (top right), W^+W^- (bottom left) and $\tau^+\tau^-$ (bottom right). In each panel, the thick solid (red) curve refers to the best-fit choice of the astrophysical parameters. The colored (yellow) area features the total uncertainty band arising from positron propagation. In each panel, the thin (brown) solid line stands for the background of refs. [25, 26]. Experimental data from HEAT [27], AMS01 [28, 29], CAPRICE [30] and MASS [31] are also plotted. Right panel: Positron fraction arising from pure cosmic rays interactions (background) as a function of the positron energy, for a soft (left panel) and hard (right panel) electron spectrum [32]. Data are taken from CAPRICE [30], HEAT [27], AMS [28, 29], MASS [31] and PAMELA [33].

8. – Discussion

A brief comparative analysis of the various detection signals of particle DM may start from stating that antideuterons [23] are the signal which possesses the strongest feature, when compared to the expected background [18]: this occurs at low kinetic energies, which is therefore the place where experimental effort should concentrate. Antideuterons in fact appear to offer the best possibility to detect a signal, even in the absence of a boost factor. Foreseen experiment (GAPS, AMS) will have a unique chance to probe this signature directly in the next decade [18].

The antiproton signal at low energies has a milder feature and when compared to the background the capability to clearly disentagle a signal from the background is hard, especially when considering that astrophysical uncertainties will still be a major component in the theoretical determination of the signal [3]. In the case DM is heavy, the spectral feature could allow discrimination against the background, but this requires pretty strong boost factors, which appear to be disfavoured by recent studies [35]. Special annihilation mechanism, like the Sommerfeld enhancement [36], could prevent the necessity of large astrophysical boost factors. Current data from PAMELA on the $\bar{p}/p$ ratio nevertheless do not exhibit an excess ascribable to DM annihilation [16, 17]. Antiprotons, instead, are suitable to set (potentially strong) bounds on an exotic component in the flux and therefore on the particle DM properties, once theoretical uncertainties are properly taken into account [3, 15, 10].

Positrons offer a very interesting possibility and have recently regained a lot of attention as a consenquence of the first release of the PAMELA data on the positron fraction [33]. The positron flux from DM annihilation may possess spectral features, depending on the final state of the particle DM annihilation [24]. Similary to the case of the other indirect detection signal, astrophysical uncertainties largely affect also the positron flux [24]. Large theoretical uncertainties affect also the background flux [32], and they have to be taken into consideration when comparison with data is attempted. Theoretical determinations agree with available experimental data [32], including the HEAT positron flux, when theoretical and experimental uncertainties are considered [32]. The most recent results are provided by the PAMELA experiment, but for the moment on the positron fraction, which requires, in comparison with theoretical determination, to consider also the electron flux. Is has been shown that once astrophysical uncertainties are taken into account, the comparison between the predicted positron fraction and the PAMELA data is indicative of an excess in the case of a hard electron spectrum, while in the case of a soft electron spectrum the identifications of an excess is not conclusive [32] and requires a detailed study which properly takes into account the galactic propagation mechanisms. Typically, the positron signal requires sizeable boost factors in order to prevail over the background: theoretical uncertainties may actually be instrumental in reducing the amount of boost factors required to explain a possibile excess in the data [37] and therefore in making the PAMELA result fully compatible with the current understanding of the astrophysical properties of DM indirect detection signals.

Gamma-rays are another important tool for studying DM annihilation in the Galaxy and to probe regions of the galactic environment which are partly different from those explored by charged cosmic rays. Spectral features of the gamma-ray signal are not typically very strong, execept for the case of direct annihilation into a gamma-line, which instead would be a striking signature of DM annihilation. The gamma line is typically strongly suppressed for suitable DM candidates, and therefore very hard to be probed. The gamma-ray signal typically requires (sizeable) boost factors in order to be observable on the top of the astrophysical gamma-rays. FERMI will be in the next years a unique laboratory to study gamma-rays and it will provide valuable insight also on the DM problem.

Finally, neutrinos from the Earth and the Sun, which can be studied at neutrino telescopes, are an important alternative which nicely complements the other indirect detection techniques. In this case, spectral and angular features may be exploited to desentangle the signal from the atmospheric neutrino background [1, 2]. Neutrino oscillation, and transport in the Sun, have been shown to be relevant effects, which cannot be neglected [1, 2]. The typical signature relies on the search for a muon neutrino flux, which induces upgoing muons in the neutrino telescope. On the other hand, since the DM annihilation and the oscillation phenomenon produce also electron and tau neutrinos, additional signatures may be worthwhile to be explored [1].

Complementary to indirect detection is direct detection. A clear signature is offered by the annual modulation of the rate. The DAMA/NaI and DAMA/LIBRA detectors actually observe annual modulation in the low-energy single-hit events and this effect has now reached a statistical significance of 8.2σ [38]. In SUSY models, this effect is compatible with neutralinos in the MSSM or in gaugino non-universal schemes [39, 40] or sneutrinos in Left-Right (LR) models or models with see-saw neutrino masses [41]. Experiments which rely on the total counting rate and exploit rejection techniques (like, *e.g.*, CDMS [42] and XENON10 [43]) allow to set bounds on the scattering cross-section

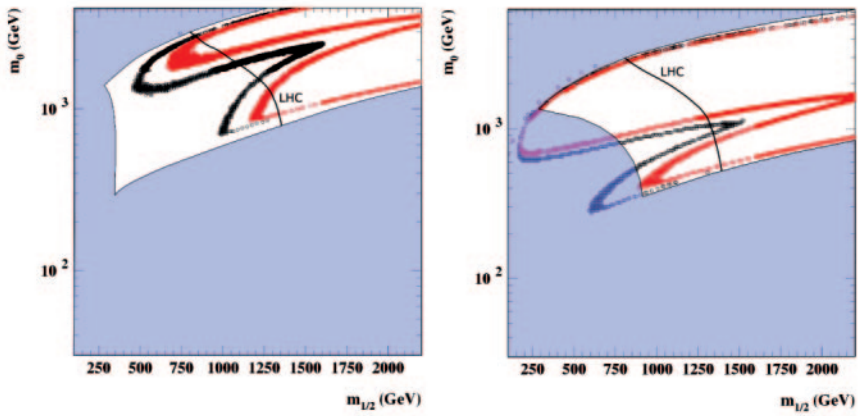

Fig. 5. – Minimal SUGRA parameter space m_0 (universal soft scalar mass) *vs.* $m_1/2$ (gaugino mass) for $\tan\beta = 45$ (left panel) and $\tan\beta = 53$ (right panel) and common trilinear coupling $A_0 = 0$. The shaded areas are excluded by bounds on supersymmetry searches and supersymmetry contribution to rare processes. The dark (black) circles show the region of parameter space where the neutralino relic abundance matches the WMAP range for cold dark matter in standard cosmology. The light (red) points refer to the same situation in a scalar tensor cosmology. From ref. [45]. The solid line denotes the expected reach of LHC.

of DM. These experiments currently probe a fraction of the MSSM parameter space for neutralino (see, *e.g.*, ref. [40, 44]) or sneutrino DM [41]. The actual extension of the probe depends on astrophysical (galactic halo properties) and nuclear physics (DM-nucleus interaction) assumptions [39]. Comparison with indirect searches may be found in refs. [10, 39].

9. – Accelerator physics and cosmology

Dark matter candidates are potentially present in almost any extension of the Standard Model of particle physics. In supersymmetric theories with R-parity conservation, both neutralinos and sneutrinos are successful cold dark matter candidates, although other possibilities are present, like, *e.g.*, gravitinos. In the next years LHC, and hopefully in the future the ILC, will probe these new physics models and a quite intriguing interconnection between high-energy physics studies, astophysics and cosmology will be posed under deep scrutiny. An example of this interplay is depicted in fig. 5, where a section of the minimal SUGRA parameter space is shown, together with the expected reach of the LHC. A fraction of this parameter space is already excluded by LEP, Tevatron and studies of rare processes. In the allowed region, fig. 5 shows the sector which is compatible with a relic neutralino able to explain the dark matter content of the Universe, a sector which is just a small fraction of the relevant parameter space. The same figure also shows the effect induced by the thermal history of the Universe: alternative cosmologies, different from the FRW cosmology, imply a modified decoupling epoch and an ensuing different relic abundance: therefore, the cosmologically relevant regions in parameter space are shifted. The example shown in fig. 5 refers to scalar-tensor cosmologies. Reconstruction of the particle physics properties of dark matter and the underlying particle physics model represent a window also on the early Universe physical properties [46].

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