Indirect searches in the PAMELA and Fermi era

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The detection of γ-rays, antiprotons and positrons due to pair annihilation of dark matter particles in the Milky Way halo is a viable indirect technique to search for signatures of supersymmetric dark matter where the major challenge is the discrimination of the signal from the background generated by standard production mechanisms. The new PAMELA antiproton data are consistent with the standard secondary production and this allows us to constrain exotic contribution to the spectrum due to neutralino annihilations. In particular, we show that in the framework of minimal supergravity (mSUGRA), in a clumpy halo scenario (with clumpiness factor $\geq 10$) and for large values of $\tan(\beta) \geq 55$, almost all the parameter space allowed by WMAP is excluded. Instead the PAMELA positron fraction data exhibit an excess that it is very difficult to explain with secondary production. The Fermi-LAT experiment recently reported high precision measurements of the spectrum of cosmic-ray electrons-plus-positrons (CRE) between 20 GeV and 1 TeV. The spectrum shows no prominent spectral features, and is significantly harder than that inferred from several previous experiments. The PAMELA excess in positron fraction combined with the new Fermi results on the electron+positron spectrum unavoidably testifies the presence of primary positrons in cosmic rays because it is not possible to explain the PAMELA ratio with a deficit of electrons at high energies. Here we discuss the status of indirect dark matter searches and a perspective for PAMELA and Fermi γ-ray space telescope experiments.

1. Antiproton to proton ratio data

The PAMELA (a Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics) experiment is a satellite-borne apparatus designed to study charged particles in the cosmic radiation with a particular focus on antiparticles (antiprotons and positrons) [1]. The PAMELA antiproton data [2] are shown in figure 1 together with the antiproton flux expected from standard secondary production. Cosmic ray propagation and production of secondary particles and isotopes is calculated using the GALPROP code [3]. The lines show the minimal and maximal fluxes as calculated in models with different propagation parameters tuned to match the boron-to-carbon ratio in cosmic rays ([4], [5], [6], [7]). The antiproton data collected by PAMELA [2] and BESS [8] are consistent with each other and with predictions for secondary antiproton flux thus excluding a strong antiproton signal from exotic processes. Figure 2 is made in the framework of minimal supergravity (mSUGRA) by fixing the less sensitive parameters $A_0$, $\tan \beta$ and $\text{sign}(\mu) = +1$ and in the case of a clumpiness factor 10 and $\tan(\beta) = 55$. Following the analysis in [6], the region below the line in figure 2 can be excluded based on antiproton data.

This result can be compared with estimates based on Fermi five-years sensitivity to WIMP annihilation photons (continuum spectrum) from the Galactic center as shown in figure 3 [11,12]. The red band is the cosmologically allowed region by WMAP [14]; the region above the blue line ($M_{\text{WIMP}} \sim 200$ GeV) is not observable by Fermi due to the higher WIMP mass as one moves to higher $M_{1/2}$. The dark matter halo used for the Fermi indirect search sensitivity estimate is a truncated Navarro, Frank and White (NFW) halo profile. For steeper halo profiles (like the Moore profile) the Fermi limits move up, covering a wider WMAP allowed region, while for less steep profile (like the isothermal profile) the Fermi limits move down, covering less WMAP allowed region. The LHC accelerator limits are from [15].
2. Positron fraction and electron + positron flux

Contrary to the antiproton to proton ratio data, the PAMELA positron fraction data [16] exhibit an excess above \( \sim 10 \) GeV that it is very difficult to explain with secondary production [4],[6] [9]. We note that the change in the positron fraction data below \( \sim 10 \) GeV is probably due to the solar modulation (e.g., [17]) and change in the polarity of the solar magnetic field compared to the previous cycle. Recently the experimental information available on the CRE spectrum has been dramatically expanded as the Fermi-LAT Collaboration has reported a high precision measure-
that inferred from several previous experiments. The temptation to claim the discovery of dark matter is strong, but there are competing astrophysical sources, such as pulsars, that can give strong flux of primary positrons and electrons (see [18], [21], [22], [19] and references therein).

At energies between 100 GeV and 1 TeV the electron flux reaching the Earth may be the sum of an almost homogeneous and isotropic component produced by Galactic supernova remnants and the local contribution of a few pulsars with the latter expected to contribute more and more significantly as the energy increases.

Two pulsars, Monogem, at a distance of $d=290$ pc and Geminga, at a distance of $d=160$ pc, can give a significant contribution to the high energy electron and positron flux reaching the Earth and with a set of reasonable parameters of the model of electron production we can have a nice fit of the PAMELA and Fermi data (see figures 5 and 6), but it is true that we have a lot of freedom in the choice of these parameters because we still do not know much about these processes, so further study on high energy emission from pulsars are needed in order to confirm or reject the pulsar hypothesis.

How can one distinguish between the contributions of pulsars and dark matter annihilations? Most likely, a confirmation of the dark matter signal will require a consistency between different experiments and new measurements of the reported excesses with large statistics. The observed excess in the positron fraction should be consistent with corresponding signals in absolute positron and electron fluxes in the PAMELA.
data and all lepton data collected by Fermi [23]. Fermi has a large effective area and long projected lifetime, 5 years nominal with a goal 10 years mission, which makes it an excellent detector of cosmic-ray electrons up to $\sim$1 TeV. Future Fermi measurements of the total lepton flux with large statistics will be able to distinguish a gradual change in slope with a sharp cutoff with high confidence [24]. The latter, can be an indication in favor of the dark matter hypothesis. A strong leptonic signal should be accompanied by a boost in the $\gamma$-ray yield providing a distinct spectral signature detectable by Fermi.

The Galactic center (GC) is expected to be the strongest source of $\gamma$ - rays from DM annihilation, due to its coincidence with the cusped part of the DM halo density profile.

The expression of the $\gamma$-ray continuum flux for a generic WIMP at a given photon energy $E$ is given by

$$\phi_{\text{wimp}}(E) = \frac{\sigma v}{4\pi} \sum_f \frac{dN_f}{dE} B_f \int_{\text{l.o.s.}} dl l \frac{1}{2} \rho(l)^2 \left(\frac{E}{m_{\text{wimp}}^2}\right)$$

(1)

This flux depends from the WIMP mass $m_{\text{wimp}}$, the total annihilation cross section times WIMP velocity $\sigma v$ and through the sum of all the photon yield $dN_f/dE$ per each annihilation channel weighted by the corresponding branching ratio $B_f$. The flux (1) also depends from the WIMP density in the galactic halo $\rho(l)$. The integral has to be performed along the line of sight (l.o.s.). As shown in figure 7, apart from the $\tau\tau$ channel, the photon yields are quite similar and depends from the neutralino mass (figure 8).

So fixing the halo density profile (for example a NFW profile), a dominant annihilation channel (that is $bb$, $tt$, $W^+W^-$, ...) and the corresponding yield, it is possible to perform a scan in the plane $(m_{\text{wimp}}, \sigma v)$ in order to determine the GLAST reach and the regions that are already excluded by the EGRET data in the 2 degrees region around the galactic center [12], [13], i.e. the flux predicted by the susy+background model must not exceed the total flux predicted from EGRET data. The result of the scan is given in figure 9 for the Galactic center and in figure 10.
Figure 9. Cross Section times WIMP velocity versus the WIMP mass for the $b\bar{b}$ annihilation channel. The red region is allowed by EGRET data and detectable by GLAST for 3σ significance for 5 years of Fermi operation.

for Sagittarius Dwarf. For every couple of values $(m_{\text{wimp}}, \sigma v)$ we compute the expected flux (1) and we performed a standard $\chi^2$ statistical analysis to see if GLAST is able to disentangle the WIMP contribution among the standard astrophysical $\pi^0$ background as used in [12]. The result is given at a 3σ confidence level. The background uncertainties are reflected in the red regions. We assumed a total exposure of $3.7 \times 10^{10}$ cm$^2$ s, for a period of 4 years of data taking and an angular resolution (at 10 GeV) of $\sim 3 \times 10^{-5}$ sr.

Finally a line at the WIMP mass, due to the $2\gamma$ production channel, could be observed as a feature in the astrophysical source spectrum [24]. Such an observation is a “smoking gun” for WIMP DM as it is difficult to explain by a process other than WIMP annihilation or decay and the presence of a feature due to annihilation into $\gamma Z$ in addition would be even more convincing.

Figure 10. Same as figure 9 but for Sagittarius Dwarf assuming Moore profile as described in [25]

3. Conclusion

Recent accurate measurements of cosmic-ray positrons and electrons by PAMELA, and Fermi have open a new era in particle astrophysics. The observed features or excesses break a boring single-power-law behavior of the cosmic-ray spectrum. Their exotic origin has to be confirmed by complimentary findings in $\gamma$-rays by Fermi and atmospheric Cherenkov telescopes, and by LHC in the debris of high-energy proton destructions. A positive answer will be a major breakthrough and will change our understanding of the universe forever. On the other hand, if it happens to be a conventional astrophysical source of cosmic rays, it will mean a direct detection of particles accelerated at an astronomical source, again a major breakthrough. In this case we will learn a whole lot about our local Galactic environment. However, independently on the origin of these excesses, exotic or conventional, we can expect very exciting several years ahead of us.
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