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Proceedings ICHEP 2022: The cosmic antiproton puzzle

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Cosmic rays antiprotons are believed to be mainly produced by the interaction of primary cosmic rays (p, He, and nuclei with Z>2) with the interstellar medium. In the last decade, thanks to high precision measurements by AMS-02 and PAMELA, a possible tension between the observed antiproton flux and different predictive models of anti-proton secondary production has been highlighted in the kinetic energy range between 1 and 500 GeV. A discrepancy that has been tentatively associated to dark matter annihilation.

However, in the 10 to 100 GeV range, the model predictions suffer from severe uncertainties coming from the limited knowledge of the antiproton production cross section, with pp, pHe and Hep interaction channels being responsible for the majority of the produced cosmic antiprotons. Future measurements, as the ones that will be done by the COMPASS++/AMBER experiment, will improve the situation with incoming pHe collisions data.

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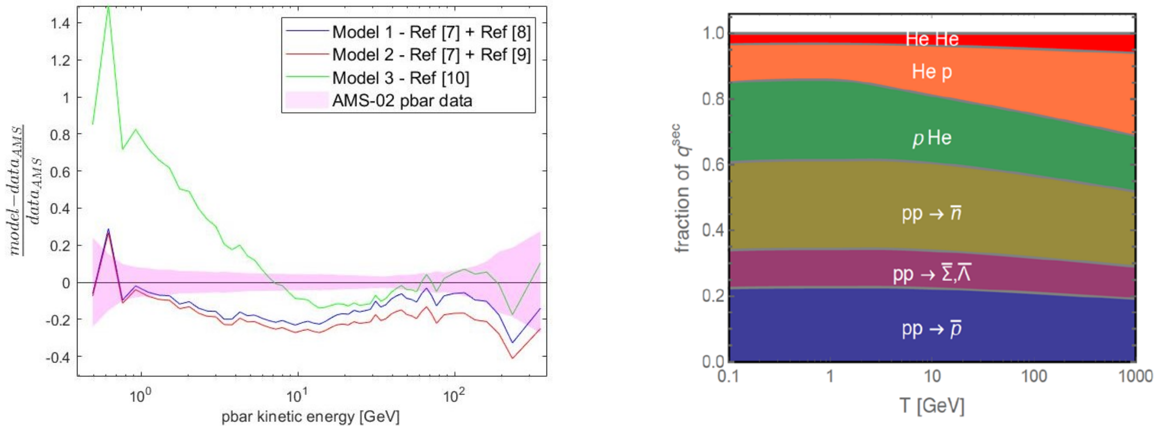

Figure 1: (Left) The residual between the AMS-02 antiproton flux and the flux predicted by GALPROP-HelMod [6] with three different models of production cross section [7–10]. (Right) Cosmic antiprotons production contributions expressed in percentage of the source term [2]. The contribution of nuclei heavier than the Helium is neglected.

1. Cosmic antiprotons production and propagation

The Alpha Magnetic Spectromer (AMS-02) is a high-energy particle detector on board of the International Space Station, able to separate all cosmic rays (CRs) species (electron, positron, proton, anti-proton, nuclei with Z>1 and anti-nuclei). This experiment measured with unprecedented accuracy the CRs antiproton flux [1] that has shown a discrepancy between model predictions and data, see Fig.1, and allowed for the search of a possible dark matter annihilation signal between 1 and 500 GeV.
Antiprotons in CRs are believed to be mostly produced by the collision of energetic primary CRs species, such as p, He and heavier nuclei, with the interstellar medium, constituded mainly by H and He (ISM). Therefore, to predict the CR antiproton flux and compare it with AMS-02 or other CRs experiment data, a good knowledge of the antiproton production cross sections of pp, pHe, HeHe collisions on a wide energy spectrum (with $\sqrt{s}$ from 5 GeV to 70 GeV) is required.
The secondary antiprotons source term includes all the possible channels where the primary CR acts as the projectile and the ISM acts as the target of a fixed-target collision weighted with the CR spectra. Figure 1 shows an estimation of the cosmic antiproton source term various contributions [2]. The pp channel is responsible for roughly 50÷55% of the total antiproton secondary production, while the helium channels are responsible for the 40÷45%. Heavier channels are neglected or contribute to 1÷5% of the whole production.
The most used model to estimate the secondary antiproton source term is based on analytic parameterizations of the antiproton production cross section of the pp channel [3], extended to heavier nuclei collision [4] by simple scaling assumptions.
Once the source term of antiprotons have been calculated, a propagation model is needed to propagate it through the galaxy. Among the comprehensive models that account for diffusion of CR in the galaxy with convection and reacceleration, and including secondary production by interaction and decay, the GALPROP code represents the state-of-the-art in this field [5].
We used GALPROP in conjunction with the model HelMod, that includes the effect of the propa-

gation of CRs in the heliosphere, as described in more detail in [6], to calculate the antiproton flux according to 3 different cross section models [7–10].
In Fig.1, the predicted flux has been compared with the antiprotons detected by AMS-02. The propagation parameters are kept constant, and the difference between models arise from differences in the production cross section. In all three cases a discrepancy with AMS-02 data is observed. Associating a dark matter signal to such a deviation is still under debate. Several estimations shown that the uncertainties on the cosmic antiproton spectrum prediction are dominated by the cross section ones between 1 and 100 GeV of antiproton energy [4]. In the worst case, they can affect a significant fraction of the antiproton flux, with the precise estimation depending on the cross section model and the analysis technique.

2. The future AMBER experiment

The data available on the production of antiprotons in collisions arise from fixed-target or collider experiments. The dataset at high center of mass energy (cms energy) have projectiles with very high momentum that are flux-suppressed in CRs because they obey roughly a power law in energy $\frac{dn}{dE} \propto E^{-\gamma}$ with γ (called spectral index) of about 2.7.
The experimental constraints on the production cross section in the 1÷100 GeV antiproton energy range arise mainly from pp collisions. About the helium channels, we have no data in the energy range we are interested in and further investigation is needed. The AMBER experiment [2] will take data in the next years at SPS using a fixed helium target and incident protons in the 60÷250 GeV/c momentum range, providing valuable informations.
We have analyzed both the phasespace of the future AMBER experiment and the one of the cosmic antiproton production to understand the future impact of the experiment and if it can significantly improve our knowledge about the cross section. In figure 2, the probability distribution functions of the production of cosmic antiprotons of different energies energies are shown (integrated in the transverse momentum). The five black vertical solid lines are roughly the five AMBER proposal for the pHe collisions. As it's shown, the AMBER experiment will be able to capture the peak- i.e. the cms energies where the most part of the cosmic production occurs- up to roughly 60 GeV of produced antiprotons.

3. Cosmic antinuclei

The anti-proton production cross section can be used to derive the anti-nuclei production cross sections via the coalescence model [11], a simple model that depends on a single parameter that can be determined experimentally, as measured by the ALICE experiment [12]. The Coalescence Model links the antinucleus spectrum with the antinucleons one: if two or more antinucleons are near enough in the phasespace (both momentum and coordinate space) they merge and form an antinucleus. In Figure 2 is presented a prediction of the anti-deuteron predicted secondary spectrum. For simple kinematic reasons the secondary anti-deuteron are at high energy and leave room for search of dark matter produced anti-deuterons at low energy. Current experiments, like AMS-02,

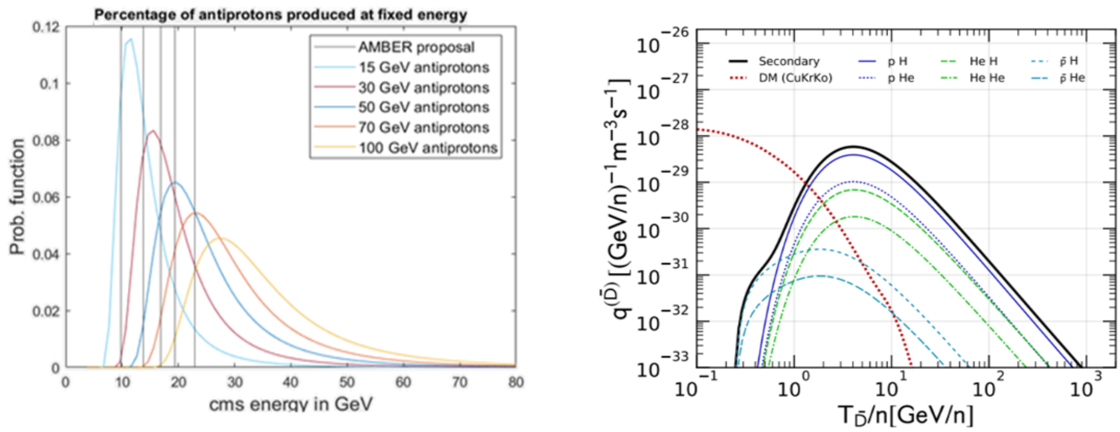

Figure 2: (Left) Probability density function, integrated in transverse momenta, of the production of the cosmic antiprotons with fixed energy in pHe collisions, according to the model in Ref [10]. The vertical solid lines are the five AMBER proposal for future data taking. (Right) Antideuteron source term function of kinetic energy, according to [11]. The DM will produce a low kinetic energy signal, clearly distinguishable from the high kinetic energy background.

and future one, like GAPS, are looking in this low energy region for a background free detection of dark matter annihilation.

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