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SOLAR MODULATION OF GALACTIC COSMIC RAY ANTIPROTONS

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In recent years, several new measurements of the antiproton component of cosmic radiation became available. These measurements significantly improved the existing statistics extending the explored energy region from few tens of MeV up to hundreds of GeV. These measurements are particularly relevant to understand the propagation of cosmic rays in the Galaxy and to investigate the nature of dark matter. However, an unambiguous interpretation of the experimental data requires a proper reconstruction of the Local Interstellar Spectrum of cosmic-ray antiprotons. Since the measurements are performed inside the Heliosphere, the solar modulation, which is a time-dependent effect following the 11-year solar activity, has to be taken into account. In this work, using a 3D state-of-art solar modulation model, a new Local Interstellar Spectrum for the cosmic-ray antiproton and its related uncertainties are presented. The Local Interstellar Spectrum was derived to match, when modulated, the data sets from AMS02, PAMELA, and BESS Polar II.

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1. Introduction

Since many years, it has been known that antimatter can shed light on the nature of Dark Matter (DM), see e.g, [1, 2]. Weakly Interacting Dark Matter Particles (WIMPs) are among the most well-motivated models for particle DM. Some of these models predict that the DM which permeates the Galaxy could decay or annihilate producing standard-model particles and antiparticles. Since antimatter in cosmic rays (CRs) is predominantly of secondary origin, produced by the interaction of primary CRs with the interstellar medium, the antimatter signal from DM could give a measurable excess. For example, a few authors recently claimed indications of a dark-matter signal resulting from an excess in the 10–20 GeV AMS02 antiproton data with respect to secondary production [3, 4]. According to these authors, this excess has a significance of at least 3 standard deviations accounting for propagation model uncertainties and could be explained with the annihilation to $b\bar{b}$ of a dark-matter particle with thermal annihilation cross-section and with mass in the range of several tens of GeV [5]. The estimated dark-matter contribution is of the order of 10-15% with respect to the secondary antiprotons signals down to a few tens of MeV. In this scenario, high statistics low-energy measurements of the antiproton component are needed in order to improve the significance of this result. For example, the future balloon-borne GAPS experiments (see e.g., [6]), expected to be launched during the Austral summer of 2022/2023, will extend the antiproton measurements down to few tens of MeV with unprecedented statistics.

It has to point out that, at the lowest energies (below $\approx$ 3 GeV), the dark-matter contribution derived in order to explain the claimed antiproton excess in the AMS-02 data produce an excess of about $20 - 30\%$ with respect to the experimental observation. In order to have a consistent scenario, the total antiproton spectrum need to reproduce the experimental data at all energies. A possible issue could originate from the modelling of the solar modulation which heavely affected the CRs at energies below $\sim$ 30 GeV and which performed with a symplified analitic model (force field model). In fact, the propagation through the Heliosphere reduces the intensity of the CRs with respect to their LIS. In addition, the 11 years solar activity cycle introduces a time dependence in the cosmic-ray flux, with higher intensity during the solar minima and lower intensity during the solar maxima. So far, all the experimental measurements of the cosmic-ray antiproton component were obtained with a near-earth detector. For this reason, the solar modulation effects and the related uncertainties have to be correctly modeled in order to correctly reproduces the low-energies experimental results.

The effect of the solar modulation on the antiproton LIS is shown in Figure 1. The LIS was obtained with the GALPROP code [7] with the set of parameters described in [8]. The dashed and dotted lines represent the modulated spectra during a period of minimum and maximum solar activity, respectively. The modulation has been performed using a state-of-art 3D numerical model (see e.g., [9]) which reproduces all the relevant propagation mechanisms inside the Heliosphere. Figure 1 shows the intensity decrease due to the solar modulation below $\approx$ 30 GeV/n and the intesity variation of the fluxes during different phases of the solar activity. For example, below 250 MeV, the flux increase by a factor of two from a solar maximum to a solar minimum period.

This numerical model also takes into account the charge-sign dependence which is introduced by the drift motions. Particles with opposite charge sign will experience opposite drift motions during the same period of solar activity and their spectra will be modulated differently. Similarly,

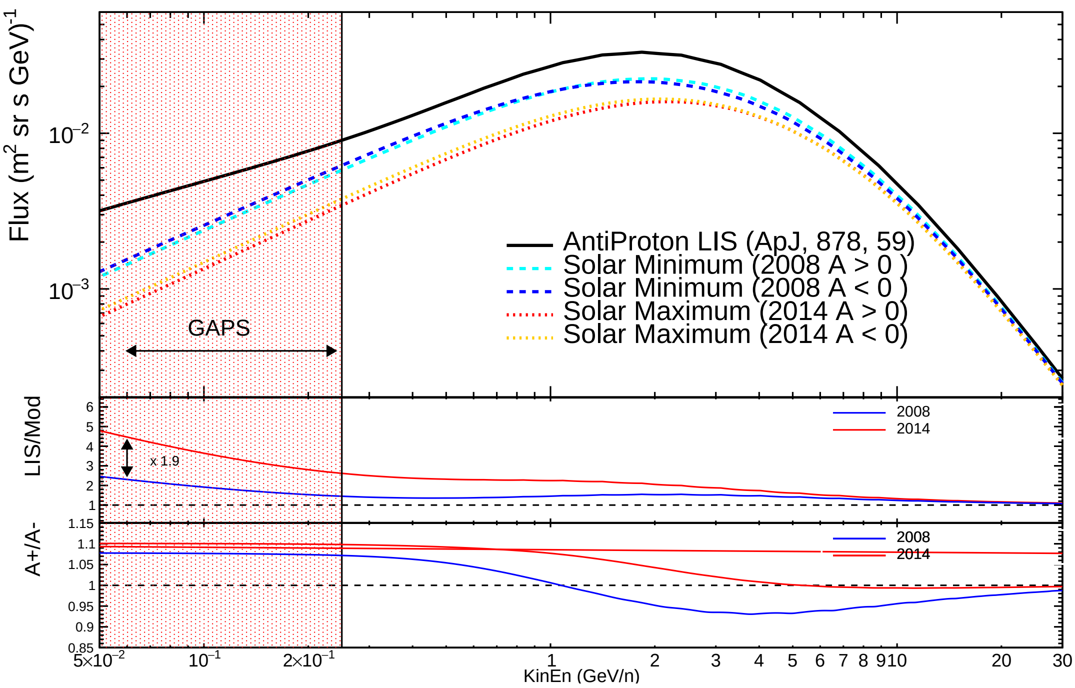

Figure 1: Top panel: the effect of the solar modulation on the secondary cosmic-ray antiproton LIS obtained from GALPROP (solid black line). The dashed lines represent the modulated spectra for a period of solar minimum activity and for opposite polarities of the HMF (blue line negative polarity, cyan line positive polarity). The dotted lines represent the modulated spectra for a period of maximum solar activity and opposite polarity of the HMF (red line negative polarity, orange line positive polarity). Middle panel: the modulation factor, i.e., the ratio between the LIS and the modulated spectra, for a solar minimum period (blue line) and for a solar maximum period (red line). Bottom panel: the ratio between the modulated spectra for a positive polarity and the modulated spectra for a negative polarity for a solar minimum period (blue line) and for a solar maximum period (red line).

particles with the same charge sign will experience opposite drift motions during a period of equal solar activity and opposite polarity of the Heliospheric Magnetic Field (HMF). The HMD polarity reverses every 11 years. The charge-sign dependence is also shown in Figure 1 where the antiprotons are modulated during opposite polarity of the HMF for a period of maximum (dotted red and orange lines) and minimum solar activity (dashed blue and cyan lines). The charge-sign dependence introduces a variation in the total amount of modulation of about 10% up to approximately 10 GeV. From these results is evident that a solar modulation model which takes into account for all the propagation mechanism is necessary in order to correctly modulate the spectra avoiding to introduce systematics.

The aim of this work is to calibrate the numerical 3D solar modulation model in order to reproduce a specific period of solar activity conditions, in particular those corresponding to the PAMELA, BESS Polar II, and AMS02 antiproton published spectra. Then, an antiproton LIS will be derived in order to, once modulated, reproduces at best the antiproton spectra over the entire experimental energy range. The uncertainties related to the solar modulation model will be derived

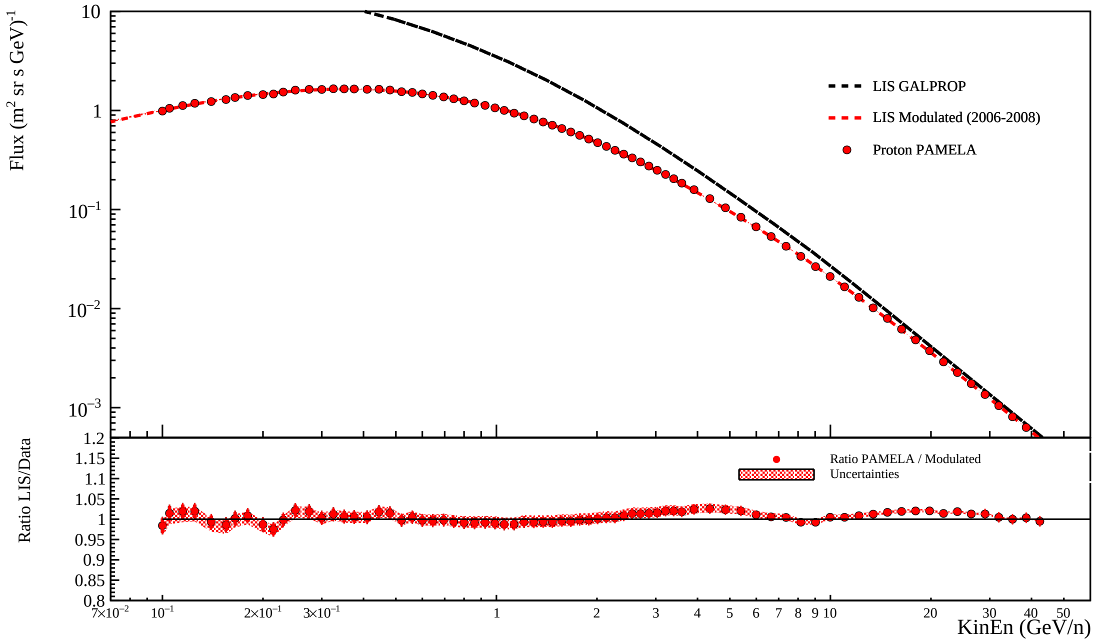

Figure 2: Top panel: the modulated proton spectrum (dashed red line) obtained with the solar modulation model tuned in order to reproduce the PAMELA data measured from July 2006 - December 2008 (red circles). The black dashed line represent the proton LIS. Bottom panel: the ratio between the modulated spectra and the PAMELA data (red circles). The red and green shadows represented the estimated uncertainties related to the model as described in the text.

as well as those related to the new LIS which will take into consideration to the experimental statistical uncertainties.

2. Analysis

In order to reproduce with the 3D numerical model the solar activity conditions which correspond to the published PAMELA (July 2006 - December 2008), BESS Polar II (December 2007 - January and AMS02 (July 2011 - May 2015) antiproton spectra, the proton spectra (measured by the same instrument in the same period of time) have been used. For example, Figure 2 shows the modulated proton spectra with a set of parameters tuned in order to reproduce the PAMELA data from July 2006 to December 2008. The parameters of the model were tuned starting for the values used in [10]. Those values were slightly modified in order to reproduce this specific period of time, but maintaining a general consistency with the previous work. In particular, three values were tuned: the normalization of the parallel diffusion and the low and high rigidity power law of the diffusion coefficient. The three parameters were tuned with a minimization approach, the best set of parameters was the one that minimizes the χ^2 of the PAMELA data and the modulated spectra. The modulated spectra reproduce the PAMELA data within 2%. An estimation of the uncertainties was also performed. Each free parameter was varied independently around its best value in order to find an interval that defines a 95% confidence level based on a χ^2 test. The same procedure was

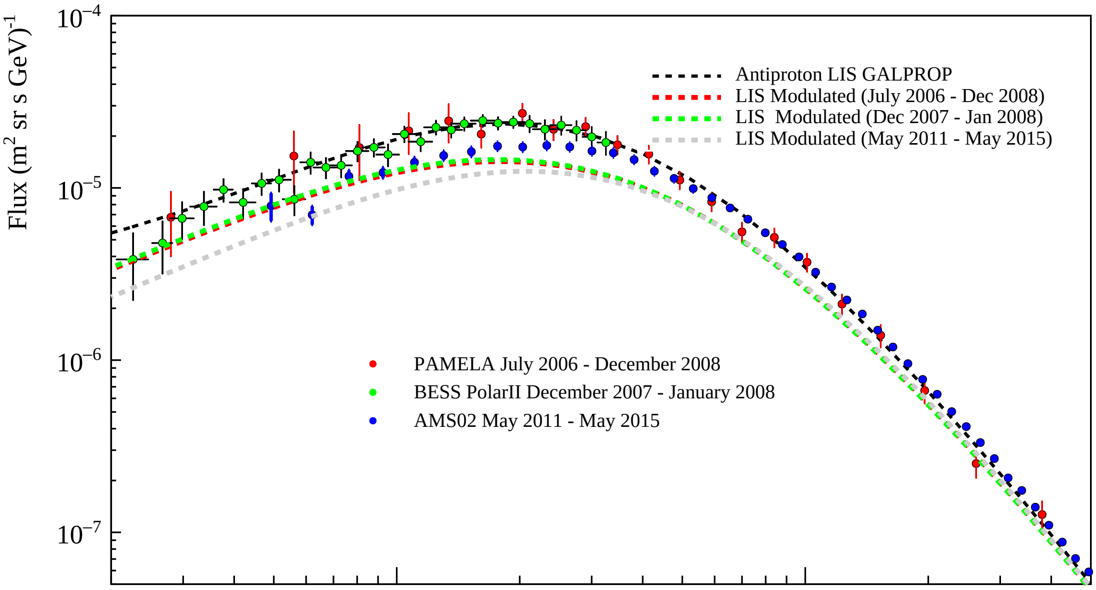

Figure 3: Top panel: the antiproton LIS from GALPROP code (black dotted line) along with the modulated spectra during three different solar activity level corresponding to the antiproton data set measured by PAMELA (red circles), BESS Polar II (green circles) and AMS-02 (blue circles). It is noticed that the modulated spectra are not able to reproduce the experimental data.

also performed for the BESS Polar II and AMS02 proton spectra and an agreement at the level of $3-5\%$ was obtained between the data and the modulated spectra.

The solar activity conditions obtained with this procedure were then applied to the secondary antiproton LIS derived with GALPROP. An opposite polarity of the HMF was considered in order to correctly account for the charge-sign dependence. The results are shown in Figure 3 where the antiproton LIS (black dashed line) is showed along with the modulated spectra for the three considered periods of time. The figure shows also the antiproton experimental measurements for PAMELA (red circles), BESS Polar II (green circles), and AMS02 (gray circles). This comparison shows that the modulated spectra always underestimates the experimental data. Since the solar modulation has been precisely tuned on the proton data, the difference is attributed to the GALPROP LIS. For this reason this LIS was modified in order to obtain a better agreement between the data and the modulated spectra.

The LIS was increased using a smooth factor. The new LIS was then modulated and compared with the experimental data. This procedure was iterated until when the modulated spectra reproduce at the best the experimental data. The antiproton LIS spectrum derived with this procedure from the PAMELA data is shown in Figure 4 (top panel). The solid red line represents the new antiproton LIS and the dashed red line is the spectra modulated with the solar activity conditions derived from the proton data. Contrarily to what was obtained with the original GALPROP LIS, the new modulated spectra nicely reproduces the experimental data as shown in the lower panel of Figure 4,

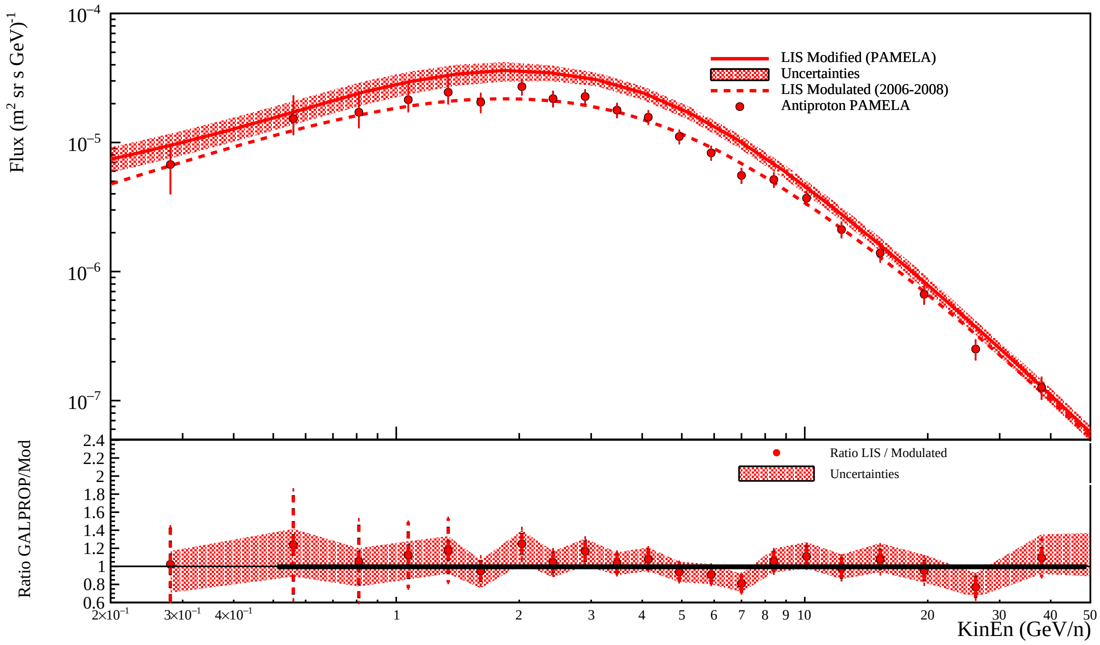

Figure 4: Top panel: the modified antiproton LIS (solid red line) in order to reproduce the PAMELA antiproton (red circles) when modulated with the proper solar condition activity. The red shadow is a systematics band which take into account for the statistics of the experimental data. Bottom panel: the ratio between the modulated spectra and the PAMELA data (red circles).

where the ratio between the modulated spectra and the PAMELA data is presented. The shaded area represents a 95% confidence level interval which takes into account the statistics of the experimental data.

The same procedure was applied to the BESS Polar II and AMS-02 data obtaining, from each data set, a LIS which reproduces the experimental data once is modulated with the proper solar activity conditions. Thus, in total, three antiproton LIS were obtained, with the corresponding systematics which account for the statistics of the data. For example the systematics associeted to the LIS obtained with the PAMELA data spans from 25% at the lowest energy, down to about 10% at energies around few GeV. The systematics related to the LIS obtained from the AMS-02 data spans from 5% in the middle energy range up to 10% at the highest energies.

3. Conclusion and perspectives

Cosmic-ray antiprotons are a promising channel to search excess due to e.g., dark-matter decay or annihilation. For example, a possible excess with respect to secondary production was claimed to be present in the AMS-02 data at energies around 10 GeV. This excess was taken into account introducing a signal from dark matter annihilation. However, this signal introduces a discrepancy between the model and the data at energies below 3 GeV, in an energy range that is heavily affected by the solar modulation. In this work, three antiproton LISs were derived in order to, when modulated with the proper solar activity conditions, reproduce the experimental data from PAMELA, BESS Polar II, and AMS-02 over their entire energy range. For this purpose, a state-of-art 3D solar modulation model was used. The model was calibrated on the proton spectra average over the same period of time of the antiproton data. A systematic uncertainties was derived for each LIS in order to take into account for the experimental uncertainties. Only the LIS obtained from the PAMELA data was showed, the complete results will be showed in a future publication.

The analysis will continu combining the three LIS to have an average LIS able to reproduce all the data. The systematics will also be combined. This will allow to obtain total uncertainties combining systematics from different experiments. The average LIS will be then compared with other (respect to GALPROP) up-to-date model for the production of secondary CRs in order to see if any excess (e.g., due to dark matter) are present.

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