SOLAR MODULATION OF GALACTIC COSMIC RAY ANTIPROTONS

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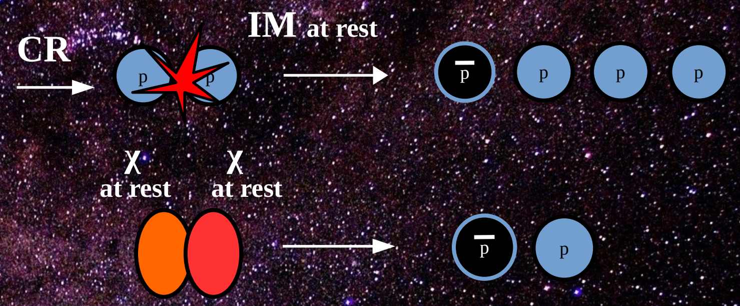
Indirect search of dark matter with antimatter in Cosmic Rays

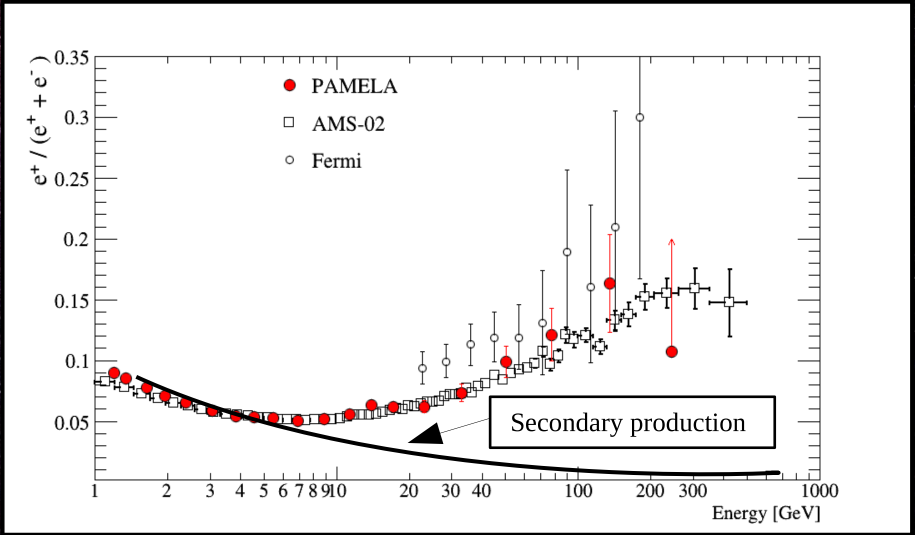
Antimatter in CRs is mainly produced by the interaction of primaries CRs with the interstellar medium (e+, antiP...).

Another antimatter source is belived to be annihilation or decay of Dark Matter (DM) in the galactic halo.

Other possible sources of antimatter in CRs are belived to be astrophysical object like pulsar (e.g. positron).

A precise knowledge of the Local Interstellar Spectrum (LIS) along with its uncertainties of the secondary CRs antimatter is essential in order to detect any excess due to e.g. DM annihilation.





Low energy antiproton excess?

Possible excess with respect to secondary production, energy range affected by solar modulation

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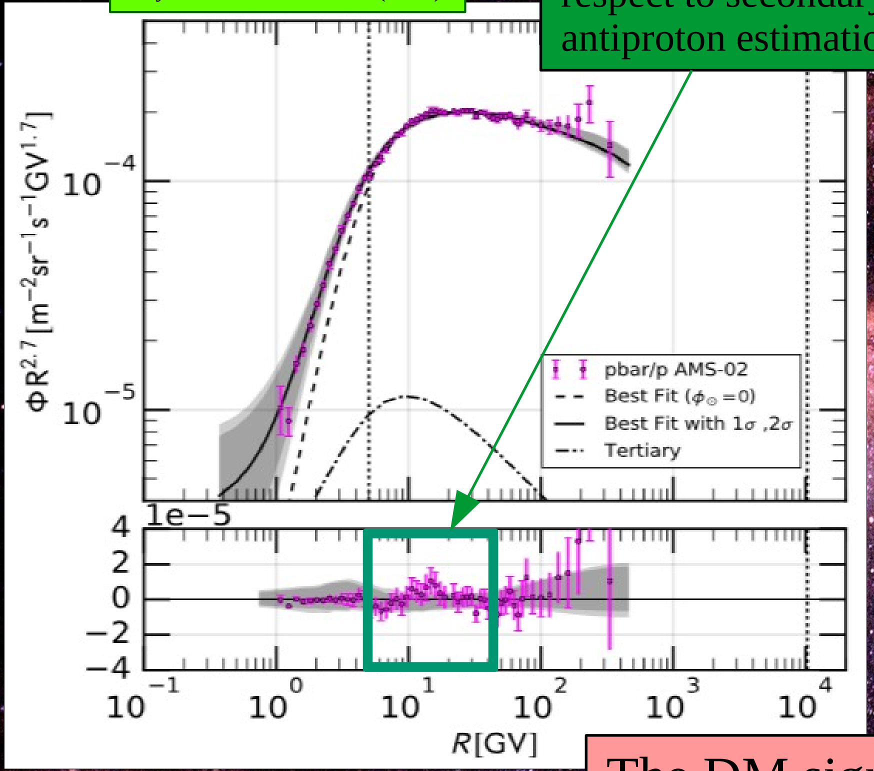
Possible excess with respect to secondary antiproton estimation.



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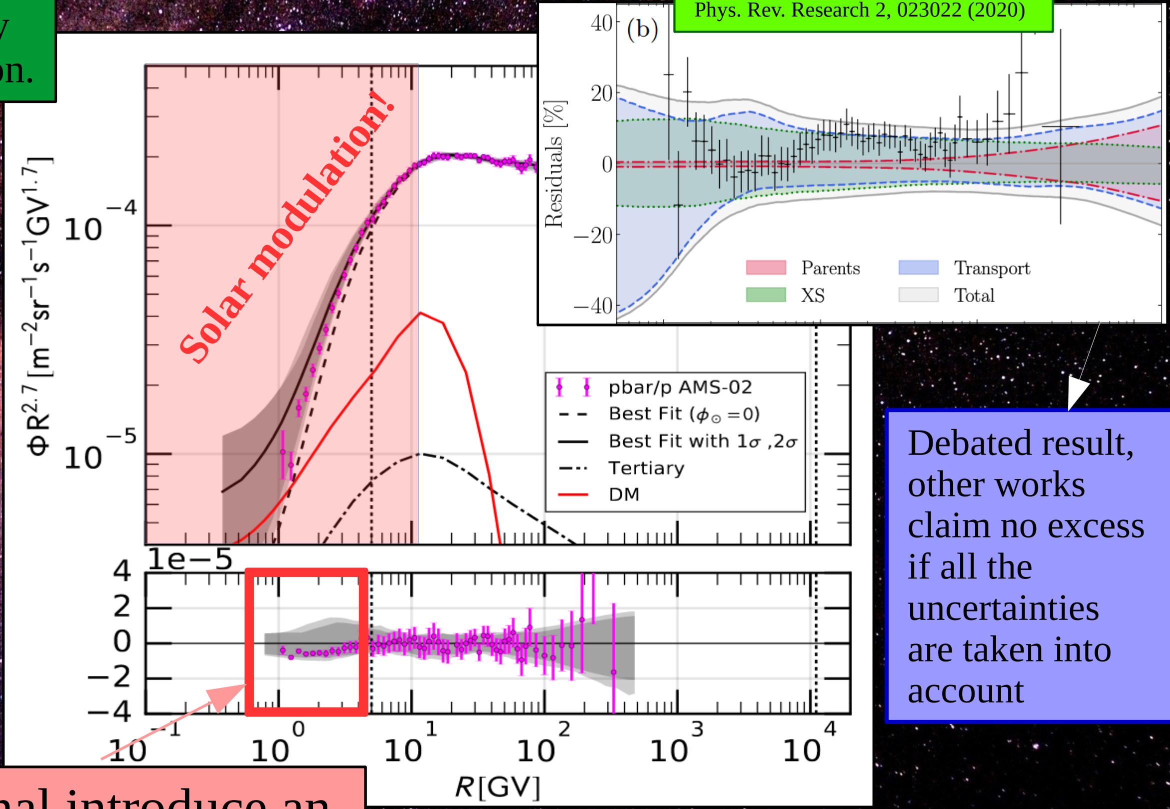
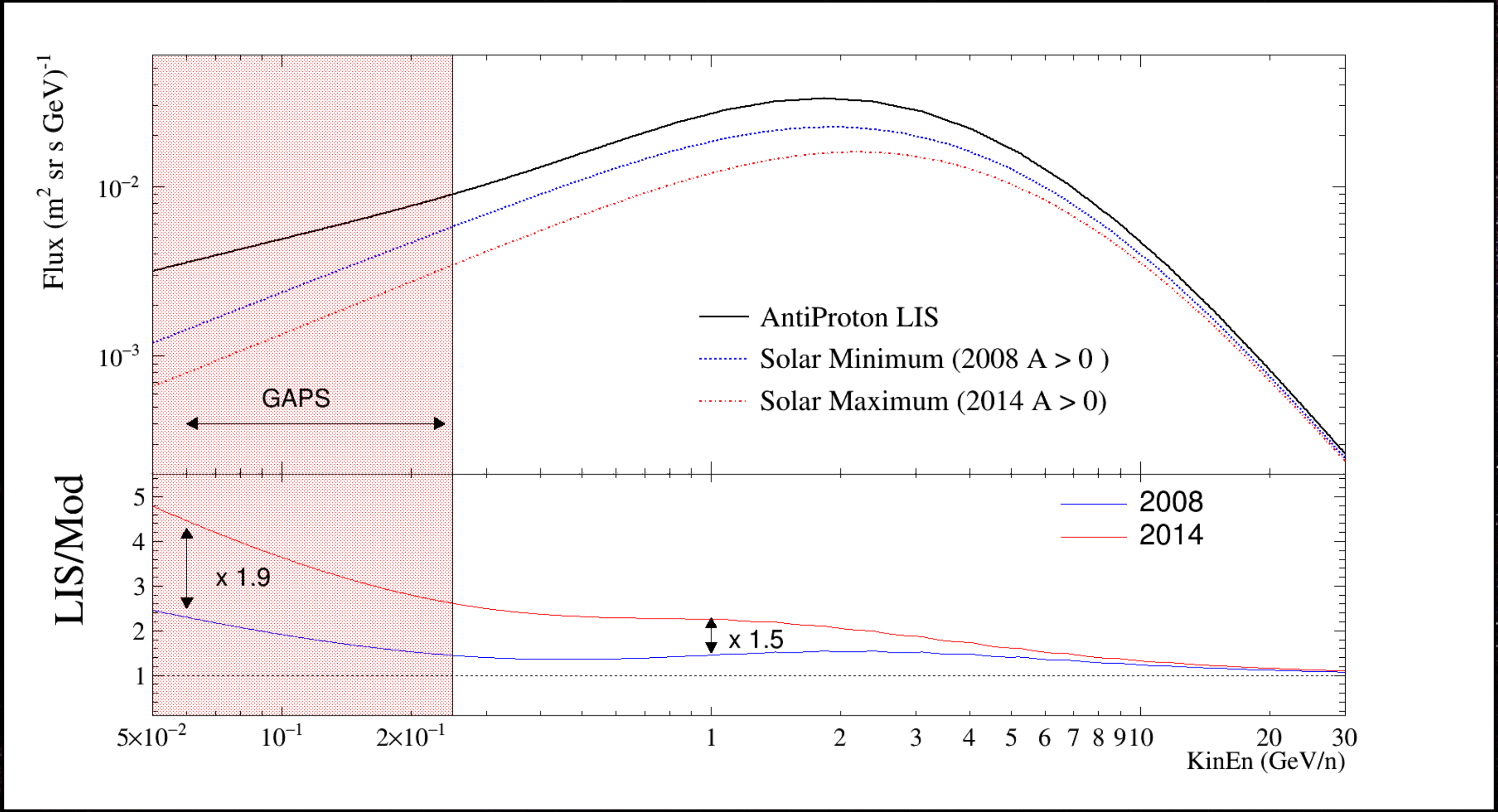


Debated result, other works claim no excess if all the uncertainties are taken into account

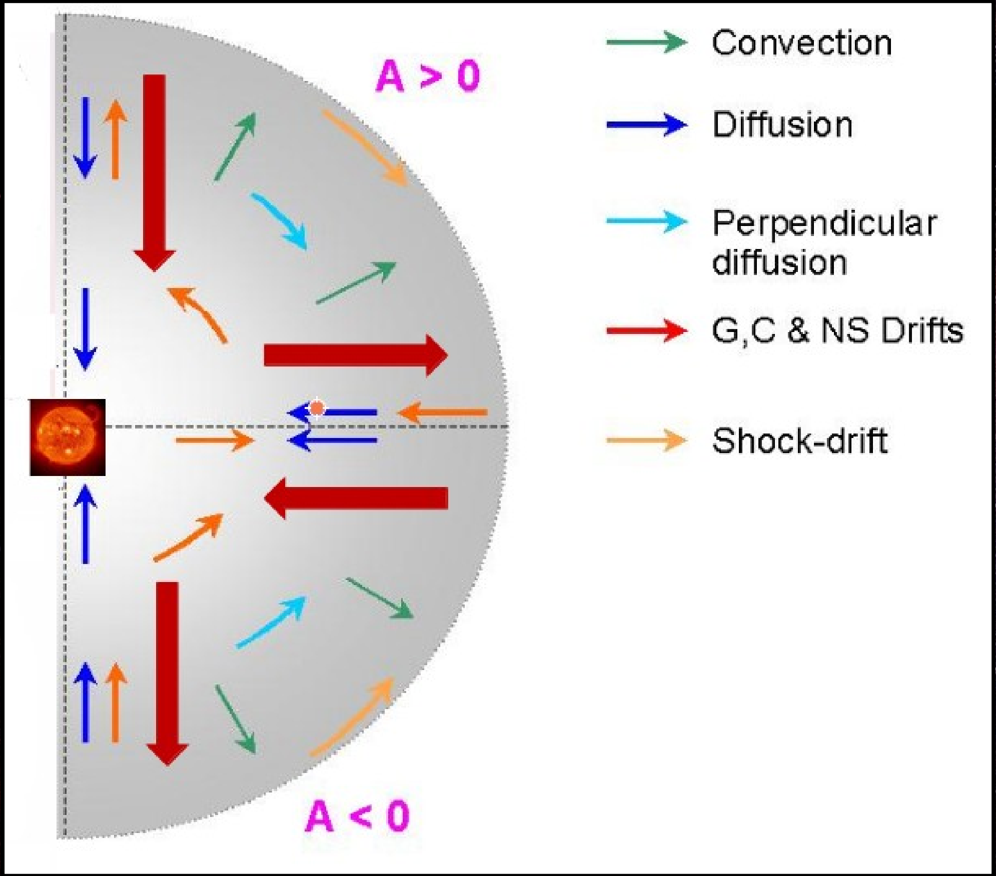
The DM signal introduce an issue at the lowest energies.

Solar modulation on the antiproton LIS



The antiproton modulation factor i.e. the ratio between the LIS and the modulated spectra during different phase of solar activity modulated with a 3D numerical model (see e.g., Aslam, O. P. M., ApJ, 873, 70).

CRs at Earth – the propagation trough the Heliosphere



Heliosphere: an ideal environment to test the theory of propagation of CRs under conditions which well approximate the cosmic condition.

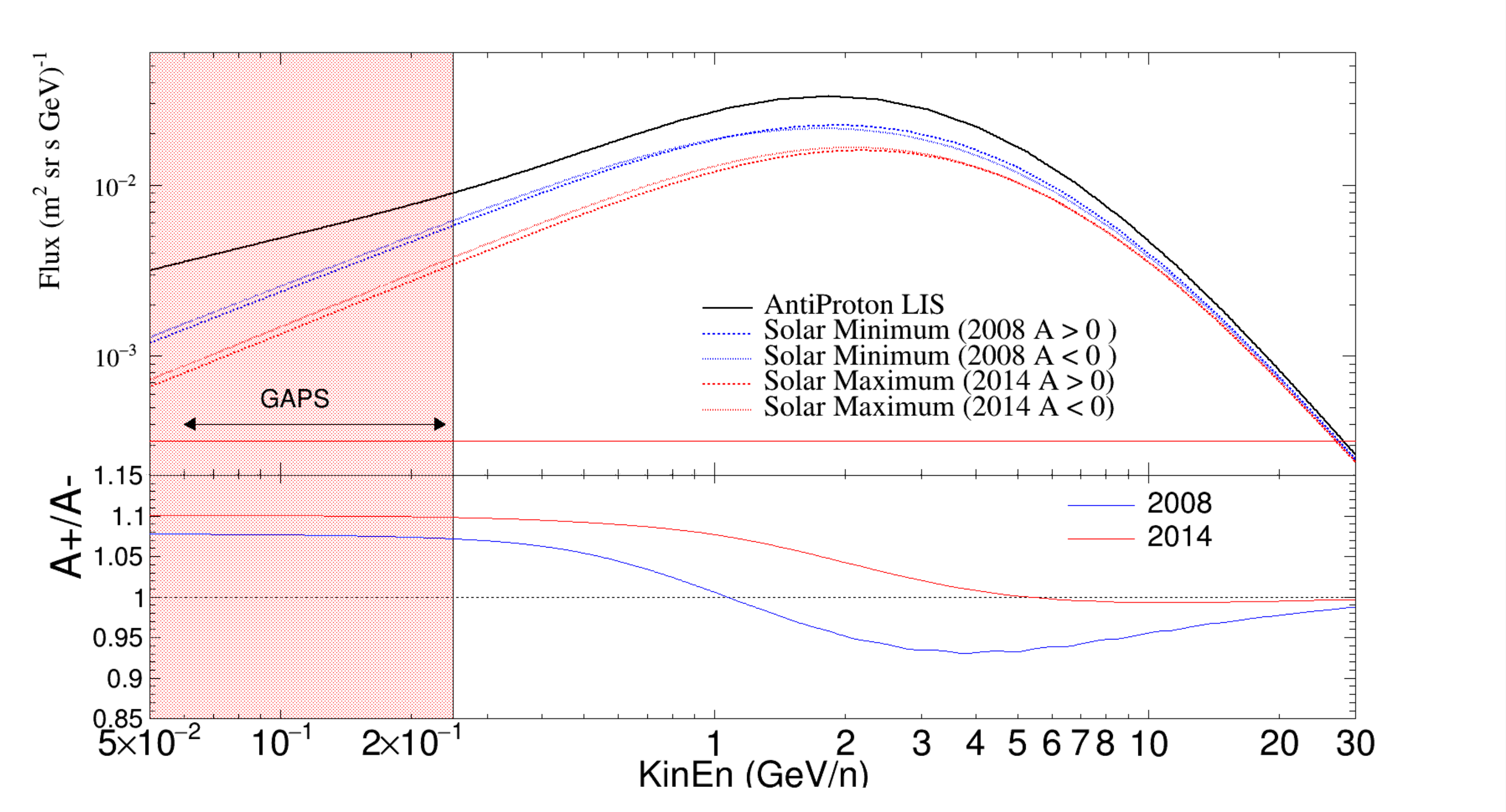
The Parker Equation

$$\underbrace{\frac{\partial f}{\partial t}}_{a} = -\underbrace{\mathbf{V}\cdot\nabla f}_{b} + \underbrace{\nabla\cdot(\mathbf{K_s}\cdot\nabla f)}_{c} - \underbrace{\langle \mathbf{v_D}\rangle\cdot\nabla f}_{d} + \underbrace{\frac{1}{3}(\nabla\cdot\mathbf{V})\frac{\partial f}{\partial \ln p}}_{e} + \underbrace{Q(\mathbf{x},p,t)}_{f}$$

(a) $f(\mathbf{x}, p, t)$, omnidirectional function distribution of CRs; **(b)** convection with solar wind $\mathbf{V}$; **(c)** diffusion by magnetic field irregularities; **(d)** drift, curvature and gradient in magnetic field; **(e)** adiabatic energy losses; **(f)** local sources (Jovian electrons);

With 3D numerical models for the CR propagation trough the Heliosphere that solves the Parker equation is possible to reproduce the measurements at Earth and fine tune the LIS of the different species

Solar modulation on the antiproton LIS

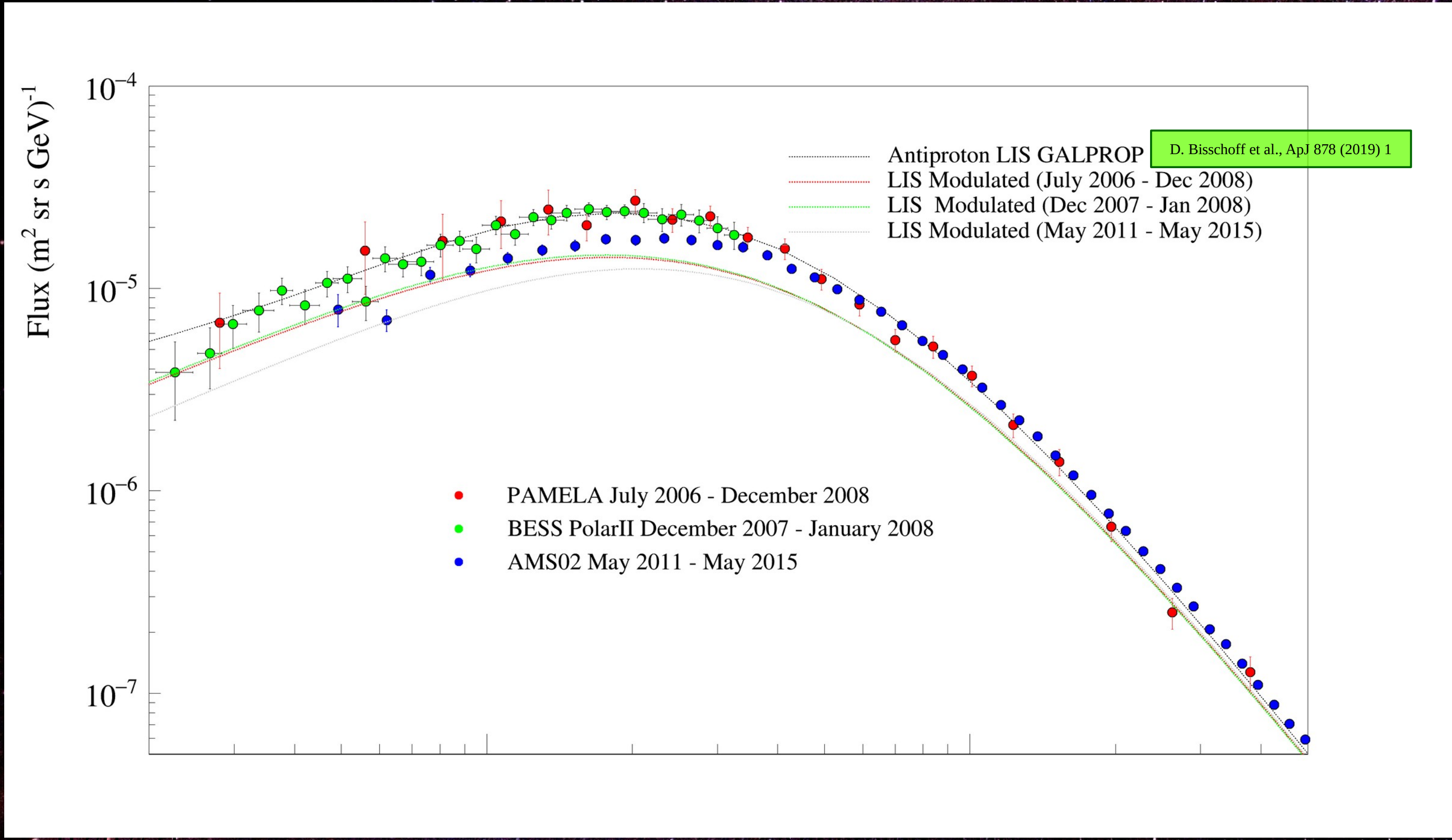


The effect of the charge sign dependece is of the order of 5-10% up to 10 GeV/n.

If a model like the force field approximation tuned on the proton spectra is used a systematics of 5-10% is introduced.

Modulation model need to take into account for all the mechanism in order to study antimatter.

Estimate antiproton LIS uncertaities due to solar modulation

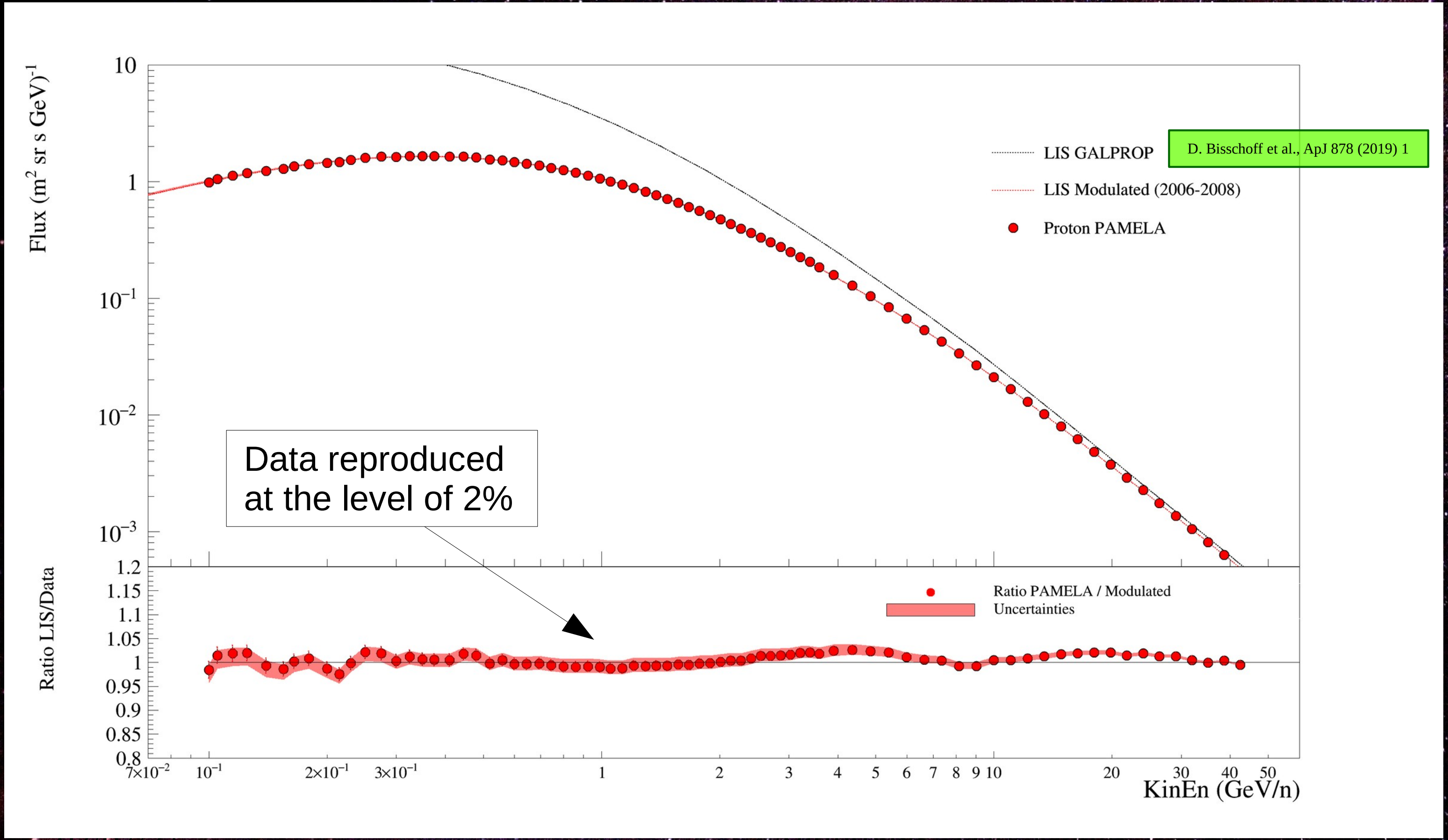


Final Goal

Estimate the best antiproton LIS and its uncertainties due to the solar modulation and the experimental data.

PAMELA, BESS PolarII and AMS02 antiproton data will be used to fine tune the antiproton Local Interstellar Spectrum obtained with GALPROP in order to reproduce, when modulated with a 3D numerical model tuned on the proton spectra, the measured antiproton spectra.

Proton modulation: model calibration PAMELA

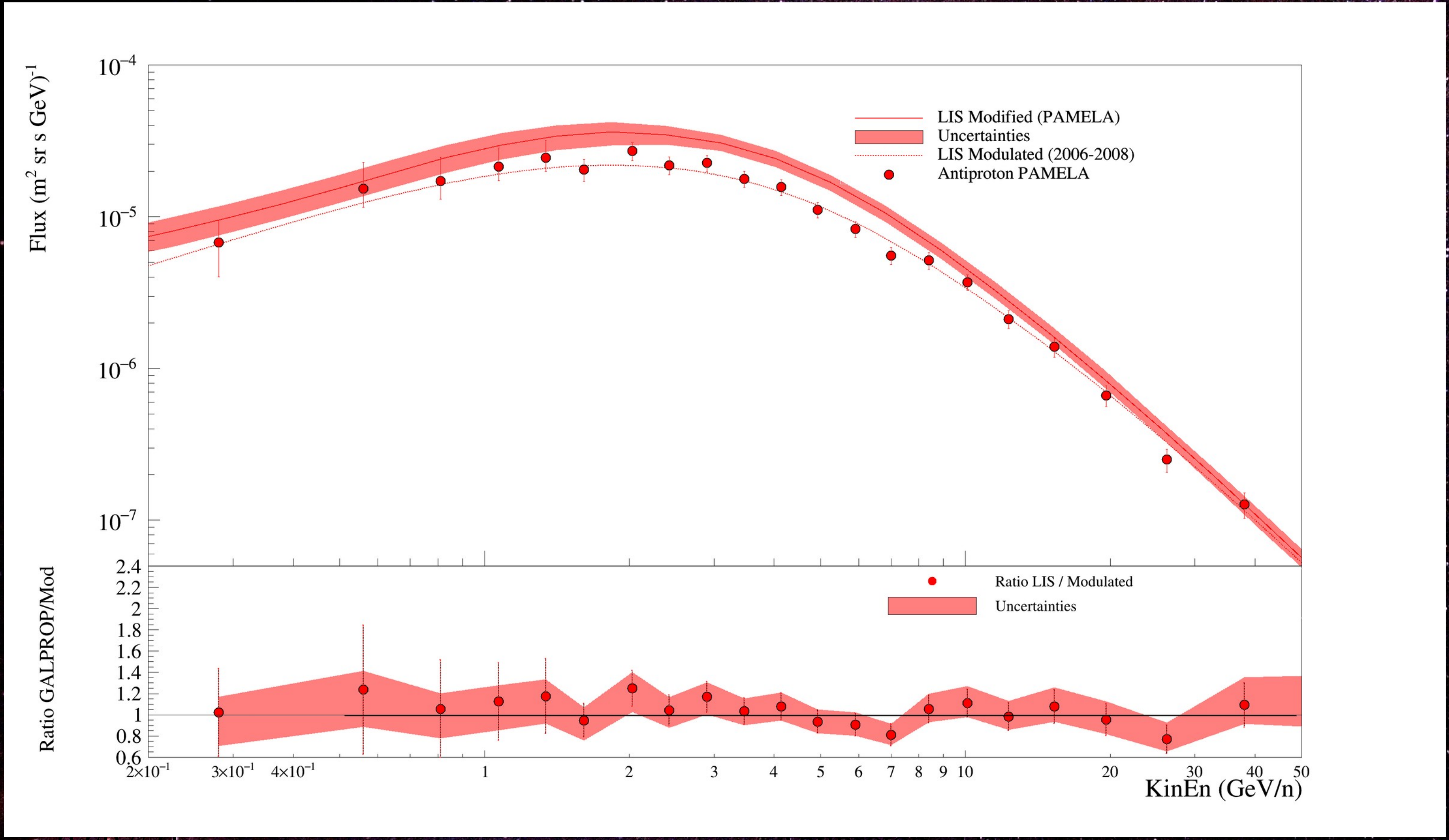


The published PAMELA proton data were averaged over the period July 2006 and December 2008.

The diffusion coefficients of the 3D numerical model were tuned in order to reproduce the PAMELA data (chi2 minimization).

The shaded area represent an estimated systematics which take into account for the experimental uncertainties.

Antiproton LIS to reproduce PAMELA data

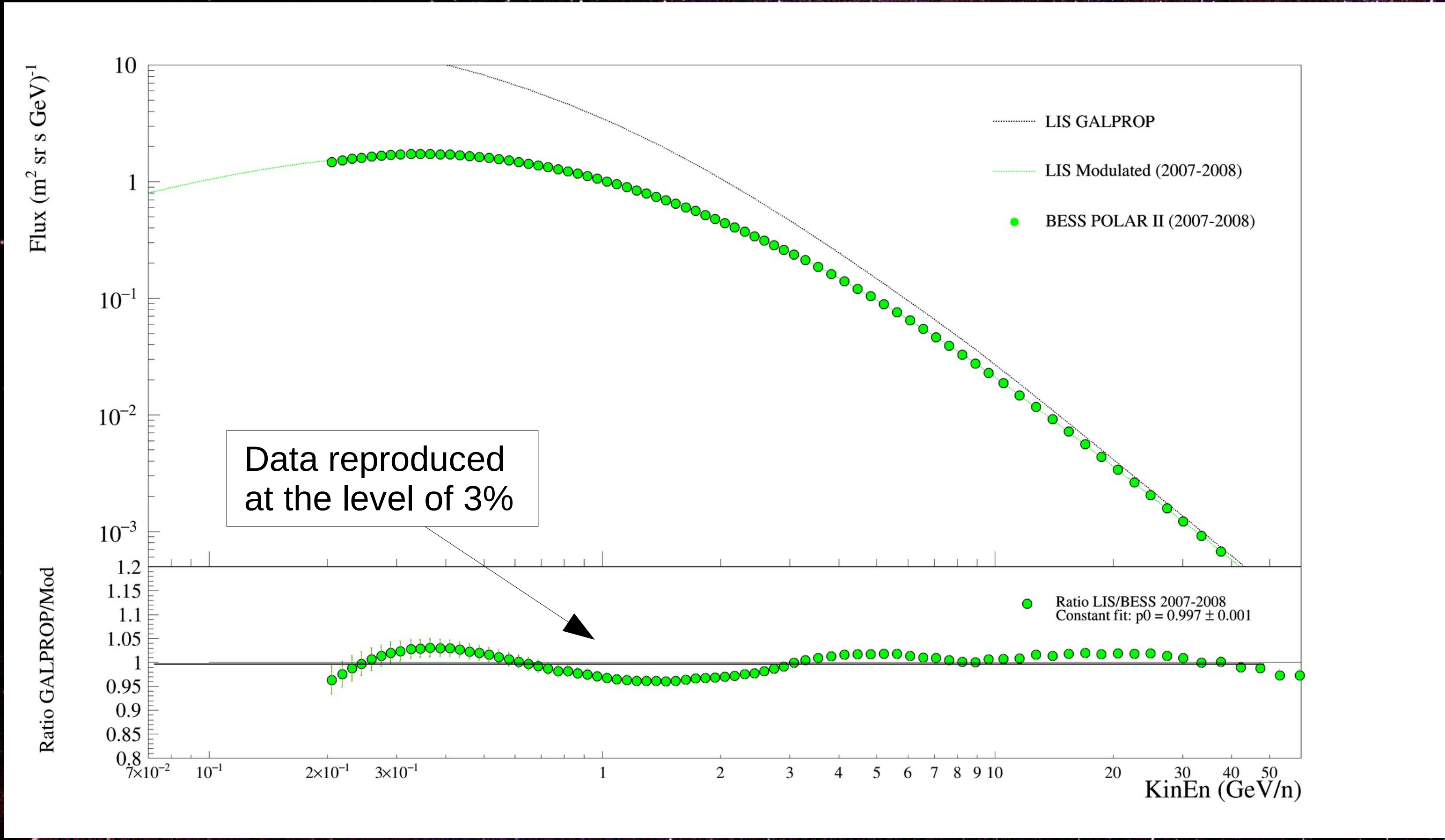


The GALPROP antiproton LIS has been modified in order to reproduce the experimental data when modulated with the parameters calibrated on the protons (opposite polarity of the HMF).

An uncertainties on the modified LIS was evaluated.

The LIS is lowered (increased) in order to obtain upper and lower limits which define a 95% confidence interval based on a chi2 calculation.

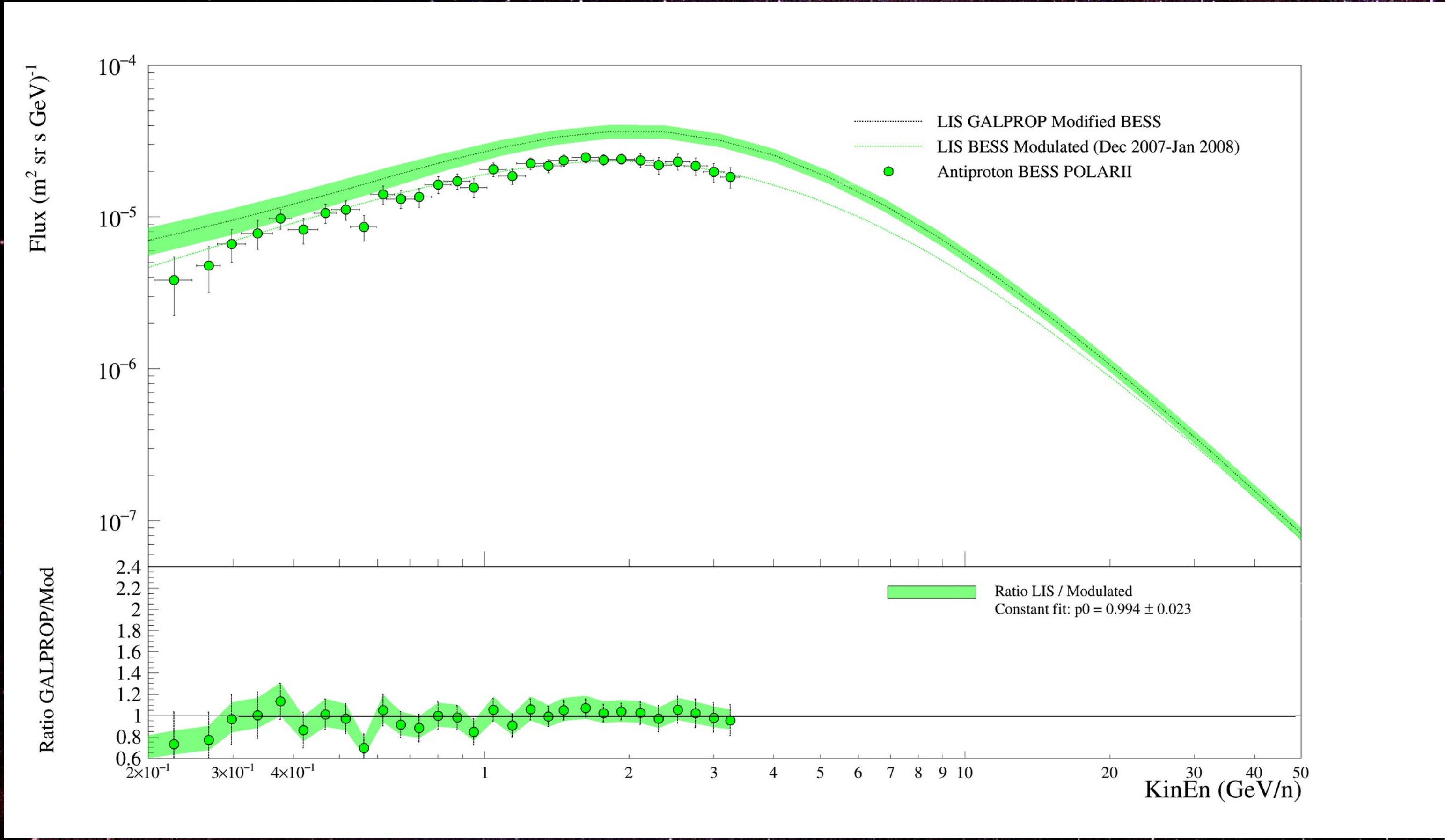
Proton modulation: model calibration BESS Polar II



The published BESS polar II data refers to the period from December 2007 to January 2008.

The diffusion coefficients of 3D numerical model were tuned in order to reproduce the experimental data.

Antiproton LIS to reproduce BESS Polar II data

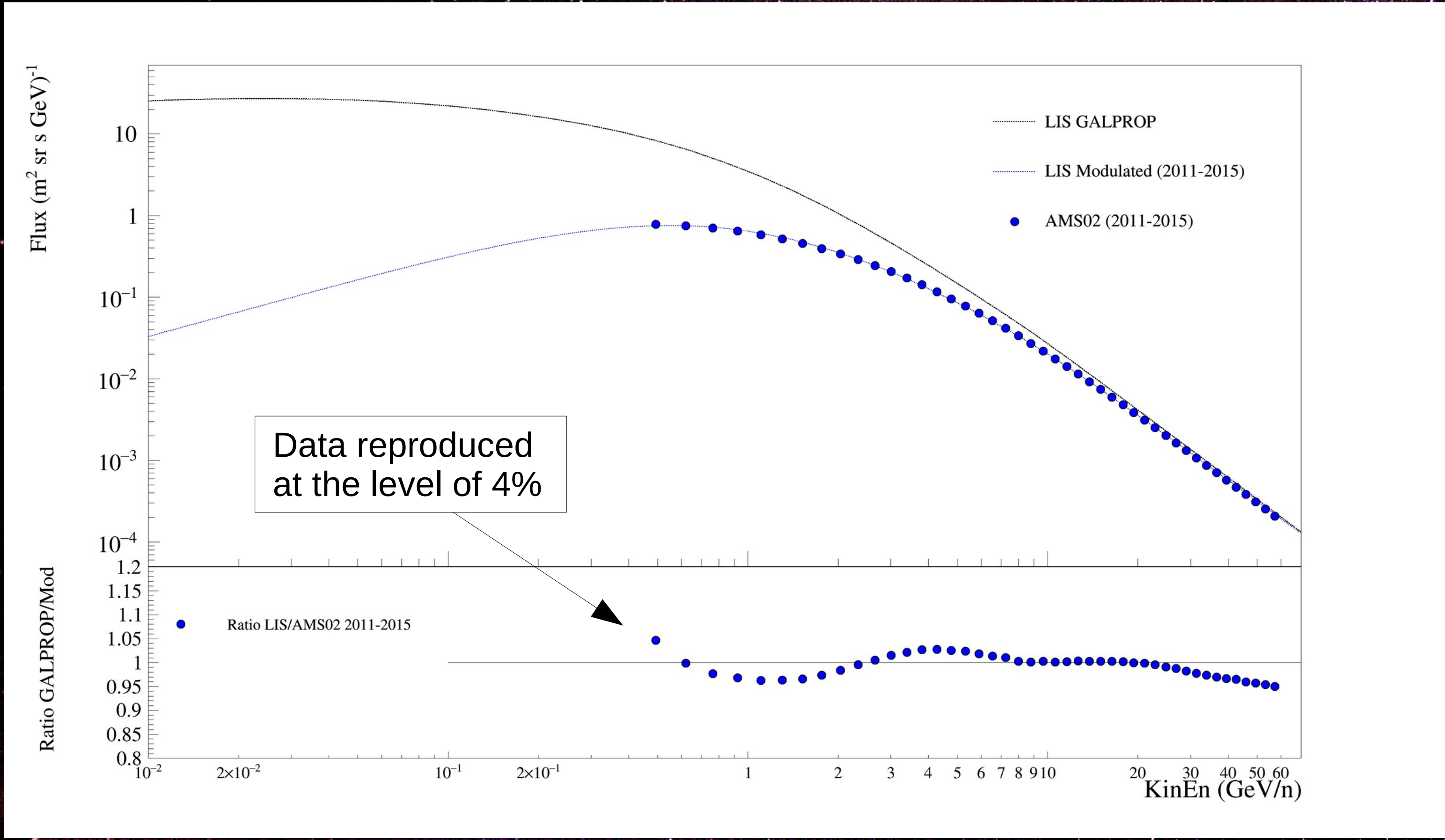


The GALPROP antiproton LIS was smoothly modified in order to reproduce, once modulated, the BESS Polar II data .

Below 2 GeV the BESS Polar II antiproton data has lower statistical with respect to PAMELA uncertainties which reflects in a smaller systematics for the LIS.

Since experimental data extend just up to 3 GeV above this energy the LIS cannot be re-defined.

Proton modulation: model calibration AMS-02

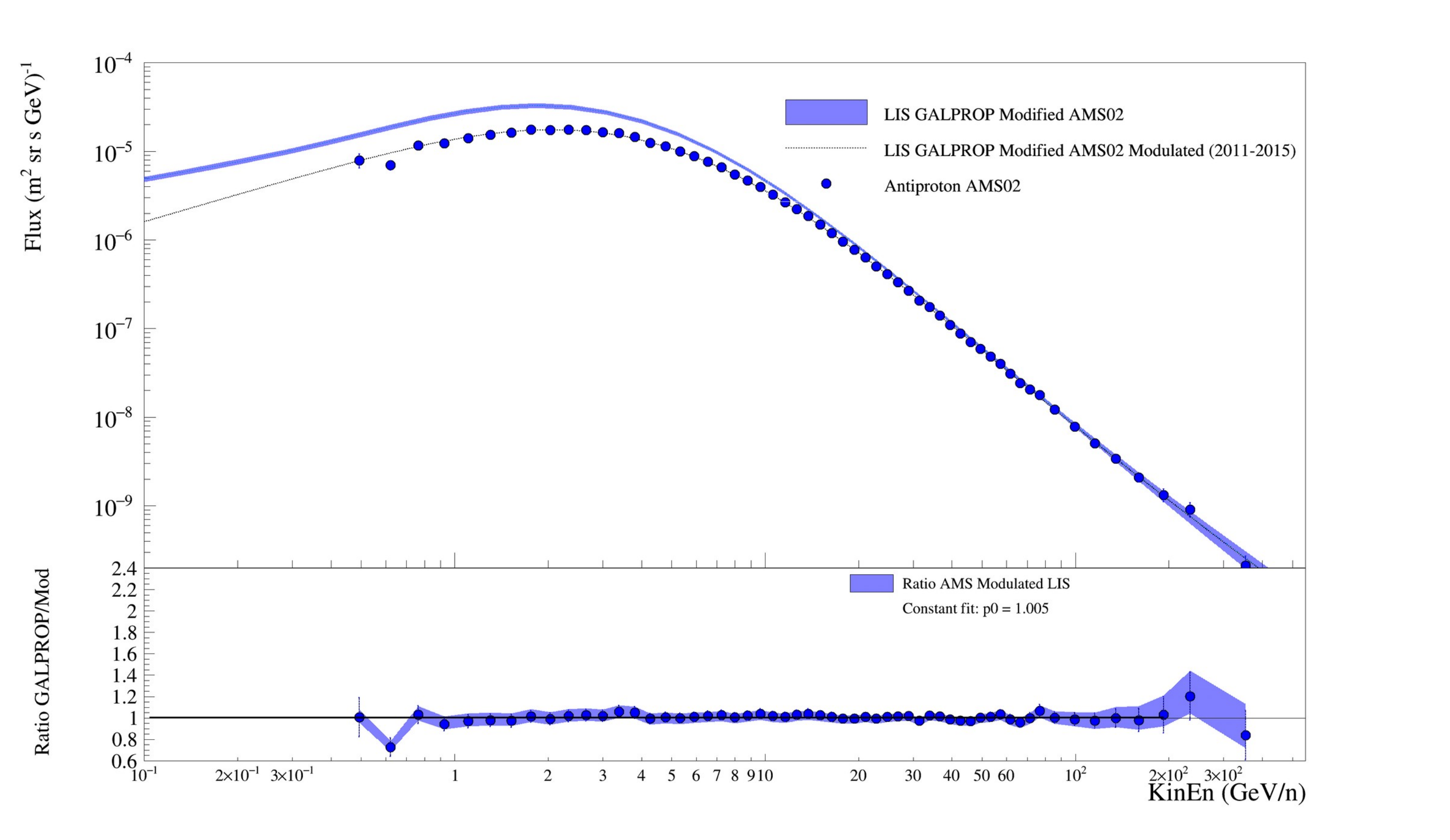


AMS-02 antiproton data extend over 4 years in a period of maxium solar activity and a polarity reversal of the HMF. Is more challenging to reproduce the appropriate solar activity conditions.

AMS-02 proton data were split into two dataset one for each HMF polarity and they were modulated separately.

Then the average spectra was considered.

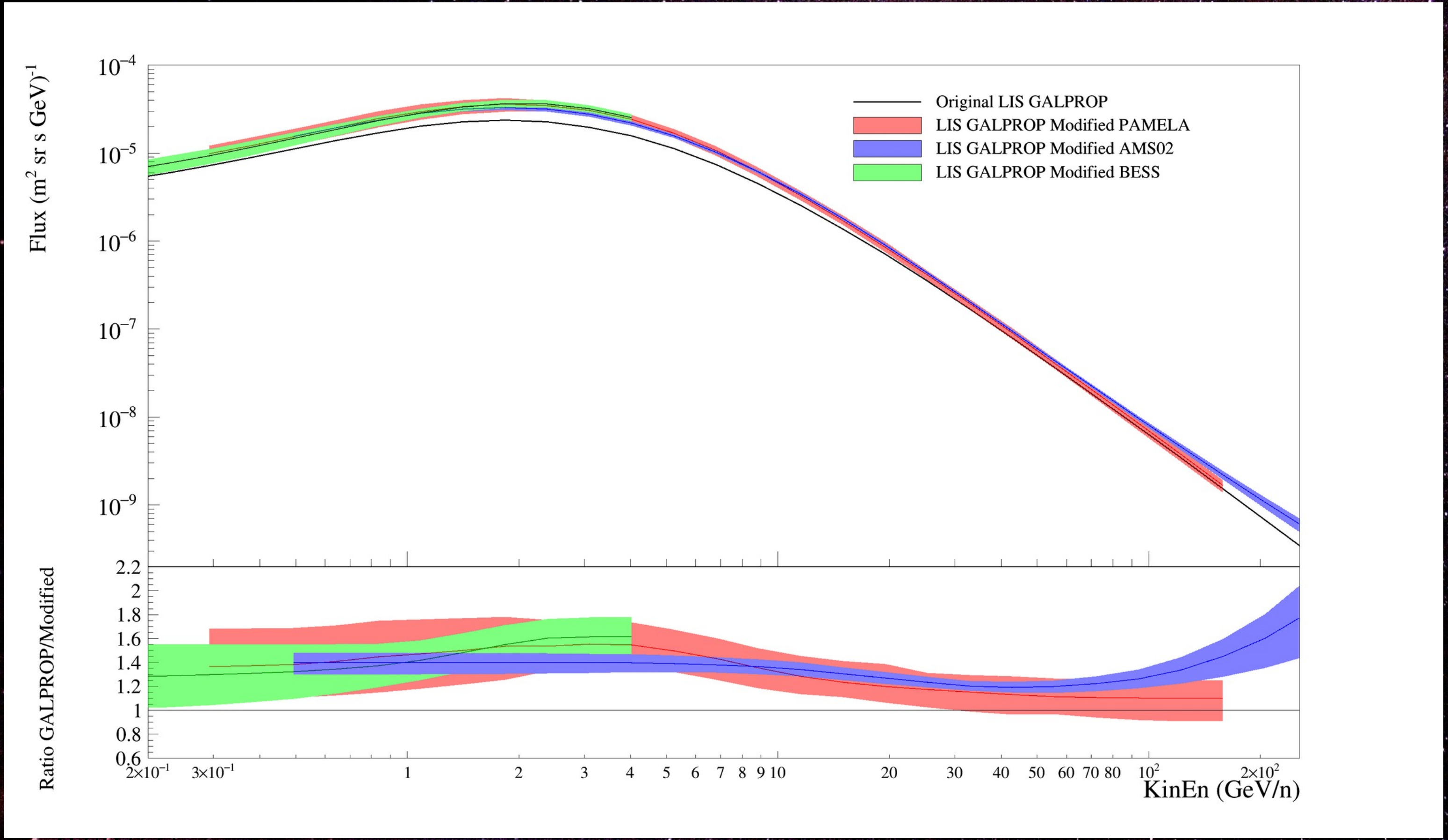
Antiproton LIS to reproduce AMS-02 data



The GALPROP antiproton LIS was smoothly modified in order to reproduce, once modulated, the AMS-02 data .

The associated uncertainties are much lower with respect to the PAMELA and BESS Polar II derived LIS due to the higher statistics.

Antiproton LIS to reproduce AMS-02 data



Comparison between the LIS derived from the antiproton measurements of PAMELA, BESS Polar II and AMS-02 and their associated uncertainties.

The lower panel represent the factor that was used to modified the original GALPROP antiproton LIS.

Conclusions

A 3D solar modulation numerical model for the CRs has been tuned to reproduce the solar activity conditions corresponding to the antiproton data set of PAMELA, BESS Polar II, and AMS-02.

An estimation of the uncertainties related to the solar modulation model has been performed obtaining maximum systematics of about 3-4 % at the lowest energies.

For each antiproton data set a LIS was obtained to reproduce, when modulated, the experimental data.

Systematics on the modified LISs were estimated to take into account for the experimental uncertainties.

The proton data are reproduced at the level of 2%

Perspectives

Combine the modified LISs and their uncertainties in order to obtain global uncertainties which take into accounts for the possible systematics between different data set.

Compare the LIS which best reproduce the experimental data set with models for secondary antiproton spectra and see if excess are present compatible with e.g., dark matter annihilation.