Addressing the Impact of Solar Modulation Systematic Uncertainties on Cosmic-Ray Propagation Models

Isabelle John*, Alessandro Cuoco
*isabelle.john@unito.it

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Abstract

While remarkable progress has been made to understand the propagation of cosmic rays, a variety of astrophysical uncertainties persists. At energies below about 40 GeV, the cosmic-ray flux is significantly modulated by solar activity, a process that is not precisely understood. Using the recently published AMS-02 data for the time-dependent cosmic-ray fluxes, we study the effects of solar modulation using force-field and extended force-field models and derive improved cosmic-ray propagation models. We find that simple solar modulation models are likely to underestimate the complexity of comic-ray propagation in the solar system and present limitations in describing the time-dependent fluxes consistently.

Solar Modulation

A combination of the solar magnetic field and solar winds strongly suppresses the local cosmic-ray flux below about 40 GV compared to the flux in the local interstellar medium (LIS flux). Solar activity varies over the Sun's 11-year cycle, reaching its maximum during the reversal of its magnetic field polarity. This change in the intensity of solar activity introduces a time-dependence in the local cosmic-ray fluxes.

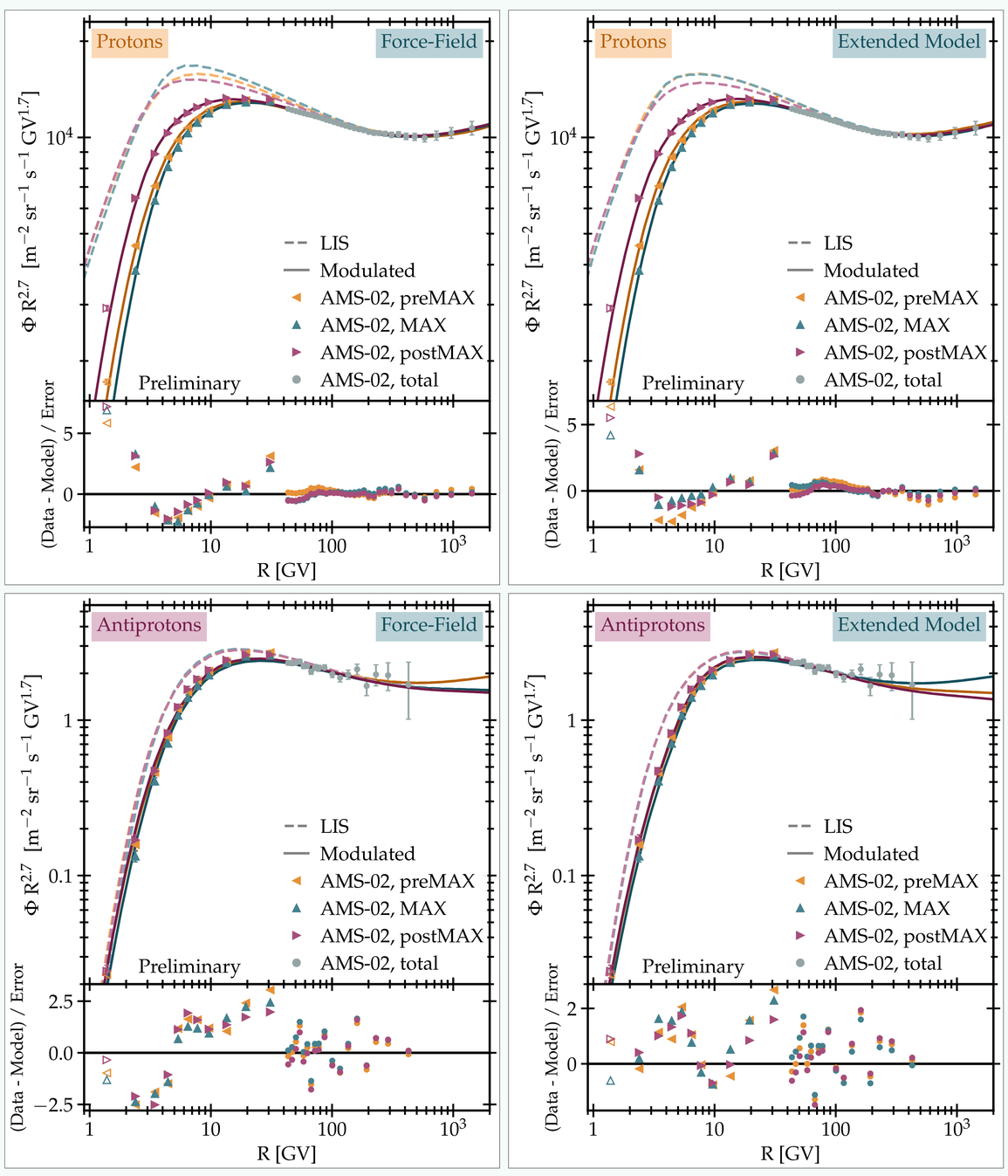
Cosmic-Ray Data

Recently, AMS-02 has published time-dependent cosmic-ray data for protons, antiprotons and many cosmic-ray nuclei over a full solar cycle [1, 2]. Crucially, AMS-02 provides the time-dependent data for antiprotons, which, due to their negative charge, are affected differently by solar modulation than other nuclei. The high statistical precision of the data allows for a detailed study of the dependence of the cosmic-ray fluxes on solar activity during the different phases of solar cycle. We define and study 3 periods, labelled as `preMAX`, `MAX` and `postMAX`.

Cosmic-Ray Modelling

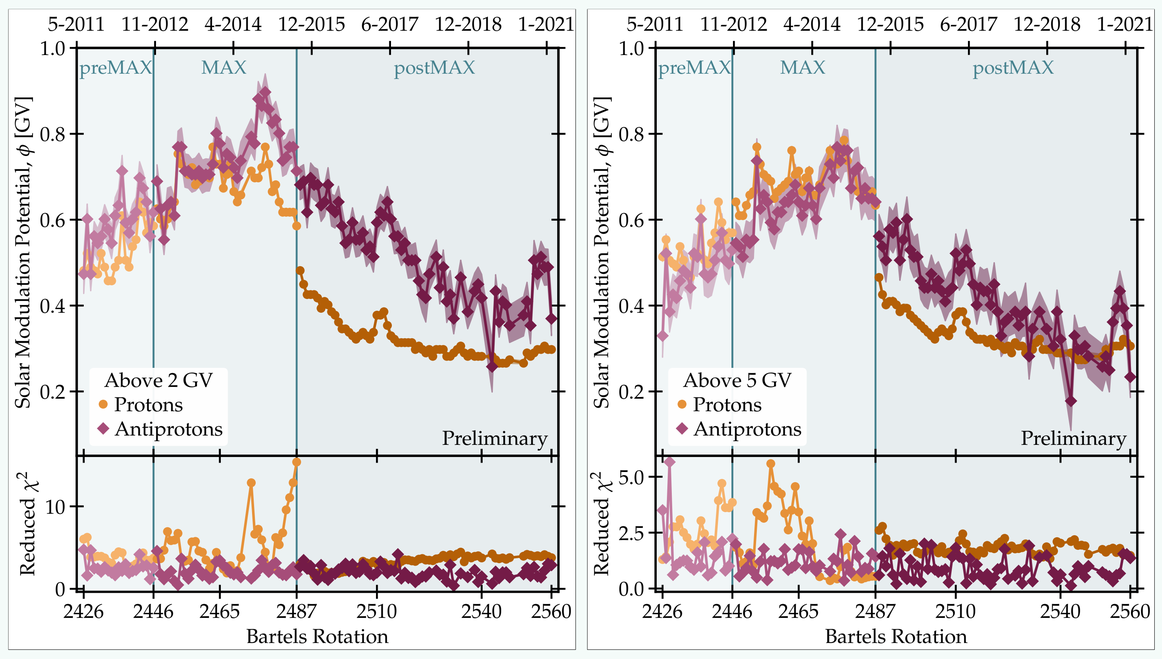
We build our analysis on the framework in [3], using the cosmic-ray propagation code GALPROP. To study the impact of solar modulation, we use two different models: the simple and widely used force-field potential [4] and an extended force-field potential [5] with a rigidity dependence of the solar modulation potential.

Cosmic-Ray Proton and Antiproton Fluxes



The Figures show the cosmic-ray fluxes from our fits for protons and antiprotons, for the force-field potential and extended model. The LIS (dashed) and modulated (solid) fluxes and AMS-02 data are given for the `preMAX`, `MAX` and `postMAX` periods in orange, blue and burgundy. For both solar modulation models, the proton LIS fluxes display some differences. This points towards inconsistencies and difficulties at reconciling solar modulation, as all three LIS should be exactly the same and uneffected by solar activity. This means that the derived solar modulation potentials and underlying propagation models include some additional systematic uncertainties. The discrepancies in the force-field model are larger than in the extended model, indicating that the additional degrees of freedom in the extended model may be able to address some of these uncertainties.

Solar Modulation Potential Over Time



The Figures show the change in the solar modulation potential over time for the force-field model. Protons are shown in orange circle and and antiprotons in burgundy diamond markers. The shaded bands indicate the 1σ uncertainty. In each of the 3 periods, we use the LIS obtained from the fit to the time-dependent AMS-02 data of that period. In the left panel, the modulation potential is calculated over the full range of rigidities chosen in the fitting procedure, starting from 2 GV. In the right panel, the modulation potential only includes rigidities above 5 GV, as suggested by the extended solar modulation model. While for protons the modulation potential is roughly consistent in both rigidity cuts, the potential for antiprotons is lower by about 15 – 20% for rigidities above 5 GV. This may indicate that the force-field potential describes solar modulation relatively well for protons and nuclei while a more complex treatment of solar modulation may be required specifically for antiprotons.

Conclusions

Throughout our analysis we find that a simple description of solar modulation by a force-field potential, or even modified force-field potential with additional parameters, has difficulties in capturing the complexity of solar modulation and in building a coherent picture. Additional analysis is needed to gain a more in-depth understanding of these crucial systematic uncertainties, and to disentangle the impact of solar modulation on the local cosmic-ray fluxes from other processes, such as re-acceleration or solar system specific diffusion, which shape the low-energy tail of the flux.

References

[1] PRL 134, 051002 (2025)
[2] PRL 134, 051001 (2025)
[3] PRD 109, 123003
[4] ApJ 154, 1011 (1968)
[5] ApJ. 975, 270 (2024)