The role of cosmic ray propagation in constraining astrophysical and dark matter sources

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AMS-02 CR data

Golden Age for Cosmic Rays: PAMELA and AMS02 providing high quality data. CR precision era is finally starting.

Very precise measurements from AMS02 of antiproton up to ~400 GV, and positrons up to ~800 GV.
AMS-02 Positron faction and B/C

B/C measured up to ~TV
Detailed inference of the CR propagation properties possible

Positron fraction up to ~800 GV.
Rising positron fraction providing evidence for primary sources of positrons, or secondaries from a very close (< 1kpc) SNR (Shaviv et al. PRL 2009)
Summary of Positron interpretation

A reasonable fit for DM can be found using a combination of different channels. Pulsars give a similar good fit.

But DM interpretation is strongly constrained by gamma-ray observations of dwarfs galaxies, and the Milky Way Halo, as well as CMB constraints.
CR ‘Anomalies’

- Unexpected difference in the slope of proton and Helium
- Unexpected break at ~300 GV
Cosmic-Ray Propagation

\[
\frac{d\psi}{dt} = q(x, p) + \nabla \cdot (D_{xx} \nabla \psi - V \psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi \\
- \frac{\partial}{\partial p} \left( \frac{dp}{dt} \psi - \frac{p}{3} \nabla \cdot V \psi \right) - \frac{1}{\tau_f} \psi - \frac{1}{\tau_r} \psi
\]

Diffusion equation is typically solved fully numerically with GALPROP or Dragon, or semi-analytically with Usine.
Sources

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Astrophysical Sources:
  • SNR or Pulsars
  ➢ Primary CRs: \( p, \text{He}, C, \ldots \)

Interaction with ISM:
  • Fragmentation or production
  ➢ Secondary CRs: \( \bar{p}, \text{Li}, B, \ldots \)
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- SNR or Pulsars
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**Possible Scenario:**
- WIMP DM?

**Annihilation of DM:**
- Production of antimatter in the particle shower
  - **DM CRs:** \( \bar{p}, (e^+) \)
Fit Parameters

- Injection spectrum (index p for protons)
  \( X_1, X_{1,p} \)
  \( X_2, X_{2,p} \)
  \( R_0 \)
  \( s \)
- Diffusion constant
  \( \delta \)
  \( D_0 \)
- Reacceleration
  \( v_{\text{Alfven}} \)
- Convection
  \( v_{0,\text{conv}} \)
- Halo size
  \( z_h \)

Complicate parameter space to explore. Monte Carlo methods are becoming the standard to perform this multi-dimensional scan and derive constraints on the parameters.

With DM additional fit parameters:
- \( m_{\text{DM}} \)
- \( \langle \sigma v \rangle \)
CR fit with AMS02 p, He and anti-p

Fit above 5GV to reduce the impact of Solar modulation effects.

Korsmeier, Cuoco, PRD 2016
Cuoco, Korsmeier, Kramer 2016 Arxiv:1610.03071
Scan is performed with MultiNest. The interpretation is in the frequentist approach.

The fit constraints not only DM but also the CR propagation scenario, providing a self consistent DM+CR joint fit.
Full Triangle Plot

- Overview of the full 13(!) parameters correlation matrix
δ is very well constrained (even within the shift caused by DM):

- In comparison MIN/MED/MAX had δ = 0.85/0.70/0.46 (!!)

Zh is not well constrained (expected since Be10/Be9 data are needed). Main uncertainty in the DM normalization (large halo more DM anti-p, small halo less DM anti-p)
CR Results

- Yuan et al., arXiv: 1701.06149, scan different propagation setups using B/C. Results are generally consistent with anti-p
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Uncertainties in the anti-p production cross section are at the level of 20–30%.

Similar uncertainties for B production cross-section.

Uncertain cross-section are at the moment one of the main challenges for a correct interpretation of AMS data.

New precise cross-section measurement are required.

Same propagation model, different anti-p production cross-sections, Lin et al., arXiv:1612.04001
Antiprotons DM limits

Until now, DM constraints from antiprotons have suffered large uncertainties due to the unknowns in the CR propagation scenario.

The precise AMS02 data allow to tackle also this issue.
Recent works on DM constraints from AMS02 use old propagation models like MIN/MED/MAX.
DM improves the fit quality by ~4.5σ! ($\Delta X^2 \sim 25$ for 2 d.o.f.)

It can be seen that the improvement in the fit is mainly due to a feature at ~18 GV, which DM is able to fit well thanks to its spectrum with a sharp cutoff.

Cuoco, Korsmeier, Kramer 2016 Arxiv:1610.03071
DM preferred region (at 1-2-3 sigma C.L.) can be derived, fully marginalized over the CR propagation parameters.

Interestingly the DM preferred region is well compatible with the Galactic center gamma-ray excess.

A difficult systematic uncertainty to estimate is the anti-p production cross-section. We tested 2 different models, and they give similar results, but other models are possible.

M. di Mauro, F. Donato, A. Goudelis, and P. D. Serpico, PRD90, 085017 (2014),
R. Kappl and M. W. Winkler, JCAP 1409, 051 (2014)
Marginalized DM limits

- Stringent DM limits outside the range in which a DM signal is preferred
- The band is the envelope of the systematic uncertainties
- Limits better than gamma-ray dwarfs by a factor of ~4-5
- Mild tension with dwarfs limits, but it got relieved with the latest dwarf limits

Cuoco, Korsmeier, Kramer 2016 Arxiv:1610.03071
Outlook

• Official AMS-02 data for Li, C, B/C, and more are on the way.
• Important to cross-check present results vs anti-p predictions from B/C fits.

• Improvement on systematic uncertainties
  • New cross section measurements by LHCb
    \[ p + \text{He} \rightarrow \bar{p} + X \]
  • Study of solar modulation with time-dependent AMS-02 fluxes
Backup
Indirect Detection of Dark Matter: the General Framework

1) WIMP Annihilation Typical final states include heavy fermions, gauge or Higgs bosons

2) Fragmentation/Decay Annihilation products decay and/or fragment into some combination of electrons, protons, deuterium, neutrinos and gamma rays

\[ \chi \chi \rightarrow W^+ W^- e^- \nu \text{ or } \pi \gamma \]
Other systematics and DM limits

- Results are stable vs various systematics as:
  - Different DM profiles
  - Imposing zero convection
  - Different model of anti-p production cross-section

- Fixing different \( z_h \) (2kpc and 7 kpc) shift the DM normalization by a factor 2-3, as expected

- Only anomaly is the ‘disappearance’ of the DM signal when fitting data down to 1 GV
- The ~18 GV feature remains when fitting to 1 GV: DM cannot fit because data below 5 GV are over-predicted.

- It could be likely accommodated within the uncertainties of the solar modulation. It requires a dedicated study (and possibly time dependent measured spectra)
Fit $W^+W^-$
Fit various channels(1)
Fit various channels(2)
Combined GCE-CR fit
“Linear” Parameters

Marginalize these parameter for each evaluation point:

- Normalization of p, He
- Solar modulation potential

Step 1: Adjust normalization
Step 2: Adjust solar modulation
Solar Modulation

- Phenomenological description: force-field approximation

Our novel approach:

- Constrain LIS flux by VOYAGER data
- Exclude data below 5 GV in the main fit
- Solar modulation potential is a “linear” parameter: marginalized for each GALPROP evaluation

\[
E = E_{\text{LIS}} - |Z|e\phi,
\]

\[
\Phi_E(E) = \frac{E^2 - m^2}{E_{\text{LIS}}^2 - m^2} \Phi_{E,\text{LIS}}(E_{\text{LIS}})
\]

\[R^2.7\text{ Flux} \]

LIS flux fitted to VOYAGER
Modulated flux fitted to AMS
### Chi2 values

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Fit without DM</th>
<th>Standard fit with DM</th>
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<tbody>
<tr>
<td></td>
<td>$\chi^2$ (Number of data points)</td>
<td></td>
</tr>
<tr>
<td>Proton (AMS-02)</td>
<td>9.6 (61)</td>
<td>6.2 (61)</td>
</tr>
<tr>
<td>Proton (VOYAGER)</td>
<td>1.8 (4)</td>
<td>0.4 (4)</td>
</tr>
<tr>
<td>Helium (AMS-02)</td>
<td>30.8 (65)</td>
<td>24.8 (65)</td>
</tr>
<tr>
<td>Helium (VOYAGER)</td>
<td>2.3 (4)</td>
<td>1.6 (4)</td>
</tr>
<tr>
<td>$\bar{p}/p$ (AMS-02)</td>
<td>26.6 (42)</td>
<td>12.6 (42)</td>
</tr>
<tr>
<td>Total</td>
<td>71.0 (176)</td>
<td>45.6 (176)</td>
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