Antiproton production cross sections and the search for dark matter

Fiorenza Donato
Torino University & INFN

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Primary and secondary cosmic rays in the Galaxy

**Primaries:** produced in the sources (SNR and Pulsars)
- H, He, CNO, Fe; e-, e+
- Possibly e+, p-, d- from Dark Matter annihilation

**Secondaries:** produced by spallation of primary CRs (p, He,C, O, Fe)
on the interstellar medium (ISM)
- LiBeB, sub-Fe; e+, p-, d-

All primary and secondary species propagate in the Galaxy, dominated by diffusion on the magnetic fields and/or by intense energy losses (leptons)
**Primaries** = present in sources:
Nuclei: H, He, CNO, Fe; e-, (e+) in SNR (& pulsars)
e⁺, p⁺, d⁺ from Dark Matter annihilation

**Secondaries** = NOT present in sources, thus produced by
*spallation* of primary CRs (p, He, C, O, Fe) on ISM
Nuclei: LiBeB, sub-Fe, ... ;
e⁺, p⁺, d⁺; ... from inelastic scatterings
Production cross sections in the galactic cosmic ray modeling

H, He, C, O, Fe,... are present in the supernova remnant surroundings, and directly accelerated into the interstellar medium (ISM)

All the other nuclei (Li, Be, B, p-, and e+, gamma, ...) are produced by spallation of heavier nuclei with the atoms (H, He) of the ISM

We need all the cross sections $\sigma^{kj}$ - from Nichel down to proton - for the production of the j-particle from the heavier k-nucleus scattering off the H and He of the ISM

Remarkable for DARK MATTER signals is productions of: antiproton, antideuteron, positron and gamma rays.
Indirect DARK MATTER searches

Dark matter can annihilate in pairs with standard model final states. Low background expected for cosmic ANTIMATTER, and for NEUTRINOS and GAMMA RAYS coming from dense DM sites.
WIMP INDIRECT SIGNALS

Annihilation inside celestial bodies (Sun, Earth):

➢ \( \nu \) at neutrino telescopes as up-going muons

Annihilation in the galactic halo:

➢ \( \gamma \)-rays (diffuse, monochromatic line), multiwavelength

➢ antimatter, searched as rare components in cosmic rays (CRs)

\[ e^+, \ \bar{p}, \ \bar{D} \]

\( \nu \) and \( \gamma \) keep directionality

⇒ SOURCE DENSITY

Charged particles diffuse in the galactic halo

⇒ ASTROPHYSICS OF COSMIC RAYS!
DM Sources are also in the diffusive halo.

- DM halo $\sim 200$ kpc
- $L_{\text{halo}} \sim 4-10$ kpc
- $R_{\text{disc}} \sim 20$ kpc
- $h_{\text{disc}} \sim 0.2$ kpc
Antiproton fluxes at the Top-of-Atmosphere

Galactic Diffusion
Energy losses
Transport in the Heliosphere

TOA Flux

DM signal

$\langle \sigma v \rangle_{\text{ann}}$

$M_{\text{DM}}$

Energy

spectral features
multiplicity (norm)

N. Fornengo  XSCRC 2017
Injection spectra from DM and CRs

\[ \sqrt{s} = 2m_\chi \]

non-nuclear process (typically weak)

\( \bar{p} \ D \ e^+ \ e^- \ \nu \ \gamma \)

PYTHIA
HERWIG
FLUKA

Hadronization: MC, tuned on accelerator data (leptonic, hadronic)

\( e^+ \ e^- \ \nu \ \gamma \)

tens GeV few TeV

at rest

\( N_1 \)

\( \bar{p} \ D \ e^+ \ e^- \ \nu \ \gamma \)

\( \begin{align*}
  p + p & \rightarrow \bar{p} \\
  p + He & \rightarrow \bar{p} \\
  He + p & \rightarrow \bar{p} \\
  He + He & \rightarrow \bar{p} \\
  (\ldots) & 
\end{align*} \)

N. Fornengo XSCRC 2017
Cosmic antiproton data

Data are very precise, and over almost 3 o.o.m.
AMS-02 antiprotons are consistent with a secondary astrophysical origin.

- The secondary bar flux is predicted to be consistent with AMS-02 data.
- Transport and cross section uncertainties are comparable.
- A dark matter contribution would come as a tiny effect.
- Precise predictions are mandatory.
Possible contribution from dark matter

**Antiproton data are so precise that permit to set strong upper bounds on the dark matter annihilation cross section, or to improve the fit w.r.t. to the secondaries alone adding a tiny DM contribution.**
Antiproton production by inelastic scatterings

\[ q_{ij}(T_{\bar{p}}) = \int_{T_{\text{th}}}^{\infty} dT_i \ 4\pi n_{\text{ISM},j} \phi_i(T_i) \frac{d\sigma_{ij}}{dT_{\bar{p}}}(T_i, T_{\bar{p}}) \]

Source term

\( i, j = \) proton, helium

(both in the CRs and in the ISM)

Cosmic antiproton data are very precise: production cross sections should be known with high accuracy in order not to introduce high theoretical uncertainties
Re-analysis of the cross section parameterization

- Fit of two most recent (analytic) parametrizations for antiproton production in \( pp \) collisions
- Fit of \( pA \) parametrization by rescaling from \( pp \)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>CM-Energy [GeV]</th>
<th>Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA49</td>
<td>17.3</td>
<td>( pp )</td>
</tr>
<tr>
<td>NA61</td>
<td>7.7, 8.8, 12.3, 17.3</td>
<td>( pp )</td>
</tr>
<tr>
<td>Dekkers</td>
<td>6.1, 6.7</td>
<td>( pp )</td>
</tr>
<tr>
<td>LHCb</td>
<td>110</td>
<td>( p\text{He} )</td>
</tr>
<tr>
<td>NA49</td>
<td>17.3</td>
<td>( pC )</td>
</tr>
</tbody>
</table>

\( \chi^2 \)-fit of the \( pp \) parametrization to \( pp \) data

\( \chi^2 \)-fit of the \( pA \) rescaling factor to \( pA \) data

**Param. I**

\[
\sigma_{\text{inv}}(\sqrt{s}, x_R, p_T) = \sigma_{\text{in}}(1 - x_R)^{C_1} \exp(-C_2 x_R) \times \left[ C_3 (\sqrt{s})^{C_4} \exp(-C_5 p_T) + C_6 (\sqrt{s})^{C_7} \exp(-C_8 p_T^2) \right]
\]

**Param. II**

\[
\sigma_{\text{inv}}(\sqrt{s}, x_R, p_T) = \sigma_{\text{in}} R C_1 (1 - x_R)^{C_2} \times \left[ 1 + \frac{X}{\text{GeV}} (m_T - m_p) \right] \frac{1}{C_3 x}
\]

\[
R = \begin{cases} 
1 & \sqrt{s} \geq 10 \text{ GeV} \\
1 + C_5 \left( 10 - \frac{\sqrt{s}}{\text{GeV}} \right)^5 & \text{elsewhere}
\end{cases}
\]

\[
\sigma_{\text{inv}}^{pA}(\sqrt{s}, x_f, p_T) = f^{pA}(A, x_f, D) \sigma_{\text{inv}}^{pp}(\sqrt{s}, x_R, p_T)
\]

\[
\sigma_{\text{inv}}^{\text{Galaxy}} = \sigma_{\text{inv}}(2 + \Delta_{\text{IS}} + 2\Delta_{\Lambda})
\]
**New fixed-target data for the antiproton XS**

FD, Korsmeier, Di Mauro PRD 2018

**pp \(\rightarrow\) pbar + X**

\[\sqrt{s} = 7.7, 8.8, 12.3 \text{ and } 17.3 \text{ GeV}\]
\[T_p = 31, 40, 80, 158 \text{ GeV}\]

**pHe \(\rightarrow\) pbar + X**

**LHCb** (Graziani et al. Moriond 2017)
\[\sqrt{s} = 110 \text{ GeV}\]
\[T_p = 6.5 \text{ TeV}\]

**Fraction of the pp source term covered by the kinematical parameters space**

**Fraction of the p-nucleus source term covered by the kinematical parameters space**


**pp→ pbar+X production cross sections**

FD, Korsmeier, Di Mauro PRD 2018

\[
q_{ij}(T_p) = \int_{T_{th}}^{\infty} dT_i \, 4\pi \, n_{\text{ISM},j} \, \phi_i(T_i) \frac{d\sigma_{ij}}{dT_p}(T_i, T_p)
\]

**Good agreement for T > 10 GeV**
High-energy data analysis

1. Fit to NA61 pp $\rightarrow$ pbar + X data
2. Calibration of pA XS on NA49 pC $\rightarrow$ pbar + X data
3. Inclusion of LHC pHe $\rightarrow$ pbar + X data

**Parametrization I**

LHCb data agree better with one of the two pp parameterizations. They select the high energy behavior of the Lorentz invariant cross section.
The antiproton source spectrum

Param II is preferred by the fits.
The effect of LHCb data is to select a h.e. trend of the pbar source term.
A harder trend is preferred.
Uncertainties still range about 10-15%, and increase at low energies.

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Uncertainties still range about 10-15%, and increase at low energies.
The antiproton source term - is affected by uncertainties of +- 10% from cross sections. Higher uncertainties at very low energies.
AMS02 accuracy is reached if pp → p̅p̅ cross section is measured with 3% accuracy inside the regions, 30% outside.
Conclusions

• The AMS data induce a remarkable progress in understanding our Galaxy. Its data reach unprecedented precision (few %).

• The production cross sections for secondary nuclei are often the main source of theoretical uncertainty.

• High energy physics is addressing new data at the service of high precision cosmic ray data.

• Improvements in calculations of the nuclear cross sections will certainly remain data driven in the near future.
LHCb pHe $\rightarrow$ p-X cross section data

G Graziani for LHCb, Moriond 2017

First data ever has been collected by LHCb in fixed target mode

Result for prompt production (excluding weak decays of hyperons)

The total inelastic cross section is also measured to be

$$\sigma_{inel}^{LHCb} = (140 \pm 10) \text{ mb}$$

The EPOS LHC prediction

[T. Pierog at al, Phys. Rev. C92 (2015), 034906] is 118 mb, ratio is $1.19 \pm 0.08$.

Run at 4 TeV p beam energy is under analysis by the collaboration
General idea for matching the accuracy

• Determine the contribution to the antiproton source spectrum from the whole parameter space

\[ \{ \sqrt{s}, x_R, p_T \} \quad \{ T, T_p, \cos(\theta) \} \]

• Assign the maximal uncertainty that the cross section should have in order to address the following requirements:

1. The total uncertainty shall match the AMS-02 accuracy
2. The parameter space with larger contribution to the source spectrum, should have the smaller uncertainties in the cross section measurements

\[
\frac{d\sigma}{dT_p}(T, T_p) = 2\pi p_p \int_{-1}^{1} d\cos(\theta) \sigma_{\text{inv}} \\
= 2\pi p_p \int_{-\infty}^{\infty} d\eta \frac{1}{\cosh^2(\eta)} \sigma_{\text{inv}} \quad \eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)
\]
Predictions for future extensions of experiments

FIG. 10. Similar to Fig. 1 and Fig. 3. Fraction of the antiproton source term originating from the kinematic parameter space of the cross section which currently is experimentally determined by NA61 data in the pp channel (left panel) and by LHCb data in the pHe (central panel) or He p (right panel) channels. We add future predictions for a possible evaluation of NA61 data at $p_s = 6.3$ GeV and LHCb measurements at $p_s = 43$ and 87 GeV. Each contribution is normalized to the total source term of the specific channel.

FIG. 11. Parameter space of the antiproton production cross section which is necessary to determine the antiproton source term at the uncertainty level of AMS-02 measurements. We require the cross section to be known by 3% within the blue shaded regions and by 30% outside of the contours. The left and right panels contain contours for different CM energies. This figure is an update of Fig. 7b in DKD17. We exchange the kinetic variable $x_R$ by $x_f$, which is suitable for the asymmetric pA cross section discussed in this paper.

Appendix C: Parameter space explorability

In DKD17 we studied the precision of cross section measurements which would be necessary to shrink the uncertainties imposed on the theoretical prediction of