Cosmic ray antiprotons: where are we?

Pierre Salati – LAPTh & Université Savoie Mont Blanc

Outline

1) Cosmic rays as an indirect probe for dark matter
2) A new estimate of the antiproton background
3) Extracting limits on DM particle properties
1) Cosmic rays as an indirect probe for dark matter

- Indirect Detection – WIMPs continuously annihilate and produce SM particles such as gamma-rays, neutrinos, but also rare antimatter species like positrons, antiprotons and even antideuterons.

\[ \chi + \chi \rightarrow q\bar{q}, W^+W^-, \ldots \rightarrow \gamma, \bar{p}, \bar{D}, e^+, \nu's \]

[Graph and image of cosmic rays and dark matter interactions]
AMS Collaboration
CERN, Geneva, 15 April 2015

“AMS Days at CERN” and Latest Results from the AMS Experiment on the International Space Station

Figure 1. Antiproton to proton ratio measured by AMS. As seen, the measured ratio cannot be explained by existing models of secondary production.

Has an antiproton excess been discovered?
“AMS Days at CERN” and Latest Results from the AMS Experiment on the International Space Station

Backgrounds to a putative DM signal need to understood

Production cross sections – solar modulation – cosmic ray ray propagation

![Graph showing antiproton/proton ratio as a function of kinetic energy.](image-url)
2) A new estimate of the antiproton background

Milky-Way seen by a cosmic-ray physicist

Cosmic rays propagate inside a diffusive halo


September 13, 2016 – Pierre Salati – TeV Particle Astrophysics Conference @ CERN
Antiprotons Production in the Galaxy

- **Secondary** antiprotons are produced through the spallations of cosmic-ray protons and He nuclei on the interstellar material.

\[
p(\text{CR}) + H(\text{ISM}) \rightarrow \bar{p} + X
\]

\[
\downarrow
\]

\[
q_{\bar{p}}^{\text{sec}}(r, E_{\bar{p}}) = 4\pi \int_{E_p^0}^{+\infty} \frac{d\sigma_{pH\rightarrow\bar{p}}}{dE_{\bar{p}}} \{E_p \rightarrow E_{\bar{p}}\} \ n_H \Phi_p(r, E_p) \ dE_p
\]

**New developments since 2008**

- CR $p$ and He fluxes measured with improved accuracy.

\[
\Phi_{\bar{p}}^{\text{sec}}(E_{\bar{p}}) \propto q_{\bar{p}}^{\text{sec}}(E_{\bar{p}}) \propto \Phi_p(E_p \sim 10 \times E_{\bar{p}})
\]

\[
\downarrow
\]

\[
\bar{p}/p(E) \propto \Phi_p(\sim 10 \times E)/\Phi_p(E) \propto 10^{-\alpha}
\]

\[
\bar{p}/p \text{ depends on the CR proton spectral index } \alpha
\]
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\(\bar{p}/p\) depends on the CR proton spectral index \(\alpha\)
Precision Measurement of the Proton Flux in Primary Cosmic Rays from Rigidity 1 GV to 1.8 TV with the Alpha Magnetic Spectrometer on the International Space Station
Secondary antiprotons are produced through the spallations of cosmic-ray protons and He nuclei on the interstellar material. 

\[
p^{\text{(CR)}} + \text{H}_{\text{(ISM)}} \rightarrow \bar{p} + X + q^{\text{sec}} \bar{p}(r, E_{\bar{p}}) = 4\pi Z + 1 \quad E_0^{p} d^2p \rightarrow \bar{p} dE_{\bar{p}} \{E_{p} \ll E_{\bar{p}}\} \quad n \quad H_{p}^{(r, E_{p})} dE_{p} \\
\]

New developments since 2008

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\[
\frac{\bar{p}}{p}(E_{\bar{p}}) / \frac{\bar{p}}{p}(E_{p}) \ll 10^{-5} \quad \bar{p} / p(E) / \bar{p} / p(E) \ll 10^{-5} \quad \bar{p} / pd e p e n d so n t h e C R p r o t o n s p e c t r a li n d e x
\]

CRAC Collaboration at TeVPA 2016

AMS02 CERN presentation 2015

Tan & Ng cross sections
PRL 102 (2009) 071301 p and He soft fluxes

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p^{\text{(CR)}} + \text{H}^{\text{(ISM)}} \rightarrow \bar{p} + X + q_{\text{sec}}\bar{p}(r, E_{\bar{p}}) = 4\pi Z + 1 E_{p} d\text{H} \rightarrow \bar{p} dE_{\bar{p}} + \bar{p}/p(\frac{E_{\bar{p}}}{E_{p}}) \ll 10 \cdot \frac{E_{\bar{p}}}{E_{p}} \}
\]

New developments since 2008

CR p and He fluxes measured with improved accuracy.

[Graph showing \( \bar{p}/p \) ratio vs. kinetic energy]
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\]

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\[
\frac{\bar{p}}{p}(E_{\bar{p}})/q_{sec}\bar{p}(E_{\bar{p}})/p \ll 10 \times \frac{E_{\bar{p}}}{E_p} - \frac{\bar{p}}{p}(E) \ll 10 \times \frac{E}{E_p}
\]

Backgrounds to a putative DM signal need to understood

Production cross sections – solar modulation – cosmic ray propagation

DM signal ?

background well determined

\[
\frac{\bar{p}}{p} \ll B/C
\]

best DM probe

Re-analysis of the CR antiproton background

New limits can be set on DM properties

Reduced CR uncertainties for secondary antiprotons

2008 background calculation

AMS02 PRL 117, 091103 (2016)
Antiprotons Production in the Galaxy

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\[ p_{\text{CR}} + \text{H}_{\text{ISM}} \rightarrow \bar{p} + X + q_{\text{sec}} \bar{p}(r, E_{\bar{p}}) = 4\pi Z + 1 \]

\[ E_{p} \cdot d\rho_{H} / dE_{\bar{p}} - N_{H} \]

\[ p(r, E_{p}) \cdot dE_{p} \]

New developments since 2008

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\[ \frac{\bar{p}}{p}(E_{\bar{p}}) / \frac{\bar{p}}{p}(E_{\bar{p}}) \sim 10 \cdot \frac{E_{p}}{E_{\bar{p}}} / \frac{E_{p}}{E_{\bar{p}}} \sim 10 \]

\[ \bar{p} / p \sim B/C \]

Renaissance of the CR antiproton background

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New developments since 2008

- New parameterization of \( d\sigma_{pH\rightarrow\bar{p}}/dE_{\bar{p}} \) from BRAHMS and NA49.
New parameterization of $d\sigma_{p\to \bar{p}}/dE_{\bar{p}}$ from BRAHMS and NA49.

A new evaluation of the antiproton production cross section for cosmic ray studies

Mattia di Mauro$^{1,2}$, Fiorenza Donato$^1$, Andreas Goudelis$^2$, Pasquale Dario Serpico$^2$

$$E \frac{d^3 \sigma}{dp^3} = \frac{\sigma_{\text{in}}(s)(1-x_R)^C_1 e^{-C_2 x_R}}{2(x_R^{C_3} + x_R^{C_4} e^{-C_5 p_T} + C_6 (\sqrt{s})^{C_7} e^{-C_8 p_T^2})}$$

<table>
<thead>
<tr>
<th>$C_1$ (error)</th>
<th>$C_2$ (error)</th>
<th>$C_3$ (error)</th>
<th>$C_4$ (error)</th>
<th>$C_5$ (error)</th>
<th>$C_6$ (error)</th>
<th>$C_7$ (error)</th>
<th>$C_8$ (error)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.499(0.040)</td>
<td>3.41(0.11)</td>
<td>0.00942(0.00083)</td>
<td>0.445(0.027)</td>
<td>3.502(0.018)</td>
<td>0.0622(0.0086)</td>
<td>-0.247(0.049)</td>
<td>2.576(0.027)</td>
</tr>
</tbody>
</table>
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\[ p_{\text{CR}} + \text{ISM} \rightarrow \bar{p} + X + q_{\text{sec}} \bar{p} (r, E_{\bar{p}}) = 4\pi Z + 1 E_{p} \frac{dH}{dE_{\bar{p}} - E_{p}} \{ E_{p} ightarrow E_{\bar{p}} \} n_{H} \]

New developments since 2008

- CR p and He fluxes measured with improved accuracy.

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Backgrounds to a putative DM signal need to be understood

Production cross sections – solar modulation – cosmic ray propagation

DM signal ? background well determined

\[ \bar{p} / p \ll B / C \]

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\[ q_{\bar{p}}^{\text{sec}}(r, E_{\bar{p}}) = 4\pi \int_{E_{\bar{p}}^{\text{min}}}^{+\infty} \frac{d\sigma_{pH\rightarrow\bar{p}}}{dE_{\bar{p}}} \{E_{\bar{p}} \rightarrow E_{\bar{p}}\} \ n_{H} \Phi_p(r, E_p) \ dE_p \]

**New developments since 2008**

- Proton collisions yield more antineutrons than antiprotons.

\[ \frac{d\sigma_{pp\rightarrow\bar{n}}}{dE_{\bar{p}}} = \frac{d\sigma_{pn\rightarrow\bar{p}}}{dE_{\bar{p}}} \]

\[ \frac{d\sigma_{pp\rightarrow\bar{n}}}{d\sigma_{pp\rightarrow\bar{p}}} \approx 1.3 \]
The Cosmic Ray Antiproton Background for AMS-02

Rolf Kappl\textsuperscript{a}, Martin Wolfgang Winkler\textsuperscript{b}

\[ x_f = \frac{p_{L}^*}{\sqrt{s}/2} \]

NA49 Collaboration, H. Fischer, Heavy Ion Phys. 17 (2003), 369–386
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\[ p_{(\text{CR})} + H_{(\text{ISM})} \rightarrow \bar{p} + X + q_{\text{sec}} \]

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\[ \frac{\bar{p}}{p}(E_{\bar{p}}) \approx 10^{-5} \times \frac{E_{p}}{E_{\bar{p}}} \]

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\[ \bar{n}/p \approx B/C \]

\[ \bar{n}/p = 1.3 \text{ at production} \]

- di Mauro et al. cross sections (2014)
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Antiproton data are compatible with the background

No $\bar{p}$ excess

But measurements are on the upper side
Recent ongoing developments with published data

AMS02 CERN presentation 2015
PAMELA 2012

Fiducial case with MED model
Full CR propagation uncertainties
\( \bar{\pi}/\pi = 1.3 \) at production
di Mauro et al. cross sections (2014)
AMS days 2015 cosmic ray p and He fluxes
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Treat $\bar{p}_F$ and $N_{IS} = \bar{n}/\bar{p}$ as nuisance parameters

Preliminary

New p & He flux parameterizations
See Manuela Vecchi’s talk @ TeVPA 2016

The positron flux constrains CR propagation
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$q_{sec} \bar{p}(T_{\bar{p}})$

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$P_{\bar{p}}(m_{DM}, h, v_i, \bar{p}_F, N_{IS})$

$P_{\bar{bkg}}(\bar{p}, 0_F, N_{0IS})$

$P_{\bar{q}}(\bar{p}, T_{\bar{p}})$

Recent ongoing developments with published data
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\[ \text{2nd} \left( m_{\text{DM}}, h_v, \bar{p}_F, N_{\text{IS}} \right) \]
\[ \text{2nd bkg} \left( \bar{p}, 0_F, N_{0\text{IS}} \right) \]
\[ \leq 4 \]

Recent ongoing developments with published data
New p & He flux parameterizations
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Positron limited CR propagation uncertainties
\( \bar{n}/\bar{p} = 1.3 \) at production
di Mauro et al. cross sections (2014)
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Primary antiprotons originate from the annihilations of the dark matter species – WIMPs in our case – concealed in the Galactic halo.

\[ \chi + \chi \rightarrow q\bar{q}, W^+W^-, HH, \ldots \rightarrow \bar{p} + X \]

\[ q^\text{susy}_p(r, z, E_p) = \frac{1}{2} \langle \sigma_{\text{ann}} v \rangle g(T_{\bar{p}}) \left\{ \frac{\rho_{\chi}(r, z)}{m_{\chi}} \right\}^2 \]
New limits can be set on DM properties
Treat \( \phi_F^\bar{p} \) and \( N_{IS} = \bar{n}/\bar{p} \) as nuisance parameters

\[
\chi^2(m_{DM}, \langle \sigma v \rangle, \phi_F^\bar{p}, N_{IS}) - \chi^2_{bkg}(\phi_F^{\bar{p},0}, N_{IS}^{0}) \leq 4
\]

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Treat $\phi_F^\bar{p}$ and $N_{IS} = \bar{n}/\bar{p}$ as nuisance parameters

$$\chi^2(m_{DM}, \langle \sigma v \rangle, \phi_F^\bar{p}, N_{IS}) - \chi^2_{bkg}(\phi_F^{\bar{p},0}, N_{IS}^{0}) \leq 4$$

Astrophysical uncertainties on the constraints

![Graph showing cross section vs. DM mass](image)

New limits can be set on DM properties
Closing thoughts

- Dark Matter indirect detection is a powerful probe provided that astrophysical backgrounds are well determined.
  - Cosmic ray propagation & X-sections

- The antiproton background has been increasing somewhat since 2008...
  (i) harder CR proton and He spectra,
  (ii) increased $\bar{n}/\bar{p}$ ratio at production,
  (iii) better determination of the cross-section uncertainties.

- The AMS-02 antiproton measurements are of exquisite quality. They are – at that stage – compatible with the background although at the upper limit of what is expected.

- To decide whether a signal is hidden inside the AMS-02 $\bar{p}/p$ data, CR propagation needs to be better constrained and the antiproton production cross-sections should be more accurately measured.

  \emph{B/C (published) measurements are eagerly awaited}
Back-up slides
Recent ongoing developments with published data

Preliminary

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\[ \theta^2_{\text{bkg}}(\bar{p}, 0, N_{\text{IS}}^0) \leq 4 \]

Preliminary

Full CR propagation uncertainties
\( \bar{n}/\bar{p} = 1.3 \) at production
di Mauro et al. cross sections (2014)
AMS02 2015 CR p and He fluxes (published)
Solar modulation is \( \phi_F = 724 \text{ MV} \)
Recent ongoing developments with published data

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Treat \( \bar{p}_F \) and \( N_{IS} = \bar{n}/\bar{p} \) as nuisance parameters

\[
\begin{align*}
    2 \ bkg (\bar{p}, \bar{p}_F, N_{IS}) & \geq 4 \\
    2 (m_{DM}, h, v_i, \bar{p}_F, N_{IS}) & \geq bkg (\bar{p}, 0, 0, N_{IS}) \\
\end{align*}
\]

Preliminary

- New fiducial case with MAX model
- Positron limited CR propagation uncertainties
- \( \bar{n}/\bar{p} = 1.3 \) at production
- di Mauro et al. cross sections (2014)
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