The impact of cross sections on the cosmic antiprotons

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JCAP 09 (2014)  R. Kappl, M.W.
JCAP 02 (2017)  M.W.

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Antiprotons in Cosmic Rays

**primary antiprotons**
- dark matter annihilation
- smooth spectrum
- propagation washes out directional information

**secondary antiprotons**
- primary cosmic rays (p,He)
  scatter on interstellar matter

\[ q^{\text{sec}}(T) \sim \int dT' \left( \frac{d\sigma_p}{dT} \right) \rho_{p,He} \Phi_{p,He} \]
Antiproton Production Cross Section


$$\sigma = \sigma_0^0 + \sigma_0^\Lambda + \sigma_0^\bar{n}$$

measured  
reconstruct from $\sigma_0^\bar{\Lambda}$  
symmetry arguments

Feynman/ radial scaling

$$E \frac{d^3 \sigma_0^p}{dp^3} = f_0^p$$  
invariant cross section

$$x_R = \frac{E}{E_{\text{max}}}$$  
scaling variable

$$f_0^p(x_R, p_T, \sqrt{s}) \quad \sqrt{s} > 10 \text{ GeV} \quad \rightarrow \quad f_0^p(x_R, p_T)$$

Martin W. Winkler (Nordita)  |  Cosmic Ray Antiprotons  |  March 29, 2017
**Prompt Antiproton Production**

- **power law dependence**
  \[ f \propto (1 - x_R)^n \]

  as predicted by constituent exchange models


- **factorization of** \( x_R \) **and** \( p_T \) **dependence**

\[
f_\bar{p}^0 = (399 \text{ mb GeV}^{-2}) (1 - x_R)^{7.8} e^{-\frac{m_T}{0.17 \text{ GeV}}}\]

Scaling

![Graph showing scaling]

- No indication of scaling violation up to $\sqrt{s} \sim 50 \text{ GeV}$

Data from Antinucci et al., Lett. Nuovo Cim. 6 (1973)
RHIC and LHC measurements of antiproton multiplicity $n_\bar{p}$ at $y = 0$

extrapolation into the full phase-space required

$$\sigma_\bar{p} = \sigma_{\text{in}} \times n_\bar{p}$$

STAR, Phys. Rev. C79 (2009),
High Energy Regime

- RHIC and LHC measurements of antiproton multiplicity $n_\bar{p}$ at $y = 0$

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feed-down:

$pp \rightarrow \bar{\Lambda} \rightarrow \bar{p}$
High Energy Regime

- RHIC and LHC measurements of antiproton multiplicity $n_{\bar{p}}$ at $y = 0$
- extrapolation into the full phase-space required

$$\sigma_{\bar{p}} = \sigma_{in} \times n_{\bar{p}}$$
Diffractive Scattering

CMS and STAR (partially) cut SD and DD events

ND events have higher multiplicity
Multiplicities

- correction for event selection, feed-down
- extrapolation and error estimate with Pythia
Multiplicity

- correction for event selection, feed-down
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Scaling Violation I: Inelastic Cross Section

- antiproton production cross section \( \sigma_{\bar{p}} = \sigma_{\text{inel}} \times n_{\bar{p}} \)


rise of inelastic cross section suggests modification of scaling

\[
f_{\bar{p}}^0 = \sigma_{\text{in}}(\sqrt{s}) \times f'(x_R, p_T)
\]
multiple scattering of protons leads to flattening of $p_T$ distribution
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transition from exponential to power law $\rightarrow$ Tsallis distribution

Multiple scattering of protons leads to flattening of $p_T$ distribution.

$$e^{-\frac{m_T}{m_0}} \rightarrow [1 + X (m_T - m_p)]^{-\frac{1}{Xm_0}}$$

Also observed for $\pi$, $K$...

Marques, Cleymans, Deppman, Phys. Rev. D91 (2015)

Transition from exponential to power law $\rightarrow$ Tsallis distribution

scaling violation in $\sigma_{\text{inel}}$
scaling violation in $\sigma_{\text{inel}}$ & $p_T$ distribution
Antineutron Production

- Baryon – antibaryon production $p\bar{p}, \bar{n}n, \bar{n}p, \bar{p}n$
- Proton neutron/nucleus scattering + symmetry arguments
- $\frac{\bar{p}}{p}$ ratio in proton proton scattering at high energy
Hyperons

- 20 - 35% of antiprotons from hyperon decay $c\tau_A \sim cm$

- Increase of strangeness with collision energy

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- 20 - 35% of antiprotons from hyperon decay $c\tau_{\Lambda} \sim cm$

- Increase of strangeness with collision energy

\[ \frac{\bar{\Lambda} + \bar{\Sigma}}{\bar{p} + \bar{n}} \approx 0.5 \]

Hadronic cross sections

\[ c_1 / \sqrt{s} + c_2 \log \sqrt{s} \]

High Energy Antiproton Flux


AMS-02

background

2015
High Energy Antiproton Flux


Kappl, Reinert, M.W. JCAP 1510 (2015)

updated propagation

High Energy Antiproton Flux


new cross section
fit without cross section uncertainties excluded at 18 $\sigma$
fit with cross section uncertainties excluded at $3.7\,\sigma$
fit with cross section uncertainties + correlations excluded at $1.2 \sigma$

uncertainties not included: primary fluxes, solar modulation, propagation
Conclusion

- scaling violation in proton proton scattering at high energy
- antiproton production by hyperon decay increases with energy
- harder cosmic ray antiproton spectrum = consistent with AMS-02
Backup Slides
scaling is approached asymptotically from above
data from CERN PS, Allaby et al. (1970 & 1972)
Comparison of Source Terms

![Graph comparing different source terms for cosmic ray antiprotons. The graph shows the normalized number density of antiprotons, \( \tilde{\dot{N}}_p \), as a function of energy, \( T \) (GeV). Different models are represented by colored lines and shaded regions, with labels for each model: this work, Tan, Di Mauro (I), Di Mauro (II), QGSJET–IIm, and EPOS–LHC. The x-axis represents energy in GeV, ranging from 1 to 1000, and the y-axis represents the normalized number density.](image-url)