Cosmic Rays in Space

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JCAP 09 (2014) with R. Kappl,
JCAP 02 (2017),
JCAP 01 (2018) with A. Reinert

Second LHCb
Heavy Ion Workshop

Chia

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Antiprotons in Cosmic Rays

primary antiprotons
- dark matter annihilation
- smooth spectrum

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

![Graph showing the energy spectra of antiprotons](Image)

![Diagram illustrating dark matter annihilation and hadronization](Image)
Antiproton Production Cross Section: Status 2014

\[ \sigma = \sigma_{\bar{p}}^0 + \sigma_{\bar{p}}^\Lambda + \sigma_{\bar{n}}^0 + \sigma_{\text{HeH, pHe, HeHe}} \]

- measure + scaling
- ignored
- assumed

Feynman scaling

\[ x_R = \frac{E}{E_{\text{max}}} \]

scaling variable

\[ E \frac{d^3 \sigma_{\bar{p}}^0}{dp^3} (x_R, p_T \sqrt{s}) \]

invariant cross section

Scaling preserved up to $\sqrt{s} \sim 50$ GeV

at higher energy it breaks down due to multiple scattering
Martin W. Winkler (Stockholm University)

Scaling Violation

extrapolation from data at central rapidity ($y \sim 0$)

scaling preserved up to $\sqrt{s} \sim 50$ GeV

at higher energy it breaks down due to multiple scattering
AMS-02 antiproton excess 2015 is explained by scaling violation and updated propagation
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Monte Carlo Approach, simple scaling law
  e.g. di Mauro et al. Phys. Rev. D90 (2014)

prediction based on pp, pC data, empirical model
  M.W. JCAP 02 (2017)

first ever measurement by LHCb-SMOG
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Proton Helium

from V. Zhukov

$\sigma_{\text{LHCb}} / \sigma_{\text{Winkler}}$


$\sigma_{\text{LHCb}} / \sigma_{\text{EPOS-LHC}}$


LHCb Preliminary

from V. Zhukov
20 - 35% of antiprotons from hyperon decay \( c\tau_A \sim cm \)

increase of strangeness with collision energy

Hyperons

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

- increase of strangeness with collision energy

$\frac{\bar{\Lambda} + \bar{\Sigma}}{\bar{p} + \bar{n}} \simeq 0.5$

hadronic cross sections $\propto \frac{c_1}{\sqrt{s}} + c_2 \log \sqrt{s}$

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- Increase of strangeness with collision energy

LHCb data would be very helpful

Isospin Effects in Antineutron Production

- (anti)baryon produced in pairs $p\bar{p}, \bar{n}n, \bar{n}p, \bar{p}n$
- accessible only through $pn \rightarrow \bar{p}$ and symmetry arguments, $\frac{\bar{p}}{p}$ ratio

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A new Excess in the Cosmic Antiproton Flux

3.1 $\sigma$ excess consistent with dark matter

lower significance 1.1 $\sigma$

Various other groups have seen the same excess at significance 1-5 $\sigma$


Reinert, M.W., JCAP 01 (2018)

antideuteron signal assuming antiproton excess is dark matter

Antideuteron Coalescence

- coalescence model: proton and neutron form deuteron if \[ |\Delta p| < p_0 \] - coalescence momentum

Schwarzschild, Zupancic, Phys. Rev. 129 (1963)

antinucleon spectra differ between MCs
model $\bar{p}n$ as Gaussian wave package

\[
\psi_{\bar{p}n}(\mathbf{r}) \propto e^{-\frac{r^2}{2\sigma^2}} e^{i\mathbf{q}\mathbf{r}}
\]

\[
\sigma/2 = R_{\text{HBT}}
\]

coalescence momentum from wave function overlap

\[
p_0^3 \propto |\langle \psi_{\bar{d}} | \psi_{\bar{p}n} \rangle|^2
\]

include phase space suppression

\[
R = \frac{\Phi_4(m_p)}{\Phi_4(0)}
\]

4 massive nucleons

4 massless particles
Coalescence Revisited

ANTIDEUTERONS

FTFP-BERT
- p+p
- p+Be
- p+Al

EPOS-LHC
- p+p
- p+Be
- p+Al

p'\_0 [MeV/c]

T [GeV]

(b)
systematic error reduced by measuring $\bar{p}$, $\bar{d}$ at same experiment
Cosmic ray modeling crucially relies on accelerator measurements

LHCb SMOG wishlist:

1) \( p \, \text{He} \rightarrow \bar{\Lambda}, \bar{\Sigma} \) from existing run
2) \( p \, p \, (\text{H}_2) \rightarrow \bar{p} \) to test scaling violation in forward hemisphere
3) \( p \, d \rightarrow \bar{p} \) to test isospin effects
4) \( p \, p, \, p \, \text{He} \rightarrow \bar{d}, \bar{\text{He}} \) to determine coalescence momentum
5) \( p \, p, \, p \, \text{He} \rightarrow \pi, \, K \) to model positron source term