Cross Section Problems for the Antiproton Flux

Martin W. Winkler

in collaboration with with R. Kappl and A. Reinert

based on JCAP 09/2014 and arXiv:1506.04145

The p-He Cross Section Measurement: A Physics Case from Cosmic Rays
Torino

universitätbonn bctp Bethe Center for Theoretical Physics

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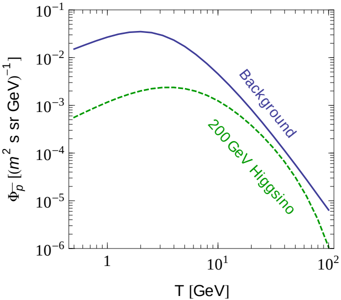
Why Antiprotons?

- low fraction of antimatter in cosmic rays $\bar{p}/p \sim 10^{-4}$
- very sensitive probe for new physics
- complemantary to gamma ray searches



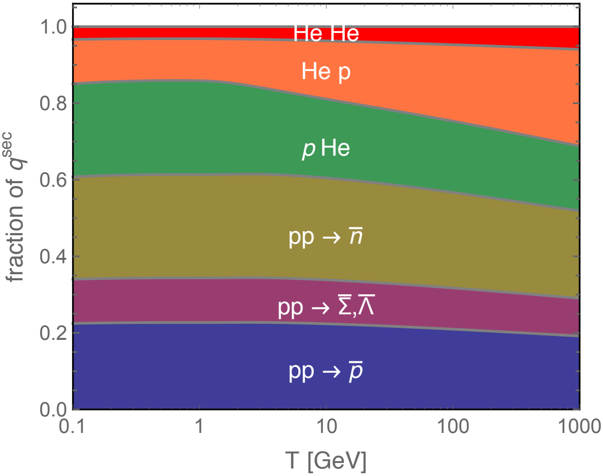
- example: dark matter pair-annihilation
- no clear spectral features expected

precise prediction for the $\bar{p}$-background is indispensable

Secondary Antiprotons

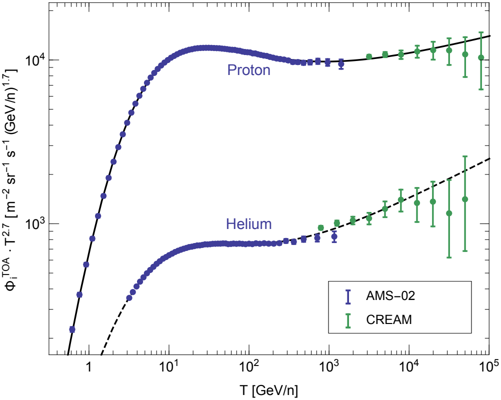
- scattering of primary cosmic rays (p,He) on the interstellar matter

$$q^{\text{sec}}(T) \sim \int dT' \left(\frac{d\sigma}{dT}\right)_{\bar{p}\,prod} n_{\text{A}_{\text{ISM}}} \Phi_A \qquad A = H, He, \ldots$$



Proton and Helium Fluxes

- primary proton and helium fluxes measured to high precision
  Yoon et al., Astrophys. J. **728** (2011), Aguilar et al., Phy. Rev. Lett. **114** (2015)



- clear indication of spectral breaks

Challenges for Cross Sections

- no theoretical calculation of cross sections
- experimental situation (old data, systematic errors) $\hookrightarrow$ *Mattia's talk* but improved with NA49
- "feed-down problem":
  - $1/4$ of $\bar{p}$ are produced via strange hyperon decay
  - decay length comparable to detector scales $c\tau_{\bar{\Lambda},\bar{\Sigma}} \sim 0.1$ m
  - measured inclusive cross section depends on experimental setup
- no experimental data on $\bar{n}$ production
- no experimental data on p-He and He-He scattering

Invariant Cross Section

- Lorentz invariant differential cross section

$$f(pp \to \bar{p} + X) = E_{\bar{p}} \frac{d^3\sigma}{dp_{\bar{p}}^3} \,,$$

- define scaling variable $x_R = \frac{E^*}{E^*_{\text{max}}}$ or $x_f = \frac{p_L^*}{\sqrt{s}/2}$
- constituent exchange models predict power law behavior
  Low, Phys. Rev. **D12** (1975), Nussinov, Phys. Rev. Lett. **34** (1975), Brodsky et al., Phys. Rev. Lett. **37** (1976)

$$f \propto (1 - x_R)^n$$

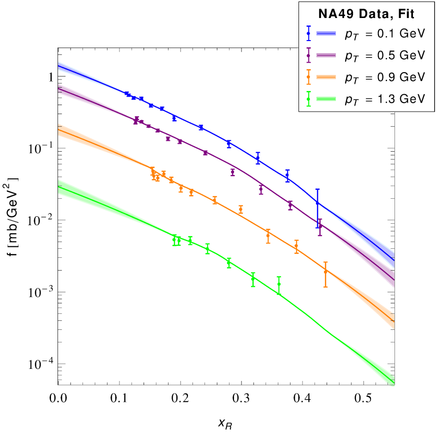
- radial scaling regime
  Taylor et al., Phys. Rev. **D14** (1976)

$$f(\sqrt{s}, x_R, p_T) \xrightarrow{\sqrt{s} \;>\; 10\text{ GeV}} f(x_R, p_T)$$

Cross section at one $\sqrt{s}$ determines cross section at all $\sqrt{s} > 10$ GeV

The Invariant Cross Section from Na49

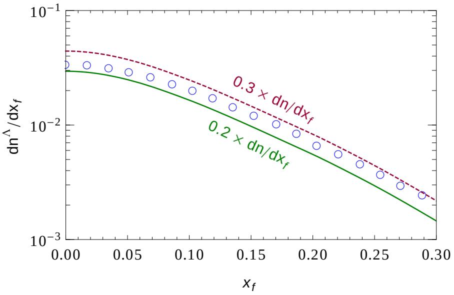
- Na49 at CERN SPS: fixed target pp collisions with $E_p = 158$ GeV
- large acceptance hadron detector, 70% of charged particles identified



- $f(x_R, p_T)$ from fit function provided by collaboration
  NA49, Eur. Phys. J. **C65** (2010)
- extrapolation with $(1 - x_R)^n$
- include uncertainties in fragmentation power, normalization

Strange Hyperons

- old data contain unknown fraction of $\sigma_{\bar{\Lambda},\bar{\Sigma}\to\bar{p}}$ $\to$ systematic error
- NA49 uses precision tracking to exclude $\bar{p}$ from hyperon decay
  NA49, Eur. Phys. J. **C65** (2010)



data from Alt et al., Eur. Phys. J. **C45** (2006)

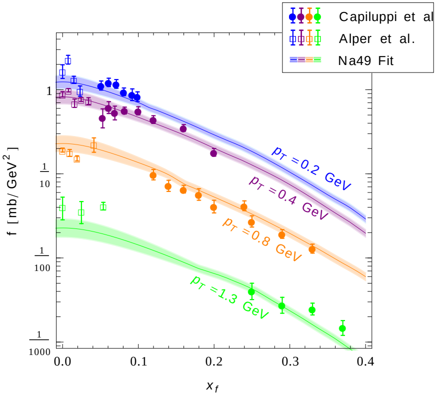
our approach

- use NA49 data and add hyperon component
- deduce $\sigma_{\bar{\Lambda},\bar{\Sigma}\to\bar{p}}$ from phase space distribution of parent hyperons

- similar phase space distribution of prompt and late $\bar{p}$ (deviations?)

Energy Scaling

- verify radial scaling with high energy data



CERN ISR data at $\sqrt{s} = 53$ GeV ($E_p = 1.5$ TeV) Nucl. Phys. **B100** (1975)

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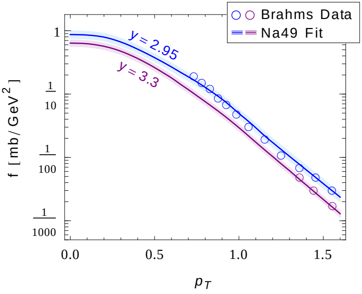

data from RHIC Brookhaven at $\sqrt{s} = 200$ GeV ($E_p = 20$ TeV)

BRAHMS, arXiv:0801.1696 (2008)

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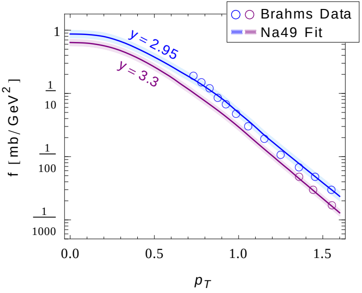
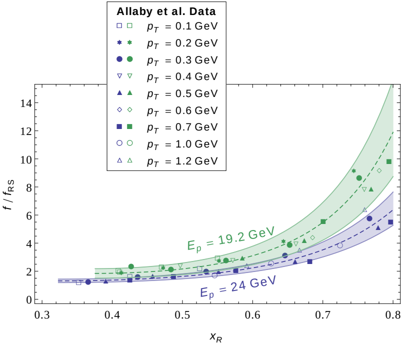


data from RHIC Brookhaven at $\sqrt{s} = 200$ GeV ($E_p = 20$ TeV)

BRAHMS, arXiv:0801.1696 (2008)

- scaling violation at $\sqrt{s} < 10$ GeV
- scaling approached faster at low x_R, weak p_T dependendence
- data rare $\hookrightarrow$ uncertainties

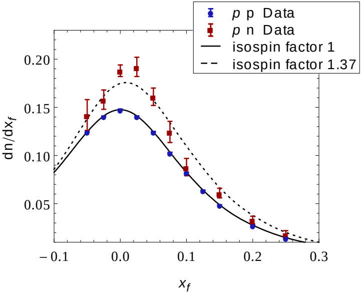
Allaby et al., CERN-70-12 (1970), Proceedings of Internat. Conference on High-Energy Collisions (1972)



Comment on Antineutrons

- standard assumption in cosmic ray physics $\sigma_{pp\to\bar{p}} = \sigma_{pp\to\bar{n}}$
- suggests equal $\bar{p}$-production in pp and pn scattering

<u>But:</u>



$$\sigma_{np\to\bar{p}} \simeq 1.4\,\sigma_{pp\to\bar{p}}$$
in projectile hemisphere

- isospin effect

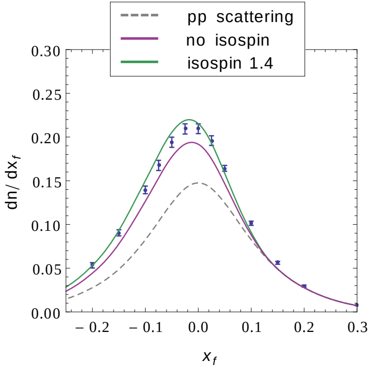
  Fischer et al., Heavy Ion Phys. **17** (2003)

projectile		n		p	
final state	$\bar{p}n$		$\bar{p}p, \bar{n}n$		$p\bar{n}$
I_3	-1	-1/2	0	1/2	1

- suggests enhanced $\bar{n}$-production in pp collisions
- consistent with nuclear scattering data ? $\bar{p}$ flux ?

Proton Nucleus Scattering

- Previous approach: fit to large set of proton-nuleus scattering data
  Duperray et al., Phys. Rev. **D68** (2003)
- for light nuclei, better to construct pA cross section from pp



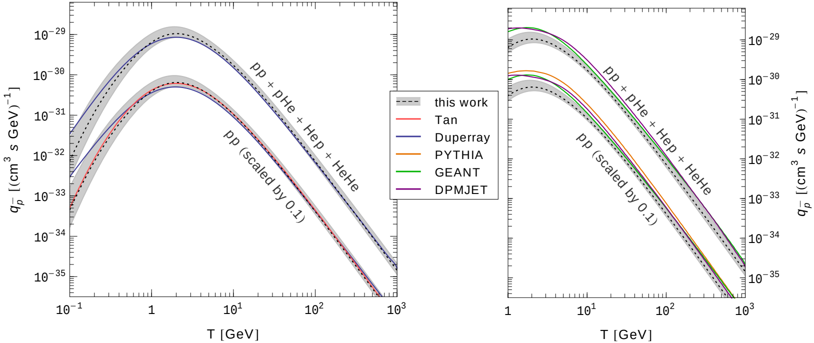
data from Na49, Eur. Phys. J. **C73** (2013)

- no pHe data available, but pC
- seperate target and projectile hemisphere
- enhancemet of multiplicity in target region due to multiple scatter and isospin effects
- nuclear medium effects subdominant

direct measurement of *p*-He highly welcome!

Source Term

- Comparison with previous work, Monte Carlos



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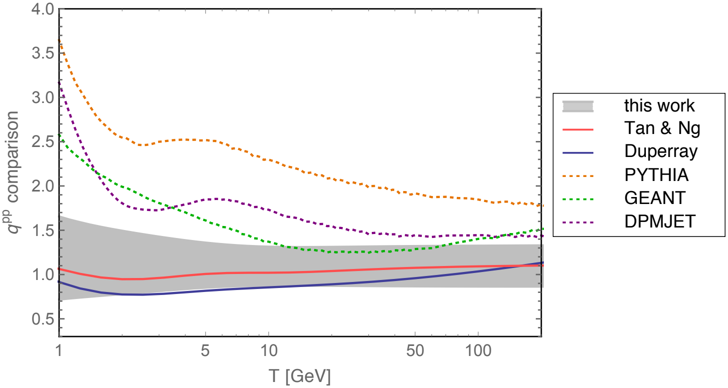
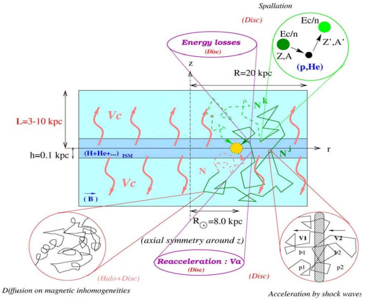


- consistent with di Mauro et al.

  Phys. Rev. **D90** (2014)

- propagation: random walk through the galaxy



from D. Maurin

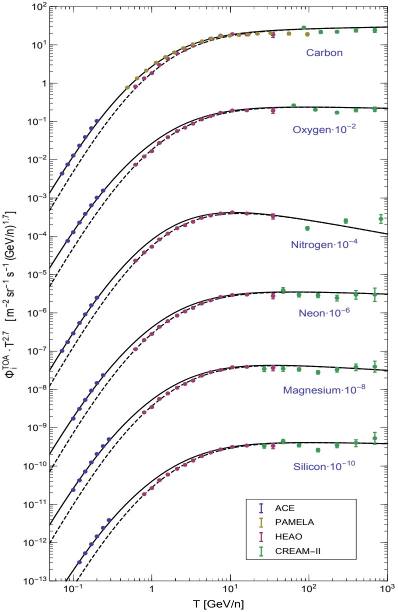
- diffusion equation

$$\nabla(-K\,\nabla N_{\bar{p}} + \mathbf{V}_c\,N_{\bar{p}}) + \partial_E(b_{\text{loss}}\,N_{\bar{p}} - K_{EE}\,\partial_E N_{\bar{p}}) + \Gamma_{\text{ann}}\,N_{\bar{p}} = q_{\bar{p}}$$

- semi-analytic solution in two-zone diffusion model
  Maurin et al., Astrophys. J. **555** (2001), Donato et al., Astrophys. J. **563** (2001)

- five transport parameters: K_0, δ, L, V_c, V_a $\Longleftarrow$ **B/C analysis**

Primary Fluxes

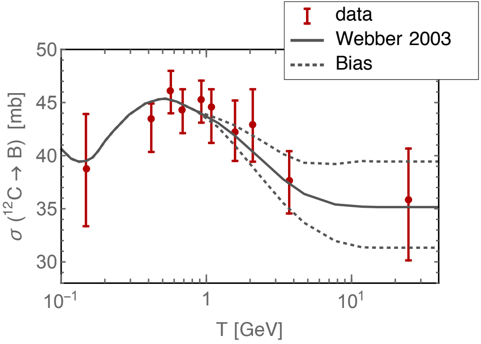


- B/C ratio used to determine propagation parameters
- B is pure secondary
- C, N, O, Ne, Mg, Si spallation contributes $\gtrsim$ 98% to B flux
- data from ACE, HEAO, CREAM-II, PAMELA

Lave et al., Astrophys. J. **770** (2013), Engelmann et al., Astronom. Astrophys. **233** (1990), Ahn et al., Astrophys. J. **707** (2009), Adriani et al., Astrophys. J. **791** (2014)

Spallation Cross Sections

- spallation cross sections: straight-ahead approximation
- σ_{spall} constant at $T \gtrsim 10$ GeV (?)



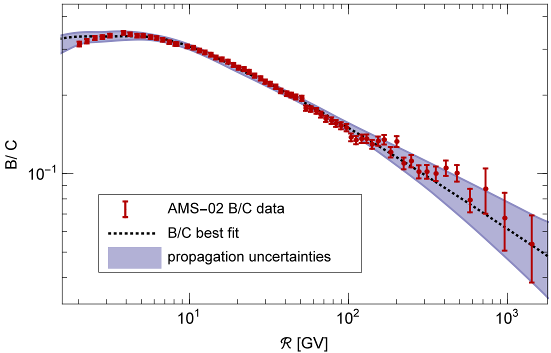
- Webber parameterization
  Astrophys. J. Suppl. **144** (2003)
- large uncertainties, no high-energy data
- introduce energy bias
  Maurin et al., Astron. Astrophys. **516** (2010)

needed: experimental data on spallation cross sections

B/C Analysis

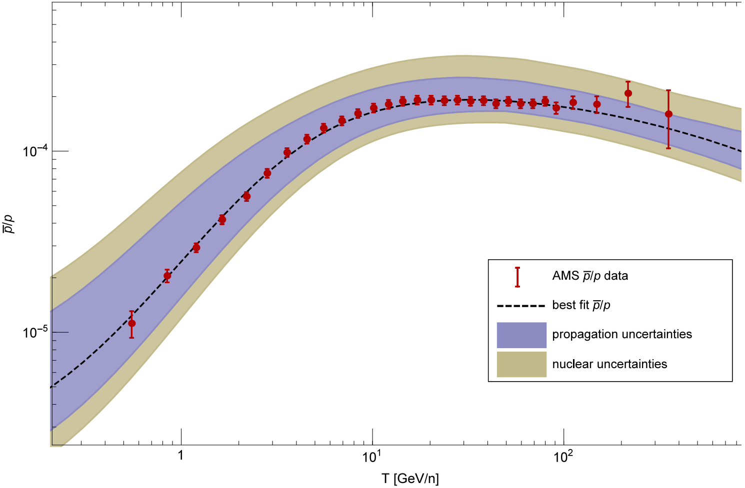
- new AMS-02 data on B/C ratio

A. Oliva, Talk at the AMS Days at CERN (2015)

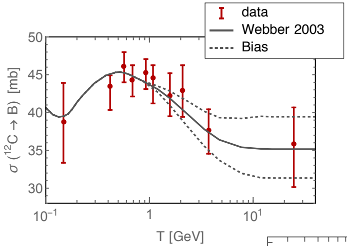


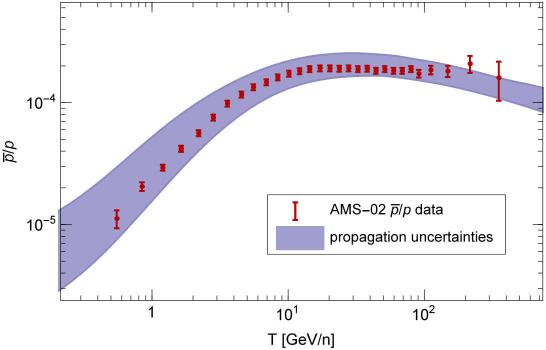
- at high energies $B/C \propto T^{-\delta}$
- selected 500 configurations, trend towards smaller $\delta = 0.3 - 0.6$

- comparison of $\bar{p}$ background with new AMS-02 data
  A. Kounine, Talk at the AMS Days at CERN (2015)

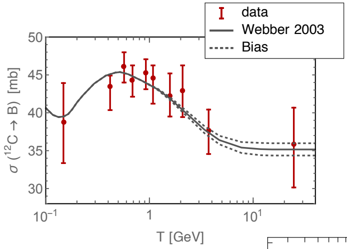


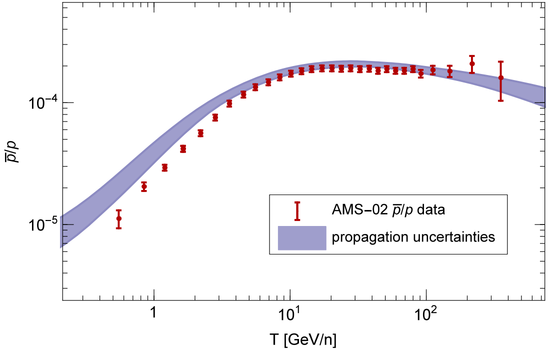
Remark on Propagation Unceratinties





Remark on Propagation Uncertainties





Conclusion

- Cosmic Ray Antiprotons play a key role in the search for new physics
- substantial progress in modeling antiproton production
- further improvement requires experimental input
    - low-energy scaling of cross sections
    - hyperon-induced $\bar{p}$ production
    - isospin effects in antineutron production
    - proton helium scattering
- propagation suffers from uncertainties in spallation cross sections