Hunting Antiprotons at Colliders and in the Sky

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in collaboration with R. Kappl and A. Reinert

based on JCAP 09/2014 and arXiv:1506.04145

Anticipating discoveries: LHC14 and beyond
MIAPP 2015, Munich

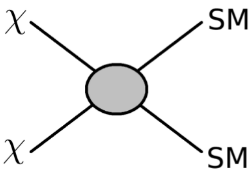
universitätbonn

bctp Bethe Center for Theoretical Physics

July 14 2015

Why Antiprotons?

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



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

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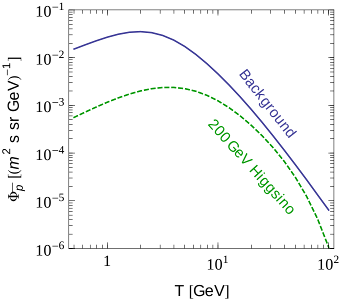

- example: dark matter pair-annihilation
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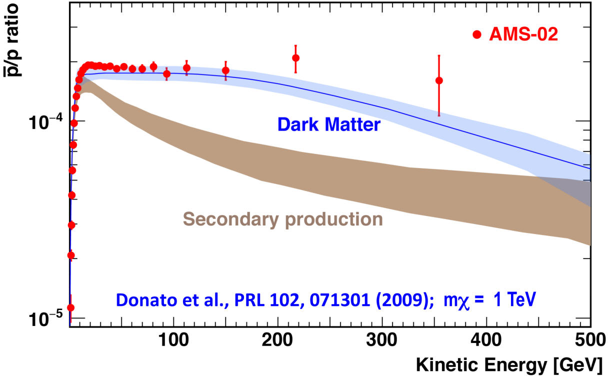
precise prediction for the $\bar{p}$-background is indispensable

Antiproton "excess" in AMS-02?

- preliminary data on the antiproton fraction in cosmic rays
  A. Kounine, Talk at the AMS Days at CERN (2015)

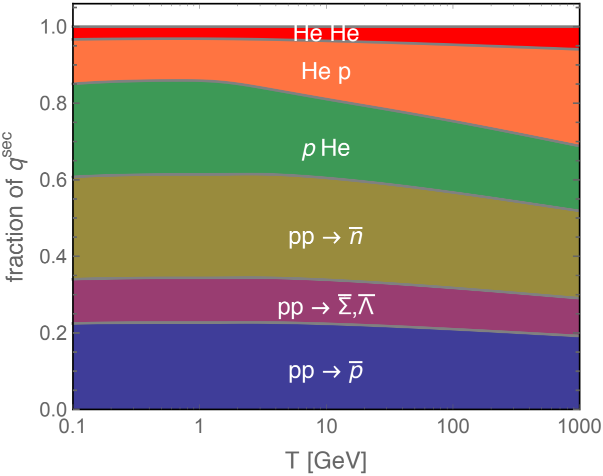


- seem to indicate excess $\rightarrow$ **Dark Matter ?**
- but: shown background is outdated

Secondary Antiprotons

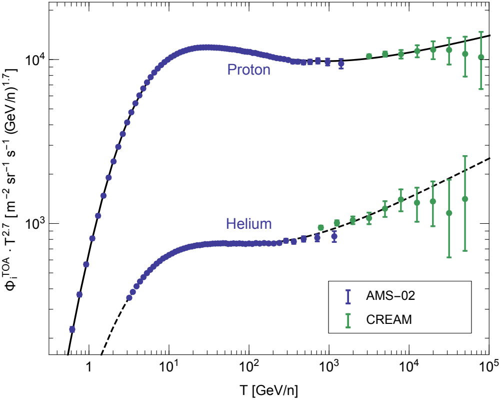
- scattering of primary cosmic rays (p,He) on the interstellar matter

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



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

Status of Cross Sections

- no theoretical calculation of cross sections
- experimental situation
  - old data from 1960s and 70s (CERN PS, ISR, Fermilab)

    $\hookrightarrow$ parameterizations by Tan, Duperray

    Tan et al., Phys. Rev. **D26** (1982), Duperray et al., Phys. Rev. **D68** (2003)
  - improved with **NA49** at CERN

    NA49 collaboration, Eur. Phys. J. **C65** (2010)
- "feed-down problem":
  - 25% of $\bar{p}$ produced via displaced decay $\bar{\Lambda}, \bar{\Sigma} \rightarrow \bar{p}$ $\quad (c\tau_{\bar{\Lambda},\bar{\Sigma}} \sim 0.1\,\text{m})$
  - measured cross section depends on experimental setup
- no experimental data on $\bar{n}$ production, p-He and He-He

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)

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

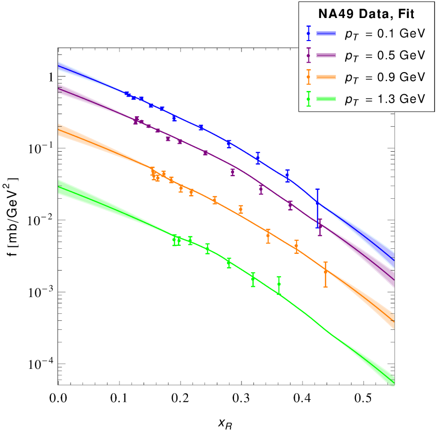
- radial scaling regime
  Taylor et al., Phys. Rev. **D14** (1976)

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

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

The Invariant Cross Section from Na49

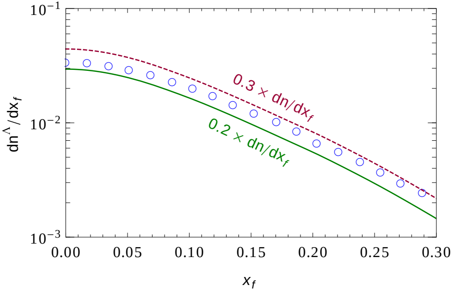
- Na49 at CERN SPS: fixed target pp collisions with $E_p = 158$ GeV
- large acceptance hadron detector, 70% of charged particles identified



- $f(x_R, p_T)$ 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 $\sigma_{\bar{\Lambda},\bar{\Sigma}\rightarrow\bar{p}}$ $\rightarrow$ 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)

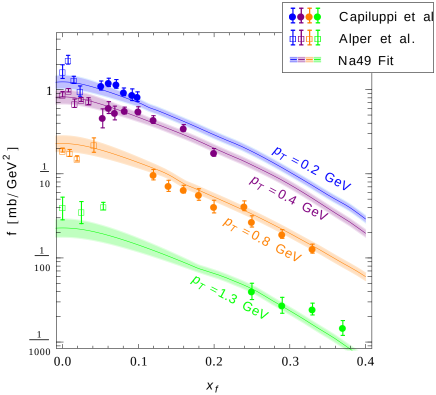
our approach

- use NA49 data and add hyperon component
- deduce $\sigma_{\bar{\Lambda},\bar{\Sigma}\rightarrow\bar{p}}$ 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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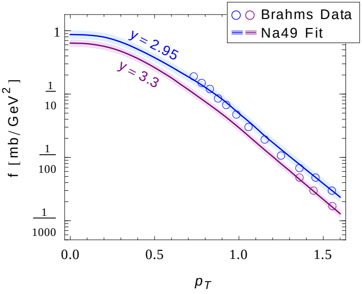

data from RHIC Brookhaven at $\sqrt{s} = 200$ GeV ($E_p = 20$ TeV)

BRAHMS, arXiv:0801.1696 (2008)

scaling violation could induce spectral hardening in $\bar{p}$ flux and fake DM signal

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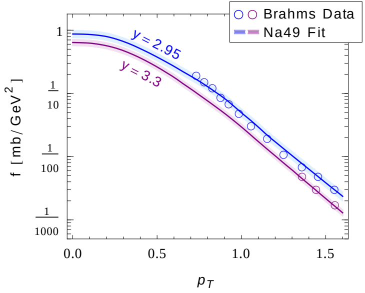

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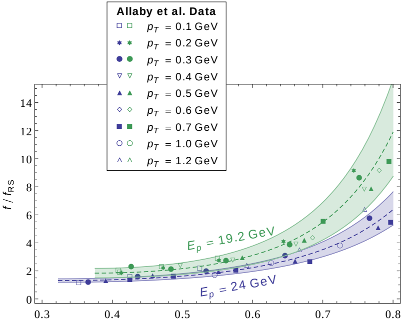
- scaling violation at $\sqrt{s} < 10\,\text{GeV}$
- scaling approached faster at low x_R, weak p_T dependendence
- data rare $\hookrightarrow$ uncertainties

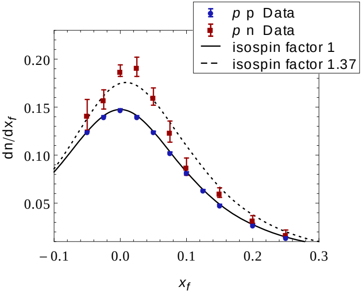
Allaby et al., CERN-70-12 (1970), Proceedings of Internat. Conference on High-Energy Collisions (1972)



Comment on Antineutrons I

- 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

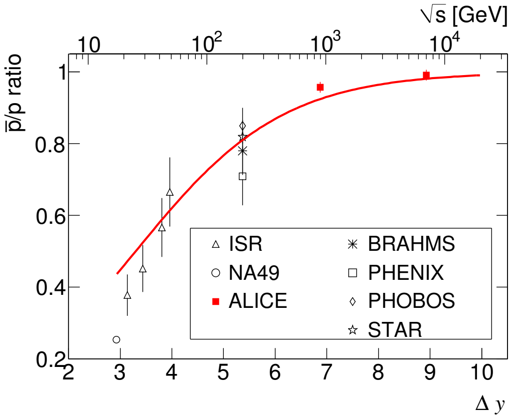
Fischer et al., Heavy Ion Phys. **17** (2003)

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 LHC data?

Comment on Antineutrons II

- isospin effects suggest asymmetry between $\bar{p}n$ and $\bar{n}p$ production

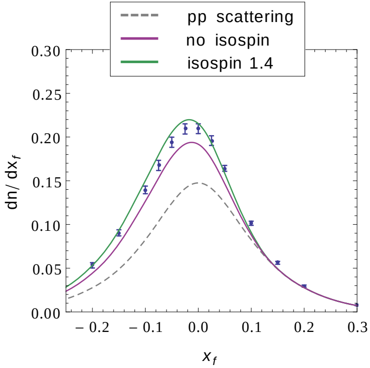


ALICE Collaboration, Phys. Rev. Lett. 105 (2010)

- but: mid-rapidity $\bar{p}/p$ ratio approaches unity at LHC

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



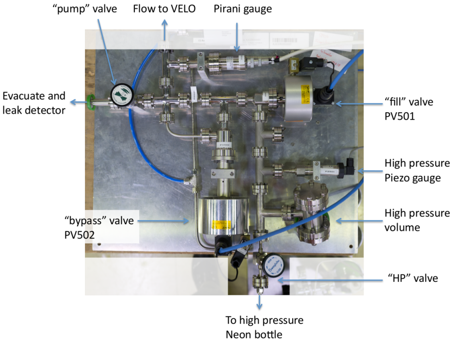
data from Na49, Eur. Phys. J. **C73** (2013)

- no p-He data available, but p-C
- seperate target and projectile hemisphere
- enhancement of multiplicity in target region due to multiple scatter and isospin effects
- nuclear medium effects subdominant

direct measurement of p-He highly welcome!

Experimental Proposals

SMOG system

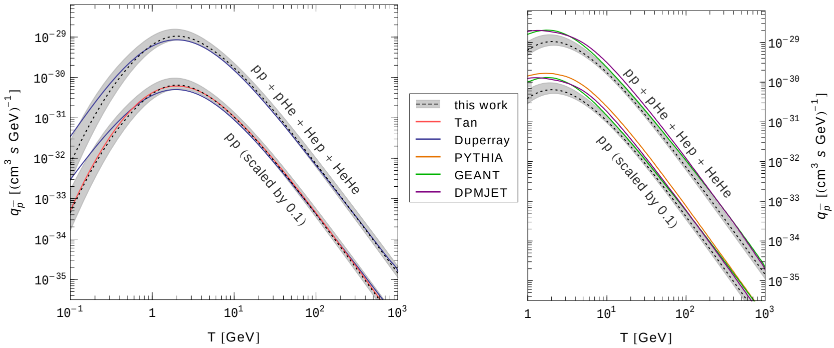


- new proposal to measure p-He scattering with LHCb
  O. Adriani, NPQCD Meeting, Cortona, 2015
- SMOG system injects gas into beam pipe
- originally intended for beam luminosity measurement
- can be used as fixed target p-He experiment

- new proposal to measure p-He with liquid helium target at COMPASS
  O. Denisov, p-He cross section measurement: a physics case from cosmic rays, Torino, 2015

Source Term

- comparison with previous work, Monte Carlos



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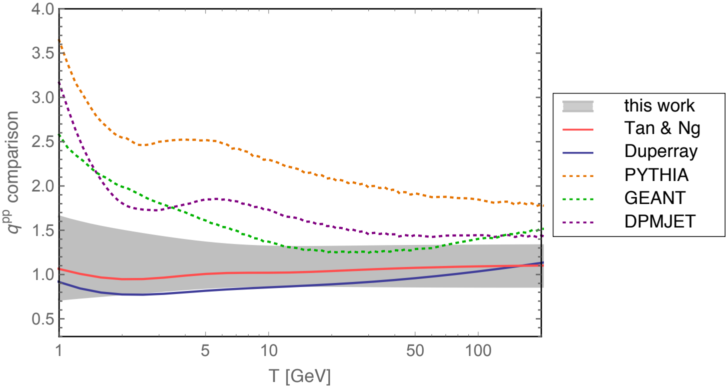
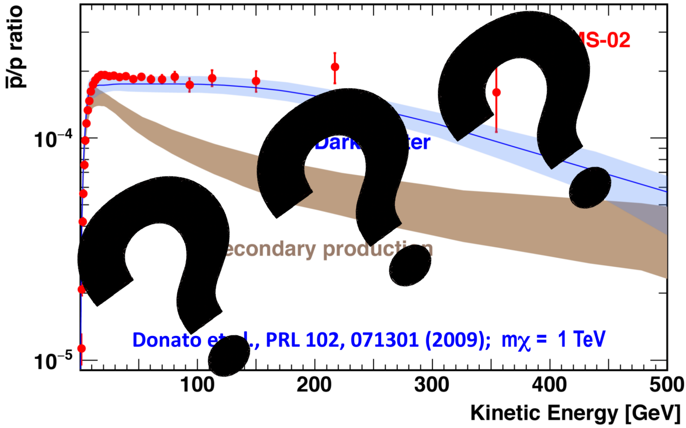


- Monte Carlos overestimate $\bar{p}$ production, in particular at low energy

Summary

- antiprotons play a key role in the search for dark matter
- discovery requires a precise understanding of astrophysical background
- we performed a state-of-the-art parameterization of antiproton cross sections and the first realistic error estimate
- cross section uncertainties remain (one of) the most limiting factor in interpreting antiproton data
- existing experimental proposals would dramatically reduce these uncertainties

Application to AMS-02



Rolf's talk