Cosmic Ray Physics at Particle Accelerators

Martin W. Winkler

JCAP 09 (2014) with R. Kappl,
JCAP 02 (2017),
JCAP 01 (2018) with A. Reinert
PRL 126 (2021) with T. Linden

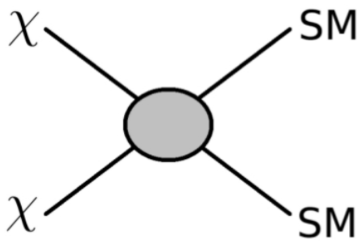
Workshop FTE@LHC

May 31, 2021

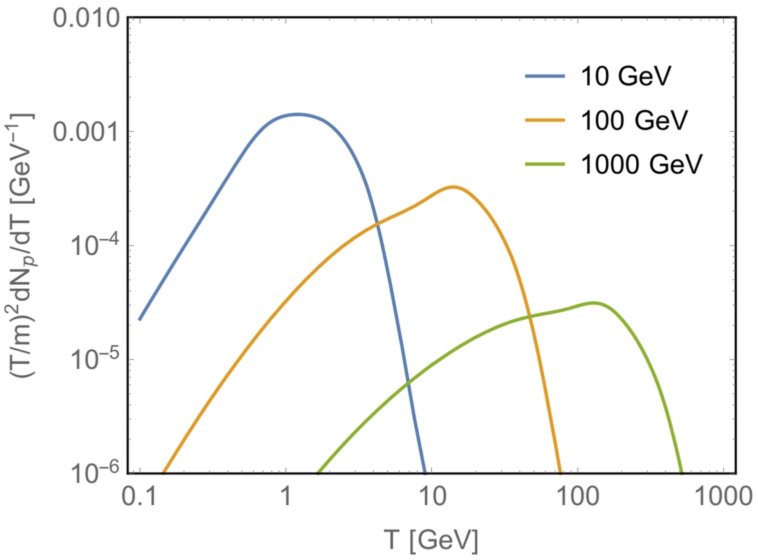
Antiprotons in Cosmic Rays

primary antiprotons

- dark matter annihilation

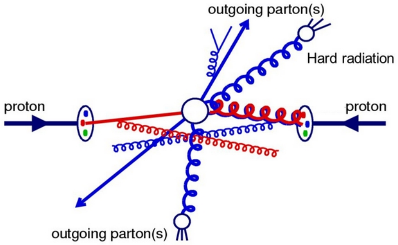


- smooth spectrum

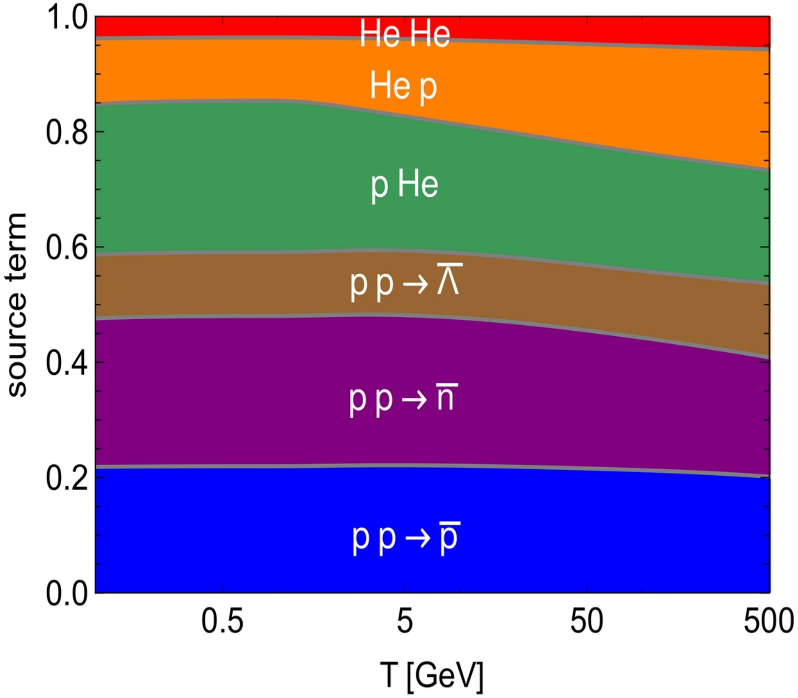


secondary antiprotons

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



hadronization



Antiproton Production Cross Section: Status 2014

see: Tan, Ng Phys. Rev. D26 (1982), Duperray et al., Phys. Rev. D68 (2003)

$$\sigma = \sigma^{0}_{\bar{p}} + \sigma^{\Lambda}_{\bar{p}} + \sigma^{0}_{\bar{n}} + \sigma^{\mathrm{Hep,pHe,HeHe}}$$

measure + scaling

ignored

$= \sigma^{0}_{\bar{p}}$ assumed

MC or simple scaling factors

- Feynman scaling

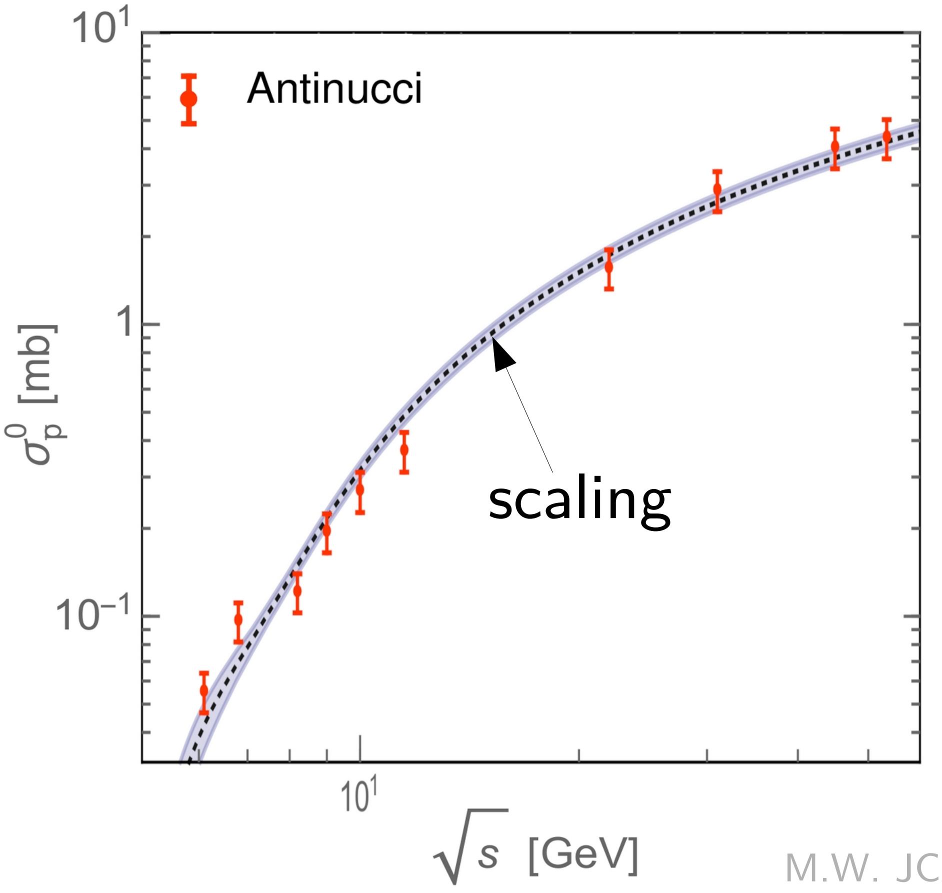
  Feynman, Phys. Rev. Lett. 23 (1969), Taylor et al. Phys. Rev. D14 (1976)

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

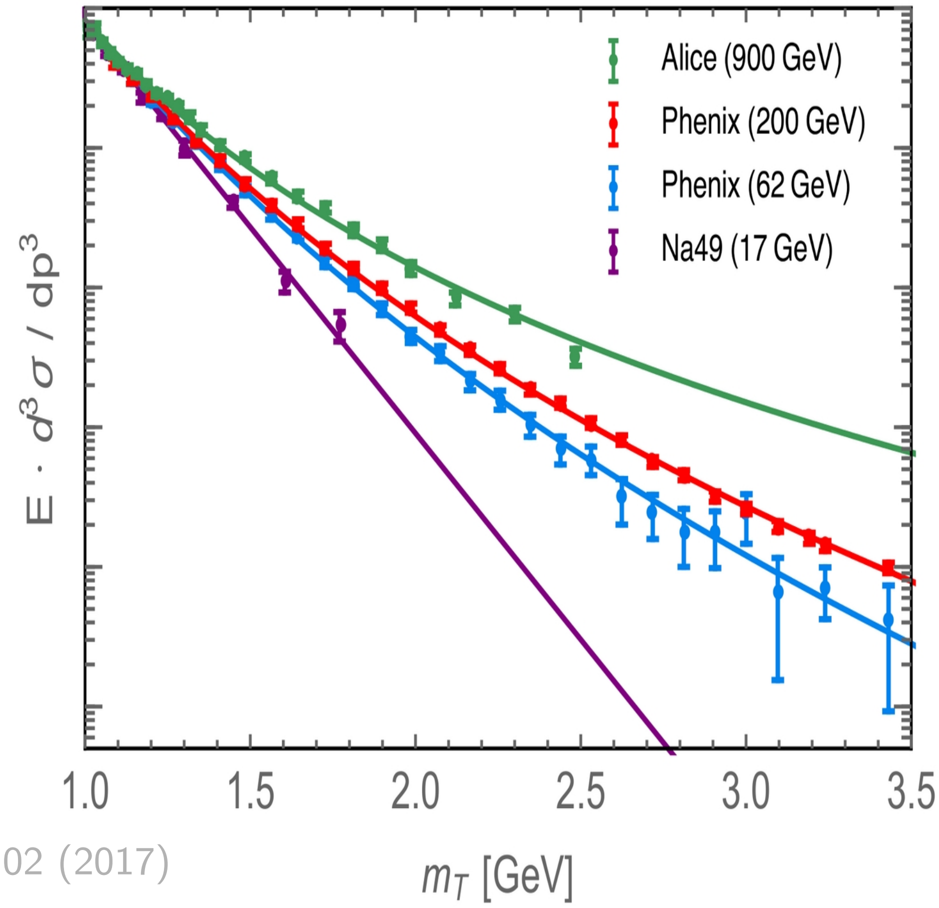
  $$E\frac{d^3\sigma^{0}_{\bar{p}}}{dp^3}(x_R,\, p_T\, \cancel{\sqrt{s}})$$ invariant cross section

updates after 2014: Kappl, M.W. JCAP 09 (2014), di Mauro et al. Phys. Rev. D90 (2014), Kachelriess et al. Astrophys. J. 803 (2015), M.W. JCAP 02 (2017), Donato et al., Phys. Rev. D 96, 043007 (2017)

Scaling Violation



M.W. JCAP 02 (2017)



scaling preserved up to

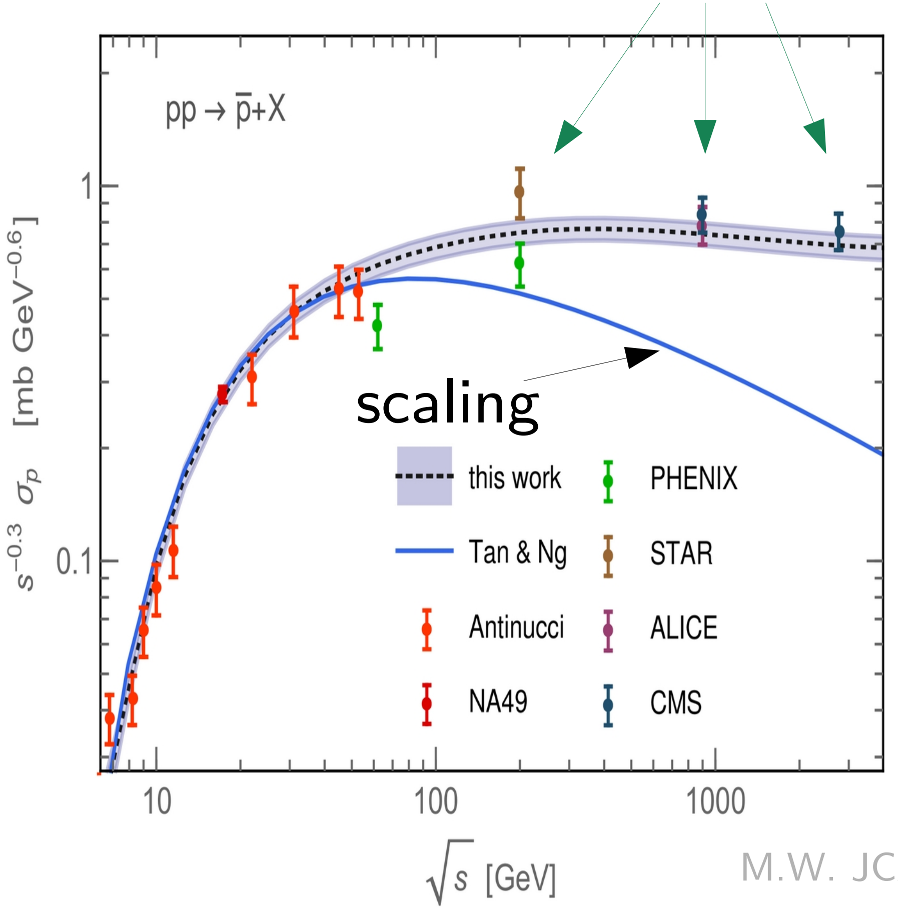
$\sqrt{s} \sim 50\,\mathrm{GeV}$

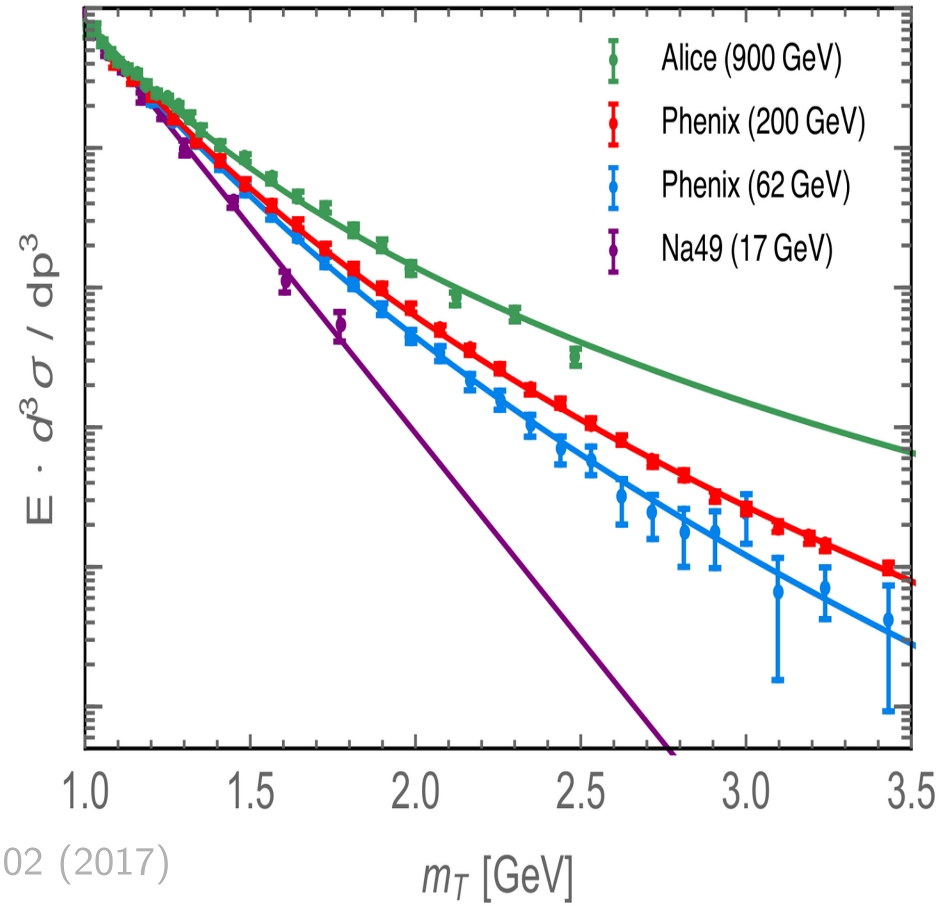
at higher energy it breaks down

due to multiple scattering

Scaling Violation

extrapolation from data at central rapidity (y~0)





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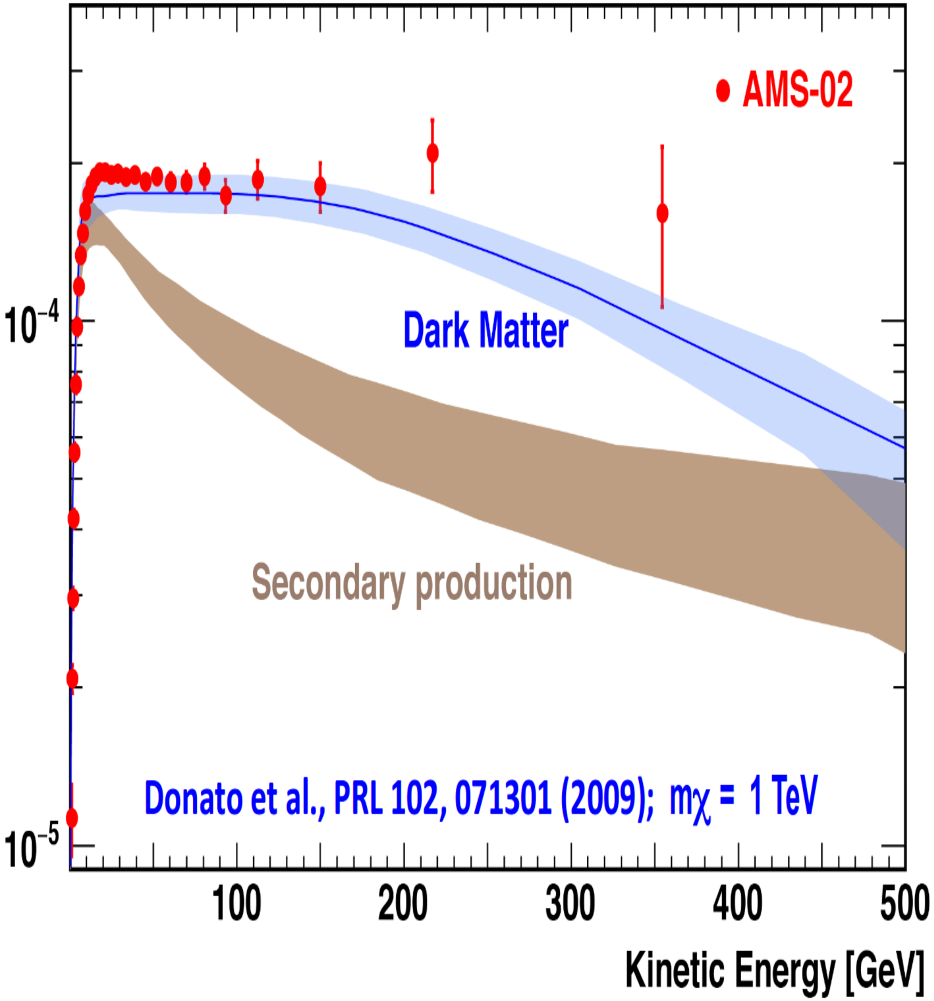
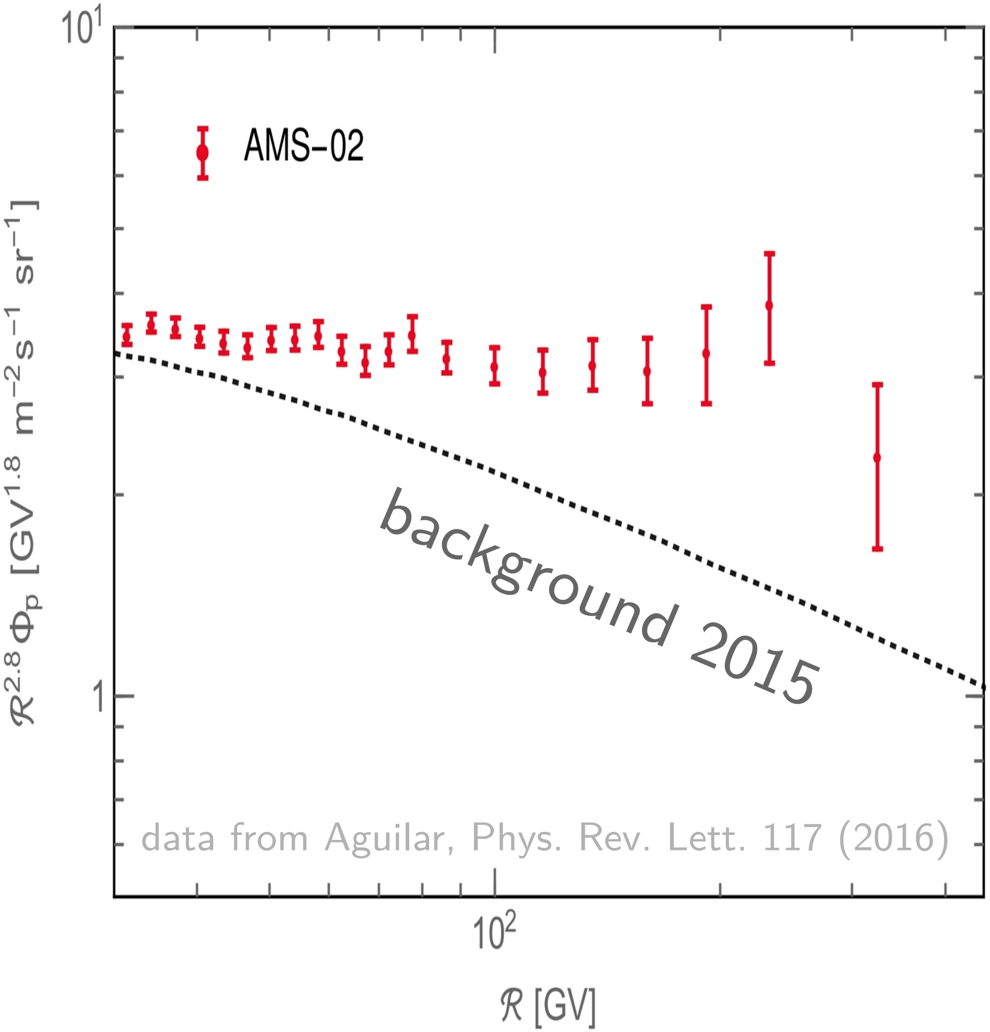
The AMS Antiproton Excess

S.Ting, A. Kounine, AMS Days at CERN (2015)





data from Aguilar, Phys. Rev. Lett. 117 (2016)

- AMS-02 antiproton excess 2015 is explained by scaling violation and updated propagation

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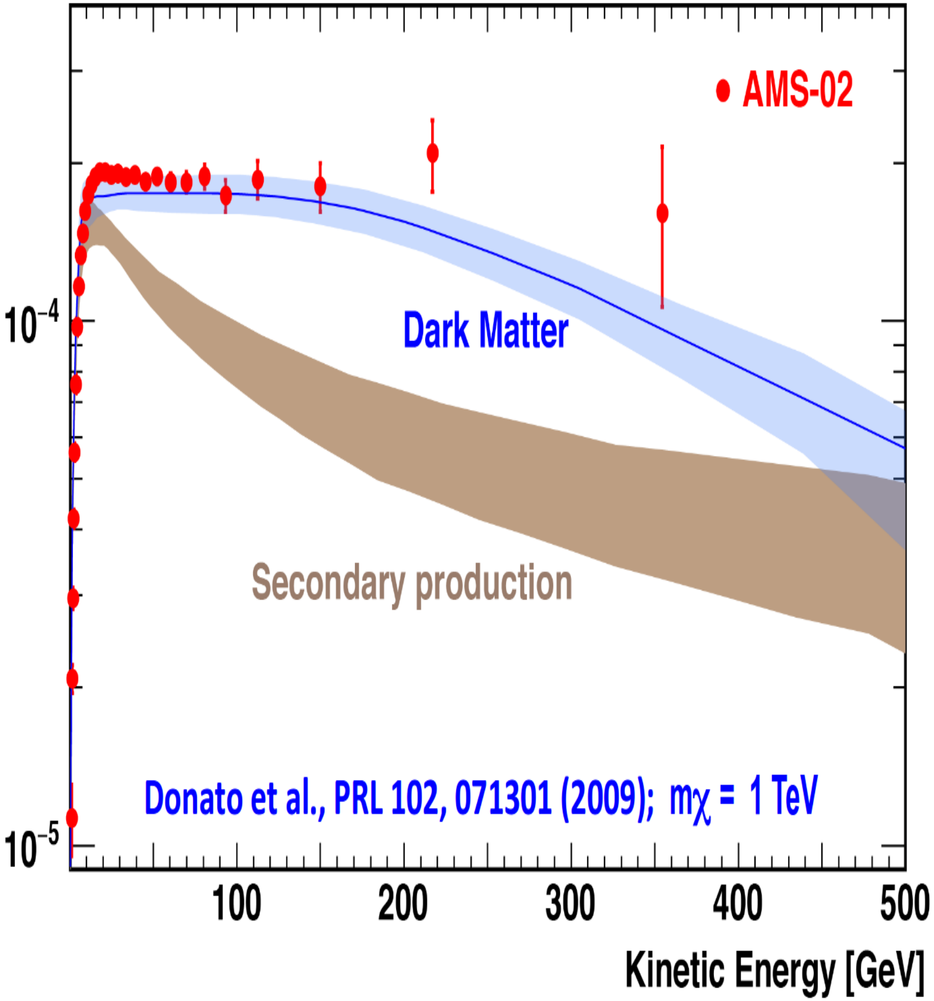

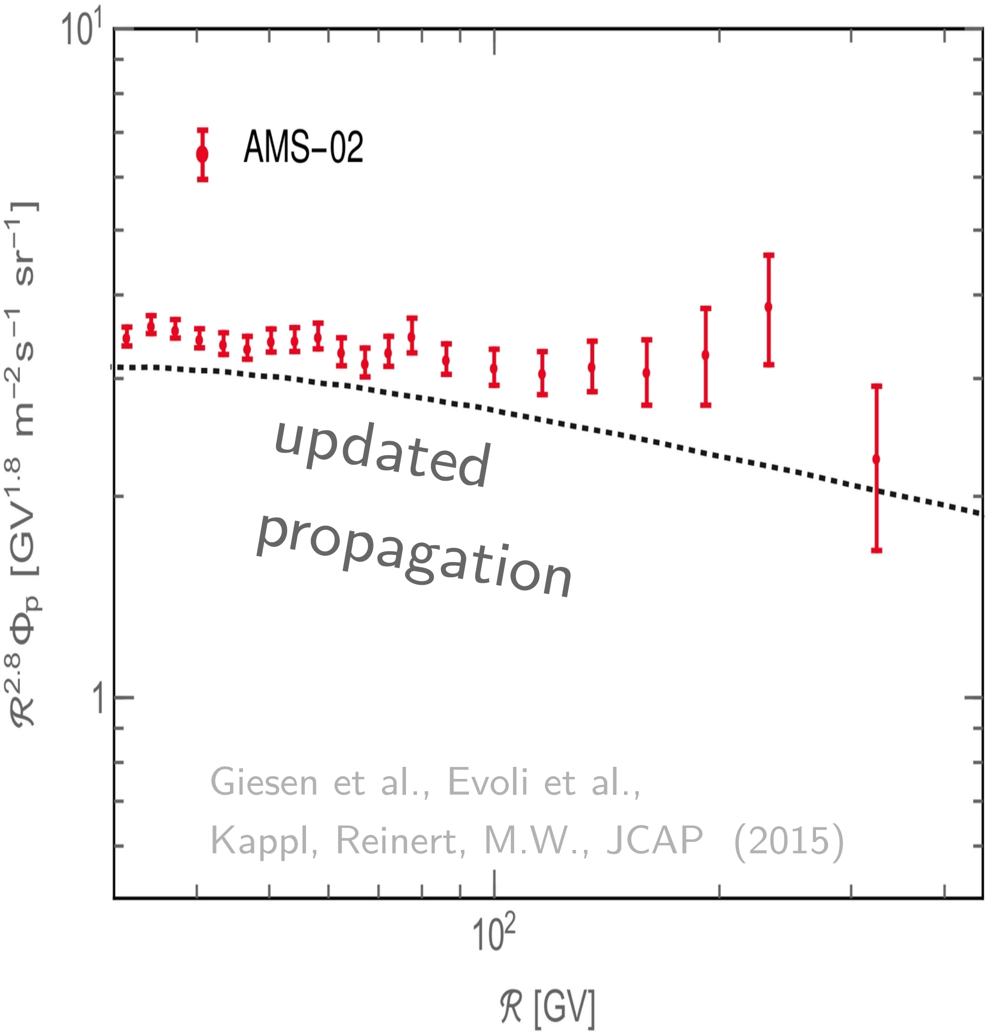

Giesen et al., Evoli et al.,
Kappl, Reinert, M.W., JCAP (2015)

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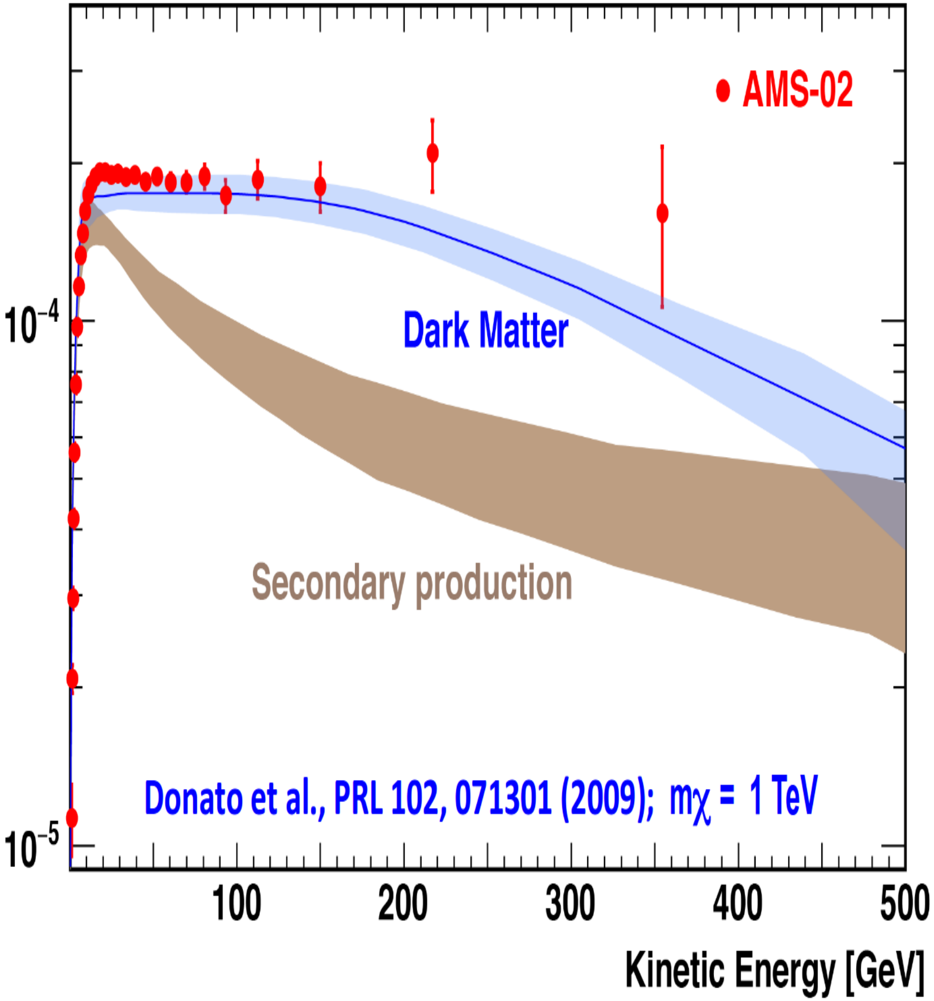

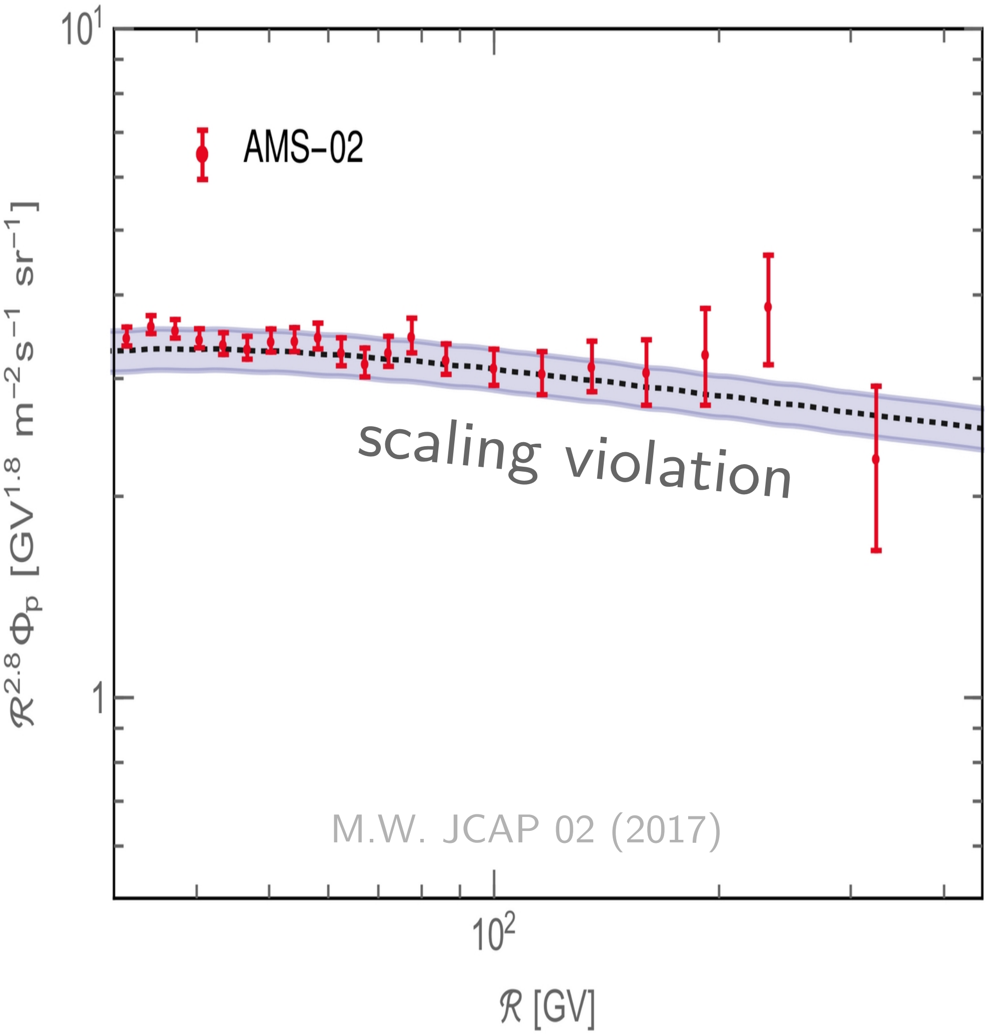

scaling violation

M.W. JCAP 02 (2017)

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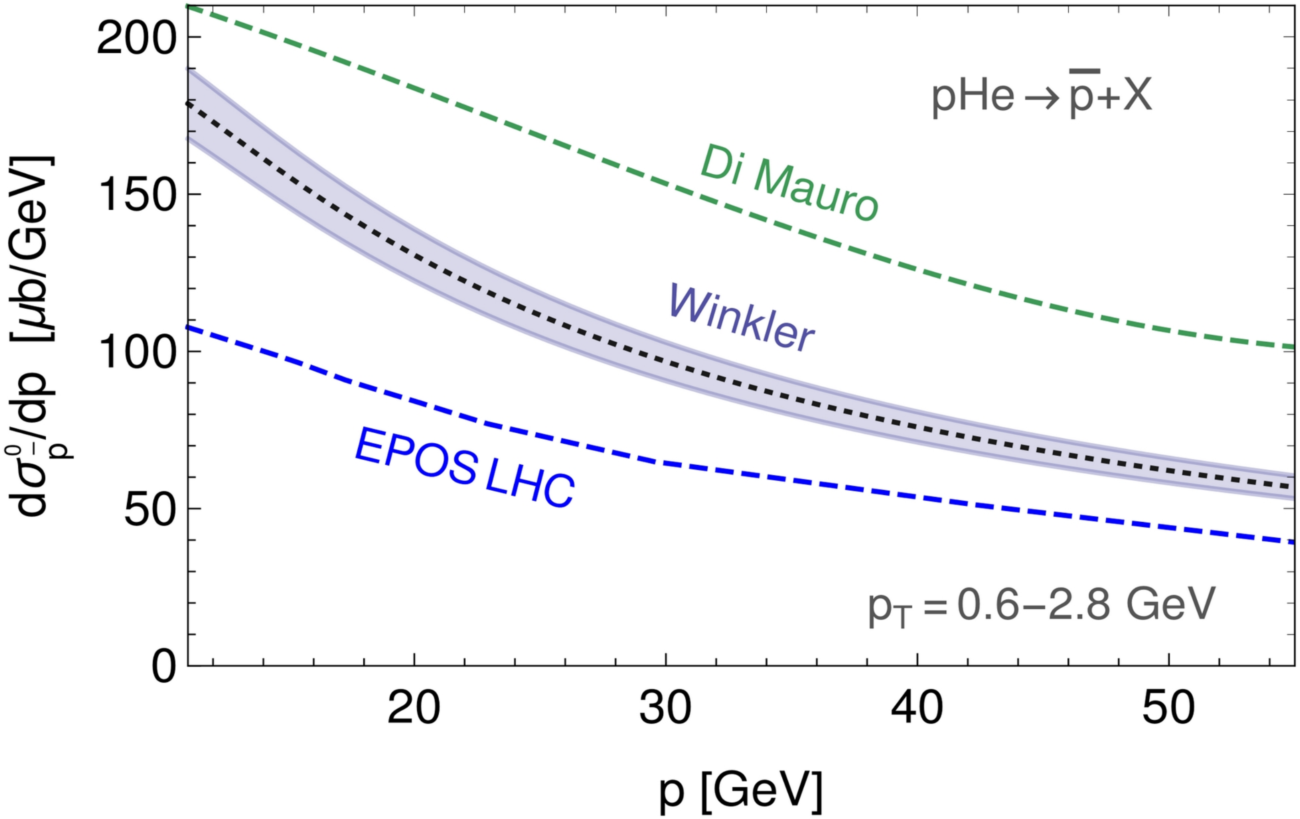
Proton Helium Scattering

- 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
  Phys.Rev.Lett. 121 (2018)



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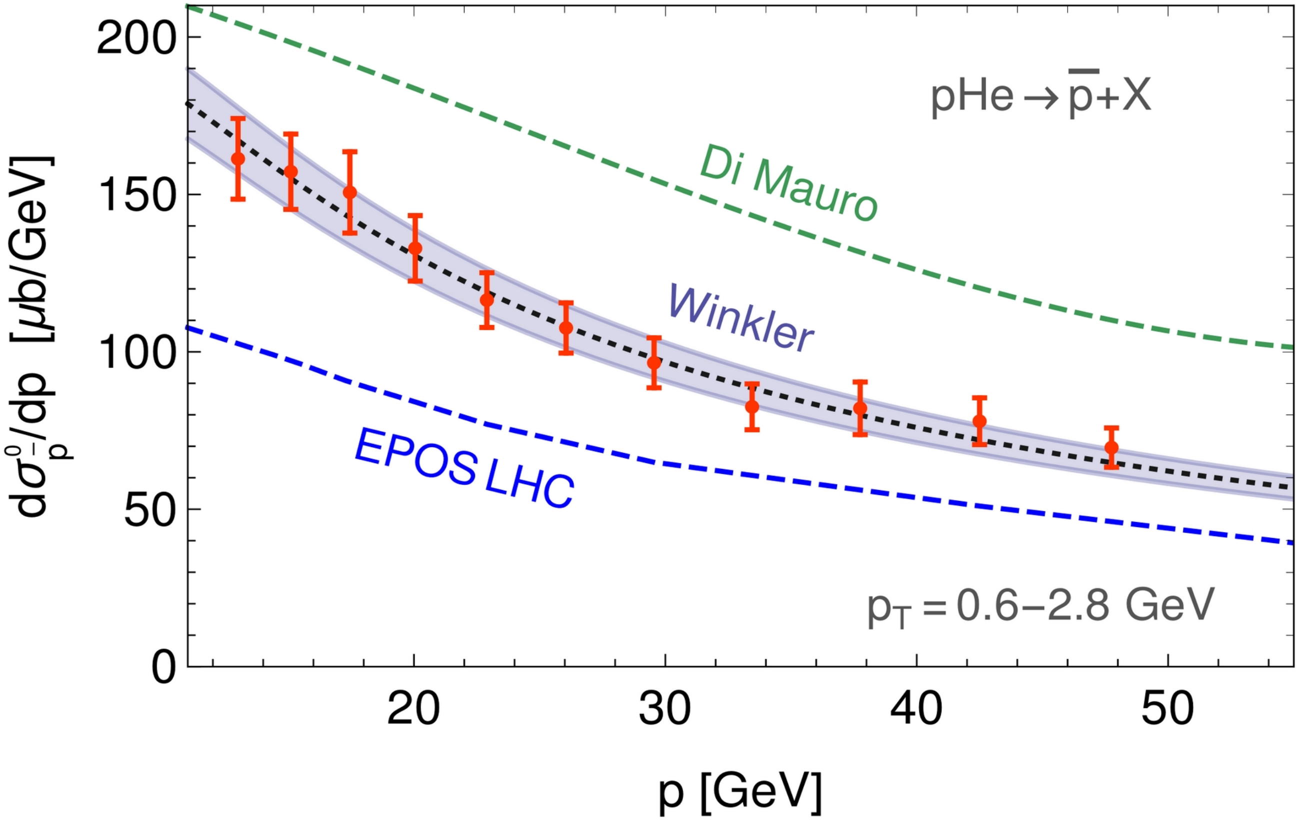
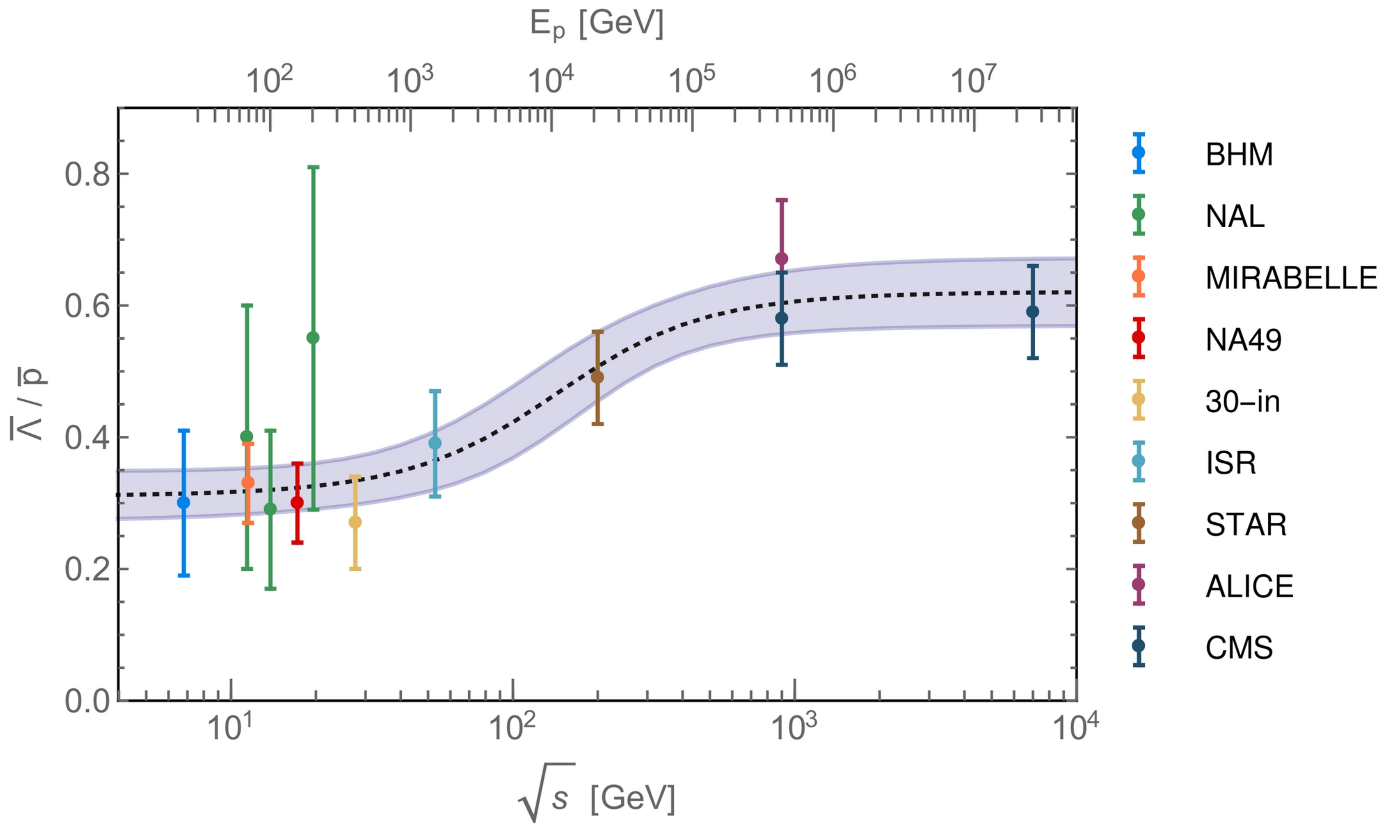


Hyperons

- 20 - 35 % of antiprotons from hyperon decay $c\tau_\Lambda \sim \text{cm}$
- increase of strangeness with collision energy



data from Blobel, Nucl. Phys. B69 (1974), Amaldi, Nucl. Phys. B86 (1975), Whitmore, Phys. Rept. 10 (1974), Kichimi, Phys. Rev. D20 (1979), Ammosov, Nucl. Phys. B115 (1976), Abelev, Phys. Rev. C75 (2007), Aamodt, Eur. Phys. J. C71 (2011), Khachatryan, JHEP 05 (2011)

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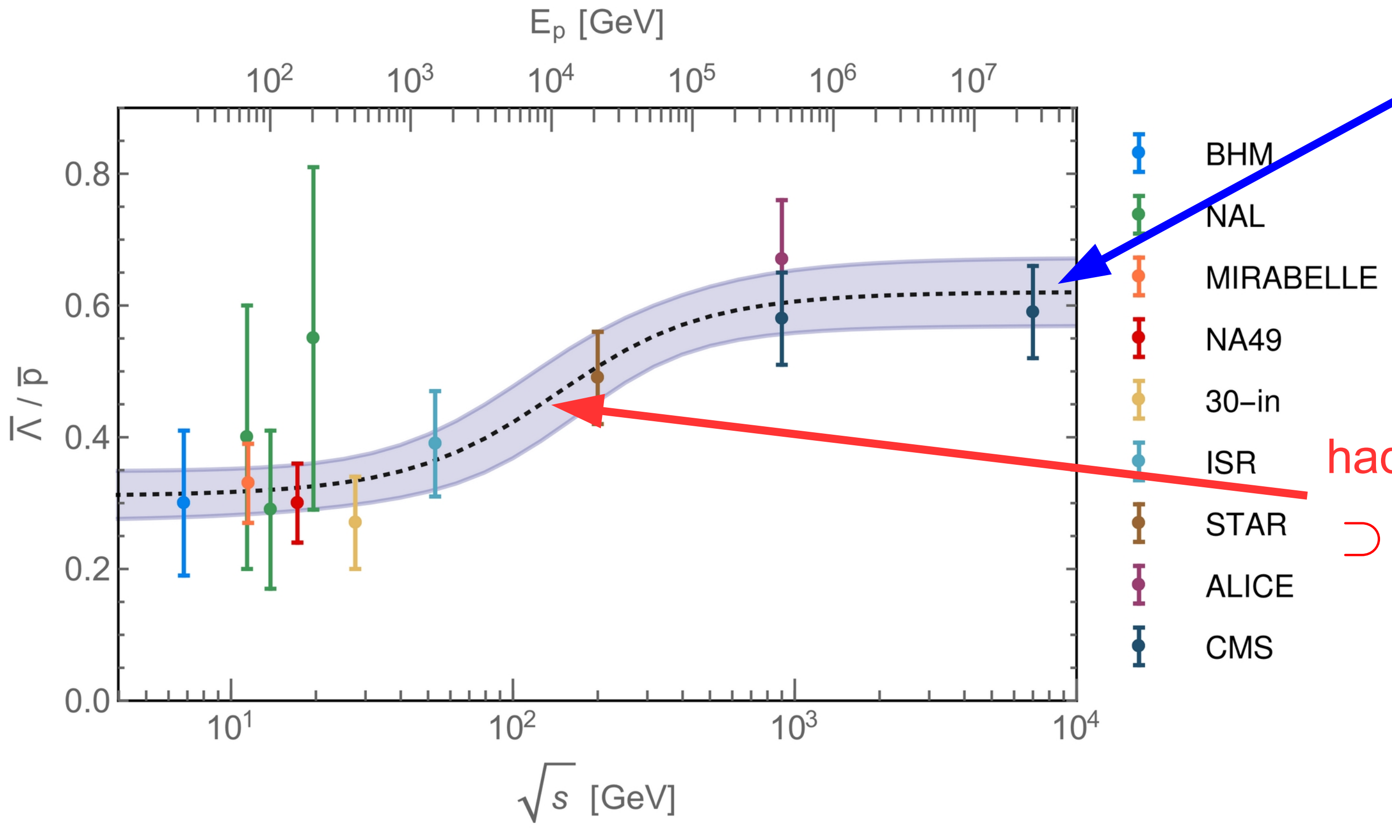

$$\frac{\bar{\Lambda}+\bar{\Sigma}}{\bar{p}+\bar{n}} \simeq 0.5$$

hadronic cross sections

$$\supset c_1/\sqrt{s} + c_2 \log \sqrt{s}$$

data from Blobel, Nucl. Phys. B69 (1974), Amaldi, Nucl. Phys. B86 (1975), Whitmore, Phys. Rept. 10 (1974), Kichimi, Phys. Rev. D20 (1979), Ammosov, Nucl. Phys. B115 (1976), Abelev, Phys. Rev. C75 (2007), Aamodt, Eur. Phys. J. C71 (2011), Khachatryan, JHEP 05 (2011)

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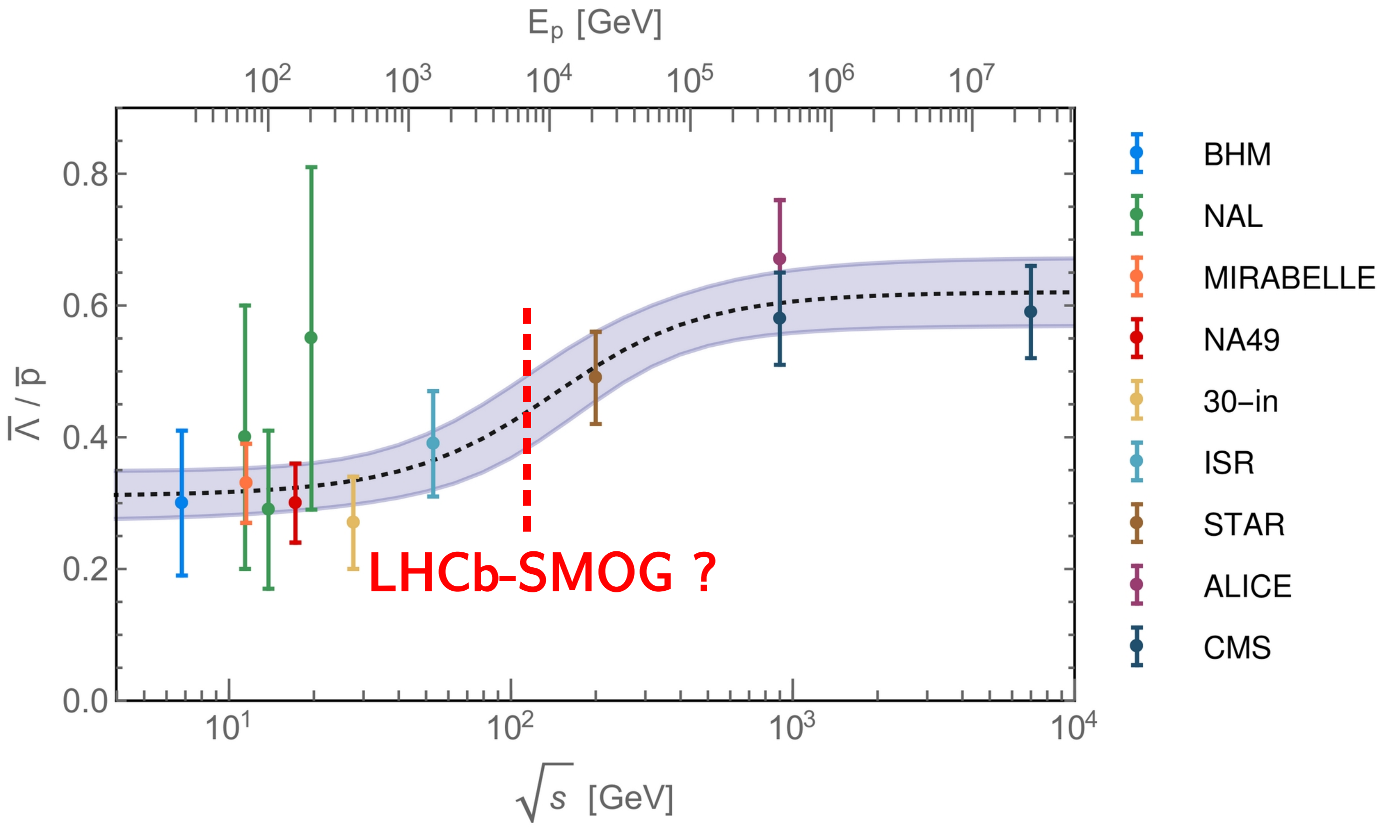

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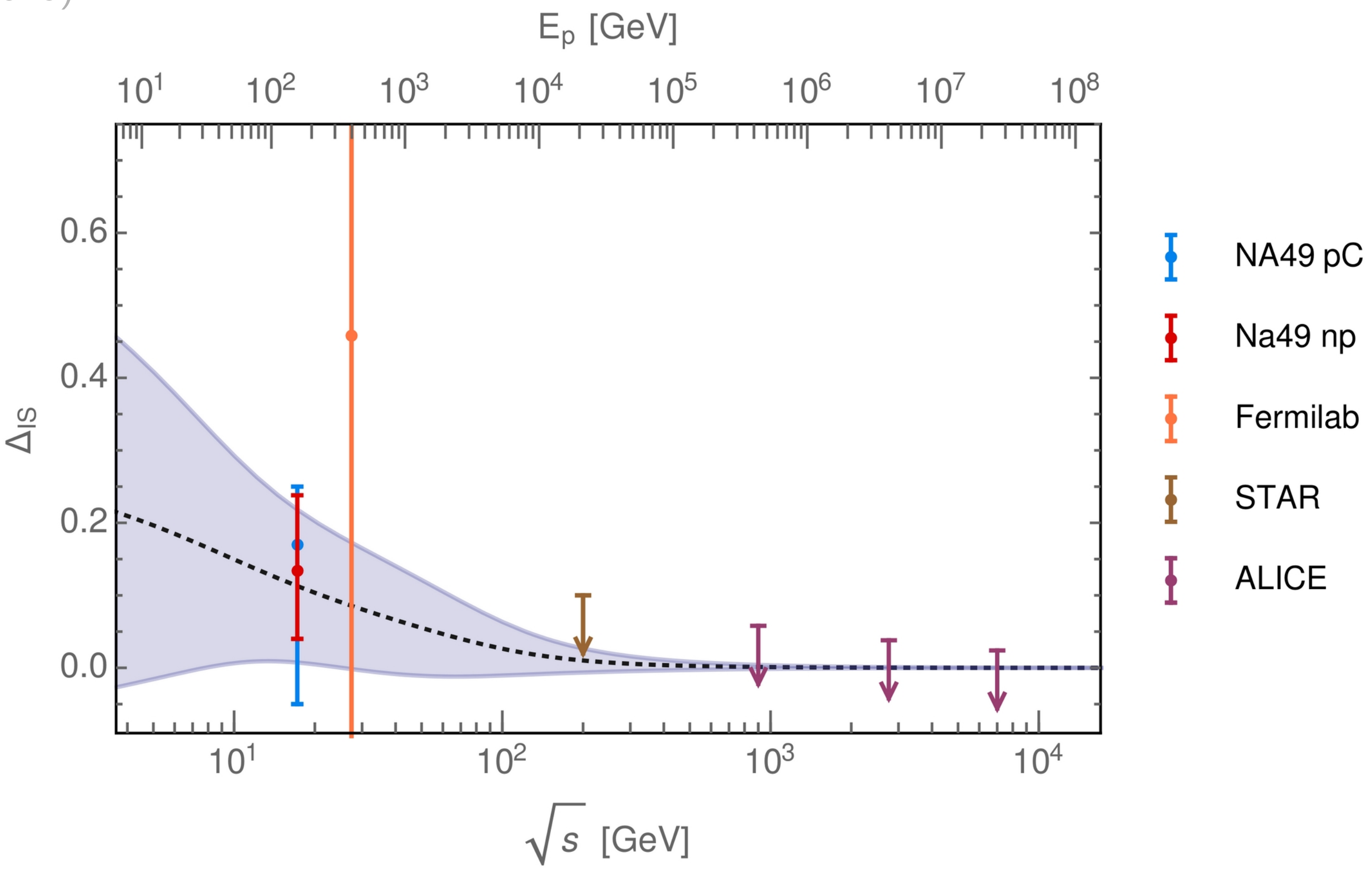
Isospin Effects in Antineutron Production

- (anti)baryon produced in pairs $\mathrm{p\bar{p}}\,,\mathrm{\bar{n}n}\,,\mathrm{\bar{n}p}\,,\mathrm{\bar{p}n}$

possible asymmetry due to isocharge

- accessible through $\dfrac{\mathrm{pn}\rightarrow\mathrm{\bar{p}}}{\mathrm{pp}\rightarrow\mathrm{\bar{p}}}$ and symmetry arguments, $\dfrac{\mathrm{\bar{p}}}{\mathrm{p}}$ ratio

Fischer, Heavy Ion Phys. 17 (2003), Baatar, Eur. Phys. J. C73 (2013), Aamodt et al., Phys. Rev. Lett. 105 (2010)



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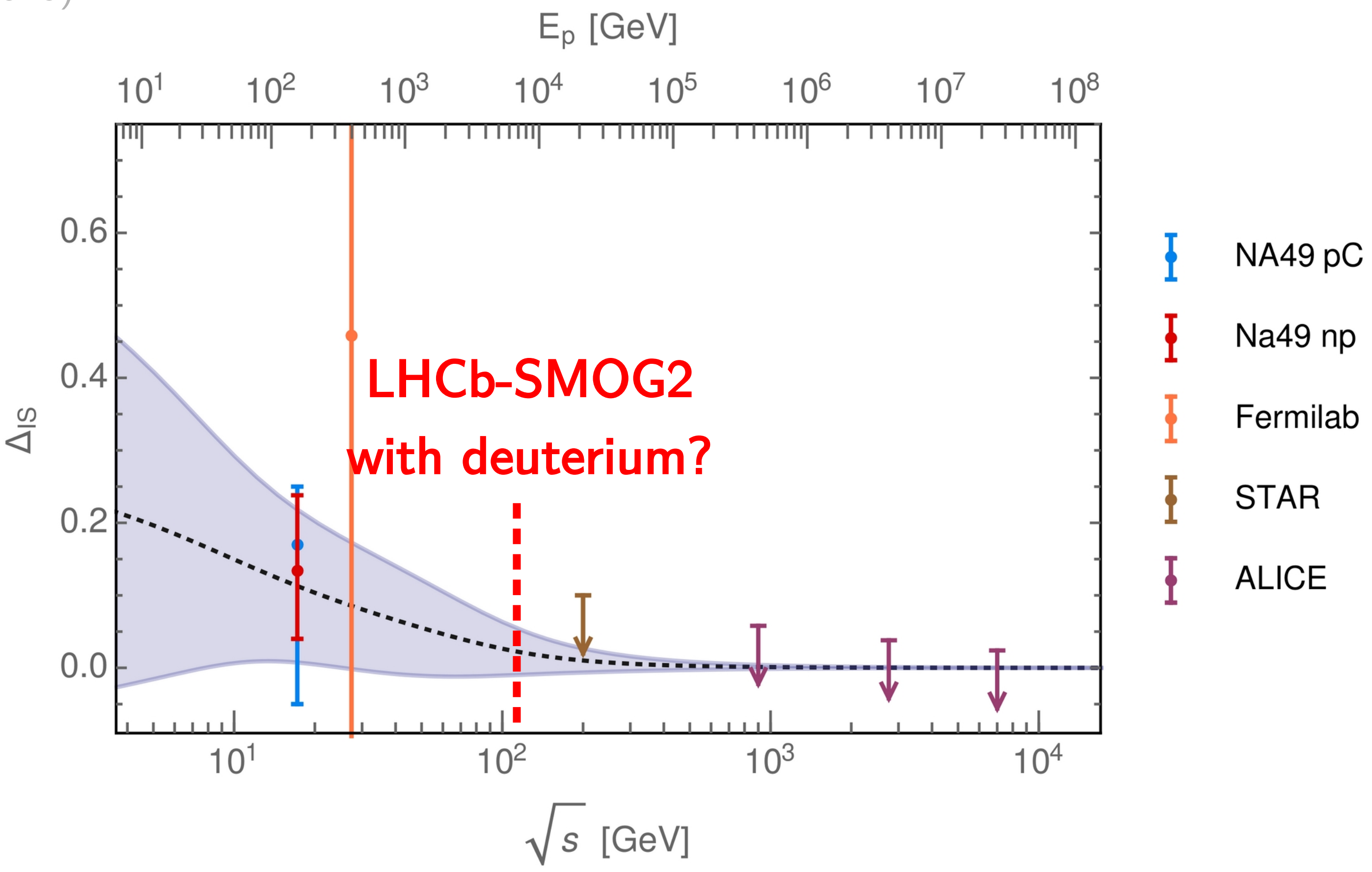
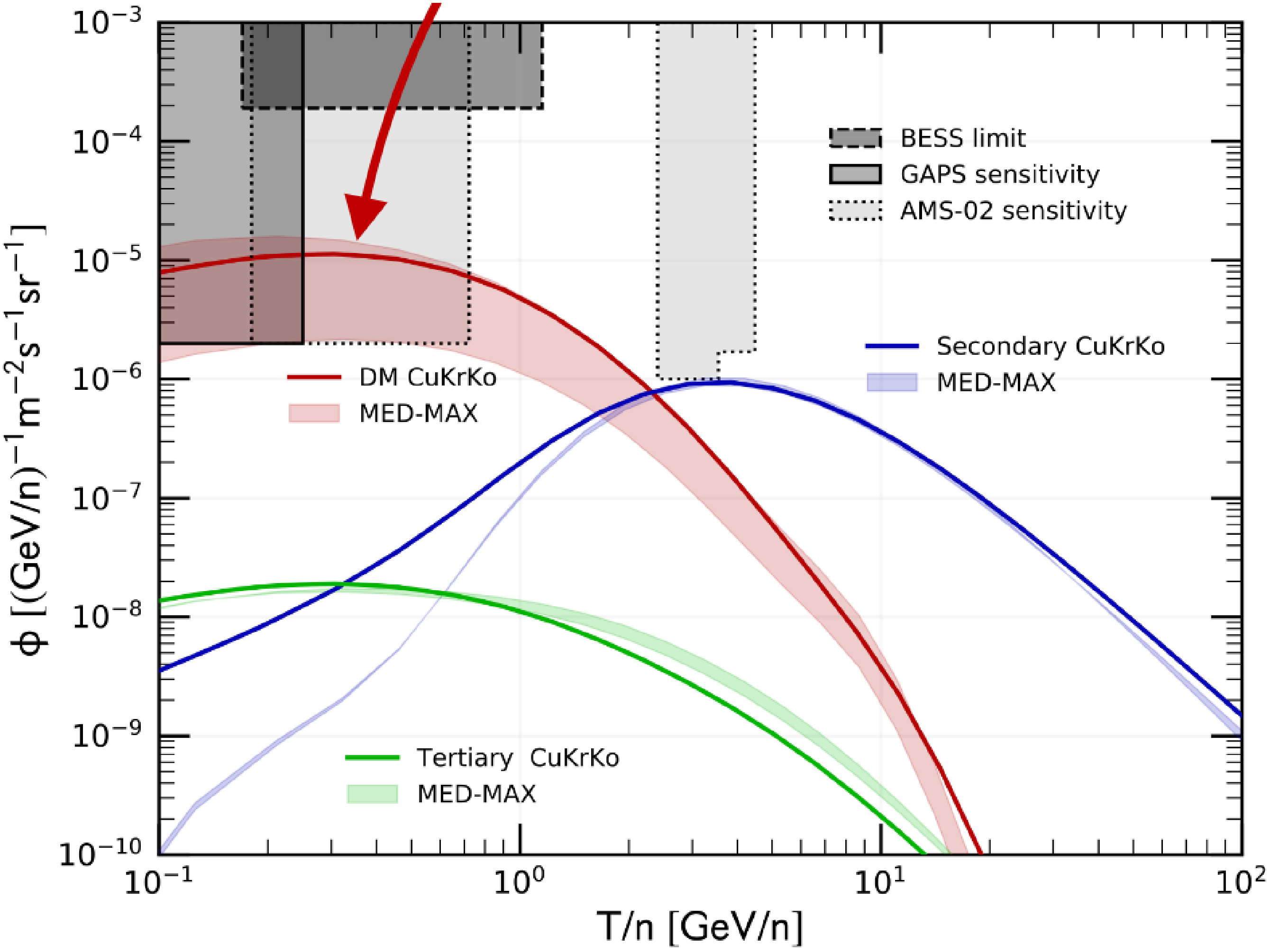


LHCb-SMOG2 with deuterium?

Antideuterons: The Smoking Gun Channel

antideuteron signal for dark matter candidate motivated by galactic center gamma ray excess



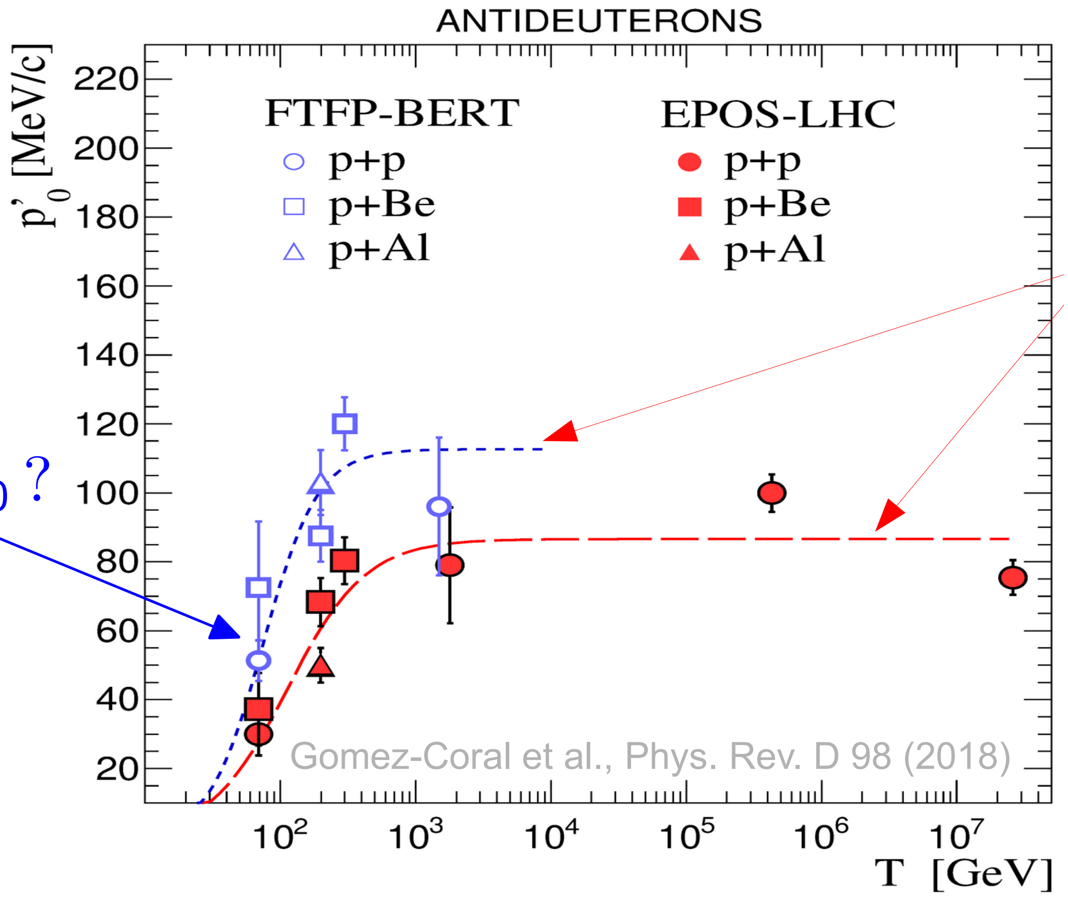
Korsmeier, Donato, Fornengo, Phys.Rev. D97 (2018)

Antideuteron Coalescence

- coalescence model: proton and neutron merge if $|\Delta \mathbf{p}| < p_0$

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

coalescence momentum



Gomez-Coral et al., Phys. Rev. D 98 (2018)

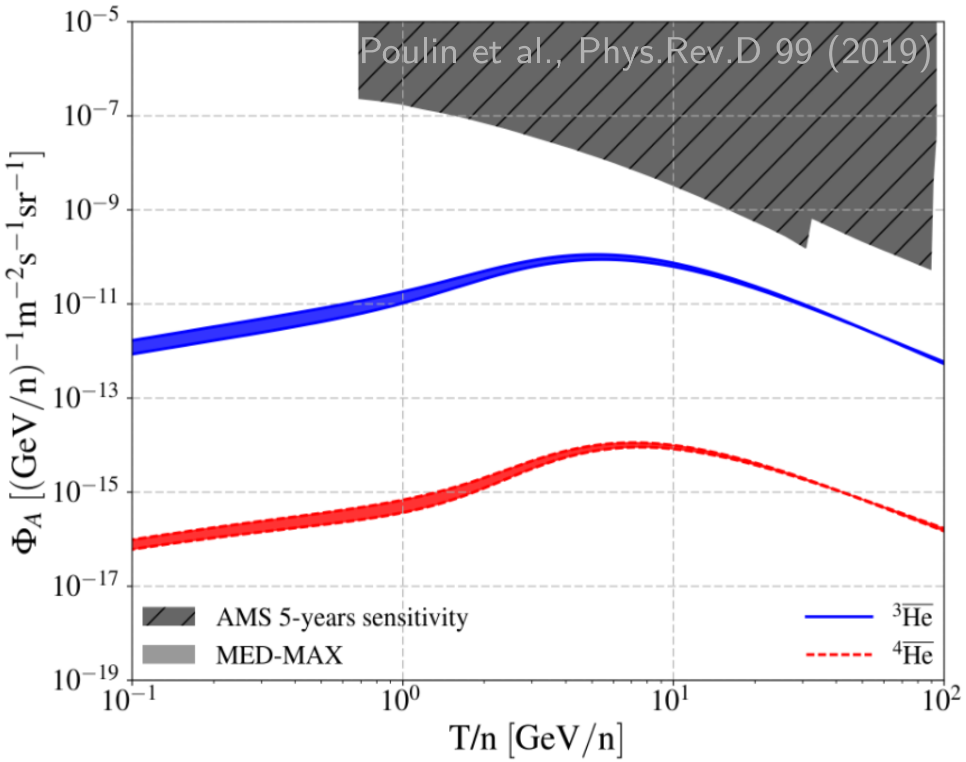
decrease of p_0 ?

antinucleon spectra differ between MCs

- $\overline{\mathrm{p}}$ and $\overline{\mathrm{d}}$ from same experiment very helpful: **NA61/SHINE, ALICE, LHCb?**

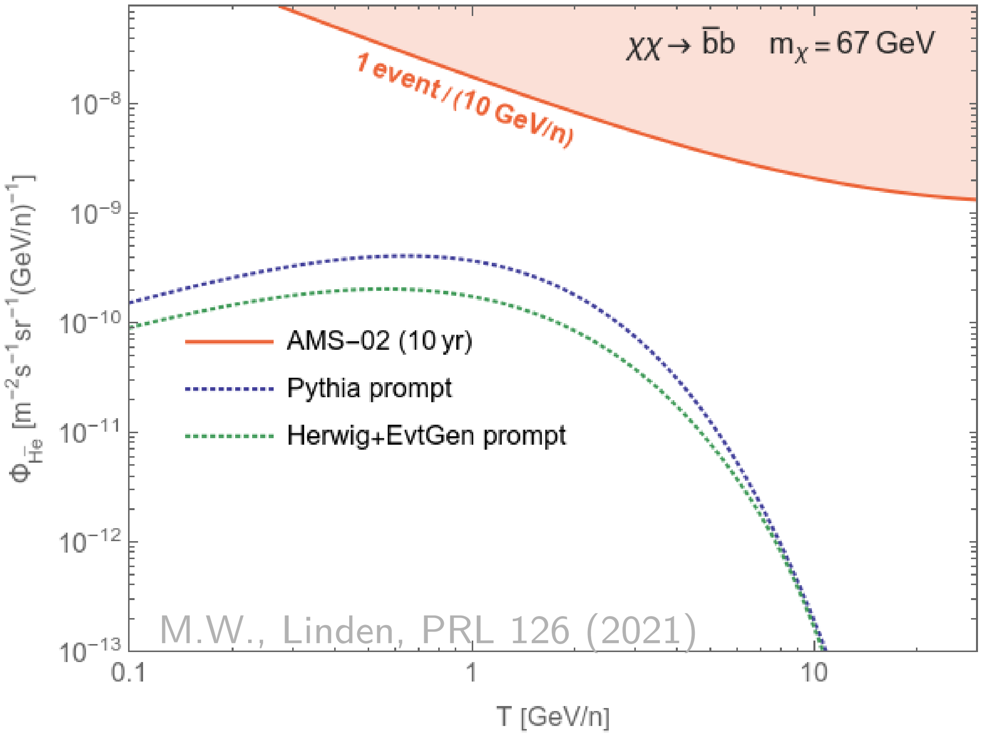
Cosmic Ray Antihelium

astrophysical background



Poulin et al., Phys.Rev.D 99 (2019)

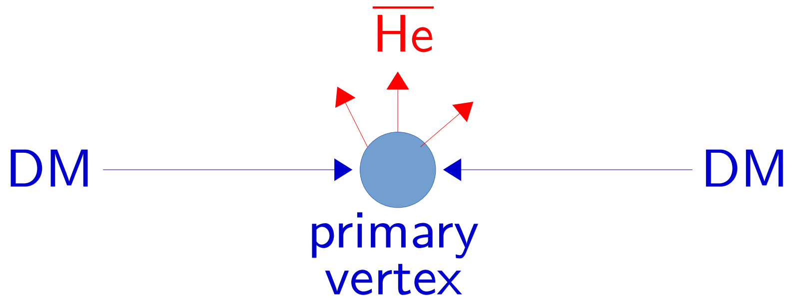
dark matter annihilation



M.W., Linden, PRL 126 (2021)

- tentative detection of ~10 He events at AMS-02

S. Ting, CERN Colloquium 2016,
Science Magazine 2017



$\overline{\mathrm{He}}$

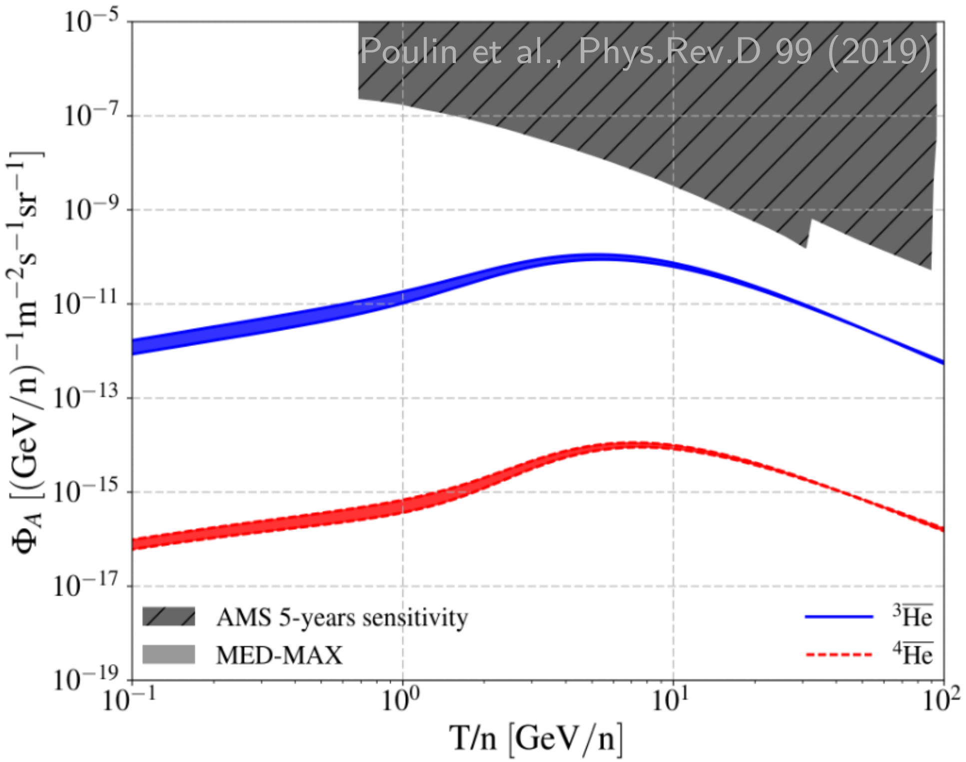
DM

DM

primary
vertex

Cosmic Ray Antihelium

astrophysical background



Poulin et al., Phys.Rev.D 99 (2019)

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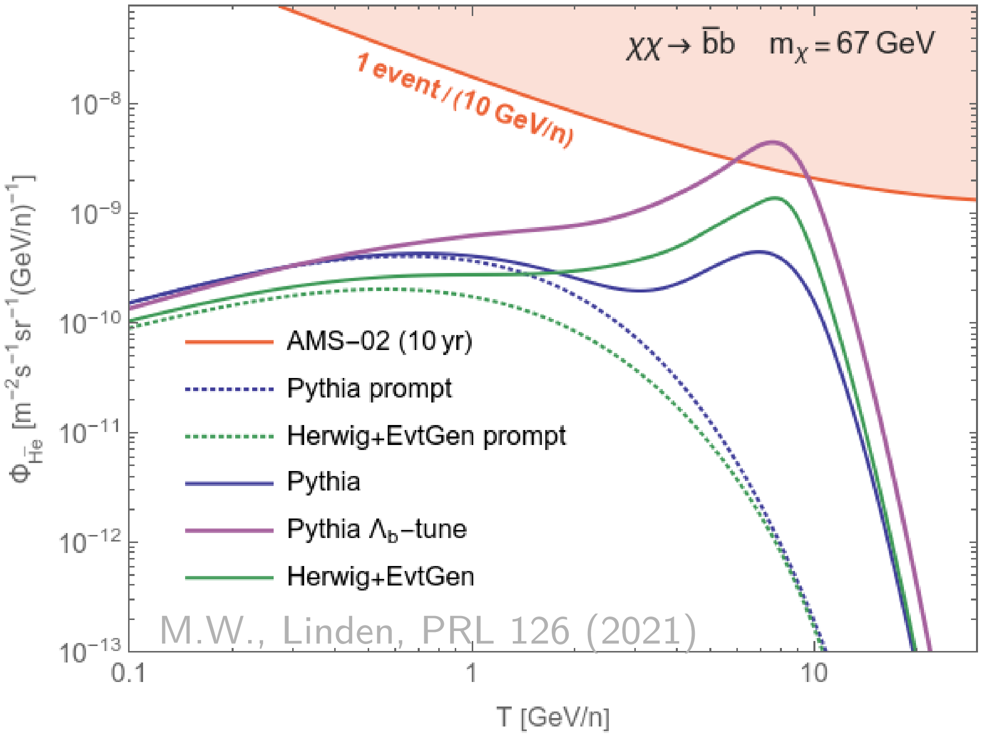

M.W., Linden, PRL 126 (2021)

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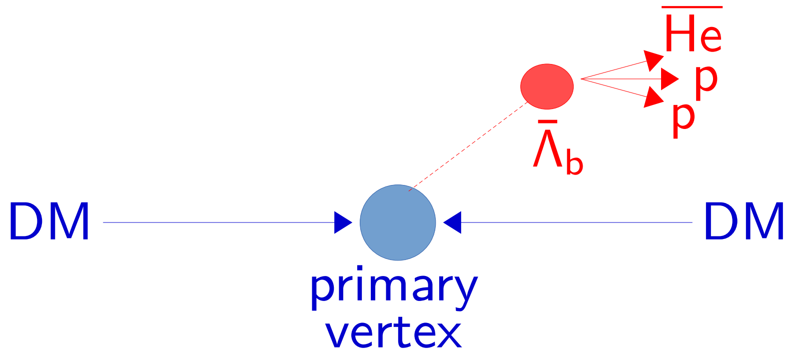
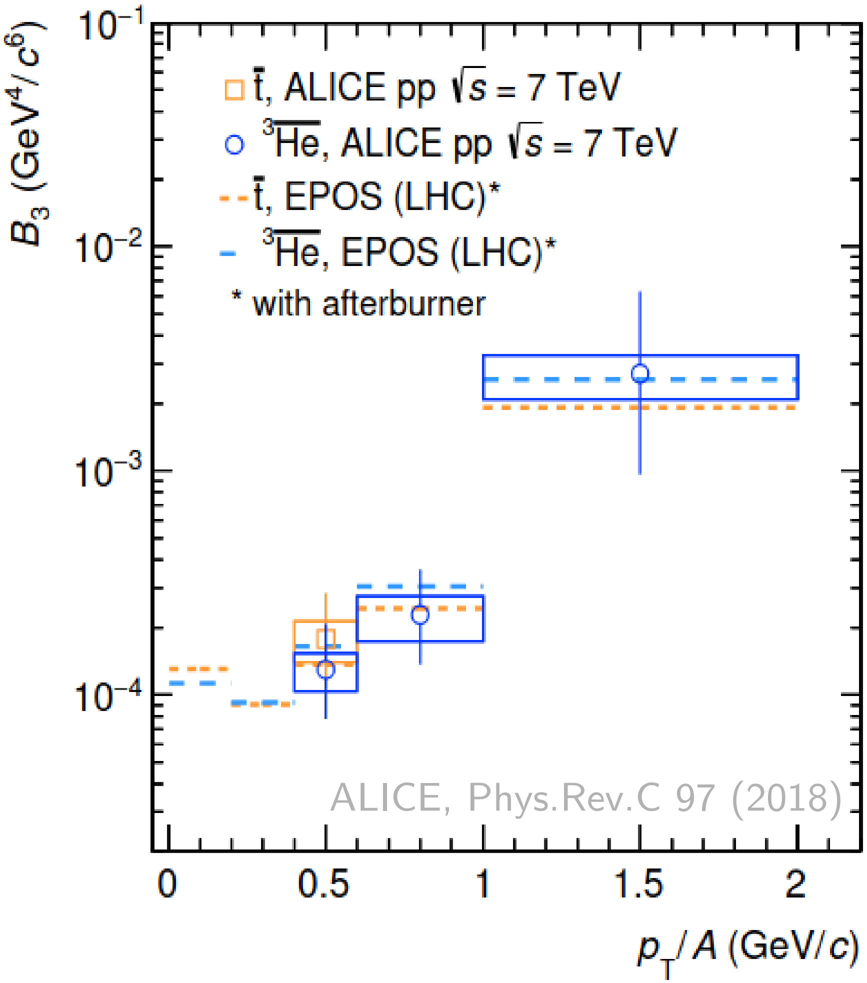


Antihelium at LHC



- first antihelium measurement in pp-collisions at ALICE

$$\int \mathrm{dt\,L} = 4\mathrm{nb}^{-1}$$

- cross section for displaced $\overline{\text{He}}$

$$\sigma_{\overline{\mathrm{He}}} = \underset{\mathcal{O}(0.1\,\mathrm{mb})}{\underset{\uparrow}{\sigma_{\mathrm{pp}\to\bar{\Lambda}_b}}} \times \underset{\mathcal{O}(10^{-6})}{\underset{\uparrow}{\mathrm{Br}(\bar{\Lambda}_b \to \overline{\mathrm{He}})}} \sim 0.1\,\mathrm{nb}$$

slightly below ALICE sensitivity

more data on **inclusive** $\overline{\textbf{He}}$ would be exciting! Direct measurement of $\bar{\boldsymbol{\Lambda}}_b \to \overline{\mathbf{He}} + \mathbf{pp}$ even better! ► ALICE, LHCb, CMS, ATLAS?

Outlook

- Cosmic ray physics crucially relies on accelerator data

- key measurements antiprotons:

$\mathrm{p\,p\,(H_2) \rightarrow \bar{p}}$	scaling violation in forward hemisphere
$\mathrm{p\,p,\ p\,He \rightarrow \bar{\Lambda},\ \bar{\Sigma}}$	hyperons
$\mathrm{p\,d \rightarrow \bar{p}}$	isospin effects

- key measurements antinuclei

$\mathrm{p\,p,\ p\,He \rightarrow \bar{d}}$	coalescence momentum
$\mathrm{p\,p \rightarrow \bar{\Lambda}_b \rightarrow \overline{He} + pp}$	antihelium from dark matter?

- many additional measurements interesting for positron flux, CR spallation, CR interaction with detector & atmosphere ...