Cosmic Rays in Space

Martin W. Winkler

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

Second LHCb Heavy Ion Workshop

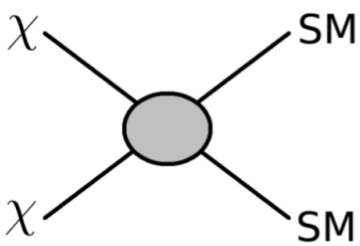
Chia

September 5, 2019

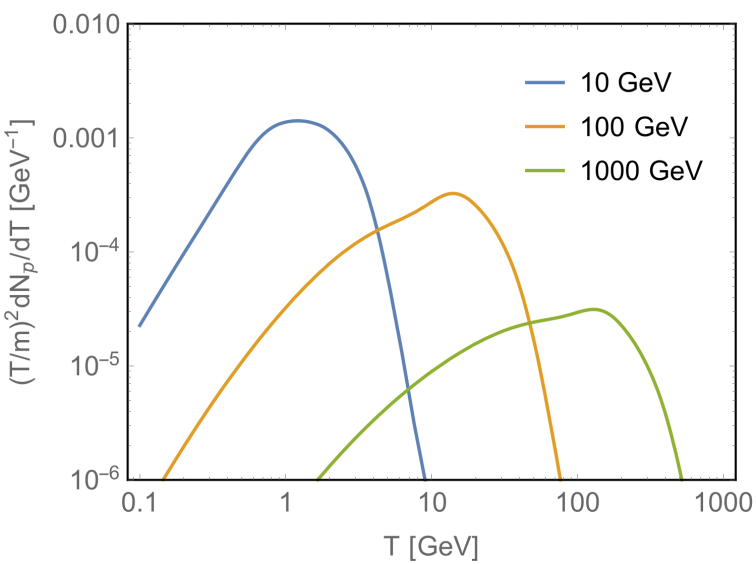
Antiprotons in Cosmic Rays

primary antiprotons

- dark matter annihilation

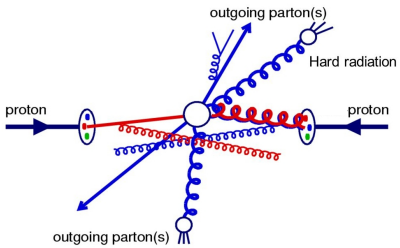


- smooth spectrum

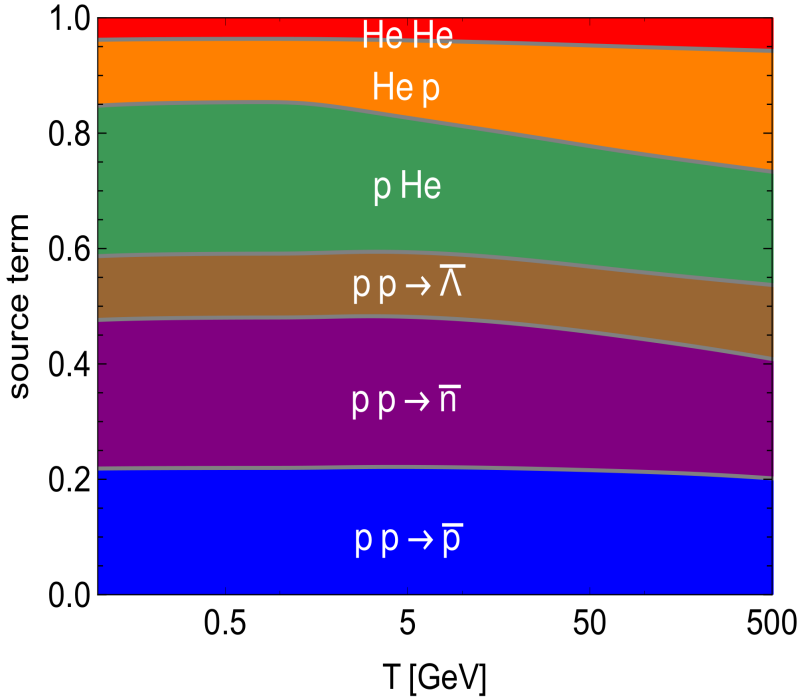


secondary antiprotons

- 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

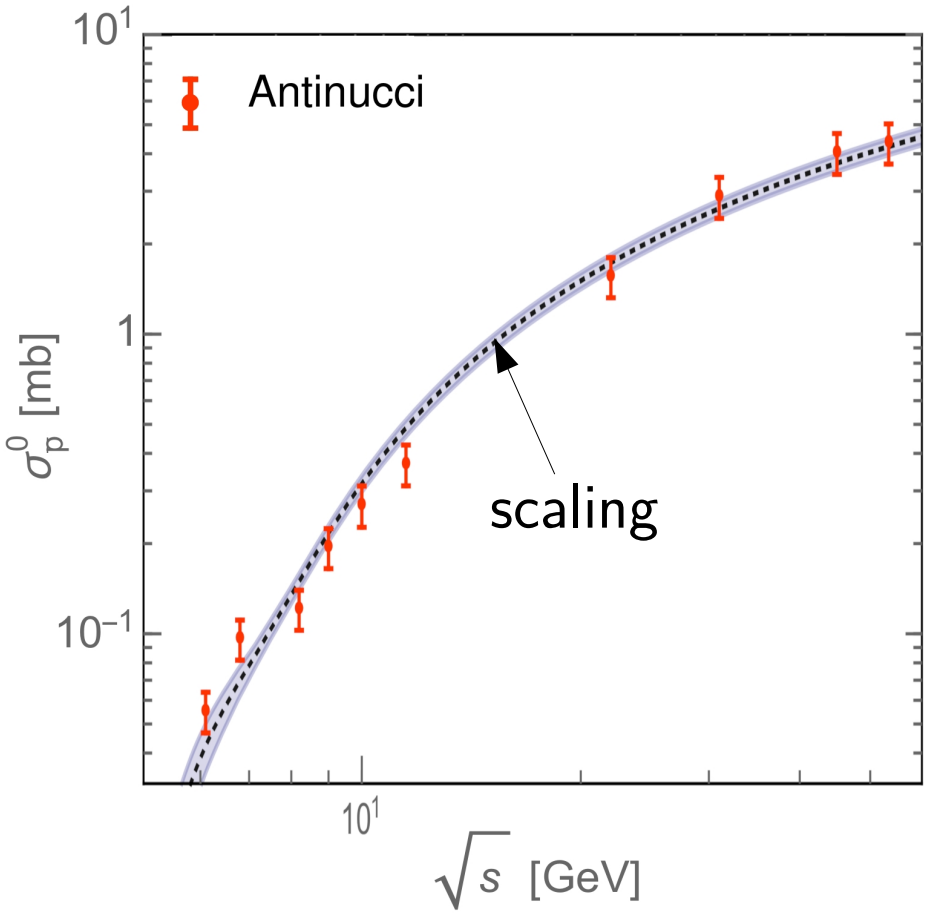
  Feynman, Phys. Rev. Lett. 23 (1969), Taylor et al. Phys. Rev. D14 (1976)

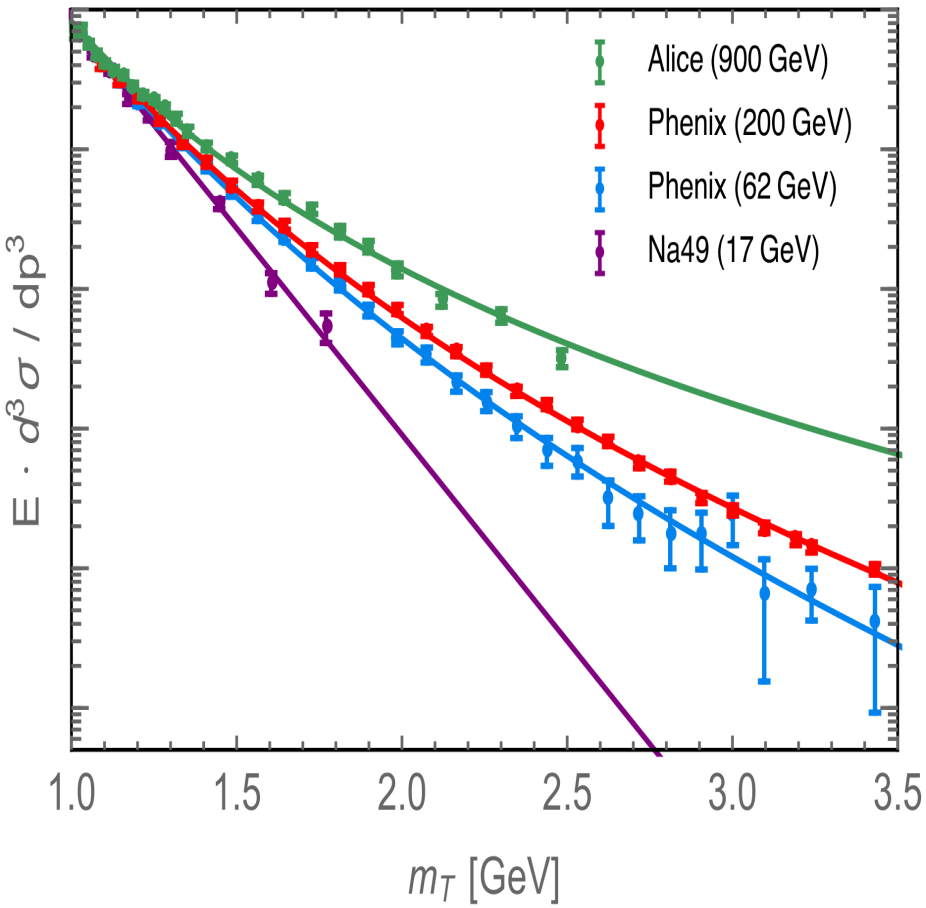
$$x_R = \frac{E}{E_{\max}}$$ scaling variable

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



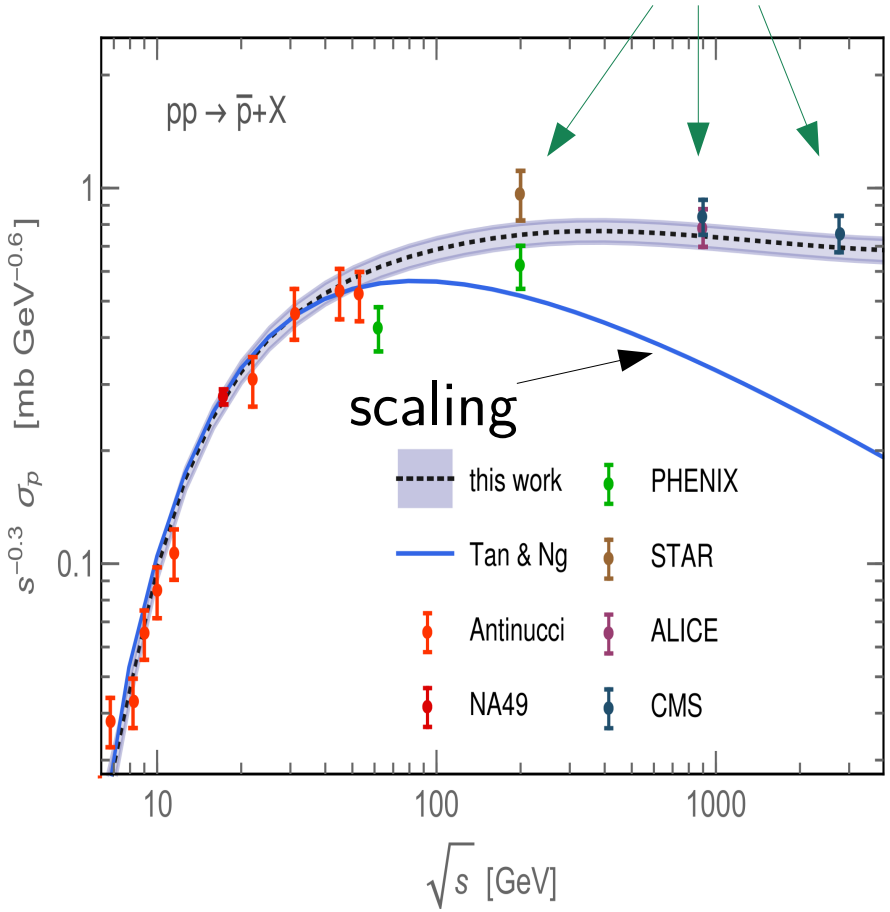


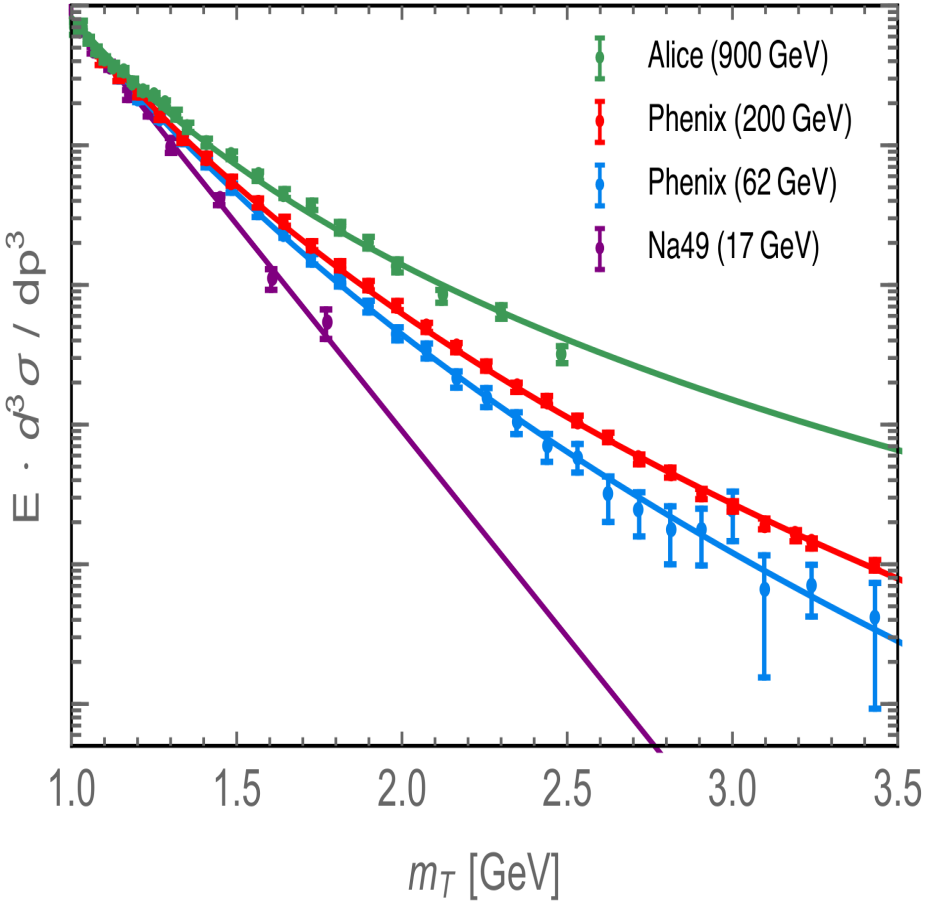
scaling preserved up to $\sqrt{s} \sim 50\ \mathrm{GeV}$

at higher energy it breaks down due to multiple scattering

Scaling Violation

extrapolation from data at central rapidity (y~0)





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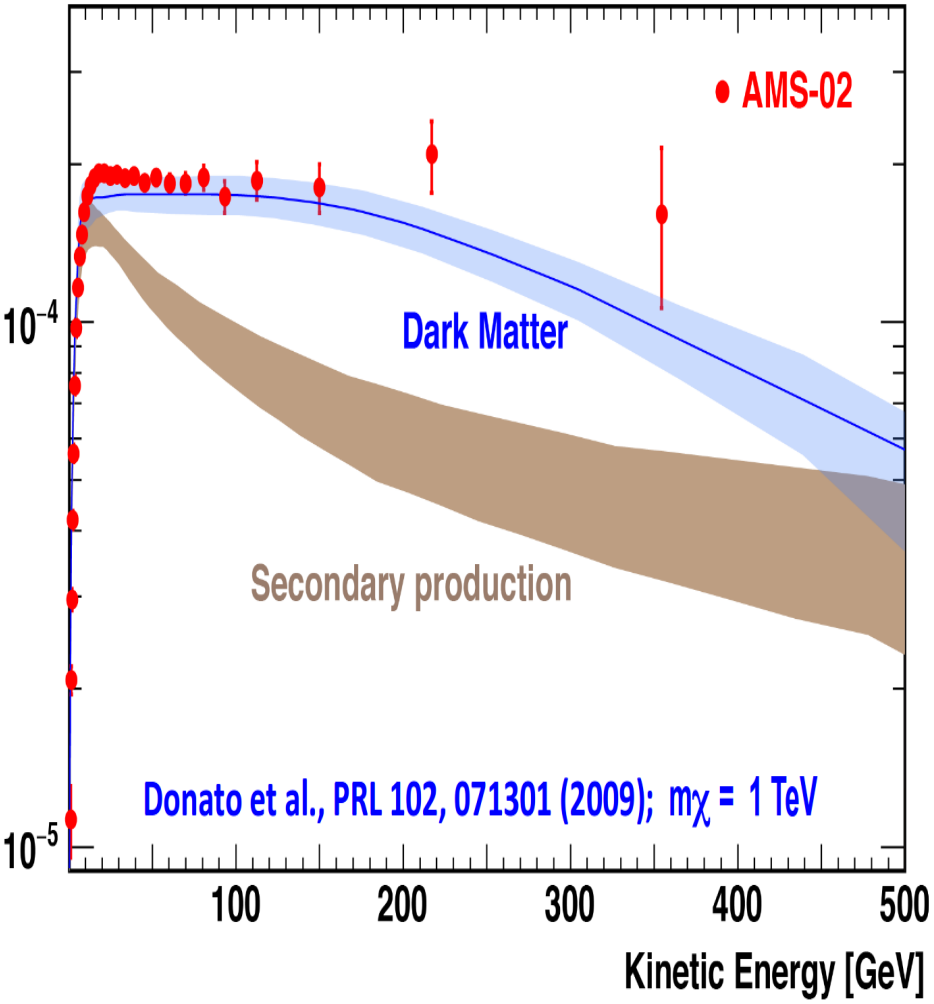
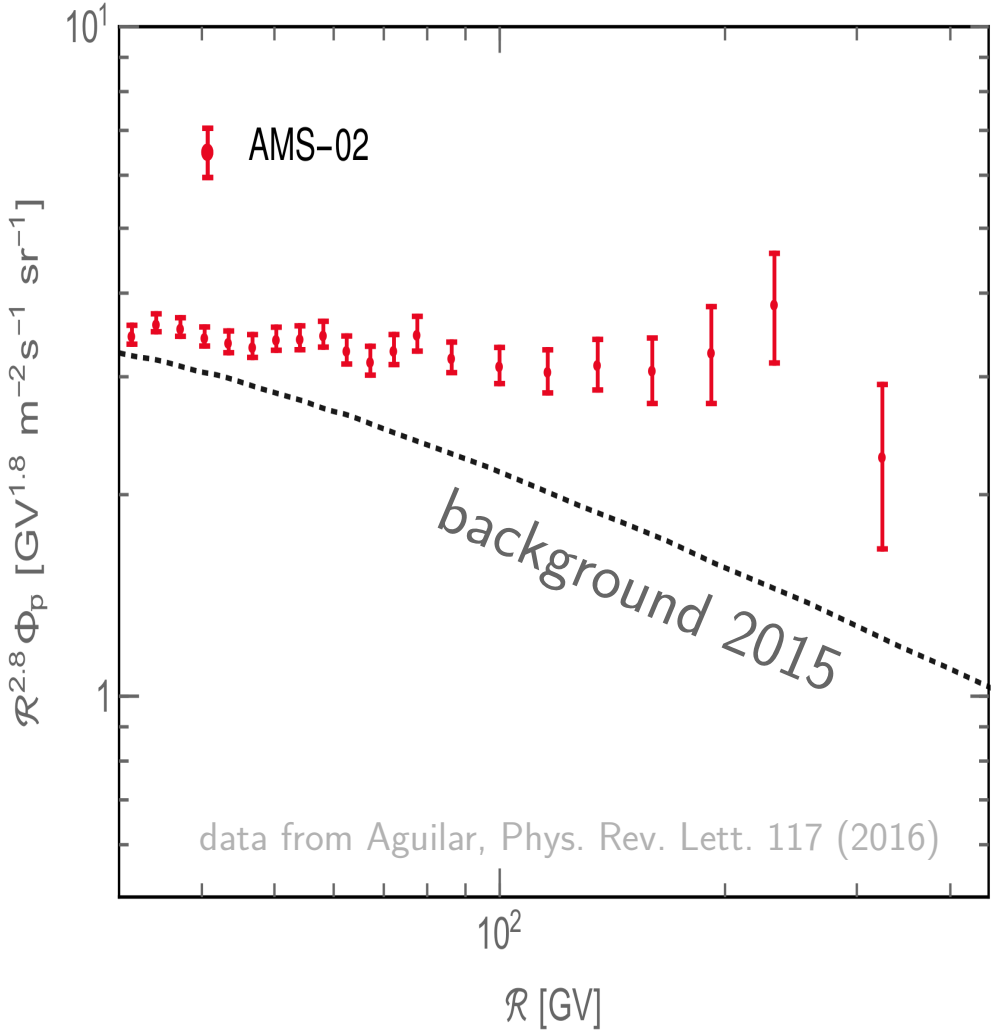
The AMS Antiproton Excess

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





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

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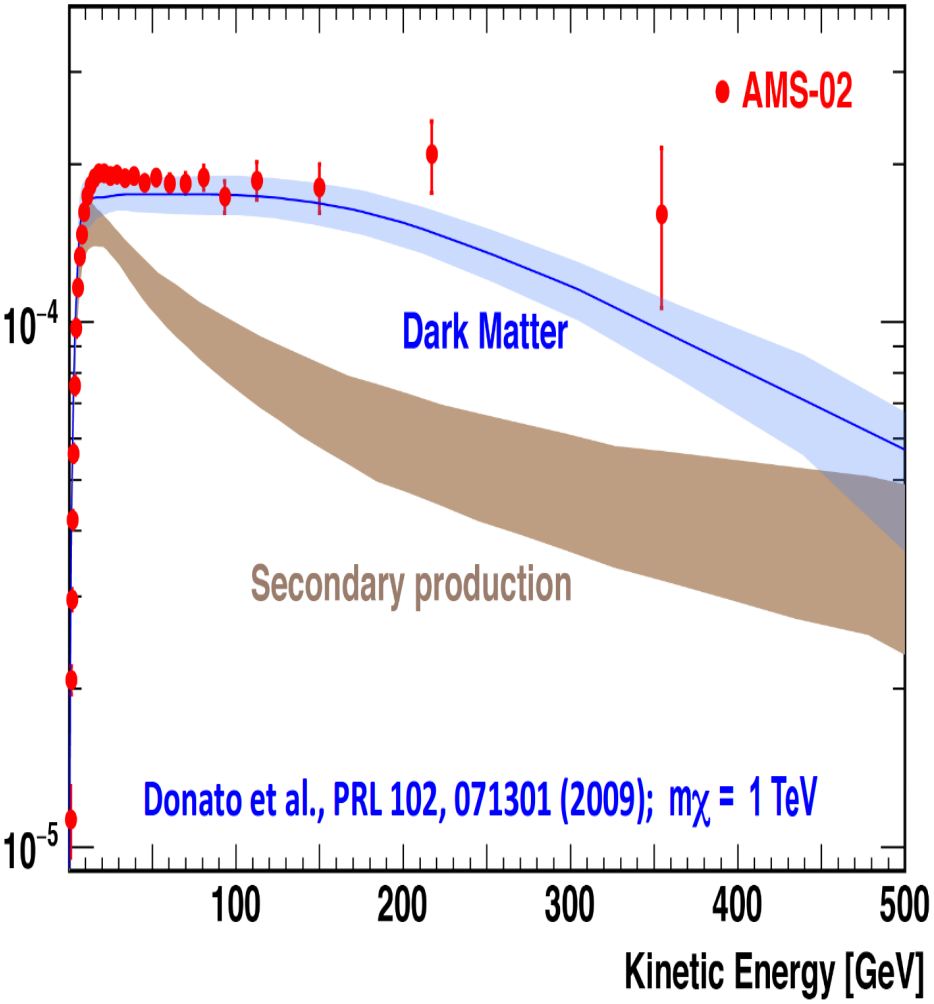

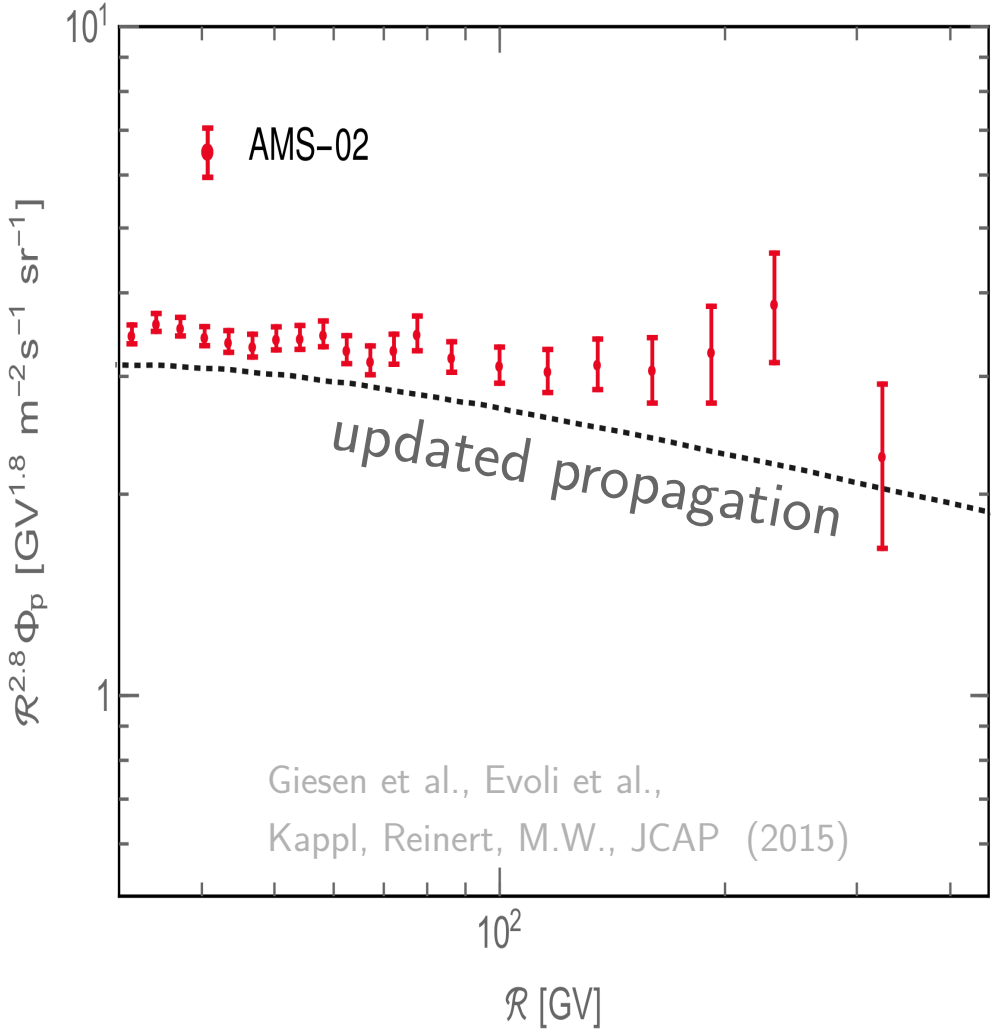

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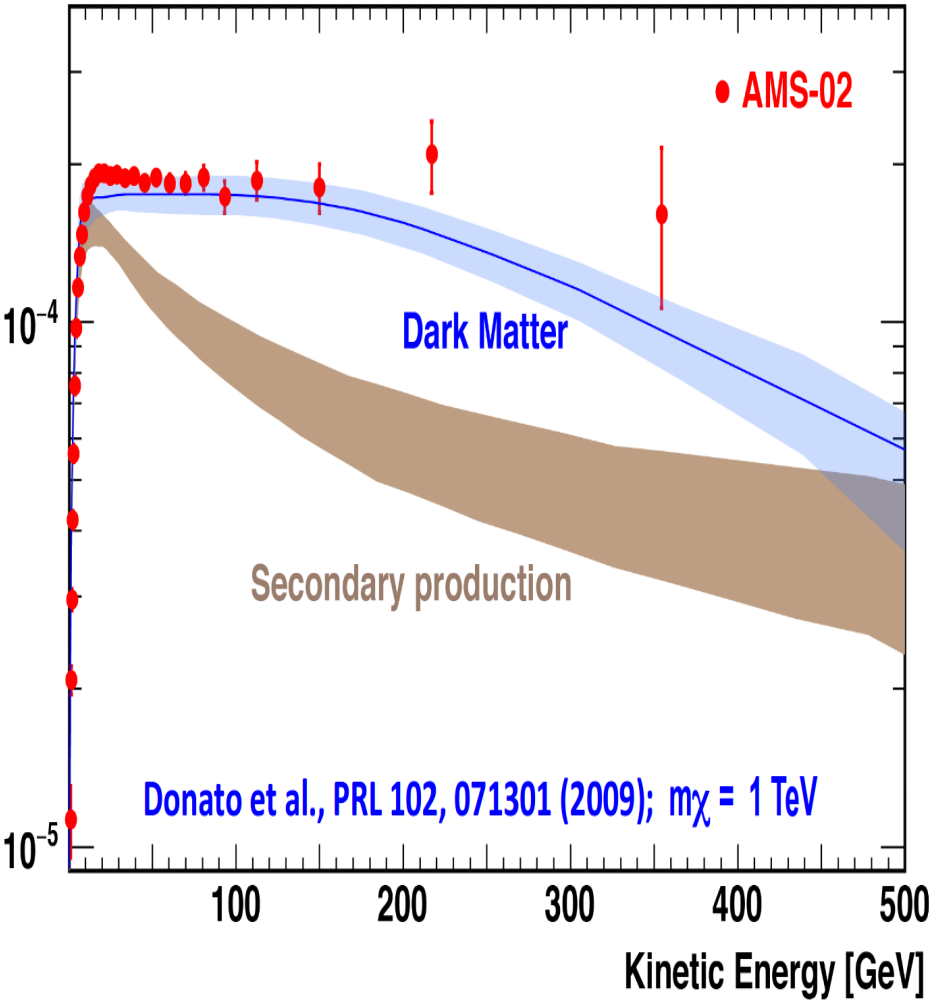

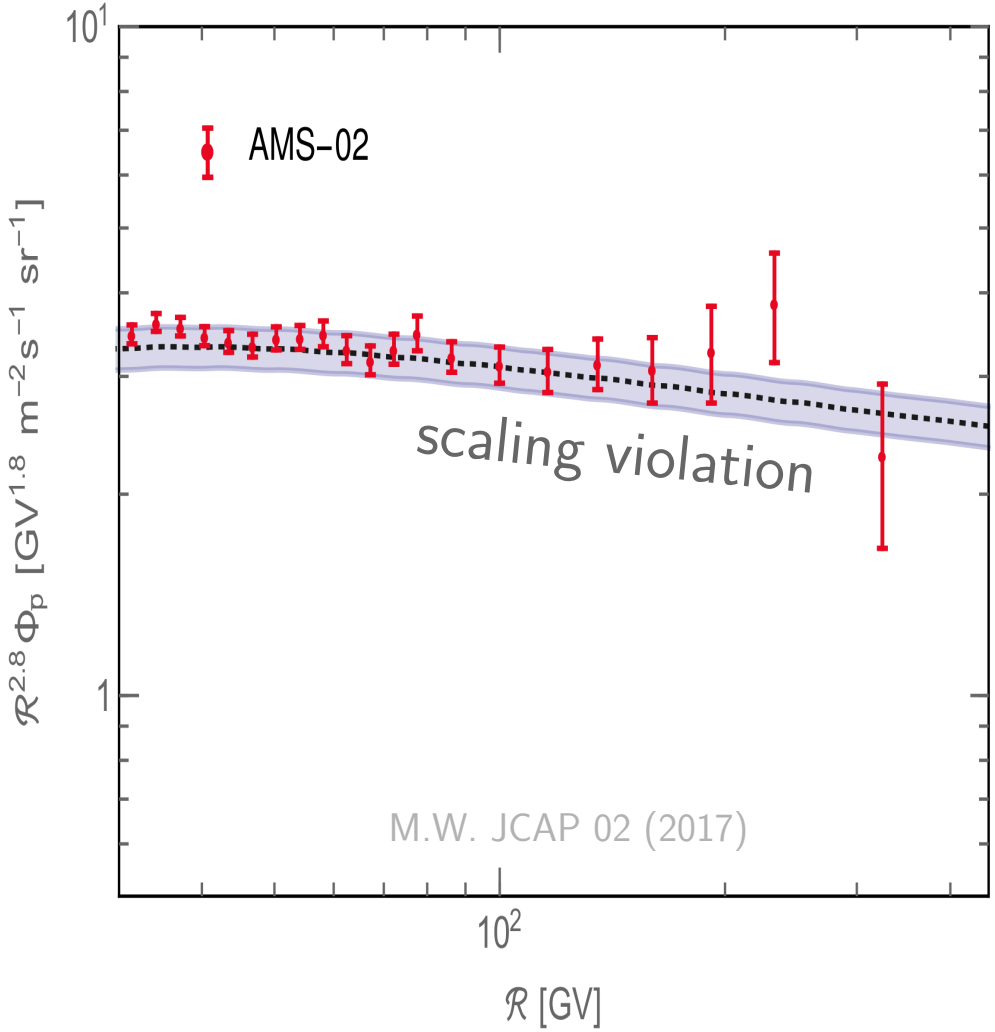

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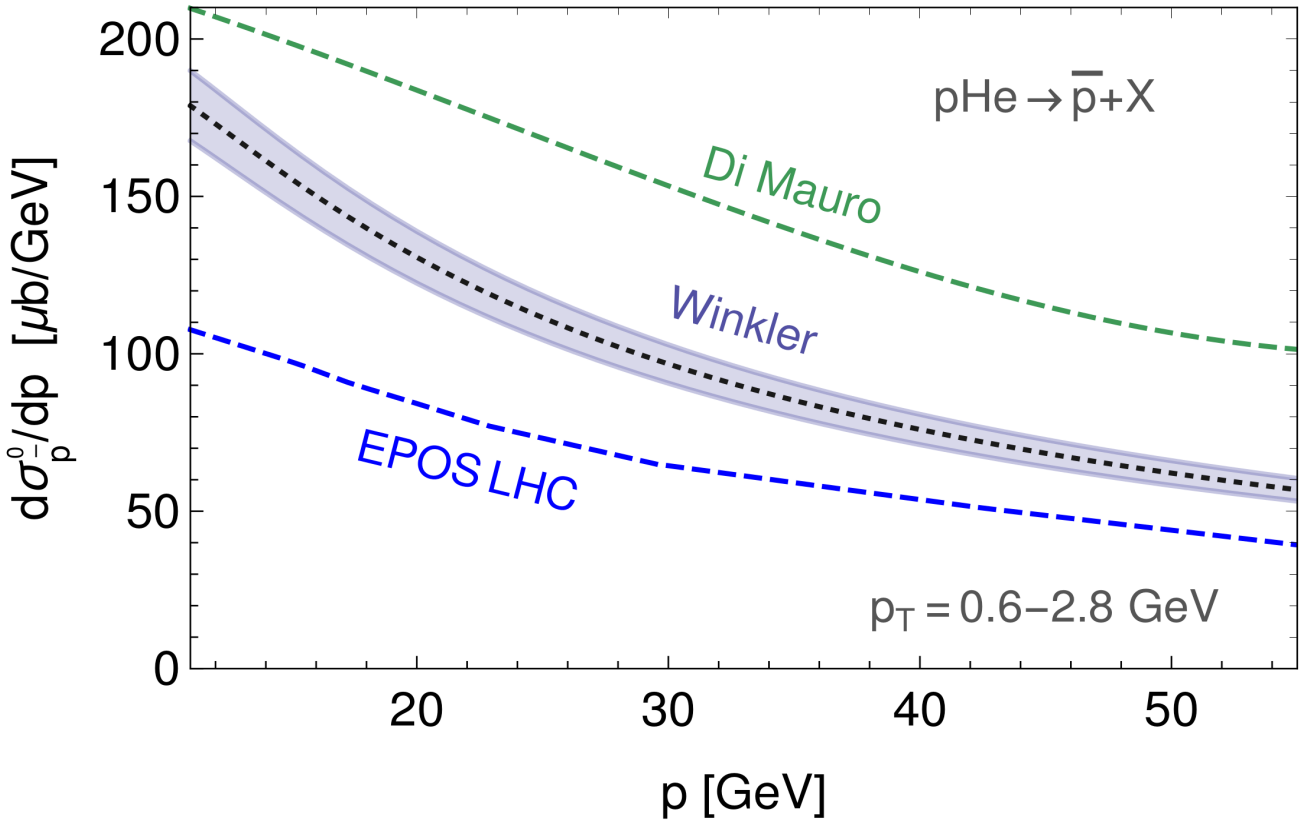
Proton Helium

- 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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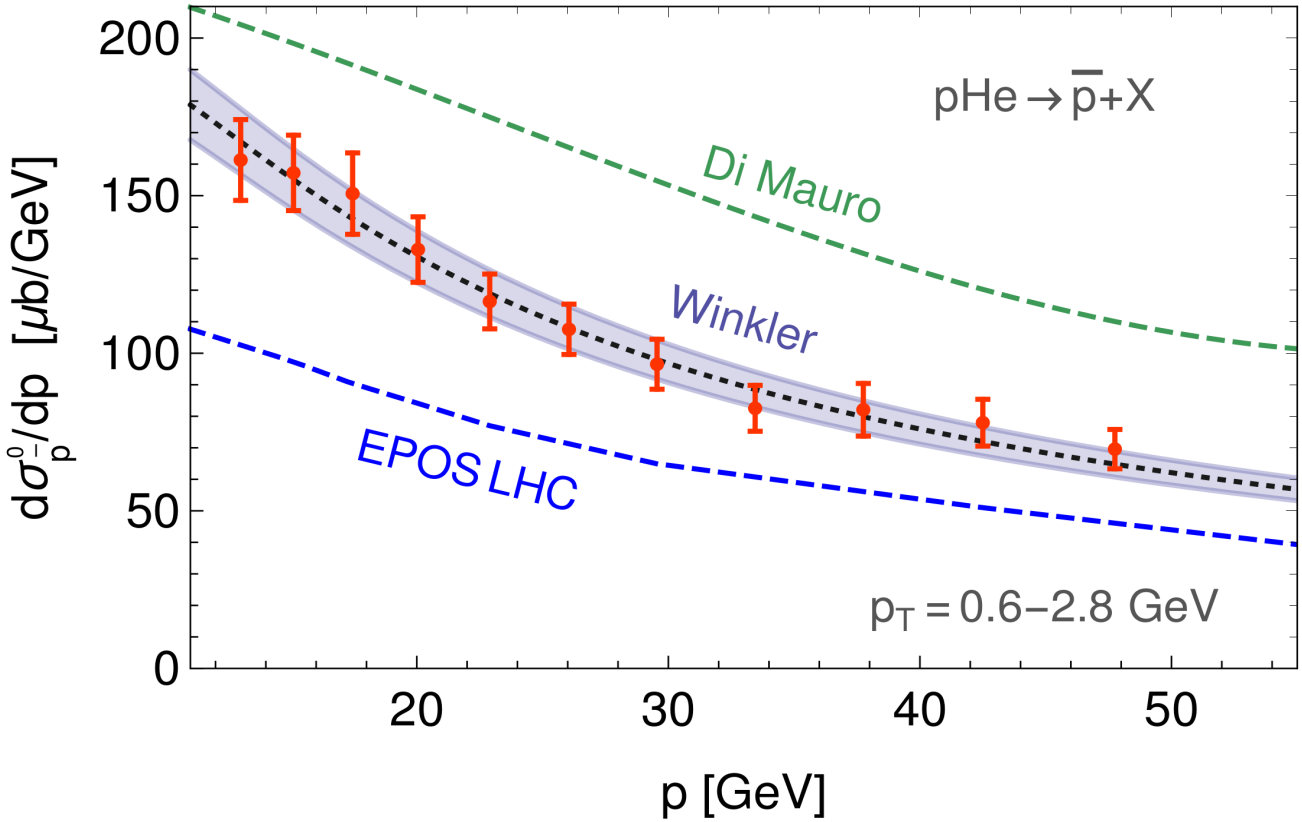

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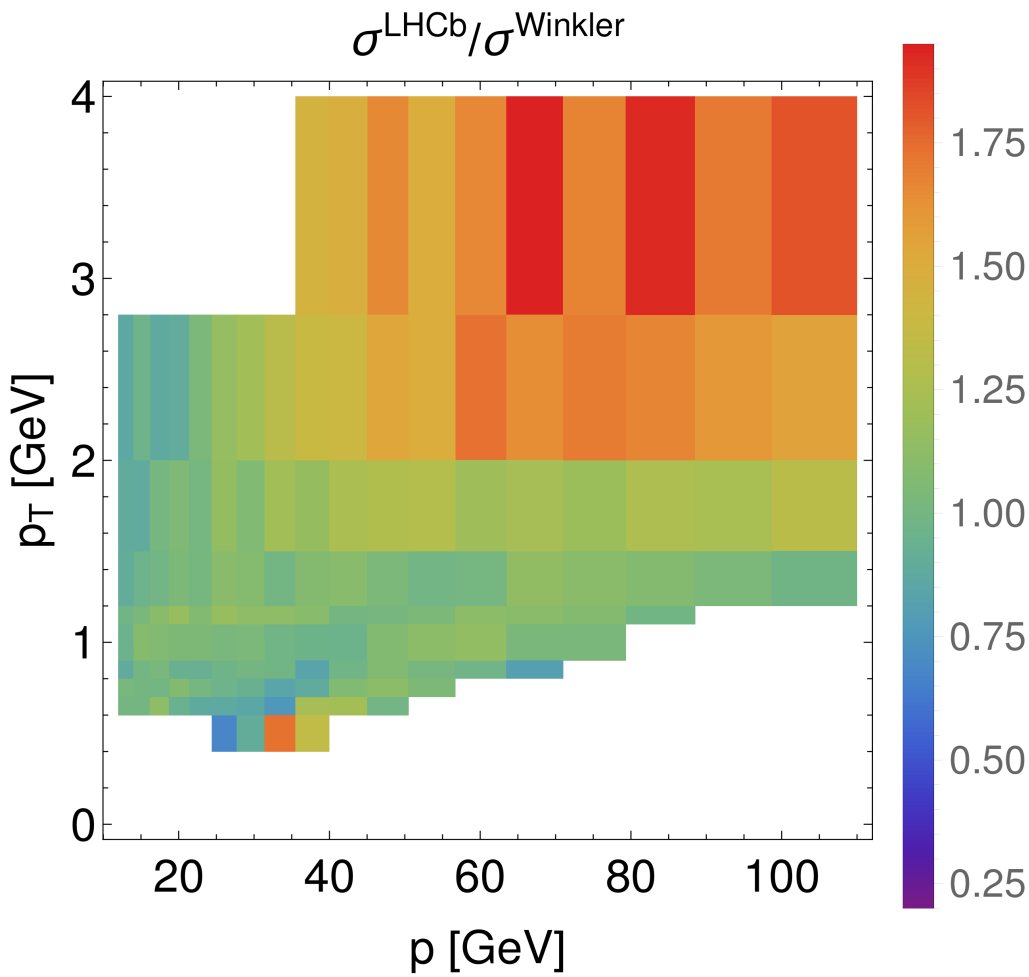
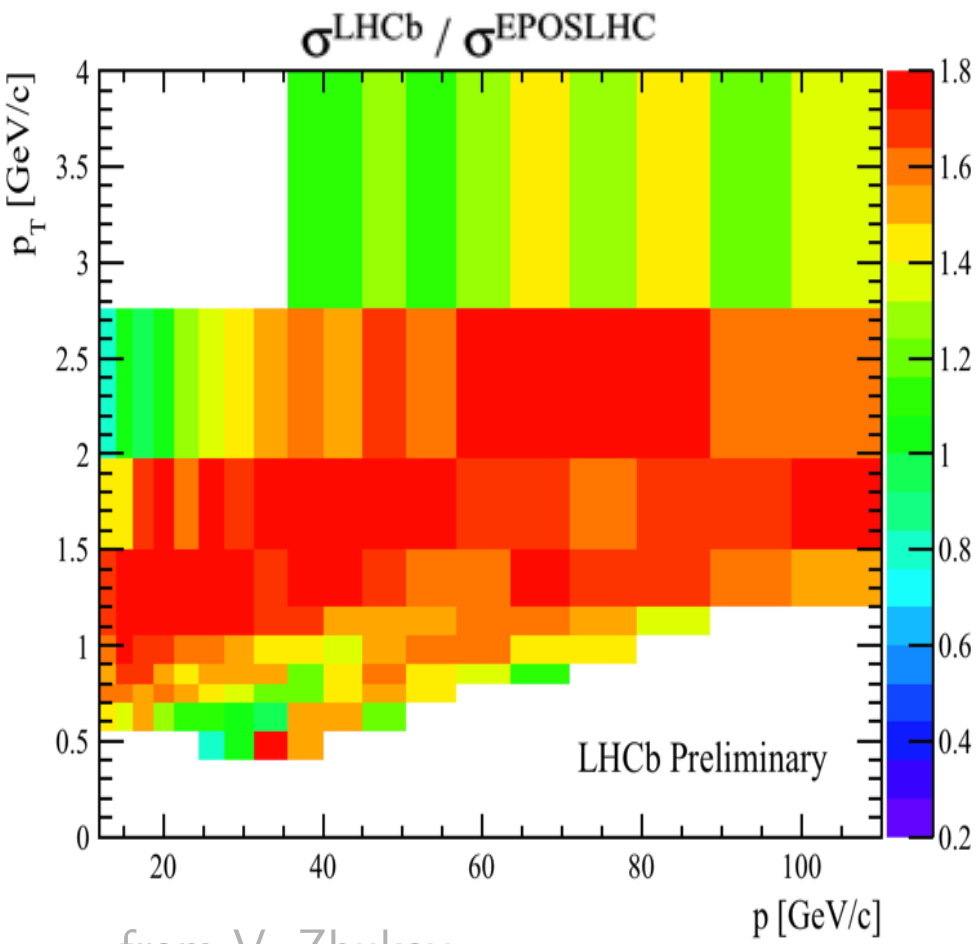
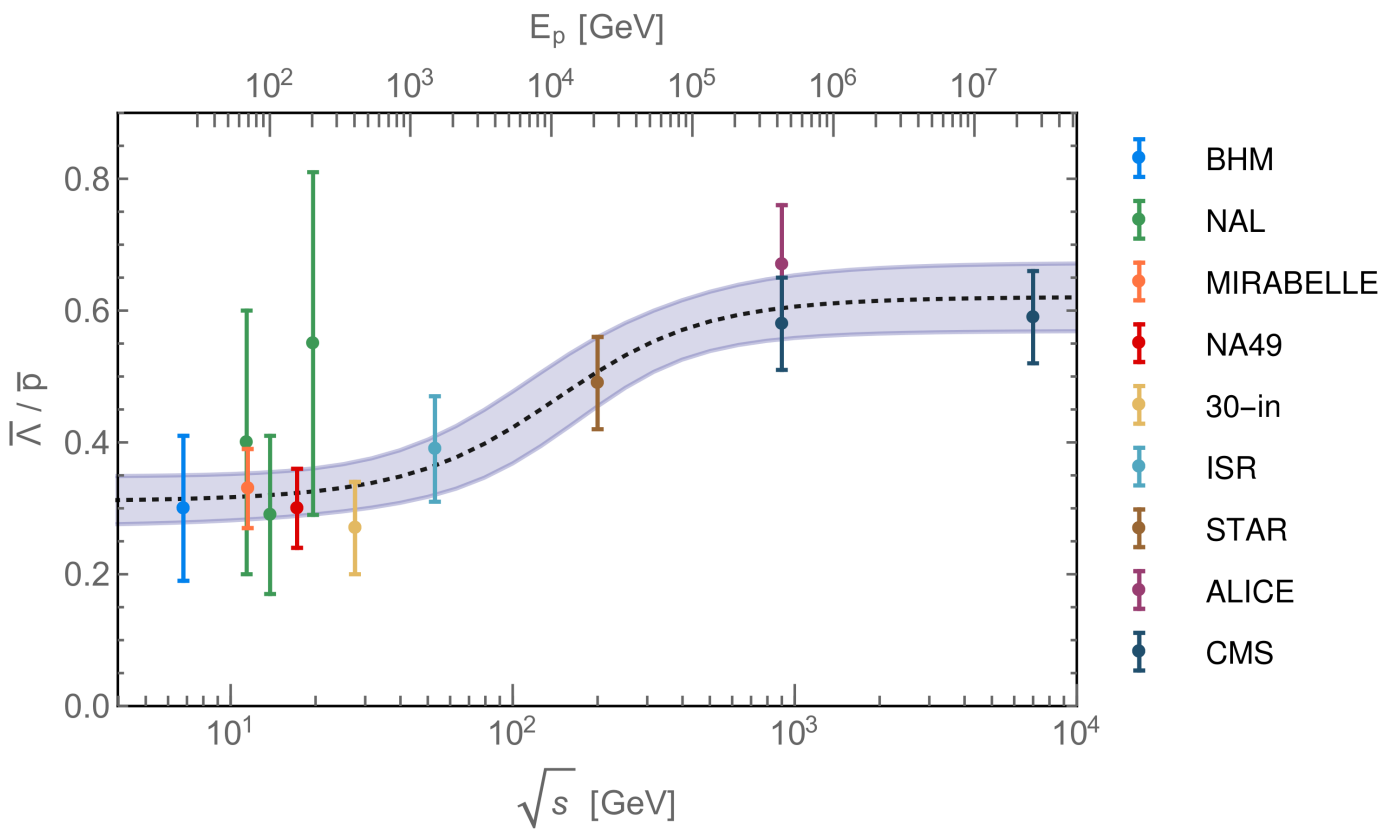




from V. Zhukov

Hyperons

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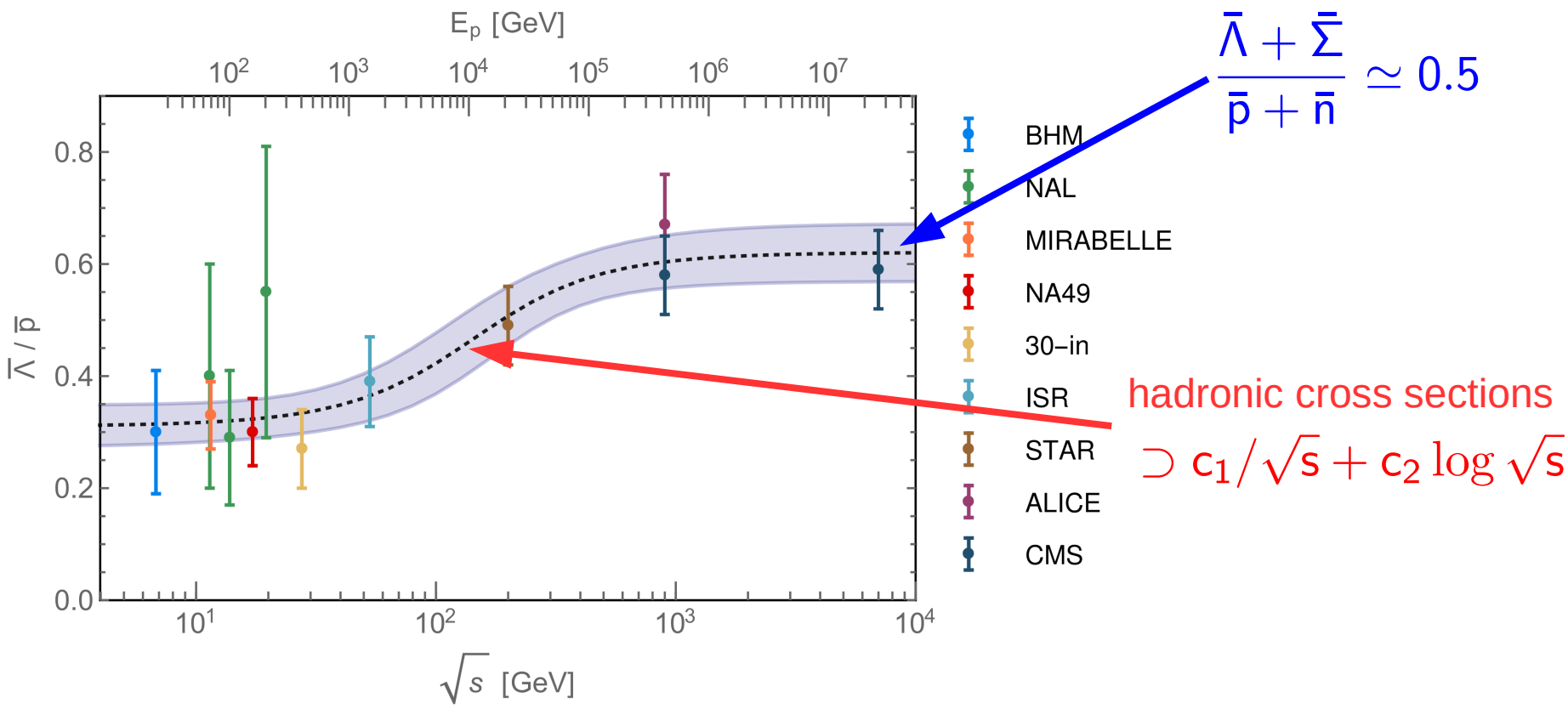

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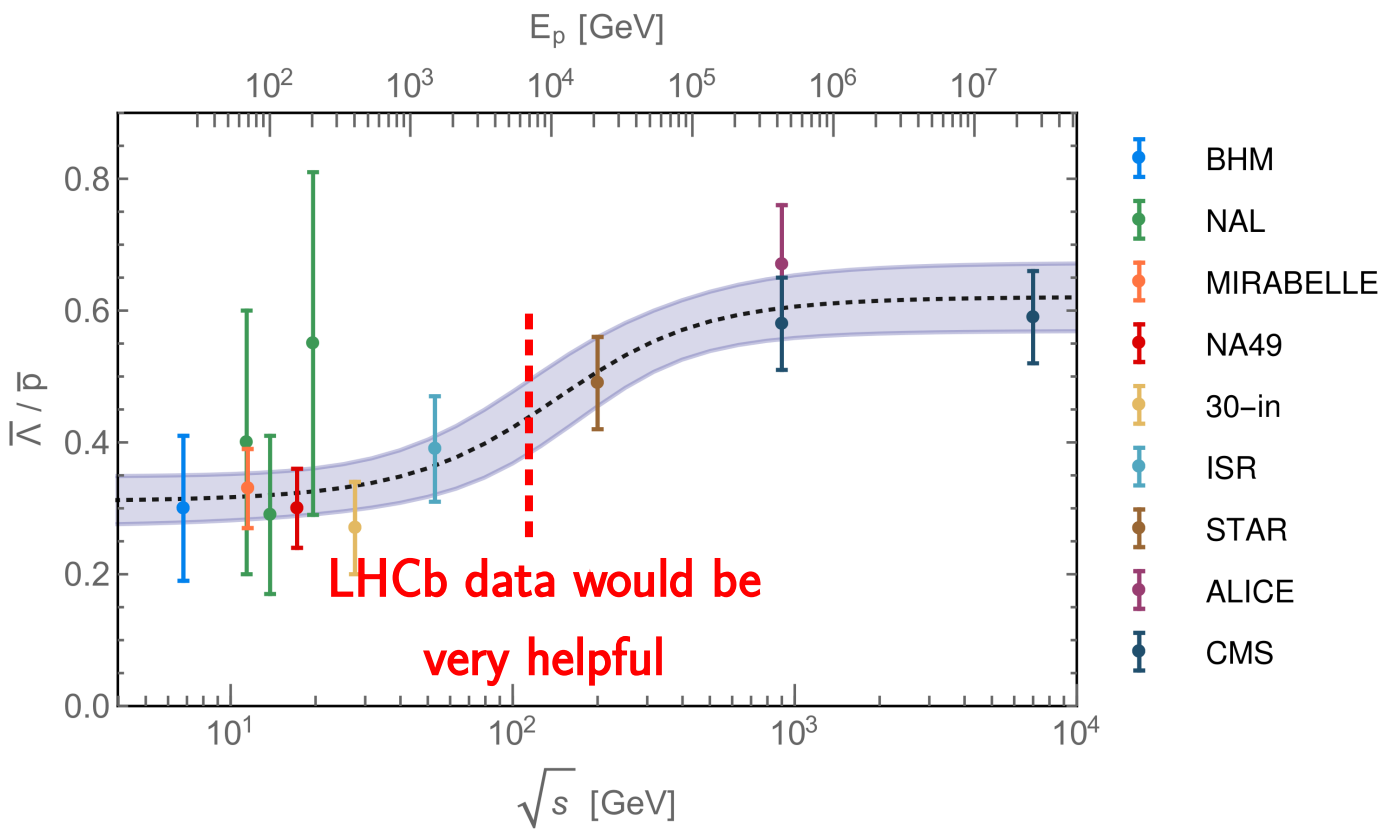

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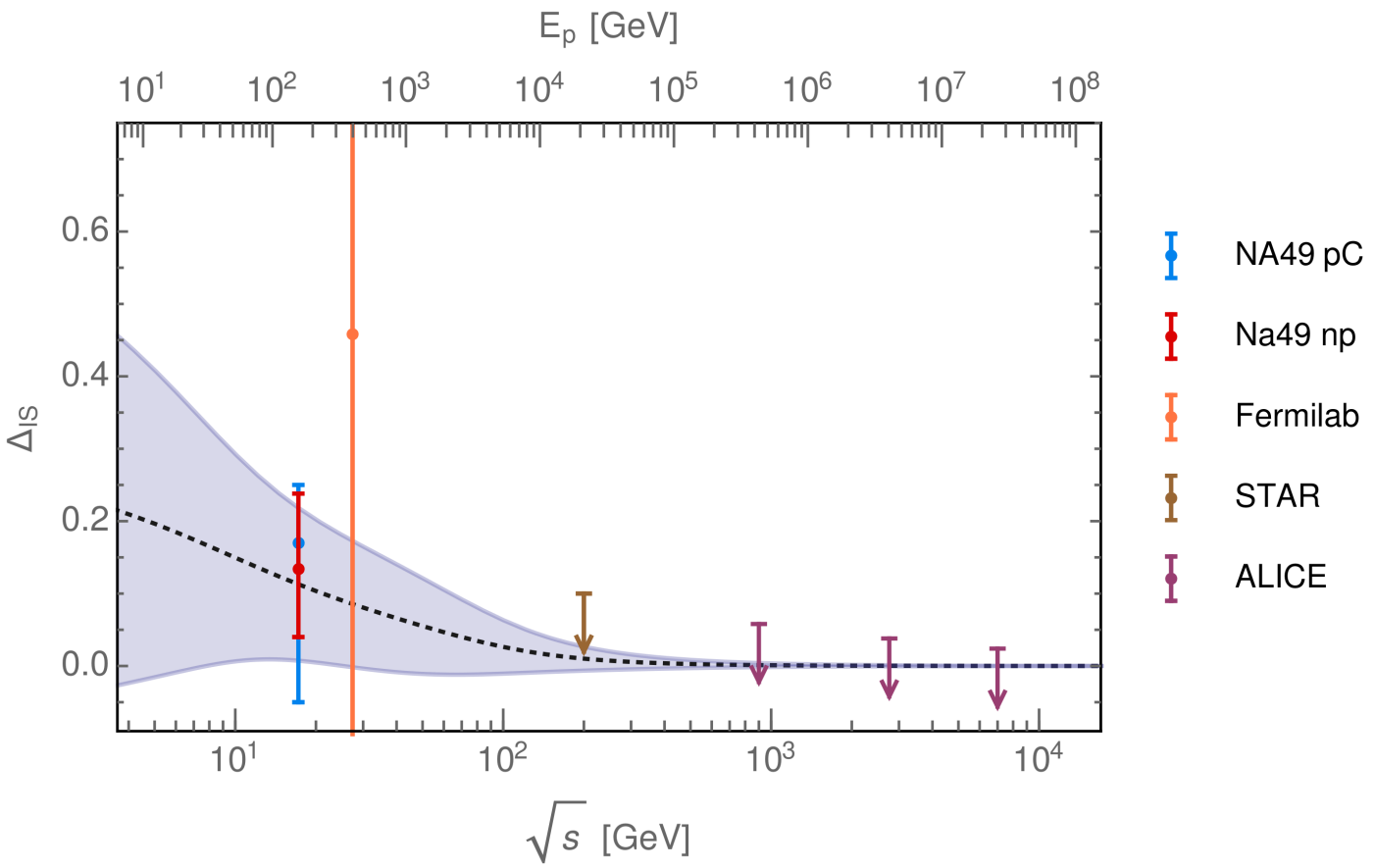
Isospin Effects in Antineutron Production

- (anti)baryon produced in pairs $p\bar{p}$, $\bar{n}n$, $\bar{n}p$, $\bar{p}n$ — possible asymmetry due to isocharge
- accessible only through $\frac{pn \to \bar{p}}{pp \to \bar{p}}$ and symmetry arguments, $\frac{\bar{p}}{p}$ 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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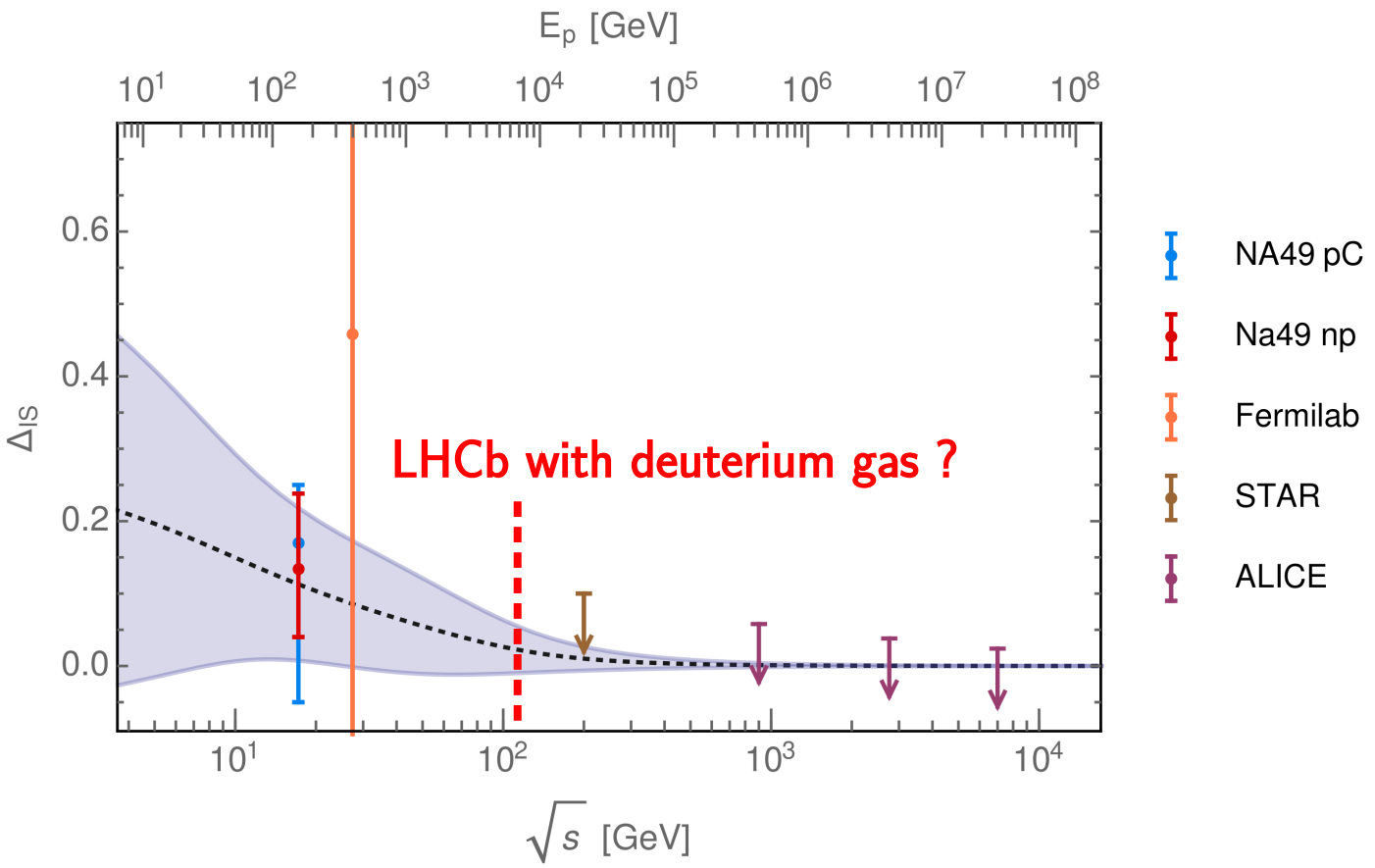
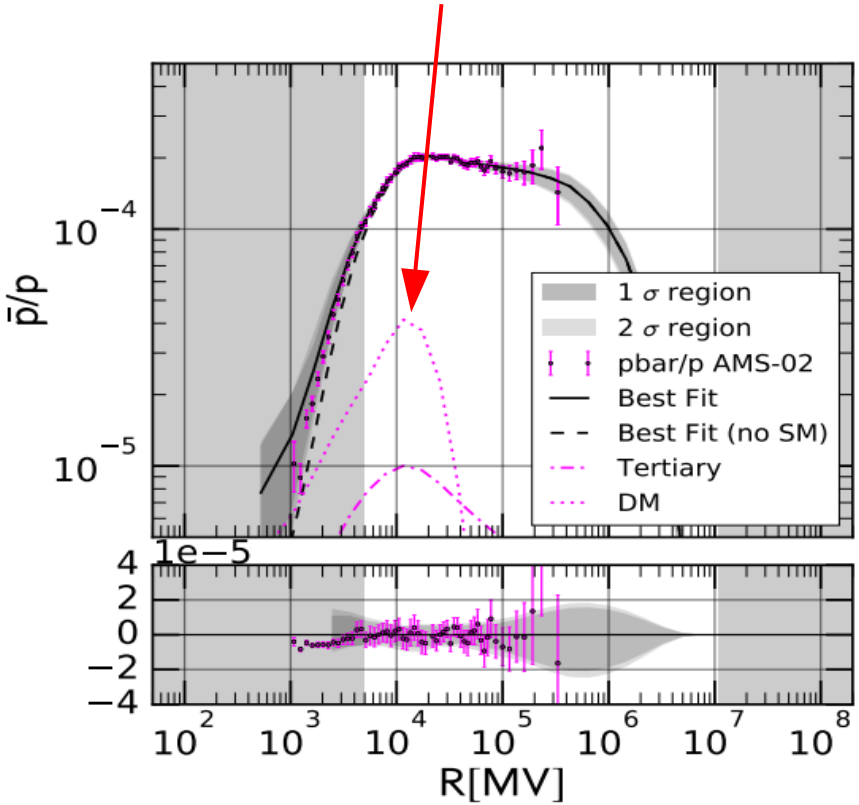


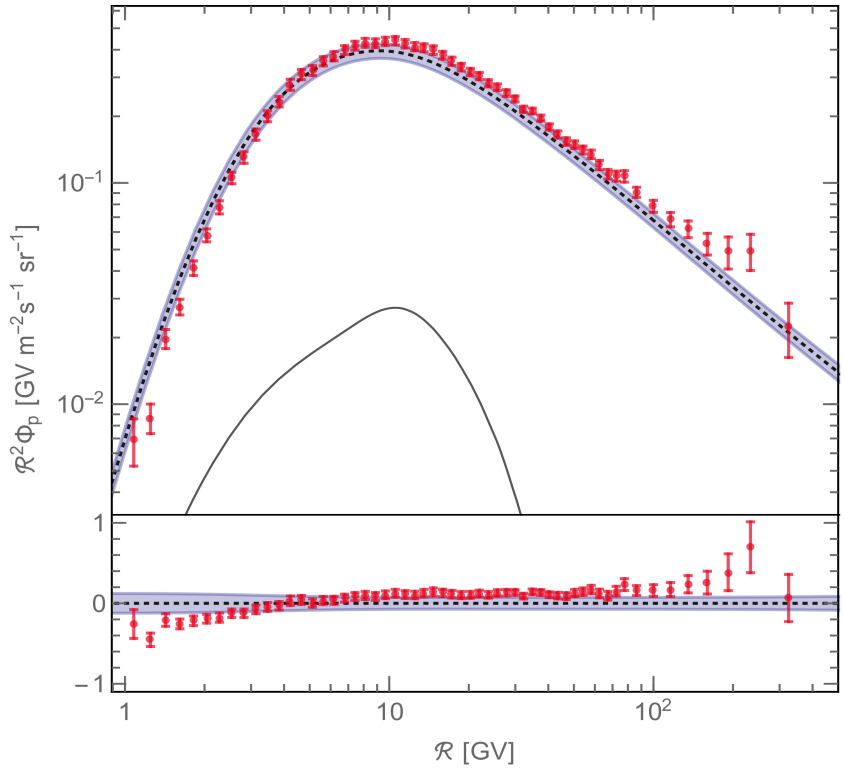
A new Excess in the Cosmic Antiproton Flux

3.1 σ excess
consistent with dark matter



Cuoco et al., PRL 118 (2017), Phys.Rev. D99 (2019)

lower significance **1.1 σ**



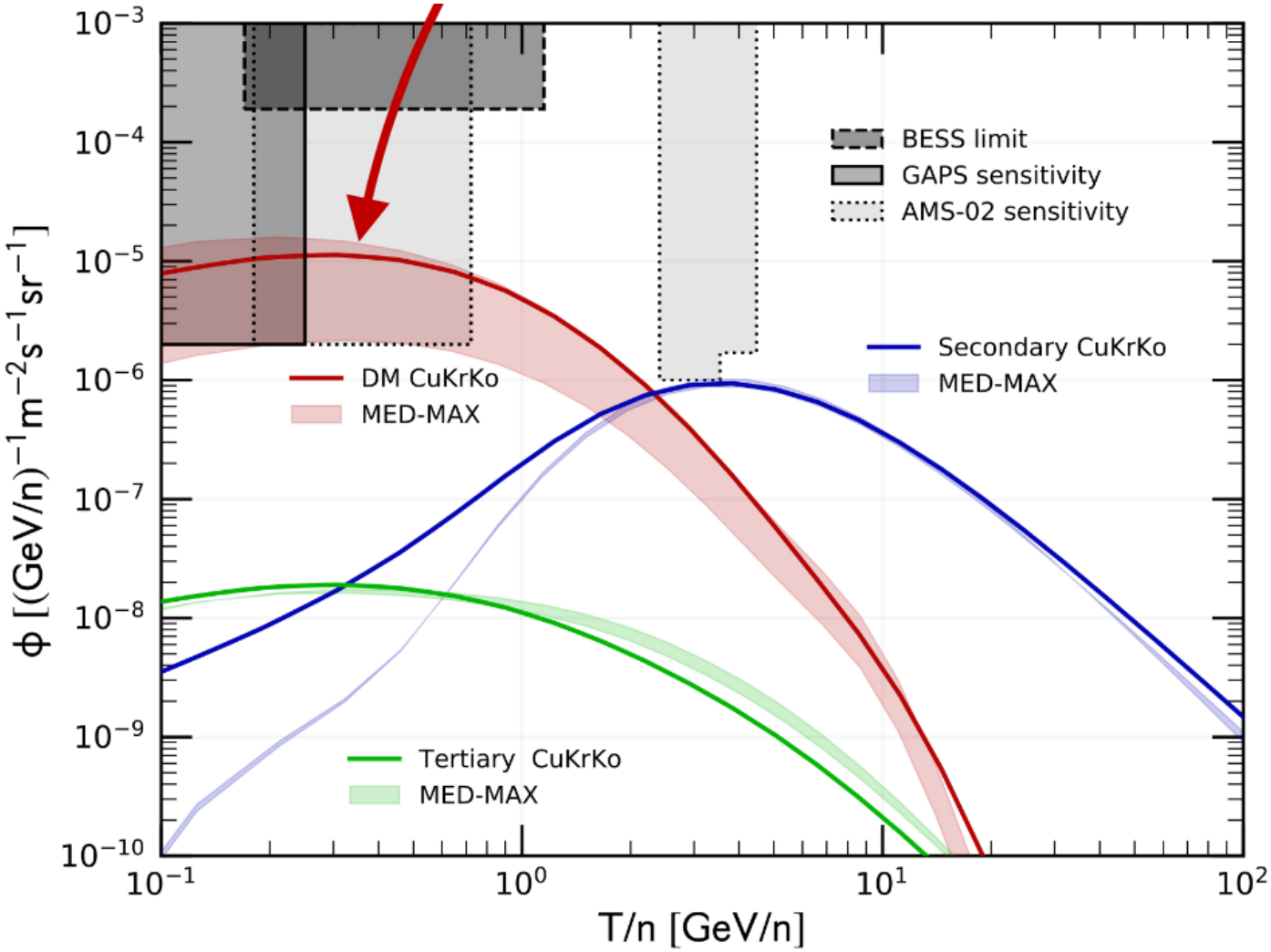
Reinert, M.W.,JCAP 01 (2018)

- Various other groups have seen the same excess at significance **1-5 σ**

Cui et al., PRL 118 (2017) and JCAP 1806 (2018), Cholis, Hooper, Linden, 1903.02549 (2019), Lin et al., arXiv:1903.09545 (2019)

Antideuterons: The Smoking Gun Channel

antideuteron signal assuming antiproton excess is dark matter



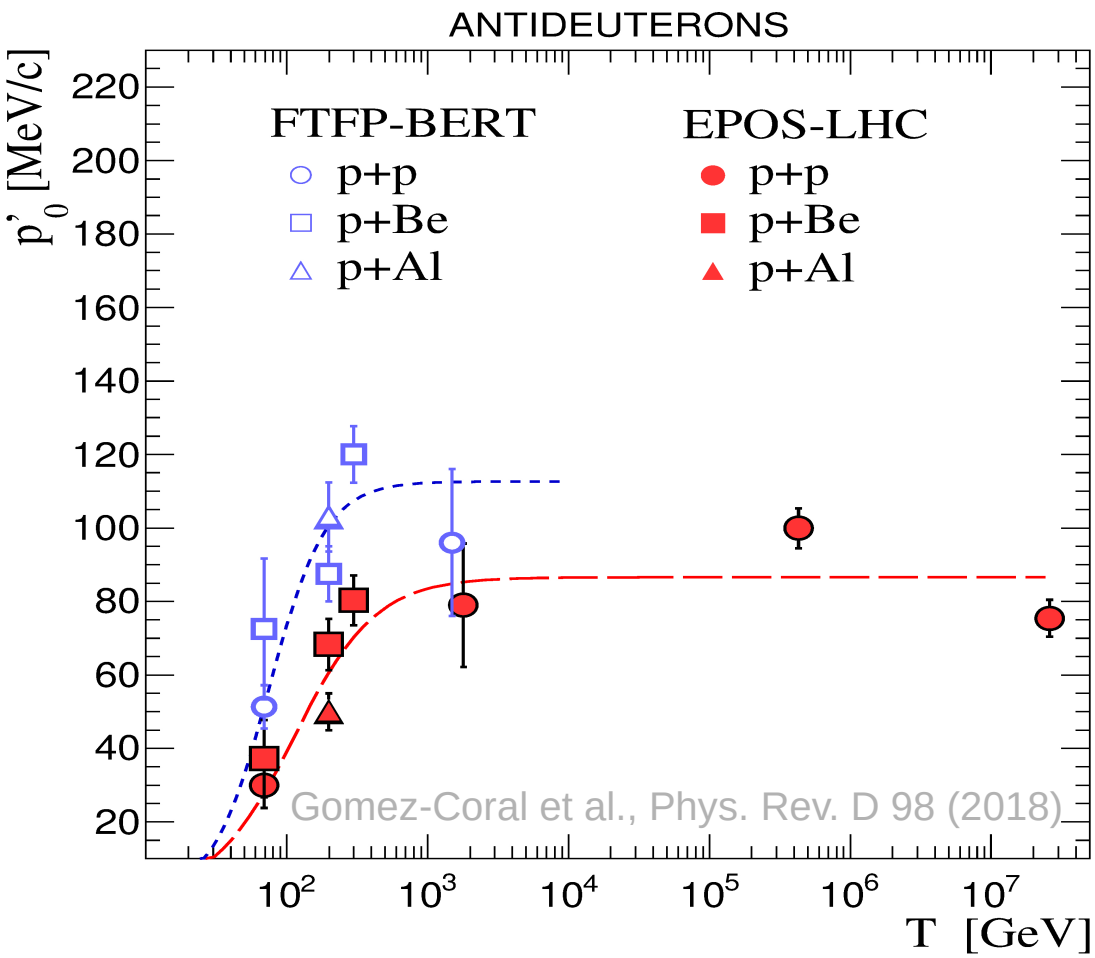
Korsmeier, Donato, Fornengo, Phys.Rev. D97 (2018)

Antideuteron Coalescence

- coalescence model: proton and neutron form deuteron if

$$|\Delta \mathbf{p}| < p_0 \longleftarrow \text{coalescence momentum}$$

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



antinucleon spectra differ between MCs

Antideuteron Theory

- model $\bar{p}\bar{n}$ as Gaussian wave package

  Gustafson, Häkkinen, Phys. C 61 (1994), Mrowczynski, Phys. Lett. B 248 (1990), Wiedemann, Ferenc, Heinz, Phys.Lett. B449 (1999)

$$\Psi_{\bar{p}\bar{n}}(\mathbf{r}) \propto e^{-\frac{\mathbf{r}^2}{2\sigma^2}} \; e^{i\mathbf{q}\mathbf{r}}$$

$$\sigma/2 = R_{HBT}$$

- coalescence momentum from wave function overlap

$$p_0^3 \propto |\langle \Psi_{\bar{d}} | \Psi_{\bar{p}\bar{n}} \rangle|^2$$

- include phase space suppression

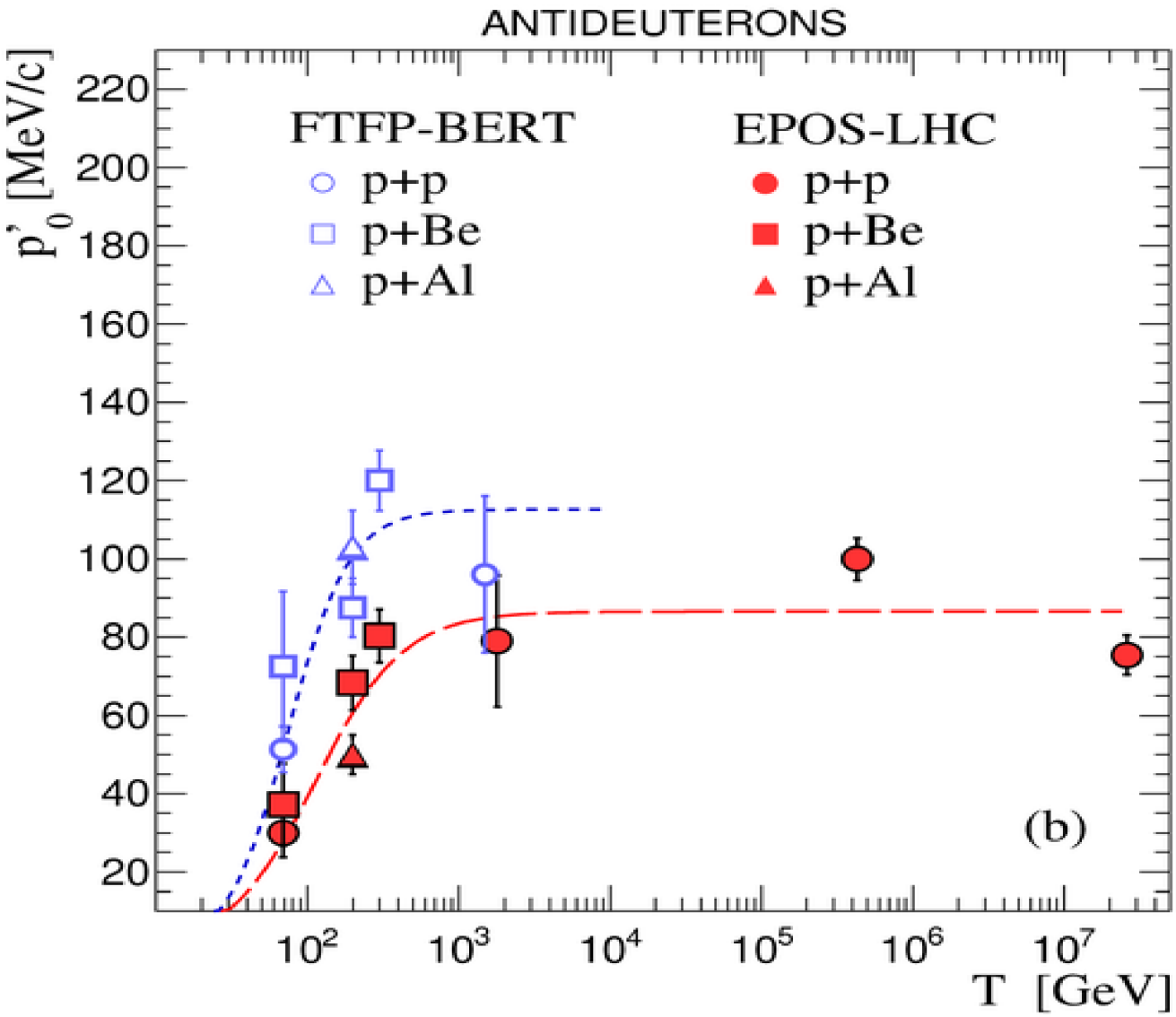
  Donato, Fornengo, Salati, Phys. Rev. D62 (2000), Duperray, Protasov, Voronin, Eur. Phys. J. A16 (2003)

$$R = \frac{\Phi_4(m_p)}{\Phi_4(0)}$$

4 massive nucleons

4 massles particles

Coalescence Revisited



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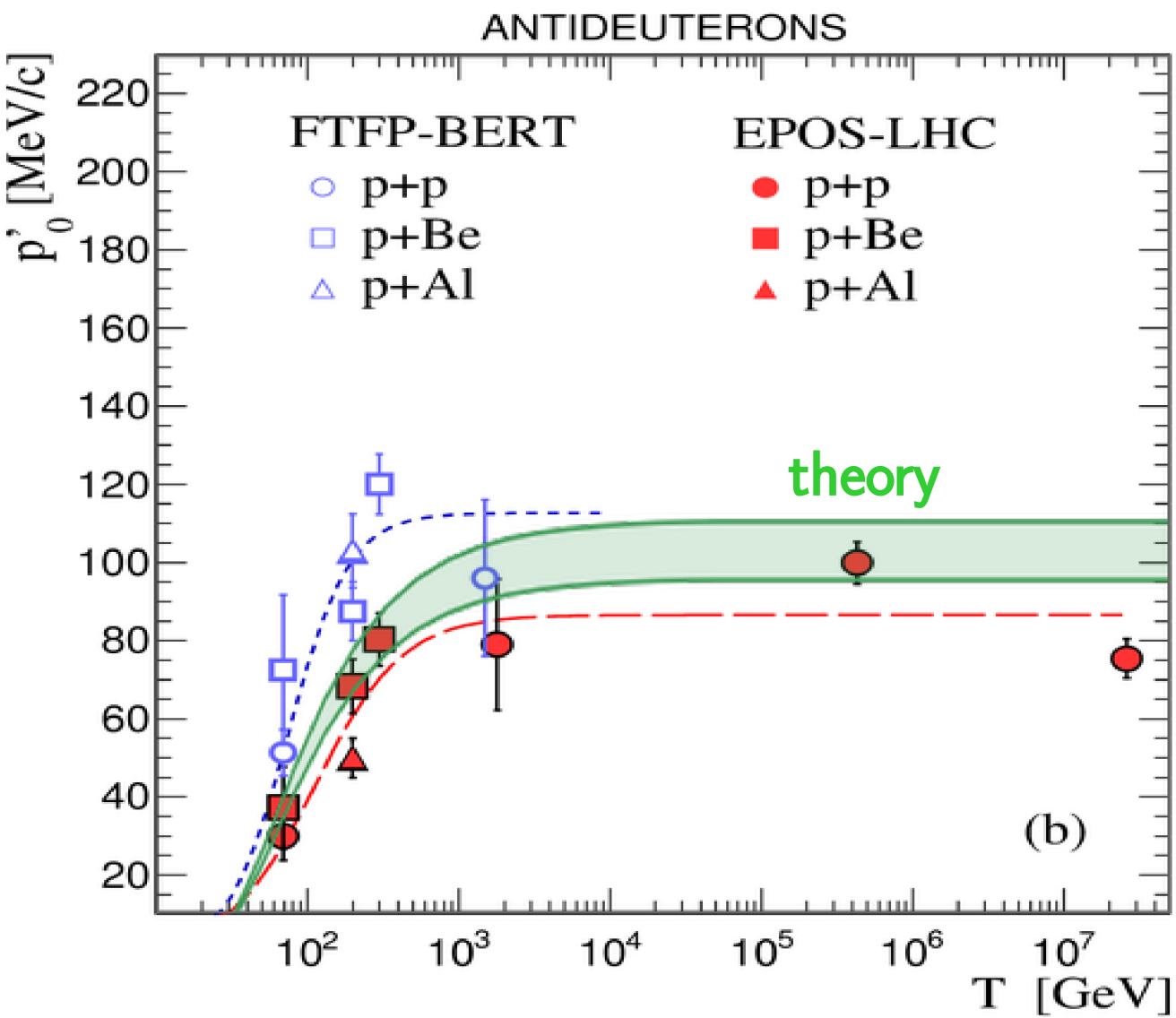

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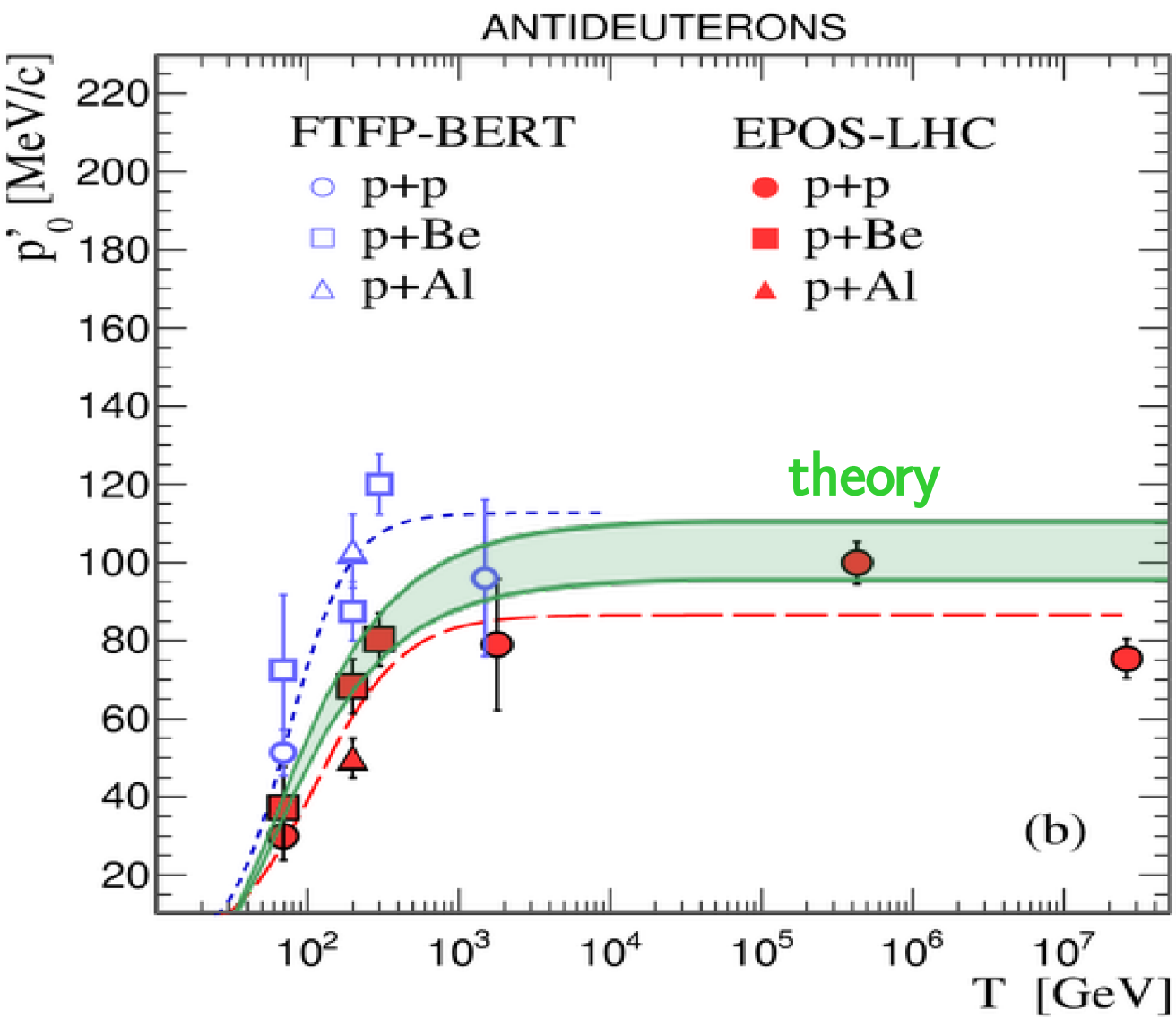

LHCb ?

- systematic error reduced by measuring $\bar{p}$, $\bar{d}$ at same experiment

Outlook

- Cosmic ray modeling crucially relies on accelerator measurements
- LHCb SMOG wishlist:

  1) $\mathrm{p\,He} \rightarrow \bar{\Lambda}, \bar{\Sigma}$ from existing run

  2) $\mathrm{p\,p}\ (\mathrm{H_2}) \rightarrow \bar{\mathrm{p}}$ to test scaling violation in forward hemisphere

  3) $\mathrm{p\,d} \rightarrow \bar{\mathrm{p}}$ to test isospin effects

  4) $\mathrm{p\,p},\ \mathrm{p\,He} \rightarrow \bar{\mathrm{d}},\ \bar{\mathrm{He}}$ to determine coalescence momentum

  5) $\mathrm{p\,p},\ \mathrm{p\,He} \rightarrow \pi,\ \mathrm{K}$ to model positron source term