No antiproton anomalies ?

Martin W. Winkler

in collaboration with R. Kappl, A. Reinert

JCAP 09 (2014), JCAP 10 (2015), JCAP 02 (2017) + work in progress

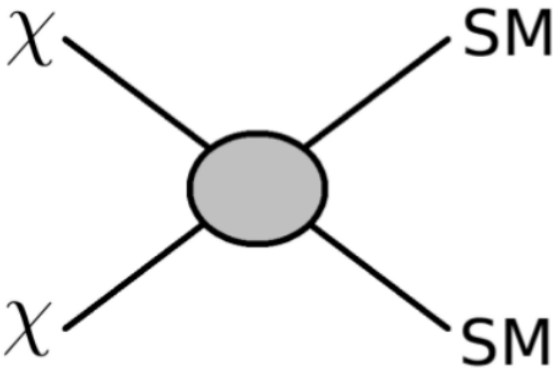
13th Rencontres du Vietnam,
Quy Nhon,
July 24, 2017

Stockholm University

Antiprotons in Cosmic Rays

primary antiprotons

- dark matter annihilation

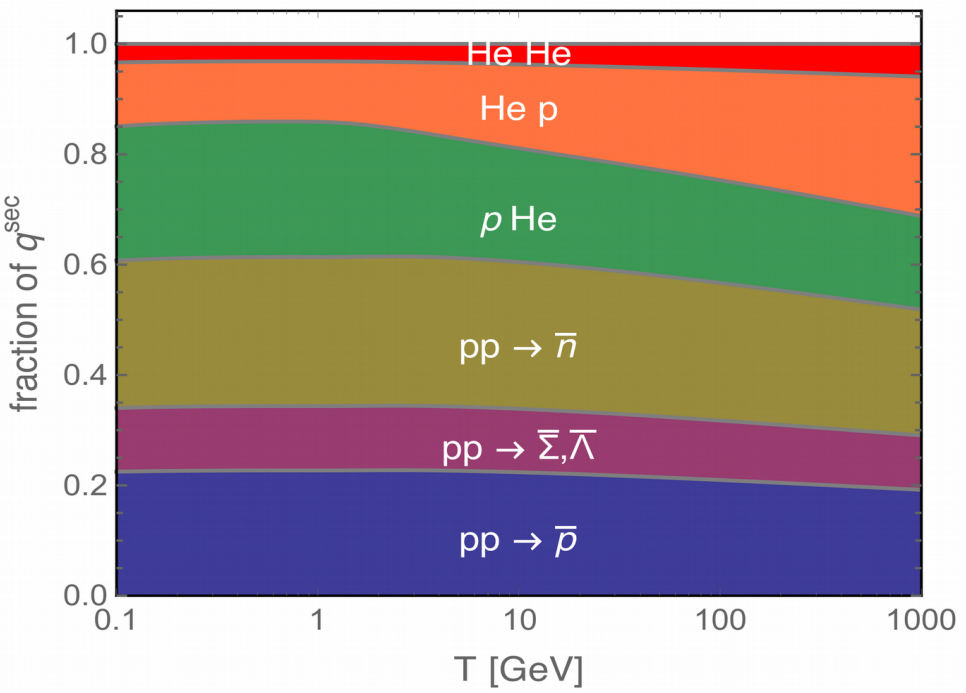


- smooth spectrum
- propagation washes out directional information

secondary antiprotons

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

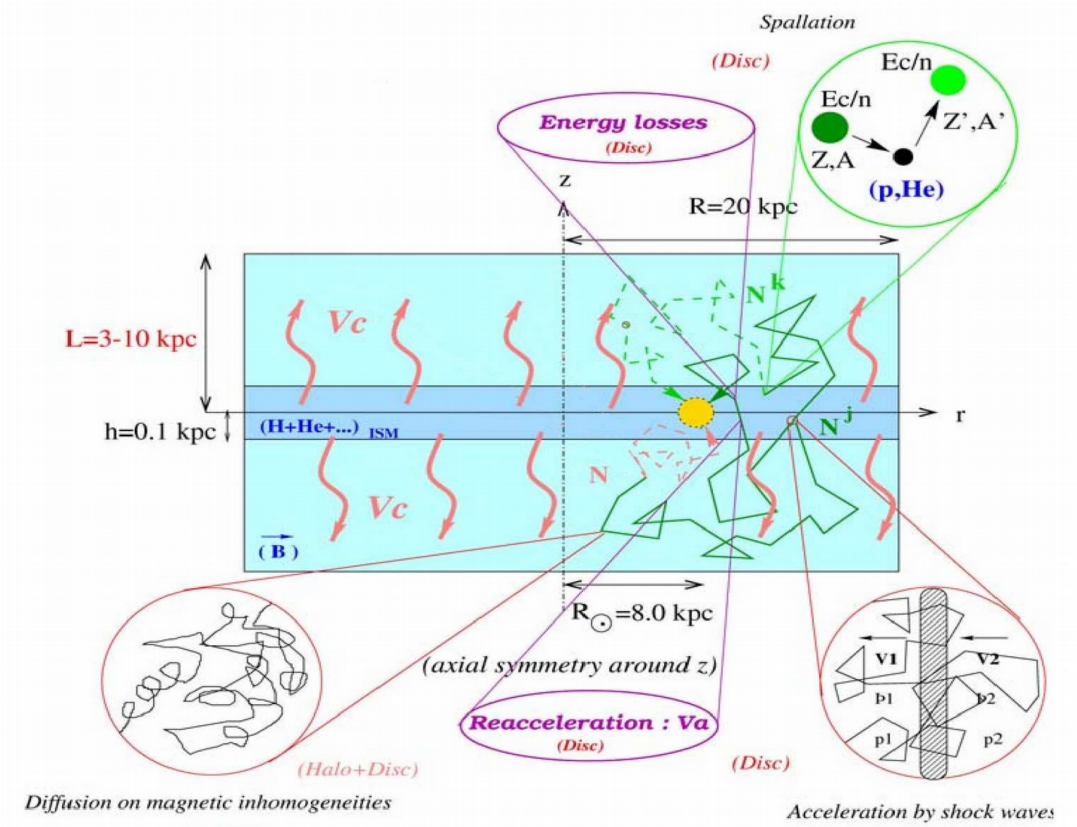
$$q^{\mathrm{sec}}(T) \sim \int dT' \left(\frac{d\sigma_{\bar{p}}}{dT}\right) \rho_{p,He}\, \Phi_{p,He}$$



Propagation

- propagation described by diffusion equation

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



- two-zone diffusion model

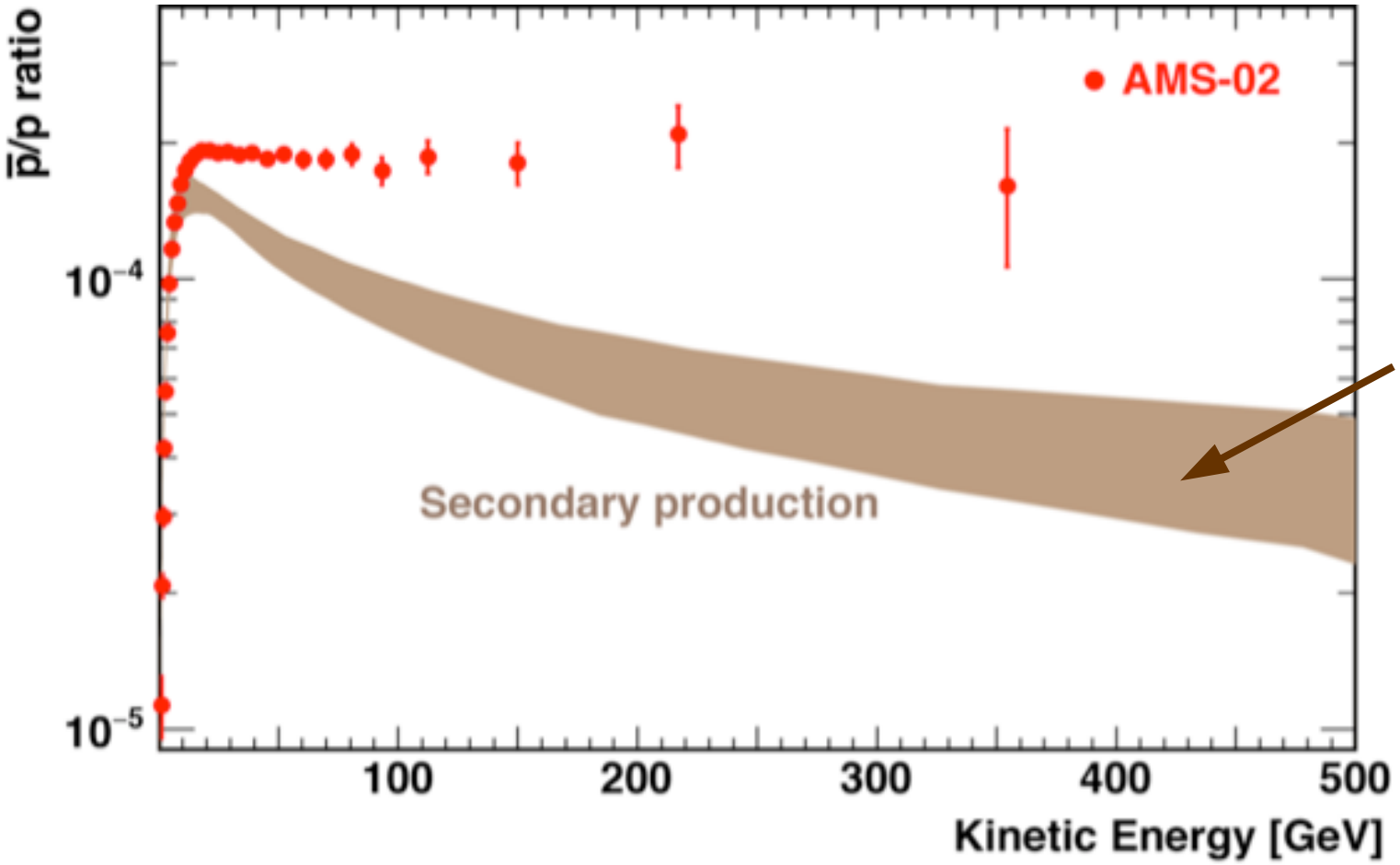
  Maurin et al., Astrophys. J. 555 (2001), Donato et al., Astrophys. J. 563 (2001)

- 5 propagation parameters: K_0, δ, L, V_a, V_c

AMS-02 Antiprotons

- 2015: surprisingly hard $\bar{p}$ spectrum observed by AMS-02

  A. Kounine, AMS Days at CERN (2015)

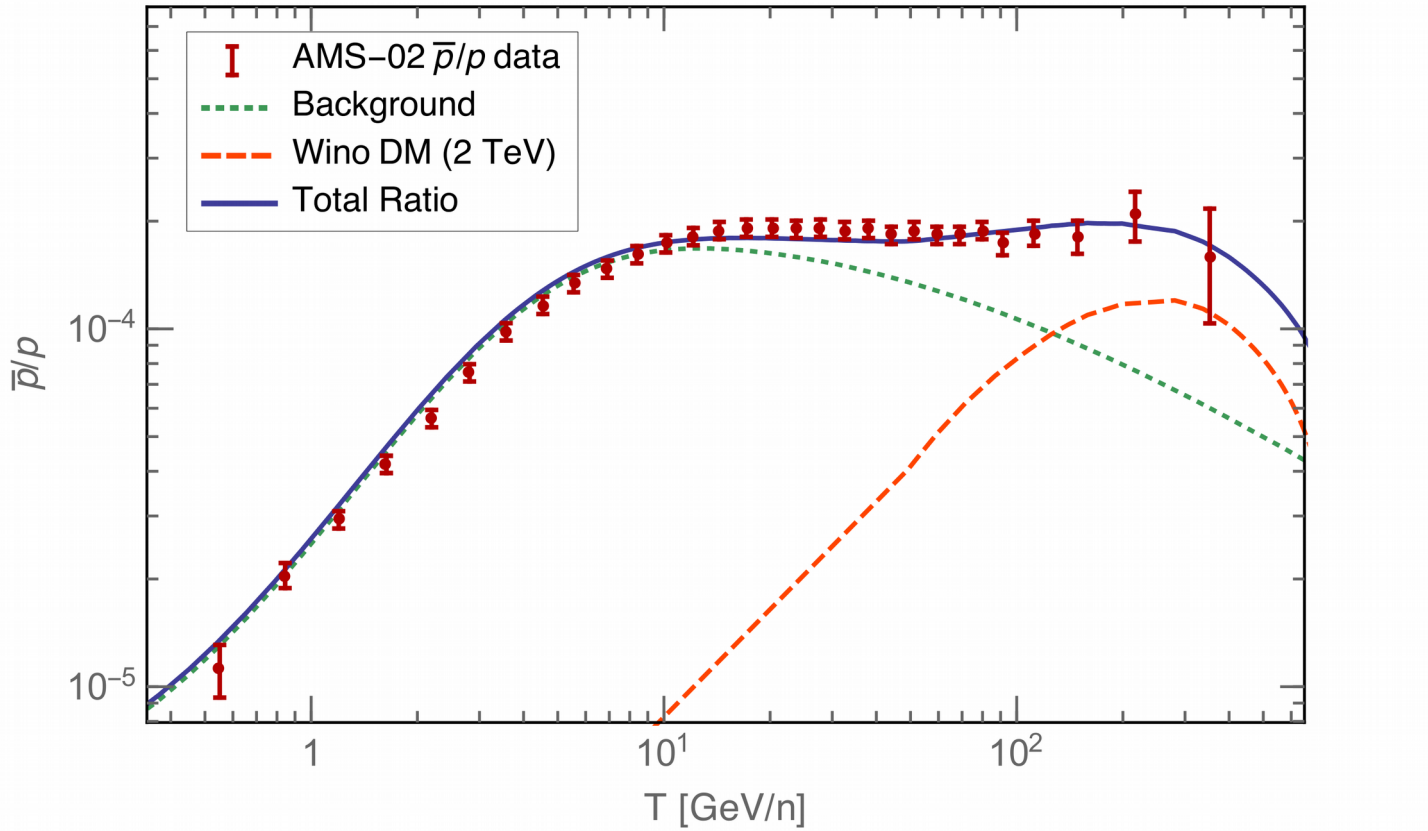


Uncertainties:
cross section,
propagation

Dark Matter Interpretation

- wino dark matter with mass of 2 TeV

  Ibe et al., Phys. Rev. D91 (2015), Hamaguchi et al., Phys. Lett. B747 (2015)

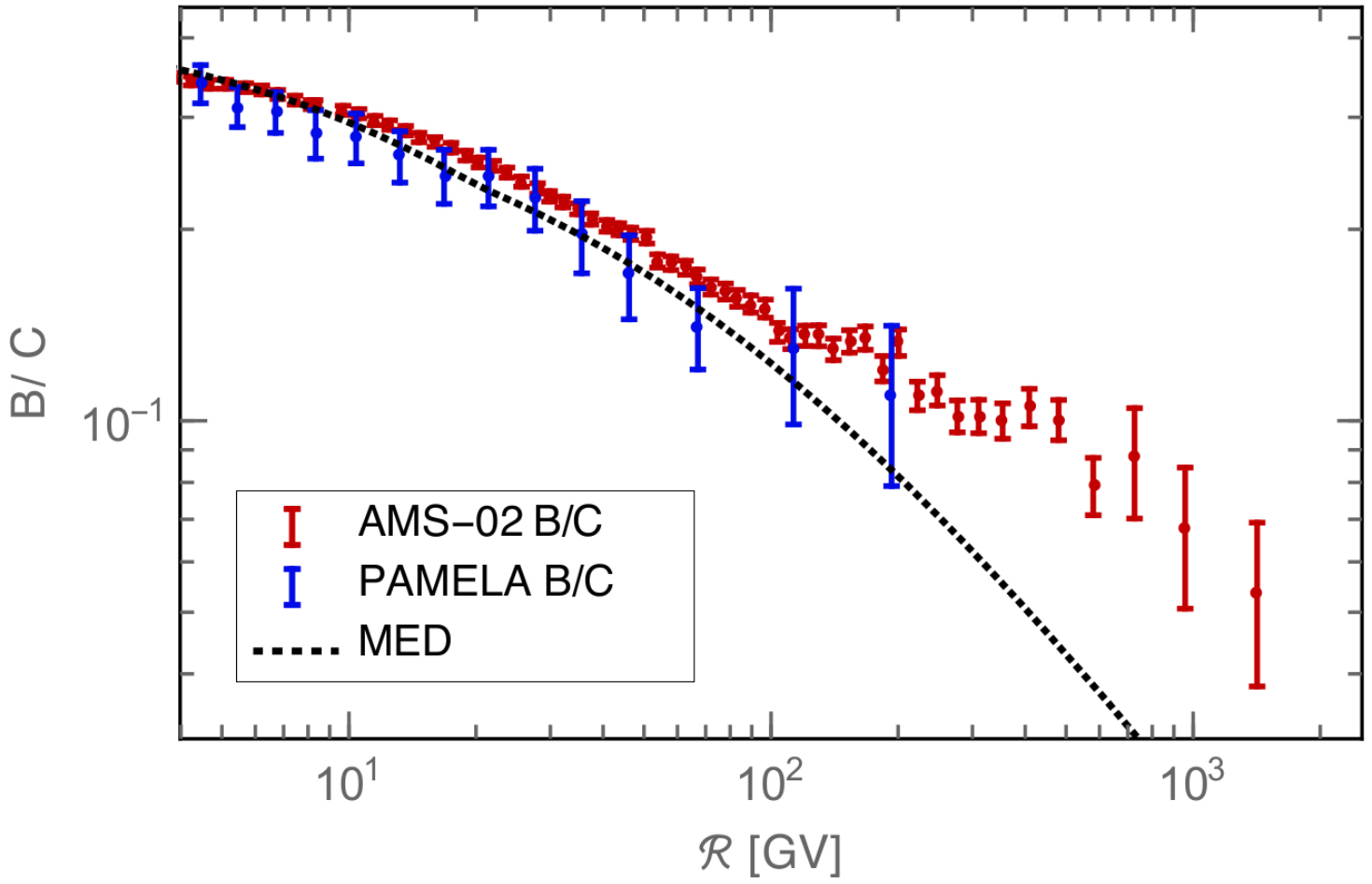


- or is the background wrong?

  Giesen, JCAP 09 (2015), Evoli et al. JCAP 12 (2015), KRW'15

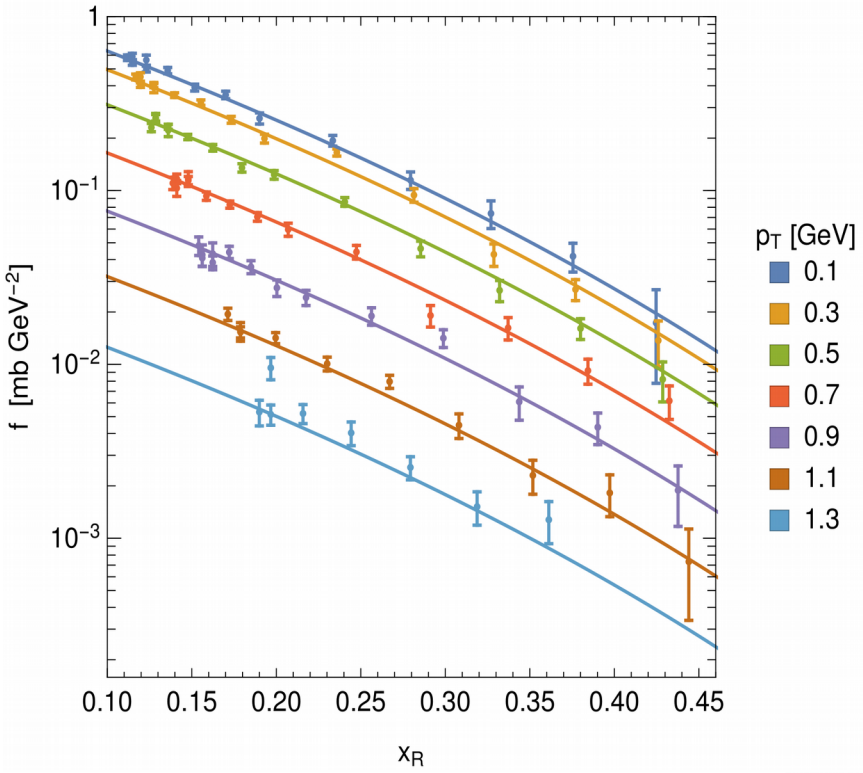
First Look at B/C

- propagation parameters were extracted from pre – AMS data



- AMS-02 B/C data indicate harder spectrum

Antiproton Cross Section



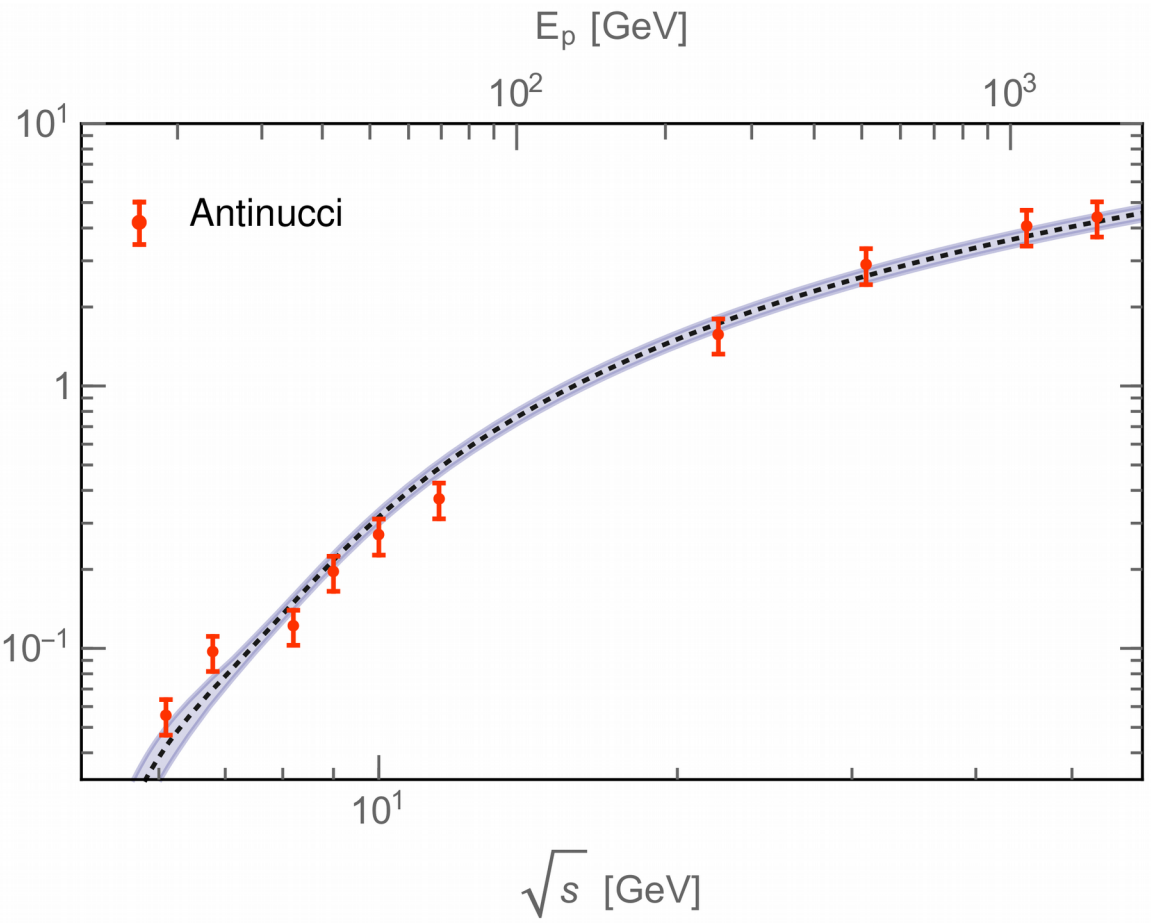
- Feynman scaling

$$E\frac{d^3\sigma_{\bar{p}}}{dp^3} \quad \sqrt{s}\text{ - independent}$$

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

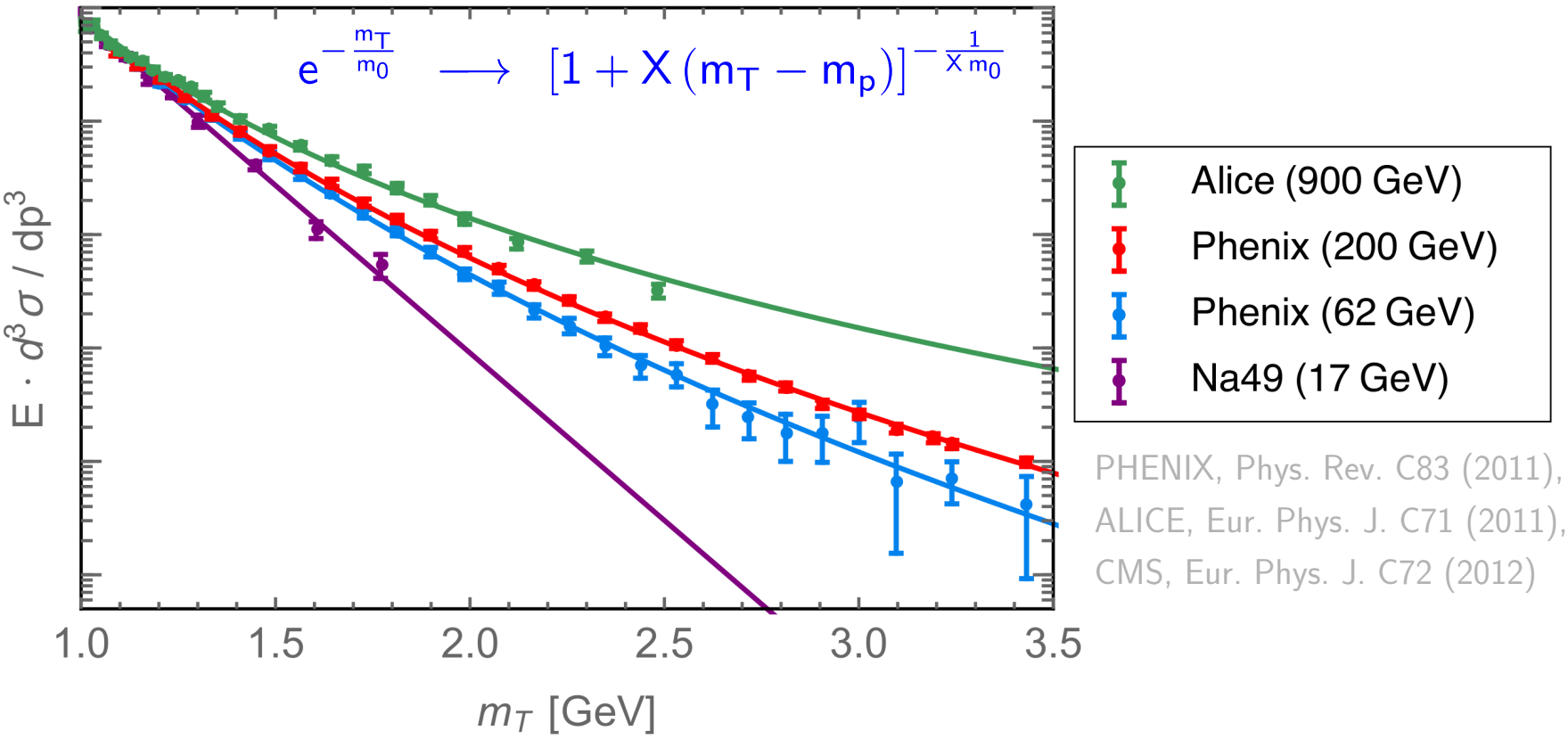
- precision measurement of $\sigma_{\bar{p}}$

NA49, Eur. Phys. J. C65 (2010)



Feynman Scaling Violation

- multiple scattering of protons induces Feynman scaling violation
- flattening of $\mathbf{p_T}$ distribution



PHENIX, Phys. Rev. C83 (2011),
ALICE, Eur. Phys. J. C71 (2011),
CMS, Eur. Phys. J. C72 (2012)

Feynman Scaling Violation

- multiple scattering of protons induces Feynman scaling violation
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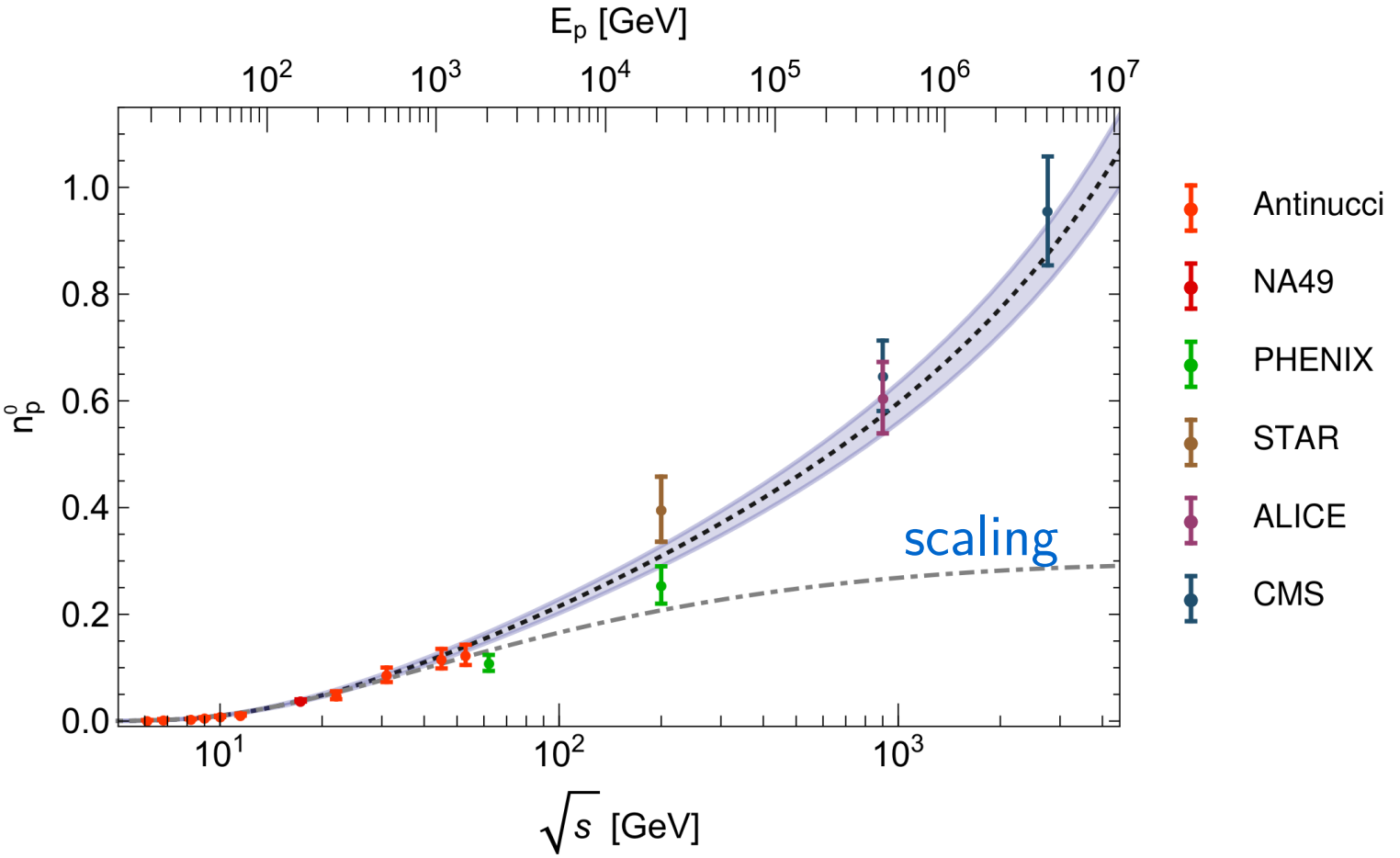
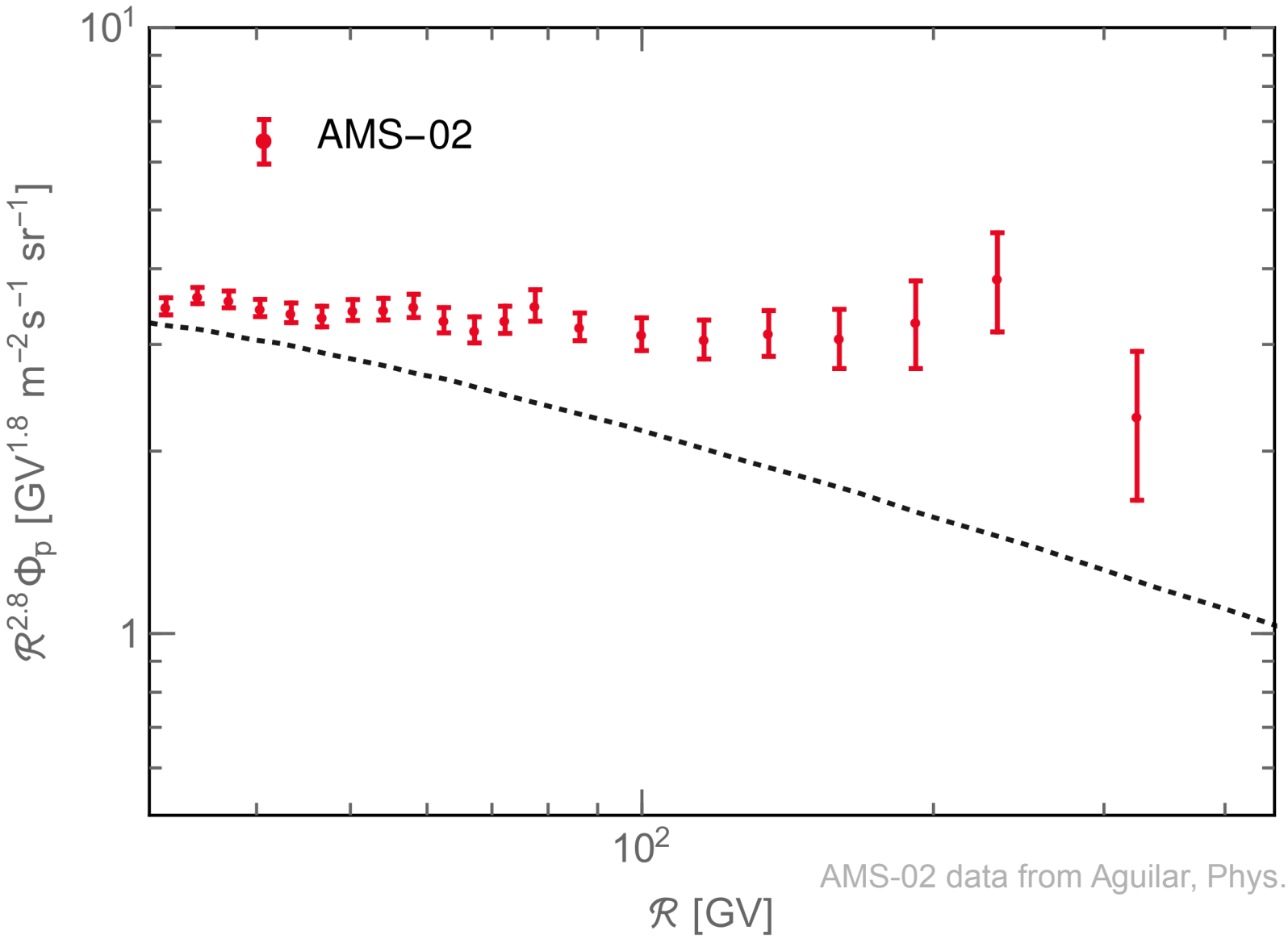


High Energy Antiproton Flux

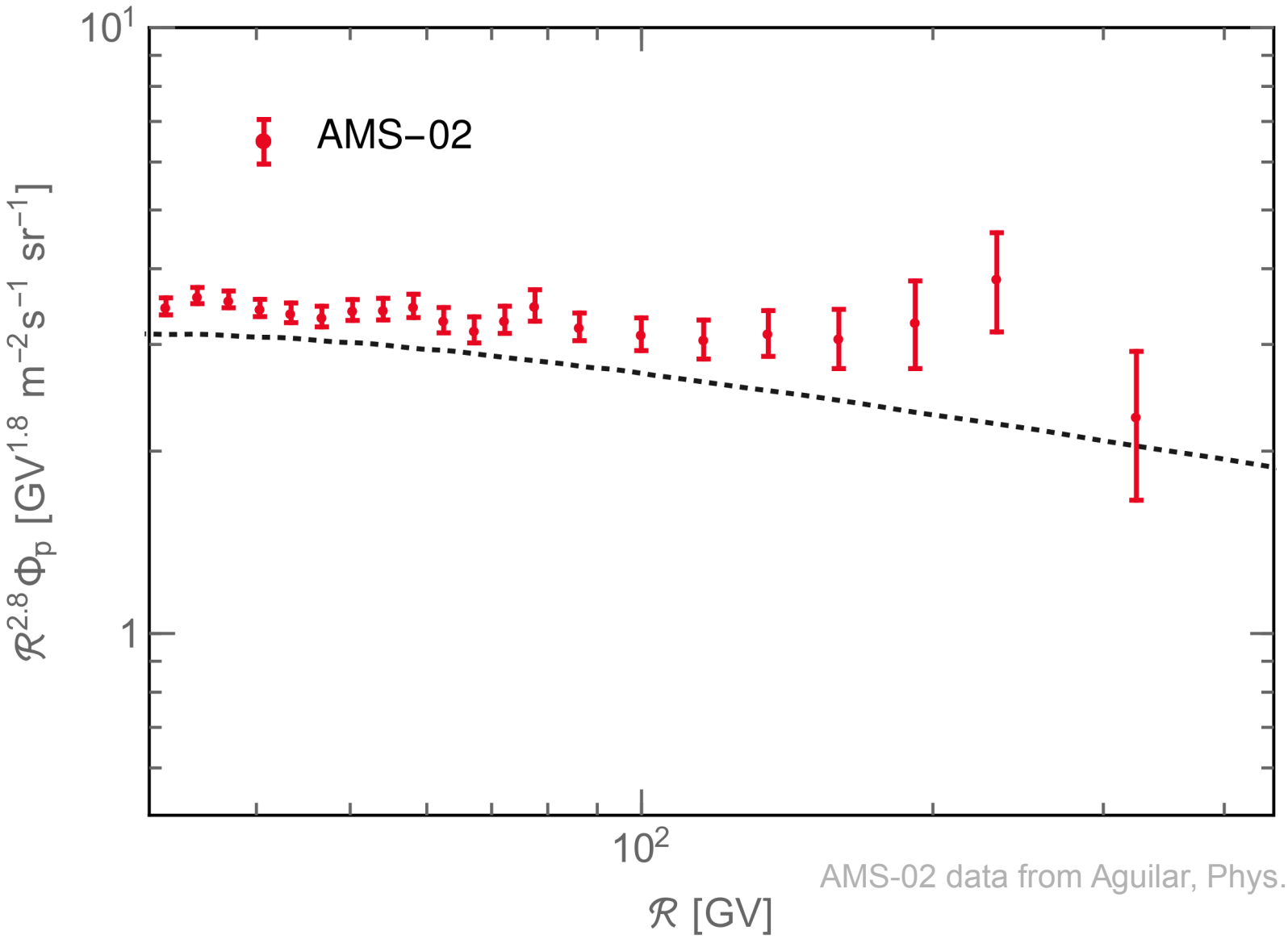


background

2015

AMS-02 data from Aguilar, Phys. Rev. Lett. 117 (2016)

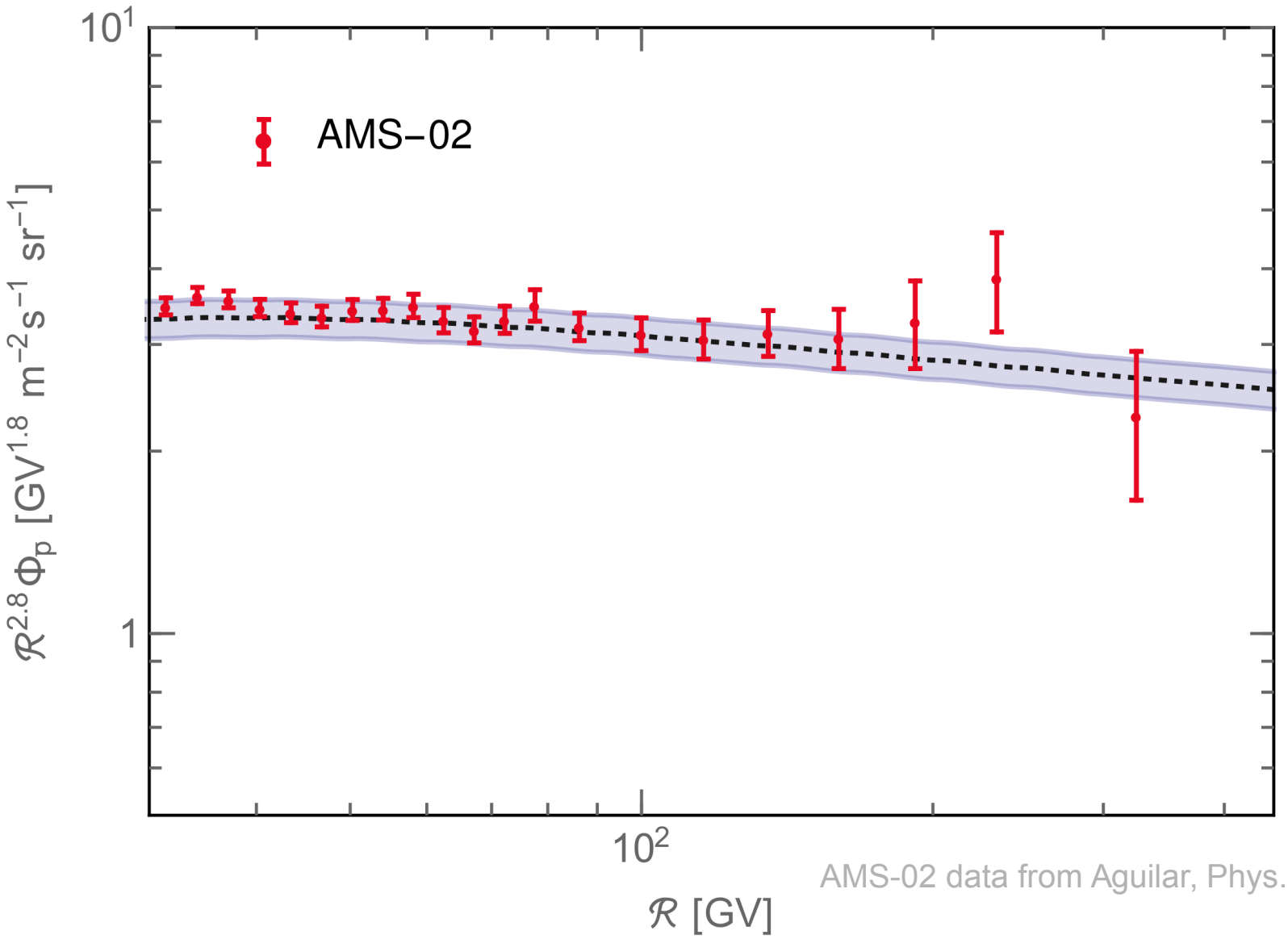
High Energy Antiproton Flux



updated propagation

AMS-02 data from Aguilar, Phys. Rev. Lett. 117 (2016)

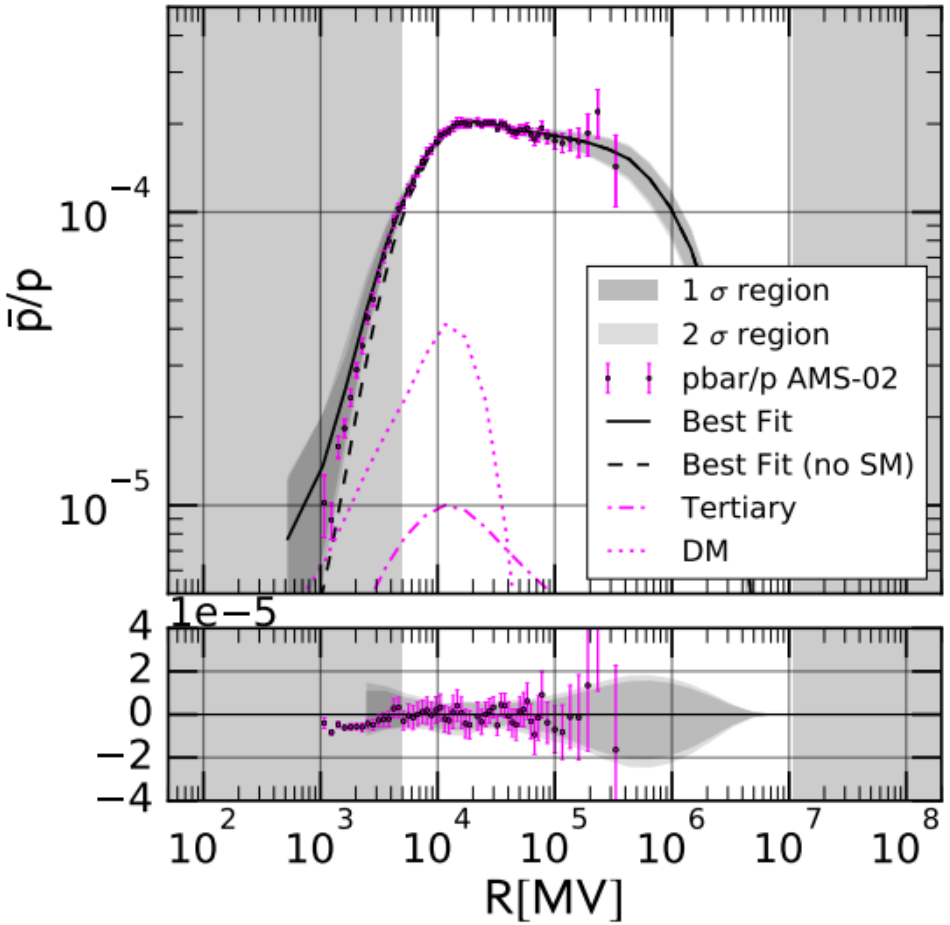
High Energy Antiproton Flux



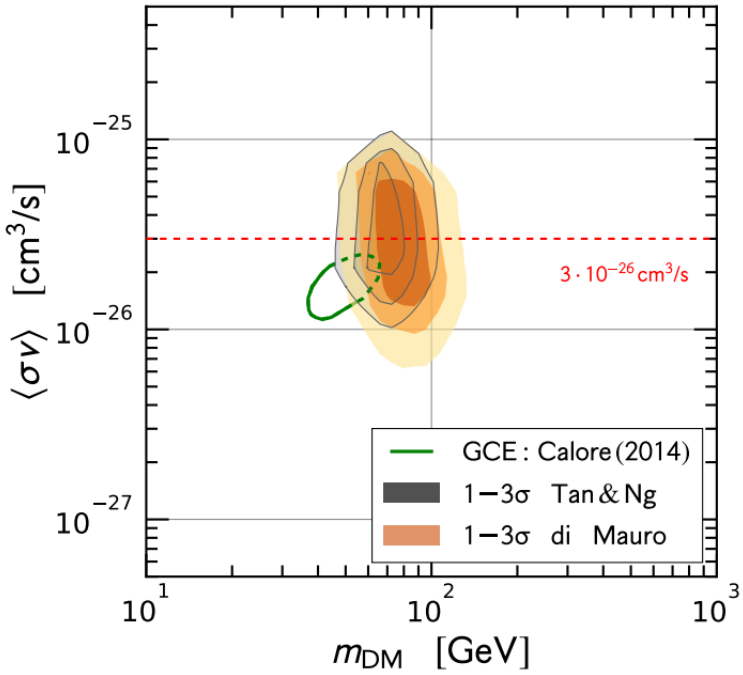
new cross section

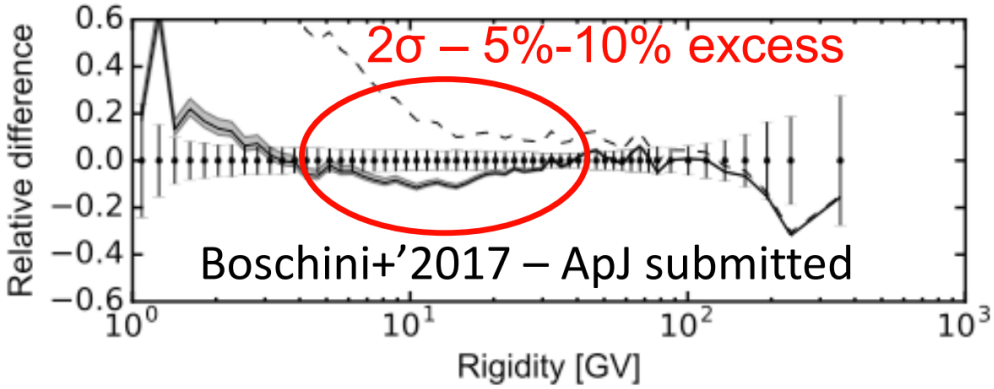
AMS-02 data from Aguilar, Phys. Rev. Lett. 117 (2016)

A new Antiproton Excess



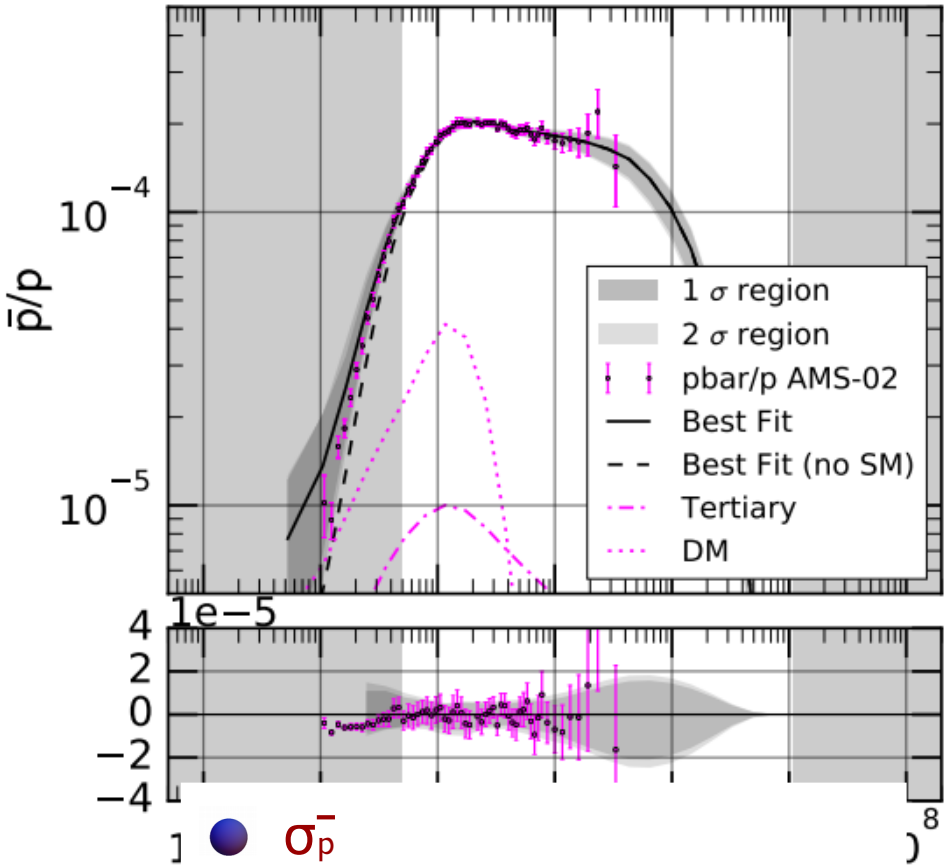
Cuoco, Krämer, Korsmeier, PRL 118 (2017)



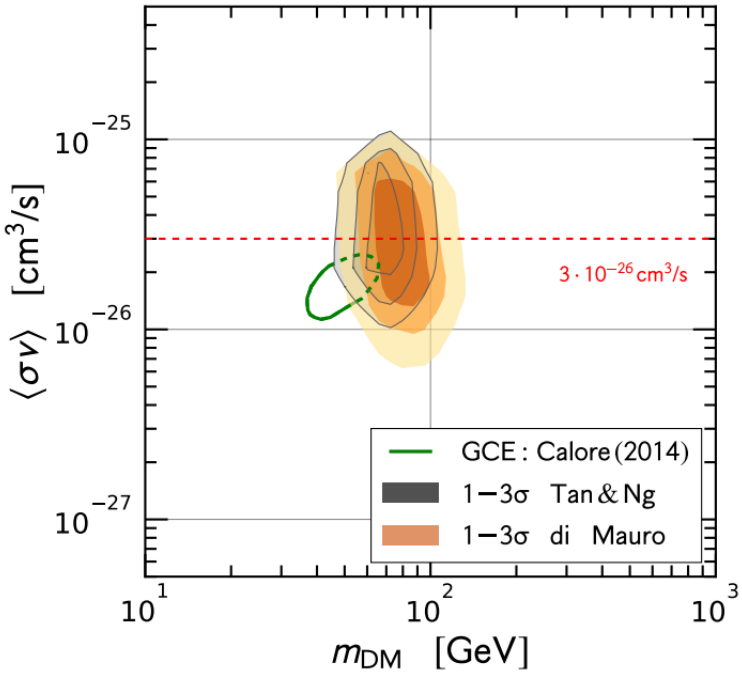


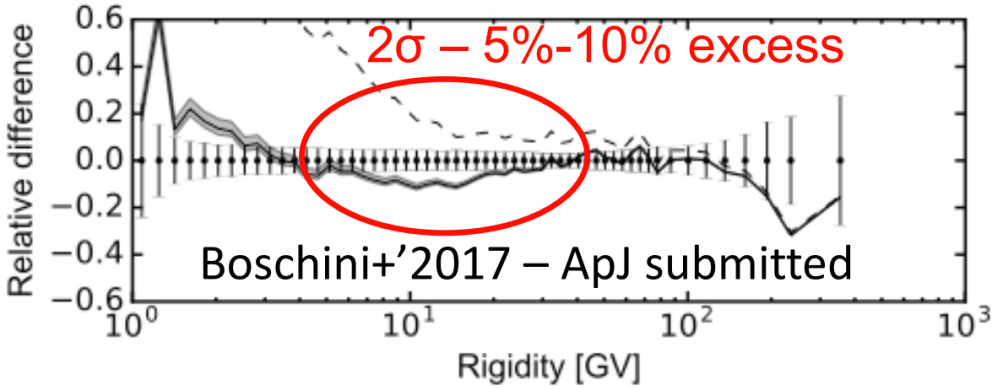
Moskalenko, XSCRC 2017, CERN

A new Antiproton Excess



- $\sigma_{\bar{p}}$
- low energy spectrum
- B/C
- diffusion halo size





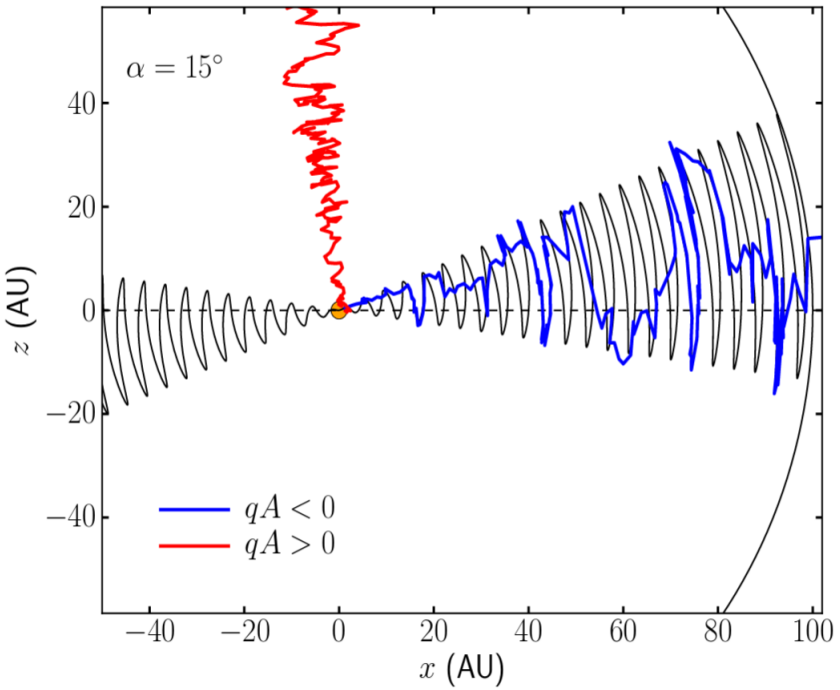
Moskalenko, XSCRC 2017, CERN

Solar Modulation

- force field approximation

  Gleeson, Axford, Astrophy. J. 154 (1968)

$$\Phi^{\mathrm{TOA}}(T) = \Phi^{\mathrm{IS}}(T+\phi) \times \frac{2mT+T^2}{2m(T+\phi)+(T+\phi)^2}$$



- heliospheric current sheet significantly affects fluxes for **qA < 0**

  Jokipii, Thomas, Astrophys. J. 243 (1981)

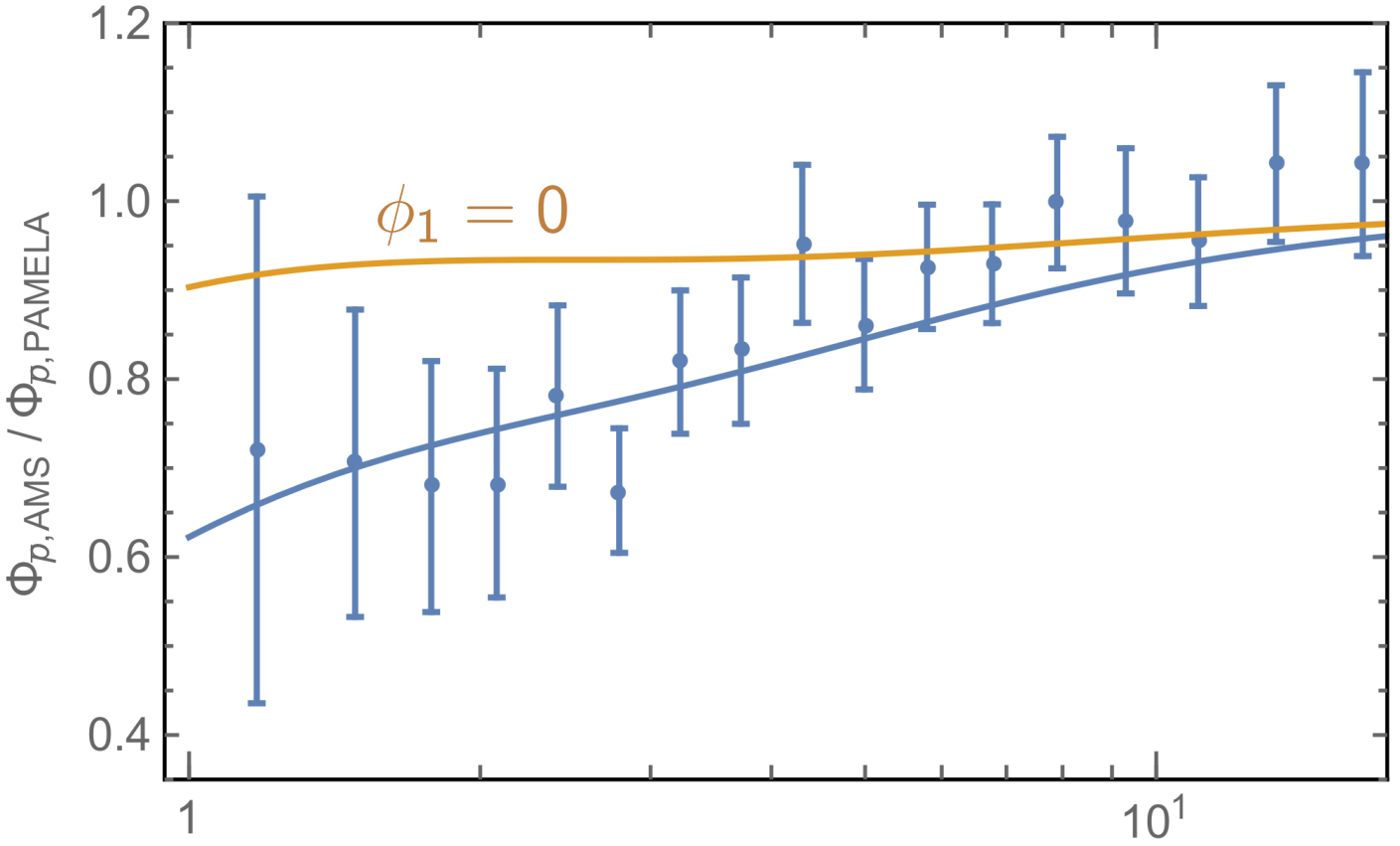
$$\phi(t) \to \phi_0(t) + \phi_1(t)\,\frac{1+\left(\frac{\mathcal{R}}{\mathcal{R}_0}\right)^2}{\beta\left(\frac{\mathcal{R}}{\mathcal{R}_0}\right)^3}$$

Cholis, Hooper, Linden, Phys. Rev. D 93 (2016)

$= 0$ for $qA > 0$

$\neq 0$ for $qA < 0$

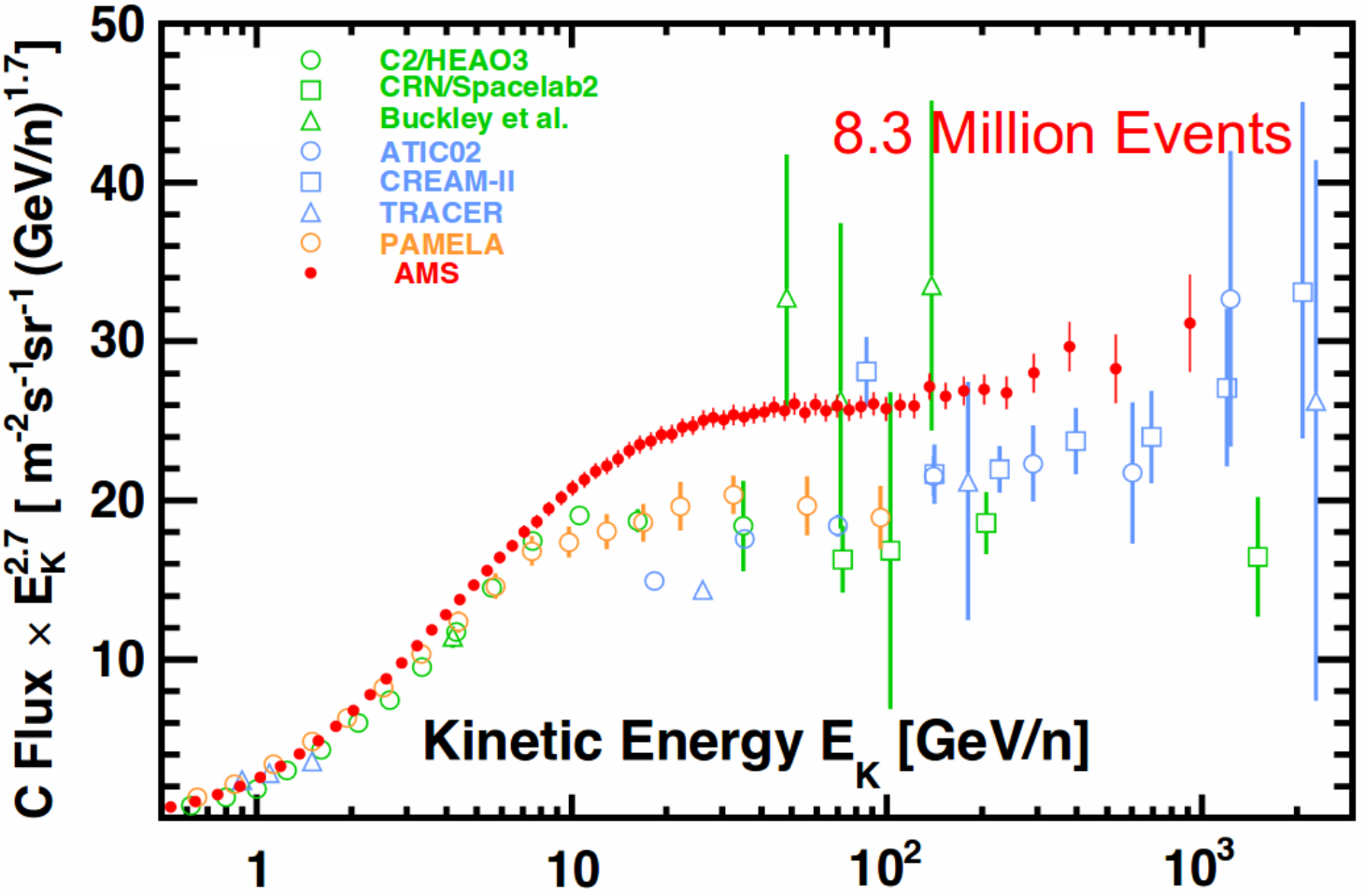
Solar Modulation



PAMELA, Adriani et al., JETPL 96 (2013),
AMS-02, Aguilar, Phys. Rev. Lett. 117 (2016)

- extract ϕ_1 from comparison between PAMELA and AMS-02

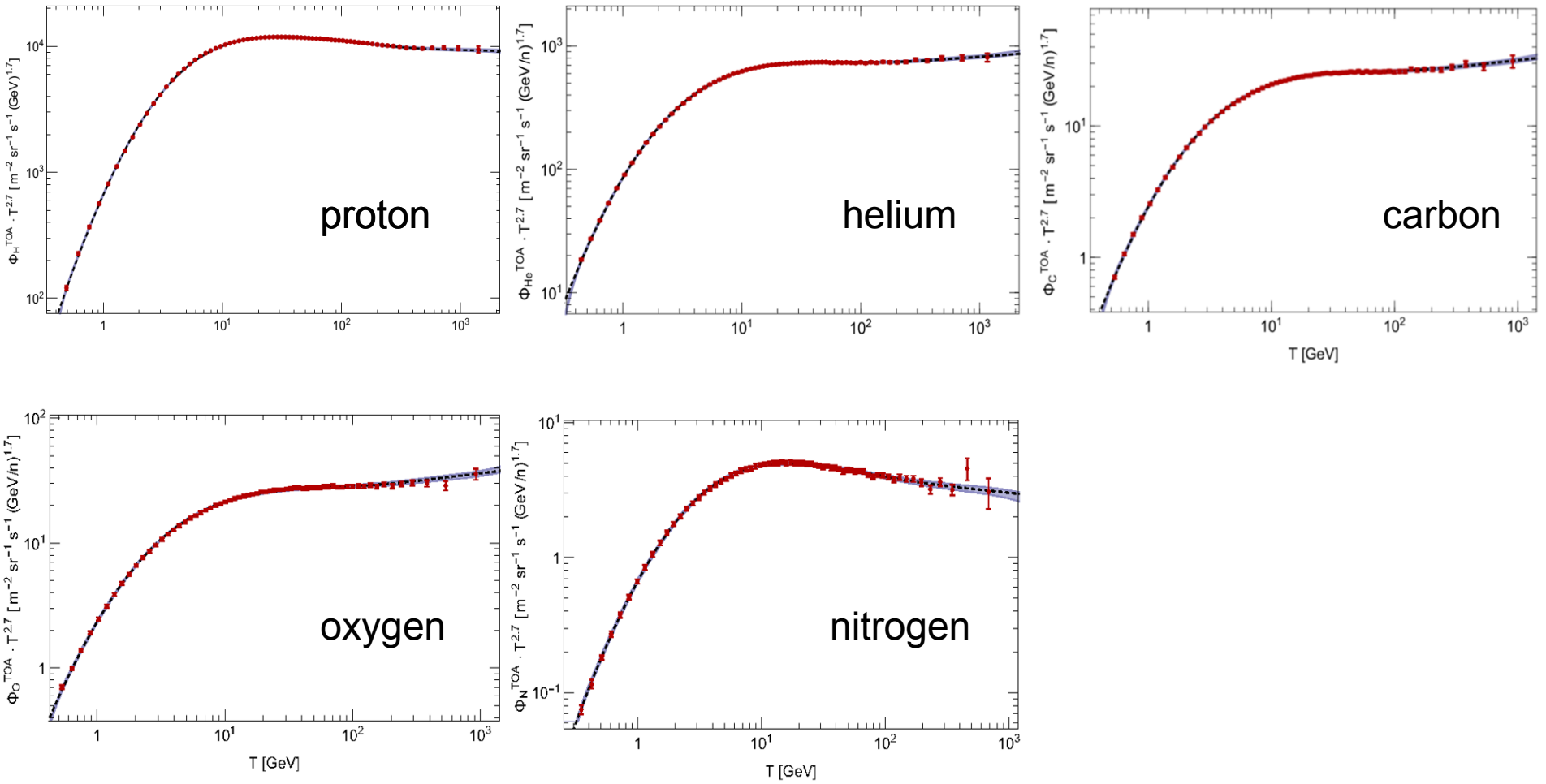
Carbon Flux



Yan, XSCRC 2017, CERN

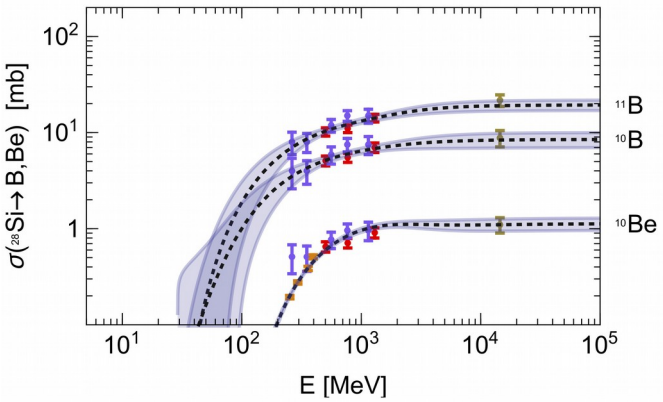
- improved measurement of primary fluxes by AMS-02

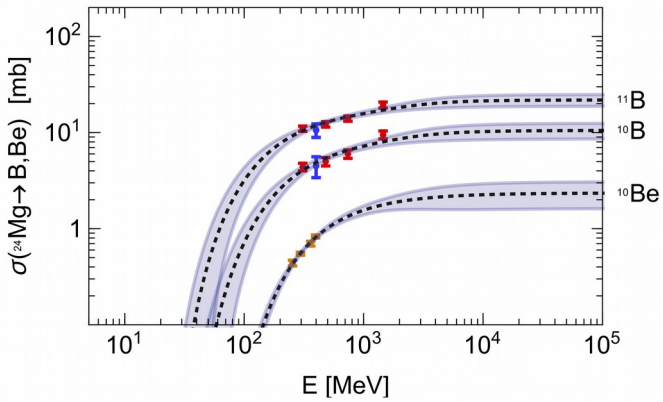
Primary Cosmic Ray Fluxes

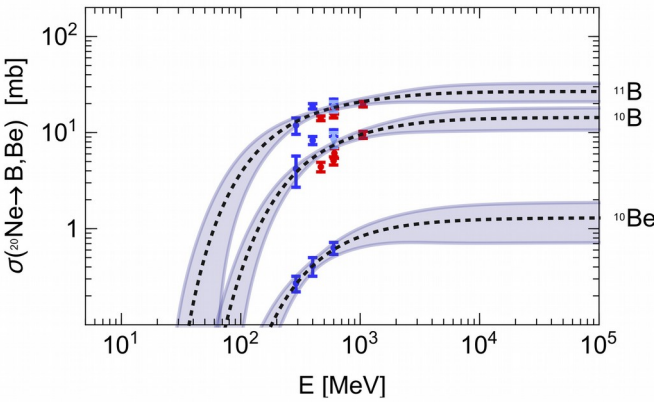


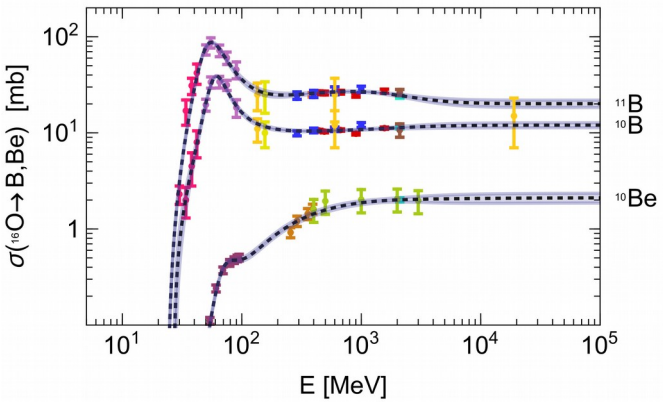
AMS-02 data from Yoon et al., Astrophys. J. 728 (2011), Aguilar et al., Phy. Rev. Lett. 114 & 115 (2015), Yan, XSCRC 2017, CERN

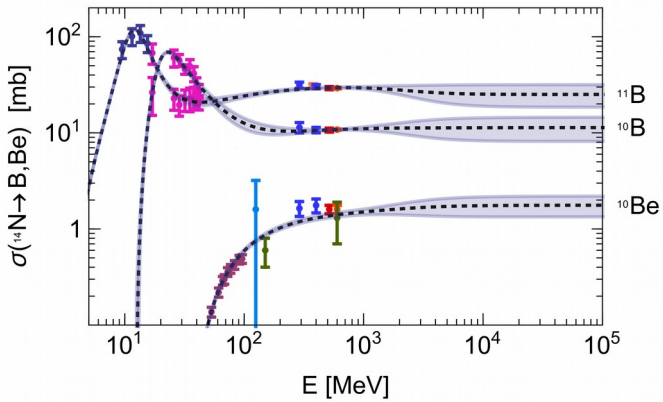
Boron Production

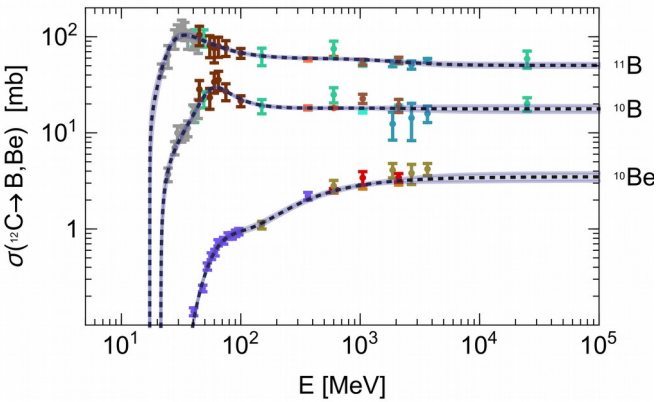


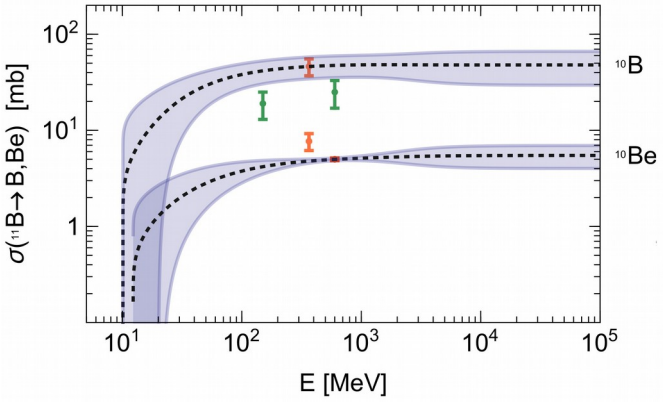












Fit to:

Bodansky et al., Astrophys. J. 202 (1975), Bodemann et al., Nucl. Instr. 82 (1993), Brechtmann et al. Phys.Rev. C39 (1989), Davids et al., Phys. Rev. C1 (1970), Epherre et al., Nucl. Phys. A139 (1969), Fontes et al.,Nucl. Phys. A165 (1971), Phys. Rev. C15 (1977), Goel et al., Nature 223 (1969), Jung et al., Phys. Rev. C1 (1970), Korejwo et al., J. Phys. G28 (2002), Laumer et al., Phys. Rev. C8 (1973), Phys. Rev. C10 (1974), Lindstrom et al., LBL-3650 (1975), Moyle et al., Phys. Rev. C19 (1979), Olson et al., Phys. Rev. C28 (1983), Raisbeck et al., Phys. Rev. C9 (1974), Raisbeck et al., PRL 27 (1971), Roche et al., Phys. Rev. C14 (1976), Schiekel et al., Nucl. Instr. 114 (1996), Webber et al. Phys. Rev. C41 (1990), Astrophys. J. 508 (1998), Yiou et al. J. of Geophy. Res. 74 (1969), Zeitlin et al. Nucl.Phys. A784 (2007), Phys.Rev. C83 (2011), Phys.Rev.C64 (2001)

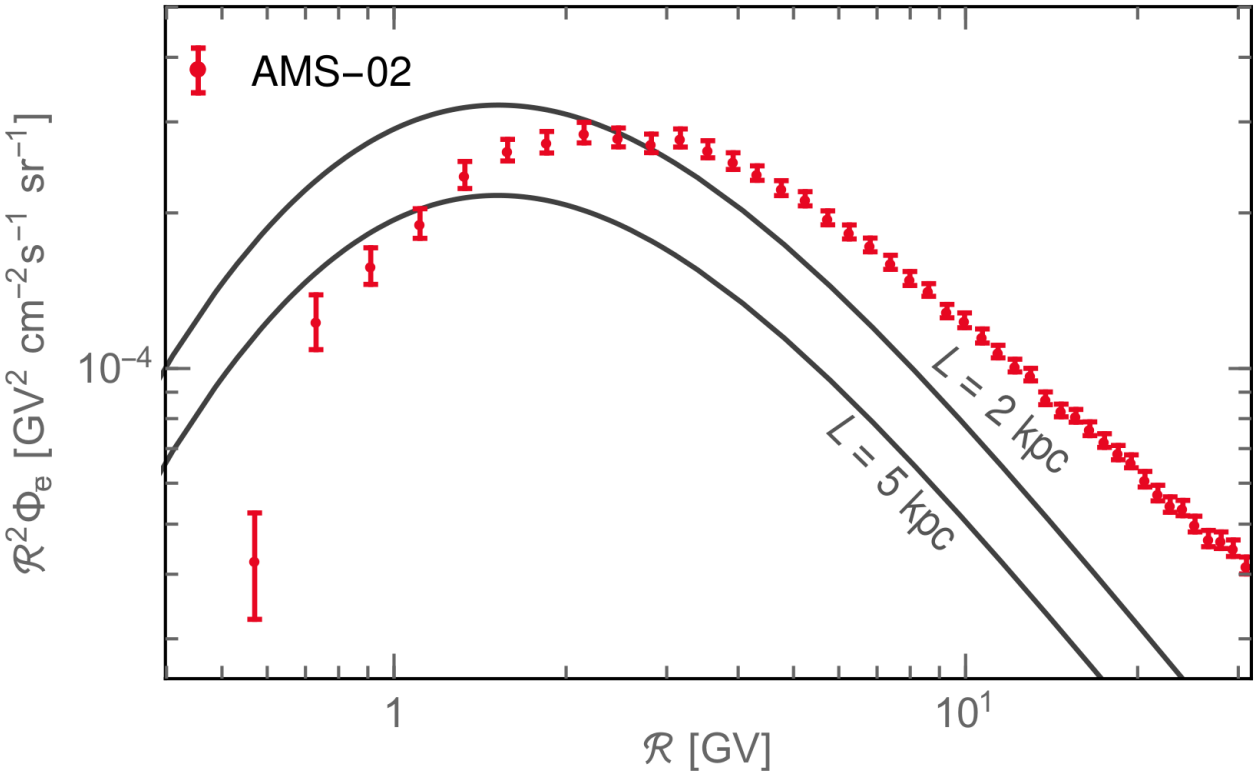
Positrons

- secondary fluxes of antiprotons, boron invariant under

$$L \to \alpha L \qquad K_0 \to \alpha K_0 \qquad V_A \to \sqrt{\alpha} V_A$$

- degeneracy is lifted by positron flux

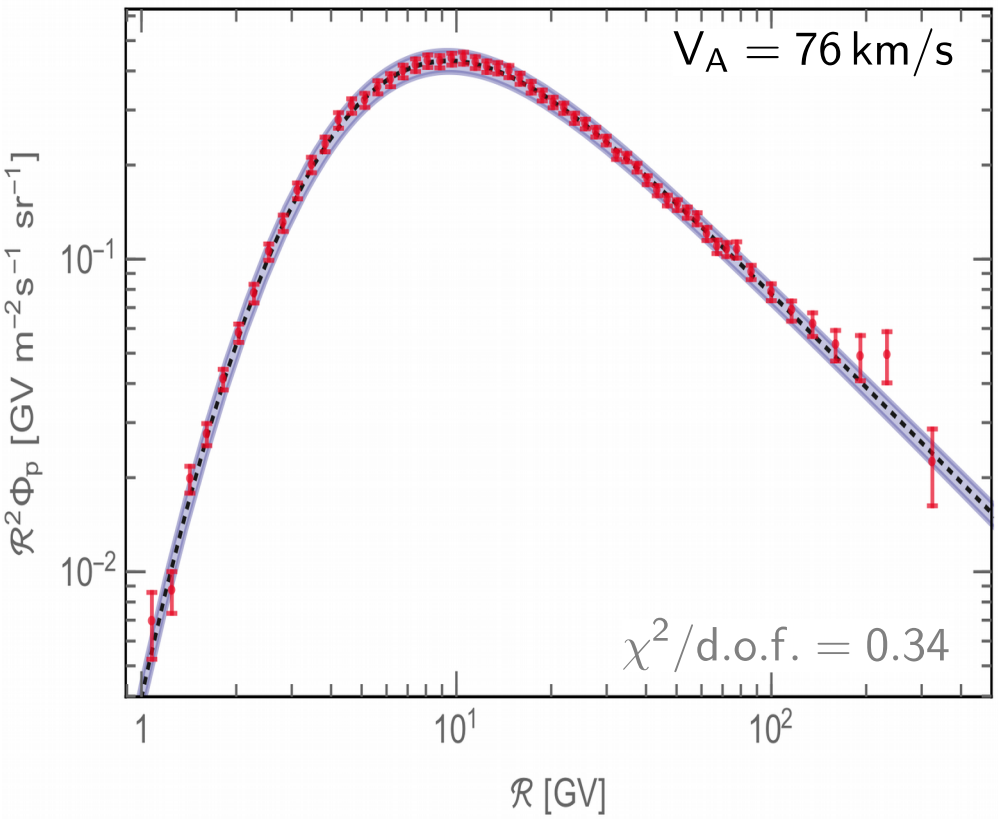
Lavalle, Maurin, Putze, Phys.Rev. D90 (2014), Boudaud et al. arxiv:1612.03924 (2016)



$L \gtrsim 5\,\mathrm{kpc}$

Antiproton Fit

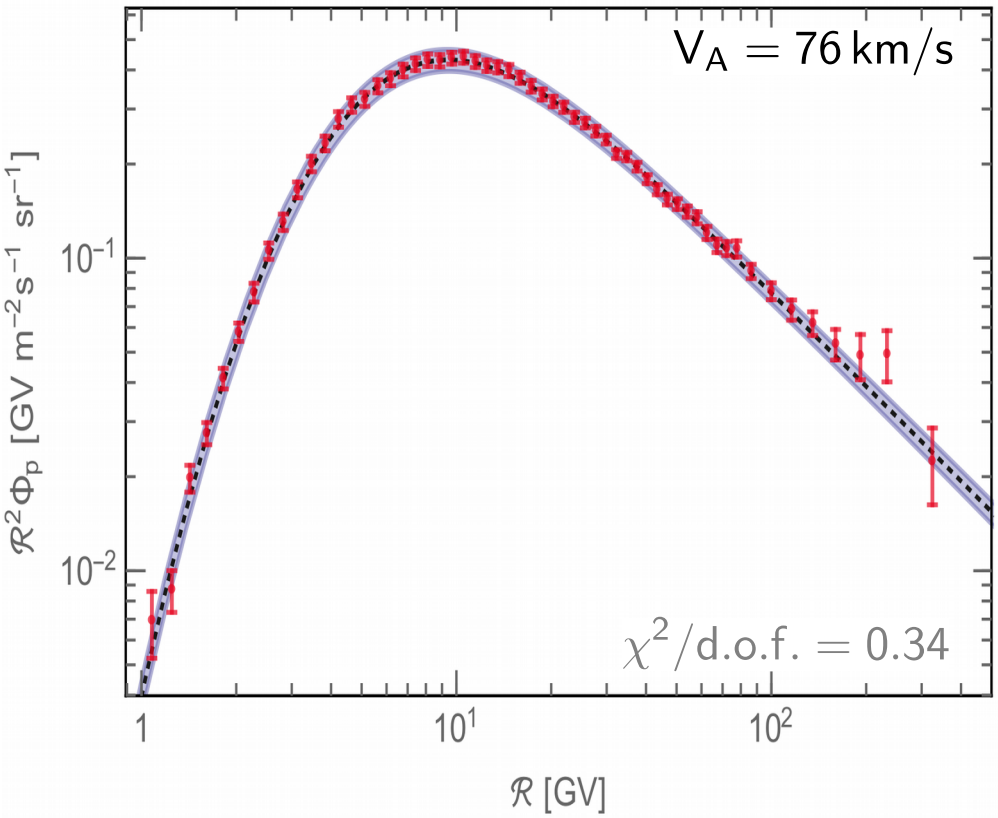
antiproton flux



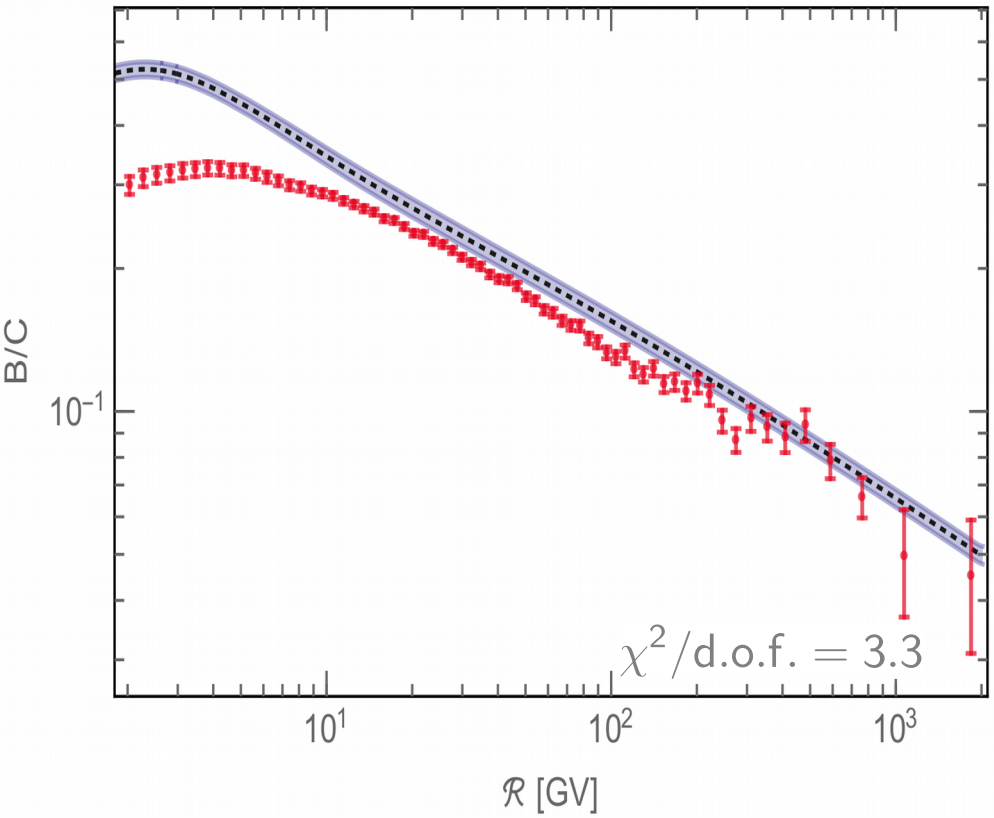
AMS-02 data: Aguilar et al., Phys. Rev. Lett. 117 (2016)

Antiproton Fit

antiproton flux



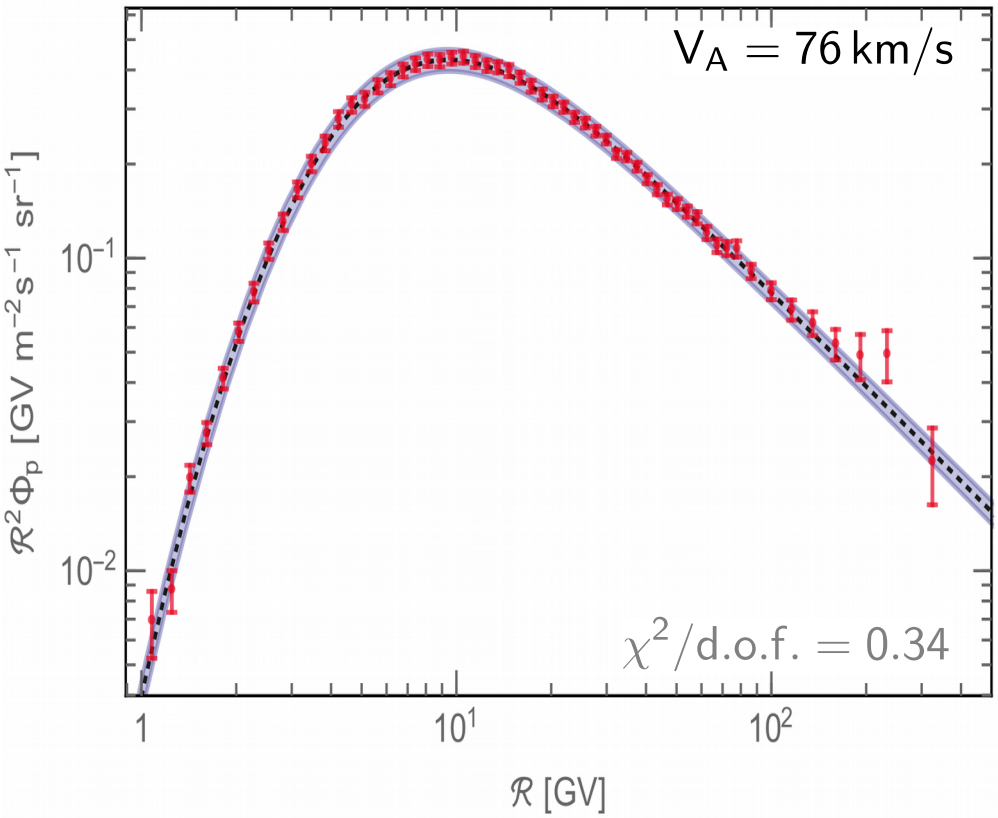
boron/carbon



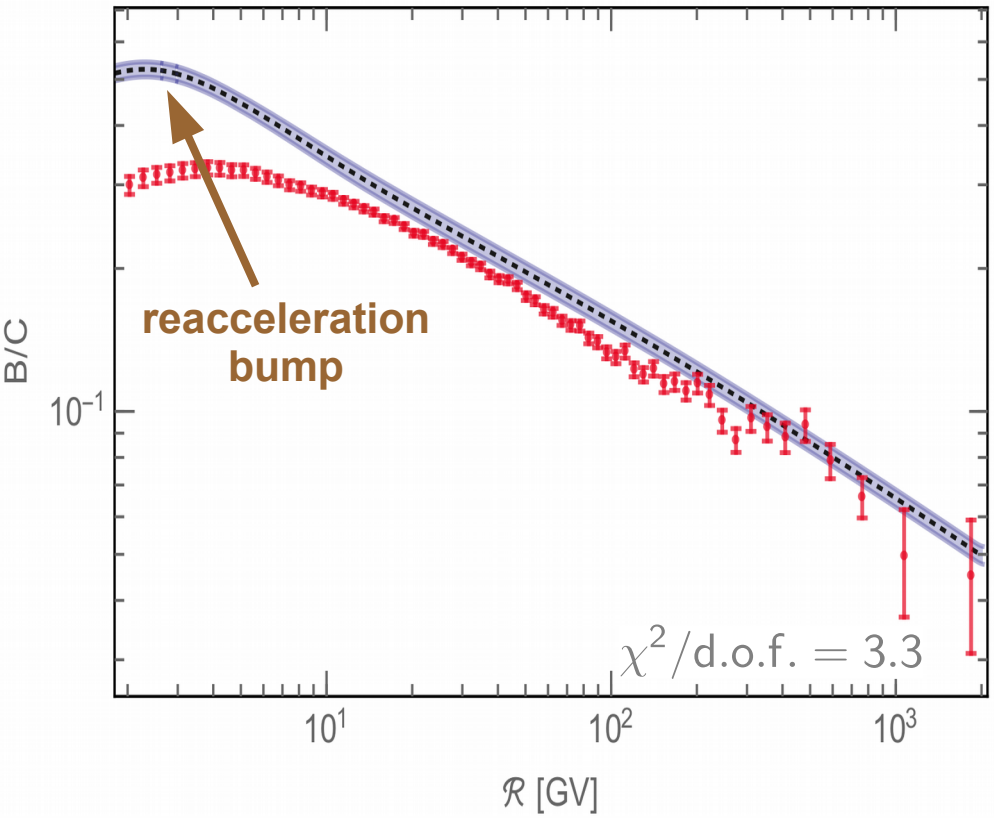
AMS-02 data: Aguilar et al., Phys. Rev. Lett. 117 (2016)

Antiproton Fit

antiproton flux



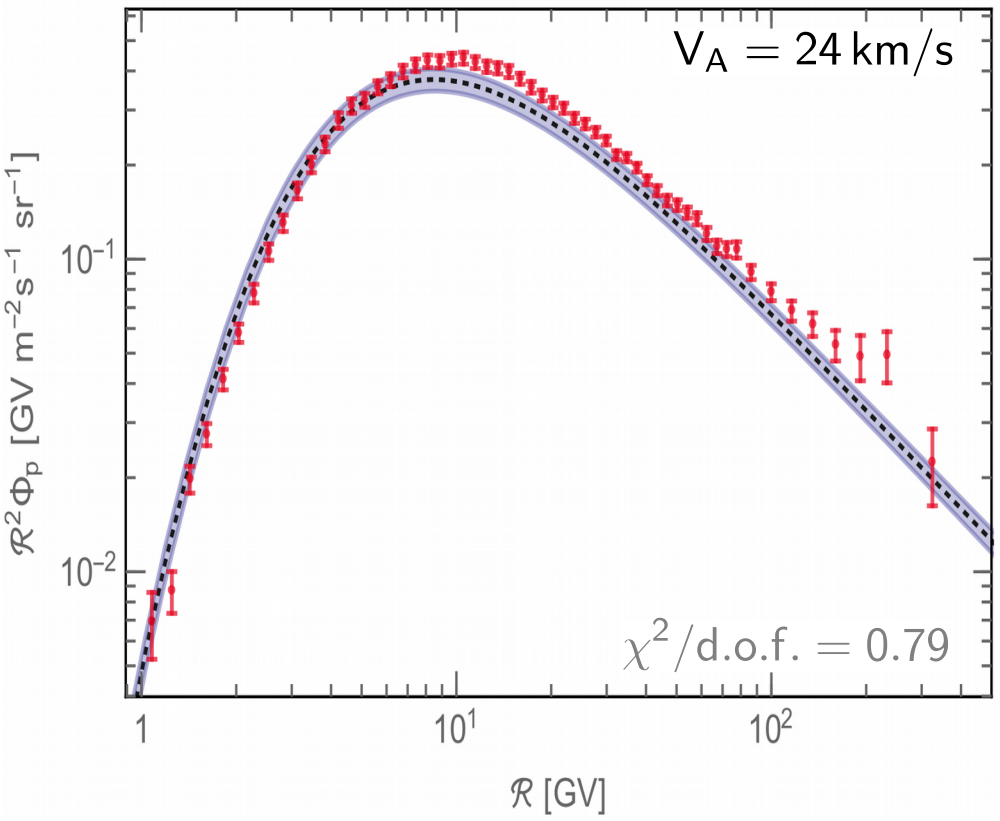
boron/carbon



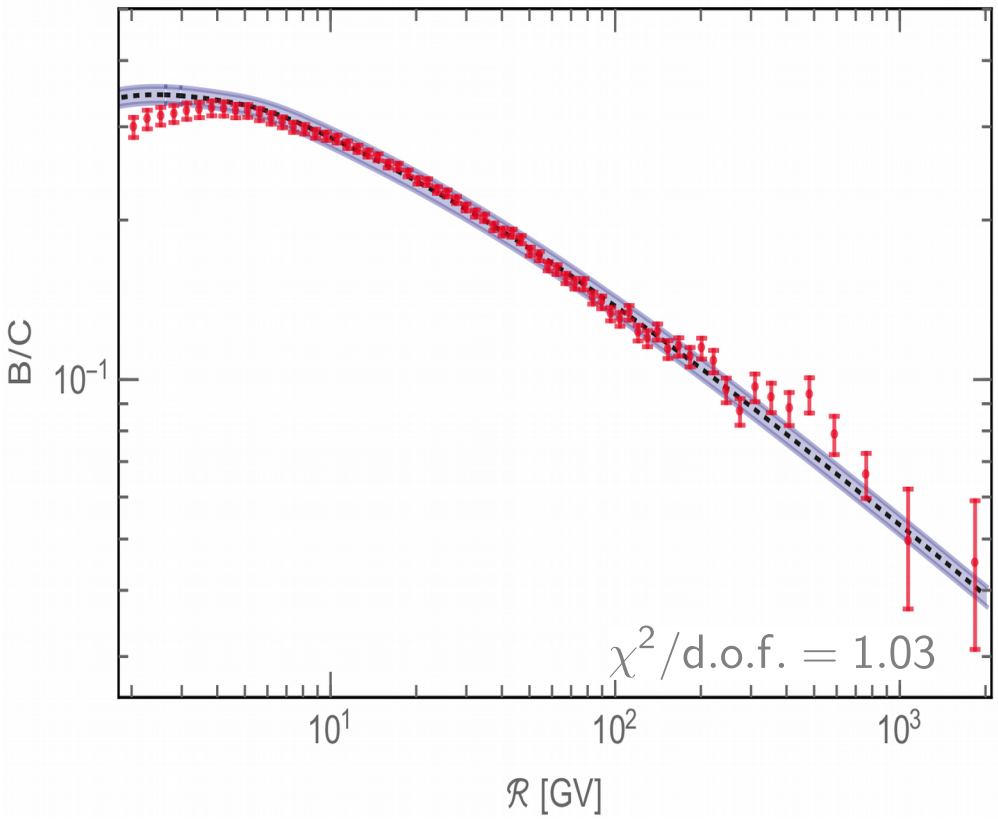
AMS-02 data: Aguilar et al., Phys. Rev. Lett. 117 (2016)

Antiproton and B/C Fit

antiproton flux



boron/carbon

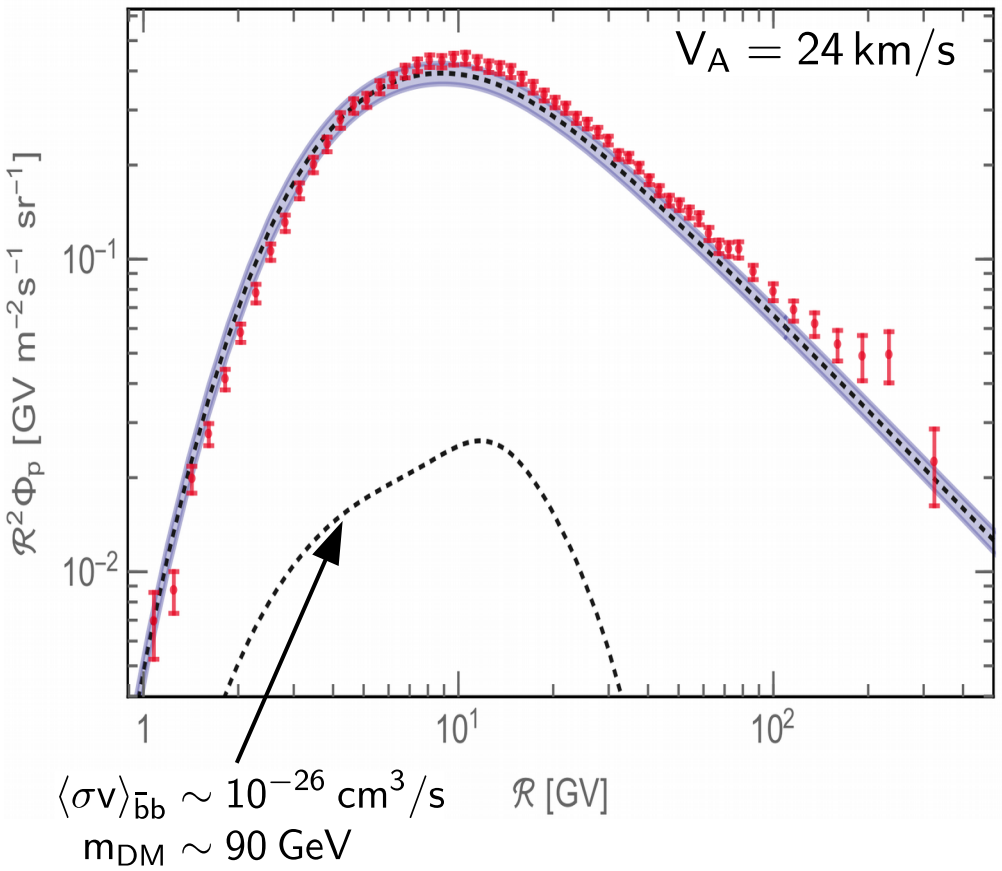


AMS-02 data: Aguilar et al., Phys. Rev. Lett. 117 (2016)

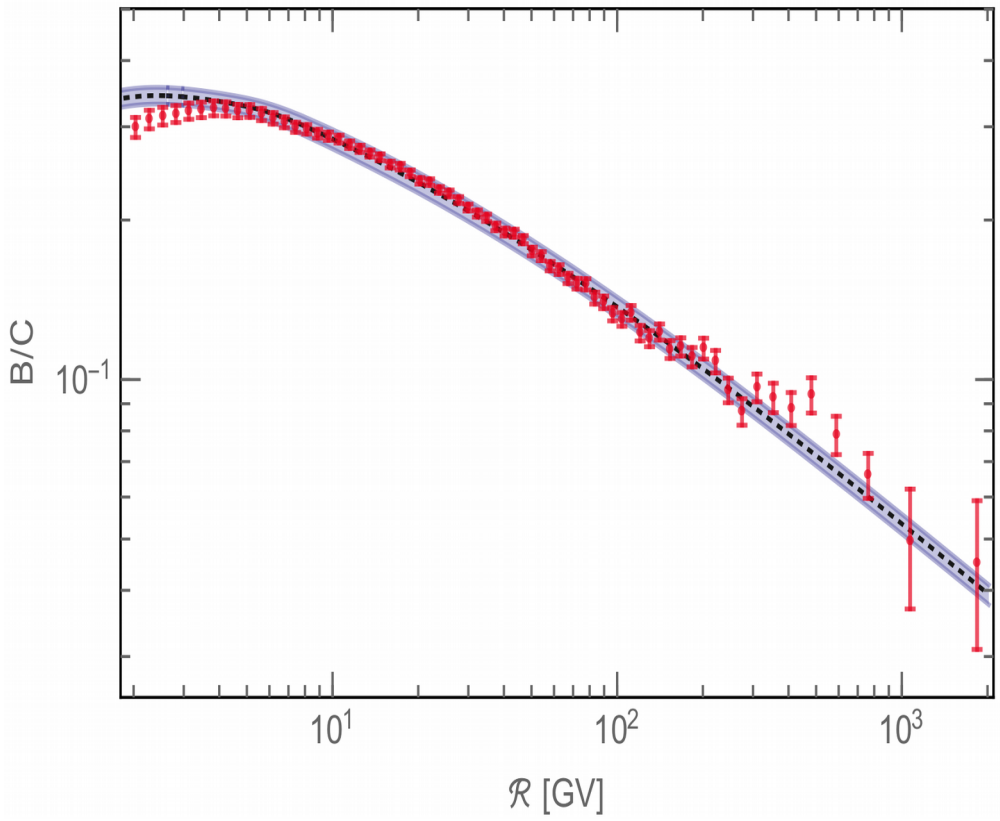
- antiproton and B/C are consistent with pure background

Fit with Dark Matter

antiproton flux



boron/carbon

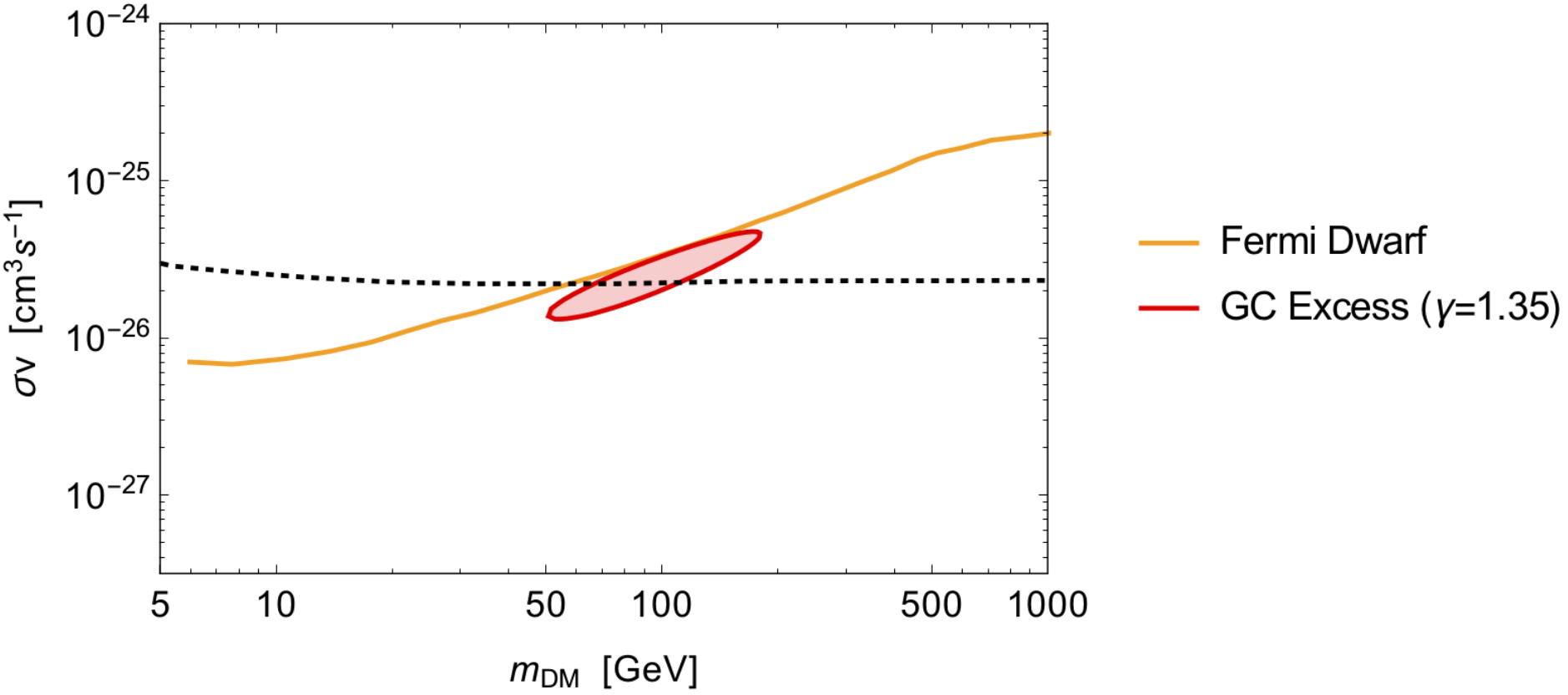


- dark matter slightly improves fit ($\lesssim 2\,\sigma$)

Dark Matter

- antiproton constraints for standard NFW profile ($\rho_0 = 0.38\ \frac{\text{GeV}}{\text{cm}^3}$)

McMillan, Mon. Not. R. Astron. Soc. 465 (2017)



Steigman, Phys.Rev. D86 (2012), Fermi-LAT, Astrophys.J. 834 (2017), Goodenough, Hooper, arXiv:0910.2998 (2009), Krauss et al., Phys. Dark Univ. 14 (2016), Cuoco, Krämer, Korsmeier, PRL 118 (2017)

Dark Matter

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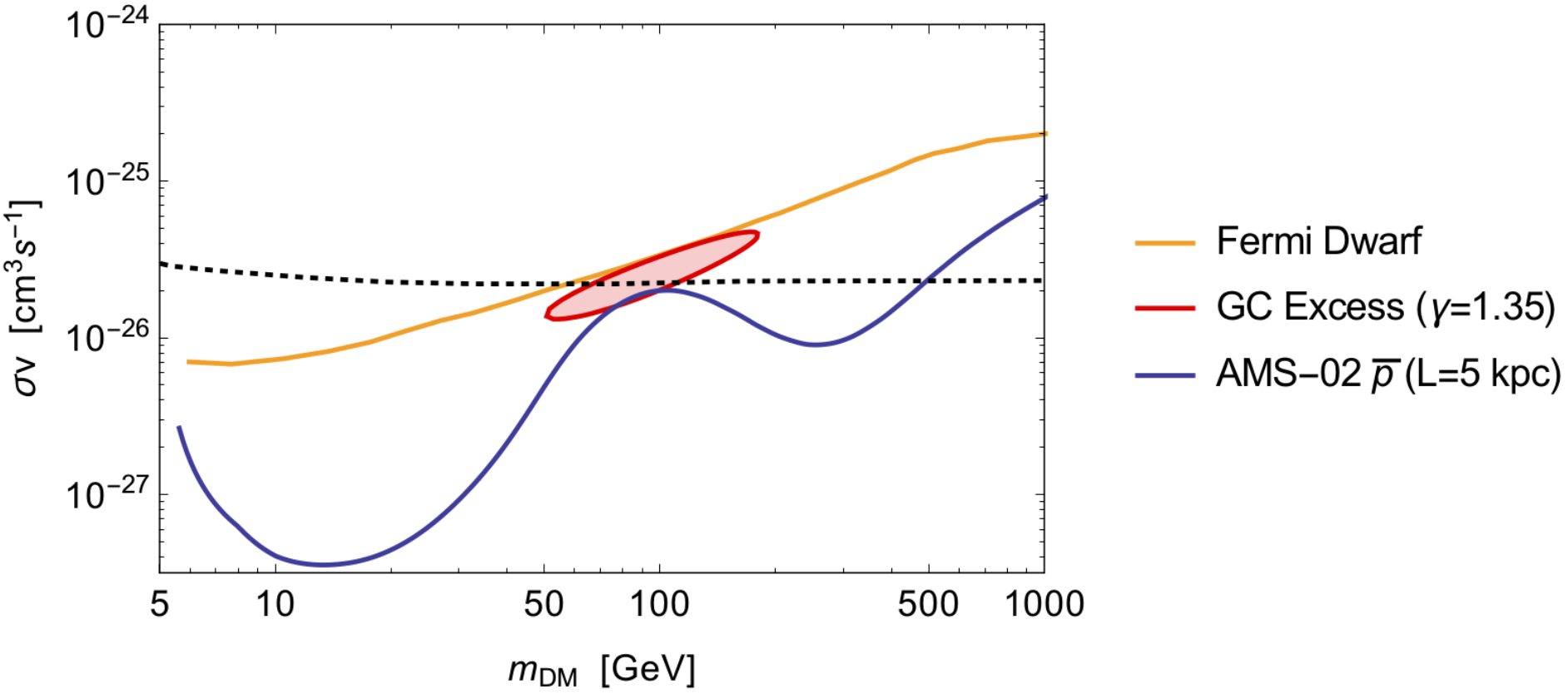

Steigman, Phys.Rev. D86 (2012), Fermi-LAT, Astrophys.J. 834 (2017), Goodenough, Hooper, arXiv:0910.2998 (2009), Krauss et al., Phys. Dark Univ. 14 (2016), Cuoco, Krämer, Korsmeier, PRL 118 (2017)

Dark Matter

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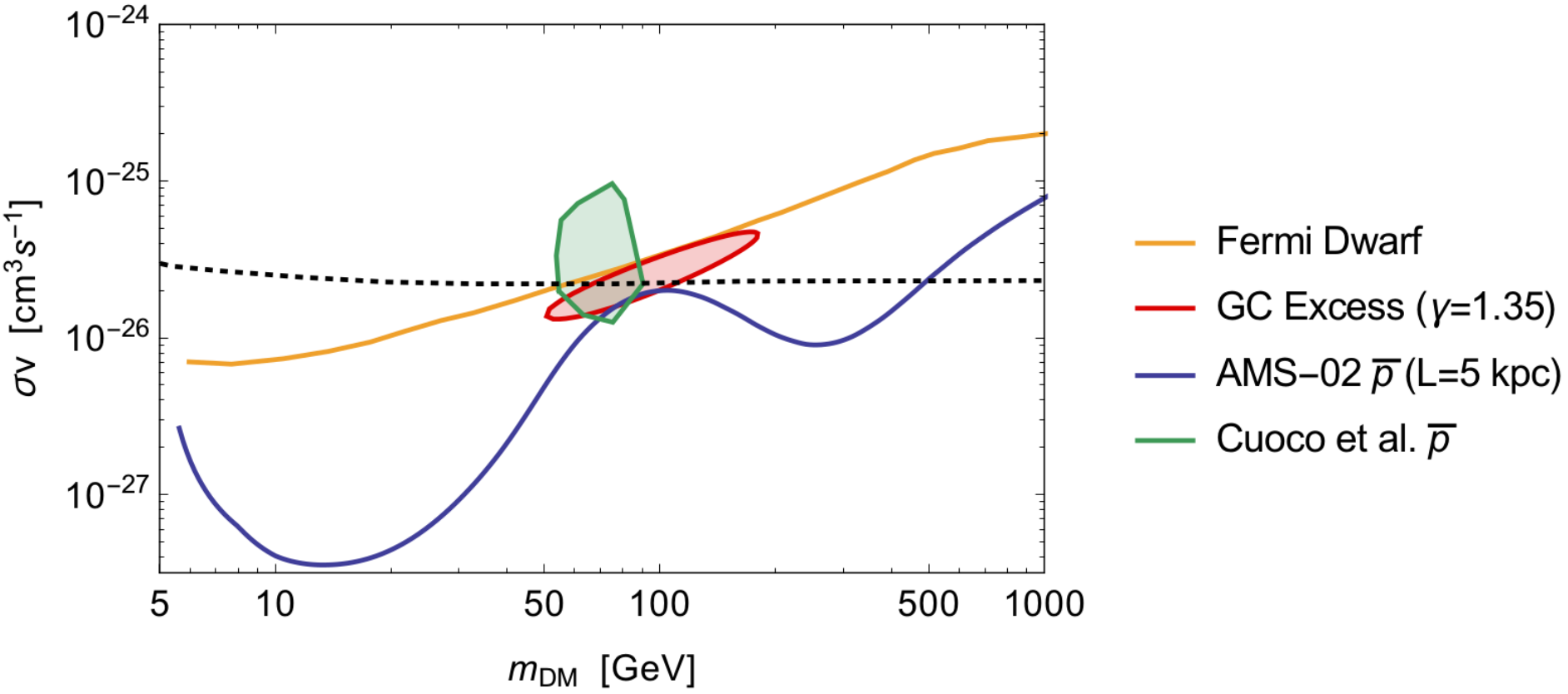
McMillan, Mon. Not. R. Astron. Soc. 465 (2017)



Steigman, Phys.Rev. D86 (2012), Fermi-LAT, Astrophys.J. 834 (2017), Goodenough, Hooper, arXiv:0910.2998 (2009), Krauss et al., Phys. Dark Univ. 14 (2016), Cuoco, Krämer, Korsmeier, PRL 118 (2017)

Dark Matter

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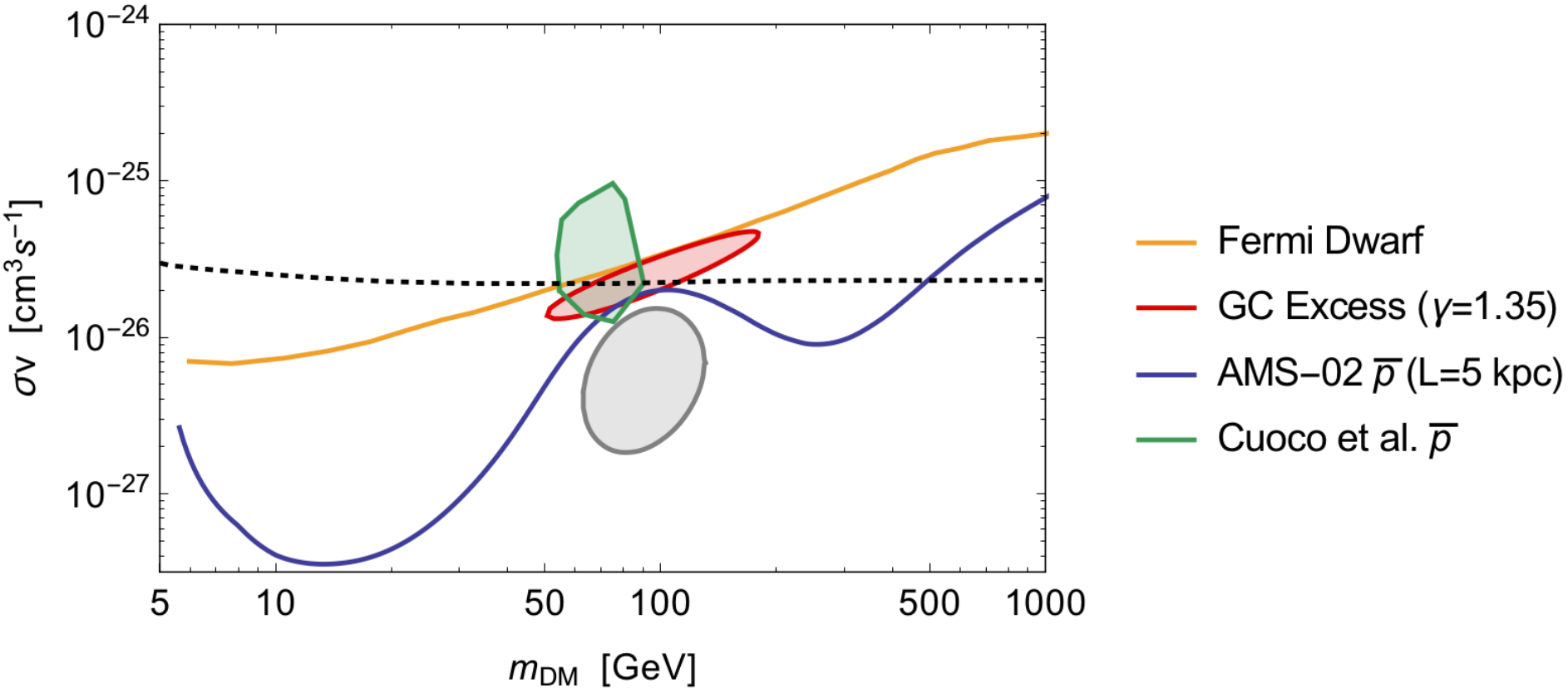
McMillan, Mon. Not. R. Astron. Soc. 465 (2017)



Steigman, Phys.Rev. D86 (2012), Fermi-LAT, Astrophys.J. 834 (2017), Goodenough, Hooper, arXiv:0910.2998 (2009), Krauss et al., Phys. Dark Univ. 14 (2016), Cuoco, Krämer, Korsmeier, PRL 118 (2017)

Conclusion

- uncertainties in the antiproton flux have been addressed systematically
- antiprotons currently set the strongest constraints on WIMP annihilation
- a slight excess around R $\sim$ 10 GV will be further investigated