Hadronic Cosmic Rays: Towards the Precision Era

Martin W. Winkler

partly based on JCAP 10 (2015) with R. Kappl, A. Reinert, JCAP 02 (2017), JCAP 01 (2018) with A. Reinert

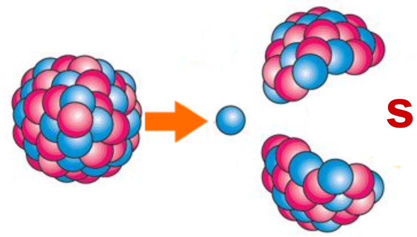
$\overline{d}$**19**

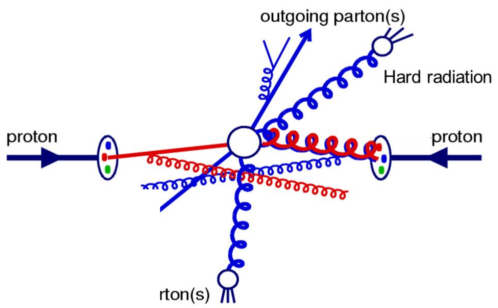
UCLA

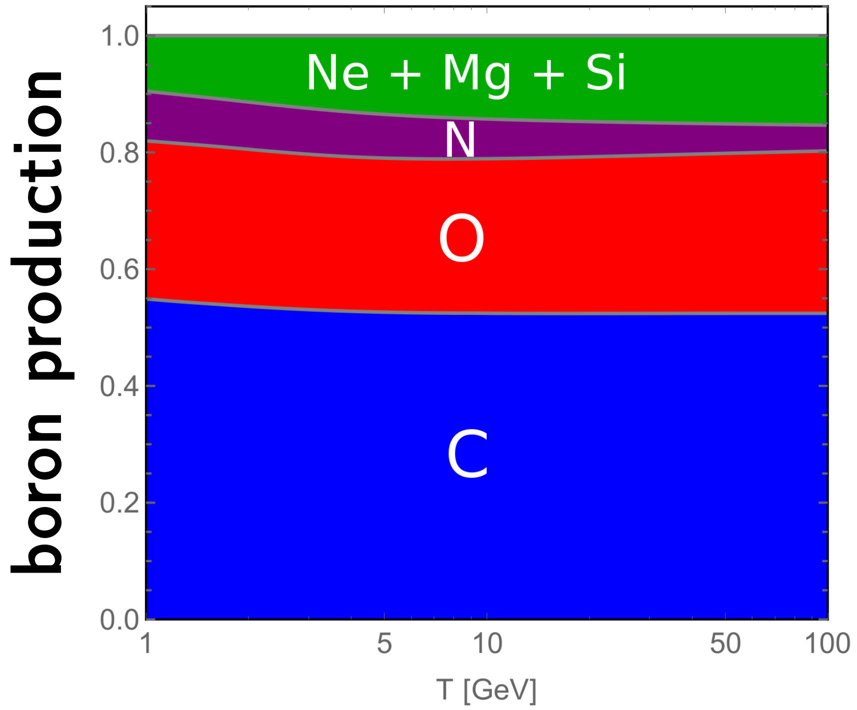
March 28

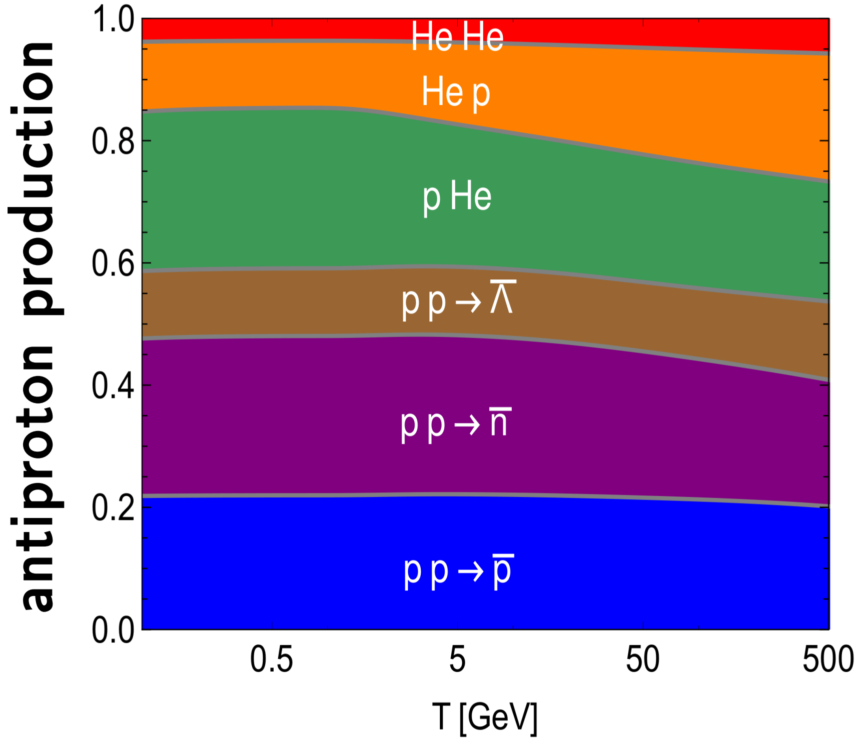
Secondary Cosmic Ray Production

- primary cosmic rays scatter on interstellar matter and produce secondaries: some nuclei (Li, Be, B), antimatter

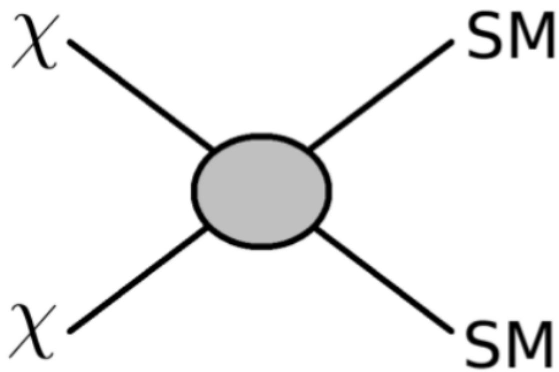




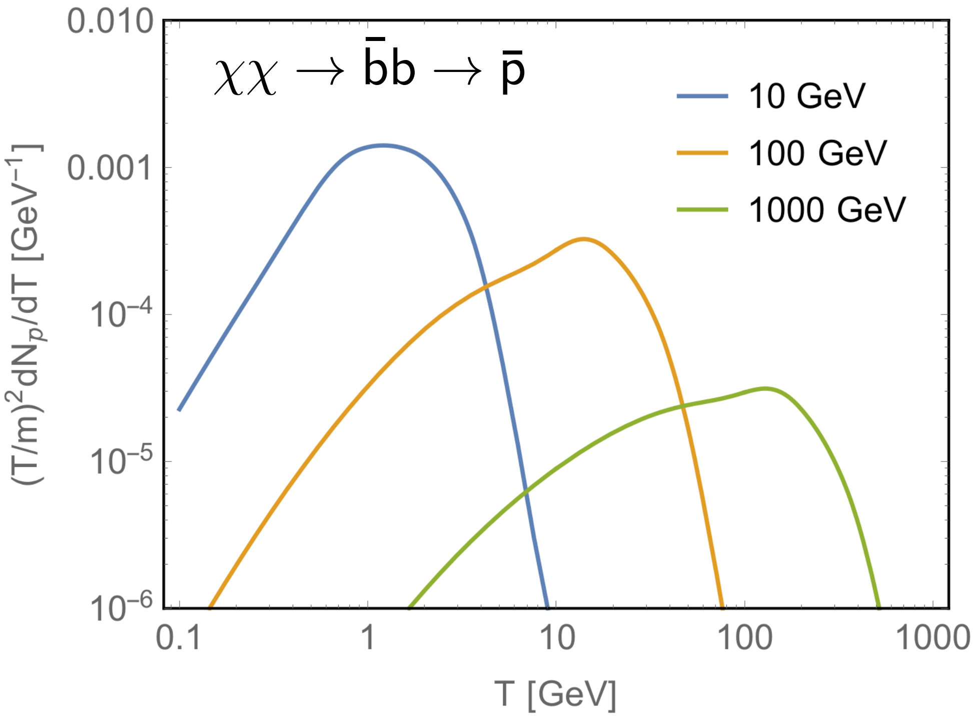




Dark Matter Annihilation



- dark matter annihilation in the galactic halo



spectra from PPPC 4 DM ID

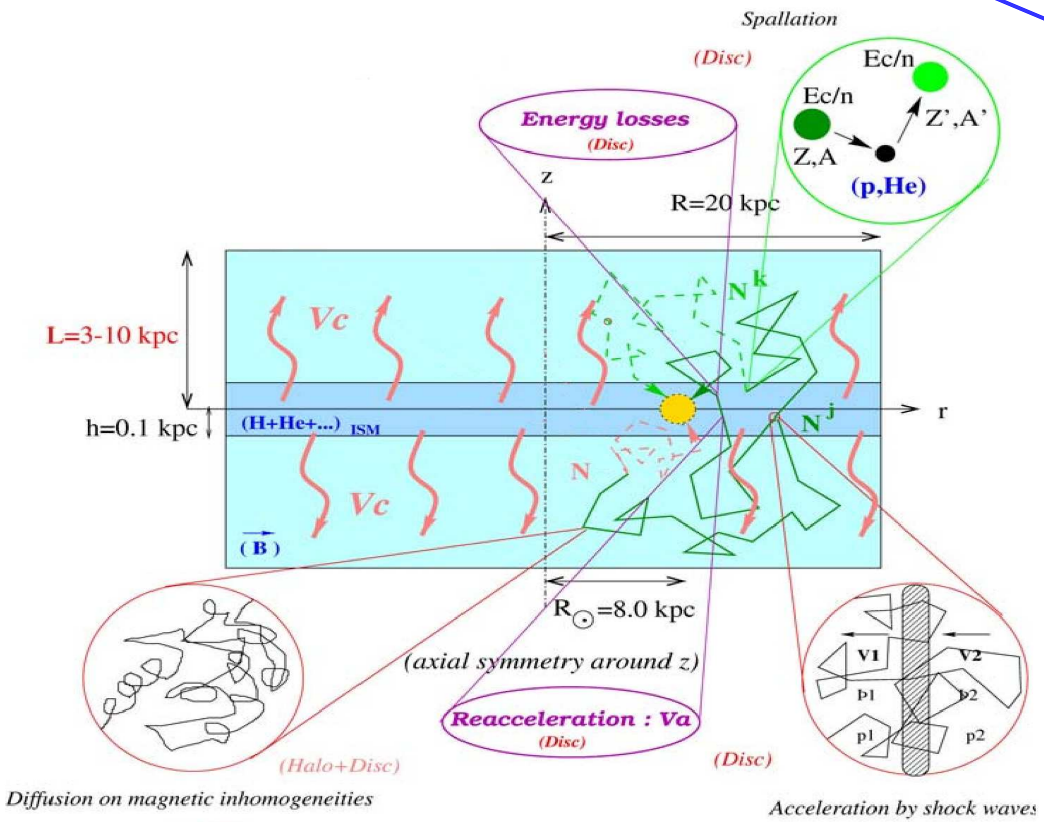
- sensitivity mostly in antimatter fluxes
- smooth $\bar{p}$ spectra, background important
- “smoking gun” $\bar{d}$

Propagation

- propagation described by diffusion equation
  e.g. Strong, Moskalenko, Astrophys. J. 509 (1998)

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

only for $e^{\pm}$



- two-zone diffusion model
  Maurin et al., Astrophys. J. 555 (2001), Donato et al., Astrophys. J. 563 (2001)

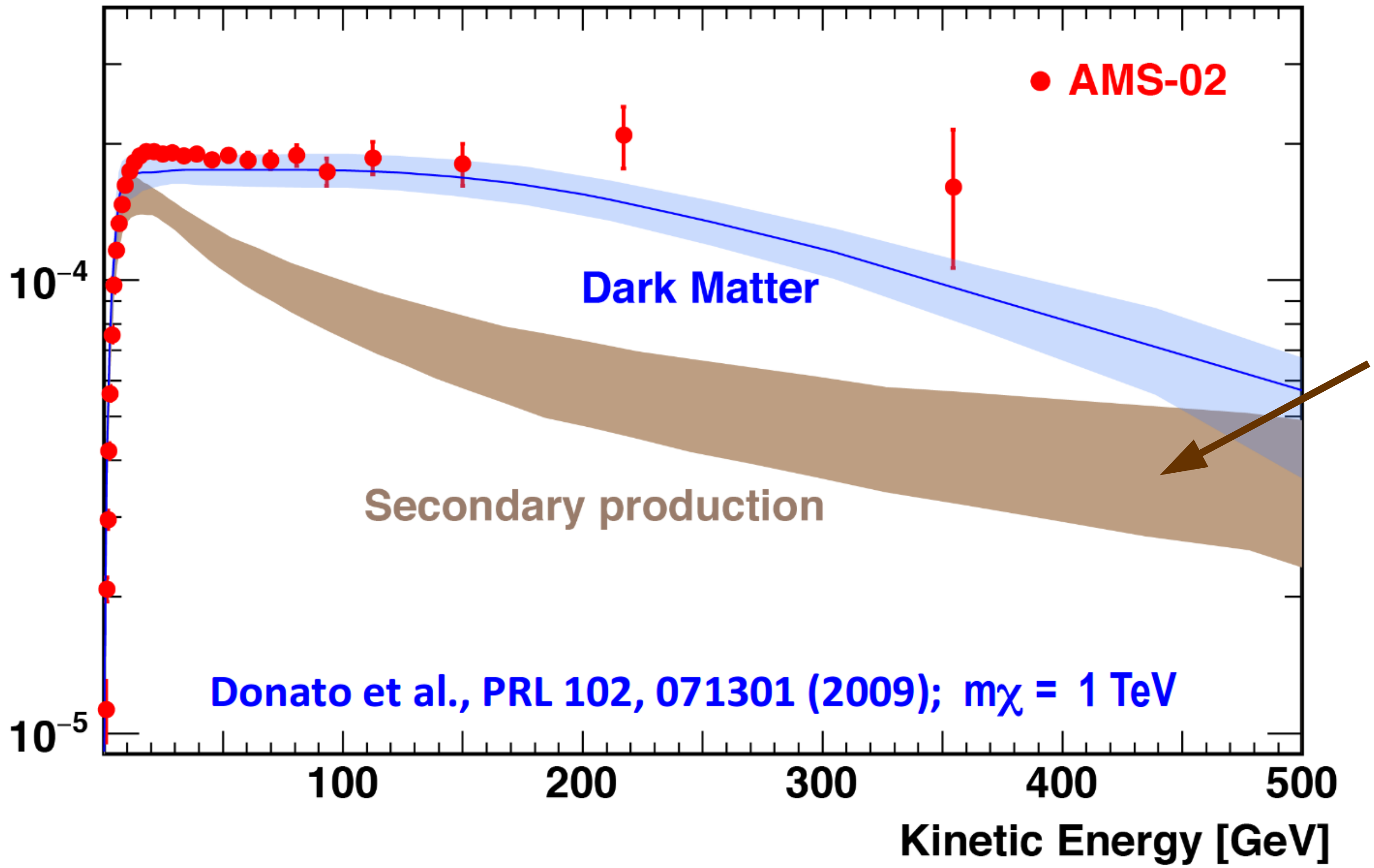
- pinching method
  Boudaud et al., A.A. 605 (2017)

- 5 propagation parameters: $K_0,\ \delta,\ L,\ V_c,\ V_a$

AMS-02 Antiprotons

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

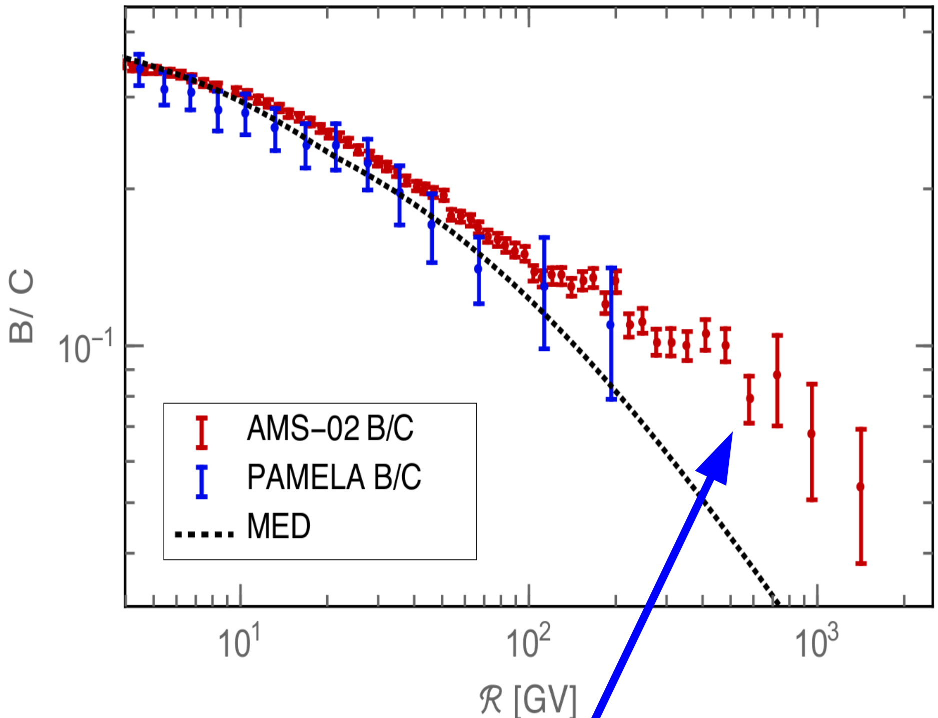
S.Ting, A. Kounine, AMS Days at CERN (2015)



Uncertainties:
cross section,
propagation

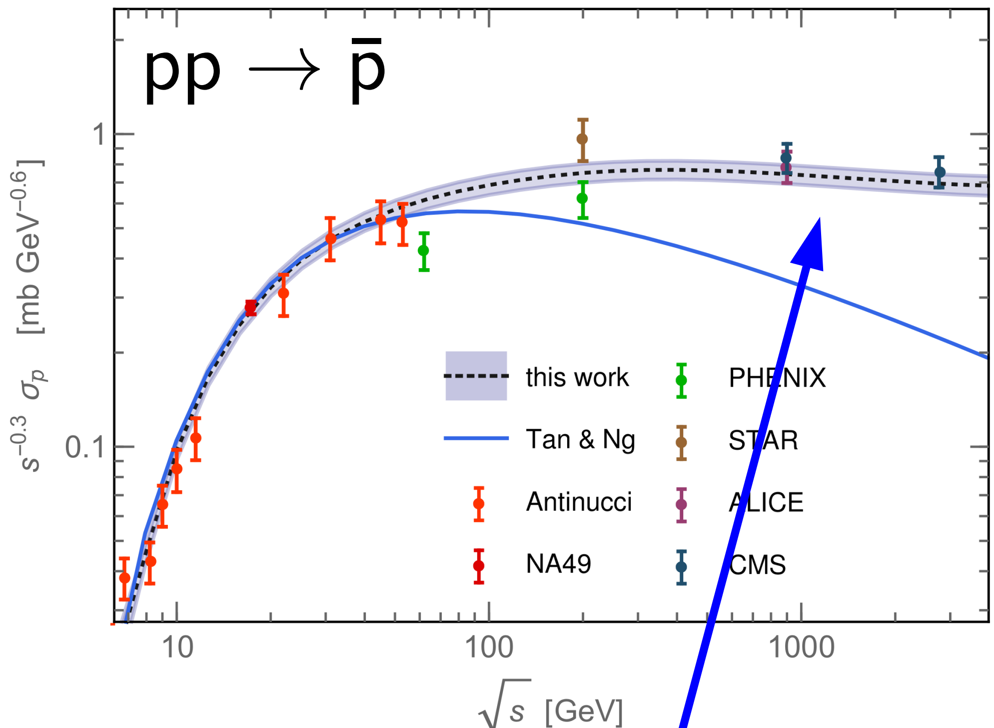
High Energy Antiprotons

- background improvements



propagation update to fit B/C

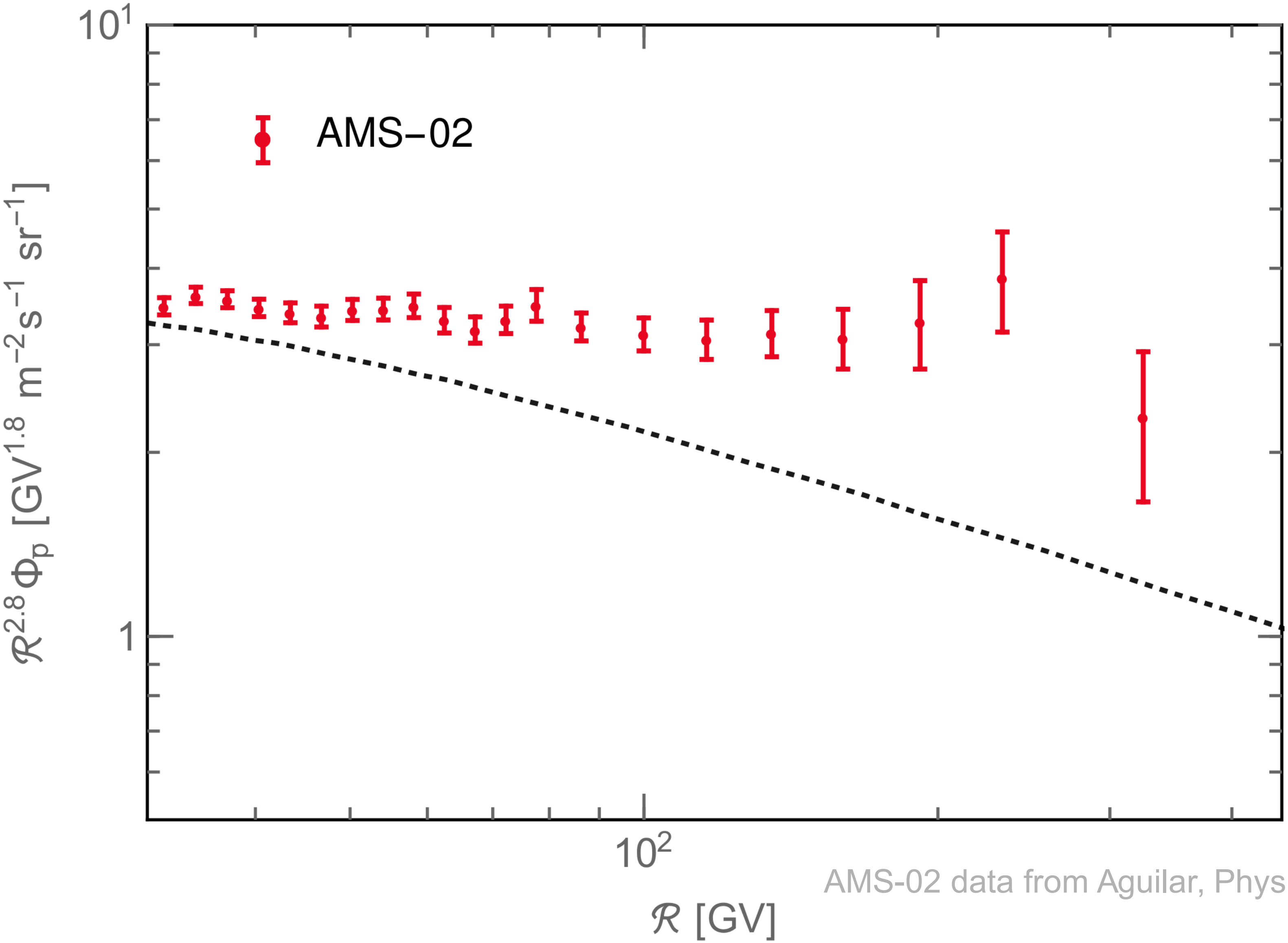
Giesen et al., Evoli et al.,
Kappl, Reinert, M.W., JCAP (2015)



cross section increase

M.W., JCAP 02 (2017)

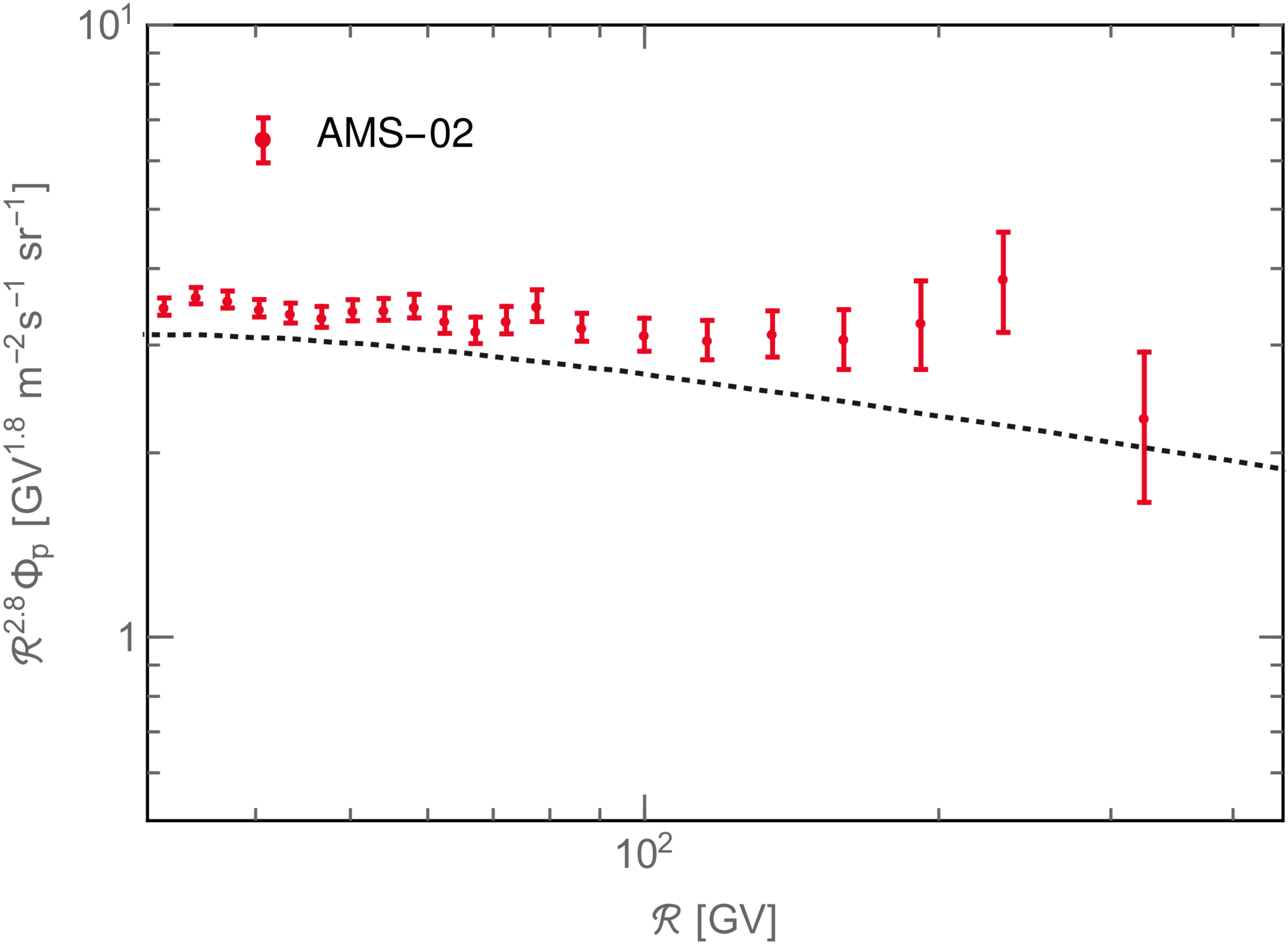
High Energy Antiproton Flux



background
2015

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

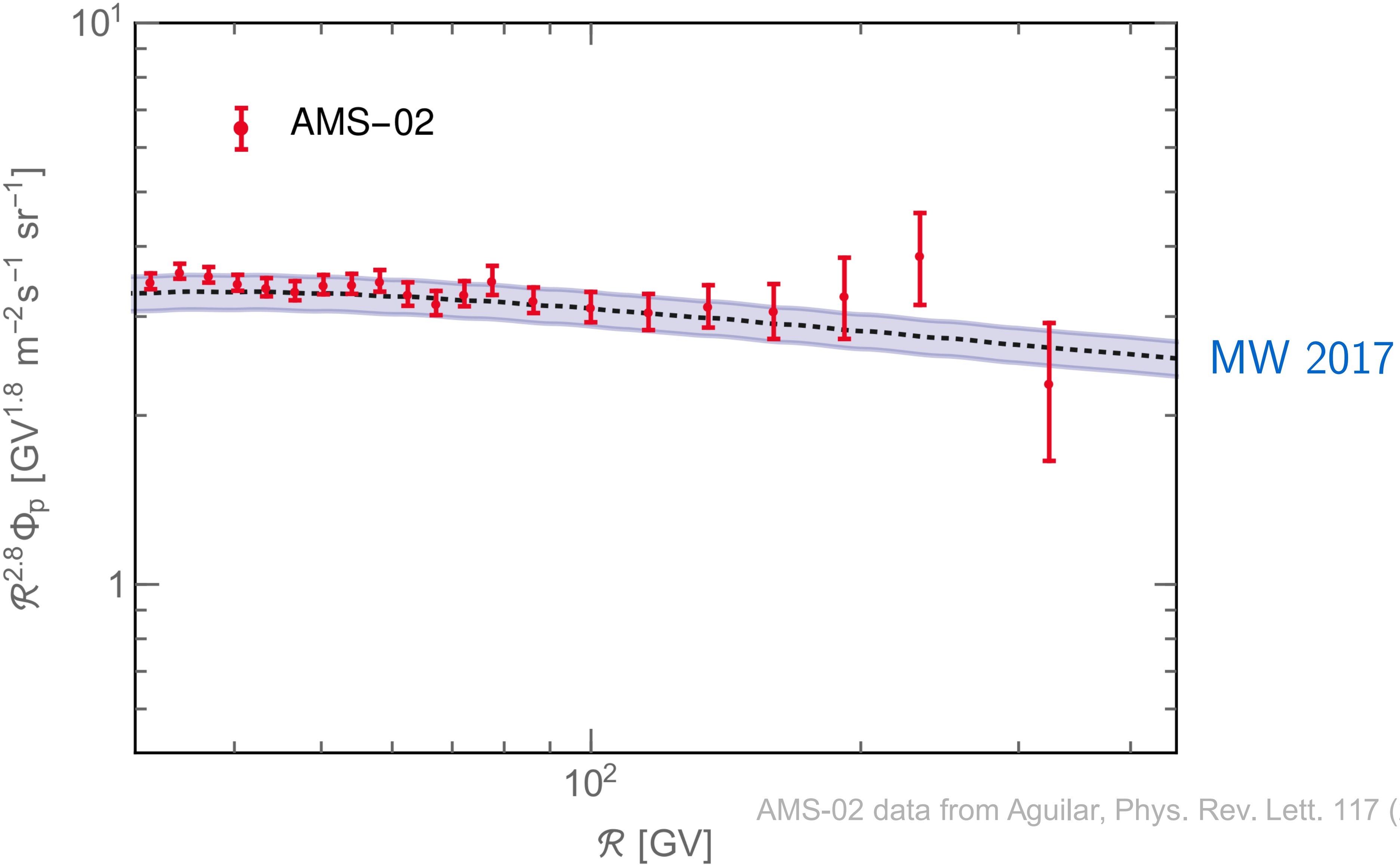
High Energy Antiproton Flux



updated propagation

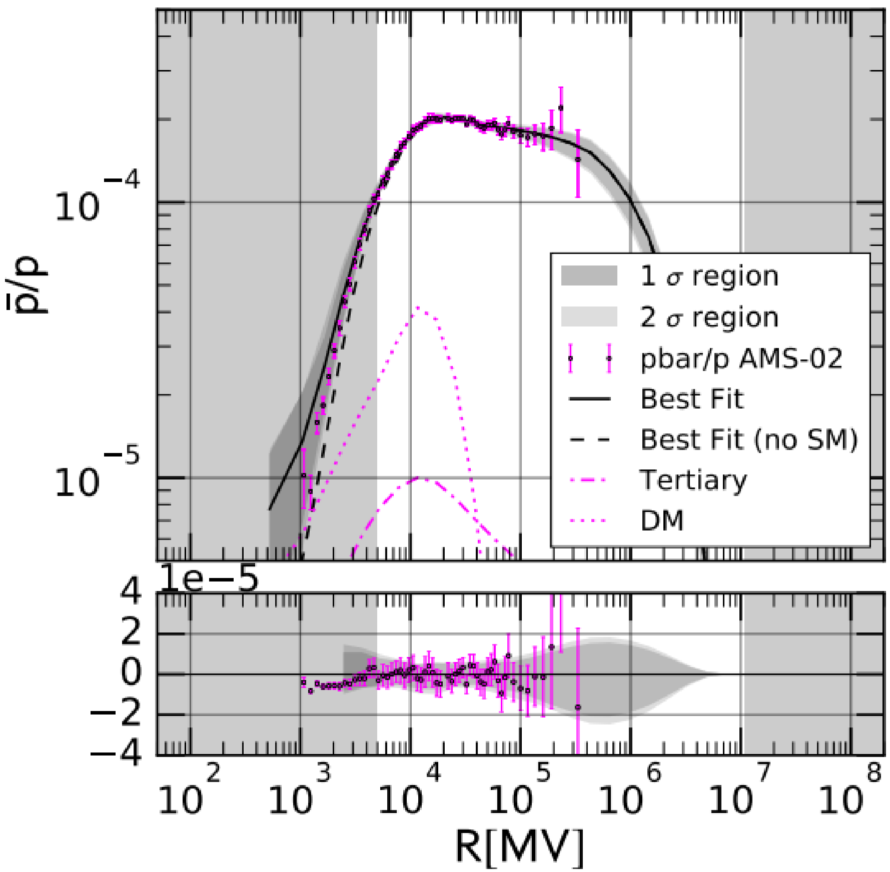
ett. 117 (2016)

High Energy Antiproton Flux



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

A new Antiproton Excess



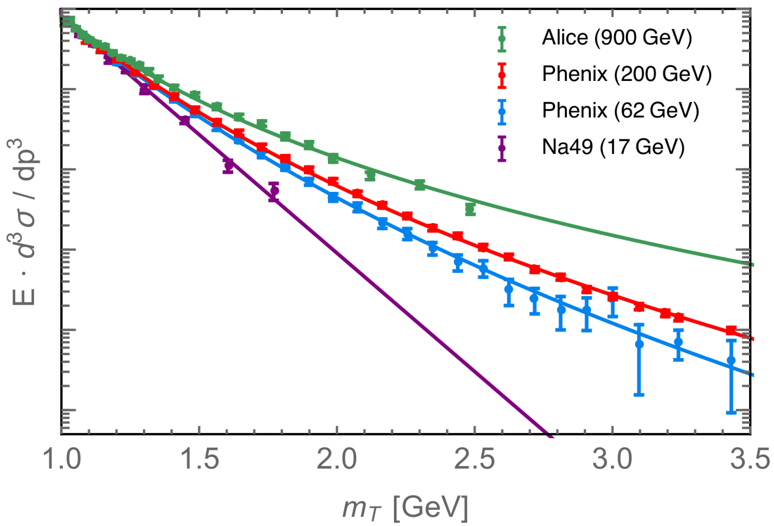
Cuoco, Krämer, Korsmeier, PRL 118 (2017),
Cui et al., PRL 118 (2017)

how robust ?

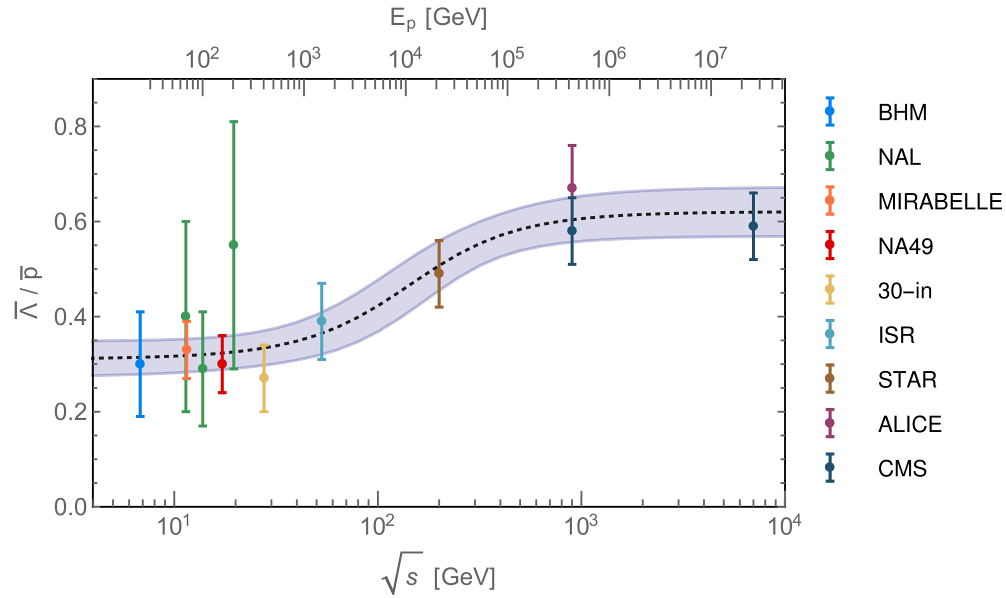
- include cross section uncertainties
- include B/C
- include low energy $\bar{p}$

Antiproton Cross Section

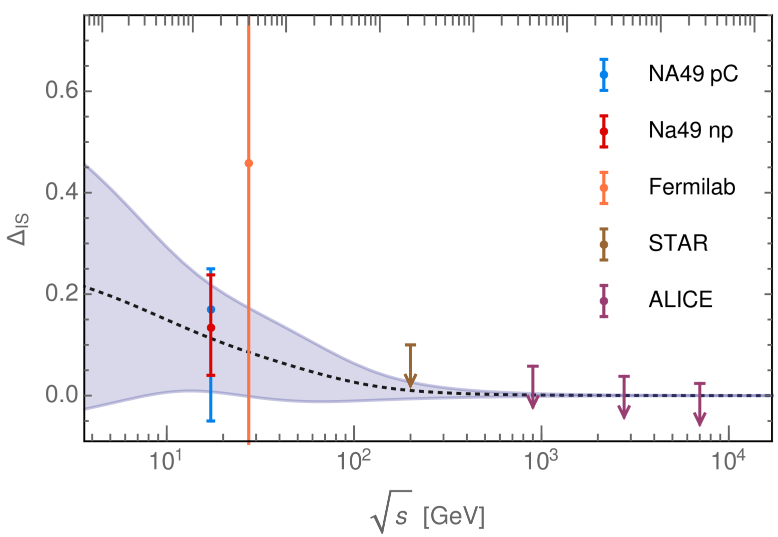
scaling violation



hyperons



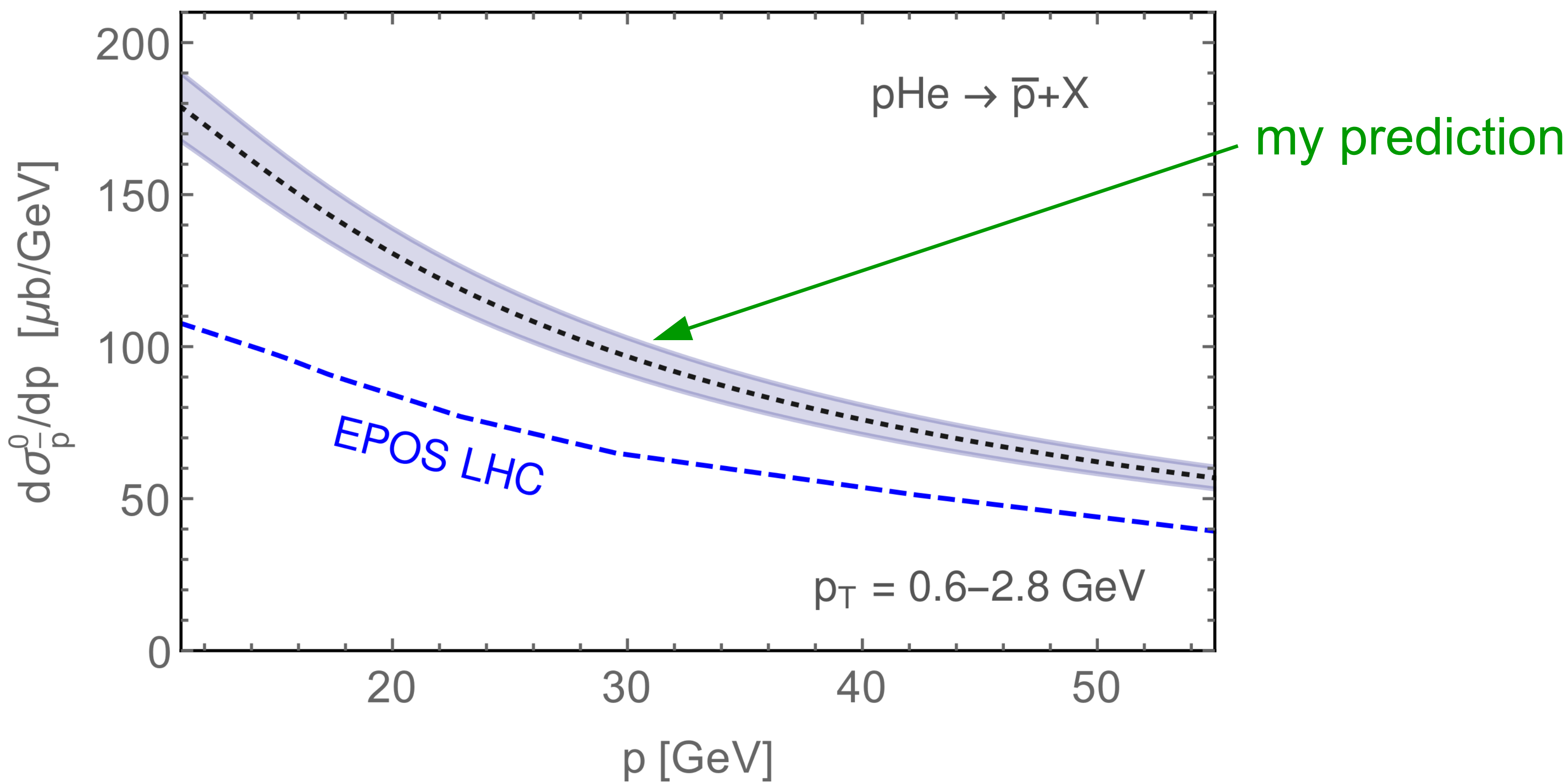
antineutrons



Data: PHENIX, Phys. Rev. C83 (2011), ALICE, Eur. Phys. J. C71 (2011), CMS, Eur. Phys. J. C72 (2012), 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), Antreasyan, Phys. Rev. D19 (1979), Fischer, Heavy Ion Phys. 17 (2003), Baatar, Eur. Phys. J. C73 (2013), Aamodt et al., Phys. Rev. Lett. 105 (2010), Abbas et al., Eur. Phys. J. C73 (2013)

Proton Helium Scattering

- p-He scattering predicted from pp and p-C data
- confirmed by first LHCB measurement
  LHCb-CONF-2017-002



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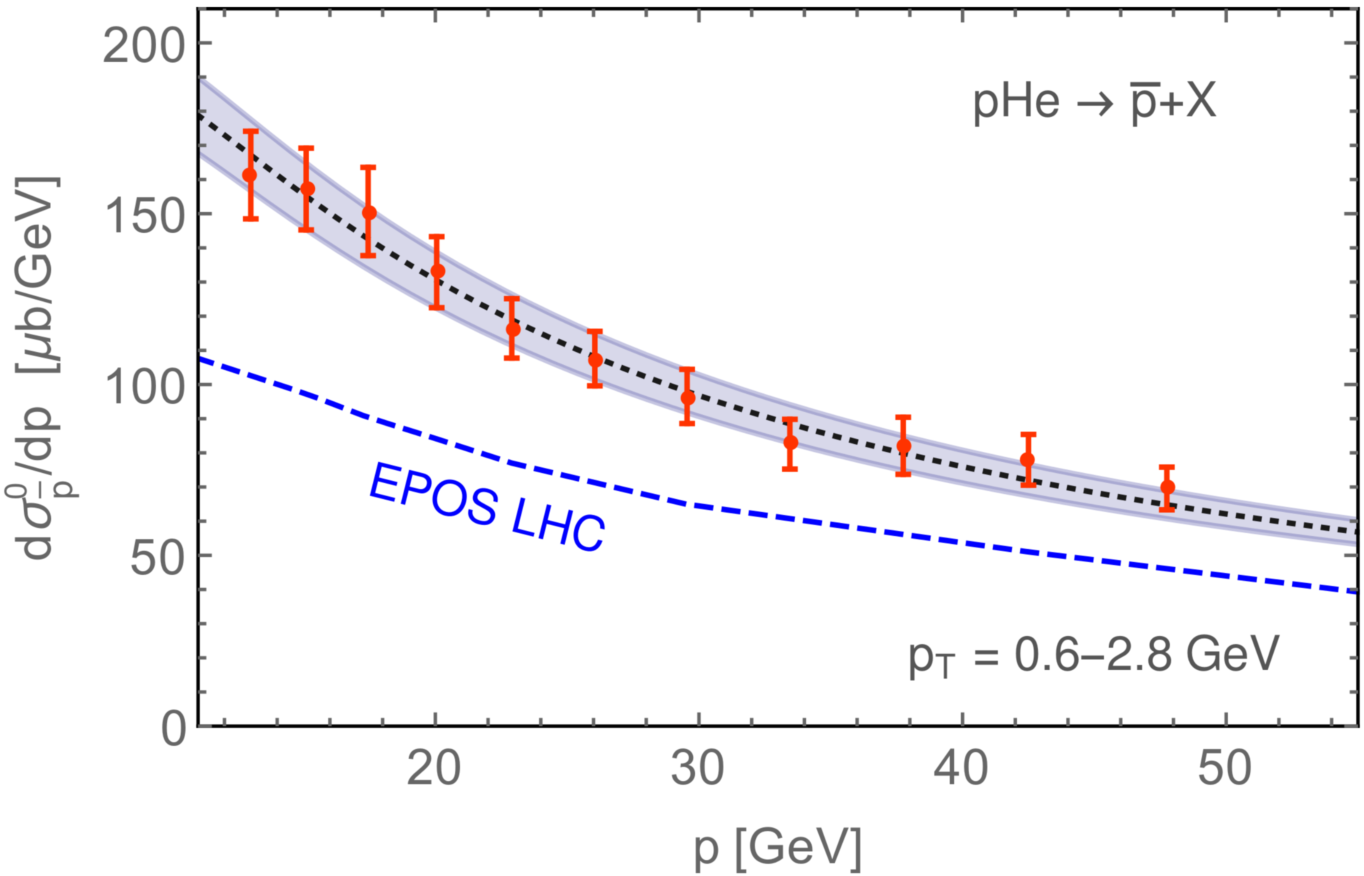
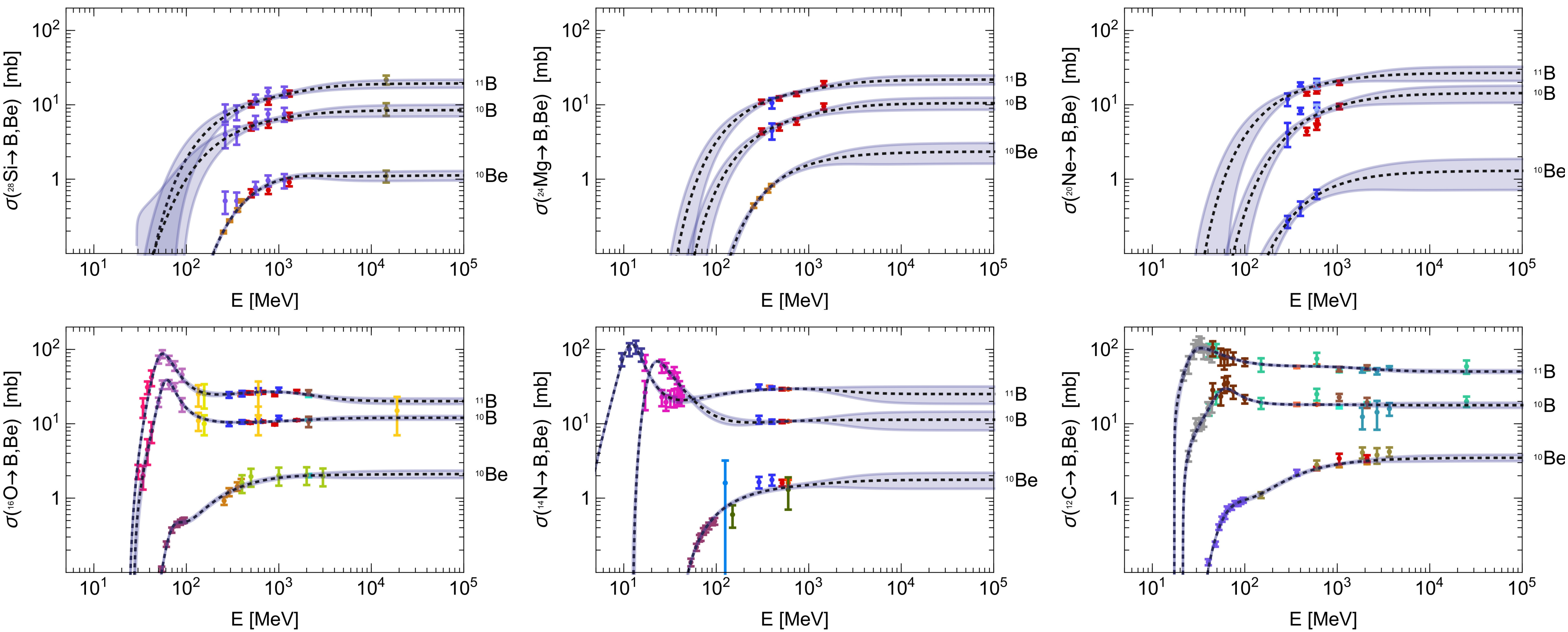
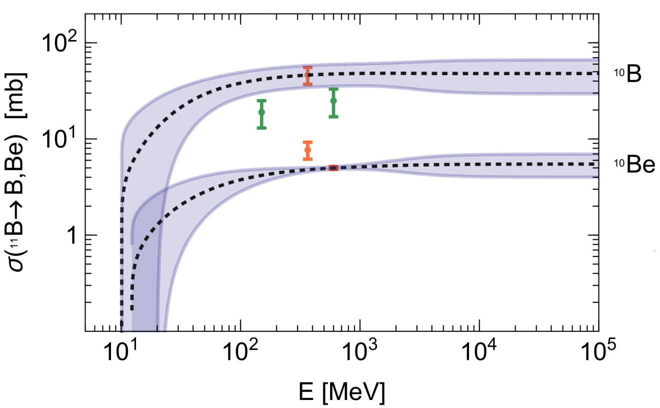


Boron Production





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)

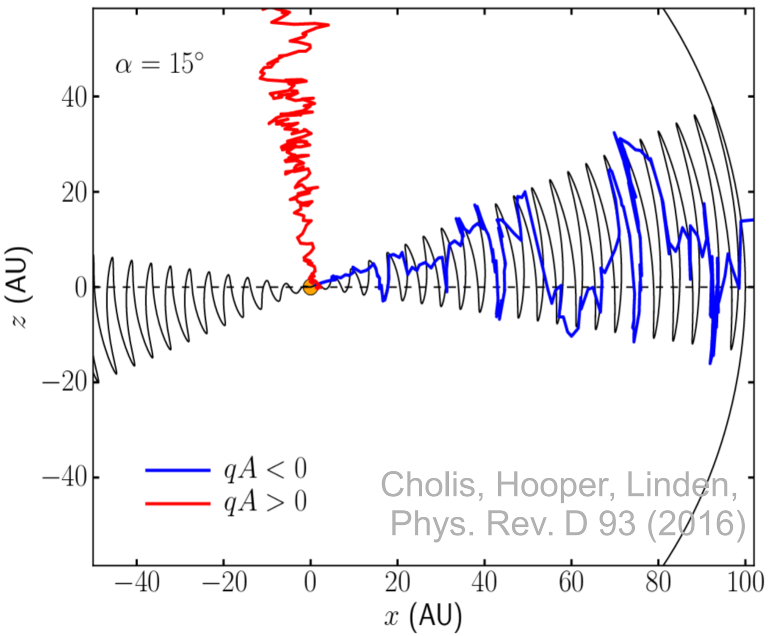
Solar Modulation

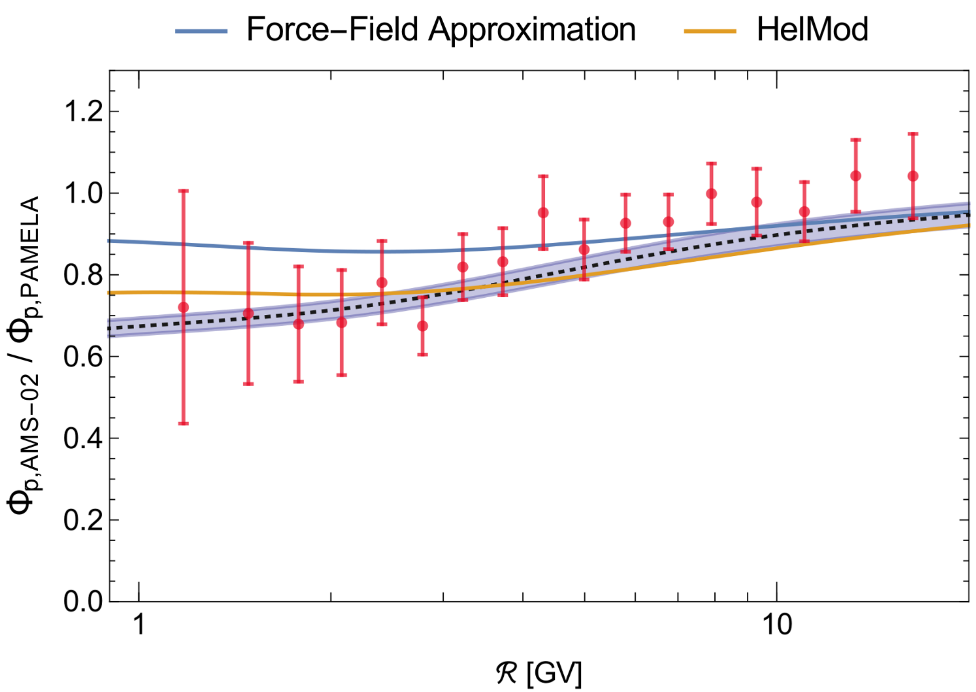
- force field approximation works reasonably for $\mathbf{qA > 0}$

$$\Phi^{\mathrm{TOA}}(T) = \Phi^{\mathrm{IS}}(T+\phi)\left(\frac{p^{\mathrm{TOA}}}{p^{\mathrm{IS}}}\right)^2$$

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

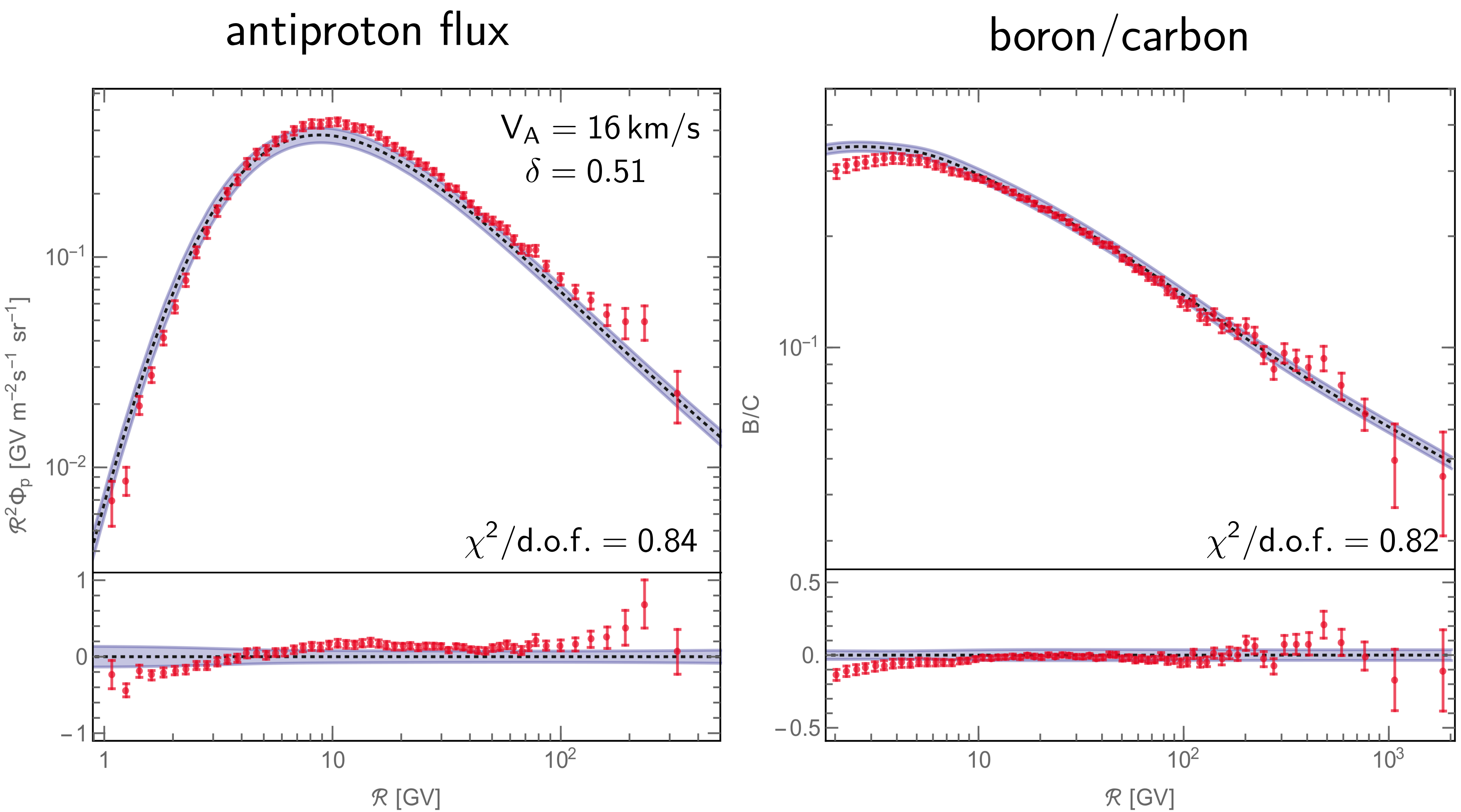
- heliospheric current sheet significantly affects fluxes for $\mathbf{qA < 0}$
  Jokipii, Thomas, Astrophys. J. 243 (1981)





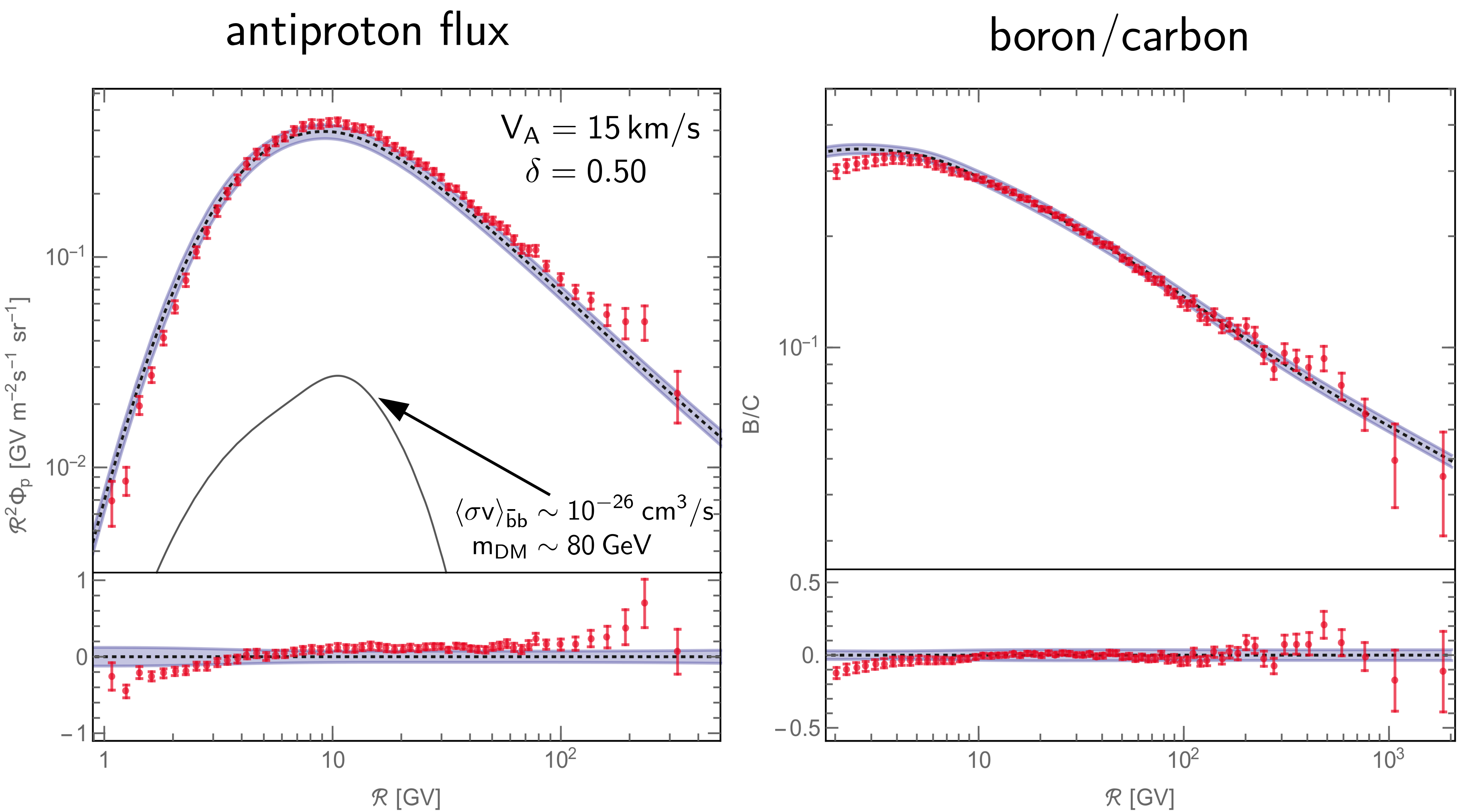
- charge-breaking extracted from PAMELA/AMS-02

Antiproton + B/C Fit



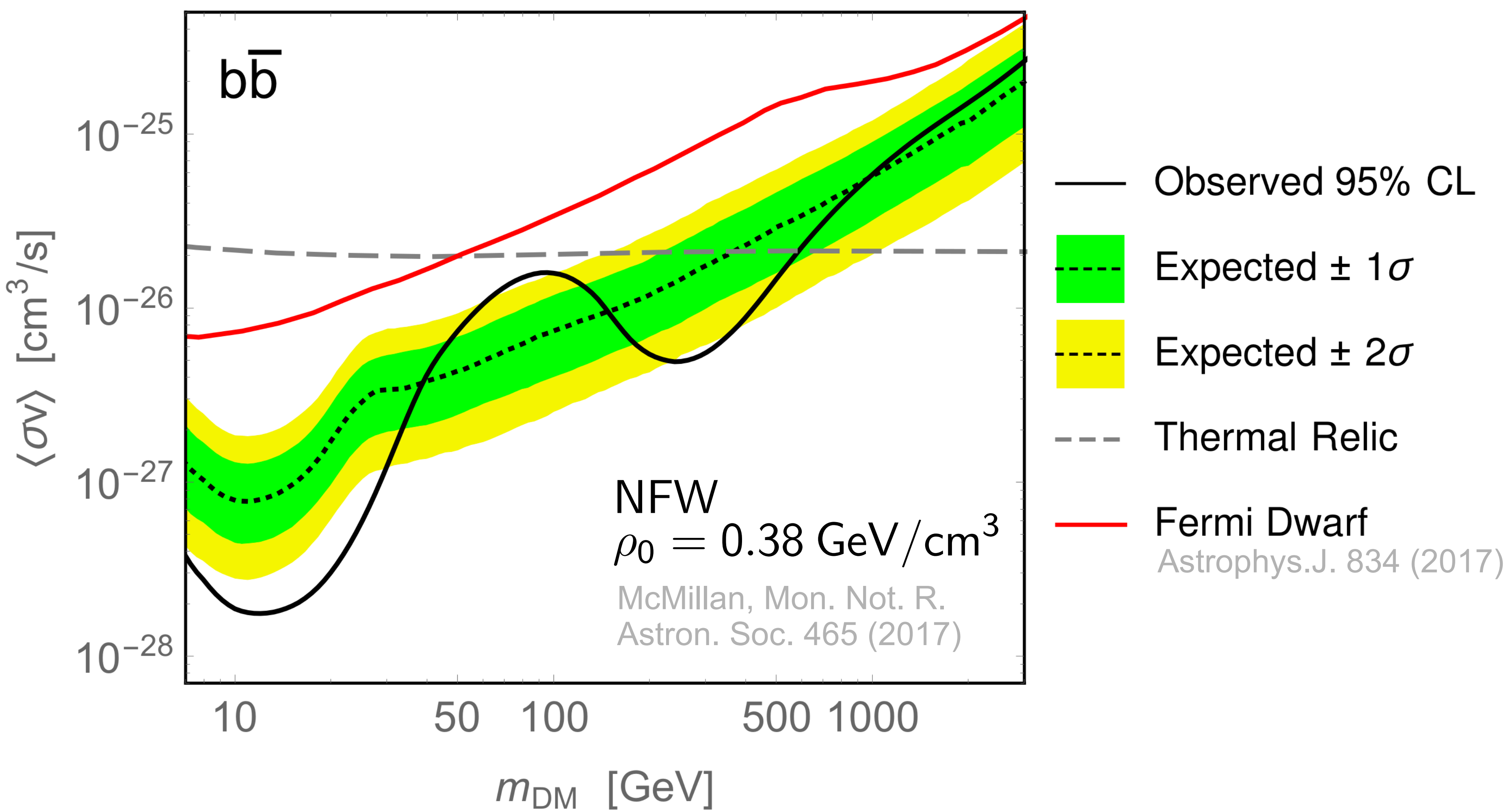
AMS-02 data: Aguilar et al., Phys. Rev. Lett. 117 (2016)

Fit with Dark Matter

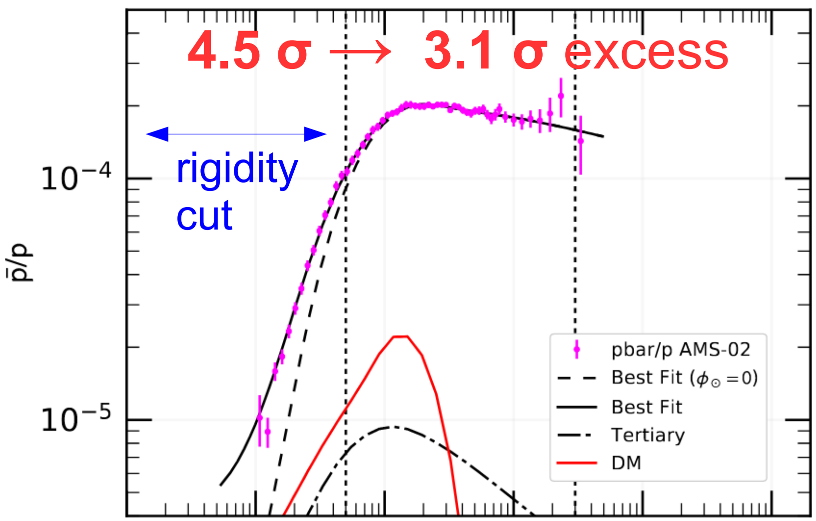


local significance 2.2σ (look-elsewhere ▶ 1.1σ)

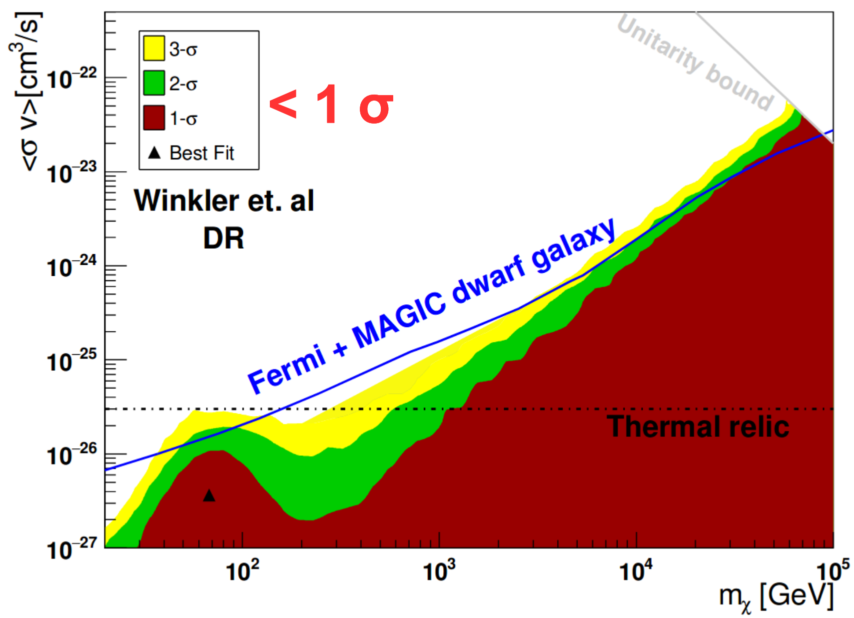
Constraints on Dark Matter



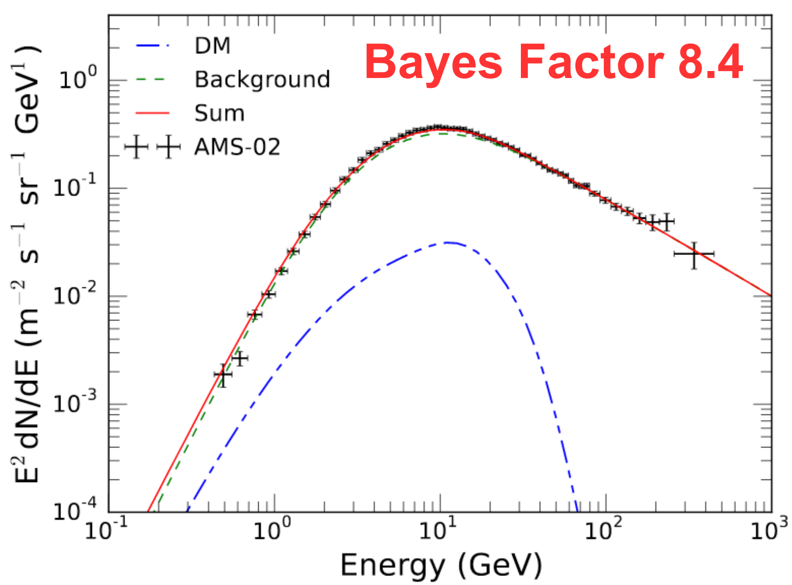
Comparison



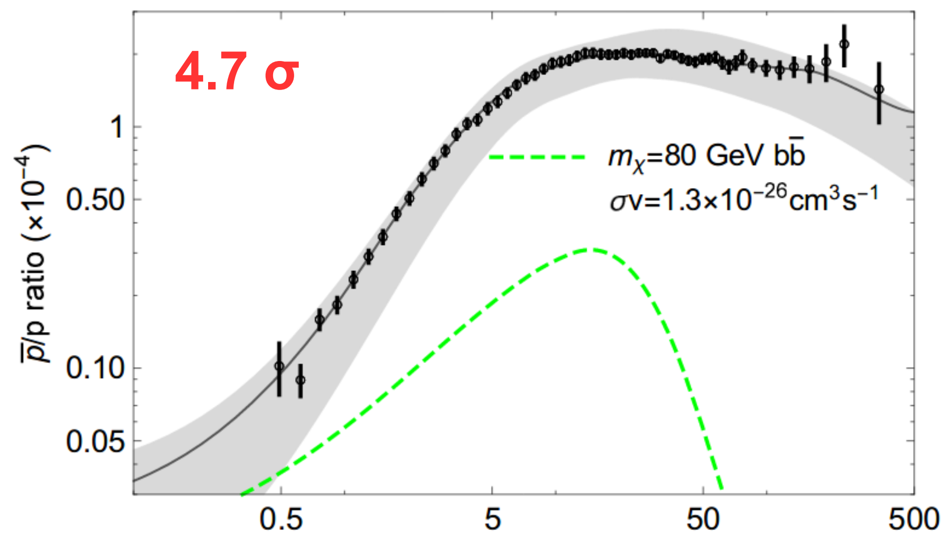
Cuoco et al., arXiv:1903:01472 (2019)



Lin et al., arXiv:1903.09545 (2019)

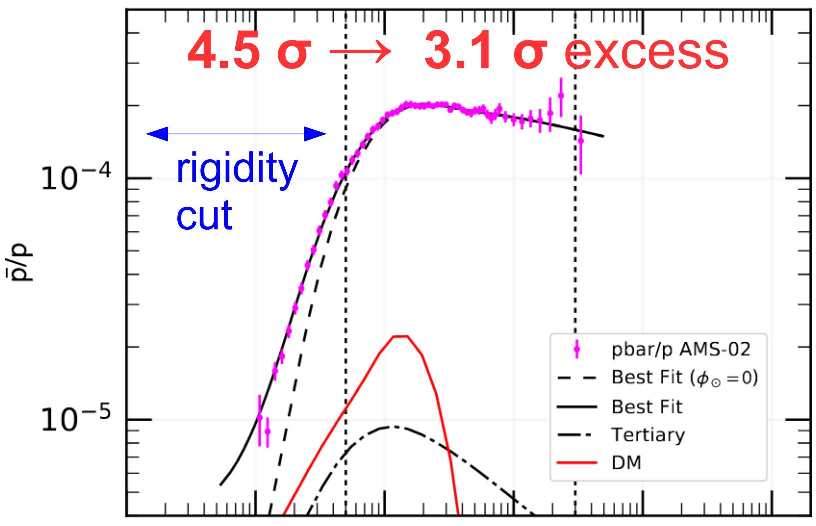


Cui et al., JCAP 1806 (2018)

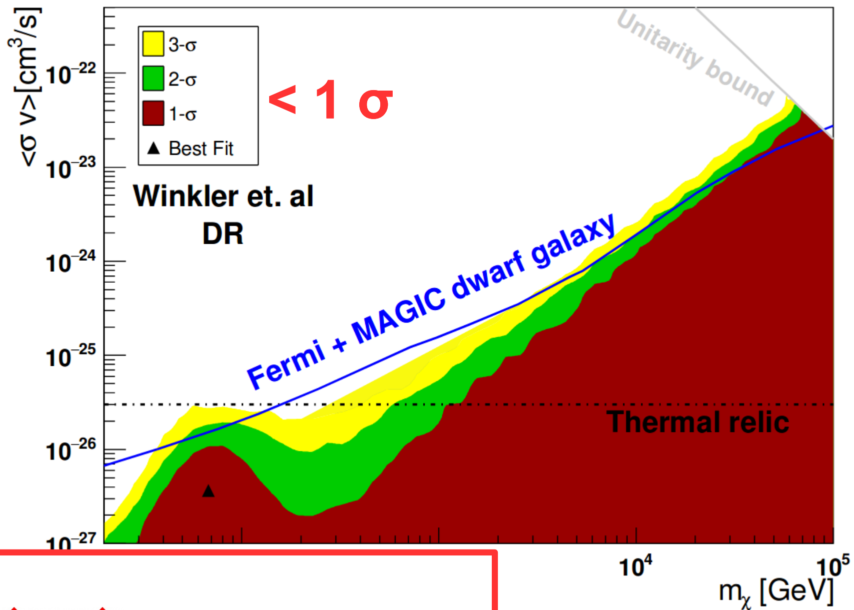


Cholis, Hooper, Linden, 1903.02549 (2019)

Comparison

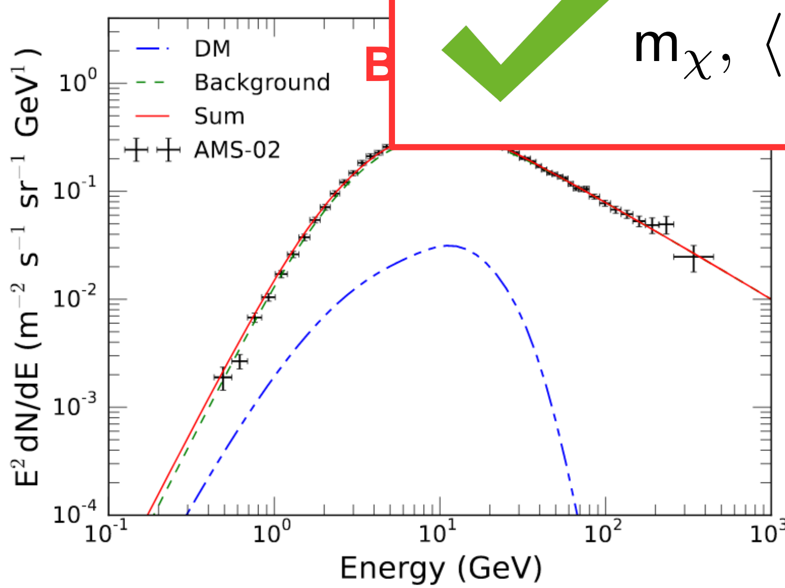


Cuoco et al., arX

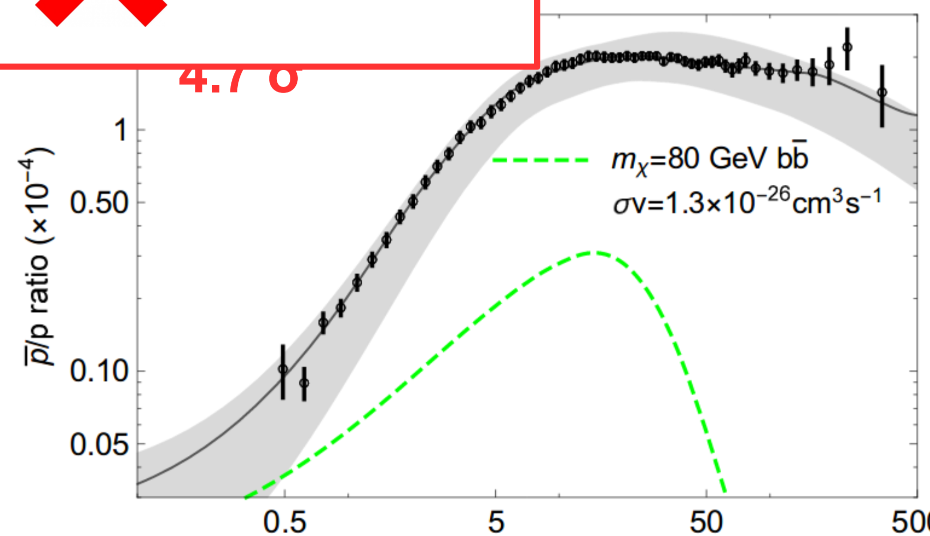


9545 (2019)

✔ m_χ, $\langle \sigma v \rangle$ ✘ significance



Cui et al., JCAP 1806 (2018)



Cholis, Hooper, Linden, 1903.02549 (2019)

Antideuteron Coalescence

- coalescence model

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

only prompt nucleons count

$$\frac{d^3 n_d}{dp_d^3} = \frac{1}{8}\int d^3q \quad \frac{d^6 n_{pn}}{dp_p^3\, dp_n^3}\bigg|_{\mathbf{p}_{p,n}=\frac{\mathbf{p}_d \pm \mathbf{q}}{2}} \quad \mathcal{P}(\mathbf{q})$$

Antideuteron Coalescence

- coalescence model

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

$$\frac{d^3 n_d}{dp_d^3} = \frac{1}{8}\int d^3q \; \left.\frac{d^6 n_{pn}}{dp_p^3\, dp_n^3}\right|_{\mathbf{p}_{p,n}=\frac{\mathbf{p}_d \pm \mathbf{q}}{2}} \mathcal{P}(\mathbf{q})$$

$$R\,\frac{d^3 n_p}{dp_p^3}\,\frac{d^3 n_n}{dp_n^3}$$

R: correlation function

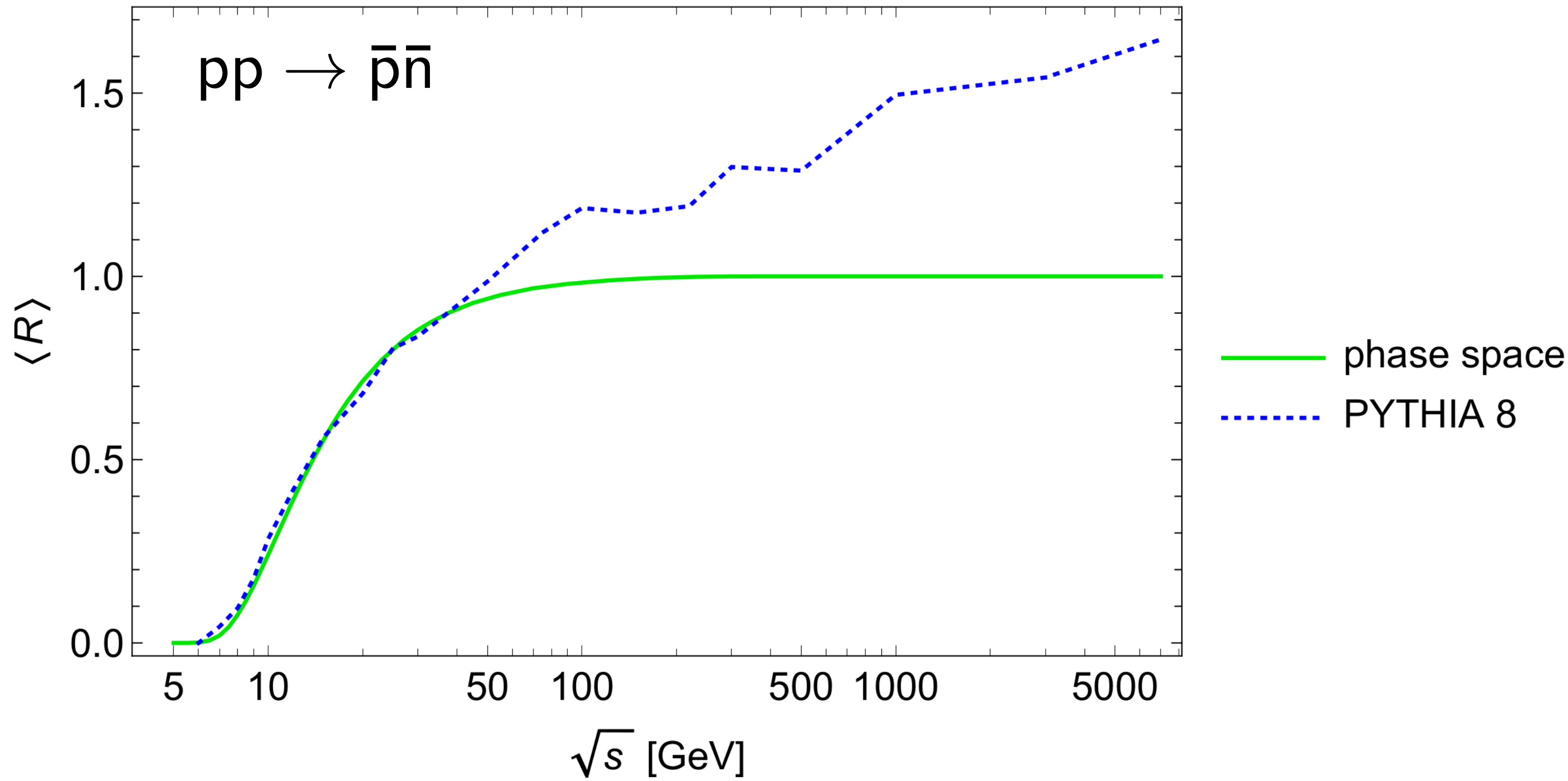
- hard correlations
- kinematics

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

$$\Theta\,(p_0 - q)$$

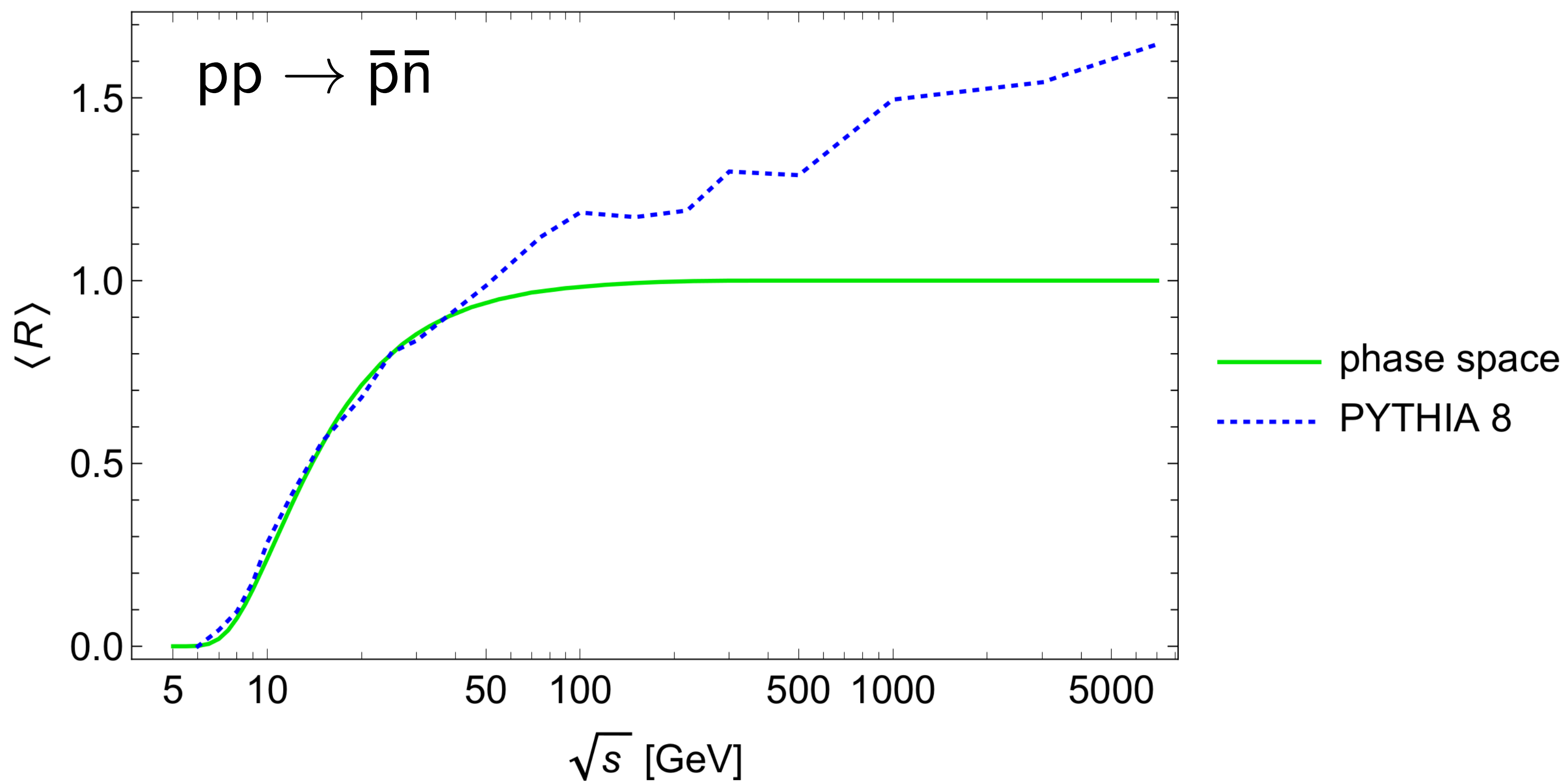
p_0: coalescence momentum

Correlations



- $\sqrt{s} \lesssim 50$ GeV : correlations purely kinematics
- $\sqrt{s} \gtrsim 50$ GeV : hard correlations

Correlations



- $\sqrt{s} \lesssim 50$ GeV : correlations purely kinematics
- $\sqrt{s} \gtrsim 50$ GeV : hard correlations

but: correlations more important for $\chi\chi \to \bar{p}\bar{n}$

Calculating the Coalescence Momentum

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

Gustafson, Häkkinen, Phys. C 61 (1994), Mrowczynski, Phys. Lett. B 248 (1990), Blum et al., Phys.Rev. D96 (2017)

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

$\sim$ source radius

$$\sigma/2 = R_{HBT} = 0.8 - 1.3 \text{ fm}$$

e.g. Wiedemann, Ferenc, Heinz, Phys.Lett. B449 (1999)

ALICE, arXiv:1805.12455(2018)

- deuteron wave function

$$\Psi_{\bar{d}}(\mathbf{r}) \propto e^{-\frac{\mathbf{r}^2}{2d^2}}$$

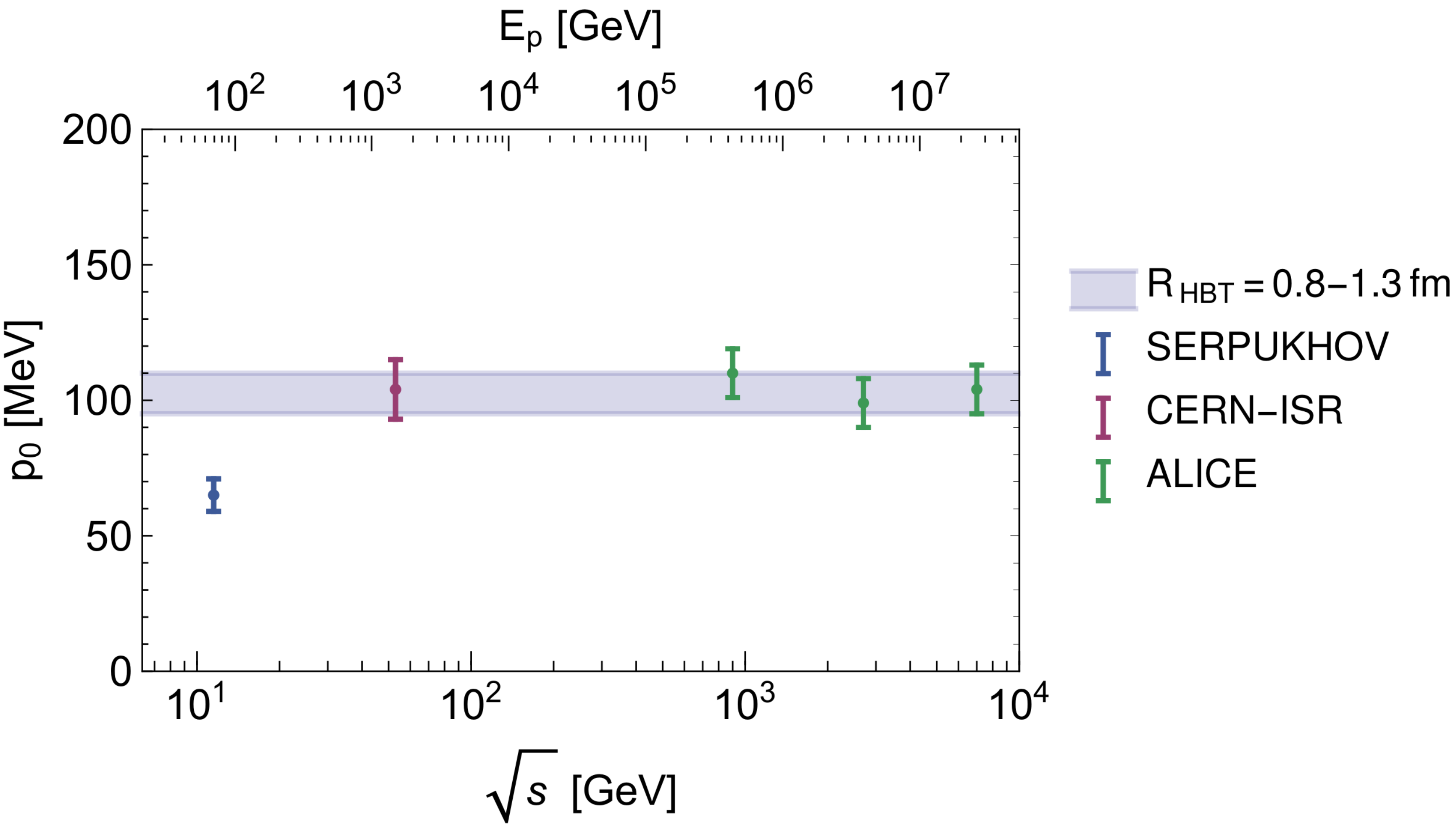
$\sqrt{\frac{8}{3}} \times$ (rms radius)

- coalescence momentum

$$p_0 \propto \left(\int d^3q \left| \int d^3r \; \Psi^*_{\bar{d}}(\mathbf{r}) \Psi_{\bar{p}\bar{n}}(\mathbf{r}) \right|^2 \right)^{1/3} = \mathbf{95\text{-}110 \; MeV}$$

Measurements of the Coalesncence Momentum

- $\bar{d}$, $\bar{p}$ from same experiment, correct for $\bar{\Lambda}$, $\bar{\Sigma}$, $\bar{n}/\bar{p}$, correlations



Gibson, Lett. Nuov. Cim. 21 (1978), Abramov, Sov. J. Nucl. Phys. 45 (1987), ALICE, Phys. Rev. C 97 (2018)

Measurements of the Coalesncence Momentum

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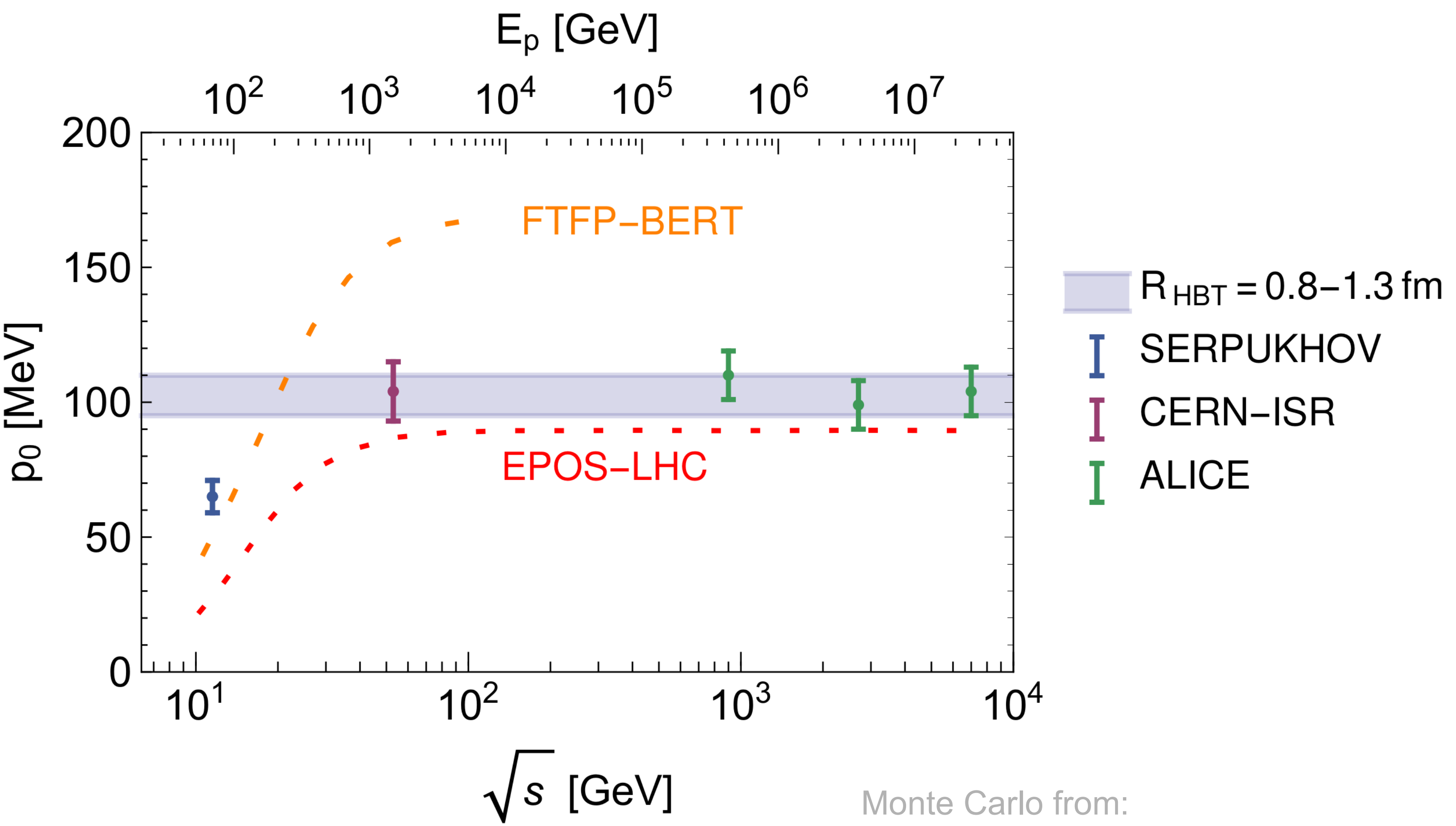

Monte Carlo from:
Gomez-Coral et al., Phys. Rev. D 98 (2018)

Measurements of the Coalesncence Momentum

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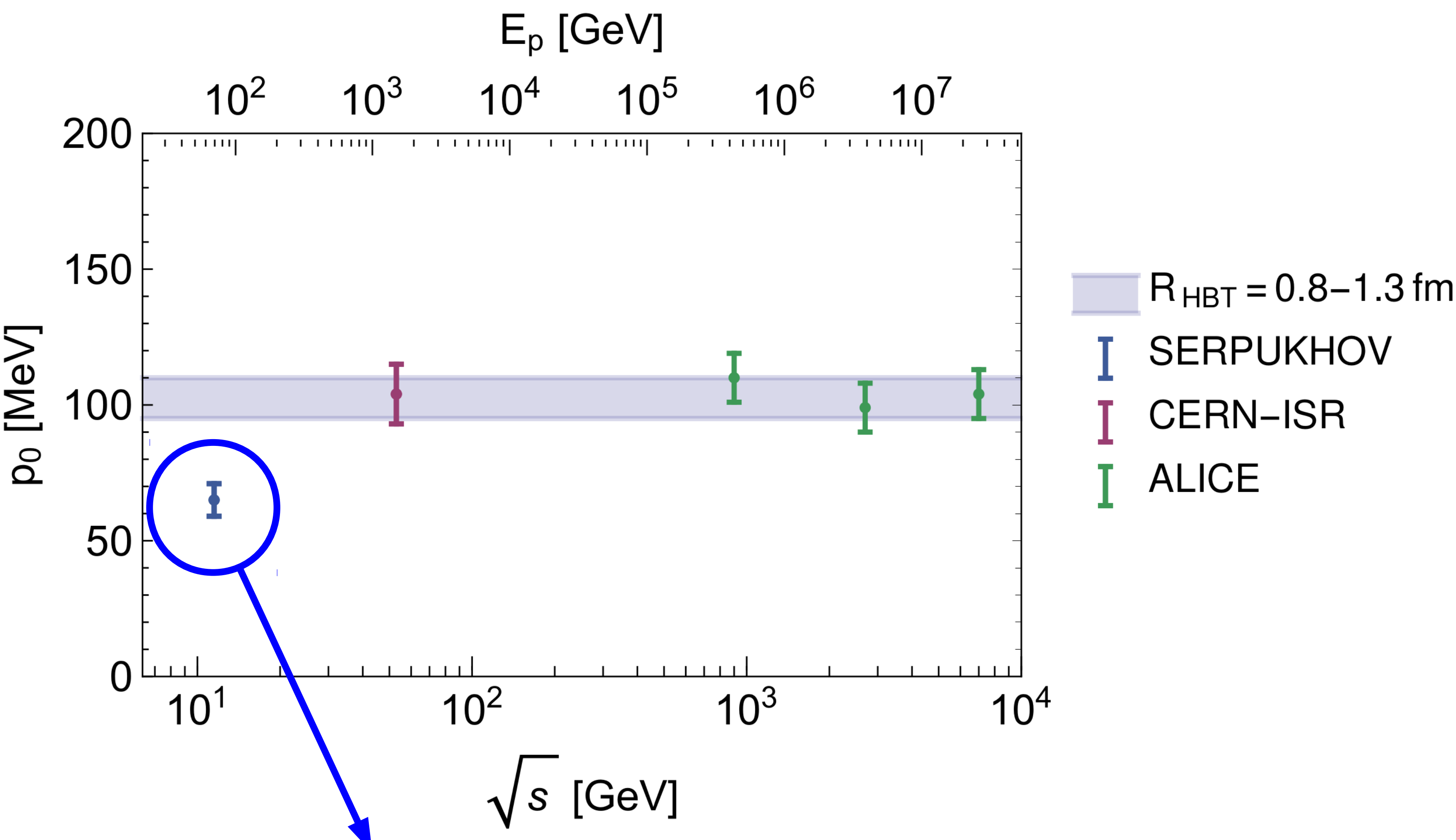
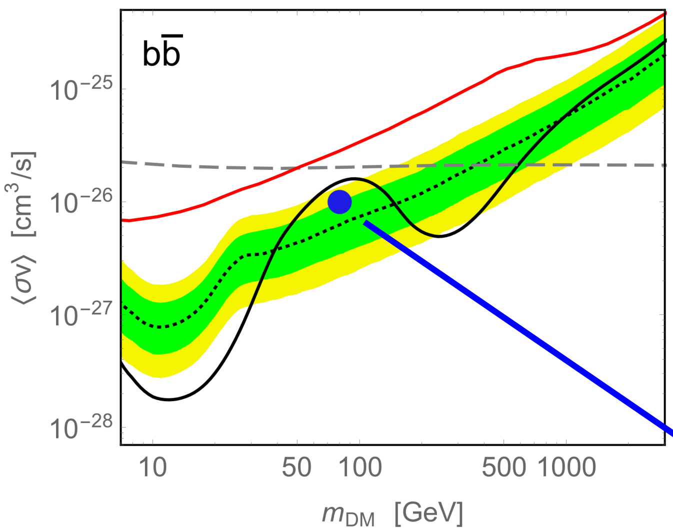


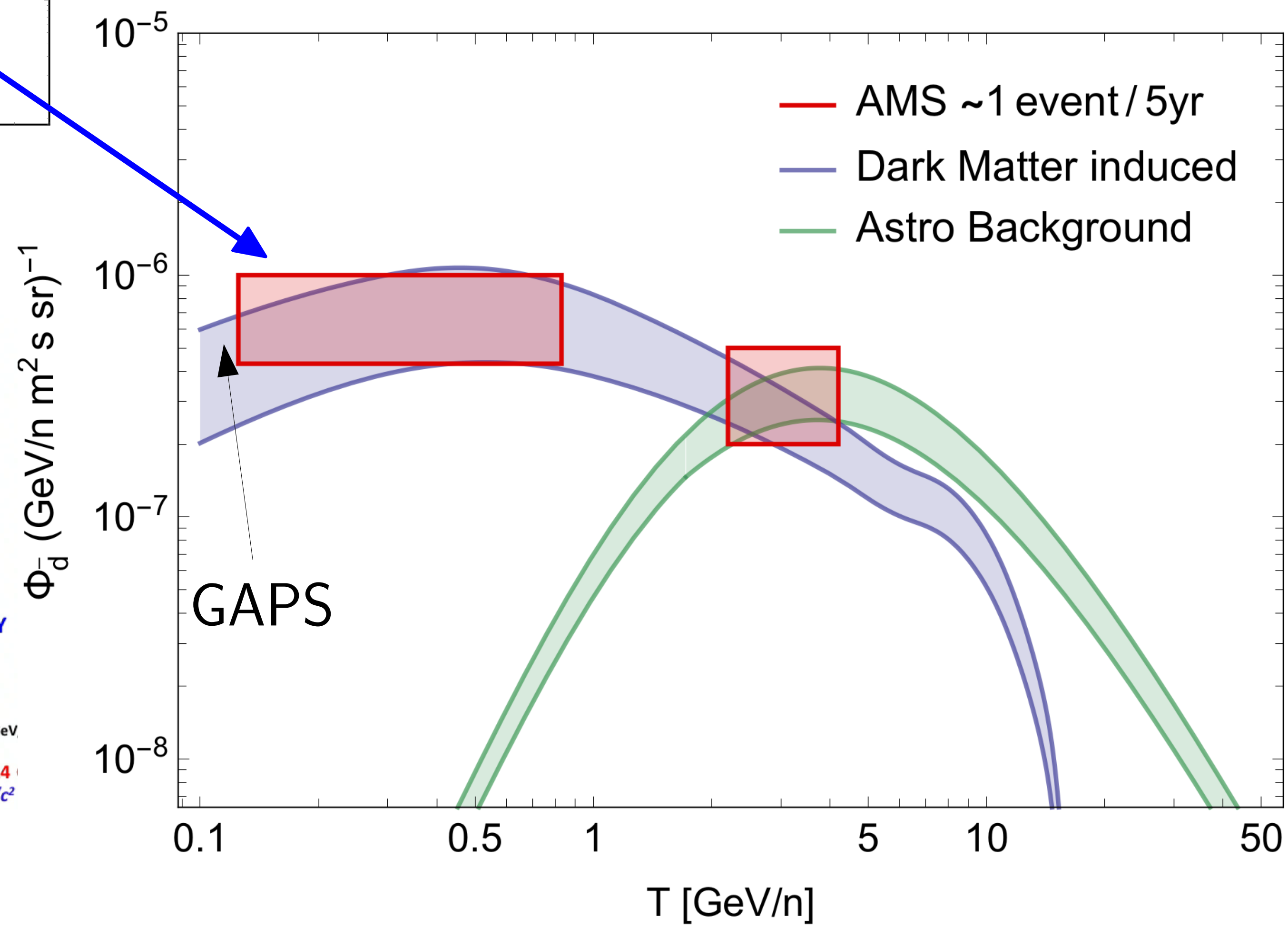
experimental error ? source size increases ? ▶ NA61/SHINE

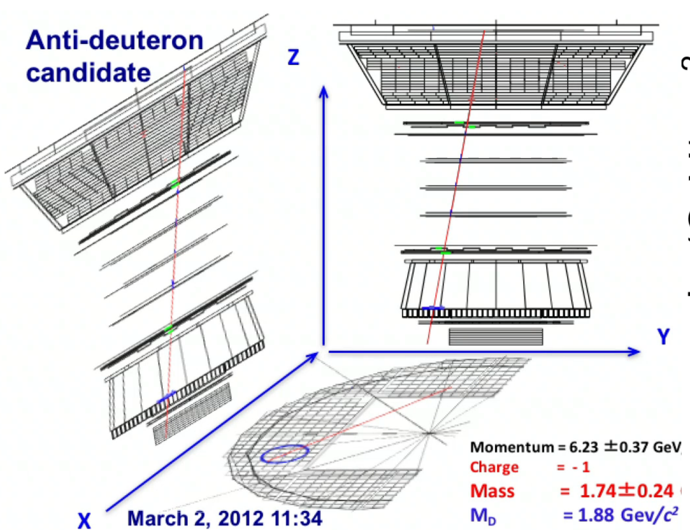
Antideuteron Sensitivity



- antideuterons might provide a test for dark matter interpretation

see also: Korsmeier, Donato, Fornengo, Phys.Rev. D97 (2018)



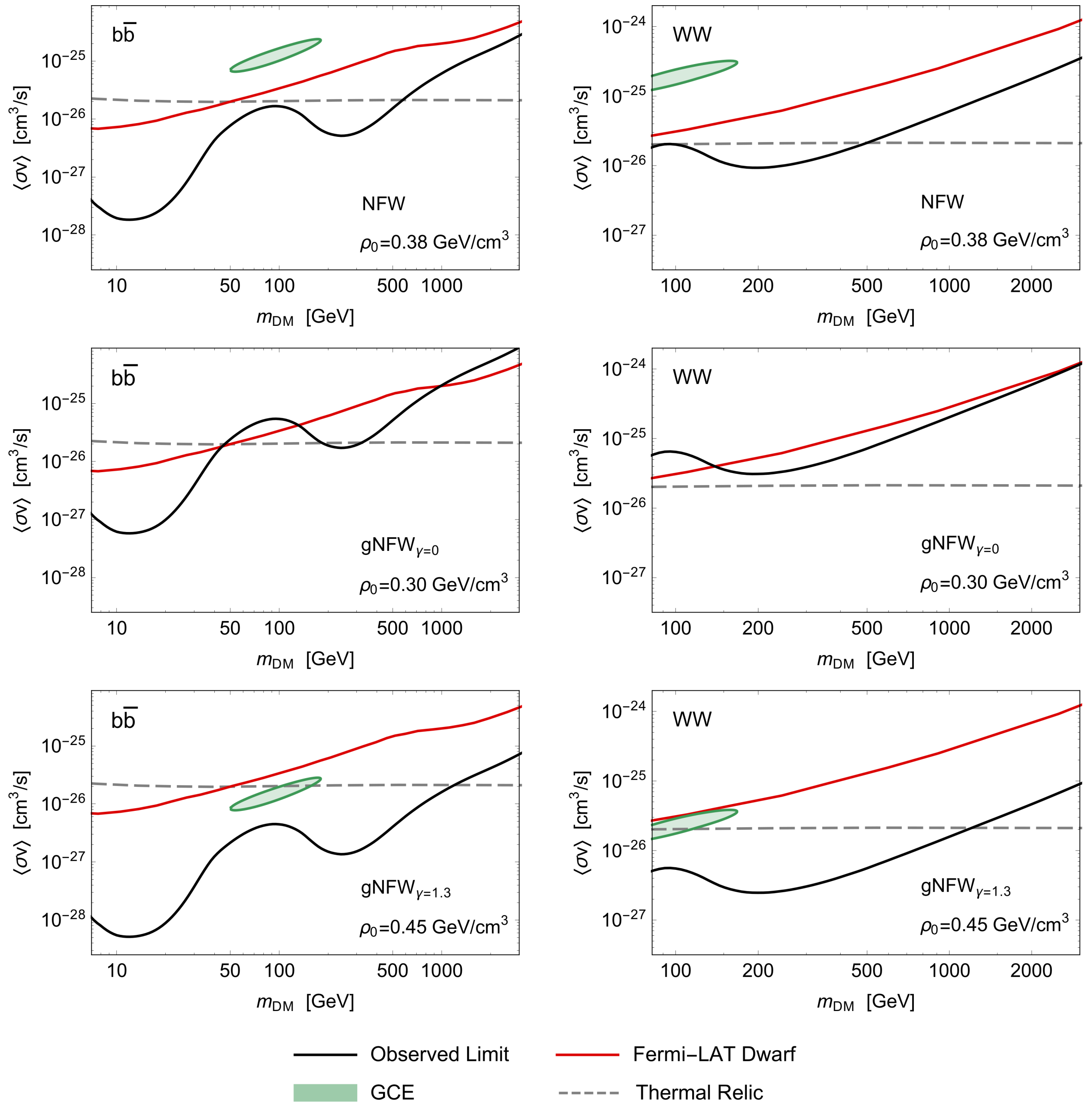


S. Ting, CERN (2018)

Conclusion

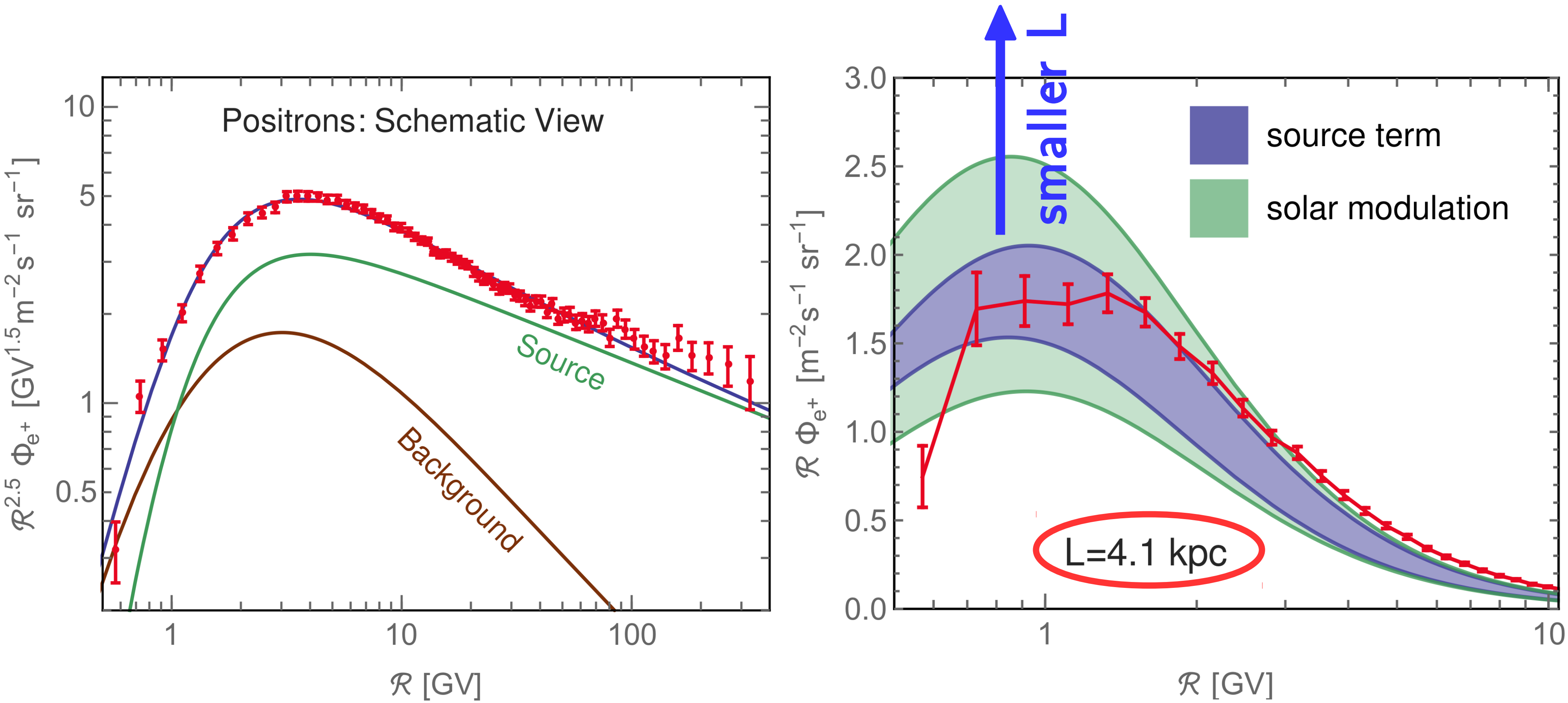
- $\bar{p}$ are dominantly secondary cosmic rays at all (measured) energies
- $\bar{p}$ set strongest constraints on hadronic WIMP annihilation
- small $\bar{p}$ excess at $R \sim 10$ GV is not significant, but defines interesting target for $\bar{d}$ searches
- progress in pinning down the coalescence momentum, but we need data at small $\sqrt{s}$

Constraints on Dark Matter



Positrons

- positron spectrum requires extra source (e.g. pulsars)
  PAMELA, Nature 458 (2009)
- low energy e^+ can still be used to constrain diffusion zone L
  Lavalle, Maurin, Putze, Phys.Rev. D90 (2014), Boudaud et al, Astron.Astrophys. 605 (2017)



Cross Section Comparison