Searching for Dark Matter with Cosmic Antiparticles

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in collaboration with
M. Di Mauro, J. Heisig, T. Linden, R. Kappl, M. Korsmeier, A. Reinert

JCAP 09 (2014), JCAP 10 (2015), JCAP 02 (2017), JCAP 01 (2018),
PRR 2 (2020), PRL 126 (2021), PRD 103 (2021)

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Outline

- Indirect Detection of WIMPs
- Antiprotons
- Antinuclei

Indirect Detection of WIMPs

WIMPs

- In the early universe dark matter particles in equilibrium with the radiation bath

- annihilation rate

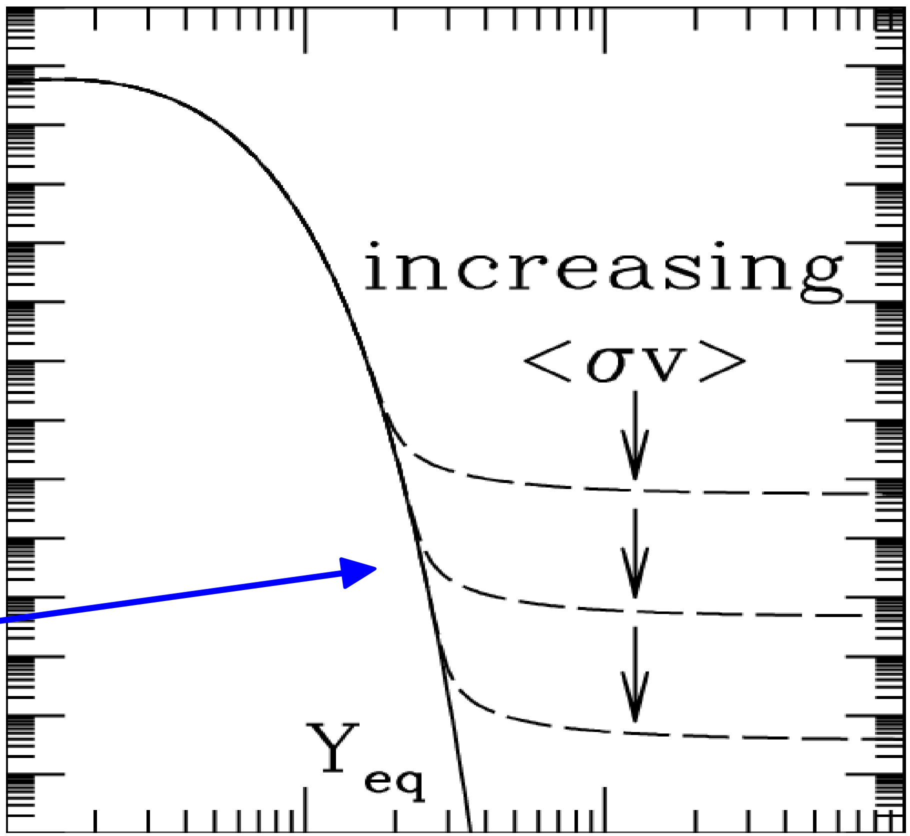
  $n_\chi \langle \sigma v \rangle \propto e^{-m_\chi/T}$

- expansion rate

  $H \propto T^2$

- freeze-out $n_\chi \langle \sigma v \rangle \simeq H$

  $$\Omega_\chi \simeq \Omega_{DM} \frac{1\,\text{pb}}{\langle \sigma v \rangle}$$



Dicus et al., PRL 39 (1977), Lee, Weinberg, ibid., Hut, Phys.Lett. B69 (1977)

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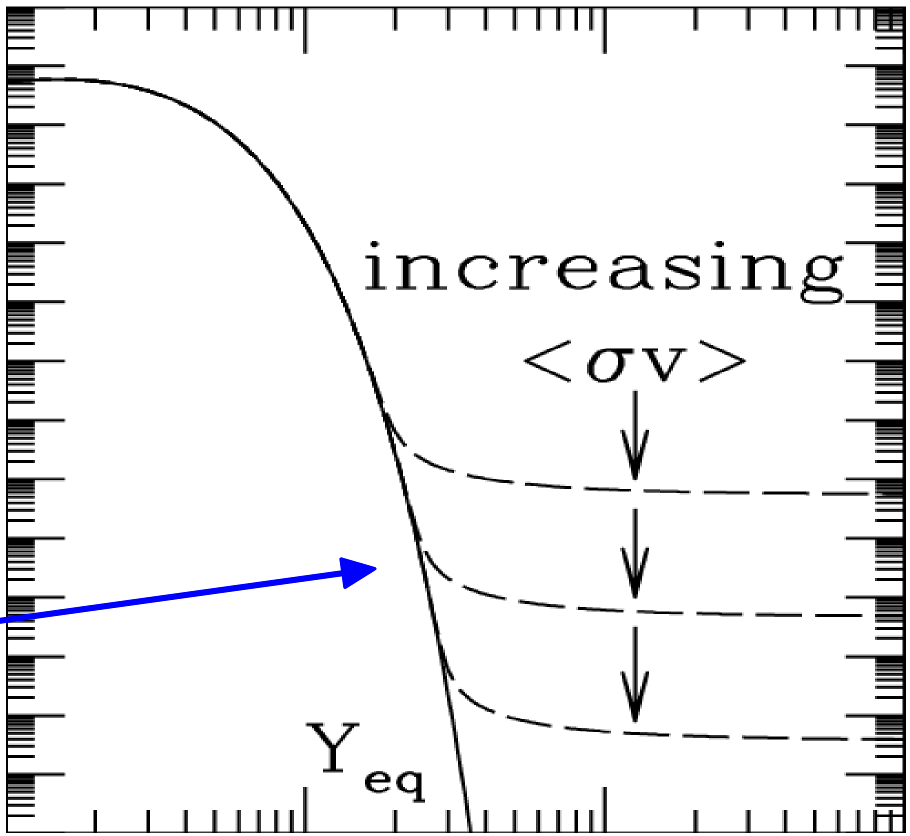
"WIMP miracle"



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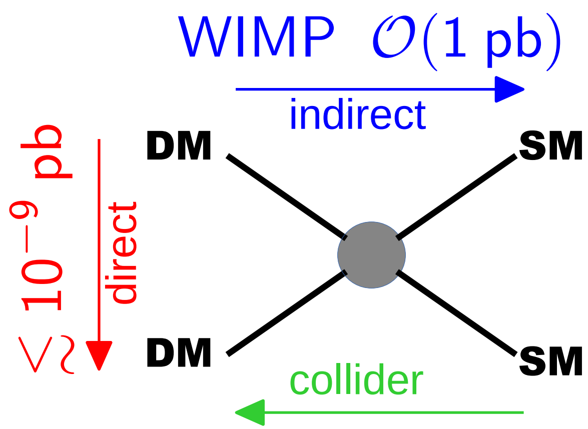
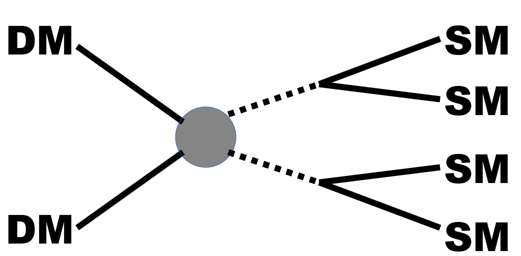
Are WIMPs alive?

- WIMP with $\langle \sigma v \rangle \sim$ pb main target for indirect detection



- strong direct detection constraints on WIMPs, but many options remain
  - ► direct detection suppressed by interaction structure
  - ► secluded WIMPs

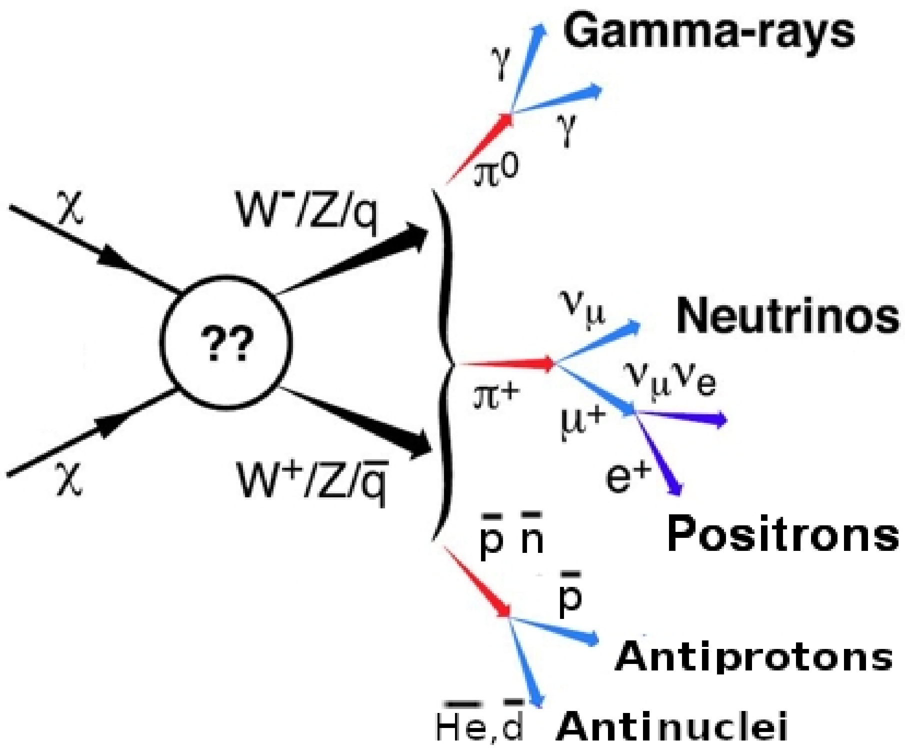
Pospelov et al., Phys .Lett. B662 (2008)



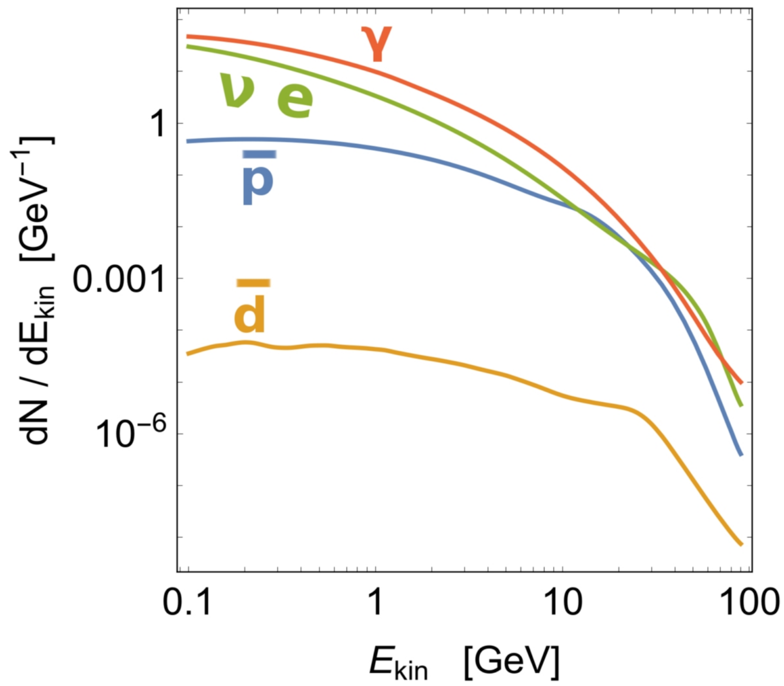
Interaction Structure	$\sigma_{\rm SI}$ suppression	s-wave?
$\bar{X}X\bar{q}q$	1	No
$\bar{X}\gamma^5 X\bar{q}q$	q^2 (DM)	Yes
$\bar{X}X\bar{q}\gamma^5 q$	0	No
$\bar{X}\gamma^5 X\bar{q}\gamma^5 q$	0	Yes
$\bar{X}\gamma^\mu X\bar{q}\gamma_\mu q$ (vanishes for Majorana X)	1	Yes
$\bar{X}\gamma^\mu\gamma^5 X\bar{q}\gamma_\mu q$	$v^{\perp 2}$ (SM or DM)	No
$\bar{X}\gamma^\mu X\bar{q}\gamma_\mu\gamma^5 q$ (vanishes for Majorana X)	$q^2 v^{\perp 2}$ (SM); q^2 (DM)	Yes
$\bar{X}\gamma^\mu\gamma^5 X\bar{q}\gamma_\mu\gamma^5 q$	$q^2 v^{\perp 2}$ (SM)	$\propto m_f^2/m_X^2$
$\bar{X}\sigma^{\mu\nu} X\bar{q}\sigma_{\mu\nu} q$ (vanishes for Majorana X)	q^2 (SM); q^2 or $v^{\perp 2}$ (DM) $q^2 v^{\perp 2}$ (SM)	Yes
$\bar{X}\sigma^{\mu\nu}\gamma^5 X\bar{q}\sigma_{\mu\nu} q$ (vanishes for Majorana X)	q^2 (SM)	Yes

Kumar, Marfatia, Phys. Rev. D88 (2013)

Indirect Dark Matter Detection



particle spectrum



emissivity: $$\frac{d^3N_X}{dV\,dt\,dE} = \frac{\langle\sigma v\rangle \rho_{DM}^{\ 2}}{2m_{DM}^2}\frac{dN}{dE}$$

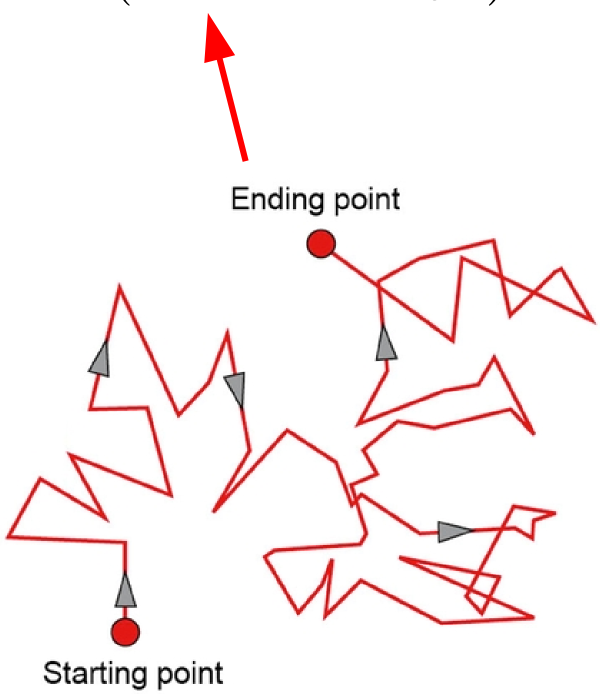
annihilation cross section
dark matter density
particle spectrum

Propagation of Charged Cosmic Rays

- diffusion equation

  Berezinskii et al., Astrophysics of cosmic ray (1990)

$$\nabla(-D\nabla n + \mathbf{v}_c\, n) + \partial_E(b\, n - K_{EE}\partial_E n) + \Gamma_{ann} n = q$$



diffusion on magnetic field inhomogeneities

- extract propagation parameters from fit to nuclear cosmic ray spectra

Propagation of Charged Cosmic Rays

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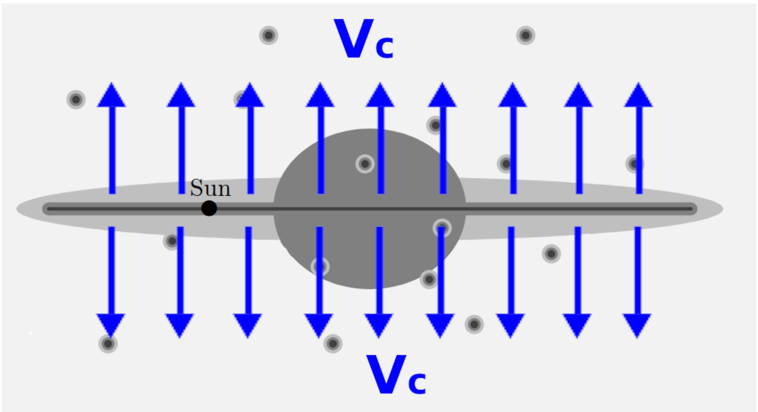
$$\nabla\left(-D\nabla n + v_c\, n\right) + \partial_E\left(b\, n - K_{EE}\partial_E n\right) + \Gamma_{ann} n = q$$



convective winds can blow charged particles away from disc

- extract propagation parameters from fit to nuclear cosmic ray spectra

Propagation of Charged Cosmic Rays

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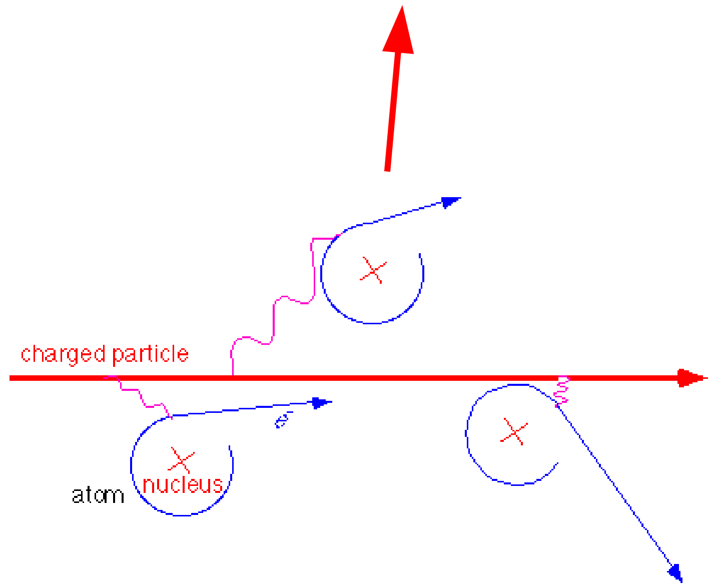

energy losses e.g. by ionizing atoms in galactic disc

- extract propagation parameters from fit to nuclear cosmic ray spectra

Propagation of Charged Cosmic Rays

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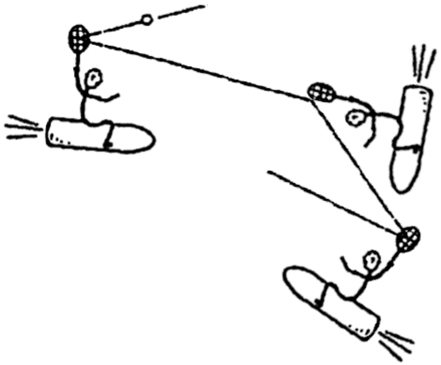
Berezinskii et al., Astrophysics of cosmic ray (1990)

$$\nabla(-D\nabla\, n + \mathbf{v}_c\, n) + \partial_E(b\, n - K_{EE}\partial_E n) + \Gamma_{ann} n = q$$

acceleration on moving magnetic clouds



- extract propagation parameters from fit to nuclear cosmic ray spectra

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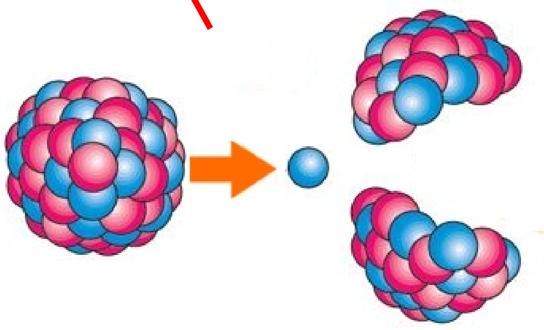
destruction by interaction with matter in the galactic disc



- extract propagation parameters from fit to nuclear cosmic ray spectra

Propagation of Charged Cosmic Rays

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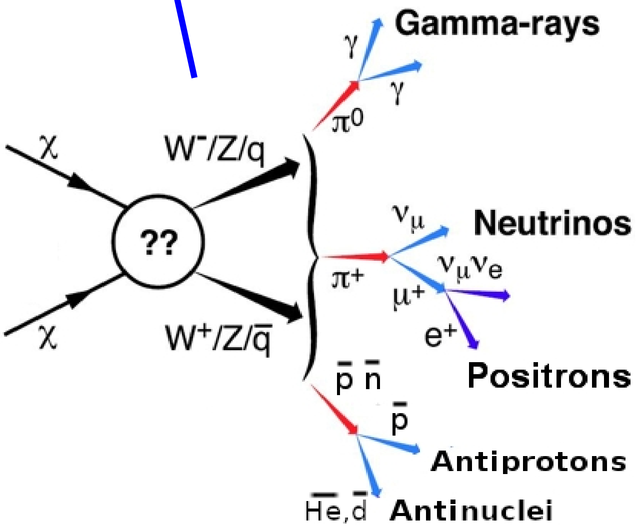
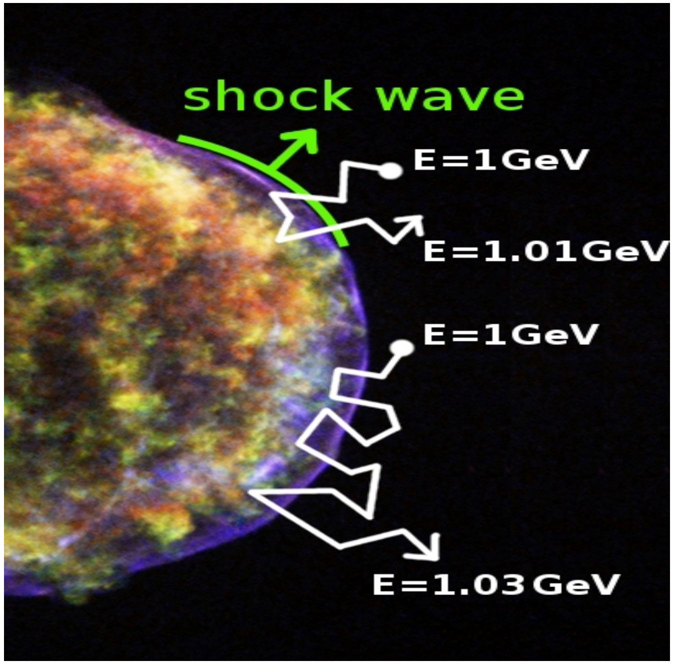
source term = emissivity

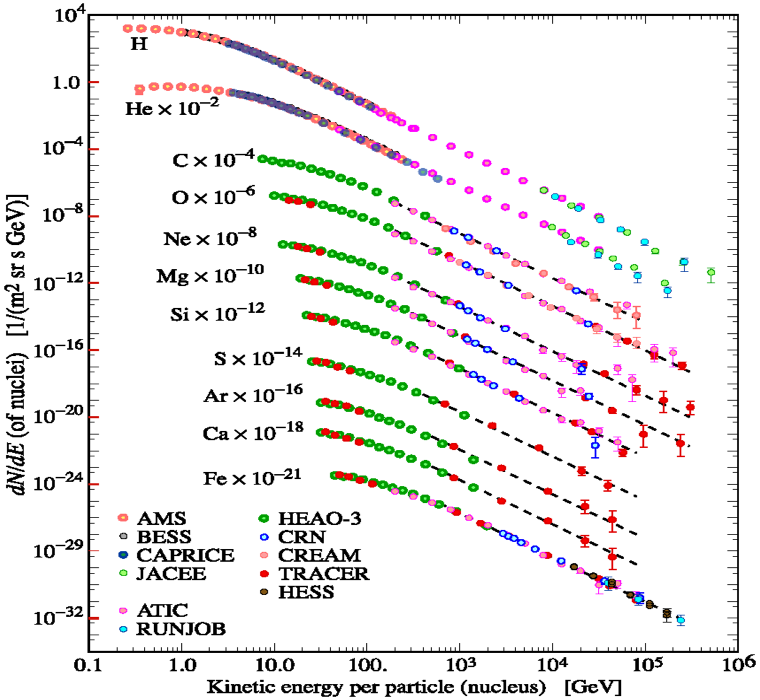


- extract propagation parameters from fit to nuclear cosmic ray spectra

Astrophysical Antimatter Background

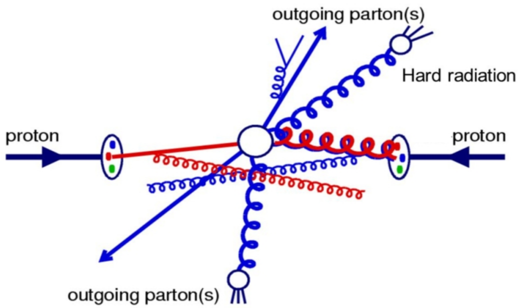
- primary cosmic rays energized by Fermi acceleration
  Fermi, Phys. Rev. 75 (1949), Krymsky Sov. Phys. Dokl. 22 (1977), Axford, Leer, Skadron, ICRC (1977)





- scattering of primaries on interstellar gas induces secondary cosmic rays

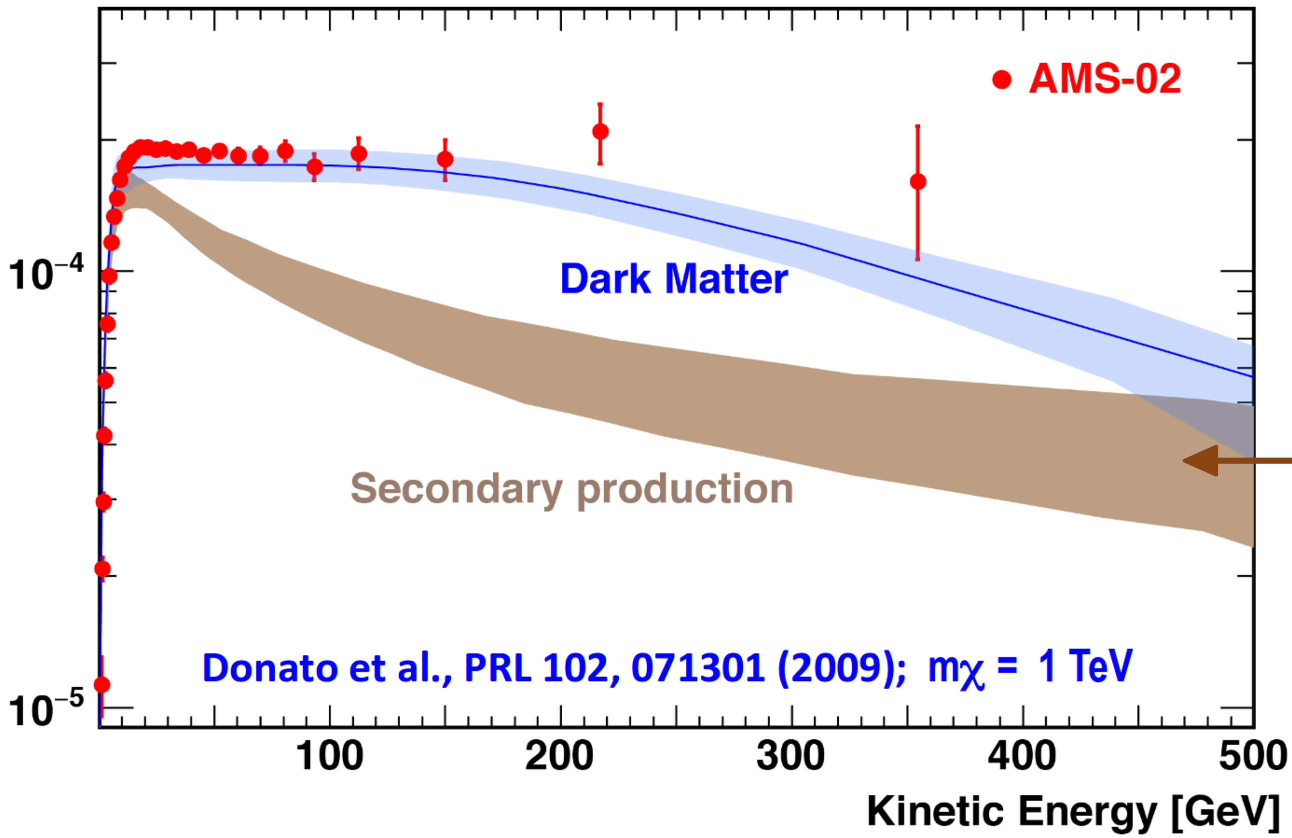
$$q_i^{\rm sec}(E) \sim \int dE' \left(\frac{d\sigma_i}{dE}\right) n_{p,{\rm He}}\, \Phi_{p,{\rm He}}(E')$$



Antiprotons

Antiproton Data

- 2015: surprisingly hard antiproton spectrum observed by AMS-02
  S.Ting, A. Kounine, AMS Days at CERN (2015)

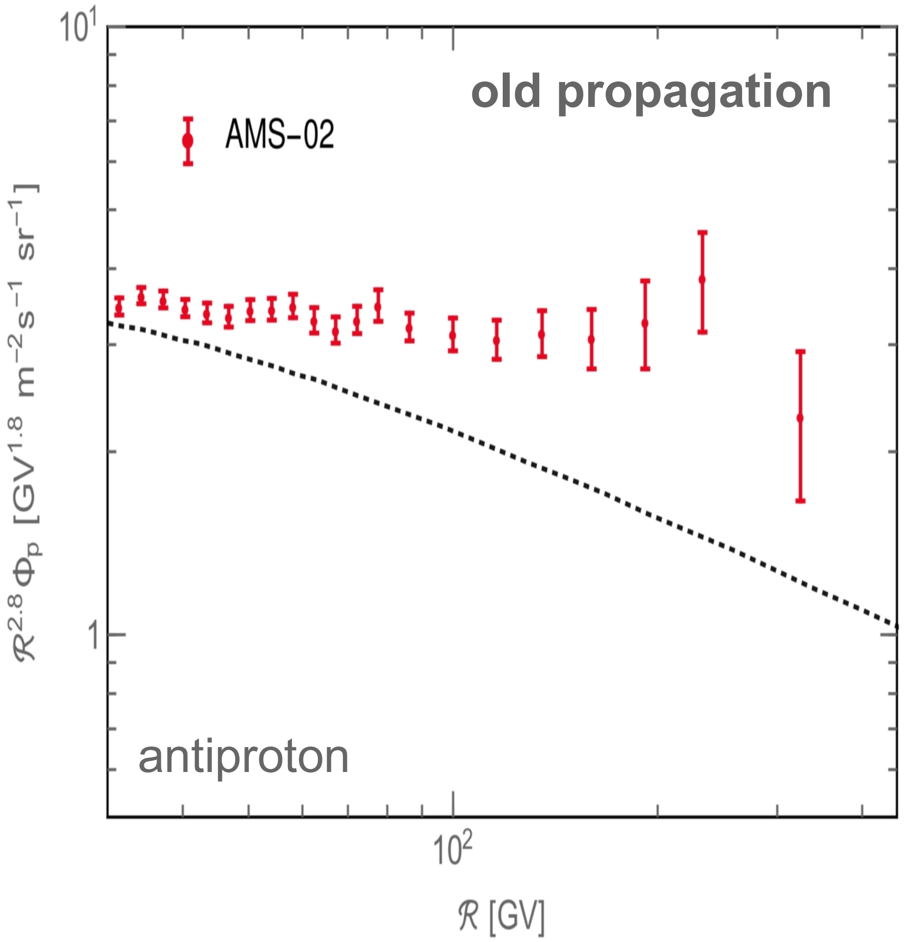


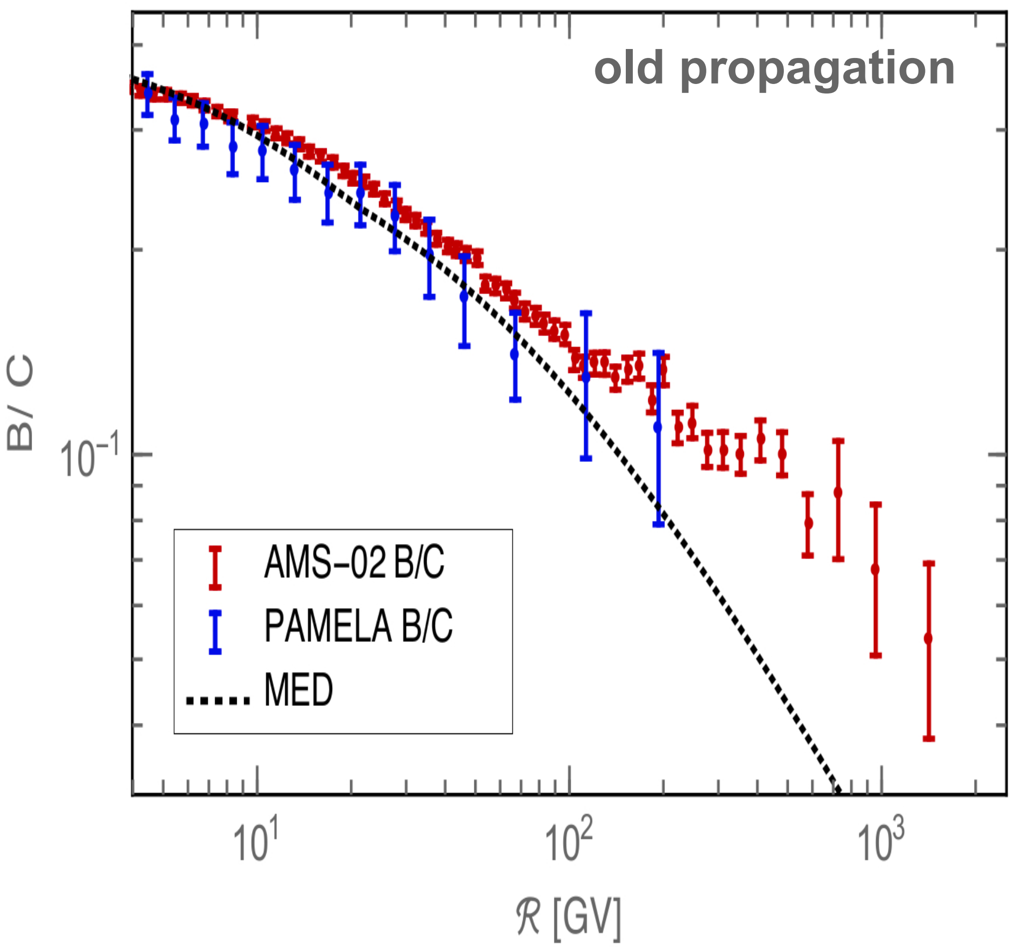
Uncertainties:
cross section,
propagation

- hint for dark matter ?

Propagation Update

- propagation parameters refitted to AMS-02 nuclear cosmic rays
  Kappl, Reinert, M.W. JCAP (2015), Giesen et al. ibid





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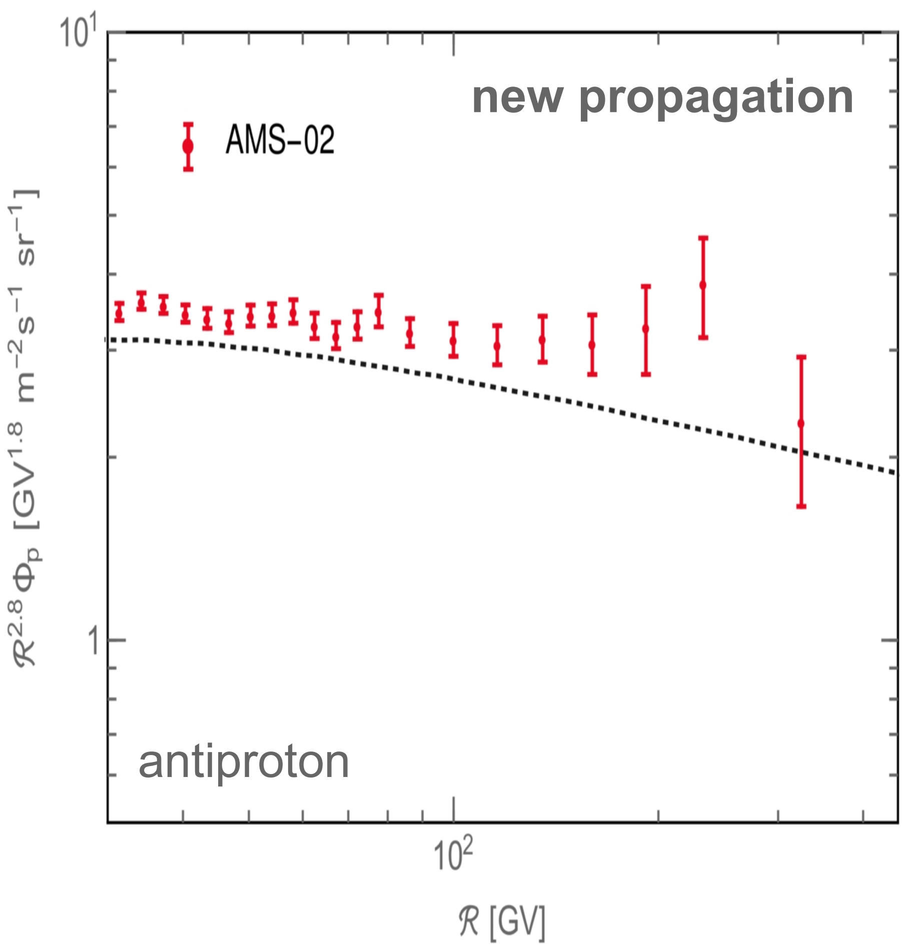
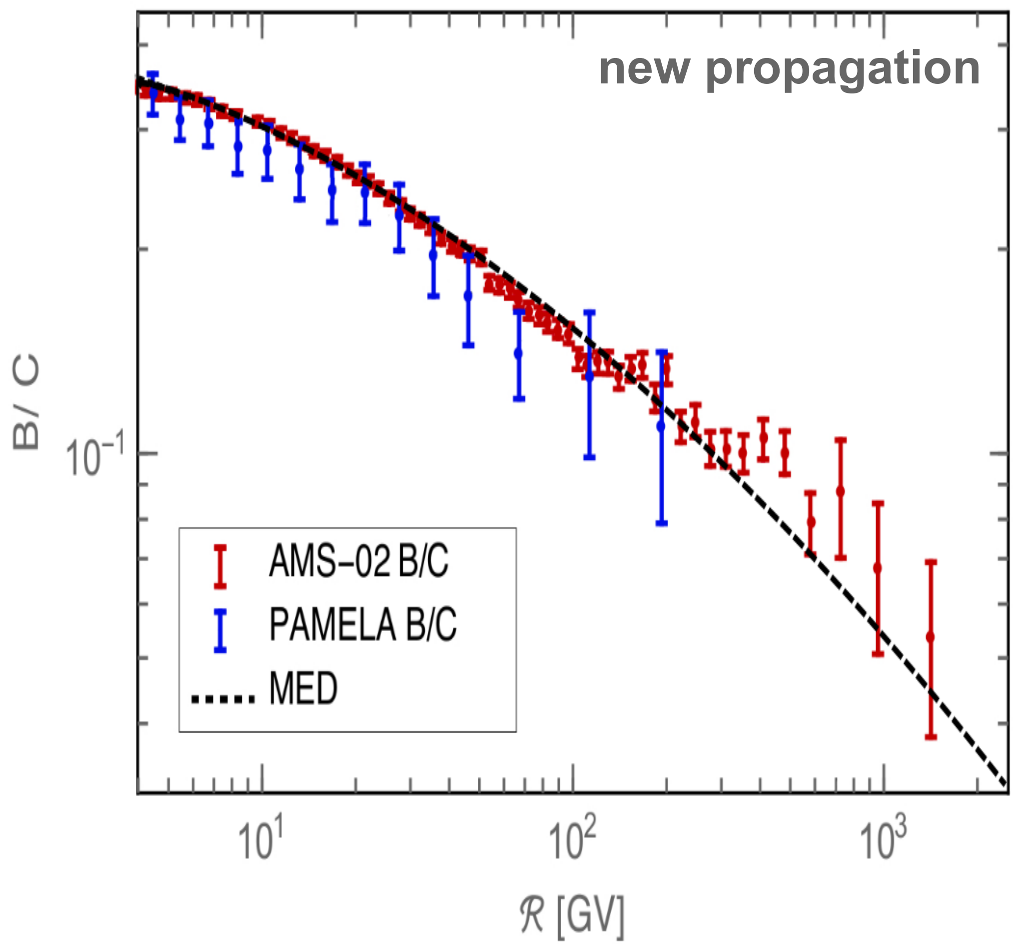




Antiproton Background: Cross Section

- background estimate based on Tan-parameterization of $\sigma_{pp\to\bar{p}}$

  Tan, Ng Phys. Rev. D26 (1982)

$$\sigma_{\bar{p}} = \sigma^{0}_{\bar{p}} + \sigma^{\Lambda}_{\bar{p}} + \sigma^{0}_{\bar{n}}$$

measure + scaling ignore $= \sigma^{0}_{\bar{n}}$

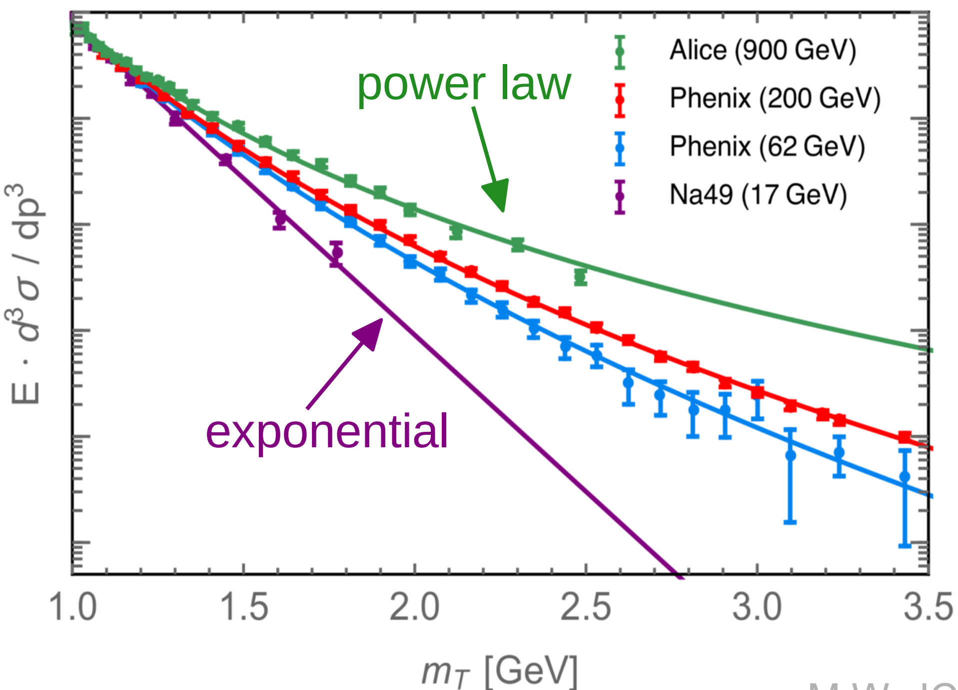
- prompt cross section

$$E\frac{d^3\sigma^0_{\bar{p}}}{dp^3} \propto (1-x_R)^{c1}\, e^{-m_T/c_2}\,, \qquad x_R = \frac{E^*}{E^*_{max}}\,, \quad m_T = \sqrt{pT^2+m^2}$$

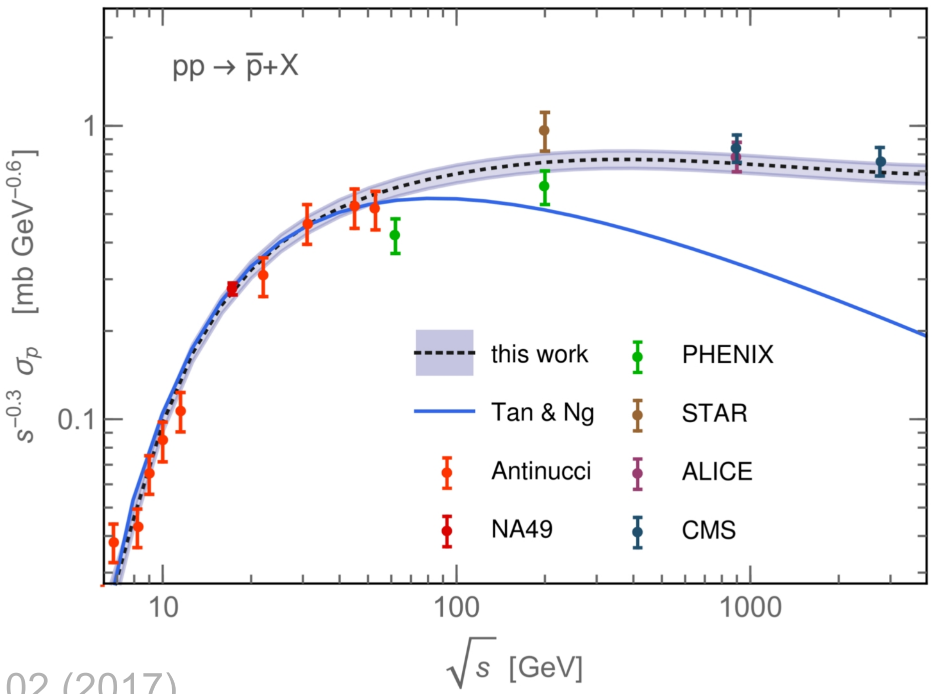
$$E\frac{d^3\sigma^0_{\bar{p}}}{dp^3}(x_R, p_T, \sqrt{s}) \xrightarrow{\sqrt{s}>10\text{ GeV}} E\frac{d^3\sigma^0_{\bar{p}}}{dp^3}(x_R, p_T)$$ Feynman scaling

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

Feynman Scaling Violation

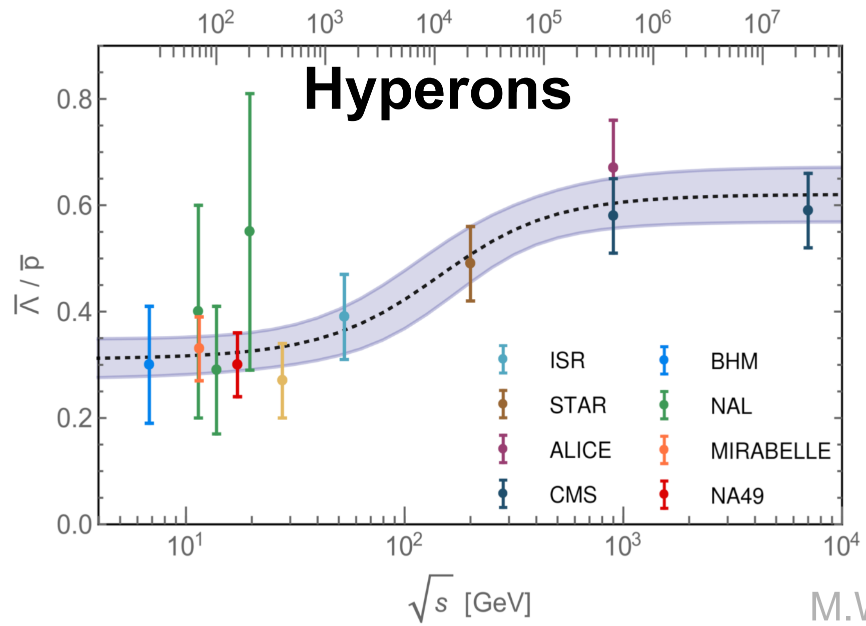


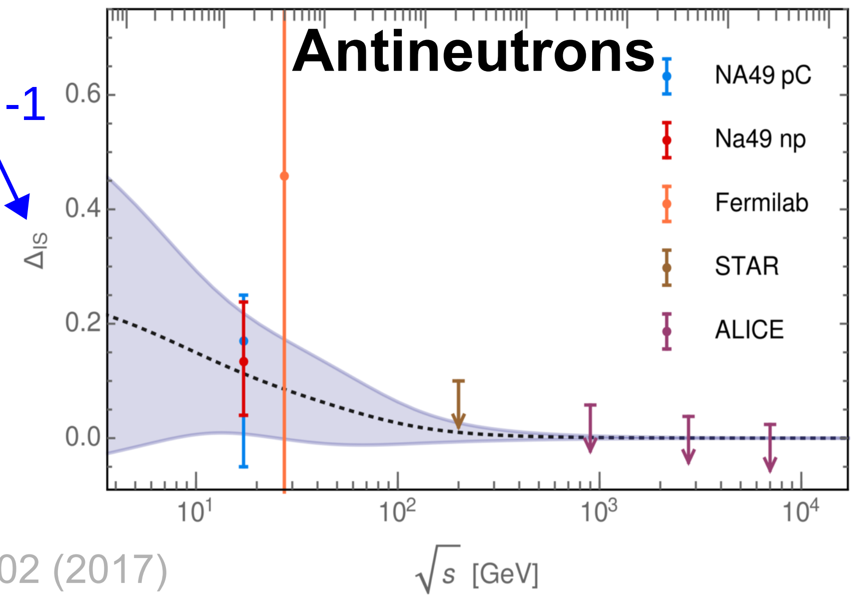
M.W. JCAP 02 (2017)



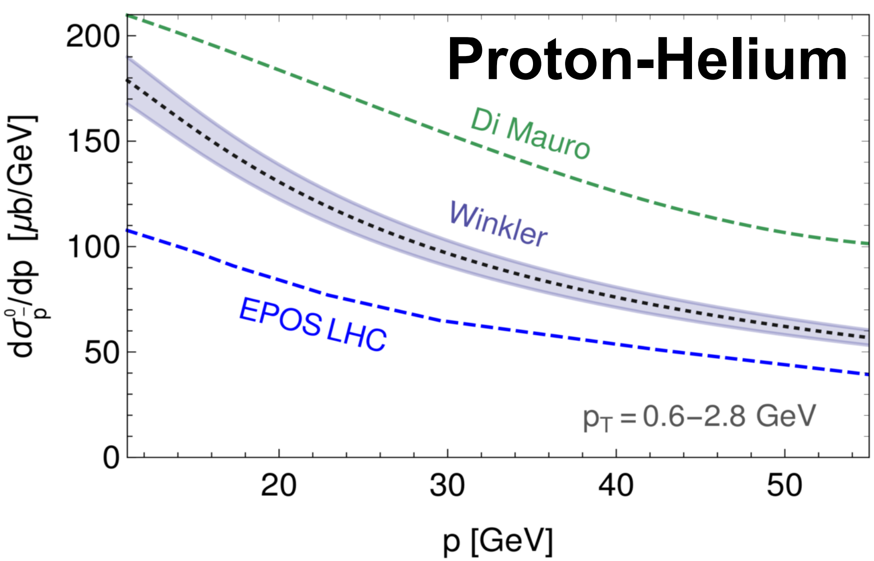
- Feynman scaling preserved up to $\sqrt{s} \sim 50$ GeV
- at high energy scaling is violated by multiple scattering
  - ► hard p_T jets

Additional Antiproton Channels





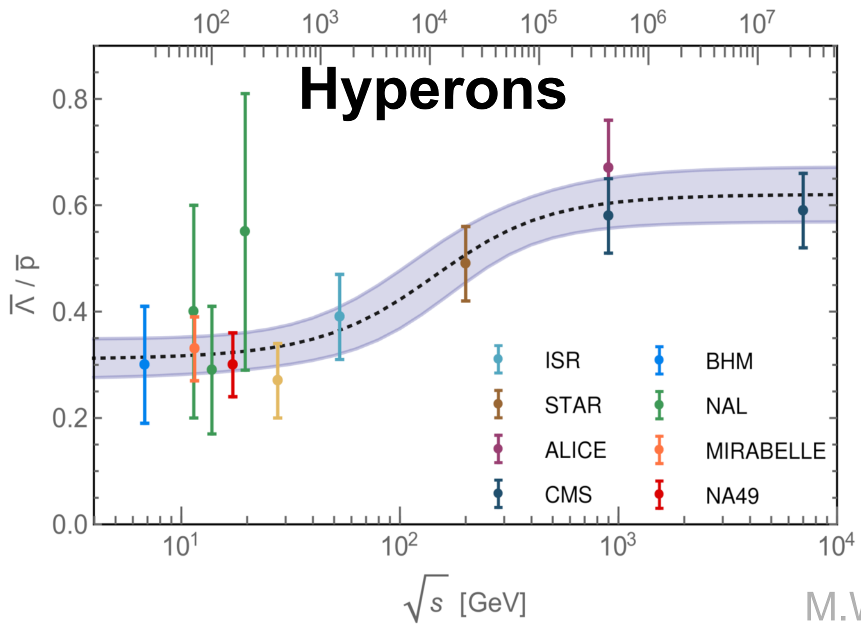
M.W. JCAP 02 (2017)

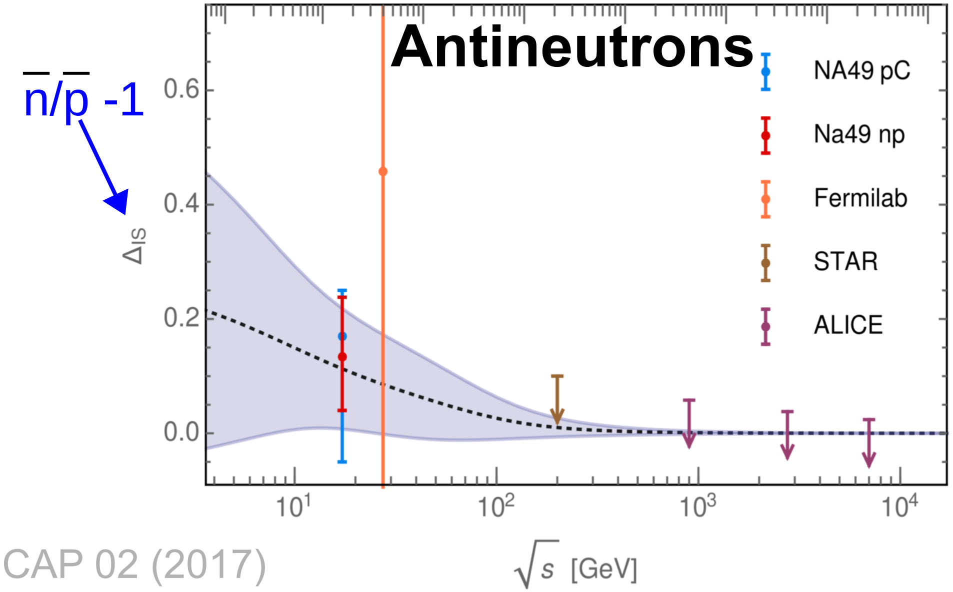


- 20-35% of $\bar{p}$ from $\bar{\Lambda}$, $\bar{\Sigma}$ decay
- antineutron asymmetry
- first measurement of $p\,He \to \bar{p}$ by LHCb-SMOG

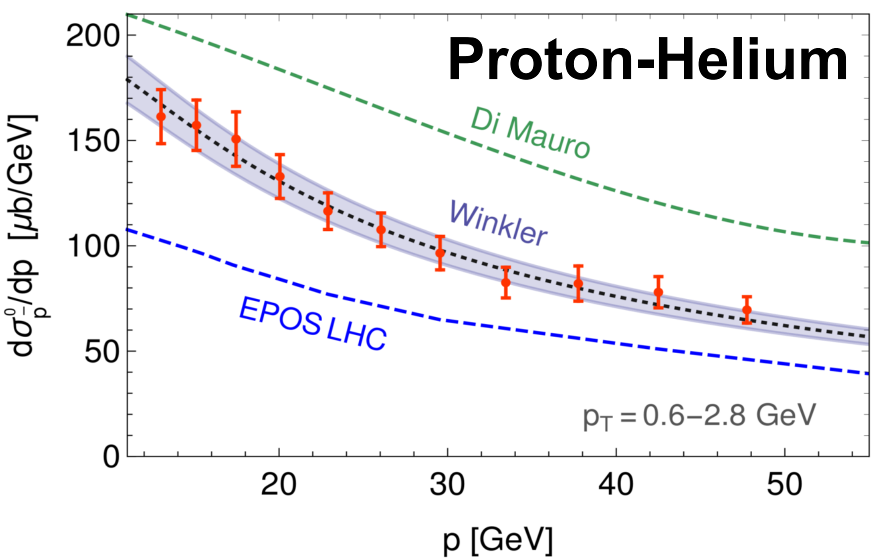
Phys.Rev.Lett. 121 (2018)

Additional Antiproton Channels





M.W. JCAP 02 (2017)



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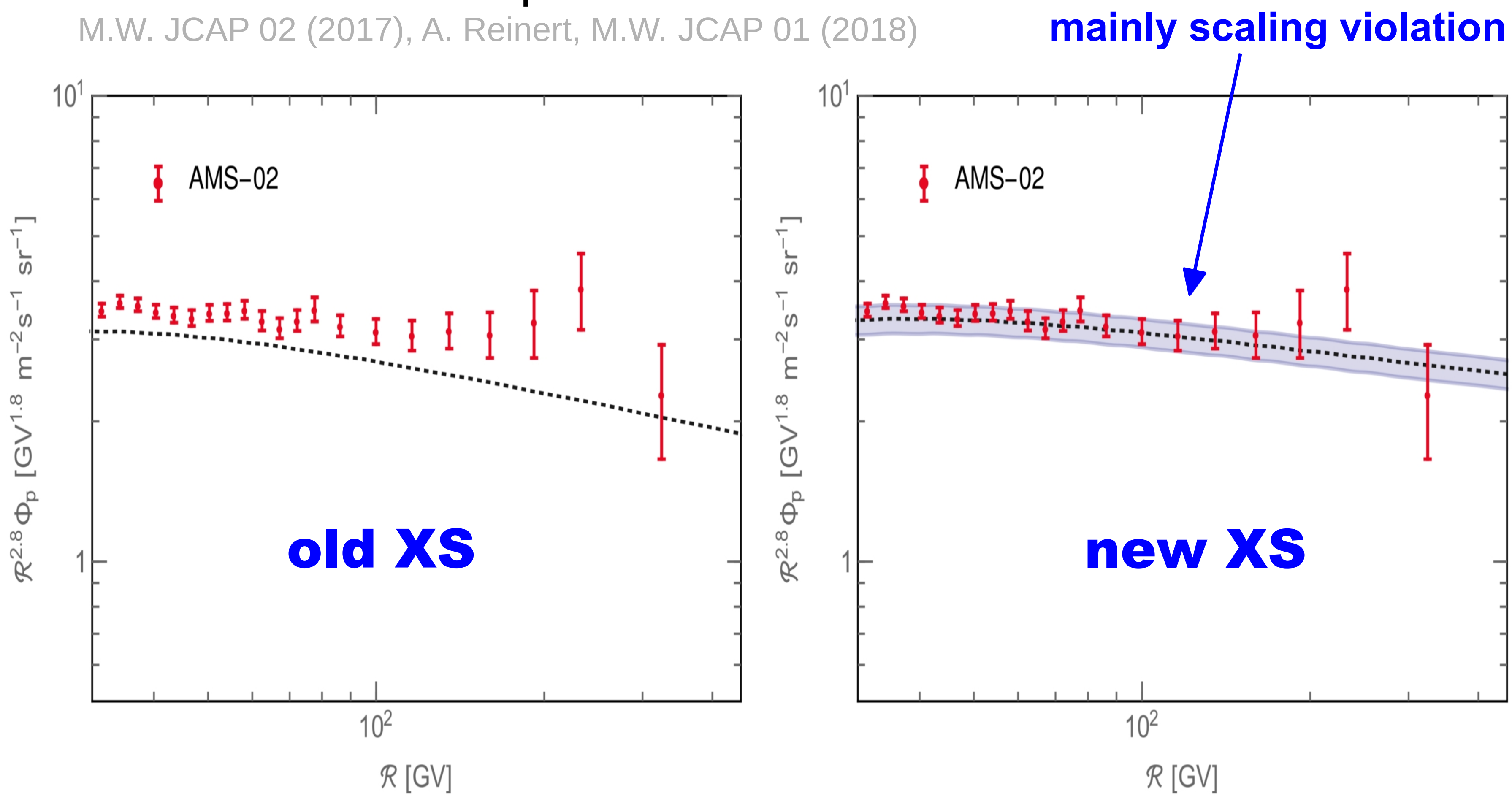
Phys.Rev.Lett. 121 (2018)

Application to Antiproton Flux

- new cross section parameterization

M.W. JCAP 02 (2017), A. Reinert, M.W. JCAP 01 (2018)

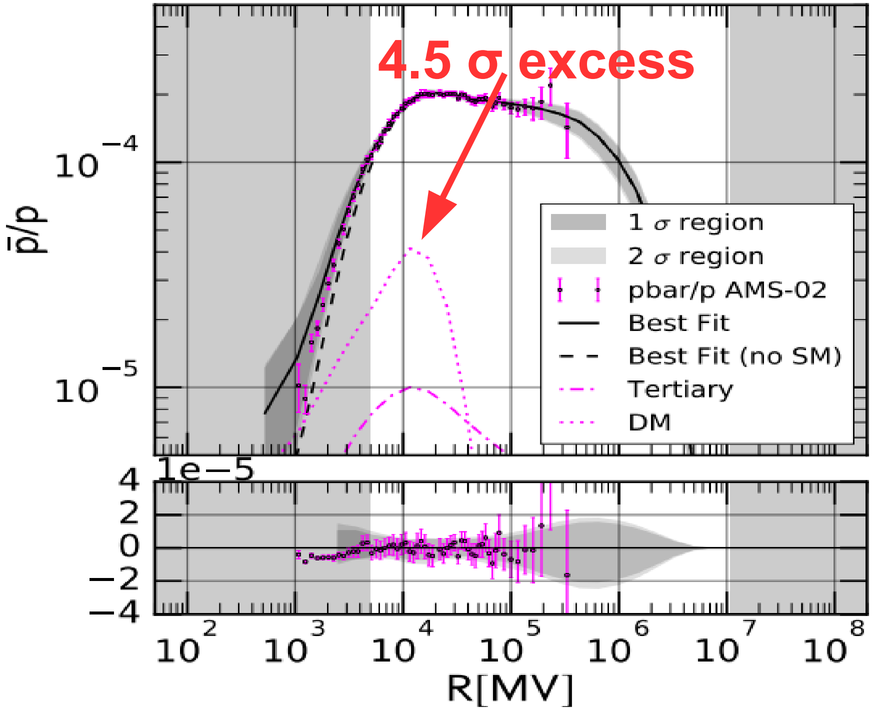


- high-energy antiproton flux consistent with expected astro-physical background, no dark matter required

New Antiproton Excess

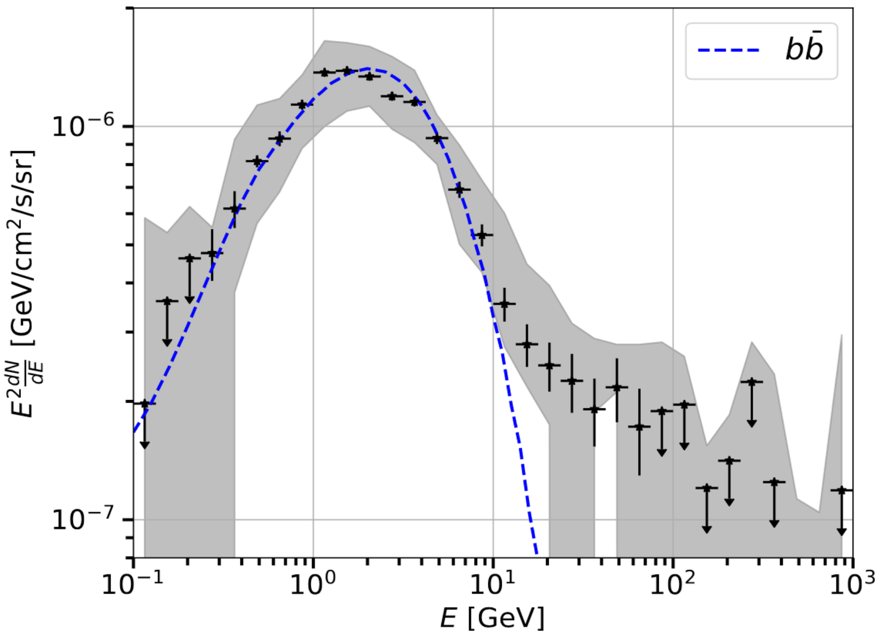
antiproton excess

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



gamma ray excess

Goodenough, Hooper, arXiv:0910.2998 (2009)



M. Di Mauro, M.W., PRD 103 (2021)

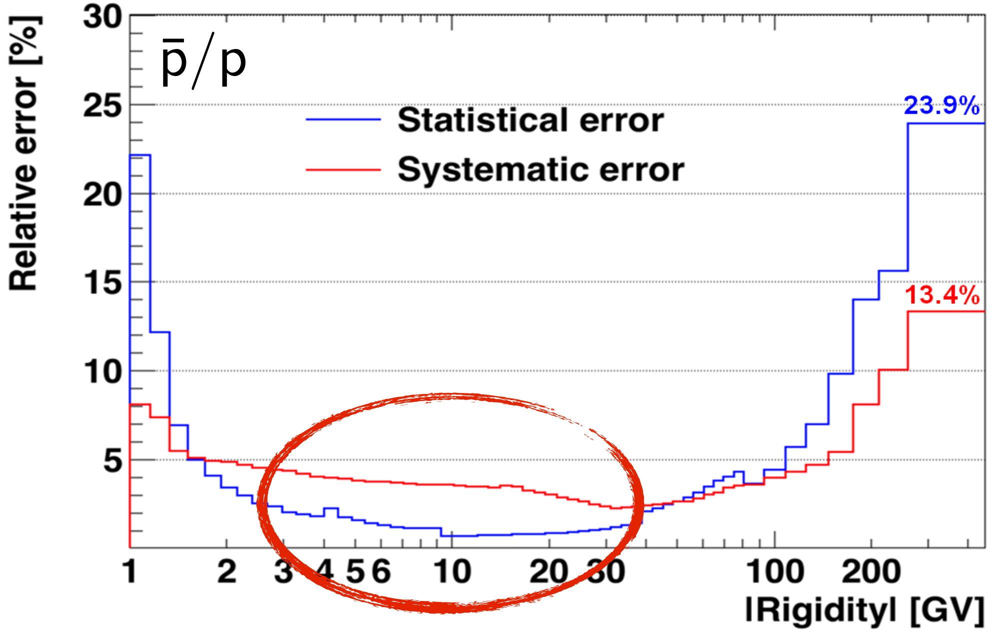
- both excesses seem to hint at similar dark matter properties

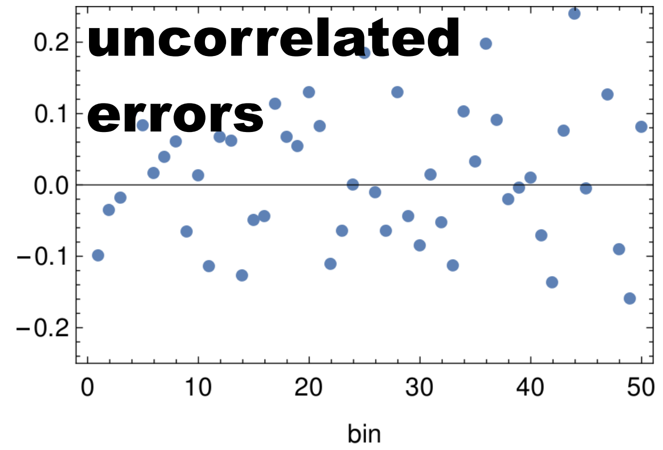
$$m_\chi \sim 40 - 80\ \text{GeV} \qquad \langle \sigma v \rangle_{\bar{b}b} \sim (1-3) \times 10^{-26}\ \text{cm}^3/\text{s}$$

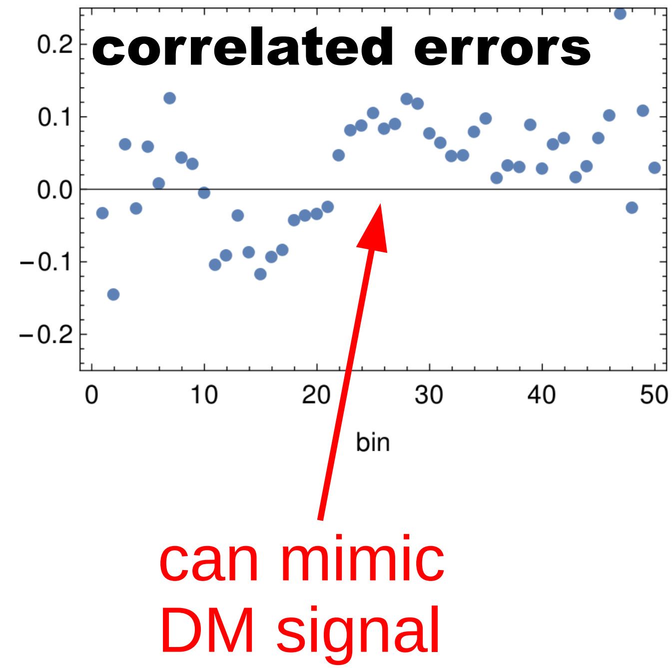
- new XS parameterization reduces antiproton excess to 2-3σ

Reinert, M.W. JCAP 01 (2018), Cui et al. JCAP 06 (2018), Cuoco et al. PRD 99 (2019)

Antiproton Systematic Errors

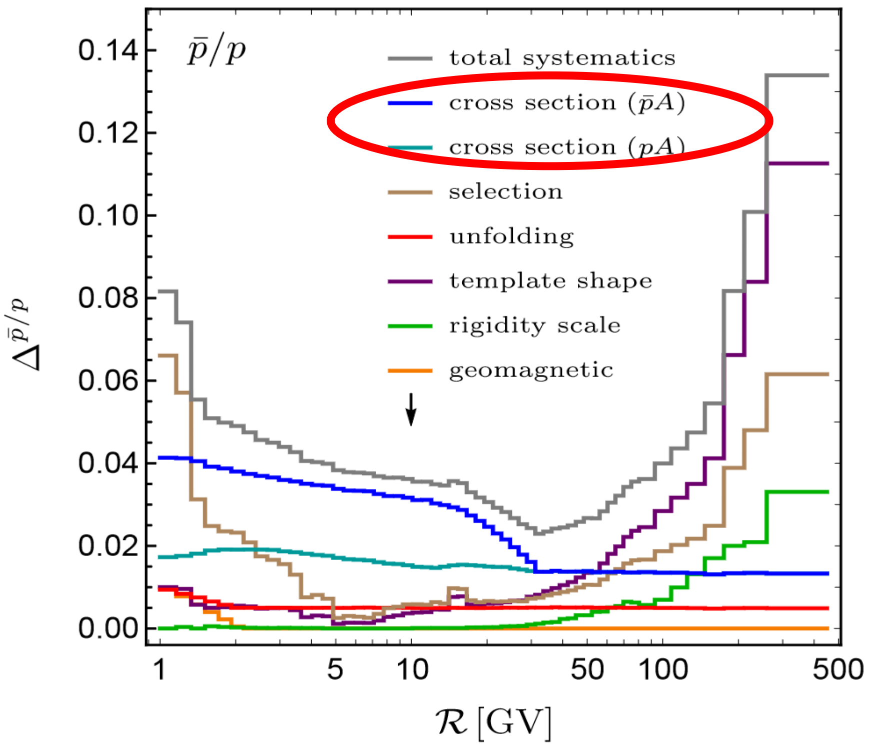


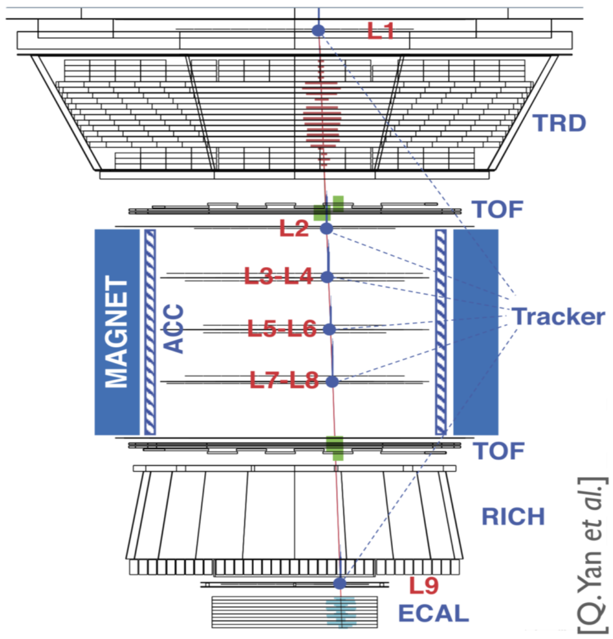




- AMS-02 error systematics-dominated at excess
- no error correlations provided by collaboration so far

Modeling of Systematic Errors





~80% carbon

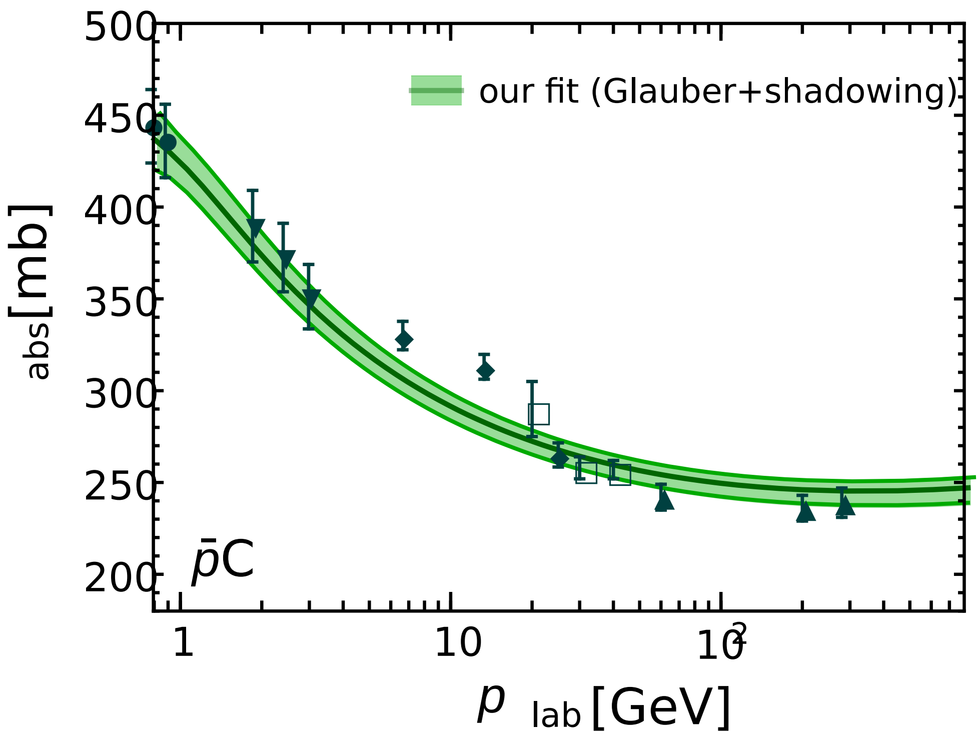
- systematic error dominantly due to absorption in detector
- $\bar{p}$C can be modeled in Glauber-Gribov theory

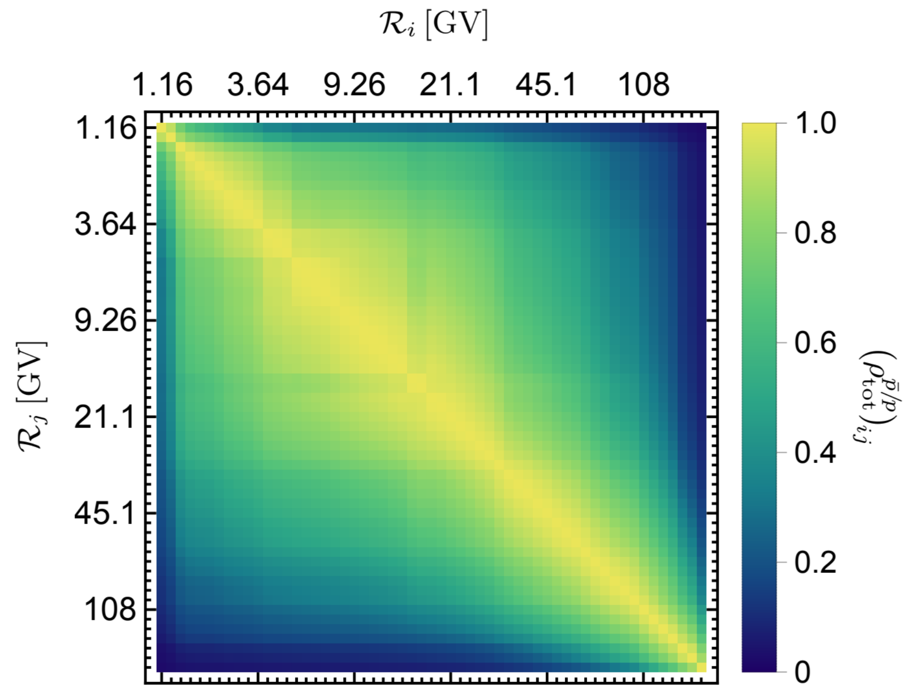
Glauber, Lect.in Theoret. Phys. (1959), Gribov, Sov. Phys. JETP 29 (1969)

$$\sigma^{\mathrm{abs}}_{\bar{p}C} = \int d^2b \left(1 - \prod_{i=1}^{12} \left[1 - \sigma_{\bar{p}n_i} \mathcal{T}_i(b)\right]\right) + \text{ inel. screening}$$

antiproton-nucleon XS **nuclear densities etc.**

Impact on Antiproton Excess





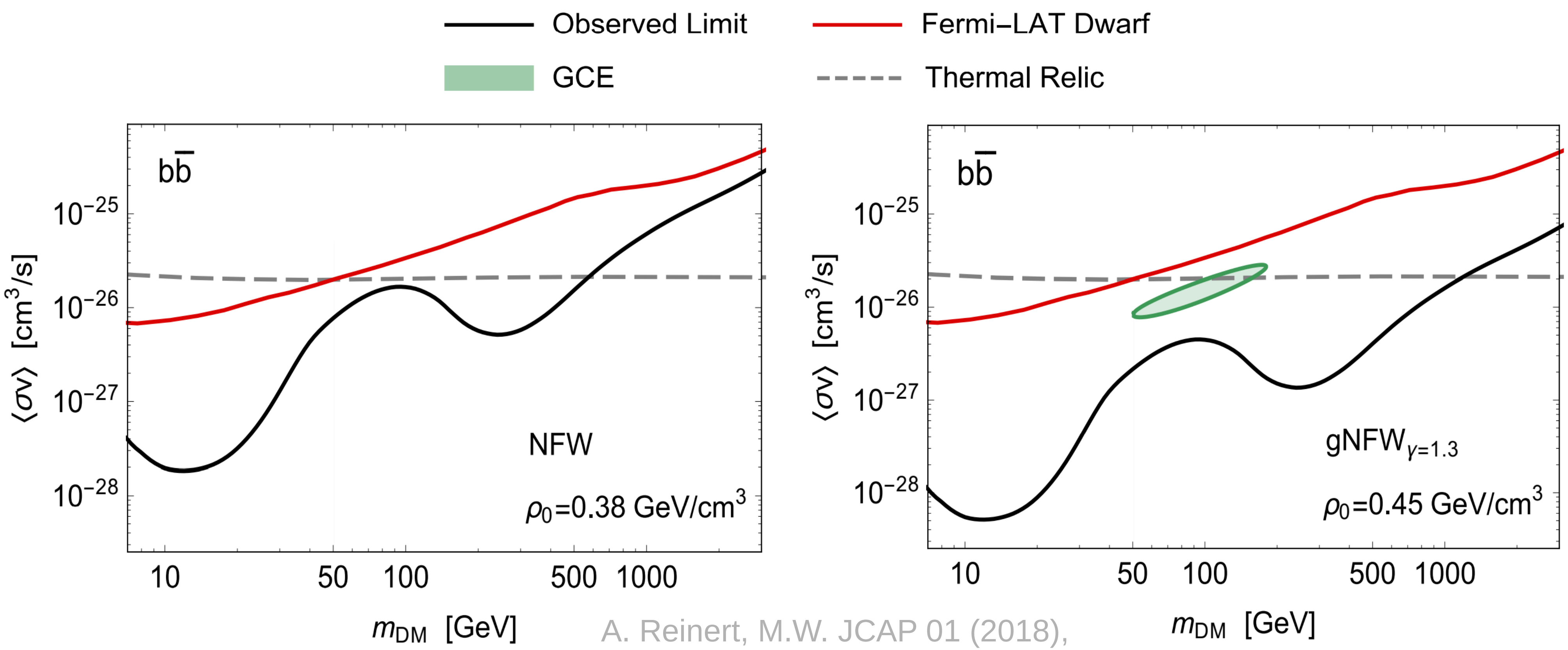
- global fit with Glauber-Gribov parameterization allows us to extract error correlations for AMS-02

Heisig, Korsmeier, M.W. Phys. Rev. Res. 2 (2020)

	w/o corr.	with corr.
$m_{\rm DM}$ [GeV]	76	66
$\langle\sigma v\rangle$ [10^{-26} cm^3/s]	0.91	0.74
$\Delta\chi^2_{\rm tot}$	6.9	3.2
local sig.	$2.6\,\sigma$	$1.8\,\sigma$
global sig.	$1.8\,\sigma$	$0.5\,\sigma$

excess reduced to < 1σ

Antiproton Constraints on Dark Matter



A. Reinert, M.W. JCAP 01 (2018),
M. Di Mauro, M.W., PRD 103 (2021)

- antiprotons set strongest indirect detection constraints on WIMP dark matter
- gamma ray excess in slight tension with antiprotons

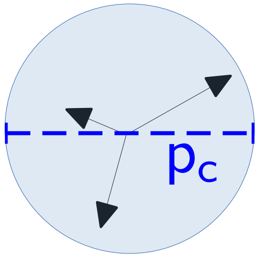
Antinuclei

Antinuclei

- antinucleons from dark matter annihilation/ cosmic ray scattering can merge into antinuclei

- coalescence condition for antinucleons
  Schwarzschild, Zupancic, Phys. Rev. 129 (1963)

$|\Delta \mathbf{p}| < p_c$ antideuteron



antihelium-3

- quantum mechanical picture
  Gustafson, Häkkinen, Phys. C 61 (1994), Blum et al., Phys.Rev. D96 (2017)

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

hadronic interaction zone $\sigma \sim \Lambda_{QCD}^{-1} \sim \mathrm{fm}$

$$p_c \propto \left(\int d^3q \left| \int d^3r\, \Psi_{\bar{d}}^{\,*}(\mathbf{r}) \Psi_{\bar{p}\bar{n}}(\mathbf{r}) \right|^2 \right)^{1/3} \sim \mathbf{200\ MeV}$$

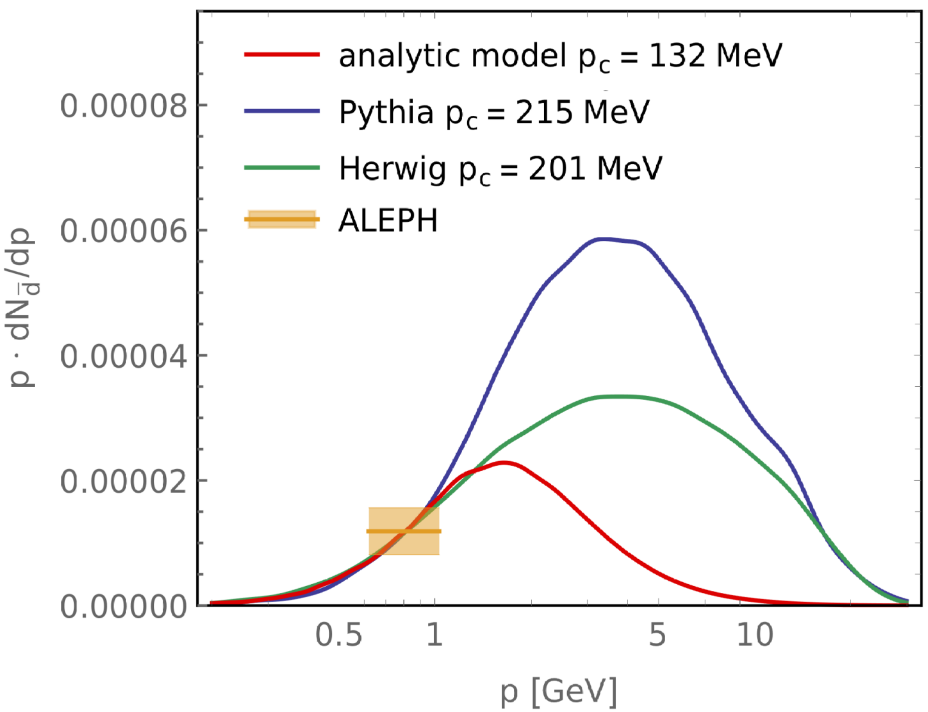
M.W., Antideuteron 19 (2019)

antideuteron wave function

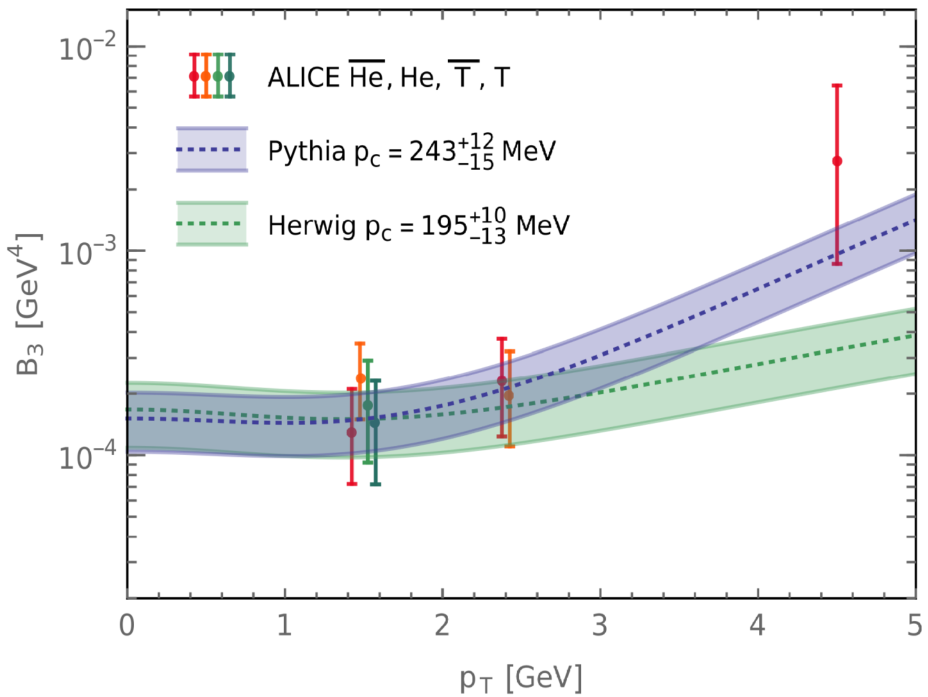
Event-by-event Coalescence Model

- implement process (e.g. dark matter annihilation) into event generator and apply coalescence condition on each event
- p_c determined by fit to experimental data

$e^+e^- \rightarrow Z \rightarrow \bar{d}$ (ALEPH)

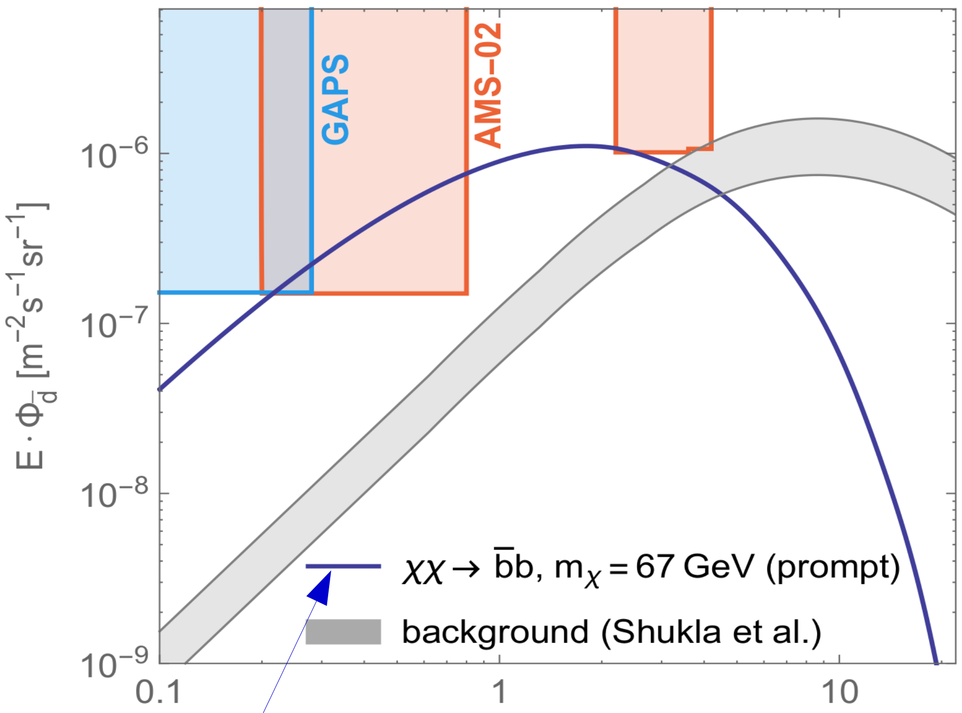


$pp \rightarrow \overline{He}$ (ALICE)



Antinuclei Fluxes (Status 2020)

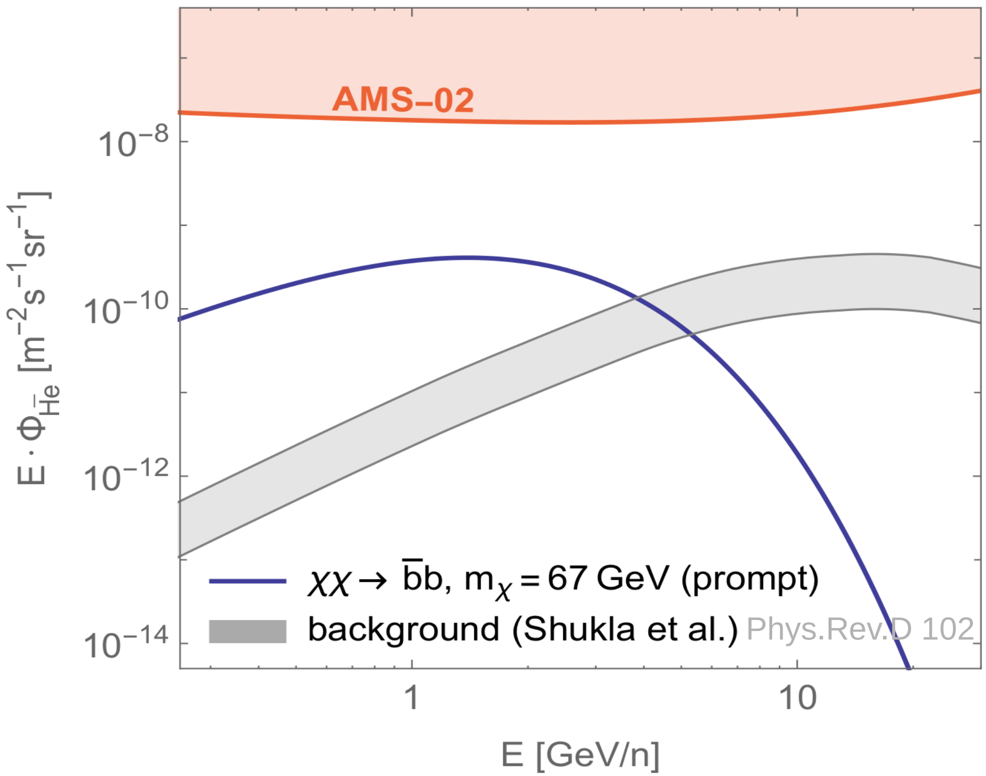
Antideuteron



motivated by GCE

"smoking gun"

Antihelium



hopeless?

BUT: tentative detection of ~10 $\overline{He}$ events at AMS-02

S.Ting, CERN Colloquium 2016, Science Magazine 2017

Exotic Antihelium Sources

- antimatter clouds or anti-stars
  Poulin et al., Phys. Rev. D 99 (2019)

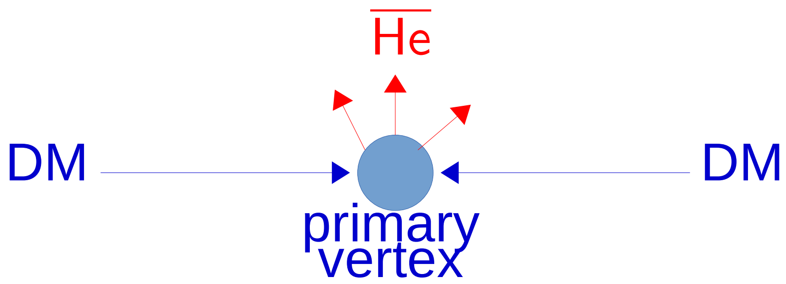
- peculiar dark sectors
  Heeck, Rajaraman, J. Phys. G47 (2020)

- Alfvén reacceleration
  Alfvén reacceleration, Phys. Rev. D 102 (2020)

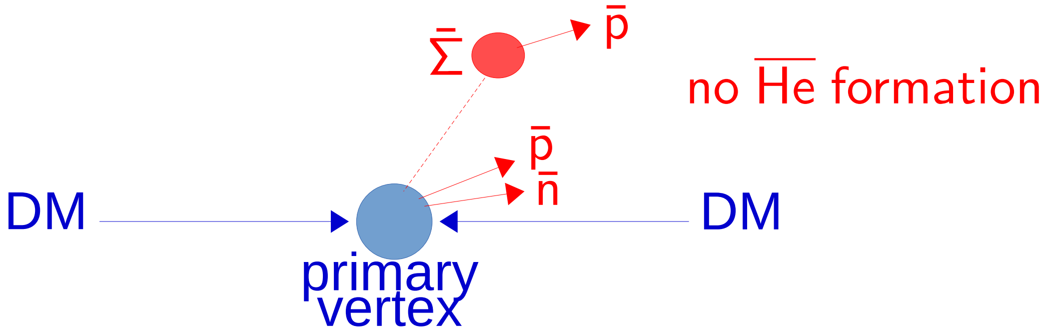
- uncertainties in coalescence model
  Blum et al., Phys. Rev. D 96, (2017), Coogan, Profumo, Phys. Rev. D96 (2017)

Displaced Cosmic Antiparticles

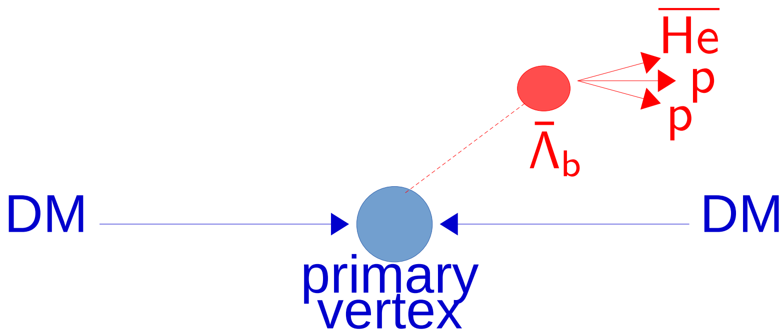
- previous analyses derived $\overline{\text{He}}$ emission by prompt antinucleons



- Idea: prompt antinuc-leons cannot merge with displaced antinucleons



- potentially **dominant** $\overline{\text{He}}$ production mode has been missed



$\overline{\Lambda}_b$: The Perfect $\overline{He}$-Catalyst

- DM annihilation yields large number of $\overline{\Lambda}_b$

$$f(\bar{b} \to \bar{\Lambda}_b) \sim 0.1$$

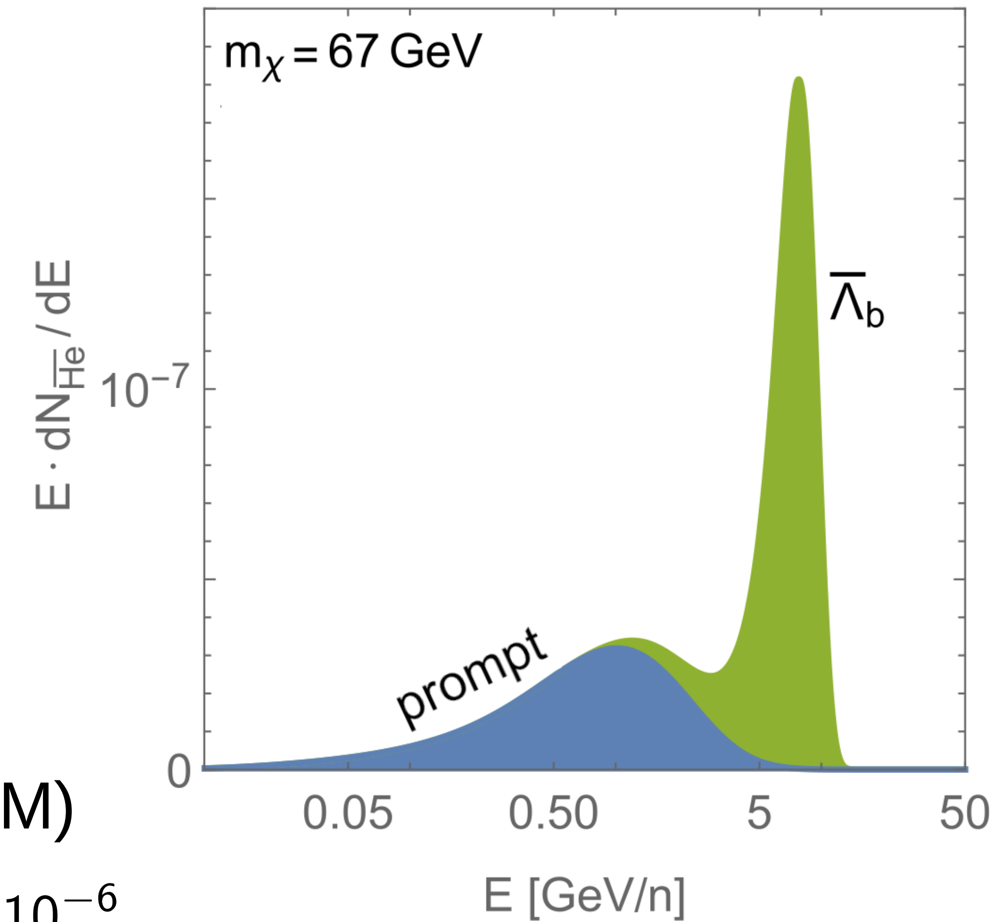
- carry antibaryon number

- antinucleons produced with low relative momentum

$$m_{\bar{\Lambda}_b} - 5m_n \simeq 1\,\text{GeV}$$

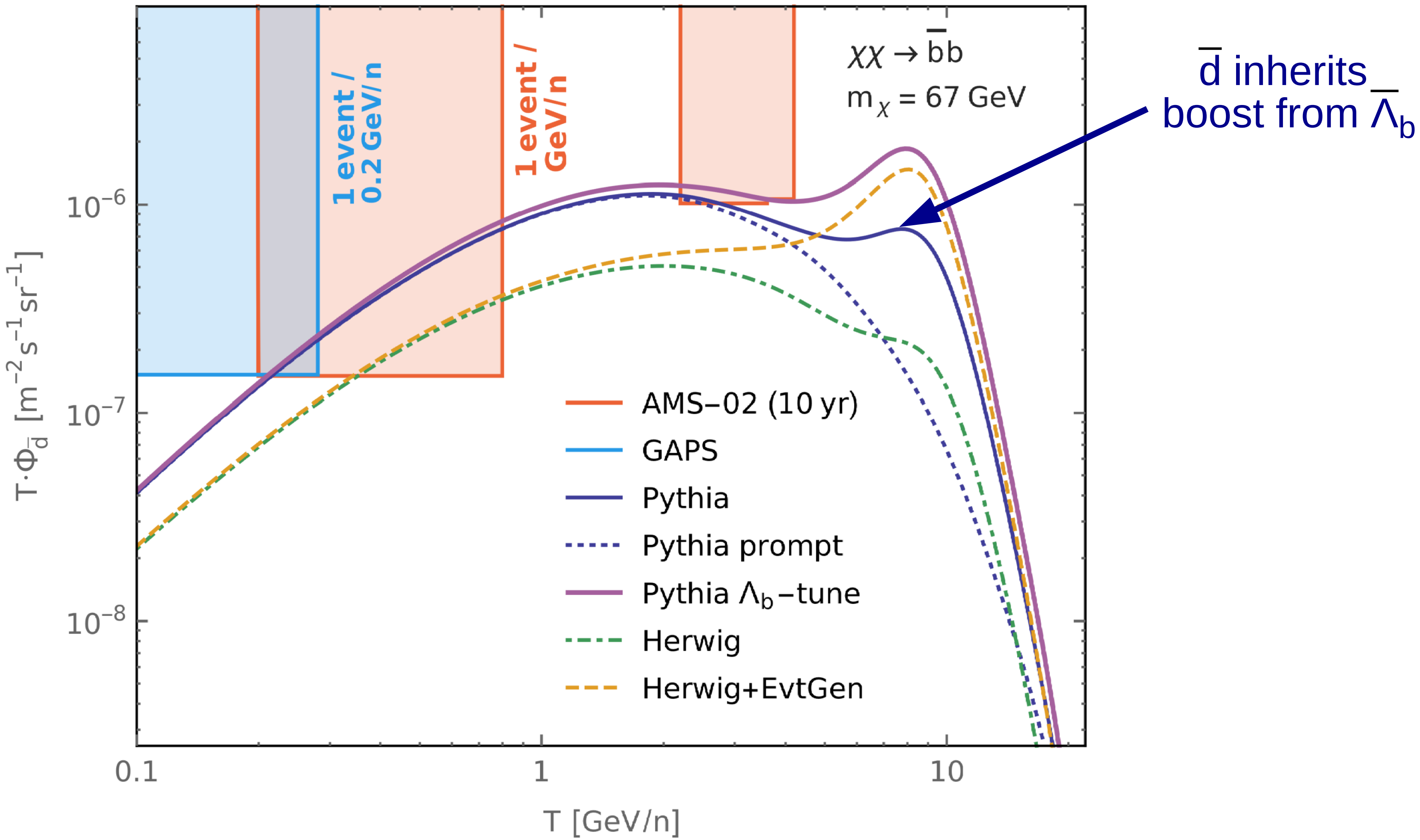
- "large" branching (despite CKM)

$$\text{Br}(\bar{\Lambda}_b \to \bar{d}u\bar{u}(\overline{ud}) \to \overline{\text{He}}) \sim 10^{-6}$$



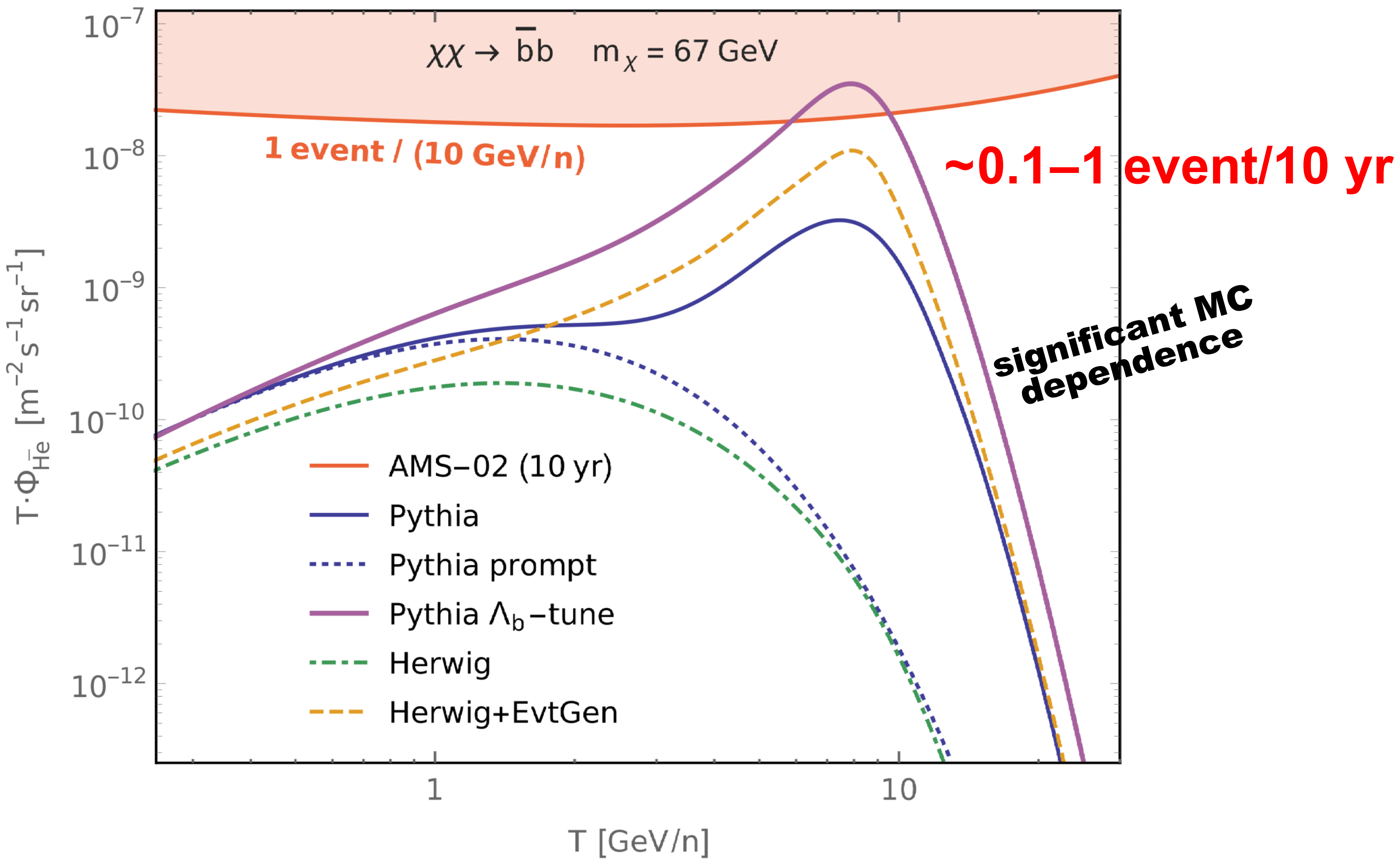
- $\overline{He}$ from $\overline{\Lambda}_b$ contributes to the high-energy flux

Impact on Antideuteron Flux



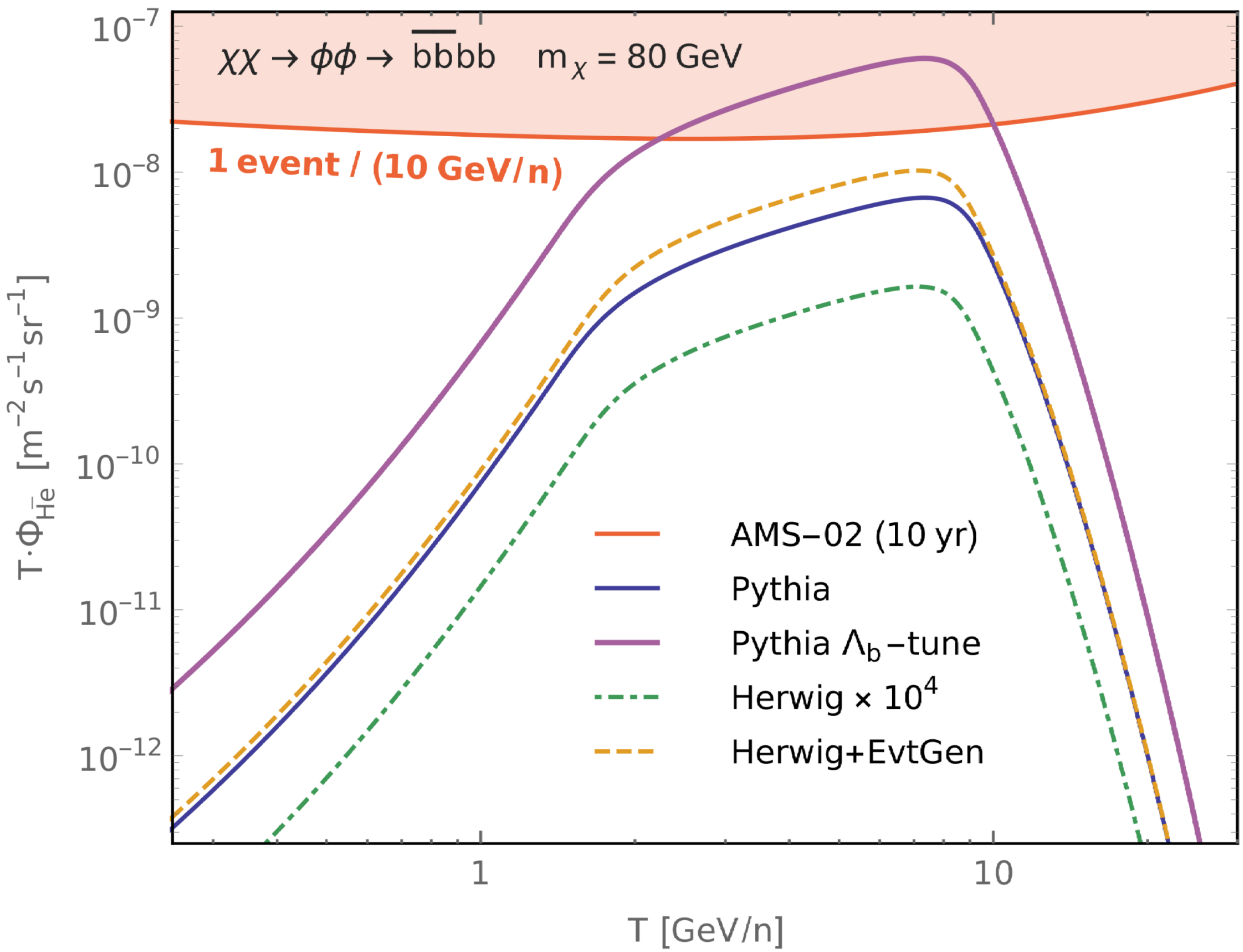
- promising new high-energy signature in antideuteron flux

Impact on Antihelium Flux



- detectable antihelium flux enhanced by O(100) due to $\overline{\Lambda}_b$

Light Mediator Model



- further increase of antihelium flux e.g. in mediator-models

Experimental Prospects

- measurement of $\bar{\Lambda}_b \to \overline{\mathrm{He}}$ within LHC reach

  $\sigma(\mathrm{pp} \to \bar{\Lambda}_b \to \overline{\mathrm{He}}) \sim \mathcal{O}(0.1\ \mathrm{nb})$

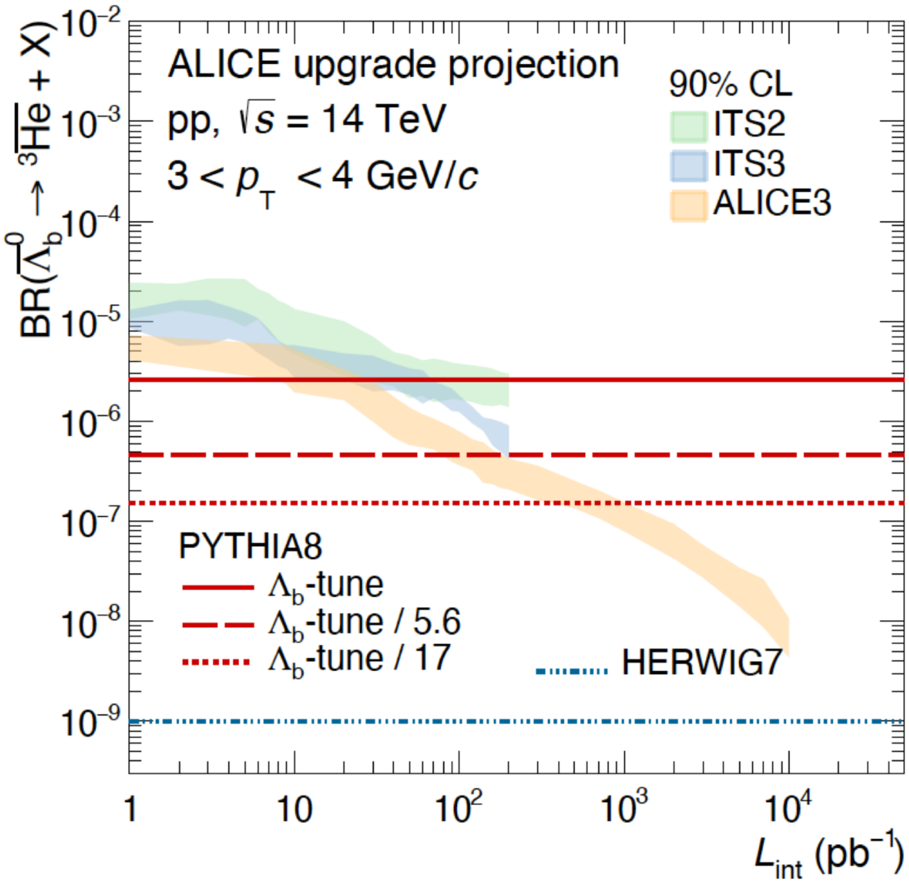
- inclusive search for (displaced) $\overline{\text{He}}$-production

  ▶ **ALICE**

- exclusive modes could provide distinct signatures

  $\bar{\Lambda}_b \to \overline{\mathrm{He}} + 2\mathrm{p}$

  doubly-charged track + two charged tracks



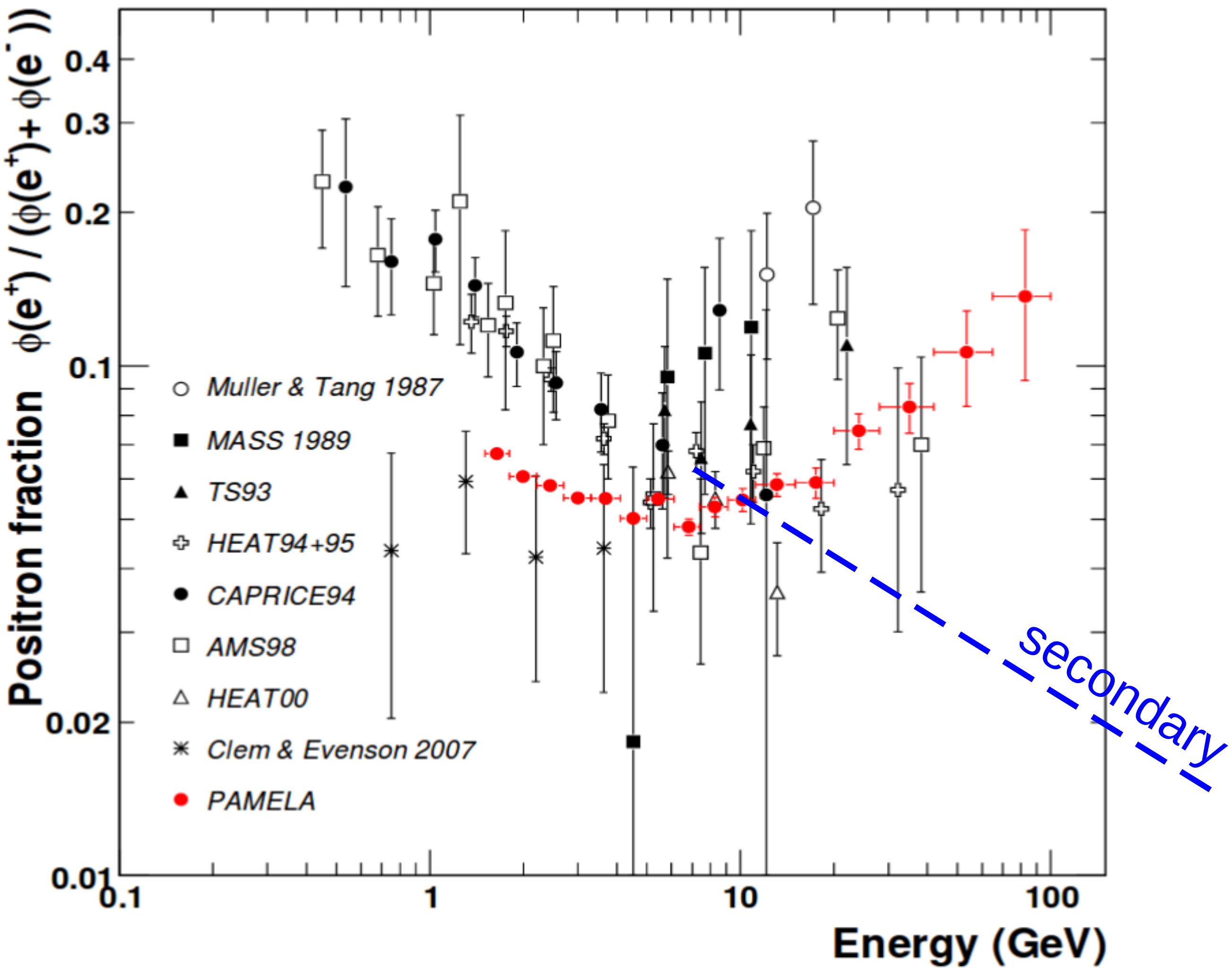
A. Kalweit, CERN ALICE 3 Workshop

Summary

- indirect dark matter searches have reached the sensitivity to probe canonical thermal WIMPs
- hadronic cross sections are the key uncertainty in cosmic ray studies, but progress on theoretical and experimental side
- claimed dark matter signals in the antiproton channel have not substantiated but define an interesting target for the future
- antideuterons can provide smoking-gun evidence for dark matter
- WIMPs can produce an observable antihelium signal due to bottom-baryon decays

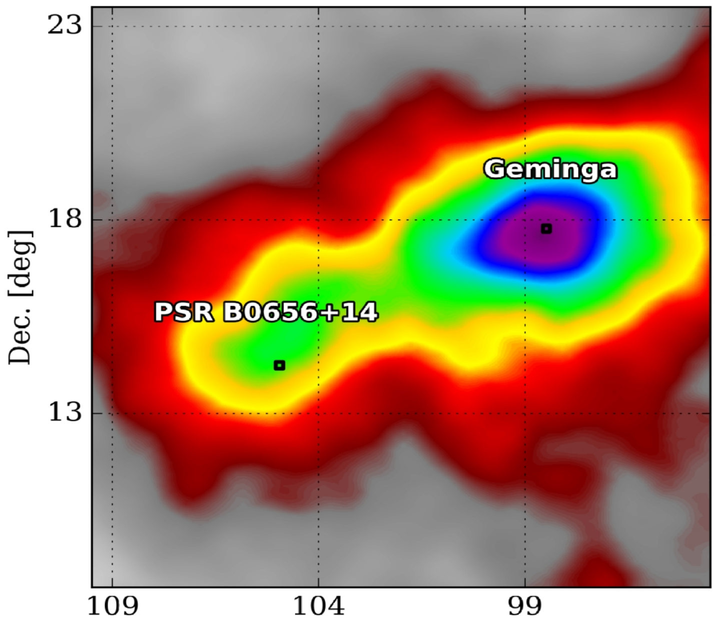
Backup

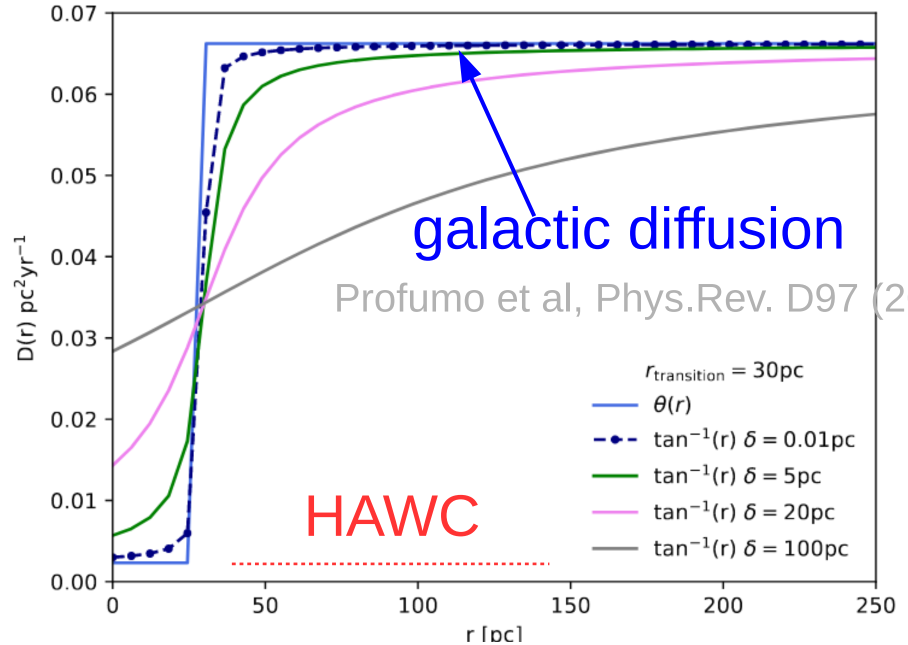
Positrons



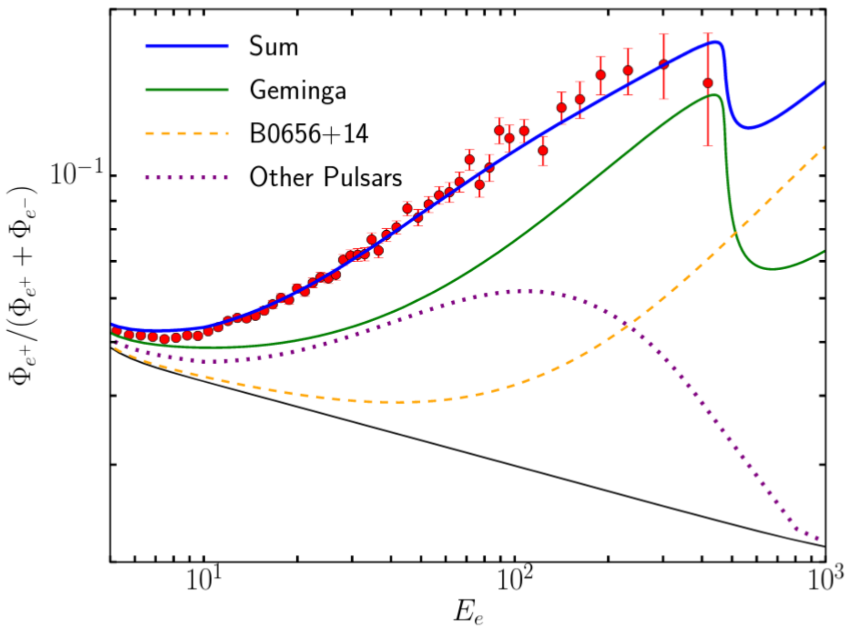
PAMELA, Nature 458 (2009)

Positrons

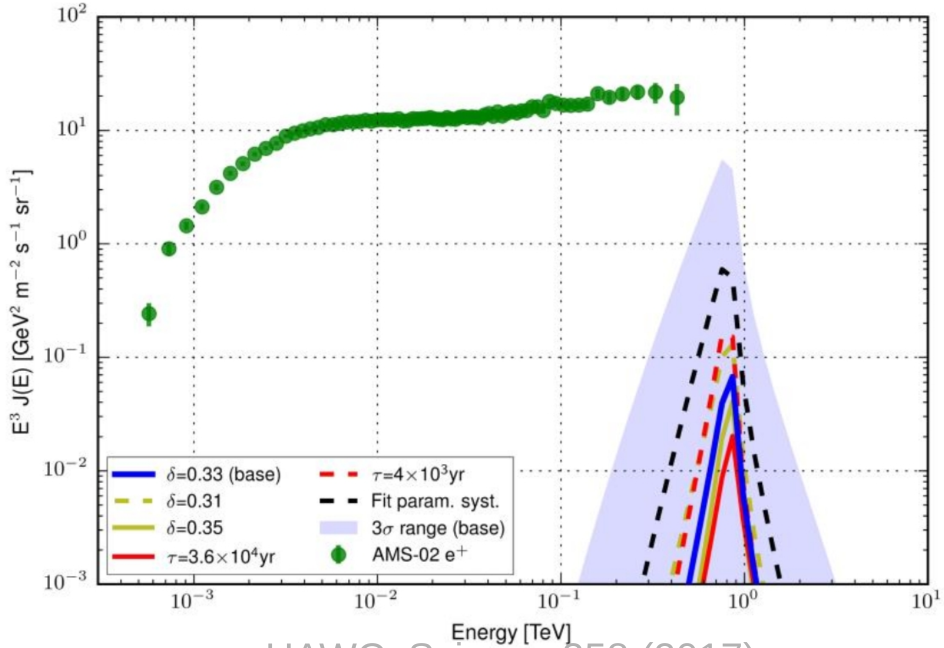




Profumo et al, Phys.Rev. D97 (2018),



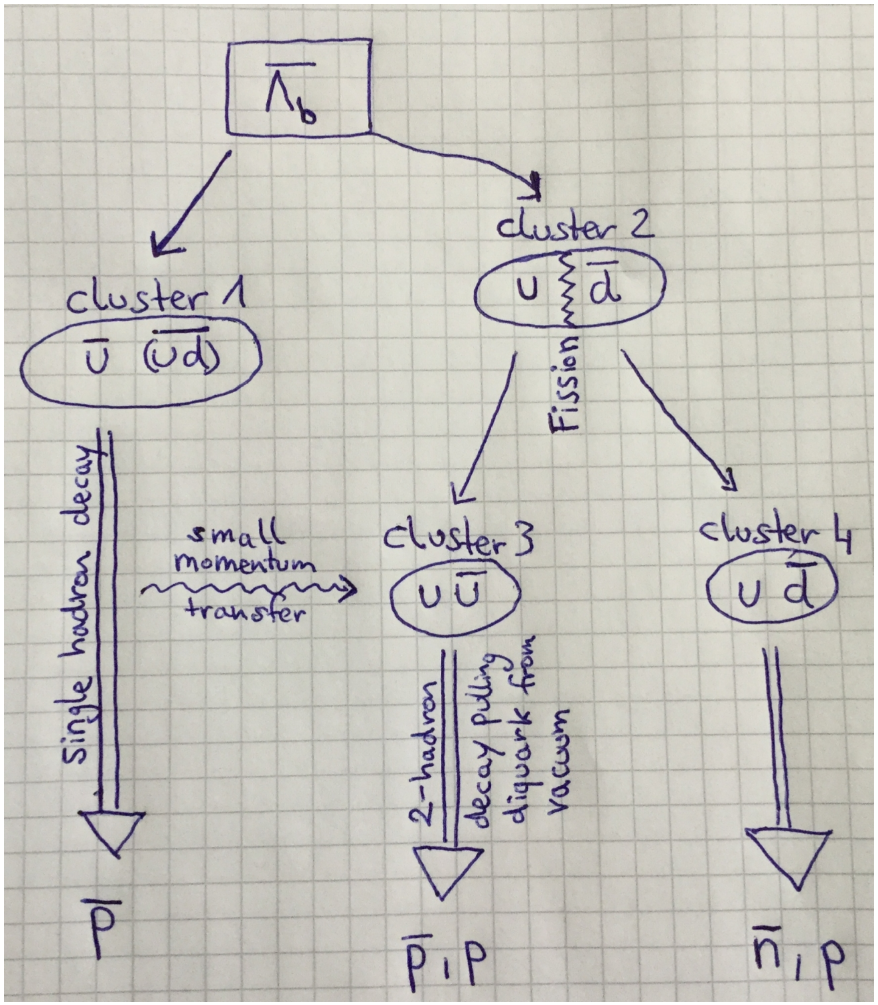
Hooper, Linden, Phys. Rev. D 96 (2017)



HAWC, Science 358 (2017)

Herwig vs. Pythia

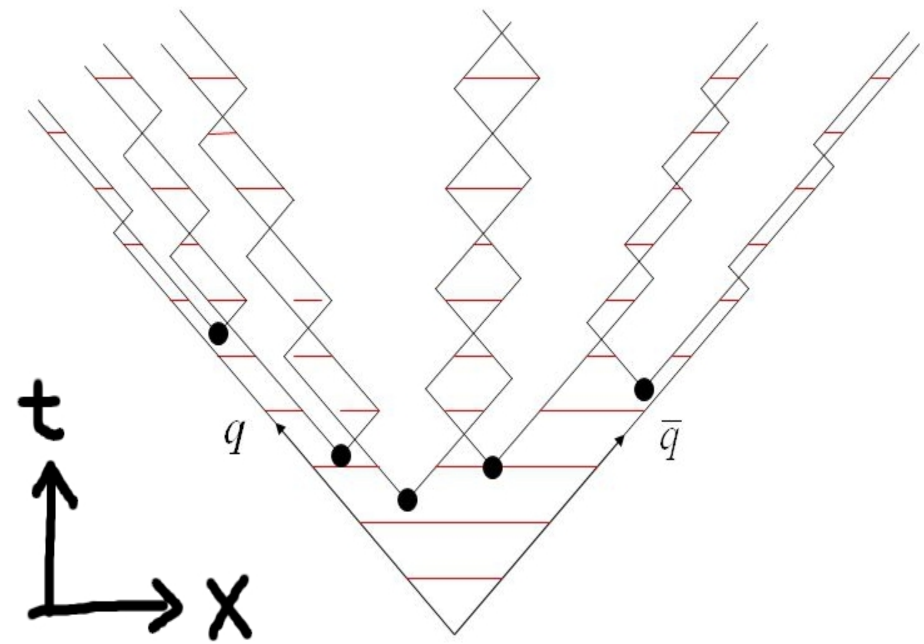
Cluster Hadronization



Herwig

Lund String Model

- Motion of quarks and antiquarks in a $q\bar{q}$ system.



Pythia