Probing dark matter through cosmic-ray antiparticles

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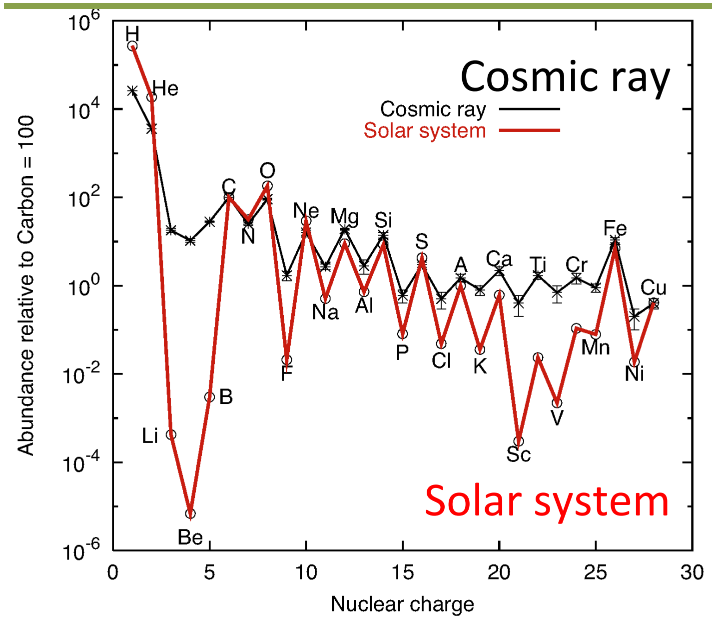
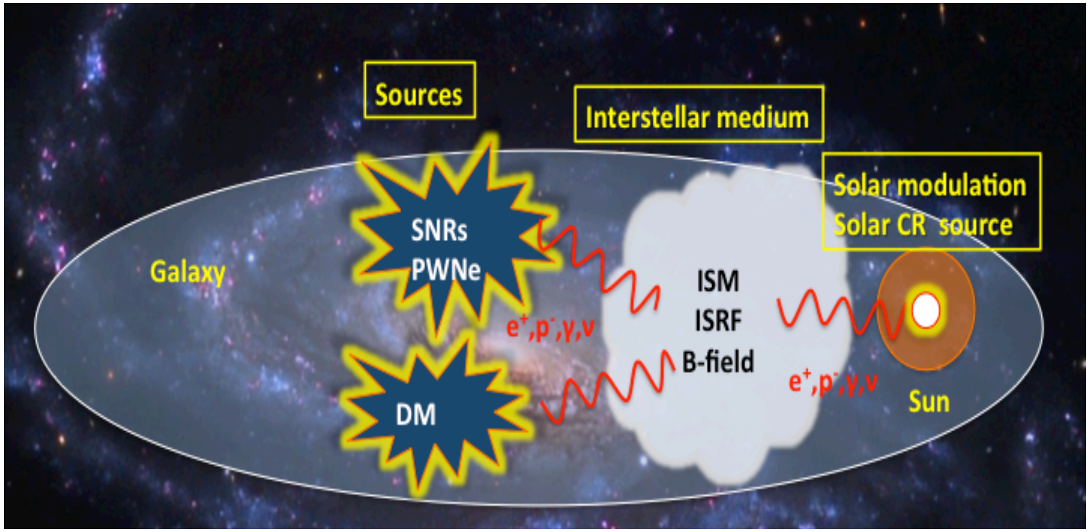
X.J.Huang, C.C.Wei, Wu ,YFZ, W.H. Zhang,1611.01983 PRD
Y.C. Ding, N. Li, C.C.Wei, Y.L.Wu, YFZ, 1808.03612 JCAP
Y.C. Ding, N. Li, C.C.Wei, YFZ, 1908.xxxxx,

2019-08-09, ESI

Introduction: propagation of CRs in the Galaxy



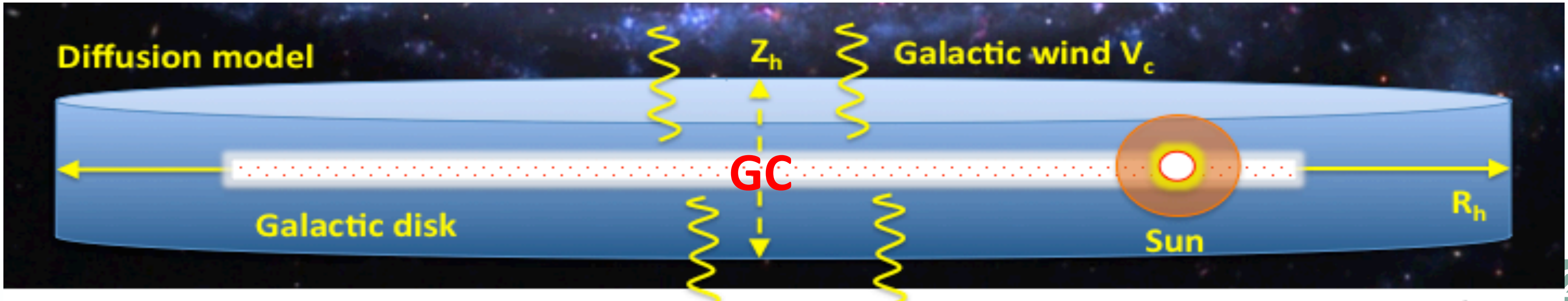


Source of CRs: SNRs, PWNe, AGNs, DM …

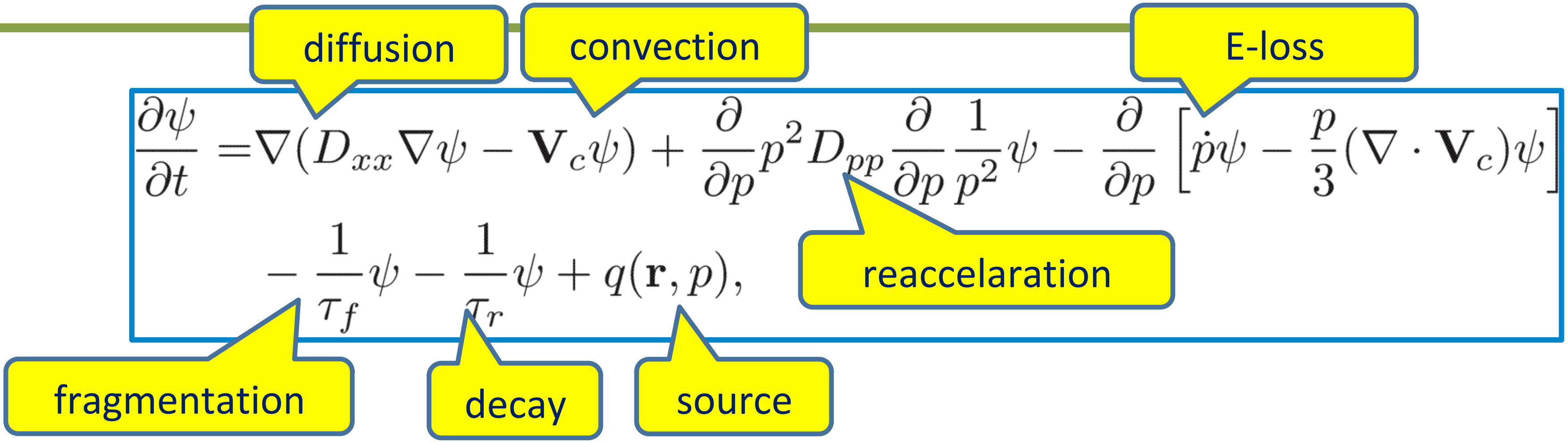
High B/C ratio: CRs trapped in the Galaxy for millions of years! (C+ H→ B+X)

Random magnetic fields: CRs move randomly in the Galaxy

Diffusion approximation: CR diffusion halo: R_h~20 kpc, Z_h~1-5 kpc with isotropic D_{xx}



Cosmic-ray transportation equation



$$\frac{\partial \psi}{\partial t} =\nabla(D_{xx}\nabla\psi - \mathbf{V}_c\psi) + \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{1}{p^2}\psi - \frac{\partial}{\partial p}\left[\dot{p}\psi - \frac{p}{3}(\nabla\cdot\mathbf{V}_c)\psi\right] - \frac{1}{\tau_f}\psi - \frac{1}{\tau_r}\psi + q(\mathbf{r},p),$$

Sources of CRs

- Primary sources from SNR, pulsars
- Primary sources from WIMP
- Secondary source from CR fragmentation

Processes in Propagation

- Diffusion (random B field)
- Convection (galactic wind)
- Reacceleration (turbulence)
- Energy loss: Ionization, IC, Synchrotron, bremsstrahlung
- Fragmentation (inelastic scattering)
- Radioactive decay (unstable species)

Solar modulation

Uncertainties

- Distribution of primary sources
- Parameters in the diffusion equation
- Cross sections for nuclei fragmentation
- Distribution of B field
- Distribution of gas

Approaches

- Semi-analytical:two-zone diffusion model.
- Numerical solution using realistic astrophysical data. GALPROP/Dragon code

Constraining the propagation parameters

Standard approach: B/C+ ^{10}Be/^{9}Be

pros: B/C source independent, only constrain D_0/Z_h,

^{10}Be: τ_{Be10} =1.4 Myr, sensitive to D_0 only, break the D_0/Z_h degeneracy

corns**:** lower precision ^{10}Be/^{9}Be data (from ACE, ISOMAX)

data come from different exps., different solar activity periods,

Alternative approach: B/C + Proton

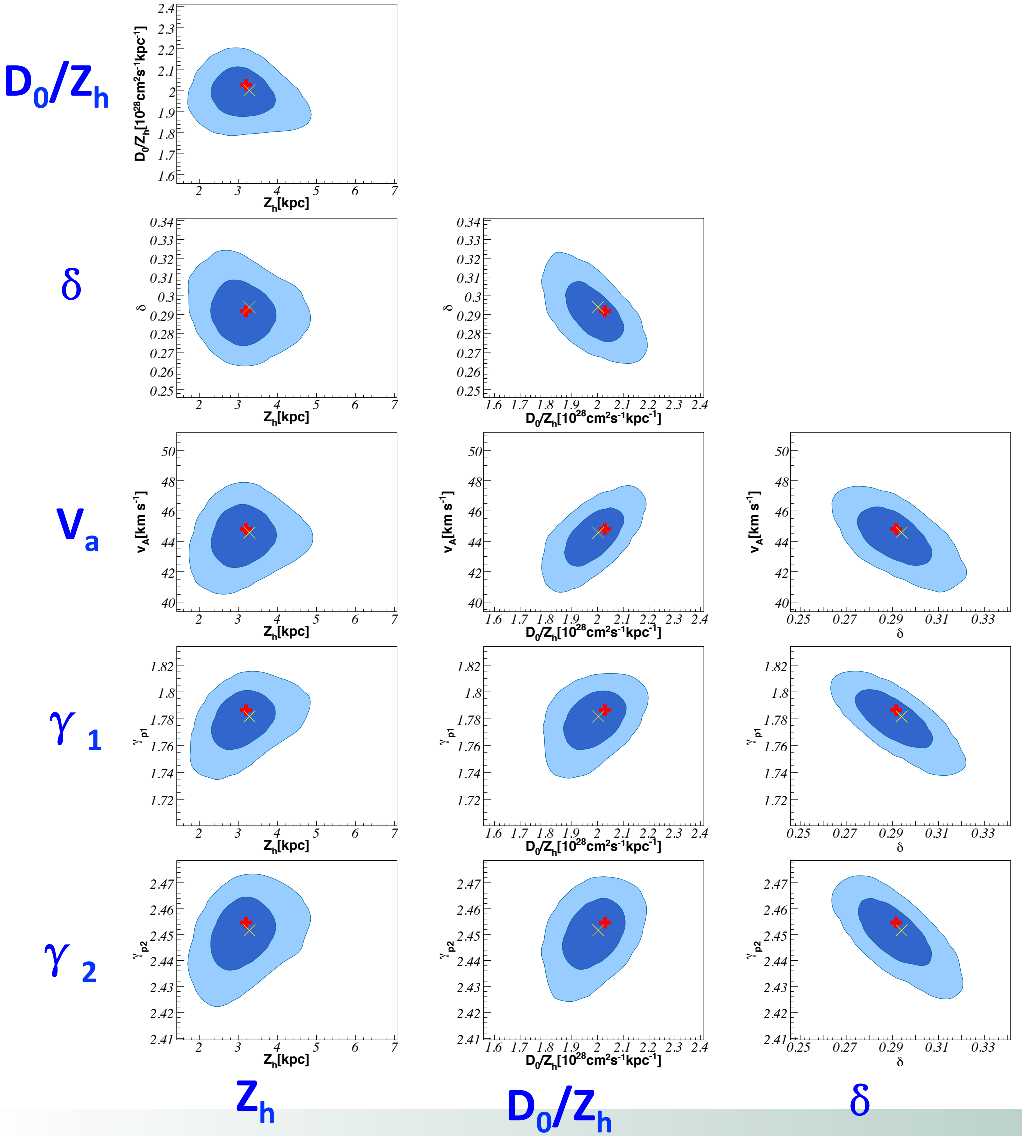
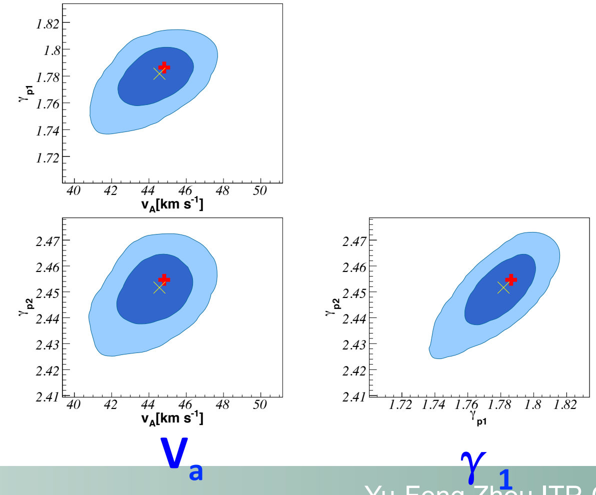
H.B.Jin, Y.L.Wu, YFZ, arXiv:1410.0171,JCAP

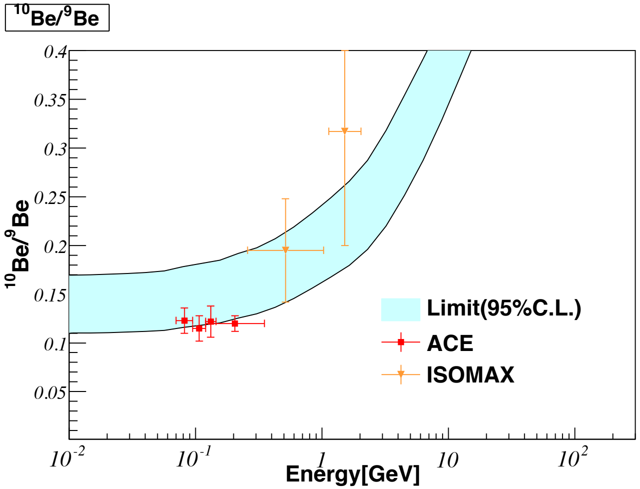
- B/C + Proton forms a complete set for determining all the propagation parameters.
- Both have been measured by AMS-02
  - Very precisely measured
  - Avoiding combination of syst. errors in different experiments
  - All data from the same period, easy to model solar modulation effects

Determination of propagation parameters: B/C + Proton

MCMC fit to AMS-02 B/C and proton spectrum

H.B.Jin, Y.L.Wu, YFZ, arXiv:1410.0171,JCAP

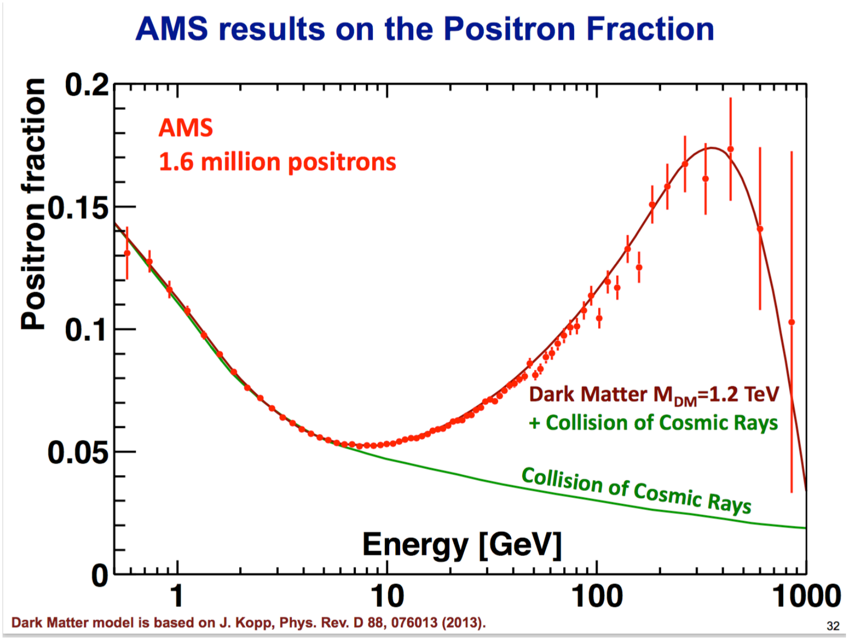





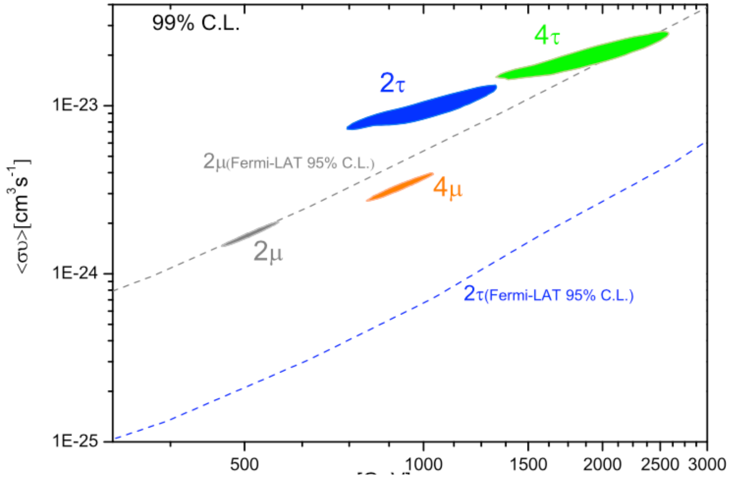
^{10}Be/^{9}Be correctly reproduced

CR electrons and positrons

The CR positron anomaly: DM interpretations



Dark Matter model is based on J. Kopp, Phys. Rev. D 88, 076013 (2013).



H.B.Jin, Y.L.Wu, YFZ,1410.0171,JCAP

Implications for DM annihilation

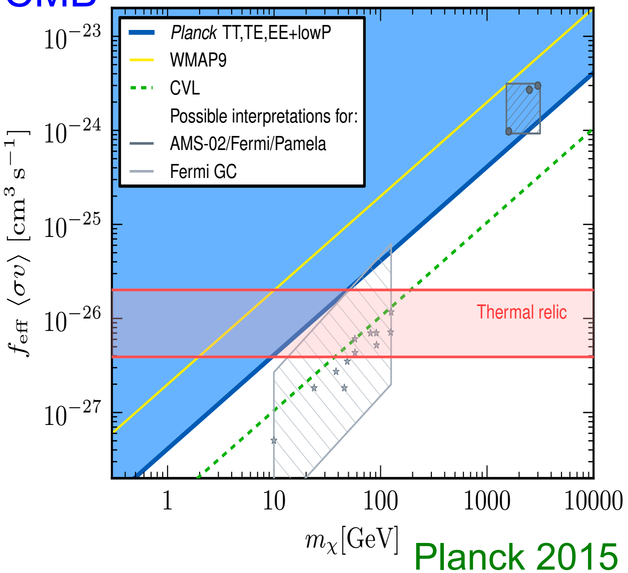
- ■ large DM mass (~0.5-1 TeV)
- ■ large annihilation cross-section ~100-1000 times larger than the typical thermal DM cross section.
  Sommerfeld enhancement
  Resonance enhancement
- ■ annihilate/decay dominantly to leptons, *not* quarks
  Annihilation through light mediators

Challenge: usually predict too many photons, in contradiction with gamma-ray observations from dwarf galaxies, GC and isotropic background

Require complicated velocity-dependence of DM annihilation cross section

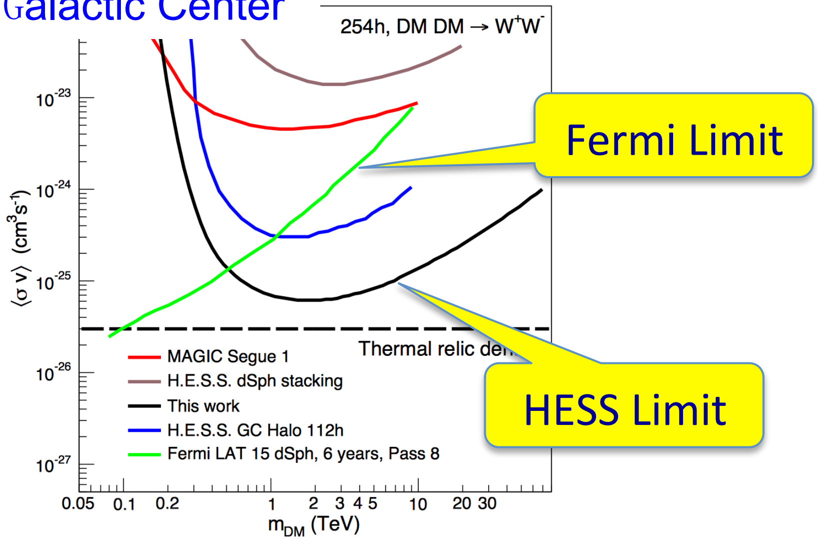
Gamma-ray /CMB constraints on DM annihilation

CMB



Planck 2015

Galactic Center

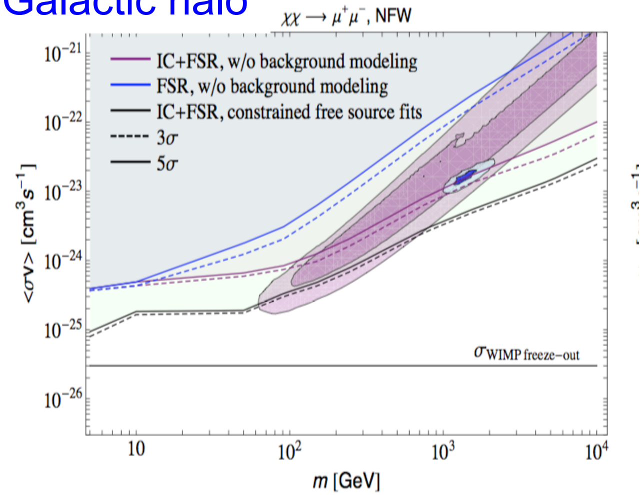


Fermi Limit

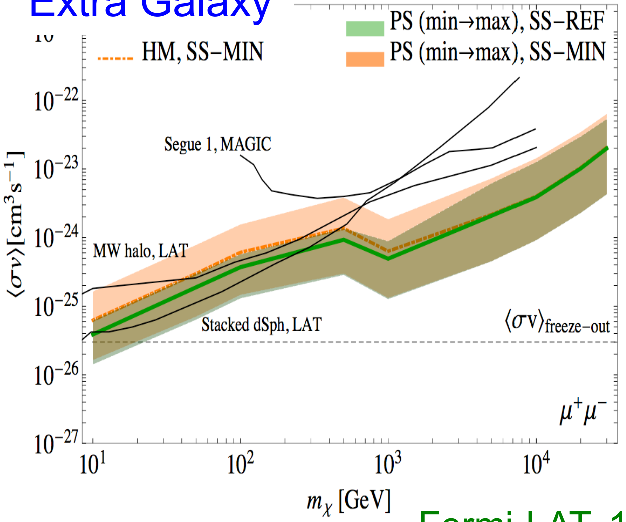
HESS Limit

HESS 2016

Galactic halo



Extra Galaxy



Fermi-LAT, 1205.6467

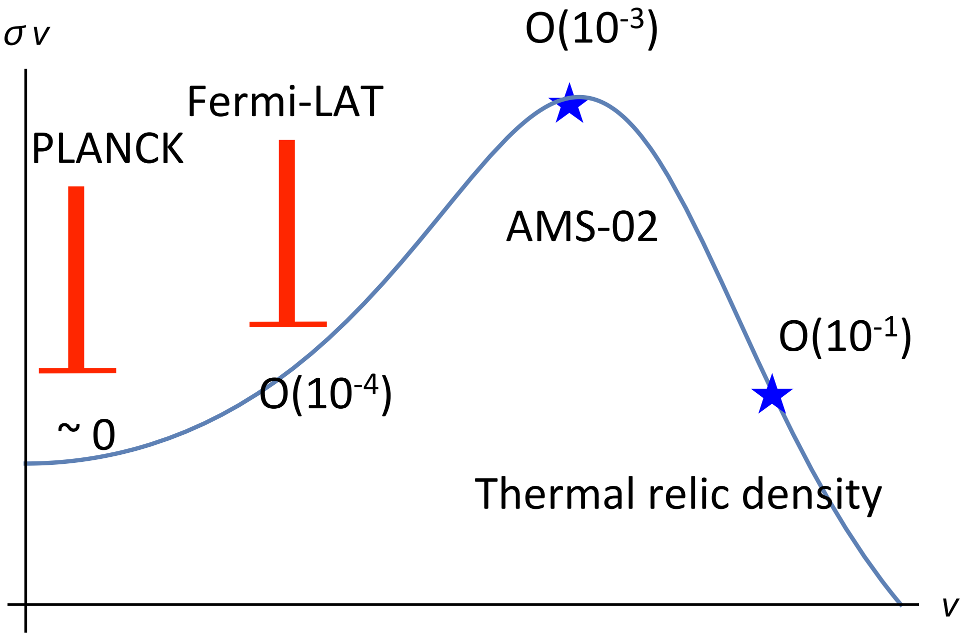
Fermi-LAT, 1501.05464

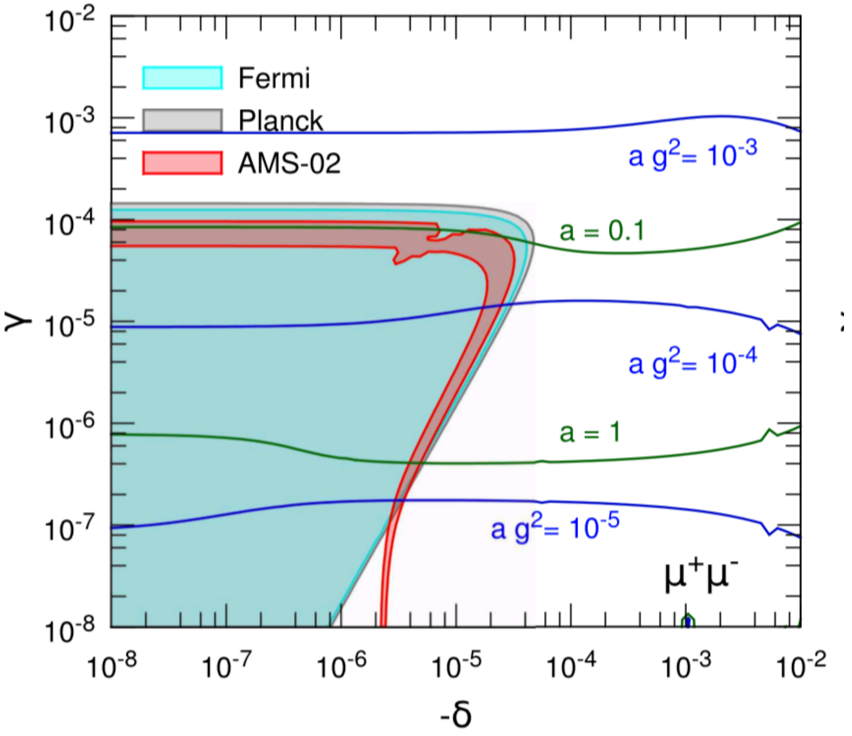
Models consistent with AMS-02, DM density, PLANK, Fermi-LAT?

Eg. DM annihilating through resonance Q.F. Xiang, X.J. Bi, S.J. Lin, P.F. Yin, 1707.09313

$$\sigma v \propto \frac{1}{16\pi m_\chi^2}\frac{1}{(\delta + v^2/4)^2 + \gamma^2}$$

With delta <0



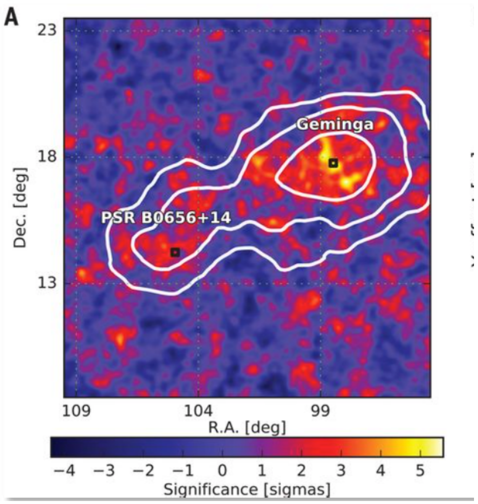


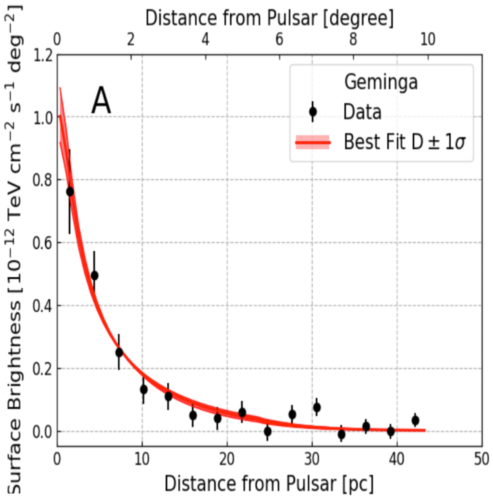
Require very fine-tuned parameters

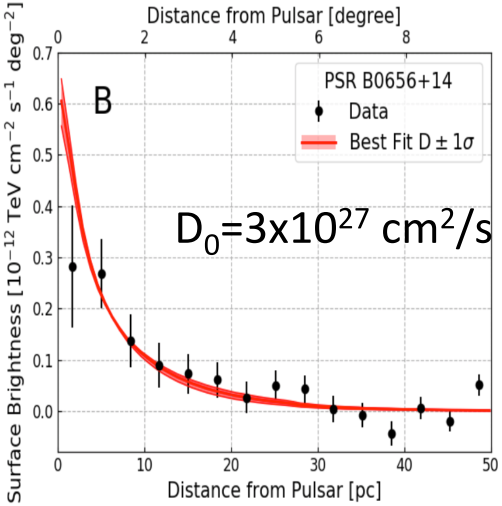
(a)$\mu^+\mu^-$ channel.

Pulsar interpretations: new challenges from HAWC

HAWC show slow diffusion of electrons from Geminga and PSR B0656+14

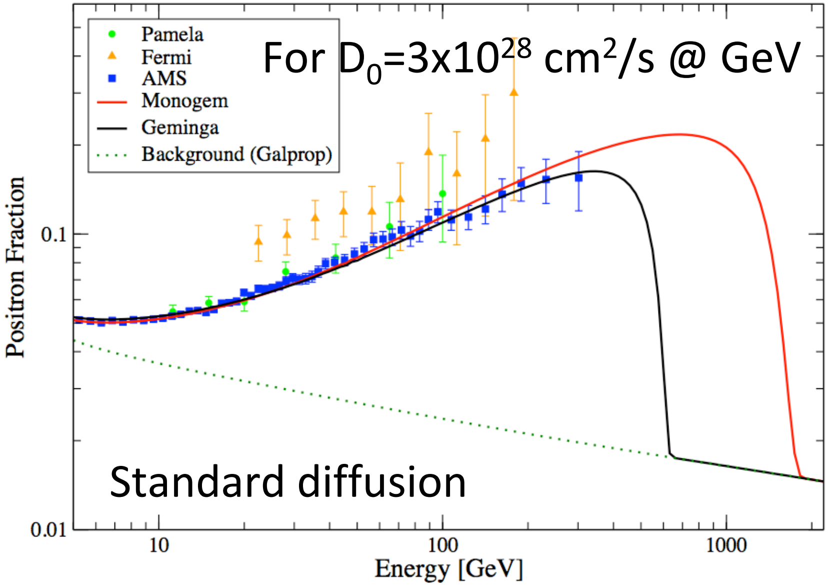






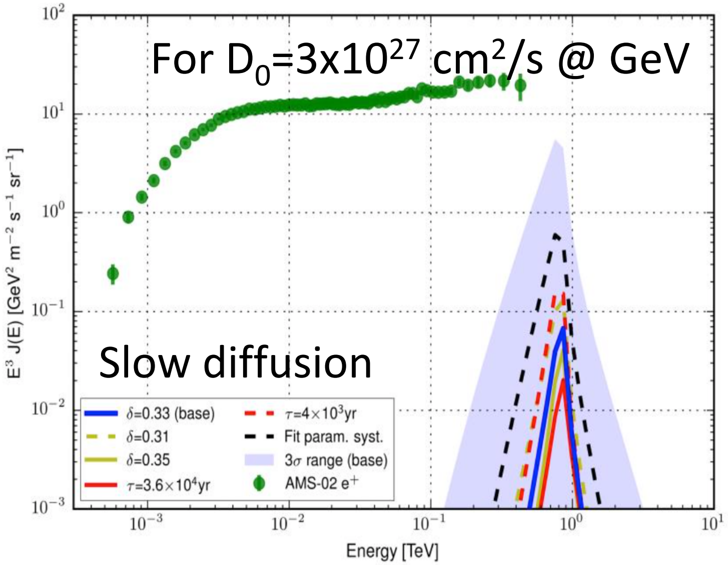
$D_0=3x10^{27}$ cm^2/s @ GeV

HAWC, 1711.06223



For $D_0=3x10^{28}$ cm^2/s @ GeV

Standard diffusion



For $D_0=3x10^{27}$ cm^2/s @ GeV

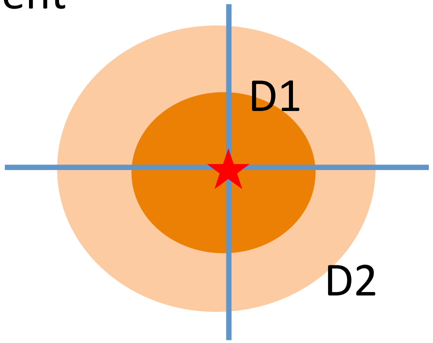
Slow diffusion

Toy models: two-zone model

Slow diffusion is likely to be a local phenomena, (as 20 TeV electrons observed by HESS)

PWNe observed by HAWC may have different local enviroment

The Two-zone model

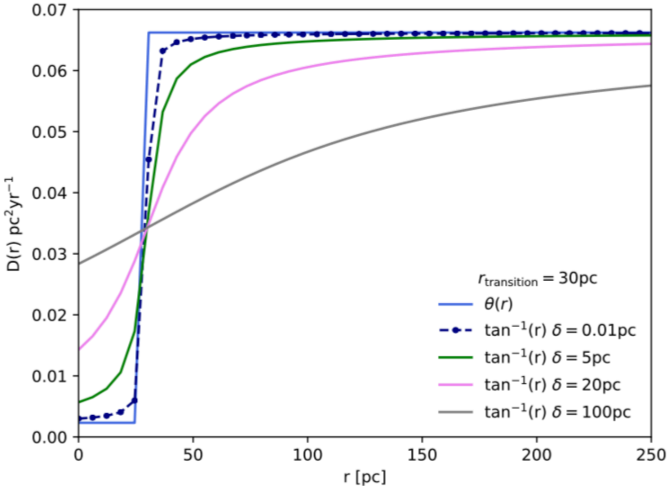


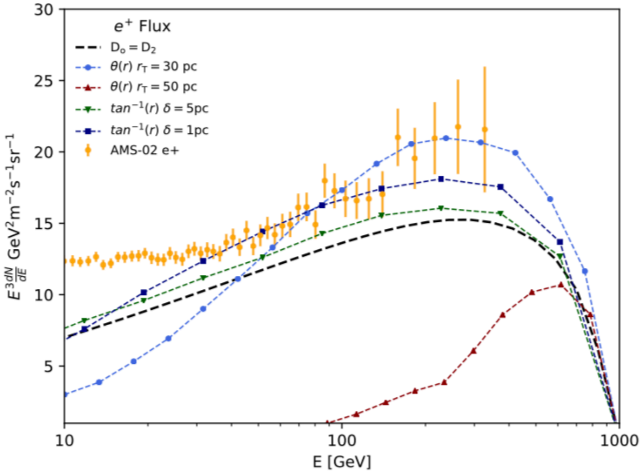
D1<<D2

Geminga

$$D_\theta(r) = D_1\theta(r_T - r) + D_2\theta(r - r_T) \qquad (10a)$$

$$D_{\rm T}(r) = D_1 + \frac{(D_2 - D_1)}{\pi}\left(\tan^{-1}\left(\frac{\rm r - r_T}{\delta}\right) + \frac{\pi}{2}\right), \qquad (10b)$$





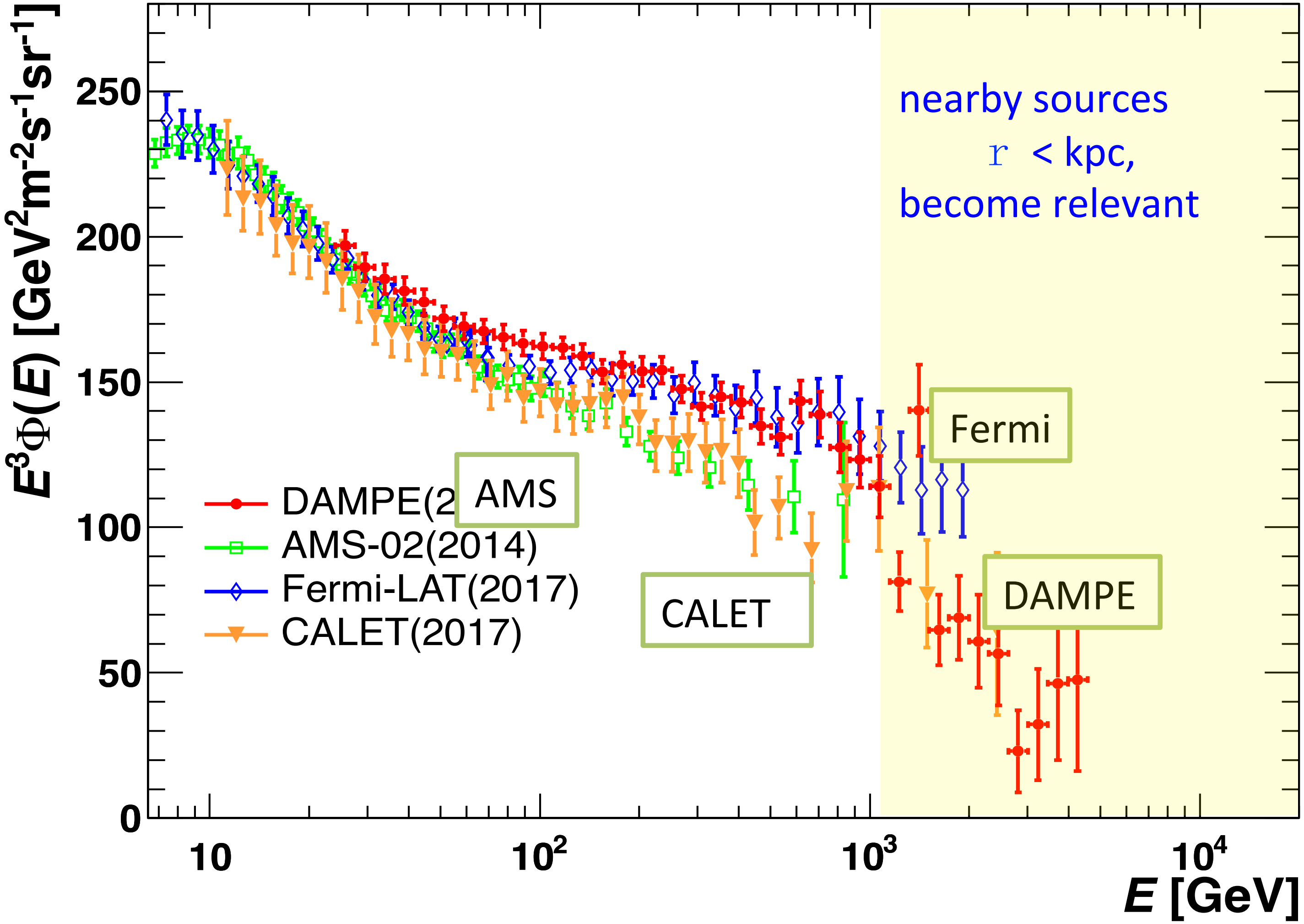
Hooper, et al., 1711.07482

Profumo, et al., 1083.09731

K.Fang, et al., 1803.02640

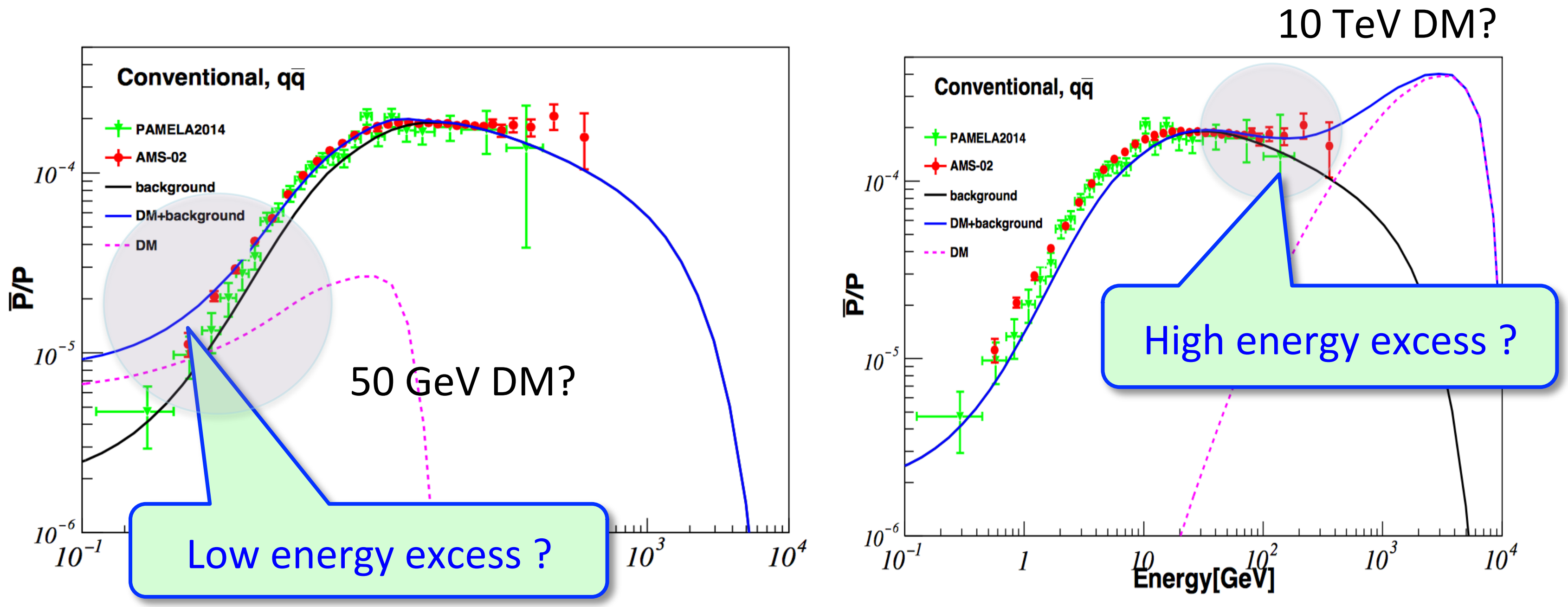
The CR all-electron flux ($e^+ + e^-$)

Fermi-LAT, AMS-02, CALET, DAMPE, not in full agreement



CR antiprotons

Small deviations and DM interpretations



10 TeV DM?

50 GeV DM?

Low energy excess ?

High energy excess ?

H.B.Jin, Y.L.Wu, YFZ arXiv:1504.04601, PRD

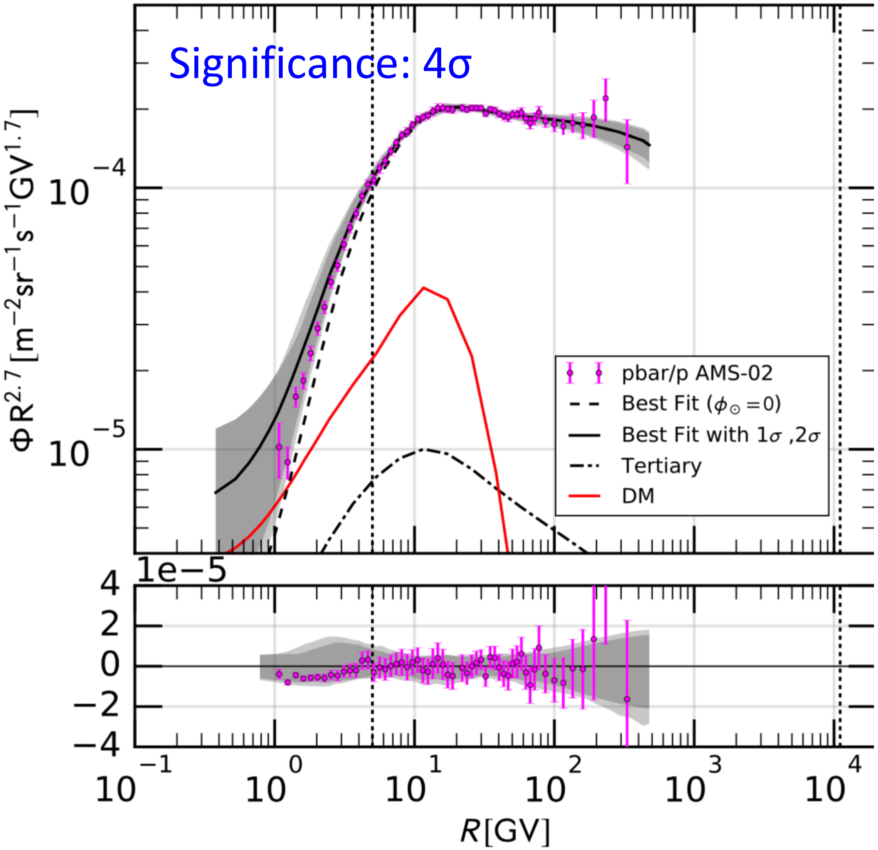
Low-energy excess: 40-50 GeV DM to 2b, thermal cross section, consistent with GC
High-energy excess: 10 TeV DM annihilation into 2W, 2b, boost factor ~10-100

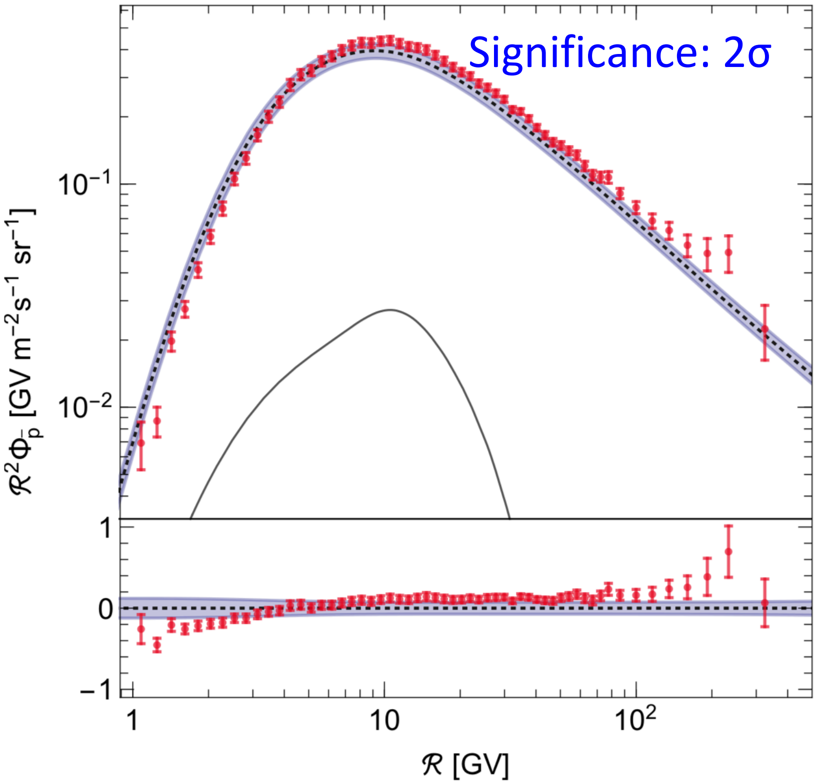
Giesen, 1504.04276; Ibe 1504.05554;
Hamaguchi, 1404.05937; Lin, 1504.07230
Chen, 1504.07848; Chen,1505.00134

In general, DM induced fluxes are in general quite smooth

The Low-energy “excess” ?

Still under debate …


Significance: 4σ


Significance: 2σ

Uncertainties are significant, but strongly correlated.

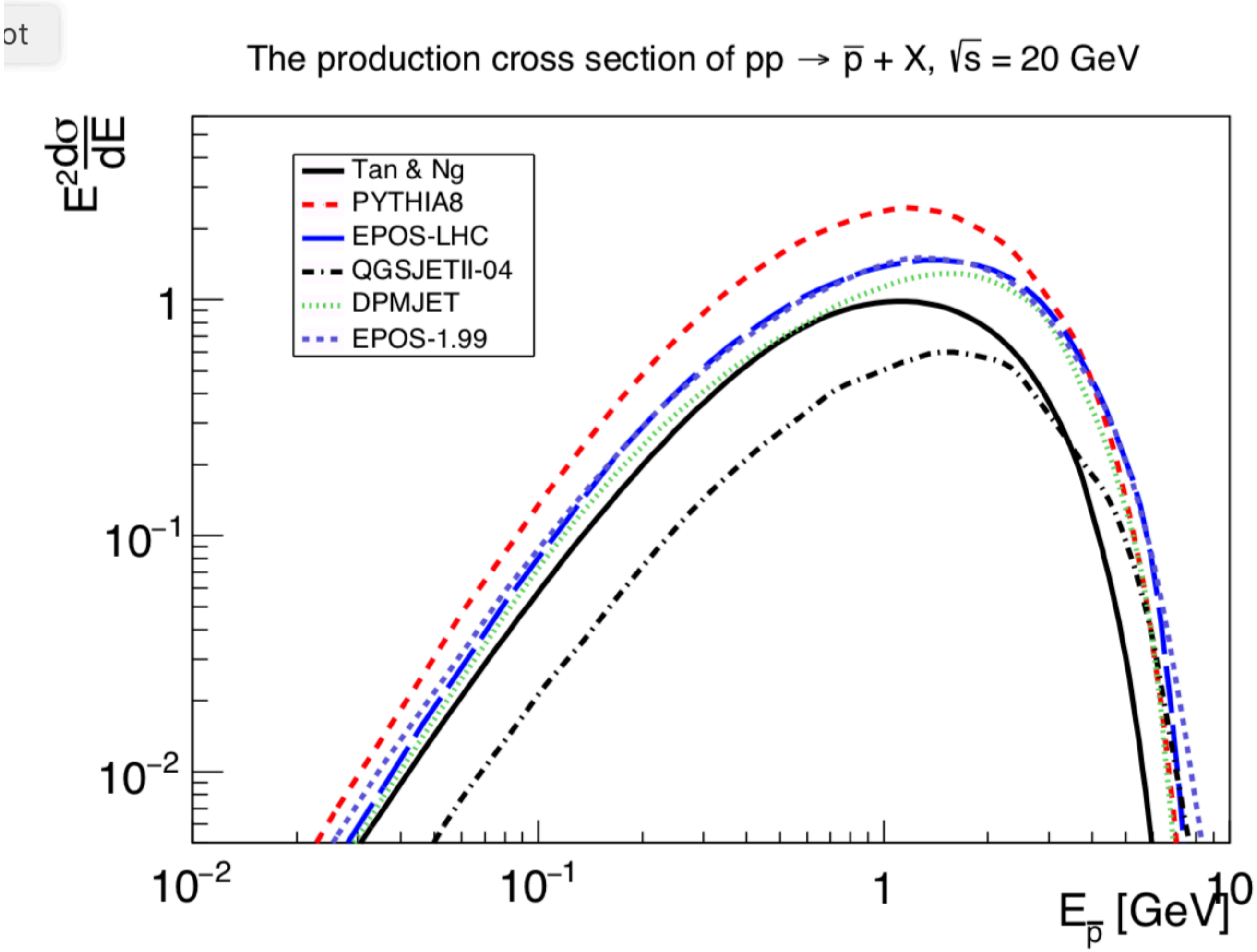
Different in treatment of : CR propagation, cross-sections, solar-modulation

Cuoco et al.,1610.03071; Cui, et al., 1610.03840
Cuoco et al.,1903.01472; Cholis et al., 1093.02549

Reinert, Winkler, 1712.00002
Lin, et al., 1093.09545

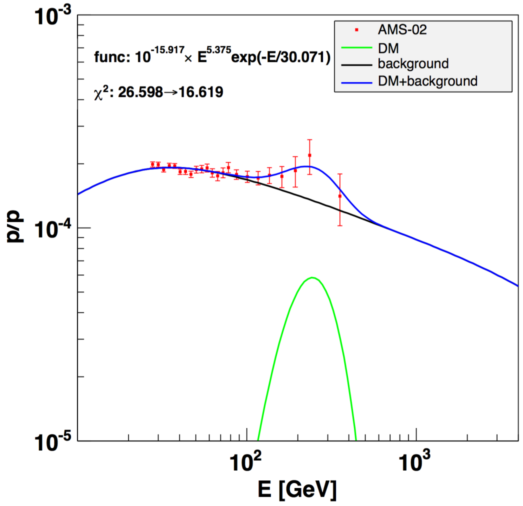
Theoretical uncertainties: cross sections

antiproton production cross-sections from different approaches

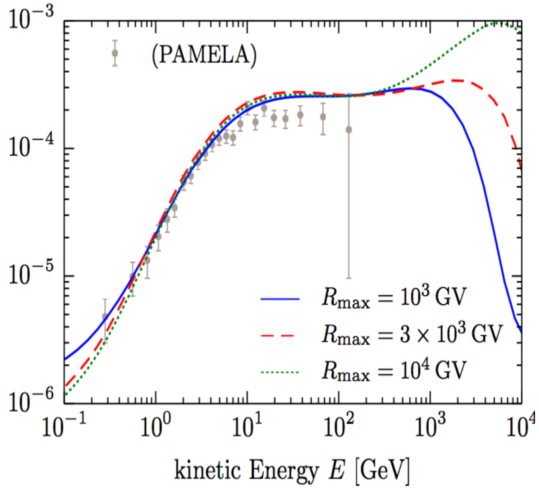


Y.C. Ding, N. Li, YFZ, arXiv:1908.xxxxx

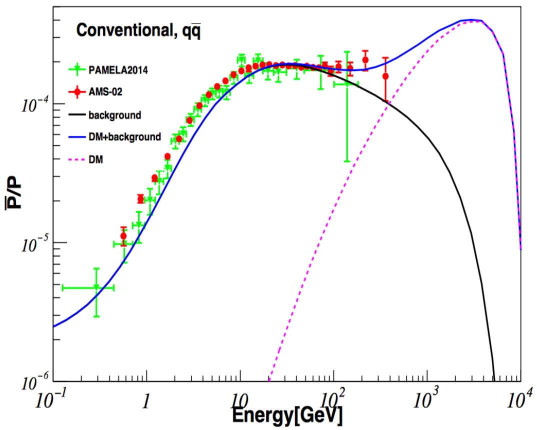
The high-energy “excess ”: origins of a rising pbar spectrum



Parametrization
(power-law with a cut off)



Secondaries in SNRs

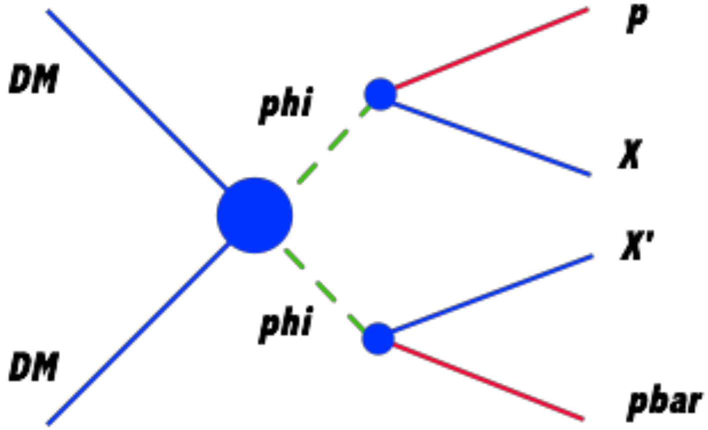


DM

Implications

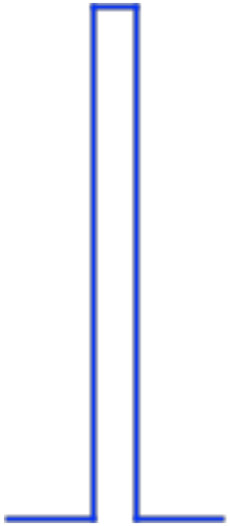
- Fit with a power law spectrum (with a cut off) , typical significance ~3σ
- Pulsars *cannot* produce energetic antiprotons.
- SNRs can produce secondary antiprotons but with a flat (or smooth rising) spectrum.
- DM direct annihilation (DM DM→f fbar→pbar +X) predicts a broad bump, too smooth to explain narrow excess.

A sharp spectrum from four-body annihilation



Lorentz boost for finite ϵ_0

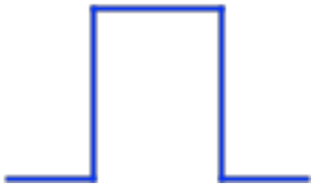
When $\phi \approx 2m_p$ small β'



Lorentz Boost

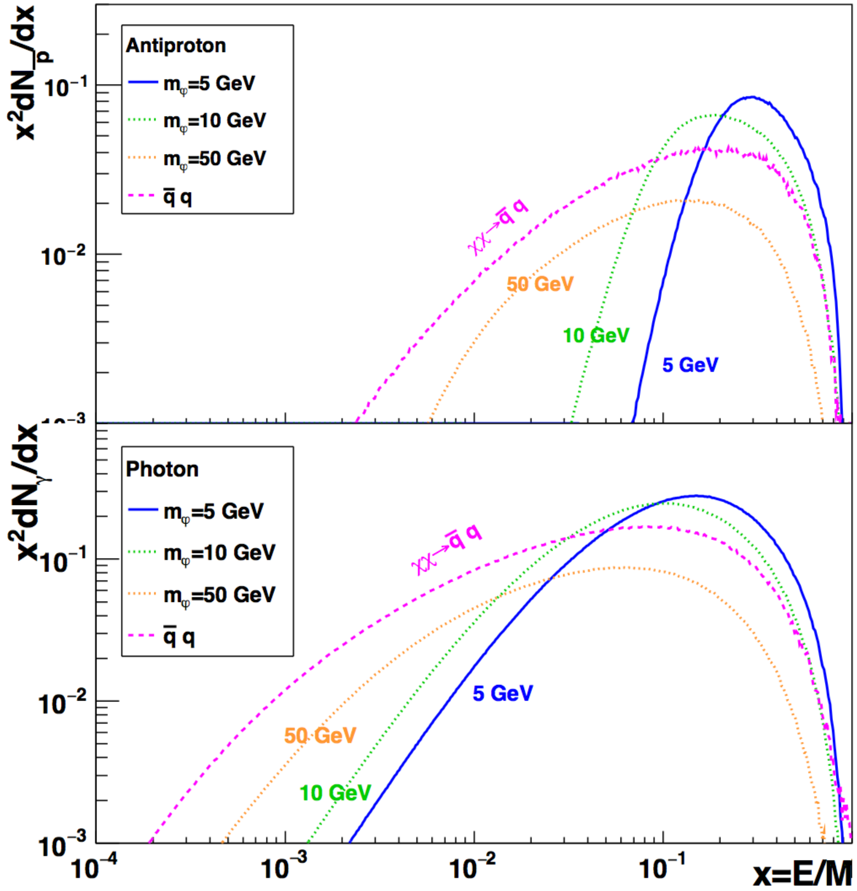
$$E = \gamma_B E'$$

$$\Delta E/E = 2\beta_B \beta'$$



ϕ rest-frame DM CM frame

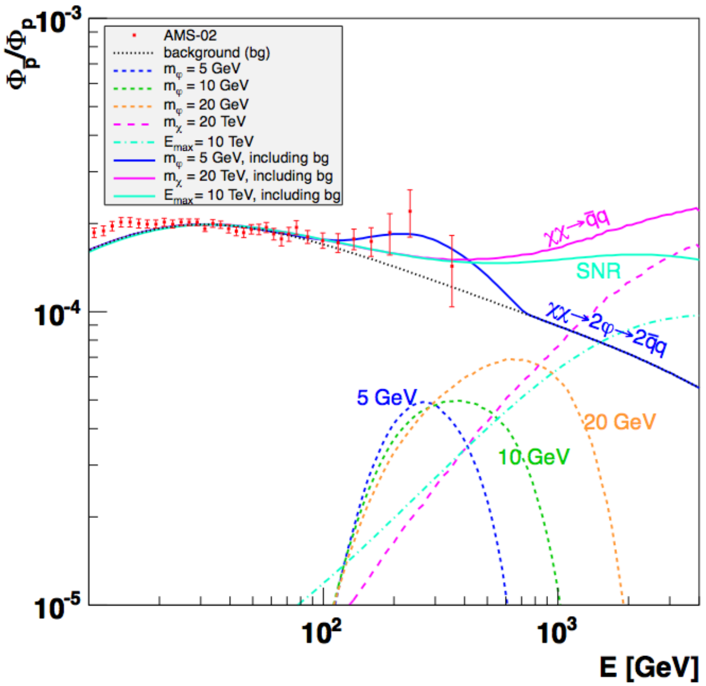
Sharp antiproton spectrum arise in the threshold limit



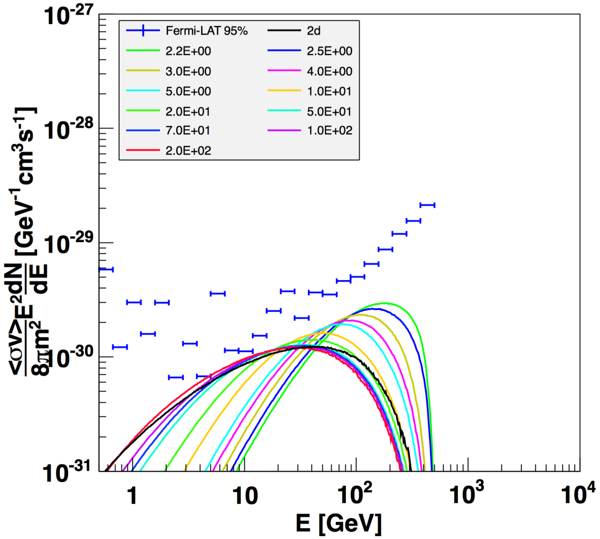
Huang, Wei, Wu ,YFZ, Zhang,1611.01983,PRD

Consistency with the Fermi-LAT gamma-ray data

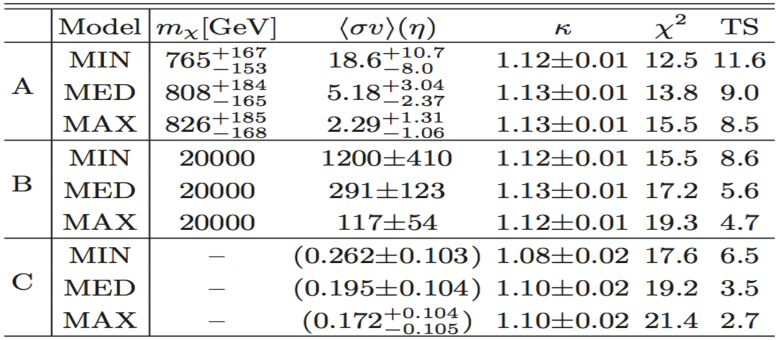
Light mediator scenario can explain the structure without violating the Fermi gamma-ray limits



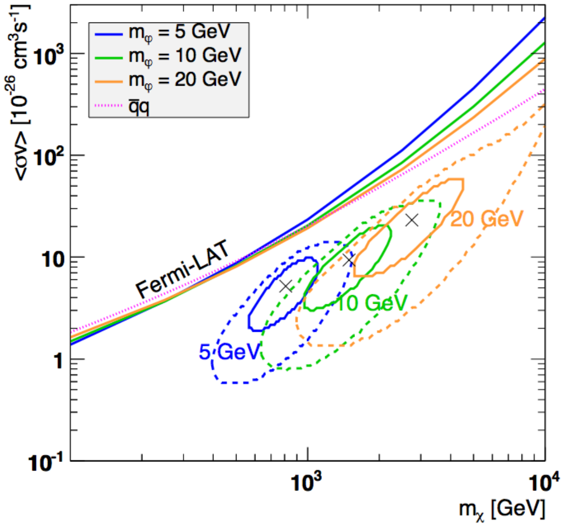
Fermi gamma-ray limits



Favored DM mass ~800 GeV with thermal cross section



	Model	m_χ[GeV]	$\langle\sigma v\rangle(\eta)$	κ	χ^2	TS
A	MIN	765^{+167}_{-153}	$18.6^{+10.7}_{-8.0}$	1.12±0.01	12.5	11.6
	MED	808^{+184}_{-165}	$5.18^{+3.04}_{-2.37}$	1.13±0.01	13.8	9.0
	MAX	826^{+185}_{-168}	$2.29^{+1.31}_{-1.06}$	1.13±0.01	15.5	8.5
B	MIN	20000	1200±410	1.12±0.01	15.5	8.6
	MED	20000	291±123	1.13±0.01	17.2	5.6
	MAX	20000	117±54	1.12±0.01	19.3	4.7
C	MIN	–	(0.262±0.103)	1.08±0.02	17.6	6.5
	MED	–	(0.195±0.104)	1.10±0.02	19.2	3.5
	MAX	–	$(0.172^{+0.104}_{-0.105})$	1.10±0.02	21.4	2.7



Huang, Wei, Wu ,YFZ, Zhang,1611.01983,PRD

CR heavy anti-nuclei

CR heavy anti-nuclei

Spectral feature of heavy secondary anti-nuclei

- Highly boosted after production

  production threshold: $17m_p$ (antideuteron), $31m_p$ (antihelium)

  low binding energy → less energy loss

  low-energy window (< GeV/A) for exotic contributions

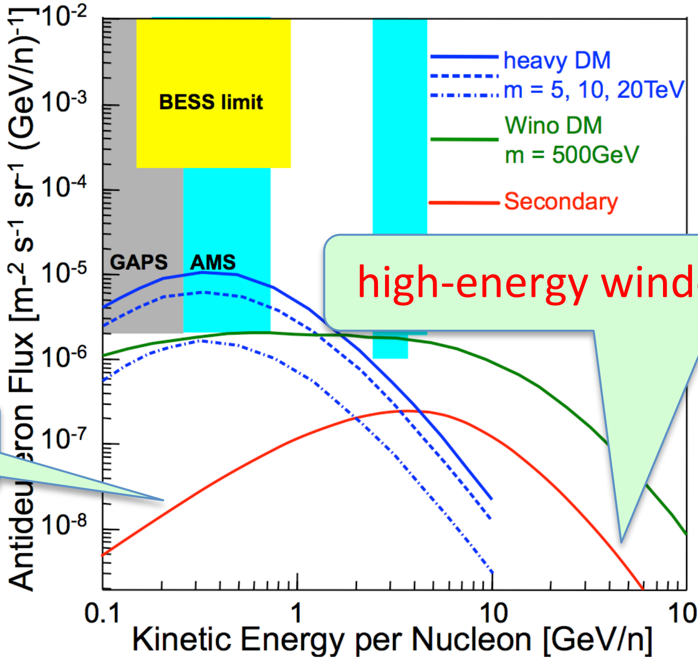
- Low production rate at high energies

  fast falling of primary CRs $\phi(E) \sim E^{-2.7}$

  high-energy window (>100 GeV/A) for exotic contributions

Major sources of theoretical uncertainties

- Models for anti-nuclei formation
  - coalescence models
  - potential models
  - thermal models
- DM profiles (NFW, Einasto, Isothermal, …)
- CR propagation models (MIN, MED, MAX, …)



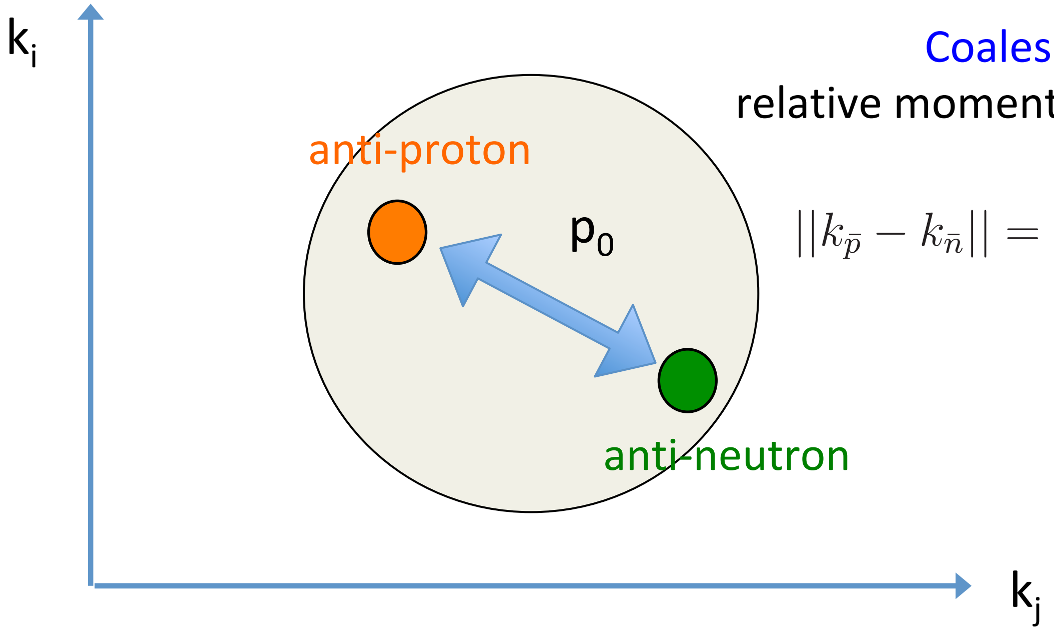
high-energy window

Low-energy window

Aramaki, etal, 1505.07785

The coalescence model

The coalescence model: A=2 case



Coalescence condition:

relative momentum must be small enough

$$||k_{\bar{p}} - k_{\bar{n}}|| = \sqrt{(\Delta\vec{k})^2 - (\Delta E)^2} < p_0^{\overline{\mathrm{D}}},$$

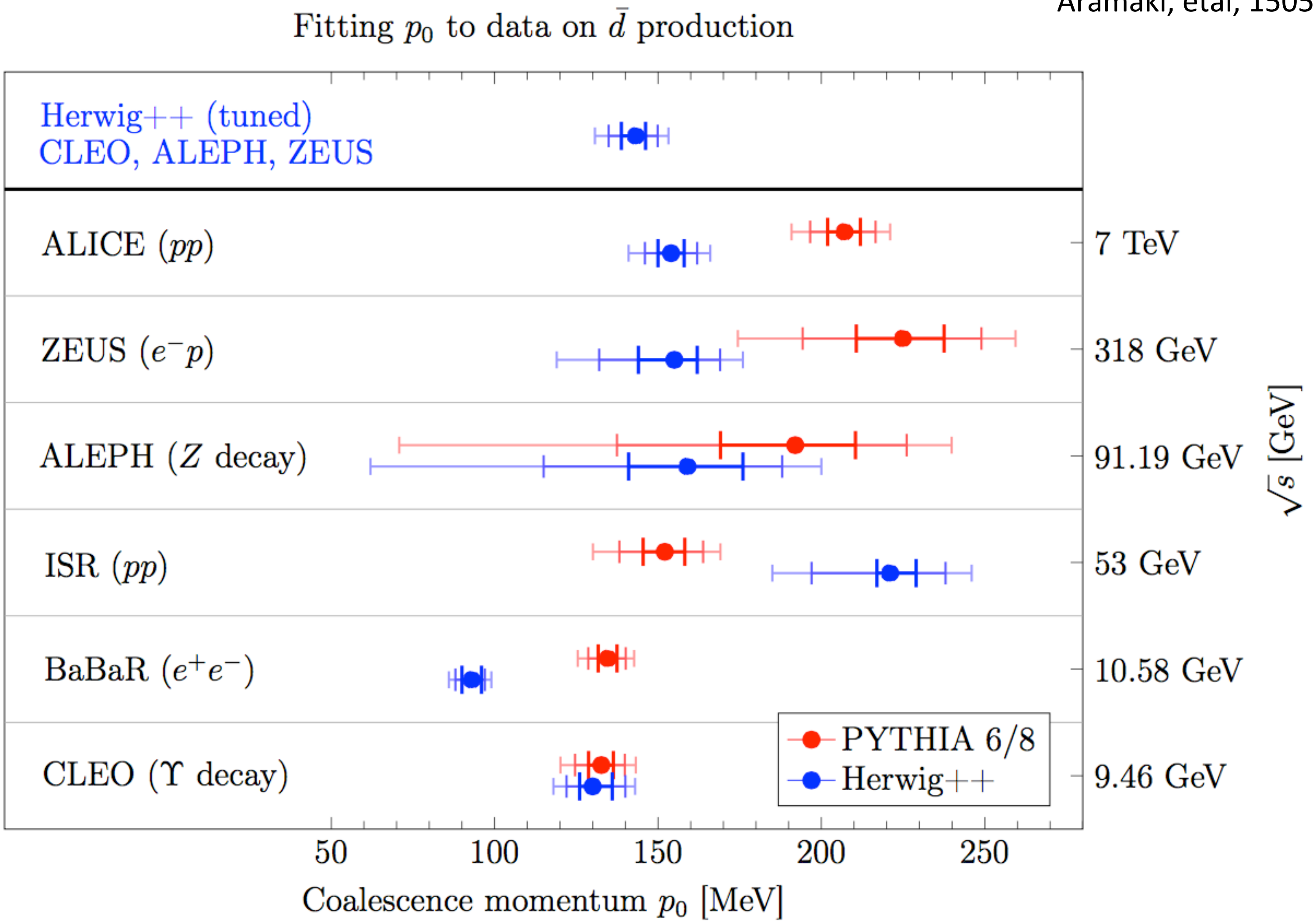
- phase-space model, no dynamics
- extremely simple, only one parameter p_0
- coalescence rate ~ $p_0^{3(A-1)}$, uncertainty in p_0 can be amplified

Energy spectrum of anti-deuteron:

$$\frac{\mathrm{d}N_{\bar{d}}}{\mathrm{d}T_{\bar{d}}} = \frac{p_0^3}{6}\frac{m_{\bar{d}}}{m_{\bar{n}}m_{\bar{p}}}\frac{1}{\sqrt{T_{\bar{d}}^2 + 2m_{\bar{d}}T_{\bar{d}}}}\frac{\mathrm{d}N_{\bar{n}}}{\mathrm{d}T_{\bar{n}}}\frac{\mathrm{d}N_{\bar{p}}}{\mathrm{d}T_{\bar{p}}},$$

Determination of p_0 for anti-deuteron formation

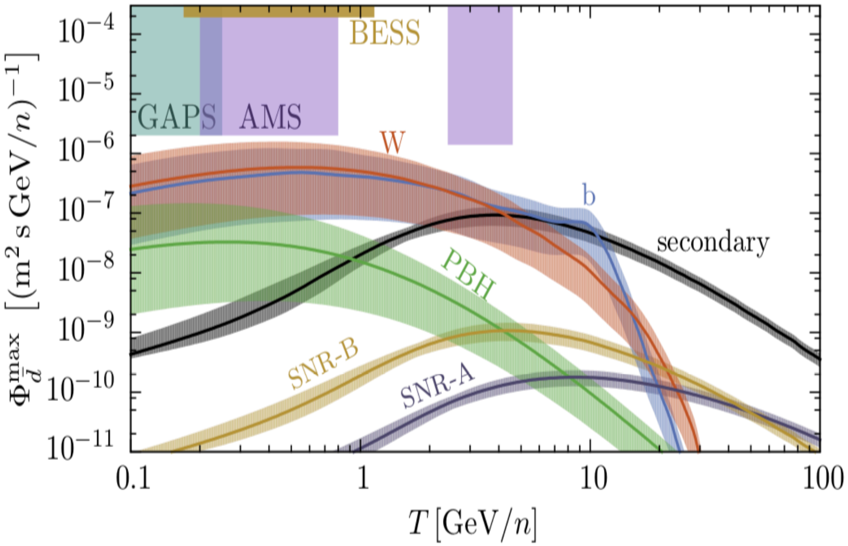
Aramaki, etal, 1505.07785



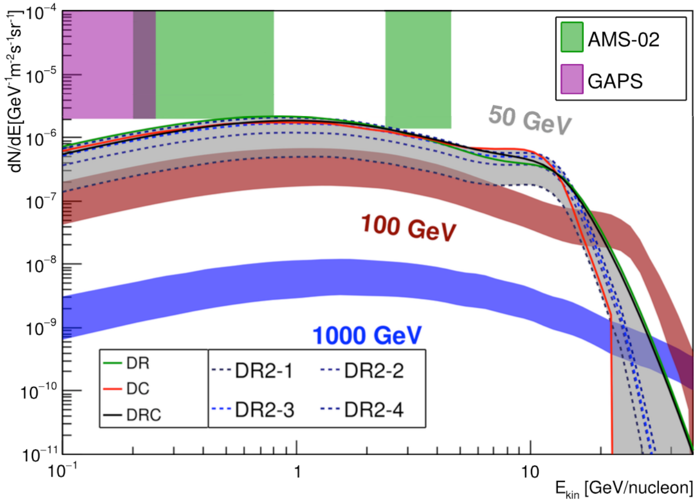
The scale of p_0 ~ 100-250 MeV, depending on processes and hadronizaiton models

CR anti-deuteron and maximal DM contribution

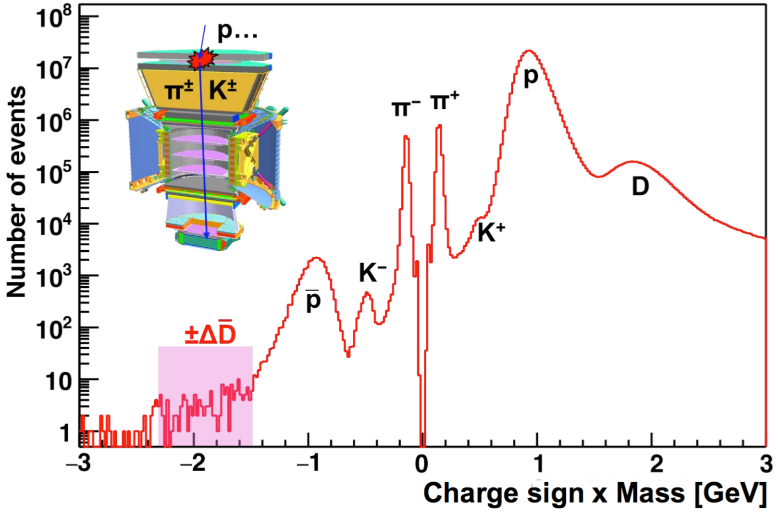
Maximal anti-deuteron flux after constraints from antiproton data



Herms et al, 1610.00699



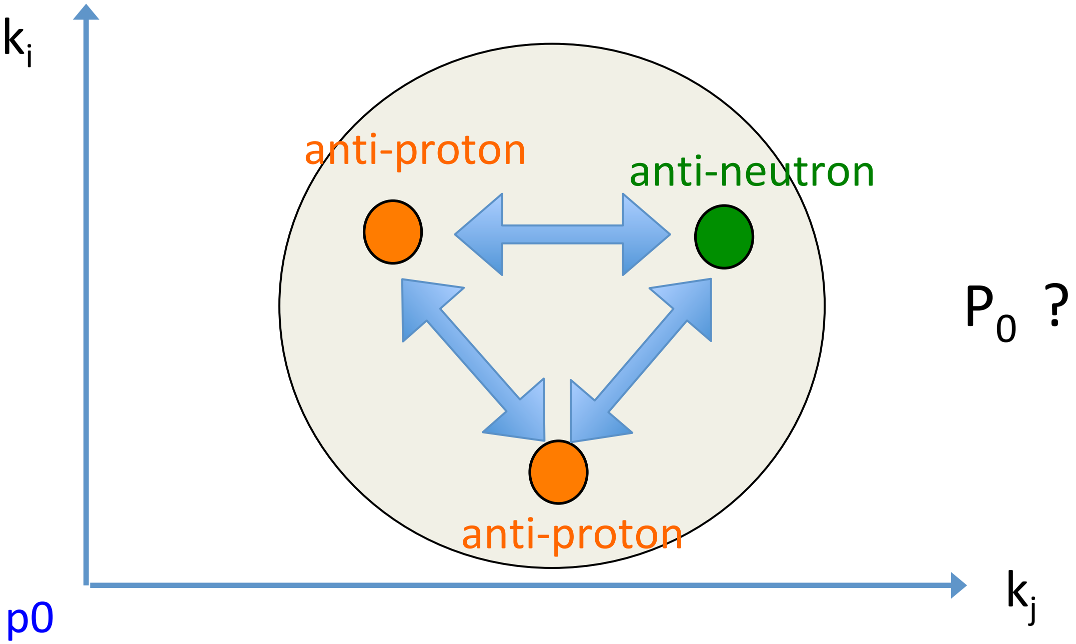
Lin et al, 1801.00997



AM02 (2016)

The case of anti-helium

The coalescence model: A=3 case (antijhelium)



Definitions of p0

- minimal circle

$$d_{\rm circ} = \frac{l_1 l_2 l_3}{\sqrt{(l_1+l_2+l_3)(-l_1+l_2+l_3)(l_1-l_2+l_3)(l_1+l_2-l_3)}} < p_0^{\overline{\rm He}}.$$

- absolute difference for each relative momenta

$$||k_i - k_j|| < p_0^{\overline{\rm He}}, \qquad (i \neq j).$$

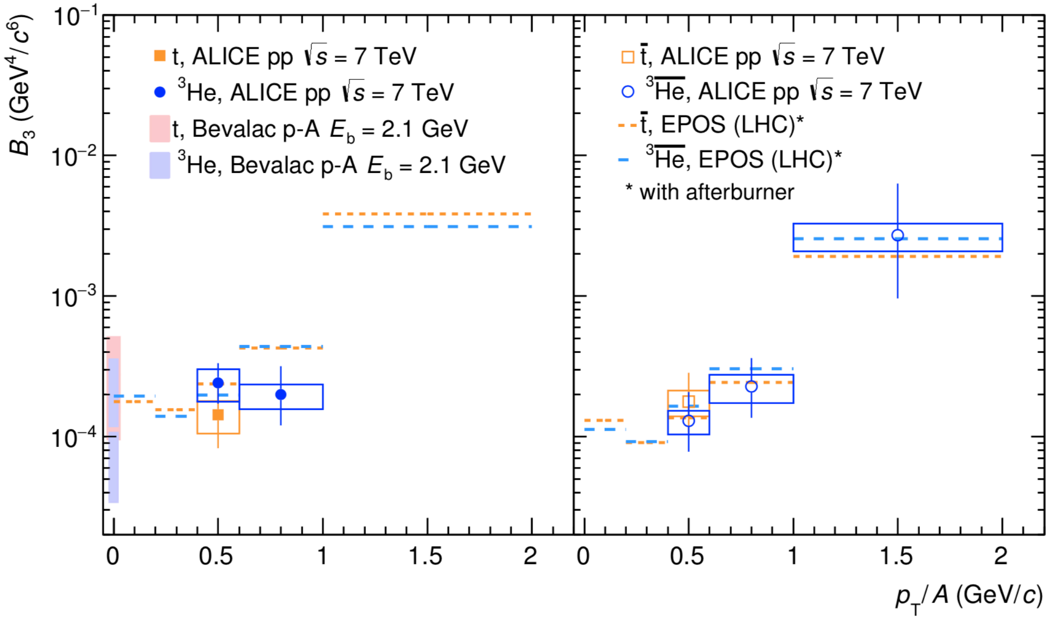
Coalescence momentum of anti-Helium

Indirect approaches

- Use the relation between nuclei: $p_{0A}^{\overline{\mathrm{He}}} = \langle p_0^{\mathrm{He}}/p_0^{\mathrm{D}}\rangle\, p_0^{\bar{\mathrm{D}}} = 1.28\, p_0^{\bar{\mathrm{D}}} = 0.246 \pm 0.038\ \mathrm{GeV}.$
- Use binding energy: $p_{0B}^{\overline{\mathrm{He}}} = \sqrt{E_b^{3\overline{\mathrm{He}}}/E_b^{\bar{\mathrm{D}}}}\, p_0^{\bar{\mathrm{D}}} = 0.357 \pm 0.059\ \mathrm{GeV}.$

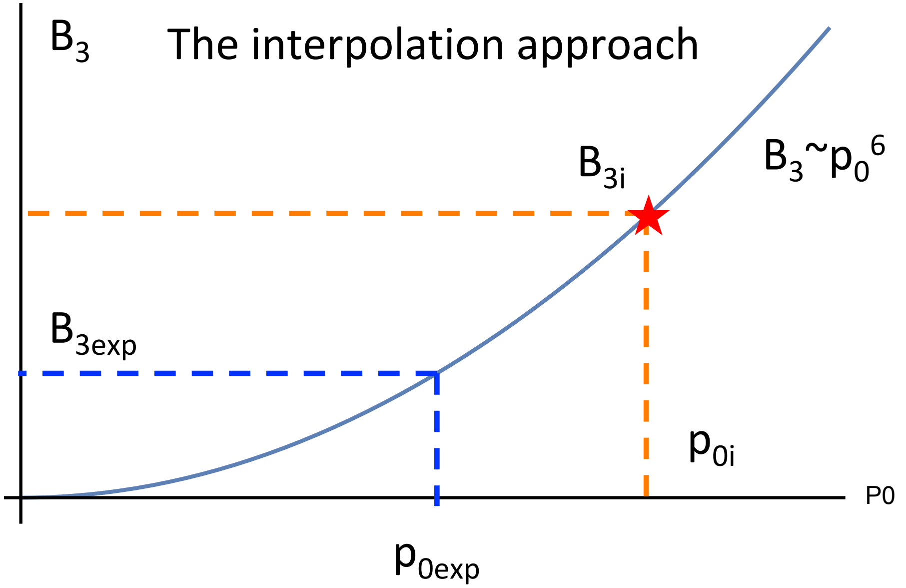
Direct approaches

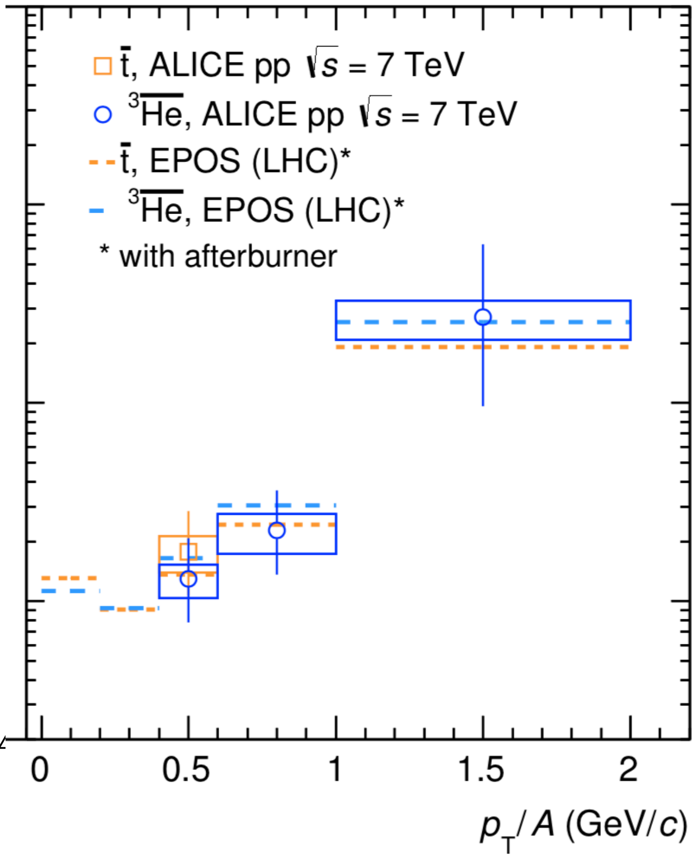
- Use Exp. data (e.g. ALICE, STAR)



ALICE, 1709.08522 (assuming rate ~ $(p_0)^6$)

Coalescence momenta: the ALICE results





$$E_A\frac{\mathrm{d}^3N_A}{\mathrm{d}p_A^3} = B_A\left(E_\mathrm{p}\frac{\mathrm{d}^3N_\mathrm{p}}{\mathrm{d}p_\mathrm{p}^3}\right)^Z\left(E_\mathrm{n}\frac{\mathrm{d}^3N_\mathrm{n}}{\mathrm{d}p_\mathrm{n}^3}\right)^N, \vec{p}_\mathrm{p} = \vec{p}_\mathrm{n} = \vec{p}_A/$$

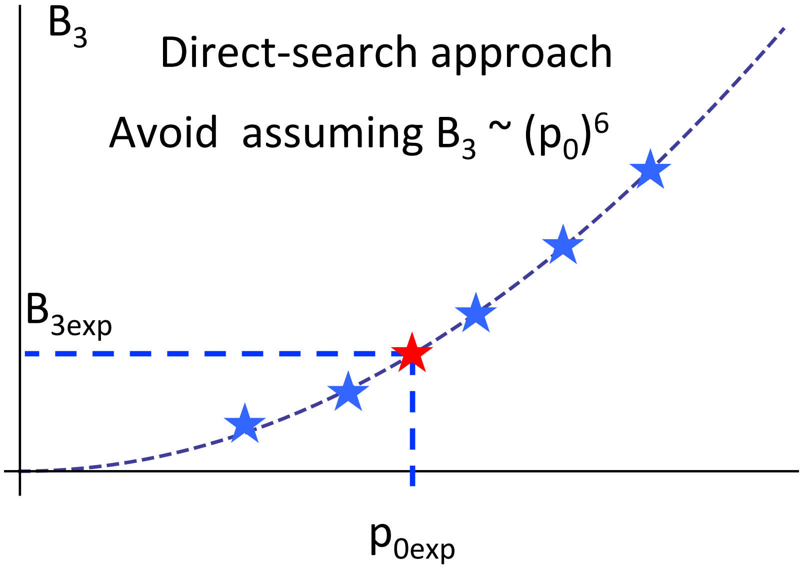
Use the relation to find p_0-B_3 relation for interpolation

$$B_A = \frac{g_A M}{m_\mathrm{p}^Z m_\mathrm{n}^N}\left(\frac{4\pi}{3}p_0^3\right)^{A-1}$$

☐ Interpolation approach is fast
☐ Assumption $B_3 \sim p_0^6$ required

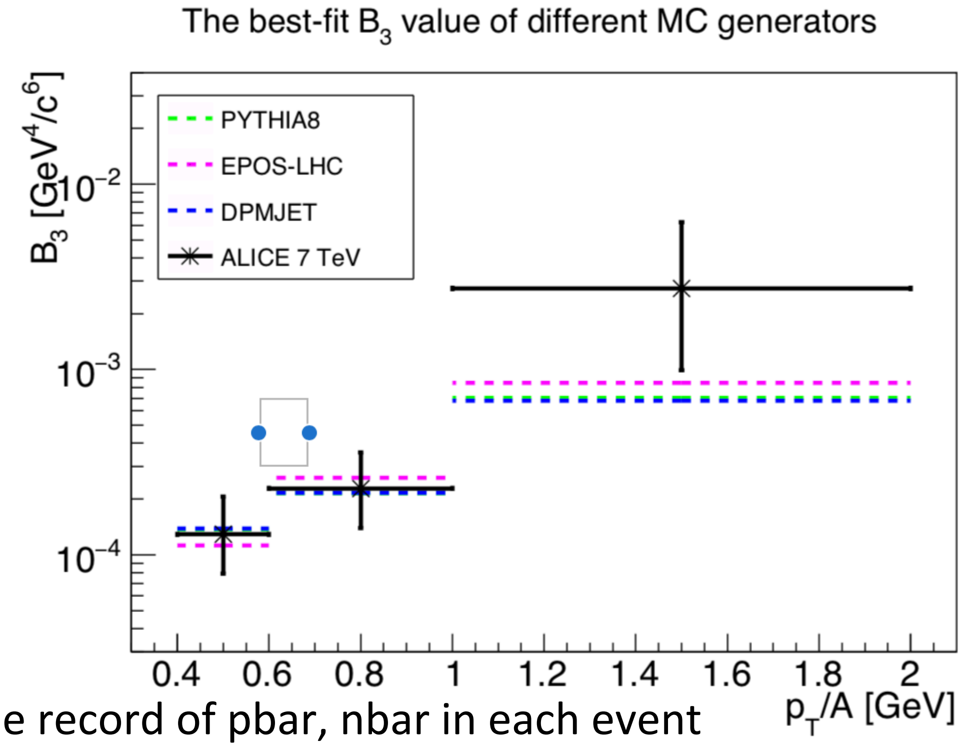
Using the measured B_3 to interpolate the value of p_0
Fit the p_0 value in all the p_T bins as constant value (p_T independ)

A straight-forward determination of p_0



Direct-search approach

Avoid assuming $B_3 \sim (p_0)^6$


The best-fit B_3 value of different MC generators

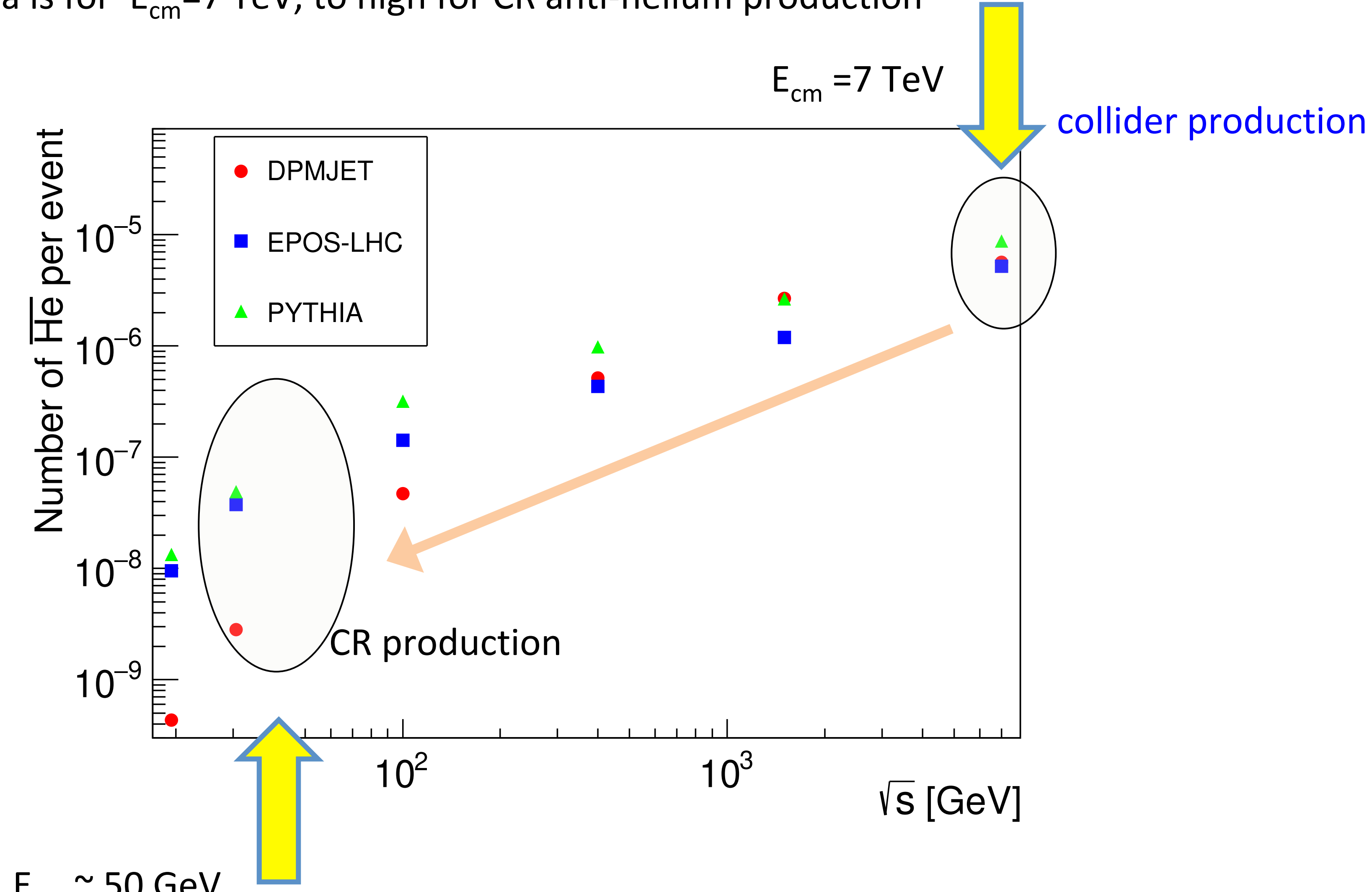
- starting with a large enough p_{0max}
- Simulate O(10^{11}) events once , keep the record of pbar, nbar in each event
- vary p_0 (in the range $p_0 < p_{0max}$) freely in the sample to fit B_3

MC generators:	PYTHIA 8.2	EPOS-LHC	DPMJET-III
$p_0^{\overline{\mathrm{He}}}$ (MeV)	224^{+12}_{-16} (254 ± 14)	227^{+11}_{-16} (254 ± 14)	212^{+10}_{-13}
$p_0^{\bar{\mathrm{T}}}$ (MeV)	234^{+17}_{-29} (266 ± 22)	245^{+17}_{-30} (268 ± 22)	222^{+16}_{-26}

We found the values of p_0 lower by ~15% compared with that from ALICE

Significant uncertainties arise when extrapolating to low energies

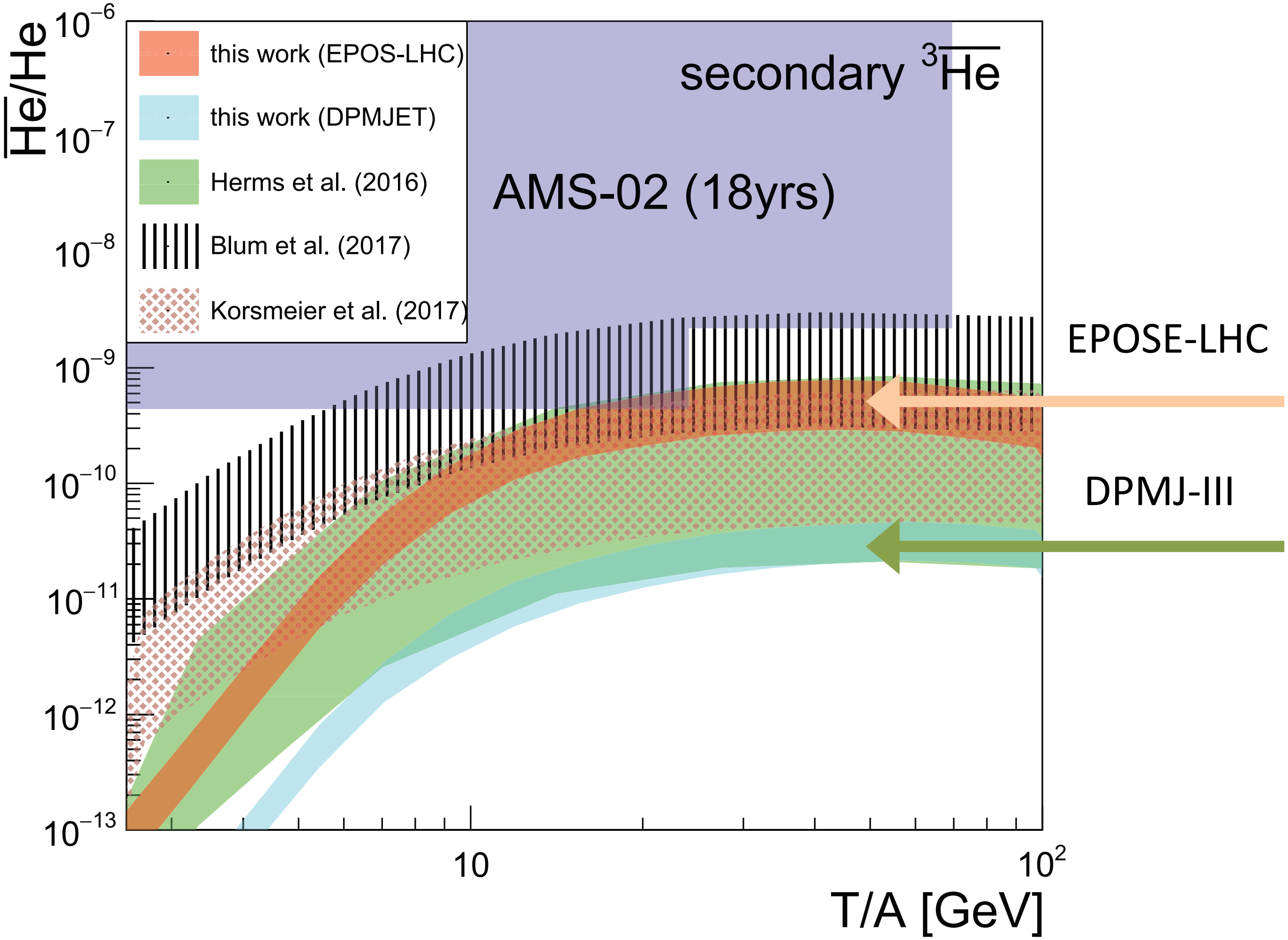
ALICE data is for E_{cm}=7 TeV, to high for CR anti-helium production



E_{cm} ~ 50 GeV

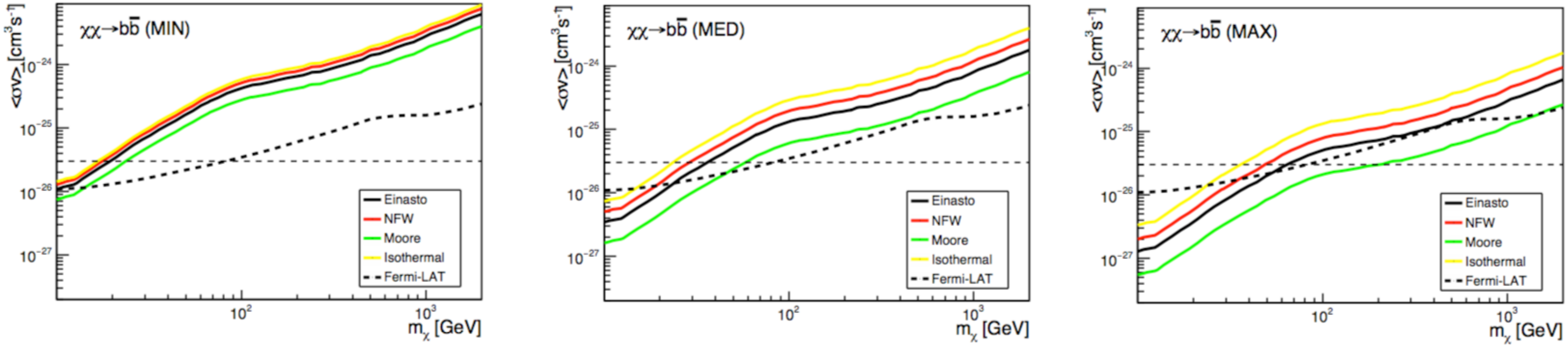
energy scale relevant to CR anti-helium production

Predicted secondary backgrounds



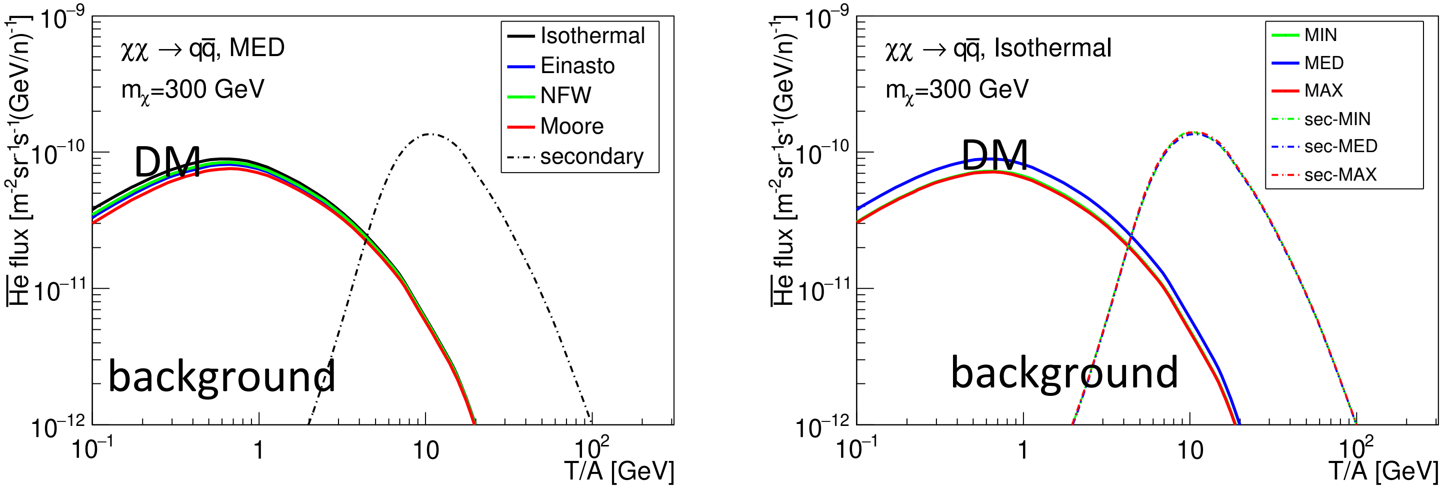
Advantages of using the antiproton data to set limits

Importance of using antiproton limits for predicting anti-nuclei



Advantages:

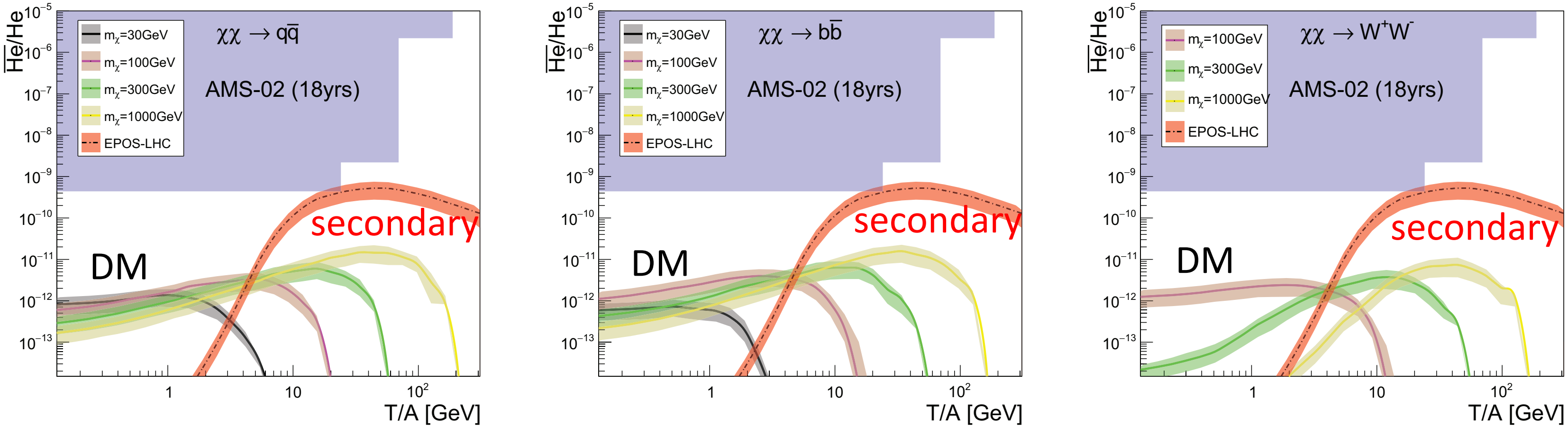
DM profile (also propagation) dependence **cancels out** in deriving the anti-helium limits



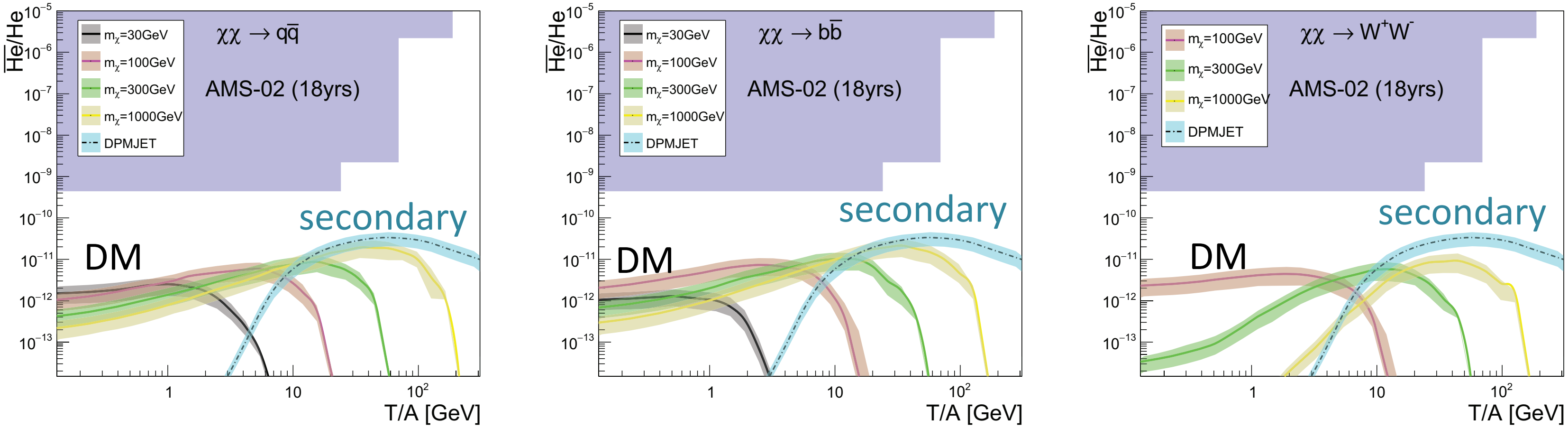
Y.C. Ding, N. Li, C.C.Wei, Y.L.Wu, YFZ, 1808.03612

Projected maximal anti-helium flux @AMS-02

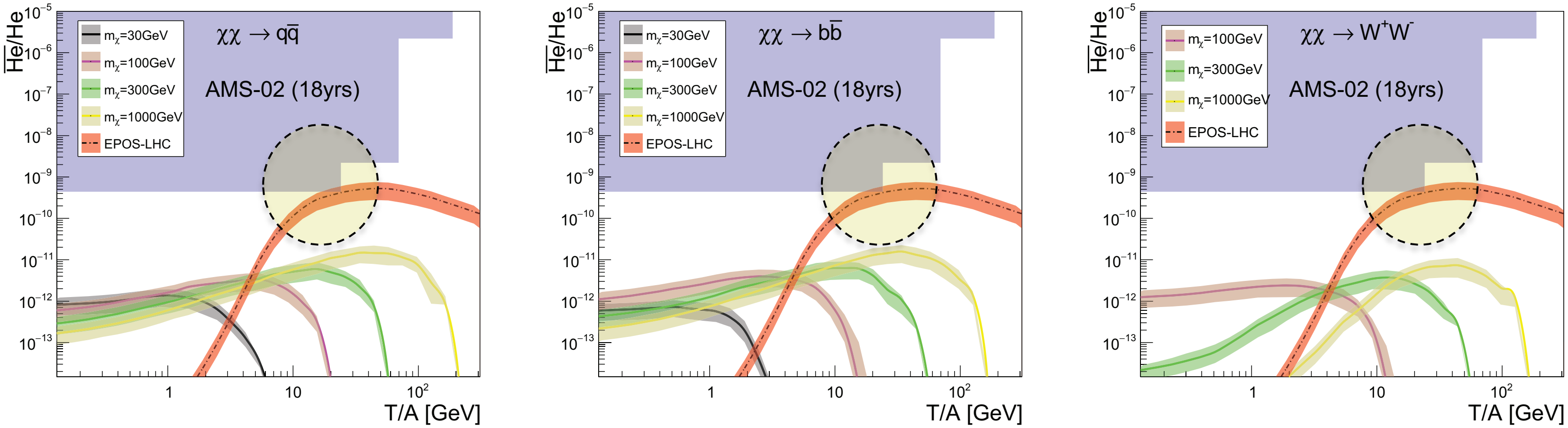
EPOS-LHC based predictions



DPMJET based predictions



The most optimistic case for antihelium@AMS-02



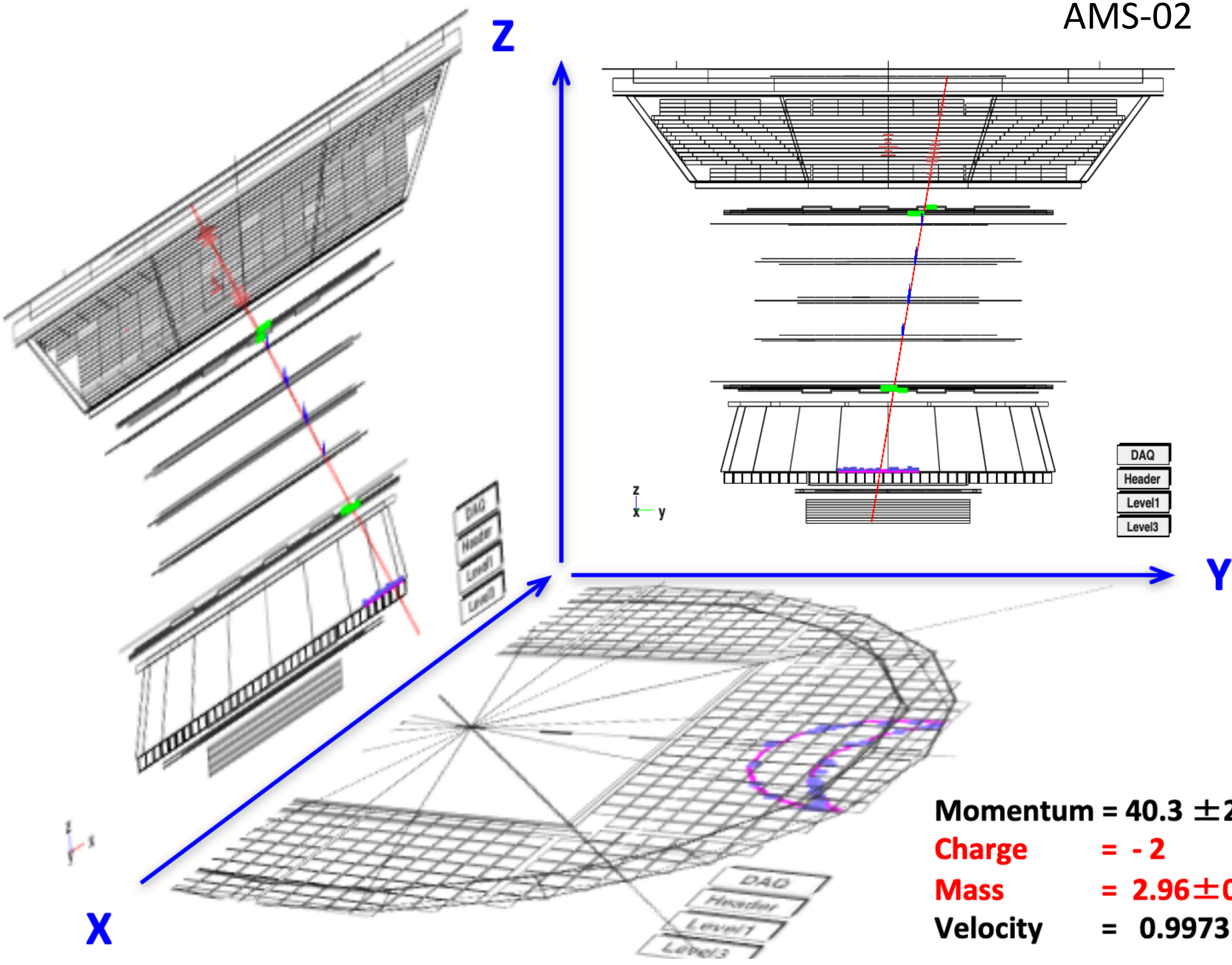
Expected anti-helium events (after 18 yrs of data collecting)

	m_χ (GeV)	$\chi\chi \to q\bar{q}$	$\chi\chi \to b\bar{b}$	$\chi\chi \to W^+W^-$
DM	30	$0.084^{+0.038}_{-0.040}$ $(0.153^{+0.070}_{-0.073})$	$0.041^{+0.020}_{-0.018}$ $(0.073^{+0.036}_{-0.032})$	—
	100	$0.153^{+0.065}_{-0.072}$ $(0.269^{+0.114}_{-0.127})$	$0.227^{+0.107}_{-0.103}$ $(0.419^{+0.198}_{-0.190})$	$0.164^{+0.077}_{-0.076}$ $(0.304^{+0.143}_{-0.141})$
	300	$0.122^{+0.055}_{-0.056}$ $(0.179^{+0.081}_{-0.082})$	$0.160^{+0.074}_{-0.074}$ $(0.256^{+0.118}_{-0.118})$	$0.054^{+0.025}_{-0.025}$ $(0.084^{+0.039}_{-0.039})$
	1000	$0.106^{+0.048}_{-0.048}$ $(0.138^{+0.063}_{-0.063})$	$0.131^{+0.058}_{-0.061}$ $(0.179^{+0.079}_{-0.083})$	$0.015^{+0.007}_{-0.007}$ $(0.019^{+0.009}_{-0.009})$
Secondary			$0.986^{+0.437}_{-0.455}$ $(0.054^{+0.021}_{-0.021})$	

- The expected antihelium events is O(1)
- Typical energy 30-100 GeV
- Dominated by secondary backgrounds, not DM annihilation

Antihelium-3 @AMS-02 ?

AMS-02　（2016）



Momentum = 40.3 ±2.9 GeV/*c*

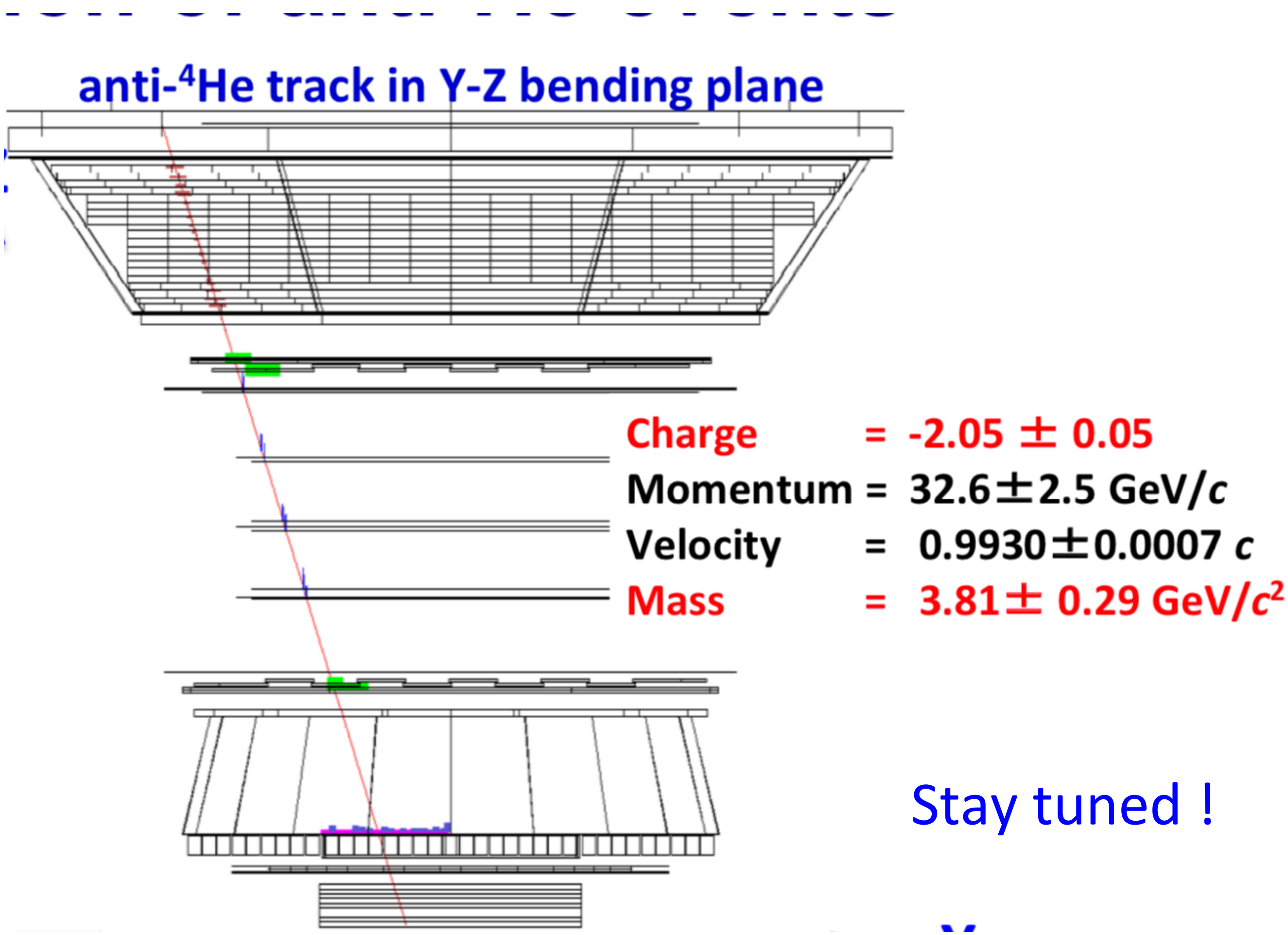
Charge = - 2

Mass = 2.96±0.33 GeV/c^2

Velocity = 0.9973±0.0005 *c*

Antihelium−4 @AMS-02 ?

AMS-02 so far find 8 anti-helium candidate events with 2 coincide with anti-helium-4



anti-^{4}He track in Y-Z bending plane

Charge = -2.05 ± 0.05

Momentum = 32.6±2.5 GeV/*c*

Velocity = 0.9930±0.0007 *c*

Mass = 3.81± 0.29 GeV/c^2

Stay tuned !

Thank you for your attention !