Dark matter constraints from antiprotons in the light of AMS-02

Based on:
Cuoco, Kraemer, Korsmeier, 2016, arXiv:1610.03071
Korsmeier, Cuoco, 2016. arXiv:1607.06093, PRD(2016)

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Oslo,
Jan. 11th 2017

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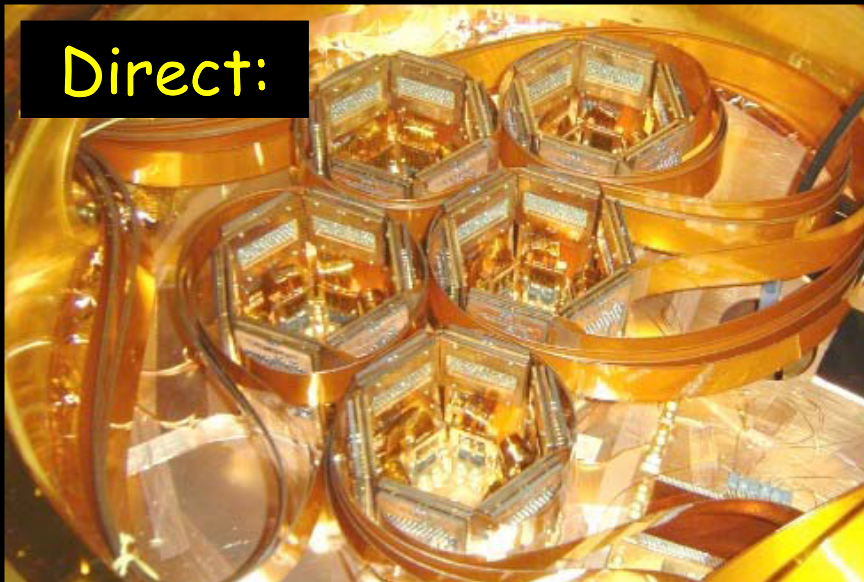
Four roads to Dark Matter

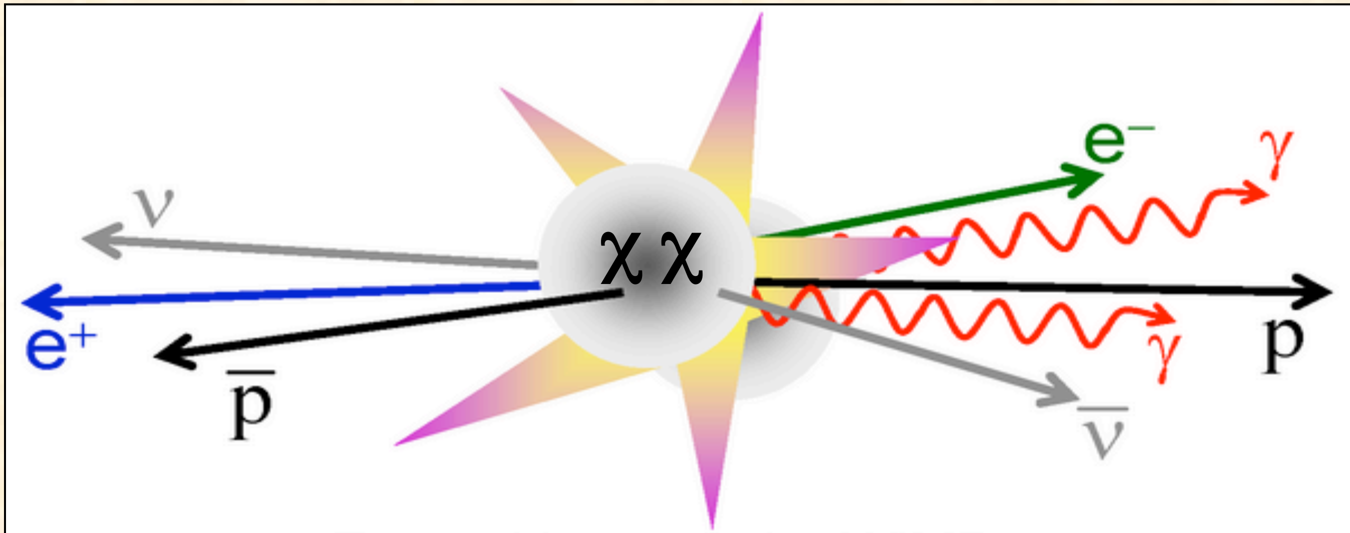


From Max Tegmark

Indirect Detection of Dark Matter: the General Framework

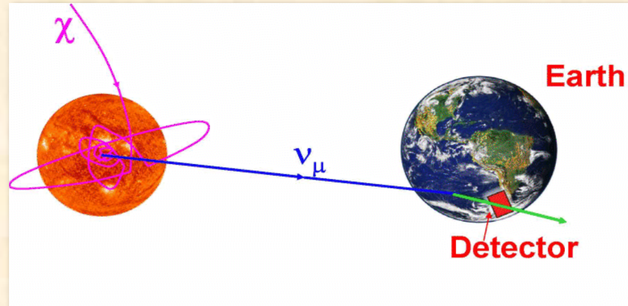
1) **WIMP Annihilation** Typical final states include heavy fermions, gauge or Higgs bosons

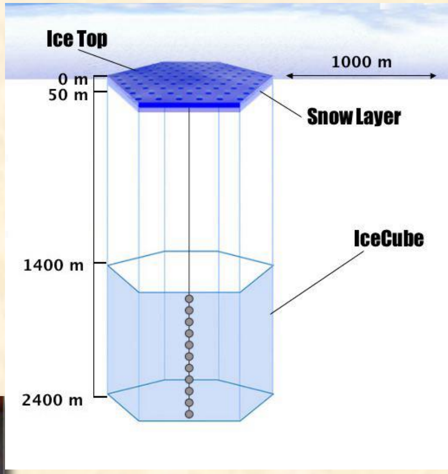
2) **Fragmentation/Decay** Annihilation products decay and/or fragment into some combination of electrons, protons, deuterium, neutrinos and gamma rays



Indirect Detection of Dark Matter

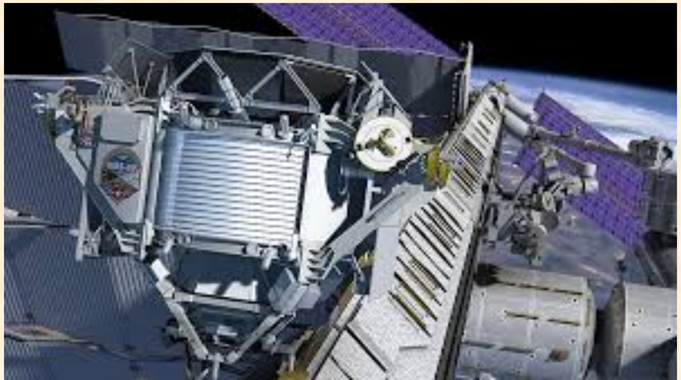
Neutrinos from annihilations in the core of the Sun



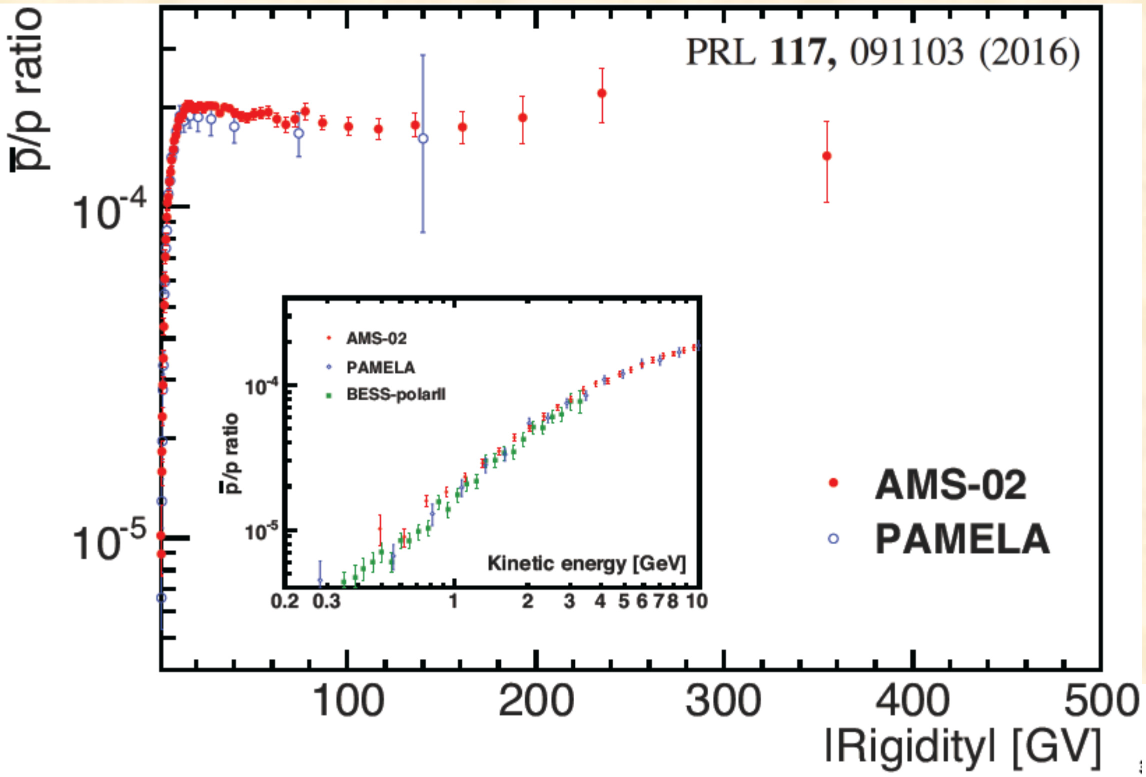


Gamma Rays from annihilations in the galactic halo, near the galactic center, in dwarf galaxies, etc.

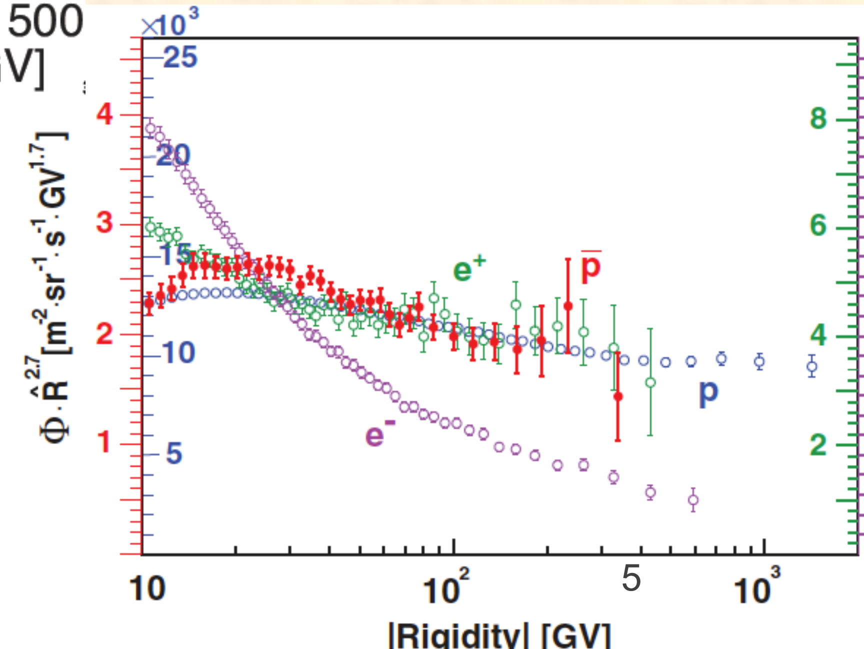
Positrons/Antiprotons from annihilations throughout the galactic halo



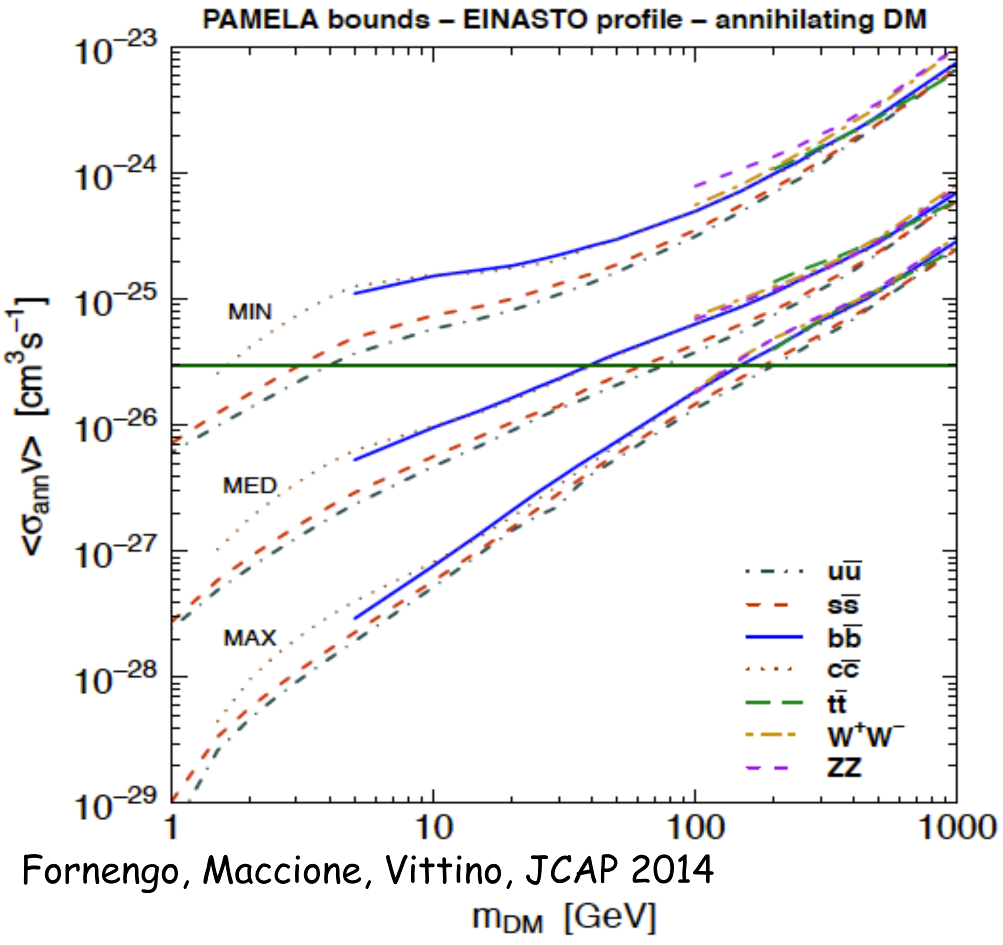
AMS-02 Antiprotons



AMS02 recently published very precise measurements of the antiprotons spectrum up to ~400 GV. Detailed DM and CR studies are now possible.



Antiprotons DM limits



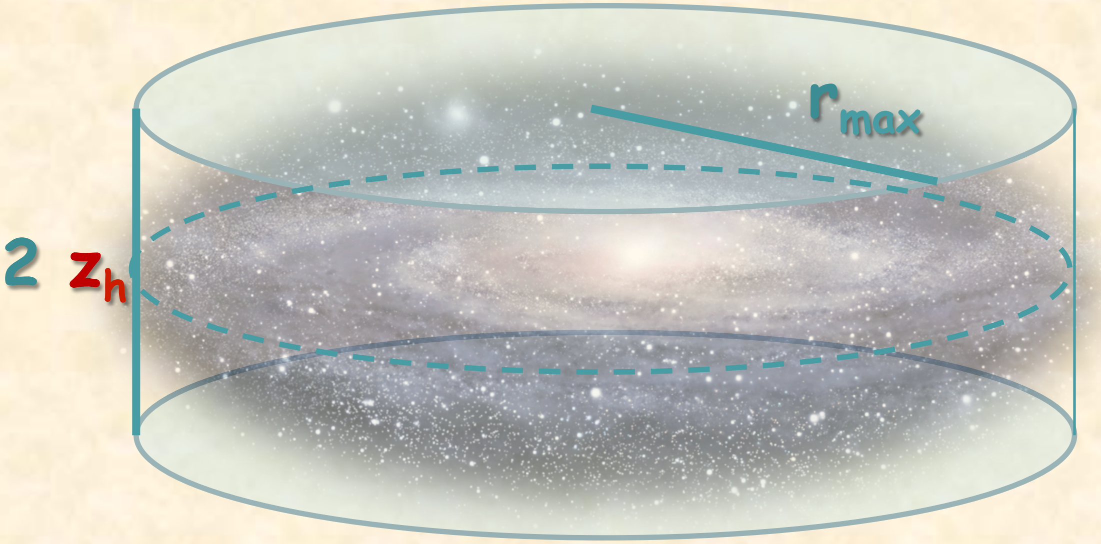
Fornengo, Maccione, Vittino, JCAP 2014

L. Bergstrom, J. Edsjo, and P. Ullio, ApJ,526,215 (1999),
F. Donato, N. Fornengo, D. Maurin, and P. Salati, PRD69, 063501 (2004),
T. Bringmann and P. Salati, PRD75, 083006 (2007),
F. Donato, D. Maurin, P. Brun, T. Delahaye, and P. Salati, PRL. 102, 071301 (2009),
N. Fornengo, L. Maccione, and A. Vittino, JCAP1404,003,
D. Hooper, T. Linden, and P. Mertsch, JCAP 1503, 021,
V. Pettorino, G. Busoni, A. De Simone, E. Morgante, A. Riotto, and W. Xue, JCAP 1410, 078 (2014),
M. Boudaud, M. Cirelli, G. Giesen, and P. Salati, JCAP1505, 013 (2015)
J. A. R. Cembranos, V. Gammaldi, and A. L. Maroto, JCAP 1503, 041 (2015)
M. Cirelli, D. Gaggero, G. Giesen, M. Taoso, and A. Urbano, JCAP 1412, 045 (2014)
T. Bringmann, M. Vollmann, and C.Weniger, Phys. Rev. D90, 123001 (2014),
G. Giesen, M. Boudaud, Y. Genolini, V. Poulin, M. Cirelli, P. Salati, and P. D. Serpico, JCAP 1509, 023 (2015)
C. Evoli, D. Gaggero, and D. Grasso, JCAP 1512, 039

- Until now, DM constraints from antiprotons have suffered large uncertainties due to the unknowns in the CR propagation scenario.
- The precise AMS02 data allow to tackle also this issue.

Cosmic-Ray Propagation

$$\frac{\mathrm{d}\psi}{\mathrm{d}t} = q(\boldsymbol{x}, p) + \boldsymbol{\nabla} \cdot (D_{xx} \boldsymbol{\nabla} \psi - \boldsymbol{V} \psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi$$
$$- \frac{\partial}{\partial p} \left(\frac{\mathrm{d}p}{\mathrm{d}t} \psi - \frac{p}{3} \boldsymbol{\nabla} \cdot \boldsymbol{V} \psi \right) - \frac{1}{\tau_f} \psi - \frac{1}{\tau_r} \psi$$



Diffusion equation is solved numerically with GALPROP assuming:

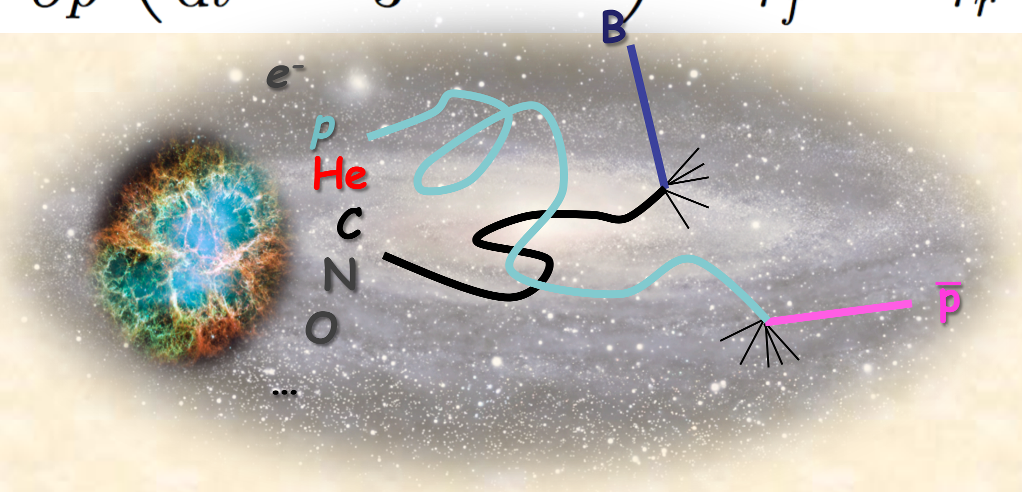
- Steady state
- Cylindrical symmetry
- Free escape at boundaries

Sources

$$\frac{\mathrm{d}\psi}{\mathrm{d}t} = q(\boldsymbol{x},p) + \boldsymbol{\nabla}\cdot(D_{xx}\boldsymbol{\nabla}\psi - \boldsymbol{V}\psi) + \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{1}{p^2}\psi$$

$$-\frac{\partial}{\partial p}\left(\frac{\mathrm{d}p}{\mathrm{d}t}\psi - \frac{p}{3}\boldsymbol{\nabla}\cdot\boldsymbol{V}\psi\right) - \frac{1}{\tau_f}\psi - \frac{1}{\tau_r}\psi$$

- Sources



Astrophysical Sources:

- SNR or Pulsars

➢ **Primary CRs:** p, He, C, …

Interaction with ISM:

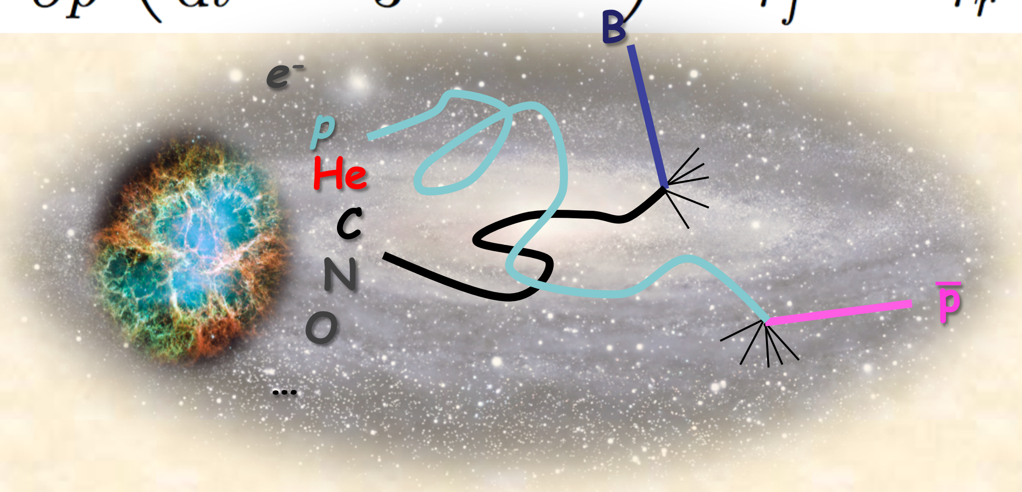
- Fragmentation or production

➢ **Secondary CRs:** $\bar{p}$, Li, B, …

Sources

$$\frac{\mathrm{d}\psi}{\mathrm{d}t} = q(\boldsymbol{x}, p) + \boldsymbol{\nabla} \cdot (D_{xx} \boldsymbol{\nabla} \psi - \boldsymbol{V} \psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi - \frac{\partial}{\partial p} \left(\frac{\mathrm{d}p}{\mathrm{d}t} \psi - \frac{p}{3} \boldsymbol{\nabla} \cdot \boldsymbol{V} \psi \right) - \frac{1}{\tau_f} \psi - \frac{1}{\tau_r} \psi$$

- **Sources**



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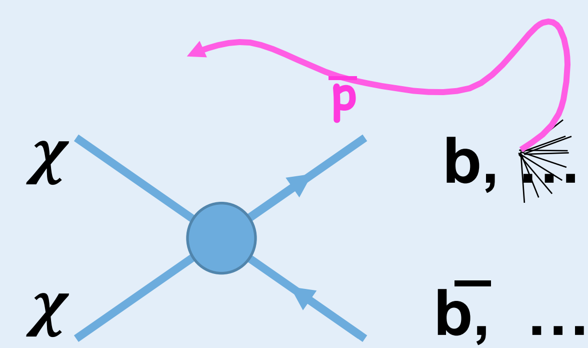
Possible Scenario: WIMP DM?



Annihilation of DM:
- Production of antimatter in the particle shower

➢ **DM CRs:** $\bar{p}$, (e^+)

Data and Fit Parameters

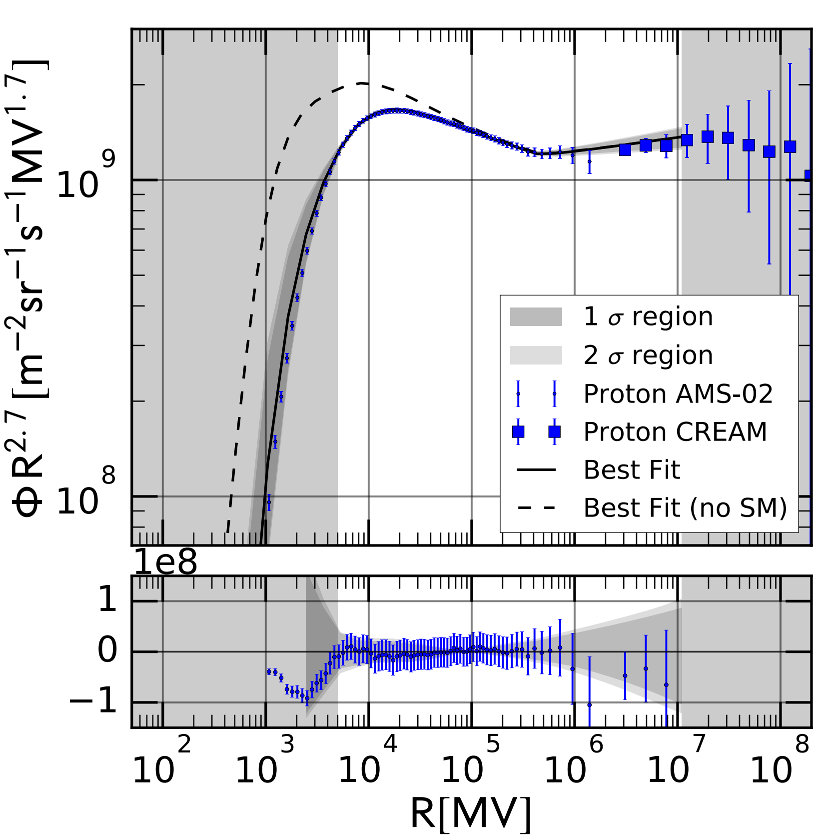
- **AMS-02**
  - **Proton**
    doi: http://dx.doi.org/10.1103/PhysRevLett.114.171103
  - **Helium**
    doi:http://dx.doi.org/10.1103/PhysRevLett.115.211101
  - **$\bar{p}/p$**
    http://dx.doi.org/10.1103/PhysRevLett.117.091103
  - **CREAM**
  - **Proton**, **Helium**
    doi: 10.1088/0004-637X/791/2/93
- **VOYAGER**
  - **Proton**, **Helium**
    http://arxiv.org/pdf/1310.6133v1.pdf

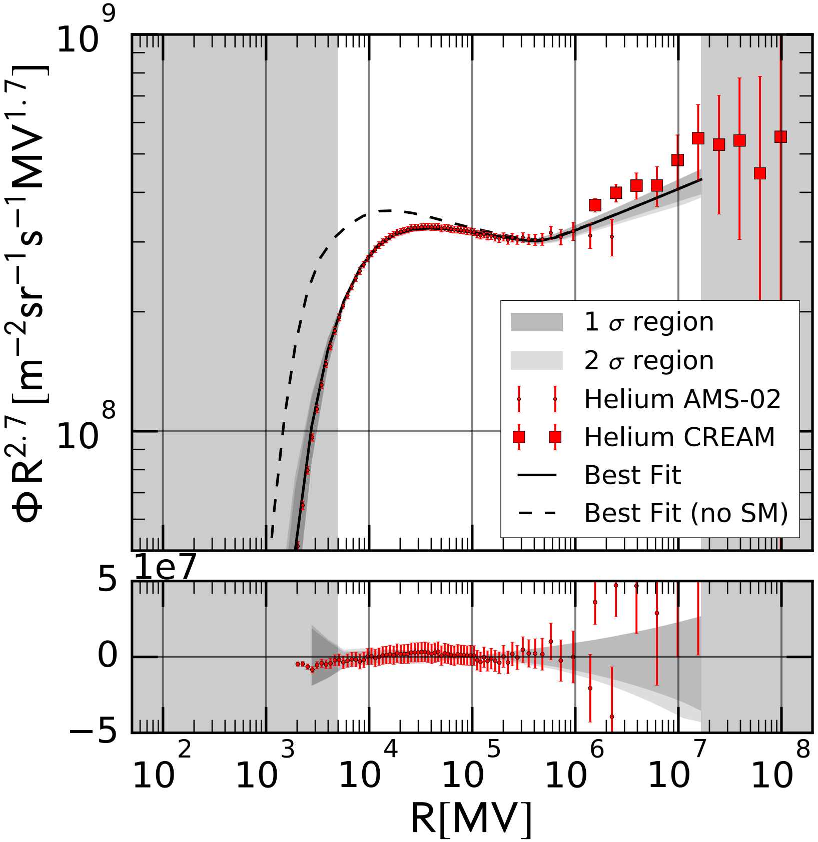
- **Injection spectrum (index p for protons)**
  - γ_1, $\gamma_{1,p}$
  - γ_2, $\gamma_{2,p}$
  - R_0
  - s
- **Diffusion constant**
  - δ
  - D_0
- **Reacceleration**
  - v_{Alfven}
- **Convection**
  - $v_{0,conv}$
- **Halo size**
  - z_h

With DM additional fit parameters:

- m_{DM}
- $\langle\sigma v\rangle$

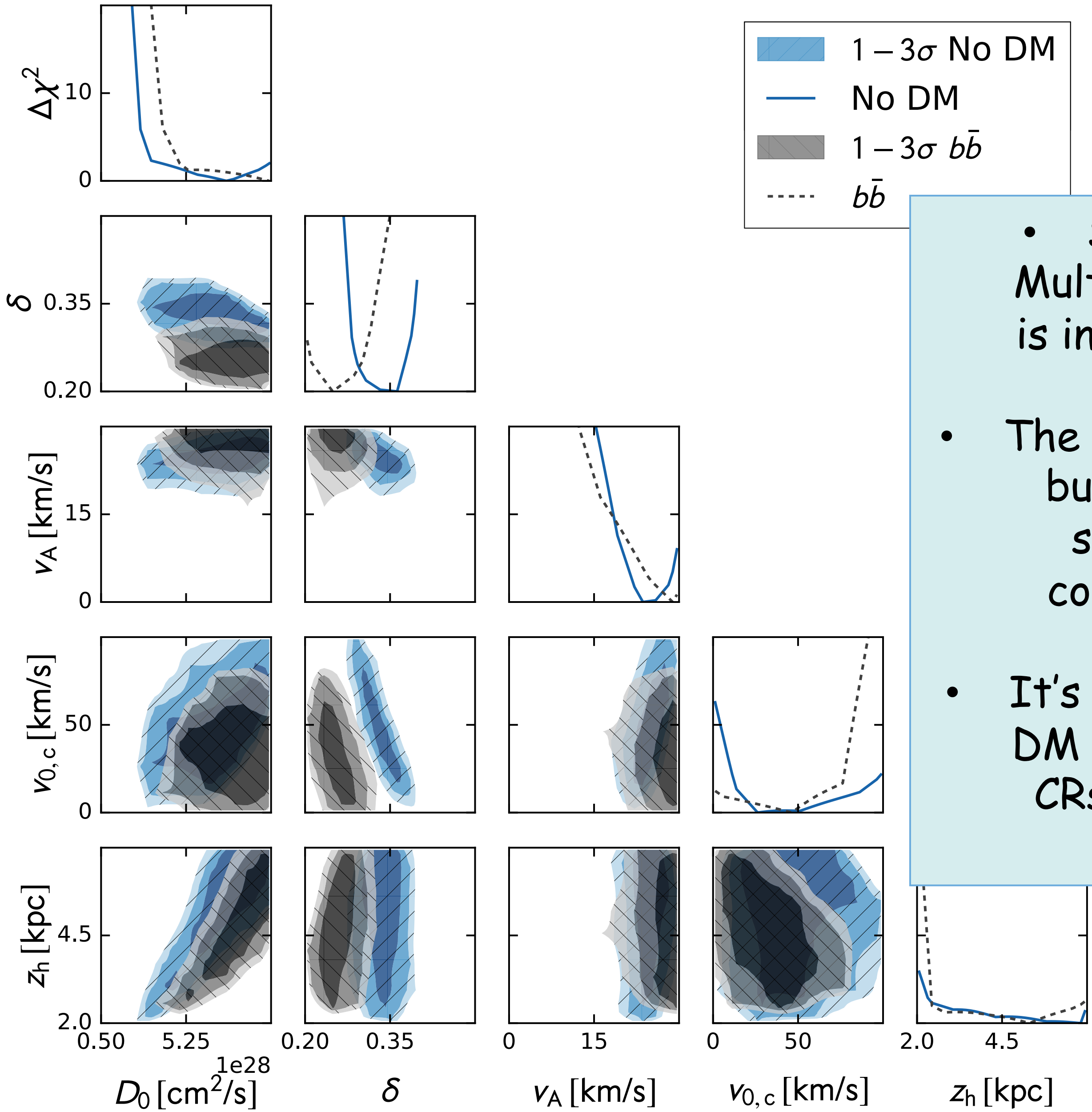
Proton and Helium spectra





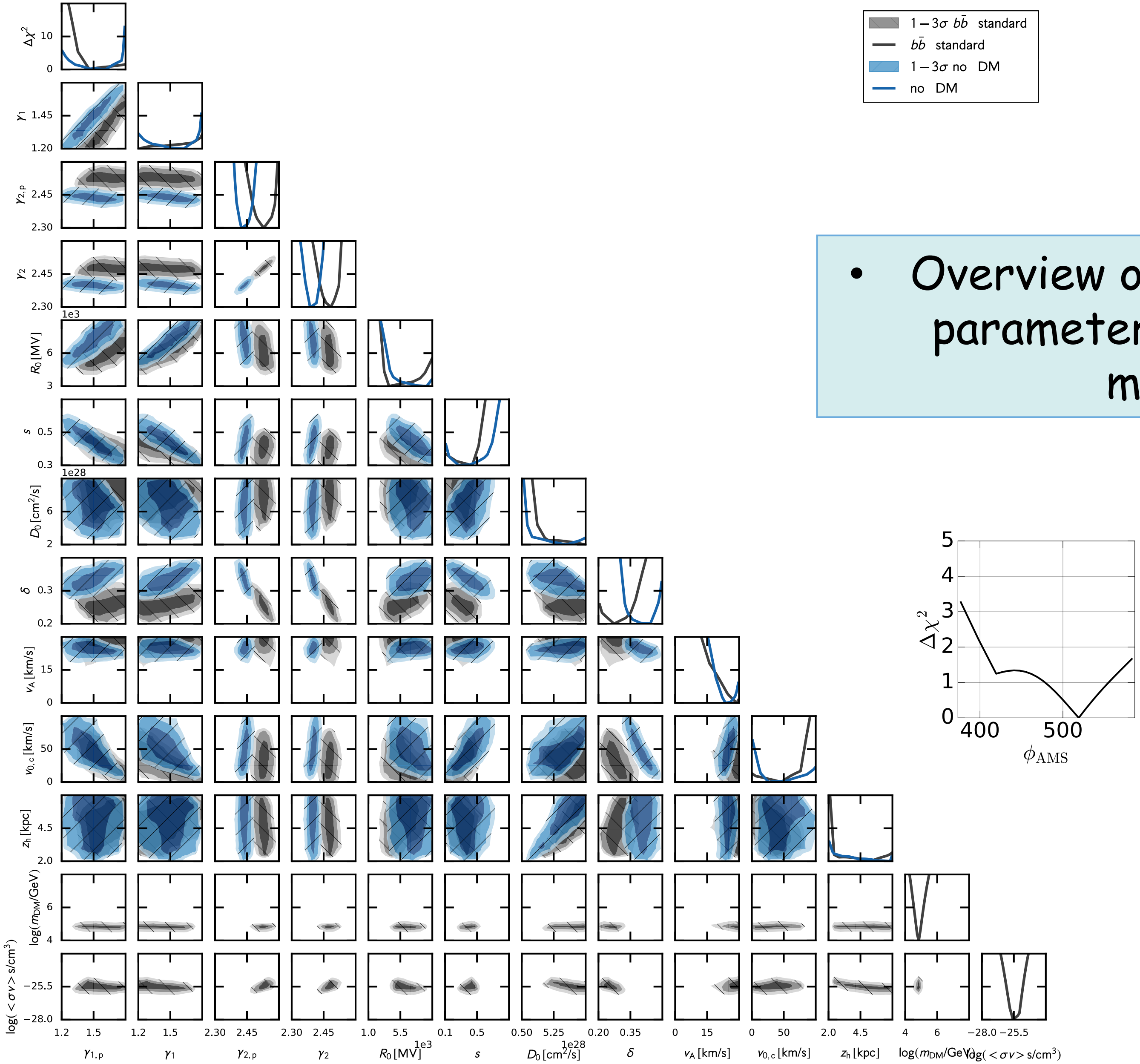
Proton and He spectra are very well fit in the rigidity range of interest (5 GV-10 TV). This is important to ensure a reliable prediction for the secondary antiproton

Parameters Sub-Triangle Plot



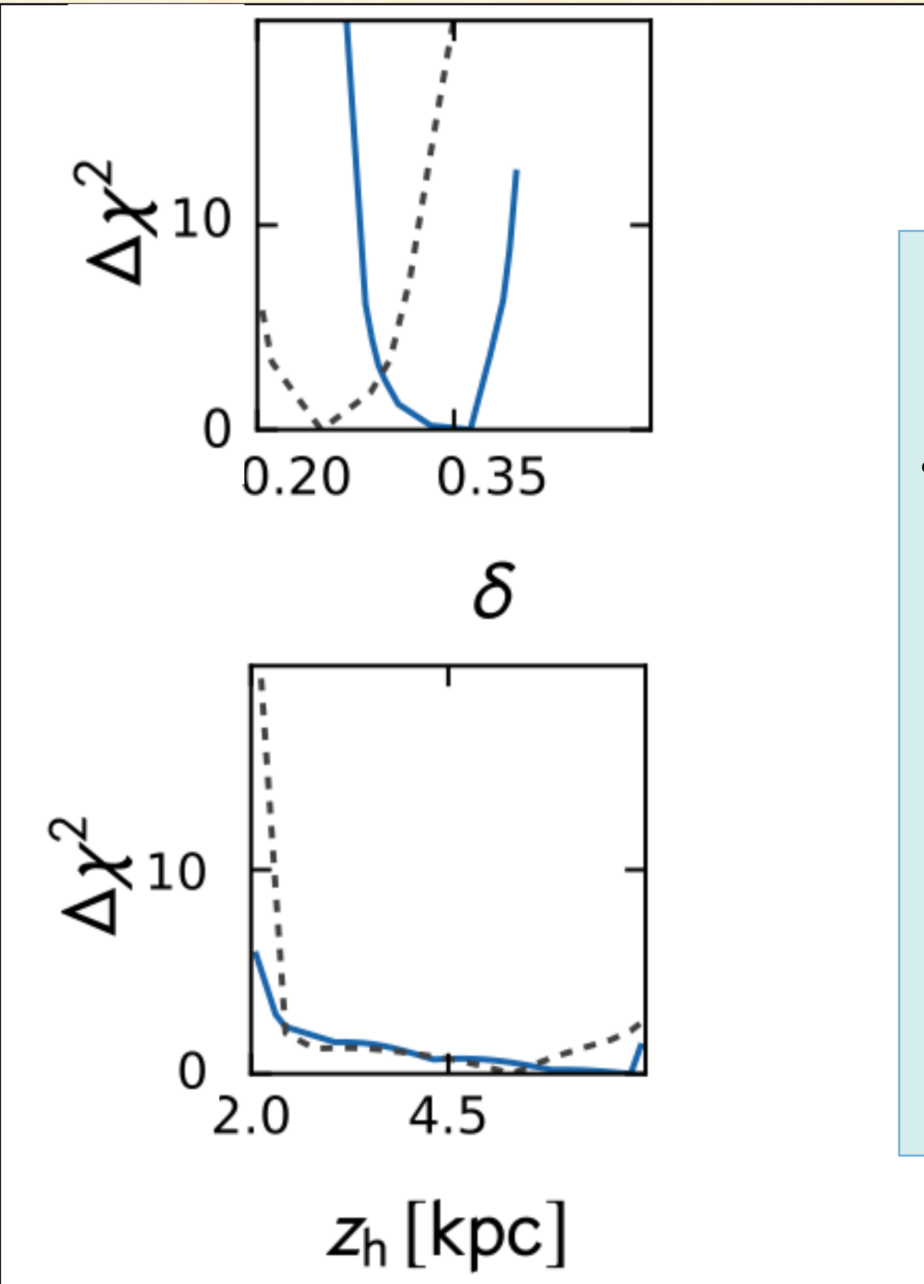
- Scan is performed with MultiNest. The interpretation is in the frequentist approach
- The fit constraints not only DM but also the CR propagation scenario, providing a self consistent DM+CR joint fit.
- It's important to fit both since DM provides some feedback to CRs and shifts their best fit values.

Full Triangle Plot



- Overview of the full 13(!) parameters correlation matrix

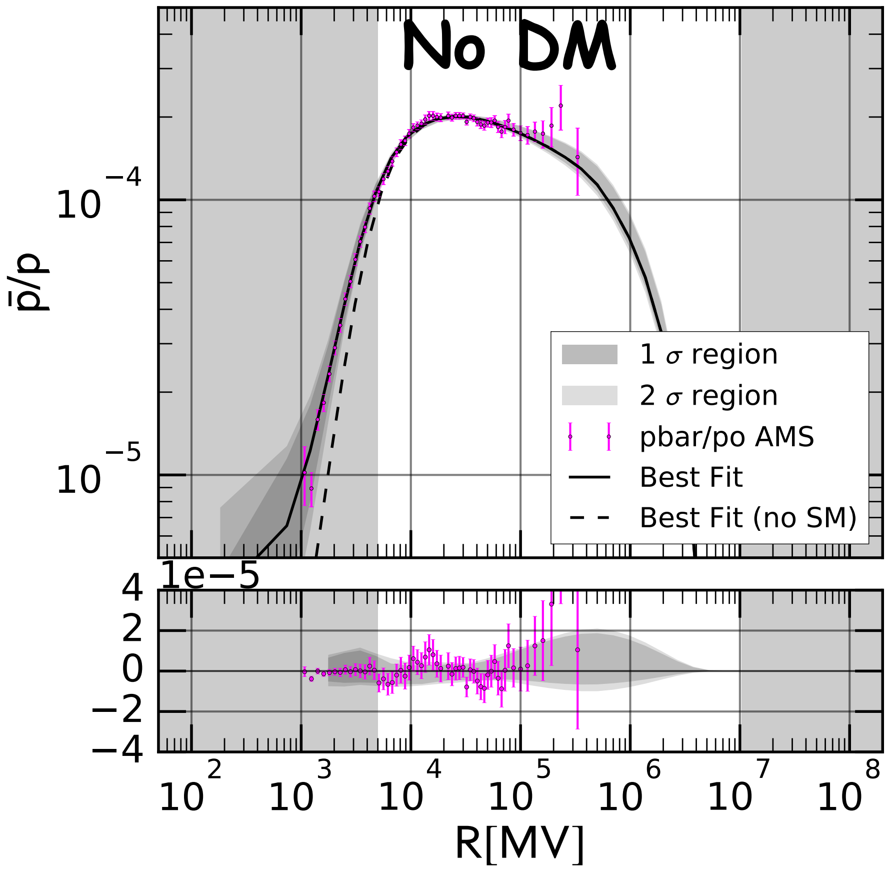
CR Results

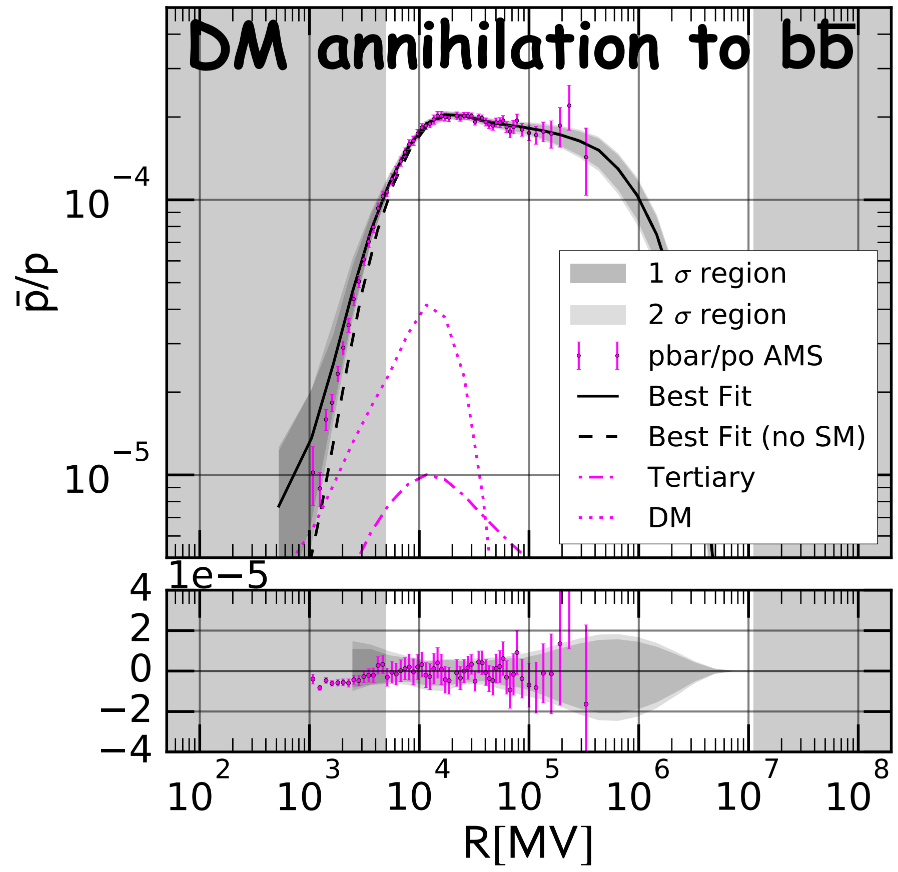


- δ is very well constrained (even within the shift caused by DM):
- In comparison MIN/MED/MAX had δ = 0.85/0.70/0.46 (!!)

- Zh is not well constrained (expected since Be10/Be9 data are needed). Main uncertainty in the DM normalization (large halo more DM anti-p, small halo less DM anti-p)

$\bar{p}/p$ ratio spectrum

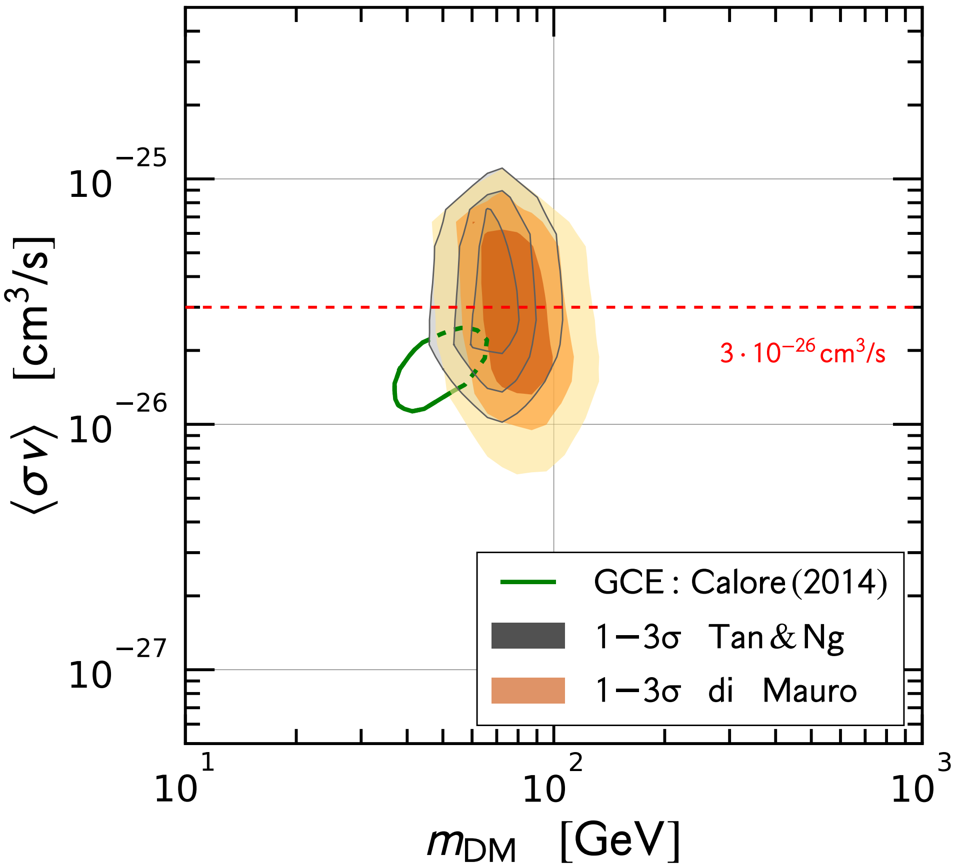




It can be seen that the improvement in the fit is mainly due to a feature at ~18 GV, which DM is able to fit well thanks to its spectrum with a sharp cutoff

DM improves the fit quality by ~4.5σ! (ΔX^2 ~25 for 2 d.o.f.)

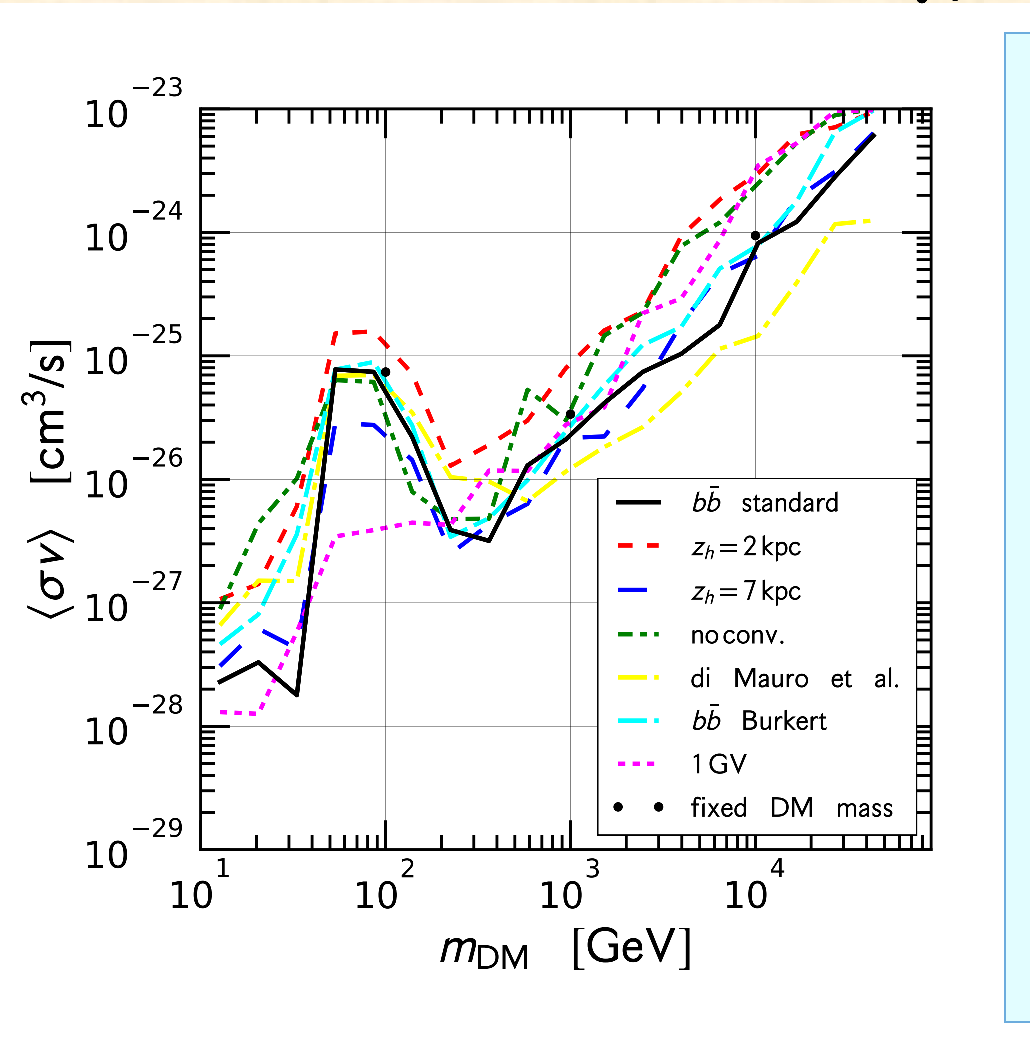
bb DM preferred region



- DM preferred region (at 1-2-3 sigma C.L.) can be derived, fully marginalized over the CR propagation parameters
- interestingly the DM preferred region is well compatible with the Galactic center gamma-ray excess
- *A* difficult systematic uncertainty to estimate is the anti-p production cross-section. We tested 2 different models, and they give similar results, but other models are possible

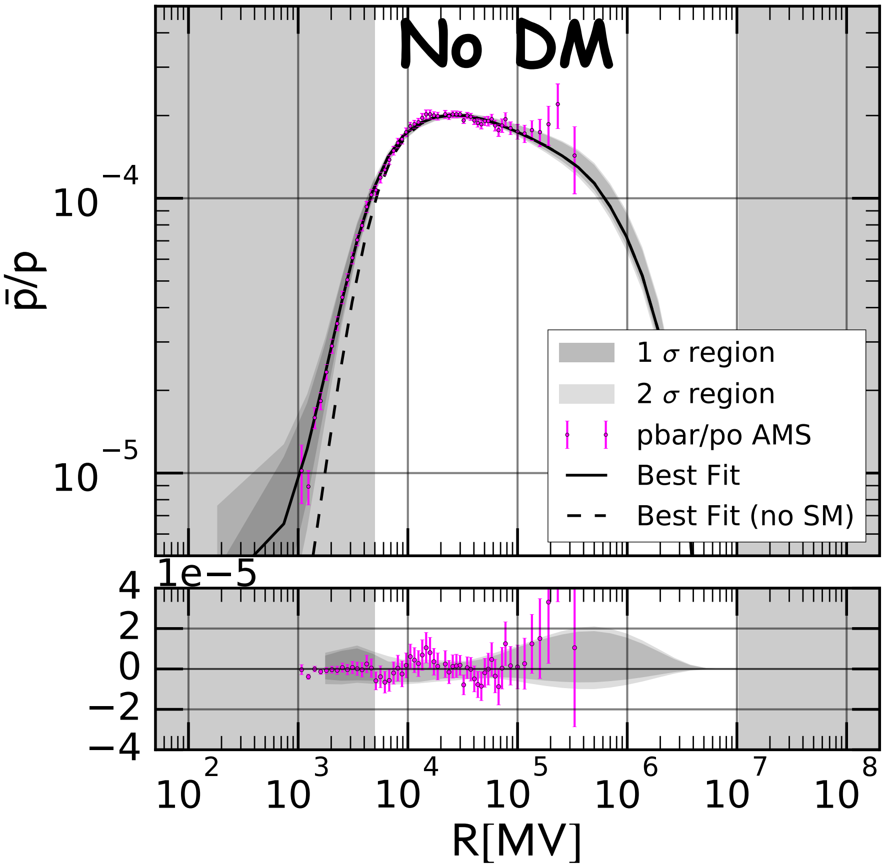
M. di Mauro, F. Donato, A. Goudelis, and P. D. Serpico, PRD90, 085017 (2014),
R. Kappl and M. W. Winkler, JCAP 1409, 051 (2014)
M. Kachelriess, I. V. Moskalenko, and S. S. Ostapchenko,ApJ. 803, 54 (2015)
L. C. Tan and L. K. Ng, J. Phys. G9, 227 (1983).

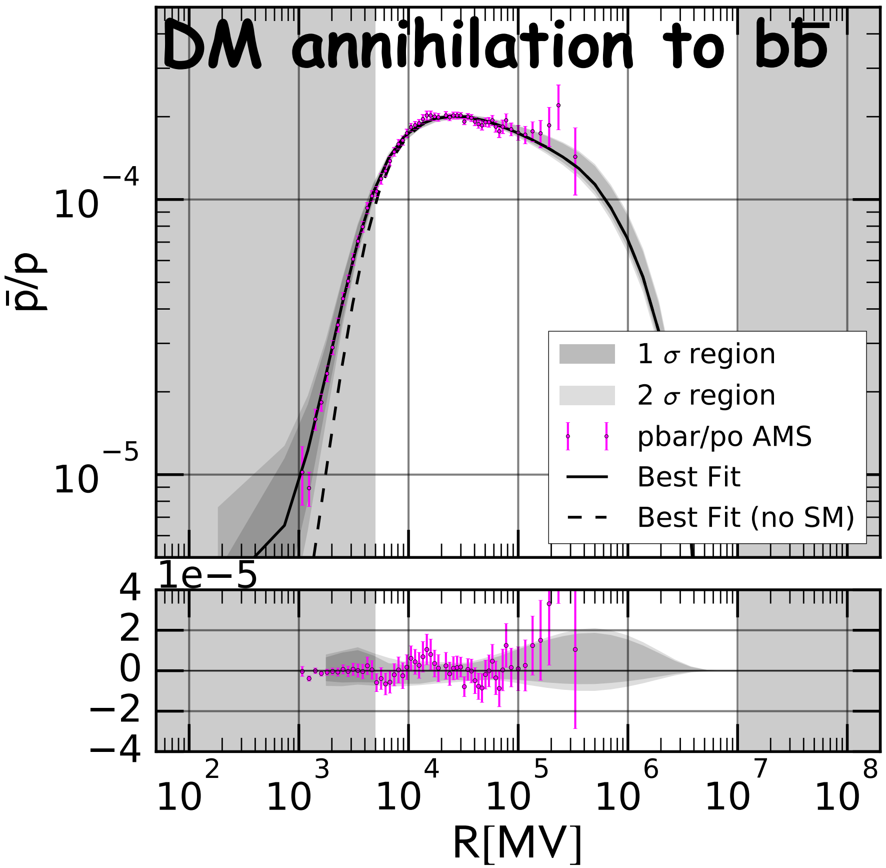
Other systematics and DM limits



- Results are stable vs various systematics as:
  - Different DM profiles
  - Imposing zero convection
  - Different model of anti-p production cross-section
- Fixing different zh (2kpc and 7 kpc) shift the DM normalization by a factor 2-3, as expected
- Only anomaly is the 'disappearance' of the DM signal when fitting data down to 1 GV

1GV vs 5 GV fit

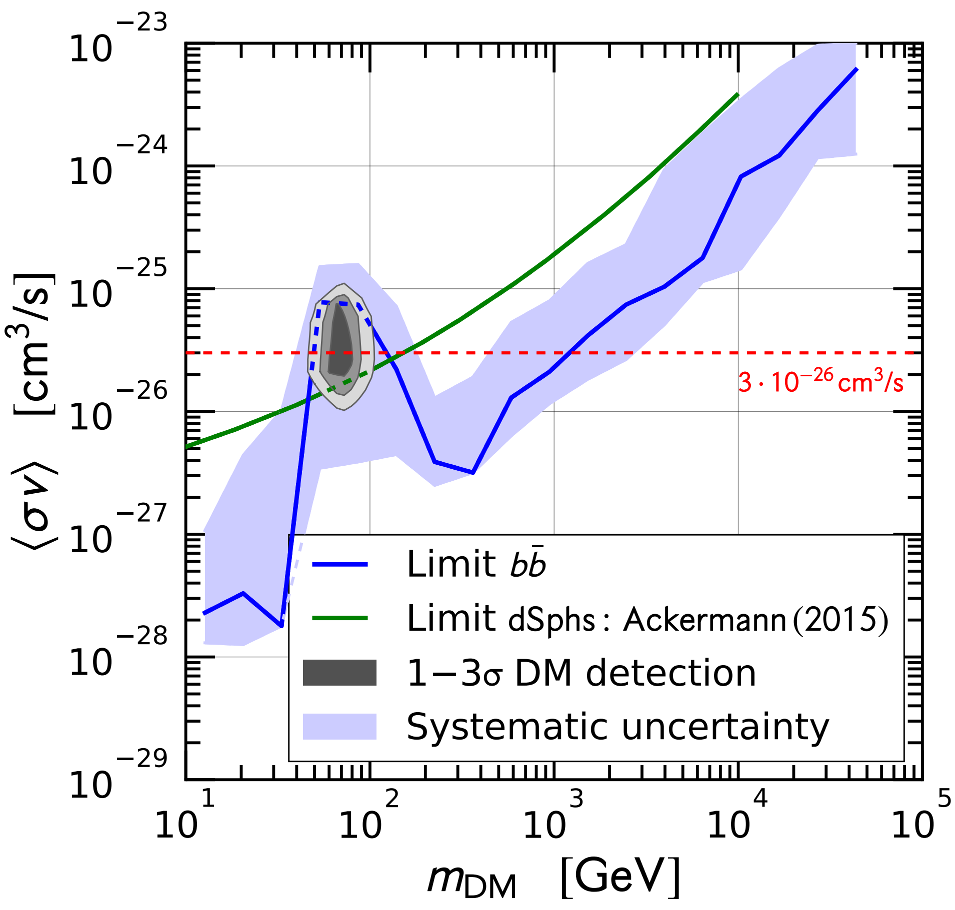




- The ~18 GV feature remains when fitting to 1 GV: DM cannot fit because data below 5 GV are over-predicted.

- It could be likely accommodated within the uncertainties of the solar modulation. It requires a dedicated study (and possibly time dependent measured spectra)

Marginalized DM limits



- Stringent DM limits outside the range in which a DM signal is preferred
- The band is the envelope of the systematic uncertainties
- Limits better than gamma-ray dwarfs by a factor of ~4-5
- There is a tension of the DM preference with dwarfs limits, although the same is true for the CG excess

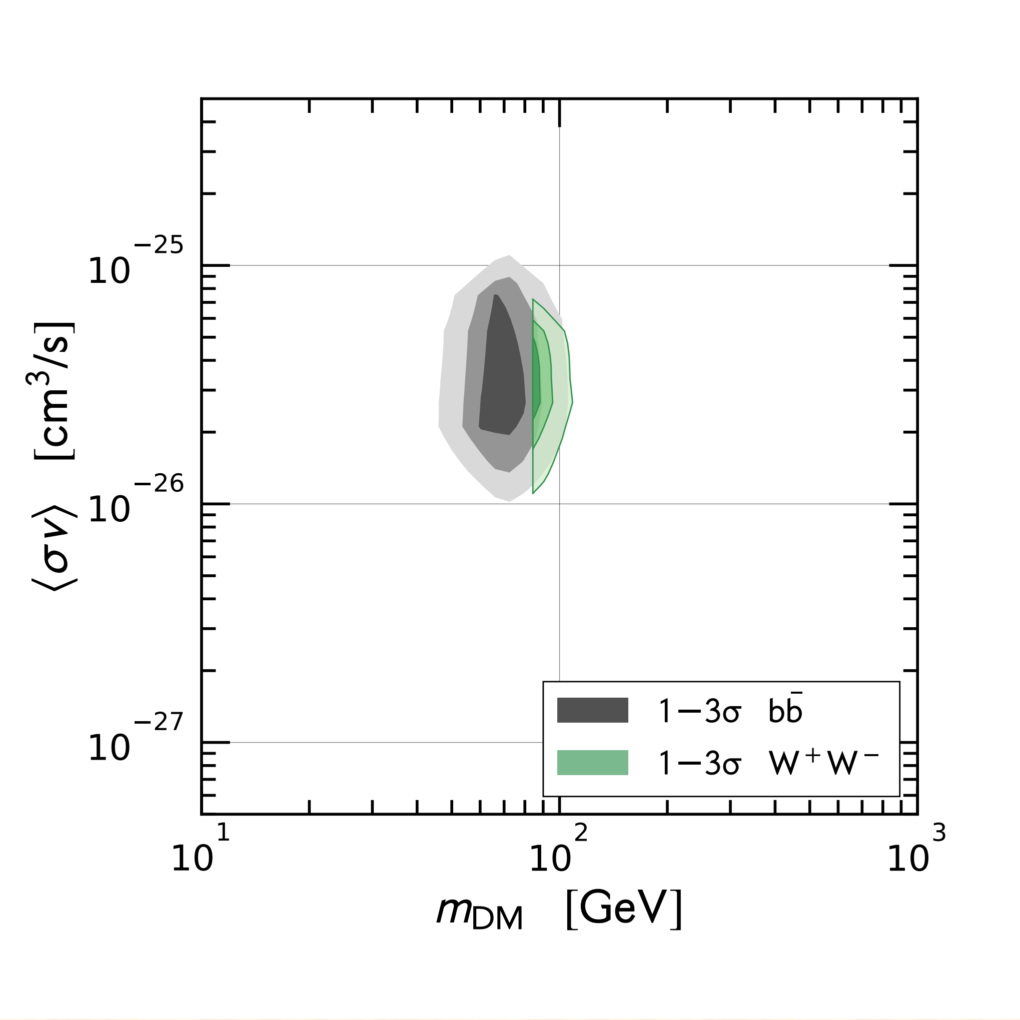
Outlook

- Official AMS-02 data for Li, C, B/C, and more are on the way.
- Important to cross-check present results vs anti-p predictions from B/C fits.

- Improvement on systematic uncertainties
  - New cross section measurements by *LHCb*
    $p + \mathrm{He} \rightarrow \bar{p} + \mathrm{X}$
  - Study of solar modulation with time-depended AMS-02 fluxes

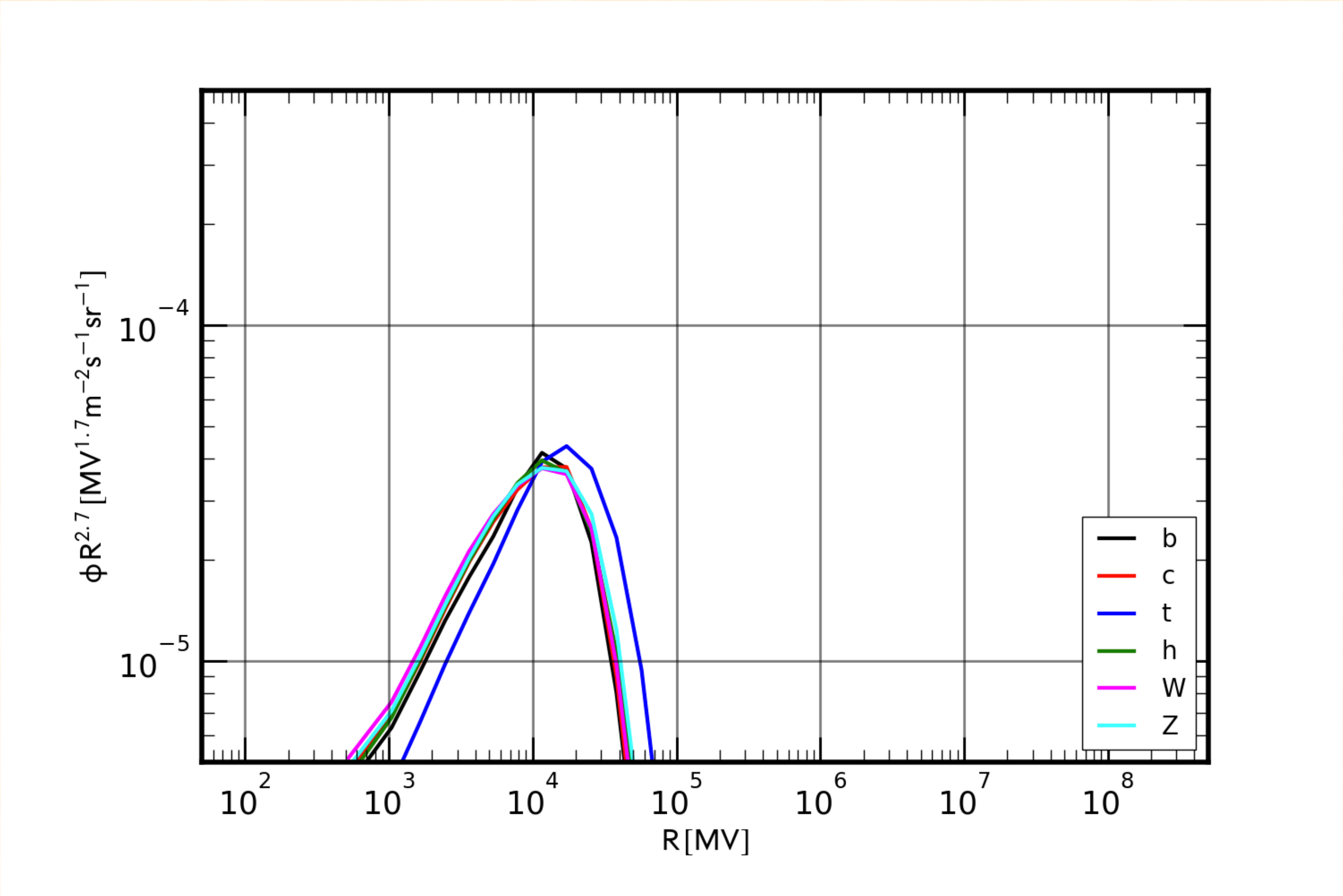
Backup

Fit W+W-

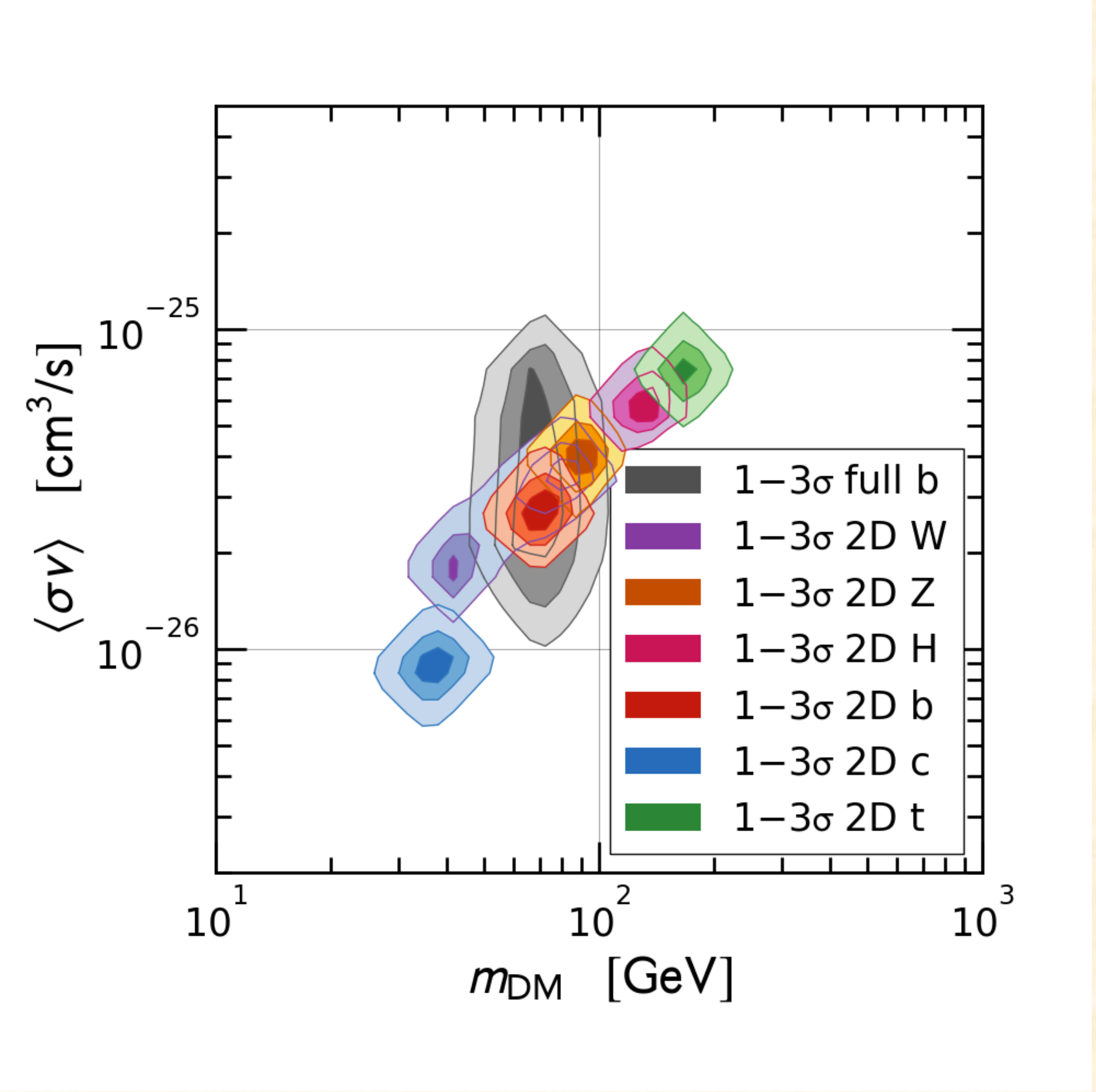


$\langle \sigma v \rangle$ [cm^3/s]
10^{-25}
10^{-26}
10^{-27}
10^1
10^2
10^3
m_{DM} [GeV]
1−3σ $b\bar{b}$
1−3σ W^+W^-

Fit various channels(1)



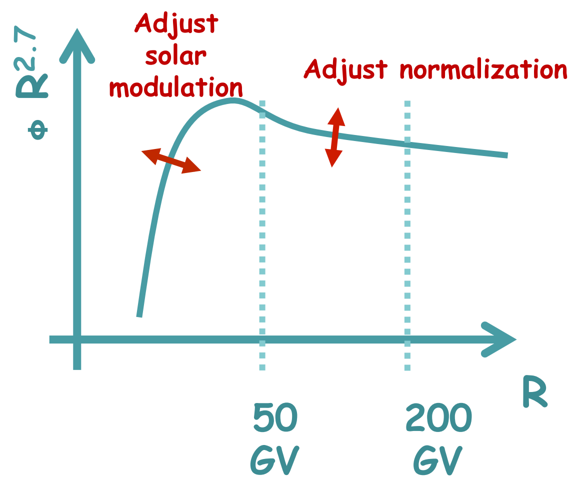
Fit various channels(2)



"Linear" Parameters

Marginalize these parameter for each evaluation point:

- Normalization of p, He
- Solar modulation potential



Step 1: Adjust normalization
Step 2: Adjust solar modulation

Solar Modulation

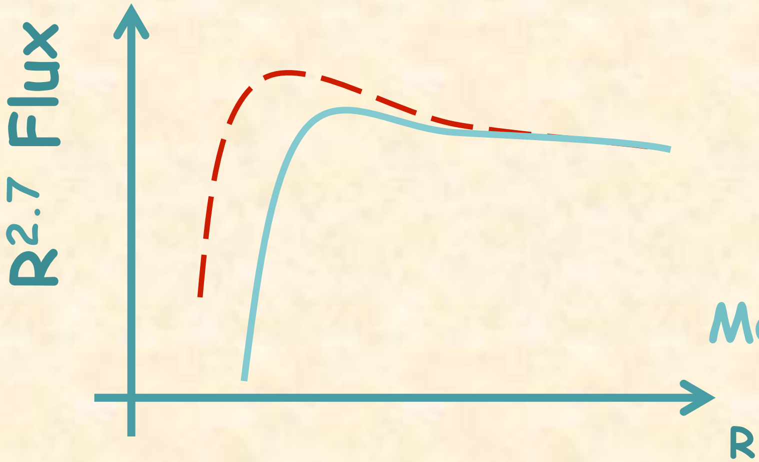
- Phenomenological description: force-field approximation

$$E = E_{\rm LIS} - |Z| e \phi,$$

$$\Phi_E(E) = \frac{E^2 - m^2}{E_{\rm LIS}^2 - m^2} \Phi_{E,{\rm LIS}}(E_{\rm LIS})$$

Our novel approach:

- Constrain LIS flux by VOYAGER data
- Exclude data below 5 GV in the main fit
- Solar modulation potential is a "linear" parameter: marginalized for each GALPROP evaluation



LIS flux fitted to VOYAGER

Modulated flux fitted to AMS

Chi2 values

Experiment	Fit without DM	Standard fit with DM
	χ^2 (Number of data points)	
Proton (AMS-02)	9.6 (61)	6.2 (61)
Proton (VOYAGER)	1.8 (4)	0.4 (4)
Helium (AMS-02)	30.8 (65)	24.8 (65)
Helium (VOYAGER)	2.3 (4)	1.6 (4)
$\bar{p}/p$ (AMS-02)	26.6 (42)	12.6 (42)
Total	71.0 (176)	45.6 (176)