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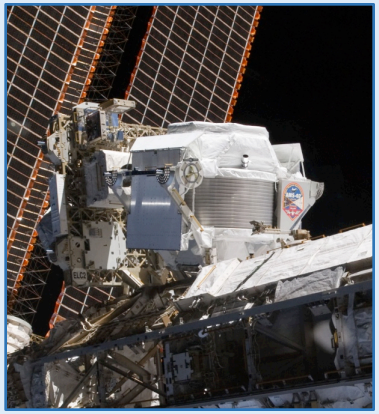
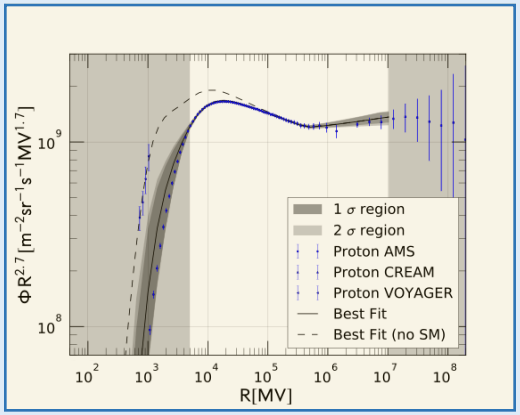
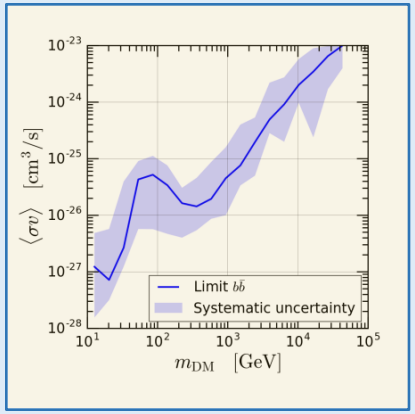
CR Propagation and DM

Global analysis of cosmic-ray propagation in the light of AMS-02 and the impact on indirect detection of dark matter







Collaborator:
Dr. Alessandro Cuoco

Partly based on:
arXiv:1607.06093

12 Sep. 2016

Outline

- Introduction
- Setup of the global parameter fit
- CR propagation of the light elements: p, He, $\bar{p}/p$
- First glance at the heavier species: Li, C, and B/C
- DM Limits from $\bar{p}/p$

Motivation

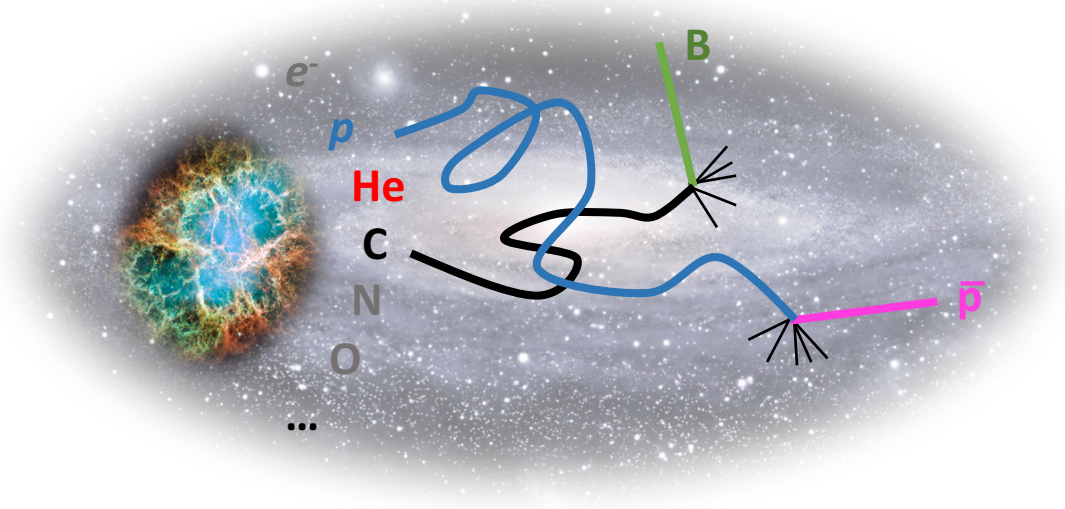
- Large uncertainties in cosmic-ray (CR) astrophysics
- New precision data from AMS-02
- DM constitutes 80% of the matter density
- Particle nature remains unknown

http://photos.up-wallpaper.com/images255/yr5nfpv13vh.jpg

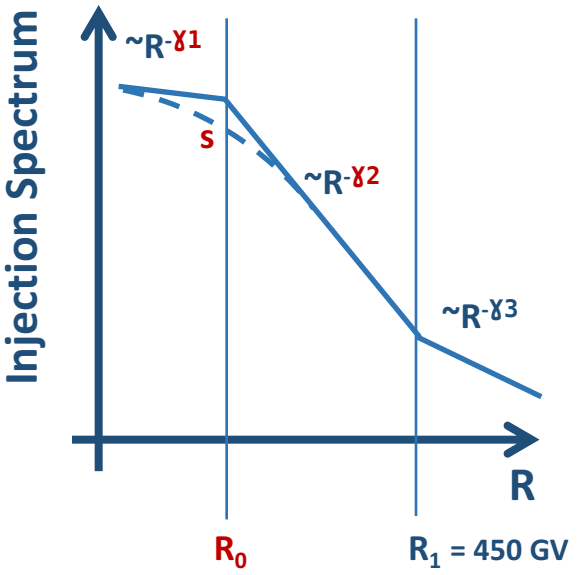
Cosmic-Ray Propagation Sources

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

- **Sources**



Injection spectrum for primaries



Astrophysical Sources:
- SNR or Pulsars

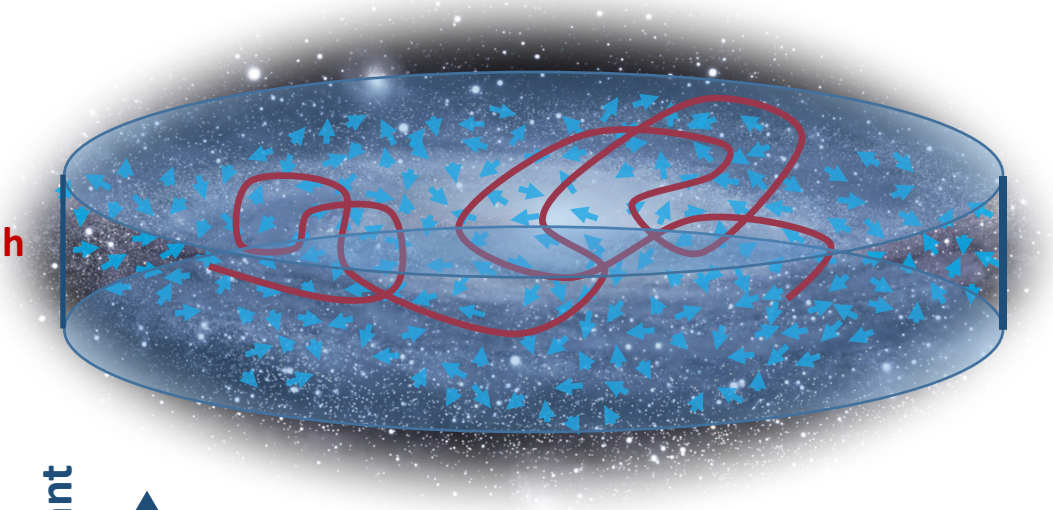
➢ **Primary CRs**:
p, He, C, …

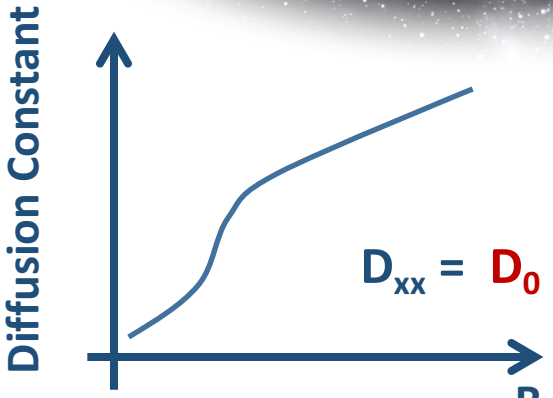
Interaction with ISM:
- Fragmentation or production

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

Cosmic-Ray Propagation Diffusion

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





$D_{xx} = D_0\,\beta\,(R/4GV)^{\delta}$

- **Sources**
- **Diffusion**
- **Convection**

  $V = v_{0,c}\ \mathrm{sign}(z)\ e_z$
- **Reacceleration**

  in terms of v_{Alfven}
- **Energy loss**
- **Fragmentation and decay**

We use ***GALPROP*** to numerically solve the diffusion equation.

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
- **AMS-02** (preliminary AMS Days 2015)
  - **$\bar{p}/p$**
    http://indico.cern.ch/event/381134/contribution/3/attachments/759339/1041605/AMS_positrons_antiprotons.pdf (25.02.2016)
  - **Carbon**
    http://indico.cern.ch/event/381134/contribution/25/attachments/759321/1041586/HeIII_AMSDays_CHe_170415.pdf (25.02.2015)
  - **B/C**
    http://indico.cern.ch/event/381134/contribution/23/attachments/759333/1041599/Oliva_150417_-_B-over-C_for_AMSDays.pdf (20.12.2015)
  - **Li**
    http://indico.cern.ch/event/381134/contributions/900575/attachments/759319/1041584/Derome_AMSdaysLi.pdf (20.12.2015)
- **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

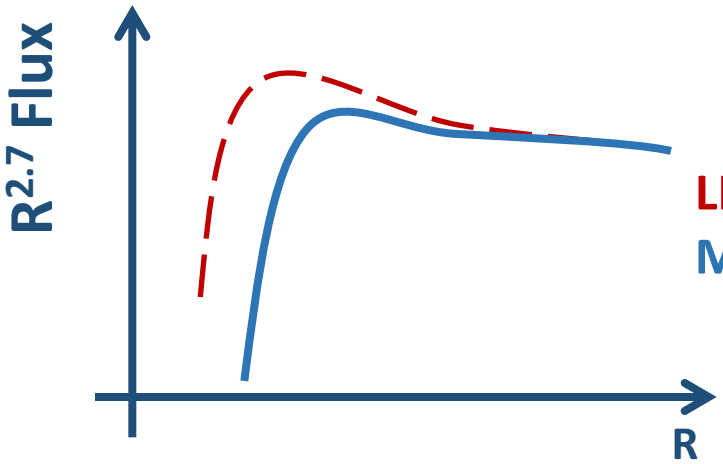
Solar Modulation

- Phenomenological description: force-field approximation

$$E = E_{\mathrm{LIS}} - |Z|e\phi,$$
$$\Phi_E(E) = \frac{E^2 - m^2}{E_{\mathrm{LIS}}^2 - m^2}\Phi_{E,\mathrm{LIS}}(E_{\mathrm{LIS}})$$

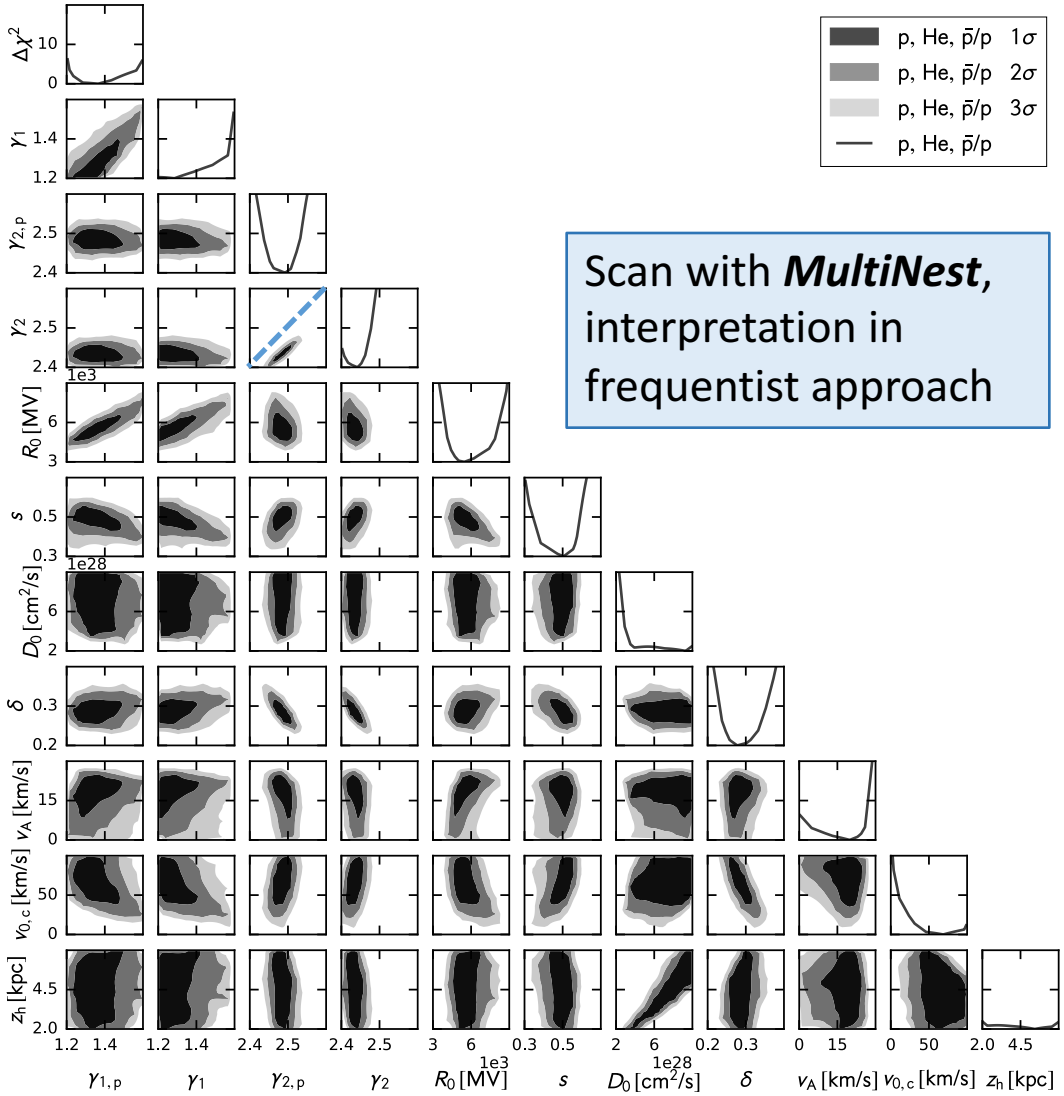
Our novel approach:

- 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



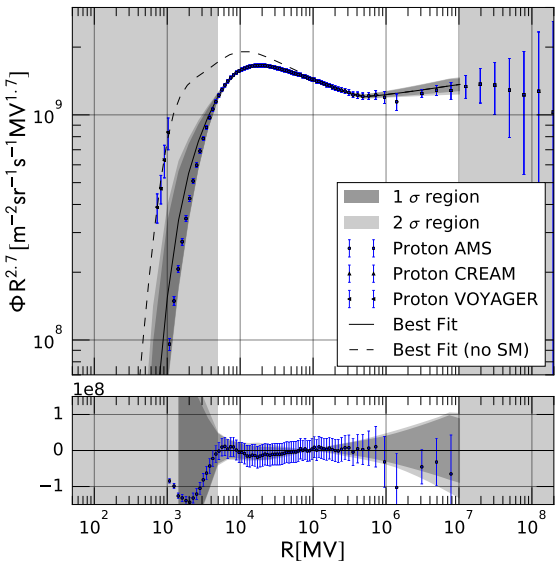
LIS flux fitted to VOYAGER
Modulated flux fitted to AMS

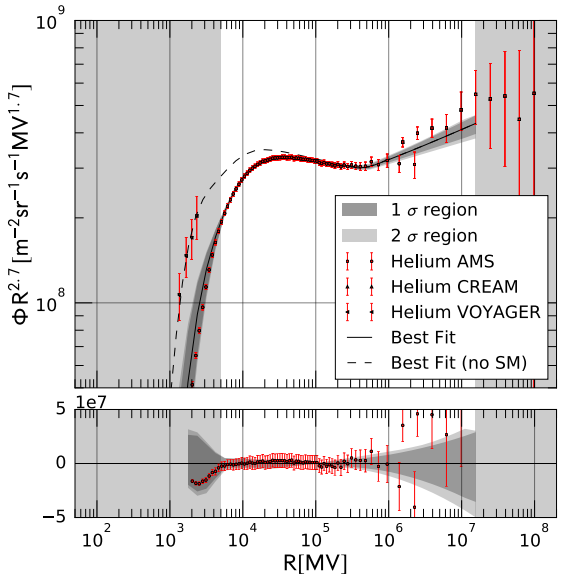
Main Fit *p*, He, $\bar{p}/p$



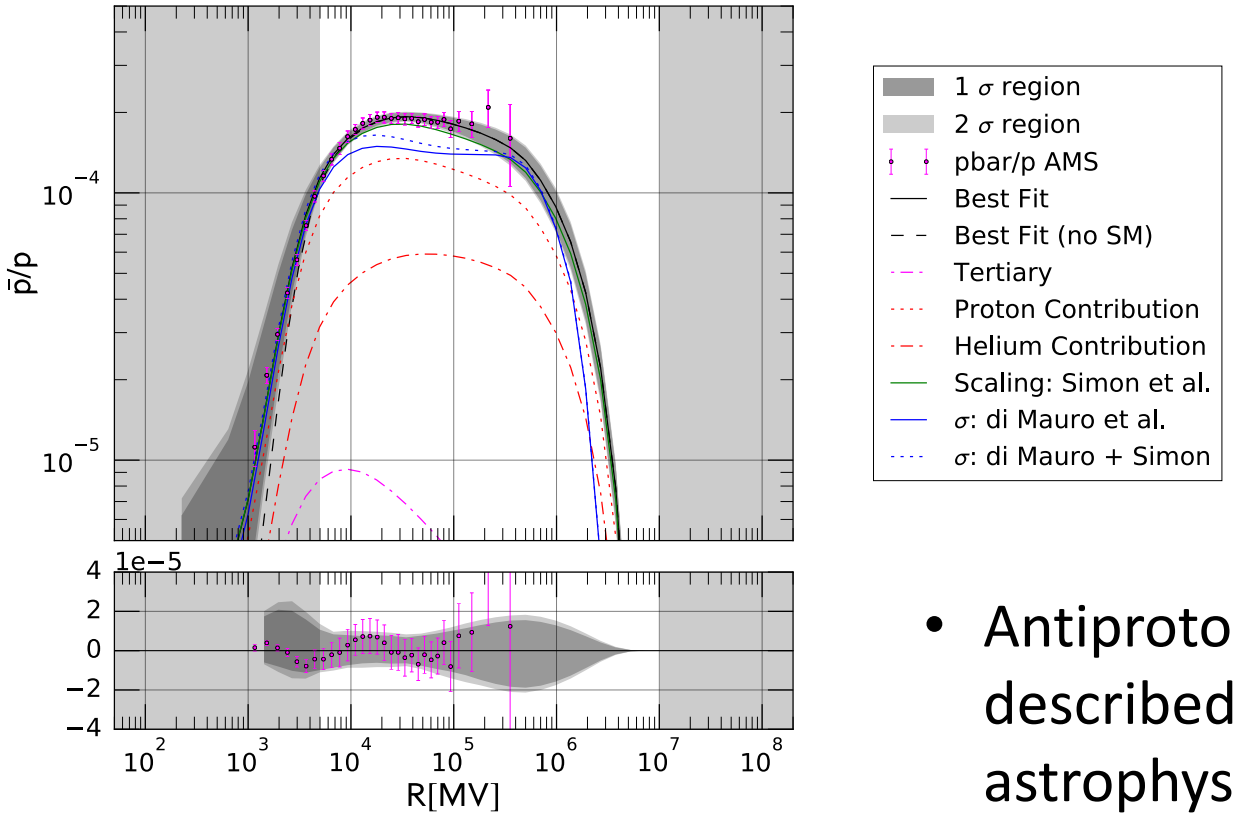
Scan with ***MultiNest***, interpretation in frequentist approach

Best Fit:





Antiproton-to-proton Ratio



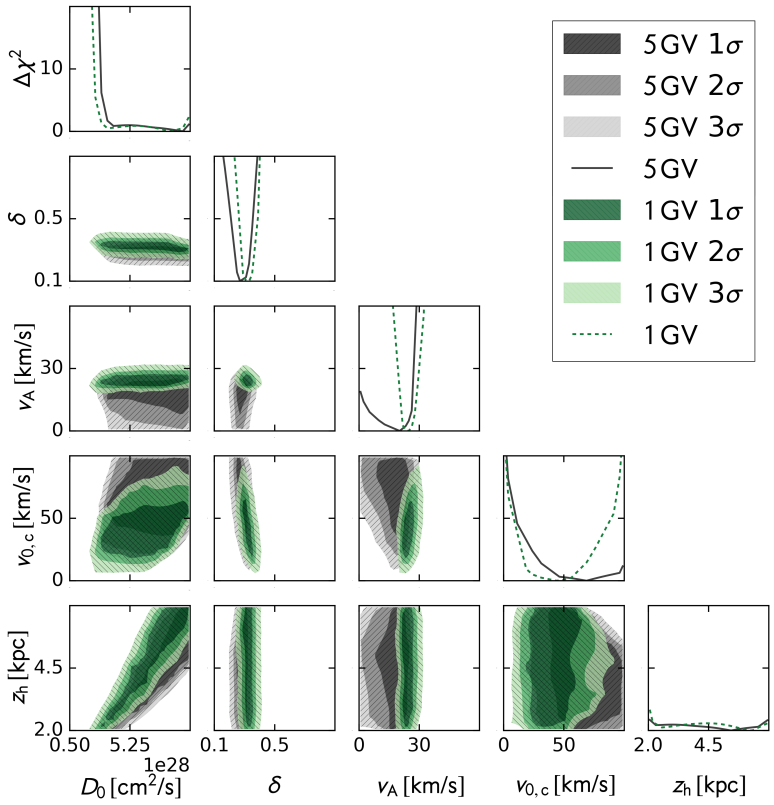
- Antiprotons are reasonably described by known astrophysical processes
- There are still large uncertainties in the production cross section

Handle on systematic Uncertainties

Several fits with different assumptions:

- Lower rigidity threshold at 1 GV
- Lower rigidity threshold at 5 GV
- Without convection
- $\bar{p}$ production cross section by di Mauro

Comparison: Fit down to 1 GV

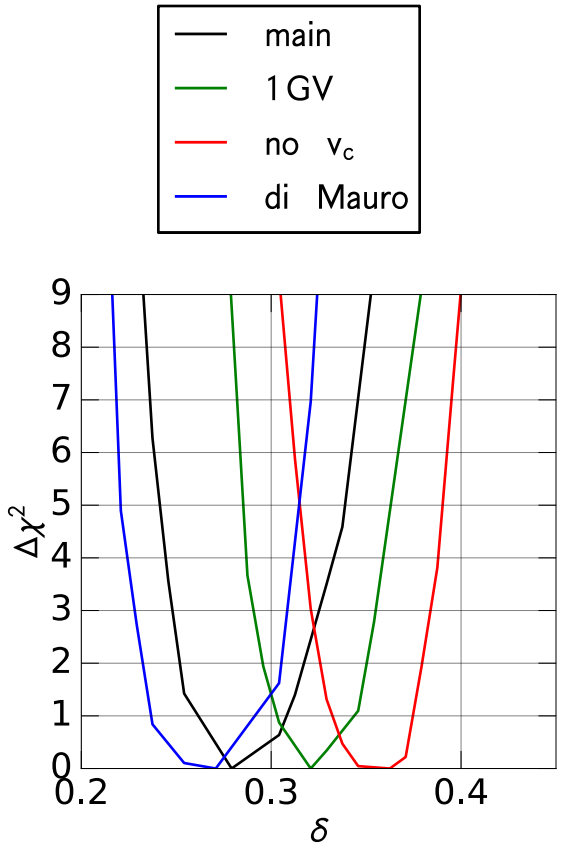


Results

- Universal injection spectrum for *p* and He is in conflict with AMS-02 data
- Systematic uncertainties dominate:
  - Solar modulation
  - Choice of diffusion model
  - Antiproton production cross section
- Value for δ is stable against systematics

$$\delta = 0.30^{+0.03}_{-0.02}(stat)^{+0.10}_{-0.04}(sys)$$

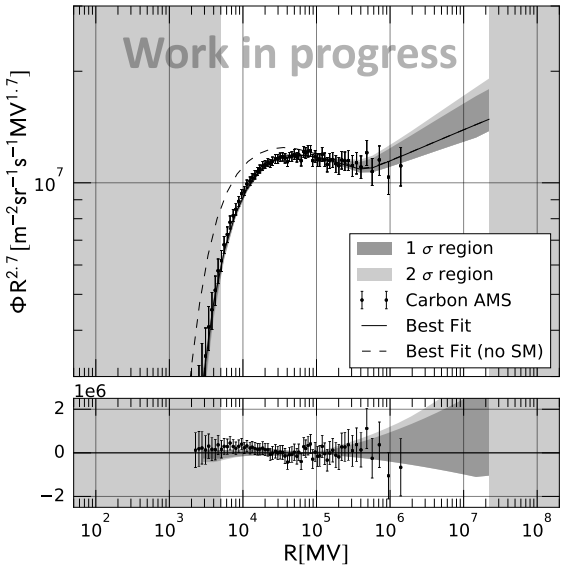
- Systematic preference for either convection or reacceleration
- Well known D_0-z_h degeneracy remains



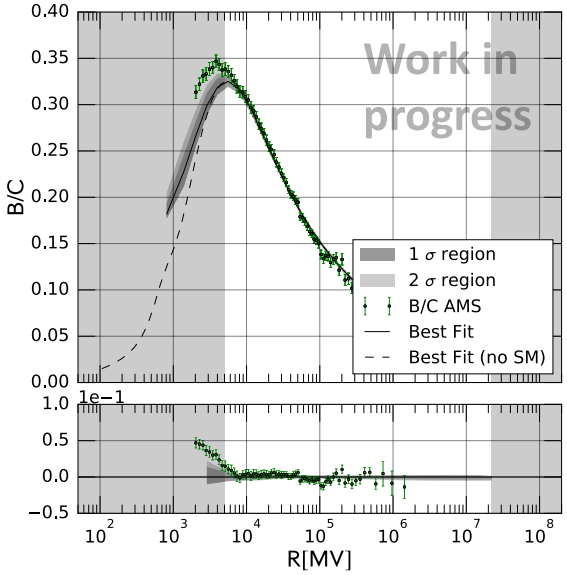
Combined fit Li, C, B/C

- Fit to preliminary AMS-02 data is possible
- Cracks in the “simple” models used until now appear: Heavy and light species are not compatible

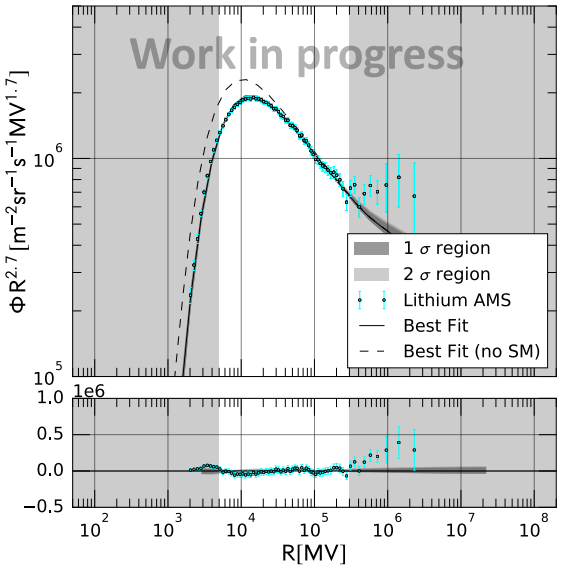
Carbon



B/C

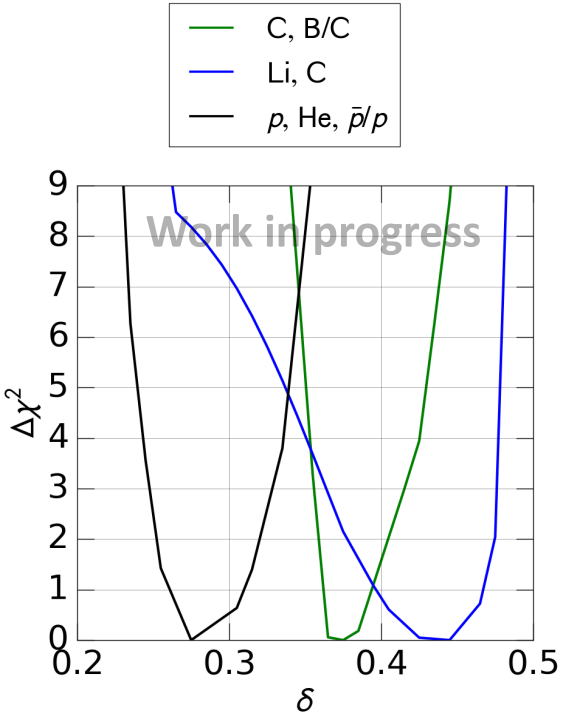


Lithium



Results

- Li, C, and B/C results are in tension with p, He, $\bar{p}$
- Li and B can be combined in one fit
- Large systematic uncertainties, also on δ, remain:
  - Solar modulation
  - Choice of diffusion model
  - Choice of the data sets
  - Abundance of C and heavier species



DM as additional Source

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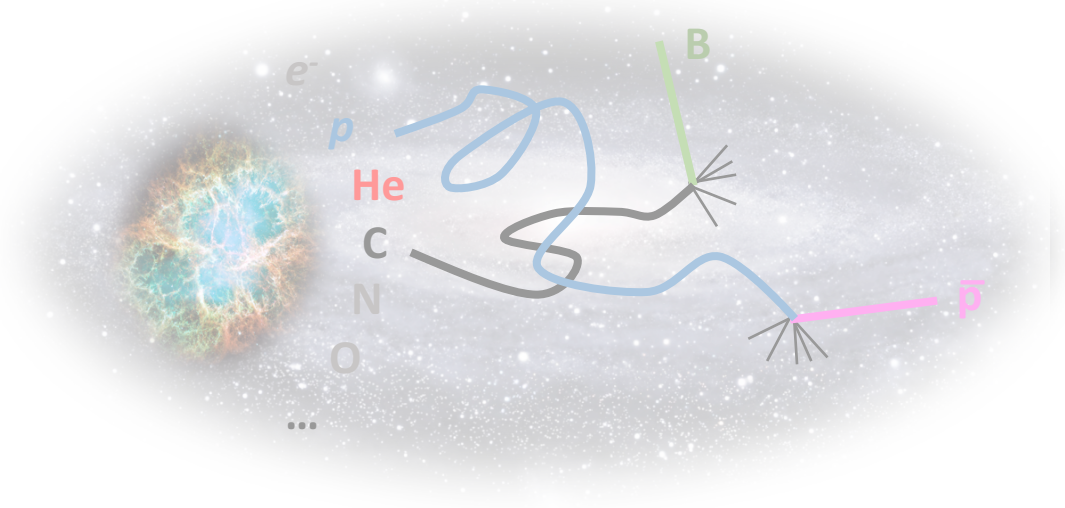
- **Sources**



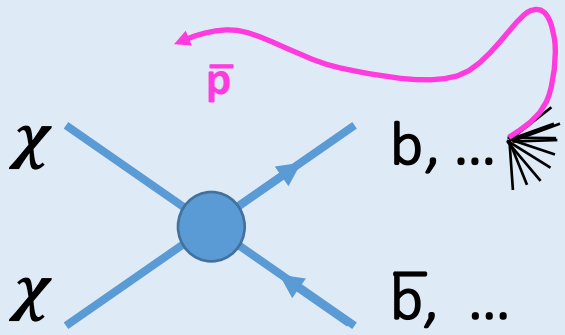
Astrophysical Sources:
- SNR or Pulsars

➢ **Primary CRs**: p, He, C, …

Interaction with ISM:
- Fragmentation or production

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

Possible Scenario: WIMP DM?



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

➢ **DM CRs**: $\bar{p}$, (e^+)

Limits on DM Annihilation Cross Section

Global CR propagation analysis with DM as antiproton source:

$$\frac{\mathrm{d}n}{\mathrm{d}t\mathrm{d}E} = \frac{1}{2}\langle\sigma v\rangle\left(\frac{\rho}{m_{\mathrm{DM}}}\right)^2\frac{\mathrm{d}N}{\mathrm{d}E}$$

Additional fit parameter:

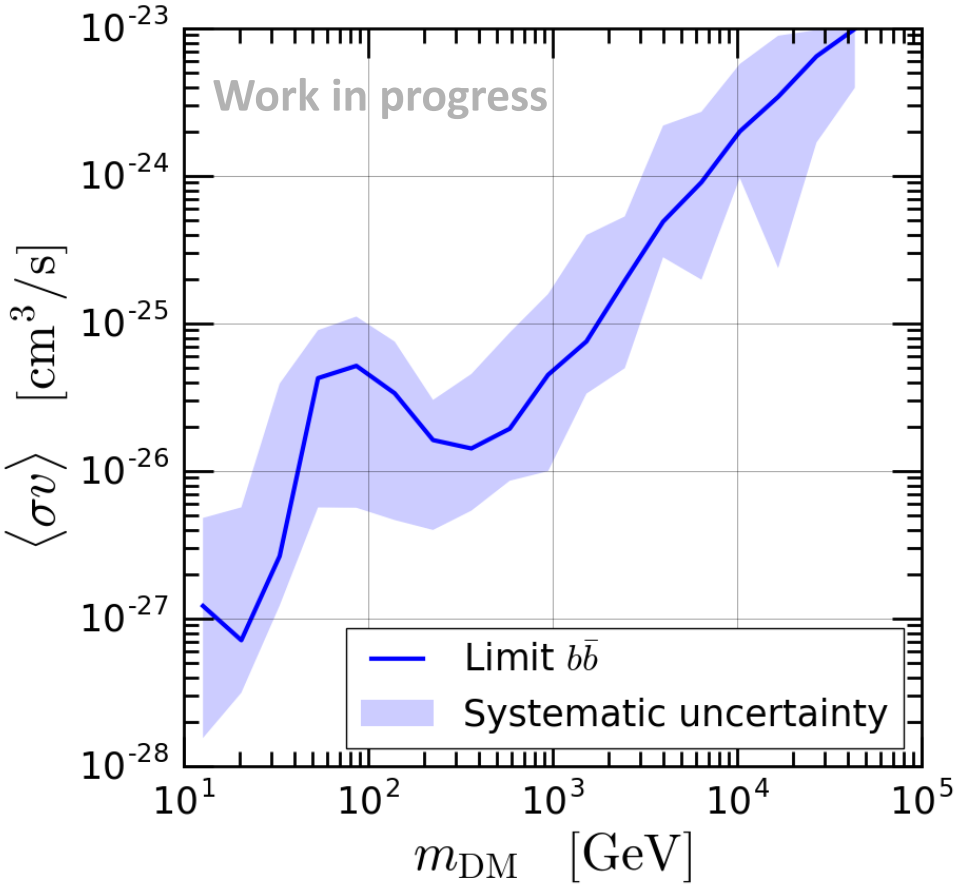
- m_{DM}
- $\langle\sigma v\rangle$

Dark Matter density:
NFW and Burkert
Local density: 0.43 GeV/cm^3

Energy spectrum of antiprotons per DM annihilation
(we use table of M. Cirelli)

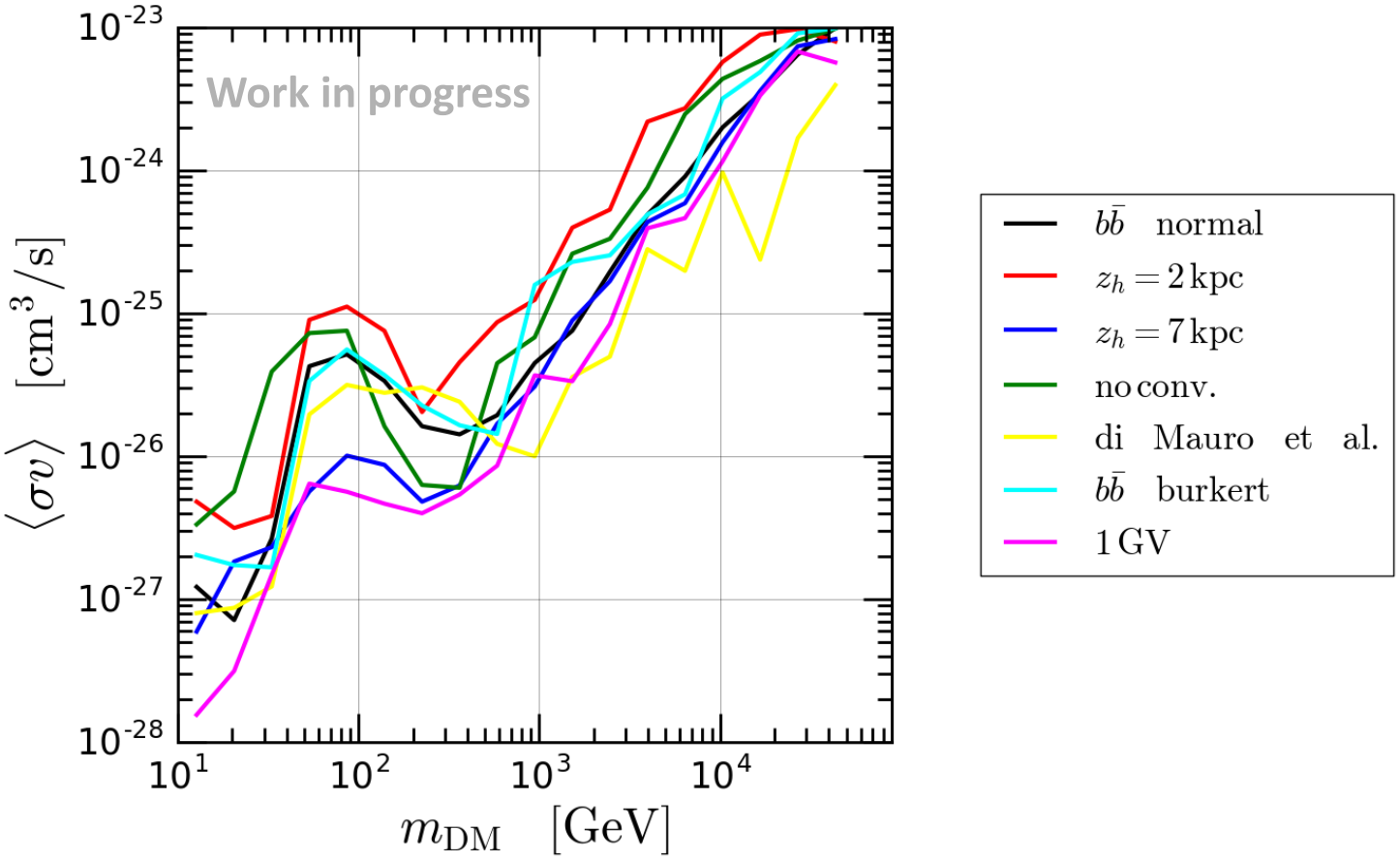
CR propagation becomes nuisance parameters

DM Limit $b\bar{b}$



- Uncertainty band contains different assumptions on diffusion model and antiproton production cross section
- Good limits (95% exclusion), below unitarity bound up to DM masses of several hundred GeV

DM Limit $b\bar{b}$

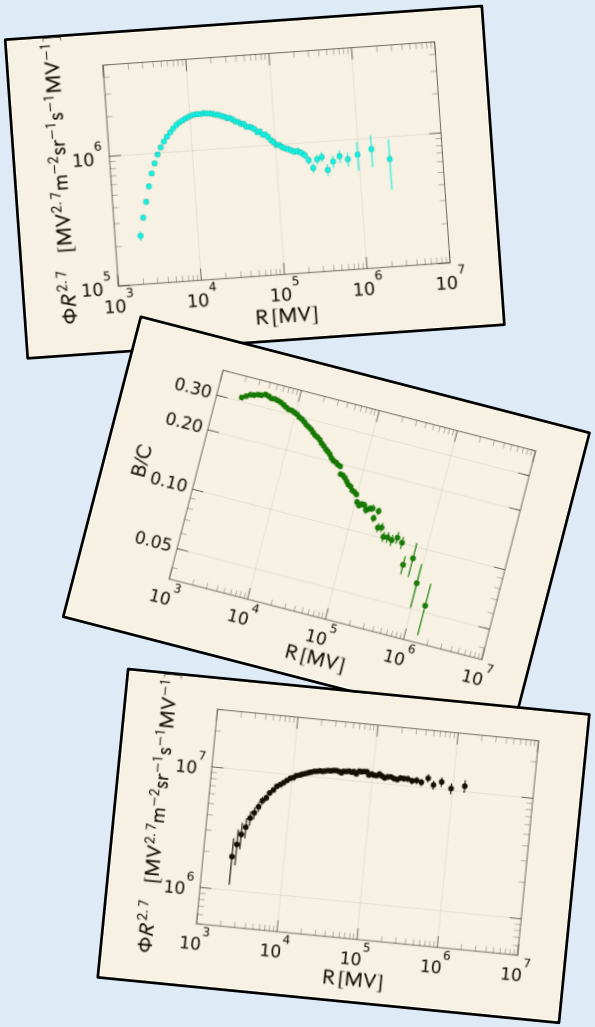


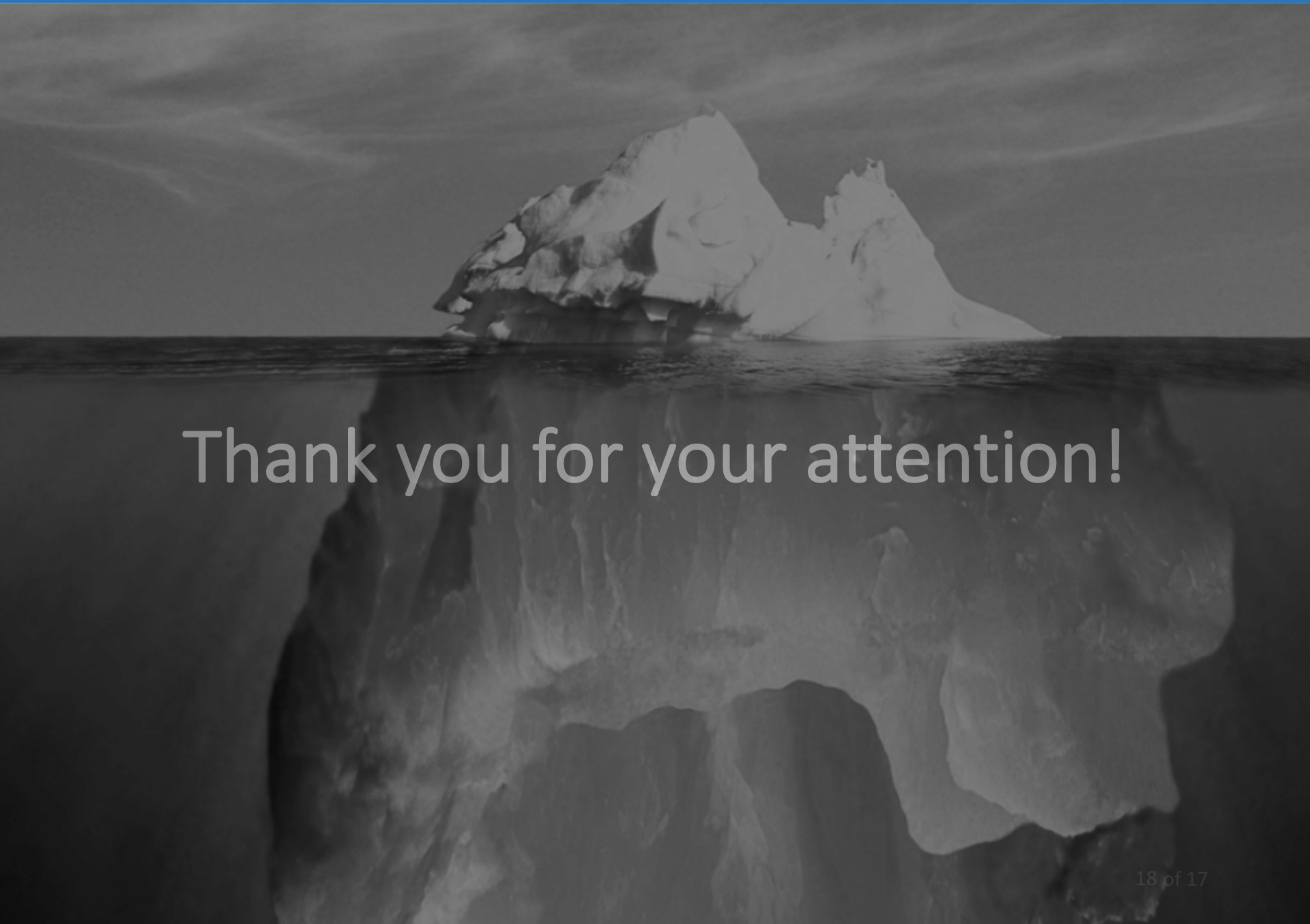
Outlook

- Official AMS-02 data for $\bar{p}$, C, B/C, and Li

- 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





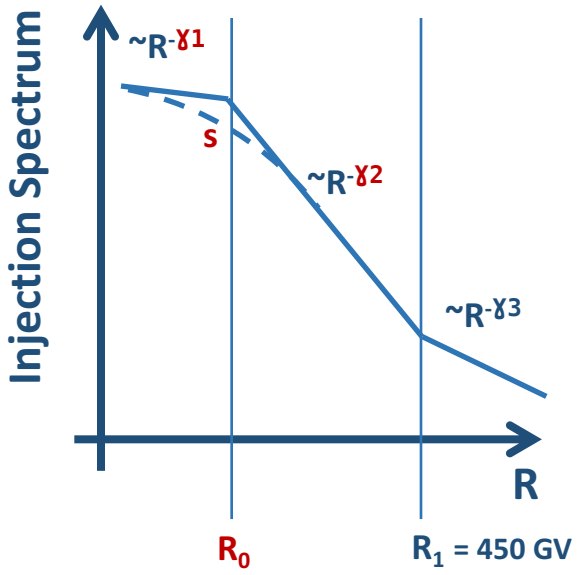
Thank you for your attention!

Backup

MultiNest Parameters

- **Injection spectrum (index p for protons)**

$\gamma_1, \gamma_{1,p}$	1.2	-	2.3	
$\gamma_2, \gamma_{2,p}$	2.0	-	2.9	
γ_3	= γ_2	-	0.14	
R_0	1	-	50	GV
s	0.05	-	1.0	



- **Diffusion constant**

δ	0.1	-	0.9	
D_0	10^{28}	-	10^{29}	cm^3/s

- **Velocity of magnetic clouds**

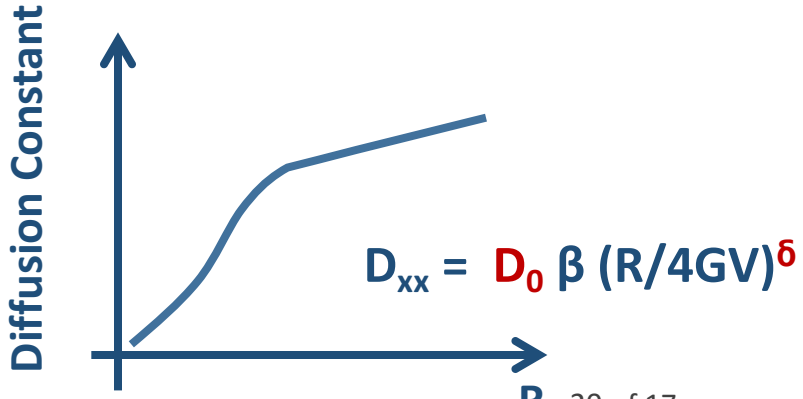
v_{Alfven}	0	-	60	km/s

- **Convection**

$v_{0,conv}$	0	-	100	km/s

- **Halo size**

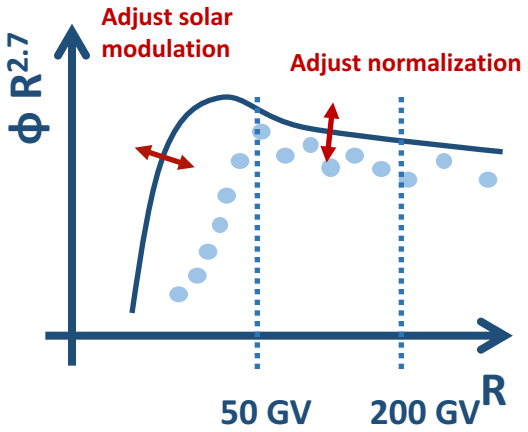
z_h	2	-	7	kpc



“Linear” Parameters

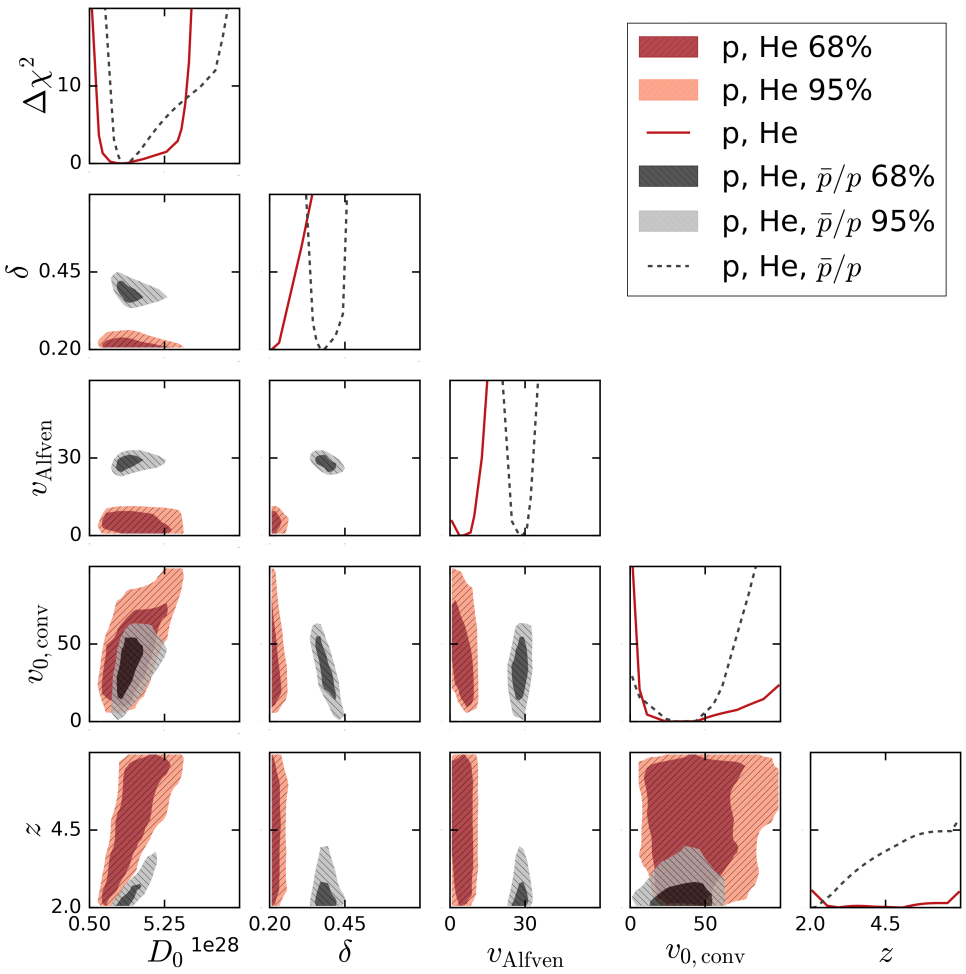
Marginalize these parameter for each evaluation point:

- Normalization of p, He, C
- Solar modulation potential

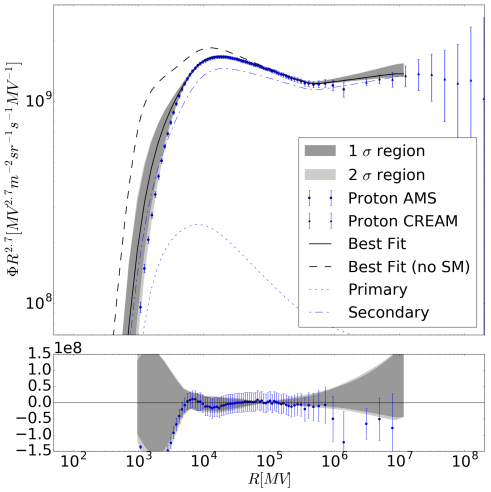


Step 1: Adjust normalization
Step 2: Adjust solar modulation

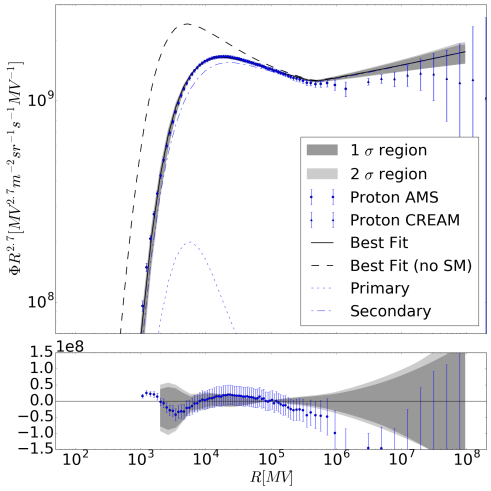
Universal injection spectrum



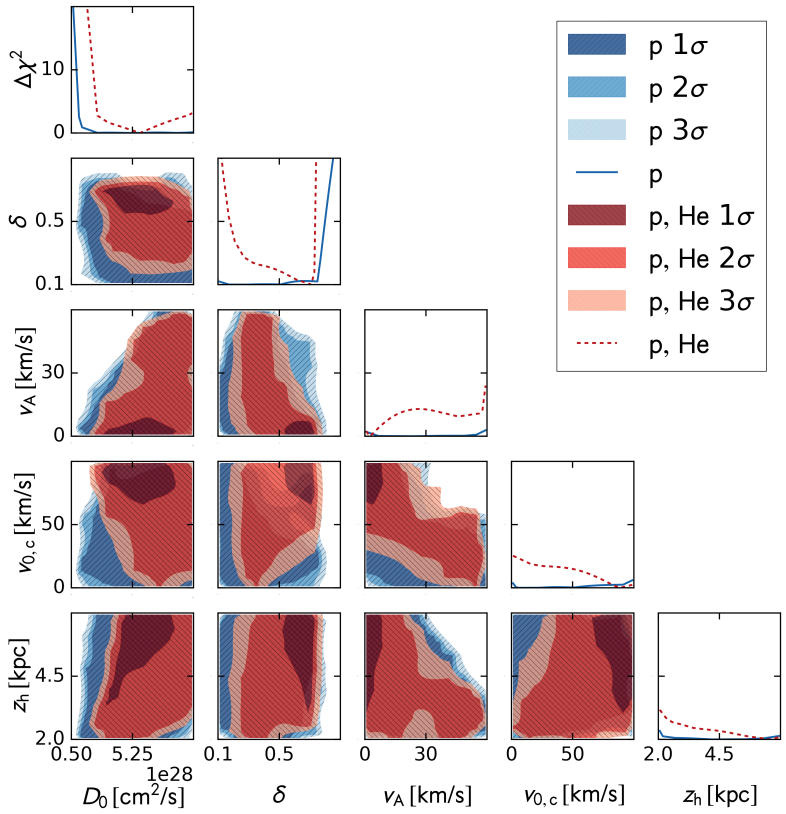
Proton, Helium

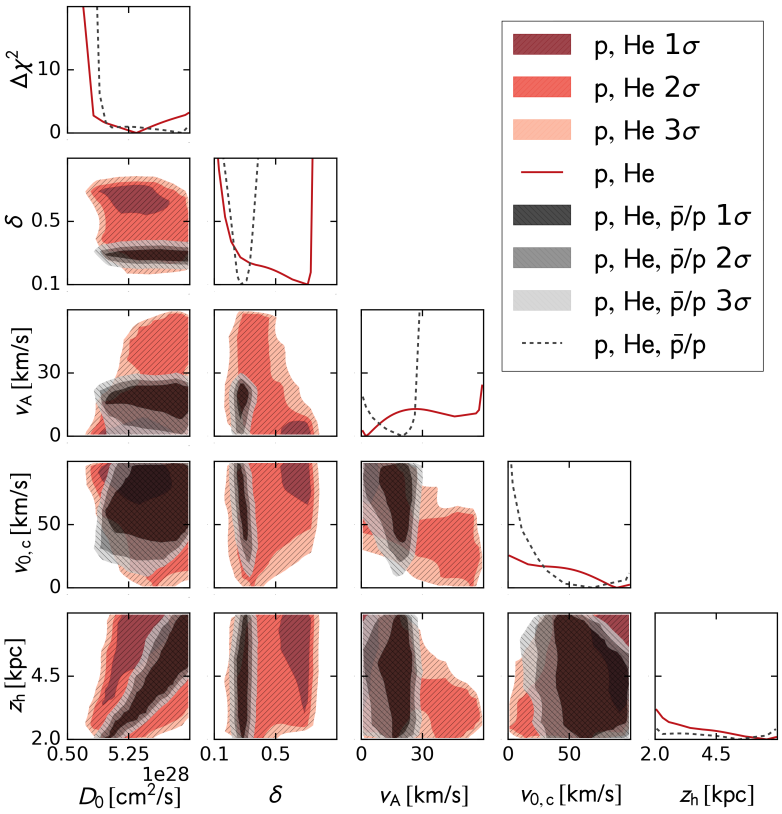


Proton, Helium, $\bar{p}/p$

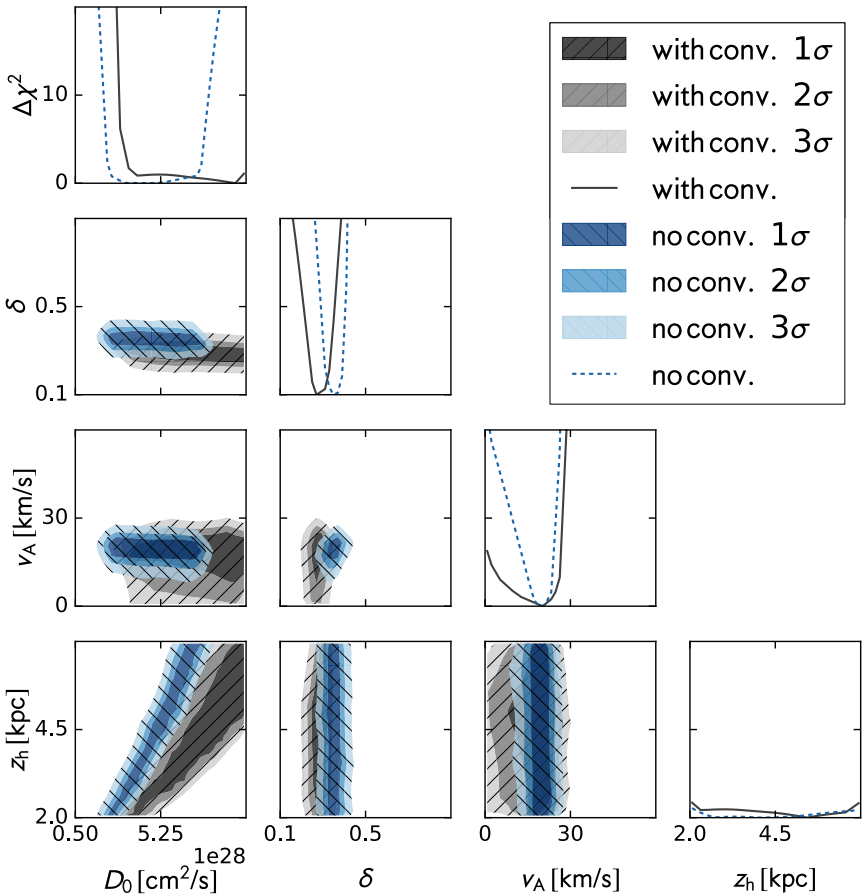


Data Compatibility

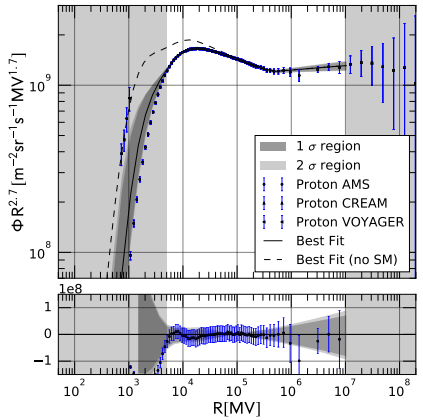


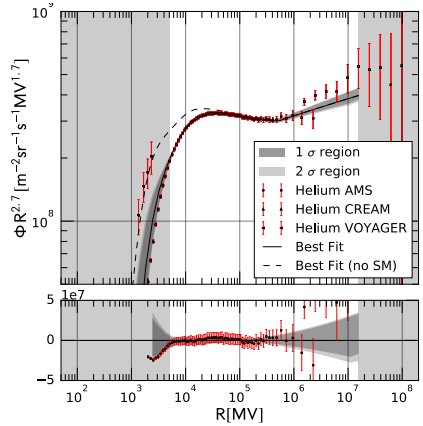


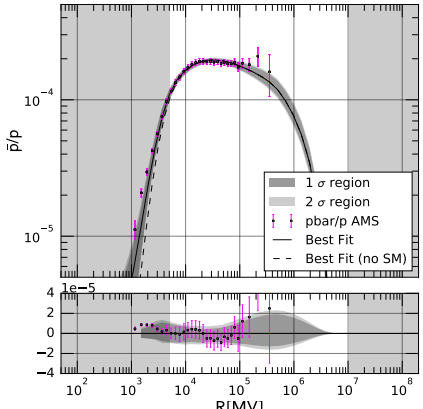
No convection p, He, $\bar{p}/p$



Best Fit:

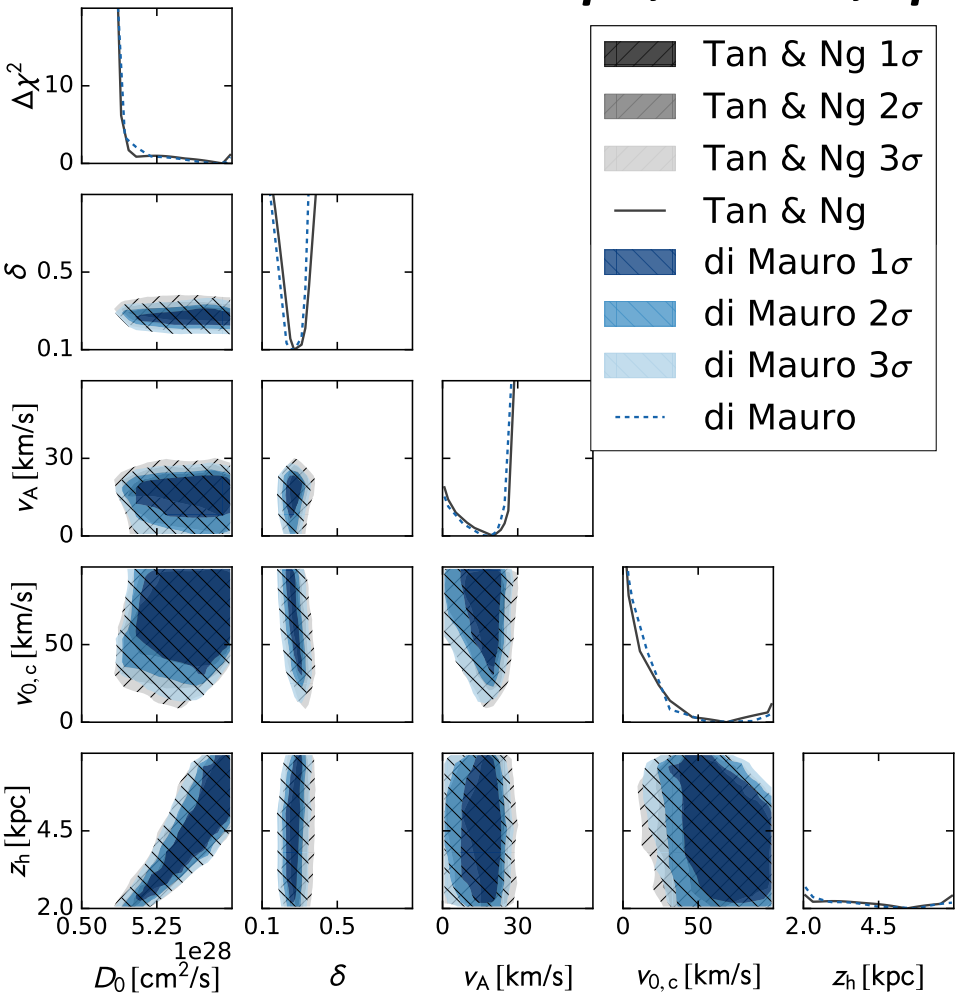




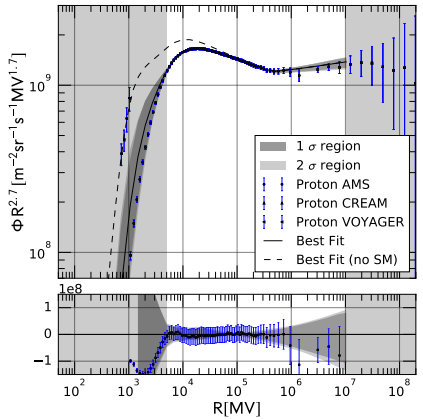


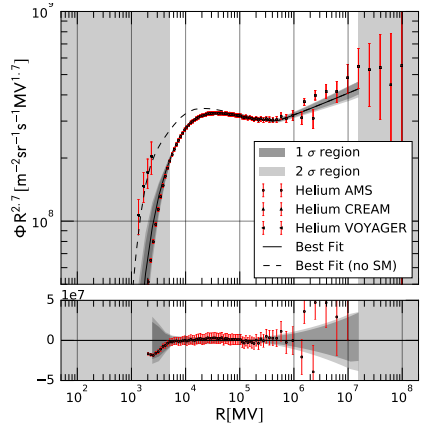
$\bar{p}$ production di Mauro

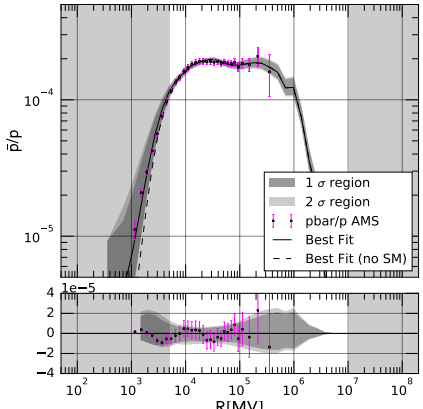
p, He, $\bar{p}/p$



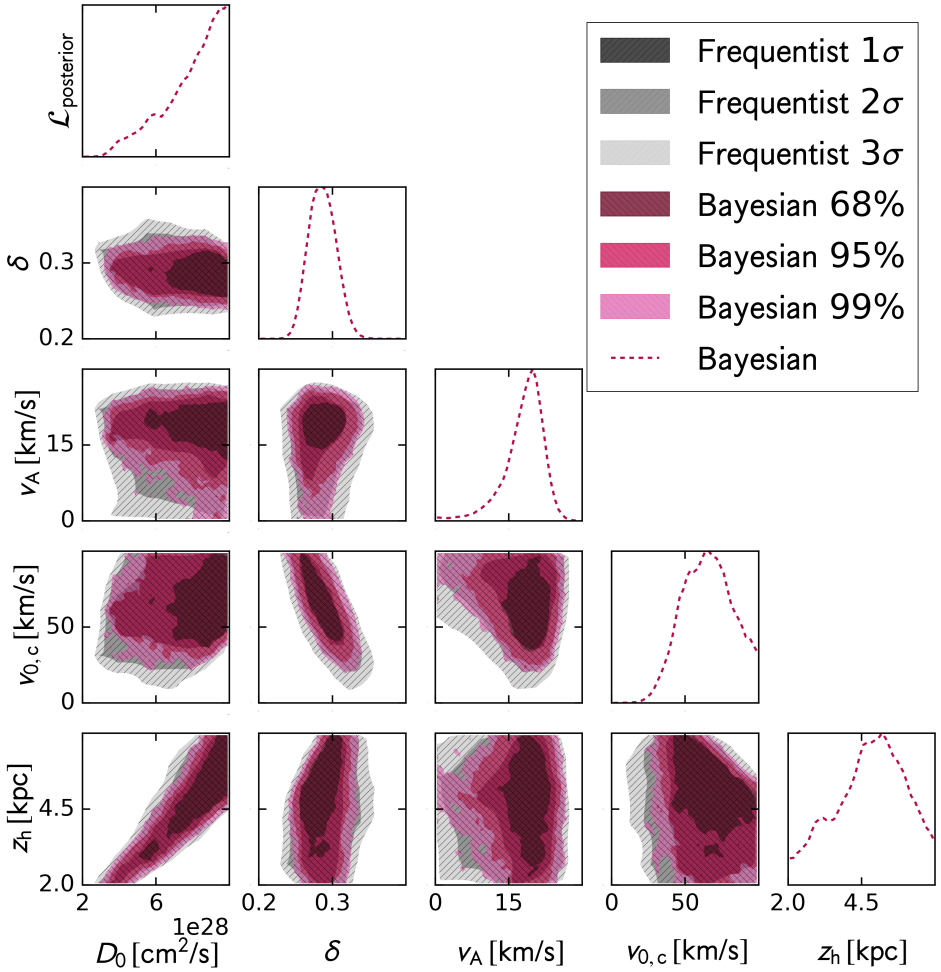
Best Fit:







Frequentist vs. Bayesian



DM limits on Annihilation Cross Section

Global CR propagation analysis with DM as antiproton source:

$$\frac{\mathrm{d}n}{\mathrm{d}t\mathrm{d}E} = \frac{1}{2}\langle\sigma v\rangle\left(\frac{\rho}{m_{\mathrm{DM}}}\right)^2\frac{\mathrm{d}N}{\mathrm{d}E}$$

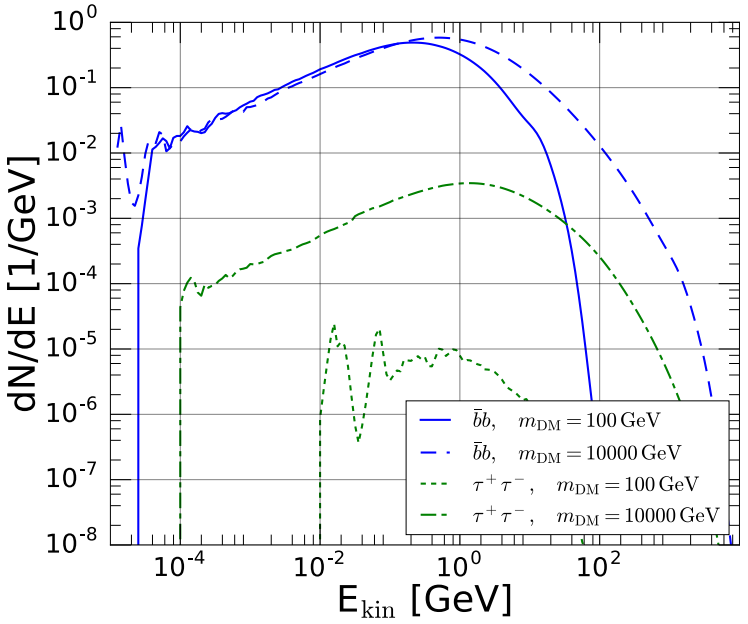
Additional fit parameter:

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

CR propagation becomes nuisance parameters

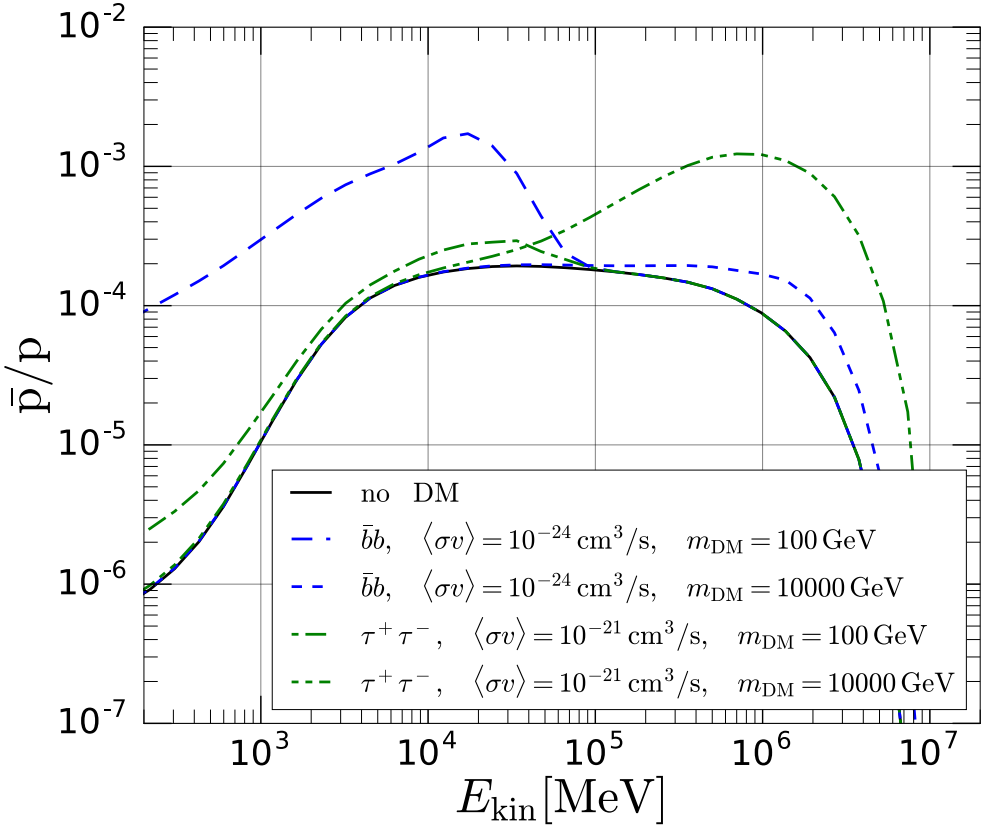
Dark Matter density:
NFW and Burkert
Local density: 0.43 GeV/cm^3

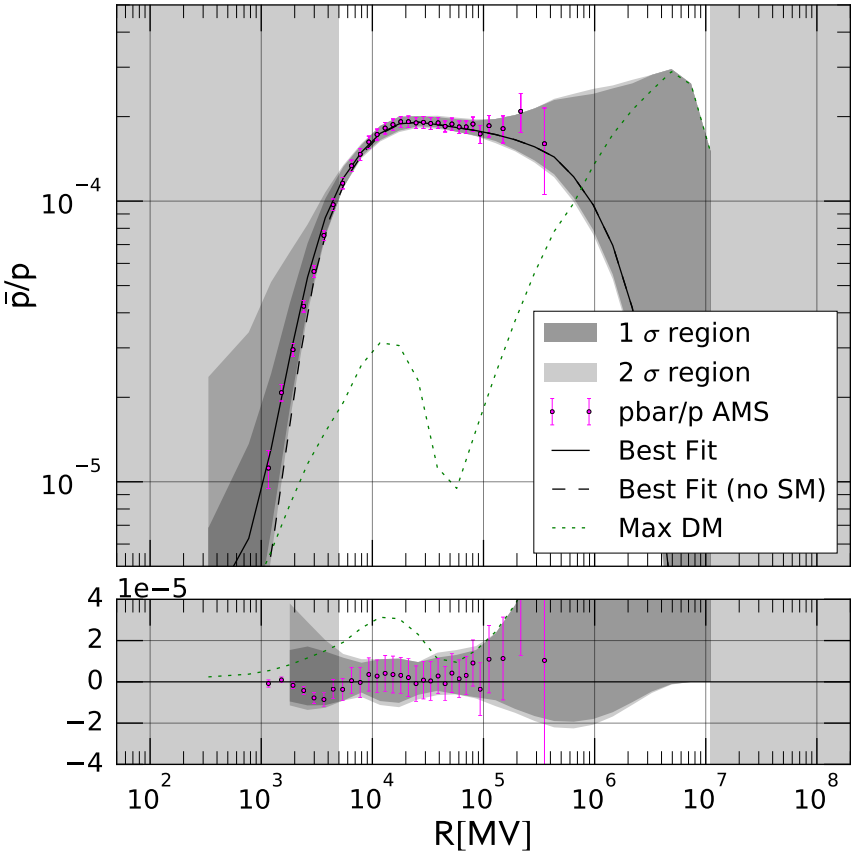
Example: dN/dE for b $\bar{b}$ and $\tau^+\tau^-$



Cirelli, M. et al., *PPPC 4 DM ID: A Poor Particle Physicist Cookbook for Dark Matter Indirect Detection*, 2012, arXiv:1012.4515v4 (http://www.marcocirelli.net/PPPC4DMID.html)

Effect of DM Antiprotons on $\bar{p}/p$



- Leptonic DM decays produce $\bar{p}$ via EW corrections
- Decay to EW gauge bosons and quarks give similar results

Best Fit $\bar{p}/p$ with $b\bar{b}$ DM