Dark Matter Searches with cosmic rays in the light of AMS-02

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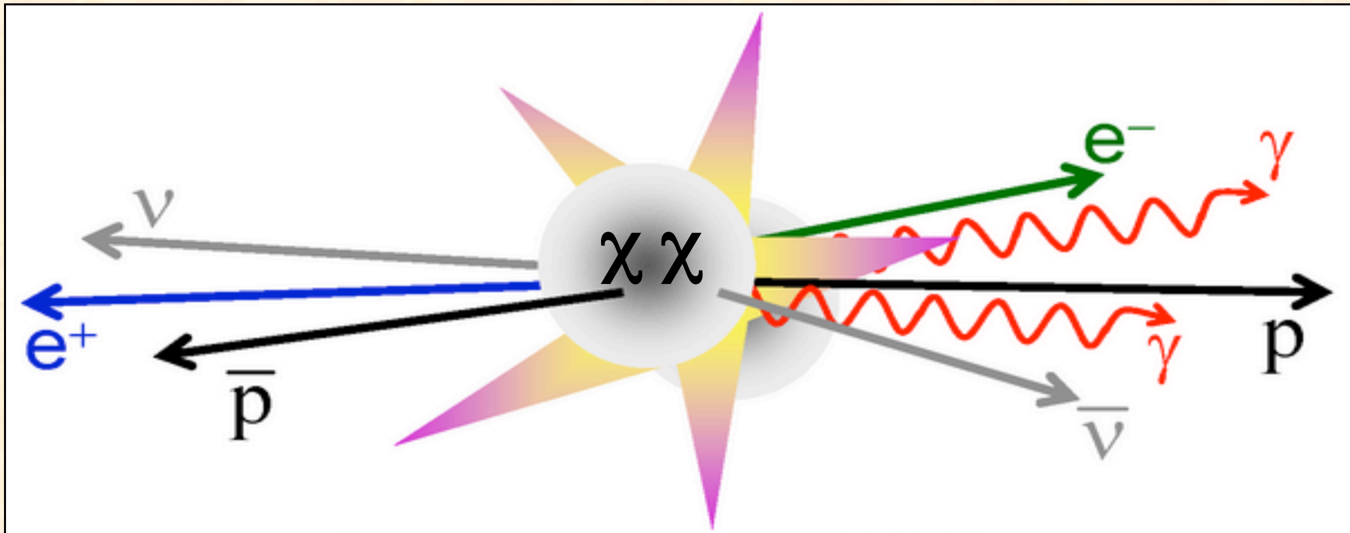
Indirect Detection of Dark Matter: the General Framework

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

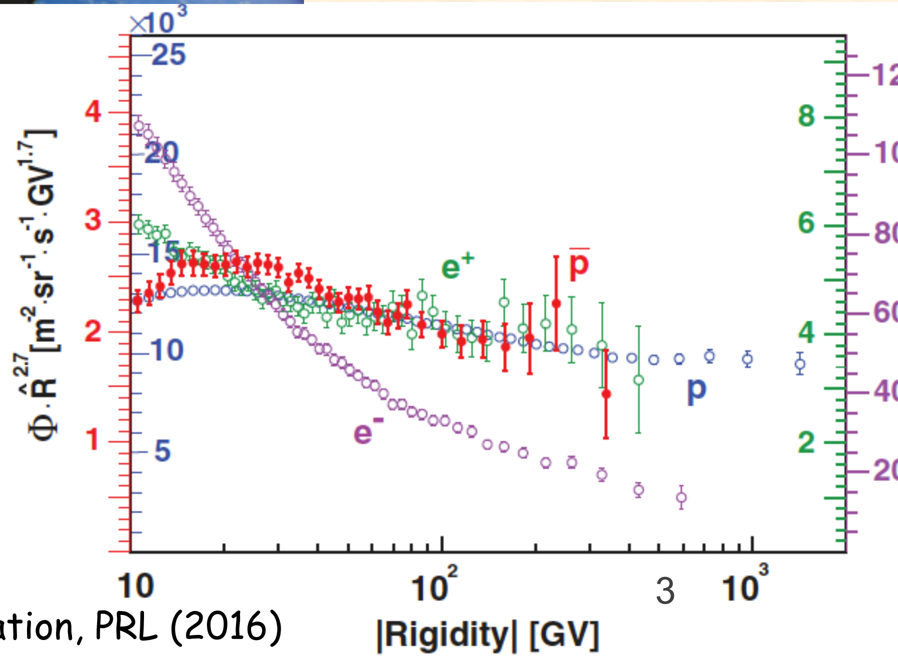
2) **Fragmentation/Decay** Annihilation products decay and/or fragment into some combination of electrons, protons, deuterium, neutrinos and gamma rays



AMS-02 CR data

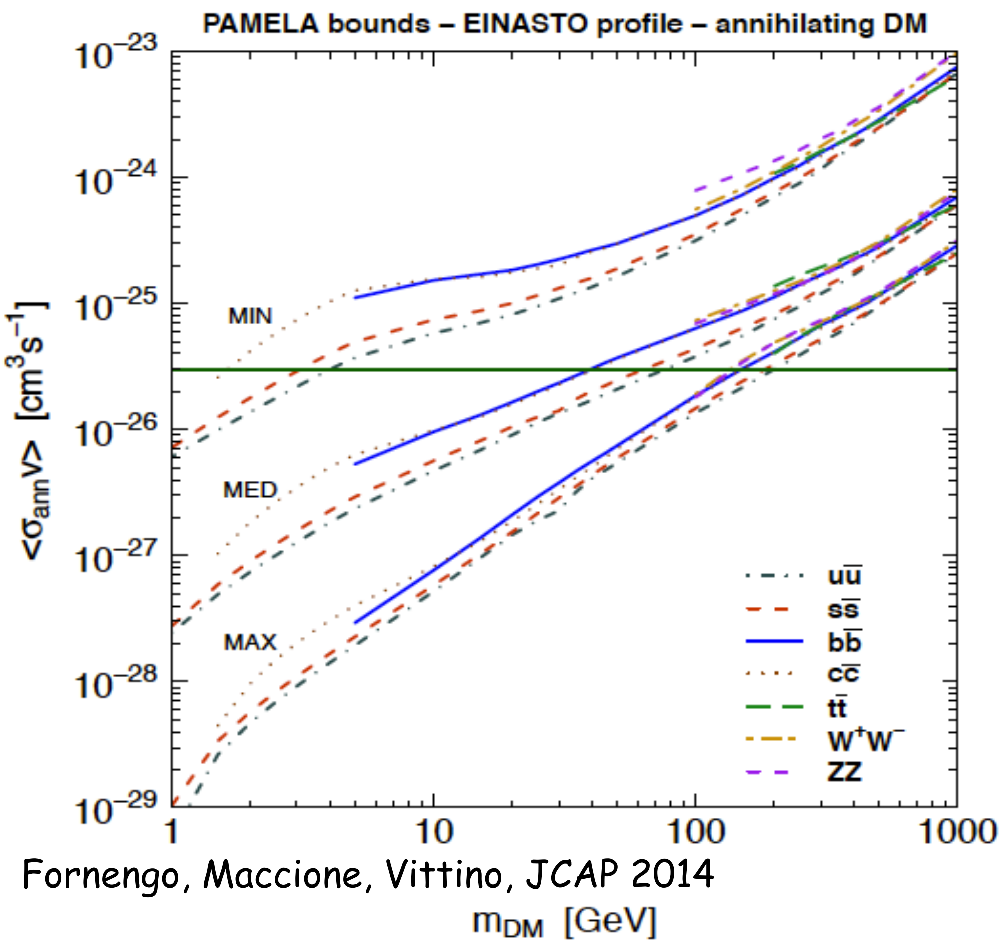
Golden Age for Cosmic Rays: PAMELA and AMS02 providing high quality data. CR precision era is finally starting

Very precise measurements from AMS02 of antiproton up to ~400 GV, and positrons up to ~800 GV



AMS02 Collaboration, PRL (2016)

Antiprotons DM limits



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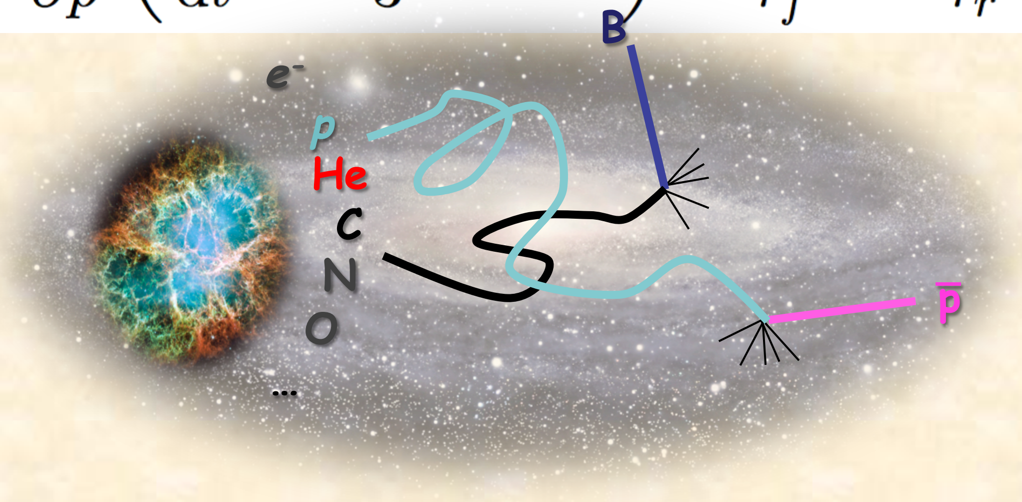
- Until now, DM constraints from antiprotons have suffered large uncertainties due to the unknowns in the CR propagation scenario.
- The precise AMS02 data allow to tackle also this issue.

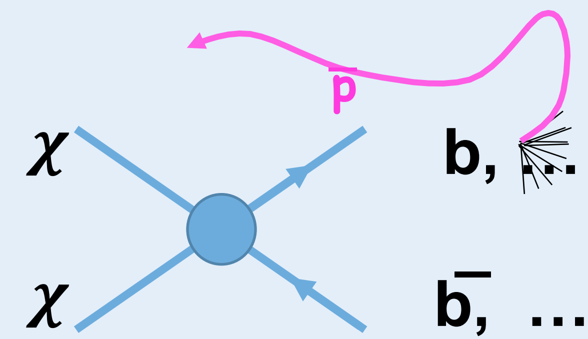
Cosmic Rays propagation

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

- **Sources**



Possible Scenario: WIMP DM?



Astrophysical Sources:
- SNR or Pulsars

➢ **Primary CRs**: p, He, C, ...

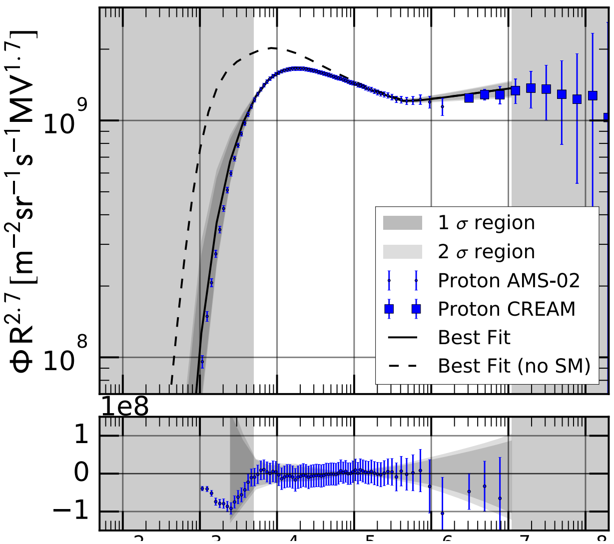
Interaction with ISM:
- Fragmentation or production

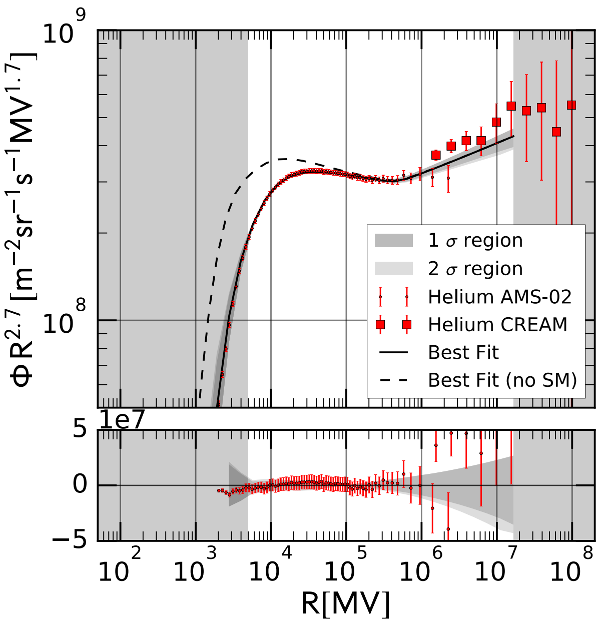
➢ **Secondary CRs**: $\bar{p}$, Li, B, ...

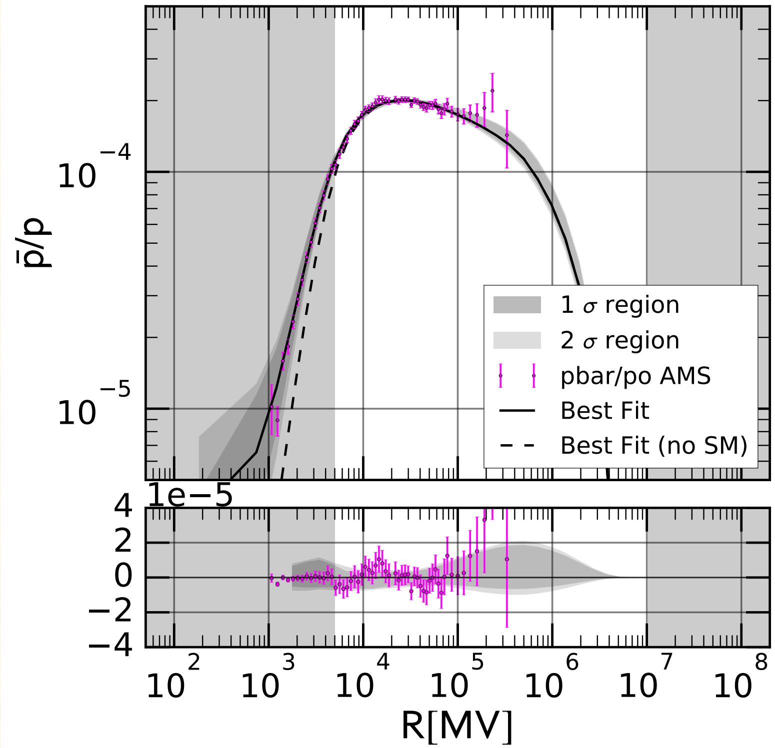
Annihilation of DM:
- Production of antimatter in the particle shower

➢ **DM CRs**: $\bar{p}$, (e^+)

CR fit with AMS02 p, He and anti-p







Fit above 5GV to reduce the impact of Solar modulation effects.

Korsmeier, Cuoco, PRD 2016
Cuoco, Korsmeier, Kramer PRL 2017

Fit Parameters

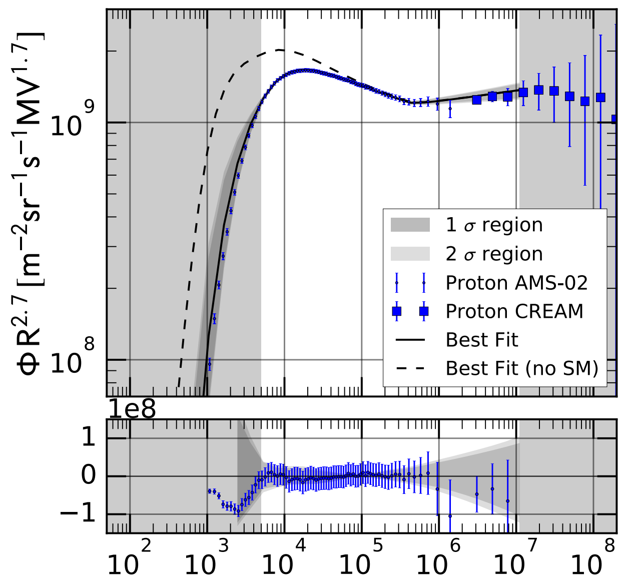
- **Injection spectrum (index p for protons)**
  - γ_1, $\gamma_{1,p}$
  - γ_2, $\gamma_{2,p}$
  - R_0
  - s
- **Diffusion constant**
  - δ
  - D_0
- **Reacceleration**
  - v_{Alfven}
- **Convection**
  - $v_{0,conv}$
- **Halo size**
  - z_h

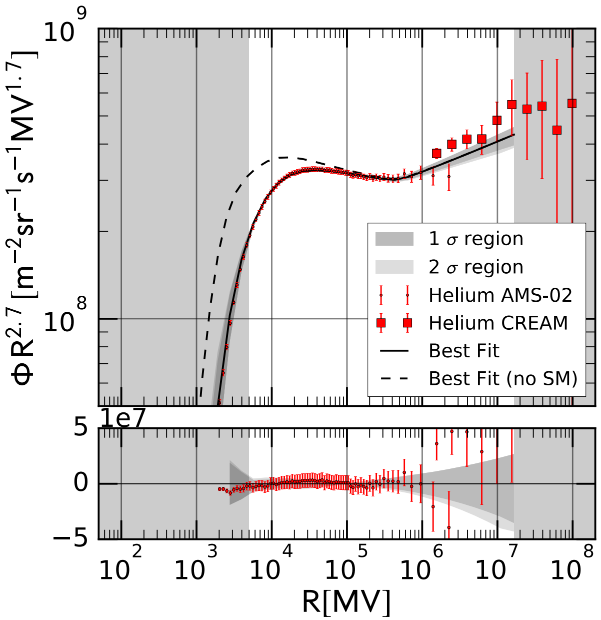
Complicate parameter space to explore. Monte Carlo methods are becoming the standard to perform this multi-dimensional scan and derive constraints on the parameters.

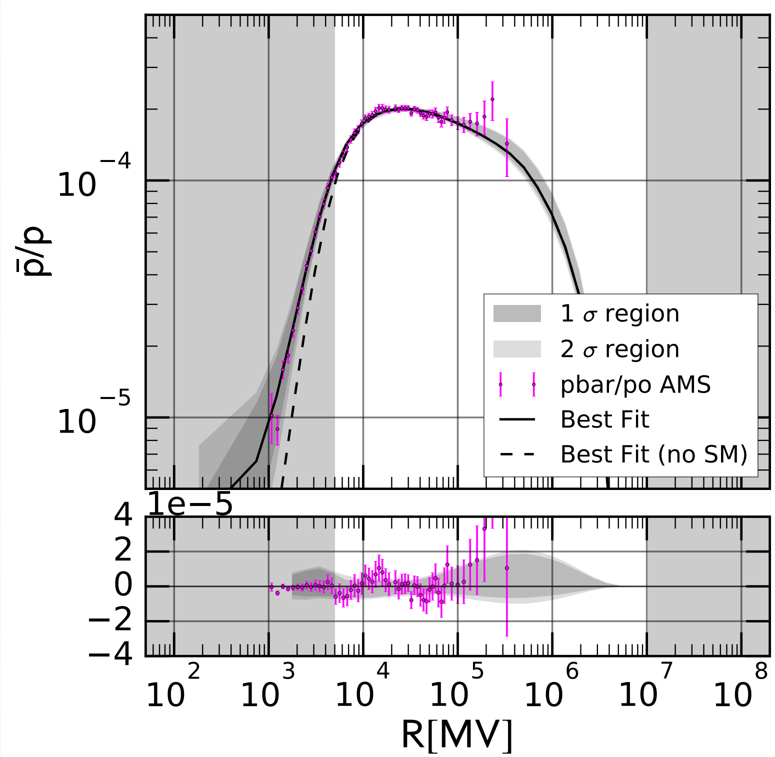
With DM additional fit parameters:

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

CR fit with AMS02 p, He and anti-p



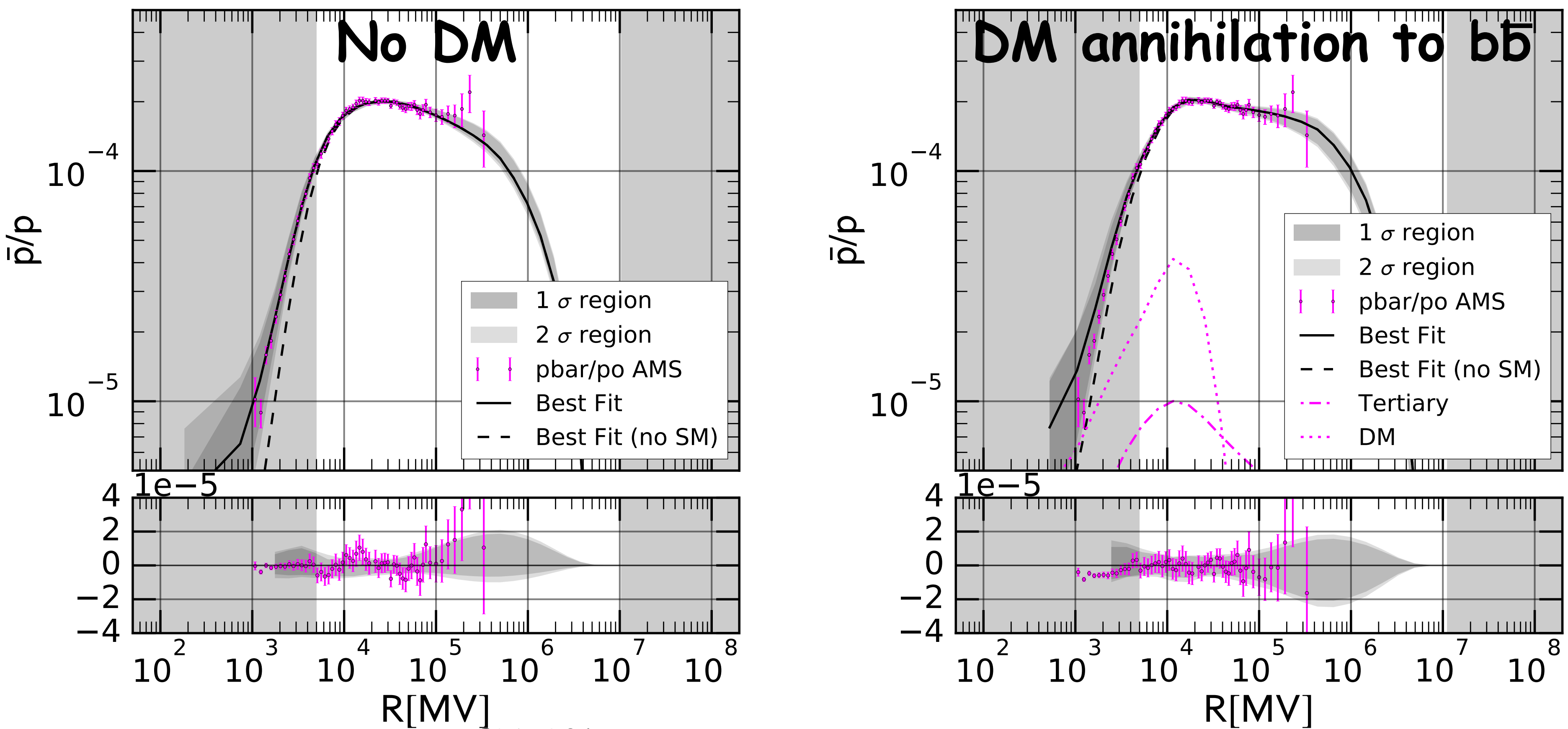




Fit above 5GV to reduce the impact of Solar modulation effects.

Korsmeier, Cuoco, PRD 2016
Cuoco, Korsmeier, Kramer PRL 2017

$\bar{p}/p$ ratio spectrum

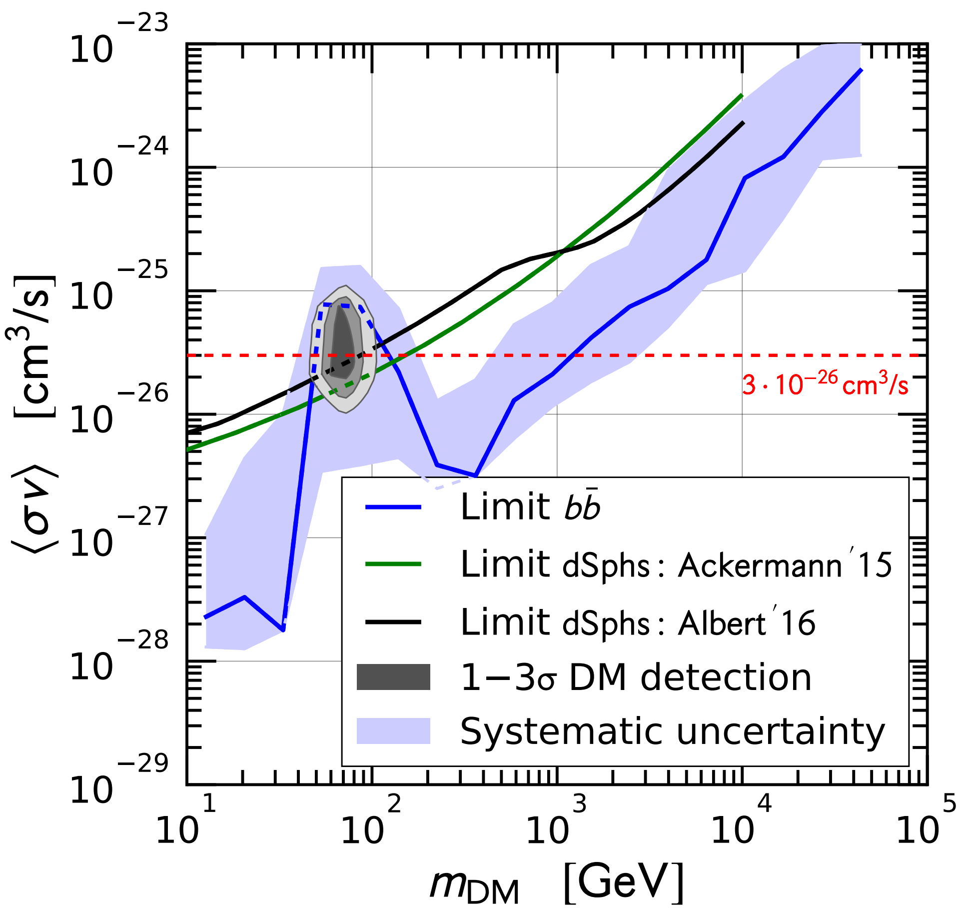


Cuoco, Korsmeier, Kramer PRL 2017

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.)

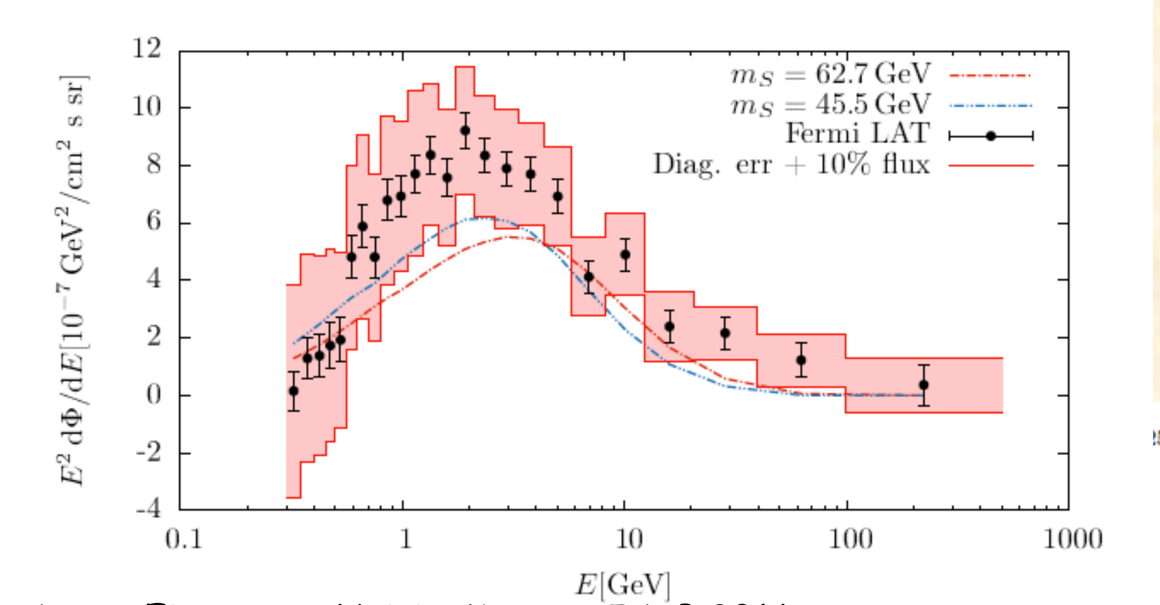
Marginalized DM limits



Cuoco, Korsmeier, Kramer PRL 2017

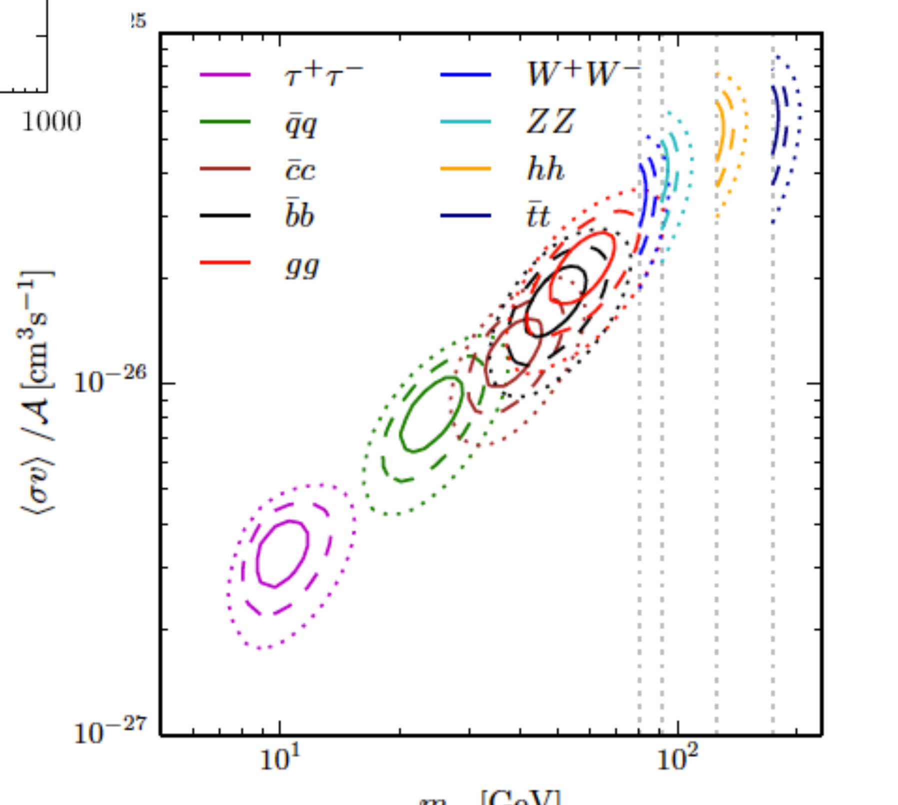
- Stringent DM limits outside the range in which a DM signal is preferred
- The band is the envelope of the systematic uncertainties
- Limits better than gamma-ray dwarfs by a factor of ~4-5
- Mild tension with dwarfs limits, but it got relieved with the latest dwarf limits

Galactic Center Excess



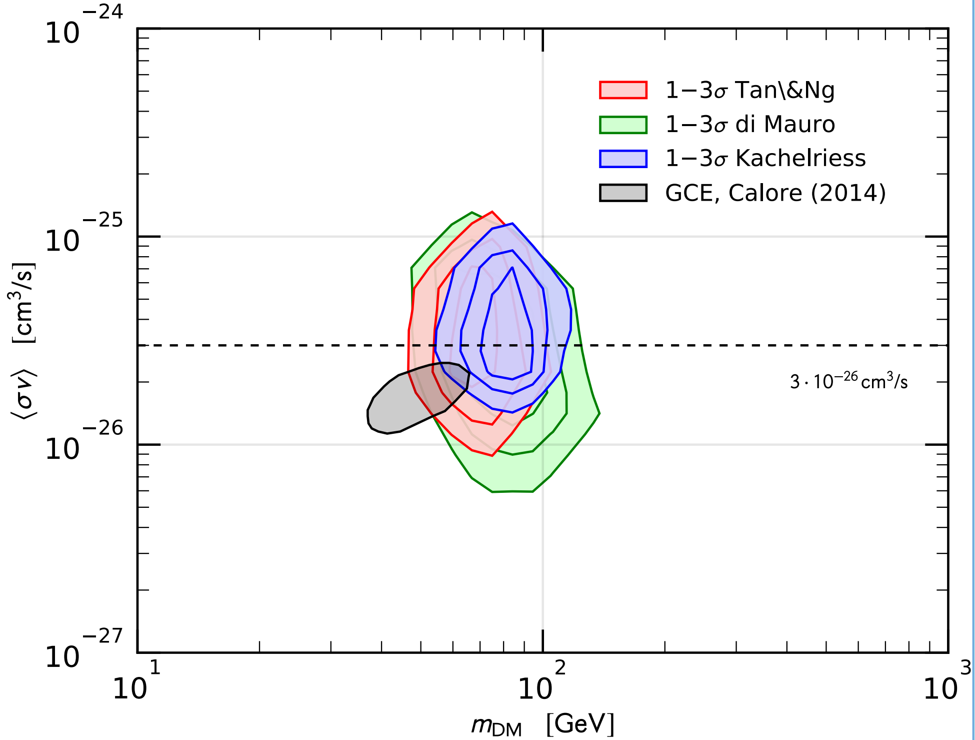
Cuoco, Eiteneuer, Heisig, Kramer JCAP 2016

- An Excess in gamma rays toward the GC has been reported by several groups
- It's compatible with a DM interpretation with masses in the range 10-100 GeV and cross section close to thermal



Calore, Cholis, Weniger, JCAP 2014

bb DM preferred region



Cuoco, Korsmeier, Kramer PRL 2017

- 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 3 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),
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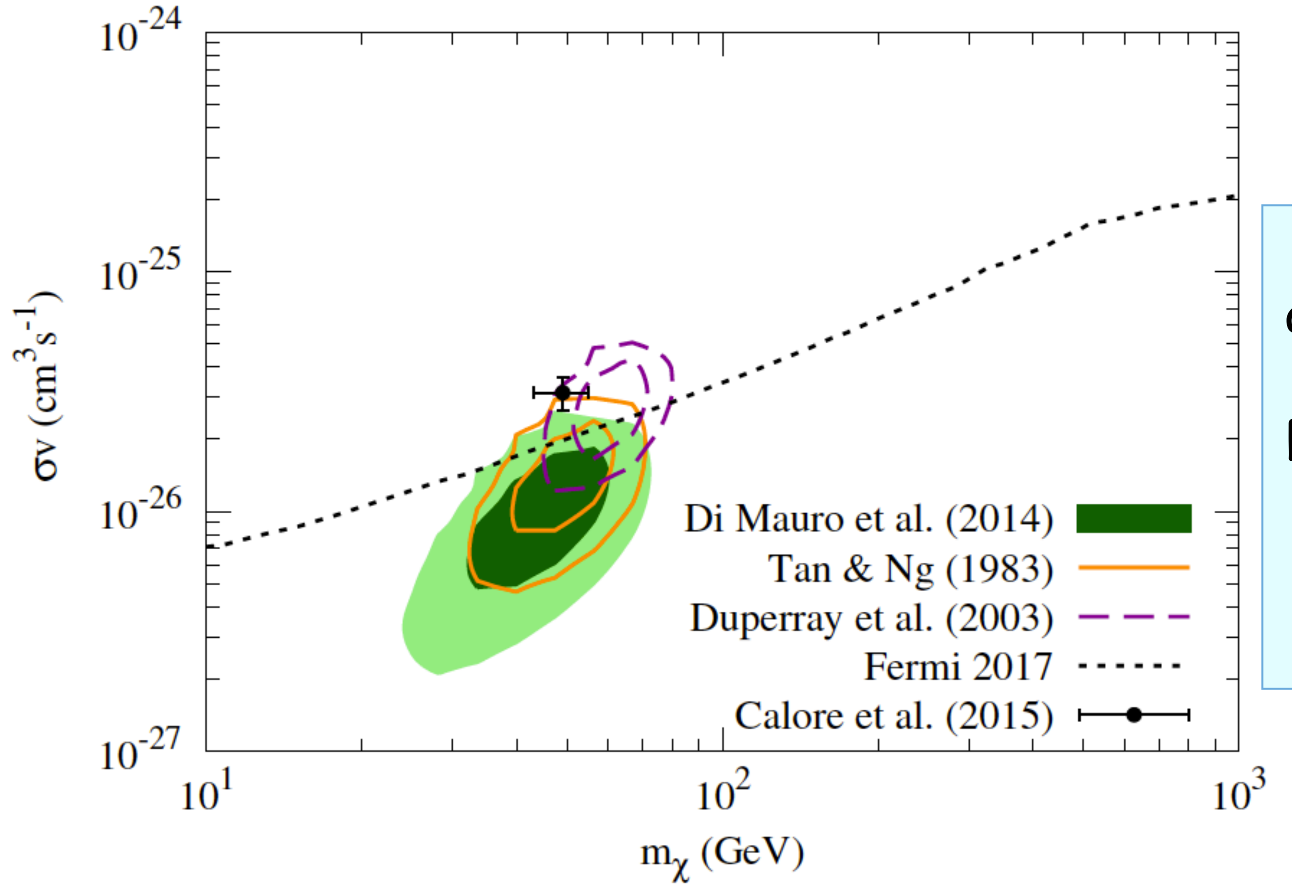
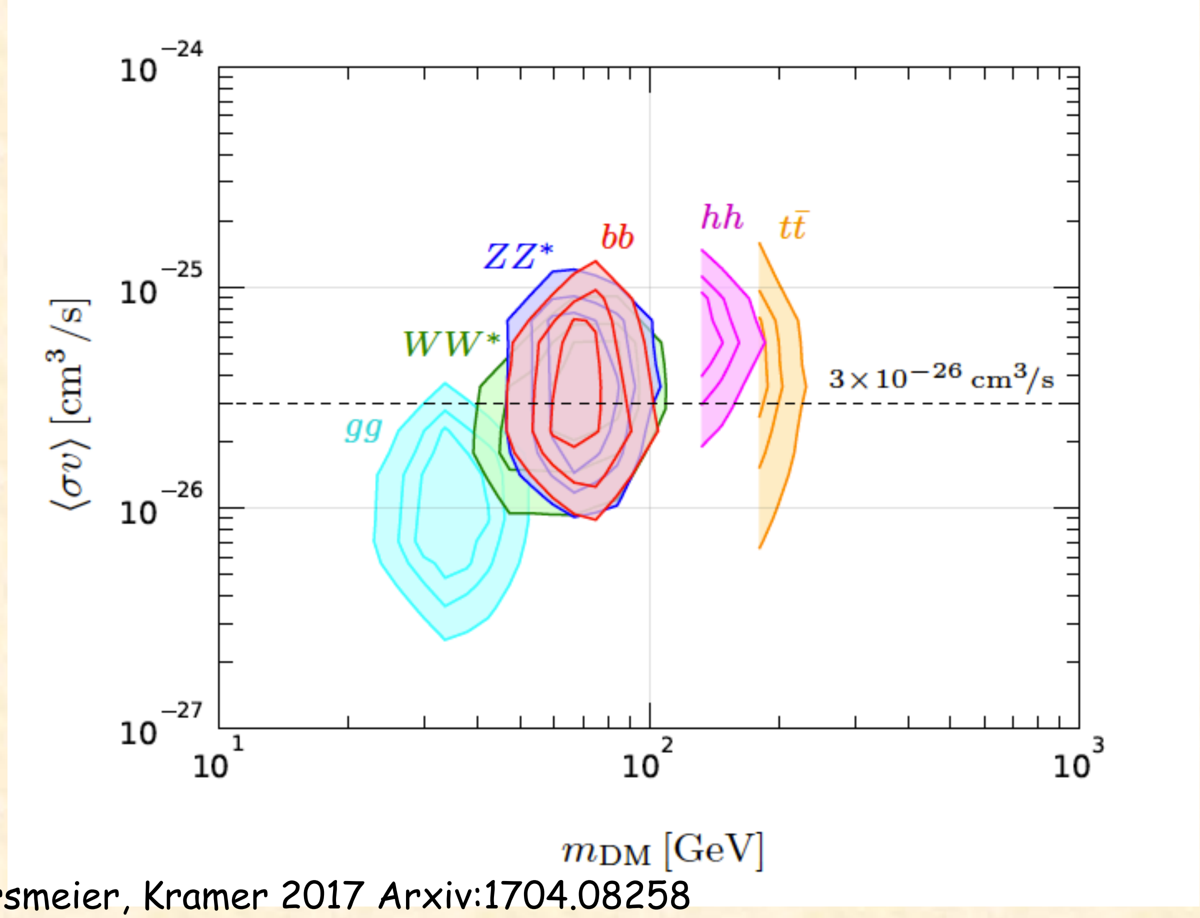
Using B/C



Cui et al. PRL 2017

A similar analysis by another group using B/C to fix the antiproton background, also find an excess and a similar preferred region for Dark Matter

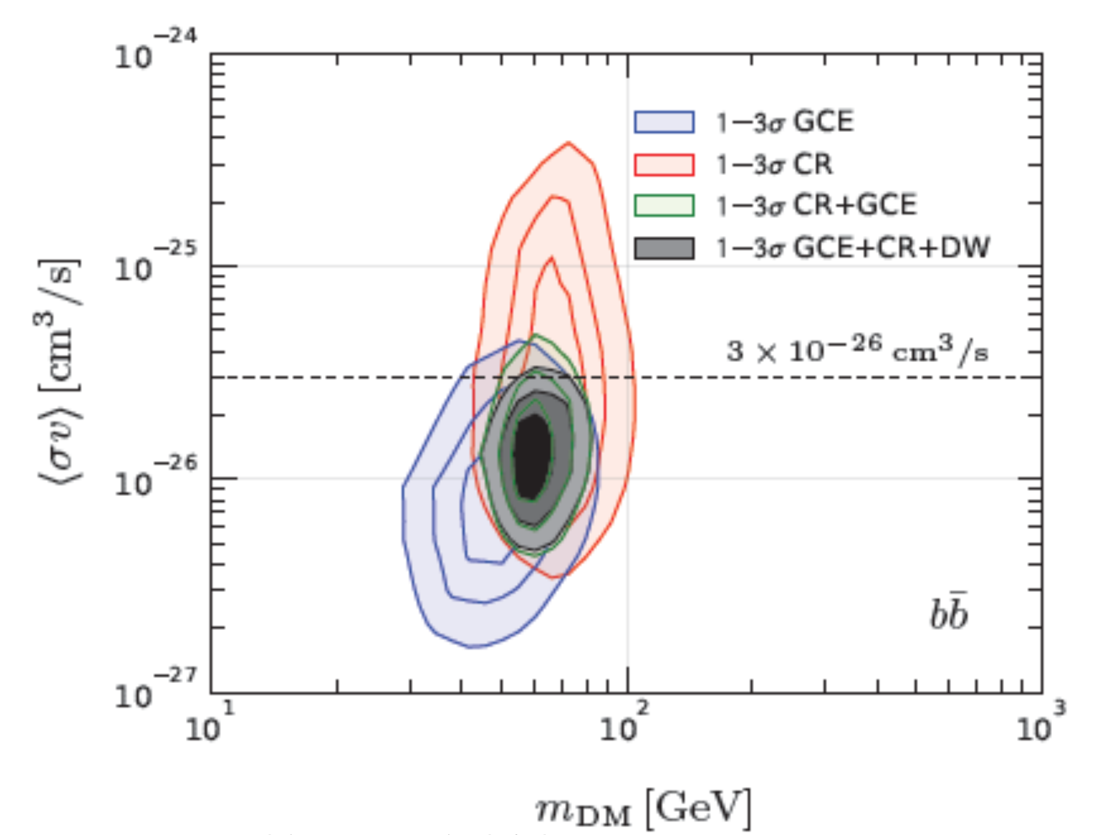
Fit for various channels



Cuoco, Heisig, Korsmeier, Kramer 2017 Arxiv:1704.08258

- Best fit mass and cross-section depends on the channel.
- All channels provide equally good fits, except t-tbar whose threshold is too high to fit the CR excess

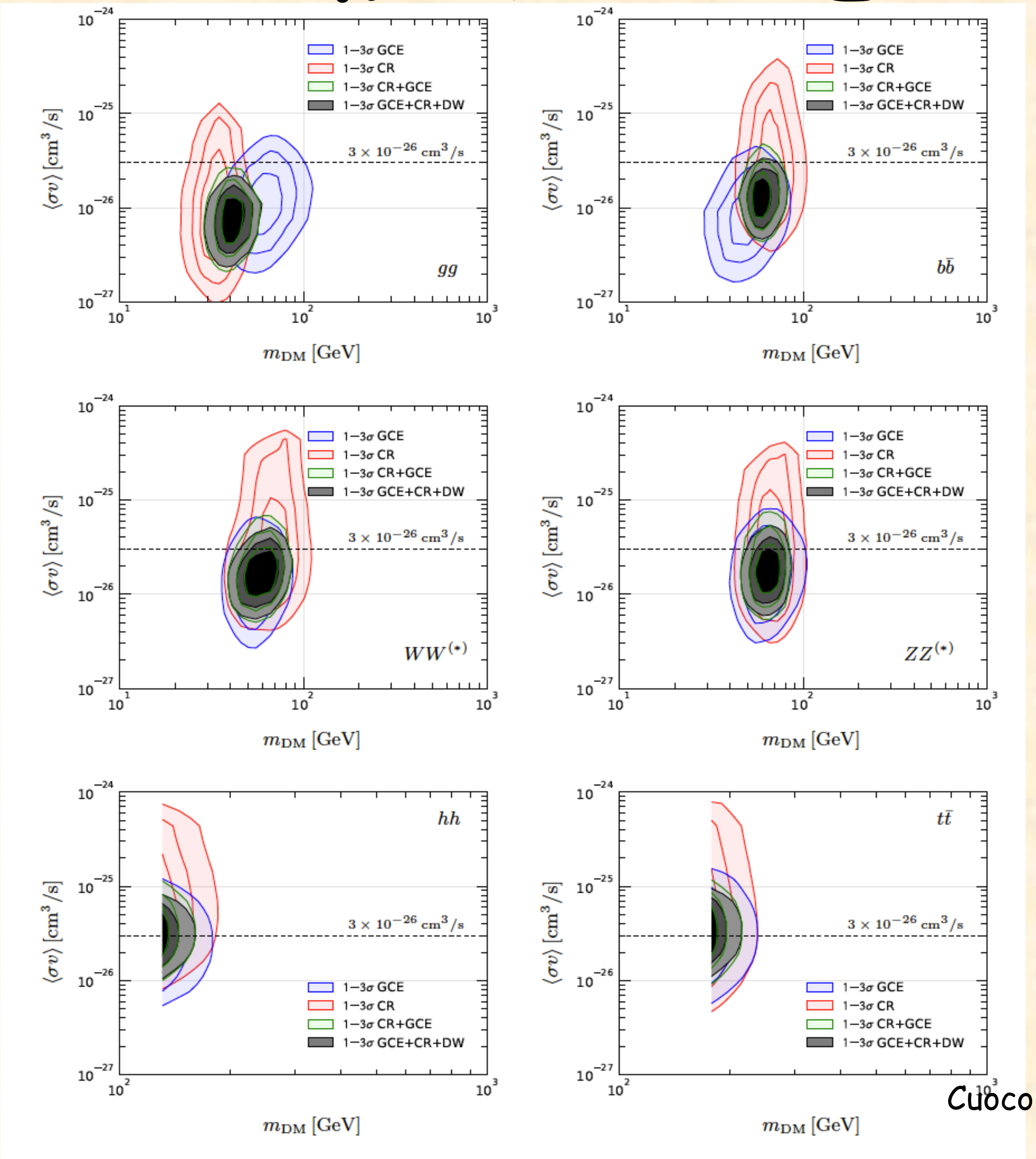
Combined GCE-CR fit



Cuoco, Heisig, Korsmeier, Kramer 2017 Arxiv:1704.08258

- We made a joint fit of the GC gamma-ray excess and of the CR excess, taking into account uncertainties in the DM distribution in the Milky Way.
- Depending on the channel there is good overlap of the two signals
- The joint-fit region is also compatible with the most recent dwarf galaxies constraints

Combined GCE-CR fit (2)



- WW, ZZ, hh are the best channels in terms of compatibility between the two signal

Cuoco, Heisig, Korsmeier, Kramer 2017
Arxiv:1704.08258

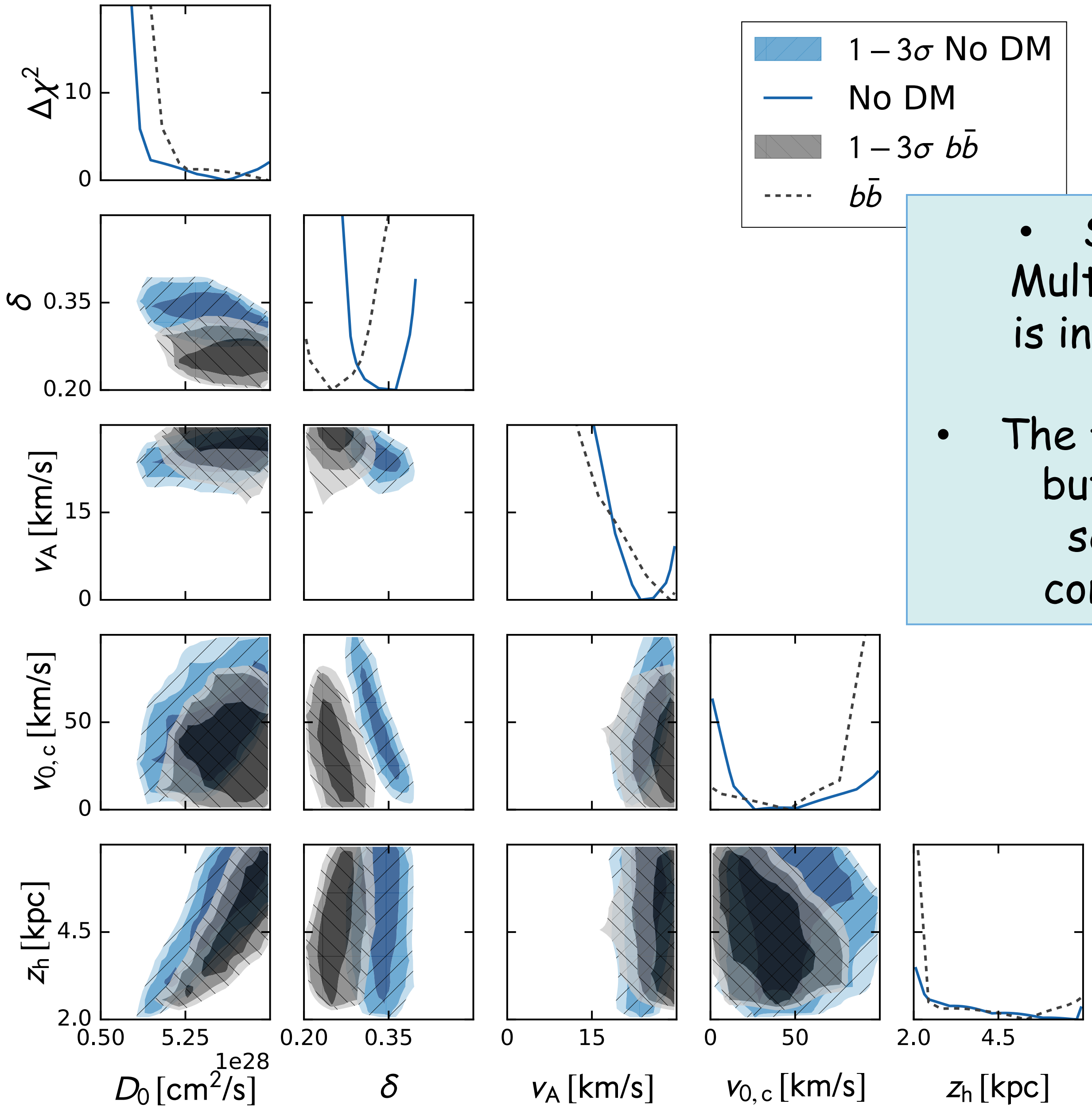
Outlook

- Official AMS-02 data for Li, 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

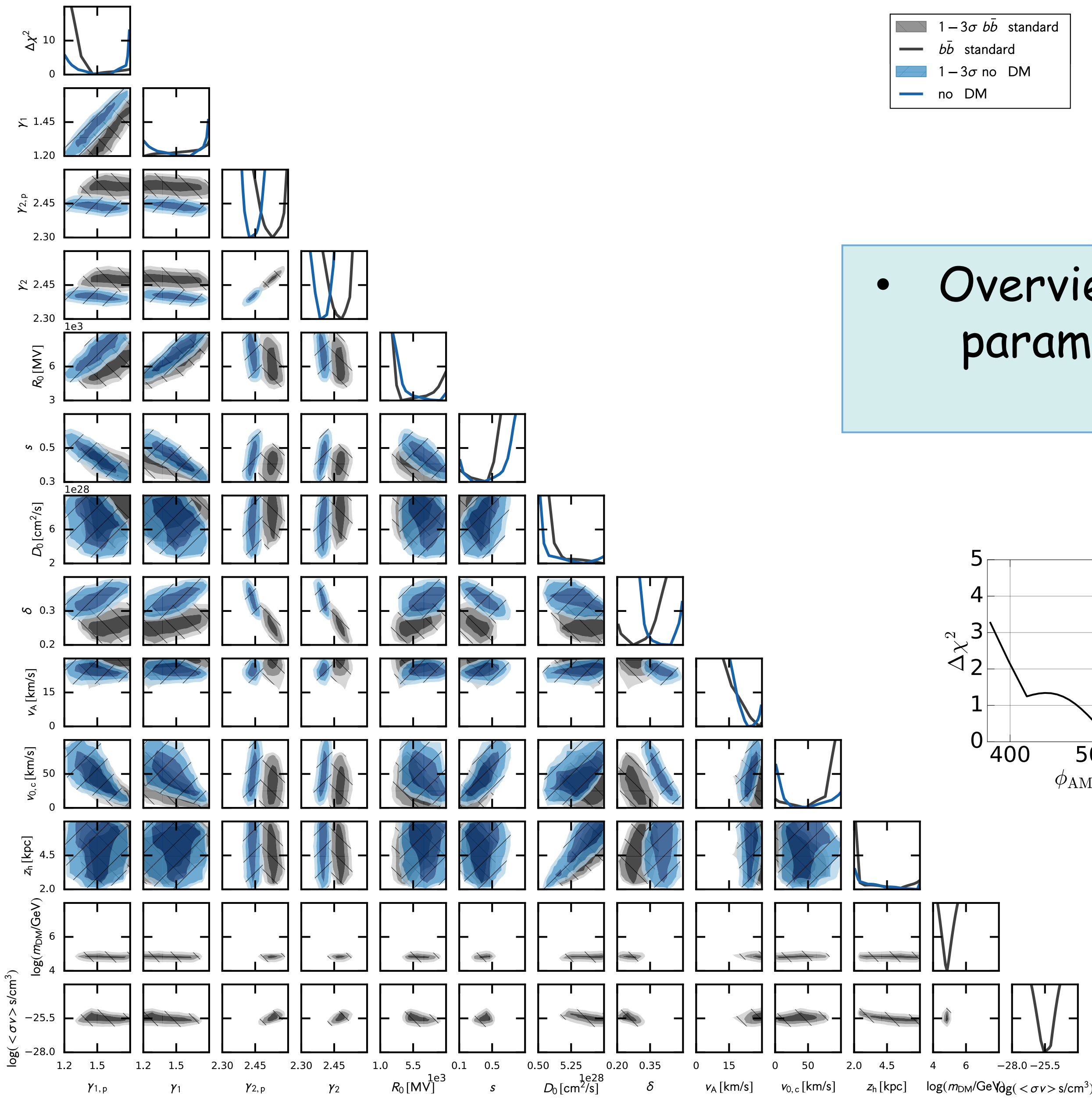
Parameters Sub-Triangle Plot



- 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.

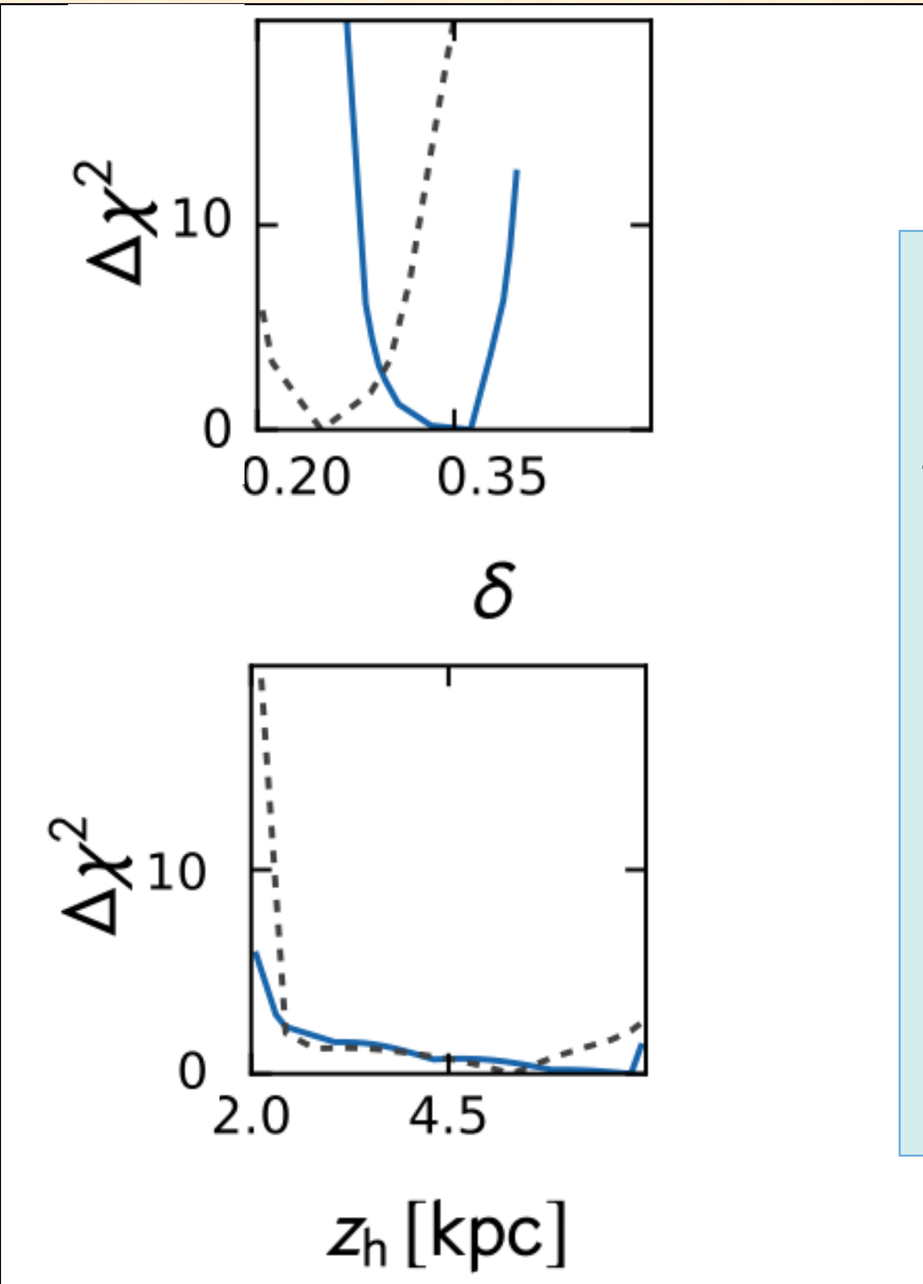
Cuoco, Korsmeier, Kramer PRL 2017

Full Triangle Plot



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

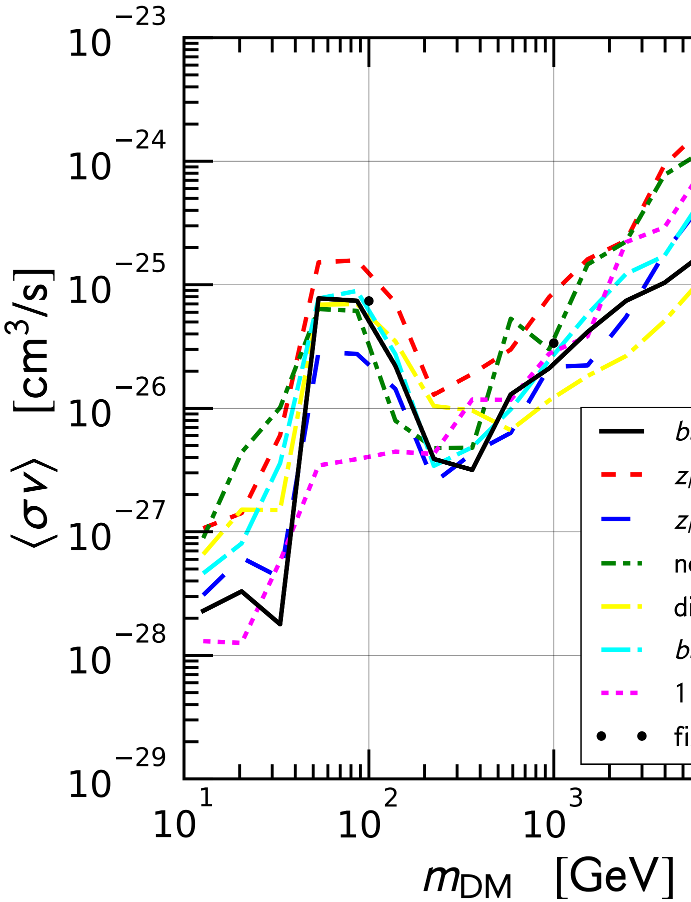
CR Results



- 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)

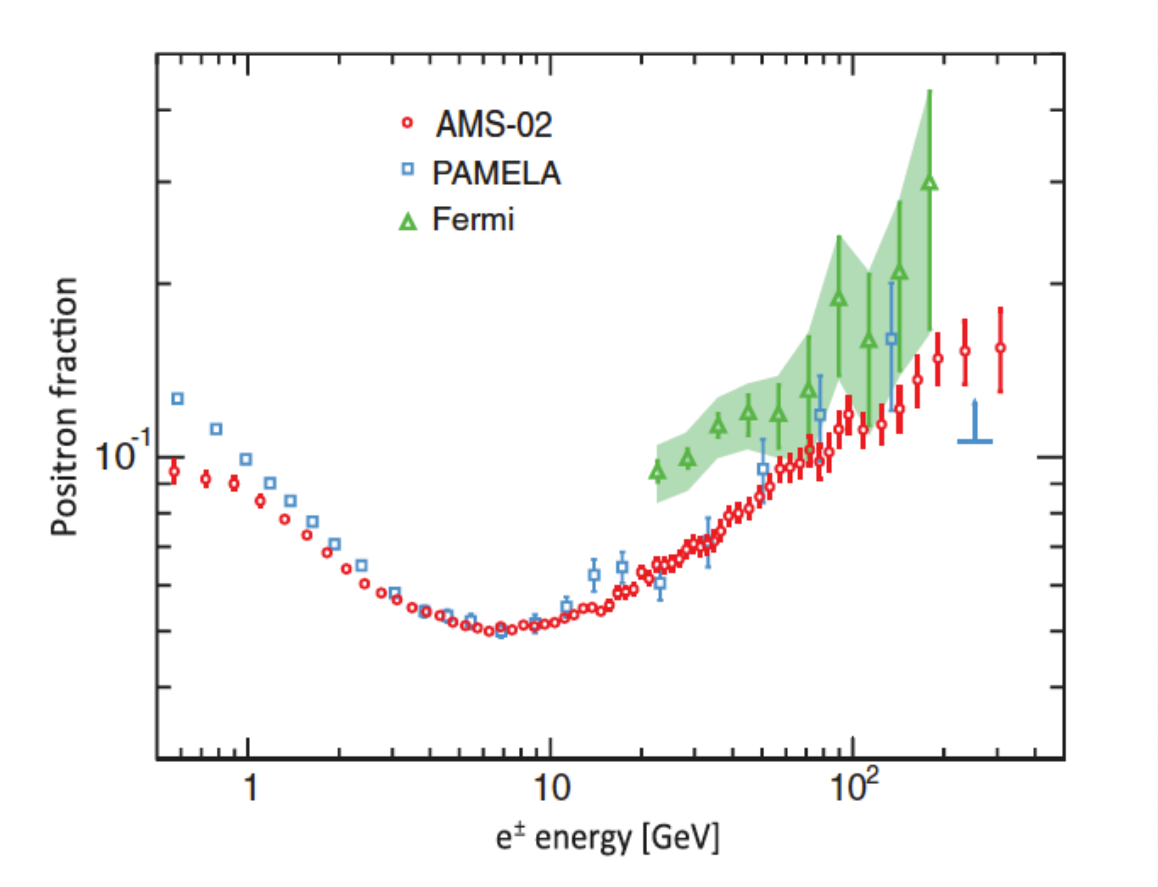
Other systematics and DM limits



- Results are stable vs various systematics as:
  - Different DM profiles
  - Imposing zero convection
  - Different model of anti-p production cross-section

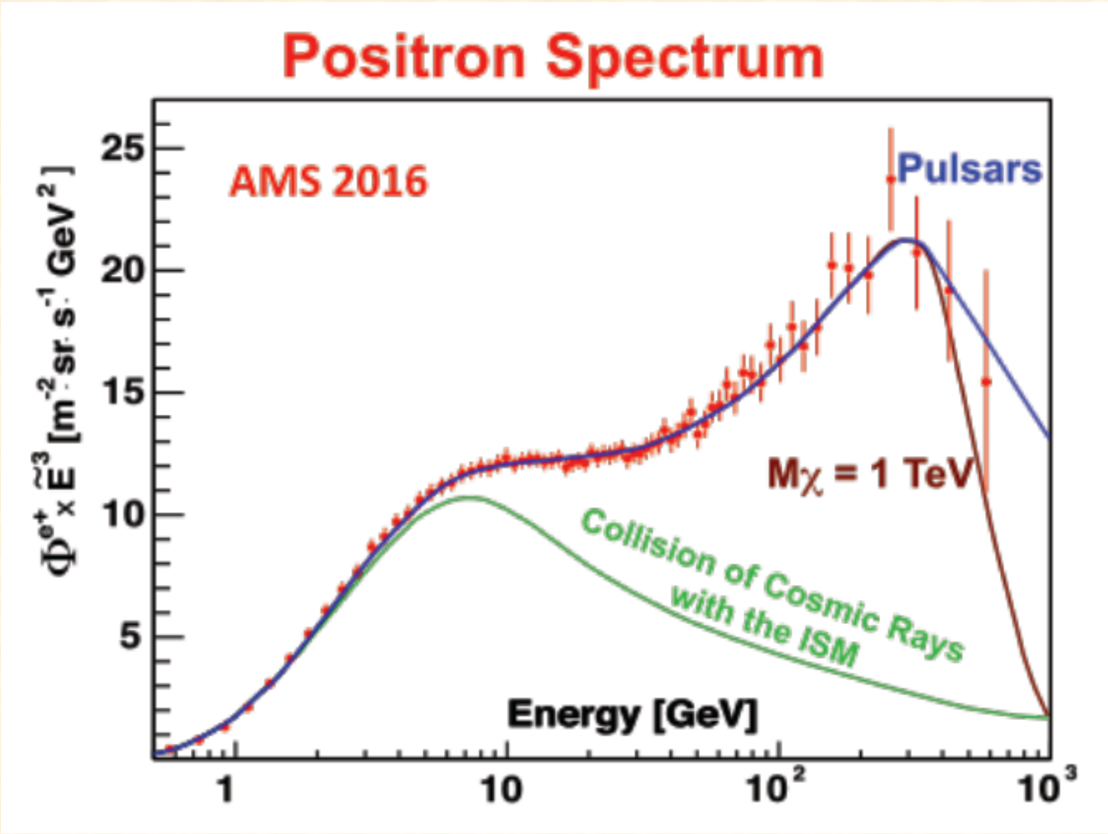
- Fixing different zh (2kpc and 7 kpc) shift the DM normalization by a factor 2-3, as expected

AMS-02 Positron fraction



Positron fraction up to ~800 GV. Rising positron fraction providing evidence for primary sources of positrons, or secondaries from a very close (< 1kpc) SNR (Shaviv et al. PRL 2009)

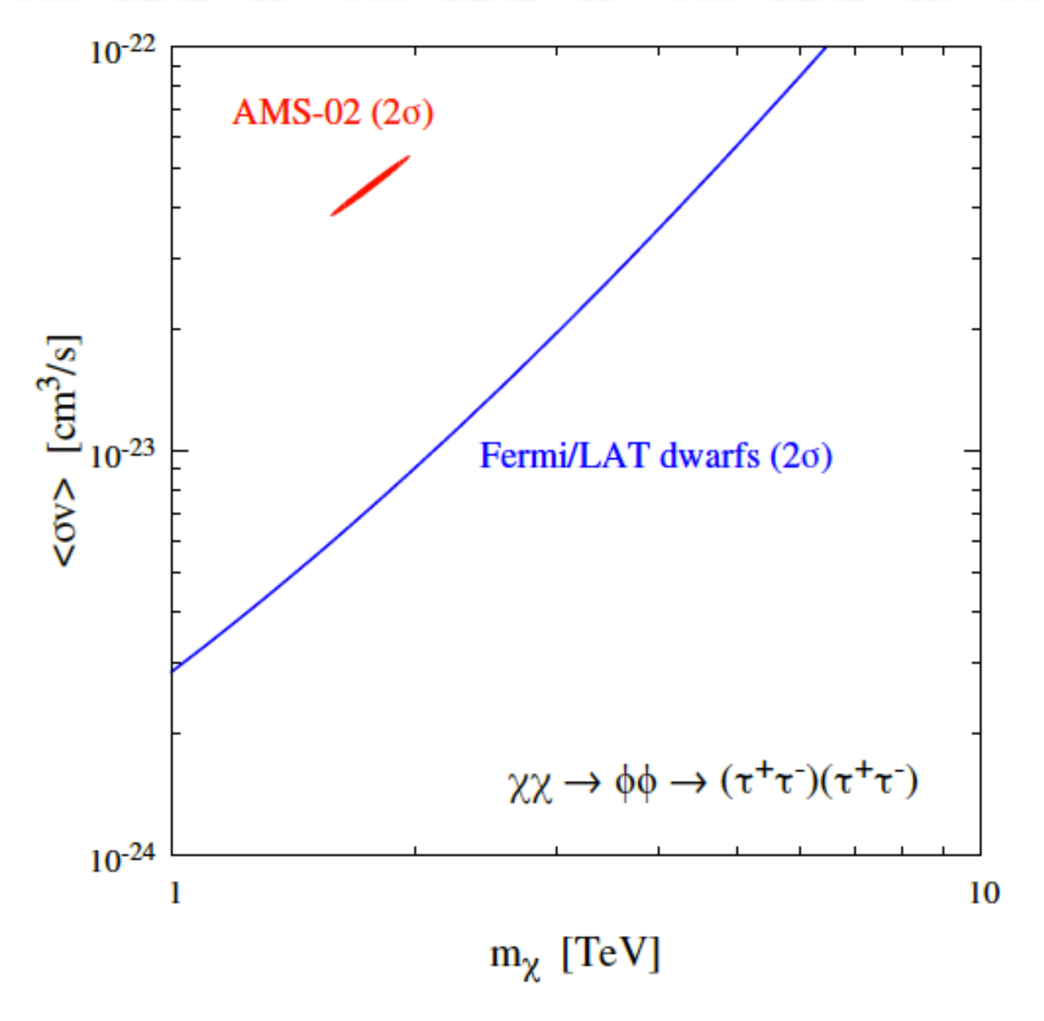
Summary of Positron interpretation



AMS Press Release Nov.2016

- A reasonable fit for DM can be found using a combination of different channels.
- Pulsars also produce e+e- and give a similar good fit.
- This kind of DM would have 'strange' properties: it mainly couples to leptons, and very little to hadrons (no signal in antiprotons)

Summary of Positron interpretation(2)

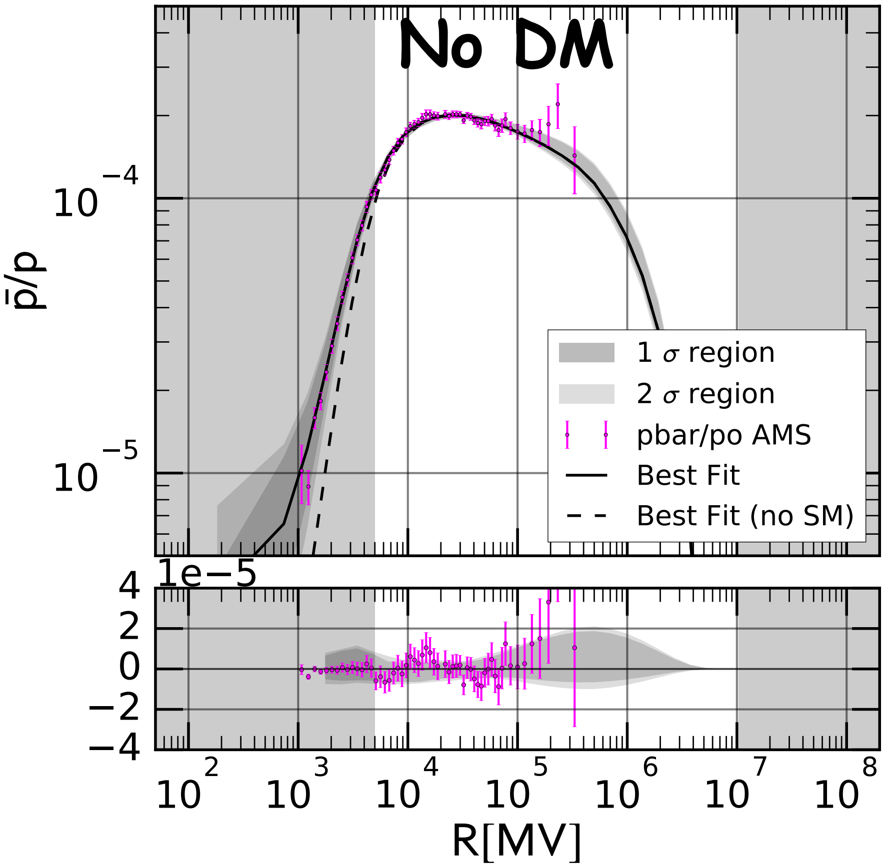


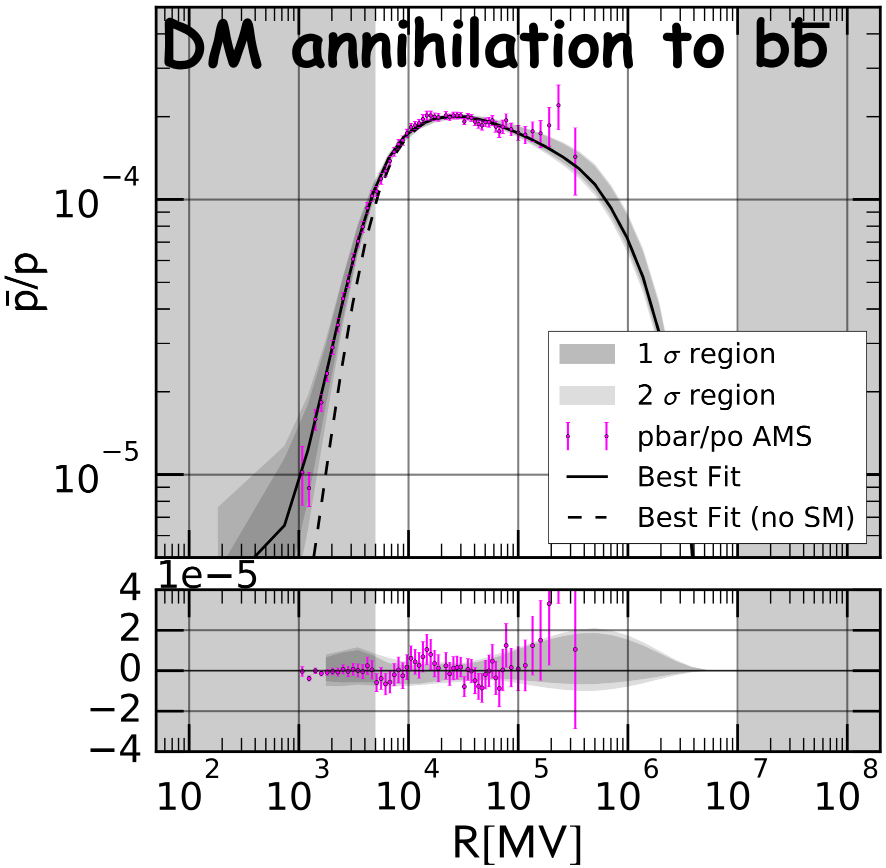
Lopez et al., JCAP 2015

DM interpretation is strongly constrained by gamma-ray observations of

- dwarfs galaxies,
- the Milky Way Halo,
- and CMB constraints.

1GV vs 5 GV fit

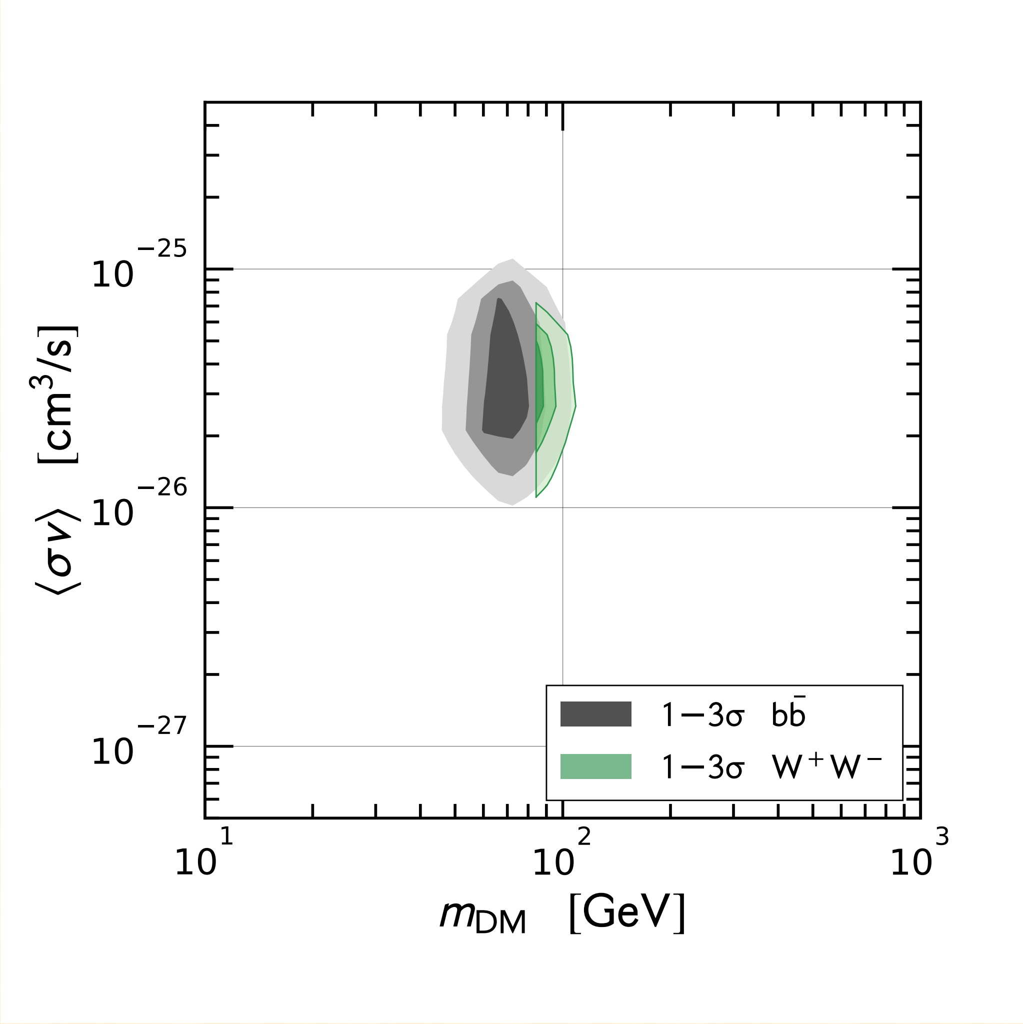




- The ~18 GV feature remains when fitting to 1 GV: DM cannot fit because data below 5 GV are over-predicted.

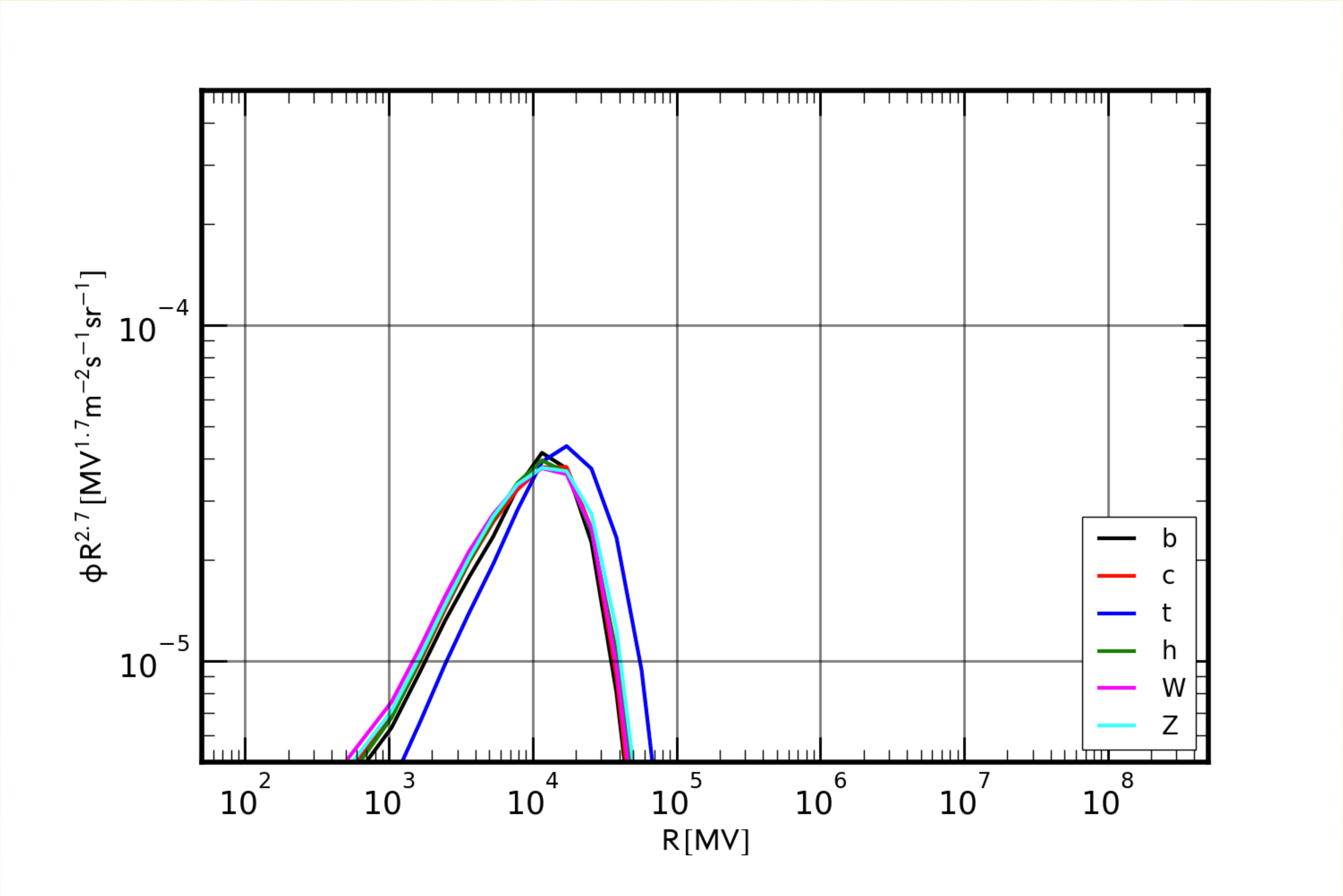
- It could be likely accommodated within the uncertainties of the solar modulation. It requires a dedicated study (and possibly time dependent measured spectra)

Fit W+W-



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

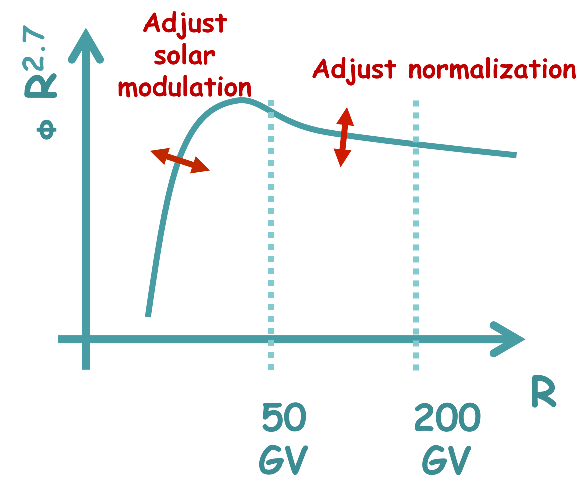
Fit various channels(1)



“Linear” Parameters

Marginalize these parameter for each evaluation point:

- Normalization of p, He
- Solar modulation potential

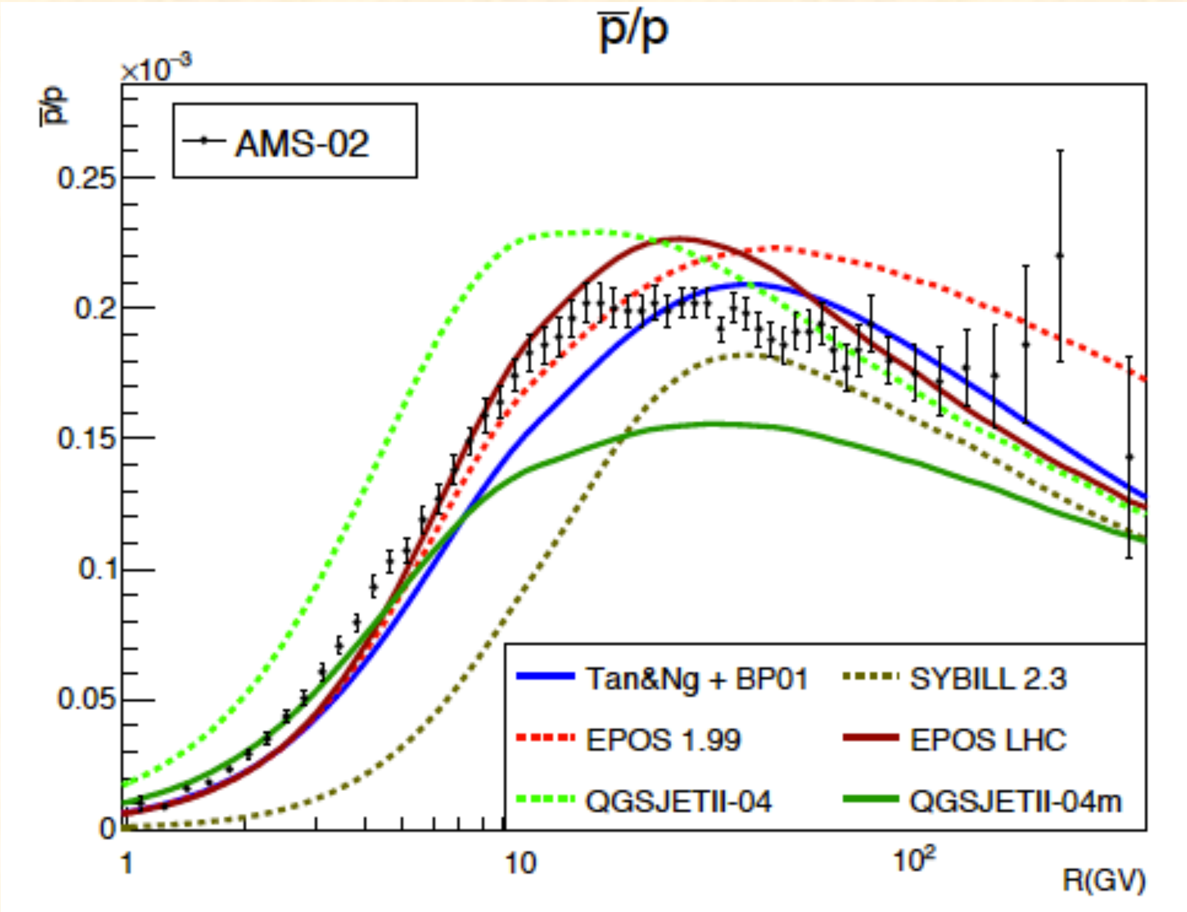


Step 1: Adjust normalization
Step 2: Adjust solar modulation

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)

Nuclear cross sections uncertainties



Same propagation model, different anti-p production cross-sections,
Lin et al., arXiv:1612.04001

- Uncertainties in the anti-p production cross section are at the level of 20-30%
- Similar uncertainties for B production cross-section
- Uncertain cross-section are at the moment one of the main challenges for a correct interpretation of AMS data
- New precise cross-section measurement are required.