Dark Matter Interpretations of the AMS Positron Excesses

Ian Low

Argonne/Northwestern

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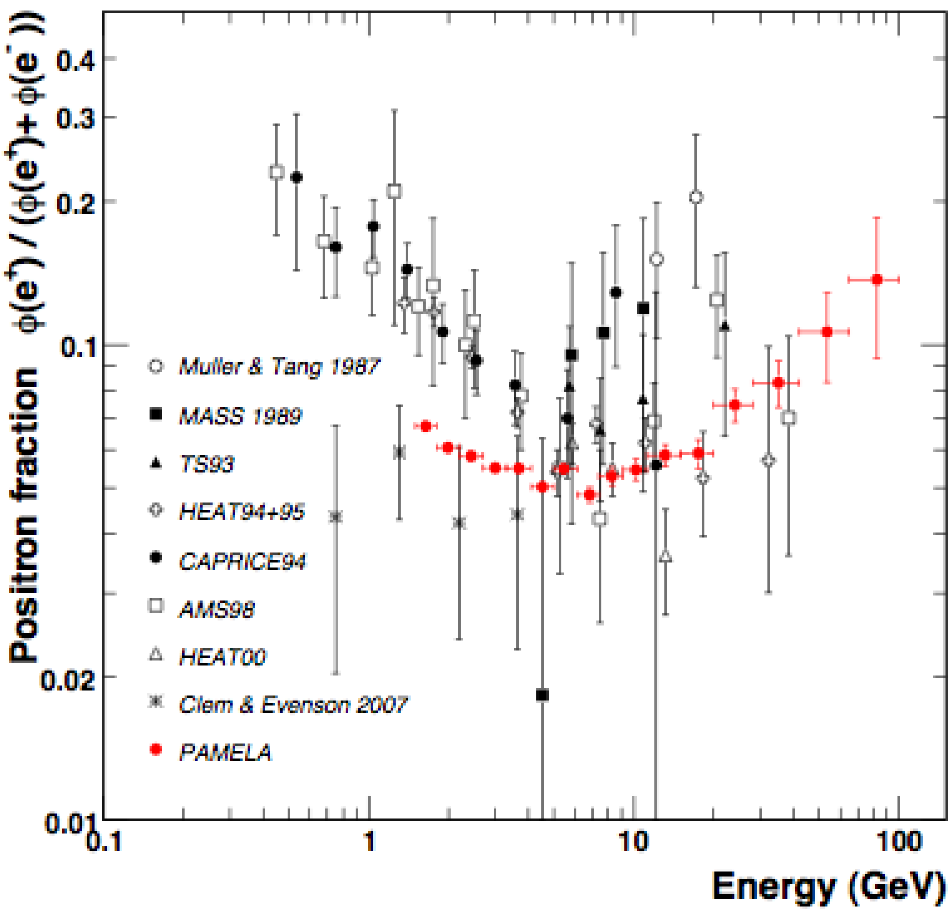
Dark Matter, Dark Energy and Matter-Antimatter Asymmetry

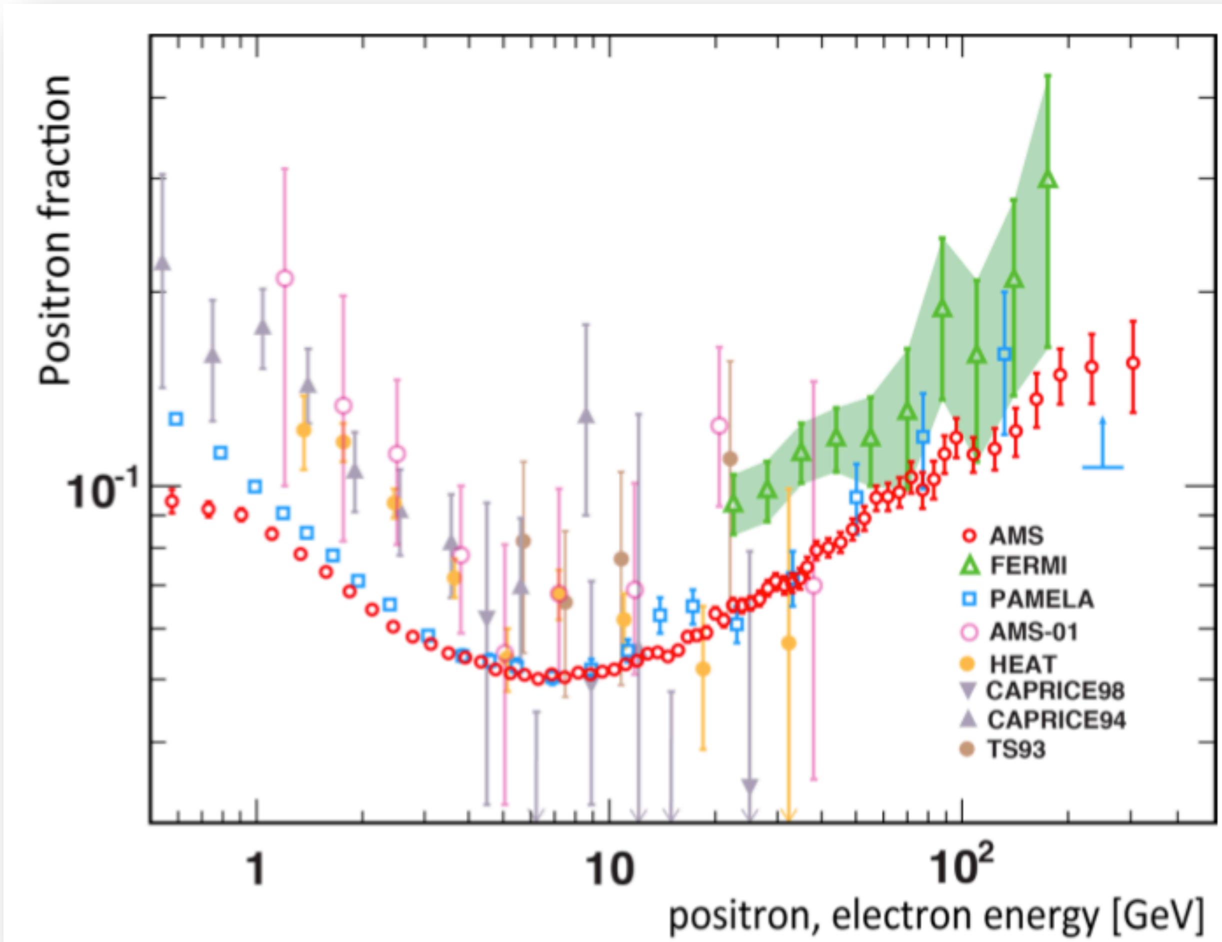
Based on 1608.06382 by H.-C. Cheng, W.-C. Huang, X. Huang, IL, Y.-L. S. Tsai and Q. Yuan

Positron Excess in cosmic rays is a long-standing mystery:



Ref: 0810.4995

AMS data "cemented" the existence of the rising feature with great precision:



Two popular explanations for such an excess are:

1. Positrons from WIMPs annihilating into 2 or 4 charged leptons in the galactic halo.

$$\mathrm{DM} \to \ell^+\ell^- \quad \text{or} \quad \mathrm{DM} \to 2\phi \to (\ell^+\ell^-)(\ell^+\ell^-)$$

2. Positrons from near-by Pulsars.

WIMPs annihilations could explain the data, but it requires

$$\langle\sigma v\rangle_{ann} \gg \langle\sigma v\rangle_{freeze} \sim 3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$

A ``boost factor'' of O(100) is introduced in order to give a large enough annihilation cross-section. (Refs: 0809.1683; 0809.2409)

Where does the boost factor come from?

- Astrophysical source: clumpiness in the dark matter halo profile??
- Particle physics source: Sommerfeld enhancement due to long-range attraction between dark matter particles?? Breit-Wigner enhancement?

- Alternatively, if the dark matter decays with a long lifetime, the annihilation cross-section (which sets the relic density) would be decoupled from the flux (due to decays) measured by AMS.

- The large flux required by AMS positron excess translates into a decay lifetime of O(10^{26}) seconds. No boost factor is needed!

Where does this number come from??

A dark matter decaying through GUT-suppressed dim-6 operators happens to give (Ref: 0811.4153)

$$\tau \sim 8\pi \frac{M_{\rm GUT}^4}{m_{\rm DM}^5} = 3\times 10^{27}\ {\rm s} \left(\frac{\rm TeV}{m_{\rm DM}}\right)^5 \left(\frac{M_{\rm GUT}}{2\times 10^{16}\ {\rm GeV}}\right)^4$$

(In SUSY the LSP could be the decaying dark matter if R-parity is violated by a small amount.)

The only problem is, for both annihilation or decays into 2 or 4 charged leptons, the resulting synchrotron radiation tend to produce too much diffuse gammay ray that was not consistent with Fermi-LAT observations.

2/4-body DM annihilations:

(Dated: February 24, 2010)

Abstract

The first published Fermi large area telescope (Fermi-LAT) measurement of the isotropic diffuse gamma-ray emission is in good agreement with a single power law,

In reasonable background and dark matter structure scenarios (but not in all scenarios we consider) it is possible to exclude models proposed to explain the excess of electrons and positrons measured by the Fermi-LAT and PAMELA experiments.

are strongly affected by the underlying distribution of dark matter, and by using different available results of matter structure formation we assess these uncertainties. We also quantify how the dark matter constraints depend on the assumed conventional backgrounds and on the Universe's transparency to high-energy gamma-rays. In reasonable background and dark matter structure scenarios (but not in all scenarios we consider) it is possible to exclude models proposed to explain the excess of electrons and positrons measured by the Fermi-LAT and PAMELA experiments. Derived limits also start to probe cross sections expected from thermally produced relics (e.g. in minimal supersymmetry models) annihilating predominantly into quarks. For the monochromatic gamma-ray signature, the current measurement constrains only dark matter scenarios with very strong signals.

Fermi-LAT: 1002.4415

The only problem is, for both annihilation or decays into 2 or 4 charged leptons, the resulting synchrotron radiation tend to produce too much galactic diffuse gammay ray that was not consistent with Fermi-LAT observations.

2/4-body DM decays:

We derive new bounds on decaying Dark Matter from the gamma ray measurements of (i) the isotropic residual (extragalactic) background by Fermi and (ii) the Fornax galaxy cluster by H.E.S.S.. We find that those from (i) are among the most stringent constraints currently available, for a large range of DM masses and a variety of decay modes, excluding half-lives up to $\sim 10^{26}$ to few 10^{27} seconds. In particular, they rule out the interpretation in terms of decaying DM of the $e^{\pm}$ spectral features in PAMELA, Fermi and H.E.S.S., unless very conservative choices are adopted. We also

Cirelli et al: 1205.5283

So the "old news" is:

The conventional 2/4-body final states of DM decays/annihilations

$$\mathrm{DM} \to \ell^+\ell^- \quad \text{or} \quad \mathrm{DM} \to 2\phi \to (\ell^+\ell^-)(\ell^+\ell^-)$$

have difficulties with diffuse gamma-ray measurements.

One way to alleviate the tension is to consider three-body decays of DM to final states containing a missing particle (eg., LSP):

$$\mathrm{DM} \to \mathrm{SM} + \mathrm{SM} + \mathrm{Missing\ Particle}$$

The physics behind the resolution is very simple:

Three-body decay kinematics with a missing particle give a softer energy spectrum for the charged particles and, as a result, softer synchrotron radiation.

Cheng, Huang, Low, and Menon: 1012.5300

Such a three-body decay occurs naturally in R-parity preserving supersymmetric theories with multiple SUSY-breaking sectors, the goldstini model. (Cheung, Nomura, and Thaler: 1002.1967)

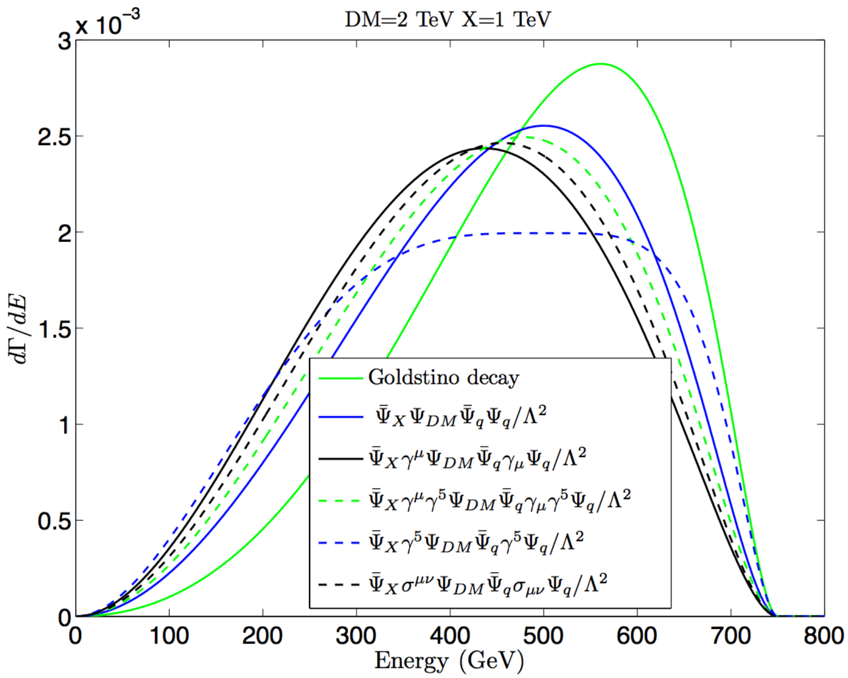
One could take a bottom-up approach and consider effective operators mediating such decays:

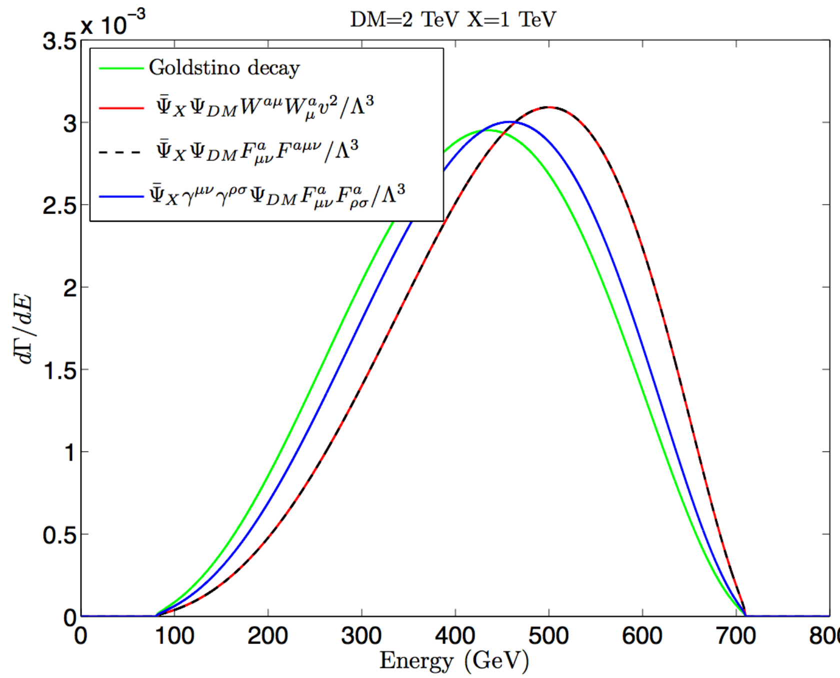
$$\frac{\lambda_1}{\Lambda^2}\overline{\Psi}_X\Psi_{DM}\overline{\Psi}_q\Psi_q + \mathrm{h.\,c.},$$
$$\frac{\lambda_2}{\Lambda^2}\overline{\Psi}_X\gamma^5\Psi_{DM}\overline{\Psi}_q\gamma^5\Psi_q + \mathrm{h.\,c.},$$
$$\frac{\lambda_3}{\Lambda^2}\overline{\Psi}_X\gamma^\mu\Psi_{DM}\overline{\Psi}_q\gamma_\mu\Psi_q + \mathrm{h.\,c.},$$
$$\frac{\lambda_4}{\Lambda^2}\overline{\Psi}_X\gamma^\mu\gamma^5\Psi_{DM}\overline{\Psi}_q\gamma_\mu\gamma^5\Psi_q + \mathrm{h.\,c.},$$
$$\frac{\lambda_5}{\Lambda^2}\overline{\Psi}_X\sigma^{\mu\nu}\Psi_{DM}\overline{\Psi}_q\sigma_{\mu\nu}\Psi_q + \mathrm{h.\,c.},$$

$$\frac{\lambda_{h'}v^2}{\Lambda^3}\overline{\Psi}_X\Psi_{DM}W^a_\mu W^{a\mu} + \mathrm{h.\,c.},$$
$$\frac{\lambda_{s'}}{\Lambda^3}\overline{\Psi}_X\Psi_{DM}F^a_{\mu\nu}F^{a\mu\nu} + \mathrm{h.\,c.},$$
$$\frac{\lambda_{v'}}{\Lambda^3}\overline{\Psi}_X\gamma^{\mu\nu}\gamma^{\rho\sigma}\Psi_{DM}F^a_{\mu\nu}F^a_{\rho\sigma} + \mathrm{h.\,c.},$$

Cheng, Huang, Low, and Shaughnessy: 1205.5270

The “Primary” decay spectra are insensitive to the details of the dynamics:

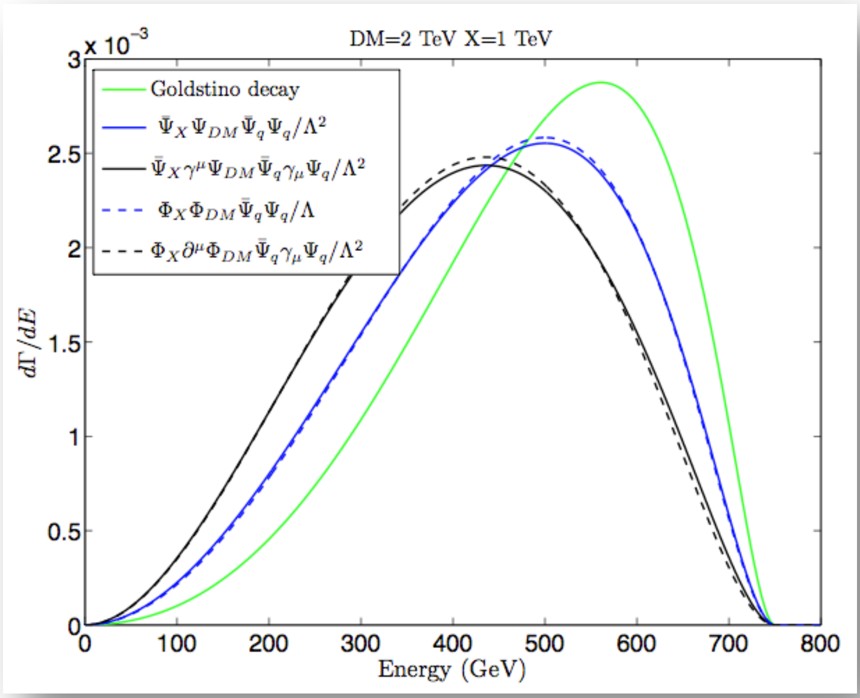




Furthermore, if the decaying DM mass is around twice the mass of the missing particle,

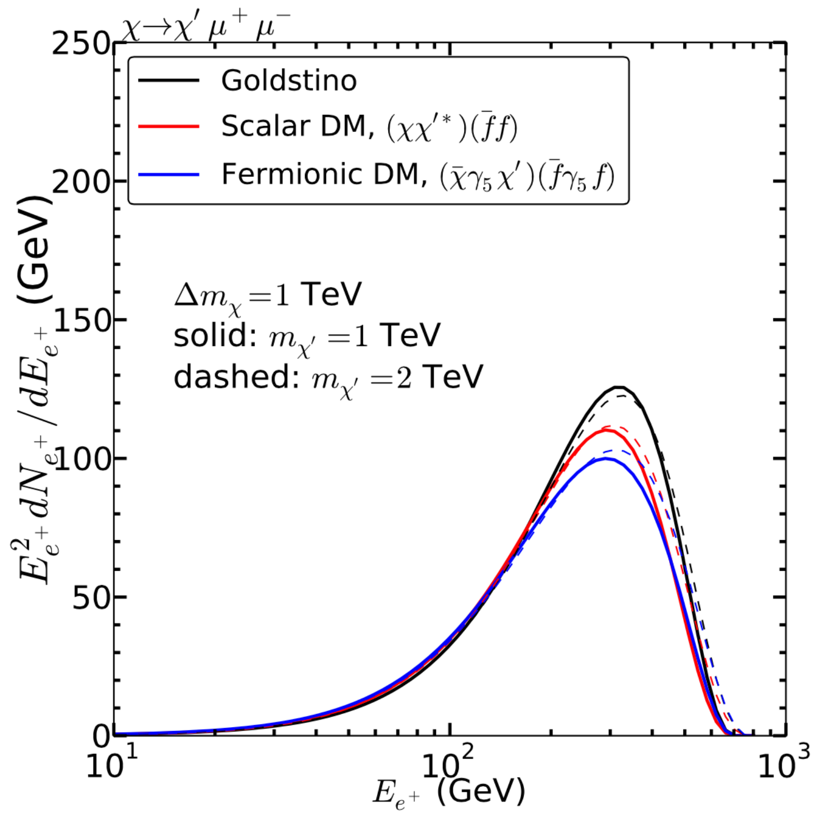
$$m_{\rm DM} = 2m_X$$

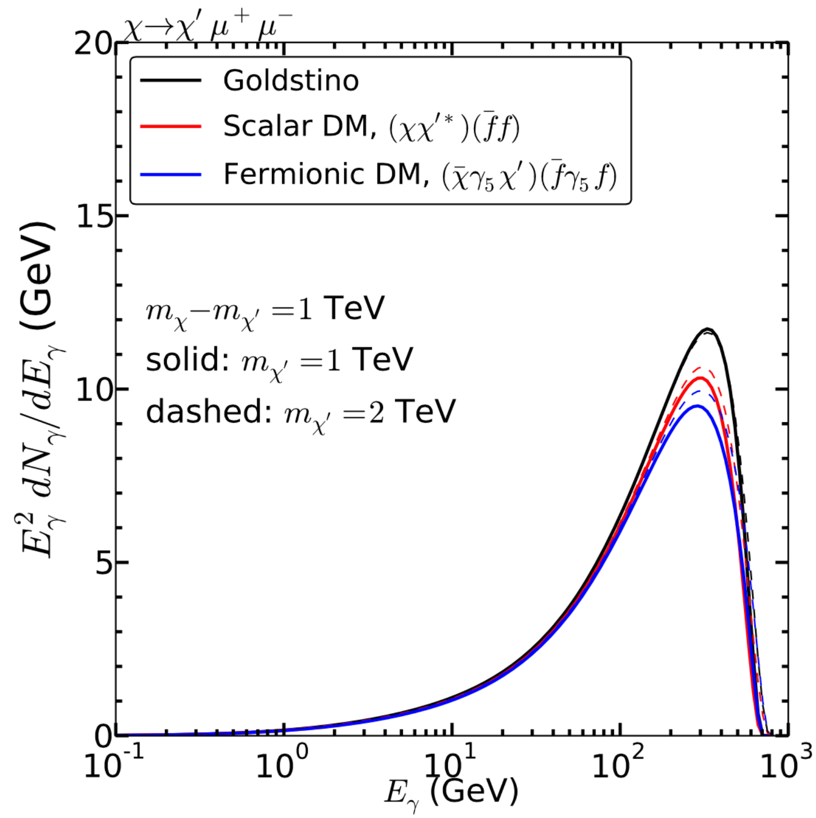
The primary spectra are insensitive to a scalar v.s. a fermionic DM:



This turns out to be the mass scales preferred by the best-fit to the positron excess!

These small differences in the primary spectra become even less significant when we consider secondary electron and photon spectra:





In fitting the cosmic ray data, propagation of electrons, positrons and anti-protons in the Milky Way is always a complicated business.

Details can be found in the paper. Very briefly,

- Assume NFW profile for the DM density.
- Propagation model using GALPROP and LIKEDM package developed by some of the authors.
- Choose propagation parameters based roughly on MIN, MED and MAX parameters.
- Solar modulation effect is treated by force-field approximation, with two different potential for electron/positron and anti-proton, respectively.
- Injection spectral parameters of background electrons are fitted simultaneously with the DM parameters.
- Use Markov Chain Monte Carlo method for global fitting.

In the end we perform the fit using a scalar DM decaying through the following interaction

$$\chi\,(\chi')^*\,\bar{f}f \qquad\qquad \chi \to \chi' + f + \bar{f}$$

And consider the following benchmarks:

TABLE II: Best-fitting DM parameters

	Unit	ee	$\mu\mu$	$\tau\tau$	$b\bar{b}$	$e\mu$	$e\tau$	$\mu\tau$	ll
Δm_χ	(TeV)	0.7	2.0	7.2	$100.0^\dagger$	1.3	4.8	3.4	2.1
$m_\chi \tau$	(10^{27}TeV s)	0.4	1.2	1.4	16.3	0.8	0.8	1.1	0.8

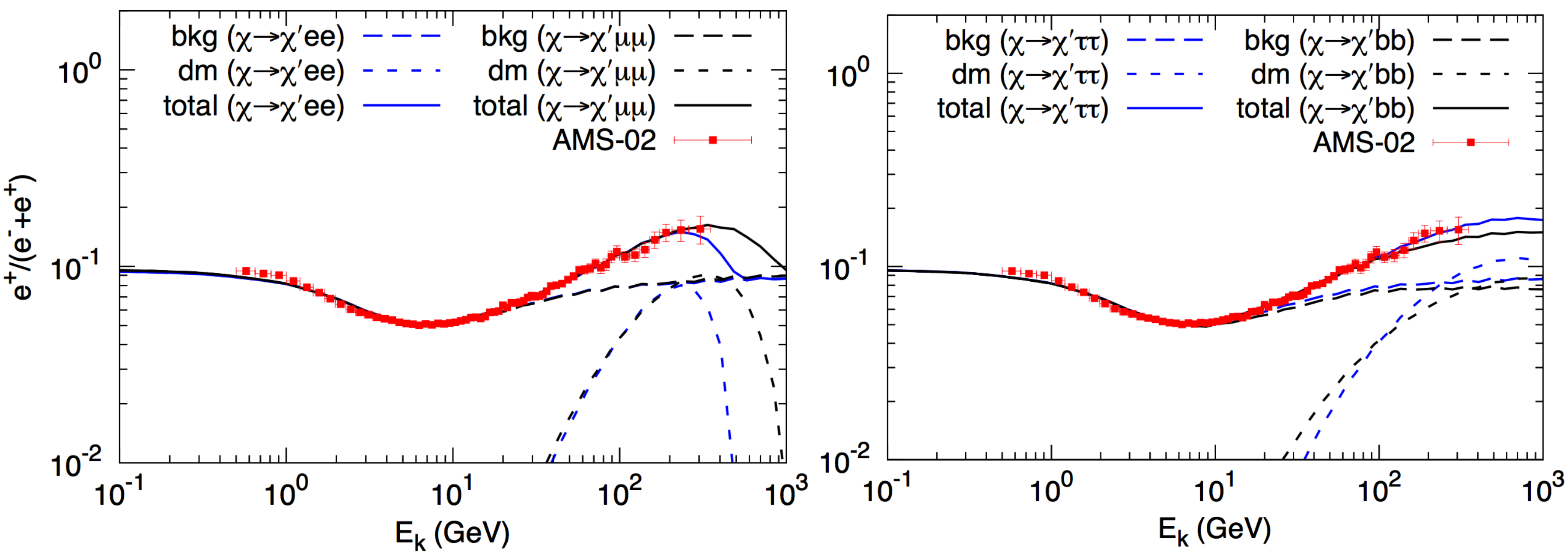
†This value is close to the upper bound of the scan.

$$m_{\chi'} = 1\,\text{TeV}$$

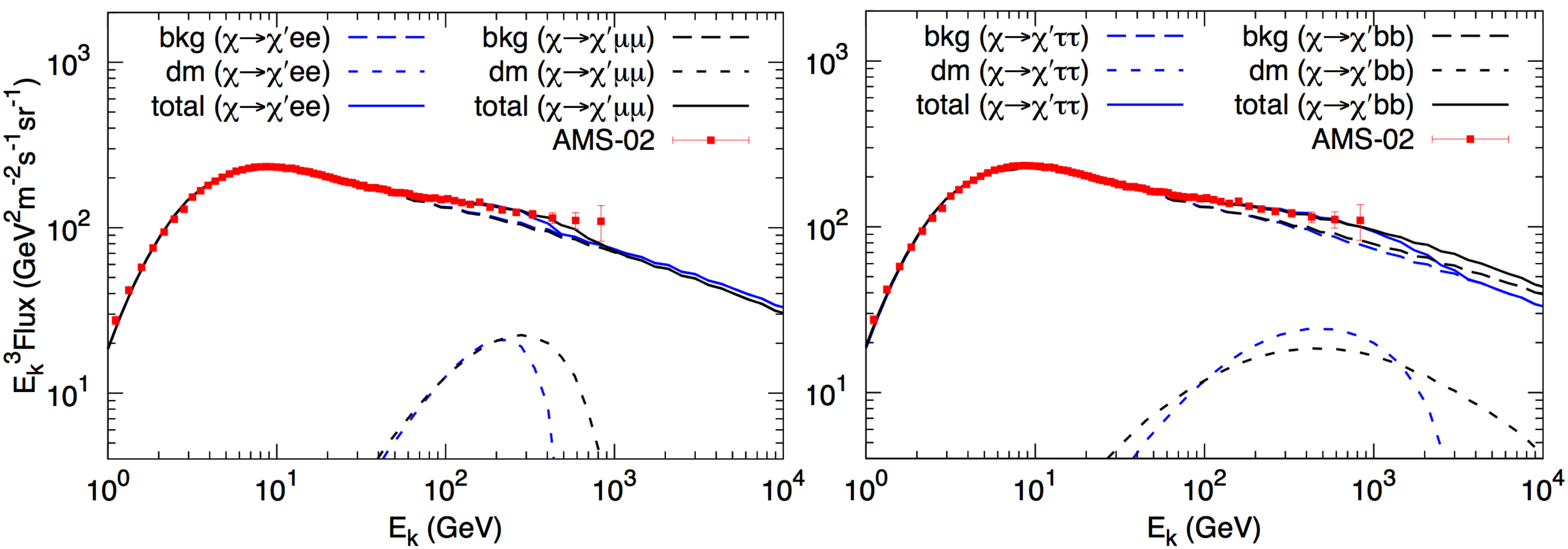
The decaying DM in general has a mass of the order of multi-TeV.

Cheng, Huang, Huang, Low, Tsai and Yuan: 1608.06382

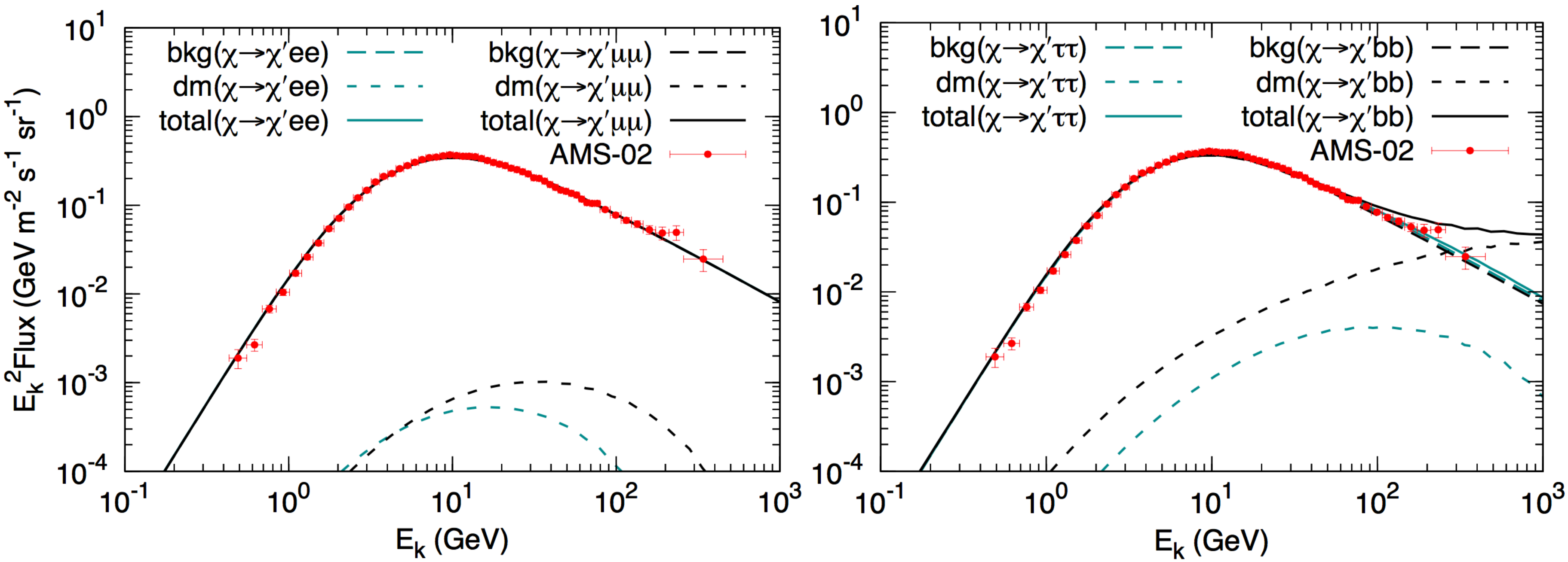
The fit to the 2014 AMS-02 positron fraction data for *ee, μμ, ττ* and *bb* channels:



The fit to the 2014 AMS-02 total electron+ positron data for *ee, μμ, ττ* and *bb* channels:



The fit to the **2016** AMS-02 anti-proton data for *ee, μμ, ττ* and *bb* channels:

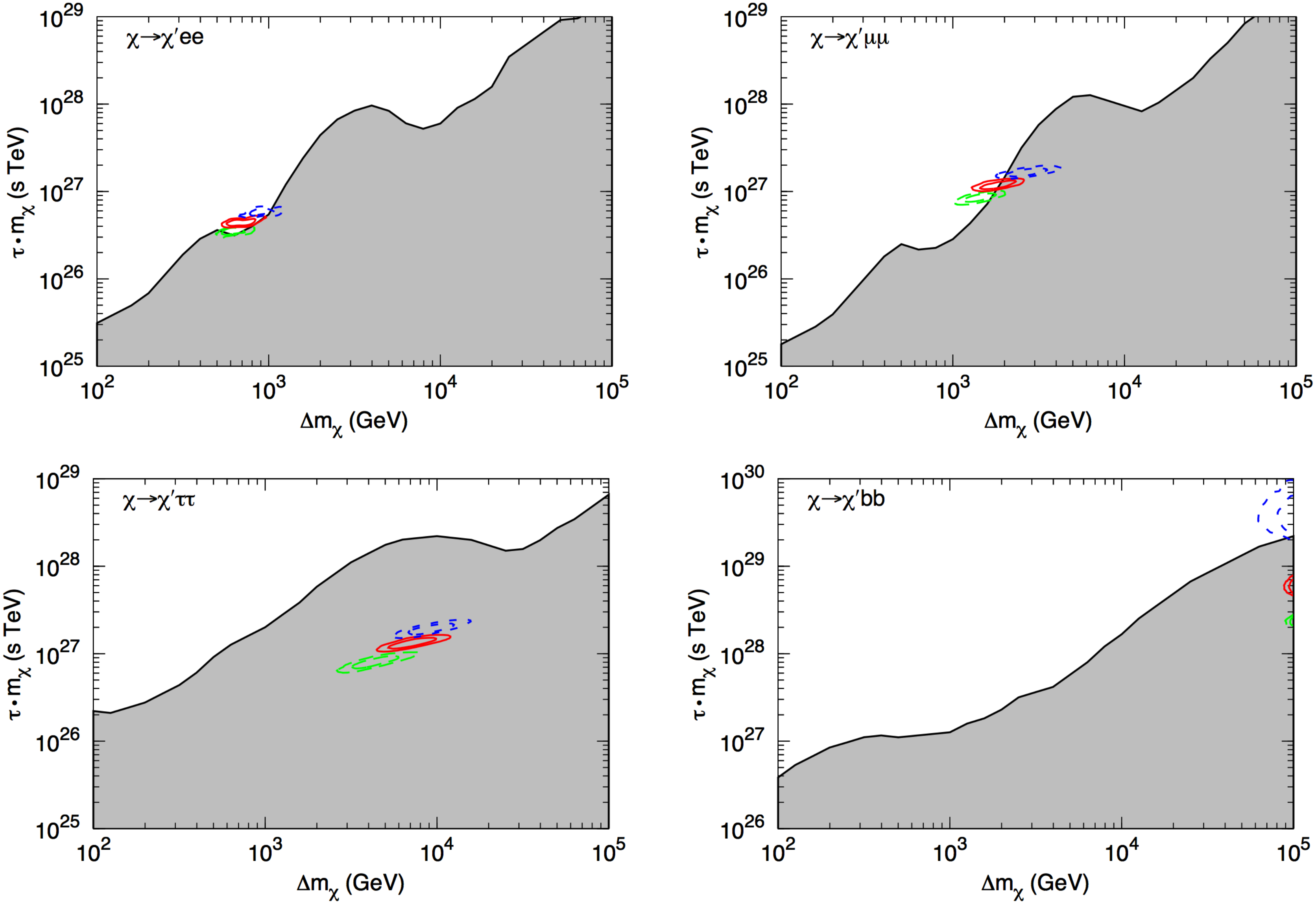


But fitting the positron/anti-proton spectra is only half of the task, as Fermi-LAT data extragalactic gamma-ray backgrounds (EGB) are very constraining.

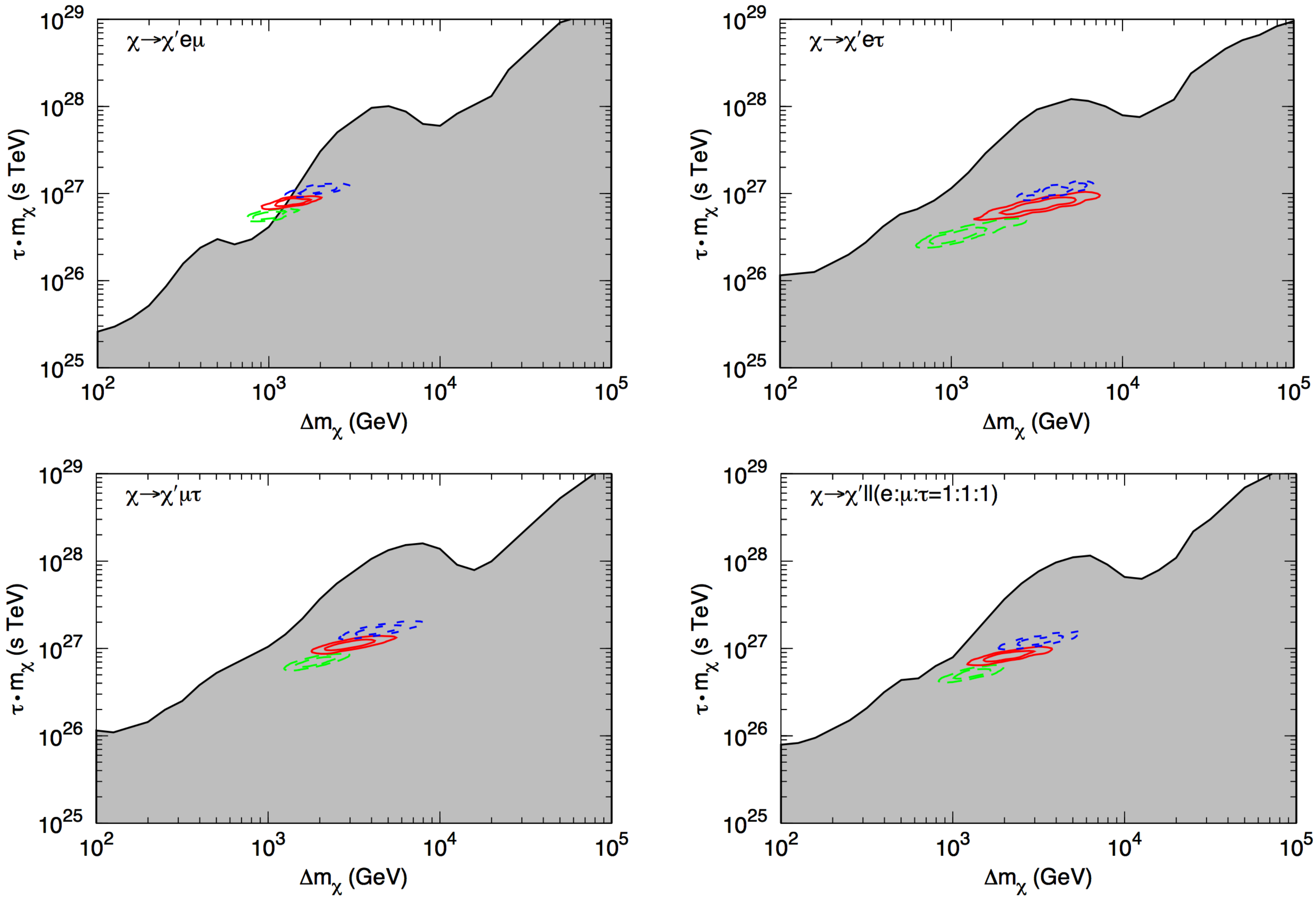
The EGB has two components:

- Prompt emissions associated with DM decays. (Have higher energy.)
- Inverse Compton (IC) scatterings of electrons and positrons from DM decays. (Have lower energy.)

After all is said and done, here are the EGB constraints for *ee, μμ, ττ* and *bb* channels:



EGB constraints for flavor-violating and flavor-universal channels:

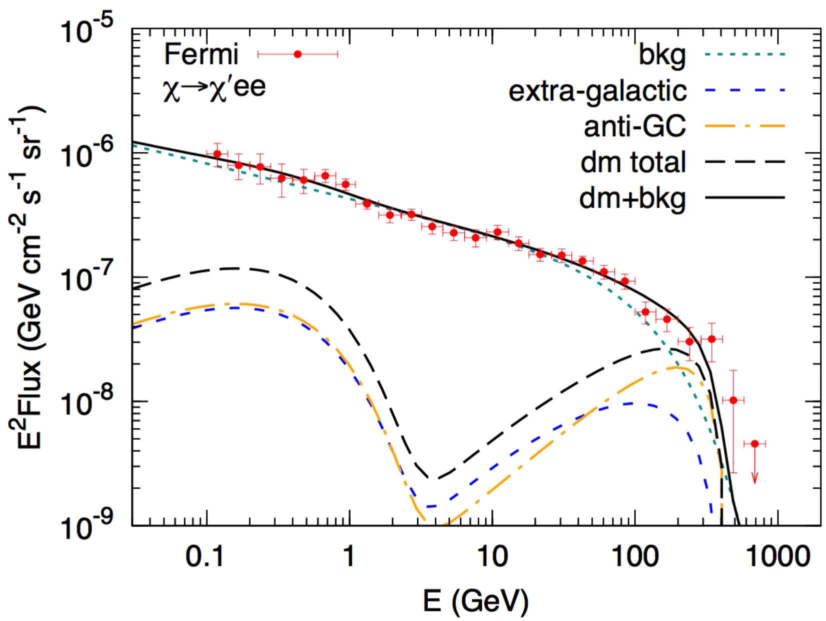


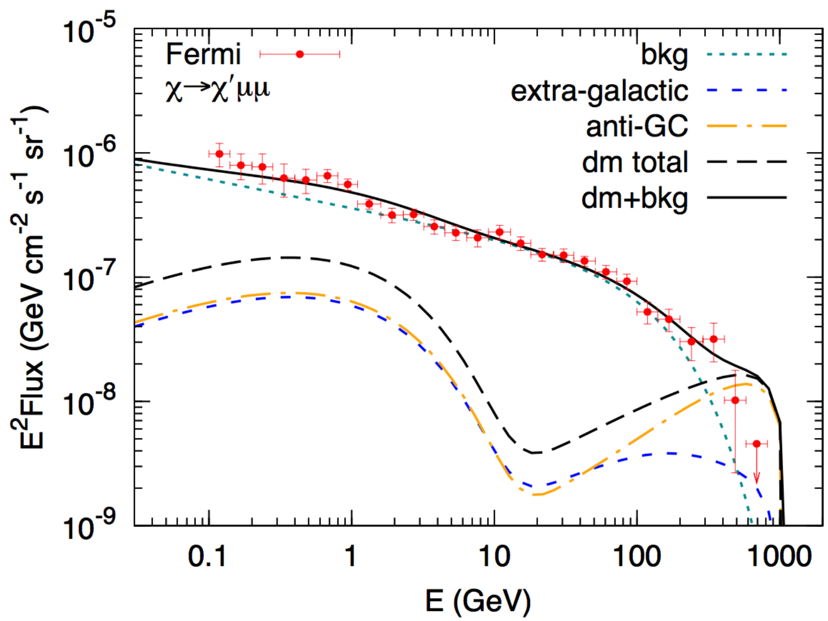
The snapshot:

Only final states containing the electron and/or the muon survive the EGB constraints.

To get an idea on the various EGB contributions:

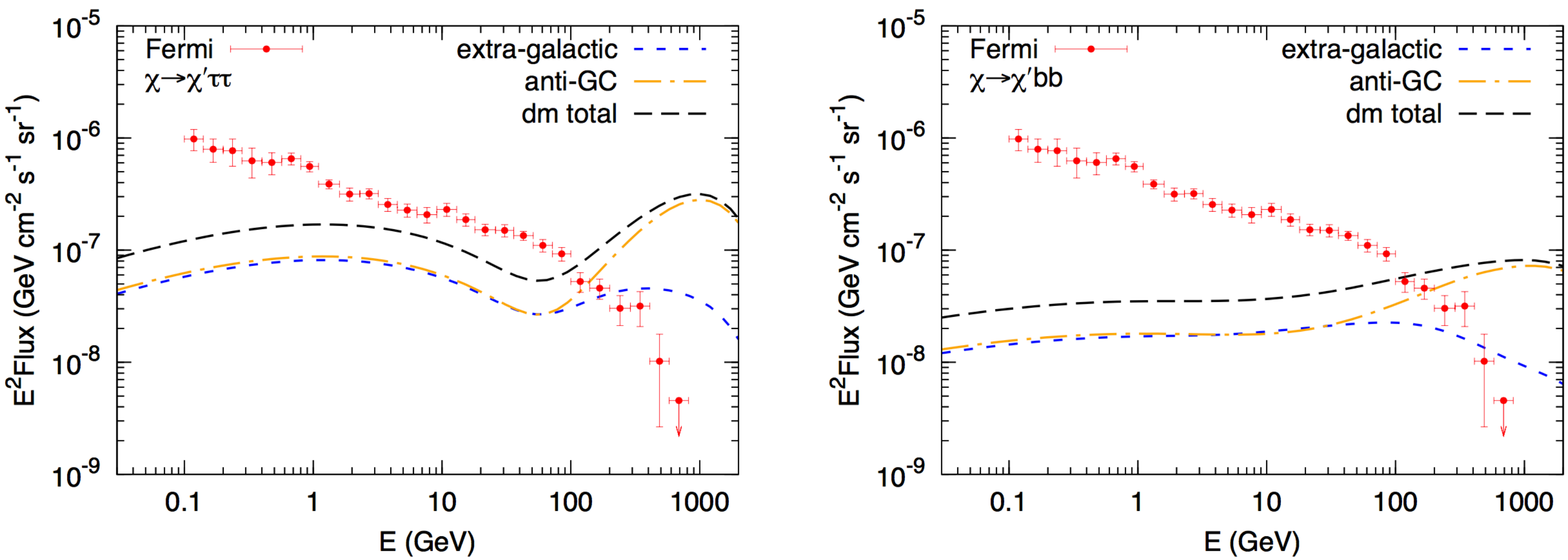
The two-hump feature is due to the Prompt component (higher energy) and IC component in the diffuse gamma-rays.



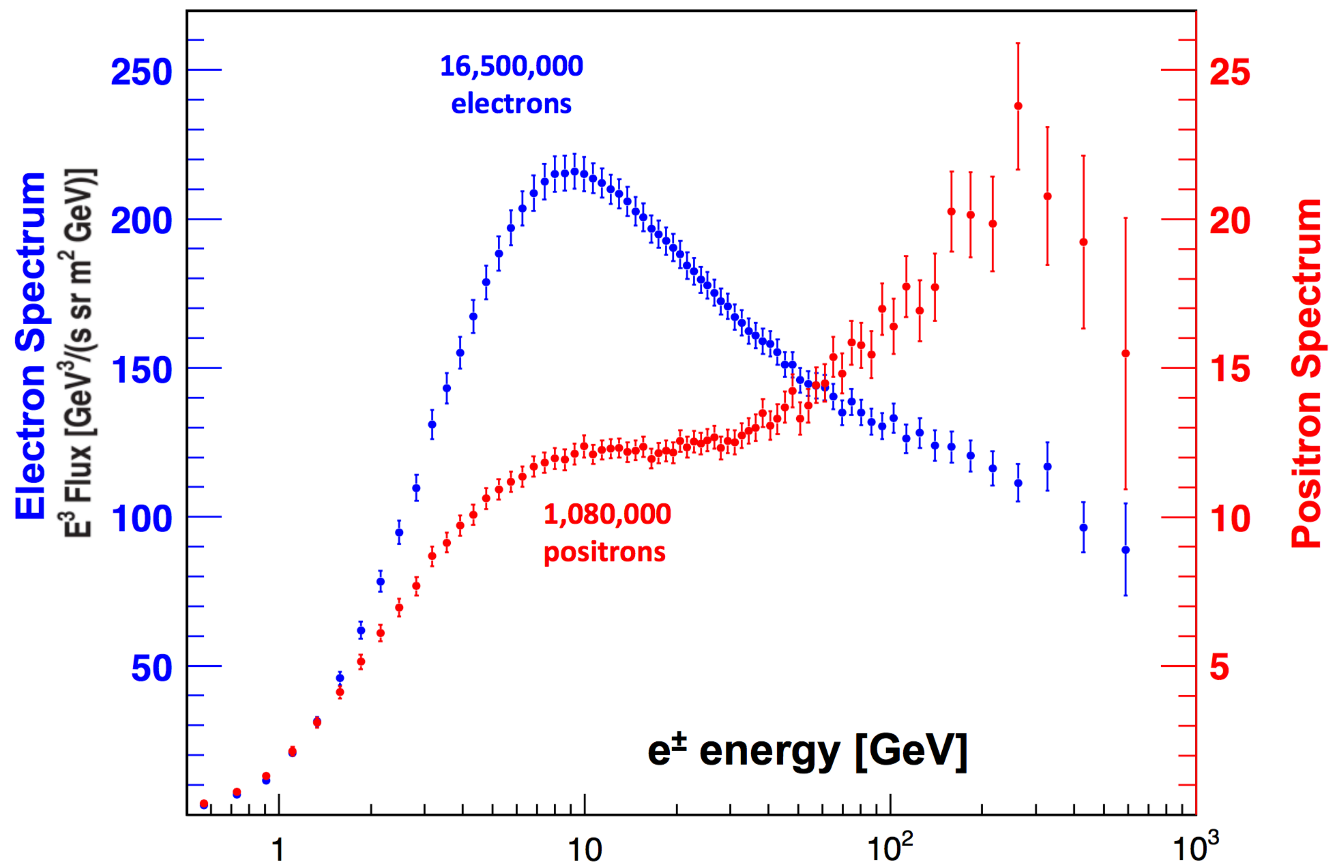


To get an idea on the various EGB contributions:

Hadronic final states (τ and bottom quarks) give a Prompt photon contribution that overshoots the data.

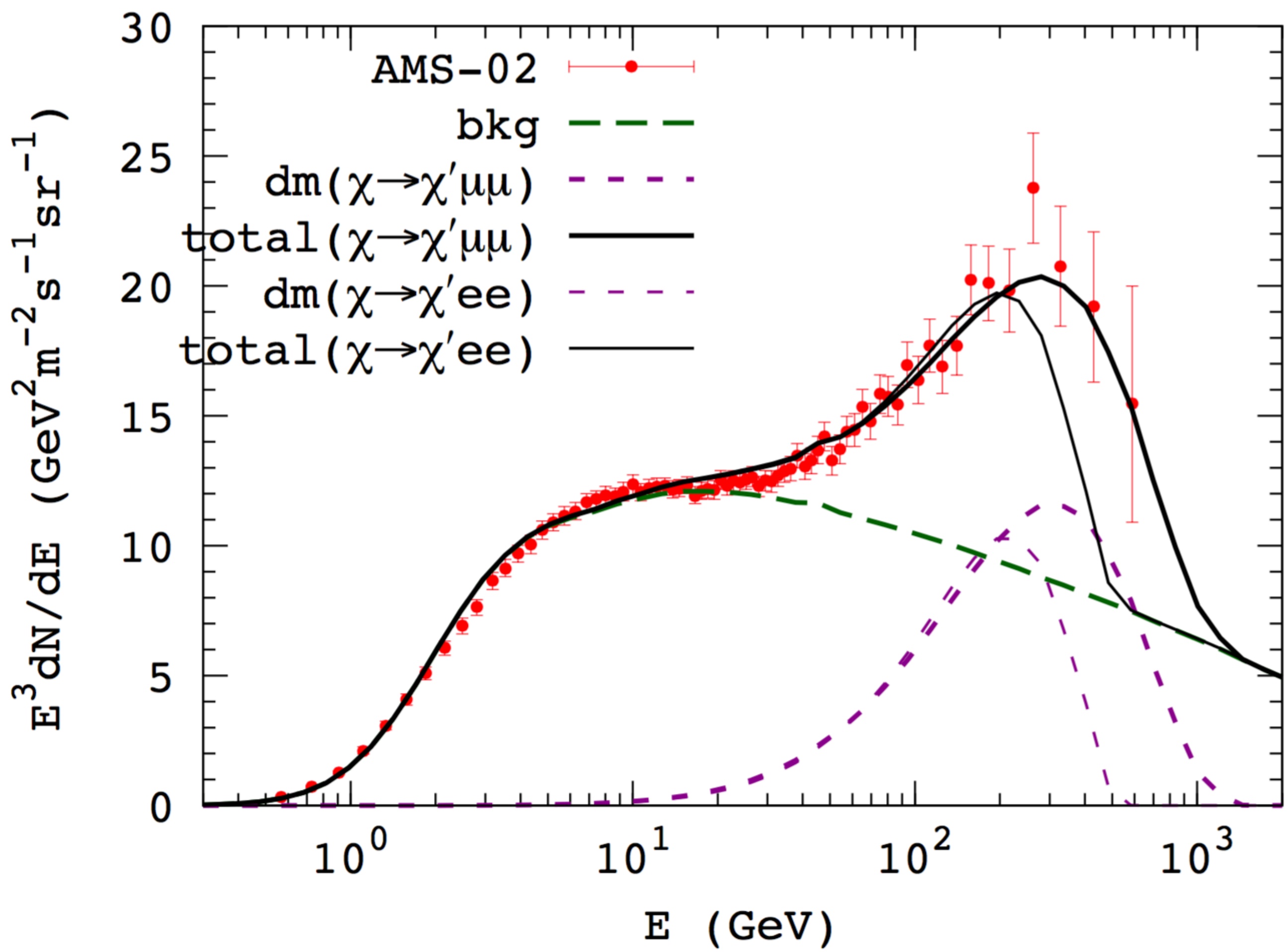


A few weeks ago (and after our paper was submitted to the arXiv), AMS announced more data on cosmic ray positrons, which exhibits a tantalizing "turn-over" feature:



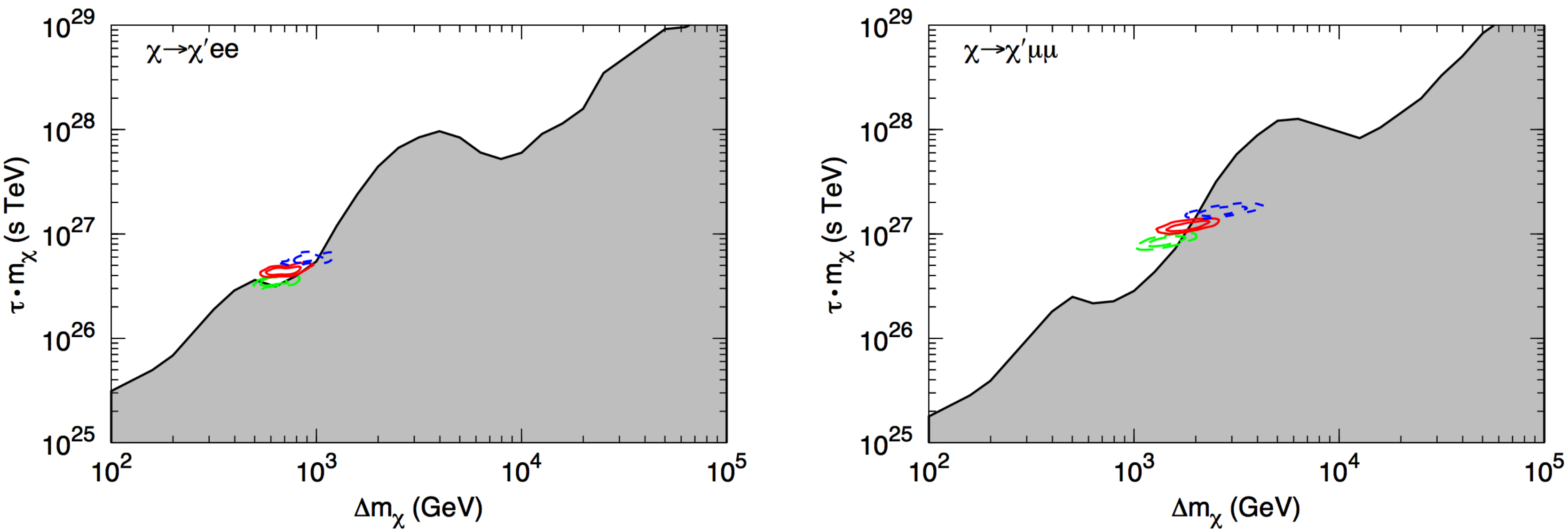
AMS-02 Press Release, Dec. 8, 2016

This is how the three-body decaying DM stack up against the new data:



Decays into muon final states seem to provide a better fit to the new data.

On the other hand, muon channel is sitting at the edge of EGB constraints:



Are we on the verge of seeing a correlated signal in the diffuse gamma-ray data in the near future?