The Case for Three-body Decaying Dark Matter

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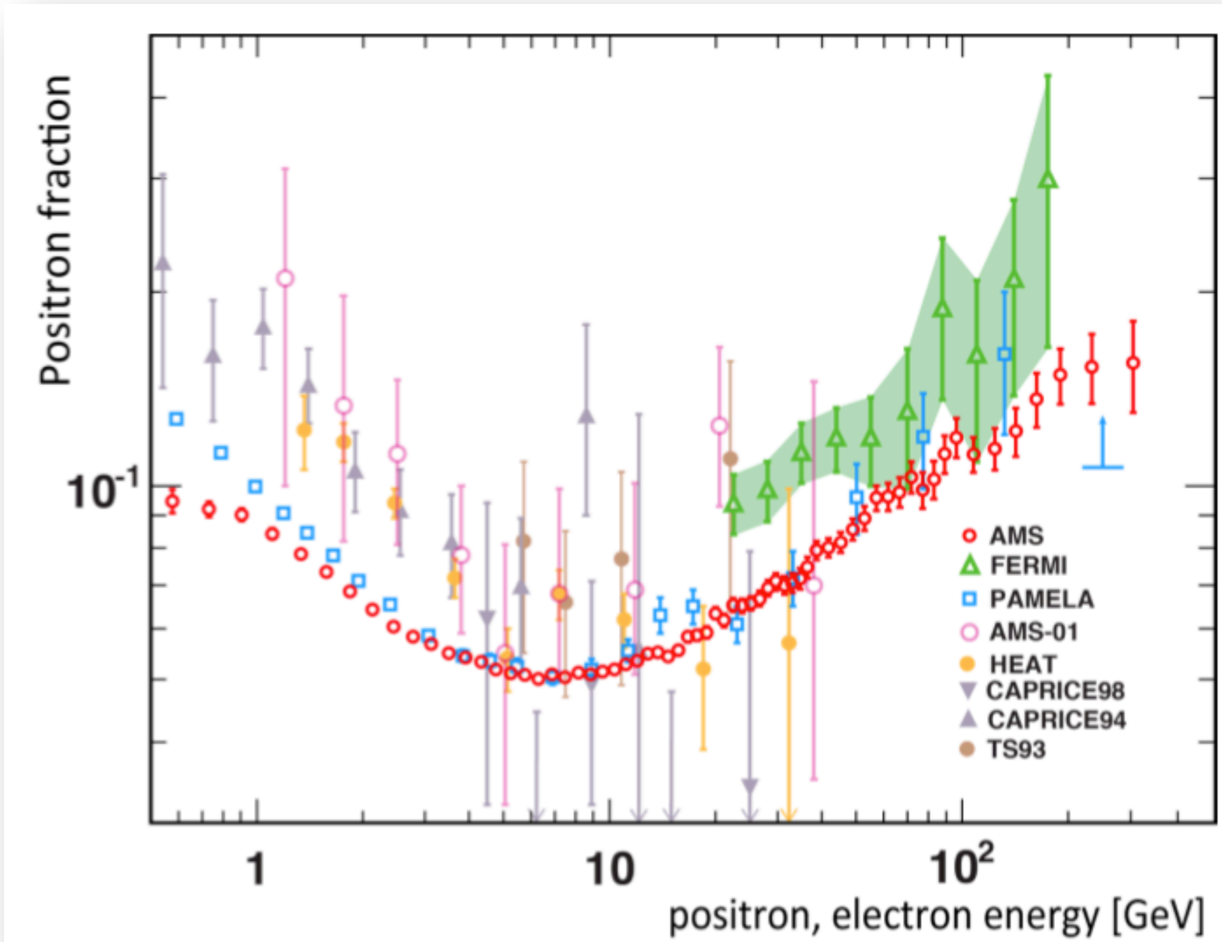
September 20, 2013 @ KICP Workshop on
"Dark Matter at the LHC"

References: 1) H.-C. Cheng, W.-C. Huang, I.L., and A. Menon: 1012.5300
2) H.-C. Cheng, W.-C. Huang, I.L., and G. Shaughnessy: 1205.5270

Disclaimer:

This talk is inspired by messages from the sky, but there are important implications for collider searches.

The PAMELA excess in cosmic positron flux below 100 GeV region, which was subsequently confirmed and extended by Fermi-LAT and AMS-02:



There are two possibilities for such an excess:

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

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

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 PAMELA.

- The large flux required by PAMELA 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 galatic 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 galatic 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 message is clear:

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

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

are having difficulty with existing diffuse gamma-ray measurements!

Our proposal is to alleviate the tension with 3-body decays with a missing particle (the LSP),

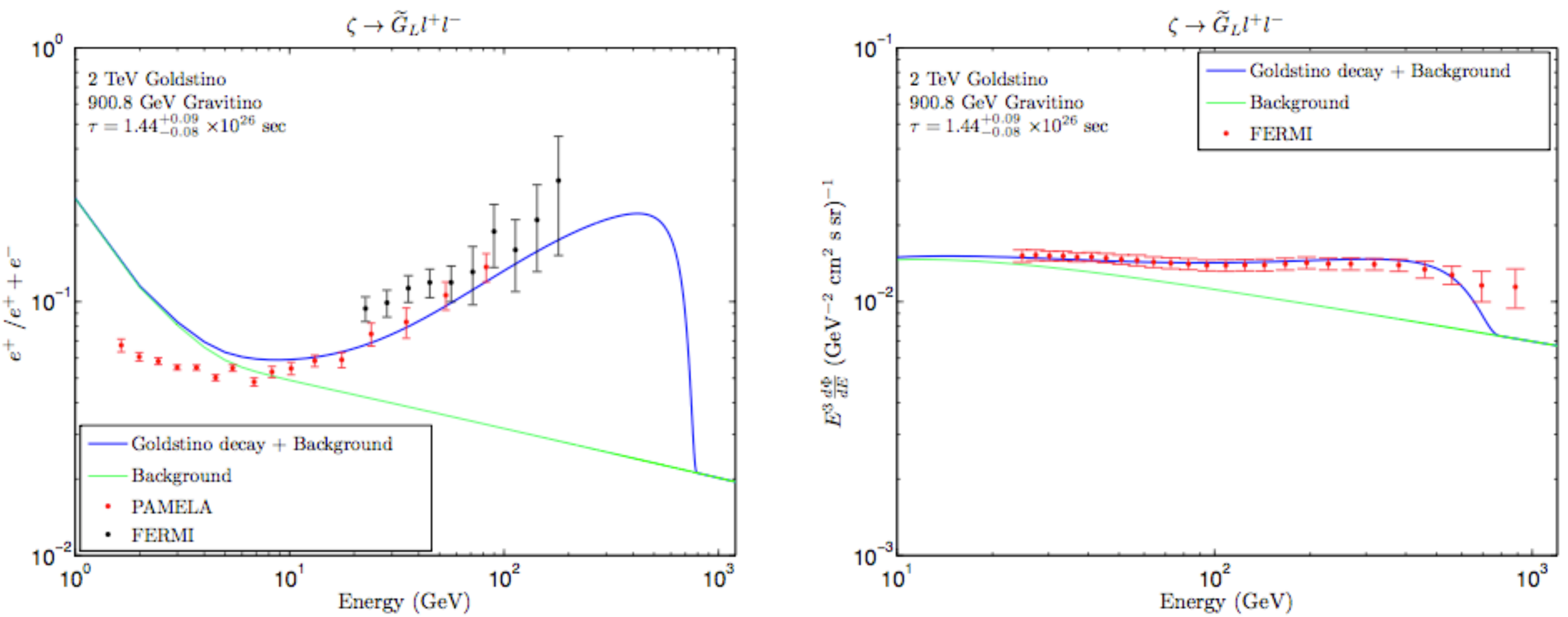
$$\zeta \to \widetilde{G}_L + \ell^+ + \ell^-$$

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

The physics behind is very simple:

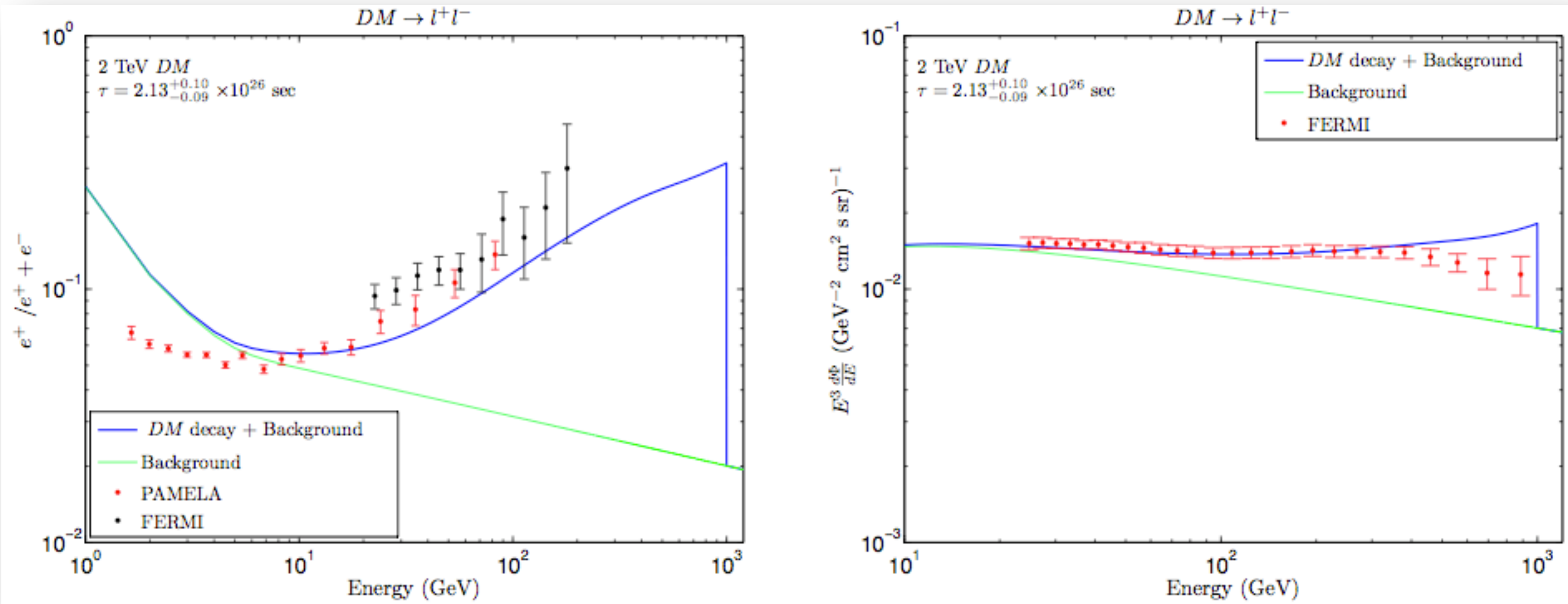
Three-body decay kinematics with a missing particle give a softer energy spectrum for the charged leptons and, as a result, softer synchrotron radiation.

We can fit both the positron fraction (PAMELA) and total $e^+ + e^-$ spectra (Fermi-LAT):

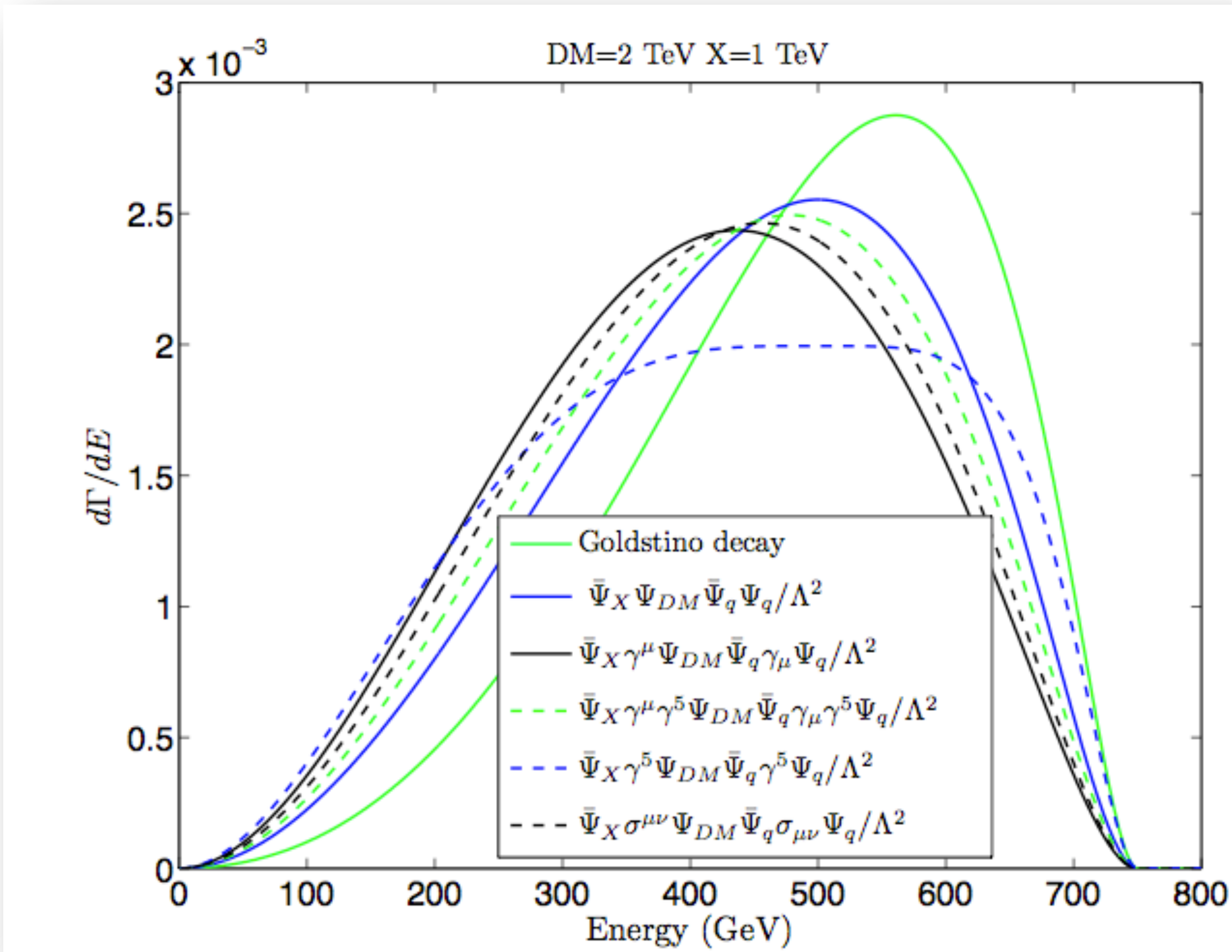


Cheng, Huang, Low, and Menon: 1012.5300
Cheng, Huang, Low, and Shaughnessy: 1205.5270

To show you the contrast with 2-body DM decays:

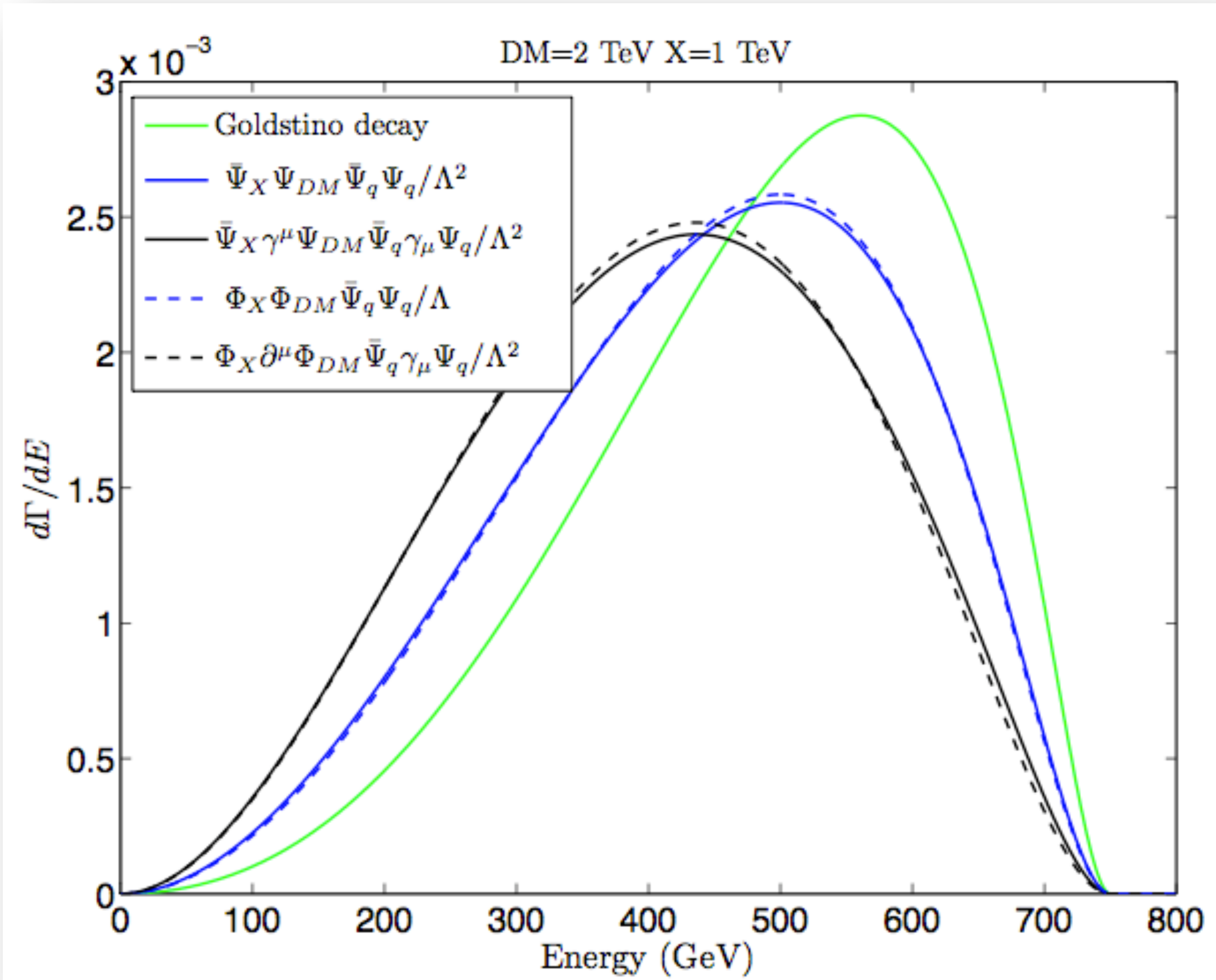


The result is generic for 3-body decaying dark matter, since the energy spectrum is similar among the different operators mediating the decays:

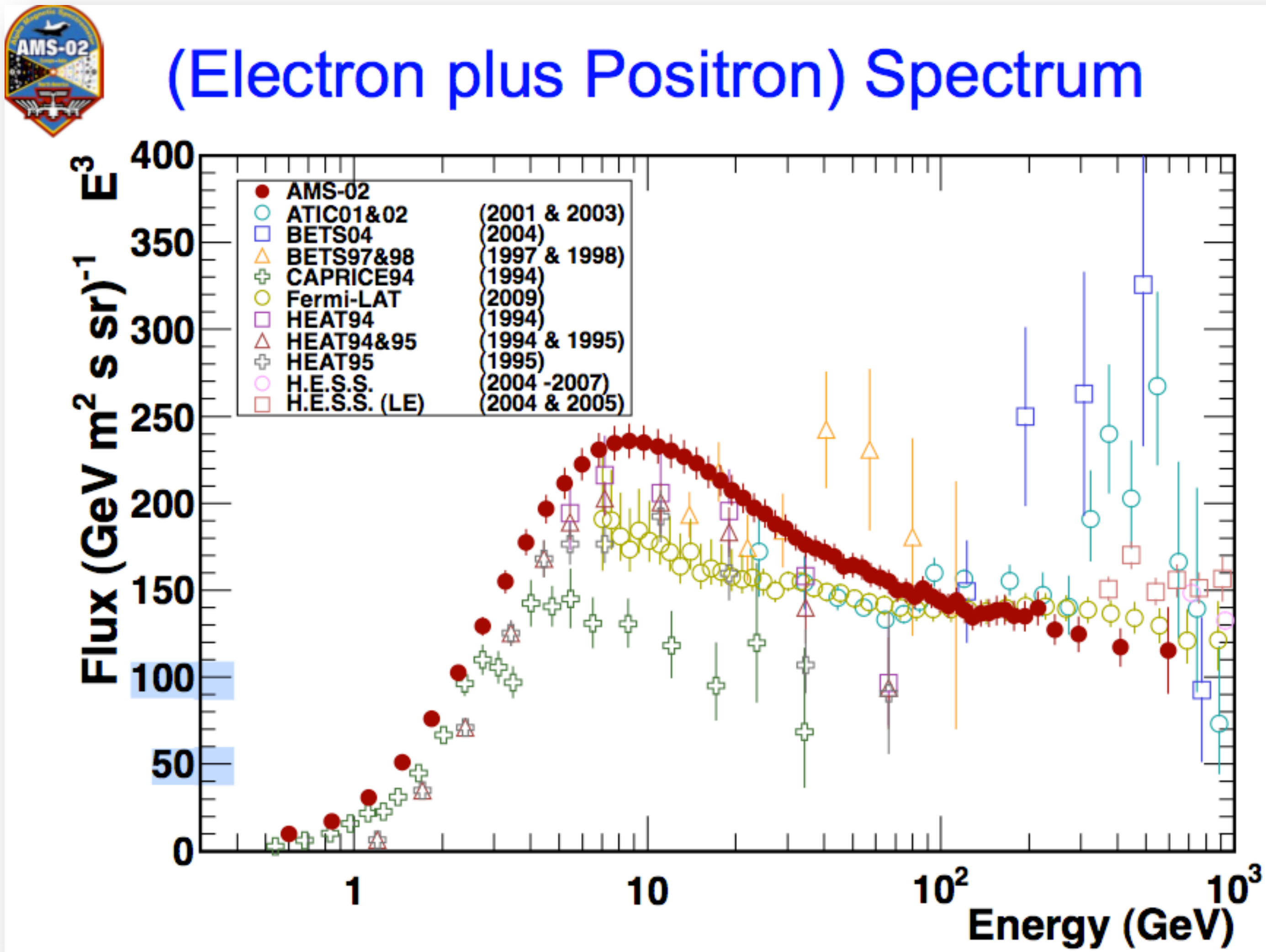


The energy spectra look similar even between a scalar and a fermionic DM, if

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



It is worth mentioning that AMS-02 released their data on total $e^+ + e^-$ flux, which is consistent with Ferm-LAT data above 100 GeV:



Three classes of astrophysical constraints:

- Diffuse gamma-rays due to inverse Compton scattering (ICS) and final state radiation (FSR).

  Directly constrain partial decay widths into charged leptons.

- Prompt photons directly from DM decays.

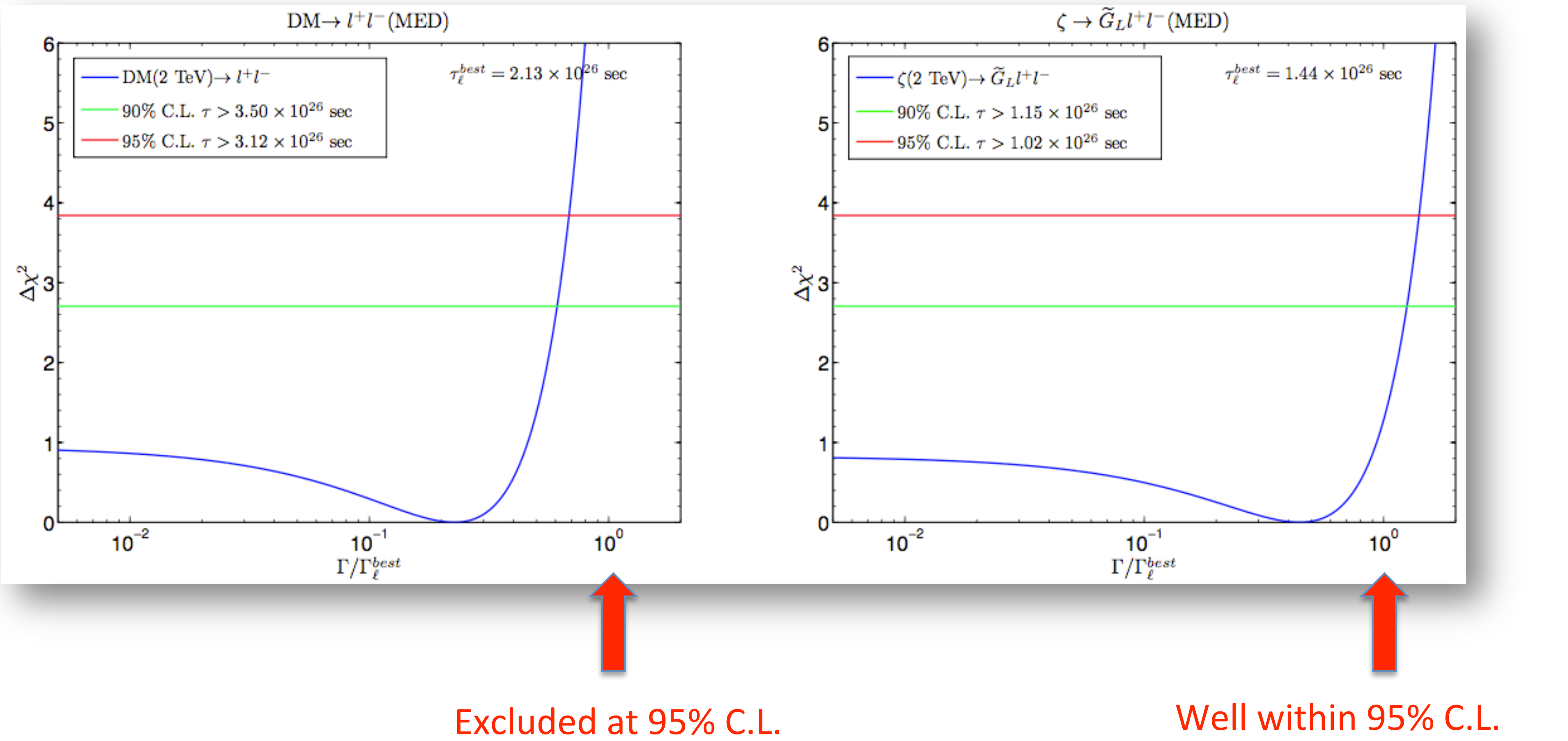
  Constrain partial widths into final states containing photons.

- Anti-proton flux measurements.

  Constrain hadronic partial widths.

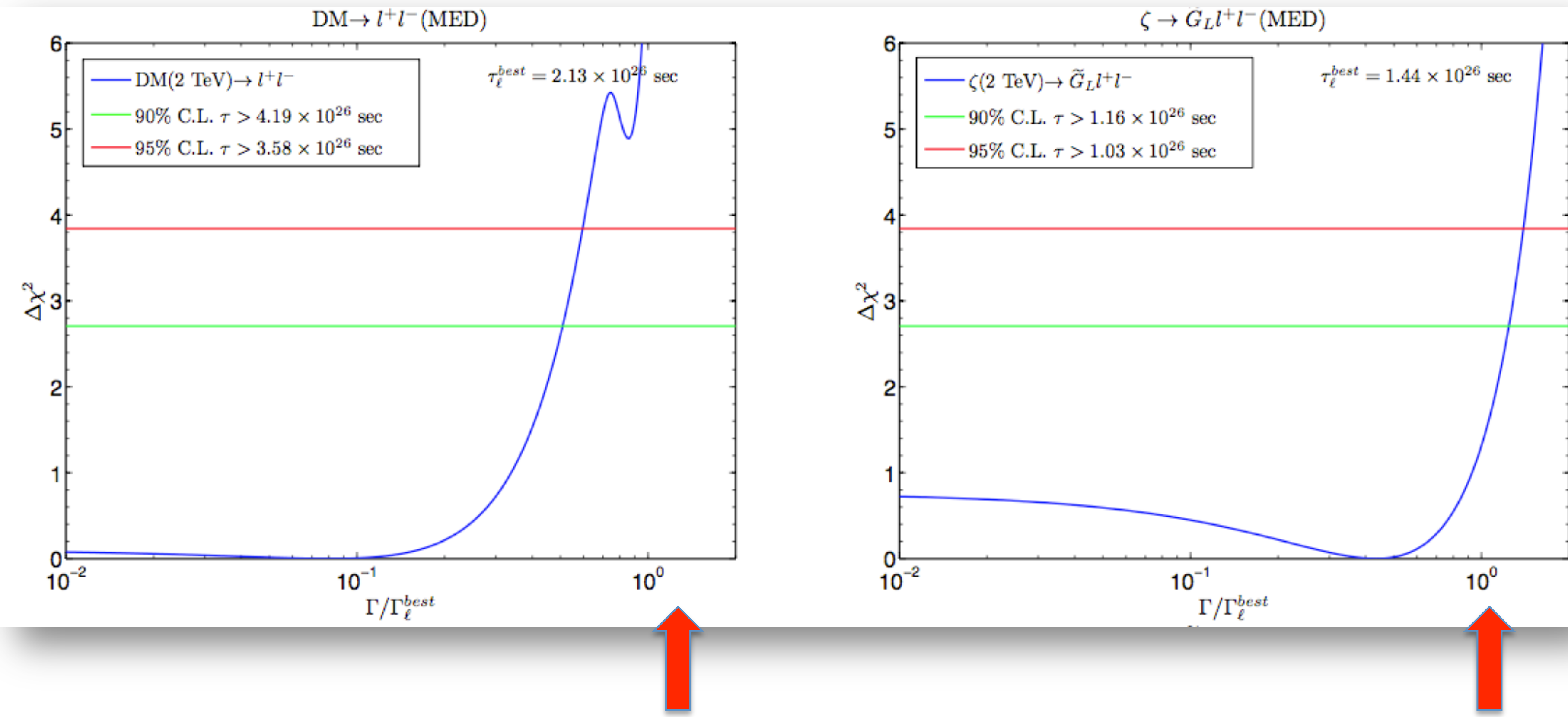
There are two kinds of diffuse gamma-ray measurements --

1) The diffuse gamma-ray emission (DGE):



There are two kinds of diffuse gamma-ray measurements –

2) The Extra-galactic gamma-ray background (EGB):



Excluded at 95% C.L.

Well within 95% C.L.

DEG and EGB constraints on prompt photon:

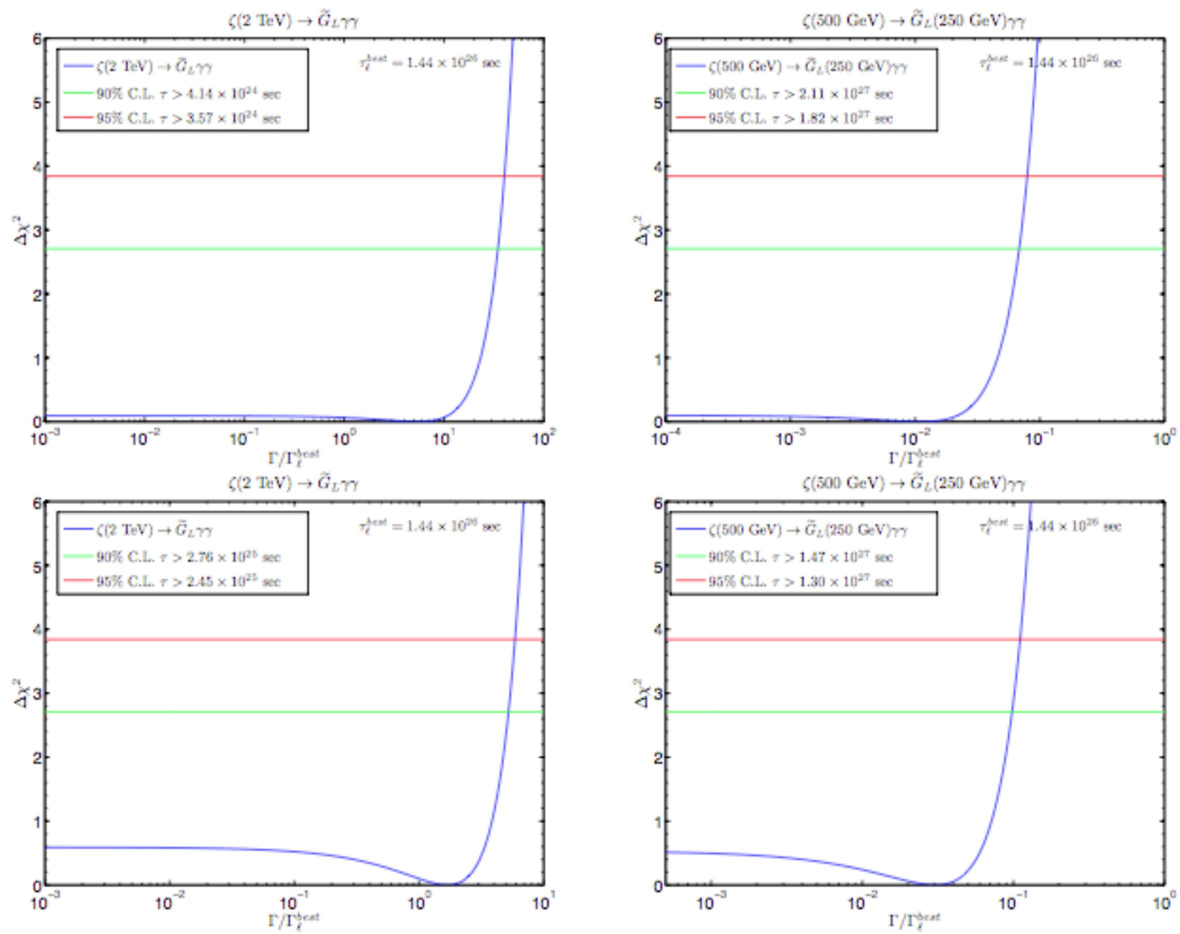
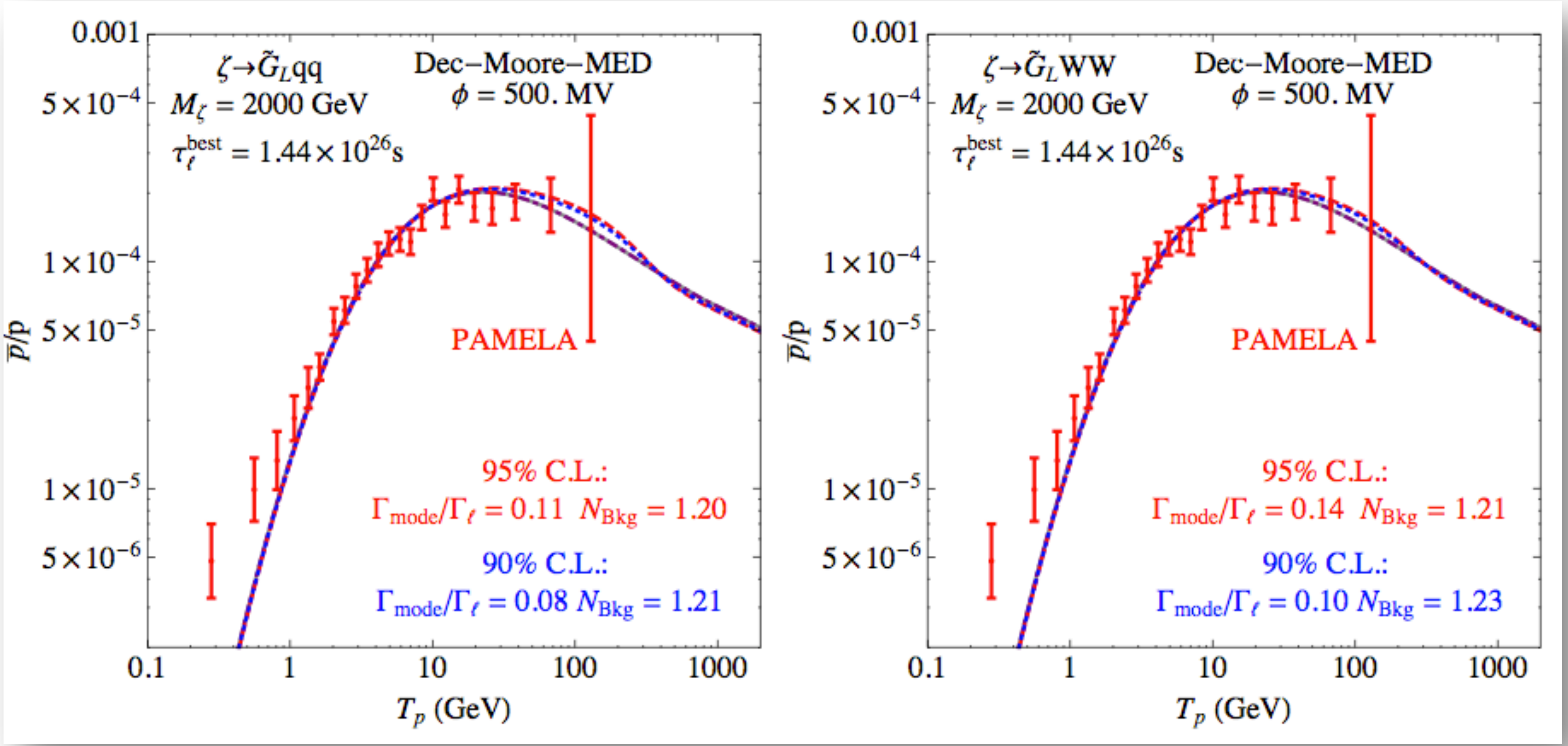


FIG. 11: *The Fermi-LAT DGE constraints (upper panels) and EGB constraints (lower panels). The 2 TeV goldstino decay to photons could easily pass the test of the Fermi-LAT gamma ray data because the injection spectrum of photons peaks well beyond 100 GeV. On the other hand, a 500 GeV goldstino is severely constrained by Fermi gamma ray data.*

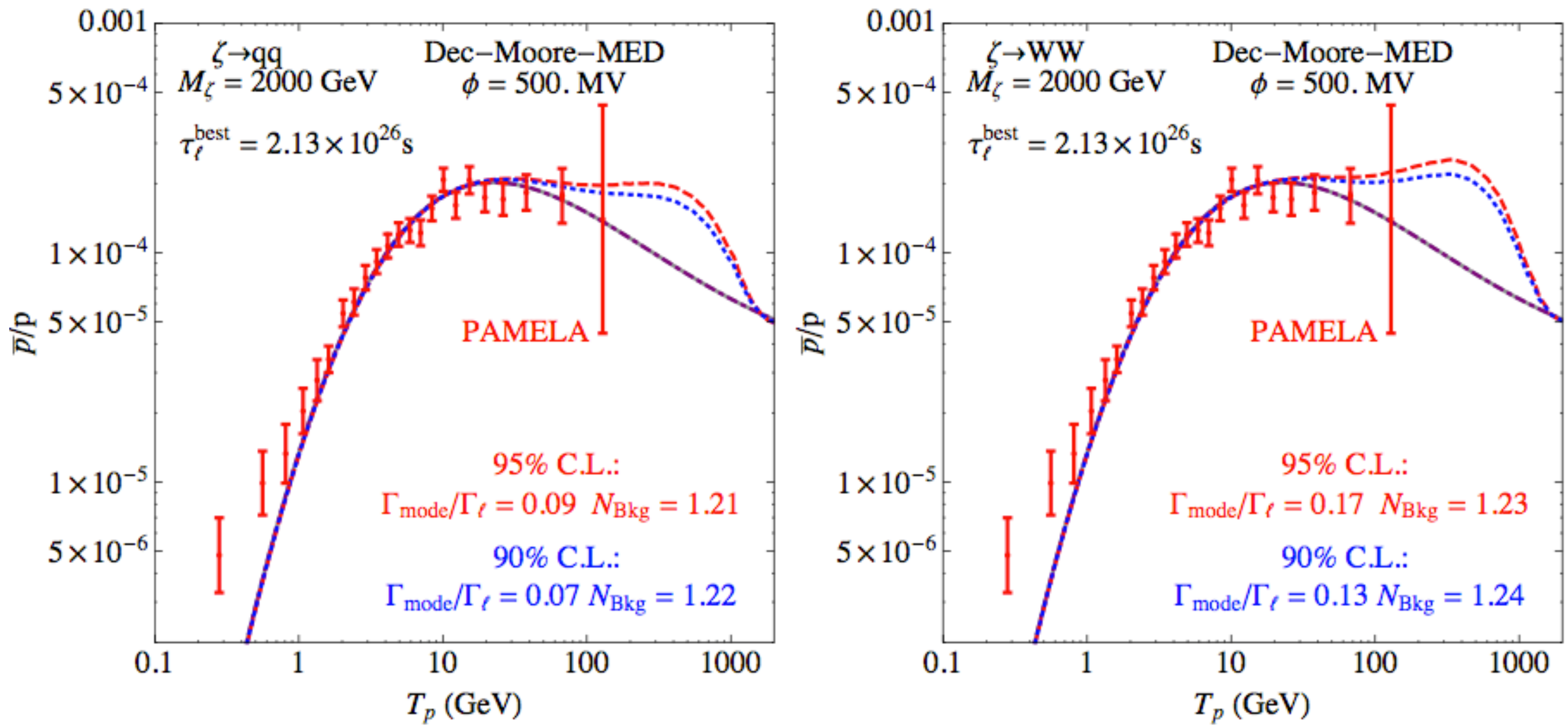
For 2-body decays, anti-proton measurements place severe constraints on hadronic final states, requiring the DM to be leptophilic.

Not surprisingly, 3-body decays can open up some hadronic channels:

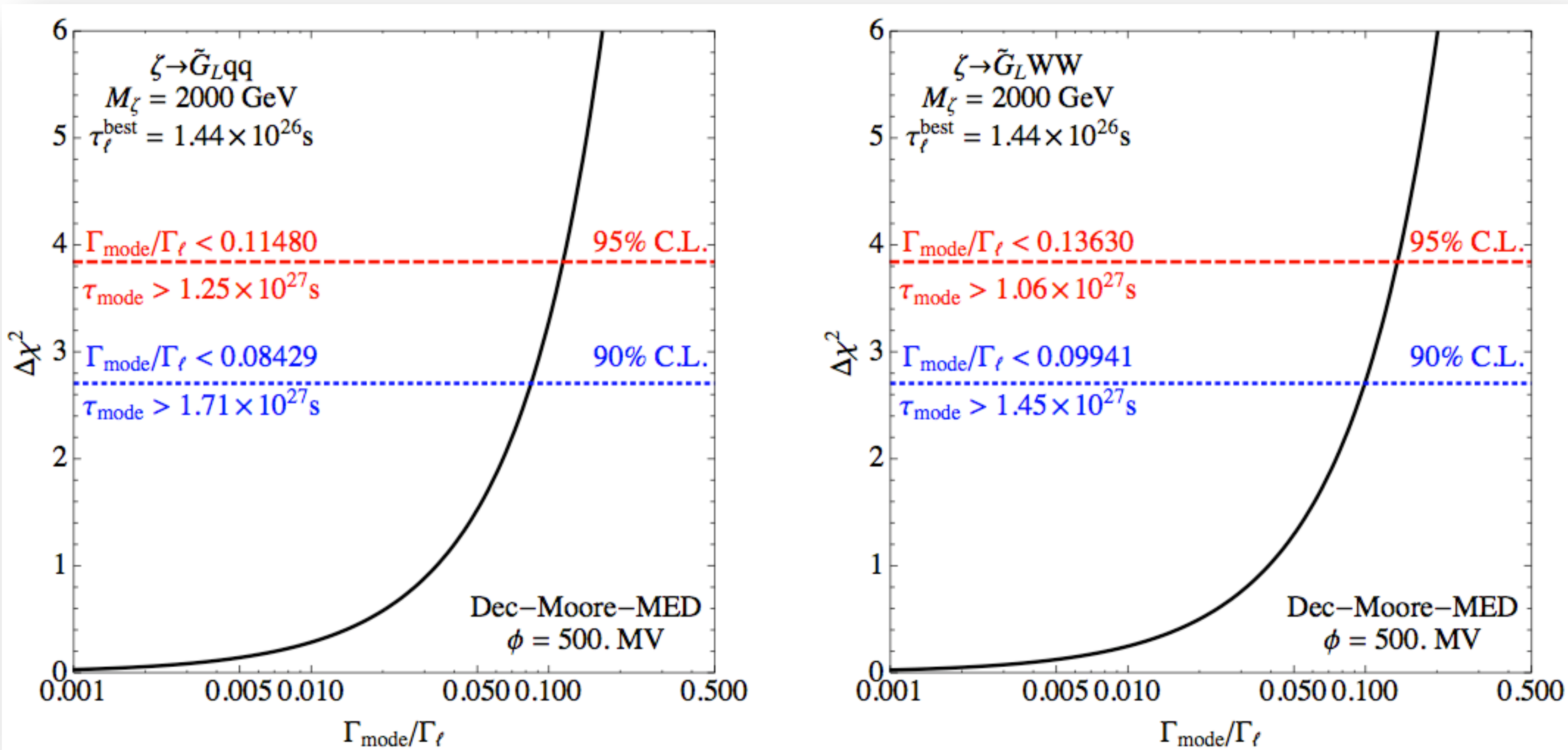


It will be interesting to see what AMS-02 has to say!

Again, to show you the contrast with 2-body DM decays:



The hadronic width can be about 10% of the leptonic width:



A factor of 10 ratio in leptonic vs hadronic widths translates, roughly, into a factor of 3 ratio in the respective couplings to DM.

This can be achieved if the DM couplings are proportional to B-L quantum numbers.

Last but not least, the LHC implications:

- Given that DM has very suppressed couplings to the visible sector (recall the DM lifetime is longer than the age of universe!), whatever particle decays to DM is likely to be non-prompt!

- The LHC collider phenomenology is then dependent on the particle that decays to the DM, whether it is electrically neutral, charged, or colored. Details are obviously model-dependent, and should be studied in more details.

- Since indirect detections suggest larger couplings to leptons, whatever decays to DM is most likely to carry lepton number.

- Missing energy signature is not the only way DM would show up at the LHC. Nature could be more subtle than that! (Non-prompt decays deserve perhaps a little more attention.)