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The GeV Excess Shining Through: Background Systematics for the Inner Galaxy Analysis

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Recently, a spatially extended excess of gamma rays collected by the *Fermi*-LAT from the inner region of the Milky Way has been detected by different groups and with increasingly sophisticated techniques. Yet, any final conclusion about the morphology and spectral properties of such an extended diffuse emission are subject to a number of potentially critical uncertainties, related to the high density of cosmic rays, gas, magnetic fields and abundance of point sources. We will present a thorough study of the systematic uncertainties related to the modelling of diffuse background and to the propagation of cosmic rays in the inner part of our Galaxy. We will test a large set of models for the Galactic diffuse emission, generated by varying the propagation parameters within extreme conditions. By using those models in the fit of *Fermi*-LAT data as Galactic foreground, we will show that the gamma-ray excess survives and we will quantify the uncertainties on the excess emission morphology and energy spectrum.

1. Introduction

One of the most challenging results for indirect dark matter searches in recent years is the discovery of an excess emission in the gamma-ray flux from the center of our Galaxy. The first indications of such an excess date back to 2009 [Goodenough and Hooper 2009, Vitale et al. 2009]. Since then, several analyses of gamma-ray data from the Large Area Telescope aboard the *Fermi* satellite [Gehrels and Michelson 1999], hereafter *Fermi*-LAT, claimed the existence of the excess above the standard astrophysical background at GeV energies [Goodenough and Hooper 2009, Hooper and Goodenough 2011, Boyarsky et al. 2011, Hooper and Linden 2011, Abazajian and Kaplinghat 2012, Macias and Gordon 2014, Abazajian et al. 2014, Daylan et al. 2014, Zhou et al. 2014]. The excess emission results from analyses of both the inner few degrees of the Galaxy [Abazajian and Kaplinghat 2012, Macias and Gordon 2014, Abazajian et al. 2014, Daylan et al. 2014, Zhou et al. 2014, Gordon and Macias 2013] and *higher* latitudes [Daylan et al. 2014, Hooper and Slatyer 2013, Huang et al. 2013], extending up to tens of degrees. Intriguingly, the observed spectral energy distribution and the spatial properties of the *Fermi* GeV excess match the expectation for a signal from dark matter particles annihilating in the halo of the Milky Way. Nevertheless, some discussion about astrophysical explanations were put forward, as, for example, about the emission from a population of point-like sources below the telescope's detection threshold [Hooper et al. 2013, Calore et al. 2014a, Cholis et al. 2014, Petrovic et al. 2014a], or violent burst events at the Galactic center with injection of leptons and/or protons some kilo-/mega-years ago [Carlson and Profumo 2014, Petrovic et al. 2014b].

Regardless of the possible interpretations, all analyses agree on the fact that an extra-emission over the *standard* astrophysical background is present in the inner region of the Galaxy. We stress here that the Galactic center is one of the most promising targets for dark matter searches since there the typically predicted profiles for the dark matter distribution lead to the largest photon flux from dark matter origin. However, the Galactic center is maybe the most challenging target for dark matter searches: our knowledge of the conditions at the Galactic center is indeed very poor and the astrophysical background (from point sources as well as from diffuse emission processes) is affected by large uncertainties.

A critical point is to answer the question "An excess above what?". The excess emission is defined with respect to specific astrophysical foregrounds and backgrounds, like the Galactic diffuse emission (which originates from the interactions of cosmic rays with gas and photons in the Galaxy), point-like and extended sources. Those components should be modelled independently. Therefore, it is crucial to explore different foreground and background models in order to robustly identify and characterise the excess emission.

We will present here part of the analysis performed in Calore et al. [2014b], where we showed for the first time that the excess is statistically robust against theoretical model systematics, bracketed by exploring previously neglected uncertainties on the Galactic diffuse emission, and that the proper treatment of background modelling uncertainties allows more freedom for models fitting the excess [Calore et al. 2014c].

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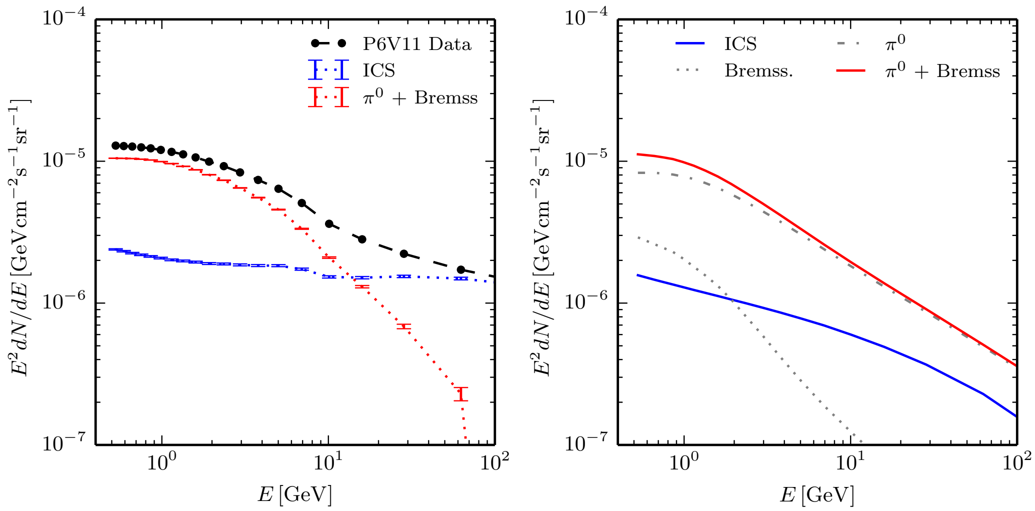

Figure 1: *Left panel:* ICS and π^0+Bremss contributions to the `P6V11` background model. *Right panel:* Spectra predicted by a typical Galactic diffuse model for ICS, π^0 and bremsstrahlung emission. Fluxes in the $40° \times 40°$ ROI, $|b| > 2°$.

2. On the importance of foreground modelling

The dominant source of background for the Galactic center analysis is the emission originating from the interaction of cosmic rays with dust and gas in the Galaxy. The three main production mechanisms of Galactic diffuse gamma rays are: the Inverse Compton scattering (ICS) of electrons on low-energy ambient photons, the decay of abundantly produced neutral pions and the bremsstrahlung of electrons in the interstellar medium. Most of previous analyses adopted the same background model to describe the Galactic diffuse emission, namely the `P6V11` background model, provided by the *Fermi*-LAT Collaboration for the *sole* purpose of point source analysis.[1] Using this model for analysis of extended sources introduces systematic effects that might lead to biased statements about the spectrum and morphology of the *Fermi* GeV excess emission.

To visualise this effect, we decomposed the `P6V11` model in the main contributions to the Galactic diffuse emission. The spectra for ICS, π^0 and bremsstrahlung (that we consider as a unique component "π^0+Bremss") are predicted by a standard model for cosmic-ray propagation in the Galaxy (see Calore et al. [2014b] for more details). We fitted simultaneously the ICS and π^0+Bremss components to `P6V11` mock-data. From Figure 1, left panel, the reader can see that an extremely hard ICS emission at energies ≥ 10 GeV is an intrinsic property of the `P6V11` background model. The effect on any analysis that employs it as Galactic diffuse emission model is to over-subtract the ICS component at high energies, forcing the GeV excess spectrum to fall-off at ≥ 10 GeV.

This exercise demonstrates the relevance of modelling *separately* the different contributions to the Galactic diffuse emission. Indeed, ICS, π^0 and bremsstrahlung possess intrinsically different morphologies because of the different targets that originate these components: the gas for the π^0 and bremsstrahlung, and the interstellar radiation field for the ICS. Moreover, given the different cosmic-ray species responsible of the gamma-ray emission (protons for π^0 and electrons for ICS and bremsstrahlung), also the way in which the morphology changes with energy is different for the three contributions.

Such arguments strongly motivated the study of the variation of the spectral and morphological properties of the excess due to the modelling of the Galactic diffuse emission.

3. Home-brew Galactic diffuse emission

In order to robustly identify the excess despite of large variations in the foreground emission, we built a set of Galactic diffuse models by varying cosmic-ray propagation parameters within a given set of assumptions. We note that the observed emission results from a line of sight integral and, as such, it receives contributions from all distances. In particular,

[1] `http://fermi.gsfc.nasa.gov/ssc/data/p6v11/access/lat/ring_for_FSSC_final4.pdf`

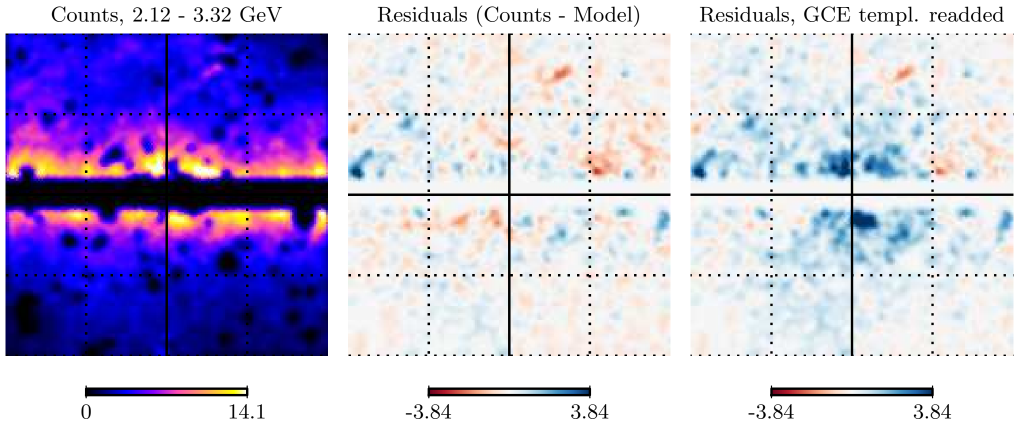

Figure 2: *Left panels:* Count maps (the $|b| > 2^\circ$ cut and the point-source mask are clearly visible). *Central panels:* Residuals when subtracting all emission model templates. *Right panels:* Residuals when re-adding the GeV excess template absorbed emission.

the emission that comes from the Galactic center is – in the models we are adopting – relatively subdominant (about 10%) and the Galactic diffuse emission is dominated by local processes. Therefore, our work should read as the characterisation of the uncertainties due to the Galactic gamma-ray emissivity along the line of sight. We worked in the framework of steady state solutions to the transport equation of cosmic-ray propagation in the Galaxy. Homogeneous diffusion, re-acceleration and convection were considered. We adopted models from the set of Ackermann et al. [2012] to test variations of the diffusion zone geometry, the source distribution, the spin temperature and the magnitude cut (for an explanation of cosmic-ray propagation parameters and their range of variation see Calore et al. [2014b]). Additionally, we generated our own Galactic diffuse models using `Galprop v54` (webrun version). With those models, we explored the remaining uncertainties related to the diffusion coefficient, re-acceleration, convection, interstellar radiation field, and Galactic center magnetic field distributions. In total, we built a set of about 60 models for the Galactic diffuse emission that test "extreme" variations in the parameter space. We here quote the explored parameter ranges:

- geometry of the diffusion zone: $4 \leq z_D \leq 10$ kpc and $r_D = 20$ or 30 kpc;
- source distributions: SNR, pulsars, OB stars;
- diffusion coefficient at 4 GV: $D_0 = 2 - 60 \times 10^{28}$ $\mathrm{cm^2\,s^{-1}}$;
- Alfvén speed: $v_\mathrm{A} = 0 - 100\ \mathrm{km\,s^{-1}}$;
- gradient of convection velocity: $dv/dz = 0 - 500$ $\mathrm{km\,s^{-1}\,kpc^{-1}}$;
- interstellar radiation field model factors (for optical and infrared emission): $0.5 - 1.5$;
- magnetic field parameters: $5 \leq r_c \leq 10$ kpc, $1 \leq z_c \leq 2$ kpc, and $5.8 \leq B(r=0, z=0) \leq 117$ μG.

We note that we did not test those models against local cosmic-ray data and large scale diffuse gamma-ray data (or even microwave data).

As already mentioned, we made a few simplifying assumptions that we summarise below and that will become relevant for future refined analyses of the GeV excess : (i) homogeneity and isotropy of cosmic-ray diffusion, re-acceleration, and convection; (ii) radial symmetry of cosmic-ray source distribution in the Galactic disk (i.e. no modelling of the spiral arms), and same source distribution for different cosmic-ray-species sources; (iii) steady state regime, excluding transient phenomena as, for example, burst events.

4. The data analysis

In order to analyse gamma rays collected by the *Fermi*-LAT from the inner Galaxy, we adopt a template-based multi-linear regression technique, see, for example, Dobler et al. [2010], Su et al. [2010]. The data sample corresponds to 284 weeks of reprocessed *Fermi*-LAT data (from 4 August 2008 on) in the energy range 300 MeV – 500 GeV. The Region-Of-Interest (ROI), i.e. the *inner Galaxy*, is defined as

$$|\ell| \leq 20^\circ \quad \text{and} \quad 2^\circ \leq |b| \leq 20^\circ\ , \tag{1}$$

The choice of the latitude cut is such to avoid the large contamination of point sources in the innermost few degrees, where the source confusion is very high. We prepare the data according to standard prescriptions provided by the *Fermi*-Science-Support-Center. We binned the data on an `healpix` grid with resolution parameter $n_{\mathrm{size}} = 256$, for each energy bin (24 in total) defined in a way such to guarantee good statistics also at the highest energies.

We compare the data maps with the model maps, obtained by the superposition of the different templates adopted in the analysis (see below). The best-fit normalisation of each model template is derived through a maximum likelihood method, based on the Poisson likelihood function (cf. Eq. (2.3) in Calore et al. [2014b]).

The spatial model templates adopted in the analysis are:

- Point-like sources template as derived from the 2FGL Abdo et al. [2011], with fixed spectra and flux normalisations.
- *Fermi* bubbles modelled by a uniform-brightness spatial template with bubbles' edges as in Su et al. [2010].
- Isotropic gamma-ray diffuse background with uniform-brightness emission template.
- Galactic diffuse emission ICS and π_0+Bremss *independent* templates as modelled from Sec. 3.
- GeV excess template whose volume emissivity is parametrised by the spherically symmetric generalized NFW profile,

$$\rho(r) = \rho_s \frac{(r/r_s)^{-\gamma}}{(1 + r/r_s)^{3-\gamma}} , \qquad (2)$$

  squared, and with (best-fit) spectral index $\gamma = 1.2$. This choice is clearly motivated by the dark matter annihilation interpretation of the GeV excess, although we tested a large range of variation for the profile parameters.

The fitted spectra of the *Fermi* bubbles and isotropic diffuse background templates are constrained to vary within the measured spectra from Franckowiak [2013] and Ackermann [2012], respectively.

In the analysis, we introduced the following technical improvements: a non-logarithmic energy binning such to counterbalance the reduced photon statistics above 10 GeV, a weighted adaptive masking of point sources, and the full treatment of the *Fermi*-LAT point spread function.

5. Selection of main results

In this section, we present a selection of the results of the analysis, and we refer the reader to Calore et al. [2014b] for a thorough explanation of our findings. Figure 2 represents the residual (i.e. data - model counts) emission obtained when subtracting from the raw data the emission associated with the model templates (central panel). The residuals are at the level of 20% in the whole ROI, but, when the GeV excess template associated to the model is re-added (right panel), the residuals in the central region of the ROI increase significantly, attesting the presence of the excess, which is, after the other components are subtracted, the most pronounced large-scale excess in our ROI.

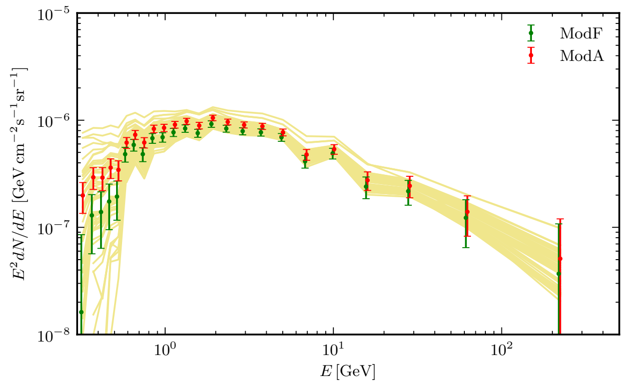

Figure 3: Spectral energy distribution of the GeV excess template, for a generalised NFW profile with an inner slope $\gamma = 1.2$. The *yellow band* corresponds to all of the 60 GDE models. Two models are highlighted: the model that provides the best fit to the data (model F, *green points*) and a reference model (*red points*).

Figure 3 represents the spectral energy distribution of the excess emission, i.e. the emission absorbed by the GeV excess template during the fitting procedure. The yellow band results from *all* the adopted Galactic diffuse models. Such a band brackets the uncertainty due to the theoretical modelling of the Galactic diffuse emission and affecting the extraction of the GeV excess spectrum. The GeV excess emission is found to be remarkably stable against the tested variations of the Galactic foreground. The typical GeV excess spectrum shows a rising below 1 GeV (with a spectral index harder than $\sim$ 2 for all Galactic diffuse models) and features a peak at energies around 1–3 GeV. Despite previous analyses, at higher energies, the spectrum is described by a power-law with slope $\sim$ -2.6. The coloured data points indicate the spectrum (with statistical errors) that corresponds to the best-fit Galactic diffuse model (model F) and another exemplary model discussed in Calore et al. [2014b] (model A).

The envelope of the yellow lines corresponds to the *theoretical model uncertainty*, which is due to the variation induced by the Galactic diffuse modelling. Such uncertainty is, at all energies, larger than the statistical errors, indicating the importance of the proper treatment of background model systematics.

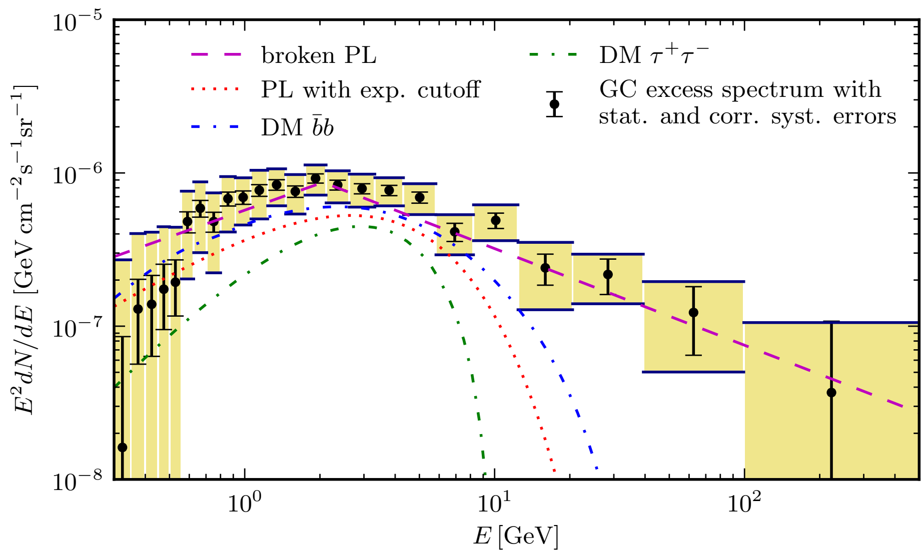

Figure 4: GeV excess emission spectrum, together with statistical and systematical errors, for model F (i.e. best-fit model). Several spectral models have been fitted to the data. All the spectra (except the $\tau^+\tau^-$) provide a quite reasonable fit to the data. This is due to the correlation of the systematic errors (see text).

Spectrum	Parameters	χ^2/dof	p-value
broken PL	$\alpha_1 = 1.42^{+0.22}_{-0.31}$, $\alpha_2 = 2.63^{+0.13}_{-0.095}$, $E_{\rm break} = 2.06^{+0.23}_{-0.17}$ GeV	1.06	0.39
DM $\chi\chi \to \bar{b}b$	$\langle\sigma v\rangle = 1.76^{+0.28}_{-0.27} \times 10^{-26}$ cm^3 s^{-1}, $m_\chi = 49^{+6.4}_{-5.4}$ GeV	1.08	0.36
DM $\chi\chi \to \bar{c}c$	$\langle\sigma v\rangle = 1.25^{+0.2}_{-0.18} \times 10^{-26}$ cm^3 s^{-1}, $m_\chi = 38.2^{+4.6}_{-3.9}$ GeV	1.07	0.37
PL with exp. cutoff	$E_{\rm cut} = 2.53^{+1.1}_{-0.77}$ GeV, $\alpha = 0.945^{+0.36}_{-0.5}$	1.37	0.12
DM $\chi\chi \to \tau^+\tau^-$	$\langle\sigma v\rangle = 0.337^{+0.047}_{-0.048} \times 10^{-26}$ cm^3 s^{-1}, $m_\chi = 9.96^{+1.1}_{-0.91}$ GeV	1.52	0.06

Table I Spectral fits to the GeV excess spectrum, with $\pm 1\sigma$ errors. We show best-ft parameters, reduced χ^2, and corresponding p-value.

As it can be already deduced from the residual plots, the Galactic diffuse models tested in the present analysis do not describe the data at the statistical level, but, still, they show large residuals in the ROI. Indeed, although the reduced χ^2 for the best-fit Galactic diffuse model (model F) in the energy range from 500 MeV to 3.31 GeV is close to one ($\simeq$ 1.10) because of the large number of free parameters, the corresponding p-value is ridiculously small, $\simeq 10^{-300}$.

On the base of this argument, it is important to find an alternative way of assessing the systematics uncertainties affecting the excess. In Calore et al. [2014b], we relied on an empirical method to derive model systematics due to how well the different Galactic diffuse models describe the data along the disk, away from the Galactic center. The derivation and definition of the *empirical model systematics* were presented during this conference in a complementary talk, "Robust Identification of the GeV Galactic Center Excess at Higher Latitudes".[2] Quantifying the background empirical model systematics turned out to be crucial for making statistics based claims on the possible interpretations of the excess.

6. Interpretations

As explained in Sec. 1, several interpretations have been proposed, ranging from purely astrophysical to dark matter explanations. As a first constraint, the predicted model spectrum must provide a good fit to the GeV excess spectrum. We performed parametric fits to the GeV excess observed spectrum fully taking into account the systematic uncertainties.

[2] C. Weniger et al., proceedings RICAP-14 (to appear soon).

To do so, we made use of a χ^2 function with a non-diagonal covariance matrix, which models the correlated empirical model systematics. The χ^2 function used writes as:

$$\chi^2 = \sum_{ij} \left(\frac{d\bar{N}}{dE_i}(\vec{\theta}) - \frac{dN}{dE_i} \right) \Sigma_{ij}^{-1} \left(\frac{d\bar{N}}{dE_j}(\vec{\theta}) - \frac{dN}{dE_j} \right) , \tag{3}$$

with Σ_{ij}^{-1} the covariance matrix. The covariance contains model uncertainties that were derived from the size of typical residuals along the Galactic disk. They amount to variations in the excess template that are similar to the ones shown in Figure 3, and are illustrated in Figure 4 by the yellow boxes. For details we refer the reader to Calore et al. [2014b].

We tested several spectra that are related to the GeV excess viable interpretations. Table I summarises our findings. In particular, parametric fits with correlated errors show equal preference for a broken power-law spectrum and for the spectrum from dark matter annihilation into b-quarks. Remarkably, the p-value for a spectrum due to dark matter annihilation into τ-leptons is higher the 0.05. The reason for which dark matter annihilation spectra provide good fit to the GeV excess is due to the fact that systematics errors are correlated in energy and can be understood in terms of the covariance matrix (we refer the interested reader to Calore et al. [2014c]).

7. Conclusion

The analysis of the *Fermi*-LAT data performed in Calore et al. [2014b] confirmed the presence of an excess emission in the *inner Galaxy* and some of its, previously found, specific properties, such as the 2–3 GeV peaked spectral energy distribution, the extension to high latitudes and the compatibility with a spherically symmetric spatial distribution. Those properties were demonstrated to be remarkably stable against theoretical model systematics, due to the variations in the modelling of the Galactic diffuse emission.

We assess empirical model systematics from a scan of the gamma-ray flux along the disk and we used those uncertainties as a proxy for the systematics affecting the GeV excess at the Galactic center.

Contrary to previous results, we do *not* confirm the fall-off of the GeV excess spectrum at $E \gtrsim 10$ GeV, but we do find a high energy tail of the spectrum extending up to 100 GeV. However, when we properly treat model systematics and include them in the spectral fits as correlated errors, we demonstrated that it is possible to equally well fit the excess spectrum with both a broken power-law and a gamma-ray spectrum typically expected from dark matter particles annihilation into $\bar{b}b$ final states. This implies a large, previously neglected, freedom for models fitting the GeV excess.

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