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Neutralino dark matter and the Fermi gamma-ray lines

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Motivated by recent claims of lines in the Fermi gamma-ray spectrum, we critically examine means of enhancing neutralino annihilation into neutral gauge bosons. The signal can be boosted while remaining consistent with continuum photon constraints if a new singlet-like pseudoscalar is present. We consider singlet extensions of the MSSM, focusing on the NMSSM, where a 'well-tempered' neutralino can explain the lines while remaining consistent with current constraints. We adopt a complementary numerical and analytic approach throughout in order to gain intuition for the underlying physics. The scenario requires a rich spectrum of light neutralinos and charginos leading to characteristic phenomenological signatures at the LHC whose properties we explore. Future direct detection prospects are excellent, with sizeable spin-dependent and spin-independent cross-sections.

I. INTRODUCTION

There is robust evidence on astrophysical and cosmological scales for the presence of particle dark matter (DM) in our universe [? ?]. A particularly well studied candidate is the neutralino and determining the properties of this particle is the subject of an intense experimental effort at colliders, direct detection and indirect detection experiments. Indirect detection experiments search for particles created from the decay or annihilation of DM particles from regions where the density of DM is expected to be high, such as the centre of our galaxy. A particularly striking signal is a monochromatic γ-ray line, arising when the DM annihilates into a two-body final state containing a photon [?].

Recently, numerous studies of the publicly available Fermi-LAT [?] data found a sharp feature in the γ-ray spectrum at $\sim$ 130 GeV coming from the vicinity of the galactic centre [? ? ? ?]. Interpreting the feature as a monochromatic line arising from DM annihilation into two photons, Weniger [?] found that DM with mass $129.8 \pm 2.4^{+7}_{-13}$ GeV and annihilation cross-section $\langle \sigma v \rangle_{\gamma\gamma} = \left(1.27 \pm 0.32^{+0.18}_{-0.28}\right) \times 10^{-27}$ cm^{3}s^{-1} fits the signal well (see also [? ? ? ? ? ? ? ?]). Intriguingly, refs. [? ?] note that two lines, one at $\sim$ 130 GeV and a weaker one at $\sim$ 111 GeV, provide a slightly better fit to the Fermi data. Such a pair of lines can be naturally explained by a DM particle of mass $\sim$ 130 GeV annihilating into $\gamma\gamma$ and γZ with a relative annihilation cross-section $\langle \sigma v \rangle_{\gamma Z}/\langle \sigma v \rangle_{\gamma\gamma} = 0.66^{+0.71}_{-0.48}$ [?]. In this paper, we address under what conditions the neutralino can fit these observations and the implications for the neutralino sector.

Doubts about a DM origin of these features have been raised in [? ? ?], although as yet there is no compelling astrophysical process that can explain the Fermi features. Searches for systematic effects associated with the Fermi-LAT instrument have been performed in [? ? ?] and a small excess of photons from the Earth's limb at $\sim$ 130 GeV for photons within a limited range of detector incidence angles was found. However, such an effect cannot account for all of the

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signal from the galactic centre [? ?]. Finally, the annihilation cross-section required to explain the feature is in mild tension with the upper limit $\langle\sigma v\rangle_{\gamma\gamma} \lesssim 1.0 \times 10^{-27}$ cm^{3}s^{-1} set by the Fermi-LAT Collaboration from the 2 year dataset [?]. Furthermore, preliminary analysis of the 4 year dataset finds a feature at $\sim$ 135 GeV but with a lower significance compared with the analyses quoted above [?]. The fate of the feature will ultimately be resolved as more data is collected. For the purposes of this paper, we assume that the features observed by Fermi are due to photons arising from neutralino annihilation and study the associated phenomenological implications.[1]

Interpreting the feature as a DM signature has its own challenges: ref. [?] find that the feature is offset from the galactic centre by 1.5^o, although this may arise due to an interplay between the galactic baryons and DM [?]. A more serious issue is explaining the relatively large size of the annihilation cross-section into photons that is required while remaining consistent with the continuum flux of photons arising from annihilation of the DM into W and Z bosons and Standard Model fermions [? ? ? ? ?]. As the DM is a neutral particle, its coupling to photons generally arises at loop-level and is suppressed relative to the coupling to W and Z bosons and Standard Model fermions, which can occur at tree-level. Cohen et. al. [?] quantified this constraint through the quantity

$$R^{\rm th} \equiv \frac{\langle\sigma v\rangle_{\rm ann}}{2\langle\sigma v\rangle_{\gamma\gamma} + \langle\sigma v\rangle_{\gamma Z}}, \tag{1}$$

where $\langle\sigma v\rangle_{\rm ann}$ is the total annihilation cross-section and $\langle\sigma v\rangle_{\gamma\gamma,\gamma Z}$ are the annihilation cross-sections into $\gamma\gamma$ and γZ respectively. When the total annihilation cross-section is $\langle\sigma v\rangle_{\rm ann} \sim 3\times10^{-26}$ cm^{3}s^{-1} (required to achieve the correct thermal relic density) and when $\langle\sigma v\rangle_{\gamma\gamma} \sim 1.2 \times 10^{-27}$ cm^{3}s^{-1} and $\langle\sigma v\rangle_{\gamma Z}/\langle\sigma v\rangle_{\gamma\gamma} = 0.7$ (to explain the lines in the Fermi-LAT data), then $R^{\rm th} \sim 9$, compatible with all continuum constraints in [?]. Thus, if the thermal relic density and line-strength for a given DM candidate are correct, it should be compatible with continuum photon constraints.[2]

Many papers have been written with methods and models that explain the monochromatic features while remaining consistent with known constraints, see e.g. [?]. Within the framework of the simplest supersymmetric extension of the Standard Model, the MSSM, the large annihilation cross-section into photons $\langle\sigma v\rangle_{\gamma\gamma}$ can be achieved [?]. However, this requires a wino- or higgsino-like neutralino and such scenarios yield a negligible thermal relic density and also give rise to a large continuum flux [?], which rule them out [? ? ?]. Said another way, if the MSSM neutralino achieves the correct thermal relic density then $\langle\sigma v\rangle_{\gamma\gamma}$ is orders of magnitude too low to explain the Fermi feature.[3] Therefore, we see what is required: we need to keep the total annihilation cross-section at the level required to obtain the correct relic density while boosting the cross-section into photons. This can be achieved by exploiting a resonance with a pseudoscalar that couples primarily to photons, as suggested in [? ? ?]. Although the MSSM does have a pseudoscalar Higgs A, this approach fails because A does not couple primarily to photons; it couples to charged states $\bar{f}f$ at tree-level, while the coupling to photons is generated at loop level. However, as discussed in [? ? ?], within extensions of the MSSM that include extra singlet states, the tree-level coupling to $\bar{f}f$ can be reduced while maintaining the coupling to photons.

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[1] Decaying DM is disfavoured as it requires an enhancement of the DM density near the galactic centre [?].

[2] Similar conclusions can also be drawn from the constraints from $p\bar{p}$ and synchrotron radiation. Again, if the thermal relic density is correct, the DM candidate is compatible with these constraints, see e.g. [? ?] and [?].

[3] In fact, even in the MSSM the 130 GeV line can be explained by internal bremsstrahlung from a bino-like neutralino annihilating to light leptons [? ?]. In order to enhance the number of photons produced, an accidental degeneracy between the mass of the exchanged t-channel slepton and the neutralino is required. We will not consider internal bremsstrahlung further in this paper.