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GAMMA-RAY LINES CONSTRAINTS IN THE NMSSM[a]

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We present the computation of the loop-induced self-annihilation of dark matter particles into two photons in the framework of the NMSSM. This process is a theoretically clean observable with a "smoking-gun" signature but is experimentally very challenging to detect. The rates were computed with the help of the `SloopS` program, an automatic code initially designed for the evaluation of processes at the one-loop level in the MSSM. We focused on a light neutralino scenario and discuss how the signal can be enhanced in the NMSSM with respect to the MSSM and then compared with the present limits given by the dedicated search of the `FERMI-LAT` satellite on the monochromatic gamma lines.

1 Introduction

The existence of Cold Dark Matter (CDM) is the most compelling paradigm to account for the wealth of cosmological and astrophysical data. Yet its presence needs to be confirmed by its detection through direct or indirect methods. With the advent of the LHC it has also started in collider experiments. A theoretically well motivated and clean observable for the indirect detection of dark matter are the so-called gamma-ray lines. Unlike charged messengers, the photons are less affected by astrophysical uncertainties and their propagation in the galaxy is easier to model. In fact, pinning down the uncertainties on this detection channel boils down to the modelisation of the galactic dark matter halo. Moreover no astrophysical source is known to mimic this spectral feature, making this signal as a "smoking gun" signature for the existence of Dark Matter (DM). On the particle physics side, the prediction for the monochromatic gamma-ray lines rates relies on the accurate computation of its self-annihilation cross section. For the two gamma mode this cross section is generically very suppressed since the CDM particle must be uncharged. Besides providing such a DM candidate, Supersymmetry (SUSY) offers a fully computable framework. In one of its extension, the NMSSM (*Next-to-Minimal Supersymmetric Standard Model*), this process is a loop-induced one (as in the most popular SUSY incarnation, the MSSM) and requires the calculation of numerous Feynman diagrams as well as an accurate calculation of loop integrals. The `SloopS` code [1,2,3] is such a tool which was designed initially for the MSSM. Concerning DM studies it has been applied to the evaluation of the two gamma mode in the MSSM [4], the NMSSM [5] and the prediction of the relic density at Next-to Leading order (NLO) [1,5,6] in the MSSM. In the present work we focus on a light neutralino NMSSM DM candidate since a DM explanation is to be advocated if one wants to explain recent direct detection measurements [8,9,10,11]. In the next section we will quickly recap the NMSSM and

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highlight in which cases its DM phenomenology is peculiar with respect to the MSSM together with an emphasis on the gamma-ray line observable.

2 Gamma-ray lines in the NMSSM

In the NMSSM the Higgs term of the superpotential involving the two Higgs doublet is modified and a singlet term is added,

$$W_{NMSSM} = W^{\mu=0}_{MSSM} + \lambda \hat{S}\hat{H}_u\hat{H}_d + \frac{\kappa}{3}\hat{S}^3 \tag{1}$$

The VEV of the singlet generates an effective μ parameter with respect to the MSSM, which is then naturally of order the EW scale[12]. The soft-SUSY breaking Lagrangian is also modified according to

$$-\mathcal{L}_{\rm soft} = m^2_{H_u}|H_u|^2 + m^2_{H_d}|H_d|^2 + m^2_S|S|^2 + \left(\lambda A_\lambda H_u \cdot H_d S + \frac{1}{3}\kappa A_\kappa S^3 + h.c\right) \tag{2}$$

This has important phenomenological consequences, as compared to the MSSM, since the Higgs and neutralino sector are extended due to the additional singlet field and its fermionic superpartner, the singlino. Therefore the DM phenomenology of the NMSSM has an extended parameter space region, the one where the neutralino is mostly singlino, which makes it peculiar from the MSSM. It has also been shown that it is easier to accommodate a light neutralino $\tilde{\chi}^0_1$ and fulfill various kind of experimental constraints in the NMSSM than the MSSM [13]. This is due to the presence of a more "natural" light pseudoscalar thanks to an approximate Peccei-Quinn symmetry. The neutralinos can then efficiently annihilate through them and be a valid DM candidate. A DM particle in the low mass region favours the indirect detection channels (i.e the self-annihilation $\tilde{\chi}^0_1\tilde{\chi}^0_1 \to SM\ SM$ in the galactic halo) since the signals are roughly inversely proportional to $m_{\tilde{\chi}^0_1}$ and can be further enhanced in the NMSSM through a light pseudoscalar A_1 s-channel resonance [14]. This kind of mechanism can be at play for the $\gamma\gamma$ line signal and typical NMSSM contributions for this process are shown in Fig. 1. We can see that this process suffers from a loop suppression and therefore generically the predicted rates are low. Hence, despite the fact that it is a theoretically clean observable, it is experimentally very challenging to detect these lines. It requires a very good rejection from the continuous gamma ray background and also a fine energy resolution. The `FERMI-LAT` satellite has a dedicated search for these gamma-ray lines and up to now do not report any observation, but limits on $\langle\sigma v\rangle_{\chi\chi\to\gamma\gamma}$ were published instead [15]. . In the next section weinvestigate how these limits can constrain the light pseudoscalar A_1 resonance in the low mass region ($m_\chi \lesssim 15$ GeV). Obviously only the $\gamma\gamma$ channel is relevant here. The computation of the γZ^0 final state has been reported elsewhere [5].

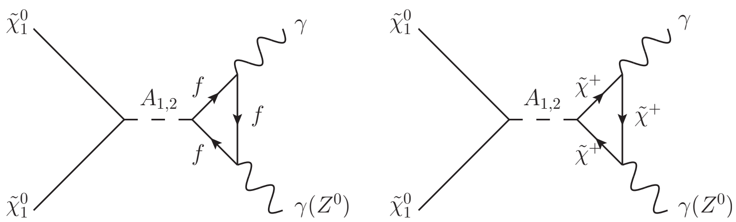

Figure 1: *Additional NMSSM diagrams with s-channel pseudoscalar exchange. The label f stands for a SM fermion and χ^+ to a chargino.*

3 FERMI-LAT constraints on the NMSSM parameter space

We performed a scan over the NMSSM parameter space focusing on a low mass neutralino, as favoured by recent direct detection results [8,9,10,11] and computed the rate $\langle \sigma v \rangle_{\chi\chi\to\gamma\gamma}$. However the published FERMI-LAT limits do not extend to dark matter particles lighter than 30 GeV. Nevertheless an analysis [16] extended these limits down to 1 GeV, using FERMI-LAT data. These are the limits we used throughout this work. The result of this scan is displayed in Fig. 2. We can

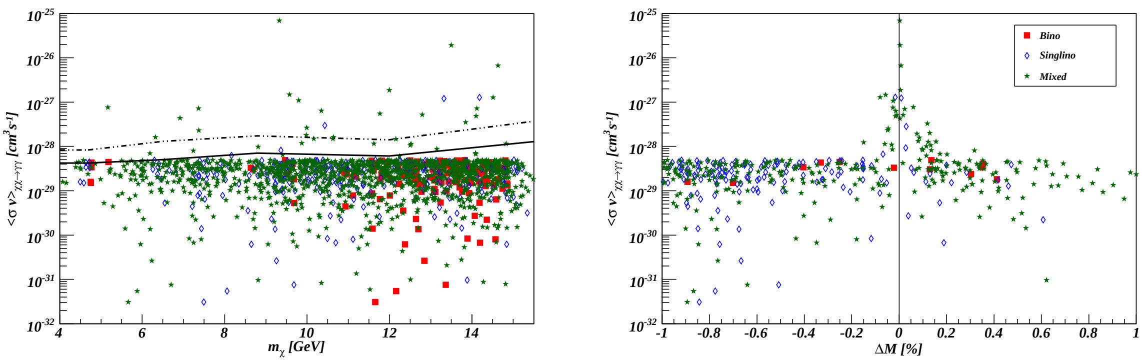

Figure 2: $\langle \sigma v \rangle_{\chi\chi\to\gamma\gamma}$ *with respect to the neutralino mass* m_χ *(left panel) and* ΔM *(right panel, see text for its definition) for several types of neutralinos. Solid lines are limit from the galactic center and the broken one from the halo.*

see on the left panel that current limits only exclude a minute portion of the parameter space and the right panel shows that the excluded points corresponds to situations where the annihilation occurs close to the resonance by less than $\Delta M \leq |0.2|\%$, with $\Delta M = (2m_{\tilde{\chi}_1^0} - m_{A_1})/m_{A_1}$. We can also observe that the highest rates are obtained when the neutralino is significantly mixed. In details it is a mixture of singlino-higgsino components, which is to be expected since these enter the couplings of the neutralino to Higgses. We then investigate if the limits on the spectral lines can further constrain the NMSSM parameter space. It has been shown[18] that the 95% limits of the FERMI-LAT collaboration on the secondary gamma rays produced in dwarf spheroidal galaxies (dSph) from the pair annihilation of DM particles into quarks and/or taus can constrain the NMSSM parameter space. The authors of this work provided us with 14 points of their MCMC scan giving a large pair annihilation cross section but safe with respect to dSph limits and direct detection searches. The points are sampled in each bins of $m_{\tilde{\chi}_1^0}$ between 1 and 15 GeV. We then used these input parameters to evaluate the rate of the gamma-lines and if we could further constrain these scenarios. The results are presented in Tab. 1. The bottom line

Table 1: Comparison between dark matter annihilation into quarks and/or taus and the loop-induced one into photons for each of the bins between 1 and 14 GeV.

$m_{\tilde{\chi}_1^0}$[GeV]	0.976	2.409	3.342	4.885	5.626	6.551	7.101
$\langle \sigma v \rangle_{\chi\bar{\chi}\to q\bar{q},\tau\bar{\tau}} \times 10^{27}[\mathrm{cm}^3\,\mathrm{s}^{-1}]$	0.209	0.297	0.345	3.298	5.389	3.547	2.425
$\langle \sigma v \rangle_{\chi\bar{\chi}\to\gamma\gamma} \times 10^{32}[\mathrm{cm}^3\,\mathrm{s}^{-1}]$	0.008	0.267	0.345	0.262	0.410	0.427	0.664
$m_{\tilde{\chi}_1^0}$[GeV]	8.513	9.274	10.27	11.50	12.74	13.51	14.48
$\langle \sigma v \rangle_{\chi\bar{\chi}\to q\bar{q},\tau\bar{\tau}} \times 10^{27}[\mathrm{cm}^3\,\mathrm{s}^{-1}]$	2.161	2.497	2.323	2.575	3.224	9.571	148.4
$\langle \sigma v \rangle_{\chi\bar{\chi}\to\gamma\gamma} \times 10^{32}[\mathrm{cm}^3\,\mathrm{s}^{-1}]$	0.220	0.665	1.881	2.456	2.003	17.49	287.5

is that the predictions on the monochromatic γ lines rates are well below the present limits of FERMI-LAT and several orders of magnitude of improvement on the experimental sensitivity are needed on this observable to have a constraining power on these best fit points.

4 Conclusion

The mono-energetic gamma-ray line signal has spectacular features: a clear smoking-gun signature and points directly to the mass of the dark matter particle. Moreover it do not suffer from astrophysical uncertainties and depends only on the assumption of the dark matter halo. However discriminating it from the overwhelming astrophysical background (supernovæ, pulsars, cosmic-rays...) remains an experimentally extremely challenging task. The current sensitivity on the $\gamma\gamma$ mode permits to exclude only very fine-tuned points where the LSP mass is close to the light pseudoscalar resonance, when focusing on the low mass region. However the FERMI-LAT mission is a long-termed one and the sensitivity is expected to be improved, raising the possibility of excluding more featureless region of the NMSSM parameter space. Finally a very recent independent paper[19] claimed an indication for a gamma-ray line at 4.6σ confidence level. We therefore look forward a refined analysis of the FERMI-LAT for a confirmation of this observation.

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