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Searches for gamma-ray lines from $\mu\nu$SSM gravitino dark matter

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CARLOS MUÑOZ[*]
Departamento de Física Teórica, Universidad Autónoma de Madrid, E-28049 Madrid, Spain
Instituto de Física Teórica UAM–CSIC, Campus de Cantoblanco UAM, E-28049 Madrid, Spain
E-mail: `carlos.munnoz@uam.es`

The *R*-parity violating model $\mu\nu$SSM is a supersymmetric standard model alternative to the MSSM, that solves the μ-problem and explains the origin of neutrino masses by simply using right-handed neutrinos. In the $\mu\nu$SSM, the gravitino is a natural candidate for decaying dark matter since its lifetime becomes much longer than the age of the Universe. It could be detectable through the emission of a monochromatic gamma ray in a two-body decay. We study constraints on the parameter space of $\mu\nu$SSM gravitino dark matter from no observation of gamma-ray lines in Fermi-LAT data.

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[*] Speaker.

1. Introduction

The presence of dark matter (DM) can be inferred at very different scales, from cosmological ones down to galactic scales. However, within the standard model of particle physics there are no viable candidates for DM, thus its existence represents one of the most compelling evidence for physics beyond the Standard Model [1]. One of the most attractive theories for this kind of physics is Supersymmetry. The "μ from ν" Supersymmetric Standard Model ($\mu\nu$SSM) was proposed in the literature to solve the so-called μ-problem [2] of supersymmetric theories and explain the origin of neutrino masses by simply introducing right-handed neutrinos [3, 4, 5]. It is therefore an interesting model that, besides, can be tested at the LHC. As a consequence, its phenomenology has been analyzed in detail [6, 7, 8].

In the $\mu\nu$SSM, R-parity is broken and therefore the lightest supersymmetric particle (LSP) decays. If the role of the LSP is played by the gravitino, $\Psi_{3/2}$, its decay is suppressed both by the feebleness of the gravitational interaction and by the small R-parity violating coupling. Thus, its lifetime can be much longer than the age of Universe and the $\mu\nu$SSM gravitino can represent a good DM candidate [7, 8]. On the other hand, the gravitino decays producing a monochromatic photon with an energy equal to half of the gravitino mass, and therefore its presence can, in principle, be inferred indirectly from the data of gamma-ray space telescopes [7, 8][1].

The expected diffuse gamma-ray emission from DM decay in the mid-latitude range ($10^\circ \leq |b| \leq 20^\circ$) was computed for a Navarro-Frenk-White (NFW) profile [10] in Ref. [7] and compared with the 5-month measurement reported by Fermi-LAT [11]. The non-observation of sharp monochromatic lines in the gamma-ray spectrum permitted to draw bounds on the parameter space of the $\mu\nu$SSM gravitino. In particular, values of gravitino mass $m_{3/2}$ larger than about 10 GeV were excluded, as well as lifetimes $\tau_{3/2}$ smaller than about 3 to 5×10^{27} s. Notice that because of this upper bound on $m_{3/2}$, three body decay modes of the gravitino [12, 13] are not relevant, and therefore we will not considered here.

In Ref. [14] ([15]), the Fermi-LAT collaboration presented constraints on monochromatic emission using 11 (23) months of data for $|b| > 10^\circ$ *plus* a $20^\circ \times 20^\circ$ square around the galactic center. However, the derived limits only refer to the emission above 30 (7) GeV, covering, in the context of the $\mu\nu$SSM, gravitinos with masses larger than 60 (14) GeV, leaving our region of interest unconstrained.

In Ref. [16], two-years Fermi-LAT data for $|b| \geq 10^\circ$ have been used to constrain the DM gamma-ray line flux in the energy range between 1 and 300 GeV. Lower bounds on $\tau_{3/2}$ of about 6×10^{28} s were obtained in our region of interest below 10 GeV. These bounds together with those obtained in [17] by analyzing the data from EGRET in the Galactic Center region, were used in [8] to constrain the parameter space of gravitino DM in the $\mu\nu$SSM. It was found that $m_{3/2}$ has to be smaller than 4 GeV, and lifetimes have to be larger than about 6×10^{28} s for $m_{3/2}$ between 2 and 4 GeV, and larger than about 7 to 3×10^{27} s for $m_{3/2}$ between 0.6 and 2 GeV. In Ref. [8], the prospects of the Fermi-LAT telescope to detect monochromatic lines in 5 years of observations of the Virgo cluster, were also analyzed. It was found that a gravitino in the mass range of 0.6–2 GeV, and with a lifetime range of about 3×10^{27} s to 2×10^{28} s would be detectable by the Fermi-LAT with a signal-to-noise (S/N) ratio larger than 3.

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[1] For a similar analysis in the case of the Bilinear R-parity Violation gravitino DM, see Ref. [9].

In what follows, we will discuss these results and briefly comment about recent ones [18].

2. Gamma-rays from gravitino decay in the $\mu\nu$SSM

In the supergravity Lagrangian an interaction term is predicted between the gravitino, the field strength for the photon, and the photino. Since, due to the breaking of R-parity, the photino and the left-handed neutrinos are mixed, the gravitino will be able to decay through the interaction term into a photon and a neutrino [19]. The gravitino lifetime $\tau_{3/2}$ turns out to be:

$$\tau_{3/2} \simeq 3.8 \times 10^{27}\mathrm{s} \left(\frac{|U_{\tilde{\gamma}\nu}|^2}{10^{-16}}\right)^{-1} \left(\frac{m_{3/2}}{10\ \mathrm{GeV}}\right)^{-3}, \tag{2.1}$$

where $|U_{\tilde{\gamma}\nu}|^2$ is the photino content of the neutrino, and is constrained to be $|U_{\tilde{\gamma}\nu}|^2 \sim 10^{-16} - 10^{-12}$ in the $\mu\nu$SSM in order to reproduce neutrino masses [7]. As a consequence, the gravitino will be very long lived. Additionally, adjusting the reheating temperature one can reproduce the correct relic density for each possible value of the gravitino mass (see [7] and references therein).

The detection of DM in several R-parity breaking scenarios has been studied in the literature [19, 20, 7, 8] considering the case of gravitinos emitting gamma-rays when decaying in i) the smooth galactic halo, ii) extragalactic regions at cosmological distances, and iii) nearby extragalactic structures.

In i), the gamma-ray signal is an anisotropic sharp line and the flux is given by

$$\frac{d\Phi}{dE}(E) = \frac{\delta(E-\frac{m_{3/2}}{2})}{4\pi\tau_{3/2}m_{3/2}} \int_{\mathrm{los}} \rho_{halo}(\vec{l})d\vec{l}\,, \tag{2.2}$$

where the halo DM density is integrated along the line of sight l, and we will use a NFW density profile for the Milky Way halo compatible with the latest observational constraints as modeled in [21]. Let us remark, nevertheless, that in our region of interest any density profile will give rise to similar results.

In ii), the photons produced by gravitinos decaying at cosmological distances are red-shifted during their journey to the observer, and we obtain the isotropic extragalactic flux applying the analysis of Refs. [19, 22] to the $\mu\nu$SSM. As can be seen e.g. in Figs. 3 and 4 of Ref. [7], the sharp line produced by the galactic halo dominates over this extragalactic signal.

In iii), the gamma-ray signal is a monochromatic line similarly to i), and Eq. (2.2) can also be used for the computation of the flux.

3. Prospects of detection of $\mu\nu$SSM gravitino DM with Fermi-LAT

Let us now study the prospects for $\mu\nu$SSM gravitino DM detection, taking into account the contributions discussed in Sect. 2. The main results are shown in 1.

As mentioned in the Introduction, in Ref. [7] the area below the red dot-dashed line was disfavored by Fermi-LAT data of the diffuse gamma-ray galactic emission in the mid-latitude range $10^\circ \leq |b| \leq 20^\circ$. In addition, in Ref. [16], the area below the black dots was also disfavored. From a likelihood analysis focused on the region $|b| \geq 10^\circ$, lower bounds on $\tau_{3/2}$ of about 6×10^{28} s

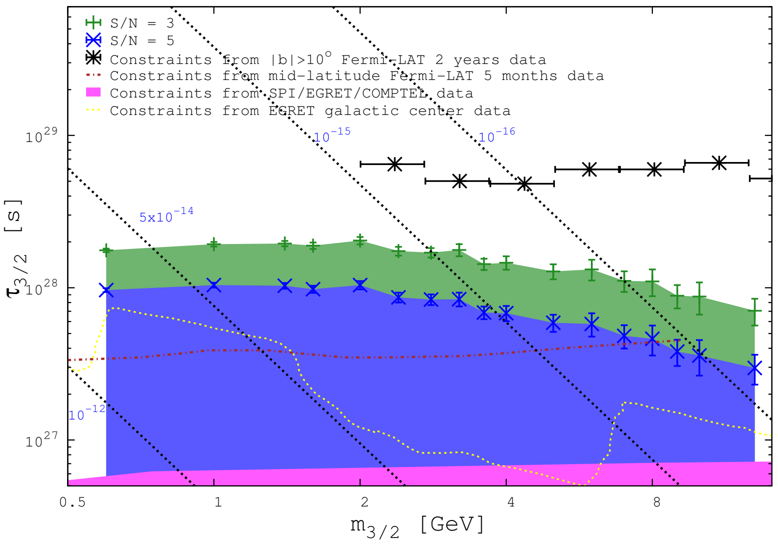

Figure 1: Constraints on lifetime versus mass for gravitino DM in the $\mu\nu$SSM. Blue (green) points indicate values of $\tau_{3/2}$ and $m_{3/2}$ of the $\mu\nu$SSM gravitino corresponding to a detection of gamma-rays with $S/N = 5$ (3) in the 5×5 degree region centered on the position of the Virgo cluster, for a 5 years simulation using the Fermi Science Tools. The blue (green) region indicates points with S/N larger than 5 (3). The red dot-dashed line indicates the lower limit on $\tau_{3/2}$ obtained from the Fermi-LAT measurements of the mid-latitude gamma-ray diffuse emission after 5 months [7]. The yellow dashed line indicates the lower limit on $\tau_{3/2}$ obtained from the EGRET measurements of the galactic center gamma-ray emission. The black dots show the lower limit on $\tau_{3/2}$ obtained in the adopted energy bands [16], from the Fermi-LAT measurements of the $|b| \geq 10^\circ$ gamma-ray diffuse emission after 2 years. The black dashed lines correspond to the predictions of the $\mu\nu$SSM [7] for several representative values $|U_{\widetilde{\gamma}\nu}|^2$=$10^{-16}$, 10^{-15}, 5×10^{-14}, 10^{-12} (see Eq. (2.1)). The magenta shaded region is excluded by gamma-ray observations such as SPI, COMPTEL and EGRET [23].

were obtained in our region of interest below 10 GeV. On the other hand, the area below the yellow dashed line is disfavored by the bounds obtained in [17] by analyzing the data from EGRET in the galactic center region. In particular, we used the upper limits on the gamma-ray line fluxes obtained in that work to constrain the $\mu\nu$SSM gravitino lifetime. Finally, points in the magenta shaded region are excluded by gamma-ray observations from the galactic center obtained with the SPI spectrometer on INTEGRAL satellite, and the isotropic diffuse photon background as determined from SPI, COMPTEL and EGRET data [23].

On the other hand, the black dashed lines correspond to the predictions of the $\mu\nu$SSM for several representative values of the R-parity mixing parameter. As mentioned in Sect. 2, this is constrained to be $|U_{\widetilde{\gamma}\nu}|^2 \sim 10^{-16} - 10^{-12}$ in the $\mu\nu$SSM [7], in order to reproduce the correct neutrino masses. As a consequence, any acceptable point must be in the area between the left and right black dashed lines. Let us remark, however, that these bounds are very conservative, as discussed in [7], and in fact the results of a scan of the low-energy parameter space of the $\mu\nu$SSM implied that the range $10^{-15} \leq |U_{\widetilde{\gamma}\nu}|^2 \leq 5\times10^{-14}$ is specially favored. The corresponding lines are also shown in the figure.

The combination of the constraints associated to red dot-dashed and black dashed lines, implies already that values of the gravitino mass larger than about 10 GeV are excluded, as well as lifetimes smaller than about 3 to 5×10^{27} s [7]. Actually, in the region of gravitino masses between 0.6 and about 1.5 GeV, lifetimes smaller than about 7 to 3 $\times10^{27}$ s, respectively, are excluded because of the constraints associated to the yellow dashed line. When constraints associated to black dots are also imposed, it turns out that the gravitino mass has to be smaller than about 4 GeV, and lifetimes have to be larger than about 6×10^{28} s for gravitino masses between 2 and 4 GeV. Thus, the combination of these results with the one obtained in ref. [8] for detection of DM from Virgo in 5 years of Fermi-LAT observations, leaves us with the blue and green areas above the yellow dashed and red dot-dashed lines, and gravitino mass smaller than 2 GeV, as those with good prospects for DM detection. However, work in progress in [18], where a circular region of interest of 20^o around the Galactic Center is analyzed, seems to imply that those areas are also excluded.

Summarizing, we find that a $\mu\nu$SSM gravitino DM is constrained to have a mass smaller than 4 GeV, and in the range between 0.5 and 4 GeV the lifetime must be larger than roughly 3×10^{28} s [18].

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