



Gamma-ray line from radiative decay of gravitino dark matter



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ABSTRACT

We study radiative decay of gravitino dark matter with trilinear R-parity violations. We show that the branching ratio of the decay of gravitino into monochromatic photon can be large enough to explain the observed gamma-ray line from the Galactic centre in the Fermi-LAT data without producing too much continuum gamma-ray and anti-proton flux. This scenario is realized when the mass of sfermions and the trilinear R-parity violating coupling are $O(1-10)$ TeV and $O(10^{-7}-10^{-6})$ respectively.

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1. Introduction

Recent studies on the four-year Fermi data have found excess of 130 GeV gamma-ray line from the Galactic Center (GC) [1–6]. There have been many papers studying various possible explanations (instrumental effects [7–10], pulsar wind effects [11] etc.) of this signal but it is most interesting if it is to be interpreted as a dark matter (DM) signature [12,13]. If this interpretation is correct, the 130 GeV gamma-ray line is the long-awaited signature of non-gravitational interactions of particle DM.

In order to explain the 130 GeV gamma-ray line with particle DM, a rather large branching ratio of DM annihilating or decaying into monochromatic photon is required, i.e. $\text{Br}(\text{DM} \rightarrow \gamma) \gtrsim 0.01$ [14–16]. Otherwise, DM to fermion and gauge boson annihilation or decay channels would produce too much continuum gamma-ray and conceal the line signal. Moreover, anti-proton flux produced by these channels are constrained by cosmic-ray observations [17]. However, in many cases, the branching ratio of DM annihilating or decaying into photons is suppressed because DM does not couple directly to photon [18,19]. It has been shown that for monochromatic photon production channel with standard model (SM) particles running in the loop, annihilating DM is typically in tension with the 130 GeV gamma-ray line scenario [20].

We consider decaying DM in this Letter. Specifically, we study gravitino DM in R-parity violating (RPV) supersymmetric (SUSY) models [21,22].¹ With bilinear RPV operators, it is difficult to realize the gamma-ray line scenario [14]. The branching ratio of the radiative decay is smaller than 0.03, which is consistent with the continuum gamma-ray bound but the allowed range of parameters are constrained due to the absence of anti-proton flux in observations. We complement the previous study by considering

trilinear RPV operators. With sfermion masses of $O(\text{TeV})$, the tree-level decay rate of gravitino is suppressed and the radiative decay can explain the 130 GeV gamma-ray line. Furthermore, there is no overproduction of continuum gamma-ray and anti-proton overproduction is avoided when one considers *LLE* RPV operators.

The model considered here is consistent with cosmology. The lightest SUSY particle of the MSSM (MSSM-LSP) decays into gravitino or other SM particles due to RPV interactions before the big-bang nucleosynthesis (BBN) begins. This prevents the late decay of the MSSM-LSP from spoiling the success of the BBN. We also note that the requirement of relatively heavy sfermions does not contradict with the recent discovery of the 126 GeV Higgs-like boson at the LHC [24,25]. In fact, negative results on SUSY searches at the LHC and a rather heavy Higgs boson favor SUSY models with large sfermion masses.

The rest of the Letter is organized as follows. First, we will discuss the theoretical framework of our model. Then, we discuss general aspects of its phenomenology. Next, we elaborate how it can explain the 130 GeV gamma-ray line. Before we comment on our model and make conclusion, we study cosmological aspects of the model.

2. Gravitino dark matter with R-parity violation

2.1. Framework

Let us write down the relevant interaction Lagrangian of gravitino:

$$\begin{aligned} \mathcal{L}_{\text{int}} = & -\frac{i}{\sqrt{2}M_{\text{Pl}}} [(D_\mu^* \phi^{i*}) \bar{\psi}_\nu \gamma^\mu \gamma^\nu P_L \chi^i \\ & - (D_\mu \phi^i) \bar{\chi}^i P_R \gamma^\nu \gamma^\mu \psi_\nu] \\ & - \frac{i}{8M_{\text{Pl}}} \bar{\psi}_\mu [\gamma^\nu, \gamma^\rho] \gamma^\mu \lambda^{(\alpha)a} F_{\nu\rho}^{(\alpha)a} + \mathcal{O}(M_{\text{Pl}}^{-2}). \end{aligned} \quad (2.1)$$

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¹ Another viable decaying SUSY DM candidate, axino, has been studied in [23].

ϕ^i , χ^i , ψ_ν , $\lambda^{(\alpha)a}$ are sfermion, the corresponding fermion, gravitino and gaugino, respectively. D_μ is the covariant derivative and $F_{\nu\rho}^{(\alpha)a}$ is the field strength tensor. $P_L(P_R)$ is the projection operator projecting onto left-handed (right-handed) spinors. All interactions are suppressed by the reduced Planck mass $M_{\text{Pl}} \simeq 2.4 \times 10^{18}$ GeV.

Next, we write down the superpotential related to RPV [26]. In the most general form, it is

$$W = \lambda_{ijk} L_i L_j E_k + \lambda'_{ijk} L_i Q_j D_k + \lambda''_{ijk} U_i D_j D_k + \mu_i L_i H_u, \quad (2.2)$$

where summation among the indices $i, j, k = 1, 2, 3$ which denote the lepton and quark generation is implicitly assumed. L_i , E_i , Q_i , D_i , U_i and H_u are chiral superfields of lepton doublet, lepton singlet, quark doublet, down-type quark singlet, up-type quark singlet and up-type Higgs doublet, respectively. The first three terms lead to trilinear RPV while bilinear RPV arises due to the last term. λ_{ijk} , λ'_{ijk} , λ''_{ijk} are dimensionless parameters and μ_i is a parameter with mass dimension one. Hereafter, we will work in the basis where $\mu_i L_i H_u$ is rotated away from the superpotential. This is done by redefining L_i and the down-type Higgs superfield H_d as $L'_i = L_i - \epsilon_i H_d$ and $H'_d = H_d + \epsilon_i L_i$ with $\epsilon_i \equiv \mu_i / \mu$, where μ is the higgsino mass parameter in the MSSM superpotential $\mu H_u H_d$. Due to this redefinition, SUSY-breaking soft terms, including those corresponding to the bilinear RPV,

$$-\mathcal{L}_{\text{soft}} = (B H_u H_d + B_i \tilde{L}_i H_u + m_{\tilde{L}_i H_d}^2 \tilde{L}_i H_d^* + \text{h.c.}) + m_{H_d}^2 |H_d|^2 + m_{\tilde{L}_i}^2 |\tilde{L}_i|^2 + \dots, \quad (2.3)$$

where $\tilde{L}_i$ is the scalar component of the chiral superfield L_i , undergo transformation as well. In the following, primes of the redefined fields and soft terms are omitted to tidy up our notations. In this basis, sneutrinos' vacuum expectation values (VEVs) are typically non-zero. By minimizing the scalar potential of sneutrino (including the SUSY-breaking soft terms), the VEVs are found to be

$$\langle \tilde{\nu}_i \rangle = - \frac{m_{\tilde{L}_i H_d}^2 \cos \beta + B_i \sin \beta}{m_{\tilde{\nu}_i}^2} v, \quad (2.4)$$

$\tan \beta \equiv v_u / v_d$ is the ratio of the VEVs of the up- and down-type Higgs fields. $m_{\tilde{\nu}_i}^2$ is the sneutrino mass and $v \equiv \sqrt{v_u^2 + v_d^2} \simeq 174$ GeV.

Note that trilinear RPV terms, *LLE* and *LQD*, are also generated by the field redefinition. They are absorbed into the parameters λ_{ijk} and λ'_{ijk} . In summary, we work with the superpotential

$$W = \lambda_{ijk} L_i L_j E_k + \lambda'_{ijk} L_i Q_j D_k + \lambda''_{ijk} U_i D_j D_k \quad (2.5)$$

and non-zero sneutrino VEVs, which we parametrize as $\kappa_i \equiv \langle \tilde{\nu}_i \rangle / v$.

2.2. Some phenomenological implications and constraints

In this subsection, we consider general phenomenological aspects of our framework. First, we focus on trilinear RPV couplings. Allowing both lepton and baryon number violation would lead to proton decay with a very short lifetime. Moreover, as will be discussed in detail in the next subsection, gravitino DM's leptonic decays are preferred over hadronic decays in order to explain the 130 GeV gamma-ray line. Therefore, we assume baryon number conservation by choosing $\lambda''_{ijk} = 0$.

Another bound on trilinear RPV couplings arises from cosmological considerations. λ_{ijk} and λ'_{ijk} has to be small enough to prevent wash-out of the baryon asymmetry before the electroweak transition. The couplings are, generically [27–30],

$$\lambda_{ijk}, \lambda'_{ijk} \lesssim 5 \times 10^{-7} \left(\frac{M_{\text{SUSY}}}{1 \text{ TeV}} \right)^{1/2} \quad (2.6)$$

where M_{SUSY} is the masses of squarks or sleptons. Other bounds on trilinear RPV couplings are known to be less stringent [26].

We can no longer distinguish between the lepton doublet and the up-type Higgs doublet under bilinear RPV. Sneutrino VEVs that mix leptons with gauginos are induced. Specifically, neutrinos mix with neutralinos whereas leptons mix with charginos. Bilinear RPV's constraints can be deduced from neutrino masses generated by sneutrino VEVs. Masses of neutrino are $m_\nu \sim g^2 \langle \tilde{\nu} \rangle^2 / m_{\tilde{B}}$, where $m_{\tilde{B}}$ is the mass of bino [31–33]. For gaugino masses of $O(\text{TeV})$, $\kappa_i = \langle \tilde{\nu}_i \rangle / v \lesssim 10^{-6}$ is required by experimental bounds on neutrino masses.

In the following, we will study the scenario where trilinear RPV is dominant and bilinear RPV is negligible.² We note that even if bilinear RPV is absent at tree level at a certain energy scale, renormalization group evolution will generate the bilinear terms at some other energy scale. Unfortunately, we have not found any model that can naturally explain the smallness of bilinear RPV in the literature. On the flip side, if the 130 GeV gamma-ray line can really be interpreted as a signature of gravitino DM with trilinear RPV, it should inspire model building efforts towards a theory with such characteristic in the future.

2.3. Trilinear R-parity violation-dominant scenario

Gravitino undergoes three-body decay via trilinear couplings at the tree level. As will be explained in the following, we will consistently be working with the *LLE* RPV operators. For leptonic decay with an intermediate mass $m_{\tilde{\tau}_R}$, the decay rate is [22]

$$\Gamma(\psi_{3/2} \rightarrow \bar{\tau} \nu_i e_j) \simeq \frac{|\lambda_{ij3}|^2}{90(32)^2 \pi^3} \frac{m_{3/2}^7}{M_{\text{Pl}}^2 m_{\tilde{\tau}_R}^4}. \quad (2.7)$$

The full analytical result has been worked out in [37]. Gravitino undergoes one-loop radiative decay as well [38]. The decay rate scales as

$$\Gamma(\psi_{3/2} \rightarrow \gamma \nu_i) \sim \frac{\alpha \lambda_{ijj}^2 m_{3/2} m_j^2}{M_{\text{Pl}}^2} \quad (2.8)$$

when the sfermion masses are large compared to gravitino and lepton masses. α is the fine structure constant. The radiative decay rate is proportional to the fermion mass. Therefore, RPV couplings involving the third generation of fermion gives the largest contribution. We also note that the radiative decay is approximately independent of the mass of sfermion running in the loop of the decay amplitude. It can be understood from the amplitude of the interaction that involves the first two terms of Eq. (2.1). These terms carry a derivative of the sfermion field that brings a momentum flow proportional to the largest loop-mass to the vertex. It balances out the contribution of the sfermion mass from the sfermion propagator.³

Gravitino also decays into gauge bosons via *LLE* RPV couplings. Similar to the radiative decay channel, in the large sfermion masses limit, the decay rate of these channels are approximately independent of sfermion masses. Ignoring numerical prefactors, the decay rate for $\psi_{3/2} \rightarrow Z \nu_i$ scales as

² See [34,35] for models that generate small *LLE* RPV operators, which will be important in the next section. See also [36].

³ See [38] for a detailed description of the radiative decay amplitude.

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