# Gravitino dark matter and neutrino masses with bilinear R-parity violation

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Bilinear R-parity violation provides an attractive origin for neutrino masses and mixings. In such schemes the gravitino is a viable decaying dark matter particle whose R-parity violating decays lead to monochromatic photons with rates accessible to astrophysical observations. We determine the parameter region allowed by gamma-ray line searches, dark matter relic abundance and neutrino oscillation data, obtaining a limit on the gravitino mass $m_{\tilde{G}} \lesssim$ 1-10 GeV corresponding to a relatively low reheat temperature $T_R \lesssim$ few $\times 10^7 - 10^8$ GeV. Neutrino mass and mixing parameters may be reconstructed at accelerator experiments like the Large Hadron Collider.

## I. INTRODUCTION

The origin of neutrino masses and mixing and the nature of dark matter are two of the most elusive open problems of modern particle physics and cosmology, which clearly indicate the need for new physics beyond the Standard Model. It has been suggested that these two apparently unrelated issues may be closely inter-linked [1–4]. Here we propose an alternative way to relate dark matter with neutrino properties within a scenario where supersymmetry (SUSY) is the origin of neutrino mass [5], thanks to the spontaneous violation of R-parity [6]. For definiteness and simplicity we adopt an effective description in terms of explicit bilinear R-parity violating superpotential terms (BRpV) [7–9].

We show how both dark matter and neutrino oscillations can be simultaneously explained in the presence of bilinear R-parity violation with gravitino lightest supersymmetric particle (LSP), in such a way that,

- gravitino dark matter properties are closely related to the scale of neutrino mass, and

- neutrino oscillation parameters may be reconstructed at accelerator experiments.

Indeed, in this model the very same lepton number violating superpotential terms that generate neutrino masses and mixing also induce dark matter gravitino decays, as this also breaks R parity.

We show how, although unprotected by R-parity, the gravitino can be stable over cosmological times and be a viable cold Dark Matter (DM) candidate. This follows from the double suppression of its decay rate, which depends on the small R-parity violating couplings and it is suppressed by the Planck scale [10, 11] [1]. Interestingly, gravitino decays produce monochromatic photons, opening therefore the possibility to test this scenario with astrophysical searches. Requiring the model parameters to correctly account for observed neutrino oscillation parameters [13] implies that

expected rates for gamma-ray lines produced by gravitino decays of mass above a few GeV would be in conflict with the Fermi-LAT satellite observation [14, 15], leading to an upper bound on the gravitino DM mass. The bound on the gravitino mass with bilinear R-parity violating couplings holds under the assumption of universality in gaugino masses (see [15] and references therein). Here we study the conditions of non-universality in gaugino masses to relax the the gravitino mass constraints. We show how the bound remains even if we assume non-universal gaugino masses, though somewhat less stringent. Turning to the implications at collider experiments such as the Large Hadron Collider (LHC) these have been discussed in a series of earlier papers [16–21]. It is important to stress the expected signatures are basically the same already studied in the usual BRpV scenarios.

In the next Section we briefly introduce the BRpV model, in section III we discuss gravitino decays and cosmological relic abundance and explain our numerical procedure. In particular we obtain an upper limit for the gravitino mass and discuss it both for universal and non-universal gaugino masses. In Section IV we briefly discuss collider implications, and finally summarize the paper in Sec.V.

## II. BILINEAR R-PARITY VIOLATING MODEL

Here we work in a constrained minimal supergravity model in which the gravitino is the lightest supersymmetric particle (LSP). The simplest R-parity violation scenario is assumed, in which the superpotential contains bilinear R-parity violating terms [7, 8]

$$W = W_{\text{MSSM}} + \epsilon_i \widehat{L}_i \widehat{H}_u, \tag{1}$$

where $W_{MSSM}$ is the superpotential of the minimal supersymmetric standard model (MSSM) and the parameters $\epsilon_i$ characterize the bilinear R-parity violation, with the flavour index $i = 1, 2, 3$ running over the generations. The soft supersymmetry breaking Lagrangian contains, in addition to the R-parity conserving operators $V_{\text{soft}}^{MSSM}$, a term associated with the R-parity violation contribution:

$$V_{\text{soft}} = V_{\text{soft}}^{\text{MSSM}} + B_i \epsilon_i \tilde{L}_i H_u. \tag{2}$$

The $\epsilon_i$ and $B_i$ terms induce vacuum expectation values $v_i$ for the scalar neutrinos, generating a mass mixing between neutrinos and neutralinos. As a result, one finds that neutrino acquires a mass at tree-level given by [8]

$$m_\nu^{\text{tree}} \approx \frac{M_1 g^2 + M_2 g'^2}{4\Delta_0} |\vec{\Lambda}|^2, \tag{3}$$

where $\Delta_0 = \det(M_{\chi_0}) = -M_1 M_2 \mu^2 + \frac{1}{2}\mu v_d v_u (M_1 g^2 + M_2 g'^2)$ is the determinant of the MSSM neutralino mass matrix and $\Lambda_i = \mu v_i + v_d \epsilon_i$ is the alignment vector. It is worth mentioning that the value of $|\vec{\Lambda}|^2$ is almost fixed by the very precise determination of the atmospheric scale, mainly by MINOS and other accelerator experiments. The other two neutrinos acquire a calculable mass only at the one-loop level [8, 9] as required to explain solar and reactor neutrino data. The BRpV model provides a scenario where all current neutrino oscillation data can be accounted for, i.e. it can accommodate the required values of the neutrino mass squared differences and mixing angles inferred from neutrino oscillation studies [13]. We refer the reader to [8, 9] for more details about the model.

For the rest of the paper, we assume the Constrained MSSM scenario (CMSSM) [22] where the soft supersymmetry breaking parameters $m_0, m_{1/2}$ and $A_0$ are assumed to be universal at the supersymmetric Grand Unification (GUT) scale. Thus, the model depends upon the following eleven free parameters:

$$m_0, \ m_{1/2}, \ \tan\beta, \ \text{sign}(\mu), \ A_0, \ \epsilon_i, \ \Lambda_i. \tag{4}$$

Here, $m_{1/2}$ and $m_0$ are the common gaugino mass and scalar soft SUSY breaking masses at the unification scale, $\tan\beta$ is the ratio between the Higgs field vacuum expectation values and $A_0$ is the common trilinear term.

When supersymmetry is promoted to be a local symmetry of nature, the resulting theory requires a supermultiplet which includes the gravitino. After supersymmetry breaking, the gravitino becomes massive via the superhiggs mechanism. Depending on details of the underlying supersymmetry breaking mechanism the gravitino mass $m_{\tilde{G}}$ can lie anywhere between $\mathcal{O}(eV)$ and $\mathcal{O}(TeV)$. We take $m_{\tilde{G}}$ as a free parameter which does not fix the scale of soft-supersymmetry breaking parameters [23].

## III.   GRAVITINO COSMOLOGY

There have been several studies of gravitino dark matter in R-parity conserving supersymmetry [23–26]. In this case the lightest supersymmetric particle is stable and is potentially a viable dark matter candidate [23–26]. Here we consider this issue within the simplest R-parity violating scenario. In order to study the region of parameter space of the model which can accomodate neutrino oscillation data, we have performed a numerical analysis using the SPheno package [27], which calculates the renormalization group equations at two loops, generating the full supersymmetric particle spectrum. It also includes the one-loop calculations of the neutrino masses in the BRpV model, required in order to account for solar neutrino conversion. For a fixed set of CMSSM parameters ($m_0$, $m_{1/2}$, $\tan\beta$, $\text{sign}(\mu)$, $A_0$) we determine the set of R-parity breaking parameters $\epsilon_i$ and $\Lambda_i$ responsible for generating neutrino mass squared differences and mixing angles consistent at $3\sigma$ with the measured values [13]. We repeat this procedure fixing $A_0 = -100$ GeV $\text{sign}(\mu) = +1$ and scanning over the other CMSSM parameters in the range:

$$240 \leq m_{1/2} \leq 3000 \text{ GeV}, \tag{5}$$
$$3 \leq \tan\beta \leq 50,$$
$$200 \leq M_0 \leq 1000 \text{ GeV}.$$

### A.   Gravitino dark matter relic density

Gravitinos are produced in the early Universe after the reheating phase through particles scattering occurring in the thermal plasma, the dominant contribution coming from SUSY quantum chromodinamycs processes [28–32]. The gravitino relic abundance critically depends on the reheating temperature $T_R$ and it is given by: [28, 29]

$$\Omega_{\tilde{G}}h^2 = \sum_{i=1}^{3} \omega_i \left[g_i(T_R)\right]^2 \left(1 + \frac{[M_i(T_R)]^2}{3m_{\tilde{G}}^2}\right) \ln\left(\frac{k_i}{g_i(T_R)}\right) \left(\frac{m_{\tilde{G}}}{100 \text{ GeV}}\right) \left(\frac{T_R}{10^{10} \text{ GeV}}\right), \tag{6}$$

with $M_i(T_R)$ and $g_i(T_R)$ respectively the gaugino mass parameters and gauge coupling constants at $T_R$ energy scale. The index $i$ runs over the Standard Model gauge group factors and the constants $\omega_i$ and $k_i$ are $\omega_i = (0.018, 0.044, 0.117)$ and $k_i = (1.266, 1.312, 1.271)$. The gaugino masses and the gauge coupling constants can be evaluated at the energy scale $T_R$ using the renormalization group equations (RGEs), which at one-loop level are given as

$$g_i(T_R) = \left[g_i(m_Z)^{-2} - \frac{\beta_i^{(1)}}{8\pi^2}\ln\left(\frac{T_R}{m_Z}\right)\right]^{-1/2}, \tag{7}$$

$$M_i(T_R) = \left(\frac{g_i(T_R)}{g_i(m_Z)}\right)^2 M_i(m_Z). \tag{8}$$

In the MSSM, the beta function coefficients are $\beta_i^{(1)} = (11, 1, -3)$. Assuming universal gaugino soft masses at the supersymmetric GUT scale, their values at the electroweak scale ($m_Z$) follow the relations $M_3 \simeq 3.1M_2 \simeq 5.9M_1$.

In figure 1 the black lines show the combination of gravitino masses and reheating temperatures for which the gravitino relic abundance is consistent with the dark matter density inferred from astrophysical observations [33],
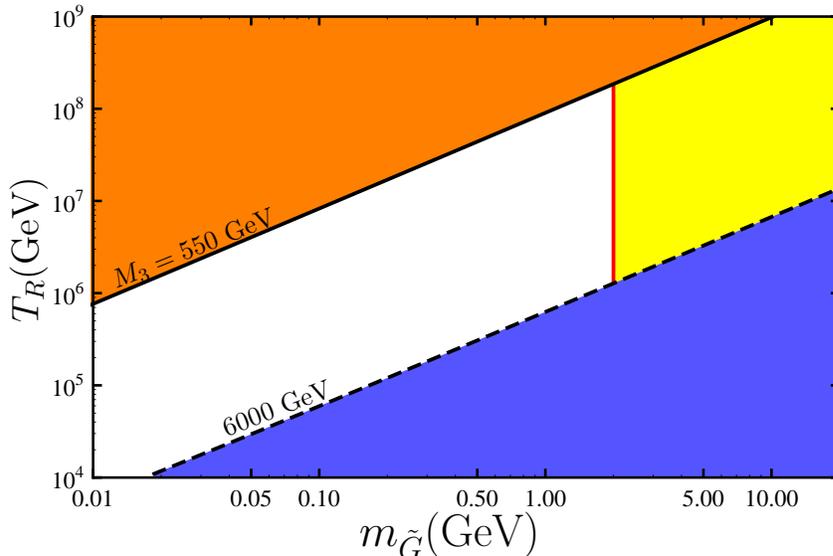
FIG. 1. Region (white) in the $(m_{\tilde{G}}, T_R)$ plane consistent with neutrino oscillations, gravitino dark matter, gamma-ray line searches, and gluino searches. In the orange area a consistent gravitino relic abundance would require gluino masses excluded by present collider searches. In contrast, the blue area is viable but requires too large gluino masses, $M_3 > 6000$ GeV. The yellow region is excluded by astrophysical gamma-ray line searches.

$\Omega_{DM} h^2 = 0.1123$. There, we have assumed gaugino universality and the two curves correspond to two different values for the soft gluino mass parameter $M_3$. The orange region (upper dark gray) requires values of $M_3$ smaller than 550 GeV in order to obtain the correct gravitino relic abundance consistent with WMAP. Present bounds on the gluino mass from recent searches at the LHC already exclude this region [34–40]. On the other hand, the blue area (lower dark grey) is viable but corresponds to $M_3 \gtrsim 6000$ GeV which, though phenomenologically acceptable, is theoretically disfavored if supersymmetry is supposed to "protect" the hierarchical problem.

We notice that for gravitinos in the mass range up to few GeV, the corresponding values of reheating temperature are relatively low and compatible with the lower bounds that can be inferred from cosmic microwave background radiation observations [41].

## B. Gravitino decays

In the presence of R-parity breaking, as in the bilinear R-parity model we have considered above, the LSP decays. In particular, if the strength of the bilinear R-parity violating parameters is chosen so as to reproduce the neutrinos masses and mixing angles indicated by neutrino oscillation experiments [13], a neutralino LSP would decay with a lifetime way too short when compared with the age of the Universe. However, if the LSP is a gravitino, the double suppression provided by the smallness of the R parity violating parameters and the Planck-scale suppression of the coupling governing the decay rate greatly increase its lifetime, making it a perfect dark matter candidate [10, 11]. It would also provide an example of the generic expectation that gravitational interactions break global symmetries [42, 43], in this case R-parity and lepton number.

The unstable gravitino dark matter scenarios can potentially be tested with indirect astrophysical dark matter

searches. In the bilinear R-parity breaking model under consideration, the gravitino decays as $\tilde{G} \to \nu\gamma$ with a width:

$$\Gamma = \Gamma(\tilde{G} \to \sum_i \nu_i \gamma) \simeq \frac{1}{32\pi} |U_{\tilde{\gamma}\nu}|^2 \frac{m_{\tilde{G}}^3}{M_P^2}, \tag{9}$$

where the R-parity breaking mixing parameter $|U_{\tilde{\gamma}\nu}|^2$ from the $7 \times 7$ neutralino mixing matrix, is [12]

$$|U_{\tilde{\gamma}\nu}|^2 = \sum_{a=i+4} |\cos\theta_W N_{a1} + \sin\theta_W N_{a2}|^2, \tag{10}$$

where the $N$-coefficients denote the neutrino projections onto the gauginos. Following [9] this can be calculated perturbatively as

$$|U_{\tilde{\gamma}\nu}|^2 \approx \frac{\mu^2 g^2 \sin^2\theta_W}{4\Delta_0^2} (M_2 - M_1)^2 |\vec{\Lambda}|^2, \tag{11}$$

with $\Delta_0 = \det(M_{\chi_0}) = -M_1 M_2 \mu^2 + \frac{1}{2}\mu v_d v_u (M_1 g^2 + M_2 g'^2)$ and $\Lambda_i = \mu v_i + v_d \epsilon_i$.

For each set of parameters generated through the scanning procedure given in Eq. (5) yielding the correct values of the neutrino oscillation parameters, we compute the gravitino lifetime, using equations (9) and (11). This decay mode is particularly interesting from the point of view of indirect dark matter detection. Indeed monochromatic photons of $\sim$ GeV energies are generally not expected to be produced by conventional astrophysical processes. For this reason, the detection of gamma-ray lines would be a striking signature of dark matter processes, pointing either to annihilations [44–50] or to decays of dark matter particles [51–56]. Search of gamma-ray lines have been recently performed using the data of the Fermi-LAT satellite [14, 15]. The derived upper bounds on the gamma-ray line fluxes can be used to constrain the unstable gravitino dark matter model under consideration.

In figure 2 we present the lower bounds on the gravitino lifetime for dark matter gravitinos decaying into $\nu\gamma$ [15]. These constraints have been computed assuming a Navarro-Frenk-White (NFW) dark matter density profile [57] and for the region of observation dubbed as "Halo" in Ref. [15]. The bounds are not too sensitive to the exact shape of the dark matter profiles or region of observation considered. At energies below $\sim$ 1 GeV we consider the bounds on gamma-ray lines obtained in Ref. [58] by analyzing the data from EGRET. We traslate the upper limits on the gamma-ray line fluxes into bounds on the gravitino lifetime for gravitino decays into $\nu\gamma$ [58]. We consider a NFW density distribution while a shallower isothermal profile would lead to a bound a factor two less stringent. Finally, we note that gravitino decays into three body final states could be relevant for gravitino masses larger than those required in our case [59, 60].

The area between the two black lines in figure 2 corresponds to the region of the parameters compatible with neutrino physics. We notice that the two curves correspond approximately to constant values of $m_{1/2} = 240$ GeV (lower line) and $m_{1/2} = 3000$ GeV (upper line). Indeed, once the constraints from neutrino oscillations are imposed, the matrix element $|U_{\tilde{\gamma}\nu}|^2$ determining the gravitino lifetime, depends mostly on $m_{1/2}$. Universal gaugino masses of $m_{1/2} = 240$ GeV and $m_{1/2} = 3000$ GeV lead at the scale $M_Z$ to $M_3 \approx 550$ GeV and $M_3 \approx 6000$ GeV respectively.

Taking into account the Fermi-LAT and EGRET bounds on gamma-ray lines from dark matter decay (yellow region in figure 2) and assuming the gravitino as dark matter particle, we can derive an upper bound on the gravitino mass of the order $m_{\tilde{G}} \sim 2$ GeV. Thus, the grey area in figure 2 corresponds to the region of the parameter space which simultaneusly explains neutrino oscillation data and satisfies the constraints from gamma-ray line searches.

We now translate the bounds from neutrino oscillation physics and gamma-ray line searches to the $(m_{\tilde{G}}, T_R)$ plane shown in figure 1. They correspond to the yellow area (light grey). We see that assuming the gravitino as dark matter candidate in BRpV and imposing the constraints from neutrino oscillations and gamma-ray line searches we can derive an upper bound on reheating temperature of the order $T_R \sim 10^8$ GeV and an upper bound on the gravitino mass of the order $m_{\tilde{G}} \sim 2$ GeV. Similar results are expected in other R-parity violation schemes, such as considered in Ref. [55].
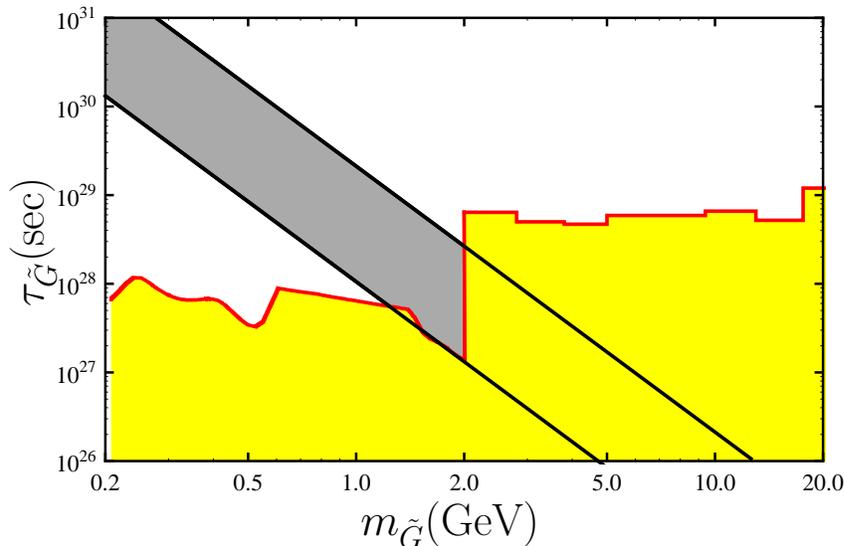
FIG. 2. Allowed gravitino mass-lifetime region (grey color) consistent with neutrino oscillation data and astrophysical bounds on gamma-ray lines from dark matter decay. The yellow region is excluded by gamma-ray line searches (Fermi and EGRET constraints are respectively above and below 1 GeV). The lower and upper black lines correspond to $m_{1/2} = 240$ and $3000$ GeV respectively.

## C. Non-universal gaugino masses

We now study the effects of non-universal gaugino masses on the gravitino mass upper bound. The non-universality effects enter in the gravitino lifetime through the neutrino-"photino" mixing parameter $|U_{\tilde{\gamma}\nu}|^2$. At the unification scale non-universal gaugino masses can be parametrized as [61]

$$M_a = m_{1/2}(1 + \delta_a), \tag{12}$$

with the parameters $\delta_a$, $a = 1, 2, 3$, characterizing the deviation from universality. For illustratation we choose the ranges $\delta_{1,2} = (-1, 1)$, keeping $\delta_3 = 0$, and fix a typical CMSSM point satisfying all the phenomenological constraints with $m_{1/2} = 500$ GeV, $m_0 = 1000$ GeV, $A_0 = -100$, $\tan\beta = 10$, and $\mathrm{sgn}(\mu) > 0$. Then we use SPheno with a random set of $\delta_a$ values to calculate $|U_{\tilde{\gamma}\nu}|^2$, with the best possible fit to neutrino masses and mixings for each point of the scan. We also check that limits on sparticle searches are obeyed, e. g. $m_{\tilde{\chi}_1^\pm} > 103$ GeV, and that a non-bino neutralino has a mass larger than 50 GeV [61, 62]. The results are shown in the yellow (light gray) region of figure 3 where the ratio $M_2/M_1$ is calculated at the electroweak scale. In the green (dark gray) region the mass neutralino is larger than 50 GeV, while in the solid black line $\delta_2 = 0$.

From the approximate expression for $|U_{\tilde{\gamma}\nu}|^2$ in eq. (11) one would expect vanishing values at $M_2 \approx M_1$. However, from the loop-corrected neutralino mass matrix calculated from SPheno, one obtains that $|U_{\tilde{\gamma}\nu}|^2$ has a minimum non-zero value at $M_2 \approx M_1$. In figure 3, the dashed lines indicate the point where the gaugino masses arises from universal conditions. From the gravitino lifetime in (9), one sees that for neutralino masses larger (smaller) than the CMSSM reference value, the gravitino mass bound is weaker (stronger). For example, for $m_{1/2} = 500$ GeV, we have $|U_{\tilde{\gamma}\nu}|^2 \approx 1.6 \times 10^{-14}$. From eq. (9) the maximum gravitino mass can be expressed as

$$m_{\tilde{G}}^{\max} \approx 2\,\mathrm{GeV} \left(\frac{3 \times 10^{27}\mathrm{s}}{\tau_{\tilde{G}}^{\min}}\right)^{1/3} \left(\frac{1.6 \times 10^{-14}}{|U_{\tilde{\gamma}\nu}|^2}\right)^{1/3}, \tag{13}$$
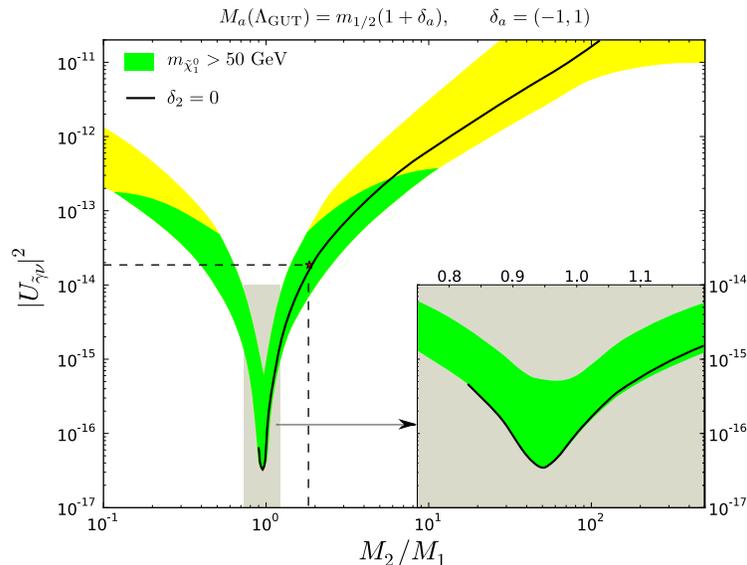
FIG. 3. Neutrino-photino mixing $|U_{\tilde{\gamma}\nu}|^2$ as a function of the low energy ratio $M_2/M_1$ when $M_a = m_{1/2}(1 + \delta_a)$ have been assumed at the unification scale (with $\delta_3 = 0$)). We have set $m_{1/2} = 500$ GeV, $m_0 = 1000$ GeV, $A_0 = -100$ GeV, $\tan\beta = 10$ and $\text{sign}(\mu) = +1$. In the green (dark gray) region $m_{\tilde{\chi}_1^0} > 50$ GeV. The explicit minimum of $|U_{\tilde{\gamma}\nu}|^2$ is shown in the zoomed gray area.

where $\tau_{\tilde{G}}^{min}$ is the minimum gravitino lifetime allowed by gamma-ray line searches (see figure 2). When $M_2 \approx M_1$, we obtain the minimum value for $|U_{\tilde{\gamma}\nu}|^2 \approx 4 \times 10^{-17}$, and an upper bound on gravitino mass of order $m_{\tilde{G}} \sim 7$ GeV. This illustrates the relative robustness of the gravitino mass bound against deviations from gaugino universality.

While this holds for a given CMSSM point, we have not been able to find other points in parameter space where the gravitino mass bound changes by more than an order of magnitude. The point is that, even though radiative effects in the neutralino mass matrix may change by three orders of magnitude (see figure 3) the bound changes only as the 1/3 power of that, according to eq. (13), hence is relative stable.

Let's now briefly comment about implications on Big Bang Nucleosynthesis (BBN). In R-parity conserving scenarios with gravitino dark matter, the neutralino has a large lifetime since its decays into the LSP are suppressed by the Planck scale thus it may decay during the Big Bang Nucleosynthesys epoch, spoiling its predictions [63] (BBN demands a NLSP lifetime less than 0.1 s [63]). In contrast, in the model under consideration, the next to lightest supersymmetric particle (NLSP) decays occur well before the BBN epoch because of the presence of the gravity unsuppressed R-parity violating interactions, keeping therefore the successful BBN predictions of the light element abundances.

## IV. PROSPECTS FOR COLLIDER SEACHES

When R-parity is conserved, all supersymmetric particles undergo cascade decays to the next to lightest supersymmetric particle, which subsequently decays (of course, with gravitational strength) to the gravitino. The implications for collider searches and cosmology strongly depend on which superpartner is the NLSP. In BRpV models, in addition to generating the neutrino masses, the neutralino-neutrino mixing also induces NLSP decays into Standard Model particles, strongly correlated with the neutrino oscillation parameters [16–18]. Since R-parity violating couplings are not so small, displaced vertices are expected in the NLSP decay [19–21]. In what follows we will consider the neutralino as the NLSP.

In R-parity conserving scenarios the neutralino as the NLSP has the following decay channels [64]

$$\tilde{\chi}_1^0 \to \gamma \tilde{G},$$
$$\tilde{\chi}_1^0 \to Z \tilde{G},$$
$$\tilde{\chi}_1^0 \to h^0 \tilde{G}, \tag{14}$$

In the presence of R-parity breaking additional decay channels exist [18], namely,

$$\tilde{\chi}_1^0 \to h^0 \nu_i,$$
$$\tilde{\chi}_1^0 \to \gamma \nu_i,$$
$$\tilde{\chi}_1^0 \to W^\pm l_i^\mp,$$
$$\tilde{\chi}_1^0 \to Z^0 \nu_i. \tag{15}$$

Neutralino can also decay to three fermions by scalar quark and scalar lepton exchange in R-parity violating models. The three channels in (14) are Planck-mass-suppressed and, for the gravitino mass range of interest, are negligible compared with those in eq. (15). Indeed, $Br(\tilde{\chi}_1^0 \to \gamma \tilde{G}) < 10^{-5}$ for $m_{\tilde{G}} > 10$ keV [12]. The decay into the Higgs boson is scalar mixing suppressed, while the radiative channel is loop suppressed. As a result, decays to gauge bosons are dominant for large $m_0$. Therefore these collider signals are independent of the fact that the gravitino is lightest supersymmetric particle or not. In particular, the predictions at colliders for a neutralino LSP in the CMSSM with BRpV studied in [16–21], such as the displaced vertex signals illustrated in figure 4, remain unchanged.
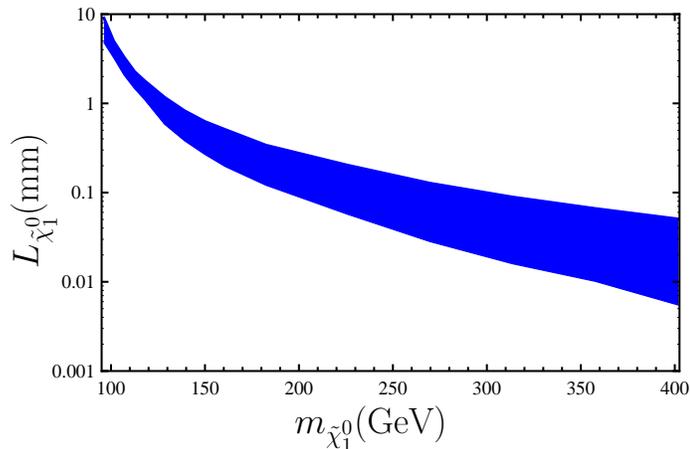


FIG. 4. Neutralino NLSP decay length as a function of its mass. For illustration we show the results of a scan with $A_0 = -100$ GeV, sign$(\mu) = +1$, $\tan\beta = 10$, $200 \le M_0 \le 1000$ GeV and $240 \le m_{1/2} \le 1000$ GeV.

## V.  SUMMARY

We have considered the CMSSM model with bilinear R-parity violation with gravitino as LSP. By imposing the constraints from neutrino oscillation data, dark matter relic density and gamma-ray line searches at Fermi-LAT and EGRET we have shown that the gravitino does provide a viable radiatively decaying dark matter particle, provided its mass and reheat temperature are bounded as $m_{\tilde{G}} \lesssim$ 1-10 GeV and $T_R \lesssim$ few $\times 10^7 - 10^8$ GeV (as we saw the bounds get looser if the universality hypothesis in gaugino masses is relaxed). The expected signatures associated to the NLSP decays at collider experiments like the Large Hadron Collider do not depend on the presence of the

gravitino and so are the same as those previously studied [16–21]. In particular neutrino mass and mixing parameters may be reconstructed at accelerator experiments by measuring the ratio of semileptonic neutralino decays branching ratios induced by the charged current.

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