MSSM in view of PAMELA and Fermi-LAT

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Abstract

We take the MSSM as a complete theory of low energy phenomena, including neutrino masses and mixings. This immediately implies that the gravitino is the only possible dark matter candidate. We study the implications of the astrophysical experiments such as PAMELA and Fermi-LAT, on this scenario. The theory can account for both the realistic neutrino masses and mixings, and the PAMELA data as long as the slepton masses lie in the $500 - 10^6$ TeV range. The squarks can be either light or heavy, depending on their contribution to radiative neutrino masses. On the other hand, the Fermi-LAT data imply heavy superpartners, all out of LHC reach, simply on the grounds of the energy scale involved, for the gravitino must weigh more than 2 TeV. The perturbativity of the theory also implies an upper bound on its mass, approximately 6 – 7 TeV.
I. INTRODUCTION

The minimal supersymmetric standard model (MSSM) [1] has become over the years the principal extension of the standard model. For this reason we study the consequences of the possibility of MSSM being a complete theory of present-day phenomena. It has all the necessary ingredients to be that: (i) it can naturally provide neutrino mass and mixings (unless one artificially forbids many gauge invariant couplings by imposing the so-called R-parity); (ii) if there is a light stop, it is tailor-fit for electroweak baryogenesis [2], and it also allows the Affleck-Dine baryogenesis through flat directions [3]; (iii) the same flat directions can provide a natural source of inflation [4]; (iv) last but not least, it has a number of neutral particles that can in principle be dark matter candidates [5]. This last issue is the subject of the present undertaking. Our work is inspired by the recent satellite experiments such as PAMELA [6], ATIC and Fermi-LAT [7] whose measurement on the high-energy positron/electron excess has attracted a lot of attention.

Here we define the MSSM as the supersymmetric extension of the minimal standard model, without any new particles but the gravitino. The parameter space of the theory will be left open and subject to the experimental determination. In particular we make no assumption about the soft supersymmetry breaking terms, that is superpartner masses and their mixings. Taking the MSSM to be the complete low energy theory leads to a number of immediate consequences. First, the only possible dark matter candidate is precisely the gravitino. Second, the gravitino decay through R-parity violation can account for the PAMELA data, provided that the R-parity violation (RPV) [8] is hadrophobic and gravitino weights at least 300 GeV. The neutrino masses can also be explained through radiative R-parity breaking corrections. Third, Fermi-LAT data can be simultaneously explained through the gravitino decay as long as its mass is greater than $2 \times 10^4$ TeV. This would unfortunately make all the superpartners too heavy to be discovered at the LHC.

There is nothing original in our taking gravitino as dark matter, or even as a decaying dark matter [9] [10] [11] [12]. In the case under study, this is forced on us, simply by taking MSSM as also a theory of neutrino masses and mixings. Without this requirement, there would be no constraint on the MSSM parameters and the sfermions could be as light as one wishes, as long as gravitino remains the LSP. The other studies tend to extend the MSSM, normally for the sake of baryogenesis and/or neutrino masses, which to us appears unnecessary.

Our main findings are the following.

• Barring fine-tuned cancellations, in order to explain PAMELA results, sleptons have to weigh between $500 - 10^6$ TeV, which in turn implies no observable lepton flavor violation in near future. For a moderately light gravitino, $m_{3/2} \leq 400 - 500$ GeV, which corresponds to the parameter space of the MSSM relevant for the LHC, the upper bound on sleptons masses goes down to $10^4$ TeV. For Fermi-LAT, the slepton mass range becomes $10^4 - 10^6$ TeV.

• Although R-parity breaking associated with the quark sector is subdominant in gravitino decay compared to that in the lepton sector, it may still play an important role in the neutrino mass. In this case, one would also end up with heavy squarks, with similar lower limits on their masses as for the sleptons. This fits nicely with a split supersymmetry picture.
• An interesting finding emerges if the next-to-lightest superpartner (NLSP) is a wino/bino. It decays through R-parity violation and its lifetime is rather long, about $10^{-7}$ sec, since the sleptons are heavy. At the Large Hadron Collider (LHC), once produced, it would still decay inside the detector [13], producing multi-lepton final states.

Before we turn to the detailed study, let us comment on the implications of our results for the two main motivations for the low-energy supersymmetry.

The stabilization of gauge hierarchy. This requires light supersymmetric partners. In particular the stop should weigh less than TeV, while the other sfermion masses depend on the associated Yukawa couplings. It is worth noting that, with a lower end mass needed to explain the PAMELA data, even stau barely destabilizes the Higgs mass naturalness, for small values of $\tan \beta$. In the case of Fermi-LAT, naturalness is gone completely. There would be no reason to worry about it, since the necessarily large gravitino mass, above a few TeV kills the MSSM as a theory verifiable at the LHC.

The unification of gauge couplings. This is a great success of the MSSM for it was predicted [14] [15] [16] [17] ten years before the LEP measurement of the weak mixing angle. It also made prophetically a case for a large top Yukawa coupling [17]. The unification works for arbitrarily large sfermion masses (as long as they are approximately equal within each generation), as in the case of split supersymmetry [18]. The heavy sleptons needed for PAMELA and Fermi-LAT thus bring some tension between naturalness and unification.

II. MSSM IMPLIES DECAYING GRAVITINO DARK MATTER

Besides the supersymmetric generalization of the standard model, the most general gauge invariant MSSM contains the following renormalizable interactions:

$$W_R = \frac{1}{2} \lambda L Le + \lambda' Q L d + \frac{1}{2} \lambda'' u^c d^c + \mu' L H_u.$$ (1)

For simplicity we suppress the indices for families. These interactions are often set ad hoc to zero, by assuming the so-called R-parity. Notice that supersymmetry by itself guarantees the stability of these interactions set to zero. Notice also that zero is neither a special point, nor is it physically preferred. We take the attitude here that experiment should decide the values of these couplings, and if MSSM is to be a complete theory, at least some of them must be non-vanishing. Otherwise neutrinos will be massless.

The third term in Eq. (1) breaks baryon number while the other terms break lepton number. The most stringent constraint comes from the proton decay [19]:

$$\lambda' \lambda'' \lesssim 10^{-27} \left( \frac{m_{\tilde{d}}}{300 \text{GeV}} \right)^2.$$ (2)

There is also the constraint from neutron-antineutron oscillation [20]

$$\lambda'' \lesssim (10^{-7} - 10^{-8}) \left( \frac{m_{\tilde{d}}}{100 \text{GeV}} \right)^2 \left( \frac{m_{\tilde{\chi}_0^1}}{100 \text{GeV}} \right)^{1/2}.$$ (3)

Upon supersymmetry breaking, in general one expects a non-vanishing sneutrino vacuum expectation value (VEV), through a lepton number breaking soft term (corresponding to the $\mu'$ term in Eq. (1)).
The neutrino masses can be generated either through $\lambda$ and/or $\lambda'$ at one-loop level or by sneutrino VEV $\langle \tilde{\nu} \rangle$ at tree level,

$$m_\nu \simeq \frac{\lambda^2 (m^2_\ell)_{LR} m_\tau}{16\pi^2 m^2_\tilde{\ell}}; \quad \frac{3\lambda'^2 (m^2_{\tilde{q}})_{LR} m_b}{16\pi^2 m^2_{\tilde{q}}}; \quad \frac{g^2 \langle \tilde{\nu} \rangle^2}{m_{\tilde{\chi}_0}},$$

where $m_\ell, m_{\tilde{q}}$ are the soft masses for sleptons and squarks, respectively and $(m^2_f)_{LR}$ are the mass-squared mixings between left- and right-handed sfermions. We take here for simplicity left- and right-sleptons to be mass eigenstates with the same mass, $m^2_\ell \equiv m^2_{\tilde{e}_L} \simeq m^2_{\tilde{e}_R}$ and similarly for squarks $m^2_{\tilde{q}} \equiv m^2_{\tilde{Q}} \simeq m^2_{\tilde{d}_R}$. It is possible that one of these states is much heavier than the other, which is of less physical interest, so we postpone it for the subsection where we address the realistic situation in the general case. Again the family indices are suppressed. The reason that $\tau$ lepton and bottom quark masses are selected is because they make the dominant contribution to neutrino mass, barring accidental cancellations and fine-tunings. In general, it is difficult to quantify individual contributions due to the possibility of destructive/constructive interference between them. It is instructive to explore the possibility that a particular term dominates the neutrino mass.

- $\lambda$ dominates: here we have the following

  $$\lambda \simeq 10^{-3} \left( \frac{m^2_\ell}{1\text{TeV}} \right) \left( \frac{m_\nu}{0.1\text{eV}} \right)^{1/2} \left( \frac{(m^2_\ell)_{LR}}{(100\text{GeV})^2} \right)^{-1/2}.$$

  If this were the sole source for neutrino mass, it could be considered as appealing radiative seesaw mechanism that produces light neutrinos for moderately small values of the “Yukawa” coupling $\lambda$. From here, one gets roughly a lower bound $\lambda \geq 10^{-4}$. As we will see later, PAMELA forces it to be essentially larger.

- $\lambda'$ dominates: for the last option, we have a similar expression for the $\lambda'$-coupling as $\lambda$ which differs only by a factor $\sim 1/3$ due to the color and $m_b$ in Eq. (2) for the same choice of sfermion mass parameters.

- $\langle \tilde{\nu} \rangle$ dominates: in this case one get a seesaw mechanism for neutrino mass where the usual right-handed neutrino gets traded for a gaugino, such as photino. This implies a mixing between neutrino and gaugino, by analogy of the left-handed and right-handed neutrino mixing in the seesaw.

A. Dark matter: whodunit?

We are now ready to see what the dark matter is. It is clear from the above discussion that none of the neutralinos/sneutrinos can be the dark matter. The size of neutrino mass forces RPV couplings to be non-negligible and thus forces the neutralinos/sneutrinos to decay well within a second. It is worth commenting that the limit on the lightest neutralino/sneutrino lifetime from Big Bang nucleosynthesis is automatically satisfied.

This leaves the gravitino as the only viable candidate for dark matter, since its interactions are suppressed by the Planck scale on top of the neutrino mass suppression. In what follows, we pursue this possibility and study the consequences of gravitino being the lightest supersymmetric particle (LSP).
The supergravity interaction \([21]\) relevant for gravitino decay is
\[
\mathcal{L} = -\frac{1}{\sqrt{2}M_{\text{Pl}}} \left[ \bar{\chi} \gamma^\mu \gamma^\nu D_\nu \phi - \frac{i}{4\sqrt{2}} \bar{\chi} a_{\mu} \gamma^\nu \sigma^{\mu\nu} F^a_{\nu\rho} \right] \psi_\mu + \text{h.c.},
\]
where \(\psi_\mu\) is the gravitino field, \((\chi_L, \phi)\) and \((\lambda^a, F^{a\mu\nu})\) belong to chiral and vector multiplet in the MSSM, respectively. The essential feature of this interaction is that gravitino couples to the supercurrent, just like graviton couples to the energy-momentum tensor. These interactions themselves are clearly not sufficient for gravitino to be able to decay, since they couple it only to heavier super partners. Under the assumption of gravitino being LSP, it can only decay into SM particles and the available channels are those in the Table I. Obviously this requires the R-parity violating interactions of Eq. (1), which are anyway necessary for neutrino masses and mixings.

Gravitino as cold DM

Gravitino Decay Mode

| \(m_{3/2} > m_{h^0}\) | \(h^0 + \nu\) |
| \(m_{3/2} > M_{W^\pm, Z^0}\) | \(Z^0 + \nu, W^\pm + \ell^\pm\) |
| \(m_{3/2} > m_q + m_{q'}\) | \(q + q' + \ell/\nu\) |
| \(m_{3/2} > m_\ell + m_{\ell'}\) | \(\ell^+ + \ell^- + \nu\) |
| \(m_{3/2} < 2m_e\) | \(\gamma + \nu\) |

TABLE I: Possible gravitino decay modes for increasing gravitino mass. \(h^0\) is the SM Higgs boson. More decay channels are open for heavier gravitino mass.

In the well-known case \([3]\) of the largest neutrino mass being dominated by sneutrino VEV, the gravitino decay rate is
\[
\Gamma(\psi_\mu \to \gamma\nu) \simeq \frac{1}{32\pi} \frac{m_\nu m_{3/2}^3}{M_{\text{Pl}}^2} \simeq 10^{-50}\text{GeV} \left( \frac{m_{3/2}}{5\text{GeV}} \right)^3 \left( \frac{1\text{TeV}}{m_{\tilde{\gamma}}} \right),
\]
where \(m_\nu\) stands for the largest neutrino mass, with \(0.03\text{eV} \lesssim m_\nu \lesssim 0.3\text{eV}\). The lower limit comes from atmospheric neutrinos and the upper limit from cosmological considerations \([22]\). This decay has a spectacular signature of monochromatic photons and neutrinos. The non-observation of such signals at Fermi-LAT \([23]\) sets a lower limit on the lifetime of gravitino \(10^{26}\) seconds, or \(\Gamma_{3/2} \lesssim 10^{-50}\) GeV. This in turn would imply \(m_{3/2} \lesssim 5\) GeV.

B. PAMELA and Fermi-LAT versus MSSM: setting the stage

The striking observation of the new cosmic-ray experiments is the substantial excess of the positrons/electrons in the range \(10 - 100\) GeV for PAMELA and up to TeV for Fermi-LAT. If confirmed, this data could be explained by astrophysical sources \([24]\), e.g., pulsars \([25]\). On the other hand, it is also possible that these phenomena are due to the decay or annihilation of dark matter particles. If the latter were to be true, what would it imply for the MSSM? In what follows, we discuss the answer to this important question, by pursuing the scenario of gravitino dark matter which immediately requires its mass to be above a few hundred GeV or so. This then clearly eliminates the possibility of sneutrino VEV, discussed above, being a dominant source of neutrino mass. Another important information from PAMELA
is the simultaneous lack of antiprotons excess. *Whoever the culprit is, it must be leptophilic.*

This uniquely select the $\lambda$-term in Eq. (1) as the main source of gravitino decay [11].

The usual problem of the MSSM, when it comes to discussing and presenting the results is the proliferation of its parameters. In order to ease the reader’s pain, we discuss first a simplified situation where $\lambda'$ coupling is simply set to zero. The result of heavy sleptons will be shown to remain valid in the general case presented in the next sub-section. Furthermore, for the sake of illustration and simplicity, we take an imaginary situation of a single $\lambda$ coupling (say $\lambda = \lambda_{133}$, the corresponding $[(m_\ell^2)_{LR}]_{33} \neq 0$, and all the other elements vanishing). We will comment on the general case in Subsection II C.

In this case the neutrino mass is given by

$$m_\nu \simeq \frac{\lambda^2 (m_\ell^2)_{LR} m_\tau}{16\pi^2 m_\ell^2}.$$  (8)

The crucial thing to notice is that the gravitino decay can result only from dimension 6 or 7 effective interactions. The essential point is that in supergravity the gravitino is coupled to the supercurrent which is diagonalized simultaneously with the Kähler potential. These effective operators are obtained by integrating the sfermions out, and as such are necessarily suppressed by the sfermion masses $^1$. The simple physical reasoning is confirmed by explicit computations which we leave for the Appendix.

Now we list the main two- and three-body decay modes that are induced by the leptophilic $\lambda$ coupling. The two-body decay rates are computed in the Appendix with the following results (we discuss the photon modes separately)

$$\Gamma_2(\psi_\mu \to W^\pm \ell^\mp) \simeq \frac{g^2 \lambda^2}{18432 \pi^5} \frac{(m_\ell^2)_{LR} m_\tau^2}{m_\ell^4 M_{Pl}^2},$$  (9)

$$\Gamma_2(\psi_\mu \to Z^0 \nu) \simeq \frac{1}{2 \cos^2 \theta_W} \Gamma_2(\psi_\mu \to W^\pm \ell^\mp),$$

$$\Gamma_2(\psi_\mu \to h^0 \nu) \simeq \frac{m_{3/2}^2}{864 M_W^2} \Gamma_2(\psi_\mu \to W^\pm \ell^\mp),$$

where $g$ is the $SU(2)_L$ gauge coupling and $\theta_W$ is the weak mixing angle. In order to explain the PAMELA data, gravitino must weigh more than about 300 GeV, which allows us to safely ignore the final state masses. The partial decay width $\Gamma_2(\psi_\mu \to h^0 \nu)$ is somewhat suppressed compared to $\Gamma_2(\psi_\mu \to W^\pm \ell^\mp)$ or $\Gamma_2(\psi_\mu \to Z^0 \nu)$, for $m_{3/2} \lesssim 1$ TeV. Hereafter, we will call $\Gamma_2$ the sum of the three partial decay rates in Eq. (9).

Notice the leptophilic nature of the $\lambda$ coupling is not sufficient to suppress the antiprotons, since $W$ and $Z$ bosons decay preferentially into hadrons. These decays must be suppressed, as much as the decays induced by $\lambda'$ (see below).

The three-body decay is given by $^2$

$$\Gamma_3(\psi_\mu \to \ell^+ \ell^- \nu) = \frac{\lambda^2}{18432 \pi^5} \frac{m_{3/2}^4 m_\tau^3}{m_\ell^4 M_{Pl}^2}. $$  (10)

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1 Here we disagree with the Ref. [26]. This leads also to the different power of the gravitino mass dependence of the two-body decay. See the Appendix for more details.

2 Notice miraculously the same coefficient as in the two-body decay.
Once again, according to PAMELA and Fermi-LAT, this decay channel must be the dominant one. We can see, at least qualitatively, that either the sleptons must be heavy or $\lambda$ is forced to be small; however a small $\lambda$ suppresses neutrino mass. We quantify this now, with the result of slepton mass lying in the $10^2 - 10^6$ TeV.

We list here our criteria to fit neutrino mass and PAMELA and/or Fermi-LAT with gravitino decays, while keeping the theory perturbative.

\[
0.03 \text{ eV} \lesssim m_{\nu} \lesssim 0.3 \text{ eV} \quad (\nu \text{ mass}) ,
\]
\[
10^{-51} \text{ GeV} \lesssim \Gamma_3 \lesssim 10^{-49} \text{ GeV} \quad (\text{PAMELA/Fermi-LAT}) ,
\]
\[
\Gamma_2 \lesssim \Gamma_3/10 \quad (\text{leptophilic DM}) ,
\]
\[
\lambda^2 \lesssim 4\pi \quad (\text{perturbativity bound}) .
\]

In view of the $\lambda$ induced three-body decay being dominant, we may safely take hereafter for the total gravitino decay rate: $\Gamma_3/2 \simeq \Gamma_3$. The reader should not be confused by our notation since we will freely interchange the above decay rates when we speak of gravitino decay.

It is a simple exercise to derive a lower bound on the slepton masses using Eqs. (8) – (10) and our criteria Eq. (11)

\[
m_\tilde{\ell} \gtrsim 600 \text{ TeV} \left(\frac{m_{3/2}}{400 \text{ GeV}}\right)^{5/2} \left(\frac{m_{\nu}}{0.1 \text{ eV}}\right)^{1/2} \left(\frac{\Gamma_3}{10^{-51} \text{ GeV}}\right)^{-1/2} .
\]

The above formula is obtained by omitting the Higgs channel in the two-body gravitino decay, which is a good approximation for gravitino mass roughly below TeV. Even for gravitino mass as large as around 3 TeV, which we take later for fitting Fermi-LAT, the correction will be only about 20%.

We normalize $\Gamma_3$ to its largest value in order to guarantee the lower limit on the slepton masses. From Eq. (10), this also implies a lower bound on $\lambda$. At the same time, there is an upper limit on $\lambda$ from the requirement of perturbativity, which when needed, we take as $\lambda^2 \lesssim 4\pi$. To be as complete as possible, we leave it free in the formulas below. In this manner, one can also obtain an upper bound on the slepton masses from the three-body decay rate Eq. (10),

\[
m_\tilde{\ell} \lesssim 10^4 \text{ TeV} \left(\frac{\lambda_{\text{max}}^2}{4\pi}\right)^{1/4} \left(\frac{m_{3/2}}{400 \text{ GeV}}\right)^{7/4} \left(\frac{\Gamma_3}{10^{-51} \text{ GeV}}\right)^{-1/4} .
\]

Since now we are interested in the upper limit on slepton masses, we must clearly normalize $\Gamma_3$ to its lowest allowed value for the sake of PAMELA.

The result of the above limits turns out to be a relatively small range of slepton masses, completely out of LHC reach. Notice that the region gets narrower as the gravitino mass increases.

Similarly, one can obtain an upper bound on the gravitino mass which depends only on its decay rate and the neutrino mass

\[
\left(\frac{m_{3/2}}{3.0 \text{ TeV}}\right) \left[0.5 + 0.5 \left(\frac{m_{3/2}}{3.0 \text{ TeV}}\right)^2\right]^{1/3} \lesssim \left(\frac{\lambda^2}{4\pi}\right)^{1/3} \left(\frac{\Gamma_3}{10^{-49} \text{ GeV}}\right)^{1/3} \left(\frac{m_{\nu}}{0.1 \text{ eV}}\right)^{-2/3} .
\]

The high-energy data of Fermi-LAT require the gravitino mass bigger than 2 TeV. We find below that the three-body gravitino decay fit of these data works optimally with $m_{3/2} =$
3.3 TeV. This points immediately to the necessarily large $\lambda$ coupling and the possible tension with perturbativity. For example

$$\frac{\lambda^2}{(4\pi)} \gtrsim \{0.14, 1.5, 14\} \text{ for } m_\nu = \{0.03, 0.1, 0.3\} \text{ eV} .$$  \hspace{1cm} (15)$$

Clearly, the perturbativity requirement favors hierarchical neutrino mass spectrum, and the degenerate spectrum could actually invalidate the gravitino decay as an explanation of the Fermi-LAT data within the perturbative MSSM. Of course, we are interested in as small values of $m_{3/2}$ as possible for the sake of experiment. Recall that the gravitino is assumed here to be an LSP and heavy gravitino, although perfectly acceptable, means no supersymmetry at colliders such as the LHC. It is interesting that at the same time, the gravitino decay solution to the electron/positron excesses in the cosmic rays favors the light gravitino.

From Eq. (15), one obtains the upper bound on gravitino mass $m_{3/2} \lesssim 6.6 \text{ TeV}$ by requiring $\frac{\lambda^2}{(4\pi)} \lesssim 1$ and by choosing $m_\nu = 0.03 \text{ eV}$. In turn, one gets the upper limit on the slepton mass $m_\tilde{\ell} \lesssim 10^6 \text{ TeV}$ form Eq. (13).

- Let us turn our attention to PAMELA first and ignore Fermi-LAT for the time being. We use the decay modes $\psi_\mu \to \ell^+ \ell^- \nu$ to fit the PAMELA observation of positron spectrum. In the left-panel of Fig. 1, we show the allowed region in the $\lambda - m_\tilde{\ell}$ plane. By choosing the gravitino mass to be 400 GeV, the PAMELA data confine the slepton masses to the range from 560 TeV to $1.7 \times 10^4$ TeV. This agrees well with our previous estimates in Eqs. (12) and (13).

If the neutrino spectrum were to be determined, or if at least we were to know the largest neutrino mass, the slepton masses would be directly correlated with the $\lambda$ coupling. In the Fig. 2 we give this dependence with $m_{3/2} = 400 \text{ GeV}$ value for PAMELA, indicated by a blue line. The different color shaded regions below the red band are forbidden for different values of neutrino mass, indicated inside the corresponding regions.

- Our fit for PAMELA data is shown in Fig. 3. We choose $m_{3/2} = 400 \text{ GeV}$ and $\tau_{3/2} = 2.3 \times 10^{30} \text{ sec}$ ($\Gamma_{3/2} = 0.3 \times 10^{-50} \text{ GeV}$). The best fit fixes the ratio $m_\tilde{\ell}^2/\lambda \simeq 1.3 \times 10^7 \text{ TeV}^2$. The leptons in final states of gravitino decay are taken to be electrons\(^3\). We have adopted the solution to the positron transportation equation from Ref. [28], and the parametrizations of the electron/positron background of Ref. [29] [30].

- It is also useful to look into the available $m_\tilde{\ell} - m_{3/2}$ plane as Fig. 4, instead of the $\lambda - m_\tilde{\ell}$ plane used so far. Notice the upper bound on the gravitino mass as discussed above.

- Next, we consider the possibility of interpreting both PAMELA and Fermi-LAT simultaneously. For decaying gravitino dark matter, Fermi-LAT data generally requires its mass to be greater than $2 - 3 \text{ TeV}$. Taking into account the same constraints as the PAMELA case discussed before, we find the sleptons even heavier, more than

\(^3\) This fit is similar to the one in Ref. [11], who however assumed the slepton mass to be in the TeV region. The issue of course is the implication for the neutrino mass, which pushes the sleptons to be much heavier.
4.5 \times 10^4 \text{ TeV} as shown in the right-panel of Fig. 1. With such heavy sleptons, all the LFV constraints become irrelevant.

In Fig. 5, we fit both PAMELA positron and Fermi-LAT positron/electron excesses using a 3.3 TeV gravitino mass. We take the gravitino lifetime $\tau_{3/2} = 5 \times 10^{25}\text{sec}$ ($\Gamma_{3/2} = 1.4 \times 10^{-50}\text{ GeV}$). The best fit fixes now the ratio $m_{\tilde{\ell}}^2/\lambda \simeq 10^{10}\text{ TeV}^2$. To guarantee the soft electron/positron spectrum observed, we demand only 10% of the final lepton states from primary gravitino decay are electrons [31]. We took the heaviest neutrino mass of 0.03 eV, i.e. the hierarchical neutrino spectrum, while the inequality $\Gamma_{3/2} \lesssim \Gamma_{3}/10$ is saturated. Taking the neutrino mass degenerate endangers the perturbativity as we discussed at length. Notice that in this simple picture, the more precise experiments with a precision improved by an order of magnitude, would have to see the excess of antiprotons too.
FIG. 2: (colored online) $\lambda -$ slepton mass dependence for $m_{3/2} = 400$ GeV and $\tau_{3/2} = 0.65 \times 10^{26}$ sec ($\Gamma_{3/2} = 10^{-50}$ GeV), for different values of neutrino mass. The three colored areas denote the forbidden parameter spaces.

FIG. 3: (colored online) The fit for the PAMELA positron excess using the three-body gravitino decay; with $m_{3/2} = 400$ GeV, $\tau_{3/2} = 2.3 \times 10^{26}$ sec ($\Gamma_{3/2} = 0.3 \times 10^{-50}$ GeV) and neutrino mass 0.2 eV. The red dots represent the data, the blue solid curve is our fit whereas the dotted black curve is the expected theoretical background. The discrepancy between the data and the theoretical prediction at low energies is commonly explained by the solar modulations.

C. Towards the general case

1. Splitting $m_{\tilde{L}}$ and $m_{\tilde{e}}$

For simplicity, we took above $m_{\tilde{L}} \simeq m_{\tilde{e}}$ and we learned that the two sleptons must be quite heavy. Let us relax this assumption and denote by $m_L$ and $m_H$ the small and large slepton masses (we treat the left- and right- slepton mixing mass $(m_{\tilde{\ell}})^2_{LR}$ as a perturbation).

Since we know the result when the masses are similar, it is worthwhile investigating only
FIG. 4: (colored online) The allowed region (white) in the $m_\tilde{\ell} - m_{3/2}$ parameter space. The red and green regions are excluded by Eq. (12) and Eq. (13), respectively, due to PAMELA. The region where the gravitino is lighter than 300 GeV is also ruled out. One can see that the LFV process $\text{Br}(\mu \to 3e)$ is safely small for the allowed region.

FIG. 5: (colored online) The three-body gravitino decay is used to fit both PAMELA and Fermi-LAT electron/positron, with $m_{3/2} = 3.3$ TeV, $\tau_{3/2} = 5 \times 10^{25}\text{sec}$ ($\Gamma_{3/2} = 1.4 \times 10^{-50}$ GeV) and neutrino mass 0.03 eV. The red dots represent the data, the blue solid curve is our fit whereas the dotted black curve is the expected theoretical background. To guarantee the soft spectrum, we demand only ten percent of the final lepton states are electrons.

the case when they are widely split, $m_H \gg m_L$. It is easy to see that all the above formulas go through, modulo the following changes.

$$m_\tilde{\ell}^2 \to m_L^2$$
$$\langle m_\tilde{\ell}^2\rangle_{LR} \to r\langle m_L^2\rangle_{LR}$$

(16)

where $r \simeq (m_L/m_H)^2 \ln(m_L/m_H)^2$. In turn, the bounds on $m_\tilde{\ell}$ become the bounds on $m_L$. 

The lower limit on $r$ emerges from the requirement that neutrino mass be large enough, $m_\nu \gtrsim 0.03$ eV. Barring cancellations, one gets $r \gtrsim 10^{-7}$. In other words, one of the two sleptons can be 3-4 orders of magnitude heavier than the other. We have assumed here that the lighter slepton is not fine-tuned to decouple; we discuss this possibility in Subsection [II C 4].

2. $\lambda$ with family indices

Before discussing the general case, let us comment on the multi-generation situation with $\lambda$ couplings. This is quite involved and basically impossible to have a simple conclusion. As such, it is beyond the scope of this paper. Up to now, we have imagined a situation with a single coupling, an extreme simplification. Another extreme possibility is the situation when all elements in $\lambda$ matrix are equal in magnitude, i.e., $\lambda_{ijk} = \lambda$ for all the nine complex elements in the physical basis.

The neutrino mass matrix and the two-body gravitino decays depend also directly on the mixings between left and right sleptons, and in principle, the end result may be similar to the simplified case with a single coupling. The three-body decay is more sensitive to the generation structure, because the final states contribute democratically. Assuming for example, universal soft masses for the sleptons, one simply obtains an enhancement of factor of nine in the total decay rate. Due to the quartic dependence on the slepton masses, even this extreme case has a minor impact on the conclusion for the single $\lambda$ case.

Clearly, barring cancellations, a generic case lies between these two opposite cases. In short, our result of heavy sleptons goes unchanged, except for a possibility of fine-tuning one of the slepton masses which we discuss in the end of this section.

3. $\lambda'$ and the fate of squarks

In the previous subsections, we have simplified the discussion by choosing $\lambda$ couplings to be the only non-vanishing ones. The motivation was the leptophilic nature of PAMELA and Fermi-LAT data, which prefers the $\lambda'$ couplings to be relatively small.

$$\lambda' \lesssim \lambda'^{\text{max}} = 4.5 \times 10^{-8} \left( \frac{m_{\tilde{q}}}{1 \text{ TeV}} \right)^2 \left( \frac{m_3/2}{400 \text{ GeV}} \right)^{-7/2},$$  \hspace{1cm} (17)

where we used the bound $\Gamma_3 \lesssim 10^{-49}$ GeV employed throughout this paper, and we demand that the hadronic gravitino partial decay rate be smaller by an order of magnitude.

However, they may still contribute to neutrino mass, in which case the main result remains unchanged: the sleptons must be heavy as before. If $\lambda'$ couplings are non negligible, the squarks also end up being heavy, for the same reason as Eq. (12).

Needless to say, the limit on squark masses depends on the degree of the $\lambda'$ contribution to the neutrino mass matrix. On pure phenomenological grounds, squark masses are completely free.

4. On a possibility of having a light slepton(s)

So far in the discussion, we have suppressed the flavor indices or assumed democratic matrix elements of $\lambda_{ijk}$. The question then arises whether there is a loophole in our argument,
i.e., whether one can adjust the parameters to make one (or more) slepton light (in TeV scale) in the general multi-generation case. This could happen for example if a slepton (or more than one) has vanishing RPV couplings in the physical basis. Although unlikely, this seems to us perfectly acceptable; and in all fairness we cannot claim that all sleptons are necessarily heavy as in the above warm-up examples. In general, to decrease the mass of a slepton $\tilde{\ell}_1$, one must also decrease its RPV couplings $\lambda_1$ in a manner that the ratio $\lambda_1/m_{\tilde{\ell}_1}^2$ does not get enhanced. This will guarantee the gravitino decay rate and neutrino masses do not receive too large contribution from $\tilde{\ell}_1$. From this requirement, using the gravitino decay rate given in Eq. (10), we have the following upper bound

$$\lambda_1 \lesssim \lambda_1^{\text{max}} = 4.5 \times 10^{-7} \left( \frac{m_{\tilde{\ell}_1}}{1 \text{ TeV}} \right)^2 \left( \frac{m_{3/2}}{400 \text{ GeV}} \right)^{-7/2},$$

where we again used the bound $\Gamma_3 \lesssim 10^{-49} \text{ GeV}$.

The fact that the light slepton (almost) decouples from RPV ensures the suppression of its contribution to the LFV processes through RPV. However, this does not prove the absence of LFV, since it can always take place through the usual soft supersymmetric breaking, which in general arises from different mixings in the sfermion and fermion sectors. The reader probably dislikes this fine-tuned possibility as much as we do, and it is fair to say that one expects the sleptons to be heavy. This was behind our statement in the introduction that PAMELA and Fermi-LAT imply heavy sleptons, barring fine-tuned cancellations. In a sense, this could be viewed as a blessing, since the flavor problem in supersymmetry is one of its weakest points and heavy sfermions automatically take care of this. We interpret our results as an argument in support of moderately split supersymmetry.

This said, we should also recall the main motivation for low energy supersymmetry: the hierarchy problem. A heavy slepton aligned mostly in a stau direction upsets mildly the Higgs mass naturalness, and so it could be appealing that this particle be light. The sleptons aligned in the smuon and selectron direction are clearly allowed to have masses on the order of $10^2 - 10^4$ TeV without upsetting the tree-level stability of the Higgs mass.

III. PHENOMENOLOGICAL AND COSMOLOGICAL IMPLICATIONS

Here we comment on salient features regarding various collider, flavour violation and cosmological phenomena that are special to gravitino decay being behind PAMELA and/or Fermi-LAT.

A. LHC signatures

As we have shown, both PAMELA and Fermi-LAT can be explained via gravitino decay, as long as the gravitino is heavier than about several TeV. In this case, clearly no collider physics will emerge in near future.

Phenomenologically, a more interesting scenario is to have gravitino behind PAMELA only, in which case, the gravitino mass can be as low as several hundred GeV. Except for heavy sleptons, if gravitino were to be this light, the rest of superpartners could be observable at the LHC. It is then important to study possible signatures of the NLSP. There are a number of NLSP candidates that we discuss in the following.
Gaugino as the NSLP. First, we consider the case where the NLSP is mainly of wino/bino–type. In the presence of the R-parity violating terms, the NLSP decays to three leptons at tree level very much like gravitino decay. When three-body decay channel dominates over that of the two-body, one can express the decay width in terms of gravitino decay rate as follows

$$\Gamma_{\text{NLSP}}(\tilde{\chi}_1^0 \rightarrow \ell^+ \ell^- \nu) = \frac{g^2 \lambda^2}{3072 \pi^3} \frac{m_{\text{NLSP}}^5}{m_{\tilde{\ell}}^2} = \frac{6g^2 M_{Pl}^2 m_{\text{NLSP}}^5}{m_{3/2}} \Gamma_{3/2}. \quad (19)$$

The squark exchange contribution is similarly subdominant as for the gravitino decay. If we fit PAMELA only, with $m_{3/2} = 400 \text{ GeV}$ and $\Gamma_{3/2} = 10^{-50} \text{ GeV}$, one obtains the NLSP lifetime

$$\tau_{\tilde{\chi}_1^0} \simeq 10^{-7} \text{sec} \left( \frac{m_{\text{NLSP}}}{600 \text{ GeV}} \right)^{-5}, \quad (20)$$

which corresponds to the decay length at the LHC $d_{\text{NLSP}} \simeq 30 \text{ m}$ for $m_{\text{NLSP}} = 450 - 600 \text{ GeV}$. We can see that the decay length of the bino/wino NLSP is generically rather long. Still, once produced at the LHC, a sizable amount of these particles appears to decay inside the detector [13], producing highly-ionizing charged tracks (if the NLSP is charged wino, it has similar decay rate) with multi-lepton final states.

Although the above expression is written with a single, generic coupling, it is valid in a general situation with arbitrary RPV couplings, for the same couplings enter in the LSP (gravitino) and NLSP three-body decays. It is a solid prediction of the MSSM being behind PAMELA.

In the less-likely scenario that the gluino be the NLSP, it would have to decay through $\lambda'$, by the analogy with the above wino/bino decay. The point is that the gluino must decay before BBN, and the Planck suppressed decay into a gravitino is too slow. This leads immediately to a lower limit on $\lambda'$

$$\lambda' \gtrsim \lambda'^{\text{min}} = 1.28 \times 10^{-11} \left( \frac{m_{\tilde{g}}}{1 \text{ TeV}} \right)^2 \left( \frac{m_{\text{NLSP}}}{600 \text{ GeV}} \right)^{-7/2}. \quad (21)$$

Light slepton as the NLSP. As discussed in the previous section, there is also the possibility of a light slepton. However, this does not upset the above prediction if the NLSP is still gaugino type, since the light slepton has to (almost) decouple from RPV coupling. It is interesting to consider the possibility of the light slepton being the NLSP. From Eq. (18), we obtain an upper bound on its two-body decay rate

$$\Gamma_{\text{NLSP}}(\tilde{\ell}_1 \rightarrow \ell_j \ell_k) = \frac{\lambda_1^2 m_{\text{NLSP}}}{8\pi} \lesssim 6 \times 10^{-13} \text{GeV} \left( \frac{m_{\text{NLSP}}}{600 \text{ GeV}} \right)^5 \left( \frac{m_{3/2}}{400 \text{ GeV}} \right)^{-7}. \quad (22)$$

At the LHC, the slepton NLSP has to be pair produced. For the charged one, there would be a displaced vertex and/or a heavily-ionizing charged track (for sufficient small RPV couplings) with di-leptons plus missing energy, whereas for sneutrino NLSP, one would see two charged leptons in the final states.

We also consider an extreme case when the slepton NLSP completely decouples from direct RPV violation in the physical basis, i.e., $\lambda_1 = 0$. Then it can only decay to four-lepton
final states through a virtual gaugino $\tilde{\chi}_1$, and a virtual heavy slepton $\tilde{\ell}_2$ which possesses RPV couplings, as shown in Fig. 6. We estimate its decay rate

$$
\Gamma_{\text{NLSP}}(\tilde{\ell}_1^{-} \rightarrow \ell^{-}\ell^{+}\nu) \simeq \frac{g^4 \lambda^2}{10^5 \pi^5} \left( \frac{m_{\text{NLSP}}}{m_{\tilde{\chi}_1} m_{\tilde{\ell}}} \right)^4 \simeq 10^{-3} \frac{M_{\text{Pl}}^2}{m_{\tilde{\chi}_1}} \left( \frac{m_{\text{NLSP}}}{m_{3/2}} \right)^7 \Gamma_{3/2} .
$$

Choosing $m_{3/2} = 400$ GeV and $\Gamma_{3/2} = 10^{-50}$ GeV, one obtains

$$
\tau_{\text{NLSP}} \simeq 10^{-3} \sec \left( \frac{m_{\text{NLSP}}}{600 \text{ GeV}} \right)^{-7} \left( \frac{m_{\tilde{\chi}_1}}{1 \text{ TeV}} \right)^2 .
$$

In this case, the NLSP would decay outside the detector.

### B. Flavor violation

As we have seen, the size of the R-parity breaking couplings (called generically $\lambda$) can be as large as $\mathcal{O}(1)$. Therefore, one needs to examine lepton flavor violating (LFV) processes. The most stringent constraint comes from the decay $\mu \rightarrow 3e$ which is induced by the $\lambda$ coupling at tree level. Its branching ratio is given by

$$
\text{B}(\mu \rightarrow 3e) \simeq \left( \frac{\lambda}{g} \right)^4 \left( \frac{M_W}{m_{\tilde{\ell}}} \right)^4 .
$$

It is worth noting that at least two non-zero elements of the $\lambda$ matrix are necessary for this decay. Here we just assume they are equal to the one responsible for gravitino decay. We find thus that the allowed region predicts very tiny $\mu \rightarrow 3e$ branching ratio ($\lesssim 10^{-16}$), as indicated in Fig. 1. The branching ratio is clearly too small to be probed in near future. The other LFV processes such as $\mu \rightarrow e\gamma$ and $\mu \rightarrow e$ conversion take place only at the loop level and are even more suppressed.

This is certainly true if the slepton masses are roughly universal in size, a natural expectation. However, as we discussed above, one (or more) sleptons can be made light by an artificial cancellation and thus can lead to LFV as in the conventional picture of low energy supersymmetry.

On the other hand, the squarks can be light, in which case the smallness of quark flavor violation would remain as a mystery.
C. Baryogenesis

One may ask whether our findings are in accord with baryogenesis in the MSSM. Clearly, gravitino behind PAMELA eliminates the electro-weak baryogenesis, for then the stop is too heavy to allow for a necessary first-order phase transition. In the MSSM defined the way we did, there is no room for the leptogenesis, but then we cannot pretend to know the physics at very high energies. In any case, even if leptogenesis takes place, or any primordial lepton number were to exist, the large L-number violating $\lambda$ couplings would definitely erase it. This is not a problem, since there is the appealing Affleck-Dine mechanism [3] which utilizes the baryon and lepton number violating flat (or almost flat) directions as inflatons [4]. This then leads to a baryon and lepton number asymmetric universe. Again, it is the baryon number that would survive today, which makes the $u^c d^c d^c$ direction preferable.

IV. THE MESSAGE TO TAKE HOME

The great virtues of the MSSM are often stressed: the stabilization of the gauge hierarchy, the prediction of the unification of gauge couplings, the connection of the Higgs and the stop mass, the radiative Higgs mechanism. Its main problem is that the parameter space of the MSSM is so big that it is really a collection of theories. The truth is that we know nothing about the supersymmetry breaking and the phenomenology of the MSSM ought to be done in its proper parameter space, unless one wishes to give only some benchmarks when say discussing the possibilities at LHC.

The main point of taking the MSSM seriously as a theory of neutrino mass is that the gravitino is the only particle stable enough to be the dark matter candidate. What happens then if one asks that the PAMELA data be explained by the dark matter? This subject is at the heart of our study reported here and the results are the following.

- Barring fine-tunings, the sleptons are heavy, with their masses lying between 500 and $10^6$ TeV. This naturally suppresses all LFV, normally a major issue in the MSSM. With the masses close to the lower end, the gauge hierarchy is barely destabilized.

- There is no limit whatsoever on the squark masses. If the squarks were to play, though, an important role in generating the neutrino masses, the leptophilic nature of gravitino decay would imply them to be heavy. This would explain in turn a mystery of small QFV. The resulting picture could then be a moderately split supersymmetry.

- The theory can also reproduce the Fermi-LAT data with the gravitino mass around 3 TeV, but there is a potential conflict with the perturbativity. We find it quite interesting that the calculability of the MSSM points towards smaller gravitino mass, which is appealing from the experimental point of view. The heavy gravitino explanation of Fermi-LAT would completely kill the hope for the MSSM to be the theory relevant for the LHC.

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Appendix: Effective Operators for Gravitino Decay

In this appendix, we explicitly present our results on all relevant operators for gravitino decays.

First, the dimension seven operators relevant for gravitino three-body decay is

\[ L_{\text{eff}} = \frac{\lambda}{\sqrt{2}M_{\text{Pl}} m_{\tilde{\ell}}^2} \left[ (\bar{\ell} \gamma_\mu \gamma_\nu \psi_\mu) (\bar{\ell} P_L e) + (\bar{e} \gamma_\mu \gamma_\nu \psi_\mu) (\bar{\ell} P_L \ell) \right] + \text{h.c.} , \]  

where we have suppressed the flavor indices in \( \lambda \)-coupling as well as the final-state leptons. The above effective interaction is obtained by integrating out the heavy sleptons exchanged, and here it is assumed all the sleptons have universal mass, i.e., \( m_{\tilde{\ell}}^2 \equiv m_{\tilde{\ell} L}^2 \simeq m_{\tilde{\ell} c}^2 \).

Second, the two-body decays are induced by the following dimension six operators\(^4\)

\[ L_{\text{vertex}} = \frac{\kappa}{6M_{\text{Pl}}} \left[ (g/\sqrt{2}) i \bar{\Psi} P_R \gamma_\alpha \sigma_{\mu\nu} \psi_\alpha W_3^{\mu\nu} - (g'/\sqrt{2}) i \bar{\Psi} P_R \gamma_\alpha \sigma_{\mu\nu} \psi_\alpha B^{\mu\nu} \right] + \text{h.c.} , \]  

where

\[ \kappa = \frac{\lambda (m_{\tilde{\ell}}^2)_{LR}}{16\pi^2 m_{\tilde{\ell}}^2} , \]  

which are obtained by explicit one-loop calculations of the diagrams listed in Fig. 9. In \( L_{\text{vertex}} \), only vertex corrections to the effective dimension six operators are included. There

\(^4\) We call them dimension six because they necessarily involves the Higgs field. This is hidden in \( (m_{\tilde{\ell}}^2)_{LR} \) which is proportional to the Higgs VEV.
are also contributions to the gravitino two-body decays through the gaugino-lepton mixing as shown in Fig. 8.

\[
L_{\text{eff}}^{\text{gaugino}} = \frac{i}{8M_{\text{Pl}}} \left[ U_{\tilde{W}_{3\mu}} \overline{P}P R\gamma_{\mu} \sigma_{\mu\nu} \psi^0 \sigma^\alpha W_{3\nu}^{\mu\nu} + U_{\tilde{B}_{3\nu}} \overline{P}P R\gamma_{\nu} \sigma_{\mu\nu} \psi^0 \sigma^\alpha B_{\mu\nu}^{\nu} + U_{\tilde{W}_{\ell}} \overline{P}P R\gamma_{\mu} \sigma_{\mu\nu} \psi^0 \sigma^\alpha W^{\nu\mu} \right],
\]

where the lepton-gaugino mixings \( U_{\tilde{W}_{3\mu}}, U_{\tilde{B}_{3\nu}}, U_{\tilde{W}_{\ell}} \) and so are the corresponding decay amplitudes, are always suppressed by the ratio of lepton mass to the gaugino mass, compared to the vertex corrections in Eq. (27).

Third, for the sake of completeness, we also calculate the decay rate of gravitino to the lightest Higgs boson plus a neutrino, induced by \( \lambda \). The corresponding Feynman diagrams are shown as the last two figures in Fig. 8. After integrating out the heavy sleptons, assuming their masses are universal (and heavy), we obtain the effective Lagrangian

\[
L_{\text{eff}}^{\text{Higgs–vertex}} = \frac{m_3/2[(m_{\tilde{\ell}}^2)_{LR}/v]}{18 \times (16\pi^2)M_{\text{Pl}} m_{\tilde{\ell}}^2} \overline{P}P R\gamma^\mu \gamma^\nu \psi_{\mu} D_{\nu} h^0 + h.c.,
\]

and the partial decay rate

\[
\Gamma_2(\psi_{\mu} \rightarrow h^0 \nu) = \frac{g^2 \lambda^2}{62208 \pi} \left[ \frac{(m_{\tilde{\ell}}^2)_{LR}}{m_{\tilde{\ell}}^2} \right]^2 \frac{m_3^3}{3/2} m_{\tilde{\ell}}^2 \left( 1 - \frac{m_{h^0}^2}{m_{3/2}^2} \right)^4.
\]

(31)
FIG. 9: Two-body gravitino decays through loops. Here the symbol $\otimes$ on the external Higgs fields are taken as the vacuum expectation values. The black boxes represent RPV couplings.

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