Multimessenger analysis of gravitino dark matter considering trilinear couplings to standard model particles

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Abstract. The flux of charged leptons measured by the space-based detectors PAMELA, AMS-02, CALET, DAMPE and Fermi-LAT presents anomalous behavior as energy increase. In particular AMS-02 observations provide compelling evidence for a new source of positrons and electrons. Its origin is still unknown, but standard and successful scenarios include the contribution of dark matter and missing astrophysical sources. It has been exposed that the dark matter scenario alone require some attention since the agreement with current data is still unclear. On the other hand, astrophysical candidates has shown good performance to solve the data but these ideas are still under scrutiny. In general, a mixture of sources would signal a good approach for future research. However, before going deeply on that direction, in this work we would like to present a dark matter scenario that is able to solve the current data alone and also offer some connections to other observables, such as neutrino physics. These results may serve as probe of concept for the dark matter possibility alone and a good motivation for future mixed searches.

Keywords: dark matter experiments, cosmic ray experiments, gamma ray experiments, dark matter theory

1 Introduction

The continuous and systematic analysis of the data collected by cosmic-ray detectors is one of the most direct and accepted ways to check and test the predictions of particle physics models that contain a candidate for dark matter which is meta-stable. The slow but acceptable decay rate of dark matter particles indeed can produce relevant fluxes of leptons, photons and heavy elements that can contribute to the number and features of detected events in current and future experiments.

Furthermore, this discussion becomes specially relevant since contemporary experiments show the presence of persistent and striking anomalies concerning the detection of cosmic-rays. For instance, the energy spectrum of electrons and positrons measured by experiments such as AMS-02, CALET, DAMPE and Fermi-LAT [] show noticeable discrepancies when compared to standard predictions. Here, we may explain the main features of these standard models or we could have a short section for that. Therefore, these experimental signals strongly suggest that extra sources of (primary) positrons are required in order to make sense of the data.

From a revision of the latest literature concerning this subject we can conclude that the source of the charged lepton excess in general could be given by a mixture of dark matter and currently unresolved astrophysical sources, such as pulsars. Here, we may add some description of previous literature or just relevant references or we could discuss it in a short sections. Although we agree that future efforts should consider this mixture as working hypothesis, here we would like to re-consider the dark matter only solution. The discussion concerning the potential presence of unresolved pulsars or other astrophysical sources is just considered for a later work, which should definitely include more observables.

Specifically, we consider a super-symmetric scenario with a low energy spectrum characterized by a gravitino as the lightest supersymmetric particle, which is able to decay to standard model particles only through trilinear leptonic R-parity violating couplings. This scenario can be compatible with the measurements of the large hadron collider by requiring a susy scale above 4-5 TeV, which is clearly unpleasant from a perspective that consider naturalness and other formal requirements as very relevant parts of the full theory but effectively viable from a phenomenological point of view given the freedom on the definition of susy parameters. This dark matter scenario is able to solve the astrophysical data considered in this work without the requirement of extra sources. We consider this solution a probe of concept concerning dark matter as an explanation of cosmic ray anomalies and a motivation to consider this particular scenario for the search of more realistic solutions that may include other astrophysical objects.

The paper is organized as follows, in the first section we discuss the data from different cosmic ray detectors that motivate and constrain the ideas about dark matter that we are supporting in this work. In the second section we discuss some general issues about the existing attempts to solve the anomalies in the data concerning charged leptons in a consistent way with the measurements of gamma-rays. In the third section we introduce our model of dark matter, including a review of allowed decay channels, emphasizing the particular aspects that we exploit in our analysis. In the fourth section we present the results of our statistical analysis and consequences. Then we conclude and propose some venues to give a step forward on this kind of analysis.

2 Data exploration

In this work we consider the recent data released by AMS-02, CALET, DAMPE and Fermi-LAT collaborations. In particular we use the energy spectrum of electrons, positrons and the sum of both collected by AMS-02, the spectrum for the sum of electrons and positrons found by CALET and DAMPE, and the EGB spectrum derived from Fermi-LAT data.

3 Dark matter and astrophysical explanations

In the existing and abundant literature considering dark matter as the explanation of the charged lepton anomaly we need some updated references here, it is quite common to find caution words and indications about tough bounds affecting these models that can be derived from the measurement of the EGB. In general it could be say that there exist a clear tension between these observables since the required flux of charged leptons produces an abundant and sometimes dangerous level of gamma-rays. Although this itself may deserve a systematic review, here we only want to call the attention about a couple of references, to show some extremal cases that illustrate the situation and in order to motivate our particular scenario.

For instance, in [**?**] the EGB signal is used only as an upper limit for the contribution from gravitino decays. Although it is not mentioned explicitly it seems that the scenario used to compute the contribution of gravitinos to the EGB is bilinear RpV, which also has been done in previous works cited in this thesis.

In this reference it is mentioned that all explanations of the rise in the positron fraction by unstable gravitino dark matter require a lifetime of the order of 10^{26} s that is in conflict with bounds from searches for a contribution to the diffuse isotropic gamma-ray flux. If we consider that the gravitino scenario analyzed in this thesis is only bilinear RpV we have to agree on these conclusions, since in our previous work we just checked the same results.

Summarizing, it is quite clear that in bilinear RpV is not possible to explain the charged lepton anomaly without entering in conflict with the bounds derived from the measurements of the EGB. For sure we could add other works where this situations appears again for different models but the revision takes its time. However, by considering these works we cannot exclude every unstable dark matter model, including the gravitino scenario with trilinear couplings, since each final state can give very particular features to the spectrum of charged leptons and gamma-rays that could help to reduce the tensions between theory and data.

More recently, in [**?**] for instance, it has been claimed that no dark matter model with the conventional isotropic density distribution can provide a satisfactory explanation of the cosmic positron excess, while being consistent with Fermi-LAT data on diffuse gamma-ray background. Leaving aside the necessary discussion about the completeness of this study and others in terms of model building, we would like to focus on the solution to the problem that they propose. They basically modify the distribution of dark matter in the galactic disc in order to agree with data, which is possible since we are still discovering dark matter and most of its features are unclear. here we could add other works along this line of thought.

On a similar direction, some works have considered more carefully the contribution of standard astrophysical objects, such as pulsars, in order to find full or partial solutions for the electron-positron excess detected by current experiments. Indeed, some of these works claim that pulsars could the main source of this apparent discrepancies. The mechanism to enhance the production of electrons and positrons from local sources involve modifications of the standard values associated with the transportation of these particles in the pulsar medium, thus this idea is still unclear.

Channel	Final State	Details	Acronym
1	$e^+\mu^-\nu$	antielectron-muon-neutrino	AEMuNue
2	$e^+\tau^-\nu$	antielectron-tau-neutrino	AETauNue
3	$e^-\mu^+\nu$	electron-antimuon-neutrino	EAMuNue
4	$\mu^-\mu^+\nu$	muon-antimuon-neutrino	MuAMuNue
5	$\tau^-\tau^+\nu$	tau-antitau-neutrino	TauATauNue
6	$\tau^-\mu^+\nu$	tau-antimuon-neutrino	TauAMuNue
7	$\tau^+\mu^-\nu$	antitau-muon-neutrino	ATauMuNue
8	$e^-e^+\nu$	electron-antielectron-neutrino	EAENue
9	$e^-\tau^+\nu$	electron-antitau-neutrino	EATauNue

Table 1. Independent channels considering prompt final states. Notice that we use ν to indicate any flavor of neutrinos.

In our opinion, we think that an intermediate scenario, where dark matter and pulsars or even other astrophysical objects are added systematically to the analysis, is probably the most reasonable way to investigate more definite solutions to explain the observed data. Indeed, we would like to think this work as the introduction of an appealing dark matter scenario to consider potential mixed solutions in later works. This particular scenario of dark matter would be strongly motivated since it is able to explain the electron positron anomaly while being able to satisfy EGB constraints, essentially case probe that this kind of approach is still possible. Based on this scenario and the potentiality of the pulsar explanation we propose other observables that could be useful to distinguish the level of each contribution.

4 Gravitino model and effective decay channels

As mentioned in the introduction we assume that the exotic source of the electron positron anomaly measured by AMS-02, CALET and DAMPE can be explained by a super-symmetric model with a gravitino as the lightest susy particle plus trilinear couplings to standard model particles, such as electrons, positrons and photons.

Basically, we are considering an extension of the standard model given by the lagrangian introduced in works such as [?] and others. In the former reference, we can also find the analytical expressions for the gravitino decay associated to each individual trilinear coupling, which we are going to use in section 7 to find a relationship between the gravitino life-time required to fit the chrged lepton anomaly and the scale of neutrino masses. Here, we can extend the discussion about the allowed channels and the relationship between the expressions shown in the mentioned paper and the phenomenological interesting channels.

For the computation of the electron-positron spectrum at earth we consider an approach similar to our previous work, therefore we suggest to follow this work and references therein for the computations of the total flux including propagation effects. On the other hand, we need to explain some details about the particular final state channels that appear in our scenario. In practice we can start by considering only the gravitino final state channels that in principle could produce different spectra of electrons and positrons, which are given in table 1. We can notice that each channel can contain any neutrino flavor, since the final state is equivalent, therefore we can see that the relation between branching fractions and trilinear couplings is not necessarily direct.

4.1 Electron-Positron spectrum

Considering the effective channels given in table 1 we may write the total contribution to the nuber of electrons and positrons at earth as given by

$$\frac{dN(e^{\pm})}{dE} \propto \frac{1}{m_G \tau_G} \sum_{i=1}^{9} BR_i \frac{dN_i(e^{\pm})}{dE} \tag{4.1}$$

where m_G is the gravitino mass, τ_G is the gravitino lifetime, the index i cover the 9 channels of table 1, BR_i are the corresponding branching ratios of each channel and $dN_i(e^-)/dE$ are the propagated gravitino decay spectra (normalized to one decay), which are obtained from the propagation of charged leptons through the galactic environment. Here we need to unify conventions with German's notation but in principle is just a matter of names, nothing deep.

In principle, we can get each BR_i as a function of the free parameters of our model, such as the trilinear couplings λ_{ijk} or the mass of scalars at some point we have to do this computation, for which we suggest to follow hep-ph/0107286, but in general we can consider the branching fractions as the effective free parameters for the fit of charged lepton measurements with the condition that $\sum_i BR_i = 1$.

Interestingly, we can still reduce a bit more the number of degrees of freedom of our model by considering that some of these final states generate the same spectrum of electrons (positrons). Here we could extend a bit more if necessary since we have all the material to back this assumptions. Thus, we can group the decay channels as follows,

$$\begin{aligned}
\frac{dN(e^-)}{dE} &\propto \frac{1}{m_G \tau_G} \Bigg[(BR_1 + BR_4 + BR_7) \frac{dN_1(e^-)}{dE} + \\
&\quad (BR_2 + BR_5 + BR_6) \frac{dN_2(e^-)}{dE} + \\
&\quad (BR_3 + BR_8 + BR_9) \frac{dN_3(e^-)}{dE} \Bigg] \\
\frac{dN(e^-)}{dE} &\propto \frac{1}{m_G \tau_G} \left[\alpha_1 \frac{dN_1(e^-)}{dE} + \alpha_2 \frac{dN_2(e^-)}{dE} + \alpha_3 \frac{dN_3(e^-)}{dE} \right]
\end{aligned}$$

where $\alpha_1 = BR_1 + BR_4 + BR_7$, $\alpha_2 = BR_2 + BR_5 + BR_6$ and $\alpha_3 = BR_3 + BR_8 + BR_9$ with $\alpha_1 + \alpha_2 + \alpha_3 = 1$. Thus, we just need to define two independent effective branching fractions for the fit of electrons. Similarly, for the positron spectrum we have that

$$\begin{aligned}
\frac{dN(e^+)}{dE} &\propto \frac{1}{m_G \tau_G} \Bigg[(BR_1 + BR_2 + BR_8) \frac{dN_1(e^+)}{dE} + \\
&\quad (BR_3 + BR_4 + BR_6) \frac{dN_3(e^+)}{dE} + \\
&\quad (BR_5 + BR_7 + BR_9) \frac{dN_5(e^+)}{dE} \Bigg]
\end{aligned}$$

Besides, we can use some equivalences between branching fractions of conjugated decay channels, to rewrite the positron spectrum as

$$\begin{aligned}
\frac{dN(e^+)}{dE} &\propto \frac{1}{m_G\tau_G}\left[(BR_9+BR_2+BR_8)\frac{dN_1(e^+)}{dE}+\right.\\
&\quad (BR_1+BR_4+BR_7)\frac{dN_3(e^+)}{dE}\\
&\quad \left.(BR_2+BR_5+BR_6)\frac{dN_5(e^+)}{dE}\right]\\
\frac{dN(e^+)}{dE} &\propto \frac{1}{m_G\tau_G}\left[\alpha_1\frac{dN_3(e^+)}{dE}+\alpha_2\frac{dN_5(e^+)}{dE}+\alpha_3\frac{dN_1(e^+)}{dE}\right]
\end{aligned}$$

Finally, we can use that the electron spectrum from a given channel must be equal to the positron spectrum of the conjugated one to find that

$$\begin{aligned}
\frac{dN(e^+)}{dE} &\propto \frac{1}{m_G\tau_G}\left[\alpha_1\frac{dN_1(e^-)}{dE}+\alpha_2\frac{dN_2(e^-)}{dE}+\alpha_3\frac{dN_3(e^-)}{dE}\right]\\
\frac{dN(e^+)}{dE} &\equiv \frac{dN(e^-)}{dE}
\end{aligned}$$

Therefore, for the fit of AMS-02, CALET or DAMPE we just need two $\alpha's$ and three independent spectra. Furthermore, we get automatically the electron-positron symmetry for (gravitino) dark matter decays which is expected from general arguments considering charge conjugation symmetry.

4.2 Gamma-ray spectrum

Analogously to the electron-positron flux, we may compute the total contribution of gravitino decays to the EGB measured at earth by considering the following expression

$$\frac{dN(\gamma)}{dE} \propto \frac{1}{m_G\tau_G}\sum_{i=1}^{9} BR_i\frac{dN_i(\gamma)}{dE} \tag{4.2}$$

where the explanation about the global factors and selection of decay channels are identical to Eq. 4.1. However, in this case we are not going to exploit the potential similarities between the gamma-ray energy spectra arising from different decay channels, if they exist at all. Instead, we are going to use the results of the previous section to find scenarios where the gamma-ray spectrum is indeed minimized, in order to maximize the chance to be compatible with the EGB measurements.

As we only can fix α_1, α_2 and α_3 from the fit of charged leptons we have some freedom to choose the individual branching fractions to generate the photon flux. Also we must notice that for the photon spectrum we do not have coincidences between the spectrum of different channels such as $e^+\mu^-\nu$ and $e^+\tau^-\nu$, as we had for positrons. Therefore we are free to choose BR_1 to BR_9 with the conditions that

$$\begin{aligned}
\alpha_1 &= BR_1+BR_4+BR_7\\
\alpha_2 &= BR_2+BR_5+BR_6\\
\alpha_3 &= BR_3+BR_8+BR_9
\end{aligned}$$

In order to decrease the possible number of photons to be produced we may choose BR_i in the following way,

$$\begin{aligned} BR_1 &= \alpha_1, \quad BR_4 = BR_7 = 0 \\ BR_2 &= \alpha_2, \quad BR_5 = BR_6 = 0 \\ BR_8 &= \alpha_3, \quad BR_3 = BR_9 = 0 \end{aligned}$$

which can be justified from the analysis of the corresponding gamma-ray spectra obtained for the corresponding channels. Basically, we prioritize the channels that produce the least amount of photons per gravitino decay. Maybe, this choice needs further justification but in principle it has allowed us to find compatible points, which can be seen from the plots shown in the analysis part.

5 Statistical data analysis

We fit measurements related to electron and positron fluxes at Earth, so we define backgrounds for each of these fluxes with power laws:

$$P_m^B(E) = C_P E^{-\gamma_P}, \tag{5.1}$$

for positrons, and for electrons:

$$\epsilon_m^B(E) = C_e E^{-\gamma_e}. \tag{5.2}$$

It is not possible to reproduce the rise in electron and positron flux above ≈ 200 GeV modeling the fluxes with decreasing power laws. Therefore, we must include a source term injecting electron and positrons at high energies. Our source term candidate is the decay of gravitino dark matter into standard model particles. It is worth noticing that gravitino decay yields equal amounts of electron and positron. We model the amount of electrons, positrons, or γ rays, labeled as η, produced by gravitino decay as:

$$\Phi_{dm}^\eta(E) = \frac{1}{m_G \tau_G} \sum_j Br_j \frac{dN_j^\eta}{dE} D_{\text{factor}}^\eta, \tag{5.3}$$

with m_G and τ_G the mass and lifetime of the gravitino respectively. The D_{factor}^η is proportional to the density of dark matter in the case of $\eta = \gamma$ rays, in the other cases is a more complex term that depends on the dark matter density and the propagation of charged particles in the Galaxy. The term $\frac{dN_j^\eta}{dE}$ is the amount of electrons, positrons, or γ rays per energy produced by decay of a gravitino per energy and propagated at the Earth position. As in the case of leptons some of the decay channels produce equal amounts of electrons and positrons we can simplify the equation to:

$$\Phi_{dm}^\eta(E) = \frac{1}{m_G \tau_G} \sum_{k=1}^{3} \alpha_k \frac{dN_k^\eta}{dE} D_{\text{factor}}^\eta, \tag{5.4}$$

with the constrain of $1 = \sum_{k=1}^3 \alpha_k$ we only need to determine two parameters. A further simplification is that we pre-compute the flux for different decay channels and gravitino masses assuming a $\tau_G = 1 \times 10^{27}$s. So, the flux of gravitino decay products at Earth is:

$$\Phi^{\eta}_{dm}(E) = \frac{f}{1\times 10^{27} s m_G} \sum_{k=1}^{3} \alpha_k \frac{dN^{\eta}_k}{dE} D^{\eta}_{\text{factor}}, \tag{5.5}$$

the factor f allow us to parametrize the amount of flux and is inversely proportional to τ_G, so determining f we determine τ_G.

Summarizing, we have 8 free parameters to fully determine signal and background for electron and positron fluxes. To compare with data, for instance positron measurements $P_D(E_i)$, we define the following likelihood form:

$$\log \mathcal{L}_{\text{Positrons}} = -\frac{1}{2} \sum_i \left(\frac{(P_D(E_i) - P_m(\theta_p, E_i))^2}{(\sigma_D^2 + j \times P_D^2(\theta_p, E_i))} - \frac{1}{(\sigma_D^2 + j \times P_D^2(\theta_p, E_i))} \right), \tag{5.6}$$

with σ_D the statistical uncertainty of the measurement. The model is defined as:

$$P_m(\theta, E) = P^B_m(C_p, \gamma_P, E) + \Phi^P_{dm}(m_G, f, \alpha_1, \alpha_2, E). \tag{5.7}$$

We introduce the parameter j in the likelihood to increase the total uncertainty as a fraction of the model, this is to account for possible systematic effects and correlations among the different data sets used. In the case of fitting the electron flux we have:

$$\log \mathcal{L}_{\text{Electrons}} = -\frac{1}{2} \sum_i \left(\frac{(\epsilon_D(E_i) - \epsilon_m(\theta, E_i))^2}{(\sigma_D^2 + t \times \epsilon_D^2(\theta, E_i))} - \frac{1}{(\sigma_D^2 + t \times \epsilon_D^2(\theta, E_i))} \right), \tag{5.8}$$

with:

$$\epsilon_m(\theta, E) = \epsilon^B_m(C_e, \gamma_e, E) + \Phi^{\epsilon}_{dm}(m_G, f, \alpha_1, \alpha_2, E). \tag{5.9}$$

We can use 3 or 4 measurements, so the parameter space can be of 11 or 12 dimensions. The measurements are:

(D_1) Positron flux, by AMS02.

(D_2) Electron flux, by AMS02.

(D_3) Positron fraction, by AMS02. It is positrons/(electrons + positrons).

(D_4) Electron + positron flux, by AMS02.

(D_5) Electron + positron flux, by CALET.

(D_6) Electron + positron flux, by DAMPE.

In multinest we put a total likelihood that combines all 3 or 4 measurements. We will explore 4 cases:

1. $D_1 + D_2 + D_3$
2. $D_1 + D_2 + D_3 + D_4$
3. $D_1 + D_2 + D_3 + D_5$
4. $D_1 + D_2 + D_3 + D_6$

6 Results

6.1 $D_1 + D_2 + D_3$

We find many points that can explain the lepton data and while not overshoot the γ-ray extragalactic background. With the bilinear model in previous work, we could not have that situation.

6.2 $D_1 + D_2 + D_3 + D_4$

We get similar results than in the previous case, but adding the electron-positron sum from the same detector (in the 0.5 GeV to 1 TeV range PRL 113, 221102) may be a problem. Not entirely sure what it means, but the parameter related to this new measurement $\log(k)$ is significantly larger than the other three (see slide 8), maybe some correlation with the other data. An interpretation is that to produce the observed points we need to degrade the likelihood in the electron+positron data in a fraction of the model.

6.3 $D_1 + D_2 + D_3 + D_5$

In this case we do not use the electron-positron sum from AMS02, but the values reported by CALET. The CALorimetric Electron Telescope is an instrument placed in the International Space Station, as well as AMS02. In arXiv:1712.01711 CALET team reported a measurement of the cosmic-ray electron + positron spectrum from 10 GeV to 3 TeV. The CALET spectrum is compatible with results from AMS02, but with Fermi and DAMPE reports. Including CALET data (but e+p AMS02) makes the fit to prefers higher gravitino masses and reduces the parameter space allowed for reproducing the lepton data while keeping the gamma-ray flux below the Fermi estimation.

6.4 $D_1 + D_2 + D_3 + D_6$

We include here e+p spectrum from DAMPE. This measurement is in tension with AMS02. We find no points compatible with lepton and gamma-ray data.

7 Bonus: Discussion about the gravitino lifetime and neutrino masses

The full expressions for the gravitino decay width, considering trilinear R-Parity violation, are given in hep-ph/017286. For instance, from these expressions we can get an approximated formula for the leptonic decay $\Gamma(\tilde{G} \to \nu_i e_j \bar{e}_k)$ by assuming that the mass of the sleptons that mediate the three body decay are equal, such that $m_{\tilde{\nu}_{iL}} = m_{\tilde{e}_{jL}} = m_{\tilde{e}_{kR}} = \tilde{m}$, and expand in taylor series around the variable $m_G/\tilde{m}$ to obtain

$$\Gamma(\tilde{G} \to \nu_i e_j \bar{e}_k) \approx \frac{1}{96(2\pi)^3} \frac{\lambda_{ijk}^2}{8M_\star^2} \frac{m_G^7}{\tilde{m}^4}, \tag{7.1}$$

where $M_\star = (8\pi G_N)^{1/2} = 2.4 \times 10^{18}$ GeV is the reduced Planck mass. This result shows that the decay width (lifetime) decreases (increases) rapidly as we increase $\tilde{m}$, as expected. We expect that a similar behavior should be obtained even when the mass of sleptons are not equal.

Indeed, we have verified this expectation numerically, by evaluating the full expression given in hep-ph/017286 using the maximum numerical precision in Mathematica. For instance, in Fig. 1 we plot the gravitino lifetime as a function of $m_{\tilde{\nu}_{iL}}$ for $m_{\tilde{e}_{jL}} = m_{\tilde{\nu}_{iL}}/2$ and

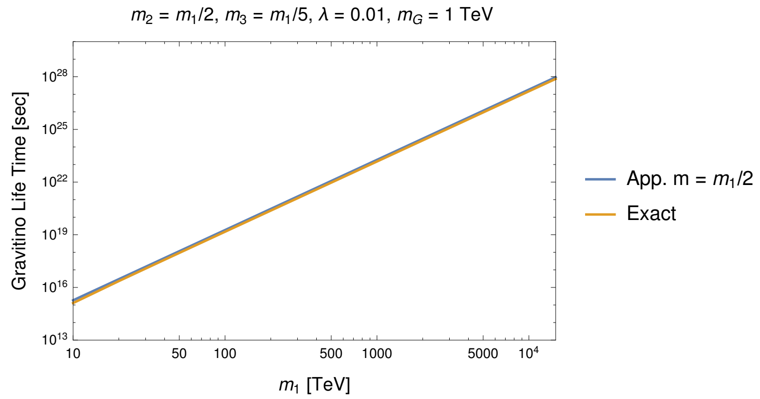

Figure 1. Gravitino life time in Trilinear RpV for $\lambda_{ijk} = 0.01$, $m_G = 1\,\mathrm{TeV}$. For simplicity we use m_1, m_2, m_3 and m instead of $m_{\tilde{\nu}_{iL}}$, $m_{\tilde{e}_{jL}}$, $m_{\tilde{e}_{kR}}$ and $\tilde{m}$.

$m_{\tilde{e}_{kR}} = m_{\tilde{\nu}_{iL}}/5$. Also, in the same figure we plot the lifetime derived from Eq. 7.1 evaluated at $\tilde{m} = m_{\tilde{\nu}_{iL}}/2$ in order to check that both approaches, exact computation and approximated formula, behave quite similarly.

Therefore, we can confidently derive the following expression for the gravitino lifetime,

$$\tau_G \approx 7 \times 10^{28}\,\mathrm{sec} \left(\frac{1}{\lambda_{ijk}\lambda_{ijk}}\right)\left(\frac{\tilde{m}}{10^8\,\mathrm{GeV}}\right)^4 \left(\frac{1\,\mathrm{TeV}}{m_G}\right)^7 \tag{7.2}$$

where we have normalized with respect to 10^{28} sec since this is the order of magnitude required by experiments such as AMS-02 and Fermi-LAT in order to fit the electron positron data in the first case or to avoid gamma ray constraints in the second.

In trilinear RpV the neutrino mass matrix receives contributions from 1-loop diagrams that contain both a charged lepton and the corresponding slepton. Indeed, we have derived the following (preliminary) expression

$$M_{ij}^{\nu\,(1)} \approx \frac{1}{16\pi^2}\sum_{gr} s_{\tilde{l}}c_{\tilde{l}}(\lambda_{igr}\lambda_{jrg} + \lambda_{jgr}\lambda_{irg})m_g \ln\frac{m_{\tilde{l}_{r2}}^2}{m_{\tilde{l}_{r1}}^2}$$

where i and j are neutrino generation indices that run from 1 to 3. g is a charged lepton index that also run from 1 to 3, as well as r which is a slepton index. Thus, it can be seen that for order one $s_{\tilde{l}}$, $c_{\tilde{l}}$ and $\ln(m_{\tilde{l}_{r2}}^2/m_{\tilde{l}_{r1}}^2)$ we can get neutrino masses around the eV scale for $\lambda_{ijk} \approx 0.01$ even for $m_g \approx m_e$.

Indeed, by following the expressions given in hep-ph/0410242 for the contribution of λ' trilinear terms, we can get by analogy that the dominant term in the leptonic sector is

$$\begin{aligned}
M_{ij}^{\nu\,(1)} &\approx \frac{1}{8\pi^2}\lambda_{i23}\lambda_{j32}\frac{m_\mu m_\tau A_\tau}{\tilde{m}^2} \\
&\approx 2 \times 10^{-2}\mathrm{eV}\,\lambda_{i23}\lambda_{j32}\left(\frac{10^8\,\mathrm{GeV}}{\tilde{m}}\right) \\
&\approx 2 \times 10^{-2}\mathrm{eV}\,(\lambda_{i23}\lambda_{j32})^{5/4}\left(\frac{\tau_G}{7 \times 10^{28}\,\mathrm{sec}}\right)^{1/4}\left(\frac{m_G}{1\,\mathrm{TeV}}\right)^{7/4}
\end{aligned}$$

where A_τ is a free parameter that can be considered of order $\tilde{m}$, as it is done in hep-ph/0410242. Thus, if we consider this formula together with Eq. 7.2 we see that we can have contributions to the neutrino mass matrix of order 10^{-2}eV for trilinear couplings and a scalar mass which are compatible with $\tau_G \approx 10^{28}$ sec.

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