Confronting recent AMS-02 positron fraction and Fermi-LAT Extragalactic $\gamma$-ray Background measurements with gravitino dark matter

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Abstract. The positron fraction measured by the space-based detectors PAMELA, Fermi-LAT and AMS-02 presents anomalous behaviour as energy increase. In particular AMS-02 observations provide compelling evidence for a new source of positrons and electrons. Its origin is unknown, it can be non-exotic (e.g. pulsars), be dark matter or maybe a mixture. We test the gravitino of R-parity violating supersymmetric models as this source. As the gravitino is a spin 3/2 particle, it offers particular decay channels, $W^{\pm}\tau^{\mp}$, $Z\nu_{i}$, and $H\nu_{i}$. We compute the electron, positron and $\gamma$-ray fluxes produced by each gravitino decay channel as it would be detected at the Earth’s position. Combining the flux from the different decay modes we can fit AMS-02 measurements of the positron fraction, as well as the electron and positron fluxes, and the flattening in the behaviour of the positron fraction recently found by AMS-02 allow us to determine that the preferred gravitino decaying mode by the fit is $W^{\pm}\tau^{\mp}$, unlike previous analyses. The corresponding $\gamma$-ray flux is in conflict with the most recent determination of the Extragalactic $\gamma$-ray Background (EGB) with the Fermi-LAT, excluding the gravitino DM as the unique source of primary positrons. We use the EGB and a model of its known contributors to restrict the gravitino lifetime to be larger than $9 \times 10^{26}$ s, $1.5 \times 10^{27}$ s, and $2 \times 10^{27}$ s at 95% CL, for $m_{3/2} = 1$ TeV, 2 TeV and 3 TeV, respectively. Thus, if gravitinos made up the whole DM of the Universe and the two body decay channels referred above are dominant, they can only produce a modest fraction of the highest energetic electron and positron fluxes detected at the Earth.

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

Over the last eight decades vast and compelling evidence of the dark matter (DM) existence at different scales in the universe have been accumulated [1]. However, its fundamental nature have remained as one of the biggest mysteries of modern science [2, 3]. The study and characterisation of different cosmic ray (CR) species arriving at the Earth could reveal the DM nature. DM decays or annihilations might inject Standard Model (SM) particles in the interstellar medium (ISM) that will appear as exotic contributions in CR measurements, challenging their interpretation in terms of known astrophysical phenomena. This is the reason why the unexpected rising in the positron fraction ($e^+/(e^++e^-)$) detected by PAMELA [4], confirmed by the Fermi-Large Area Telescope (Fermi-LAT) [5], and measured with precision by AMS-02 [6] caused an avalanche of works attributing the origin of this anomaly to DM, see e.g. [7–18]. The interpretation of these data in terms of DM is not easy since DM candidates explaining the rise in the positron fraction, could also predict unseen excesses in the antiproton and $\gamma$-ray spectrum, see e.g. [19–23]. Other non-exotic hypothesis came out as well, see e.g. [25, 26]. Nevertheless, to explain the positron rise as due to a pulsar contribution, or as due to a secondary origin, has its own difficulties in each case [27]. Thus, the rise in the positron fraction remains not understood yet.

Recently, the AMS Collaboration has extended the measurement of the positron fraction and flux to 500 GeV, and the electron flux to 700 GeV, with the Alpha Magnetic Spectrometer (AMS), installed on the International Space Station [28, 29]. The main highlights of these measurements are that: i) the positron fraction rise starts to flatten at energies above 500 GeV [28], and ii) that precision measurements of electron and positron fluxes allow determination of different behaviour of their spectral indexes as the energy increases [29]. Therefore, in the light of the latest AMS-02 release [28, 29] we can better determine the properties of the cosmic source responsible for the rise in the positron fraction.

Indeed, the AMS Collaboration itself uses a minimal model for the electron and positron fluxes in order to account for the anomalous behaviour of the positron fraction [6, 28, 29], which is given by,

$$
\Phi_e^-(E) = C_e^-(E/1 \text{ GeV})^{-\gamma_e^-} + C_s(E/1 \text{ GeV})^{-\gamma_s} e^{-E/E_s},
$$

$$
\Phi_e^+(E) = C_e^+(E/1 \text{ GeV})^{-\gamma_e^+} + C_s(E/1 \text{ GeV})^{-\gamma_s} e^{-E/E_s},
$$

(1.1)

where each flux is determined by the sum of a diffuse term (modelled with a power-law spectrum), and a single source term (modelled with a power-law spectrum with an exponential cutoff energy) which is common to the electron and positron flux. The diffuse term in the electron flux attempt to model primary and secondary production, while in the electron flux represent only secondary production. This minimal model offers satisfactory fits to the positron fraction and the combined electron and positron flux. Therefore, the data can be described by a common source of primary electrons and positrons [6].

In this work we assume the single common source term in eq. 1.1 consisting of decaying DM particles, which preserves CP symmetry, and thus contribute an equal amount to the electron and positron flux. In particular, we study a decaying gravitino DM scenario, which

\footnote{Note that decaying DM particles could affect the physics of dense stars implying strong constraints on the DM properties [24]. These constraints are avoided by the gravitino because its elastic scattering cross section on nuclei is proportional to $1/M_P^2$ [49], therefore there is no chance that they can be trapped in the core of dense stars.}
is possible in the context of R-parity violating (RpV) supersymmetric (SUSY) models, see e.g. [21, 30–37]. We assume that the relic density produced by our gravitino DM, is consistent with the observations, as already has been shown in several places [38–42]. It is worth noting that these works assume that the gravitino is sufficiently long-lived in order to maintain its comoving density from the period of decoupling until the present. In fact, since RpV terms are in general quite small and the gravitino interactions are suppressed by the Planck mass, the latter condition is naturally obtained [30].

In SUSY with RpV, the gravitino decay channels are fixed (see for instance [31, 43, 44]). In this work we just consider the primary \textit{two body} decay channels which could produce electrons and positrons in the final state. In models with trilinear R-parity violation two body decay channels are possible at one-loop level, but for heavy gravitinos the behaviour of the total decay rate is dominated by three-body decay channels at tree level [36, 37]. Therefore, we implicitly assume negligible R-parity violation due to trilinear couplings. For several values of the gravitino mass, final gravitino decay products are computed using Pythia 8.185 [45] and propagated from regions with non-zero DM densities towards the Earth. The obtained spectrum produced by each of the different decay channels are combined in order to fit the most recent AMS-02 data. From the results of this fitting procedure, we can extract the best values for the corresponding branching ratios (BR), which is equivalent to restrict the parameter space of the underlying SUSY model. We then compute the corresponding diffuse \(\gamma\)-ray emission produced by the obtained gravitino parameters at high Galactic latitudes, which turns out to significantly exceeds the flux of the extragalactic \(\gamma\)-ray background (EGB) recently measured using the \textit{Fermi}-LAT [46]. Finally, we compute the residual upper limit flux of the EGB removing known contributors, in particular the integrated emission from blazars as modelled in [47], and then compare it to the prompt gravitino-induced \(\gamma\)-ray flux to obtain the magnitude of the possible gravitino DM contribution to the electron and positron flux at the high energy end.

This work extends and update previous studies in several respects. As we try to be as model independent as possible, we are not fixing the branching ratios for the different gravitino decay channels, neither the flavour structure in our theory, but rather, this is the outcome of the fits to the AMS-02 data. Furthermore, we are using the most up to date results from AMS-02 and \textit{Fermi}-LAT collaborations, which considerably extends previous measurements. It allows a more precise characterisation of the source responsible for the positron fraction excess and reduce the window for exotic contributors to the \(\gamma\)-ray sky. In particular, the flattening in the behaviour of the positron fraction at about 500 GeV and the high statistics measurement of electron and positron fluxes allow us to determine the mass scale of the gravitino DM (\(\sim 1\) TeV ) and that the gravitino decaying mode preferred by AMS-02 data is \(W^\pm \tau^\mp\). The last differs from previous analyses where the favoured channel is \(W^\pm \mu^\mp\) [20, 21]. We also set stringent constrains on the gravitino DM contribution to the electron and positron flux using the latest determination of the EGB [46] and its main contributor, the blazar emission [47].

The paper is organised as follows: In section 2 we introduce the primary gravitino decay channels which are available in SUSY with RpV models. In section 3 we consider the propagation of electrons and positrons produced by the gravitino decays through the ISM. Afterwards we fit the most recent data published by the AMS Collaboration using a model

\footnote{Unlike [30, 32–35] we focus on gravitino DM with mass above 1 TeV motivated by the flattening of the positron fraction spectrum at \(\sim 500\) GeV. The study of the consistency between this gravitino mass scale and other observables, as neutrino physics, is beyond the scope of this work.}
that consider a power-law background plus a source given by the gravitino decays. In section 4 we use the results obtained from the fit to AMS-02 data in order to determine the γ-ray signal from gravitino DM decay at high latitudes and we confront these results with the new Fermi-LAT EGB measurement and latest modelling of integrated blazar emission. Finally, in section 5 we conclude.

2 Gravitino decay modes

Gravitino interactions in SUSY theories with RpV determine its possible decay modes, and those are well documented in the literature (see for instance [31, 34, 35, 44]). Thus, in this work, we just recall them from a phenomenological point of view. For $m_{3/2} \gtrsim 1 \text{TeV}$, which is the regime that we are considering throughout this work, the primary gravitino decay modes are the following two body decays,

$$\Psi_{3/2} \rightarrow Z\nu_i, W^{\pm}l^{\mp}_i, H\nu_i$$

(2.1)

where $i$ is the family index and $H$ is the Higgs particle\(^3\). We do not consider two body decays into heavy higgs bosons because in general they are heavier than the LSP. Furthermore, the amount of electrons, positrons and photons in final states including heavy higgs bosons is highly dependent on the complete higgs spectrum. We consider the gravitino mass, lifetime and BRs as the free parameters of our effective model. For simplicity we introduce the following notation for the BRs:

$$BR_{\lambda l_i} \equiv BR(\Psi_{3/2} \rightarrow \lambda l_i)$$

with $\lambda = Z, W^{\pm}, H$ and $l_i = \nu_i, l^{\pm}_i$.

Notice also that the decays $\Psi_{3/2} \rightarrow \lambda \nu_i$ produce an equivalent spectra of $e^{\pm}$ and photons, independently of the neutrino flavour then, for a given $\lambda$, we just consider the total sum over the $\nu_i$ final states, as three times the corresponding result obtained for a given neutrino flavour.

In order to obtain the total number of final state electrons, positrons and photons produced by the decay of a heavy gravitino of a given mass, we use the Pythia event generator, were gravitino decays are produced at rest. The program will also further simulate the decays of the known particles as the weak gauge bosons, and the $\mu$ and $\tau$ leptons, and furthermore, the corresponding hadronizations and decays, ending up with a final number of highly energetic stable particles. The energy spectra of electrons, positrons and γ rays from the different gravitino decay modes obtained with Pythia are shown in fig. 1.

3 AMS-02 positron excess and gravitino dark matter

3.1 Cosmic ray propagation

Once a gravitino decay in the halo of the Milky Way (MW), some of the resulting charged particles will propagate through the ISM towards the Earth, where they could be observed. Theoretically, the propagation of electrons and positrons in the MW can be treated as a diffusive process [50]. If we assume that this is a steady state process, we can estimate the electron and positron density per unit energy at position $r$ (in Galactic coordinates) i.e. $f(E, r)$, by solving the following diffusion equation,

$$- \nabla (K(E, r) \nabla f) - \frac{\partial}{\partial E} (b(E, r) f) = Q(E, r),$$

(3.1)

\(^3\)The gravitino decay to $\gamma \nu_i$ is suppressed in the limit where $m_{3/2}$ is heavier than weak gauge bosons [22, 48, 49].
where \( K(E, r) = K_{0}(E/\text{GeV})^6 \) is the diffusion coefficient that accounts for the transport of electrons and positrons through the Galactic magnetic fields, \( b(E, r) \) is the energy loss coefficient due to different types of interactions of electrons and positrons with the ISM, like synchrotron radiation, bremsstrahlung, and inverse Compton scattering (ICS), and \( Q \) is the source term which models how electrons and positrons are injected in the ISM, in our case, this is due to the gravitino decays, and is given for each \( \lambda_l \) channel as:

\[
Q(E, r) = \left( \frac{\rho(r)}{m_{3/2}} \right) \frac{1}{\tau_{3/2}} \frac{dN_{3/2}^{\lambda_l \rightarrow e^\pm}}{dE}.
\]  

Replacing this expression for \( Q(E, r) \) in eq. 3.1, we can determine the flux of electrons and positrons as a function of the energy \( E \) and position \( r \), i.e.

\[
\frac{d\Phi_{3/2}^{\lambda_l \rightarrow e^\pm}}{dE}(E, r) = \frac{v_{e^\pm} f(E, r)}{4\pi}.
\]

using the following equation [52]:

\[
\frac{d\Phi_{3/2}^{\lambda_l \rightarrow e^\pm}}{dE}(E, r) = \frac{v_{e^\pm}}{4\pi b(E, r)} \left( \frac{\rho(r)}{m_{3/2}} \right) \frac{1}{\tau_{3/2}} \int_{E}^{M_{DM}/2} dE_{a} \frac{dN_{3/2}^{\lambda_l \rightarrow e^\pm}}{dE_{a}}(E_{a}) I(E, E_{a}, r),
\]

where \( v_{e^\pm} \) is the velocity of the electrons and positrons, \( E_{a} \) is their energy at the source and \( I(E, E_{a}, r) \) are the generalized halo functions (GHF), which are essentially the Green functions connecting a source with a fixed energy \( E_{a} \) to a given energy \( E \) (see [51] for more details of the GHF). In this work we use the Navarro, Frenk and White (NFW) [53] density profile

\[
\rho_{\text{NFW}}(r) = \rho_{s} \frac{r_{s}}{r} \left( 1 + \frac{r}{r_{s}} \right)^{-2},
\]

where we adopt \( r_{s} = 24.42 \text{kpc} \) and \( \rho_{s} = 0.184 \text{GeV cm}^{-3} \) following [52], where at Earth position \( r_{\odot} = 8.33 \text{kpc} \) [54] the local DM density is \( \rho_{\odot} = 0.3 \text{ GeV cm}^{-3} \). The diffusion

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**Figure 1.** The positron (a) and photon (b) energy spectrum produced by the different gravitino decay modes as a function of energy. The electron distribution is equivalent to the positron case.
model is defined by $K_0$, $\delta$ and the half-thickness $L$ of the diffusion zone\footnote{It is define as a solid flat cylinder with height $2L$ in the $z$ direction and radius $R = 20\, \text{kpc}$ in the radial direction.}. We use the set of propagation parameters called MED described in Table II of [51] which provides the best fit to the CR measurements of the boron-to-carbon ratio at the Earth’s position [55]. In fig. 2 we show the propagated electron spectra at the Earth’s position for different gravitino masses. We show the propagated spectra of electrons from gravitino decays with masses of 1, 2 and 3 TeV. We use this set of curves in the following section as the inputs to the fit of the AMS-02 data.

3.2 Determination of gravitino parameters from AMS-02 data

In this section, we consider a decaying gravitino scenario as describing the anomalous behaviors of the electron and positron flux, and the positron fraction, all of them recently measured with high precision by the AMS-02 experiment [28, 29]. In practice we fit the electron and positron flux above 10 GeV and the positron fraction above 1 GeV [56]. We do not consider the positron or electron flux below 10 GeV because the features in which we are interested on appear at energies larger than 20 GeV. Besides this, AMS-02 data below 10 GeV is strongly affected by the Solar activity.

Motivated by eq. 1.1 we model the electron and positron flux by considering the sum of a non-symmetric power law background plus the contribution of a symmetric source, in our case, produced by gravitino decays in the the Galactic halo, which is assumed to make the whole DM density in the MW. The latter assumption can be relaxed when we consider...
that a different value of the average density can be absorbed by a redefinition of the gravitino lifetime. The only constraint would come from the metastability condition, that roughly speaking requires \( \tau_{3/2} > 10^{17} \text{s} \). The electron and positron fluxes are given by

\[
\Phi_{e^-}(E) = C_{e^-} E^{-\gamma_{e^-}} + \Phi_{3/2}(E, m_{3/2}, \tau_{3/2}, BR_{M_i}), \\
\Phi_{e^+}(E) = C_{e^+} E^{-\gamma_{e^+}} + \Phi_{3/2}(E, m_{3/2}, \tau_{3/2}, BR_{M_i}).
\] (3.5)

The asymmetric contribution to the \( e^\mp \) flux is determined by the corresponding normalization factors \( C_{e^\mp} \) and spectral indexes \( \gamma_{e^\mp} \). The term \( \Phi_{3/2}^\mp(E, m_{3/2}, \tau_{3/2}, BR_{M_i}) \) corresponds to the symmetric contribution to the \( e^\mp \) flux arising from the decay of gravitinos. From section 3.1 we see that the gravitino contribution depends on its mass \( m_{3/2} \), lifetime \( \tau_{3/2} \) and decay branching ratios \( BR_{M_i} \). Notice that one of the gravitino BRs is not independent because we have assumed that the sum of them must be equal to unity. Apart from the latter restriction, during the fit we consider these variables as free parameters.

Since the computation of the gravitino contribution to the \( e^\mp \) flux is quite sensitive to the value of its mass, for simplicity we have considered just three specific cases given by \( m_{3/2} = 1, 2 \) and \( 3 \text{ TeV} \). We will see later that these cases are enough in order to extract general conclusions from the fit to the data. For each of these masses we compute a set of standard fluxes for each channel by fixing the lifetime to \( \tau_{3/2} = 10^{26} \text{s} \). These spectra are showed in fig. 2. The flux obtained for this specific lifetime can be linearly scaled in order to obtain the flux for any other value of \( \tau_{3/2} \). Thus, the expression for the gravitino flux that we use to implement the fit is given by

\[
\Phi_{e^\mp}^3(E, m_{3/2}, \tau_{3/2}, BR_{M_i}) = \frac{\tau_{3/2}}{\tau_{3/2}} \sum_{M_i} BR_{M_i} \Phi_{M_i \rightarrow e^\mp}^3(E, m_{3/2}, \tau_{3/2}).
\] (3.6)

Finally, in order to determine the best fit values of the free parameters, for each value of \( m_{3/2} \) we minimize a Chi-squared function \( \chi^2(C_{e^\pm}, \gamma_{e^\pm}, C_{e^\mp}, \gamma_{e^\mp}, \tau_{3/2}, BR_{M_i}) \) by considering the eq. 3.5 and the data points and systematic errors from the electron and positron fluxes and the positron fraction \([28, 57]\). Indeed, we sum three semi-independent Chi-squared functions constructed from each data set. We use 49 points from electron flux \( (E \geq 10 \text{ GeV}) \) plus 48 points from positron flux \( (E \geq 10 \text{ GeV}) \) plus 65 points from positron fraction \( (E \geq 1 \text{ GeV}) \).

In table 1 we report the values of the best fit parameters. Also, we compute the error intervals at 1\( \sigma \) confidence level for the free parameters, for which we follow \([58]\). From these results, we notice that the lifetime is close to the nominal value \( \tau_{3/2} = 10^{26} \text{s} \) for the three scenarios, while the dominant BRs are given by the channels \( \Psi_{3/2} \rightarrow W^\pm \nu^\mp \), \( \Psi_{3/2} \rightarrow Z\nu \) and \( \Psi_{3/2} \rightarrow W^\mp e^\mp (\mu)^\mp \) in descending order. These results differ from conclusions in \([20, 21]\) where the gravitino decay mainly into the second lepton generation. It is due to the better characterisation of the source responsible for the positron rise reached through new AMS-02 data. It is worth noting that the BRs structure found in our fit is consistent, within 1 – \( \sigma \) level, with the theoretical expectation for gravitinos with mass in the TeV range, 50\% \( W^\pm t^\mp \), 25\% \( Z\nu^i \), and 25\% \( H\nu^i \) \([22, 43, 49]\).

Besides, the positron fraction obtained from the best fit values are compared to the Pamela and AMS-02 data in fig. 3, while a similar comparison concerning the electron and positron flux are shown in fig. 4. Notice that a gravitino with \( m_{3/2} = 1 \text{ TeV} \) fails to adjust the highest data point of the electron flux spectrum reported by AMS-02 (see left panel of fig. 4),
Figure 3. The positron fraction measured by AMS-02 and Pamela (blue and cyan points respectively), and fits using the gravitino decay products + background for three different values of the gravitino mass (in red), 1 (continuum line), 2 (dot-dashed) and 3 TeV (dashed). The background and gravitino contributions are also shown separately in grey and pale brown respectively.

Figure 4. The electron (a) and positron (b) flux measured by AMS-02 and Pamela (blue and cyan points respectively), and fits using the gravitino decay products + background for three different values of the gravitino mass (in red), 1 TeV (continuum line), 2 TeV (dot-dashed) and 3 TeV (dashed). The background and gravitino contributions are also shown separately in grey and pale brown respectively.

which therefore disfavours scenarios with $m_{3/2} < 1$ TeV. On the other hand, it can be seen that the scenario with $m_{3/2} = 3$ TeV over predicts the positron fraction above $E \sim 400$ GeV (see fig. 3). Furthermore, from the behaviour of the line corresponding to $m_{3/2} = 2$ TeV we
can see that we are at the edge of the measured spectrum, and that any higher mass value will overpredict the data at high energies, as it is for the 3 TeV mass case. Thus, we estimate that the favoured gravitino mass range is given by $1 \text{ TeV} < m_{3/2} < 2 \text{ TeV}$. In the next section we confront the $\gamma$-ray flux associated to the gravitino parameters suitable to fit AMS-02 data to the EGB recently measured by the Fermi-LAT Collaboration [46].

## 4 Gravitino decay and the Extragalactic Gamma-ray Background measured by Fermi-LAT

The $\gamma$-ray sky has been observed by the Fermi-LAT Telescope with unprecedented detail. Most of the $\gamma$ rays detected come from: i) punctual or small extended sources and ii) a strong diffuse emission correlated with Galactic structures [59]. In addition, a tenuous diffuse component has been detected, the Isotropic $\gamma$-ray Background (IGRB) [60]. The origin of the IGRB can be sources that remains below the detection threshold of the Fermi-LAT, as blazars or star-forming galaxies, or diffuse processes as intergalactic shocks [61–63], interactions of ultra high energy CRs with the Extragalactic Background Light (EBL) [64], CR interactions in small solar system bodies [65] or DM decay/annihilation [66, 67]. The observed IGRB depends on the point source detection threshold of the instrument. A physical quantity is the total EGB, defined as the combination of resolved sources and the IGRB. We contrast the

| $m_{3/2}$ [GeV] | 1000 | 2000 | 3000 |
|----------------|------|------|------|
| $\chi^2_{min}/N$ | 0.63 | 0.58 | 0.56 |
| Free parameter                  | Best Fit | $\pm 1\sigma$ | Best Fit | $\pm 1\sigma$ | Best Fit | $\pm 1\sigma$ |
| $C_{e^+}[1/\text{GeV cm}^2 \text{s str}$ | 436.74 | 464.1 | 438.12 | 465.6 | 438.67 | 464.1 |
| $\gamma_{e^+}$      | 3.29 | 3.31 | 3.30 | 3.31 | 3.30 | 3.31 |
| $C_{e^-}[1/\text{GeV cm}^2 \text{s str}$ | 39.45 | 42.36 | 40.04 | 43.01 | 40.23 | 42.36 |
| $\gamma_{e^-}$      | 3.81 | 3.89 | 3.80 | 3.85 | 3.78 | 3.89 |
| $\tau_{3/2}$ [10$^{26}$ s] | 0.99 | 1.03 | 0.78 | 0.88 | 0.67 | 1.03 |
| $BR_{W^\pm e^\mp}$ | 0.10 | 0.13 | 0.06 | 0.12 | 0.03 | 0.13 |
| $BR_{W^\pm \mu^\mp}$ | 0.07 | 0.07 | 0.0 | 0.21 | 0.06 | 0.07 |
| $BR_{W^\pm \tau^\mp}$ | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| $BR_{Z\nu}$ | 0.90 | 0.92 | 0.79 | 1.0 | 0.65 | 0.92 |
| $BR_{H\nu}$ | 0.0 | 0.31 | 0.14 | 0.41 | 0.26 | 0.31 |

**Table 1.** Results of AMS fit in a decaying gravitino scenario. During the fit we have considered $BR_{H\nu}$ as the dependent branching ratio, however in order to compute their confidence intervals we consider $BR_{Z\nu}$ as the dependent one. We use $N = 153$ as the effective number of degree of freedom.
\( \gamma \)-ray flux predicted by the gravitino DM that can fit the AMS-02 measurements with \textit{Fermi-LAT} Telescope EGB. The reason is that in the region of interest (RoI) used for subtracting the EGB (the whole sky but the Galactic plane) the uncertainty in the \( \gamma \)-ray emission associated to Galactic DM decays is lower than in the Galactic plane. It is so because the DM density profiles, for instance NFW and Einasto, are similar and the DM-induced ICS emission is significant smaller than prompt emission.

4.1 \( \gamma \)-ray flux at Earth from gravitino decays

EGB contributions from gravitino DM decays can has 3 different sources: i) the smooth Galactic halo, ii) sub haloes hosted by the Galactic halo and iii) extragalactic structures. The emission from the smooth Galactic halo provides a lower limit on the \( \gamma \)-ray total gravitino contribution to the EGB and is the least uncertain component, we only use this emission in the analysis. The signal from extragalactic gravitino decay is expected to be isotropic, but it is subject to large uncertainties since it depends on the amount of DM clustering at each given redshift [68–70]. We calculate the differential flux of \( \gamma \) rays from gravitino decays in the Galactic halo by integrating the DM distribution around us along the line of sight. We consider gravitino decays producing \( \gamma \) rays in the final state. In this case the flux reads:

\[
\frac{d\Phi_{\gamma}}{dE d\Omega} = \frac{1}{4\pi} \frac{1}{m_{3/2}} \frac{dN_{\gamma}^{\text{total}}}{d\Omega} \frac{d\Omega}{d\Omega} \int_0^\infty ds \rho_{\text{halo}}(r(s, b, \ell)) ,
\]

where \( b \) and \( \ell \) denote the Galactic latitude and longitude, respectively, and \( s \) denotes the distance from the Solar System. Furthermore, \( \Delta \Omega \) is the region of interest (ROI). The radius \( r \) in the DM halo density profile of the Milky Way, \( \rho_{\text{halo}} \), is expressed in terms of these Galactic coordinates

\[
r(s, b, \ell) = \sqrt{s^2 + r_\odot^2 - 2 s r_\odot \cos b \cos \ell}.
\]

For gravitino masses above the Z boson mass, the total number of photons produced in gravitino decays can be expressed as

\[
\frac{dN_{\gamma}^{\text{total}}}{dE} = \sum_{\lambda_i} \frac{dN_{\lambda_i \rightarrow \gamma}}{dE},
\]

where \( \frac{dN_{\lambda_i \rightarrow \gamma}}{dE} \) is the photon energy spectrum produced by different gravitino decay channels computed in section 2, see panel b) of fig. 1.

4.2 Gravitino contribution to the Extragalactic Gamma-ray Background

The \textit{Fermi-LAT} Collaboration has a new determination of the EGB from 50 months of data that expands from 100 MeV to 820 GeV [46]. In the extraction of the EGB a relevant source of systematic uncertainty is the modelling of the Galactic foreground (FG) emission. In order to test this systematic, the fitting procedure to obtain the EGB was applied to many different Galactic FG models. In particular, reference FG model A is derived from the class of models presented in [60]. Models B and C have more degrees of freedom in electron and diffusion coefficient, for details on FG models A, B and C we refer to [46].

In fig. 5 we contrast the \textit{Fermi-LAT} EGB (cyan points with error bars [46])\(^6\) to the \( \gamma \)-ray emission yield by the gravitino DM needed to account for the rise in positron fraction. The

\(^6\)This is the EGB measurement using FG model A.
Figure 5. We contrast the predicted $\gamma$-ray flux in the three scenarios obtained from the fit to AMS-02 data (red lines) to the EGB as measured by Fermi-LAT using FG model A (cyan points). The gravitino DM-induced $\gamma$-ray emission clearly exceeds the EGB limits.

gravitino DM-induced $\gamma$-ray flux clearly exceeds the EGB limits, ruling out the possibility of the gravitino as the only source of primary positrons responsible of the AMS-02 anomaly. Notice that similar results were found in [22] by analysing the antiproton emission of gravitino DM and contrasting to the results in [21]. In the present work we have a better determination of the gravitino DM parameters needed to explain the high energy positrons seen by AMS-02, moreover we consider a different tracer, $\gamma$ rays, and a more recent measurement to contrast with, the EGB from 50 months of Fermi-LAT data [46].

Now we estimate the magnitude of the posible gravitino DM contribution to the electron and positron flux allowed by the EGB emission. In fig. 6 in addition to the Fermi-LAT EGB (cyan points with error bars [46]) we present the $\gamma$-ray emission due to known EGB contributors, star-forming galaxies (red band [71]) and radio galaxies (blue band [72]) as well as the integrated emission of blazars with EBL absorption as recently modelled in [47] (green band). The grey band represents the sum of all these components, it accounts for the observed amplitude and spectral shape of the EGB. From this figure we can see that there is little room for other contributors, such as DM.$^7$ We compute the 95% CL upper limit flux subtracting the average emission from non-exotic contributors (black line) to the EGB (cyan points) and adding 1.64 times the sum of data and model uncertainties in quadratures.$^8$ Finally, in fig. 6 we compare the residual upper limit flux (brown points) to the emission from gravitino

$^7$Note that Galactic templates of DM decay can be degenerate with ICS templates of the Galactic FG emission model as pointed out in [73]. Nevertheless, we only contrast the gravitino $\gamma$-ray emission to the EGB in an energy range ($>500$ GeV) where the ICS component is not very important, as shown in [73].

$^8$We assume Gaussian errors, therefore 95% of the area of a Gaussian distribution is within 1.64 standard deviations of the mean.
decays in the smooth Galactic halo. We use the $BR_{\lambda_l l_i}$ theoretically expected for gravitinos with masses $>1$ TeV, $50\% \ W^\pm l_\tau^\pm$, $25\% \ Z\nu_i$, and $25\% \ H\nu_i$. We restrict the gravitino lifetime to be larger than $9 \times 10^{26}$ s, $1.5 \times 10^{27}$ s, and $2 \times 10^{27}$ s, for $m_{3/2} = 1$ TeV, $2$ TeV and $3$ TeV, respectively. These results are in agreement with antiproton constraints within systematic uncertainties in the Galactic propagation model [22]. Thus, if gravitinos made up the whole DM of the Universe, they can only contribute modestly to the electron and positron fluxes detected at the Earth.

5 Conclusions

Recent AMS-02 results provide new insights on the anomalous rise in positron fraction, presenting the first evidence of a flattening spectrum at higher energies [28]. In addition, the measurement of electron and positron fluxes allow a better characterisation of the phenomenon behind the positron fraction rise [29]. We model positron and electron fluxes as decreasing-with-energy power laws plus an extra source injecting equally electrons and positrons in the ISM, we test the gravitino of R-parity violating SUSY models as the source term (e.g., [30–35]). We compute the electron, positron and $\gamma$-ray spectra produced by gravitino DM decays as would be detected in the Earth. We have shown that the gravitino DM with mass in the range $1 - 2$ TeV and lifetime of $\sim 1 - 0.8 \times 10^{26}$s, mainly decaying to $W^\pm \tau^\mp$ can reproduce the energy spectra of the positron fraction and the electron and positron fluxes at the same
time. The corresponding $\gamma$-ray emission significantly exceeds most recent Fermi-LAT EGB measurement [46] using 50 months of data, excluding in this way the possibility of gravitino DM in bilinear R-parity violation models as unique source of primary positrons\(^9\). We use the EGB and a model of its known contributors, star-forming galaxies, radio galaxies, and blazars\(^10\), to restrict the gravitino lifetime to be larger than $9 \times 10^{26}$ s, $1.5 \times 10^{27}$ s, and $2 \times 10^{27}$ s at 95\% CL, for $m_{3/2} = 1$ TeV, 2 TeV and 3 TeV, respectively. Thus, if gravitinos of bilinear R-parity violating models made up the whole DM of the Universe, they can only contribute modestly to the highest energetic electron and positron fluxes detected at the Earth.

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\(^9\)Note that we are not including the gravitino two body decay into heavy higgs since, in general, they are heavier than the LSP.

\(^10\)The integrated emission of blazars include the EBL absorption we use the model in [47]
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