Decaying gravitino dark matter and an upper bound on the gluino mass

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Abstract

We show that, if decaying gravitino dark matter is responsible for the PAMELA and ATIC/PPB-BETS anomalies in the cosmic-ray electron and positron fluxes, both a reheating temperature and a gluino mass are constrained from above. In particular, the gluino mass is likely within the reach of LHC, if the observed baryon asymmetry is explained by thermal leptogenesis scenario.
The PAMELA experiment \cite{1} reported an excess of the positron fraction above 10 GeV, which extends up to about 100 GeV. The excess could be a signal of the annihilation or decay of dark matter. Among many decaying dark matter models \cite{2, 3, 4, 5}, we consider here the gravitino dark matter with broken $R$-parity \cite{2} (see also Refs. \cite{6}). In fact, it was shown in Ref. \cite{7} that the gravitino decaying via the bilinear $R$-parity violation can explain the PAMELA data.

The positron spectrum needed to explain the PAMELA excess is rather hard. If the positron fraction continues to rise above 100 GeV, the cosmic-ray electron flux as well may be significantly modified at high energies. Interestingly enough, the ATIC balloon experiment collaboration \cite{8} has recently released the data, showing a clear excess in the total flux of electrons plus positrons peaked around $600 - 700$ GeV, in consistent with the PPB-BETS observation \cite{9}. It is highly suggestive of the same origin for the PAMELA and ATIC/PPB-BETS anomalies, if both are to be accounted for by dark matter. As will be shown in Appendix, the decaying gravitino scenario can actually account for both excesses. We focus on this scenario in this letter.

The gravitino is assumed to be the lightest supersymmetric particle (LSP). In the presence of the $R$-parity violation, its longevity is due to a combination of the Planck-suppressed interactions and a tiny $R$-parity violating coupling. For the latter we assume the so-called bilinear $R$-parity violating coupling, which is parametrized by a dimensionless coupling $\kappa_i$ defined as the ratio of the vacuum expectation values (VEVs) of the sneutrinos to that of the standard-model like Higgs boson, where the subindex $i (= 1, 2, 3)$ denotes the flavor dependence, $e$, $\mu$ and $\tau$ (see Ref. \cite{10} for more details). We assume that the decay of an electron-type dominates over the others throughout this letter, i.e., $\kappa_1 \gg \kappa_2, \kappa_3$, since one cannot fit well the sharp cut-off in the ATIC data otherwise. Then the mass and lifetime of the gravitino should be in the following range to account for the PAMELA and ATIC/PPB-BETS excesses:

$$m_{3/2} \approx (1.2 - 1.4) \text{ TeV},$$  

(1)

$$\tau_{3/2} \approx \mathcal{O} \left(10^{26}\right) \text{ sec}.$$  

(2)

Since all the other supersymmetric (SUSY) particles must be heavier than the gravitino, we expect a typical mass scale for the SUSY particles, especially the gluino, may be out of the reach of LHC. This would be quite discouraging for those who expect SUSY discovery
at LHC. In this letter, however, we show that the gluino mass is bounded from above and is likely within the reach of LHC, if the baryon asymmetry is explained by the thermal leptogenesis scenario.

Let us first discuss the gravitino production in the early universe. The gravitino is produced by thermal scatterings,\(^1\) and the abundance is given by \[ Y_{3/2} \sim 4 \times 10^{-12} g_3^2(T_R) \ln \left( \frac{1.3}{g_3(T_R)} \right) \left( 1 + \frac{M_3^2(T_R)}{3m_{3/2}^2} \right) \left( \frac{T_R}{10^{10} \text{ GeV}} \right) , \] where \( g_3 \) and \( M_3 \) are the \( SU(3)_C \) gauge coupling and the gluino mass, respectively, and both are evaluated at a scale equal to the reheating temperature, \( T_R \), in Eq. (3). For simplicity we have dropped contributions involving the \( U(1)_Y \) and \( SU(2)_L \) gauge interactions, which are subdominant unless the bino and wino masses, \( M_1 \) and \( M_2 \), are much larger than \( M_3 \). Thus, the reheating temperature and the gluino mass are constrained from above for the gravitino abundance not to exceed the observed dark matter abundance, \( \Omega_{DM}h^2 \approx 0.1143 \pm 0.0034 \).\(^2\)

In Fig. 1 we have shown the upper bound on the gluino mass and the reheating temperature, where we have included contributions from \( U(1)_Y \) and \( SU(2)_L \) neglected in Eq. (3). We have imposed a requirement that the gravitino abundance should not exceed the 95\% C.L. upper bound on the dark matter abundance. We used the code SuSpect2.41\(^1\) to calculate the gravitino abundance and the physical spectra for the superparticles, with the following boundary conditions at the GUT scale \( \simeq 2 \times 10^{16} \text{ GeV} \); \( \tan \beta = 10 \), \( \text{sgn}[\mu] > 0 \), the vanishing \( A \)-terms, the universal scalar mass \( m_0 = 2 \text{ TeV} \) for the squarks and sleptons, \( m_{H_u}^2 = m_{H_d}^2 = 5 \times 10^5 \text{GeV}^2 \), and the \( U(1)_Y \) and \( SU(2)_L \) gaugino masses \( M_1 = 3.5 \text{ TeV} \) and \( M_2 = 1.8 \text{ TeV} \). Those parameters are chosen so that the gravitino is LSP\(^2\).

The origin of the baryon asymmetry is a big mystery of the modern cosmology. The thermal leptogenesis scenario\(^1\) is appealing, and the reheating temperature must be higher than about \( 2 \times 10^9 \text{ GeV} \)\(^1\) for the scenario to work. The precise value of the lower limit depends on flavor effects\(^2\) and the mass spectrum of the right-handed neutrinos. The detailed study showed the lower bound as \( T_R \gtrsim 10^9 \text{ GeV} \), which is represented by the horizontal gray band in Fig. 1. We can see from Fig. 1 that the gluino mass is bounded

\(^1\) The inflaton decay may also contribute to the gravitino abundance\(^1,11,12\). We focus on the thermal production, since the non-thermal gravitino production depends on the inflation models.

\(^2\) In the case of \( m_{3/2} = 1.4 \text{ TeV} \), the gravitino is LSP for \( M_3 \gtrsim 600 \text{ GeV} \) for the adopted parameters. This does not affect the following discussion.
FIG. 1: The upper bounds on the gluino mass $M_3$ and the reheating temperature $T_R$, for the gravitino mass $m_{3/2} = 1.2$ TeV (solid red) and 1.4 TeV (dashed blue). The horizontal thick gray (thin orange) line shows the lower bound on $T_R \gtrsim 10^9(1.4 \times 10^9)$ GeV for the thermal leptogenesis to work. Here we set the bino and wino masses to be $M_1 = 3.5$ TeV and $M_2 = 1.8$ TeV. We also show the gluino mass in the low energy, $m_{\text{gluino}} = 1.5, 2.0, 2.5, 3.0$ TeV, as the vertical dotted (green) lines from left to right.

from above, $M_3 \lesssim 1.5$ TeV at the GUT scale, for $T_R$ to satisfy the lower bound $T_R \gtrsim 10^9(1.4 \times 10^9)$ GeV for the thermal leptogenesis to work. Here we set the bino and wino masses to be $M_1 = 3.5$ TeV and $M_2 = 1.8$ TeV. We also show the gluino mass in the low energy, $m_{\text{gluino}} = 1.5, 2.0, 2.5, 3.0$ TeV, as the vertical dotted (green) lines from left to right.

This constraint can be translated into that the gluino mass should be lighter than about 3 TeV in the low energy, taking account of the renormalization group evolution. If we take a slightly tighter bound on $T_R$, say, $T_R \gtrsim 1.4 \times 10^9$ GeV, for which the leptogenesis becomes easier, the gluino mass in the low energy must be lighter than about 2 TeV for $m_{3/2} = 1.2$ TeV. This is a surprising result. If the ATIC anomaly is to be explained by the decay of the gravitino dark matter, we may worry that the SUSY particles are so heavy that they may not be produced at LHC. However, if we believe in the thermal leptogenesis scenario and impose the lower bound $T_R \gtrsim 1.4(1) \times 10^9$ GeV, the gluino mass turned out to be lighter than about 2(3) TeV. This is a good new for those who anticipate the LHC to discover SUSY.

#3 The upper bound on the gluino mass was also discussed in Refs. [21, 22] in different contexts.
Several comments are in order. In the presence of the \( R \)-parity violation, it is quite non-trivial whether the SUSY particles can be detected at LHC, even if they are produced. If the gluino is the standard-model LSP, they will escape the detector before it decays. The collider signature will look like a split SUSY model \[23\], and it is not easy to collect and analyze those collider data properly. On the other hand, if the lightest SUSY particle is the neutralino, we will observe a large missing transverse energy. Note that we cannot impose the GUT relation on the gaugino masses, \( M_1 = M_2 = M_3 \), since the bino would be lighter than the gravitino in the low energy. We have implicitly assumed that \( M_1 \) and \( M_2 \) are not much larger than \( M_3 \), throughout this letter. Our argument will not be significantly modified unless \( M_1 \) and \( M_2 \) are much larger than \( M_3 \).

In order to realize the lifetime \( \kappa_1 \) the \( \kappa_1 \) must be chosen to be \( \kappa_1 \sim 10^{-10} \). Such a tiny \( R \)-parity violation can be realized in a scenario that the \( R \)-parity violation is tied to the \( B - L \) breaking \[24\].

In this letter we have argued that, if the both PAMELA and ATIC/PPB-BETS anomalies are accounted for by the decaying gravitino dark matter, the gluino mass as well as the reheating temperature are bounded from above. In particular, the gluino is likely well within the reach of LHC if we assume the thermal leptogenesis scenario. Unexpected good news from the indirect dark matter experiments may be indicative of a bright future in the new physics search at LHC.

**APPENDIX A: THE DECAYING GRAVITINO AND THE PAMELA AND ATIC/PPB-BETS EXCESSES**

Here let us show that the decaying gravitino of mass 1.2 – 1.4 TeV can account for both the PAMELA and ATIC/PPB-BETS excesses. For simplicity we assume the isothermal distribution for dark matter profile, although our results are not sensitive to the dark matter profile. The electron and positron obey the following diffusion equation,

\[
\nabla \cdot [K(E, \vec{r})\nabla f_e] + \frac{\partial}{\partial E} [b(E, \vec{r})f_e] + Q(E, \vec{r}) = 0, \tag{A1}
\]

where \( f_e \) is the electron number density per unit kinetic energy, \( K(E, \vec{r}) \) a diffusion coefficient, \( b(E, \vec{r}) \) the rate of energy loss, and \( Q(E, \vec{r}) \) a source term of the electrons. The electron and positron fluxes are related to the number density by \( \Phi = (c/4\pi)f \), where \( c \) is the speed...
FIG. 2: The predicted positron fraction for the decaying gravitino dark matter, together with the PAMELA data.

of light. The analytic solution of Eq. (A1) was given in Ref. [25]. In the following analysis we fix $m_{3/2} = 1.2$ TeV and $\tau_{3/2} = 1.0 \times 10^{26}$ sec. See Ref. [26] for the values of the diffusion constant and the energy loss rate, and the details of the diffusion model parameters.

The bilinear $R$-parity violating operators depend on the lepton flavor. We consider the gravitino decay of the electron-type, that is, $\kappa_1 \gg \kappa_2, \kappa_3$. In Fig. 2 we show the positron fraction for the three different diffusion models, M1, MED and M2, together with the PAMELA data. The MED and M1 models give a better fit to the data. Similarly we show the predicted electron plus positron flux together with the ATIC data in Fig. 3. We have adopted the background for the primary electrons and the secondary electrons and positrons given in Ref. [27, 28], with a normalization factor $k_{bg} = 0.75$ for the primary electron flux. As can be seen from Figs. 2 and 3 the gravitino dark matter can nicely fit both the PAMELA and ATIC data.

For the $R$-parity violating operators of the $\mu-$ and $\tau-$type, the PAMELA data may be explained, while they give a very poor fit to the ATIC data.
FIG. 3: The predicted electron plus positron flux for the decaying gravitino dark matter, together with the ATIC data.

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