Antiprotons and Antideuterons from Gravitino Decay

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Motivation for Decaying Gravitino Dark Matter

Antiprotons from Gravitino Decays

Antideuterons from Gravitino Decays

Trilinear $R$-Parity Violation

Conclusions
Motivation for
Decaying Gravitino Dark Matter
What Do We Know about Dark Matter?

- Observed on various scales through its gravitational interaction
- Contributes significantly to the energy density of the universe

Dark matter properties known from observations:

- No electromagnetic and strong interactions
- At least gravitational and at most weak-scale interactions
- Non-baryonic
- Cold (maybe warm)
- Extremely long-lived but can be unstable!
Gravitino Dark Matter: Stable or Unstable?

▶ Stable Gravitino Dark Matter
- Typical in gauge mediation with conserved $R$-parity
- No direct detection signal expected: $\sigma_N \sim M_{Pl}^{-4}$
- No annihilation signal expected: $\sigma_{ann} \sim M_{Pl}^{-4}$
- Collider signals from long-lived NLSP expected
- Long-lived NLSP can be in conflict with BBN

▶ Unstable Gravitino Dark Matter
- Typical candidate in models with $R$-parity violation
- Lifetime larger than the age of the universe
- No direct detection signal expected: $\sigma_N \sim M_{Pl}^{-4}$
- Decays could lead to observable cosmic-ray signals
- Collider signals from long-lived NLSP expected
Motivation for Decaying Gravitino Dark Matter

Models with Gravitino DM and $R$-Parity Violation

- **Bilinear $R$-parity violation (BRpV)**
  - $R$-parity violation is source of neutrino masses and mixings
  - Predictive model: gravitino mass constrained to be below few GeV
  
  [Takayama, Yamaguchi (2000), Restrepo et al. (2011)]

- **”μ from ν” Supersymmetric SM ($\mu\nu$SSM)**
  - Electroweak see-saw mechanism for neutrino masses
  - Solves the $\mu$-problem similar to the NMSSM
  - Predictive model: gravitino mass constrained to be below few GeV

  [López-Fogliani, Muñoz (2005)]

- **Bilinear $R$-parity violation from $B$–$L$ breaking**
  - Consistent gravitino cosmology with thermal leptogenesis and BBN
  - $\mathcal{O}(10)$ GeV $< m_{3/2} < \mathcal{O}(500)$ GeV, gluino mass below a few TeV

  [Buchmüller et al. (2007)]

- **Trilinear $R$-parity violation**
  - Phenomenological study, trilinear terms generically expected without $R$-parity

  [Moreau et al. (2001), Lola et al. (2007)]
Motivation for Decaying Gravitino Dark Matter

Gravitino Dark Matter with Bilinear $R$-Parity Violation

- Bilinear $R$-parity violation:
  - $W_{R_p} = \mu_i H_u L_i$, $-\mathcal{L}_{R_p}^{\text{soft}} = B_i H_u \tilde{\ell}_i + m_{H_d\ell_i}^2 H_d^* \tilde{\ell}_i + \text{h.c.}$
  - Only lepton number violated $\Rightarrow$ Proton remains stable!

- $R$-parity violation can be parametrized by sneutrino VEV: $\xi = \frac{\langle \tilde{\nu} \rangle}{\nu}$

- Gravitino LSP becomes unstable:
  - Two-body decay into $\gamma\nu$
  - For heavier gravitinos also $Z\nu, W\ell, h\nu$ $\Rightarrow$ $\bar{p}$ and $\bar{d}$

- Gravitino decay suppressed by Planck scale and small $R$-parity violation
  - $\tau_{3/2} \approx \frac{48 \pi M_{\text{Pl}}^2}{\xi^2 m_{3/2}^3} \approx 5.7 \times 10^{28} \text{ s} \left(\frac{10^{-10}}{\xi}\right)^2 \left(\frac{100 \text{ GeV}}{m_{3/2}}\right)^3$
  - The gravitino lifetime by far exceeds the age of the universe ($\tau_{3/2} \gg 10^{17} \text{ s}$)
Gravitino Branching Ratios

- Four two-body final states possible: $\gamma \nu$, $Z \nu$, $W \ell$ and $h \nu$
  
  - Branching ratios are independent of strength of $R$-parity violation
  
  - Exact ratio between channels is model-dependent, in particular $\gamma \nu$

\[
M_1 = 1.1 \, m_{3/2} \quad M_2 = 1.1 \, m_{3/2} \quad \mu = 1.1 \, m_{3/2}
\]
Antiprotons from Gravitino Decay
Gravitino decays produce stable cosmic rays: $\gamma, \, e, \, p, \, d, \, \nu_{e/\mu/\tau}$

- $\bar{p}$ production simulated in PYTHIA 6.4 ($5 \times 10^7$ events per mass and channel)
- No $\bar{p}$ from $\gamma\nu$; $\sim 1.6 \bar{p}$ per decay to $Z\nu$ or $W\ell$; $\sim 2.4 \bar{p}$ per decay to $h\nu$

\[
\frac{dN}{dT} = \text{BR}(Z\nu) \frac{dN_{Z\nu}}{dT} + \text{BR}(W\ell) \frac{dN_{W\ell}}{dT} + \text{BR}(h\nu) \frac{dN_{h\nu}}{dT}
\]
Cosmic-Ray Propagation

- Cosmic rays from gravitino decays propagate through the Milky Way halo

Experiments observe spectra of cosmic rays at Earth
Cosmic-Ray Propagation

- Diffusion equation for cosmic-ray density $\psi$:

$$\vec{\nabla} \cdot (\vec{V}_c \psi - K_0 \beta p^\delta \vec{\nabla} \psi) + 2 h \delta(z) \partial_E (b_{\text{loss}} \psi - D_{EE} \partial_E \psi)$$

$$= Q^{\text{prim}} + 2 h \delta(z) (Q^{\text{sec}} + Q^{\text{ter}}) - 2 h \delta(z) \Gamma^{\text{ann}} \psi$$

+ boundary conditions

- $\vec{V}_c$: velocity of the convective wind from stars in the Galactic plane
- $K_0 \beta p^\delta$: spatial diffusion from irregularities of the Galactic magnetic field
- $b_{\text{loss}}$: energy losses from interaction with interstellar gas
- $D_{EE}$: coefficient for diffusion in energy
- $Q^{\text{sec}}$: antiprotons from collisions of cosmic-ray protons or $\alpha$ with interstellar gas
- $Q^{\text{ter}}$: antiprotons from inelastic collisions of antiprotons with interstellar gas
- $\Gamma^{\text{ann}}$: annihilation of antiprotons with interstellar hydrogen

- Gravitino decays are a primary source for $\bar{p}$ and $\bar{d}$ in the Galactic halo:

$$Q^{\text{prim}}(T, r) = \frac{\rho_{\text{halo}}(r)}{m_{3/2} \tau_{3/2}} \frac{dN}{dT}$$
Cosmic-Ray Propagation

- Two approaches to solve diffusion equation:
  - Numerical: GALPROP, DRAGON
  - Semi-analytical: Two-zone diffusion model for the Milky Way (USINE)

- Propagation parameters constrained by secondary-to-primary ratios

- Typical approach: 3 parameter sets to estimate uncertainty

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- Our approach: Scan over all allowed propagation parameters
  - Roughly 1600 parameter sets
  - Allows to reliably estimate the uncertainty from cosmic-ray propagation

[Sources: [Maurin et al. (2001)]]
Gravitino Decay Signals in Antiproton Spectra

- Observed antiproton spectrum well described by astrophysical background
  - No need for contribution from dark matter

- Propagation uncertainty roughly one order of magnitude for DM signal
  - Expected to be improved by AMS-02 cosmic-ray data
Limits on the Gravitino Lifetime

- Bounds on gravitino lifetime derived from latest PAMELA antiproton data

- Gravitino lifetimes below a few times $10^{28}$ s to $10^{26}$ s excluded
  - Scan over propagation parameters can change highest/lowest limits by up to 60 %
  - AMS-02 $\bar{p}$ data and low-energy GAPS $\bar{p}$ data are highly anticipated
Antiprotons from Gravitino Decay

Comparison with other Cosmic-Ray Limits

- Antiproton constraints dominate in the 100 GeV to 10 TeV mass range
  - Gamma line searches dominate for low masses; above $m_W$ branching ratio drops
  - EGB limits could improve with subtraction of astrophysical contributions
  - Neutrinos become relevant around 10 TeV; will improve with full IceCube data
  - Antiprotons exclude gravitino explanation of AMS-02 positrons [Ibe et al. (2013)]
Limits on the Amount of $R$-Parity Violation

- Gravitino lifetime limits constrain $R$-parity violation:

$$\frac{\tau_{3/2}}{2} \propto \frac{M_{Pl}^2}{\xi^2 m_{3/2}^3}$$

Antiprotons and Antideuterons from Gravitino Decay

Antiproton searches set strong limits on $R$-parity violation!
Antideuterons from Gravitino Decay
Coalescence Momentum: Total $\bar{d}$ Yield from $Z$ Decays

- Use constraints from ALEPH on $\bar{d}$ production in hadronic $Z$ decays
  - Appropriate to constrain $\bar{d}$ formation in gravitino two-body decays ($Z\nu$, $W\ell$, $h\nu$)

Simulated $10^9$ $Z$ decays with PYTHIA 6.4 to determine $p_0$

- only $p > p_0$: $p_0 = 173^{+18}_{-19}$ MeV
- $p > p_0$ and $t = 0$: $p_0 = 203^{+20}_{-25}$ MeV
Better experimental data needed to understand $\bar{d}$ formation well

Correct coalescence mechanism chosen by theoretical arguments

- $\bar{p}$ and $\bar{n}$ need to be close in space and momentum space to form $\bar{d}$ (red curve)
Antideuteron Yield in Gravitino Decays

- Antideuteron yield is independent of gravitino mass, $\mathcal{O}(10^{-4})$ per decay
- Gravitino two-body decays produce on-shell gauge/Higgs bosons
- Boosted spectra of $\bar{d}$ formation in $Z/W/h$ boson fragmentation in their rest frame
- Spherical coalescence clearly leads to unphysical behavior
- Spatial coalescence condition ($t = 0$) has negligible impact on total yields

![Graph showing the yield of deuterons and antideuterons as a function of dark matter mass.](Delahaye & Grefe (2014))

- Preliminary results
- $t = 0$ and $\Delta p < p_0 = 203^{+20}_{-25}$ MeV
- Only $\Delta p < p_0 = 173^{+18}_{-19}$ MeV
- Spherical coalescence, $p_0 = 141^{+14}_{-15}$ MeV
Antideuterons from Gravitino Decay

Final State Particle Spectra: Antideuterons

- Gravitino decays produce stable cosmic rays: $\gamma$, $e$, $p$, $d$, $\nu_{e/\mu/\tau}$
- $\bar{d}$ production simulated in PYTHIA 6.4 ($10^9$ events per mass value and channel)
- No $\bar{d}s$ from $\gamma\nu$; $Z\nu$ and $W\ell$ are very similar; $h\nu$ a factor $\sim 2$ larger
- Uncertainty of $\sim \pm 30\%$ in the normalization from $p_0$ uncertainty
- Factor of $\sim 2$ difference between Monte Carlo generators

[Dal et al. (2012)]
AMS-02 and GAPS are potentially sensitive to lower mass gravitinos

- Propagation uncertainty roughly one order of magnitude for DM signal
- Propagation estimated using parametrization of Cirelli et al. 2010
- More detailed propagation study (similar to $\bar{p}$ case) is work in progress
Gravitino Decay Signals in Antideuteron Spectra

- Lifetime fixed to lower lifetime limits from antiproton analysis (see slide 15)
  - Antideuteron propagation is very similar to antiproton propagation
  - Antideuteron flux from gravitino decay may exceed the astro BG by a factor 10
  - Detection prospects are not very optimistic with current experimental designs
  - Flux uncertainty coming from uncertainty on $p_0$ is $\sim \pm 30\%$
Trilinear $R$-Parity Violation
Gravitino DM with Trilinear $R$-Parity Violation

- **Trilinear $R$-parity violation:**
  - \[ W_{R_p} = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k + \text{soft terms} \]
  - Both, lepton and baryon number may be violated
    \[ \Rightarrow \quad \text{Proton stability has to be guaranteed!} \]

- **Gravitino undergoes three-body decays:**
  - $\nu \ell^+ \ell^-$, $\nu d \bar{d}$, $\ell^- u \bar{d}$, $\bar{u} \bar{d} \bar{d}$
  - Flavor structure model dependent
  - No antideuterons from leptonic-only channels

- **Gravitino lifetime:**
  - $\tau_{3/2} \propto \frac{1}{\lambda^2} \frac{1}{m_{3/2}} \frac{\tilde{m}^4}{m_{3/2}^4}$
Antideuterons from Trilinear Gravitino Decays

- Decay spectra depend on flavor structure
- Heavier gravitinos produce more antideuterons (different from bilinear)
- Semi-leptonic final states produce significantly less antideuterons

Purely hadronic operators allow a $\bar{d}$ signal within the sensitivity of GAPS and AMS-02 while being compatible with $\bar{p}$ constraints
Conclusions
Conclusions

- Gravitino in models with $R$-parity violation is a well-motivated DM candidate
- Decaying gravitino DM can be probed through various cosmic-ray channels
- Strong constraints on the lifetime from PAMELA antiproton data
- Other cosmic-ray channels provide complementary constraints
- Antideuteron flux larger than astrophysical background is possible
- AMS-02 and GAPS appear not to have sufficient sensitivity for a detection
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Thanks for your attention!