Antiprotons and Antideuterons from Gravitino Decay

Universität Hamburg
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Michael Grefe

II. Institut für Theoretische Physik
Universität Hamburg

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invisibles neutrinos, dark matter & dark energy physics

MARIE CURIE ACTIONS

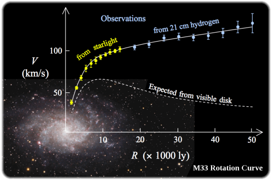
Outline

- Motivation for Decaying Gravitino Dark Matter
- Antiprotons from Gravitino Decays
- Antideuterons from Gravitino Decays
- Trilinear *R*-Parity Violation
- Conclusions

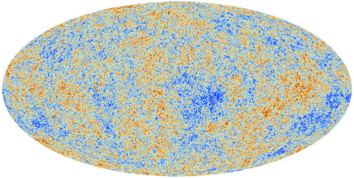
Motivation for Decaying Gravitino Dark Matter

What Do We Know about Dark Matter?

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



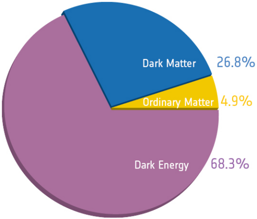
[M. Whittle]



[ESA / Planck Collaboration]

[NASA / Clowe *et al.*]

- 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!



[ESA / Planck Collaboration]

Gravitino Dark Matter: Stable or Unstable?

▶ Stable Gravitino Dark Matter

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

[The Particle Zoo]

▶ Unstable Gravitino Dark Matter

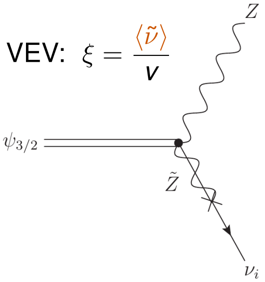
- Typical candidate in models with R-parity violation
- Lifetime larger than the age of the universe
- No direct detection signal expected: $\sigma_N \sim M_{\rm Pl}^{-4}$
- Decays could lead to observable cosmic-ray signals
- Collider signals from long-lived NLSP expected

Models with Gravitino DM and *R*-Parity Violation

- **Bilinear *R*-parity violation (BRpV)** [Takayama, Yamaguchi (2000), Restrepo *et al.* (2011)]
  - *R*-parity violation is source of neutrino masses and mixings
  - Predictive model: gravitino mass constrained to be below few GeV
- **"μ from ν" Supersymmetric SM ($\mu\nu$SSM)** [López-Fogliani, Muñoz (2005)]
  - Electroweak see-saw mechanism for neutrino masses
  - Solves the μ-problem similar to the NMSSM
  - Predictive model: gravitino mass constrained to be below few GeV
- **Bilinear *R*-parity violation from *B*–*L* breaking** [Buchmüller *et al.* (2007)]
  - 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
- **Trilinear *R*-parity violation** [Moreau *et al.* (2001), Lola *et al.* (2007)]
  - Phenomenological study, trilinear terms generically expected without *R*-parity

Gravitino Dark Matter with Bilinear *R*-Parity Violation

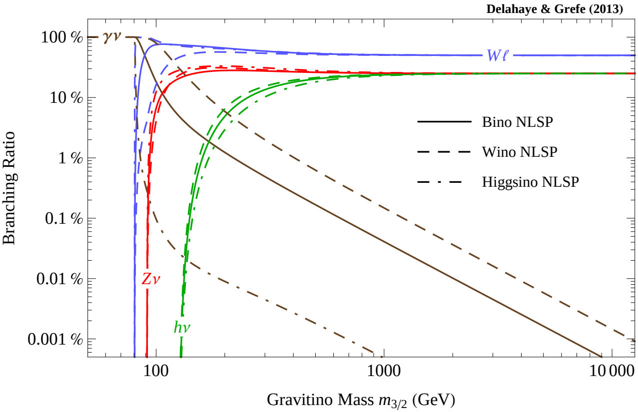
- Bilinear *R*-parity violation:
  - $W_{\not R_p} = \mu_i H_u L_i, \qquad -\mathcal{L}^{\text{soft}}_{\not R_p} = B_i H_u \tilde{\ell}_i + m^2_{H_d \ell_i} H_d^* \tilde{\ell}_i + \text{h.c.}$
  - Only lepton number violated $\Rightarrow$ Proton remains stable!
- *R*-parity violation can be parametrized by sneutrino VEV: $\xi = \dfrac{\langle \tilde{\nu} \rangle}{v}$
- 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
  - $\tau_{3/2} \simeq \dfrac{48\,\pi\, M_{\text{Pl}}^2}{\xi^2\, m_{3/2}^3} \approx 5.7 \times 10^{28}\,\text{s} \left(\dfrac{10^{-10}}{\xi}\right)^2 \left(\dfrac{100\,\text{GeV}}{m_{3/2}}\right)^3$
  - The gravitino lifetime by far exceeds the age of the universe ($\tau_{3/2} \gg 10^{17}$ 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 $\gamma\nu$

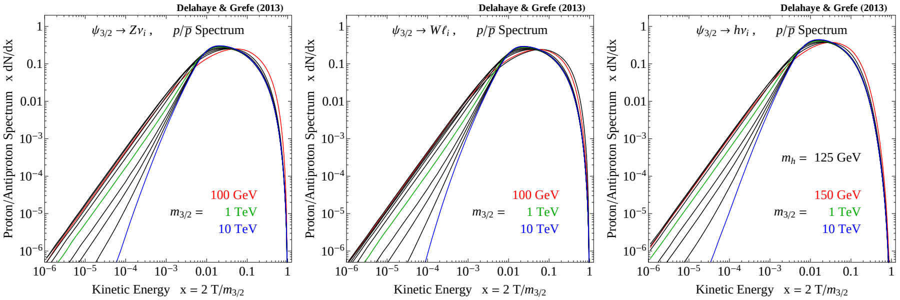


$M_1 = 1.1\, m_{3/2}$
$M_2 = 1.1\, m_{3/2}$
$\mu = 1.1\, m_{3/2}$

Antiprotons from Gravitino Decay

Final State Particle Spectra: Antiprotons

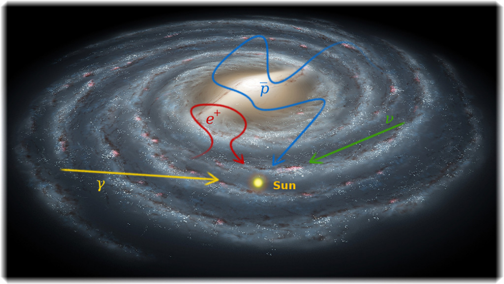
- Gravitino decays produce stable cosmic rays: γ, e, p, d, $\nu_{e/\mu/\tau}$
  - $\bar{p}$ production simulated in PYTHIA 6.4 (5×10^7 events per mass and channel)
  - No $\bar{p}$ from $\gamma\nu$; ~ 1.6 $\bar{p}$ per decay to $Z\nu$ or $W\ell$; ~ 2.4 $\bar{p}$ per decay to $h\nu$



$$\frac{dN}{dT} = \mathrm{BR}(Z\nu)\,\frac{dN_{Z\nu}}{dT} + \mathrm{BR}(W\ell)\,\frac{dN_{W\ell}}{dT} + \mathrm{BR}(h\nu)\,\frac{dN_{h\nu}}{dT}$$

Cosmic-Ray Propagation

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

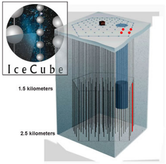


- Experiments observe spectra of cosmic rays at Earth

[Fermi Coll.]

[PAMELA Coll.]

[AMS Coll.]



[IceCube Coll.]

[GAPS Coll.]

Cosmic-Ray Propagation

- Diffusion equation for cosmic-ray density ψ:

$$\vec{\nabla} \cdot (\vec{V}_c \, \psi - K_0 \, \beta \, p^\delta \, \vec{\nabla}\psi) + 2\,h\,\delta(z)\,\partial_E\,(b_{\text{loss}}\,\psi - D_{EE}\,\partial_E\psi)$$
$$= Q^{\text{prim}} + 2\,h\,\delta(z)\left(Q^{\text{sec}} + Q^{\text{ter}}\right) - 2\,h\,\delta(z)\,\Gamma^{\text{ann}}\,\psi$$
$$+ \text{boundary conditions}$$

  - $\vec{V}_c$: 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_{loss}: energy losses from interaction with interstellar gas
  - D_{EE}: coefficient for diffusion in energy
  - Q^{sec}: antiprotons from collisions of cosmic-ray protons or α with interstellar gas
  - Q^{ter}: antiprotons from inelastic collisions of antiprotons with interstellar gas
  - Γ^{ann}: annihilation of antiprotons with interstellar hydrogen

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

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

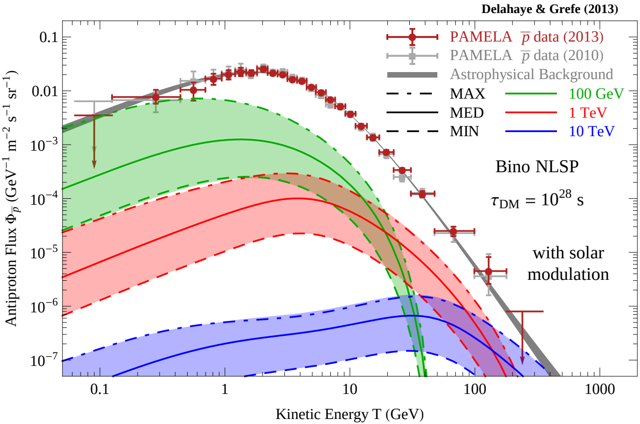
Cosmic-Ray Propagation

- 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

	L (kpc)	K_0 (kpc^2/Myr)	δ	$\lVert\vec{V}_c\rVert$ (km/s)	V_a (km/s)
MIN	1	0.0016	0.85	13.5	22.4
MED	4	0.0112	0.70	12	52.9
MAX	15	0.0765	0.46	5	117.6

- Our approach: Scan over all allowed propagation parameters
  - Roughly 1600 parameter sets [Maurin *et al.* (2001))]
  - Allows to reliably estimate the uncertainty from cosmic-ray propagation

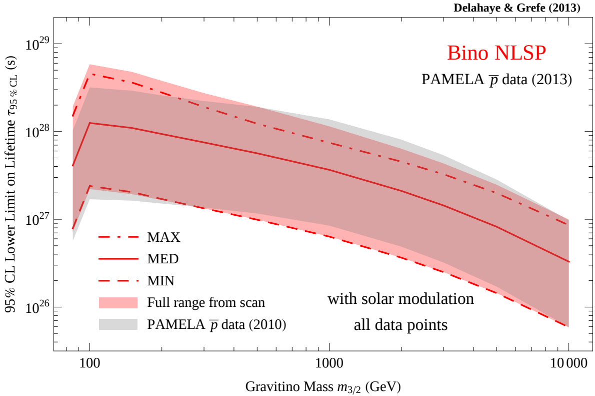
Gravitino Decay Signals in Antiproton Spectra



- 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

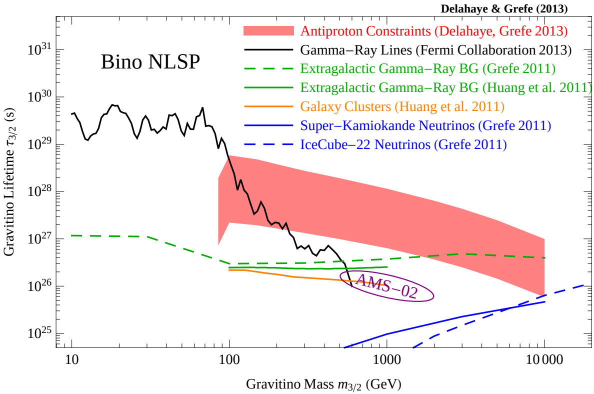
Limits on the Gravitino Lifetime

- 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

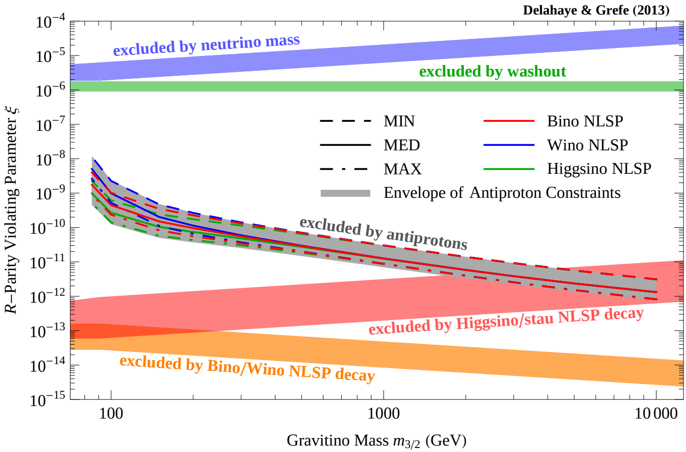
Comparison with other Cosmic-Ray Limits



- 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: $\tau_{3/2} \propto \frac{M_{\text{Pl}}^2}{\xi^2\, m_{3/2}^3}$

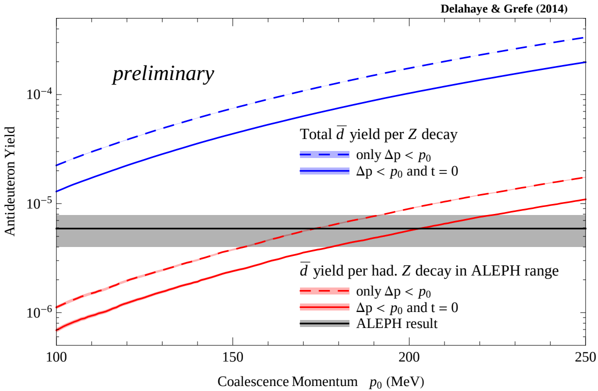


Antiproton searches set strong limits on *R*-parity violation!

Antideuterons from Gravitino Decay

Coalescence Momentum: Total $\bar{d}$ Yield from Z Decays

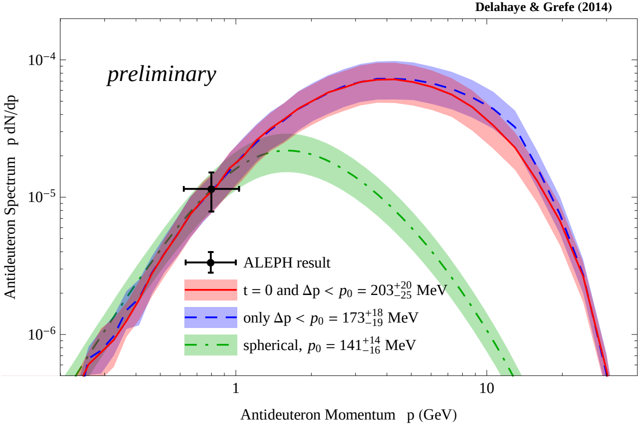
- Use constraints from ALEPH on $\bar{d}$ production in hadronic Z decays
  - Appropriate to constrain $\bar{d}$ formation in gravitino two-body decays ($Z\nu$, $W\ell$, $h\nu$)



- 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

Coalescence Momentum: $\bar{d}$ Spectrum from Z Decays

- Better experimental data needed to understand $\bar{d}$ formation well

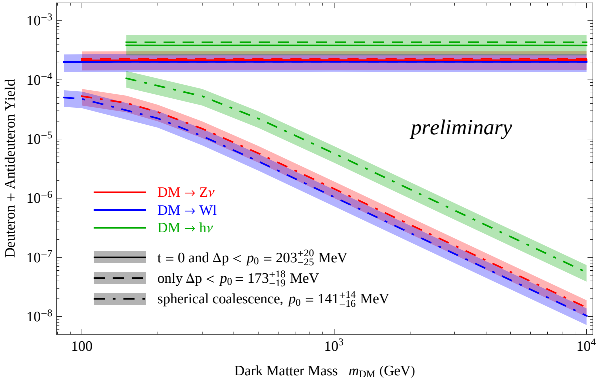


- Correct coalescence mechanism chosen by theoretical arguments
  - $\bar{p}$ and $\bar{n}$ need to be close in space and momentum space to form $\bar{d}$ (red curve)

Antideuteron Yield in Gravitino Decays

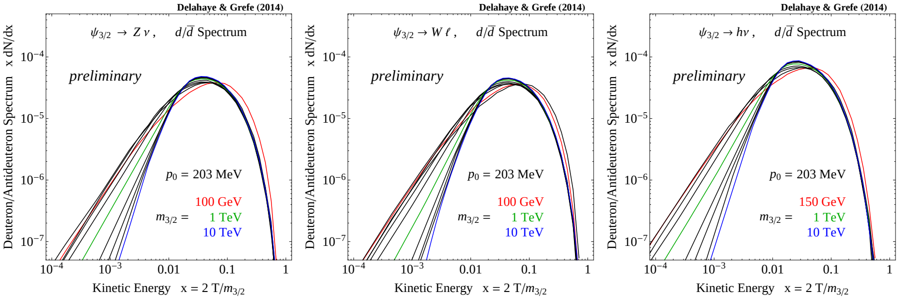
- Antideuteron yield is independent of gravitino mass, $\mathcal{O}(10^{-4})$ per decay
  - Gravitino two-body decays produce on-shell gauge/Higgs bosons
  - Boosted spectra of $\bar{d}$ formation in $Z/W/h$ boson fragmentation in their rest frame
  - Spherical coalescence clearly leads to unphysical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

Delahaye & Grefe (2014)

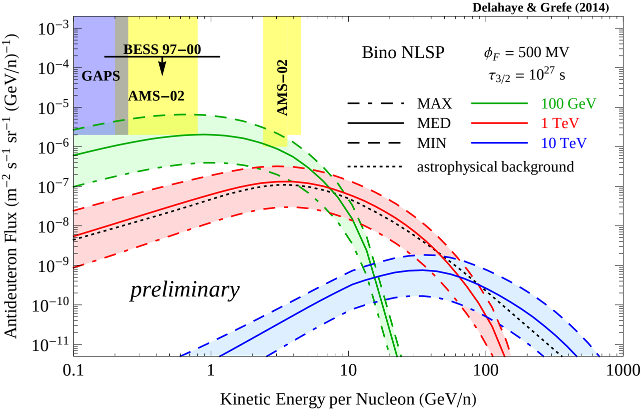


Final State Particle Spectra: Antideuterons

- Gravitino decays produce stable cosmic rays: γ, 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 ~ 2 larger
  - Uncertainty of $\sim \pm 30\%$ in the normalization from p_0 uncertainty
  - Factor of ~ 2 difference between Monte Carlo generators [Dal *et al.* (2012)]

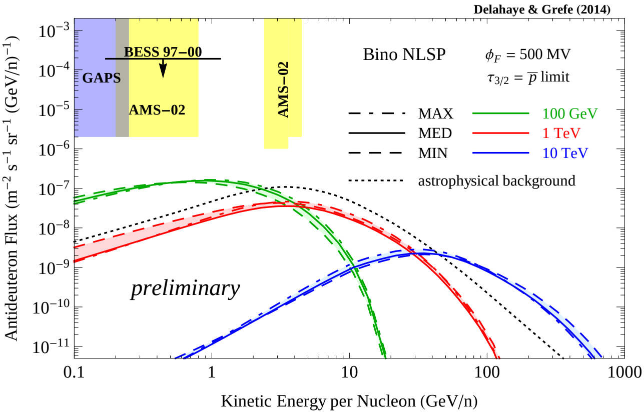


Gravitino Decay Signals in Antideuteron Spectra



- 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 $\sim \pm 30\%$

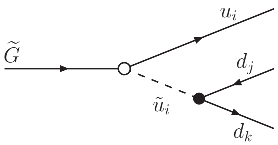
Trilinear *R*-Parity Violation

Gravitino DM with Trilinear *R*-Parity Violation

- Trilinear *R*-parity violation:
  - $W_{\not R_p} = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k \quad + \quad$ soft terms
  - Both, lepton and baryon number may be violated

    $\Rightarrow$ 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

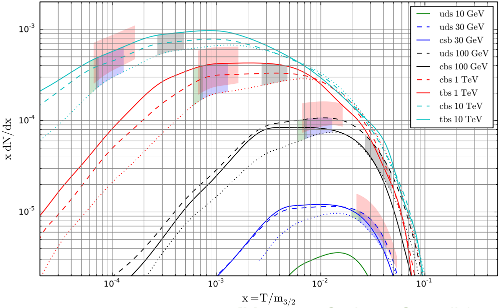


[Monteux, Carlson, Cornell (2014)]

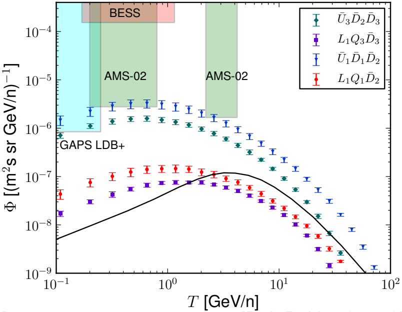
- Gravitino lifetime:
  - $\tau_{3/2} \propto \frac{1}{\lambda^2} \frac{1}{m_{3/2}^3} \frac{\tilde{m}^4}{m_{3/2}^4}$

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



[Monteux, Carlson, Cornell (2014)]



[Dal, Raklev (2014)]

- 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!