Antideuterons from Dark Matter and Hadronization Uncertainties

Based on arXiv:1207.4560 [hep-ph], arXiv:1402.6259 [hep-ph]

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From Higgs to Dark Matter 2014,
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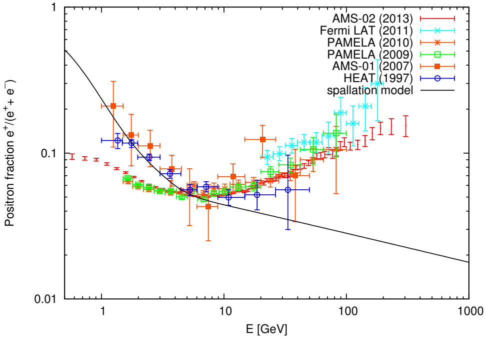
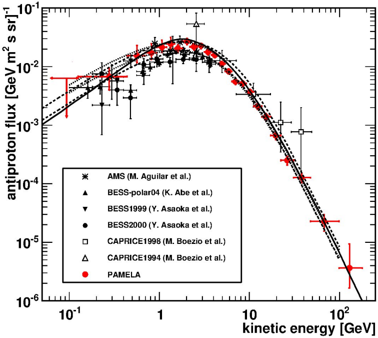
Indirect DM Detection

- Dark matter couples weakly to ordinary matter by definition ⇒ Low decay/annihilation rate ⇒ Small cosmic ray signature
- Need particle channels where the signal is not drowned by background
- Neutral cosmic rays (ν, γ)
  - Unaffected by Galactic magnetic fields. No deflection
  - Background can be overcome by looking at DM rich targets
- Charged cosmic rays
  - Diffusion thrugh turbulent magnetic fields. No directional information
  - Low background is a must. Antimatter

Status: Positrons and Antiprotons

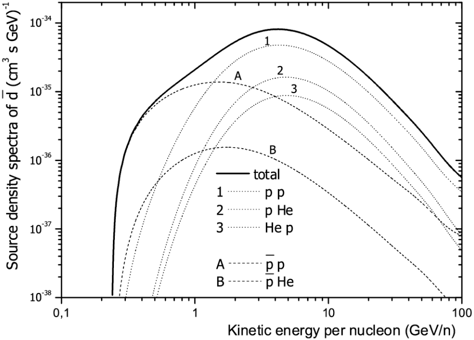




- Large excess of positrons at high energies – pulsar source?
- No sign of an excess in the antiproton channel
- Logical next step? Antinuclei

The Antideuteron Channel

- Lightest antinucleus: $\bar{p}\bar{n}$
- Low background at low energies from cosmic ray collisions on interstellar matter

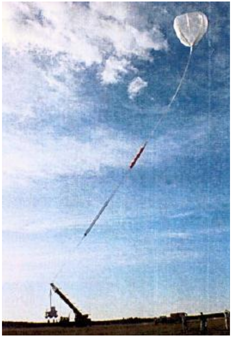


Duperray *et al.*, arXiv:astro-ph/0503544

- Energy losses during propagation populate the spectrum at low energies. The picture after propagation is less extreme.

Antideuteron detection

The Past



The BESS experiment. Current upper limit on the antideuteron flux.

The Present

The AMS-02 experiment. Currently collecting data onboard the ISS.

The Future

The upcoming GAPS dedicated antideuteron balloon experiment.

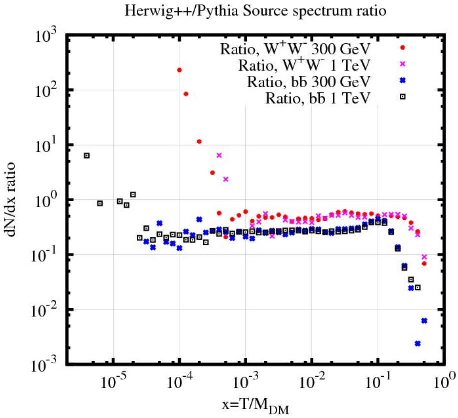
Antideuteron Formation

- Formation of atomic nuclei not handled in Monte Carlos. Simple model: Coalescence
  - Nucleons with $\Delta p < p_0$ coalesce to form a nucleus
  - Additional condition: Close in position space – weakly decaying particles considered stable
  - p_0 calibrated against experimental data, typically large spread in best fit p_0-values between experiments and Monte Carlos
  - $p_0 \sim 100$ MeV$\lesssim \Lambda_{\text{QCD}}$, highly sensitive to 2-particle correlations from hadronization

Hadronization and antideuterons

My work: Estimate uncertainty from hadronization arXiv:1207.4560 [hep-ph]

- Comparison of antideuteron spectra generated with Herwig++ and Pythia
- Large discrepancies, especially at high and low energies



Tuning of Hadronization Models

- Several free parameters in hadronization models tuned to fit experimental data
- Not specifically tuned to produce correct (anti)nucleon spectra or 2-particle correlations
- My work: Tune 3 most important Herwig++ hadronization parameters + p_0 to reproduce experimenal antideuteron spectra

  arXiv:1402.6259 [hep-ph]
- Antideuteron data: ALEPH, ZEUS, CLEO, antiproton data: ALEPH, OPAL
- 10^9 Monte Carlo events required per parameter point. Challenging to find best fit point with finite CPU time

Best Fit Parameters

Some 40000 CPU core hours later...

Parameter	Default value	Best fit value	Uncertainty $(1\sigma)^*$
p_0 [MeV]	–	143.2	$^{+6.2}_{-5.5}$
`ClMaxLight`	3.25	3.03	$^{+0.18}_{-0.15}$
`PSplitLight`	1.20	1.31	$^{+0.19}_{-0.32}$
`PwtDIquark`	0.49	0.48	$^{+0.15}_{-0.04}$

Best fit $\chi^2/\mathrm{d.o.f} = 10.6/14.2$

- Likelihood function in the parameters can be used to find uncertainty on antideuteron flux from tuned parameters

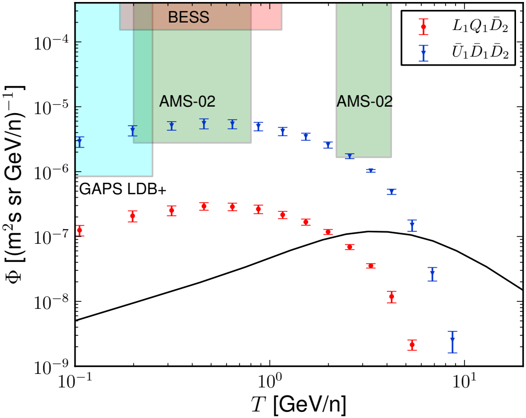
[*] Non-parabolic uncertainty calculated using the `MINOS` algorithm in `Minuit`

Application: Gravitino Dark Matter

- Gravitino: SUSY partner of the Graviton
- R-parity conservation: Gravitino LSP ”absolutely” stable
- R-parity violation (RPV): Gravitino is unstable but long-lived. Operators of interest: $\lambda'_{ijk} L_i Q_j \bar{D}_k$, $\lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$
- $\bar{U}_i \bar{D}_j \bar{D}_k$ operators allows decays into 3 antiquarks. Larger antideuteron yield than typical DM decays/annihilations (to $q\bar{q}$).
- $\Phi_{\bar{d}} \propto \Gamma \propto \lambda^2$; results can easily be re-scaled to any value of λ

Antideuteron Spectrum Near Earth

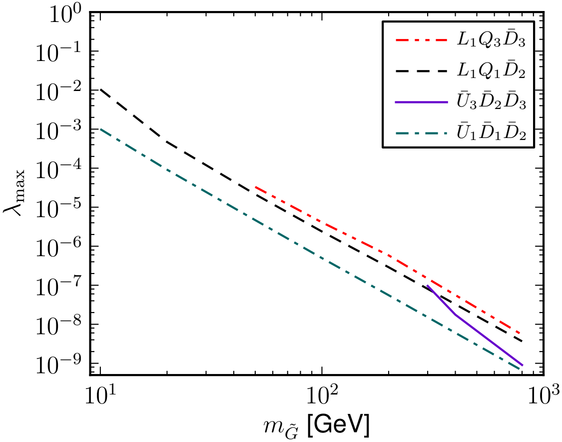
- Propagation: NFW DM density profile, 'med' set of diffusion parameters



- $m_{\tilde{G}} = 50$ GeV, $\lambda = 10^{-5}$
- Flux increases with increasing mass and RPV coupling
- Can set limits on mass and RPV coupling from experiments

Limits on RPV couplings

Prospective upper limits from GAPS



- 95% CL exclusion limits assuming 0 observed events
- Factor $2-4$ Stronger than existing limits on RPV couplings

Summary

- Antideuteron channel suitable for DM searches due to low background
- Antideuteron spectrum is highly sensitive to hadronization model, factor ~ 3 difference between Herwig++ and Pythia
- Tuning necessary for giving a consistent description
- Uncertainty from tuned parameters of factor < 2 after re-tuning
- Antideuterons can be used to set stronger limits on RPV couplings

Backup Slides

Backup Slides

Tuned Hadronization Parameters

Tuned Herwig++ hadronization parameters:

- `ClMaxLight`: Involved in specifying mass threshold for fission of clusters of light quarks
- `PSplitLight`: Controls mass distribution of clusters (of light quarks) produced in cluster fission
- `PwtDIquark`: Controls the probability of creating a diquark pair during cluster decay

Experiments: Number of bins

Experiment	N_{bins}
ALEPH	1
CLEO	5
ZEUS	3
CERN ISR	4+4
ALICE	9
ALEPH, $p/\bar{p}$	26

χ^2 from ALEPH proton data weighted down by factor 1/25 to keep it from dominating the parameter determination

Gravitino Dark Matter

- Thermal production of Gravitinos during reheating can give the right relic density

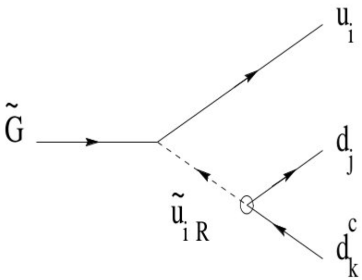
$$\Omega_{\tilde{G}} h^2 \simeq 0.21 \left(\frac{T_R}{10^{10}\ \text{GeV}} \right) \left(\frac{100\ \text{GeV}}{m_{\tilde{G}}} \right) \left(\frac{m_{\tilde{g}}(\mu)}{1\ \text{TeV}} \right)^2$$

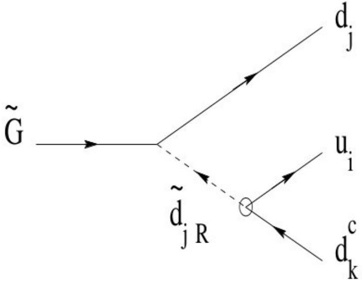
Bolz, Brandenburg, Buchmuller; arXiv:hep-ph/0012052

- The reheating temperature T_R is weakly constrained, thus so is $m_{\tilde{G}}$

Gravitino RPV decays

Tree-level Feynman diagrams for decays through $\bar{U}_i\bar{D}_j\bar{D}_k$-operators

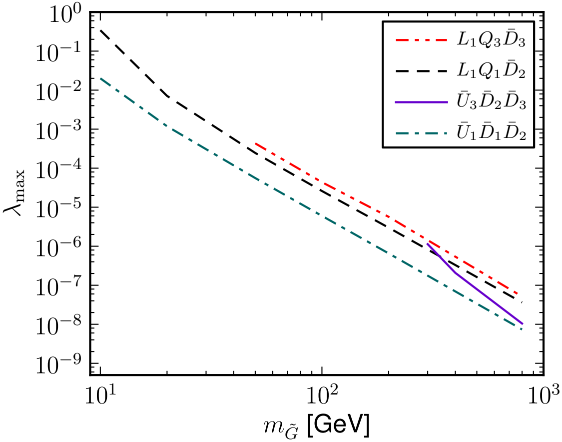




Circle indicates RPV coupling

Coupling limits: BESS

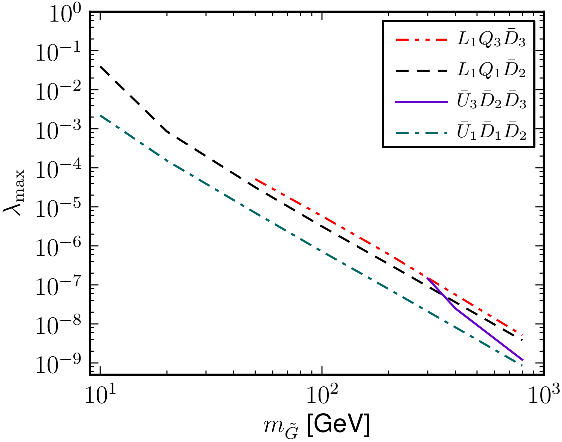
Current upper limits from GAPS



- 95% CL exclusion limits assuming 0 observed events
- Somewhat weaker than existing limits on RPV couplings from PAMELA $\bar{p}$ data

Coupling limits: AMS-02

Prospective upper limits from AMS-02



- 95% CL exclusion limits assuming 0 TOF events and 1 RICH event
- $\lesssim 1$ expected background event in the RICH detector
- $L_iQ_j\bar{D}_k$: Slightly weaker than $\bar{p}$ limits at low energies, roughly equal above a few hundred GeV
- $\bar{U}_i\bar{D}_j\bar{D}_k$: Factor ~ 1.5 Stronger than $\bar{p}$ limits