Antideuterons as a Dark Matter signature

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27.09.2012

Detection of Dark Matter

- Assume Dark Matter in the form of unknown particles
- Most DM candidates have couplings to standard model particles, allowing them to scatter or decay
- 3 ways to explore:
  - Missing energy signatures in collider experiments
  - Direct detection: Scattering on baryonic matter
  - Indirect detection: Observation of DM decay/annihilation products as cosmic rays

Indirect detection: Antideuterons

- Dark matter couples weakly to ordinary matter by definition $\Rightarrow$ Low decay/annihilation rate $\Rightarrow$ Small cosmic ray signature
- Need particle channels where the signal is not drowned by background. Antimatter
- Antideuterons:
  - Lightest antinucleus: $\bar{p}\bar{n}$
  - Very difficult to produce in cosmic ray collisions on interstellar matter
- So far only an upper limit exists on the cosmic ray antideuteron spectrum. Ongoing experiment: AMS-02

Fancy picture of AMS-02

Calculating the spectrum

- Same tree level processes are relevant for most DM types. Examples:
  - $XX \to W^+W^-$ or $XX \to q\bar{q}$ for annihilating DM
  - $X \to W^\pm l^\mp$ for decaying fermionic DM
  - $X \to W^+W^-$ for decaying scalar DM
- Spectrum for individual process depends only on $M_{\rm DM}$ (in most models)
- Total spectrum in "any" model: Combine spectra using branching ratios of the specific model
- Spectrum for each process calculated using a Monte Carlo event generator
- Spectrum at Earth found using a Galactic propagation model
- Problem with antideuterons: Nucleus formation not handled by event generators, has to be implemented manually

The Coalescence Model

- Simple model for nucleus formation: Coalescence
  - Nucleons with $\Delta p < p_0$ coalesce to form a nucleus
  - p_0 calibrated against experimental data (LEP)
- Traditional approach: Assume isotropic and uncorrelated $\bar{p}$ and $\bar{n}$ spectra. Analytic solution:

$$\left(\frac{dN_{\bar{d}}}{dT_{\bar{d}}}\right) = \frac{p_0^3}{6} \frac{m_{\bar{d}}}{m_{\bar{n}} m_{\bar{p}}} \frac{1}{\sqrt{T_{\bar{d}}^2 + 2m_{\bar{d}} T_{\bar{d}}}} \left(\frac{dN_{\bar{n}}}{dT_{\bar{n}}}\right) \left(\frac{dN_{\bar{p}}}{dT_{\bar{p}}}\right), \quad T_i = E_i - p_i$$

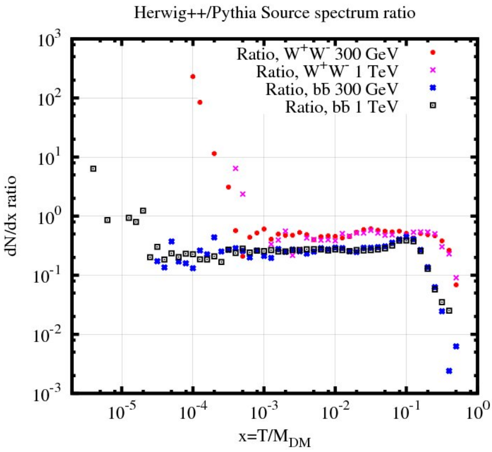
- Why not coalescence per-event? Requires factor $\sim 10^3$ more events
- Isotropic assumption does not hold. Coalescence must be done per-event afterall. Requires huge number of events ($\sim 10^8$)

Uncertainty from Hadronization

- Hadronization:
  - The formation of hadrons from final state quarks and gluons
  - Non-perturbative effects are important, only phenomenological models available
  - Antideuteron production: Correlations between antinucleons are highly important. Very sensitive to the hadronization process
  - Two dominant models: Cluster Model and Lund String model. Herwig++ and Pythia
- Compare $\bar{d}$ results from Herwig++ and Pythia to get an estimate on uncertainty from hadronization
- Article: L.A. Dal, M. Kachelriess. arXiv:1207.4560 [hep-ph]

Ratios of the spectra

- Consider 2 processes: $XX \to W^+W^-$ and $XX \to b\bar{b}$
- Ratio of spectra: Herwig++ / Pythia
- Large ratios at very high and very low energies. Interpretation: Large uncertainties



Uncertainty after Propagation

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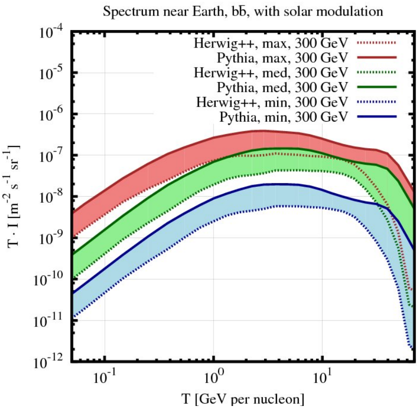
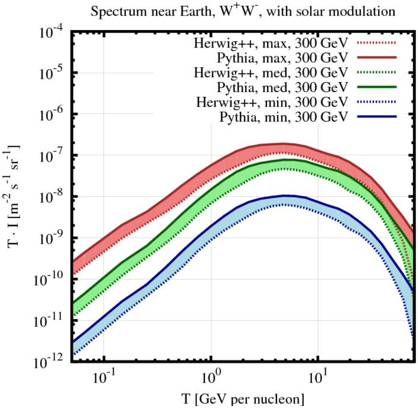
The Faculty of Mathematics and Natural Sciences





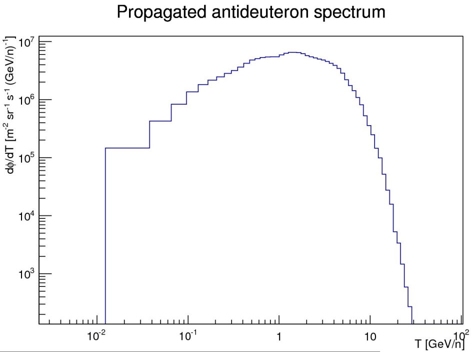
- Two-zone propagation model; max, med, min parameters
- Uncertainty from propagation dominant for most energies
- Hadronization: Uncertainty of factor 2-4 for most energies

Gravitino RPV Decays

- Gravitino: Supersymmetric partner of the graviton
- RPV: R-parity violation
- What is R-parity?
  - Multiplicatively conserved quantum number $R = (-1)^{3B+2s+L}$
  - Introduced to remove couplings that allow the proton to decay
  - SUSY particles can only be created or destroyed in pairs
  - LSP absolutely stable, good DM candidate
  - No *a priori* reason to be conserved
- RPV and Dark Matter:
  - Neutralino unstable, poor DM candidate
  - Gravitino unstable but long lived, good DM candidate
  - Gravitino decays do not have the typical tree-level processes

Antideuterons from $\tilde{G}$ decays

- Goal: Set limits on RPV couplings λ
- RPV couplings set to 1 in calculations. $\frac{d\Phi}{dT} \propto \lambda^2$.
- Estimated AMS-02 limit: $\frac{d\Phi}{dT} \sim 4.5 \times 10^{-7}$ (m^2 s sr GeV/n)$^{-1}$ in the ranges $0.2 - 0.8$ GeV/n and $2.2 - 4.2$ GeV/n*



- Example: $m_{\tilde{G}} = 200$ GeV, coupling: $L_1 Q_3 \bar{D}_3$
- Prospective AMS-02 limit: $\lambda < \sim 10^{-7}$

* V. Choutko and F. Giovacchini, on behalf of the AMS Collaboration, Proceeding of the 30th International Cosmic Ray Conference (2007).

Summary

- Antideuteron channel suitable for DM searches due to low background
- Spectrum calculated using Monte Carlo event generator + Coalescence model
- Hadronization leads to uncertainty of factor 2-4 for most energies, higher for very high or very low energies
- Current work: Gravitino RPV decays. Promising results for limits on RPV couplings