Formation models for antideuterons from dark matter

Are Raklev

Why search for antideuterons?

- Antideuterons ($\bar{d}$) from dark matter annihilation/decay have extremely low standard astrophysics backgrounds at low energies. [Donato, Fornengo and Salati, Phys. Rev. D62 (2000) 043003]
  - Not a primary cosmic ray.
  - Standard model production from spallation (pH-collisions).
  - In galactic rest frame the kinematic threshold is $\sim16m_p$. (baryon number conservation)
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- Experimental interest: AMS-02 and GAPS (planned 2020).
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- Are antideuterons any better than antiprotons? Depends…
  
  
  [Ibarra and Wild, JCAP 1302 (2013) 021]
  
  [see also Johannes Herms’ talk today]
Main uncertainties on $\bar{d}$ spectrum (at Earth)
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  - Monte Carlo generators are used to handle $\bar{p}$ & $\bar{n}$ production. 
    (Correlation between $\bar{p}$ & $\bar{n}$ dependent on hadronization model.)

- $\bar{d}$ formation is nuclear physics.

- Usually (simple) **coalescence models**

  [Schwarzschild and Zupancic, Phys. Rev. 129 (1963) 854–862]
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    [Schwarzschild and Zupancic, Phys. Rev. 129 (1963) 854–862]
    - Nucleons with relative momentum $k$ less than $p_0$ coalesce.
      
      $$ P(\bar{p}\bar{n} \to \bar{d}X|k) = \theta(p_0 - k) $$

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    - $p_0$ can in principle be calibrated against data (~100 MeV).

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  - $\bar{p}$ & $\bar{n}$ need to be produced at the same space-time location. [Ibarra and Wild, JCAP 1302 (2013) 021]
Coalescence

- State-of-the-art is **event by event coalesence** on MC data for $\bar{p}$ & $\bar{n}$ spectra with a choice of $p_0$. (As opposed to **statistical coalesence**.)

  - Very CPU expensive.

  - $p_0$ often tuned on **one** data point (ALEPH).

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  \text{BR}(Z \to \bar{d}X) = (5.9 \pm 1.8 \pm 0.5) \times 10^{-6}
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[Coalescence](Dal and Kachelriess, Phys. Rev. D86 (2012) 103536)
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  - Step-function model too simple?
  - What about $p_0$-dependent (CoM energy) probability?
  - Why do pp experiments seem so different?
Coalescence

Fitting $p_0$ to data on $\bar{d}$ production

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Source</th>
<th>Coalescence momentum $p_0$ [MeV]</th>
</tr>
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<tbody>
<tr>
<td>ALICE (pp)</td>
<td></td>
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</tr>
<tr>
<td>ZEUS ($e^-p$)</td>
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<td>ALEPH ($Z$ decay)</td>
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<td>BaBar ($e^+e^-$)</td>
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<td>CLEO ($\gamma$ decay)</td>
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Coalescence

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Improving coalescence

- Fit of $p_0$ to a set of experiments (ALEPH, CLEO, ZEUS + LEP proton spectra) including HERWIG++ hadronization parameters

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<tr>
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<tr>
<td>$p_0$</td>
<td>$-$</td>
<td>143.2</td>
<td>$+6.2$ $^{-5.5}$</td>
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Total $\chi^2 = 10.6$ with 14.2 effective dof.

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- Sounds simple, but 120 CPU hours per parameter point.

A toy model / test case

- Unstable gravitino dark matter (R-parity violation)
  - Interesting as model because of UDD-operators in superpotential:

\[ W \sim \lambda_{ijk} L_i L_j \bar{E}_k + \chi'_{ijk} L_i Q_j \bar{D}_k + \chi''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k \]
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\]
Gravitino $\bar{d}$ spectrum

Bar d flux at Earth

\[ \Phi [(m^2 \text{sr GeV/n})^{-1}] \]

\[ \lambda = 10^{-5} \]

\[ m_{\tilde{\chi}} = 50 \text{ GeV} \]

Prospective limits from GAPS

\[ \lambda_{\text{max}} \]

\[ m_{\tilde{G}} \text{ [GeV]} \]

- \( L_1 Q_3 \bar{D}_3 \)
- \( L_1 Q_1 \bar{D}_2 \)
- \( \bar{U}_3 \bar{D}_2 \bar{D}_3 \)
- \( \bar{U}_1 \bar{D}_1 \bar{D}_2 \)

Prospective limits from GAPS

![Graph showing prospective limits for various particle configurations. The x-axis represents the mass of the particle, $m_{\tilde{G}}$ in GeV, ranging from $10^1$ to $10^3$. The y-axis represents the maximum value of a parameter, $\lambda_{\text{max}}$, ranging from $10^{-9}$ to $10^0$. The graph includes lines for $L_1 Q_3 \bar{D}_3$, $L_1 Q_1 \bar{D}_2$, $\bar{U}_3 \bar{D}_2 \bar{D}_3$, and $\bar{U}_1 \bar{D}_1 \bar{D}_2$. There is a note indicating the previous best limit on $U_1 D_1 D_2$ from PAMELA $\bar{p}$ data.]

ALICE means trouble for coalescence
A new formation model
A new formation model

- Taking a step away from the step function, a probabilistic coalescence:

\[
P(\bar{p}\bar{n} \rightarrow \bar{d}X|k) = \frac{\sigma_{\bar{p}\bar{n} \rightarrow \bar{d}X}(k)}{\sigma_0}
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[Dal and AR, Phys. Rev. D91 (2015) 123536]
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[Dal and AR, Phys. Rev. D91 (2015) 123536]

- Based on cross section data. One free parameter \(\sigma_0\).
Comparison to ALICE data

ALICE vs. Pythia 8
$\sqrt{s} = 7$ TeV
$|y| < 0.5$
Conclusions

• Searches for antideuterons can be a useful way to constrain (or discover!) certain models for dark matter.

• There are significant uncertainties in antideuteron formation models which we have quantified.

• We have introduced a new cross section based model as an alternative to the standard per event coalescence.

  - Code to evaluate coalescence probability available on arXiv as ancillary material.
Bonus material
Antideuteron data fit to new coalescence model

<table>
<thead>
<tr>
<th>Monte Carlo</th>
<th>Experiments</th>
<th>Data points</th>
<th>Best fit $p_0$ [MeV]</th>
<th>$\chi^2_{p_0}$</th>
<th>Best fit $1/\sigma_0$ [barn$^{-1}$]</th>
<th>$\chi^2_{\sigma_0}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Herwig++</td>
<td>ALICE ($\bar{d}$), ISR</td>
<td>38</td>
<td>187</td>
<td>646</td>
<td>3.50</td>
<td>196</td>
</tr>
<tr>
<td></td>
<td>BABAR, CLEO, LEP</td>
<td>16</td>
<td>96</td>
<td>73.6</td>
<td>0.68</td>
<td>29.2</td>
</tr>
<tr>
<td></td>
<td>All experiments</td>
<td>54</td>
<td>123</td>
<td>2859</td>
<td>1.43</td>
<td>2146</td>
</tr>
<tr>
<td>Pythia 8</td>
<td>ALICE ($\bar{d}$), ISR</td>
<td>38</td>
<td>193</td>
<td>255</td>
<td>2.63</td>
<td>58.2</td>
</tr>
<tr>
<td></td>
<td>BABAR, CLEO, LEP</td>
<td>16</td>
<td>140</td>
<td>30.5</td>
<td>1.18</td>
<td>16.7</td>
</tr>
<tr>
<td></td>
<td>All experiments</td>
<td>54</td>
<td>174</td>
<td>888</td>
<td>2.13</td>
<td>510</td>
</tr>
</tbody>
</table>

Dof 37 for ALICE & ISR, 15 for BABAR, CLEO & LEP
Why you should be careful with Pythia & Herwig

[Graph showing ALICE data compared to Pythia 8 and Herwig++ predictions.]

\[ \sqrt{s} = 7 \text{ TeV} \]

\[ |y| < 0.5 \]
Statistical coalescence
Statistical coalescence

- Models traditionally used **statistical coalescence**

\[
\frac{dN_{\bar{d}}}{dT_{\bar{d}}} = \frac{p_0^3}{6} \frac{m_{\bar{d}}}{m_{\bar{n}} m_{\bar{p}}} \frac{1}{\sqrt{T_{\bar{d}}^2 + 2m_{\bar{d}}T_{\bar{d}}}} \frac{dN_{\bar{n}}}{dT_{\bar{n}}} \frac{dN_{\bar{p}}}{dT_{\bar{p}}}
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\]

• Shown to be bad.

Improving coalescence

- Individual and common fits of HERWIG++ to a set of antideuteron measurements

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\chi^2$, best fit $p_0$</th>
<th>$\chi^2$, $p_0 = 152$ MeV</th>
<th>$N_{bins}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALEPH</td>
<td>0.0</td>
<td>0.2</td>
<td>1</td>
</tr>
<tr>
<td>CLEO</td>
<td>7.6</td>
<td>10.5</td>
<td>5</td>
</tr>
<tr>
<td>ZEUS</td>
<td>3.7</td>
<td>3.8</td>
<td>3</td>
</tr>
<tr>
<td>CERN ISR</td>
<td>5.0</td>
<td>33.2</td>
<td>4+4</td>
</tr>
<tr>
<td>ALICE</td>
<td>5.1</td>
<td>5.5</td>
<td>9</td>
</tr>
</tbody>
</table>

[Dal and ARR, Phys. Rev. D89 (2014) 103504]
Propagation

dbar spectrum in rest frame → PhD-student → dbar spectrum at Earth
Propagation

\[ - D(T) \nabla^2 f + \frac{\partial}{\partial z} (\text{sign}(z) f V_c) = Q - 2h \delta(z) \Gamma_{\text{ann}}(T) f \]

<table>
<thead>
<tr>
<th>Model</th>
<th>(L) in kpc</th>
<th>(\delta)</th>
<th>(D_0) in kpc(^2) Myr(^{-1})</th>
<th>(V_c) in km s(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>max</td>
<td>15</td>
<td>0.46</td>
<td>0.0765</td>
<td>5</td>
</tr>
<tr>
<td>med</td>
<td>4</td>
<td>0.7</td>
<td>0.0112</td>
<td>12</td>
</tr>
<tr>
<td>min</td>
<td>1</td>
<td>0.85</td>
<td>0.0016</td>
<td>13.5</td>
</tr>
</tbody>
</table>
The standard plot

\[
\phi_D (m^{-2} s^{-1} sr^{-1} GeV^{-1})
\]

solar maximum

F. Donato, N. Fornengo, P. Salati (1999)