Dark Matter searches with antideuterons

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This talk will be about DM indirect detection, that is realized by looking for SM (anti)particles produced by DM annihilation/decay that can appear in the CR flux.

Concerning charged CRs, we have 3 possible channels for indirect detection:

- Antiprotons
- Positrons
- Anti-nuclei (antideuteron and antiHelium)

Why (and when) should we choose antideuterons?
Why antideuterons?

Basically because we expect the DM signal to dominate over the astrophysical background at low energies.

The background flux is given by spallation of cosmic ray particles over the interstellar medium.

\[
\begin{align*}
    p + p & \rightarrow \overline{d} + X \quad E_{\text{thr}} = 17m_p \\
    p + p & \rightarrow ^3\text{He} + X \quad E_{\text{thr}} = 31m_p
\end{align*}
\]

The large energy thresholds, together with the steeply falling primary spectra make the astrophysical background highly suppressed at low energies.

Anti-nuclei are a promising tool to detect low or intermediate mass WIMPs.

Donato, Fornengo, Salati, 2000
1 - Production
2 - Propagation in the galaxy
3 - Solar modulation
1 - Production

2 - Propagation in the galaxy

3 - Solar modulation

How are antideuterons produced?
Antideuteron production

An antideuteron is the result of the merging (coalescence) of a \( \bar{p} \bar{n} \) pair.

A simple idea: the two antinucleons merge if they are close enough in the phase space.

How is coalescence implemented in practice?

Butler and Pearson, 1961
Schwartzschild and Zupancic, 1963
Antideuteron production

The spectrum can be written as:

\[ \frac{dN^d}{dT} \propto \int d^3\vec{k}_p d^3\vec{k}_n F_{\bar{p}\bar{n}}(\sqrt{s}, \vec{k}_p, \vec{k}_n)C(\Delta k, \Delta r) \]

\( F_{\bar{p}\bar{n}} \) is the **probability that the anti-nucleons are formed**:

\[ F_{\bar{p}\bar{n}}(\sqrt{s}, \vec{k}_p, \vec{k}_n) = \frac{dN_{\bar{p}\bar{n}}}{d^3\vec{k}_p d^3\vec{k}_n} \]

The function \( C \) is the **probability that the anti-nucleons merge**:

\[ C(\Delta p, \Delta r) = \theta(\Delta p^2 - p_0^2)\theta(\Delta r^2 - r_0^2) \]

We take \( r_0 \approx 2 \text{ fm} \) (radius of the anti-deuteron)

(given the large spatial resolution of Pythia our results are insensitive to the exact value of \( r_0 \))

We sample it directly from the MonteCarlo (event-by-event coalescence)

\( p_0 \) is a **free parameter**. Which is its value?
Antideuteron production

The coalescence momentum $p_0$ **cannot be calculated** from first principles and should be determined from **fitting** MonteCarlo event-by-event predictions to experimental measurements.

No value of $p_0$ can simultaneously fit all the data!
Antideuteron production

The coalescence momentum $p_0$ cannot be calculated from first principles and should be determined from fitting MonteCarlo event-by-event predictions to experimental measurements.

For the results shown here we use

$$p_0 = (195 \pm 22) \text{ MeV}$$

No value of $p_0$ can simultaneously fit all the data!
The large uncertainty on the coalescence momentum arise from **two factors**:

- $p_0$ is **smaller or comparable to** $\Lambda_{QCD}$ and therefore coalescence is sensitive to **non-perturbative effects** of the hadronization model of the MC event generator.
- $p_0$ is highly sensitive to **two-particle correlation** between the antinucleons, and MC event generators are **not tuned** to reproduce this observable.

The uncertainty on $p_0$ has a large impact on our results, since the DM yield is proportional to $p_0^3$. 

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*Dal, Kachelriess 2012*

*Dal, Raklev 2014*
How do antideuterons propagate across the Galaxy?
\[ -\nabla [K(r, z, E)\nabla N(r, z, E)] + V_c(z)\frac{\partial}{\partial z}N(r, z, E) + 2h\delta(z)\Gamma_{\text{ann}}N(r, z, E) + 2h\delta(z)\partial_E(-K_{EE}(E)\partial_EN(r, z, E) + b_{\text{tot}}(E)N(r, z, E)) = Q(r, z, E) \]

Two-zone diffusion model

\[ K(r, z, E) = \beta K_0 \left( \frac{R}{1\, \text{GV}} \right)^\delta \]

\[ \vec{V}_c = \text{sign}(z)V_c \]

The model is defined by these parameters:

<table>
<thead>
<tr>
<th></th>
<th>(\delta)</th>
<th>(K_0) (kpc(^2)/Myr)</th>
<th>(L) (kpc)</th>
<th>(V_c) (km/s)</th>
<th>(V_a) (km/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min</td>
<td>0.85</td>
<td>0.0016</td>
<td>1</td>
<td>13.5</td>
<td>22.4</td>
</tr>
<tr>
<td>Med</td>
<td>0.70</td>
<td>0.0112</td>
<td>4</td>
<td>12</td>
<td>52.9</td>
</tr>
<tr>
<td>Max</td>
<td>0.46</td>
<td>0.0765</td>
<td>15</td>
<td>5</td>
<td>117.6</td>
</tr>
</tbody>
</table>

- \(K_0, V_c, V_a\) and \(\delta\) constrained by B/C data
- \(L\) can be constrained (\(L>2\, \text{kpc}\)) by synchrotron measurements

**Maurin+ 2001, Donato+ 2002**

**Donato+ 2004**
Since we are interested in low-energy antideuterons, solar modulation is extremely relevant.
Charged CRs in the heliosphere

- The Sun is surrounded by the **heliosphere** that extends up to 100 AU.
- The heliosphere hosts the **solar wind**, originated by the expansion of the hot plasma generated by the solar corona.
- This wind of charged particles determines the existence of the **Heliospheric Magnetic Field** (HMF).

- HMF appears as an **Archimedean spiral**.
- In the heliosphere, charged CRs **interact** with the HMF and with the solar wind.

This mechanism is the **solar modulation**.
Solar modulation

two possible approaches:

1) **Force field approximation**

\[
\Phi_{\text{TOA}}(T_{\text{TOA}}) = \frac{T_{\text{TOA}}(T_{\text{TOA}} + 2m)}{T_{\text{IS}}(T_{\text{IS}} + 2m)} \Phi_{\text{IS}}(T_{\text{IS}}) \quad \frac{T_{\text{TOA}}}{A} = \frac{T_{\text{IS}}}{A} - \frac{|Z|}{A} \varphi
\]

Gleeson, Axford, 1967

\(\varphi\) is a **free parameter** tuned to reproduce the observed fluxes

2) **Numerical solution of the transport equation in the heliosphere**

\[
-(\vec{V}_{\text{sw}} + \vec{v}_d) \cdot \nabla f + \nabla \cdot (\vec{K} \cdot \nabla f) + \frac{p}{3} (\nabla \cdot \vec{V}_{\text{sw}}) \frac{\partial f}{\partial p} = 0
\]

Parker, 1965

In this way, we allow for a **charge dependence**

(we use the Helioprop code Maccione, 2013)
Astrophysical background

The background is assumed to be of purely secondary origin:

\[
Q^{\text{sec}}(T_{\bar{d}}) = \sum_{i \in \{p, He, \bar{p}\}} \sum_{j \in \{p, He\}} 4\pi n_{\text{ISM}}^{i} \int_{T_{\text{min}}}^{\infty} dT_{i} \Phi_{i}(T_{i}) \frac{d\sigma(T_{i}, T_{\bar{d}})}{dT_{\bar{d}}}
\]

\[
\phi_{\bar{d}}(T_{\bar{d}}) = \phi = 0 \text{ GV (IS)} \quad \text{MED flux}
\]
Astrophysical background

-additional contributions-

An example: secondary antideuterons accelerated within SNRs

J. Herms, A. Ibarra, AV, S. Wild, in preparation

Diffusive shock acceleration (DSA) is the mechanism through which CRs are accelerated

As a possible interpretation of the rise in the positron fraction observed by PAMELA, it has been suggested that DSA can accelerate also particles created by pp collisions that take place inside the shock region

Blasi 2009, Blasi, Serpico 2009
Ahlers, Mertsch, Sarkar 2009
Donato, Tomassetti 2012 ...
Antideuterons from SNRs

propagation within the shock region:

\[ u \frac{\partial f}{\partial x} = D \frac{\partial^2 f}{\partial x^2} + \frac{1}{3} \frac{du}{dx} p \frac{\partial f}{\partial p} - \Gamma f = Q \]

Solution:

\[ f(x, p) = f_0(p) + \left[ \frac{q_2(p)}{u_2} - \Gamma f_0(p) \right] x \]

**Blasi, Serpico 2009**

\[ f_0(p) = \gamma \int_0^p \frac{dp'}{p'} \left( \frac{p'}{p} \right)^\gamma \frac{D(p') q_1(p')}{u_1^2} \left( \frac{1}{\xi(p)} + r^2 \right) \]

\[ r = \frac{u_1}{u_2} \quad \gamma = \frac{3r}{r - 1} \quad \xi = \frac{p d}{p_p} \]
Antideuterons from SNRs

J. Herms, A. Ibarra, AV, S. Wild, in preparation

Prediction for antideuteron fluxes:

very preliminary!

Contribution of the SNRs to the total flux:

~30%
Antideuterons from SNRs

Prediction for antideuteron fluxes:

The contribution from of SNRs seems subdominant
(Anyway we are still investigating if this is true for any choice of the SNR parameters...)

very preliminary!
Prospects for DM observation
Prospects for DM observation

An update of N.Fornengo, L.Maccione, AV, 2013

bb channel – $m_{DM} = 20$ GeV

bb channel – $m_{DM} = 100$ GeV

Annihilation cross sections compatible with PAMELA antiproton bounds

Boudaud+ 2014
Prospects for DM observation

An update of N. Fornengo, L. Maccione, AV, 2013

bb channel – $m_{DM} = 20$ GeV

- BESS bound
- GAPS (3 LDB flights)
- AMS (TOF) 5 years
- AMS (RICH) 5 years

$p_0 = 239$ MeV

$\langle \sigma v \rangle = 4 \times 10^{-27}$ cm$^3$s$^{-1}$

MED fluxes

$p_0 = 151$ MeV

Background

$\langle \sigma v \rangle = 1 \times 10^{-26}$ cm$^3$s$^{-1}$

MED fluxes

Annihilation cross sections compatible with AMS-02 antiproton bounds

Giesen+ 2015
Conclusions

Anti-deuterons are a promising channel for the indirect detection of DM particles with low or intermediate mass. For this DM candidates, in fact, the signal-to-background ratio is extremely large.
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However, **antiproton constraints** are becoming stronger and stronger.
Conclusions

Anti-deuterons are a **promising channel** for the indirect detection of DM particles with low or intermediate mass. For this DM candidates, in fact, the **signal-to-background** ratio is extremely **large**.

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For the current and future generation of experiments, the **detection of DM** in the antideuteron channel will probably be **challenging**.
Conclusions

Anti-deuterons are a **promising channel** for the indirect detection of DM particles with low or intermediate mass. For this DM candidates, in fact, the **signal-to-background** ratio is extremely **large**.

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For the current and future generation of experiments, the **detection of DM** in the antideuteron channel will probably be **challenging**.

Thank you!
Extra slides
Coalescence - the $\Delta r$ condition

What is the impact of the $\Delta r < 2$ fm condition?

- $m = 10$ GeV
  - $\Delta p = 195$ MeV
  - $m_{DM} = 10$ GeV
  - Without $\Delta r$
  - With $\Delta r = 2$ fm

- $m = 100$ GeV
  - $\Delta p = 195$ MeV
  - $m_{DM} = 100$ GeV
  - Without $\Delta r$
  - With $\Delta r = 2$ fm
Solar modulation

The propagation in the heliosphere is described by the following equation:

\[
\frac{\partial f}{\partial t} = - (\mathbf{V}_{sw} + \mathbf{v}_d) \cdot \nabla f + \nabla \cdot (\mathbf{K} \cdot \nabla f) + \frac{P}{3} (\nabla \cdot \mathbf{V}_{sw}) \frac{\partial f}{\partial P}
\]

Convection   Drifts   Diffusion (random walk)   Adiabatic losses

We vary 2 parameters:

- The tilt angle $\alpha$: it describes the spatial extent of the HCS. It is proportional to the intensity of the solar activity ($\alpha \in [20^\circ, 60^\circ]$)
- The mean free path $\lambda$ of the CR particle along the magnetic field direction

We exploit the code HELIOPROP to solve **numerically** the transport equation and explore the solar parameters space.

Solar modulation

In our sample, energy losses vary significantly from particle to particle (they depend on the path):

The modulated flux at $E_{TOA}$ is given by a weighted average of LIS fluxes in the corresponding range of $E_{LIS}$.

Above 10 GeV solar mod is negligible

Solid lines $\rightarrow$ Force field approximation ($p\bar{b}$, $d\bar{b}$)

Dots $\rightarrow$ CD solar modulation ($p\bar{b}$, $d\bar{b}$)
Number of expected events

\[
\begin{align*}
\text{uū} &- 10 \text{ GeV} - \text{EIN MED} - \text{CD}_60_{0.60}\_1 \\
\text{b\bar{b}} &- 100 \text{ GeV} - \text{EIN MED} - \text{CD}_60_{0.60}\_1
\end{align*}
\]

- \(p_0 = 195\text{ MeV}\)
- \(p_0 = 217\text{ MeV}\)
- \(p_0 = 239\text{ MeV}\)
- \(p_0 = 261\text{ MeV}\)

Antiproton bound

\(2-6\) events

\(1-2\) events
The anti-Helium case

- For the anti-Helium, we have the coalescence of **three anti-nucleons**

- We consider only the pnn case, since for the ppn case we expect to have a suppression due to **Coulombian repulsion**

- Our algorithm is very simple: we compute the relative momentum of every anti-nucleon pair in the rest frame of the anti-He (i.e. the c.m. frame of the pnn system) and we consider the **three particles as a bound state** if:

  \[
  |\Delta p|_{\text{max}} \leq p_0
  \]

- Experimental data on anti-He production are very scarce and relative to pp or pA collisions whose dynamics is different from the one of a DM pair annihilation. Thus, the coalescence momentum can be considered as a **free parameter** (we set it equal to the one of the anti-deuteron)
The anti-Helium case

Prospects for detection are rather weak, unless the coalescence momentum is really large (~600 MeV)

on this topic see also Carlson, Coogan, Ibarra, Linden, Wild Physical Review D, 89, 076005 (2014)
The anti-Helium background

The background anti-helium flux is the one produced by spallation of primary (and secondary) cosmic rays impinging on the interstellar medium. The source term associated to the dominant contribution (due to pp collisions) is:

\[
Q_{\text{sec}} = \int_{E_{\text{thr}}}^{\infty} dE' \left( 4\pi \phi_p(E') \right) \frac{d\sigma_{pp \to \overline{\text{He}}+X}}{dE} (E, E') n_H
\]

we evaluate this source term with our event-by-event coalescence algorithm:

\[
\frac{d\sigma_{pp \to \overline{\text{He}}+X}}{dE} (E, E') = \sigma_{pp,\text{tot}}(E, E') \frac{dn_{\overline{\text{He}}}}{dE} (E, E')
\]

consistently with the DM case, \( p_0 \) is tuned to reproduce the observed anti-deuteron flux measured in pp collisions (at the ISR experiment)

\[ p_0 = 167 \ \text{MeV} \]
The anti-Helium background

We compare our background flux with the one computed in Duperray et al. Phys.Rev. D71 2005

They have a simpler coalescence model but
They compute the background by taking into account also other contributions (pHe, HeHe collisions, etc...) and they have a more detailed treatment of the galactic propagation