The dark side of ALICE: from antinuclei interactions to dark matter searches in space

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Introduction and motivation

Antinuclei ($\bar{d}$, $^{3}\text{He}$, $^{4}\text{He}$) in space (studied by AMS-02, GAPS) may result from:

- Dark matter annihilation (or decay) $\rightarrow$ signal
- Interaction of high energy cosmic rays with the interstellar gas $\rightarrow$ background

- Low background is expected in the low energy range
- Vital to determine exact primary and secondary antinuclei fluxes
- Requires precise knowledge of antinuclei inelastic interaction with interstellar gas
Antinuclei $\sigma_{\text{inel}}$ measurements (before ALICE)

Relevant inelastic cross sections ($\sigma_{\text{inel}}$) only poorly constrained for antinuclei heavier than $\bar{p}$:

- Antihelium inelastic c.s. have never been measured at any momenta

\[ \text{No data} \]

LHC as an antimatter factory

\[ p, d, t, ^3\text{He}, \ldots \]

\[ \bar{p}, \bar{d}, \bar{t}, ^3\text{He}, \ldots \]

High energy collisions at LHC = the most suitable environment to study production of (anti)nuclei and their annihilation

- At LHC energies matter and antimatter are produced in almost equal amounts
- ... propagate through detector material
- ... and get absorbed inside the detector
  - in ALICE we are in a unique position to quantify \( \sigma_{\text{inel}} \)!
LHC as an antimatter factory

$p, d, t, \overline{3He}, \ldots$

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High energy collisions at LHC = the most suitable environment to study production of (anti)nuclei and their annihilation

This talk: focus on $A = 3$
**ALICE apparatus and its particle identification capabilities**

**Time Projection Chamber:**
- Gas-filled, MWPC readout
- PID via dE/dx

**Time of Flight:**
- Multigap RPC
- PID via time-of-flight measurement
Methods to measure $\sigma_{\text{inel}}$

**Antiparticle/particle raw ratio** (pp, p-Pb collisions):
- Measure reconstructed $d/d$, $^3\text{He}/^3\text{He}$... and compare with MC simulations
  
  + Access to low momenta ($p \leq 1 \text{ GeV/c}$)
  
  - Relies on $\sigma_{\text{inel}}(\text{nuclei})$
  
  - Background from secondary particles

**TOF/TPC ratio** (Pb-Pb collisions):
- Measure reconstructed $N_{^3\text{He}}^{\text{TOF}}/N_{^3\text{He}}^{\text{TPC}}$ and compare with MC simulations
  
  + High statistics, wide momentum range
  
  + Independent of $\sigma_{\text{inel}}(\text{nuclei})$
  
  - No access to very-low momenta ($p \leq 1 \text{ GeV/c}$)
Antiparticle/particle raw ratio

- Antiparticle-to-particle ratios are sensitive to the variation of the inelastic cross section
- Vary $\sigma_{\text{inel}}(\bar{d}, \text{He})$ in simulations until MC describes the experimental results
  - constraints on $\sigma_{\text{inel}}(\bar{d}, \text{He})$

**Method 1**

**ALICE**

$p$–$\text{Pb} \sqrt{s_{\text{NN}}} = 5.02$ TeV

**Raw $(\bar{p}/p)$ for MC with varied $\sigma_{\text{inel}}(\bar{p})$ and data**

- MC simulations with $\sigma_{\text{inel}}(\bar{p}) \times 0.75$
- MC simulations with default $\sigma_{\text{inel}}(\bar{p})$
- MC simulations with $\sigma_{\text{inel}}(\bar{p}) \times 1.25$
- Data $\pm 1\sigma$ ($1\sigma = \text{stat.} \oplus \text{syst.} \oplus \text{global}$)

Antiparticle/particle raw ratio: $\sigma_{\text{inel}}(\bar{d})$

- First measurement of antideuteron inelastic cross section at low momenta!
- Exp. $\sigma_{\text{inel}}$ is approx. 15% smaller w.r.t. Geant4 at high momenta, steeper rise in low $p$ region
- Published: PRL 125, 162001 (2020)
How we measure $\sigma_{\text{inel}}$ with TPC-TOF matching

- Identify $N_{\text{TOF}} / N_{\text{TPC}}$ in data and simulations
- Monte Carlo simulations with scaled $\sigma_{\text{inel}}$ (0.5x, 1x, 1.5x)
- In each momentum bin compare the TOF-TPC ratio in MC to the one in data

[arXiv:2202.01549]
How we measure $\sigma_{\text{inel}}$ with TPC-TOF matching

- Identify $N_{\text{TOF,track}} / N_{\text{TPC,track}}$ in data and simulations
- Monte Carlo simulations with scaled $\sigma_{\text{inel}}$ (0.5x, 1x, 1.5x)
- In each momentum bin compare the TOF-TPC ratio in MC to the one in data

- Fit MC points with an exponential according to the Lambert-Beer law:
  $N = N_0 \times \exp(-\sigma \rho L)$
- extract $\sigma_{\text{inel}} / \sigma_{\text{inel}}^{\text{def}}$ scaling factor
- calculate the inelastic cross section on $\langle A \rangle$:

$$\sigma_{\text{inel}}(^3\text{He}) = \sigma_{\text{inel}}^{\text{Gean}4}(^3\text{He}) \times \text{scaling factor}$$

[arXiv:2202.01549]
Results: $^3\text{He}$ inelastic cross section
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- $\sigma_{\text{inel}}(^3\text{He})$: Results for antiparticle-to-particle raw ratio and TOF-to-TPC ratio:
  
  First ever measurement of $^3\text{He}$ inelastic cross section!
  
  - Results from both methods are compatible (higher precision in TOF-to-TPC ratio)
  - Bands: statistical $\oplus$ systematic uncertainties

![Graph showing $\sigma_{\text{inel}}(^3\text{He})$ on averaged ALICE material](graph.png)

$^3\text{He}$ on averaged ALICE material

ALICE pp $\sqrt{s} = 13$ TeV

$|\eta| < 0.8$

- $\langle A \rangle = 17.4$
- $\langle A \rangle = 31.8$
- $\langle A \rangle = 17.4$

95% confidence upper limit

Method 1

[arXiv:2202.01549]
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\[ \sigma_{\text{inel}}(^3\text{He}) \text{ on averaged ALICE material} \]

ALICE
0–10% Pb–Pb $\sqrt{s_{NN}} = 5.02$ TeV
$|\eta| < 0.8$
\[ \langle A \rangle = 34.7 \]

\[ \text{Data} \quad \text{GEANT4} \]

[arXiv:2202.01549]
Results: $^3\text{He}$ inelastic cross section

- $\sigma_{\text{inel}}(^3\text{He})$: Results for antiparticle-to-particle raw ratio and TOF-to-TPC ratio:
  
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$\rightarrow$ Next: impact on $^3\text{He}$ propagation in space
Propagation of $^3\text{He}$ in the Galaxy: ingredients

\[ \frac{\partial \psi}{\partial t} = q(r, p) \]

\[ \nabla \cdot (D_{xx} \nabla \psi - V \psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \psi - \frac{\partial}{\partial p} \left[ \psi \frac{dp}{dt} - \frac{p}{3} (\nabla \cdot V) \psi \right] - \frac{\psi}{\tau_f} + \frac{\psi}{\tau_r} \]

- Can be numerically solved using publicly available \texttt{GALPROP} package
- \textbf{Propagation parameters} (common for all (anti)nuclei) can be constrained using available cosmic ray measurements [1]

- Calculation of antinuclei flux requires:
  - \textbf{X} source function: differential production cross section [2, 3]
  - \textbf{X} annihilation cross section

$^3\text{He}$ source (l): dark matter

Source function

$$q(r, E_{\text{kin}}) = \frac{1}{2} \frac{\rho_{\text{DM}}^2(r)}{m_{\chi}^2} \langle \sigma v \rangle (1 + \epsilon) \frac{dN}{dE_{\text{kin}}}$$

- $\rho_{\text{DM}}$ - Navarro–Frenk–White profile [1]
- $m_{\chi} = 100$ GeV for $W^+W^-$
- $\langle \sigma v \rangle = 2.6 \times 10^{-26} \text{ cm}^3\text{s}^{-1}$ [2]
- $(1 + \epsilon) = 2$ [1]
- $^3\text{He}$ spectrum from [1] PYTHIA 8 + coalescence afterburner
  $\rightarrow$ peak at $E_{\text{kin}} \sim 0.1$ GeV/A

$^3\text{He}$ density distr.

$\chi\bar{\chi} \rightarrow W\bar{W}, m_{\chi} = 100\text{GeV}$

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Another relevant $^3\text{He}$ source from interactions of cosmic rays (CR) with interstellar medium (ISM)

- Collision systems: pp, p-$^4\text{He}$, $^4\text{He}$-p, $^4\text{He}$-$^4\text{He}$
- Production cross section in pp from [1]: EPOS LHC + coalescence afterburner
- Scaling factor ($A_T A_P$)$^{2.2/3}$ for the other collision systems
- Validated by ALICE data [2]

**Cosmic rays**

- $^3\text{He}$ 8 %
- $^3\text{He}$ 9 %
- Protons 91 %
- Protons 90 %

**ISM**

- $^3\text{He}$ 9 %
- Protons 90 %

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Another relevant $^3$He source from interactions of cosmic rays (CR) with interstellar medium (ISM)

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See talk by Chiara Pinto
Tue 14.06 at 9:20

Comparison with ALICE results [1,2]
$^3\text{He}$ nuclei may interact inelastically with the interstellar gas ($A = 1, A = 4$)

- ALICE results for $\sigma_{\text{inel}}(^3\text{He})$ are for heavy elements with $\langle A \rangle = 17.4$ to 34.7
- Rescaled for proton and helium targets
- 8% uncertainty from A scaling [1] is valid for all targets
Annihilation

$^3\text{He}$ nuclei may interact inelastically with the interstellar gas ($A = 1, A = 4$)

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Results: $^3\text{He}$ fluxes
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- Effect of various inelastic cross sections on $^3\text{He}$ fluxes
- Uncertainty only from $\sigma_{\text{inel}}$ from ALICE data: small compared to other uncertainties in the field!
- $^3\text{He}$ transparency (at low $E_{\text{kin}}$): 25% from CR interactions, 50% from typical DM candidates
- Flux outside heliosphere

\[ \text{Transparency} = \frac{\text{Flux}(\sigma_{\text{inel}})}{\text{Flux}(\sigma_{\text{inel}} = 0)} \]

\[ m_\chi = 100 \text{ GeV/}c^2 \]
\[ \chi + \chi \rightarrow W^+W^- \rightarrow ^3\text{He} + \chi \]

Outside heliosphere

Results: $^3\text{He}$ fluxes

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- $^3\text{He}$ transparency (at low $E_{\text{kin}}$): 25% from CR interactions, 50% from typical DM candidates
- Solar modulation: flux near Earth

High transparency of the Galaxy to $^3\text{He}$ nuclei!

Summary and outlook

ALICE performed **groundbreaking measurements** of antinuclei inelastic cross sections:

- $\bar{d}$ at low energy published: **PRL 125, 162001 (2020)**
- $^{3}\text{He}$ paper submitted: **arxiv.org/2202.01549**

Impact on antinuclei flux near Earth:

- **High transparency of the Galaxy to $^{3}\text{He}$**
- Small uncertainties on cosmic ray fluxes from $\sigma_{\text{inel}}(^{3}\text{He})$ compared to other uncertainties in the field
- $\sigma_{\text{inel}}(\bar{d})$ used to re-evaluate the antideuteron cosmic ray fluxes: **Phys. Rev. D 105 (2022) 8, 083021**

Thank you for your attention!
Backup slides
Solar environment effects

- Solar magnetic field forms heliosphere which shields cosmic rays
- Solar modulation is accounted for using Force–Field approximation [1] with Fisk potential $\phi = 0.4$ GV:

$$F_{\text{mod}}(E_{\text{mod}}, \phi) = F(E) \frac{(E - Z\phi)^2 - m_{\text{He}}^2}{E^2 - m_{\text{He}}^2}, \text{ where } E_{\text{mod}} = E - Z\phi$$