Astrophysical Background of Antideuterons in Cosmic Rays.

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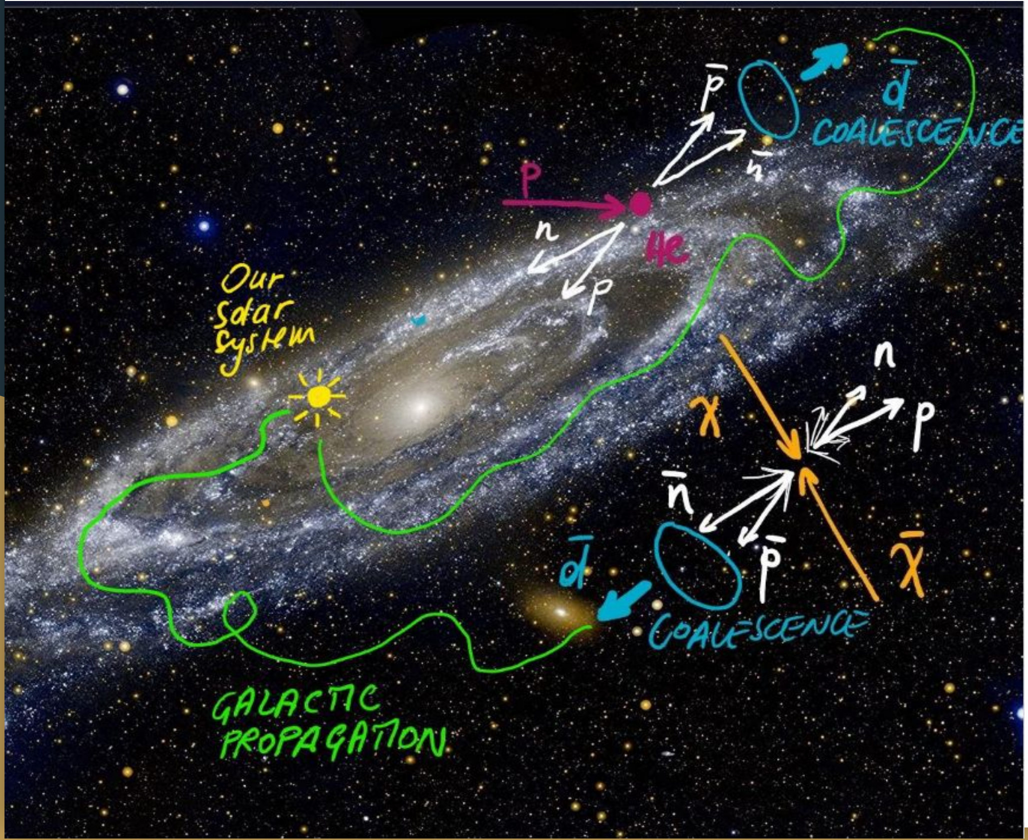
CosmicAntiNuclei

Indirect DM Searches with Antinuclei



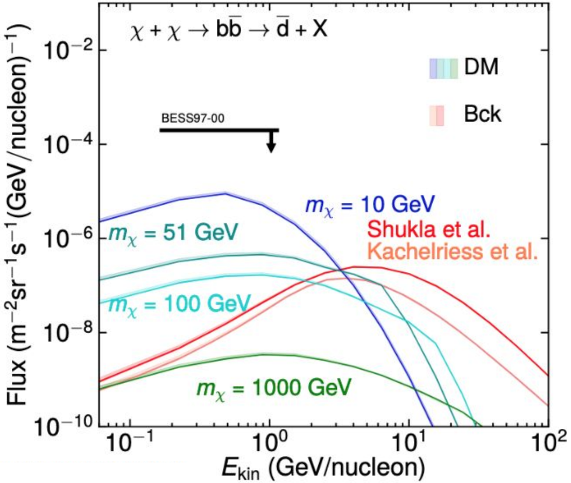
Signal: Antinuclei from Dark Matter annihilation

$$\chi + \chi \to \bar{d} + X$$

Background: Antinuclei from CRs interactions with ISM:

$$p + p \to \bar{d} + X \qquad p + {}^4He \to \bar{d} + X$$

and heavier channels.



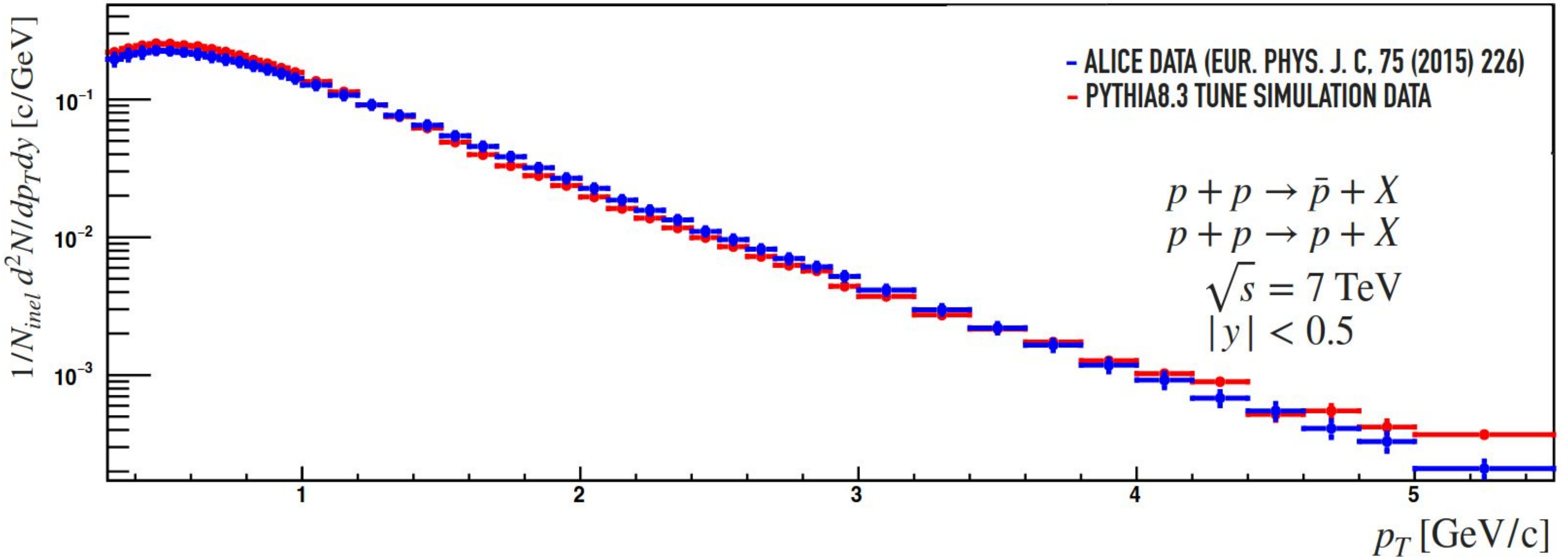
IDEA OF THE PROJECT

Extract the astrophysical background flux estimation using state-of-the-art tools, such as:

- Tailor-made Pythia8.3 tuning reliable in a wide energy spectrum for **antiproton and antineutron production cross section**. NA49 and ALICE data were used in the tuning procedure.
- Realistic Coalescence Model event-by-event based on the Wigner function formalism for **antideuteron production cross section** [*Eur. Phys. J. C* **83**, 804 (2023)]
- Implementation of the antideuteron and antiproton production cross section in the Galprop framework.
- Full solution of the CRs transport equation with Galprop.

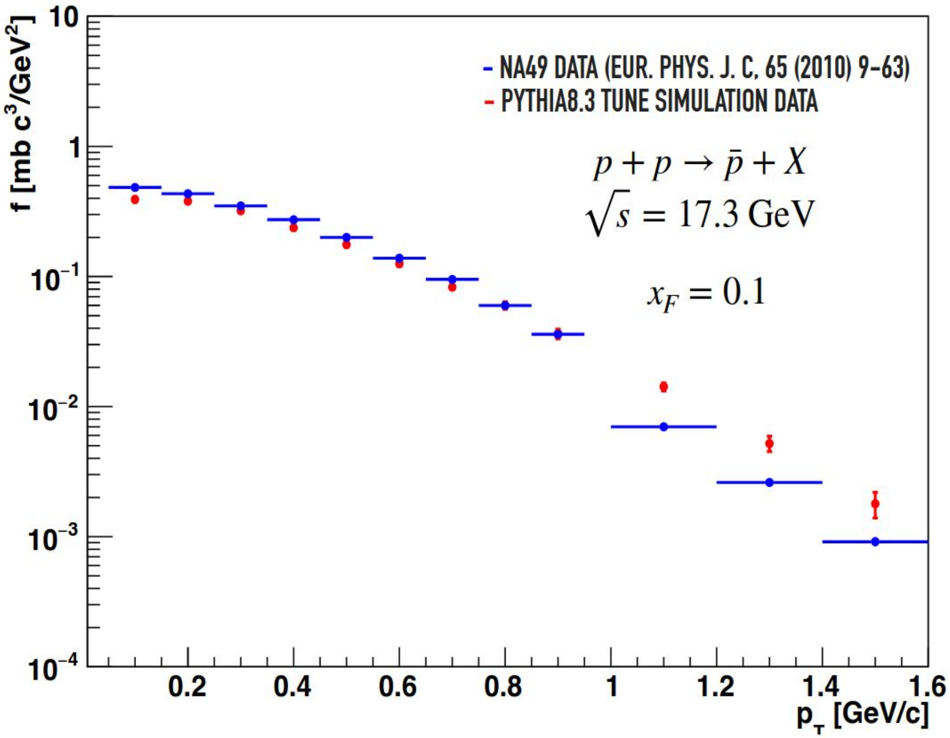
Antiproton (and Antineutron) production cross section with Pythia8.3 CosmicAntiNuclei tuning.

Antiproton production cross section: tuning with ALICE data at 0.9, 7, 13 TeV



Very good agreement through the transverse momentum range [0,5] GeV/c. Similar results hold true at the c.m. energies 0.9 TeV and 13 TeV. ALICE data have been used to make the tuning.

Antiproton production cross section: tuning with NA49 data at 17.3 GeV

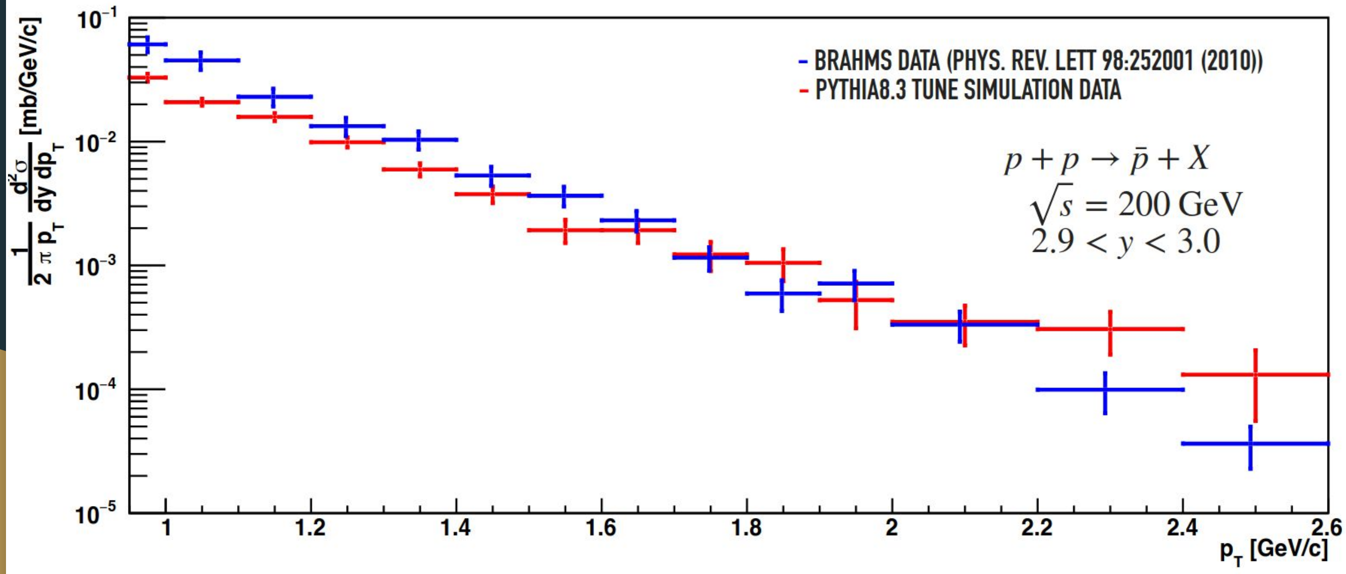


f is the invariant cross section defined as:

$$f = E\frac{d^3\sigma}{dp^3}$$

The tune makes reliable predictions in a wide range of energies, from 17 GeV up to 13 TeV, especially at low transverse momentum values.

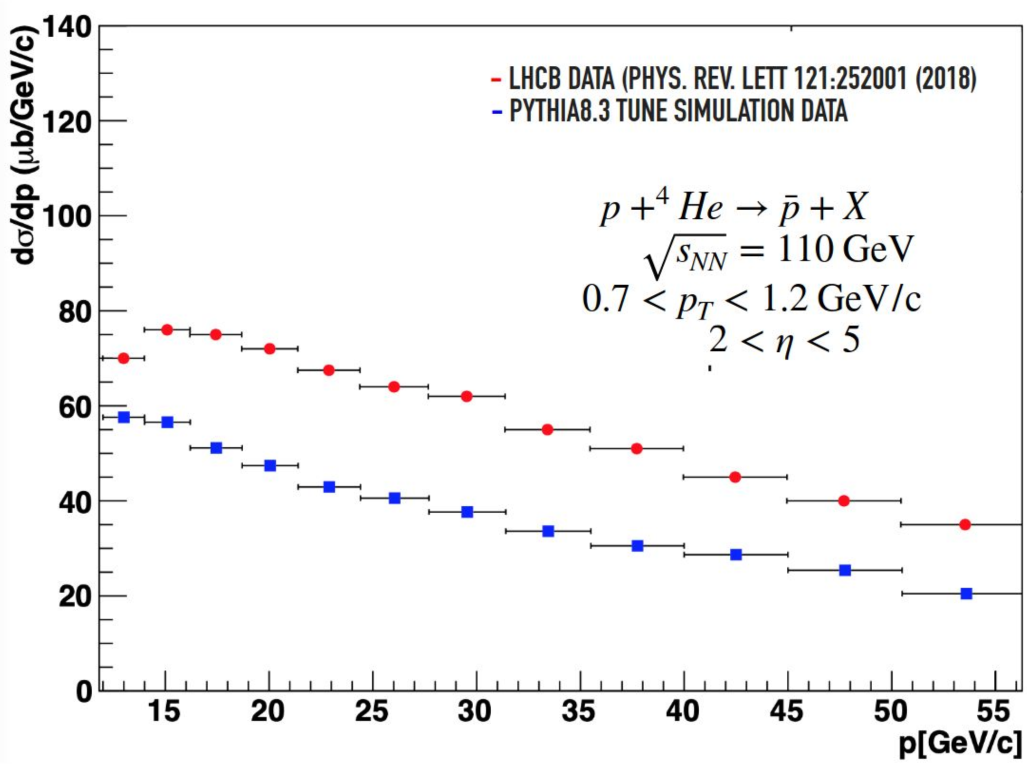
Testing the tune with BRAHMS data at 200 GeV



The tune is reliable also at **intermediate energies** and in **forward rapidity** regions.

Note that the BRAHMS dataset was not used in the tuning procedure.

Testing the tune with p-He collisions in LHCb-SMOG data at 110 GeV

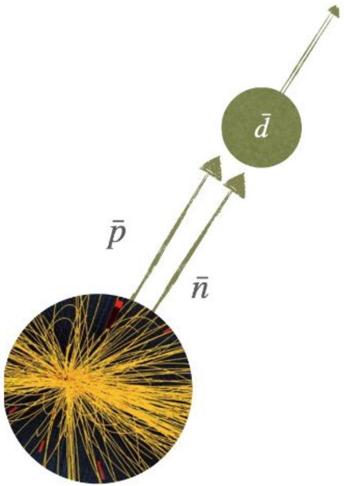


- Discrepancy in p-He collisions is observed.
- An improvement in the tune is necessary to correctly describe p-He collisions.

Antideuteron production cross section with the event-by-event Coalescence Afterburner

Coalescence model

Coalescence model is a **microscopic** approach to the formation of light nuclei produced in high-energy processes successfully applied to e-h, h-h and heavy ion collisions.



The invariant nuclei yield is defined as: $$E_A \frac{d^3N}{d^3p_A} = B_A \left(E_p \frac{d^3N_p}{dp_p^3} \right)^Z \left(E_n \frac{d^3N_n}{dp_n^3} \right)^{A-Z}$$

Coalescence parameter

Simple and Quantum Coalescence Model

Simple model:

- Coalescence takes place when two (anti)nucleons are close enough in the phase space:

$$|\vec{p_n} - \vec{p_p}| < p_0$$

- The **coalescence momentum** is tuned on data.

$$B_A = \left(\frac{4\pi}{3}p_0^3\right)^{(A-1)} \frac{1}{A!}\frac{M}{m^A}$$

Quantum model:

- Coalescence is treated as a quantum multi-body process.
- Takes into account the source radius, the nucleus radius and the transverse momentum. Crucial to describe coalescence in A-A collision systems with high multiplicity.

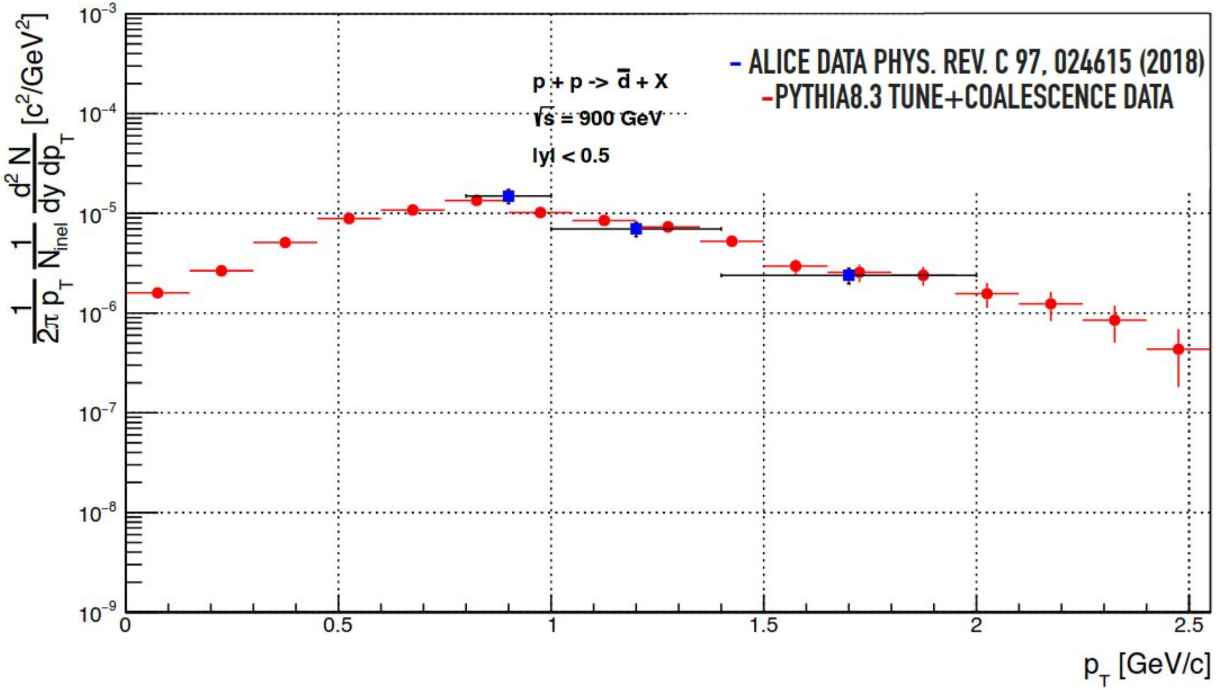
$$B_A = \frac{2J_A+1}{2^A}\frac{1}{\sqrt{A}}\frac{1}{m_T^{A-1}}\left(\frac{2\pi}{R^2+\left(\frac{r_A}{2}\right)^2}\right)^{3/2(A-1)}$$

Transverse mass

Source radius

Nucleus radius

Test of Coalescence Afterburner on ALICE data @ 900 GeV c.o.m. energy



The application of the coalescence afterburner to the tuned Pythia8.3 output provides the Pt spectrum of the antideuterons.

Data are well reproduced by the Argonne wave function.

GALPROP Implementation and Full solution of the transport equation

CRs transport equation and Source term

$$\frac{\partial\psi}{\partial t} = \boxed{q(\vec{r},p)} + \boxed{\vec{\nabla}(D_{xx}\vec{\nabla}\psi - \vec{V}\psi)} + \boxed{\frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{\psi}{p^2} - \frac{\partial}{\partial p}\left[\psi\frac{dp}{dt} - \frac{p}{3}(\vec{\nabla}\cdot\vec{V})\psi\right]} - \boxed{\frac{\psi}{\tau_f}} - \boxed{\frac{\psi}{\tau_r}}$$

Source Space diffusion Momentum diffusion Fragmentation Decay

Galprop is a software that solves the CRs transport equation, providing as output the expected flux of a given species.

$$q = \sum_{i\in[p,He]}\sum_{j\in[p,He]} 4\pi n_j \int_{T_{min}}^{\infty} dT_i \boxed{\frac{d\sigma_{i,j}}{dT_{\bar{d}}}} \boxed{\phi_i(T_i)}$$

Secondary Source Term:

$$\boxed{\frac{d\sigma_{ij}(T_i, T_{\bar{d}})}{dT_{\bar{d}}} = \sigma_{ij,\mathrm{inel}}\frac{dN_{\bar{d}}(T_i, T_{\bar{d}})}{dT_{\bar{d}}}}$$

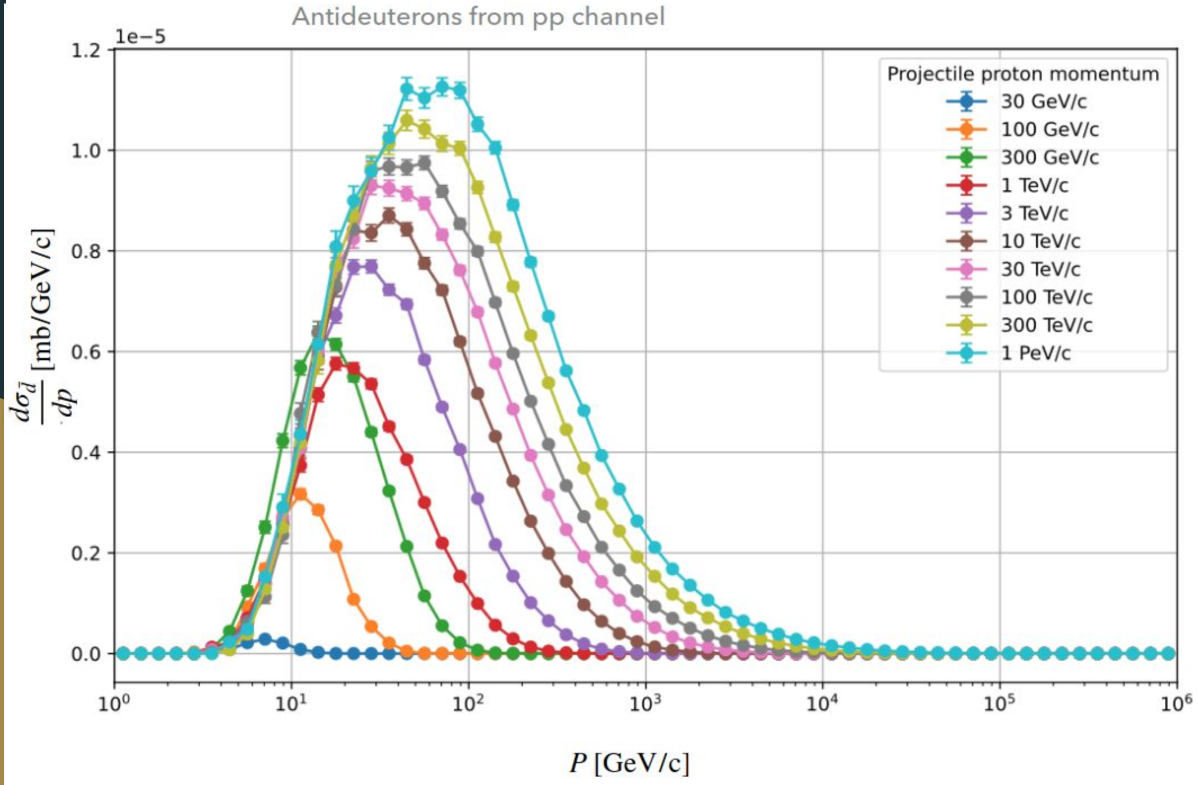
From Pythia-tune + Coalescence model

(Verified with Collider Data)

From GALPROP

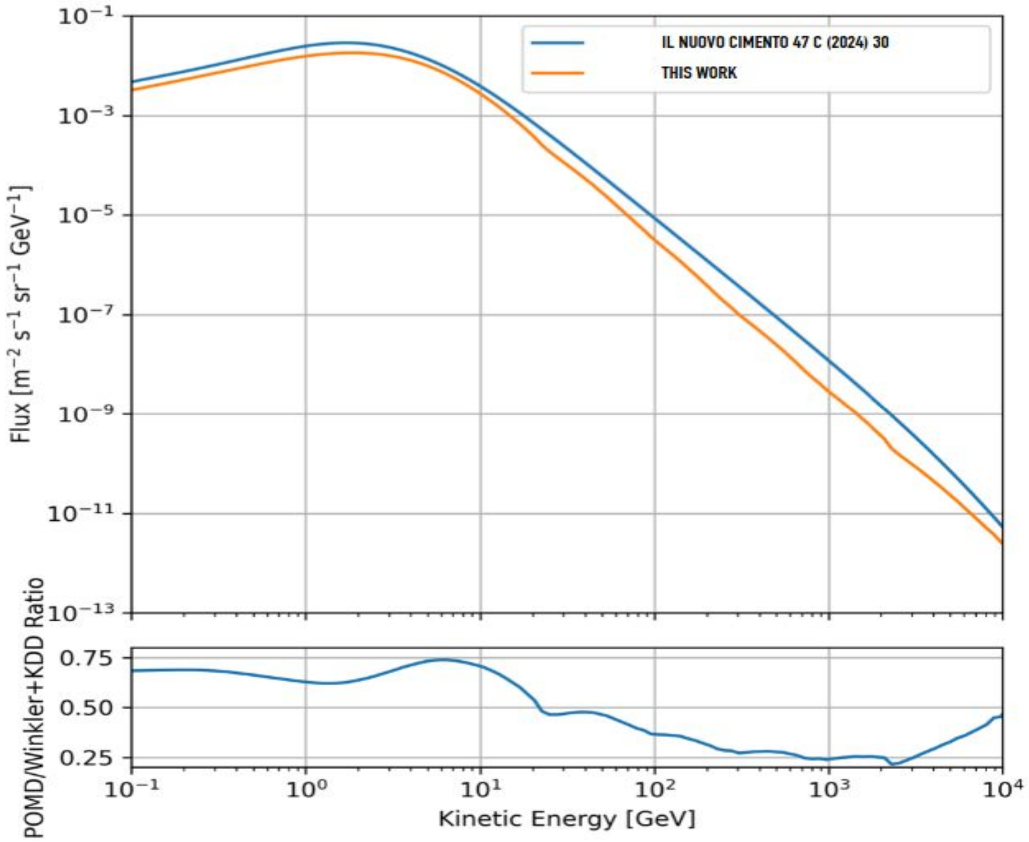
(Verified with AMS-02 data)

Antideuteron production cross section



- Implementation of a momentum grid from 1 GeV/c to 10^6 GeV/c with ten bins per decade.
- Simulation of O(10^9) events for each projectile momentum.
- Run of the event-by-event coalescence algorithm for each simulation
- Extraction of the momentum distributions.
- Similar computation was performed for antiprotons.

Antiproton Astrophysical Background



- The result of this thesis is compared with the latest estimate based on IL NUOVO CIMENTO 47 C (2024) 302

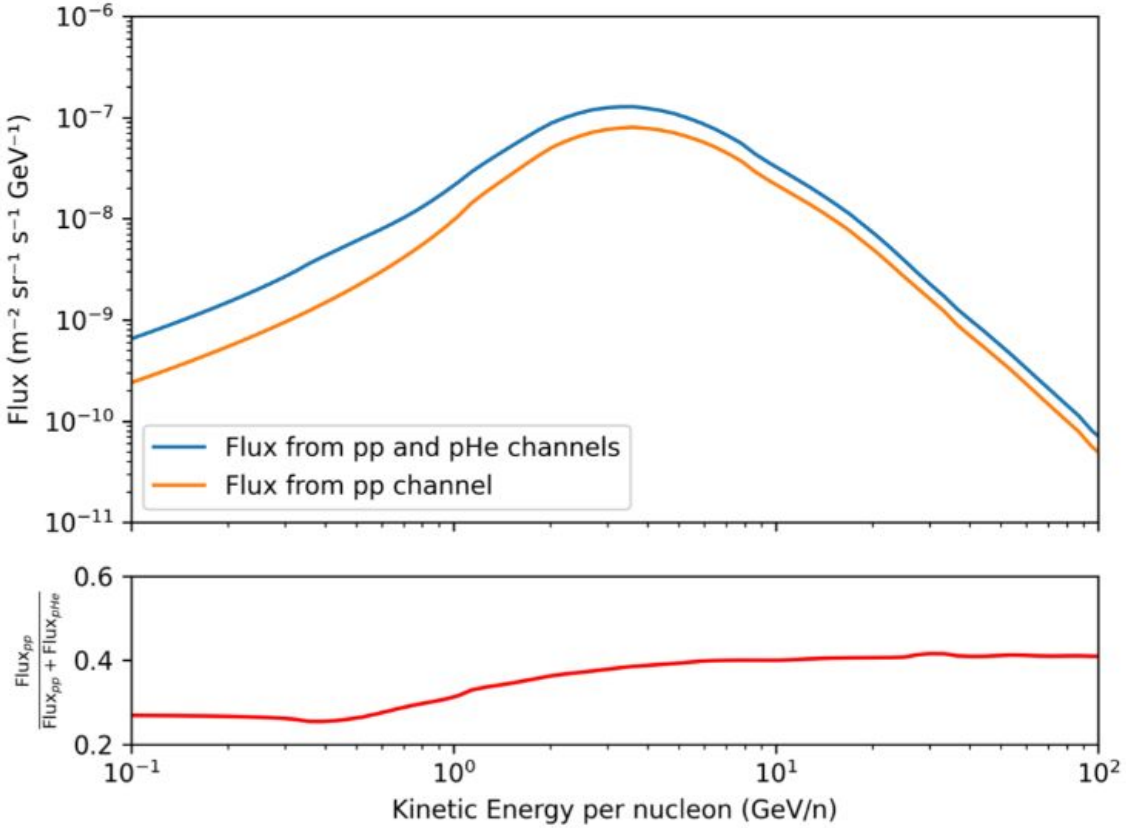
Differences between the two models:

- He-p, He-He and heavier nuclei collisions need to be included.
- Discrepancy between PYTHIA prediction on antiprotons in p-He collisions, as seen in LHCb comparison.

Propagation model used:

[1] M. J. Boschini et al. Astrophys. J. Supp. 250 (2020) 27.

Antideuteron Astrophysical Background



- The subject of the thesis is up-to-date estimation of antideuteron Astrophysical Background based on an interdisciplinary approach

- The result is obtained using the state-of-art GALPROP model, modern Coalescence algorithm based on QM an CRs-tailored Pythia tune

- Similar to the antiproton case possible future development is the inclusion of heavier channels

Perspectives

We used state-of-art coalescence model and propagation model to compute the secondary flux of antideuterons. Future work may include:

- Inclusion of the He-p and, He-He and heavier channels.

Evaluation of uncertainties in:

- Production cross sections, inclusion of new data (AMBER?) to improve the Pythia tuning.
- Astrophysical parameters

What else is missing?

- Solar modulation of negative particles
- Estimation of the fragmentation of the antideuterons