A coalescence afterburner for antinuclei production in hadronic collisions with Monte Carlo generators

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ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

Istituto Nazionale di Fisica Nucleare
Sezione di Bologna

CosmicAntiNuclei

European Research Council
Established by the European Commission

Outline

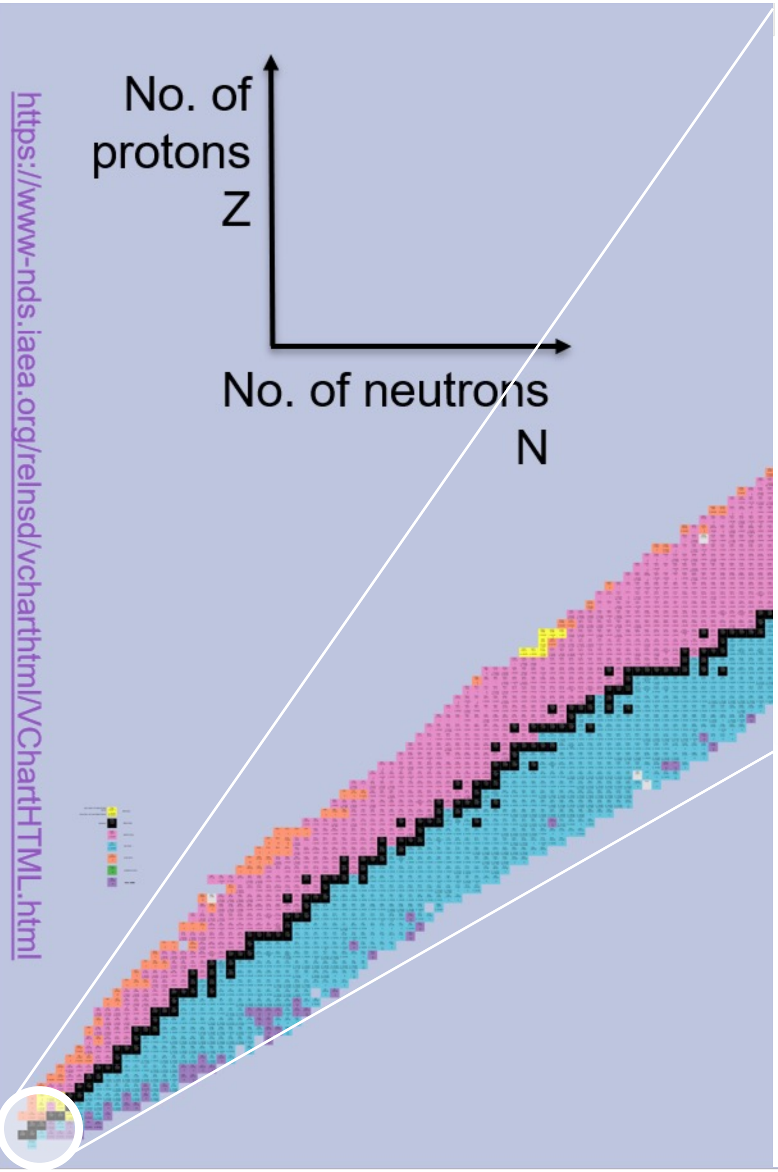
- Setting the stage: light nuclei and antinuclei in high-energy collisions
- Coalescence modelling
- Event-by-event coalescence afterburner to Monte Carlo generators
- Summary and prospects

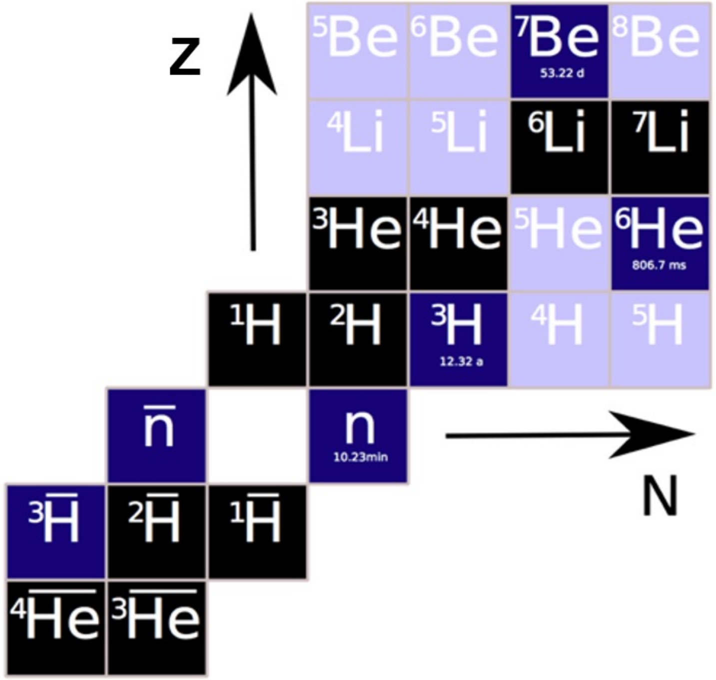
Based on

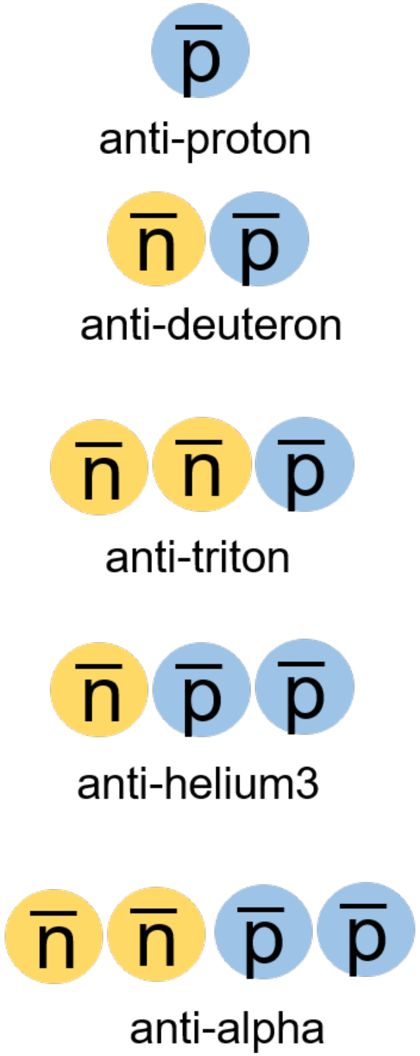
- **Novel parameter-free coalescence model for deuteron production**, arXiv:2302.12696
  M. Mahlein[1], L. Barioglio[2,1], F. Bellini [3,4] , L. Fabbietti[1], C. Pinto[1], B. Singh[1], S. Tripathy [4],
  [1] TUM, [2] INFN Torino, [3] University of Bologna, [4] INFN Bologna

- **Antideuteron from tuned PYTHIA plus a coalescence afterburner,** in preparation
  F. Bellini [1,2], M. Di Mauro[3], S. Tripathy[4,2],
  [1] University of Bologna, [2] INFN Bologna, [3] INFN Torino, [4] CERN

Setting the stage #1: **light antinuclei**







A = 1
Z = -1

A = 2
Z = -1

A = 3
Z = -1

A = 3
Z = -2

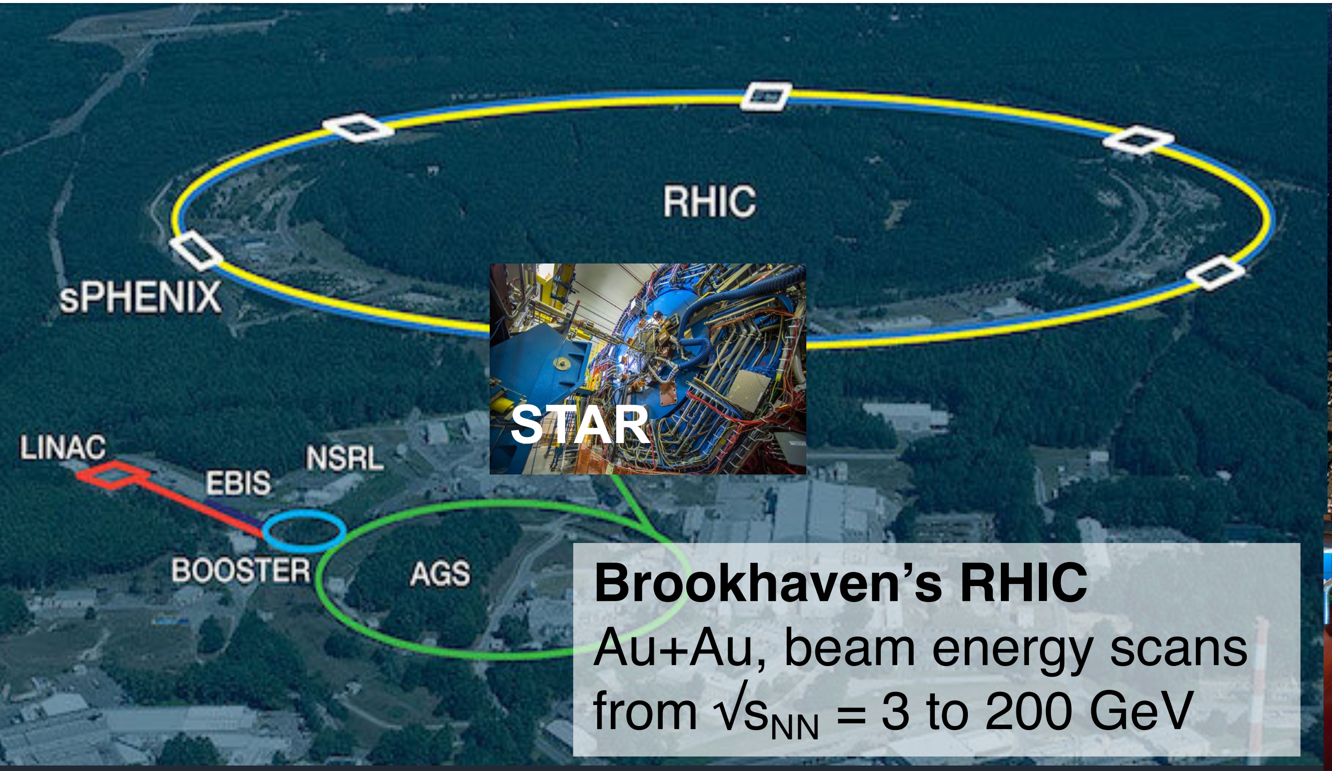
A = 4
Z = -2

Setting the stage #2: **antinuclei in the laboratory**

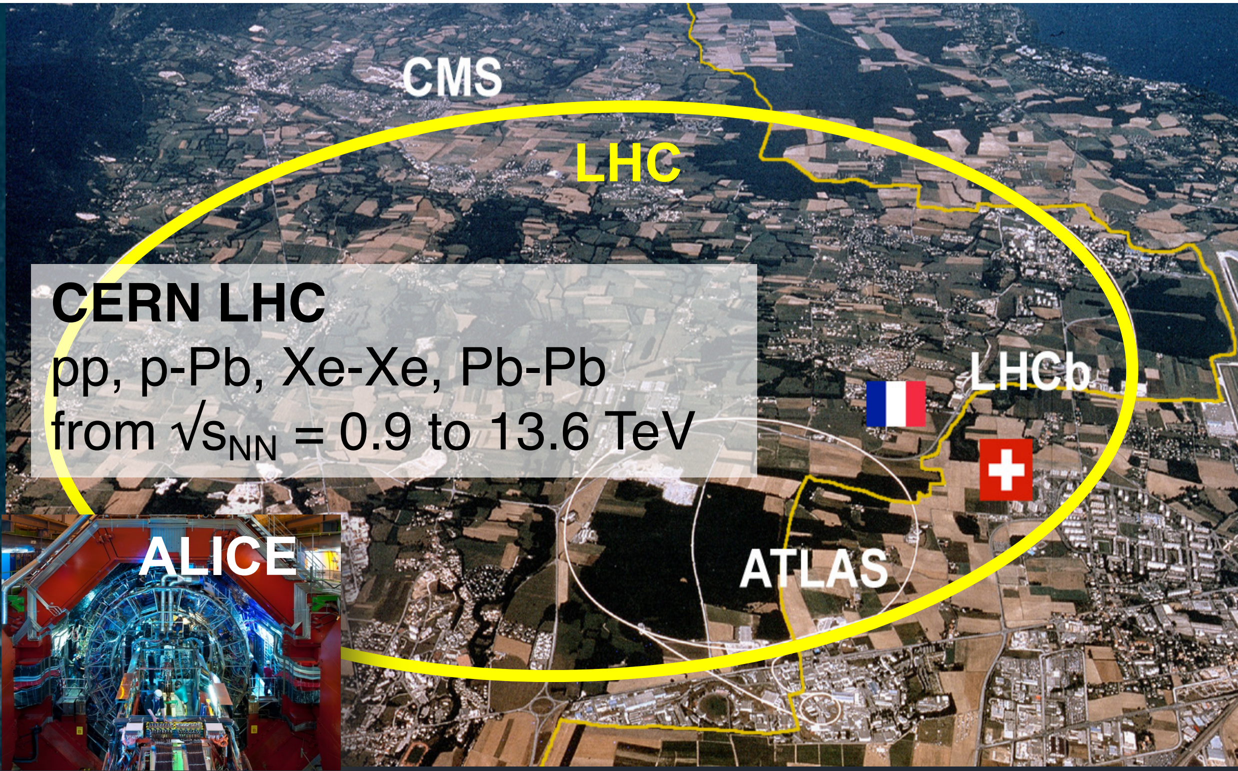
The discovery of light antinuclei was possible using relativistic nuclear collisions.

Antinuclei up to A = 4 are currently in reach at accelerators.
The anti-alpha is the heaviest observed so far, first seen by the STAR experiment at RHIC in 2011, measured by ALICE in Pb-Pb collisions at the LHC: $[^{4}\overline{\mathrm{He}}/\mathrm{p}]_{\mathrm{PbPb}} \sim 10^{-8}$

ALICE Coll., Nucl. Phys. A 971 (2018) 1-20



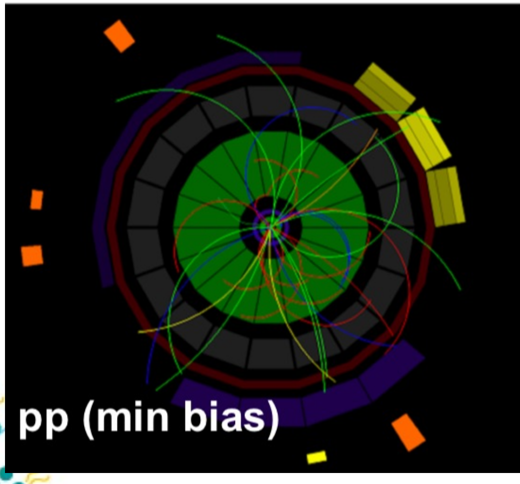
Brookhaven's RHIC
Au+Au, beam energy scans
from $\sqrt{s_{NN}}$ = 3 to 200 GeV



CERN LHC
pp, p-Pb, Xe-Xe, Pb-Pb
from $\sqrt{s_{NN}}$ = 0.9 to 13.6 TeV

High-energy proton-proton collisions

- Complex final-state involving multi-parton interactions, color reconnection...
- Small source (R ~ 1 fm)
- Up to $\langle dN_{ch}/d\eta \rangle$ ~ 40 at the top LHC energy



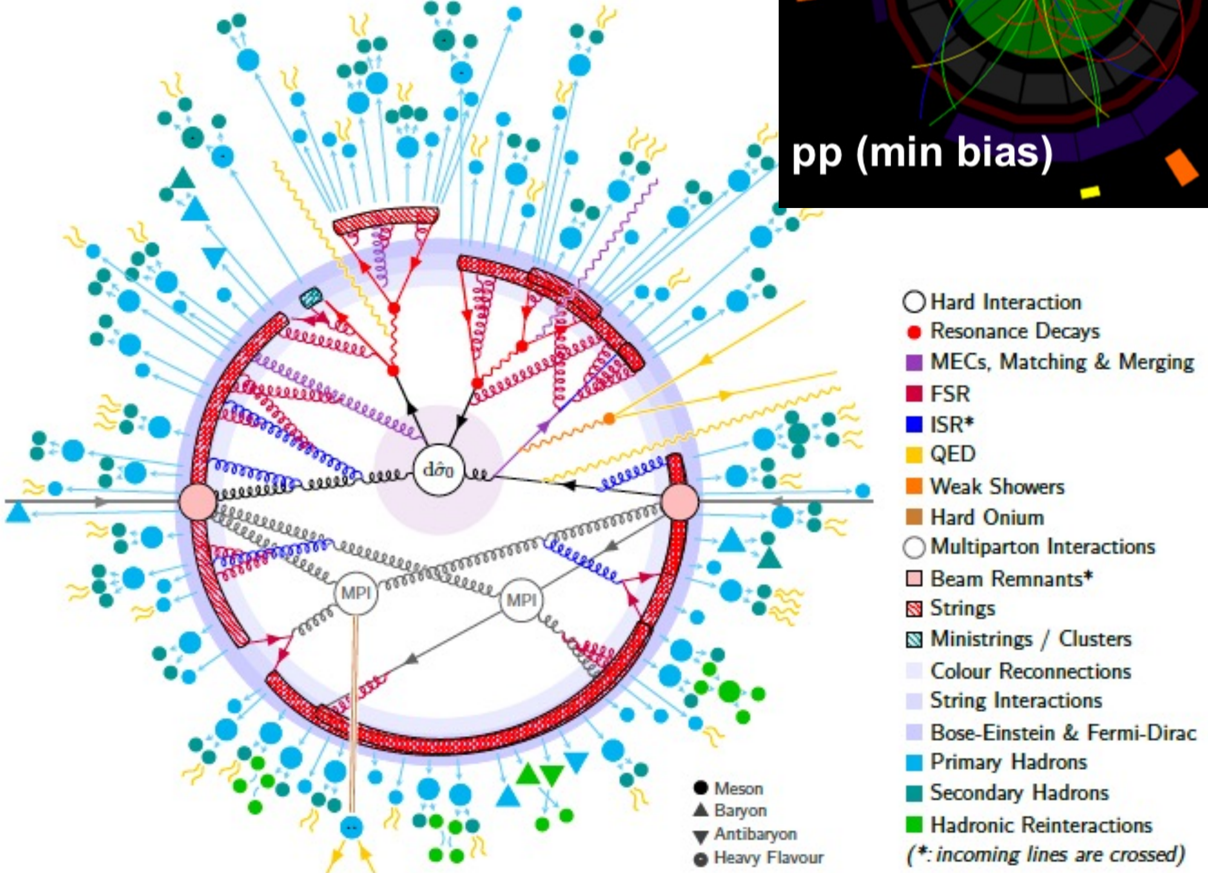


Figure from C. Bielrich et al, *arXiv:2203.11601*

Setting the stage #3: **final state of high-energy collisions**

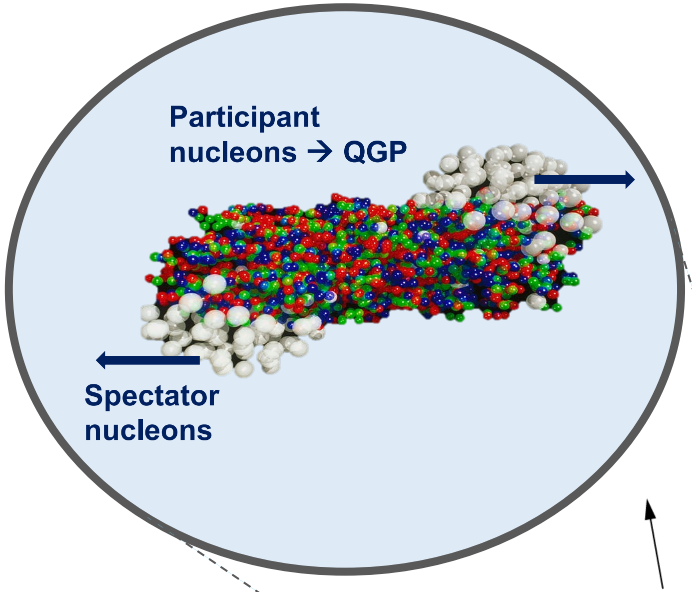
High-energy proton-proton collisions

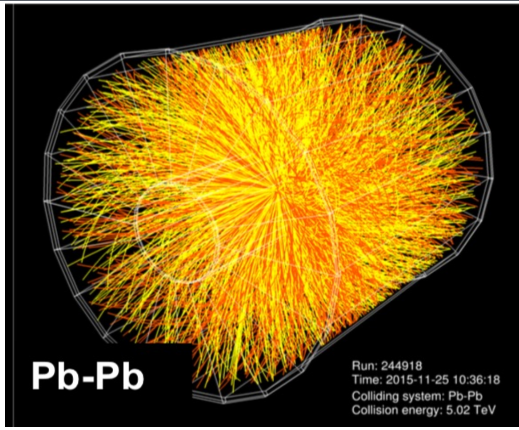
- Complex final-state involving multi-parton interactions, color reconnection...
- Small source (R ~ 1 fm)
- Up to $\langle dN_{ch}/d\eta \rangle$ ~ 40 at the top LHC energy

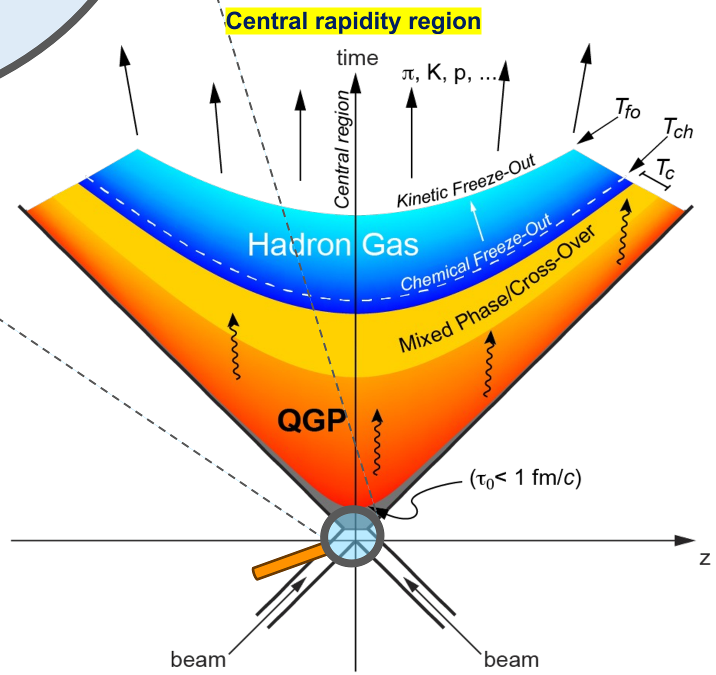
High-energy heavy-ion collisions

- production of a quark-gluon plasma (QGP)
- fast, collective expansion and cooling → hadronisation
- Spatially extended system (R ~ few fm)
- Up to $\langle dN_{ch}/d\eta \rangle$ ~ 2000 at LHC

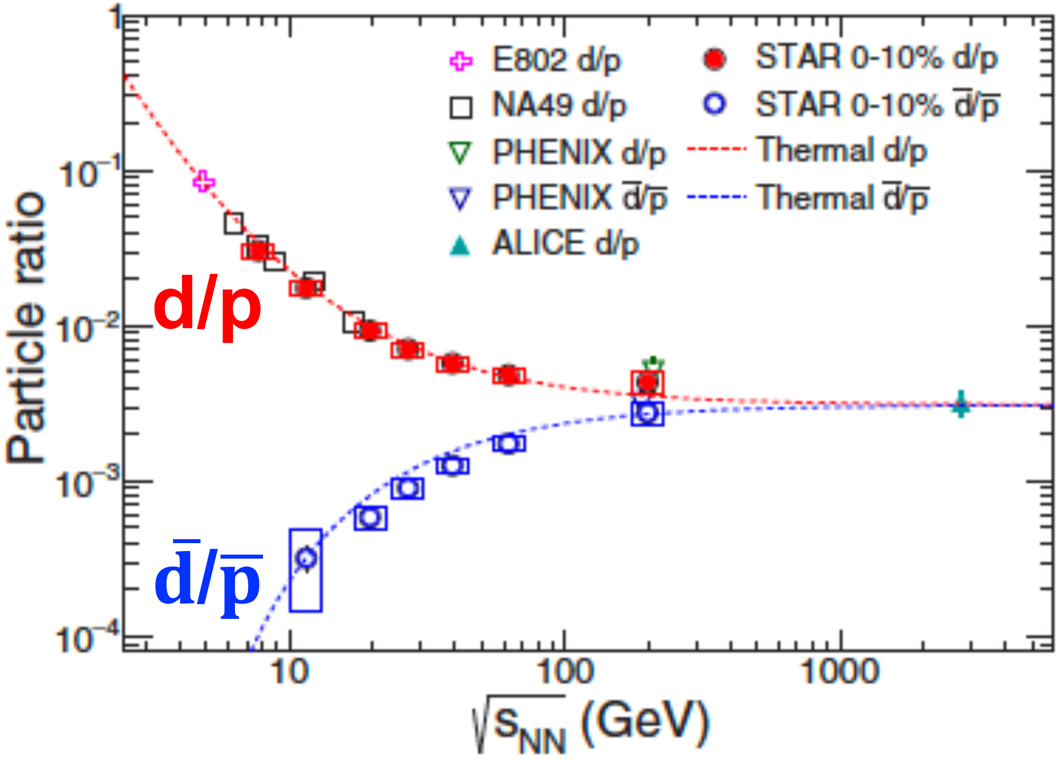
→ (anti)nuclei are produced after hadronisation in a hot (T ~ 100-155 MeV) and crowded environnment





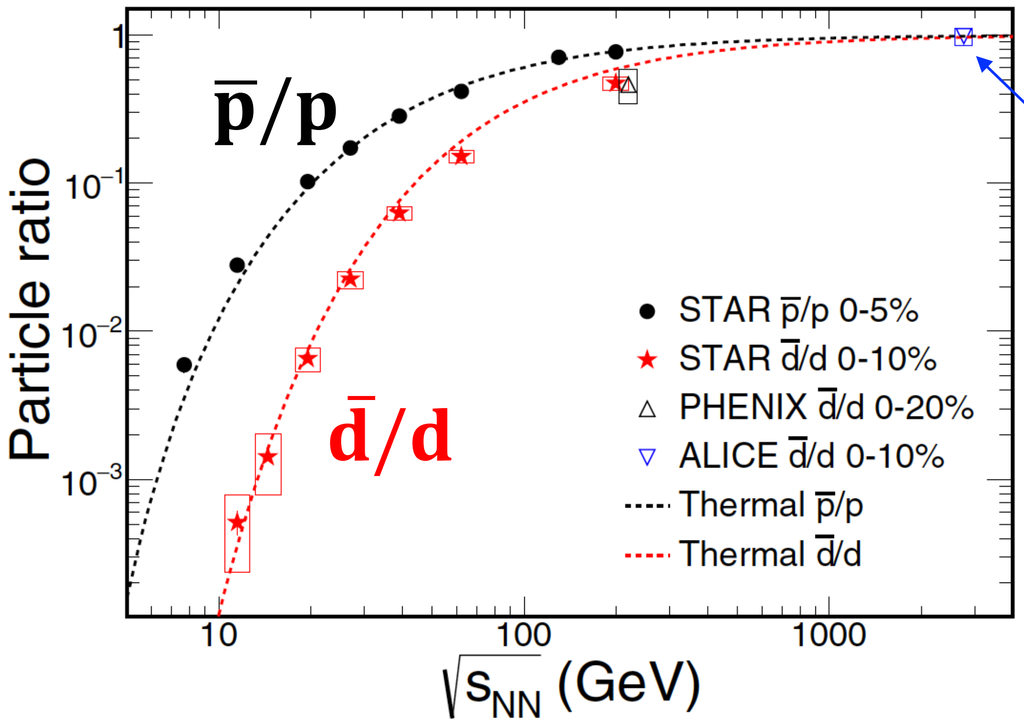


Setting the stage #4: **antinuclei at LHC energies**



The production of antideuteron relative to antiproton increases with the CoM energy, while d/p decreases.

Setting the stage #4: **antinuclei at LHC energies**



The production of antideuteron relative to antiproton increases with the CoM energy, while d/p decreases.

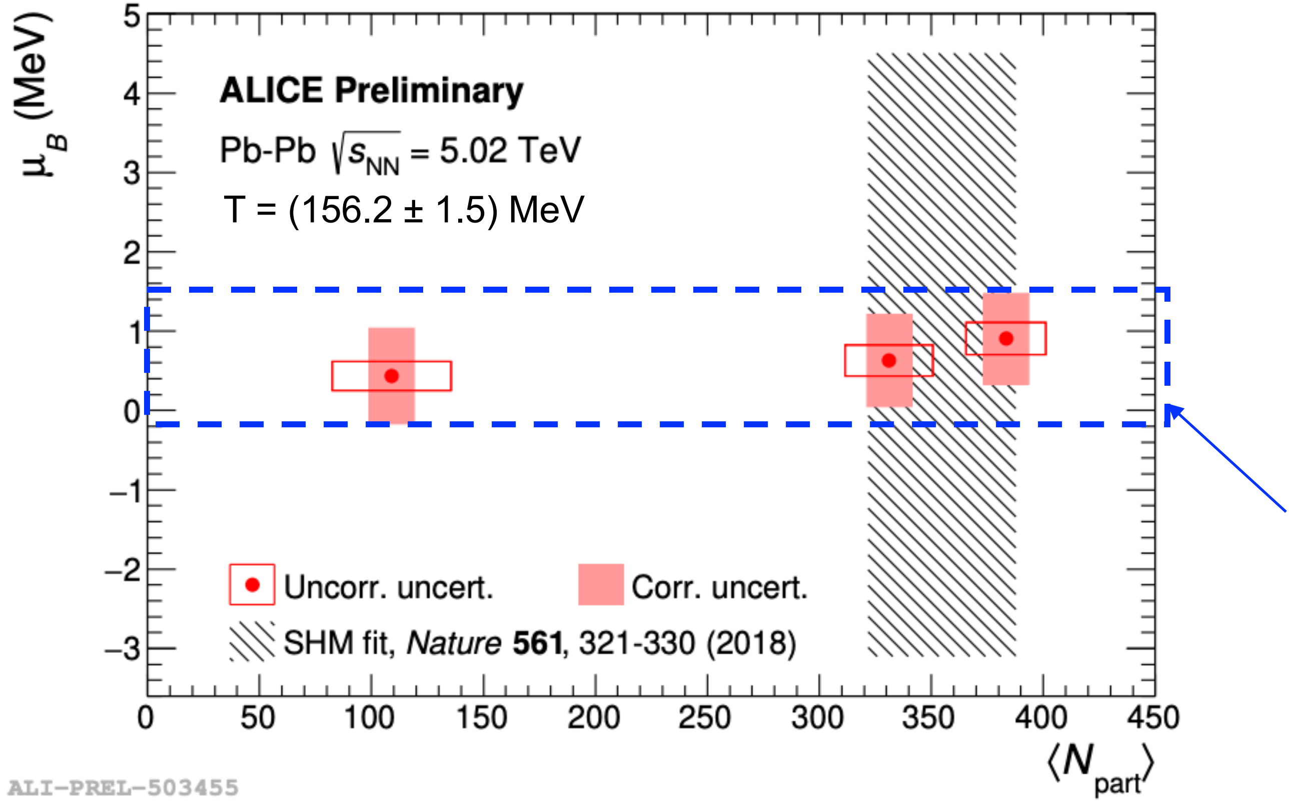
At the LHC, at central rapidity nuclei and antinuclei are produced with same abundances

$$\bar{d}/d \sim \bar{p}/p \sim 1$$

In thermal models, (anti)nuclei are originating from a thermal source, the antimatter/matter ratio depends on μ_B and T

$$\frac{n_{\bar{p}}}{n_p} = \exp(-2\mu_B/T) \qquad \frac{n_{\bar{d}}}{n_d} = \exp(-4\mu_B/T)$$

Setting the stage #4: **antinuclei at LHC energies**



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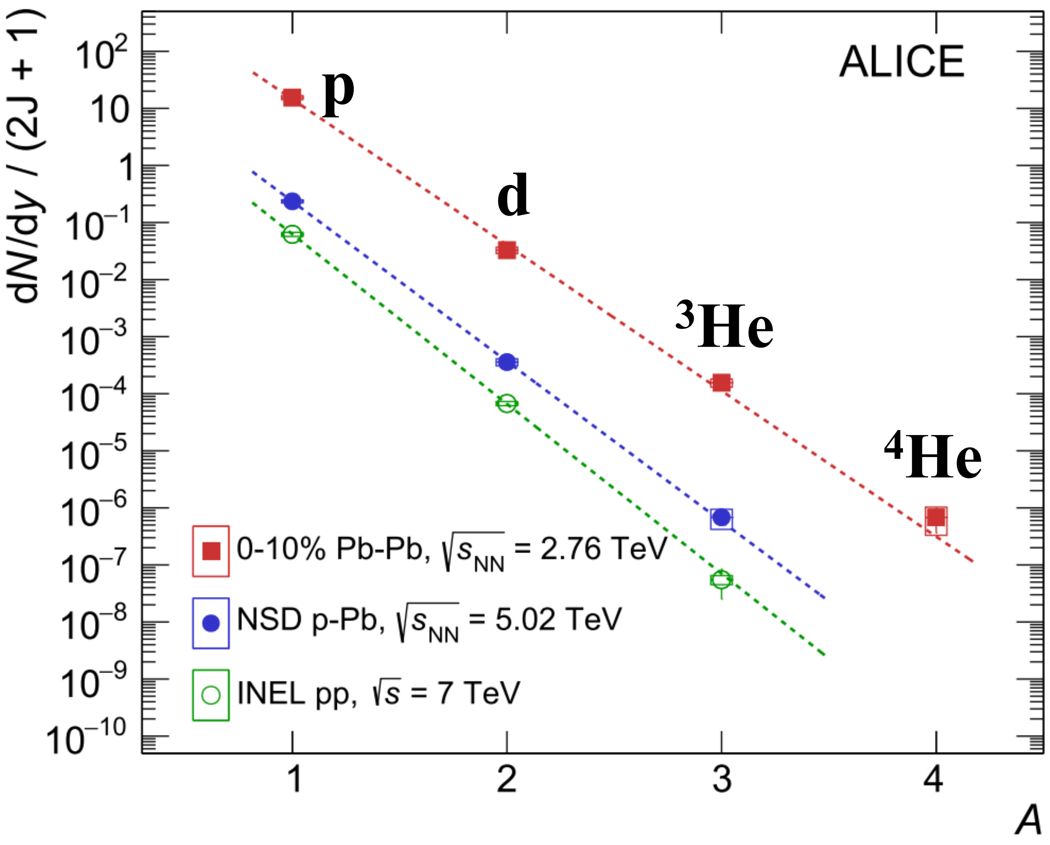
At the LHC, at central rapidity nuclei and antinuclei are produced with same abundances

$$\bar{d}/d \sim \bar{p}/p \sim 1$$

→ Baryochemical potential: $\mu_B \sim 0$

SQM 2022, M. Ciacco, arXiv:2209.05369
STAR, PRC 99, 064905 (2019)
Thermal model: Cleymans et al.,PRC 84, 054916 (2011)



LHC is an antinucleus factory.
Production is still rare but large integrated luminosities allow for precision measurements.

The production of antideuteron relative to antiproton increases with the CoM energy, while d/p decreases.

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→ Baryochemical potential: $\mu_B \sim 0$

The **penalty factor** for increasing the mass number by one unit at the LHC is

~ 1/350 in central Pb-Pb collisions

~ 1/600 in p-Pb collisions

~ 1/10^3 in pp collisions

Setting the stage #5: **cosmic antinuclei**

Antideuterons ($\overline{d}$) and antihelium nuclei ($^{3}\overline{He}, ^{4}\overline{He}$) in cosmic rays have been proposed as a promising **smoking gun** signature of dark matter

- Produced **from annihilation or decay of dark matter WIMPs** into Standard Model particles in the Galactic halo

  e.g. $\chi + \overline{\chi} \rightarrow \overline{\mathrm{d}} + X$

- **Low background** of secondary cosmic rays from **hadronic interactions** of primary CR with the interstellar matter (**pp, p-He**…), √s ~ 10 – 20 GeV

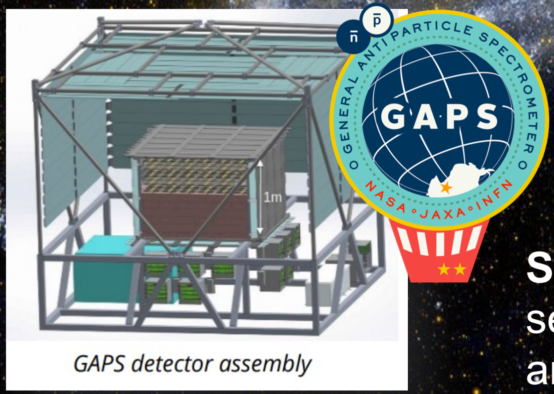
  e.g. $\mathrm{p} + \mathrm{p} \rightarrow \overline{\mathrm{d}} + X \quad \overline{\mathrm{p}} + {}^{3}\mathrm{He} \rightarrow \overline{\mathrm{d}} + X$ + …

- **Searches** with space-based experiments, like AMS-02 (ongoing) and GAPS (scheduled).

AMS@ISS

Operating since 2011, until lifetime of ISS. It can separate CR chemical and isotopic composition in GeV-TeV range, >200 billion CR so far

→ **Any antinuclei?**



GAPS detector assembly

Scheduled in Dec. 2022, will search for low-energy cosmic-ray antinuclei (E<0.25 GeV/n)

Setting the stage #5: **cosmic antinuclei**

Signal = antinuclei from dark matter source

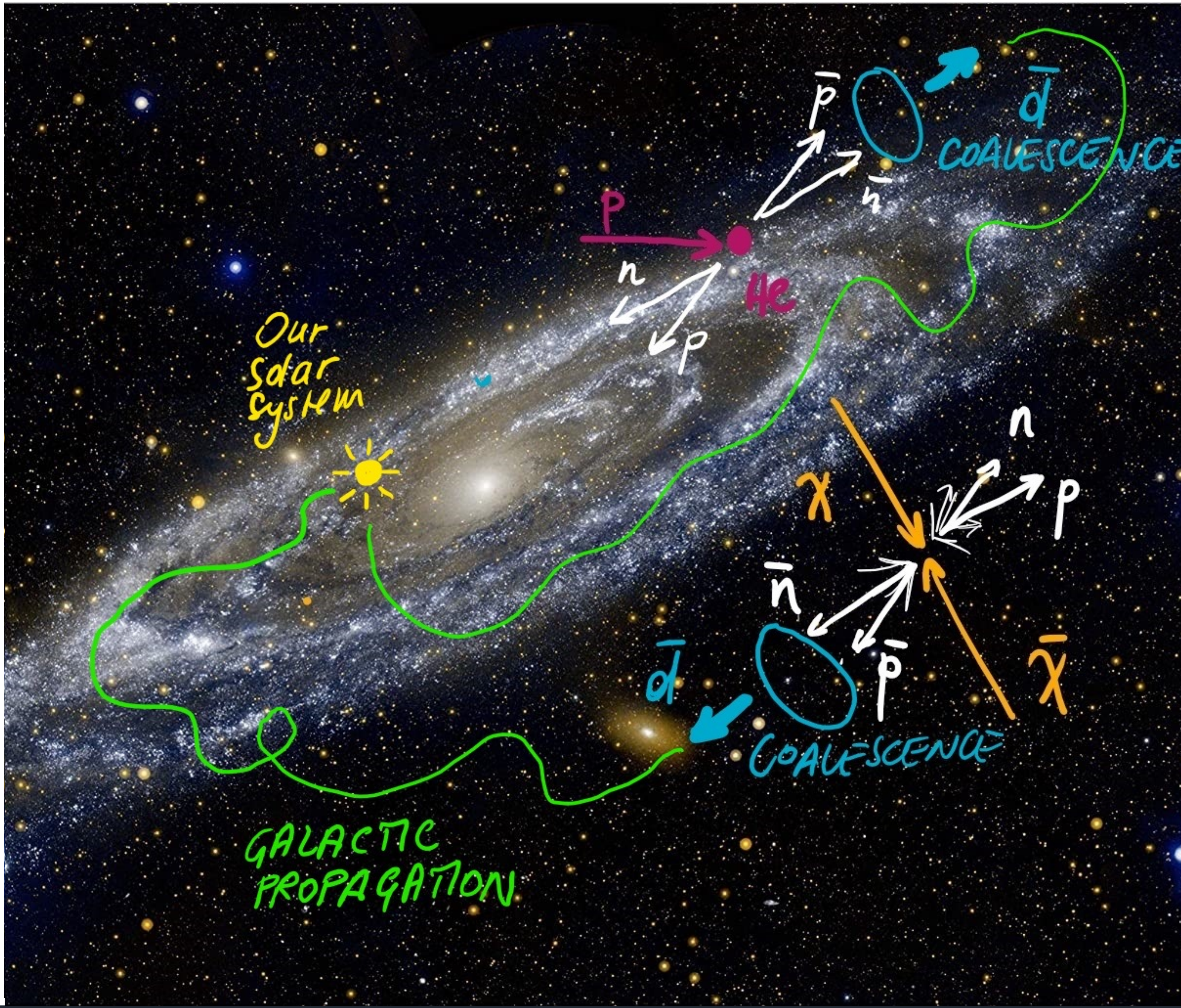
Background = secondary cosmic rays from hadronic interactions of primary CR with the InterStellar Matter (pp, p-He…) in the Galaxy

Ingredients needed to predict rates:

- **model formation of antinuclei**

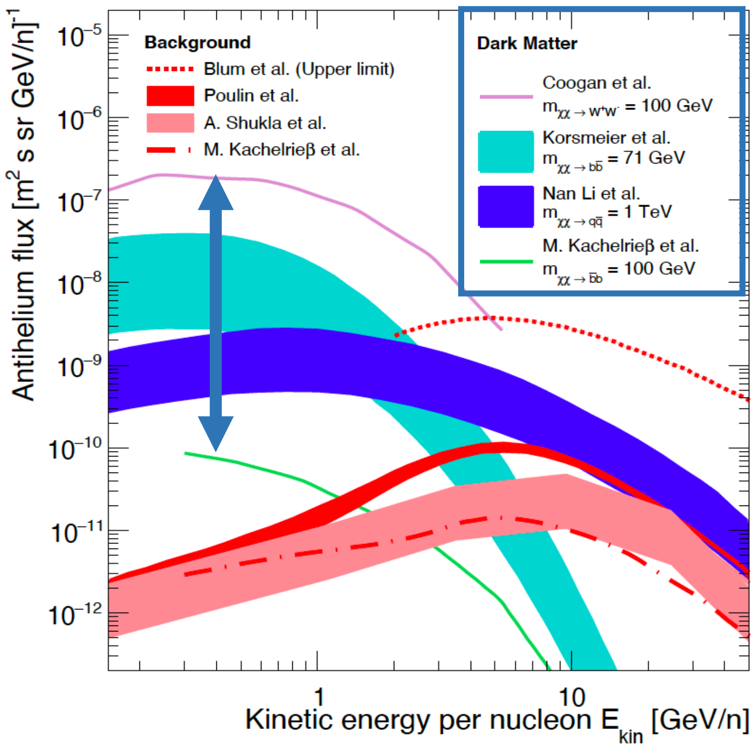
- model **cosmic ray propagation** in the Galaxy and the heliosphere
  [e.g. Boschini et al. Astrophys. J. Suppl. Ser. 250, 27 (2020)]

- estimate **absorption** cross section of antinuclei in the ISM and the detector materials
  [see ALICE Coll., Nature Physics vol. 19, 61–71 (2023)]



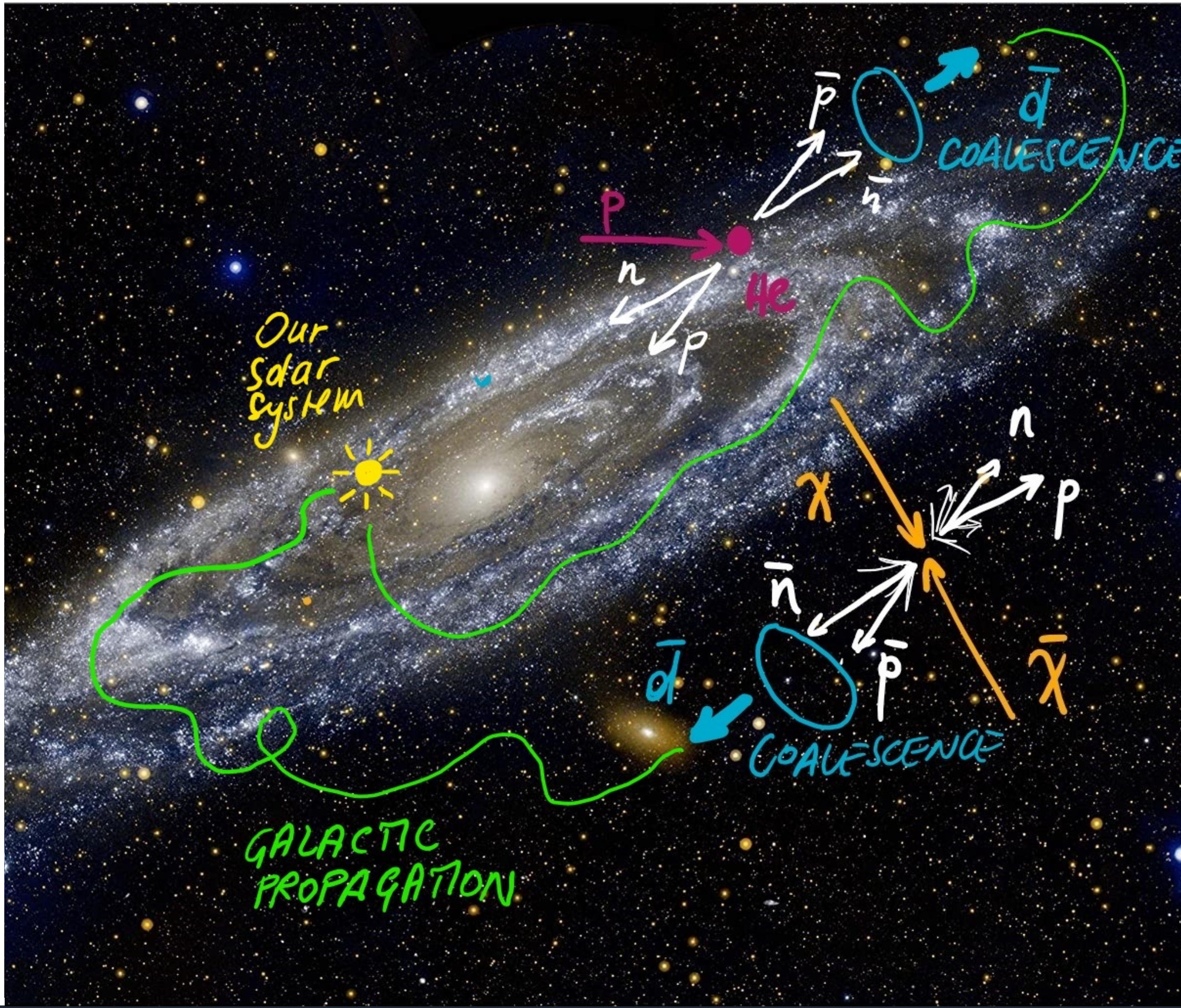
Setting the stage #5: **modelling formation of antinuclei**

P. von Doentichem et al., JCAP08(2020)035



Typically, **coalescence models** are applied to both DM and CR source with different input nucleon spectra.

→ Still **significant uncertainties** associated with production models

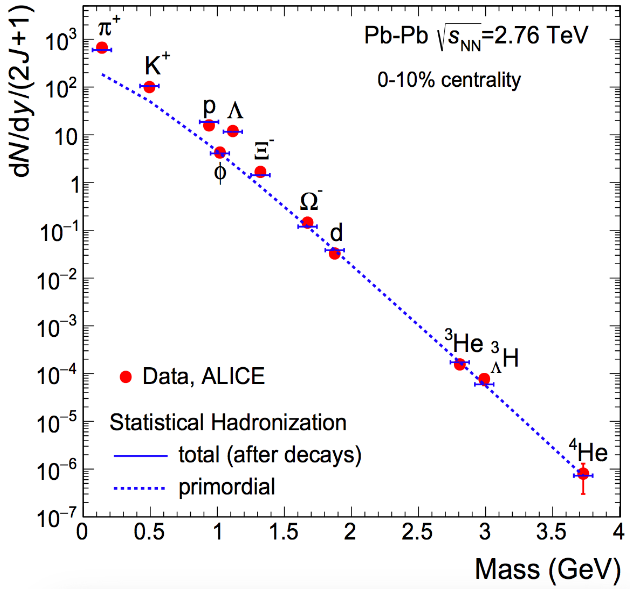


Production models

Statistical hadronisation (SHM)

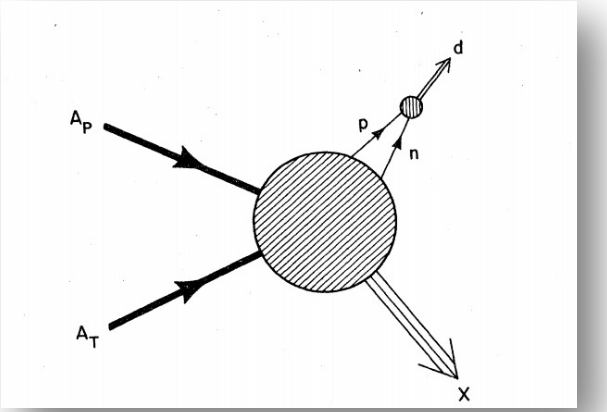
- (anti)nuclei are emitted from a source at thermal and chemical equilibrium at T_{ch}
- Abundances: $\mathbf{dN / dy \sim exp(-m / T_{ch})}$
- No detailed information on the structure of bound objects
- At the LHC, $T_{ch} \approx$ 156 MeV >> B_E (d) = 2.2 MeV
- Macroscopical approach

A. Andronic et al., Nature 561, 321 (2018



Coalescence

- Nuclei form at kinetic freeze-out by coalescence of nucleons that are close in momentum and coordinate space
- Result of final state interactions between p ($\bar{p}$) and n ($\bar{n}$)
- Microscopical approach → applicable in event-by-event simulations
- Simple/spherical vs Wigner-function based approach



Butler and Pearson, PR 129, 836 (1963)
Kapusta, PRC 21, 1301 (1980)

Coalescence probability

Production depends on the coalescence probability B_A,

$$E_A \frac{d^3 N_A}{dp_A^3} = B_A \left(E_p \frac{d^3 N_p}{dp_p^3}\right)^Z \bigg|_{\vec{p}_p = \frac{\vec{p}_A}{A}} \left(E_n \frac{d^3 N_n}{dp_n^3}\right)^N \bigg|_{\vec{p}_n = \frac{\vec{p}_A}{A}}$$

Nucleus distributions

Nucleon distributions

Butler and Pearson, PR 129, 836 (1963);
Kapusta, PRC 21, 1301 (1980);
Sato and Yazaki, PLB 98, 153 (1981);
Nagle et al., PRC 53, 367 (1996);
Scheibl and Heinz, PRC 59, 1585 (1999);
Blum et al., PRD 96,103021 (2017) + …

For nuclei that are large w.r.t. the source, the phase space is reduced to the momentum space → coalescence momentum p_0

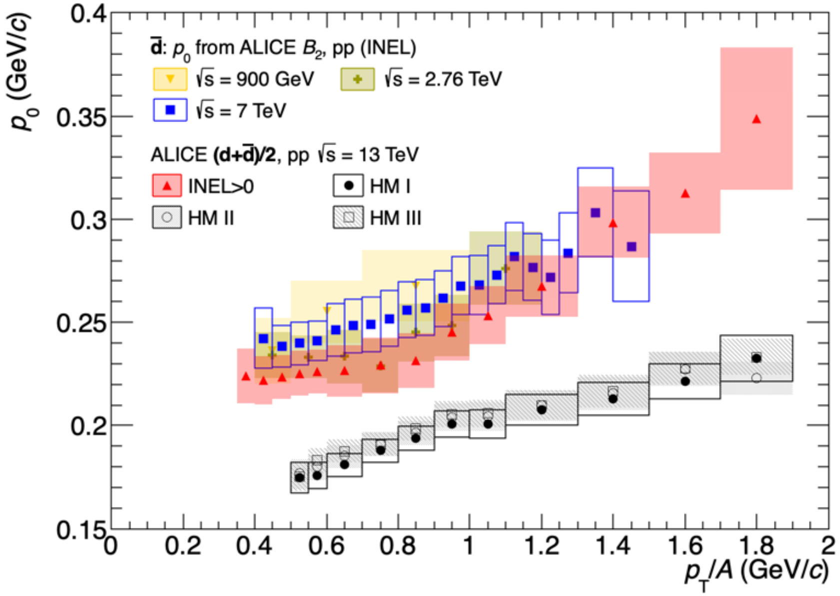
- p_0 ***a priori* unknown**
- "spherical" approach: $|\overrightarrow{p_n} - \overrightarrow{p_p}| < p_0$

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

Nucleus mass

Nucleon mass

Coalescence momentum



In most astrophysical and CR applications, p_0 is tuned on data and assumed to be momentum-independent but process-dependent.

Coalescence probability in **state-of-the art models**

Coalescence is a quantum-mechanical multi-body problem: state-of-the-art models are based on density matrix approach and Wigner formalism.

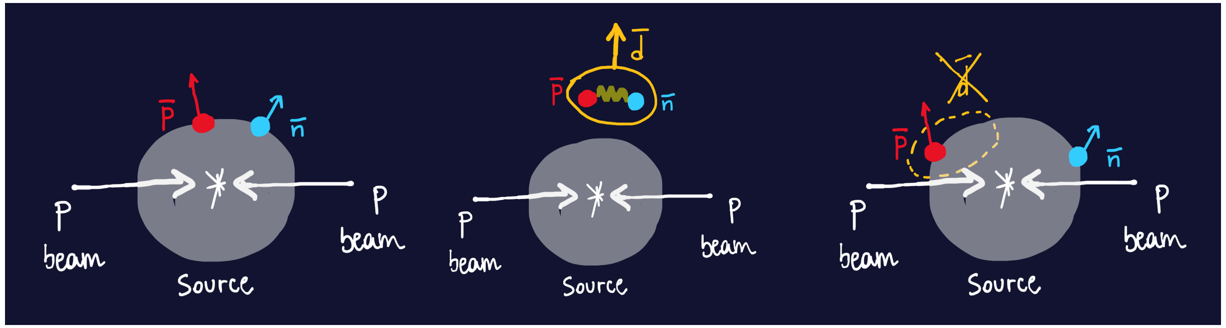
Analytical* calculations show that probability depends on
- the (transverse) **momentum**
- the **size of the nucleon source**
- the **nucleus size** (*gaussian wavefunction)

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

Nucleon transverse mass (including momentum)

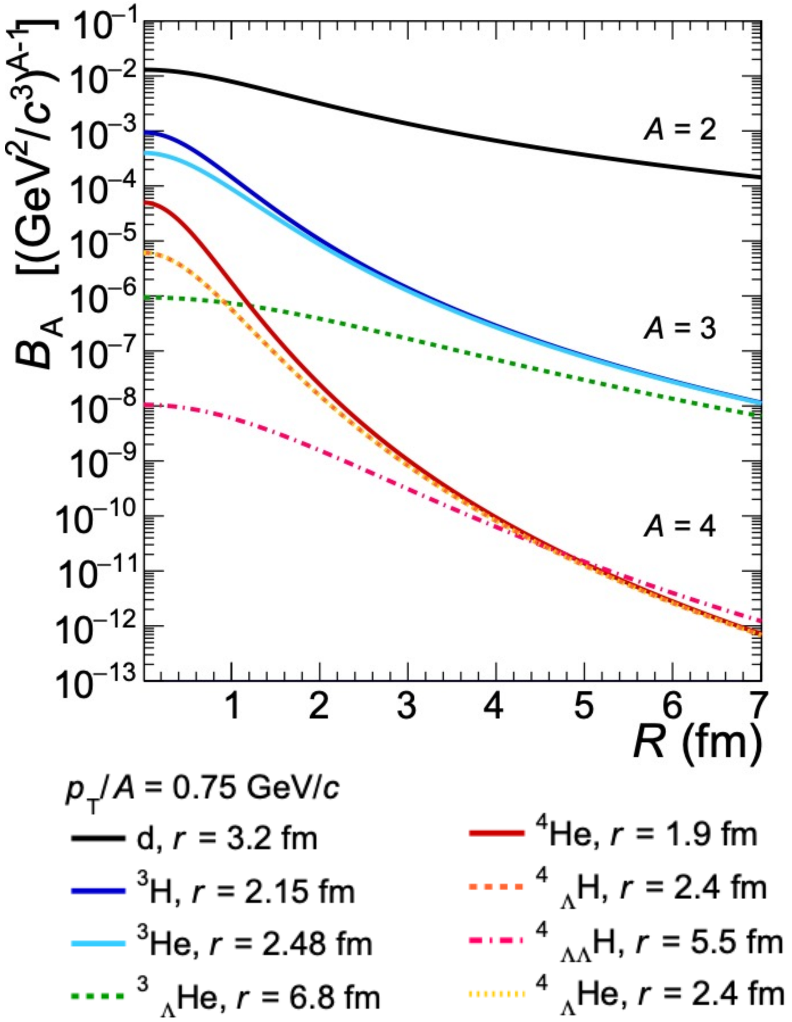
Source radius

Nucleus radius



R. Scheibl, U. Heinz, PRC 59. 1585-1602 (1999)

F.Bellini and A. Kalweit, PRC 99, 054905 (2019)



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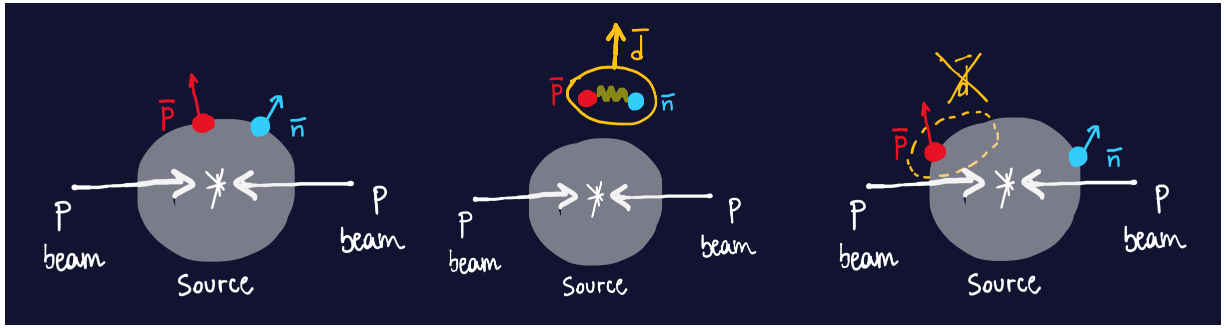
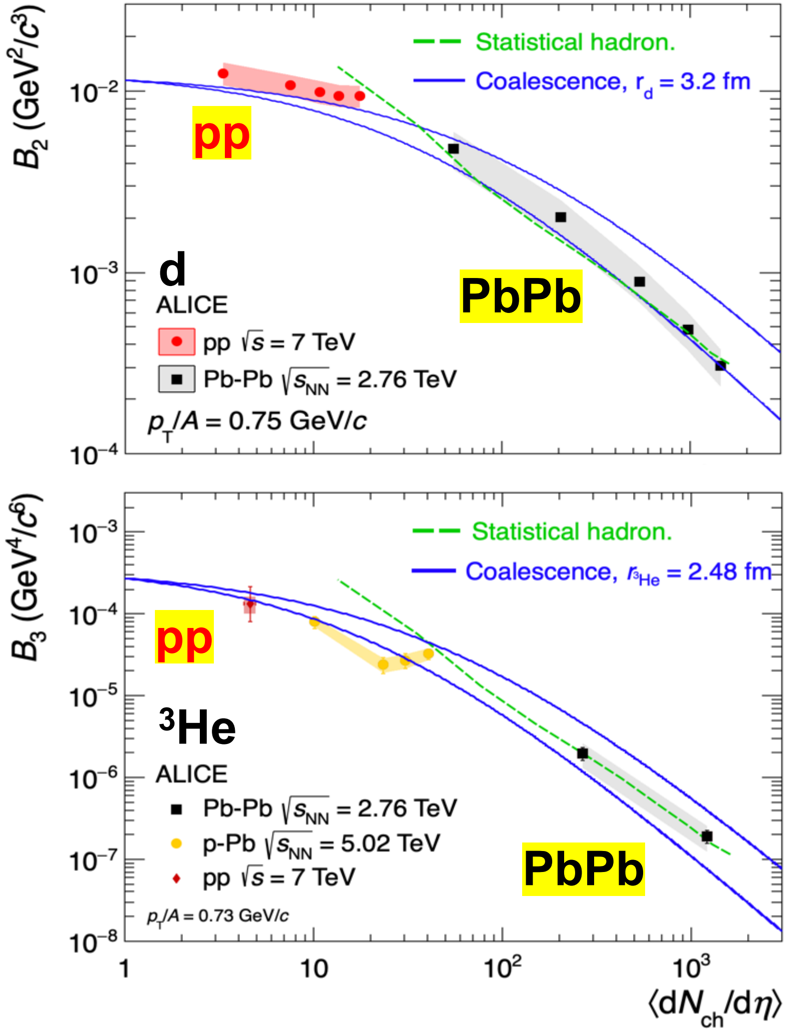
Nucleon transverse mass (including momentum)

Source radius

Nucleus radius



Simplified from *PLB 794 (2019) 50-63, PRC 101 (2020) 044906*

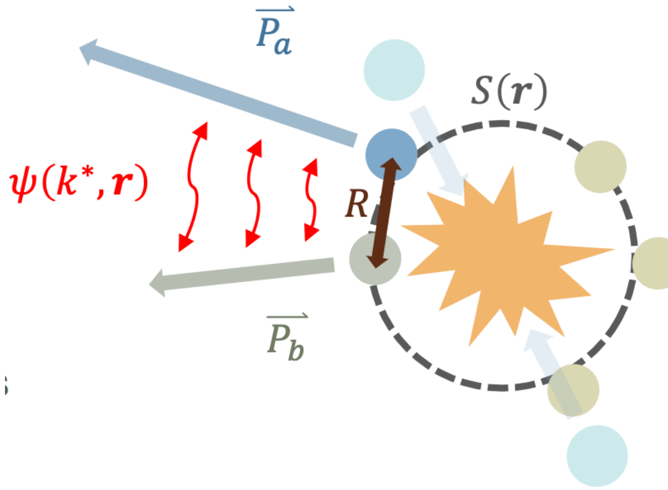


Relation between **femtoscopic correlations and coalescence**

Two-particle momentum correlations provide information about the final-state interaction among particles

→ powerful technique to gain access to interaction potentials

L. Fabbietti, et al., Ann.Rev.Nucl.Part.Sci. 71 (2021) 377-402



Credits: ALICE/TUM

Quantum-mechanical 2-body problem:

- Discrete bound state solutions ⟶ coalescence
  K.Blum, M. Takimoto, PRC 99, 044913 (2019); S. Bazak, S. Mrowczynski, EPJA 56, 193 (2020)
- Continuum solutions ⟶ information about the source
  Two-particle momentum correlations used to measure size and lifetime of the system created in pp and heavy-ion collisions (Hanbury-Brown-Twiss interferometry)

$$\mathcal{B}_2(p) \approx \frac{2(2s_d+1)}{m(2s_N+1)^2}(2\pi)^3 \int d^3\mathbf{r}\, |\phi_d(\mathbf{r})|^2\, \mathcal{S}_2(\mathbf{r}) \quad \Leftrightarrow \quad \mathcal{B}_2(p) \approx \frac{2(2s_d+1)}{m(2s_N+1)^2} \int d^3\mathbf{k}\, \mathcal{F}_d(\mathbf{k})\, \mathcal{C}_2(p, \mathbf{k})$$

Coalescence probability (d case)

Nucleus wave function ⟺ Form factor

Source ⟺ Momentum correlation function

Motivation for a **coalescence afterburner**

Recap:

- ✓ Multi-differential and high-precision data from ALICE at the LHC available → A. Mastroserio's talk on 14/6
- ✓ Recent developments in coalescence modelling in relation to the source
- ✓ Possibility to gain new insights into formation mechanisms for light (anti)nuclei
- ✓ Possible applications to CR physics

add the fact that the **production of light nuclear bound states is not modelled in Monte Carlo event generators commonly-used in HEP, like PYTHIA 8.3 or EPOS.**

→ **Motivation to apply coalescence as an afterburner to particle production from MC generators**

Focus on (anti)**deuteron**: simplest system, high-precision multi-differential data

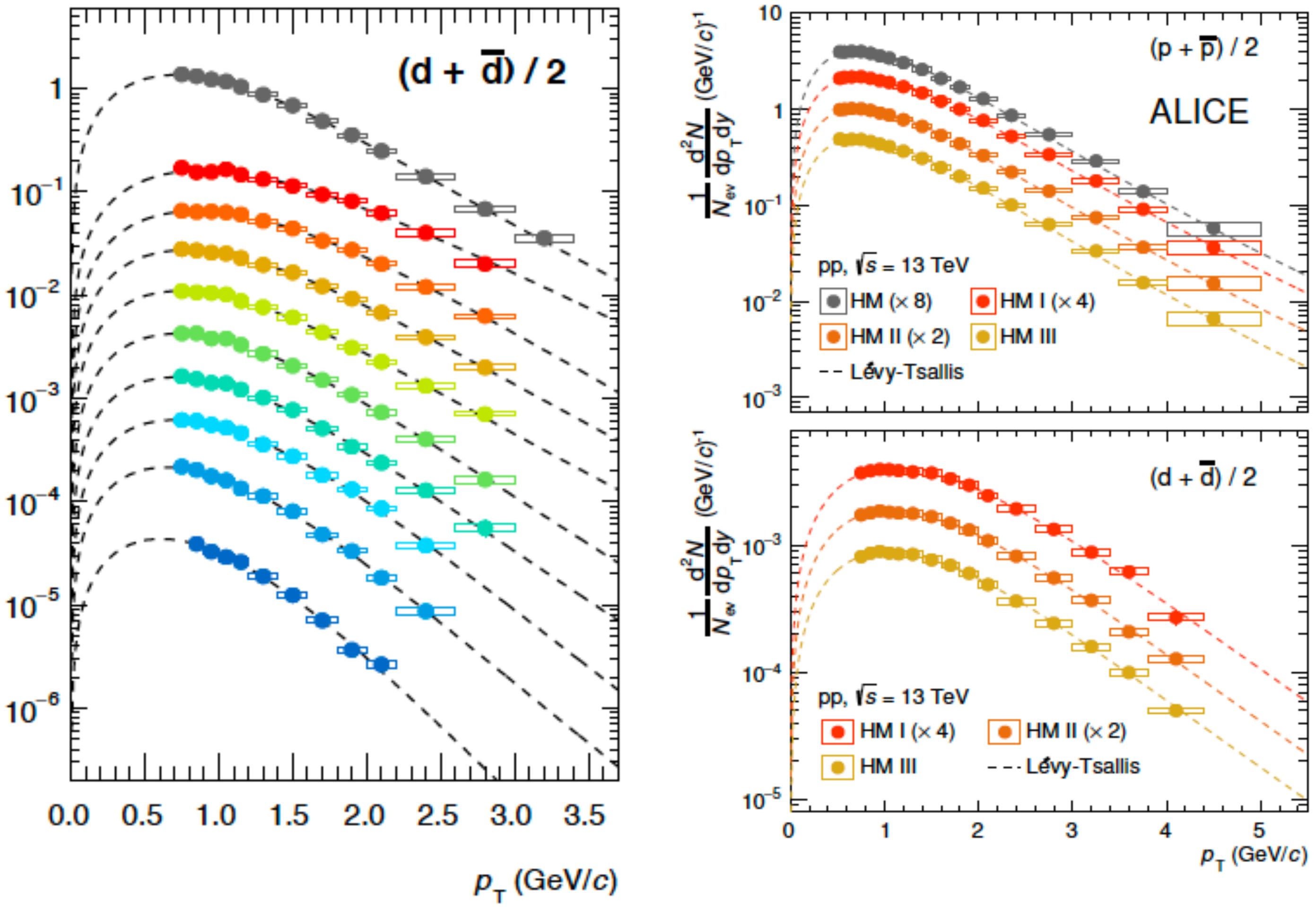
Focus on **pp collisions**: relevance for cosmic ray antinuclei

Choice of **EPOS3** and **PYTHIA 8.3** generators

Validation with precise ALICE high-energy pp data

Inspired by *Kachelriess et al., EPJA 57, 167 (2021)*

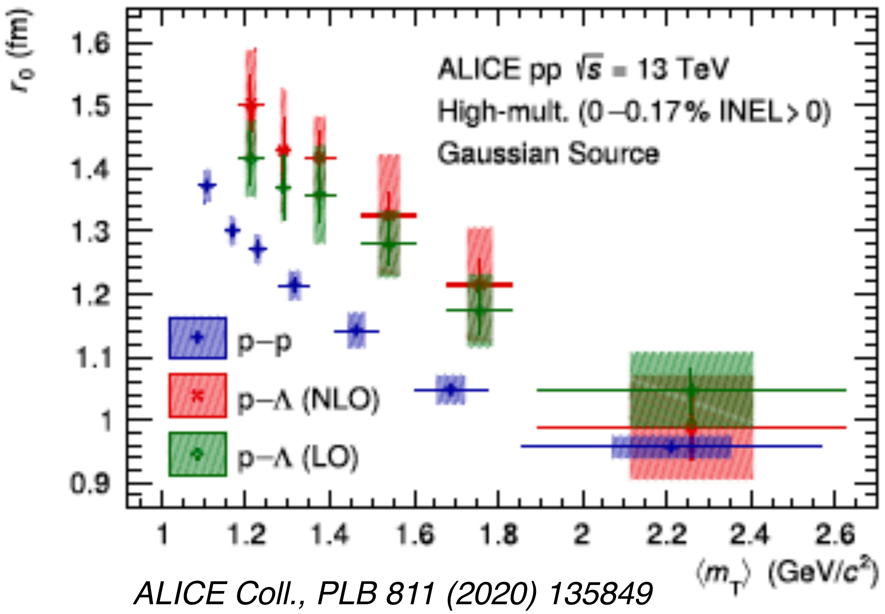
Data: p, d and baryon source in high-multiplicity pp collisions



ALICE Coll. JHEP 01 (2022) 106, EPJC 82, 289 (2022)

ONLY event class in which measurement of p, d production AND baryon source radius are available **simultaneously**

→ investigate the d wave function
→ validate the coalescence afterburner with an improved source model.



ALICE Coll., PLB 811 (2020) 135849

Forming **deuteron**

The momentum-dependent production (or spectrum) of a d can be obtained by projecting the final-state density matrix of the nucleus onto the initial-state density matrix for a proton-neutron pair.

See arXiv:2302.12696 and K.Blum et al., PRC 103, 014907 (2021) for derivation.

The nucleus wavefunction is $\phi_{\mathrm{d}}(\mathbf{r}_{\mathrm{d}}, \mathbf{p}_{\mathrm{d}}) \propto \varphi_{\mathrm{d}}\, e^{i\,\mathbf{p}_{\mathrm{d}}\cdot\mathbf{r}_{\mathrm{d}}}$

$$\mathbf{r} = \mathbf{r}_{\mathrm{p}} - \mathbf{r}_{\mathrm{n}}$$
$$\mathbf{q} = (\mathbf{p}_{\mathrm{p}} - \mathbf{p}_{\mathrm{n}})/2.$$
$$\mathbf{r}_{\mathrm{d}} = \mathbf{r}_{\mathrm{p}} + \mathbf{r}_{\mathrm{n}}$$

$\mathbf{r_0}$ = size parameter of the source

$$\frac{\mathrm{d}^3 N_{\mathrm{d}}}{\mathrm{d}p^3_{\mathrm{d}}}(\mathbf{p}_{\mathrm{d}}) = \frac{3}{8} \int \frac{\mathrm{d}^3 r_{\mathrm{d}}\, \mathrm{d}^3 r\, \mathrm{d}^3 q}{(2\pi)^6} \mathcal{D}(\mathbf{r}, \mathbf{q})\, W_{\mathrm{pn}}(\mathbf{p}_{\mathrm{d}}/2 + \mathbf{q}, \mathbf{p}_{\mathrm{d}}/2 - \mathbf{q}, \mathbf{r}_{\mathrm{p}}, \mathbf{r}_{\mathrm{n}})$$

Spin and isospin factor ($\frac{3}{8}$)

Deuteron Wigner function ($\mathcal{D}(\mathbf{r}, \mathbf{q})$)

Proton–neutron Wigner function (W_{pn}) →

$$H_{\mathrm{pn}}(\mathbf{r}_{\mathrm{p}}, \mathbf{r}_{\mathrm{n}})\, G_{\mathrm{pn}}(\mathbf{p}_{\mathrm{d}}/2 + \mathbf{q}, \mathbf{p}_{\mathrm{d}}/2 - \mathbf{q})$$

assuming that

1. the nucleon momenta are independent from their positions within the particle emitting source, factorize space and momentum term
2. The spatial distributions of protons and neutrons are not correlated

G_{pn}: Includes single-particle momentum distributions and their correlation **→ from MC generator**

$$H_{\mathrm{pn}}(\mathbf{r}, \mathbf{r}_{\mathrm{d}}; r_0) = \frac{1}{(2\pi\, r_0)^3} \exp\left(-\frac{r^2 - r_{\mathrm{d}}^2}{4\, r_0^2}\right)$$

Forming deuteron: **nucleon source**

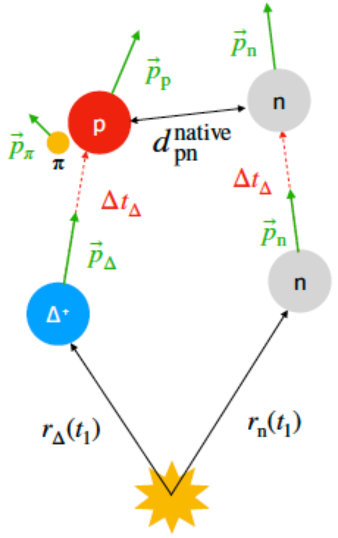
$$H_{pn}(\mathbf{r}, \mathbf{r}_d; r_0) = \frac{1}{(2\pi\, r_0)^3} \exp\left(-\frac{r^2 - r_d^2}{4 r_0^2}\right)$$

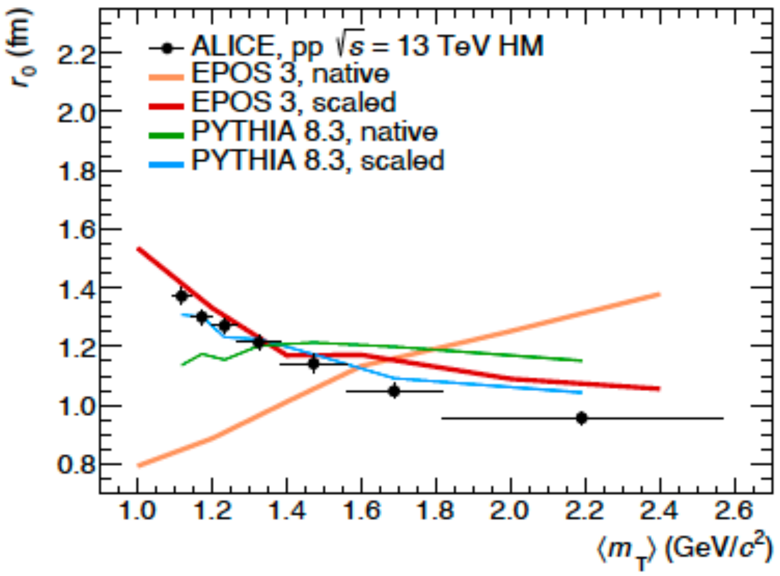
Contributions to the source term:
- prompt nucleon emission
- delayed nucleons from strong resonance decay (e.g. Δ, N*, ..., lifetimes ~ 10^{-23}s ~ fm/c)

To obtain a **realistic modelling of the source**

- **resonance cocktail**, hence prompt/feedown fractions tuned based on SHM Thermal-FIST

- **m_T scaling** of the p-n distance after time equalization, based on the available ALICE data





Forming deuteron: **nucleon spectrum**

$$H_{\mathrm{pn}}(\mathbf{r}, \mathbf{r}_{\mathrm{d}}; r_0) = \frac{1}{(2\pi\, r_0)^3} \exp\left(-\frac{r^2 - r_{\mathrm{d}}^2}{4\, r_0^2}\right)$$

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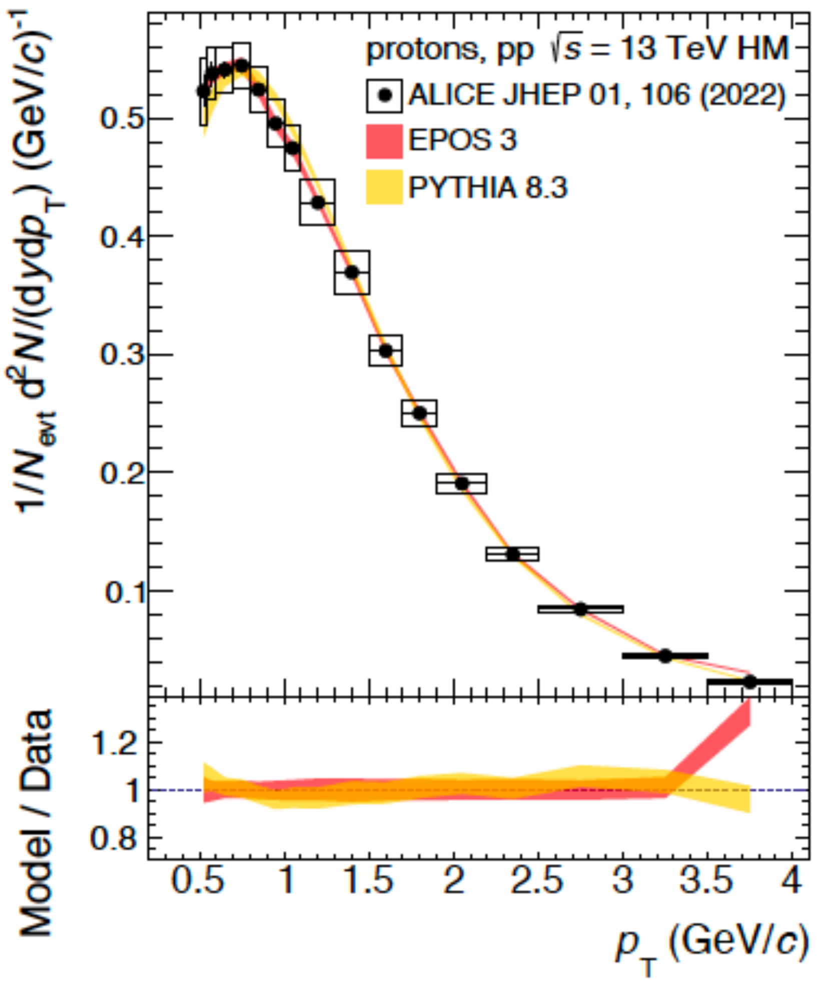
- **m_T scaling** of the p-n distance after time equalization, based on the available ALICE data

Nucleon spectra are scaled to reproduce ALICE data



Forming deuteron: **wavefunction**

$$\frac{d^3N_d}{dp_d^3}(\mathbf{p}_d) = \boxed{\frac{3}{8}} \int \frac{d^3r_d\, d^3r\, d^3q}{(2\pi)^6} \boxed{\mathcal{D}(\mathbf{r},\mathbf{q})} \boxed{W_{pn}(\mathbf{p}_d/2+\mathbf{q}, \mathbf{p}_d/2-\mathbf{q}, \mathbf{r}_p, \mathbf{r}_n)}$$

Spin and isospin factor

Deuteron Wigner function

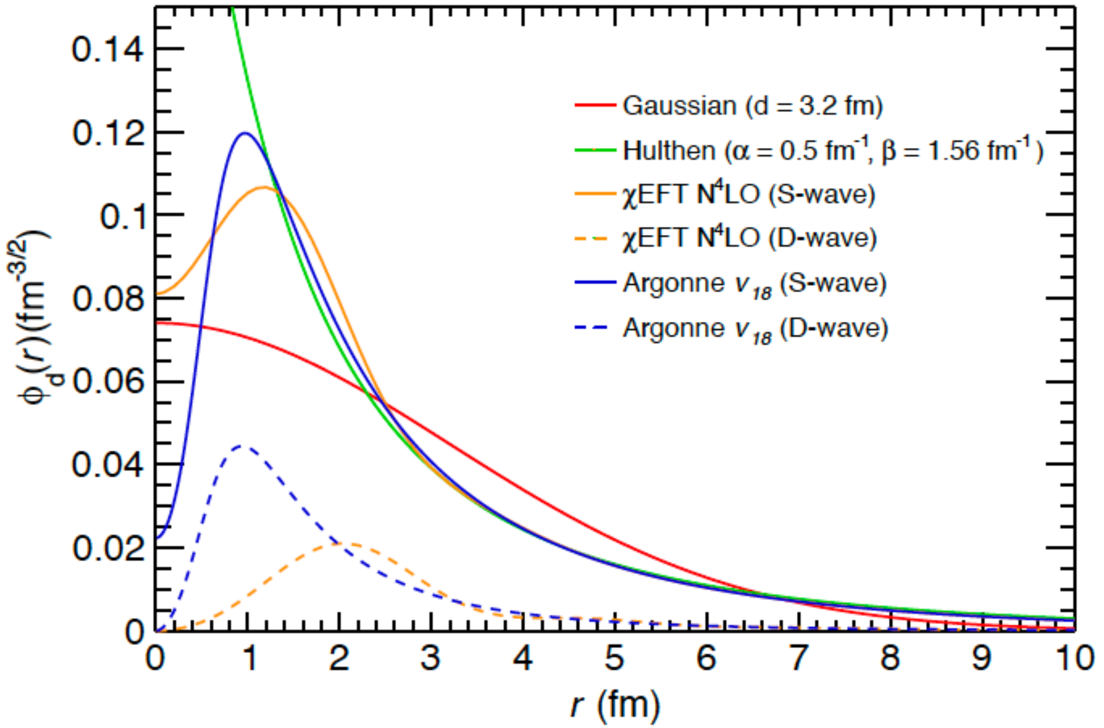
Proton–neutron Wigner function

Deuteron Wigner function:

- Analytical solution only for gaussian wavefunction

$$\varphi_d(\mathbf{r}) = (\pi d^2)^{-3/4} e^{-r^2/2d^2} \qquad \mathcal{D}(\mathbf{r},\mathbf{q}) = 8e^{-r^2/d^2} e^{-q^2d^2}$$

- Numerical solutions for other wavefunctions
  ** obtained for the first time*
  - Hulthen
    Heinz and Jacak, Ann. Rev. Nucl. Part. Sci. 49, 529 (1999)
  - Argonne v18 *
    Wiringa et al., Phys. Rev. C 51, 38 (1995)
  - χ_{EFT} N^{4}LO *
    Entem et al, Phys. Rev. C 96, 024004 (2017)



Forming deuteron: **wavefunction**

$$\frac{d^3N_d}{dp_d^3}(\mathbf{p}_d) = \frac{3}{8}\int \frac{d^3r_d\, d^3r\, d^3q}{(2\pi)^6} \mathcal{D}(\mathbf{r},\mathbf{q}) W_{pn}(\mathbf{p}_d/2+\mathbf{q}, \mathbf{p}_d/2-\mathbf{q}, \mathbf{r}_p, \mathbf{r}_n)$$

Spin and isospin factor

Deuteron Wigner function

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After spatial integration

$$\frac{d^3N_d}{dp_d^3} = \frac{3}{8}\frac{1}{(2\pi)^6}\int d^3q\, \mathcal{W}(q; r_0) G_{pn}(\mathbf{p}_d/2+\mathbf{q}, \mathbf{p}_d/2-\mathbf{q})$$

represents a probability that can be used as a weighting factor on an event by-event basis coalescence

Forming deuteron: **results**

Input #1: (anti)proton and (anti)neutron p_T distributions

Input #2: baryon source size and its m_T dependence

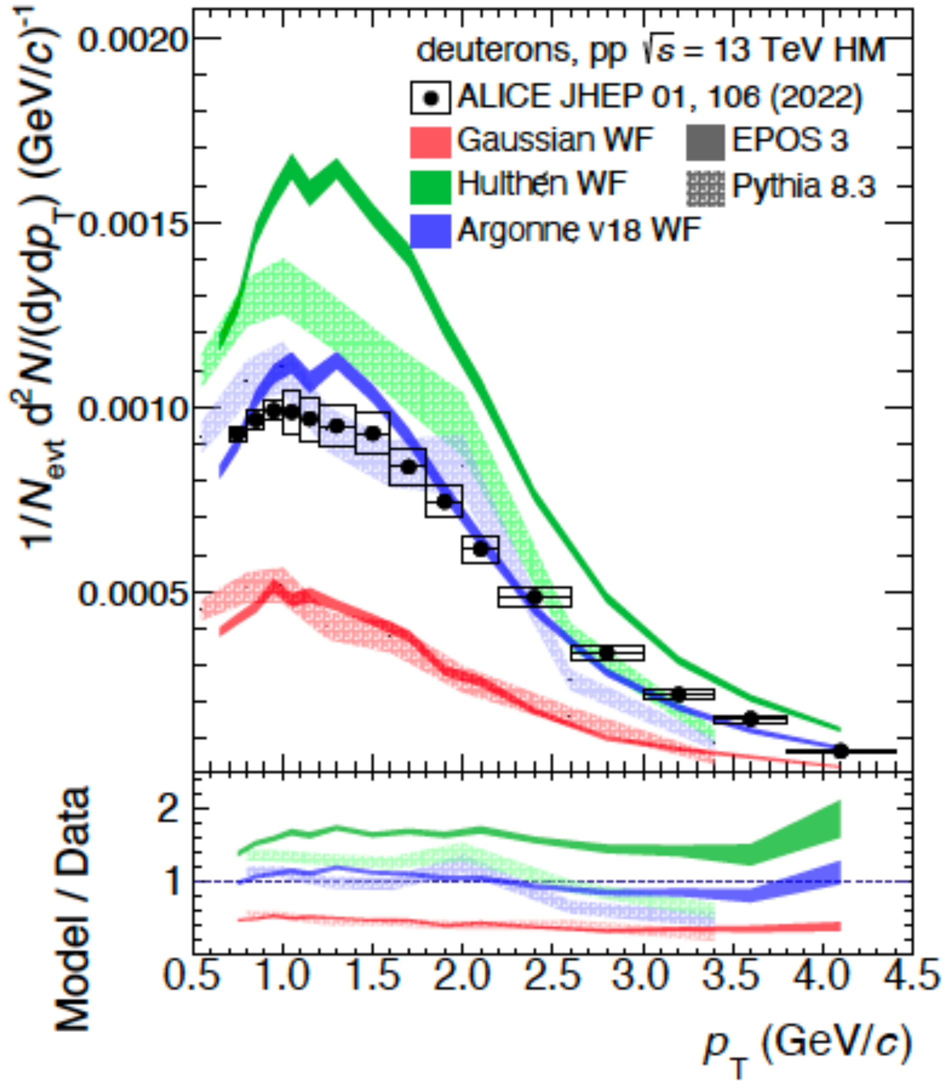
Input #3: hypothesis for deuteron internal wavefunction

Mechanism: coalescence

- for each p-n pair, the source is remodelled
- the coalescence weight is computed
- coalescence is implemented as a statistical rejection method

Output: (anti)deuteron p_T distribution compared to ALICE data

Good agreement with data:
given the correct source size, nucleon spectra, and a realistic wavefunction, it is possible to predict deuteron yields using no free parameters.



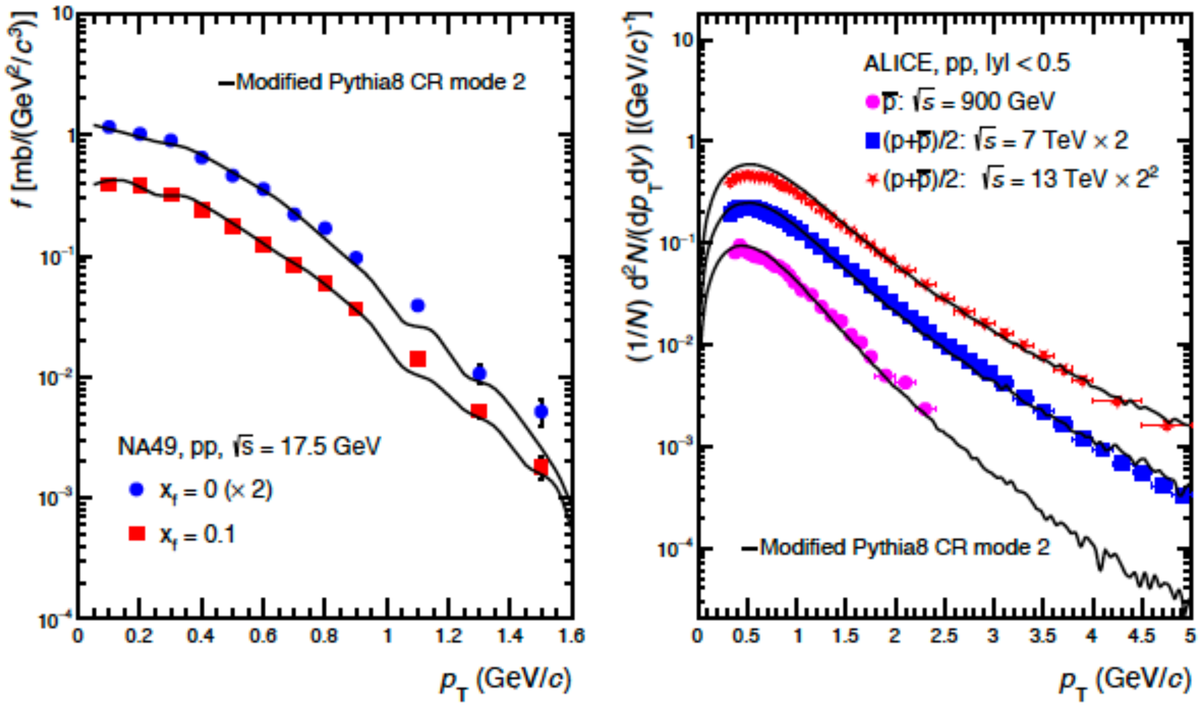
Extension to lower energies: **generator tuning**

Attempt at tuning the generator to reproduce production **over a broad range of √s**

→ **PYTHIA8.3** (Monash tune + CR mode 2) is **tuned** to reproduce the p_T distributions of **p, $\bar{p}$** in inelastic pp collisions

- ALICE data: √s = 0.9, 7 and 13 TeV
- NA49 data: √s = 17.2 GeV

→ Parametrization of tuning variables with √s allows ≤10% agreement with p spectra, worse at high √s



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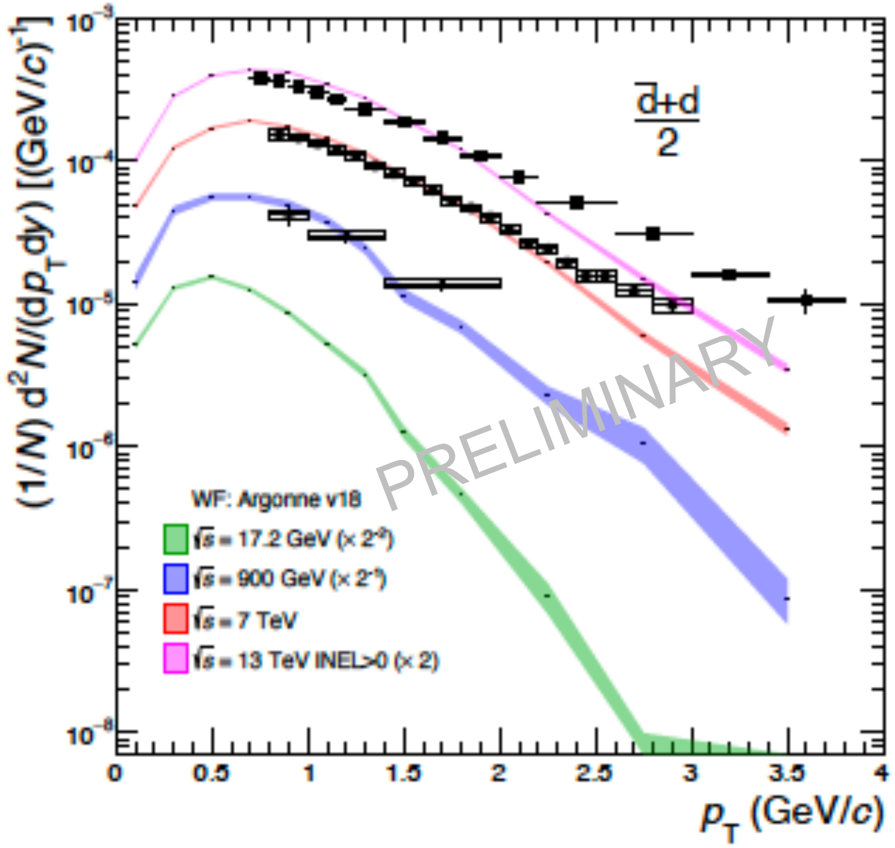
→ Coalescence afterburner so far applied without source rescaling (no measurements available)

→ **Promising, but work to be still done** to improve, especially on the high p_T



As **no data** for d, $\bar{d}$ are available at the energies mostly relevant for cosmic rays, √s ~ 10-25 GeV
→ obtain **predictions** with the coalescence model validated at high energy

Summary and outlook

By combining state-of-the-art coalescence model and LHC data, we provided a coalescence afterburner that takes into account realistic particle emission and correlation

- EPOS3 and PYTHIA struggle in providing a realistic picture of the baryon emitting source and of nucleon spectra

- Exploiting the measurements of the proton spectra and emitting source we provide a **parameter-free model for deuteron production**
  → **importance of measurements in the same event class!**

- Good agreement using Argonne v18 wave-function

- Effort ongoing to **tune PYTHIA generator** in order to reproduce nucleon spectra over a broad range of energies
  → improvement wrt standard tunes of PYTHIA but more work needed
  → prospects for application to cosmic antinuclei flux predictions

Thank you!

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