Formation of (anti)nuclei in high-energy collisions

F. Bellini (University and INFN, Bologna)

Physics at AMBER international workshop 2024

Chateau de Bossey, 18 March 2024

ALMA MATER STUDIORUM
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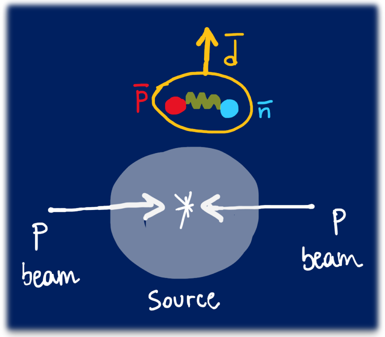
INFN BOLOGNA
Istituto Nazionale di Fisica Nucleare
Sezione di Bologna

CosmicAntiNuclei

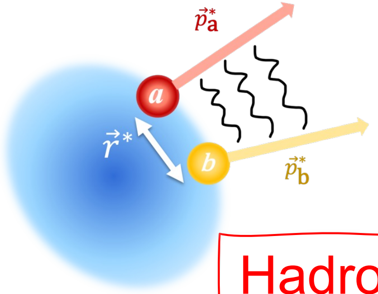
erc
European Research Council
Established by the European Commission

Light **(anti)nuclei** as a laboratory

- Bound by the nuclear interaction as a “residual” strong interaction → fundamental QCD
- Properties of nuclei with hyperons (hypernuclei) give access to the strength of the Y-N interaction → relevant for neutron stars *(but not the topic of this talk)*
- LHC as a factory of antinuclei + favourable experimental conditions
  → unprecedentedly large data samples and precision at the TeV energy scale
- Antideuteron and antihelium proposed as smoking guns for DM due to low astrophysical background → searches for cosmic antinuclei



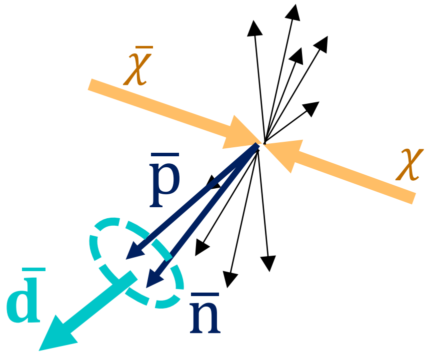
Production mechanisms



Hadron-hadron interactions

Input for astrophysics

Antinuclei from **Dark Matter source**



1. $\bar{p}, \bar{n}$ are produced by **WIMP annihilation into SM channels**

   Model ingredients:
   - particle physics model

     e.g. *M. Korsmeier, et al, PRD 97 (2018) 103011:* $\langle\sigma v\rangle_{\chi\chi\to \mathrm{bbar}}$ ~ 3 x 10^{-26} cm^3/s, 30 < m_{DM} < 100 GeV
   - DM density in a given point of the Galaxy

     M. Tanabashi et al. (PDG), PRD 98 (2018) 030001: $\boldsymbol{\rho}^{\mathrm{local}}_{\mathrm{DM}}$ ~ 0.4 GeV/cm^3

$$q_{\mathrm{DM}}(E_{\bar{D}}, \vec{x}) = \frac{1}{2}\left(\frac{\rho(\vec{x})}{m_{\mathrm{DM}}}\right)^2 \langle\sigma v\rangle_{b\bar{b}} \frac{dN^{b\bar{b}}_{\bar{D}}}{dE_{\bar{D}}}$$

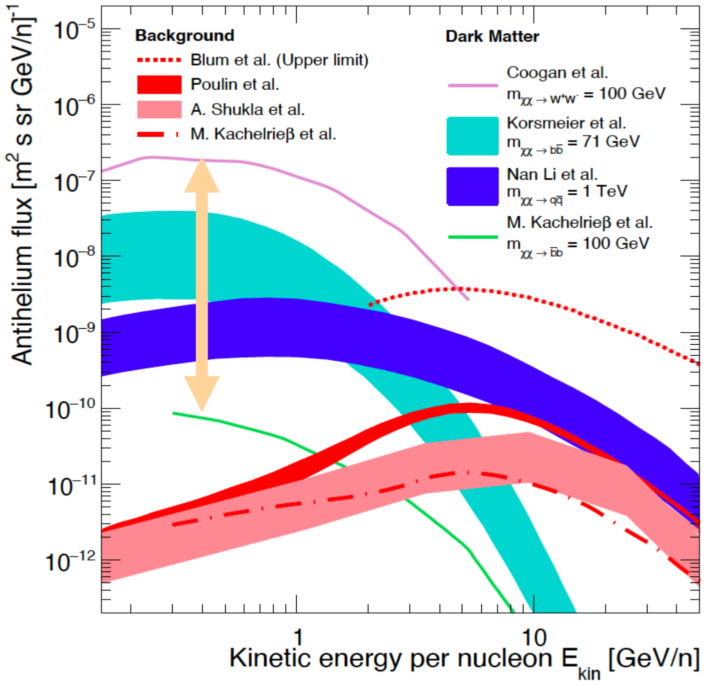
2. $\bar{d}$ and $^3\overline{\mathrm{He}}$ produced via **coalescence** of anti-nucleons

$$E_A \frac{dN_A}{d^3P_A} = B_A \left(E_p \frac{dN_p}{d^3P_p}\right)^Z \left(E_n \frac{dN_n}{d^3P_n}\right)\Bigg|^N_{P_p=P_n=P_A/A}$$

   Model ingredients.
   - antinucleon cross section
   - coalescence probability B_A or momentum p_0

     e.g. tuned to e+e- data from ALEPH, PLB 639 (2006) 129
   - model and size of the particle-emitting source (?)

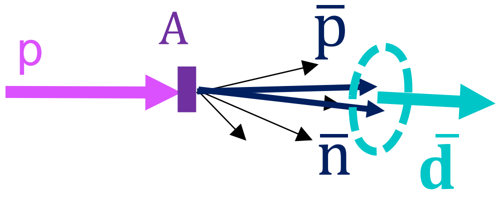
P. von Doentichem et al., JCAP08(2020)035



Antinuclei from **Cosmic Ray source**

Production by **spallation** reactions of primary CR with ISM

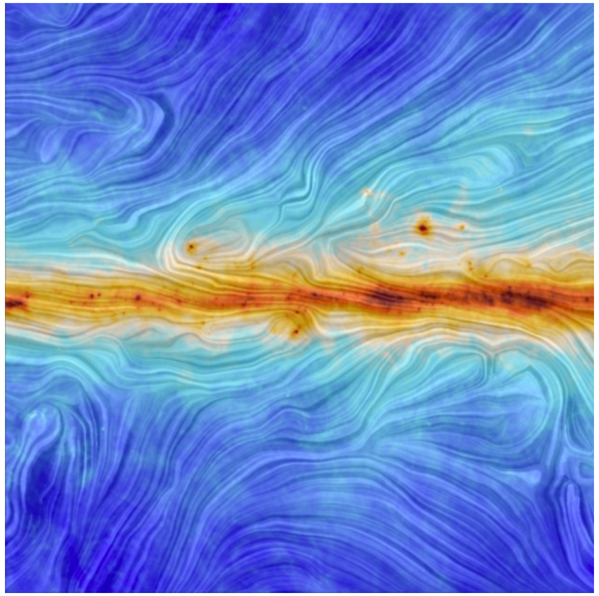
1. $\bar{p}, \bar{n}$ are produced in pp, p-He, p-A reactions
   - threshold: cm frame $\sqrt{s} \geq 6\ m_p \longrightarrow$ lab frame/Galaxy: $E_{kin} \geq 17 m_p$
2. $\bar{d}$ and $^{3}\overline{\mathrm{He}}$ **produced by coalescence**
   - same as the DM signal, but different $\bar{p}, \bar{n}$ distributions
   - coalescence momentum unknown *typically tuned to pp data e.g. ALICE*



Flux calculations sensitive to the astrophysical details

→ model dependency:

- Acceleration by Super Novae remnants
- Diffusion in the galactic magnetic field (~μGauss)
- Energy loss / gain (for loosely bound nuclei, break-up dominates)
- Solar modulations (matter mostly at low *E*, where DM signal prominent)



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Antinuclei from **Cosmic Ray source**

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MEASURE at FXT EXP.

2. $\bar{d}$ and $^{3}\overline{\mathrm{He}}$ **produced by coalescence**
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CONSTRAIN w/ LHC DATA

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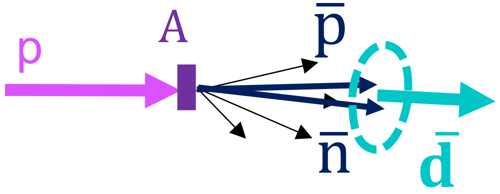
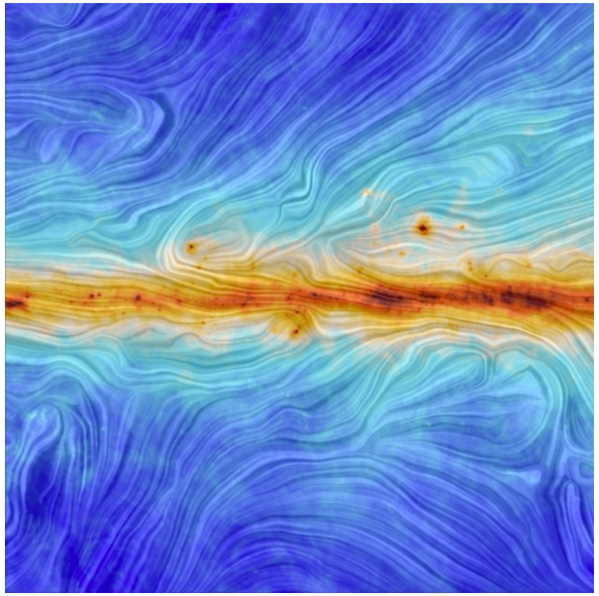
TUNE ON ASTRO DATA





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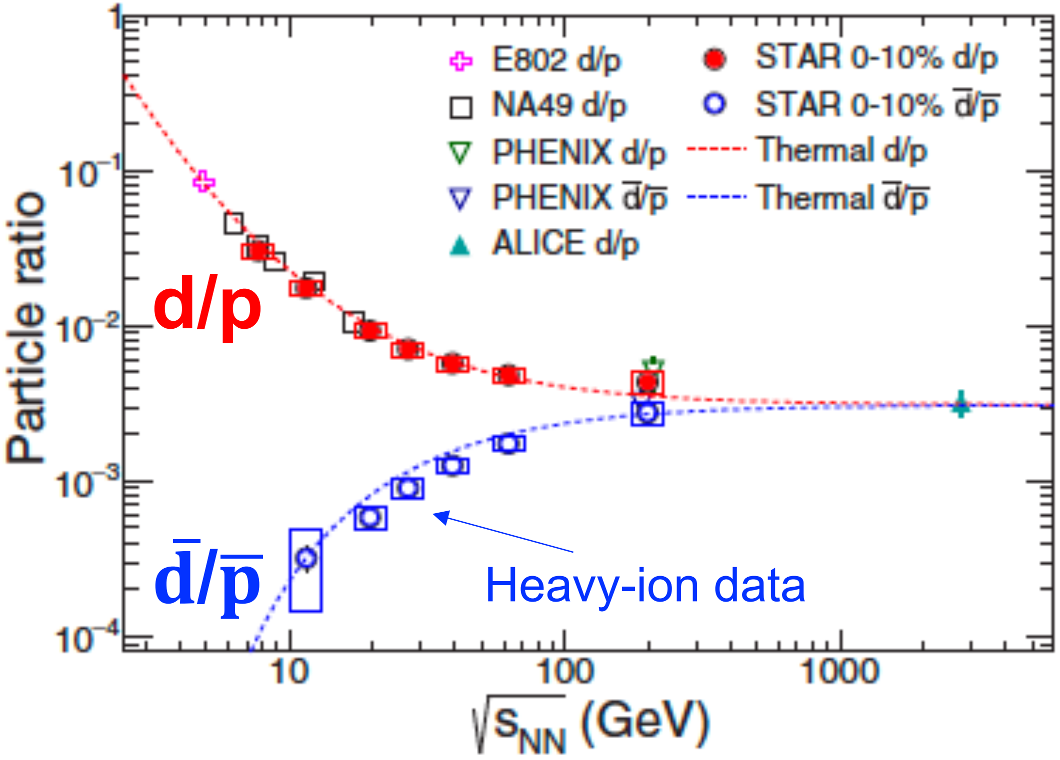
Setting the stage: **antinuclei at LHC energies**



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

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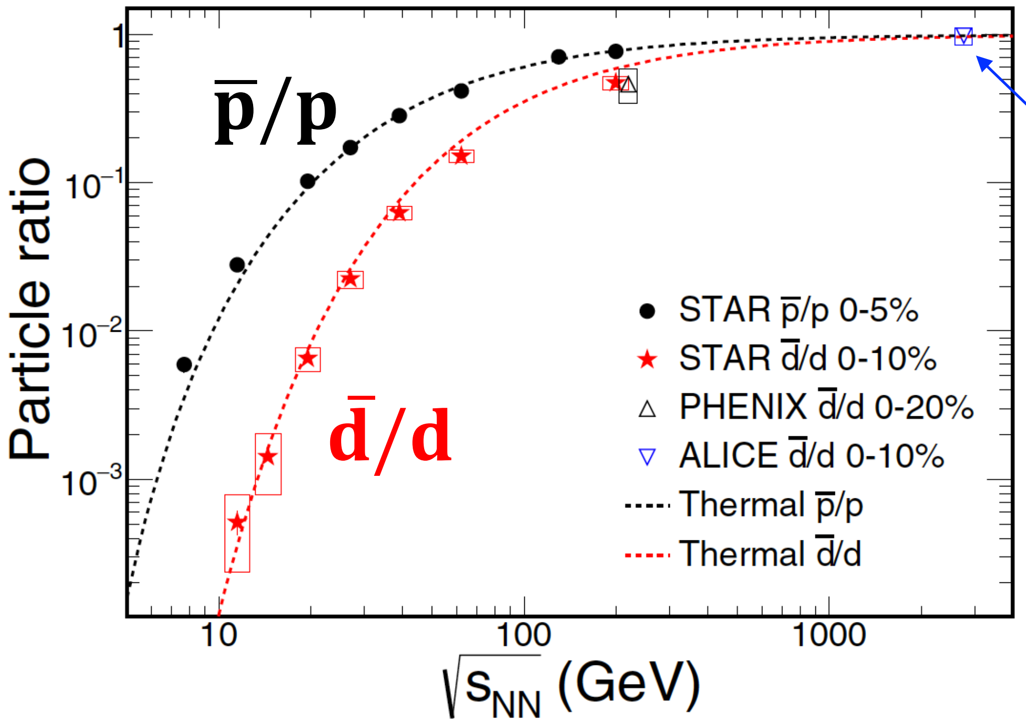


The production of antideuteron relative to antiproton increases with the CoM energy, while d/p decreases.

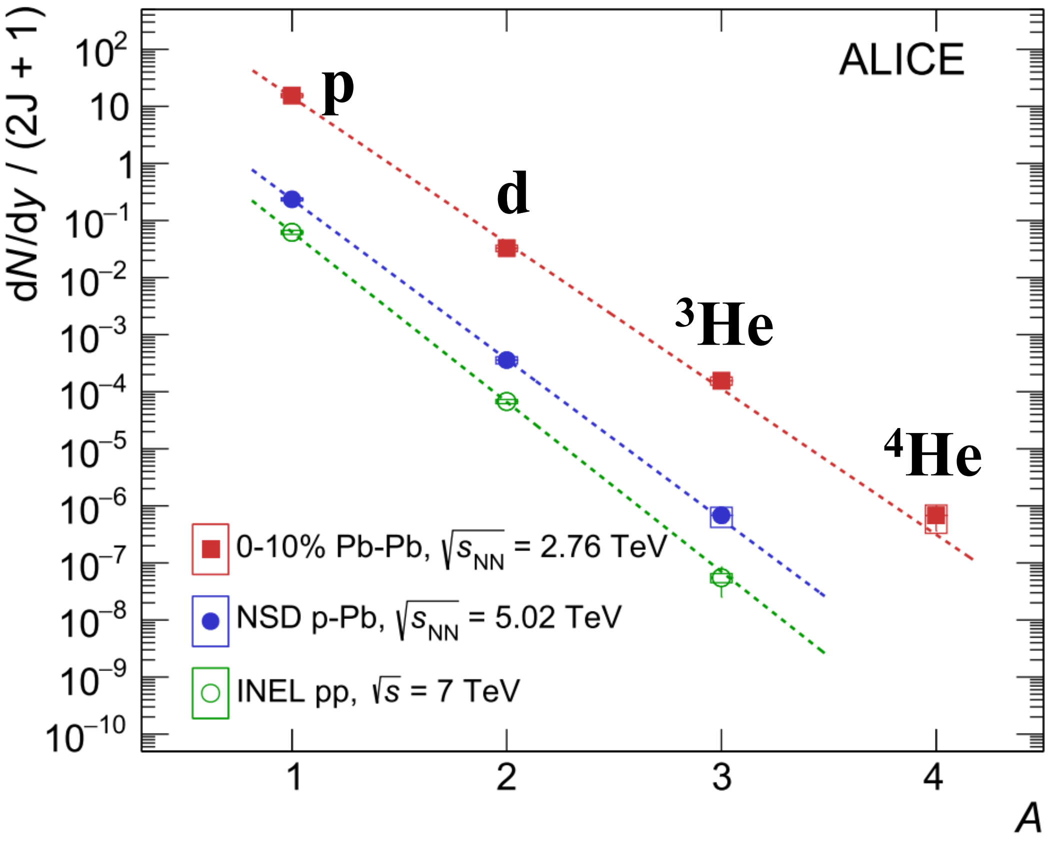
At the LHC, at central rapidity nuclei and antinuclei are produced with same abundances

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

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: **antinuclei at LHC energies**



LHC is an antinucleus factory. Production is still rare but large integrated luminosities allow for precision measurements (Run 2 + ongoing Run 3!)

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

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

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: **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

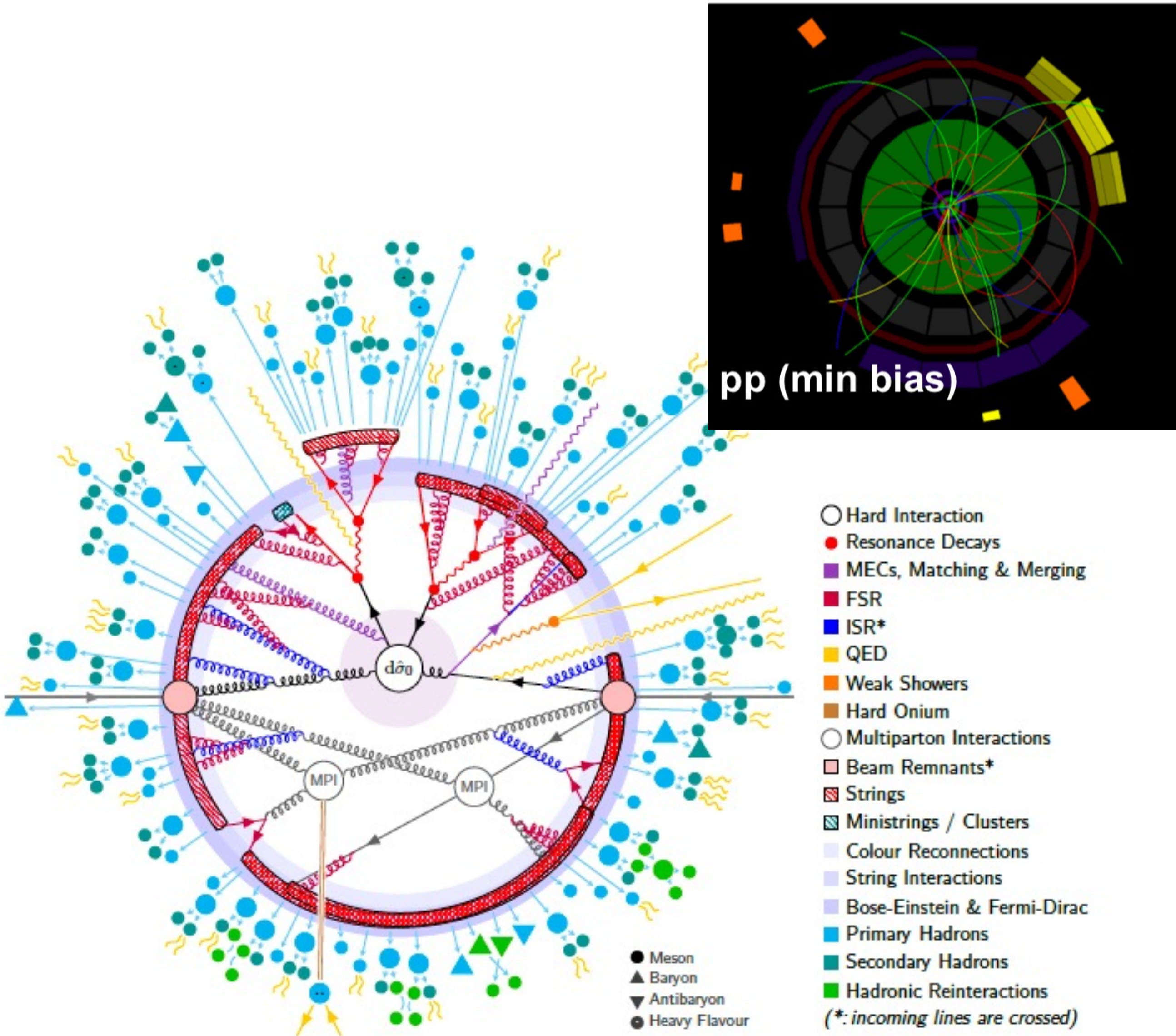


Figure from C. Bielrich et al, *arXiv:2203.11601*

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

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- Complex final-state involving multi-parton interactions, color reconnection...
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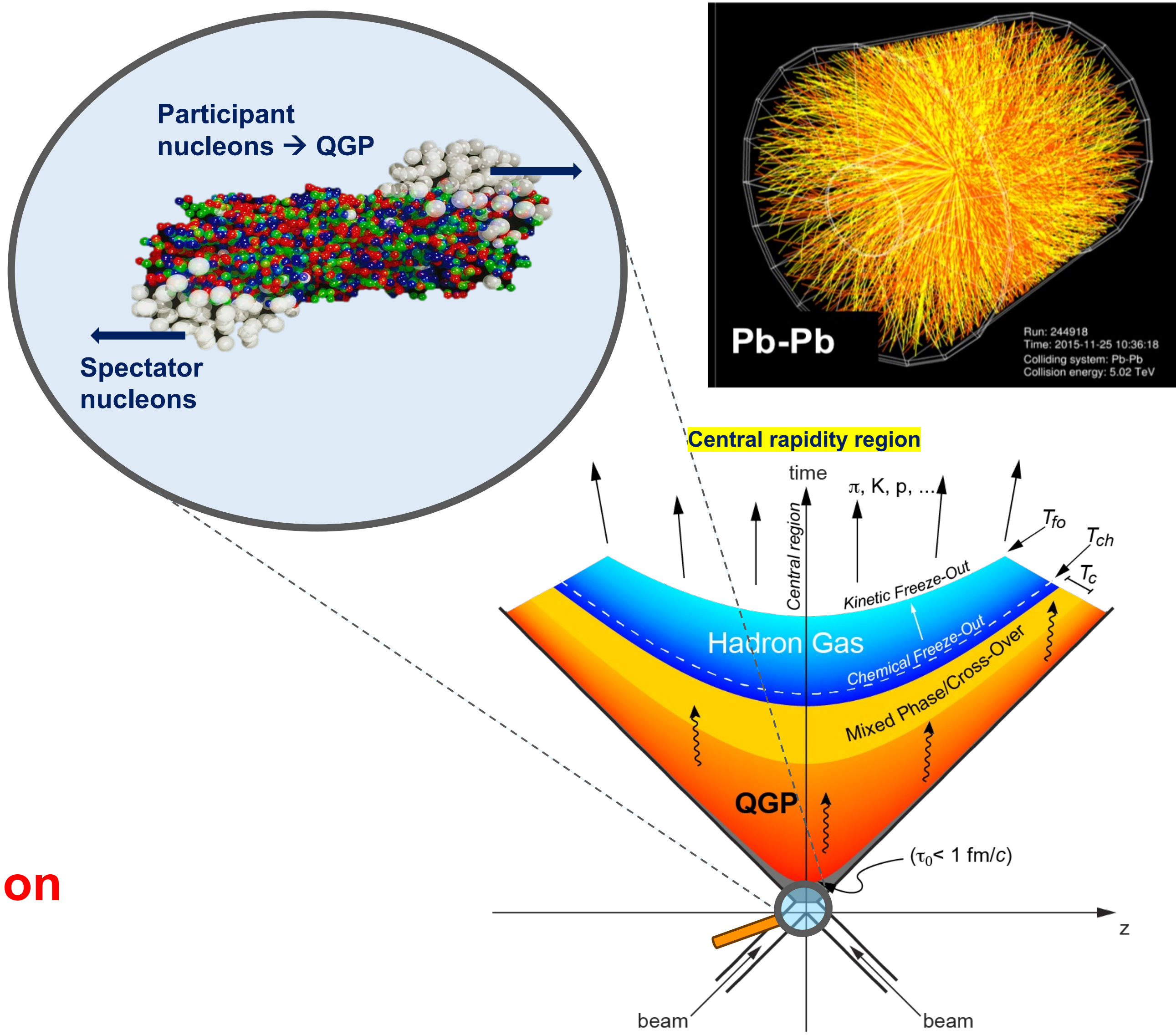
High-energy heavy-ion collisions

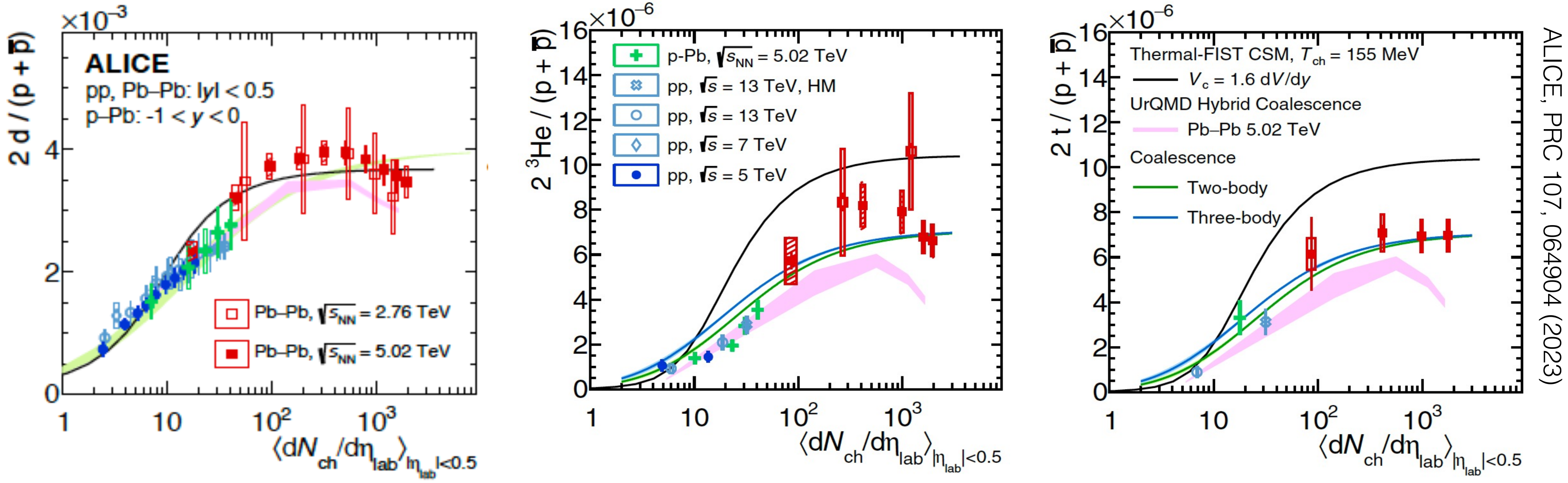
- production of a quark-gluon plasma (QGP)
- fast, collective expansion and cooling → hadronisation
- Spatially extended system (R ~ few fm)
- Up to $\langle dN_{ch}/d\eta \rangle$ ~ 2000 at the LHC

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



System-size dependence of **d, ^{3}He and t** production at the LHC

Production of light (anti)nuclei at the LHC **depends on final-state multiplicity** ⇔ system size $(R \sim \langle dN/d\eta \rangle^{1/3})$



ALICE, PRC 107, 064904 (2023)

- **d reproduced by models of coalescence** (analytical, UrQMD hybrid) **and statistical hadronisation** (but no momentum distribution)
- **Tensions for A=3 nuclei,** where more data and higher precision are advocated
  → **LHC Run3 ongoing!**

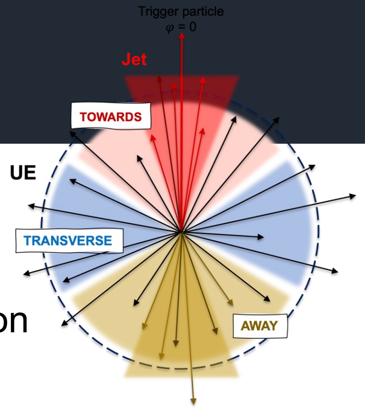
Enhanced deuteron production **in jets**

Enhanced d coalescence probability in jets wrt UE observed in pp collisions,
→ due to reduced distance in phase space of nucleons within jets

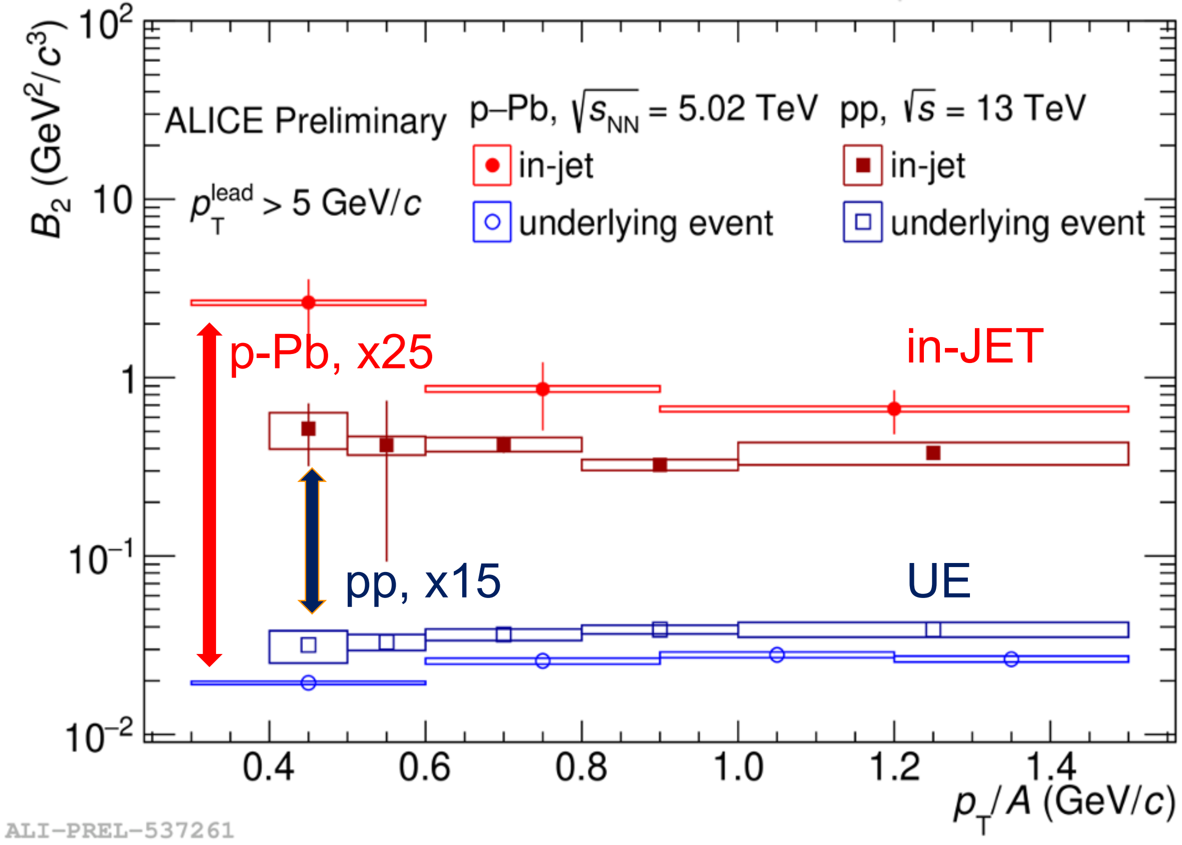
Larger enhancement in p-Pb wrt pp
→ *particle composition in jets and broader source in UE?*

Wishlist:

- Higher precision with run3 data
- Measurements with full jet reconstruction



In-jet vs UE classification based on $\Delta\varphi$



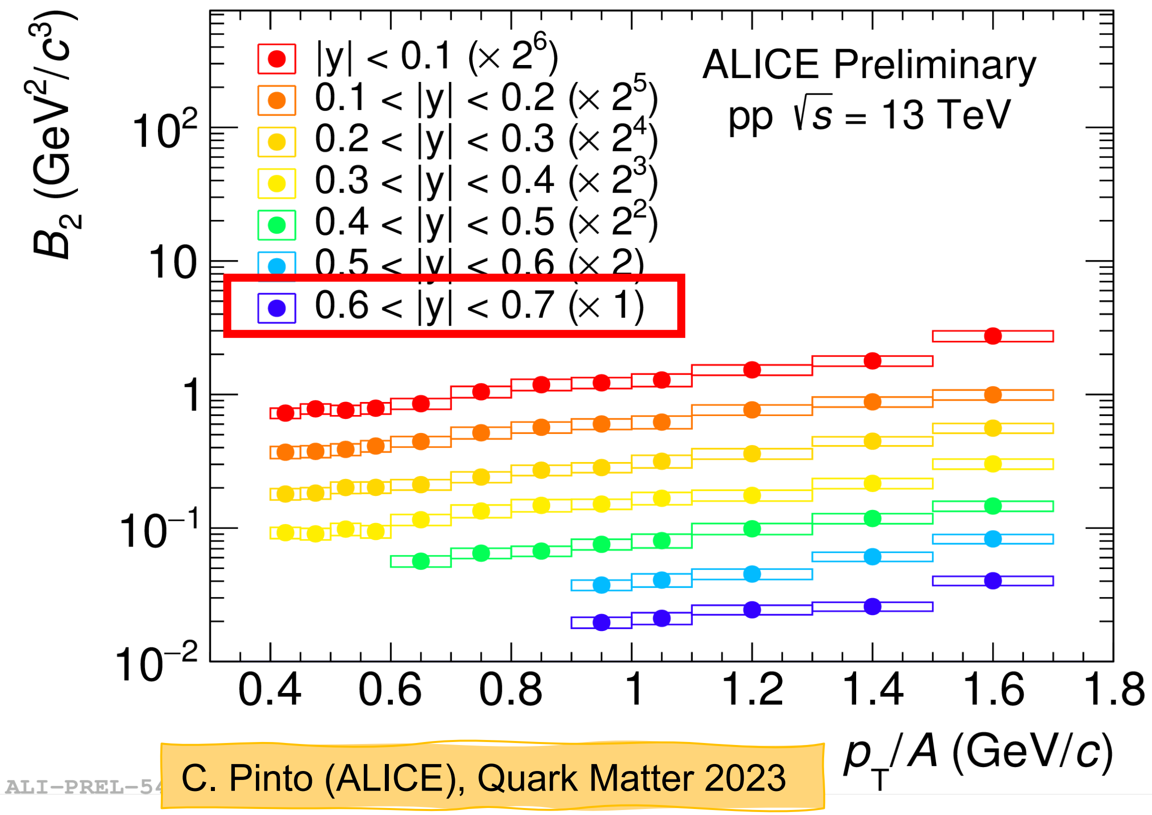
pp: ALICE, PRL 131 (2023) 4, 042301, p-Pb: ALICE@Quark Matter 2024

Rapidity dependence of d production

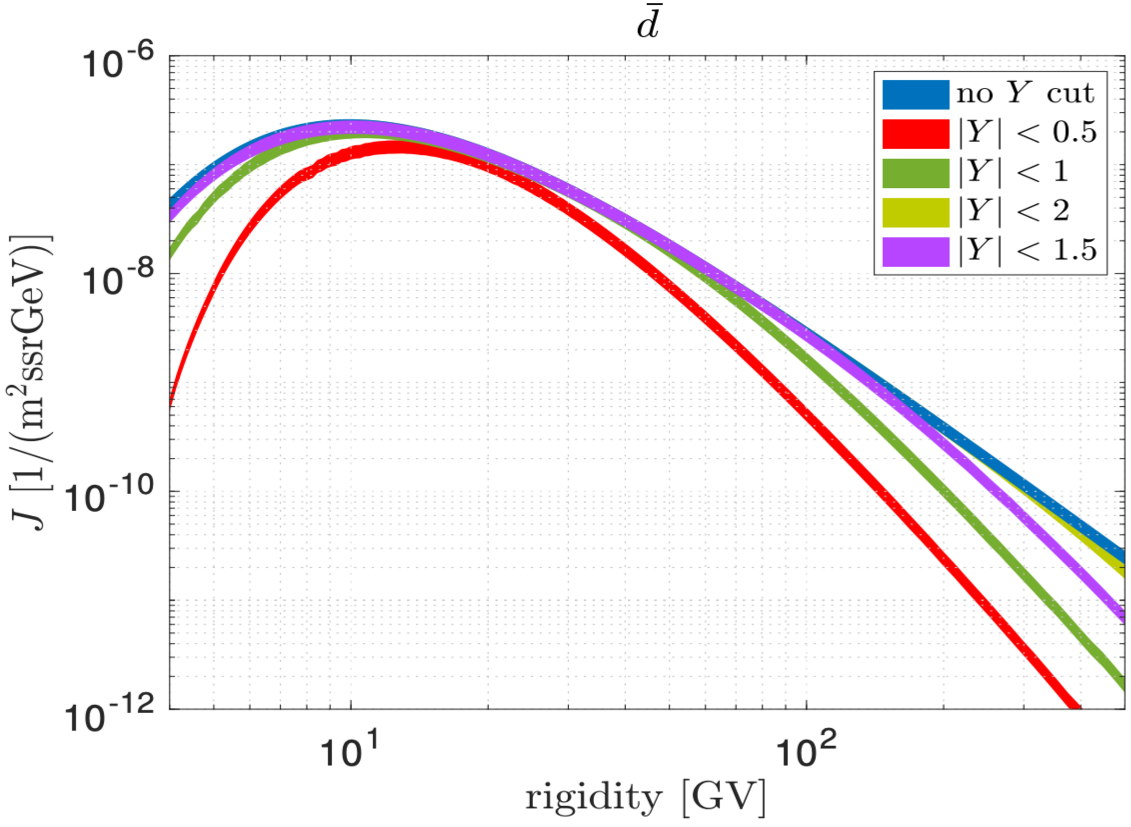
ALICE measurements used as input to extract expected flux of cosmic antideuterons

→ Most of the flux is for |y| < 2

At ALICE, rapidity reach is limited by current detector acceptance → ALICE 3 after Run 4



C. Pinto (ALICE), Quark Matter 2023



K. Blum, arxiv:2306.13165

Coalescence momentum

Production depends on the coalescence probability B_A,

$$E_A \frac{\mathrm{d}^3 N_A}{\mathrm{d}p_A^3} = B_A \left(E_\mathrm{p} \frac{\mathrm{d}^3 N_\mathrm{p}}{\mathrm{d}p_\mathrm{p}^3} \right)^Z \Bigg|_{\vec{p}_\mathrm{p} = \frac{\vec{p}_A}{A}} \left(E_\mathrm{n} \frac{\mathrm{d}^3 N_\mathrm{n}}{\mathrm{d}p_\mathrm{n}^3} \right)^N \Bigg|_{\vec{p}_\mathrm{n} = \frac{\vec{p}_A}{A}}$$

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

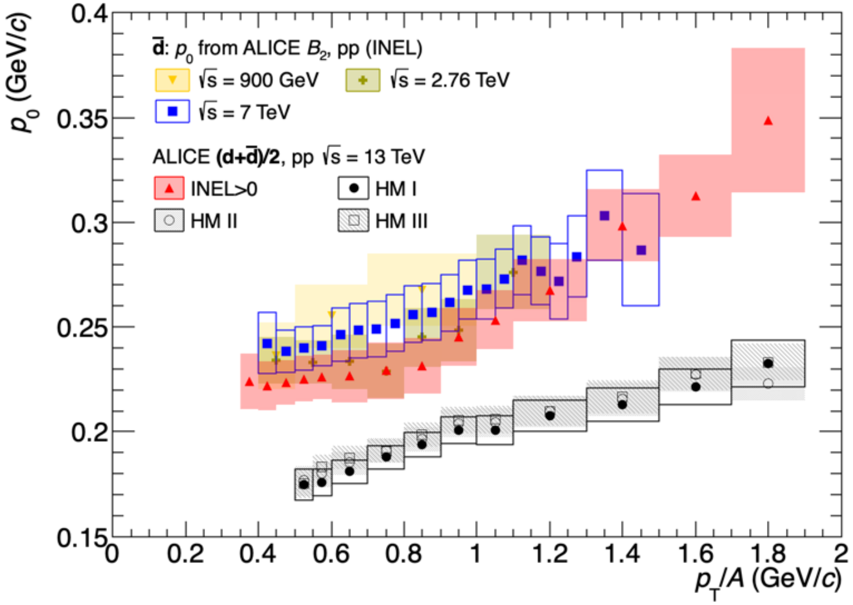
- p_0 ***a priori* unknown**
- "spherical" approach: $|\vec{p_n} - \vec{p_p}| < p_0$

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

Nucleus mass

Nucleon mass

Coalescence momentum



In most astrophysical and CR applications, p_0 is tuned on data, 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 based on the Wigner formalism.

Analytical* calculations show that probability depends on

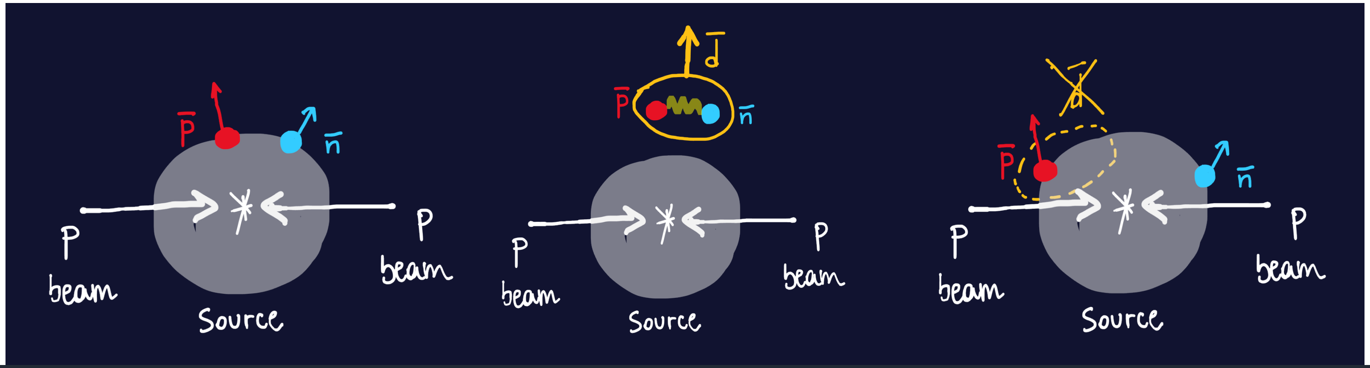
- the (transverse) **momentum**
- the **nucleus size and wavefunction** (*gaussian)
- the **size of the nucleon source**

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

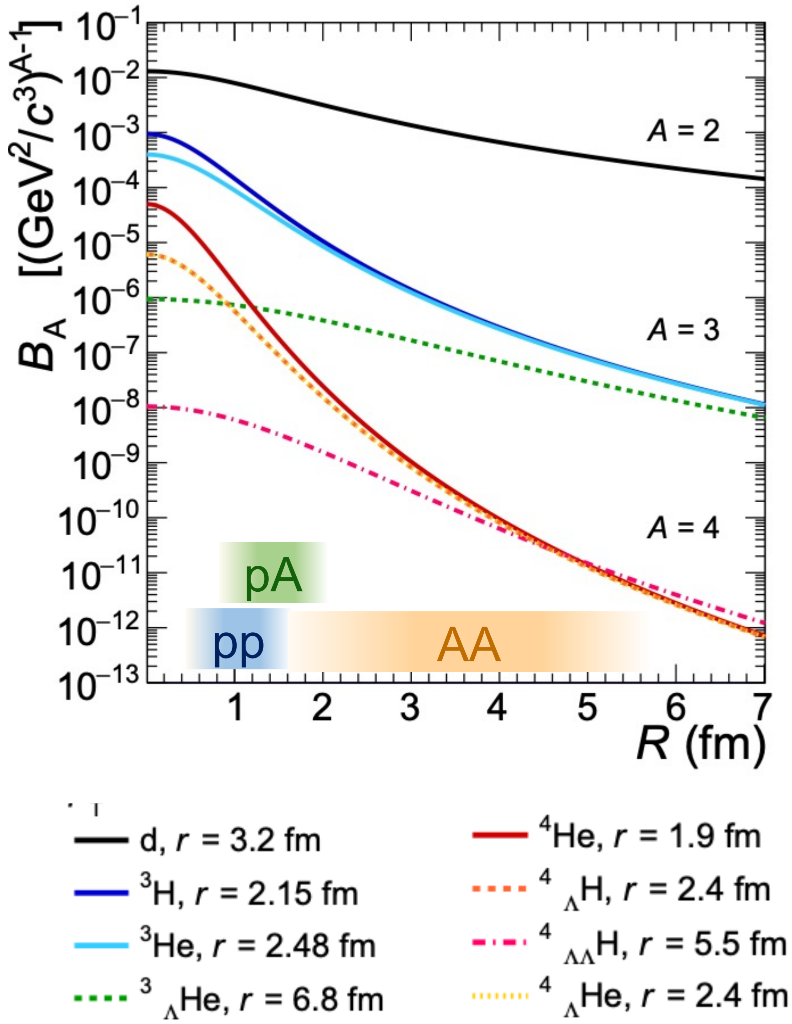
Nucleon transverse mass (including momentum)

Source radius

Nucleus radius



*R. Scheibl, U. Heinz, PRC 59. 1585-1602 (1999)
*F.Bellini and A. Kalweit, PRC 99, 054905 (2019)



Source radius

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

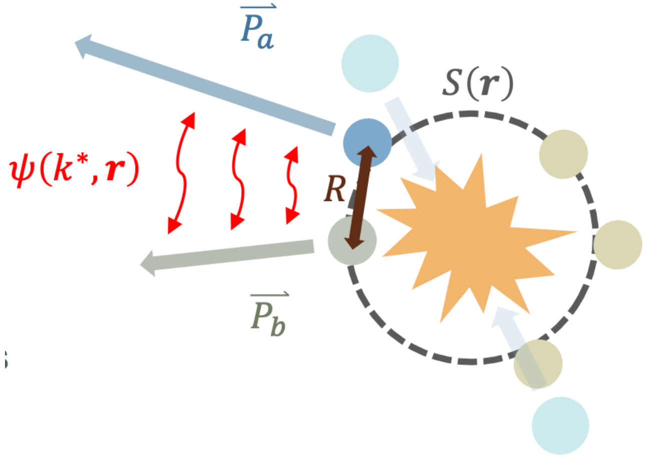
$$\mathcal{B}_2(p) \approx \frac{2(2s_d+1)}{m(2s_N+1)^2}(2\pi)^3 \int d^3\mathbf{r}\, |\phi_d(\mathbf{r})|^2\, \mathcal{S}_2(\mathbf{r}).$$

Coalescence probability (d case)

Nucleus wave function
⟺ Form factor

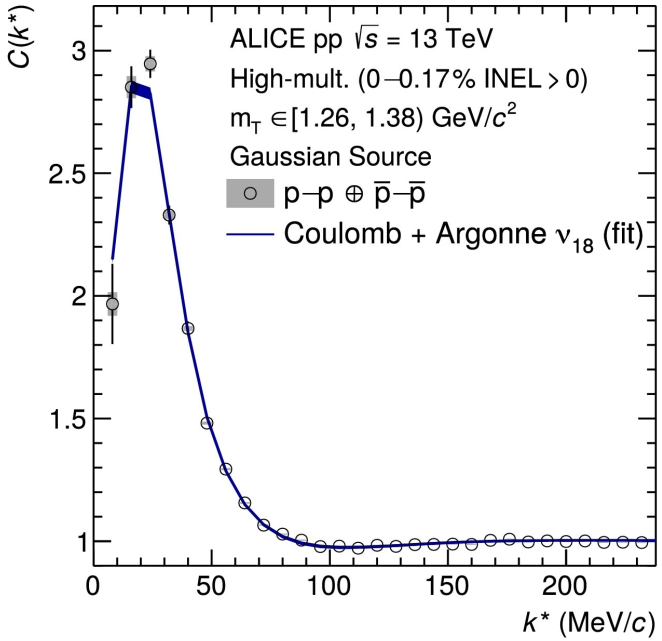
Source function
⟺ Momentum correlation function

The size of the source can be extracted with **femtoscopy**
i.e. measure the two-particle momentum correlation function and fitting it with a known interaction potential
L. Fabbietti, et al., Ann.Rev.Nucl.Part.Sci. 71 (2021) 377-402



Credits: ALICE/TUM

ALICE Phys. Lett. B 811 (2020) 135849



Motivation for a **coalescence afterburner**

Recap:

✓ Multi-differential and high-precision data from ALICE at the LHC available

✓ 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**

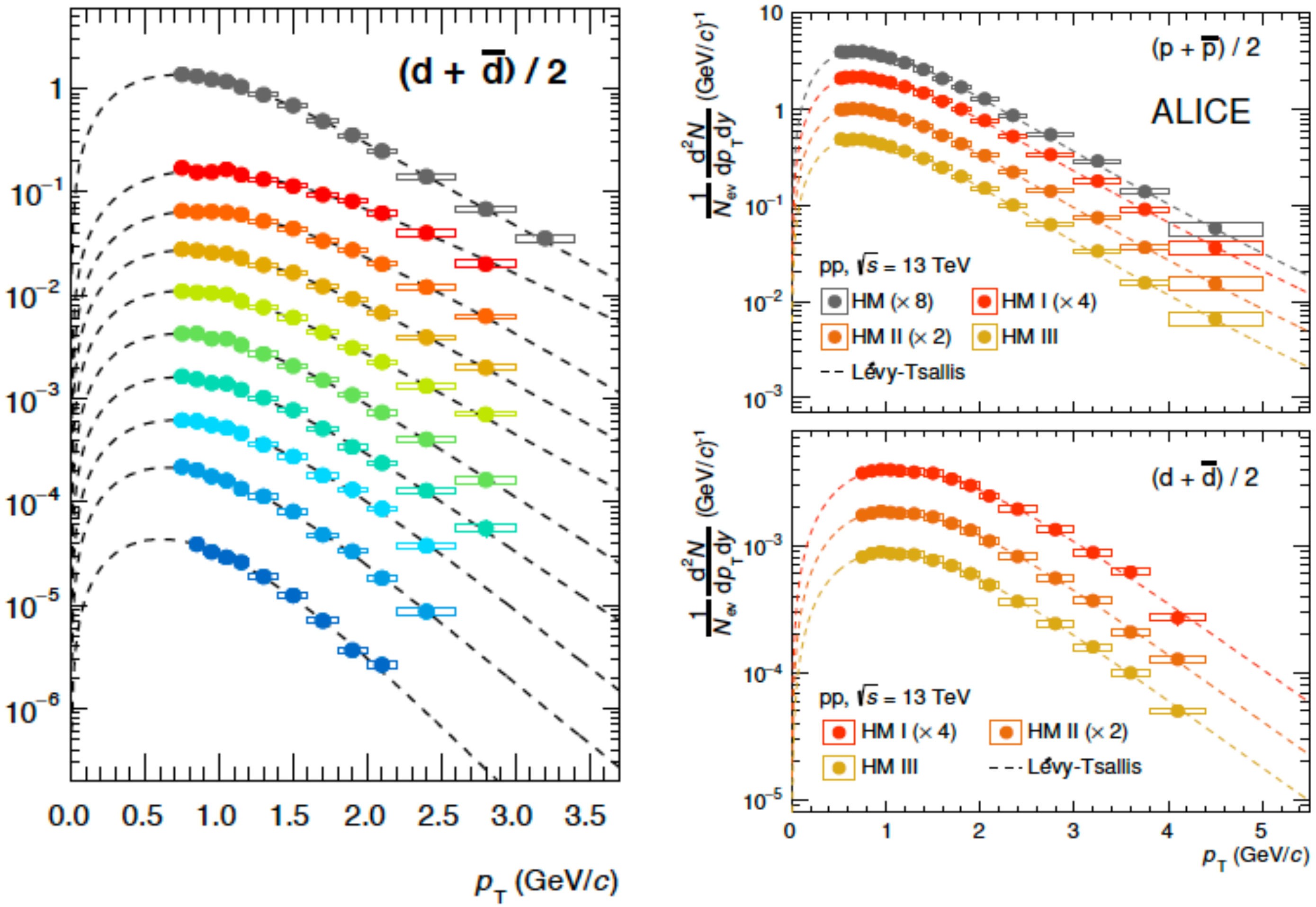
Focus on (anti)**deuteron**: simplest system, high-precision multi-differential data

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

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

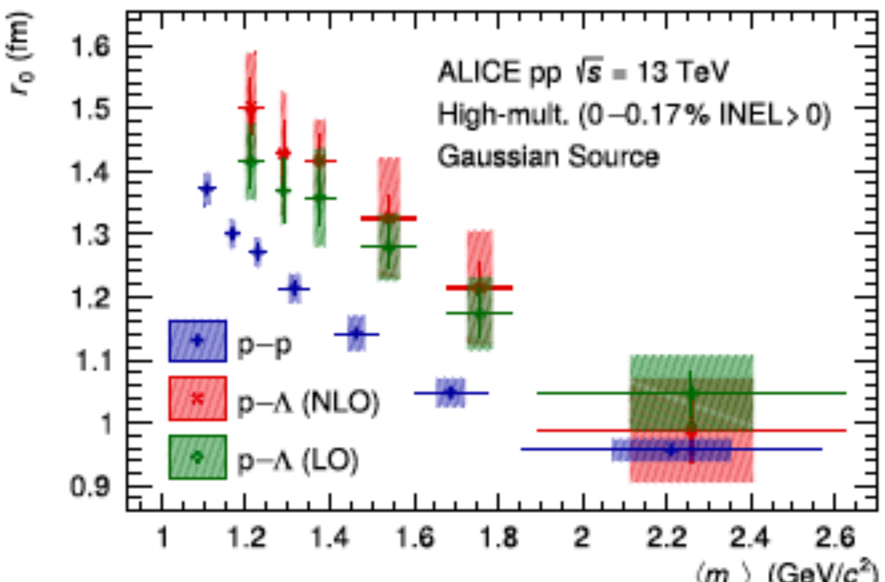


ALICE Coll. JHEP 01 (2022) 106, EPJC 82, 289 (2022)

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.

M. Mahlein, FB, L. Fabbietti et al, EPJC 83 (2023) 804, K.Blum et al., PRC 103, 014907 (2021)

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

r_0 = size parameter of the source

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

$$\frac{\mathrm{d}^3 N_\mathrm{d}}{\mathrm{d}p_\mathrm{d}^3}(\mathbf{p}_\mathrm{d}) = \underbrace{\boxed{\frac{3}{8}}}_{\text{Spin and isospin factor}} \int \frac{\mathrm{d}^3 r_\mathrm{d}\, \mathrm{d}^3 r\, \mathrm{d}^3 q}{(2\pi)^6} \underbrace{\boxed{\mathcal{D}(\mathbf{r}, \mathbf{q})}}_{\text{Deuteron Wigner function}} \underbrace{\boxed{W_\mathrm{pn}(\mathbf{p}_\mathrm{d}/2 + \mathbf{q}, \mathbf{p}_\mathrm{d}/2 - \mathbf{q}, \mathbf{r}_\mathrm{p}, \mathbf{r}_\mathrm{n})}}_{\text{Proton–neutron Wigner function}}$$

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

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

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

Includes single-particle momentum distributions and their correlation
→ **from MC generator**

Forming deuteron: **nucleon source**

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

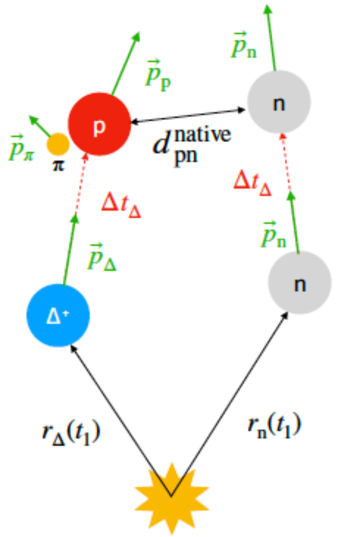
Contributions to the source term:

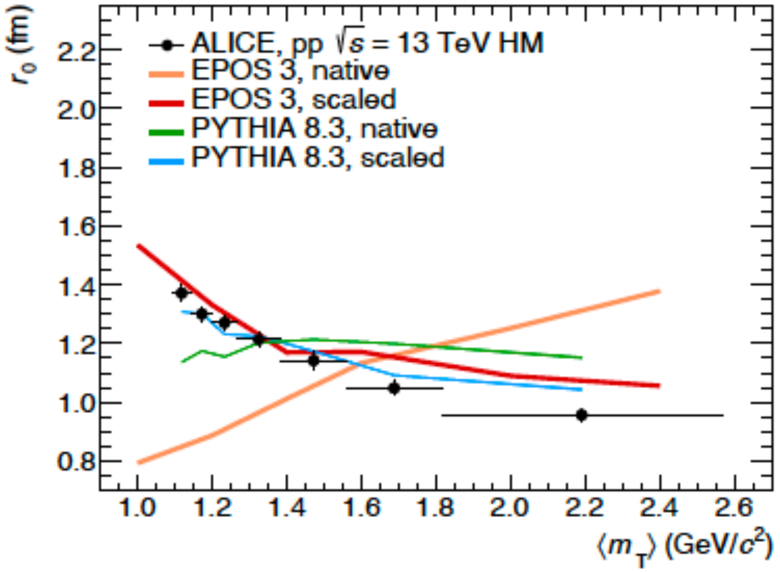
- **prompt** nucleon emission
- **delayed** nucleons from strong **resonance decay** (e.g. Δ, N*, ..., lifetimes ~ 10^{-23}s ~ fm/c)

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

- **resonance cocktail**, hence prompt/feeddown fractions tuned based on statistical—hadronisation model

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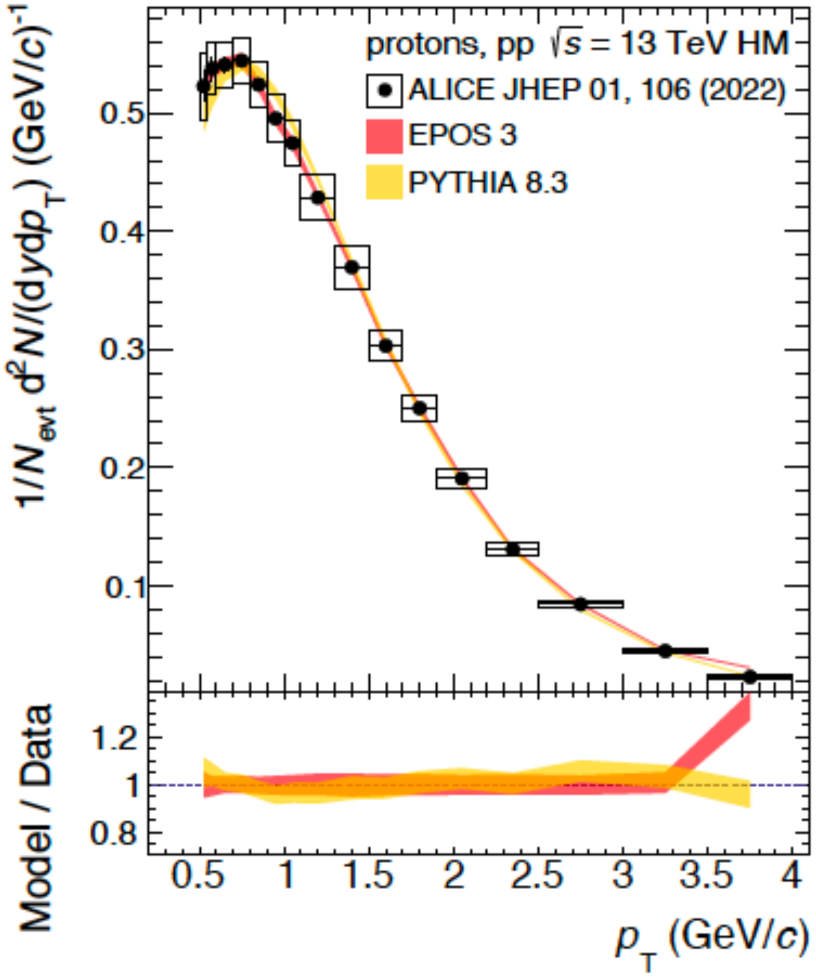
- **m_T scaling** of the p-n distance after time equalization, based on the available ALICE data

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

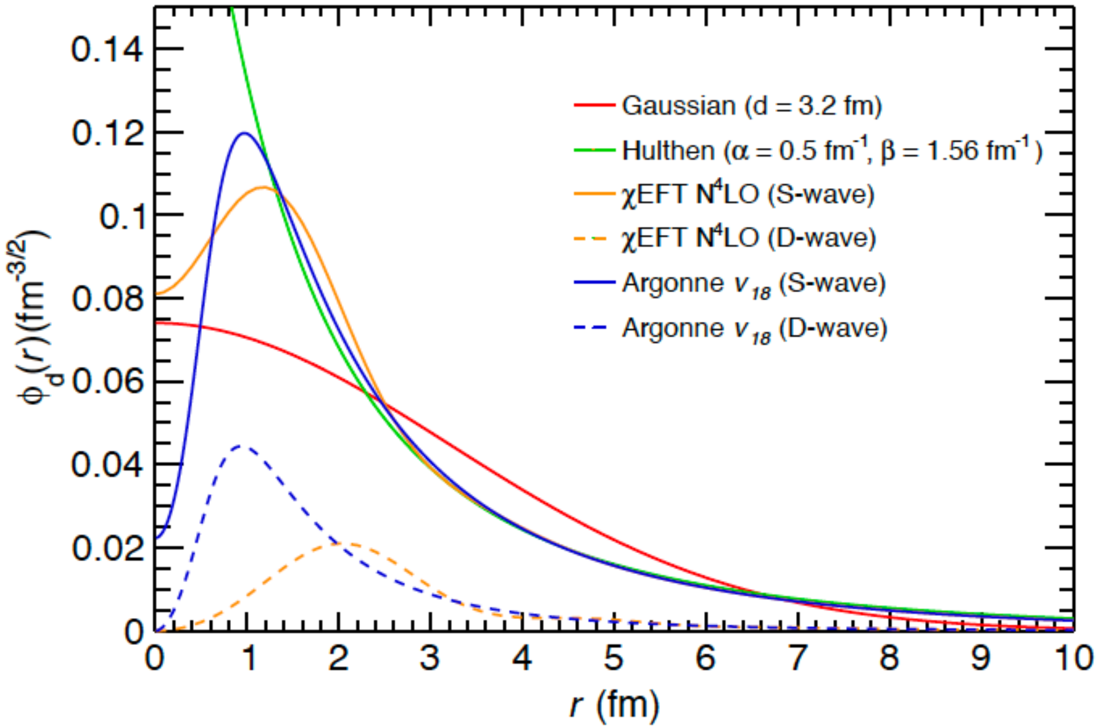
Proton–neutron Wigner function

Deuteron Wigner function:

- Analytical solution only for gaussian wavefunction

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

- Numerical solutions for other wavefunctions
  ** obtained for the first time in EPJC 83 (2023) 804*
  - 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^4LO *
    Entem et al, Phys. Rev. C 96, 024004 (2017)



Forming deuteron: **results**

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

Input #2: baryon source size and its m_T dependence

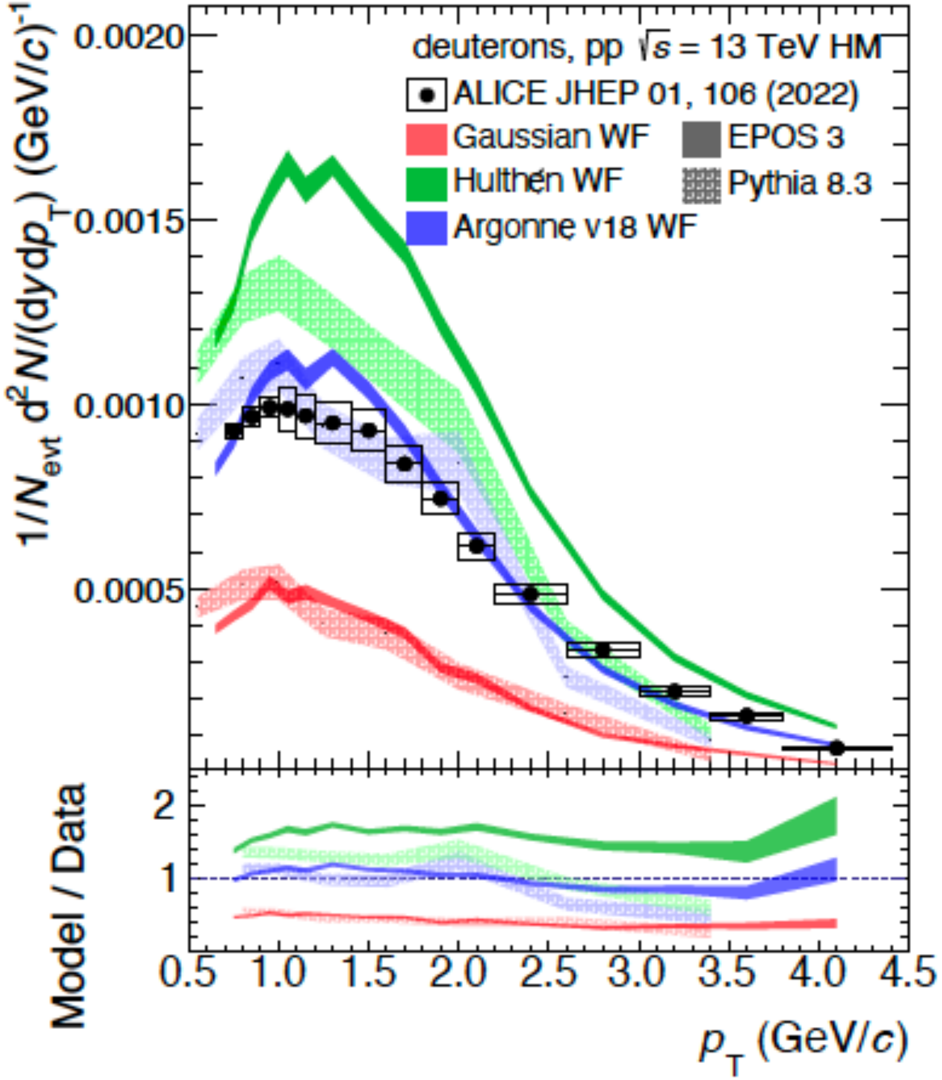
Input #3: hypothesis for deuteron internal wavefunction

Mechanism: coalescence

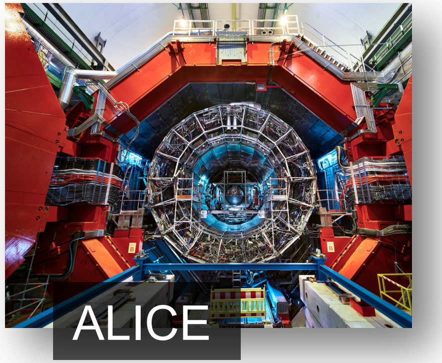
- for each p-n pair, the source is remodelled
- the coalescence weight is computed
- coalescence is implemented as a statistical rejection method

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.



Summary and outlook



Precision measurements of light (anti)nuclei at the LHC by ALICE

- $\sqrt{s}$ = 0.9 to 13.6 TeV
- Midrapidity ($|y|<0.5$)
- pp, p-Pb, Xe-Xe, Pb-Pb
- *Analysis of A=3 and A=4 in pp ongoing at the LHC Run 3*

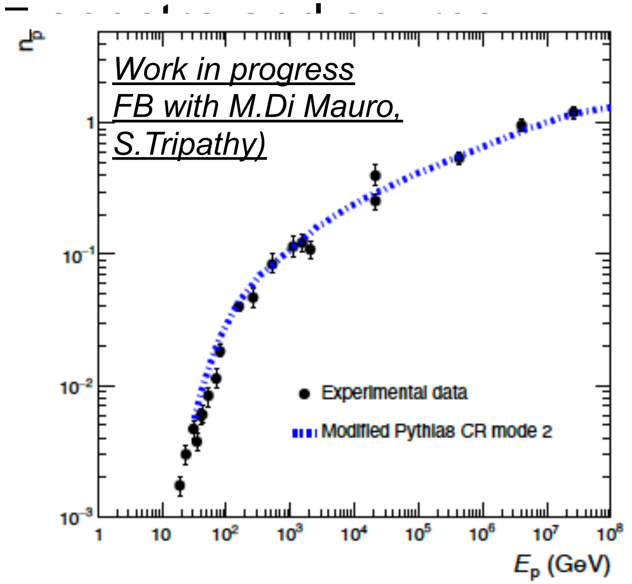
More from LHCb in previous talk

Progress in modelling - one example today

- state-of-the-art coalescence model combined to measurements of the p,
  → **realistic model for (anti)deuteron production event-by-event**

- Ongoing developments **for astrophysical applications**
  - **tune** PYTHIA generator to reproduce $\bar{p}$ as a function of energy
  - Improve coalescence modelling for both DM and CR production
  - Extend to A=3 (non trivial!)

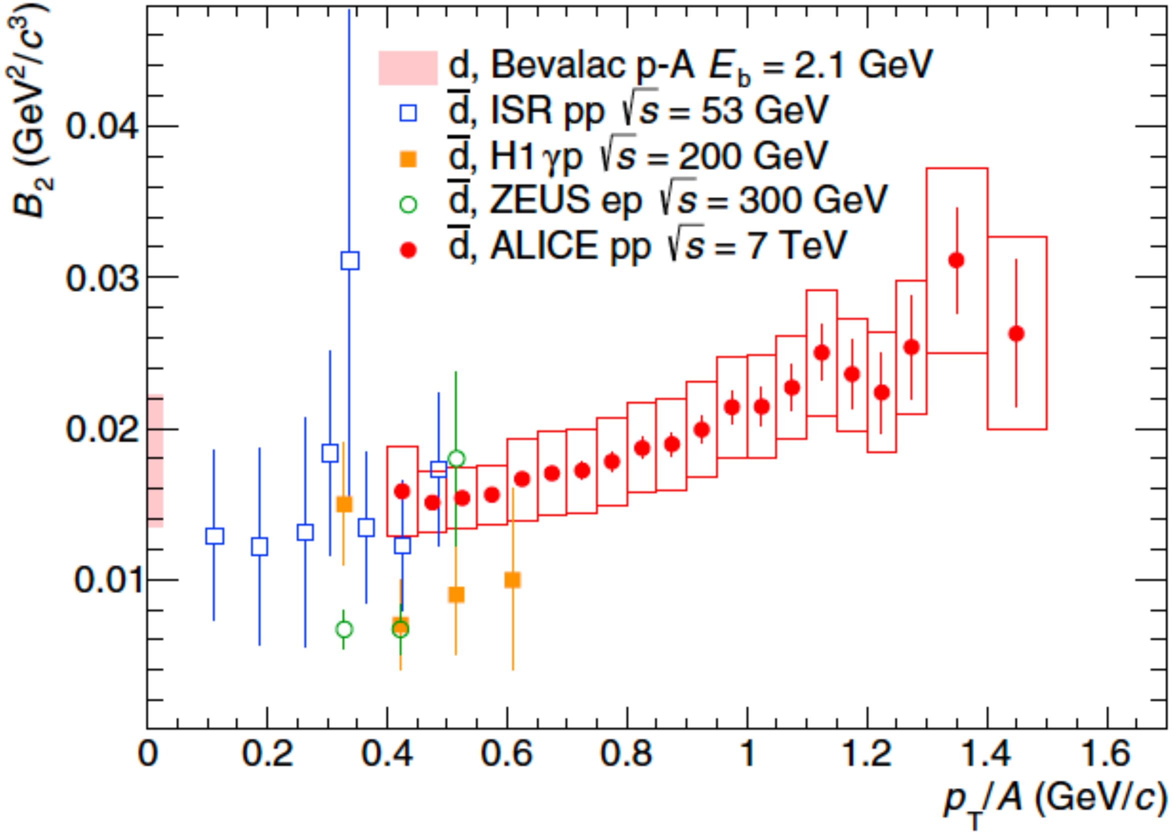
CRUCIAL EXPERIMENTAL INPUT: $\bar{p}$ yields and spectra, $\bar{d}$ at low energy



Thank you!

Contact: fbellini@cern.ch

Coalescence parameter B_2



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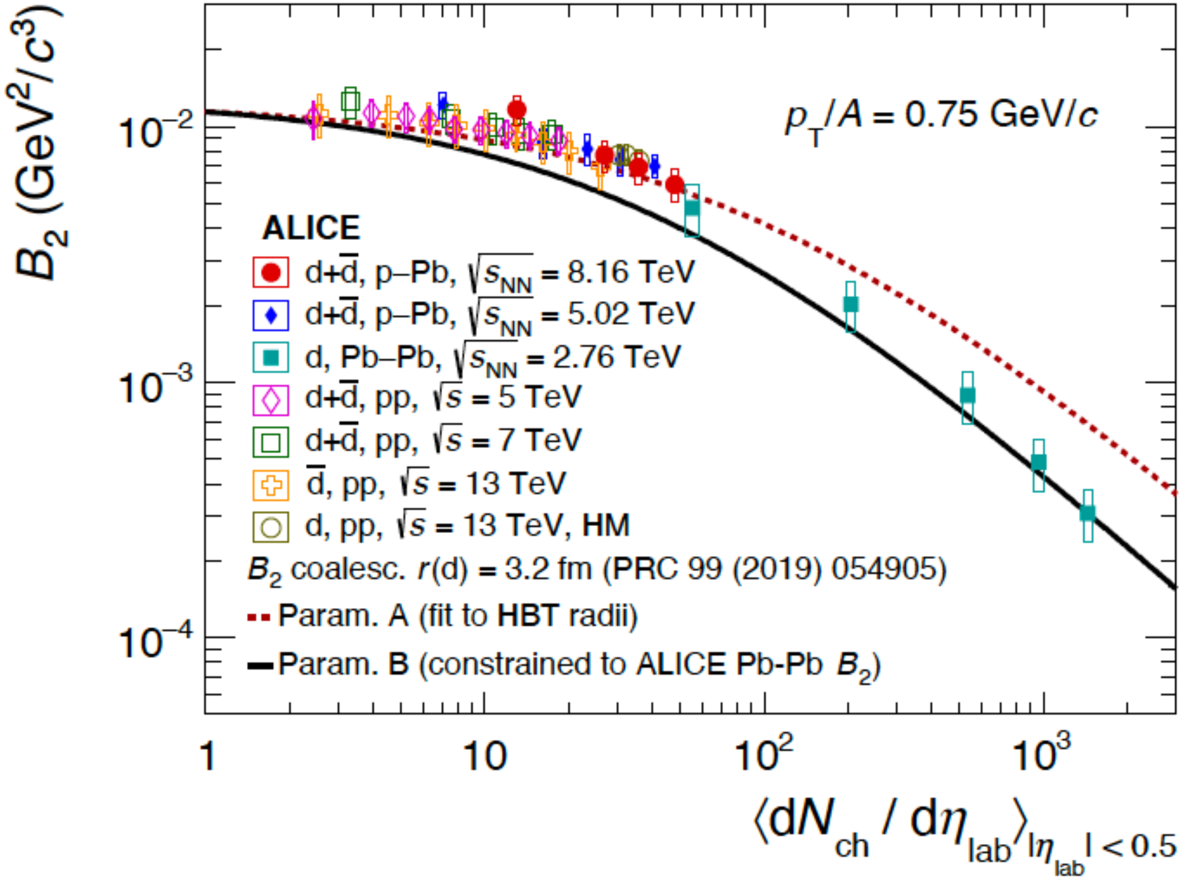

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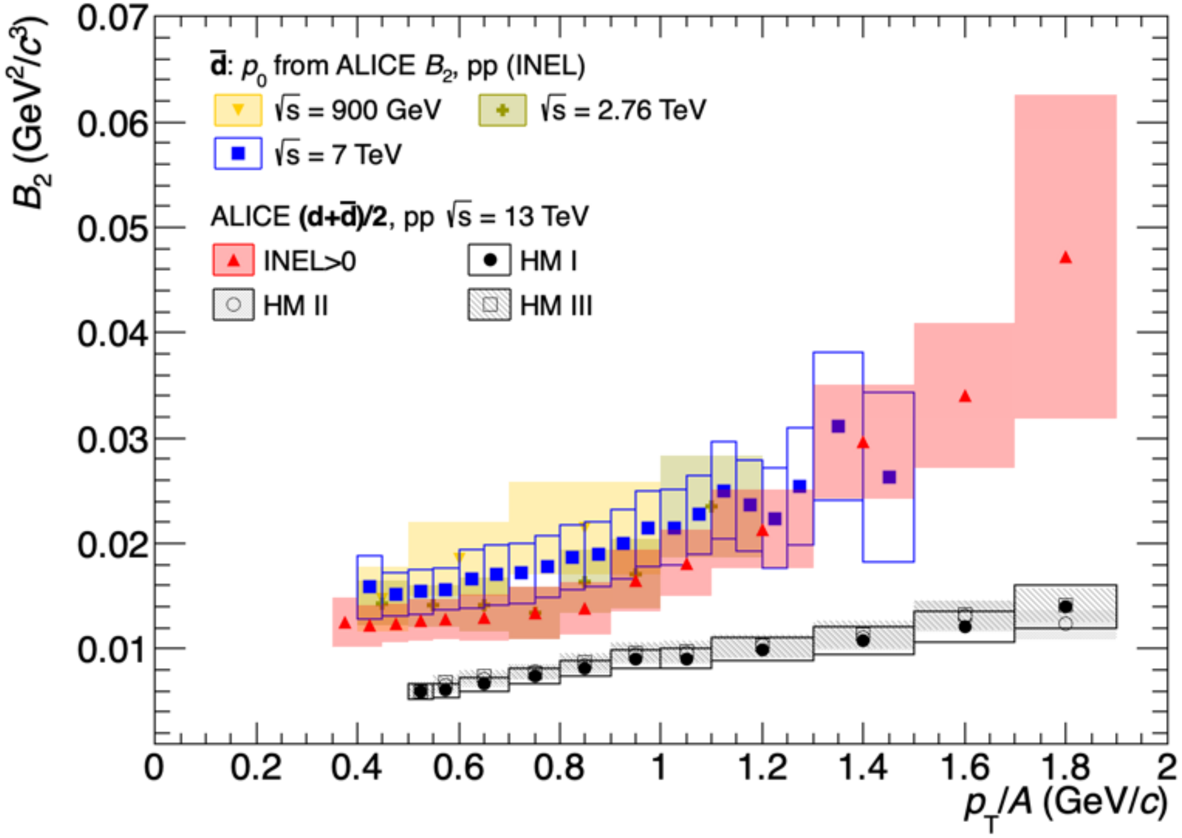
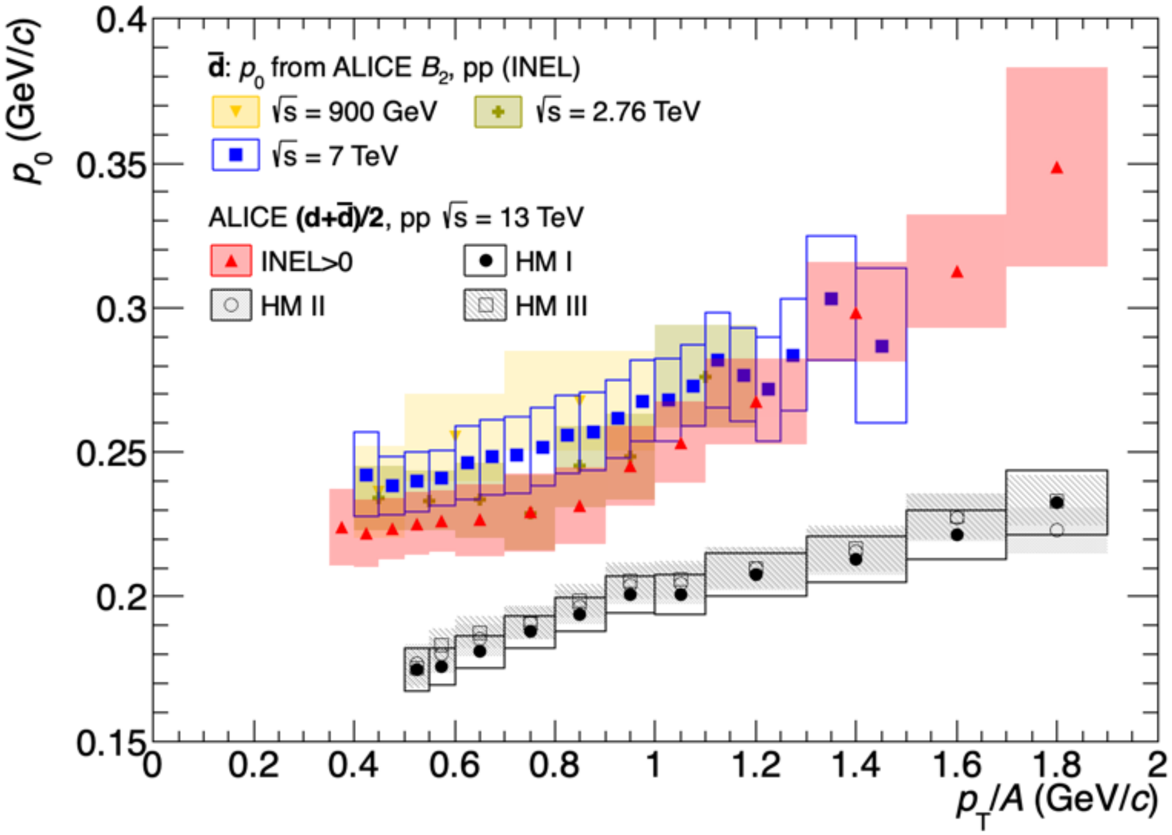
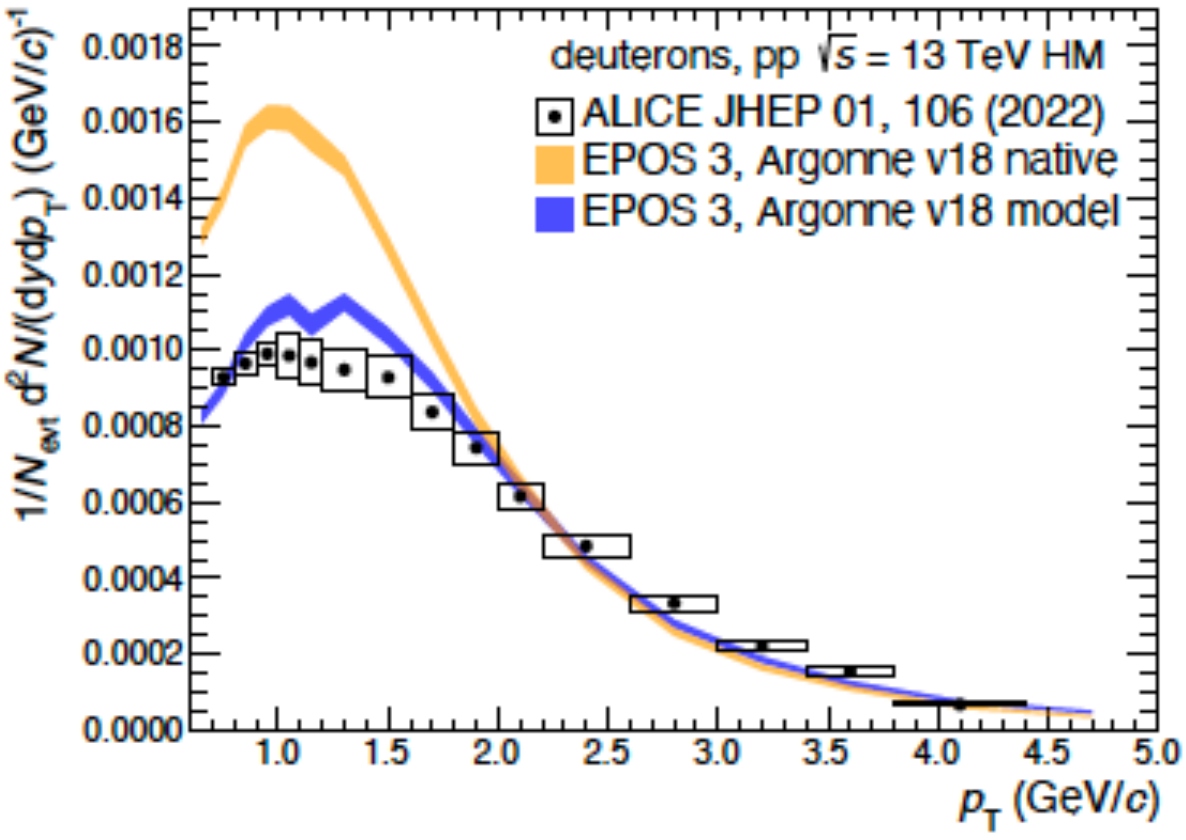
Simple coalescence: from B_2 to p_0

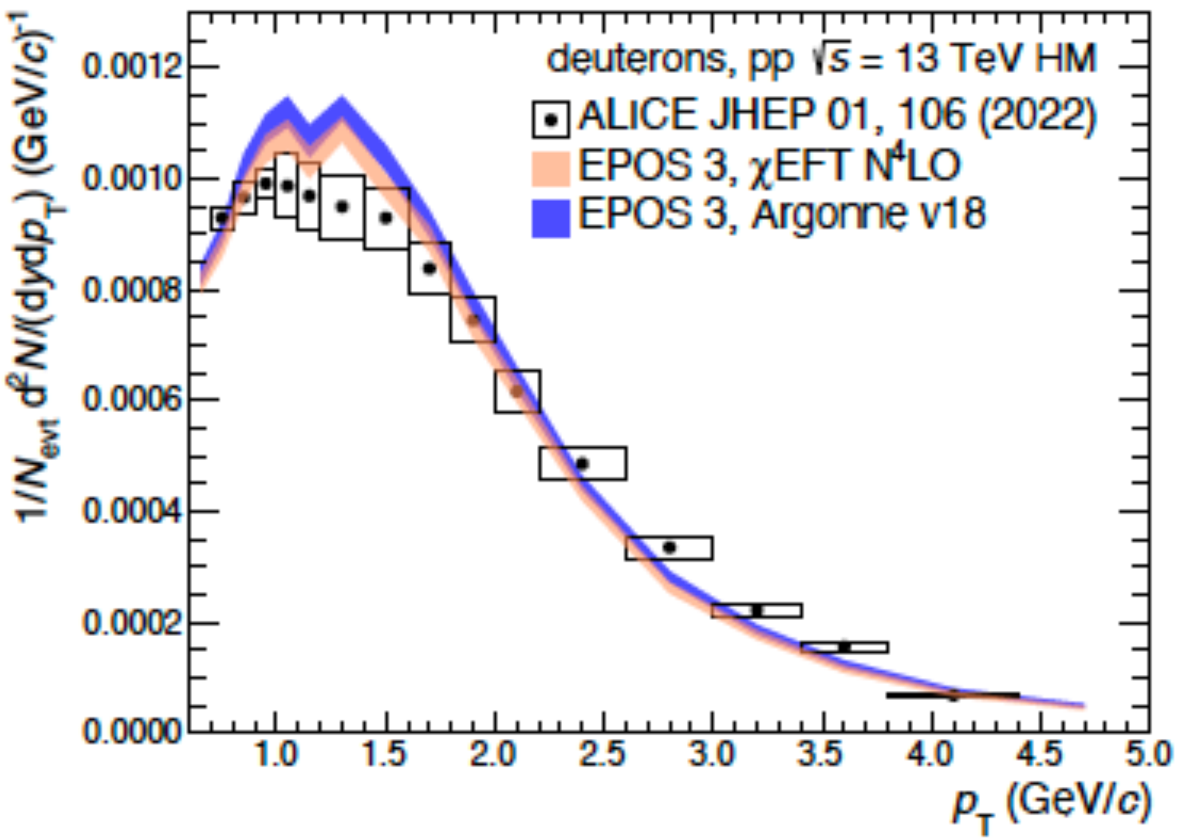




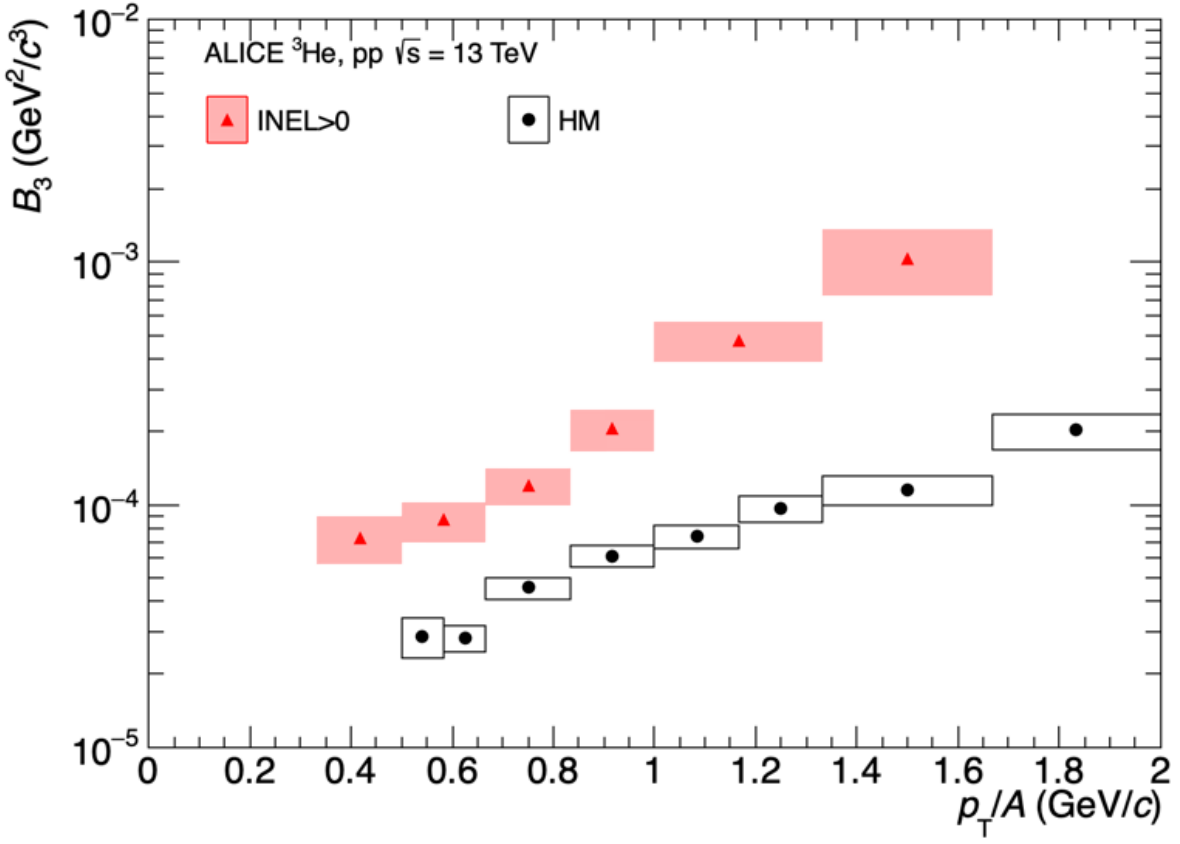
$$B_2 = \frac{m_D}{m_p m_n}\frac{\pi p_C^3}{6}$$

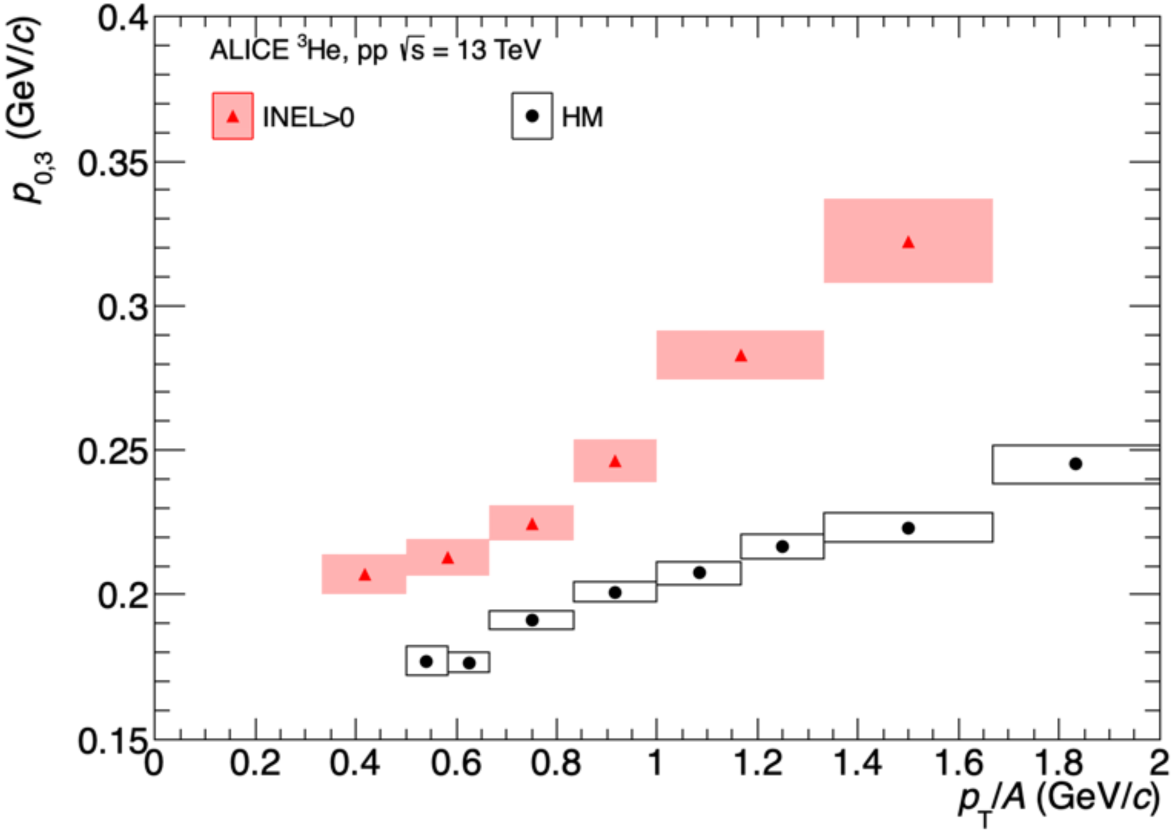
Afterburner - Comparison to data for different w.f.





Simple coalescence: from B_3 to $p_{0,3}$





$$B_3 = \frac{m_{\mathrm{He}}}{m_p^2 m_n}\left(\frac{\pi}{6}p_C^3\right)^2$$

We observe that p_0 and $p_{0,3}$ are rather similar:
in this picture, the penalty factor of the A=3 is
dominantly due to the numerosity of final-state nucleons