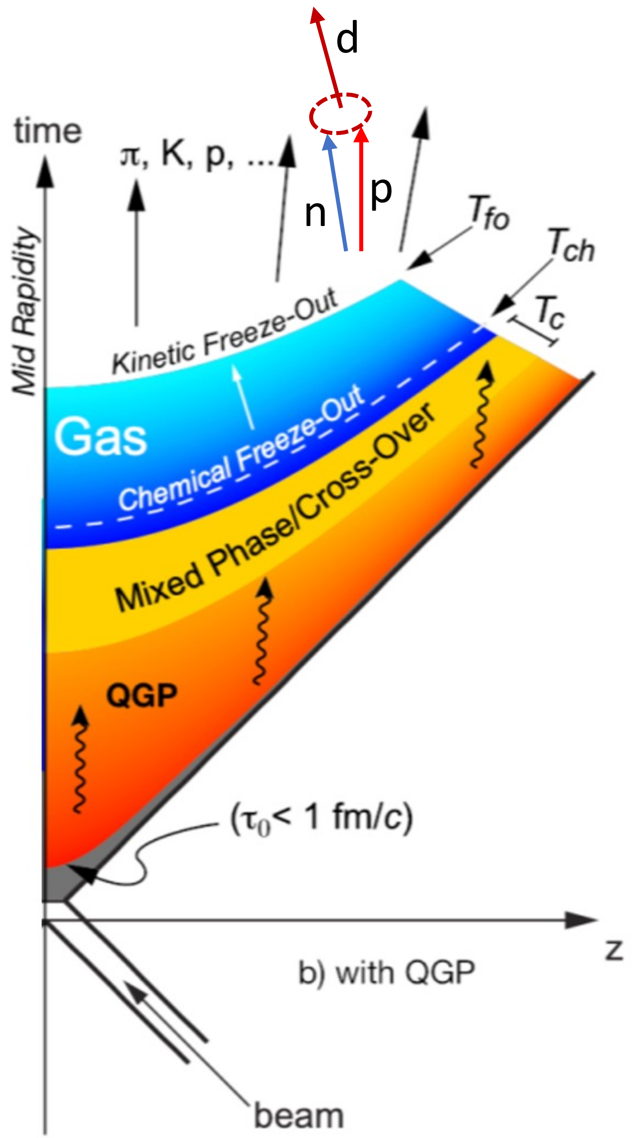
Probing the nuclear production mechanism by measuring nuclei in and out of jets with ALICE

Chiara Pinto (CERN)
on behalf of the ALICE Collaboration

HP2024 NAGASAKI
Hard Probes 2024
Nagasaki – Sept., 25th

Production of (anti)nuclei at the LHC



- At LHC energies ($\sqrt{s}$ ~ 1–13 TeV) same amount of matter and anti-matter is measured[1] (μ_B ~ 0)
- Production measurements useful to investigate the **hadronization mechanism**
- Three classes of phenomenological models available:
  - **statistical hadronization** → works very well for integrated yields (even for nuclei!)
  - **coalescence** → describes fairly well the ratio to protons of integrated yields
  - relativistic **hydrodynamics** + coalescence afterburner → survival of bound states in hadron gas phase with intense rescattering
- Interesting also for astrophysics applications
  - **Cosmic ray** fluxes of antinuclei → dark matter searches
  - **Particle interactions** → neutron stars and equation of state

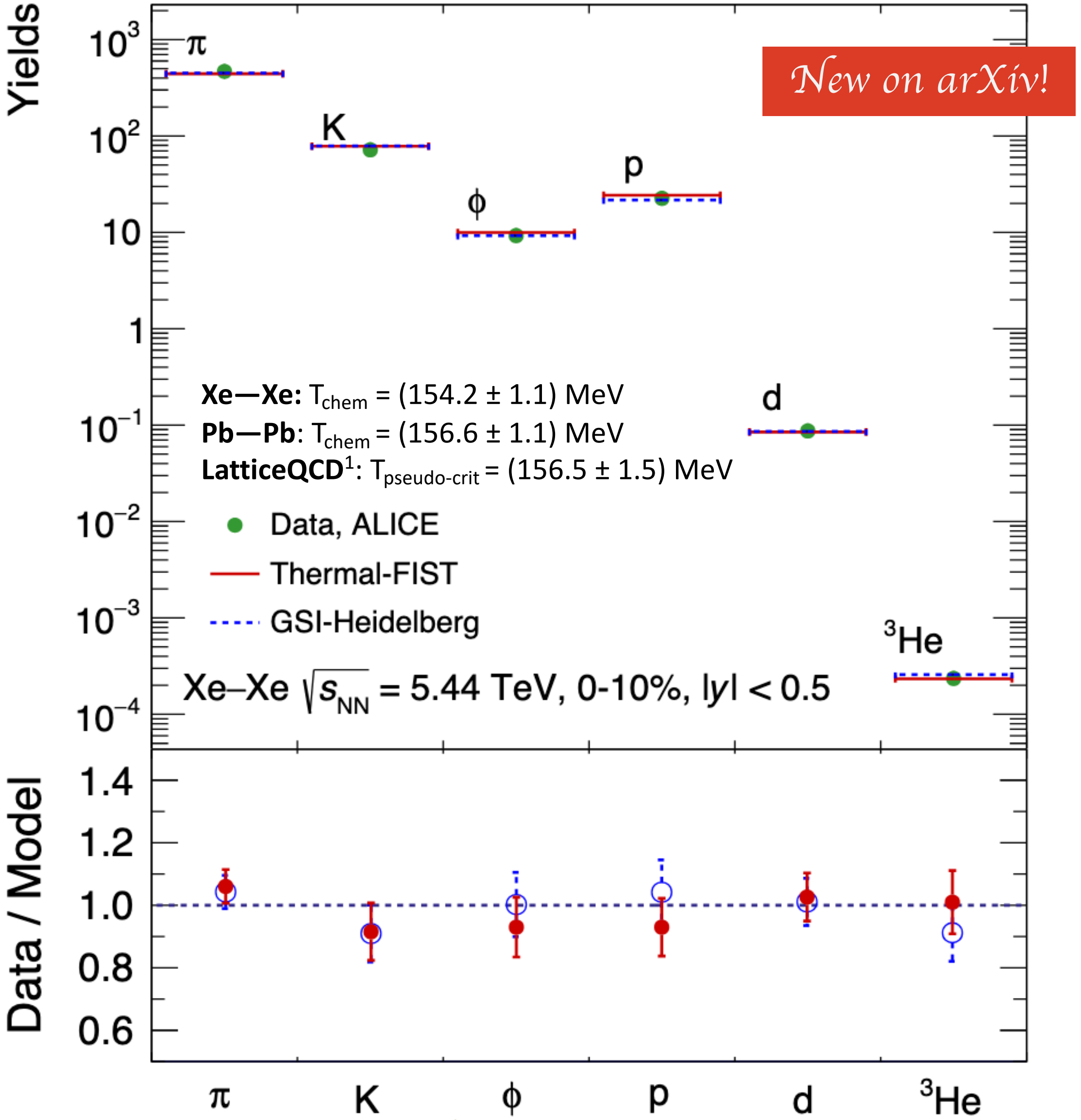
[1] ALICE Collaboration, arXiv:2311.13332

Modelling the production of (anti)nuclei

Statistical models (SHMs)

- Hadrons emitted from a system in chemical equilibrium
- 3 free parameters: V, T_{chem}, μ_B
  – Particle ratios → volume V cancels
  – Baryochemical potential μ_B fixed by $\bar{p}/p$ ratio
  → one remaining parameter T_{chem}
- $dN/dy \propto \exp(-m/T_{chem})$

  ⇒ Nuclei (large m): large sensitivity to T_{chem}
- Typically used in heavy ions, for small systems the canonical ensemble is needed (CSM) → exact conservation of B, Q and S is required only in the correlation volume (V_c)



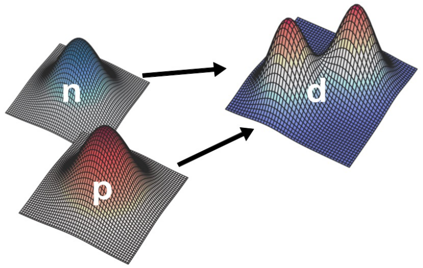
Andronic et al., Nature 561, 321–330 (2018)
[1] HotQCD Coll., Phys.Lett.B 795 (2019) 15

B:baryon number, Q:charge, S: strangeness content

ALICE Collaboration, arXiv:2405.19826

Modelling the production of (anti)nuclei

Coalescence models

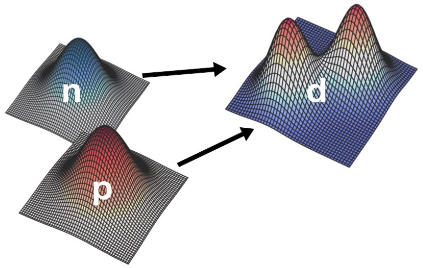


- State-of-the-art models use the *Wigner function formalism* → (anti)nuclei arise from the overlap of the (anti)nucleons phase-space distributions with the Wigner density of the bound state

Butler et al., Phys. Rev. 129 (1963) 836
Mahlein et al., EPJC 83 (2023) 9, 804

Modelling the production of (anti)nuclei

Coalescence models



- State-of-the-art models use the *Wigner function formalism* → (anti)nuclei arise from the overlap of the (anti)nucleons phase-space distributions with the Wigner density of the bound state

- Microscopic description

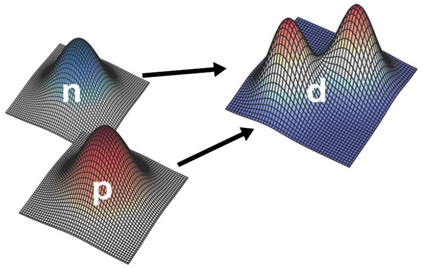
- Key observable is the coalescence parameter B_A → experimental observable tightly connected to the coalescence probability: Larger B_A ⟺ Larger coalescence probability

Butler et al., Phys. Rev. 129 (1963) 836
Mahlein et al., EPJC 83 (2023) 9, 804

$$B_A(p_T^p) = E_A \frac{d^3 N_A}{d\, p_A^3} \Big/ \left(E_p \frac{d^3 N_p}{d\, p_p^3} \right)^A \Bigg|_{p_T^p = p_T^A / A}$$

Modelling the production of (anti)nuclei

Coalescence models

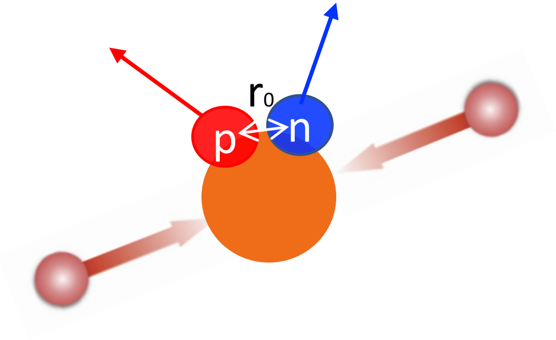


- State-of-the-art models use the *Wigner function formalism* → (anti)nuclei arise from the overlap of the (anti)nucleons phase-space distributions with the Wigner density of the bound state
- Microscopic description
- Key observable is the coalescence parameter B_A → experimental observable tightly connected to the coalescence probability: Larger B_A ⟺ Larger coalescence probability

Butler et al., Phys. Rev. 129 (1963) 836
Mahlein et al., EPJC 83 (2023) 9, 804

$$B_A(p_T^p) = E_A \frac{d^3 N_A}{d\,p_A^3} \Big/ \left(E_p \frac{d^3 N_p}{d\,p_p^3} \right)^A \Bigg|_{p_T^p = p_T^A/A}$$

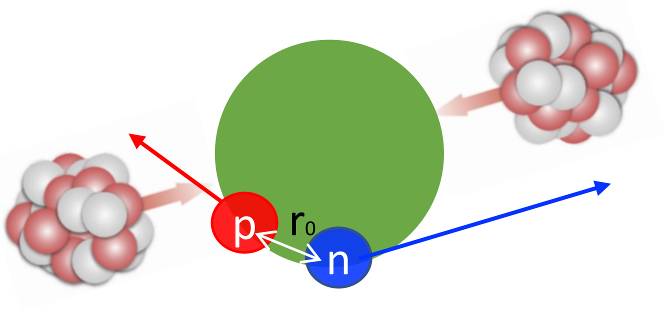
[1] PRC 99 (2019) 024001
[2] PRL 123 (2019) 112002
[3] PRC 96 (2017) 064613



Small distance in space
(Only momentum correlations matter)

pp[1], p—Pb[2]: r_0 = 1–1.5 fm

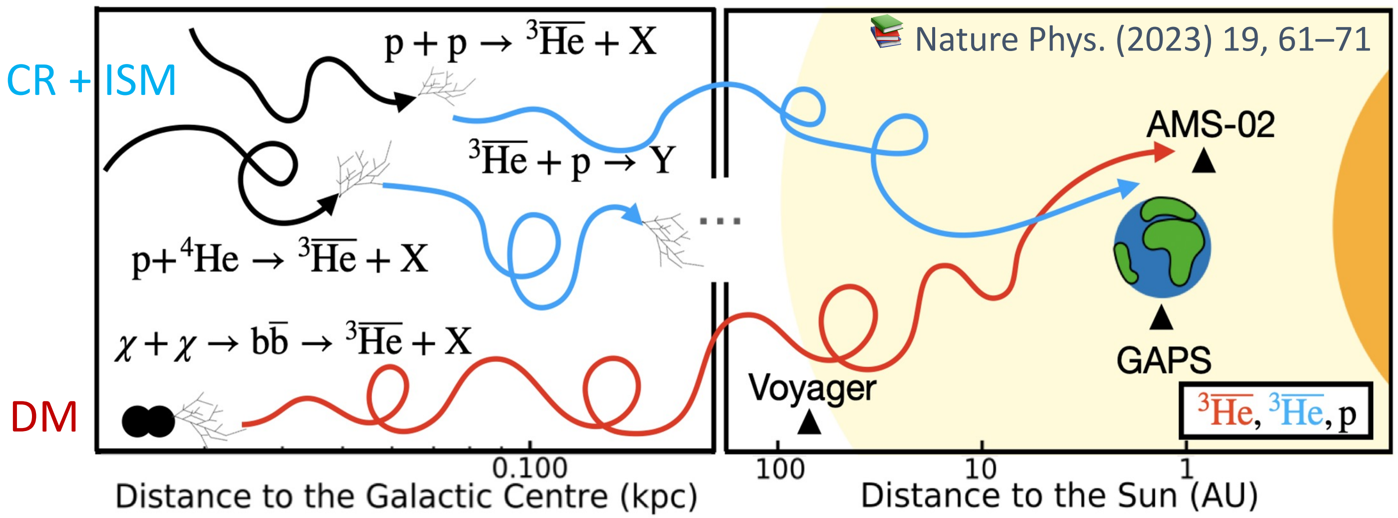
⟺ large B_A



Large distance in space
(Both momentum and space correlations matter)

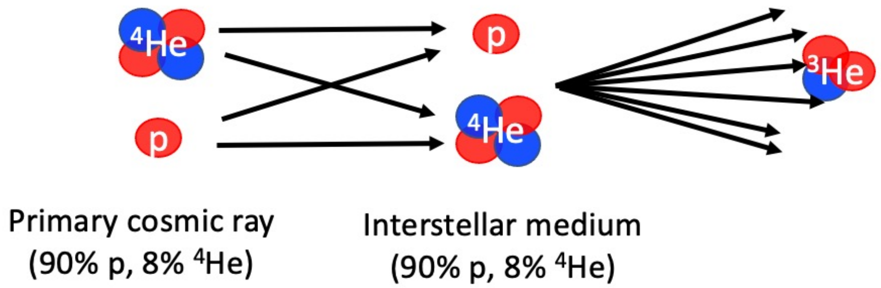
Pb—Pb[3]: r_0 = 3–6 fm

⟺ small B_A



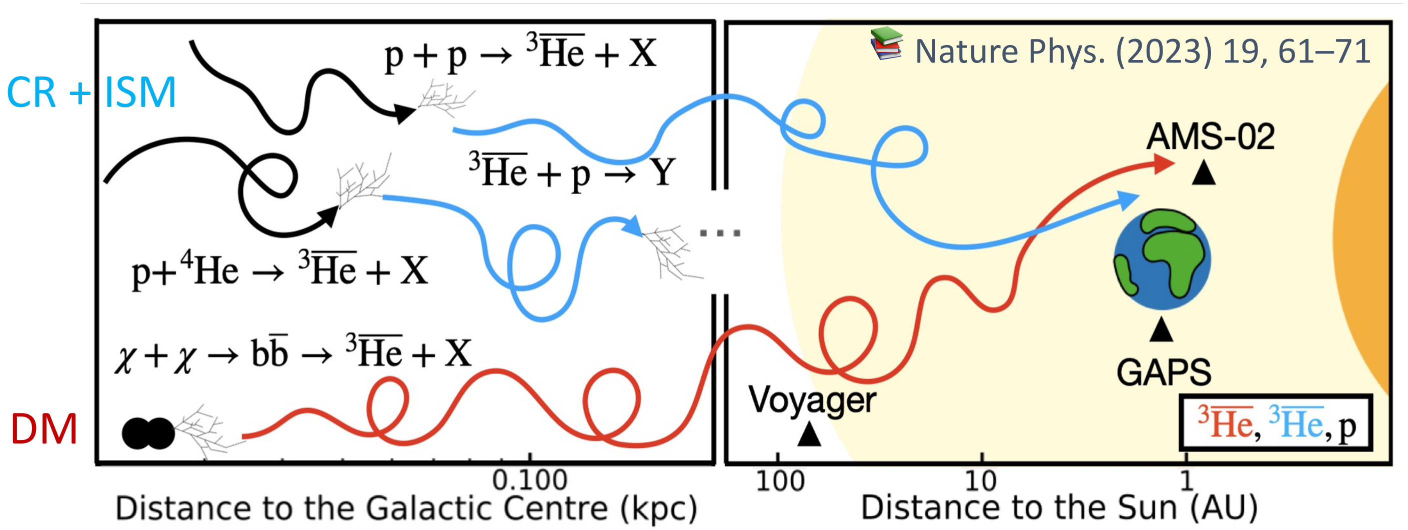
Antinuclei production in our Galaxy:

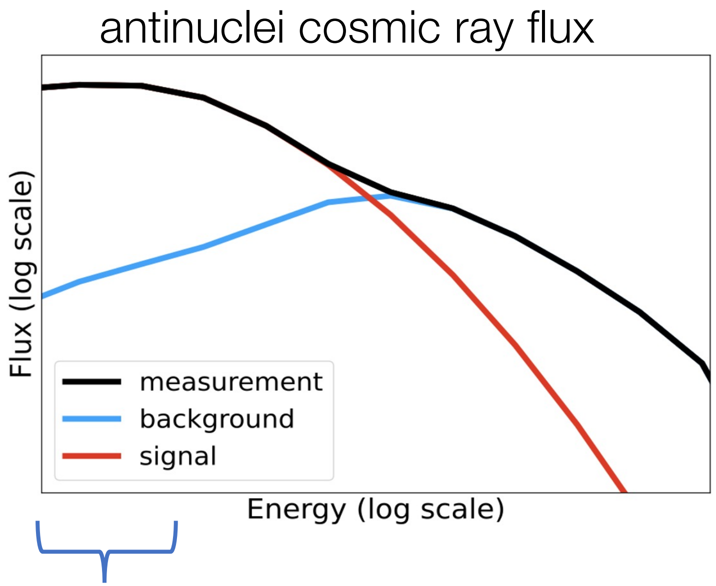
- pp, pA and (few) AA reactions between primary cosmic rays (CR) and the interstellar medium (ISM)



- dark-matter (DM) annihilation processes

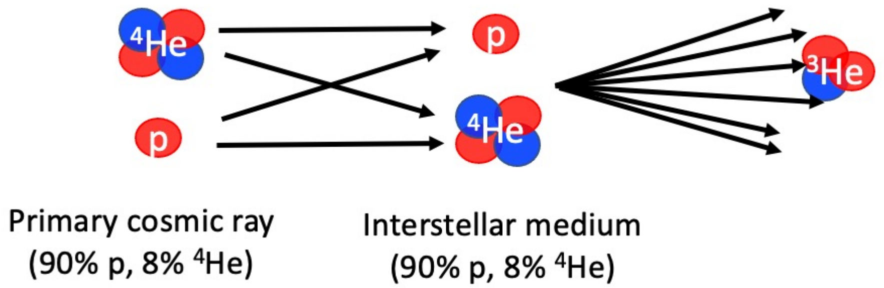
Astrophysics applications: Dark Matter





Antinuclei production in our Galaxy:

- pp, pA and (few) AA reactions between primary cosmic rays (CR) and the interstellar medium (ISM)



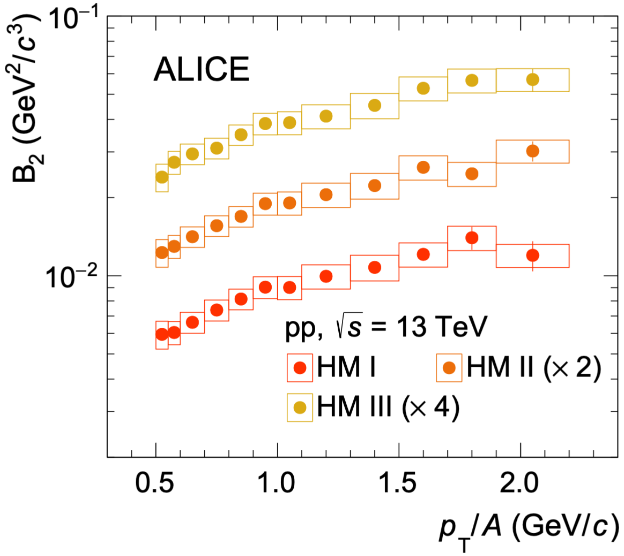
- dark-matter (DM) annihilation processes

- High Signal/Noise ratio (~$10^2 - 10^4$) at low E_{kin} expected by models
- To correctly interpret any future measurement, we need precise knowledge of
  1. production of antinuclei
  2. annihilation

Testing coalescence model using B_2

- Important observable in accelerator measurements: coalescence parameter B_A

$$B_A\left(p_T^p\right)=\frac{1}{2\pi p_T^A}\frac{d^2N_A}{dy dp_T^A}\Bigg/\left(\frac{1}{2\pi p_T^p}\frac{d^2N_p}{dy dp_T^p}\right)^A$$



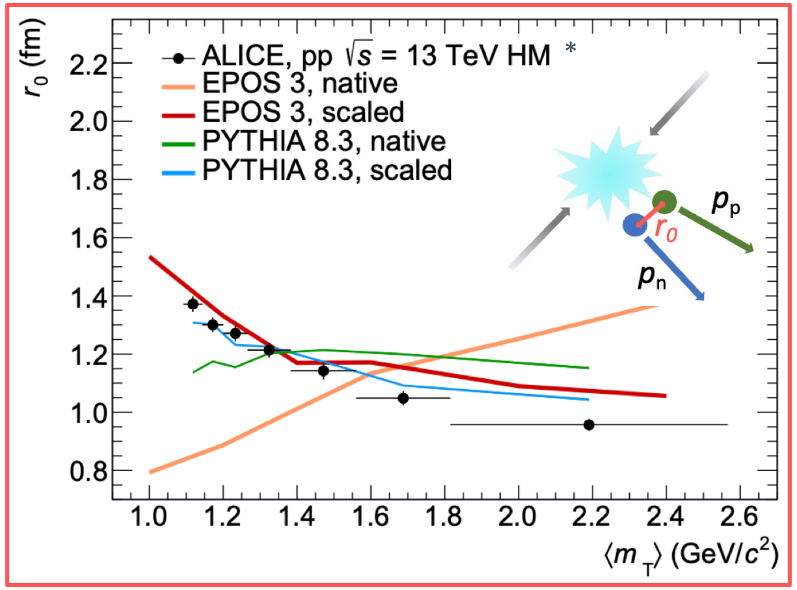
ALICE Collaboration, JHEP 01 (2022) 106

Testing coalescence model using B_2

- Important observable in accelerator measurements: coalescence parameter B_A

$$B_A\left(p_T^p\right) = \frac{1}{2\pi p_T^A}\frac{d^2N_A}{dy dp_T^A} \Bigg/ \left(\frac{1}{2\pi p_T^p}\frac{d^2N_p}{dy dp_T^p}\right)^A$$

- Comparison to state-of-the-art coalescence models based on Wigner formalism showed that there are two key ingredients:
    - *emission source size*



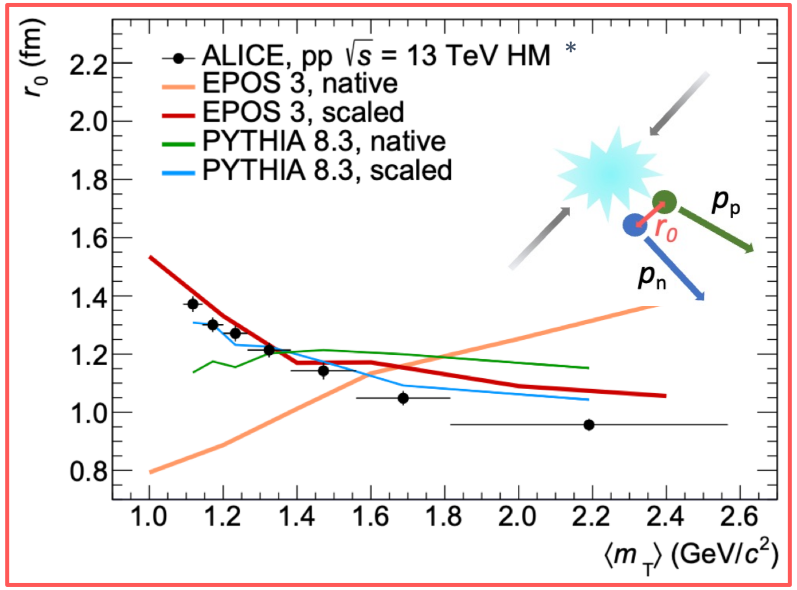
* ALICE Collaboration, PLB 811 (2020) 135849
ALICE Collaboration, JHEP 01 (2022) 106
Kachelrieß et al., EPJA 56 1 (2020) 4
Kachelrieß et al., EPJA 57 5 (2021) 167
Mahlein et al., EPJC 83 (2023) 9, 804

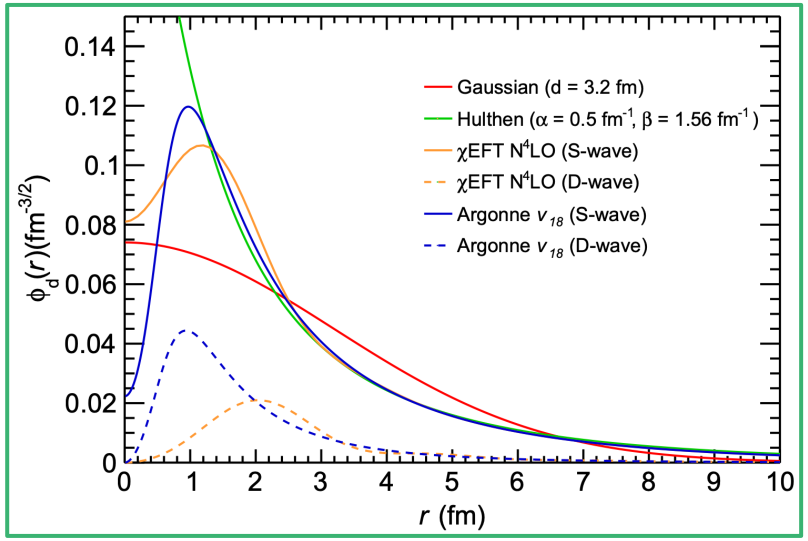
Testing coalescence model using B_2

- Important observable in accelerator measurements: coalescence parameter B_A

$$B_A\left(p_{\mathrm{T}}^{\mathrm{p}}\right) = \frac{1}{2\pi p_{\mathrm{T}}^{\mathrm{A}}} \frac{\mathrm{d}^2 N_{\mathrm{A}}}{\mathrm{d}y \mathrm{d}p_{\mathrm{T}}^{\mathrm{A}}} \Bigg/ \left(\frac{1}{2\pi p_{\mathrm{T}}^{\mathrm{p}}} \frac{\mathrm{d}^2 N_{\mathrm{p}}}{\mathrm{d}y \mathrm{d}p_{\mathrm{T}}^{\mathrm{p}}} \right)^A$$

- Comparison to state-of-the-art coalescence models based on Wigner formalism showed that there are two key ingredients:
  - *emission source size*
  - *deuteron wave function*





* ALICE Collaboration, PLB 811 (2020) 135849
ALICE Collaboration, JHEP 01 (2022) 106
Kachelrieß et al., EPJA 56 1 (2020) 4
Kachelrieß et al., EPJA 57 5 (2021) 167
Mahlein et al., EPJC 83 (2023) 9, 804

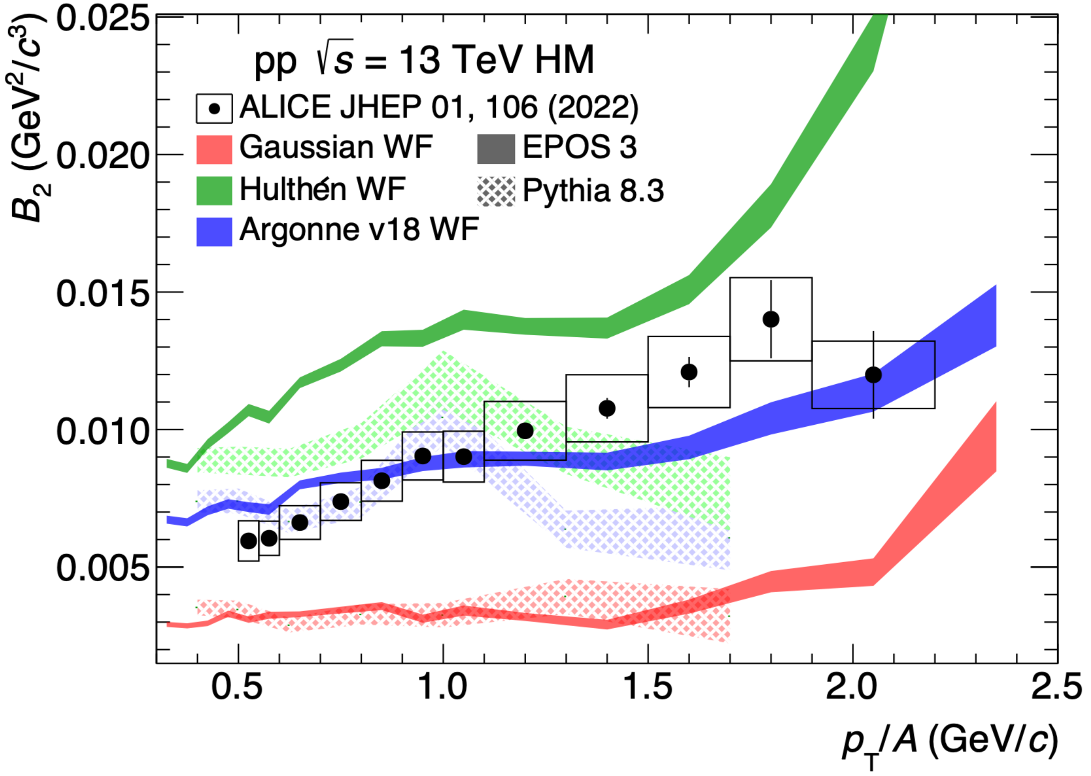
chiara.pinto@cern.ch

Testing coalescence model using B_2

- Important observable in accelerator measurements: coalescence parameter B_A

$$B_A\left(p_T^p\right) = \frac{1}{2\pi p_T^A}\frac{d^2N_A}{dy dp_T^A} \Bigg/ \left(\frac{1}{2\pi p_T^p}\frac{d^2N_p}{dy dp_T^p}\right)^A$$

- Comparison to state-of-the-art coalescence models based on Wigner formalism showed that there are two key ingredients:
  - *emission source size*
  - *deuteron wave function*



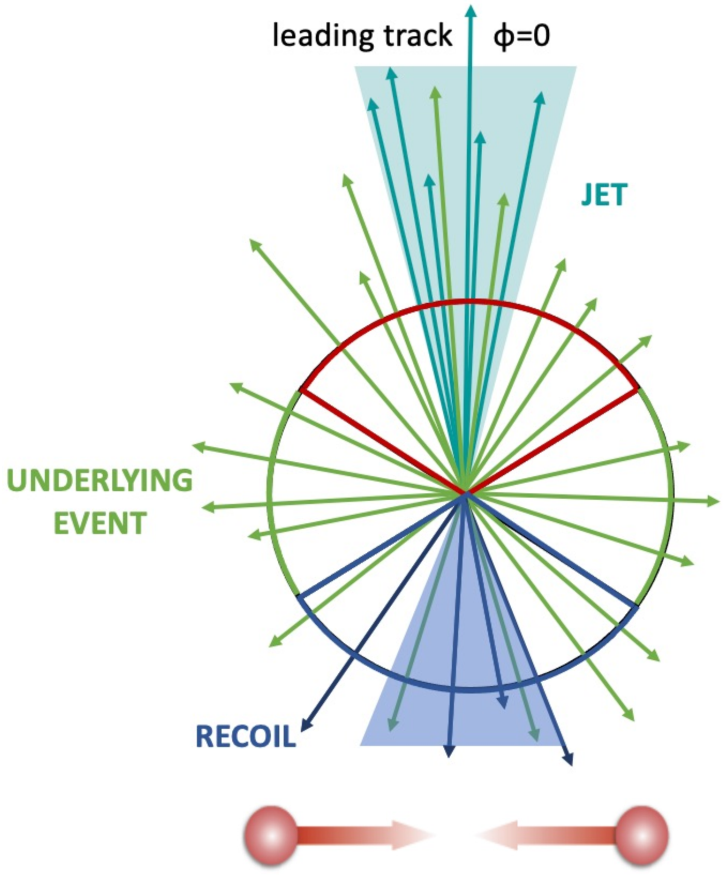
State-of-the-art coalescence model describes deuteron momentum distributions and coalescence parameter, using realistic WF and measured r_0!

* ALICE Collaboration, PLB 811 (2020) 135849
ALICE Collaboration, JHEP 01 (2022) 106
Kachelrieß et al., EPJA 56 1 (2020) 4
Kachelrieß et al., EPJA 57 5 (2021) 167
Mahlein et al., EPJC 83 (2023) 9, 804

Nuclear production in and out of jets

- Powerful tool to investigate coalescence mechanism is the study of nuclear production in and out of jets
- In jets nucleons are created close to each other in phase-space

→ **Study B_2 in and out of jets**: jets obtained simply by subtracting the UE from the Toward region (Jet + UE)



Toward: $|\Delta\phi| < 60°$
Transverse: $60° < |\Delta\phi| < 120°$
Away: $|\Delta\phi| > 120°$

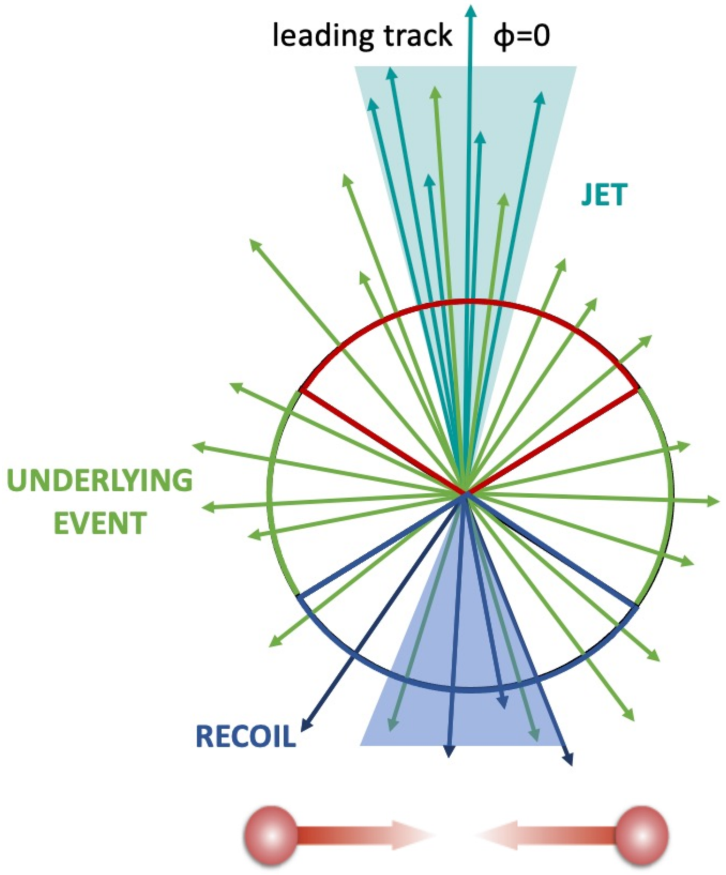
T. Martin et al., Eur. Phys. J. C (2016) 76: 299

Nuclear production in and out of jets

- Powerful tool to investigate coalescence mechanism is the study of nuclear production in and out of jets
- In jets nucleons are created close to each other in phase-space

→ **Study B_2 in and out of jets**: jets obtained simply by subtracting the UE from the Toward region (Jet + UE)

- Studying the antideuteron production in jets in small systems (pp, p—A) is important to understand and model nuclear production
- Production models are crucial to study cosmic rays
- Antideuteron in the Galaxy is produced in interactions of cosmic rays (p, ^{4}He) with kinetic energies of ~300 GeV

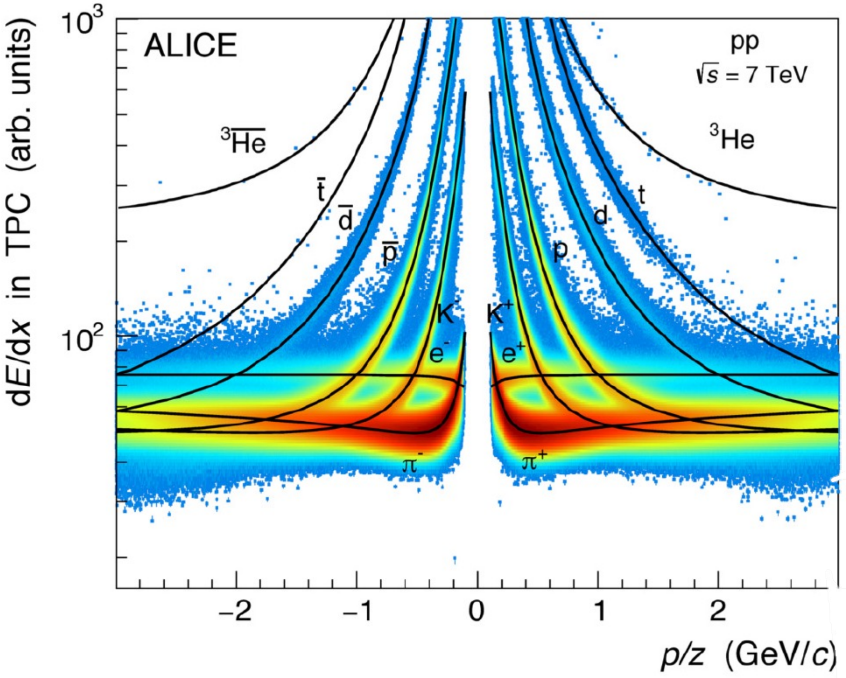


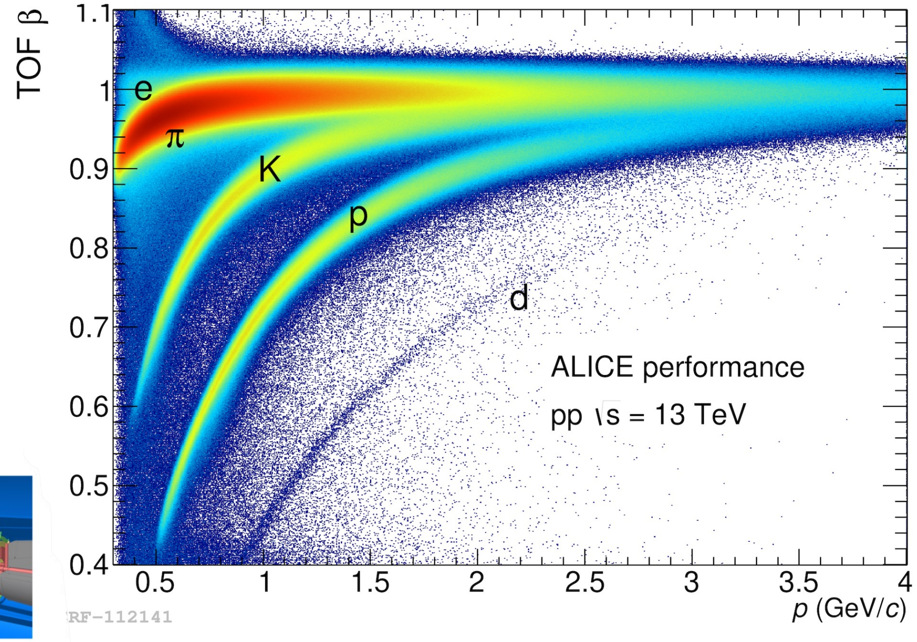
Toward: $|\Delta\phi| < 60°$
Transverse: $60° < |\Delta\phi| < 120°$
Away: $|\Delta\phi| > 120°$

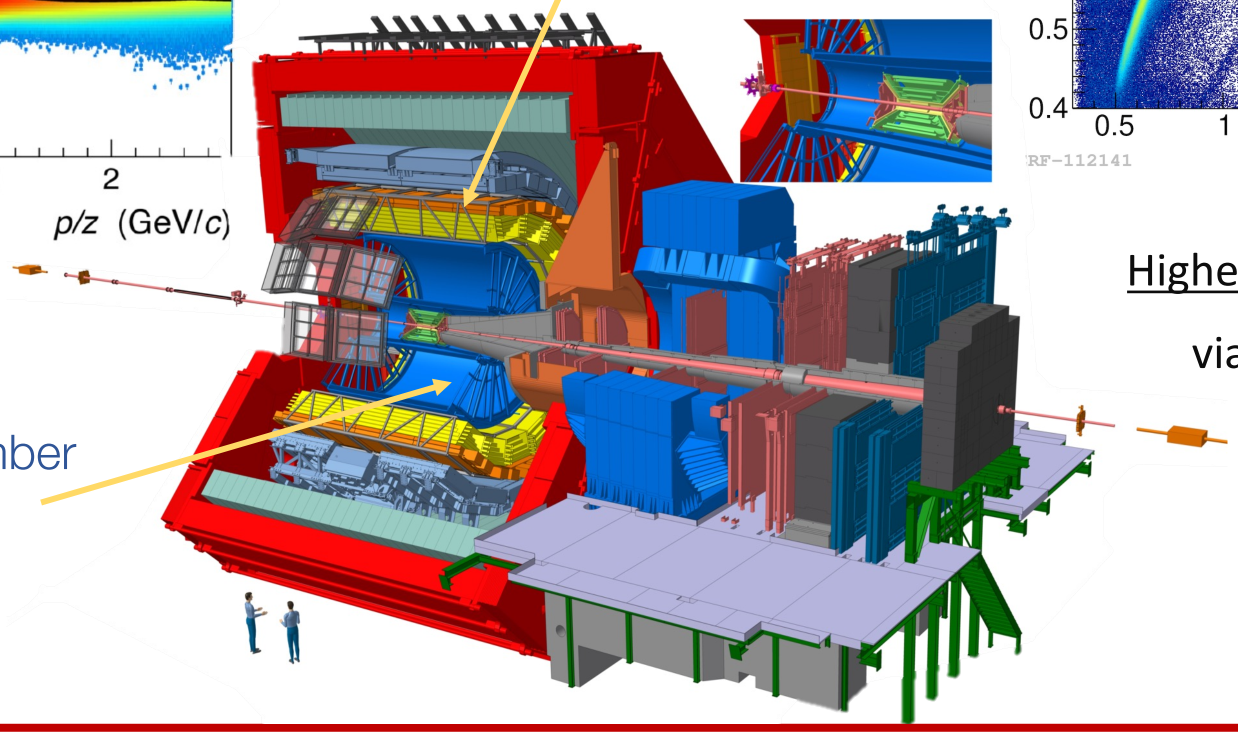
T. Martin et al., Eur. Phys. J. C (2016) 76: 299
Serksnyte et al., Phys. Rev. D 105 (2022) 8, 083021

Identification of nuclei with ALICE

Low *p* region (below 1 GeV/*c*) → PID via d*E*/dx measurements in TPC







Time Of Flight

PID via β

σ_{PID} ~ 70 ps

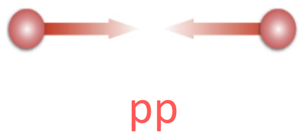
Time Projection Chamber

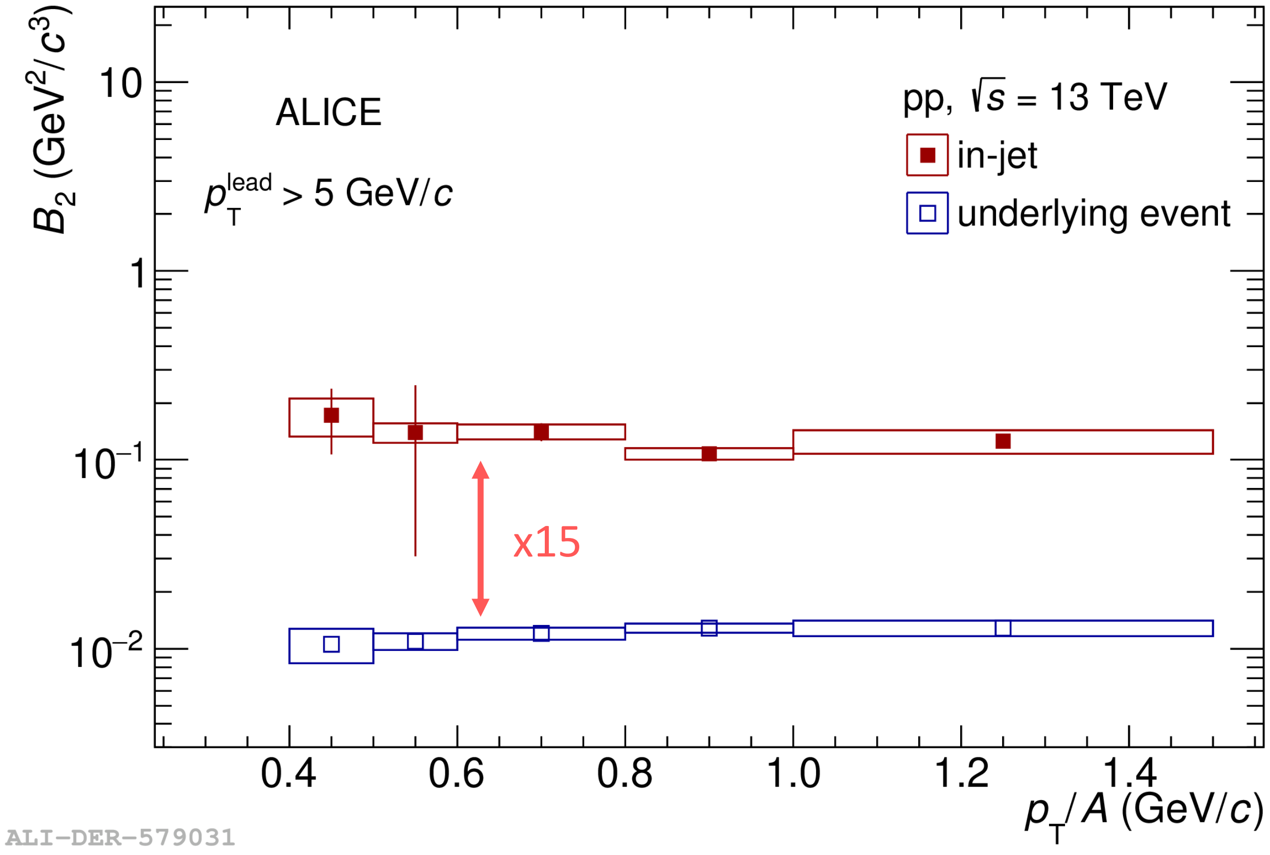
tracking, PID via d*E*/dx

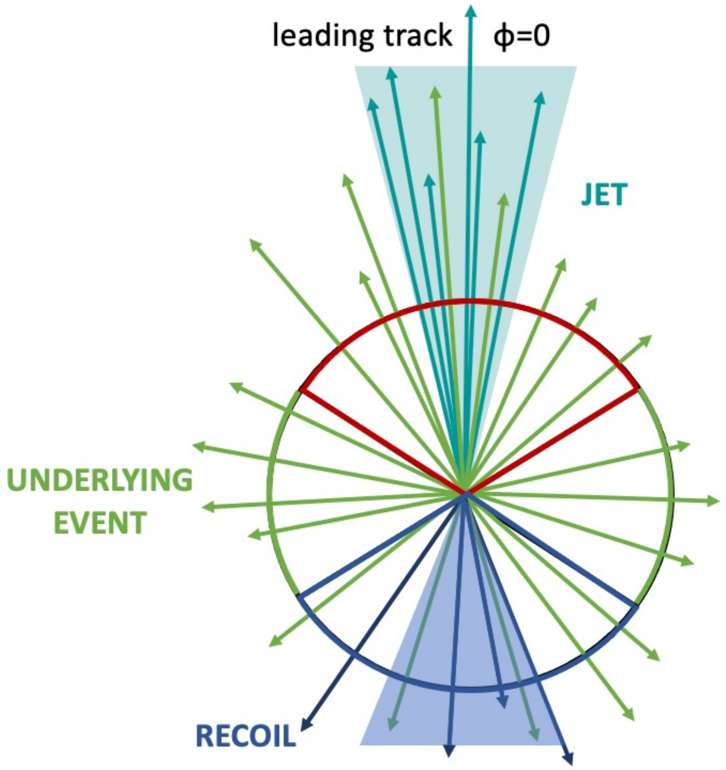
$\sigma_{dE/dx}$ ~ 6%

Higher *p* region (above 1 GeV/*c*) → PID via velocity β measurements in TOF

Coalescence parameters in and out of jets



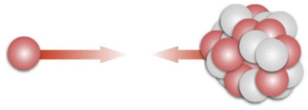




- *Enhanced deuteron coalescence probability in jets wrt UE is observed for the first time in pp collisions*
- Due to the reduced distance in phase space of hadrons in jets compared to those out of jets → favors coalescence picture

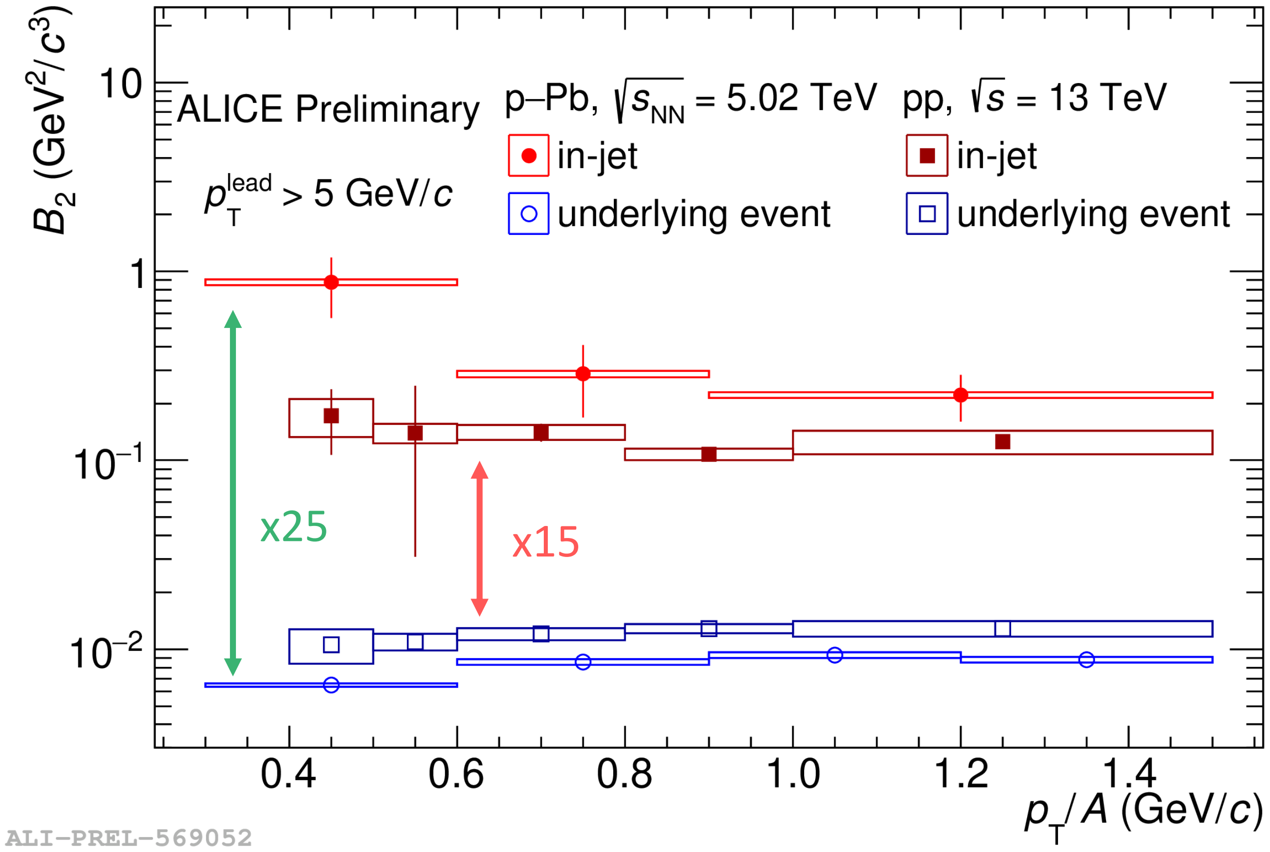
Phys.Rev.Lett. 131 (2023) 4, 042301

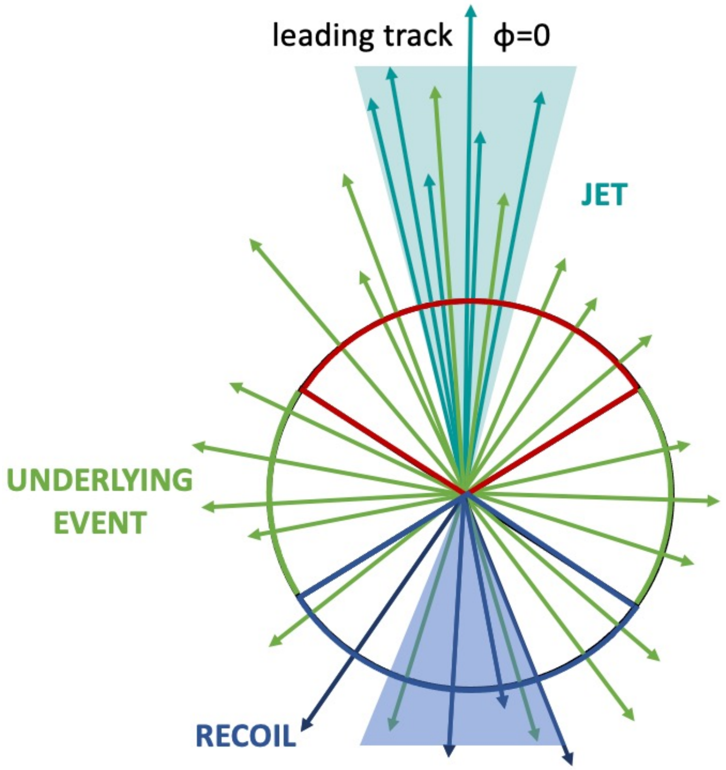
Coalescence parameters in and out of jets



p—Pb

pp

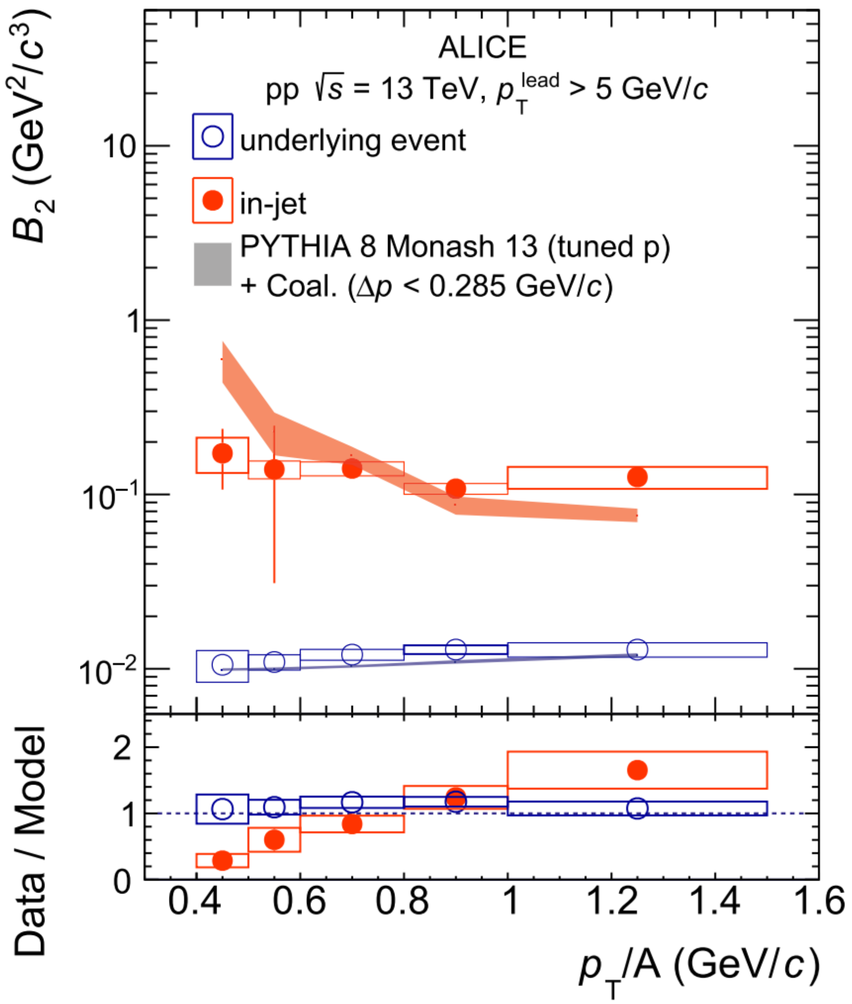




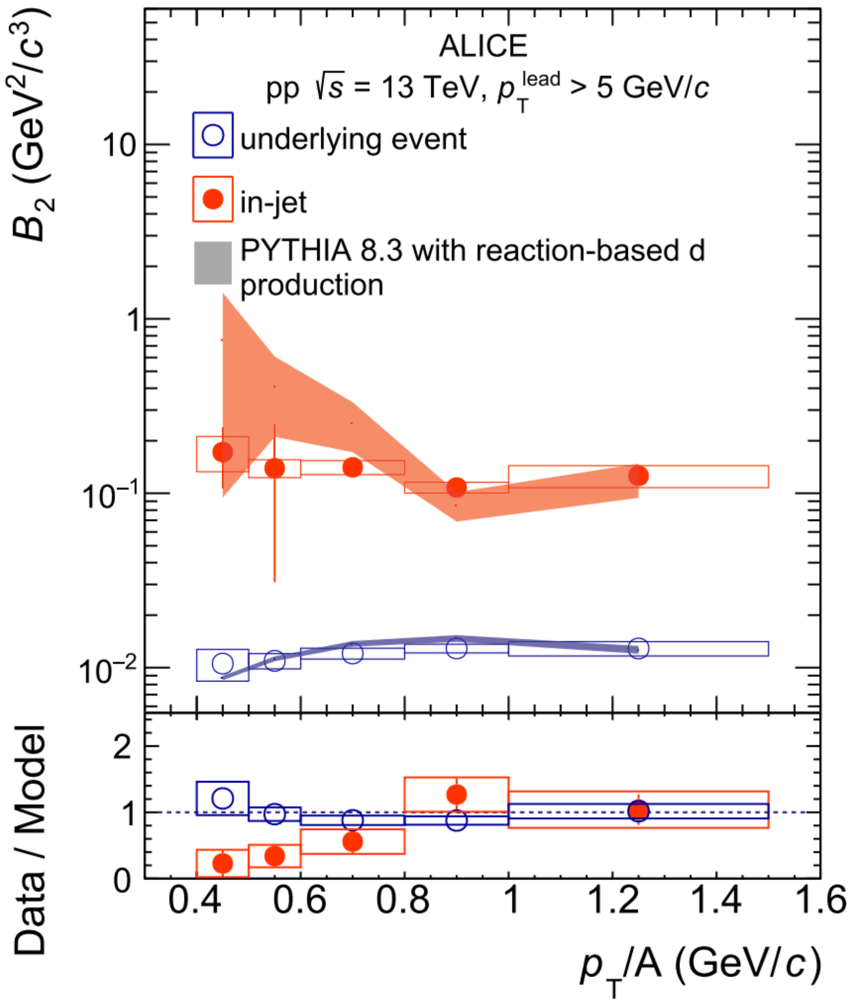
- B_2 in-jet in p—Pb is larger than B_2 in-jet in pp
  → *could be* related to the different particle composition of jets in pp and p—Pb
- B_2 in UE in p—Pb is smaller than B_2 in UE in pp due to the larger source size in p—Pb (pp[1]: r_0~ 1 fm, p—Pb[2]: r_0~ 1.5 fm)

1 Phys.Rev.C 99 (2019) 024001
2 Phys.Rev.Lett. 123 (2019) 112002
Phys.Rev.Lett. 131 (2023) 4, 042301

Model comparison



PYTHIA 8 [1]+ simple coalescence



PYTHIA 8.3 [2]: d production based on reactions
(e.g., p+n $\rightarrow \gamma$ + d, p+p $\rightarrow \pi^+$ + d)

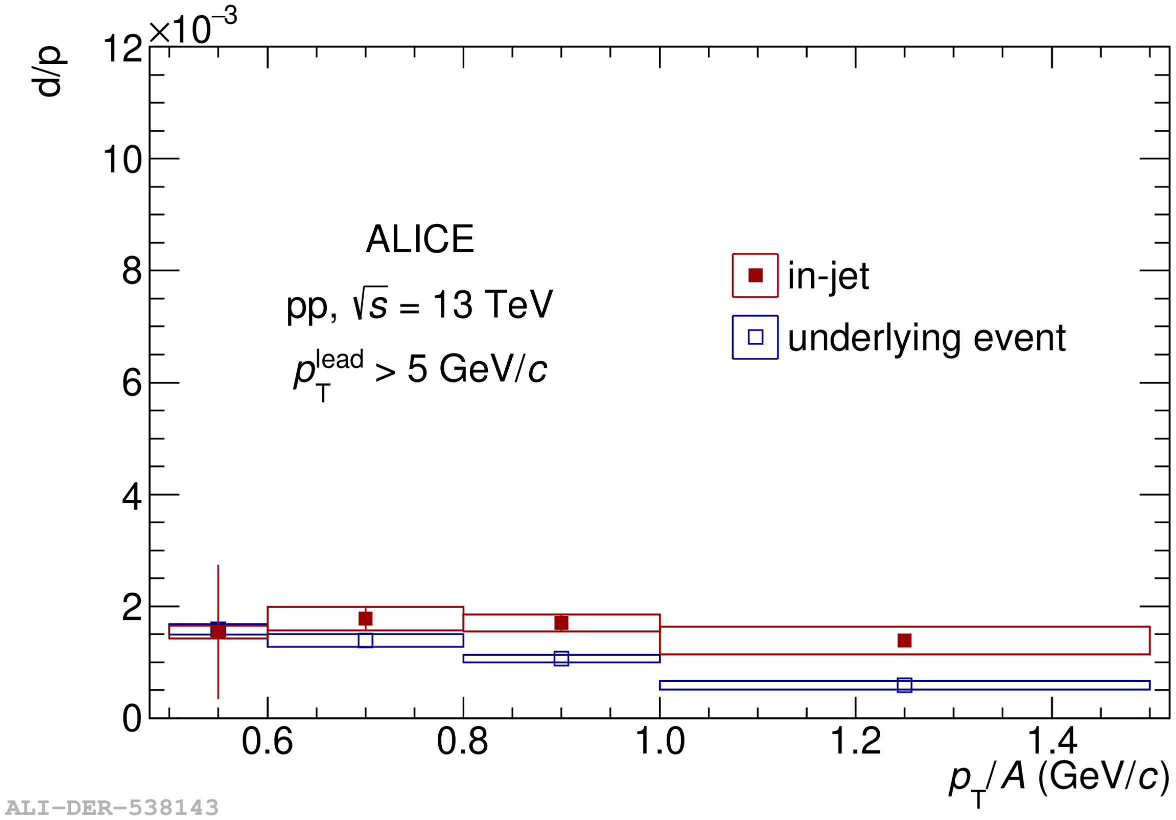
- Models qualitatively reproduce the difference between UE and jet in data

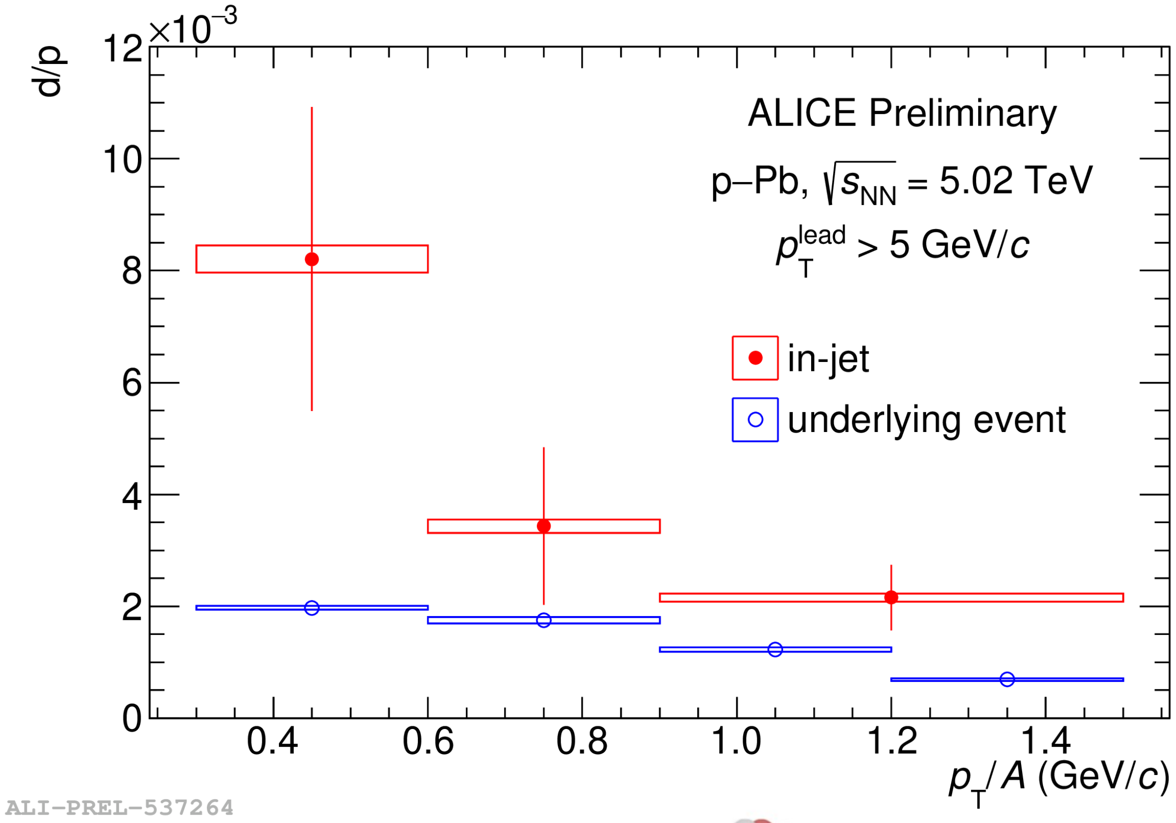
- B_2 UE PYTHIA describes the trend of data
- B_2 in-jet PYTHIA shows a decreasing trend not observed in data

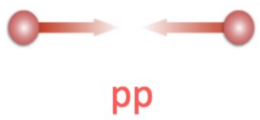
→ Further developments of models are needed

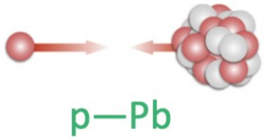
[1] Skands et al., EPJC 74 (2014) 8, 3024
[2] Bierlich et al., arXiv:2203.11601
Phys.Rev.Lett. 131 (2023) 4, 042301

Deuteron-to-proton ratio: pp vs. p—Pb









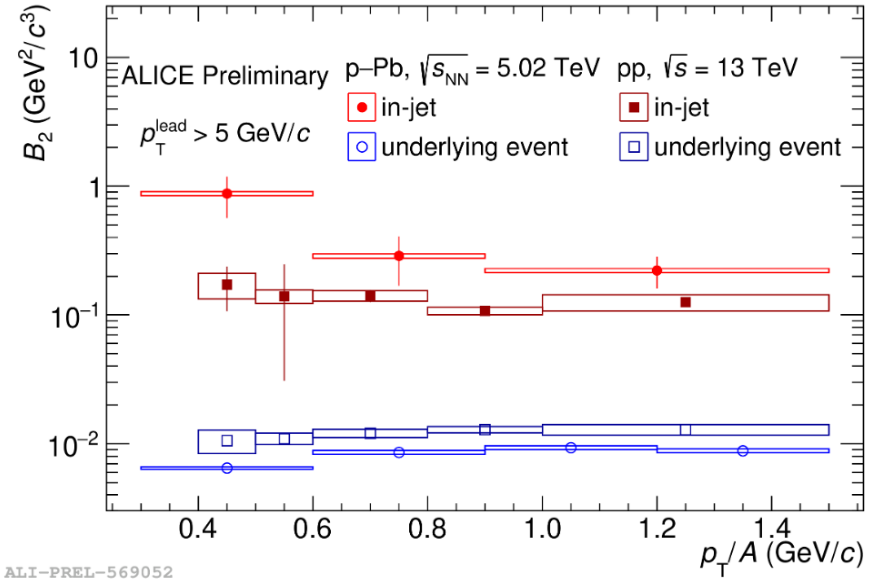
- d/p ratio in jets is larger than d/p ratio in UE
- Higher d/p jet in p–Pb collisions wrt pp collisions

Possible hint of different particle composition in and out of jets

Summary and outlook

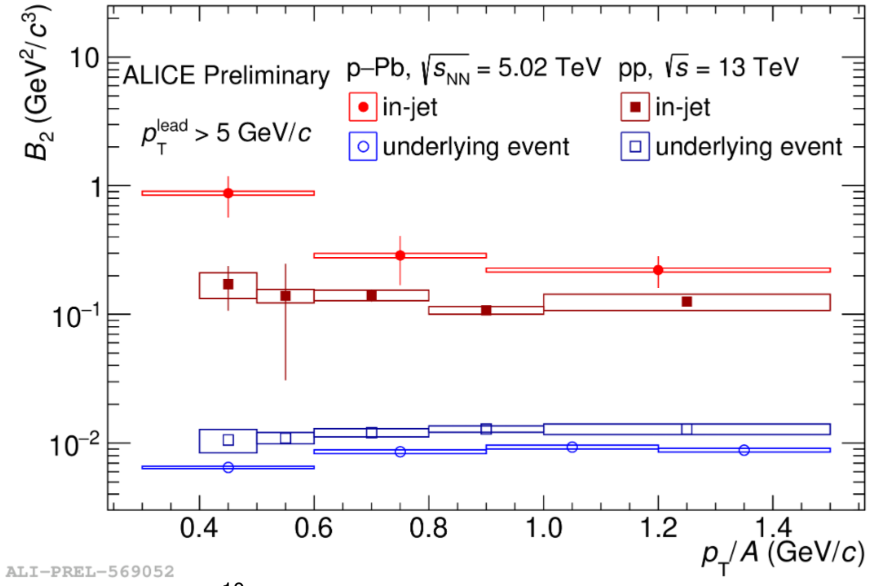
- Production of antinuclei measured at accelerators are crucial input in **astrophysical searches** for dark matter

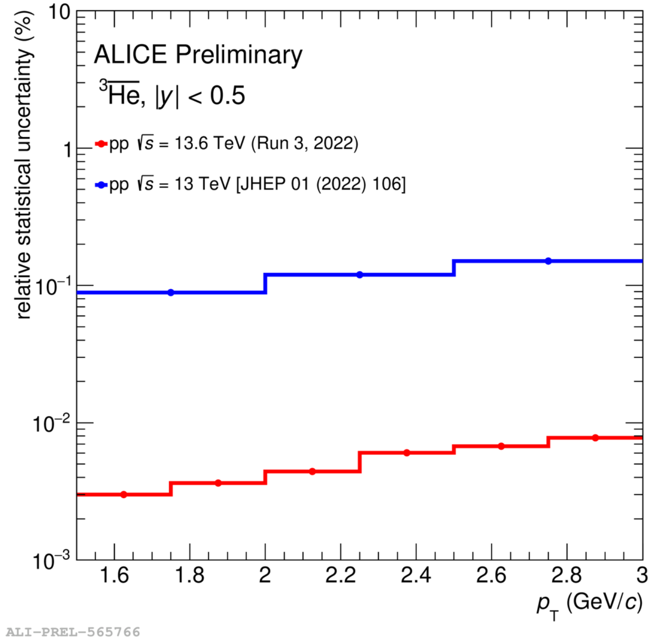
- Antinuclear production **measurements in and out of jets** in pp and p—Pb collisions helps to further constrain the **coalescence** model



Summary and outlook

- Production of antinuclei measured at accelerators are crucial input in **astrophysical searches** for dark matter
- Antinuclear production **measurements in and out of jets** in pp and p—Pb collisions helps to further constrain the **coalescence** model
- Large dataset of **Run 3**:
  - about 1000 more data wrt Run 2
  - systematic and high-precision measurements of d/p and B_2 in jet and UE with **anti-k_T jet finder** algorithm
  - **more differential measurements**: e.g., as a function of jet radius, jet multiplicity, …





Spares

PYTHIA simulations

1. PYTHIA 8.3 (including d production via ordinary reactions, with energy-dependent cross sections parametrized based on data)

- d production in PYTHIA :

1. Bierlich et al., arXiv:2203.11601

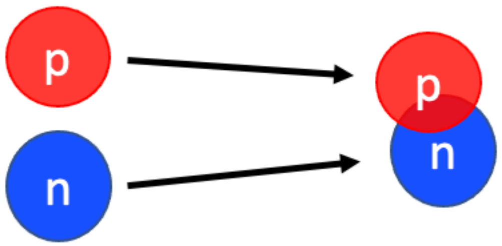
p+ n → γ + d
p+ n → π^0 + d
p+ n → π^0 + π^0 + d
p+ n → π^+ + π^- + d

p+ p → π^+ + d
p+ p → π^+ + π^0 + d
n+ n → π^- + d
n+ n → π^- + π^0 + d

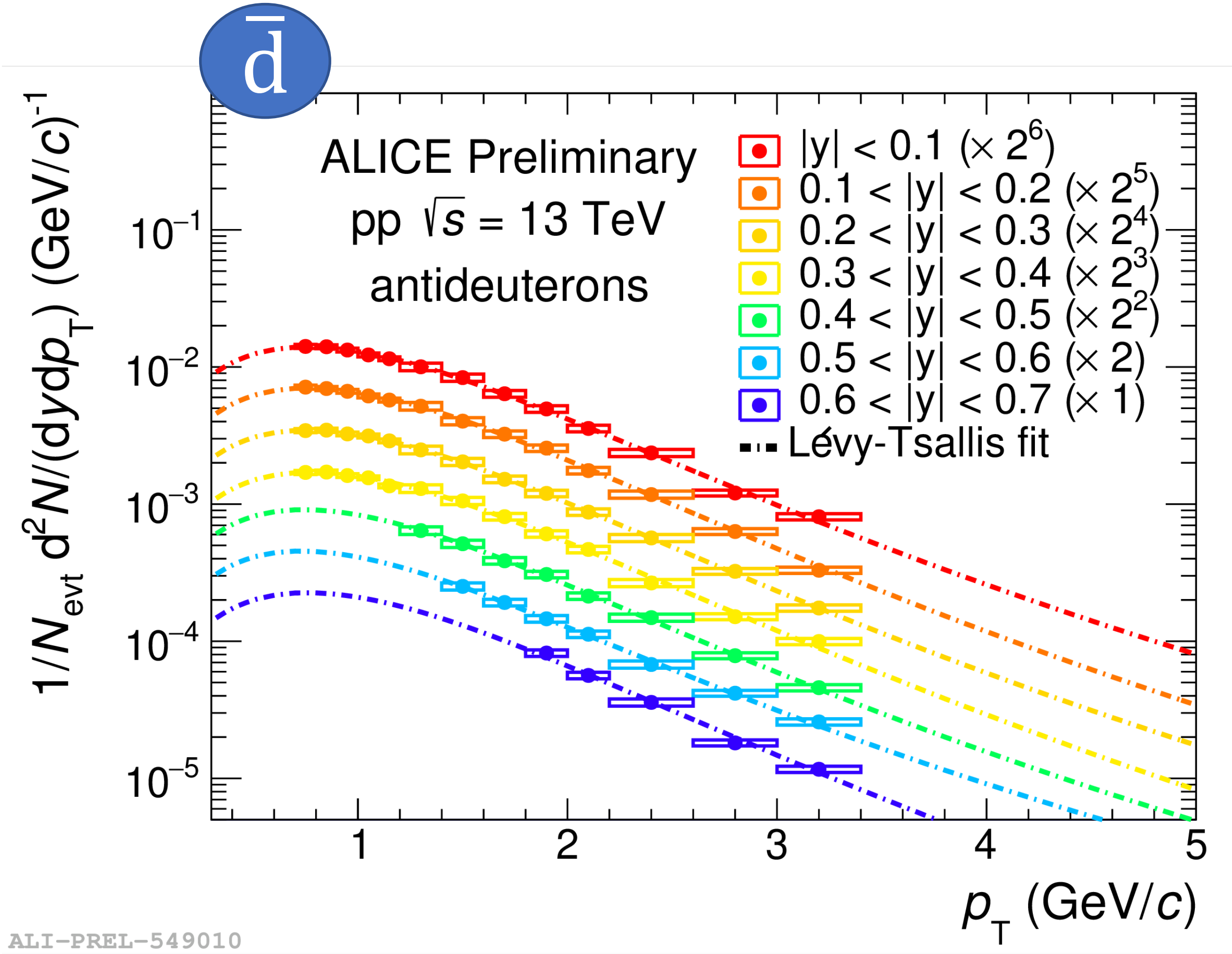
2. PYTHIA 8 + simple coalescence

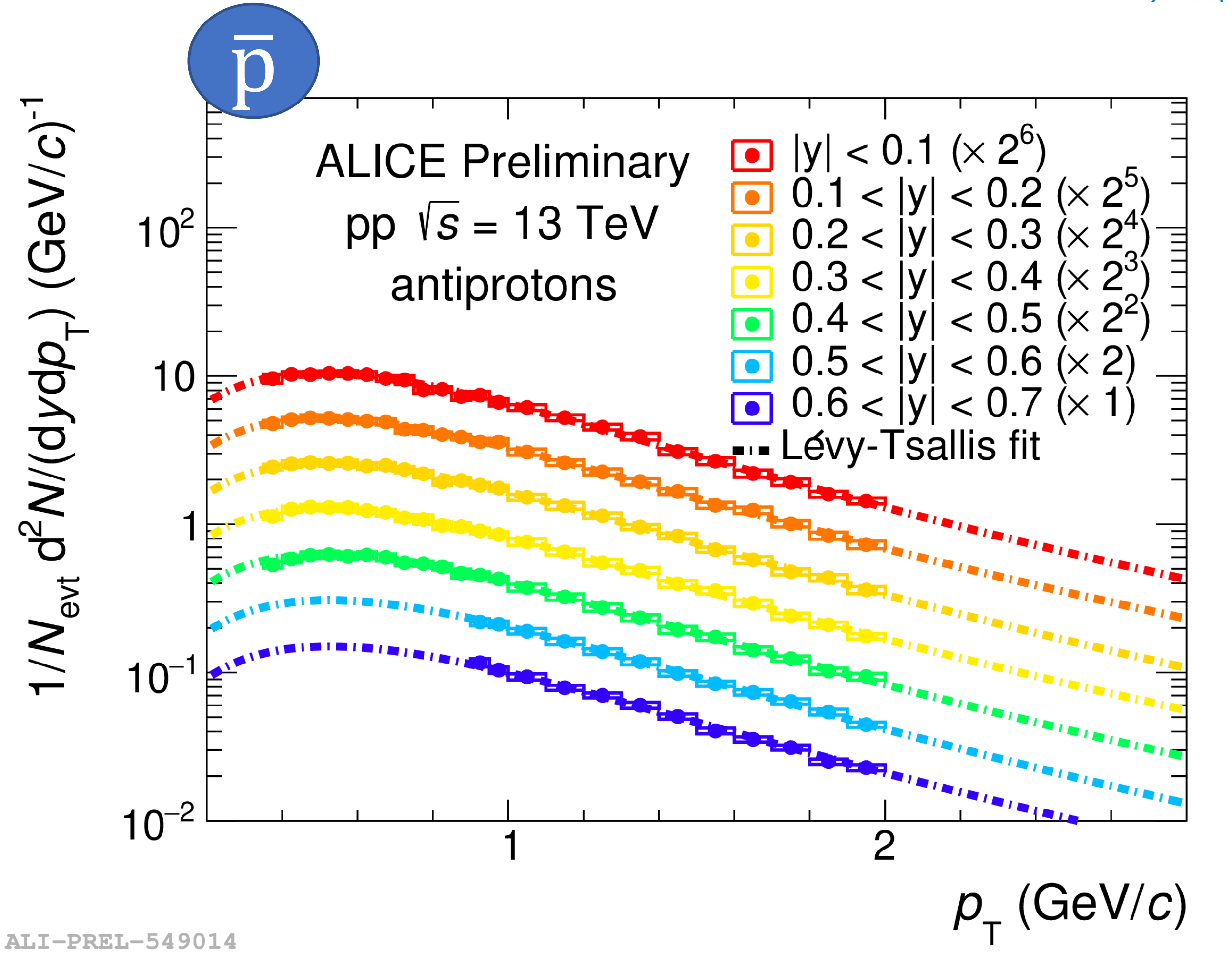
- $\Delta p < p_0$

Skands et al., EPJC 74 (2014) 8, 3024



Spectra as a function of rapidity

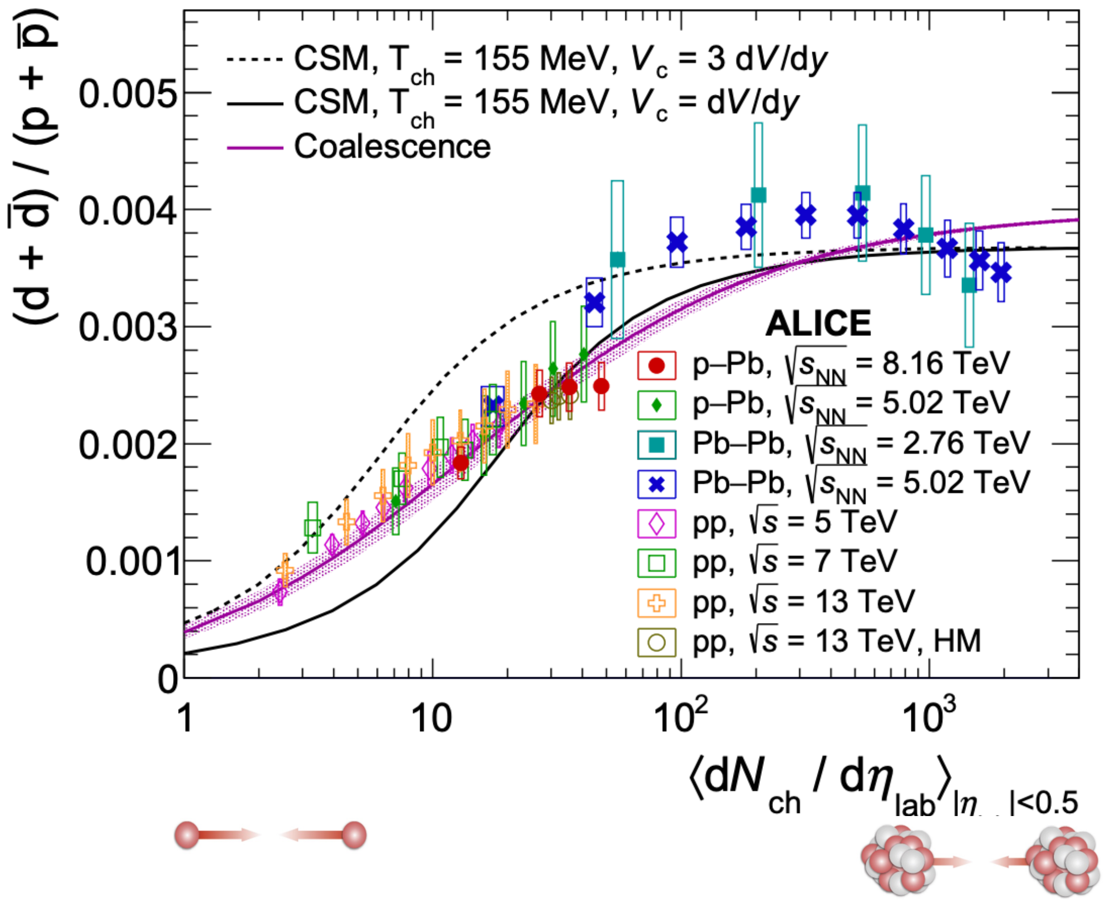


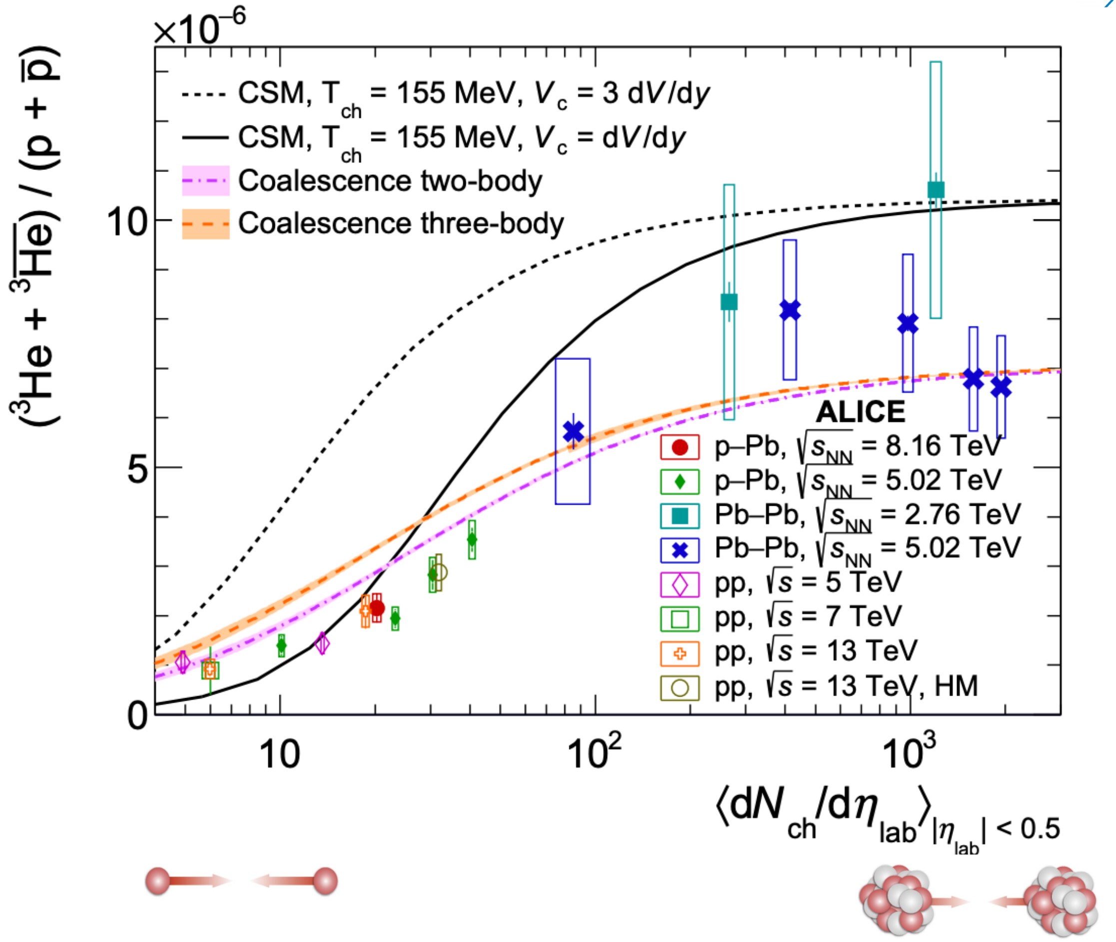


- Current acceptance of ALICE detector allows to extend the measurement of antinuclei up to $y = 0.7$
- All rapidity classes show a common trend with y, for both species (ratio to $|y| < 0.1$ is ~1)

New!

Production of (anti)nuclei



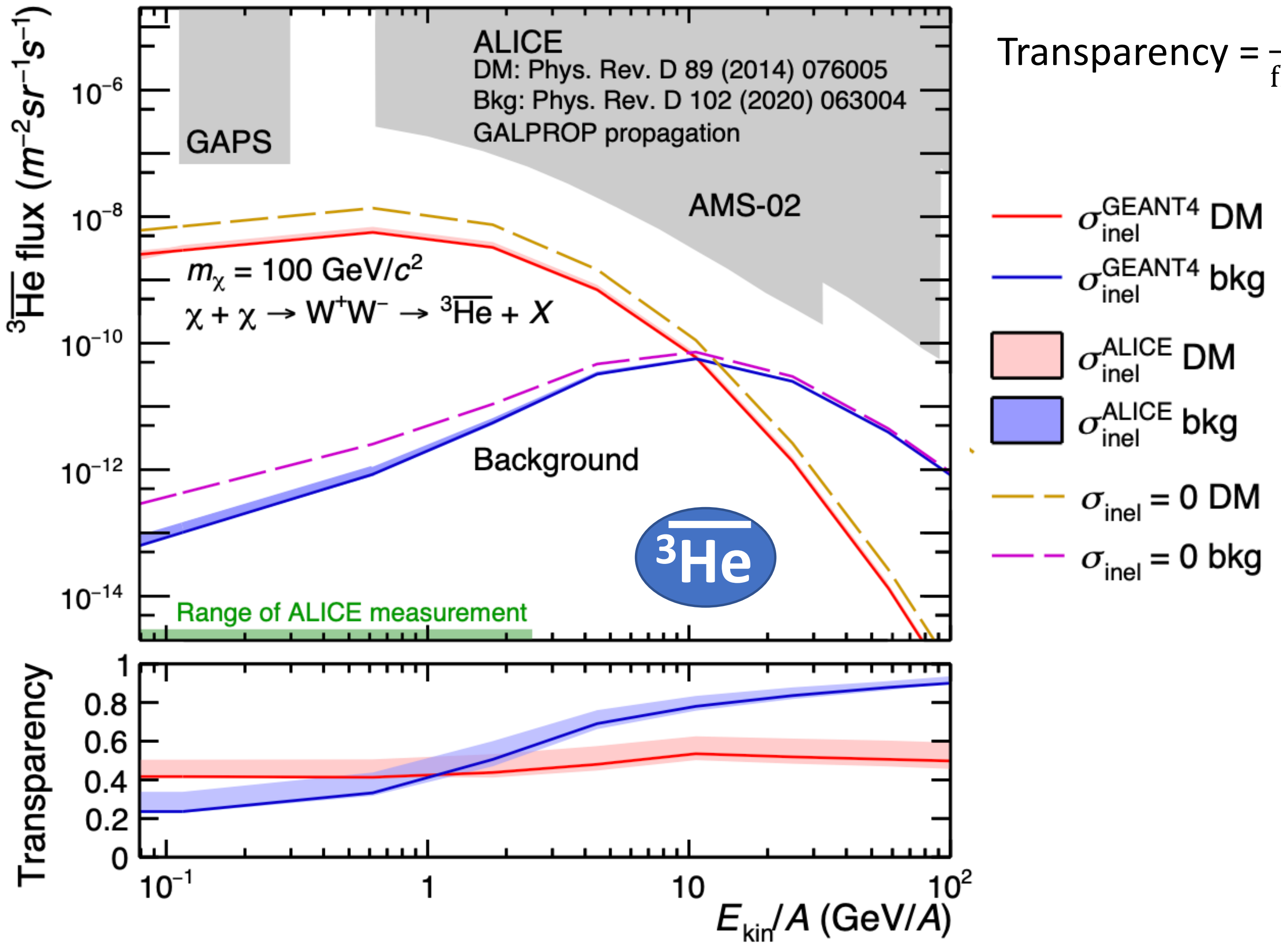


- Production of (anti)nuclei has been extensively measured by ALICE
- Coalescence model describes well the data for A = 2, 3
- ALICE measurements cover the midrapidity region (|y|<0.5), while astrophysical models extrapolate to forward region

arxiv:2212.04777

Transparency of Galaxy to anti^{3}He

Solar modulated flux



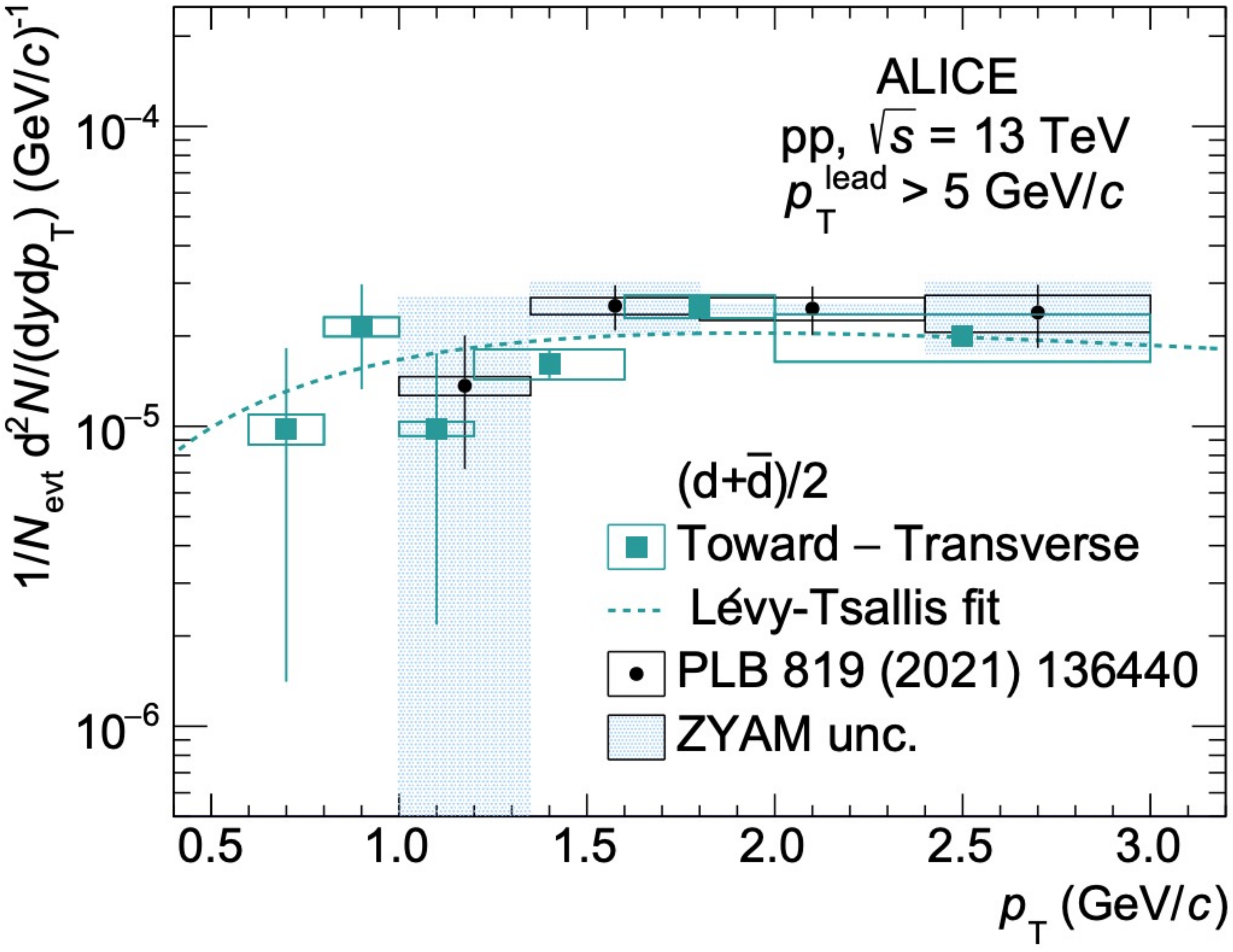
Transparency = $\frac{\text{flux with annihilation}}{\text{flux without annihilation}}$ = (——) for bkg (DM)

Fluxes are model dependent

- **Our Galaxy is rather constantly transparent to ^{3}He passage**
- Data are in good agreement with Geant4 predictions
- Uncertainties on Transparency only due to absorption measurements (10-20%)

anti^{3}He: Nature Phys. (2023) 19, 61–71

Jet-like transverse momentum distribution



- Jet-like spectrum can be obtained by subtracting the UE from the Toward region (Jet + UE)
- Results consistent with the the two-particle correlation method [PLB 819 (2021) 136440]
- Jet: ∼10% of production in UE

Jet = Toward – Transverse