(Anti)(hyper)nuclei production in small collision systems measured with ALICE

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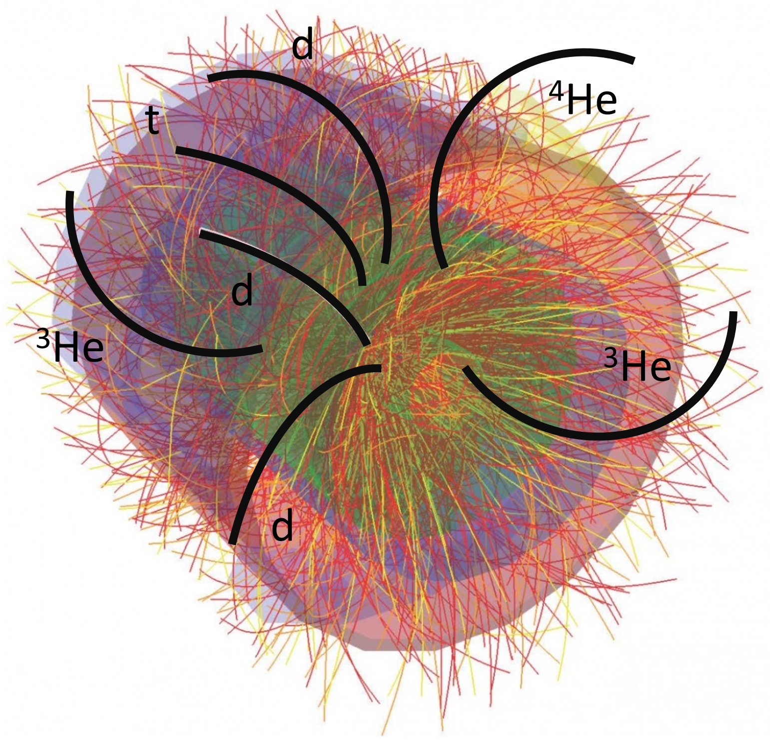
FAIRness, Paralia (Greece) – 27 May 2022

(Anti)(hyper)nuclei production



- At LHC energies same amount of matter and anti-matter is expected ($\mu_B \sim 0$)
- (Anti)(hyper)nuclei measurement studies are crucial
  - *microscopic production mechanism*
  - input in the indirect dark matter searches
- Production mechanism still under debate

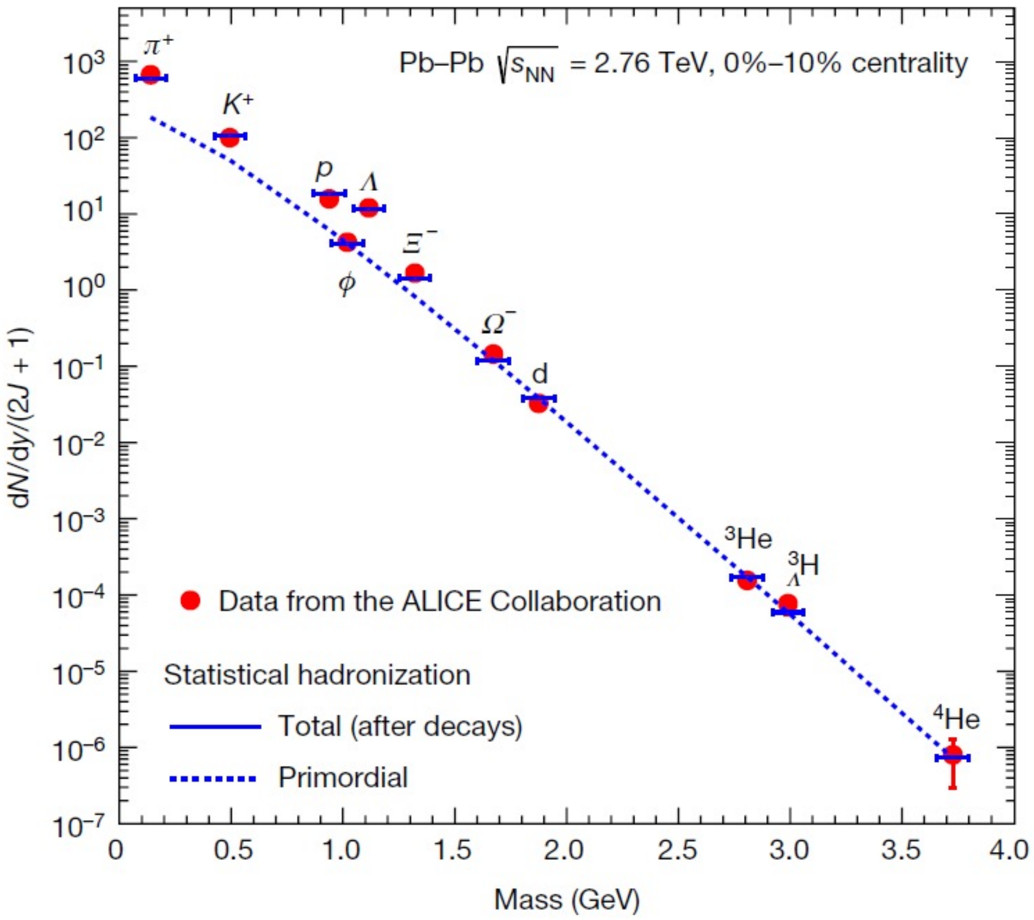
  → Two classes of phenomenological models:
    - **statistical hadronization**
    - **coalescence**
- Focus on small collision systems:
  - Deuteron (minimum bias & underlying event)
  - Hypertriton

Statistical models

- Hadrons emitted from a system in statistical and chemical equilibrium
- $dN/dy \propto \exp(-m/T_{chem})$

  $\Rightarrow$ Nuclei (large m): large sensitivity to T_{chem}
- Light nuclei are produced during phase transition (as other hadrons)
- Typical binding energy of nuclei ~ few MeV (E_B ~ *2 MeV for d*)

  $\Rightarrow$ how can they survive the hadronic phase environment (T_{chem} ~ 153 MeV)?

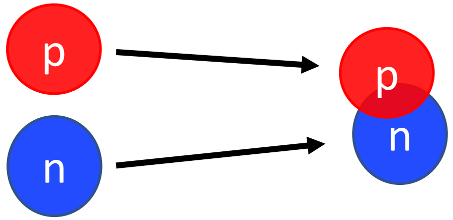


→ In Pb–Pb collisions, particle yields of light-flavour hadrons are described over 9 orders of magnitude with a **common** chemical freeze-out temperature of T_{chem} ≈ **153 MeV**.

Andronic et al., Nature vol. 561, 321–330 (2018)

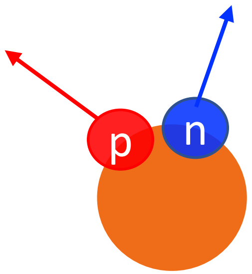
Coalescence models

S. T. Butler et al., Phys. Rev. 129 (1963) 836



- If (anti)nucleons are close in phase space ($\Delta \boldsymbol{p} < \boldsymbol{p}_0$) and match the spin state, they can form a (anti)nucleus
- Coalescence parameter B_A is the key parameter

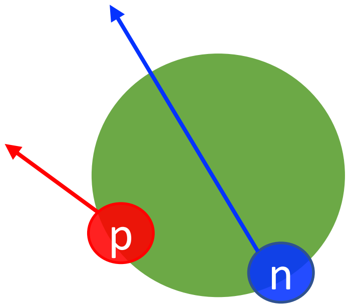
$$B_A(p_\mathrm{T}^p) = E_A \frac{\mathrm{d}^3 N_A}{\mathrm{d}\, p_A^3} \Big/ \left(E_p \frac{\mathrm{d}^3 N_p}{\mathrm{d}\, p_p^3} \right)^A \Bigg|_{p_\mathrm{T}^p = p_\mathrm{T}^A / A}$$



- Experimental parameter tightly connected to the coalescence probability

Larger B_A ⟺ Larger coalescence probability

- Coalescence probability depends on the system size



Small distance in space	Large distance in space
(Only momentum correlations matter)	(Both momentum and space correlations matter)
⟺ large B_A	⟺ small B_A

- More sophisticated coalescence models are available, with quantum mechanical properties considered

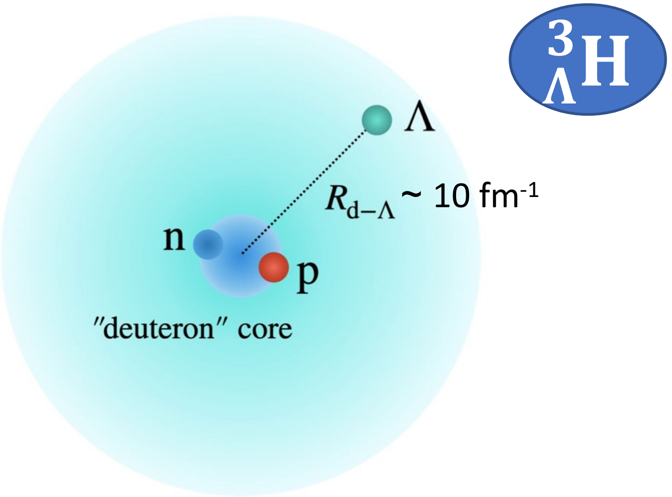
Small collision systems

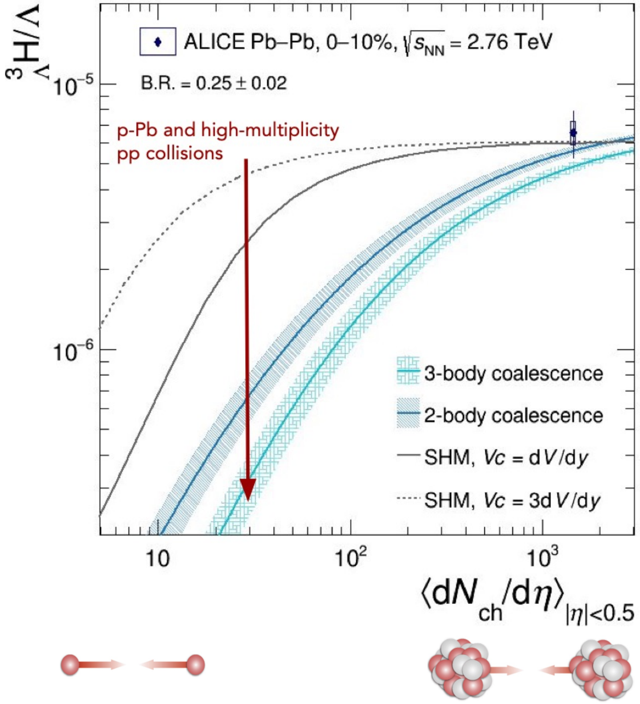
Small collision systems as pp are particularly interesting:

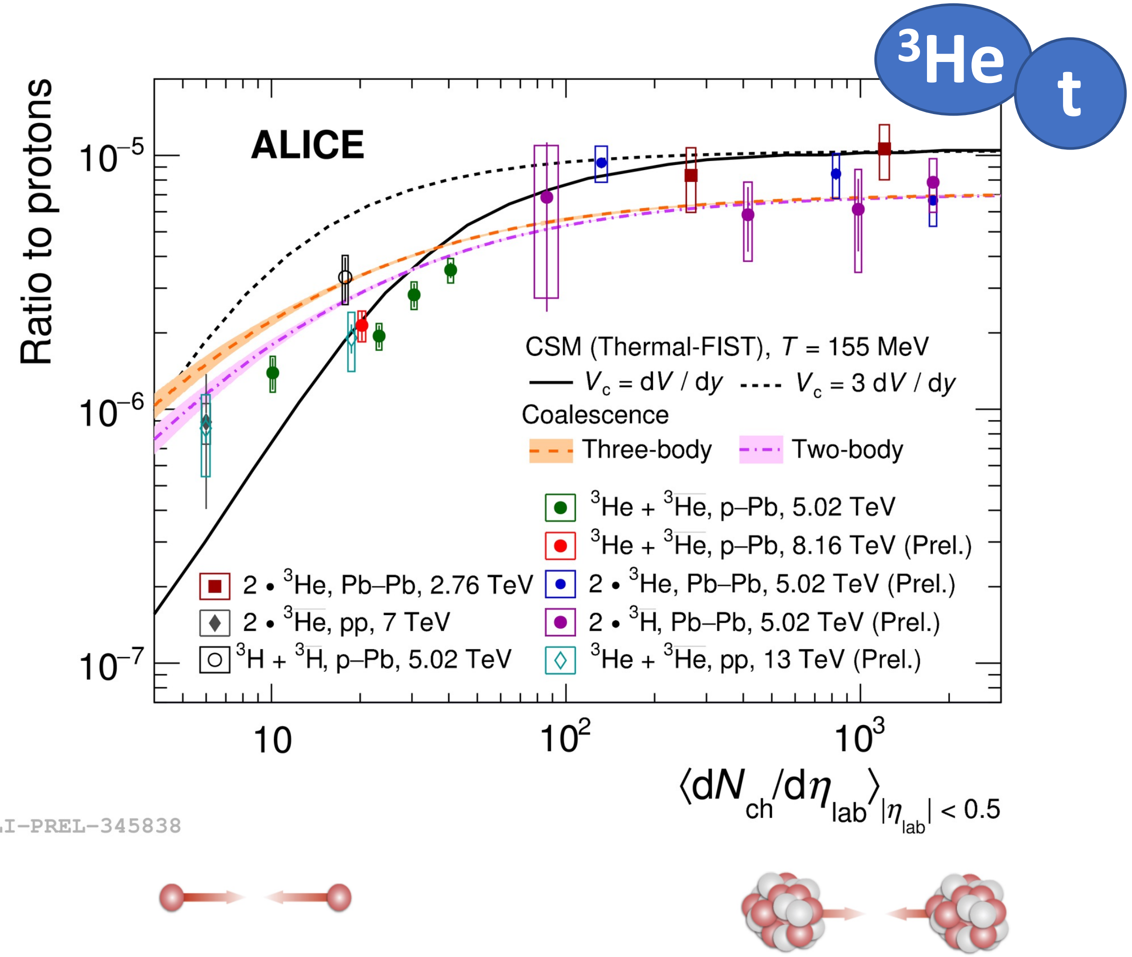
→ system created in the collision has a size smaller or equal to that of the nucleus

→ allows for the study of coalescence since nucleons are created close to each other

→ for small systems model predictions are quite different





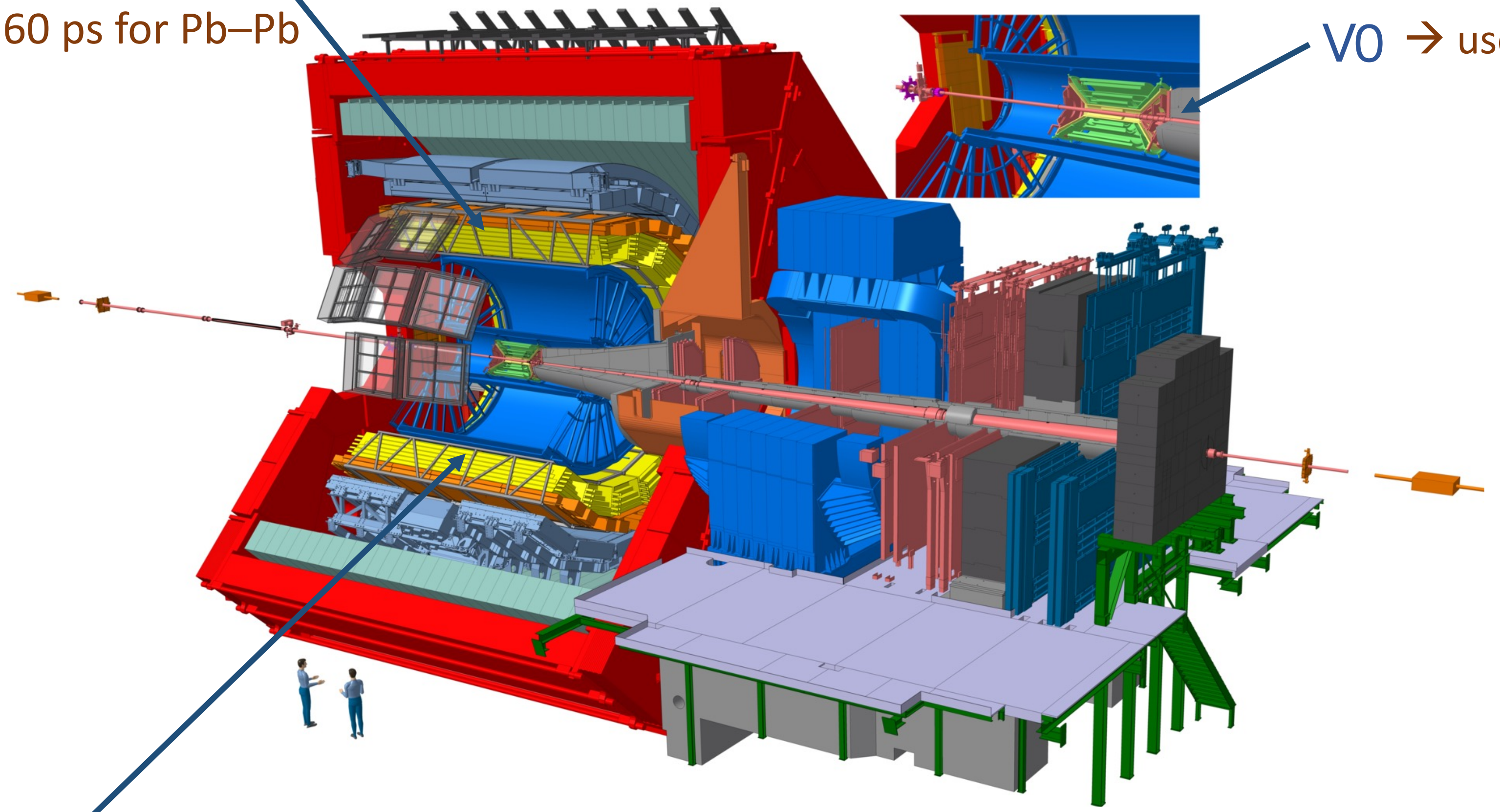


The ALICE detector

Time Of Flight

$\sigma_{PID} \sim$ 70 ps for pp

$\sigma_{PID} \sim$ 60 ps for Pb–Pb



V0 → used as trigger and as multiplicity estimators:

Minimum Bias → 0 – 100%

High Multiplicity → 0 – 0.1%

- pp, p—Pb, Pb—Pb collisions at various centre-of-mass energies
- excellent tracking and PID capabilities over a broad momentum range
- low material budget

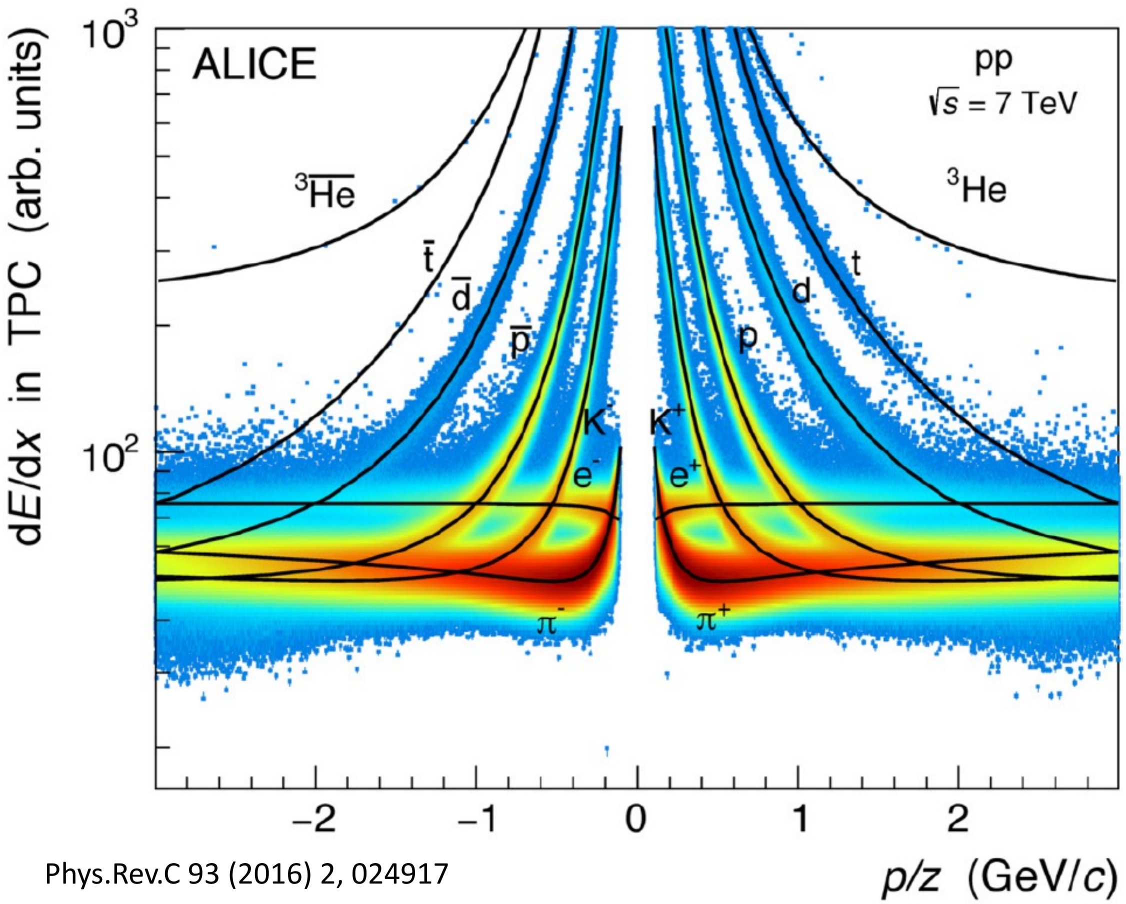
→ Most suited detector at the LHC for the study of (anti)(hyper)nuclei produced in high energy collisions

Time Projection Chamber → $\sigma_{dE/dx} \sim$ 5.5% for pp

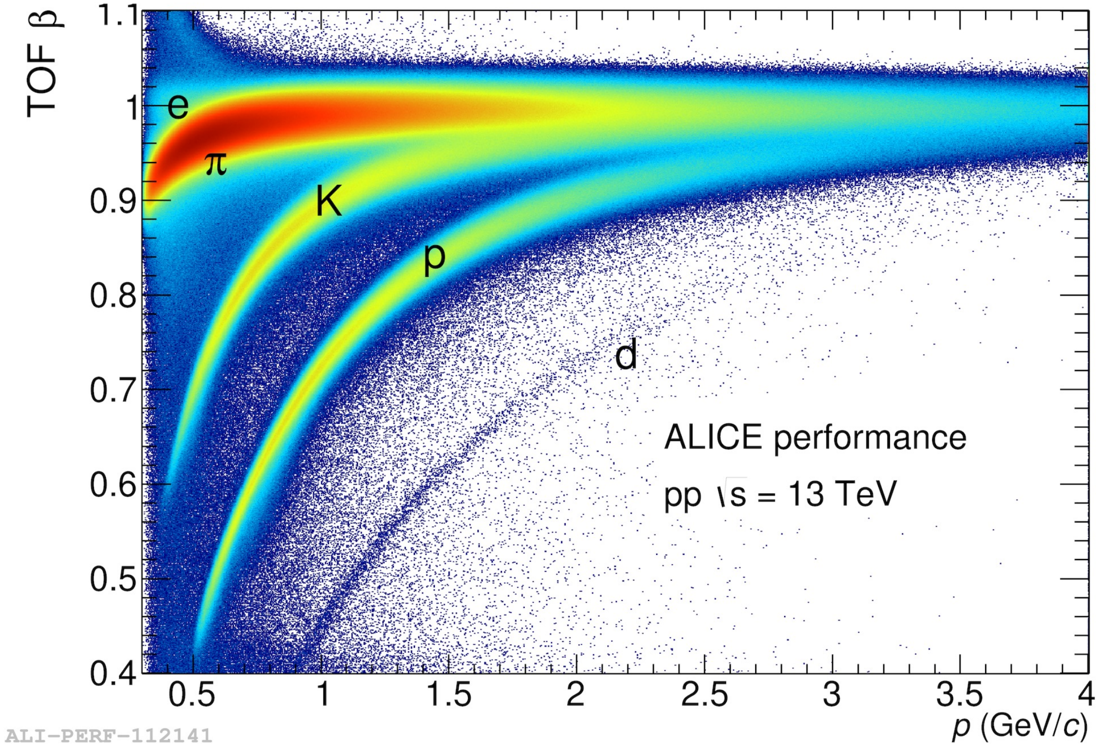
$\sigma_{dE/dx} \sim$ 7% for Pb—Pb

Nuclei identification

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



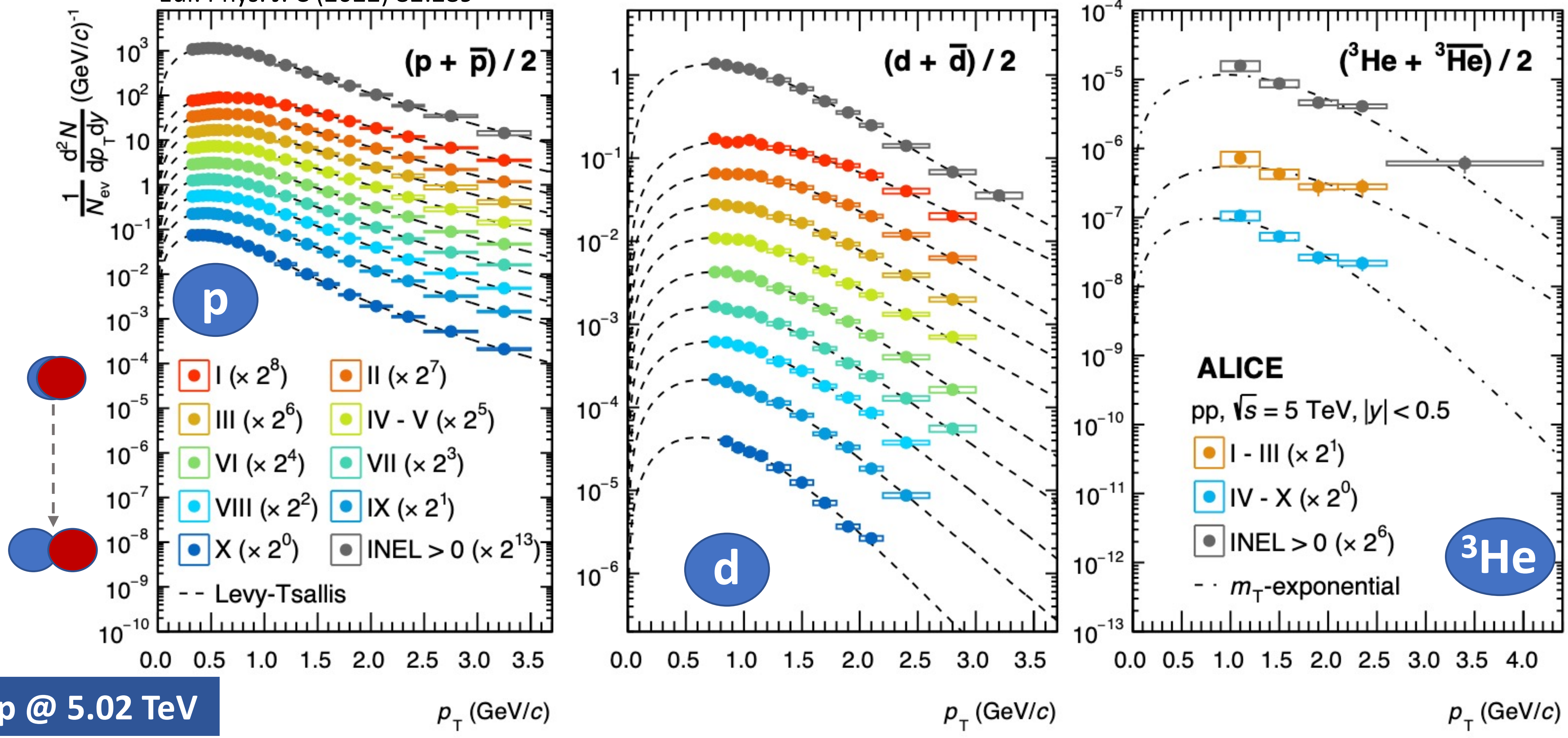
Phys.Rev.C 93 (2016) 2, 024917



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

Light (anti)nuclei in small systems (I)

Eur. Phys. J. C (2022) 82:289

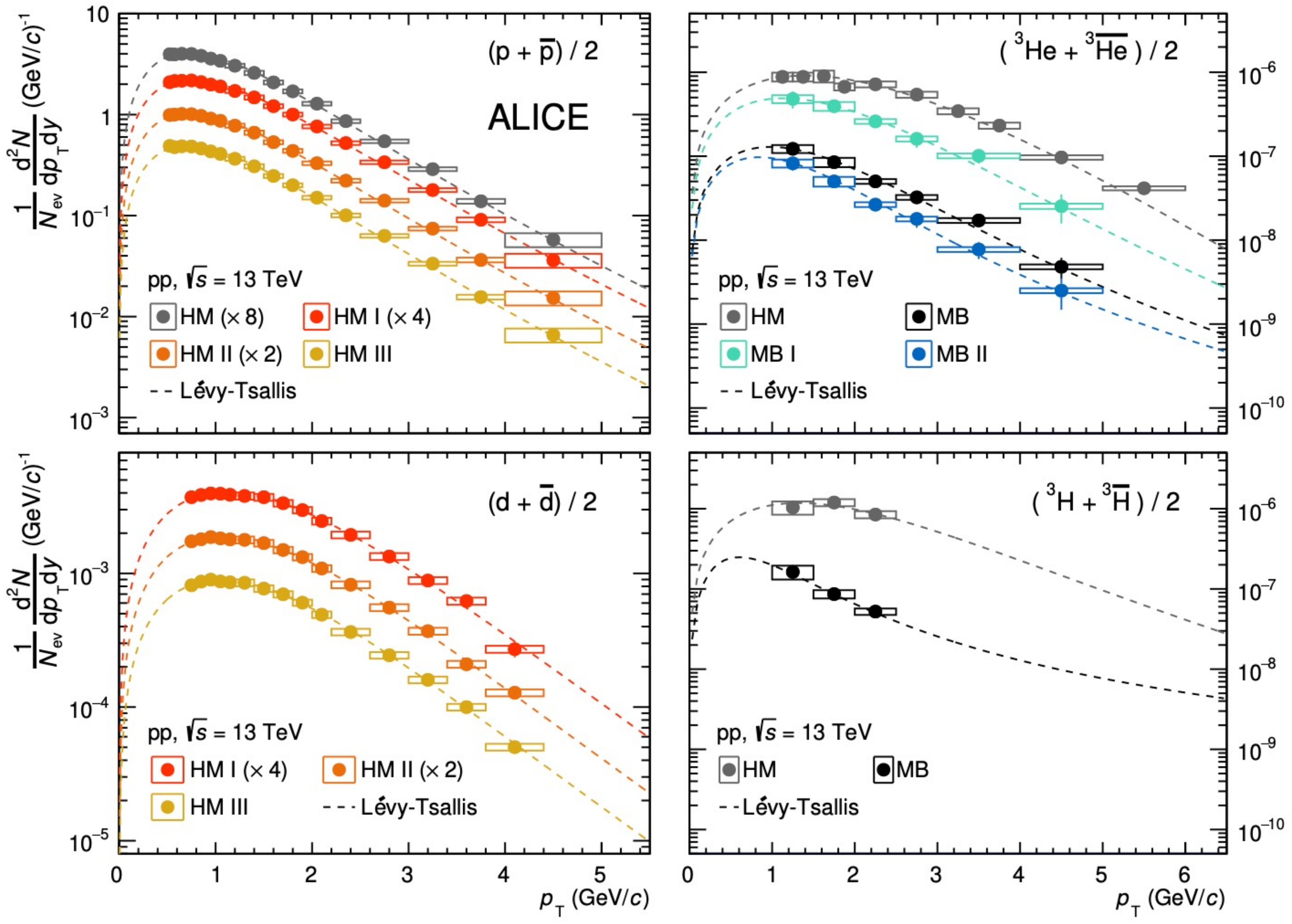


pp @ 5.02 TeV

p_T spectra fitted with Lévy-Tsallis / m_T-exponential function ⇒ extrapolation to unmeasured regions

Light (anti)nuclei in small systems (II)

JHEP 01 (2022) 106

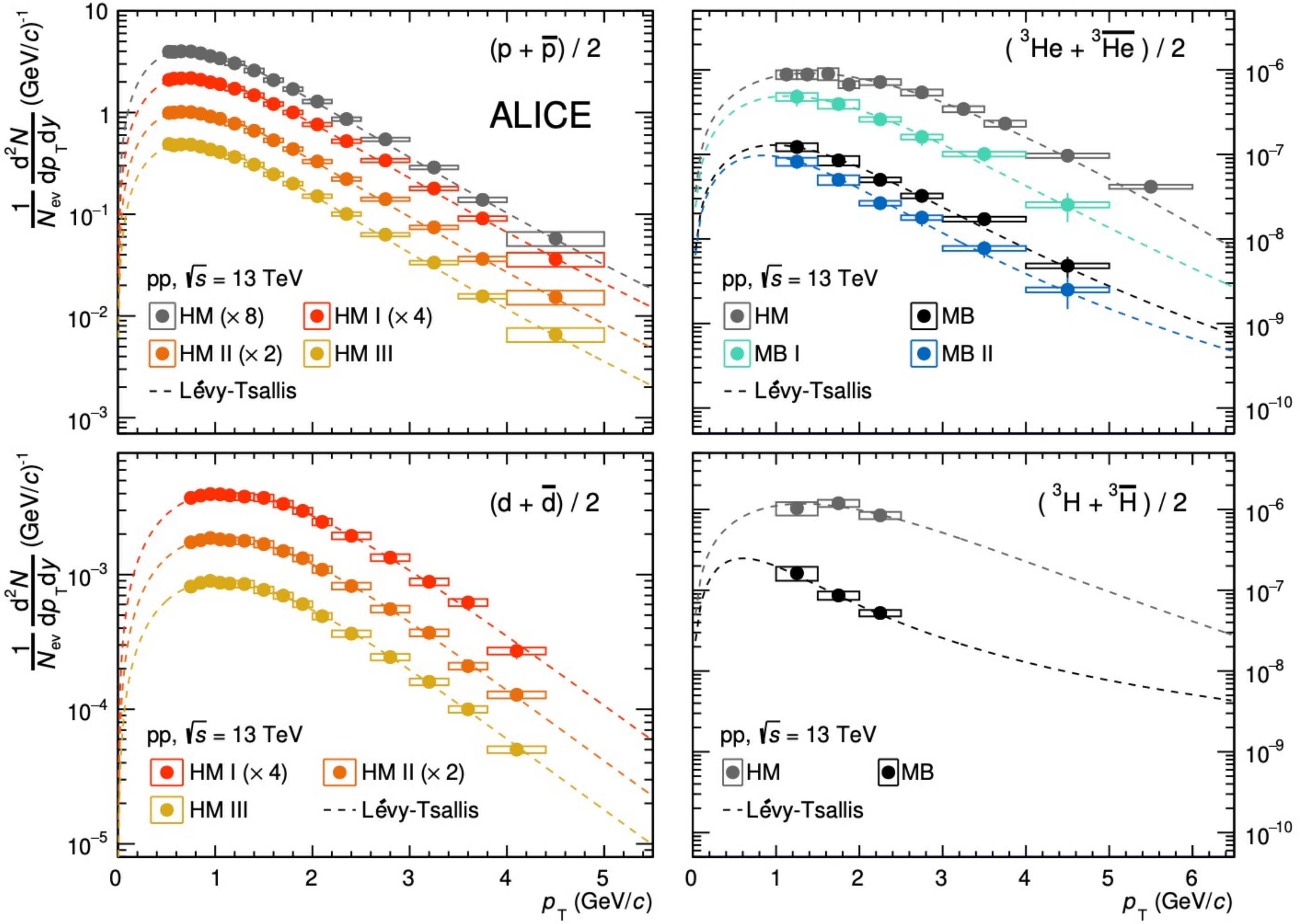


HM pp @ 13 TeV

- Focus on the HM data sample → narrow multiplicity interval covered

Light (anti)nuclei in small systems (II)

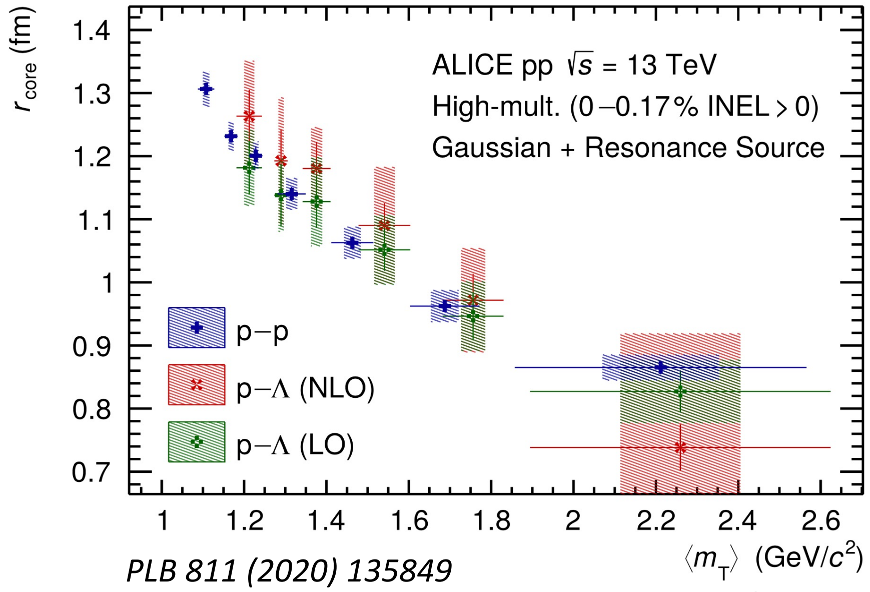
JHEP 01 (2022) 106



HM pp @ 13 TeV

- Focus on the HM data sample → narrow multiplicity interval covered
- Precise measurement of the emission source size r_{core} using femtoscopy is available

→ **crucial to test the coalescence model**



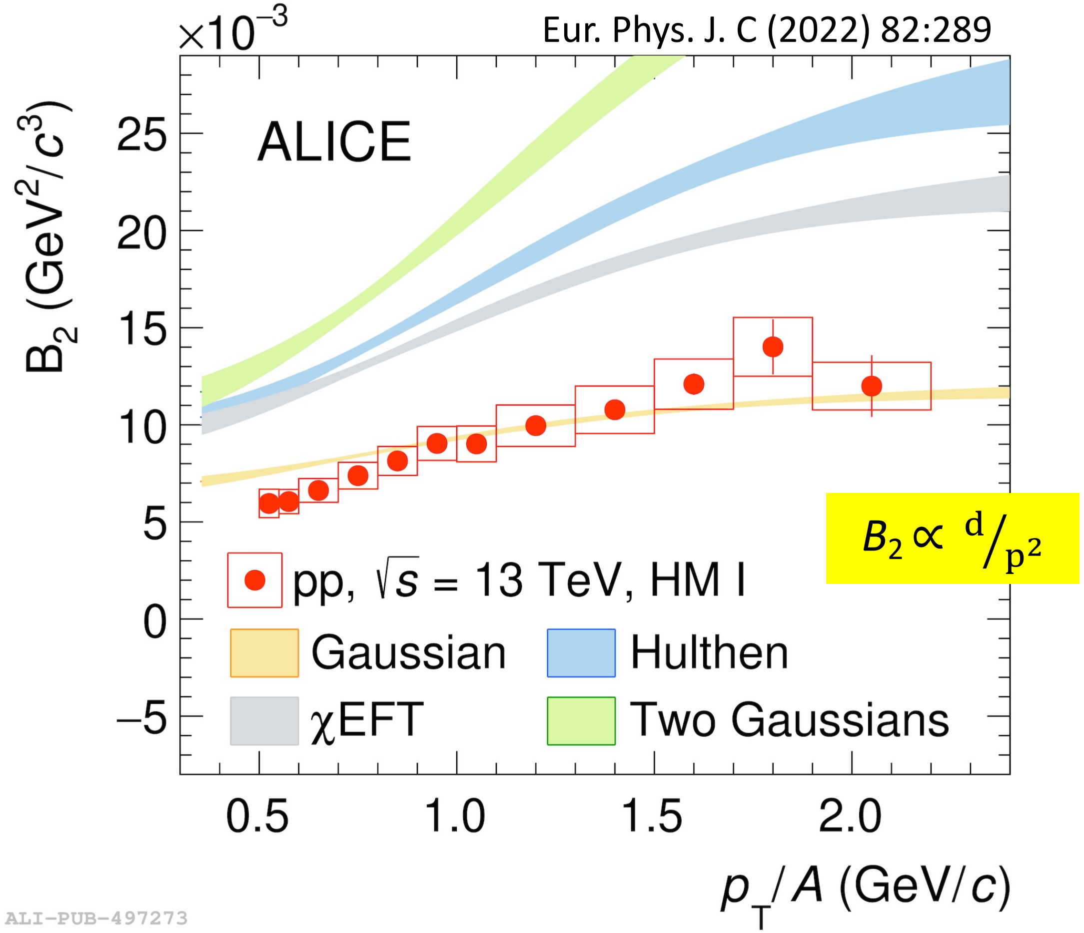
PLB 811 (2020) 135849

$\propto p_T$

Testing coalescence model

- B_A measurements sensitive to the nuclear wave function
  - HM data sample also used for the precise measurement of the source radii (*PLB 811 (2020) 135849*)

HM pp @ 13 TeV



emission source size

$$B_2(p_T) \approx \frac{3}{2m} \int d^3q D(q) e^{-R_{p_T}^2 q^2}$$

$$D(q) = \int d^3r |\phi_d(r)|^2 e^{-iq\cdot r}$$

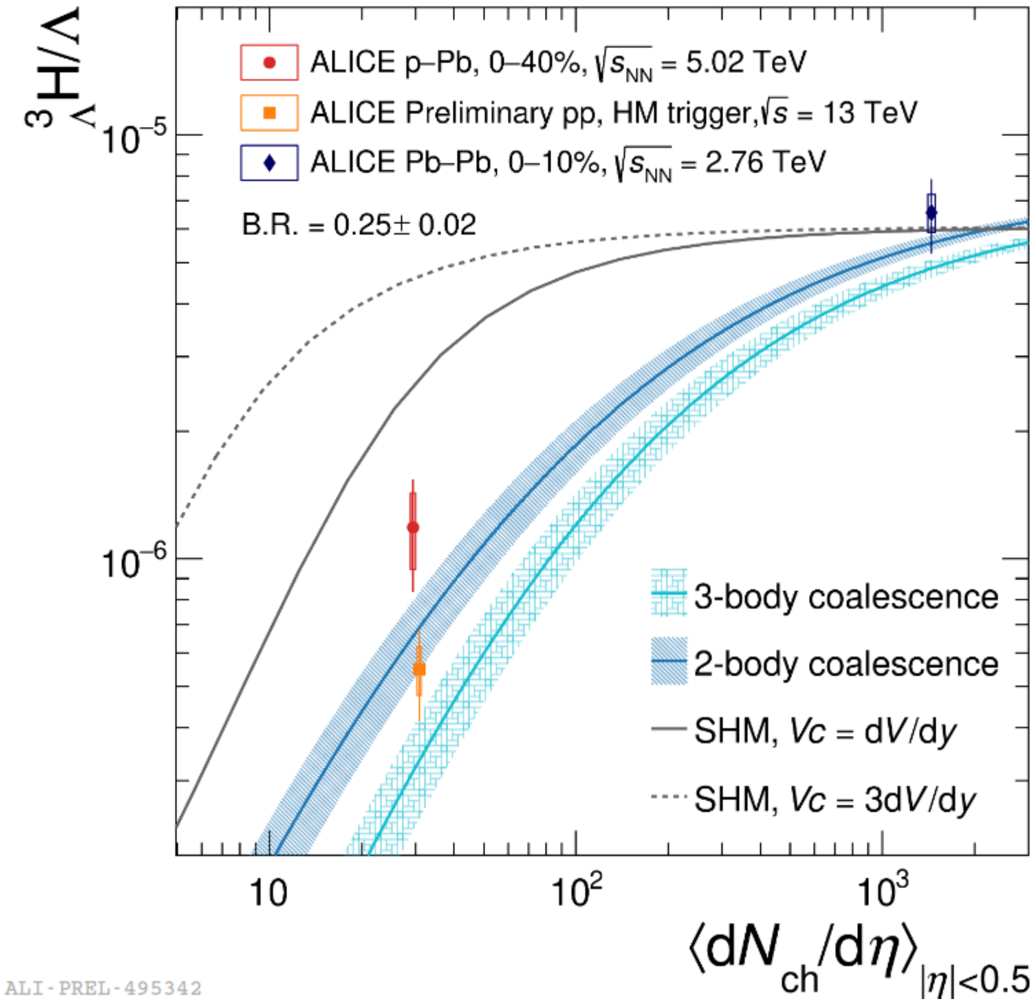
deuteron wave function (*size d = 3.2* fm)

Blum, Takimoto PRC 99 (2019) 044913

Different wave functions are tested:

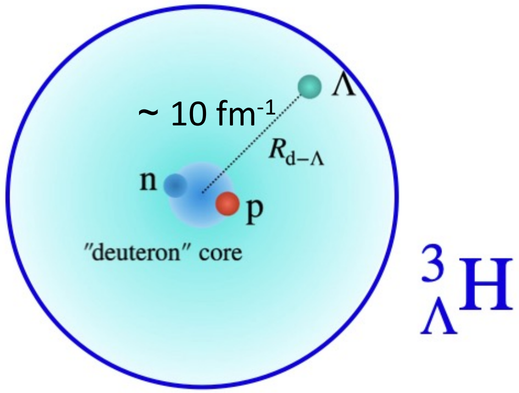
- **Hulthen** [Scheibl, Heinz, Phys. Rev. C 59, 1585-1602 (1999)]: favoured by low-energy scattering experiments
- **Gaussian** [Kachelrieß et al., Eur. Phys. J. A 1, 4 (2020)]: best description of currently available ALICE data

Hypertriton production



p—Pb: https://arxiv.org/abs/2107.10627
Pb—Pb: Phys. Lett. B 754 (2016) 360-372

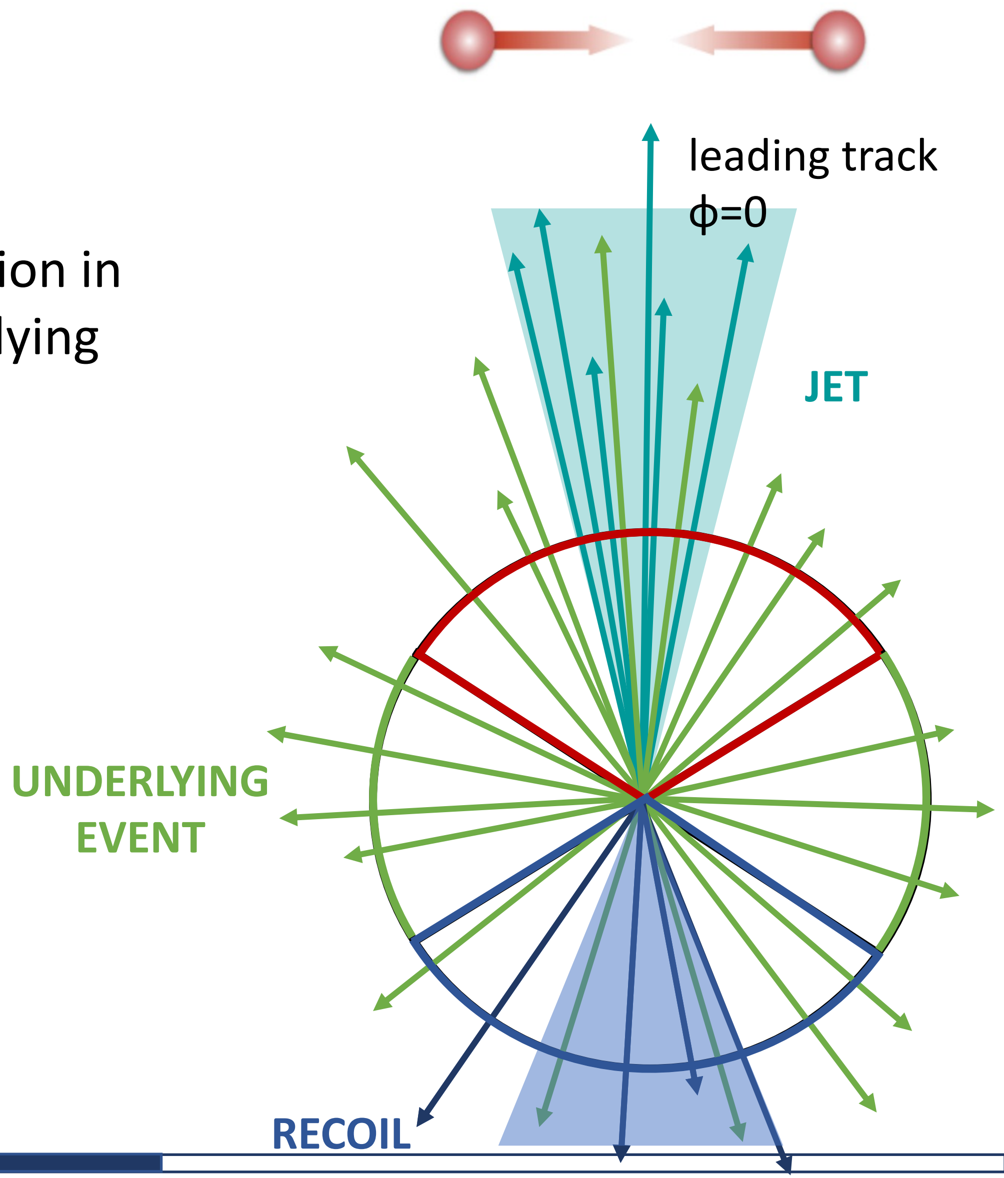
$^{3}_{\Lambda}$H/Λ ratio provides a powerful tool to investigate nuclear production mechanism



- **Pb—Pb collisions:**
  - small difference between the predictions from SHM and coalescence
- **pp and p—Pb collisions:**
  - large separation between production models
  - **measurements are in good agreement with 2-body coalescence**
  - tension with SHM at low charged-particle multiplicity density
    → configuration with V_C = 3dV/dy is excluded by more than 6σ

Underlying event activity

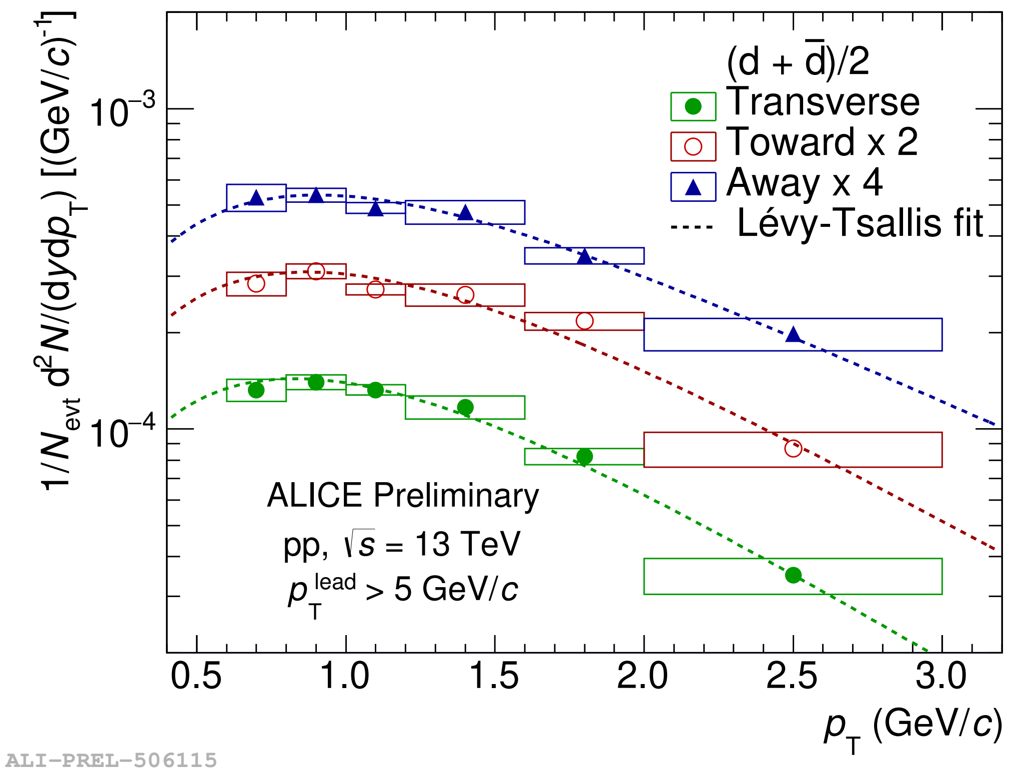
- Production in small collision systems is also explored using the underlying event (UE) activity
- Coalescence mechanism can be tested comparing the production in jets, where nucleons are already closer, with that in the underlying event
- Highest p_T particle (p_T^{lead} > 5 GeV/c) used as jet proxy
- 3 regions in the event plane wrt leading track:
  - Toward: $|\Delta\phi| < 60°$
  - Transverse: $60° < |\Delta\phi| < 120°$
  - Away: $|\Delta\phi| > 120°$

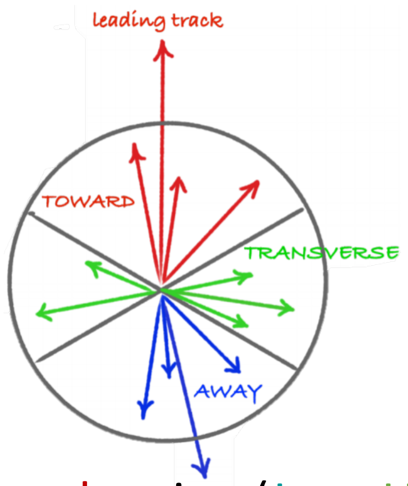


T. Martin et al., Eur. Phys. J. C (2016) 76: 299

Deuteron spectra vs azimuthal regions

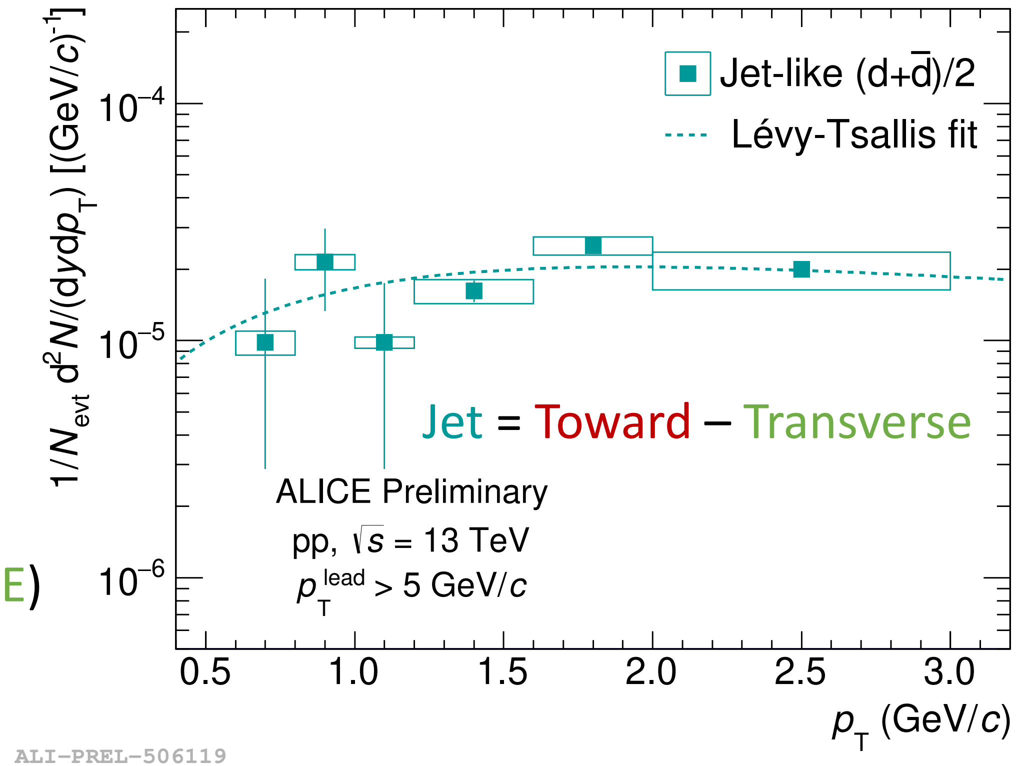
pp @ 13 TeV





Toward region (Jet + UE)

Transverse region (UE)

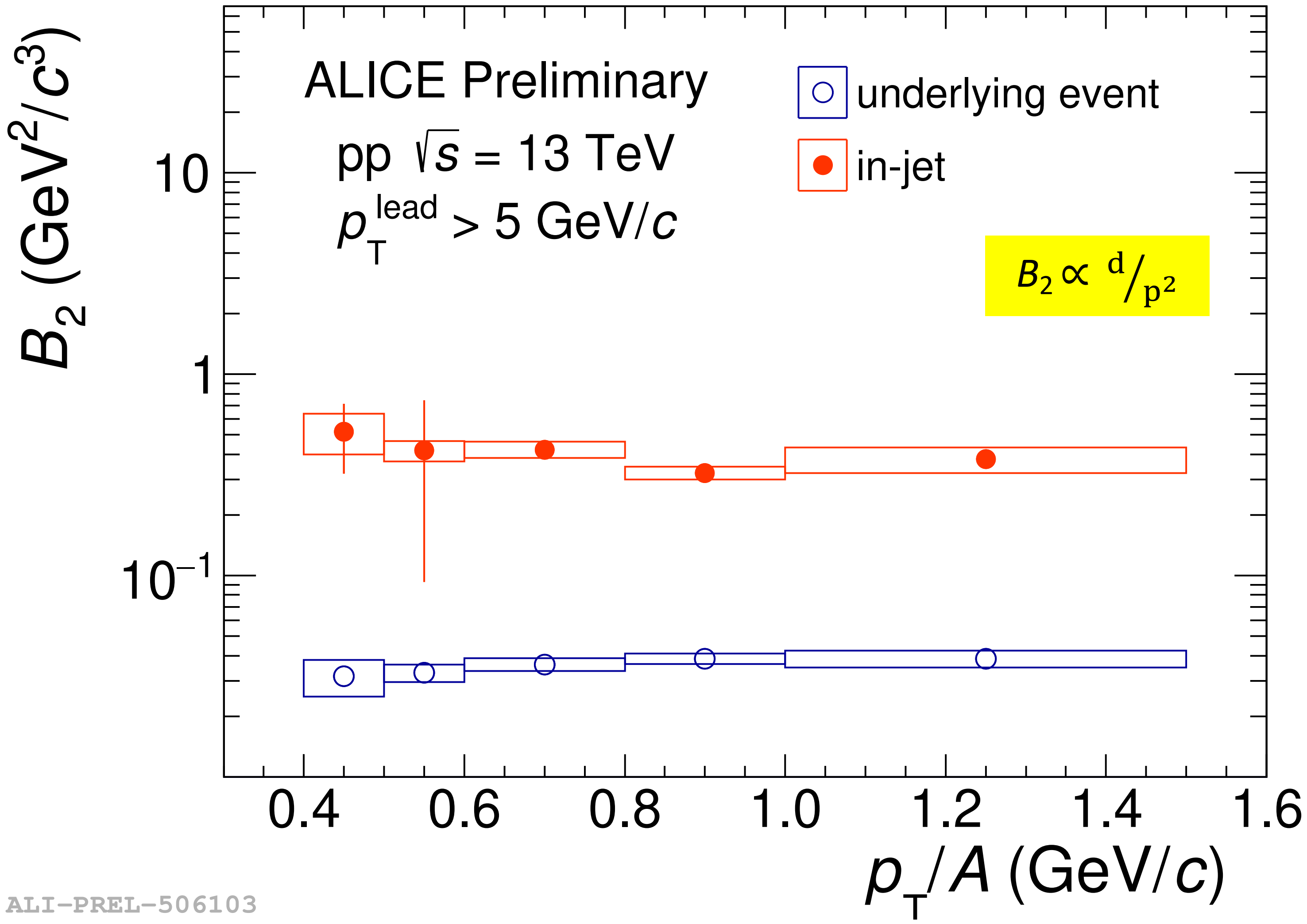


- Deuteron production from hard processes: $p_T^{lead} > 5$ GeV/c
- Jet: ~10% of total production

- Jet results consistent with the previous results based on two-particle correlation method [Phys.Lett.B 819 (2021) 136440]

➢ The majority of deuterons are produced in the underlying event

B_2 in and out of jets



- B_2 parameter flat vs p_T/A → in agreement with simple coalescence
- B_2 in-jet ~ 15 times larger than B_2 in UE

→ ***Enhanced deuteron coalescence probability in jets is observed for the first time!***

Comparison with 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:

Bierlich et al., arXiv:2203.11601 [hep-ph]

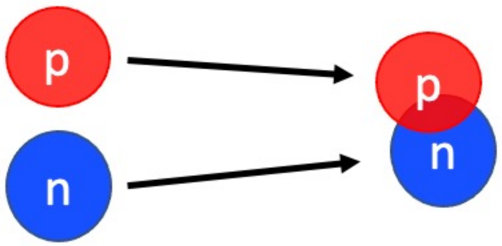
p+ n → γ + d
p+ n → π^0 + d
p+ n → $\pi^0 + \pi^0$ + d
p+ n → $\pi^+ + \pi^-$ + d

p+ p → π^+ + d
p+ p → $\pi^+ + \pi^0$ + d
n+ n → π^- + d
n+ n → $\pi^- + \pi^0$ + d

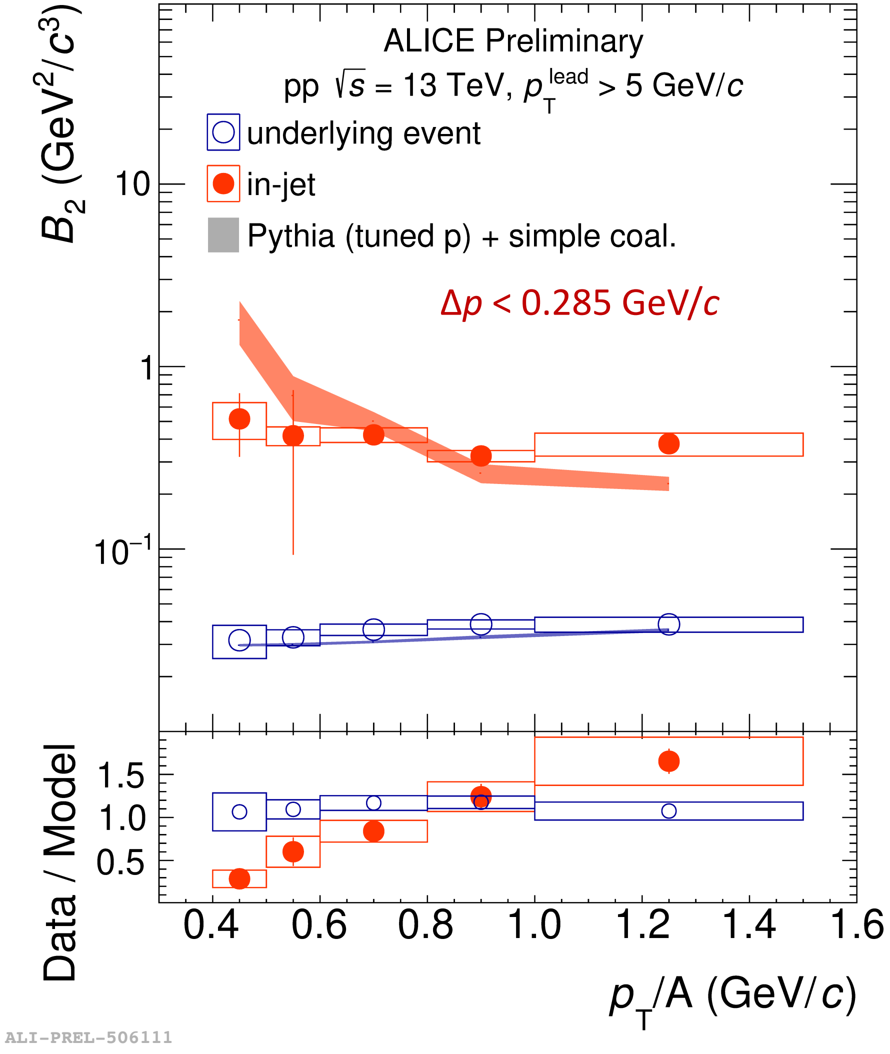
2. Pythia 8 + simple coalescence

- $\Delta p < p_0$

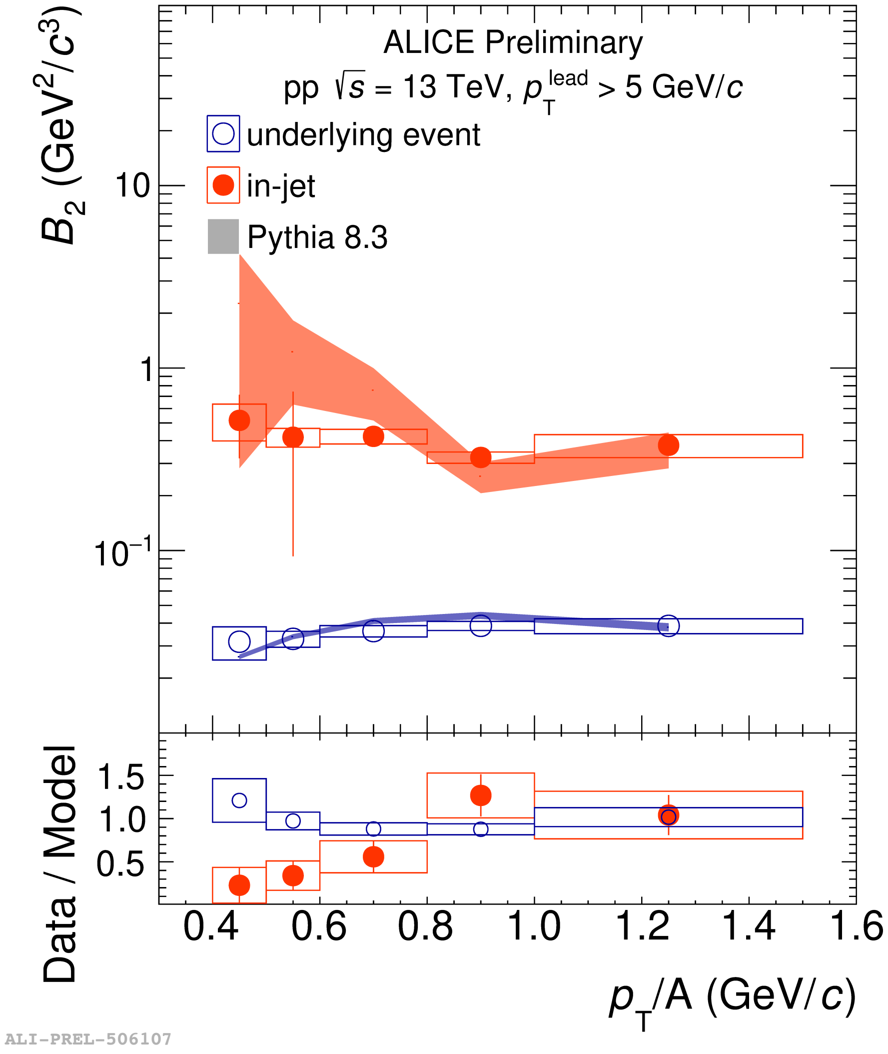
Skands et al., Eur.Phys.J.C 74 (2014) 8, 3024



Comparison with Pythia simulations



Pythia 8 + coalescence



Pythia 8.3

B_2 UE Pythia describes the trend of data

B_2 in-jet Pythia reproduces difference between UE and jet but shows a decreasing trend not observed in data

→ Further developments of models are needed

Summary

- **Small collision systems** (pp and p—Pb) are particularly interesting
  - ➢ tension between models at low charged-particle multiplicity densities can be explored

- $\boldsymbol{B_A}$**, d/p, ^{3}He/p and ^{3}H/p**
  - ➢ observed smooth trend with increasing multiplicity
  - ➢ no discrimination power on nuclei production mechanism

- $^{3}_{\Lambda}\mathrm{H}$ **production in small collision systems**
  - ➢ concrete possibility to distinguish with high significance between the two nucleosynthesis mechanisms: hint for coalescence

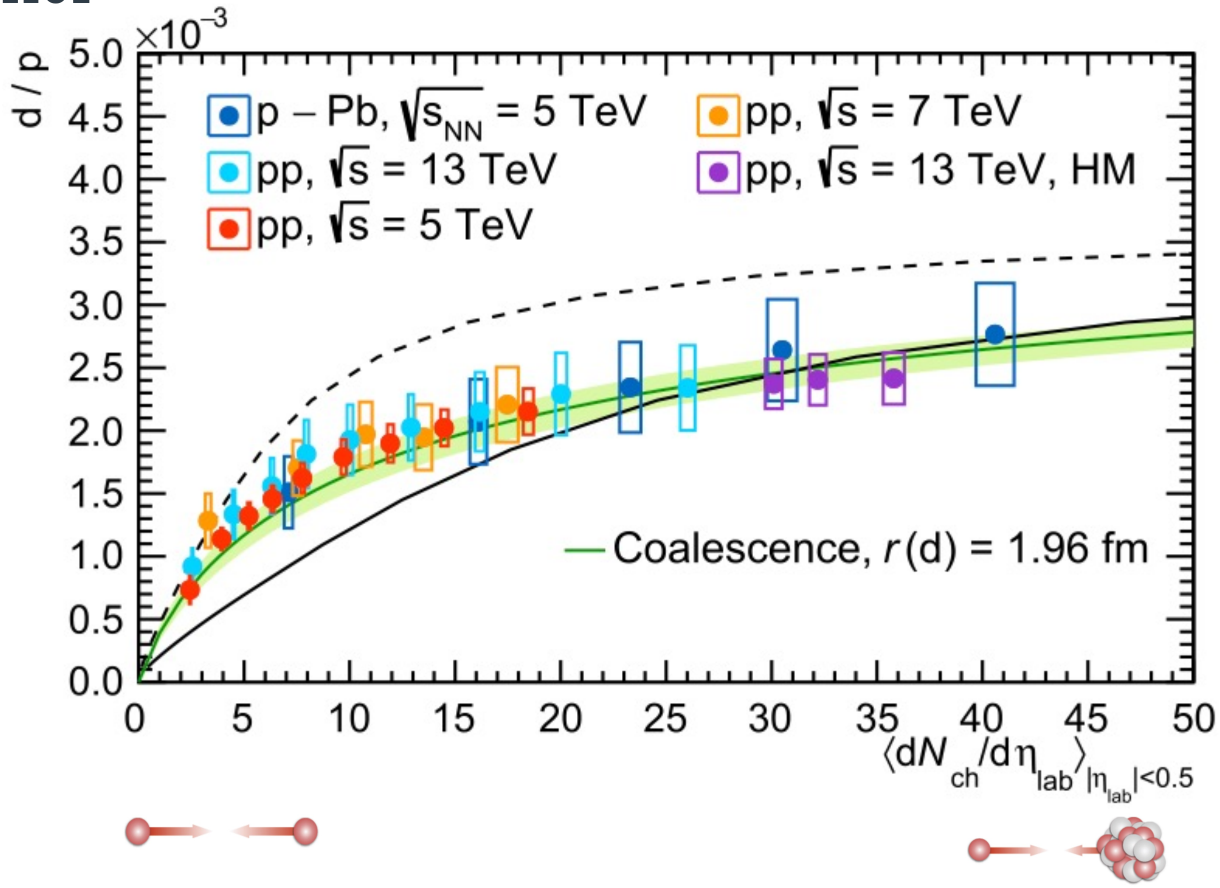
- $\boldsymbol{B_2}$ **in and out of jets**
  - ➢ enhanced coalescence probability in the jet wrt UE by one order of magnitude is observed
  - ➢ agreement with coalescence picture

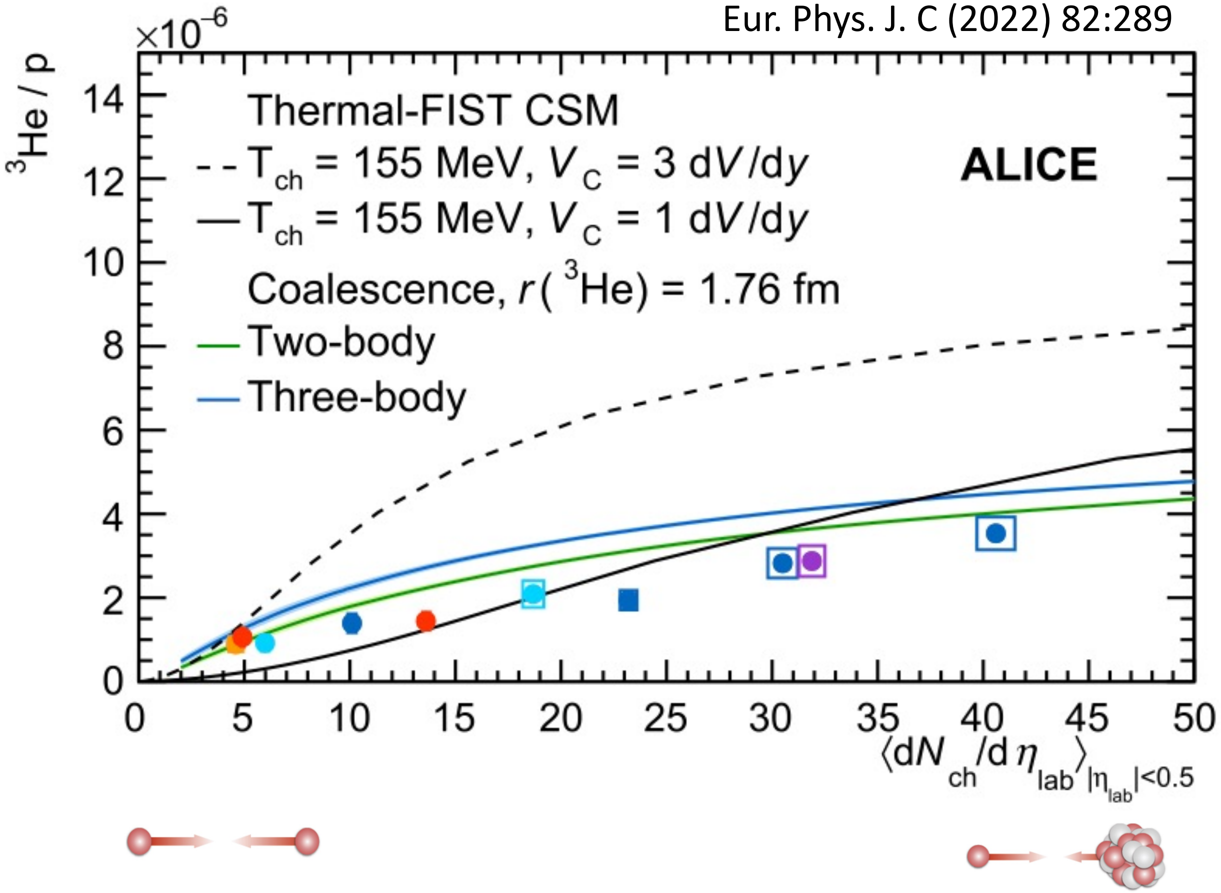
- Light (anti)(hyper)nuclei production mechanism still not completely clear
  - ➢ stay tuned for new results with the upcoming LHC Run 3!

Backup

Model comparisons in small systems

Eur. Phys. J. C (2022) 82:289

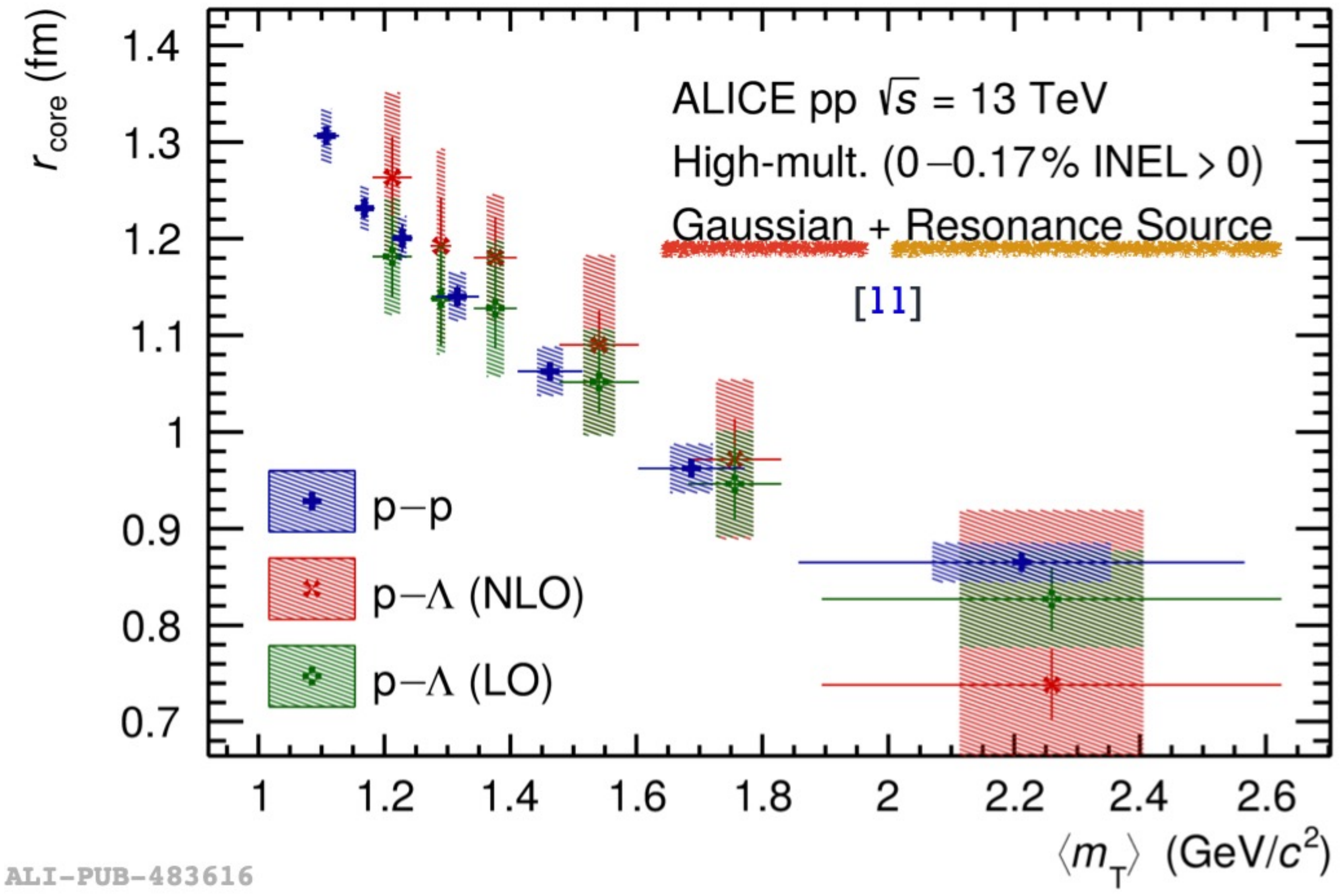




- Light nuclei production seems to depend only on multiplicity → smooth transition across different collision systems and energies
- Coalescence favored in d/p integrated yield ratios
- Results challenge the models for A=3 nuclei

Characterization of emission source

- If the interaction is well known, hadron-hadron correlation can be used to test the emission source
- Assumption: particle emission from a **gaussian core** source
- Short-lived strongly decaying **resonances** ($c\tau \lesssim 10$ fm) also taken into account: mainly Δ (Σ*) resonances for protons (Λ)
- Same m_T scaling obtained from both p-p and p-Λ correlations

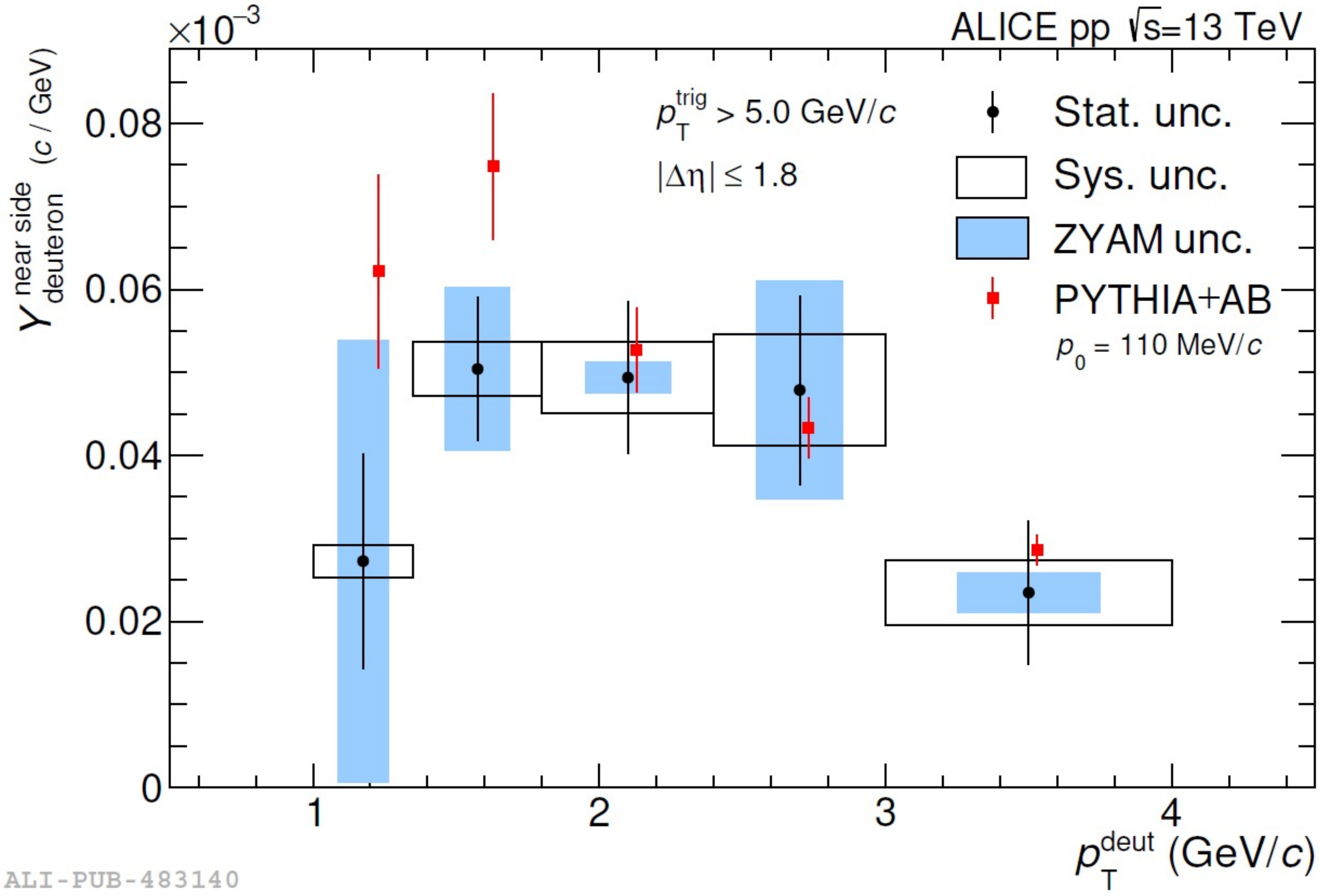


PLB 811 (2020) 135849

d production in jets

- Deuteron production from hard processes: $p_T^{lead} > 5$ GeV/c
- Fraction of deuterons produced in the jet is ~ 8–15%, increasing with increasing p_T
- The majority of the deuterons are produced in the underlying event

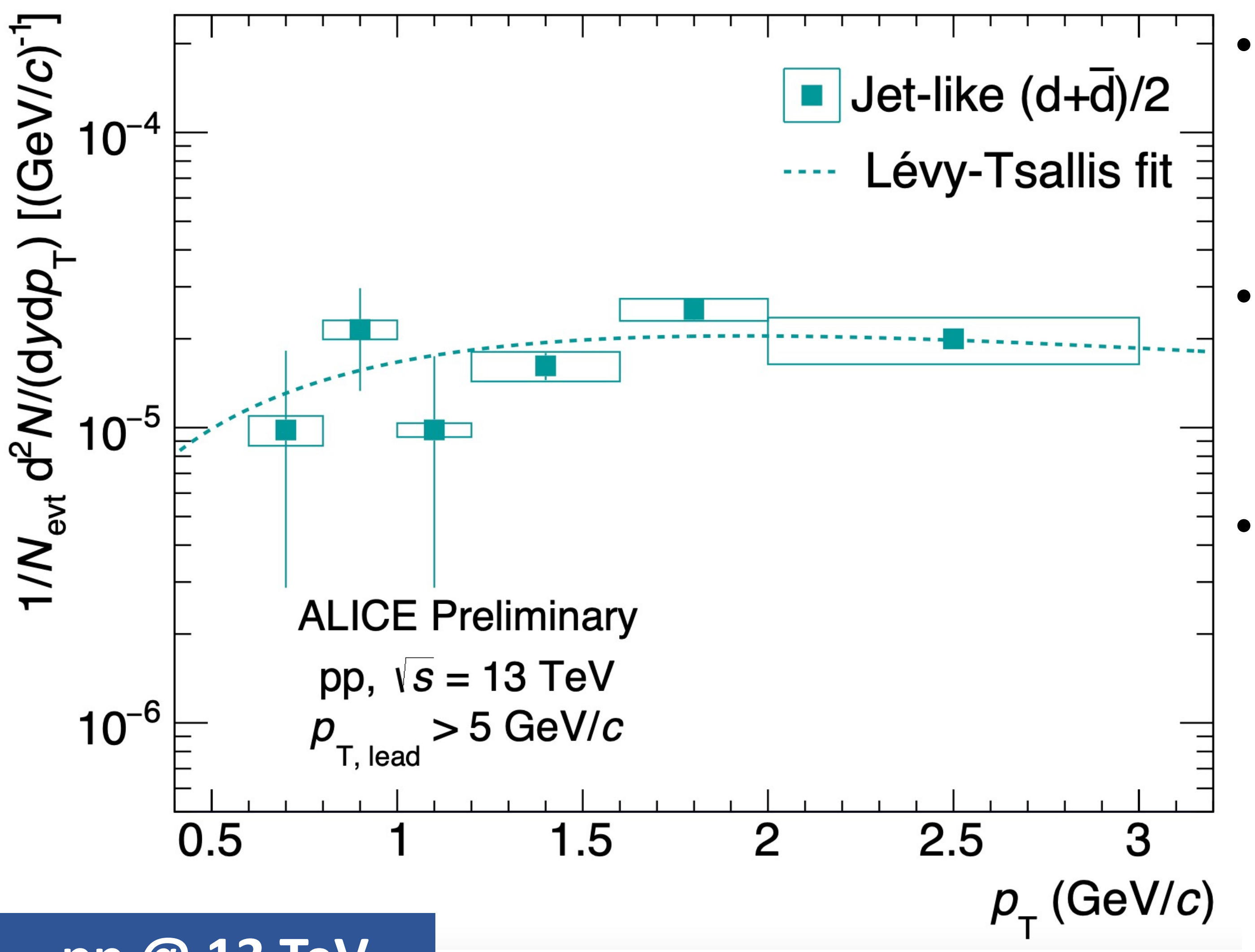
→ Towards region contains a large contribution from UE



pp @ 13 TeV

Phys.Lett.B 819 (2021) 136440

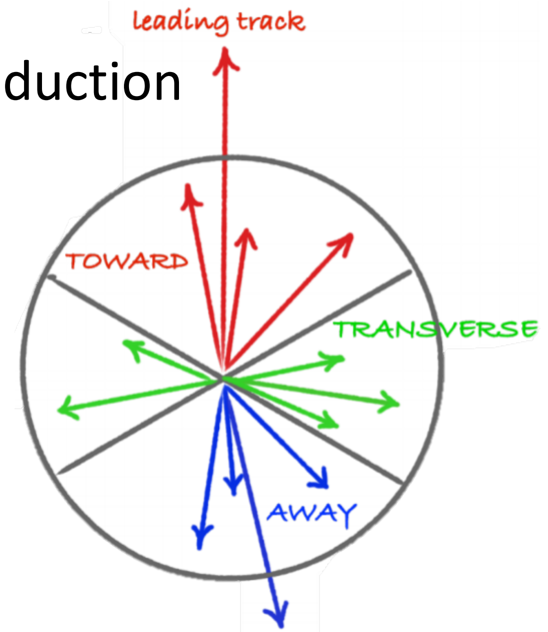
Jet-like deuteron spectrum



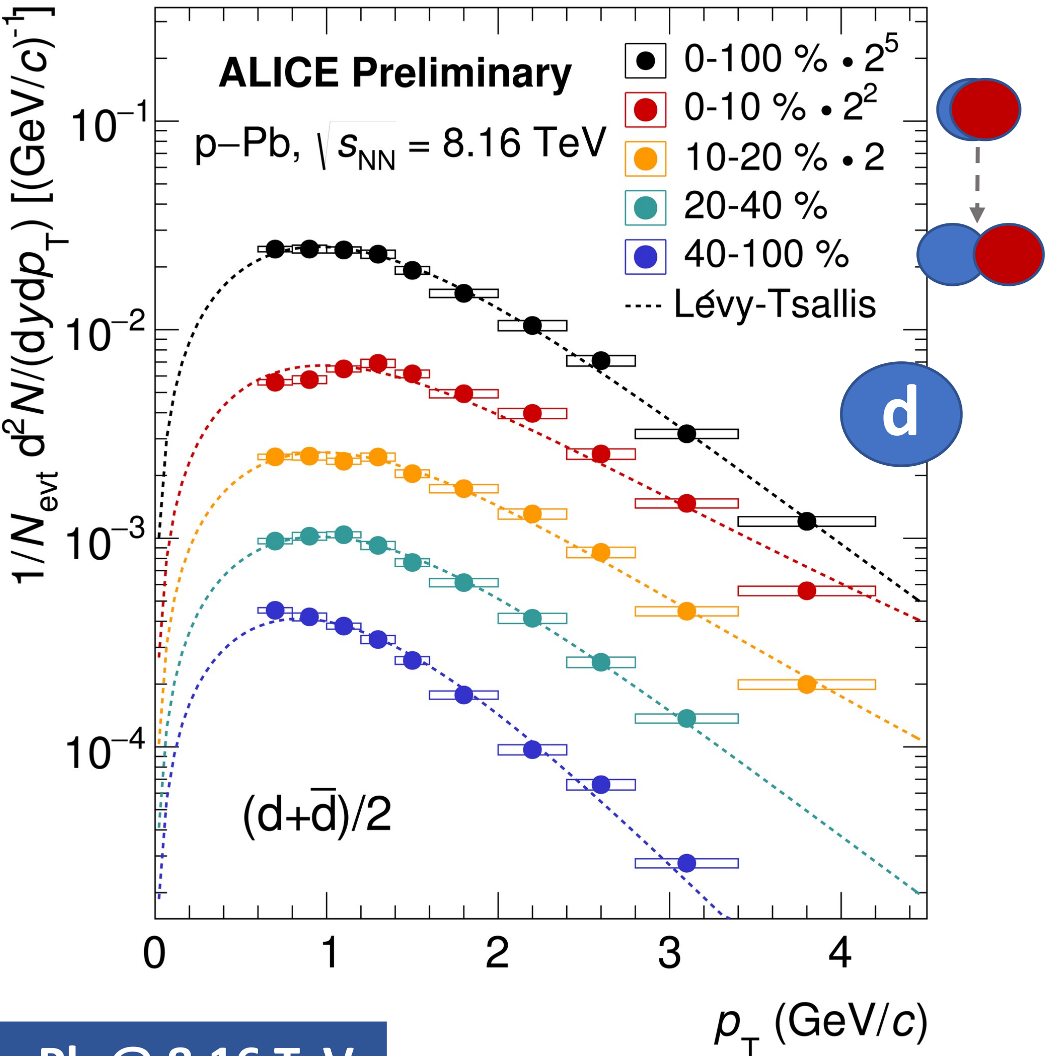
pp @ 13 TeV

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

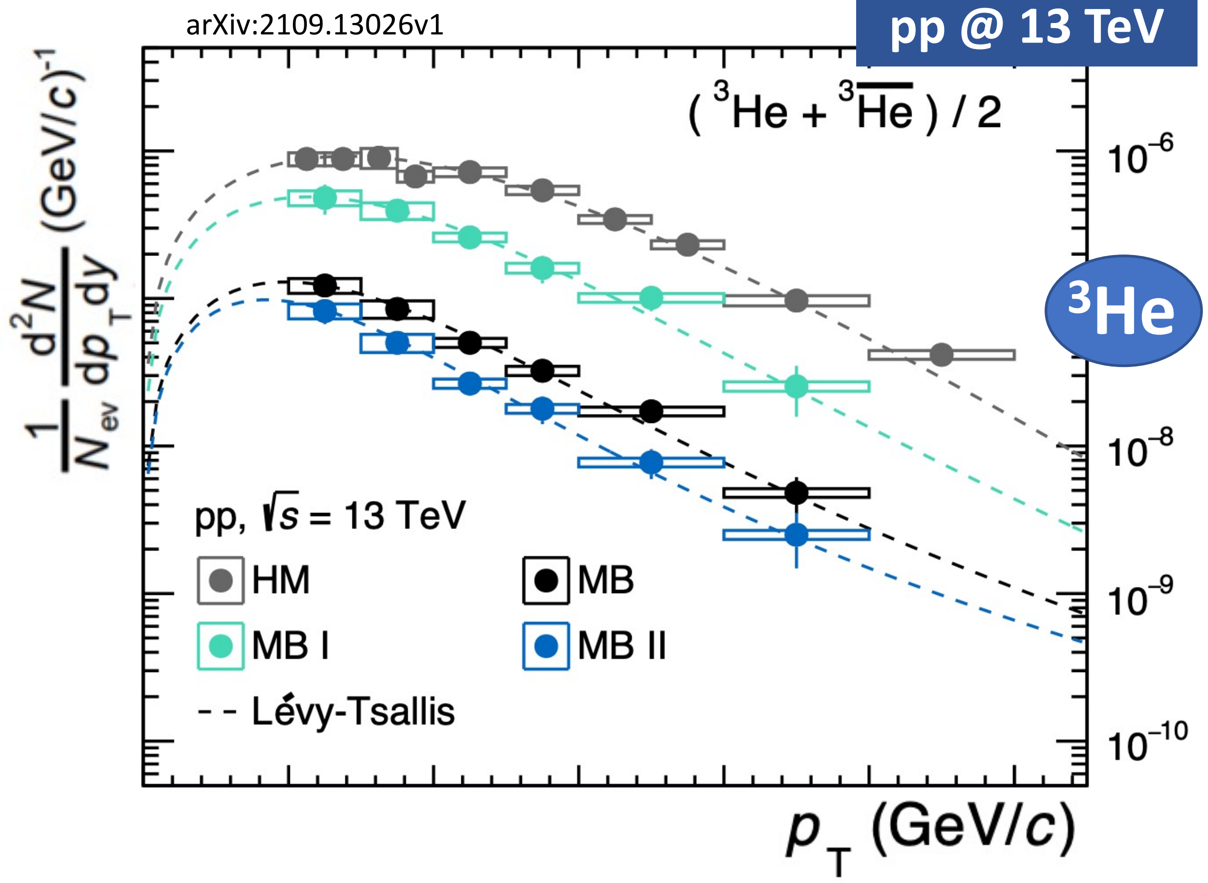
Jet = Toward – Transverse



Light (anti)nuclei in small systems

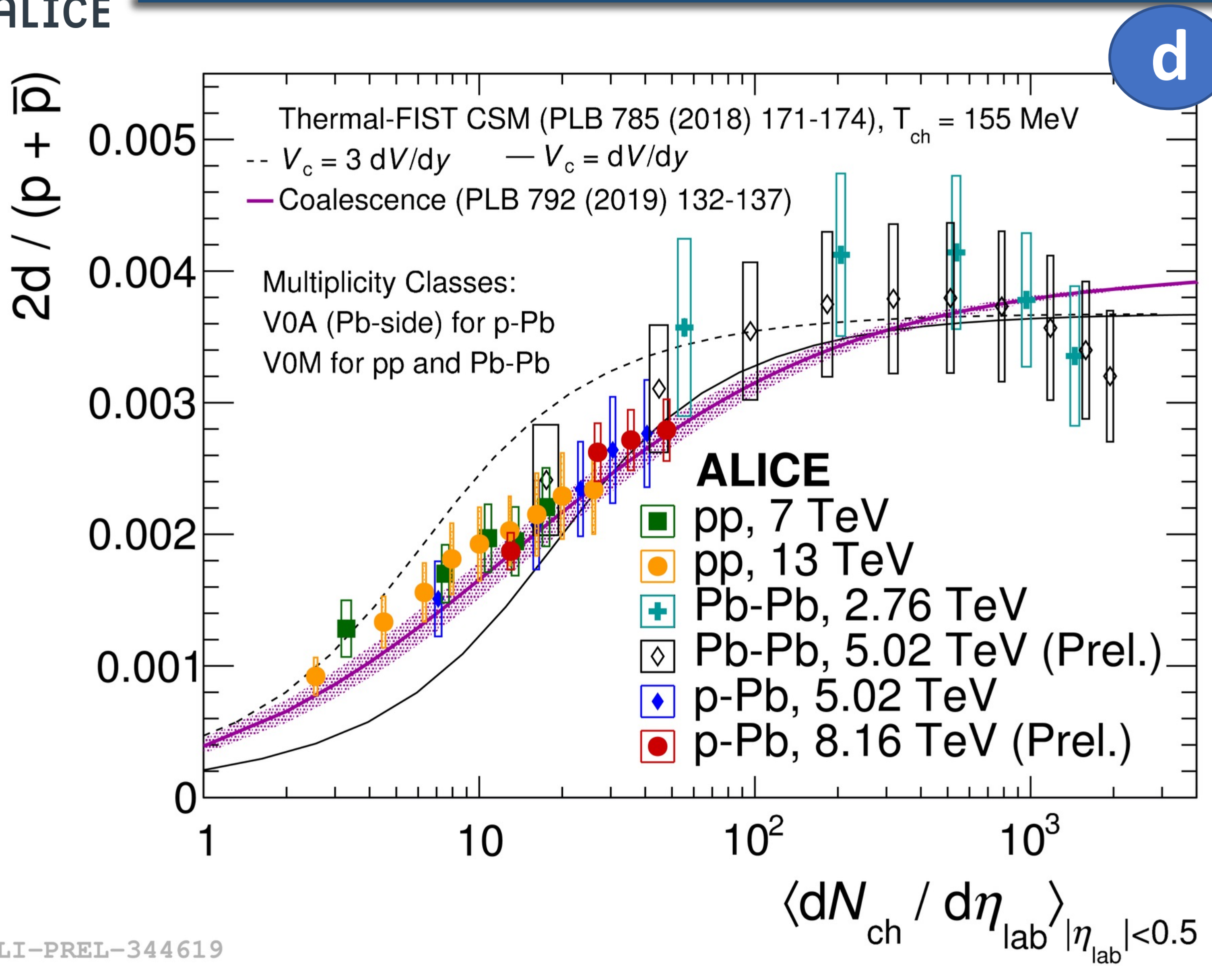


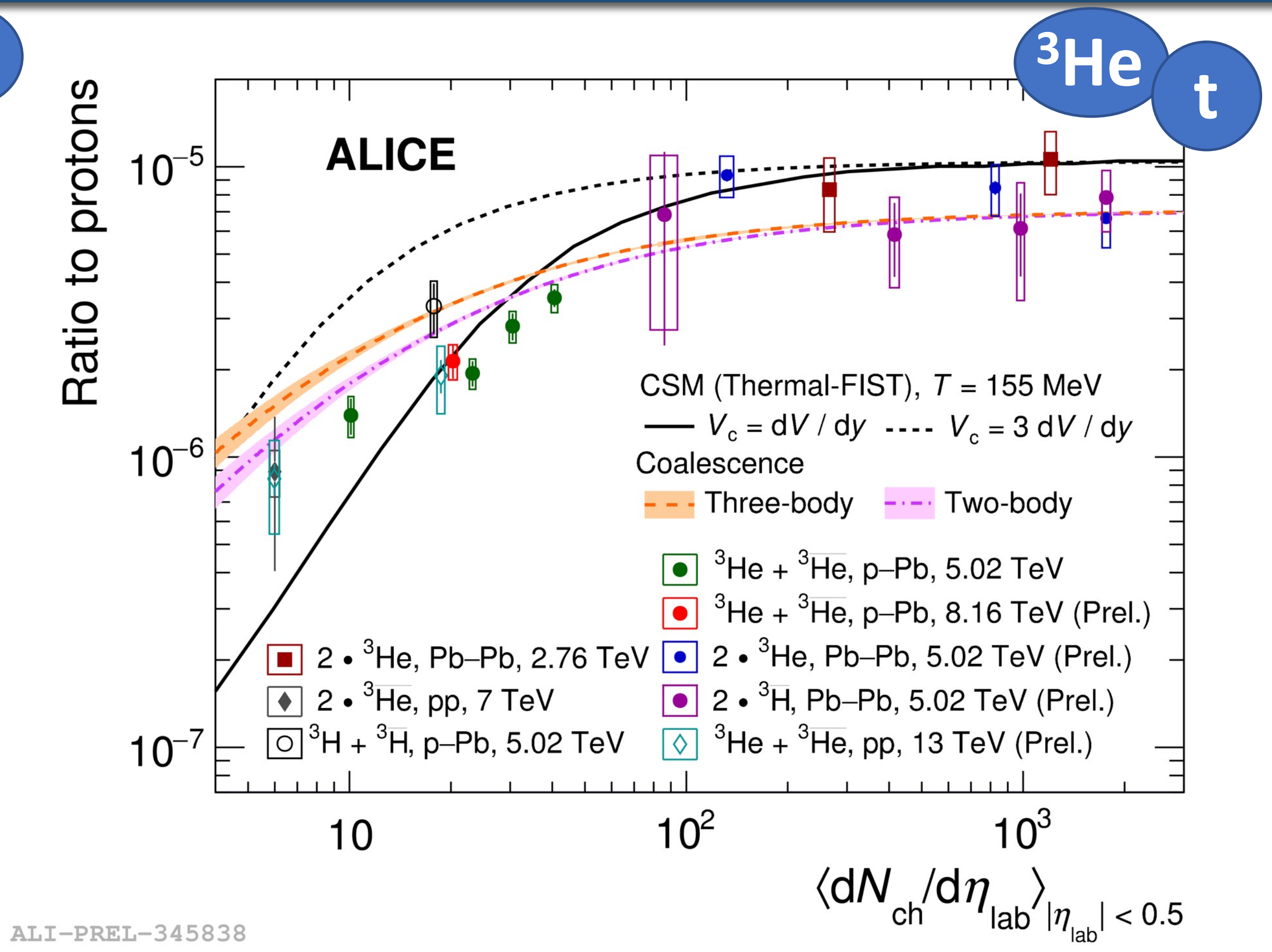
p–Pb @ 8.16 TeV



- p_T spectra fitted with Lévy-Tsallis function
  ⇒ Extrapolation to unmeasured regions

Ratio to protons – models comparison

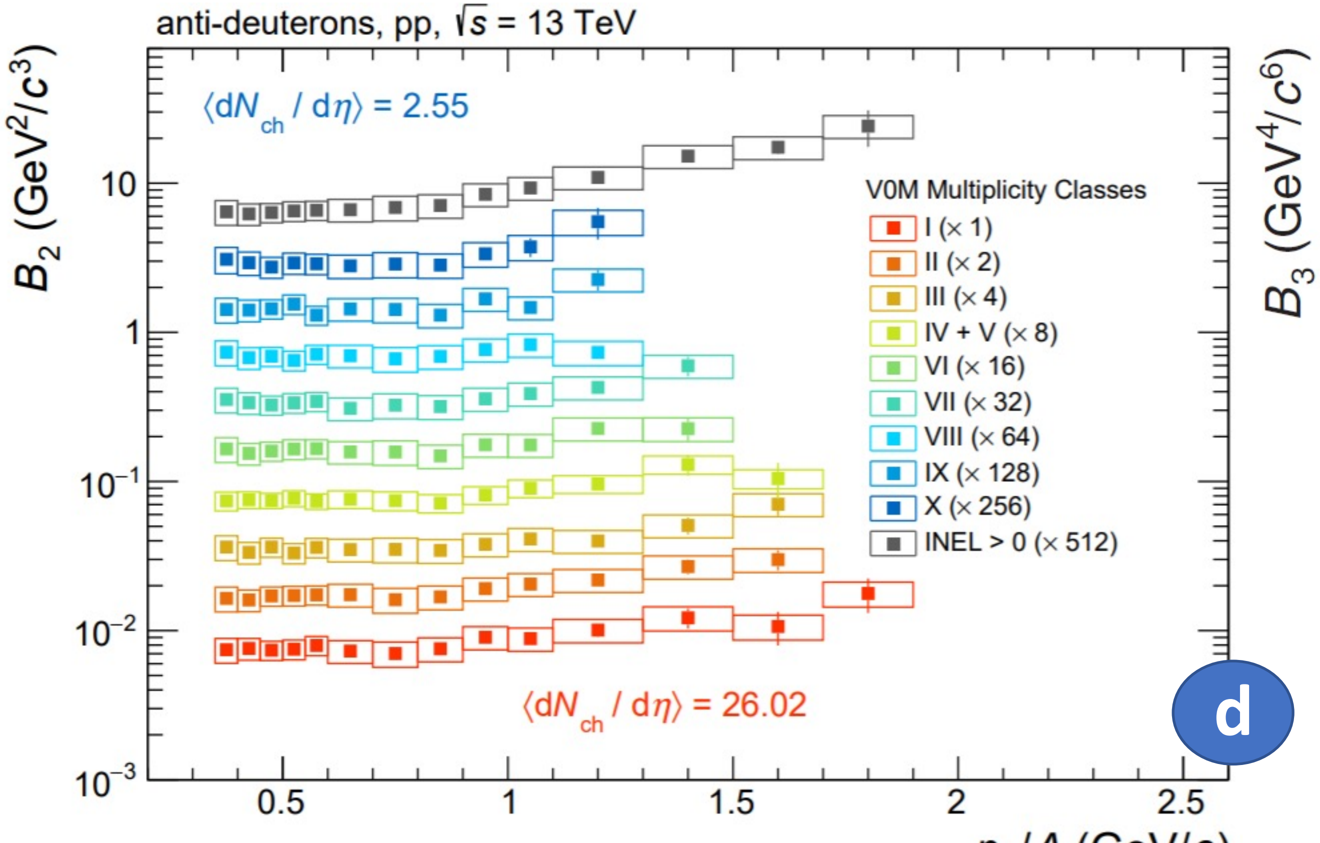




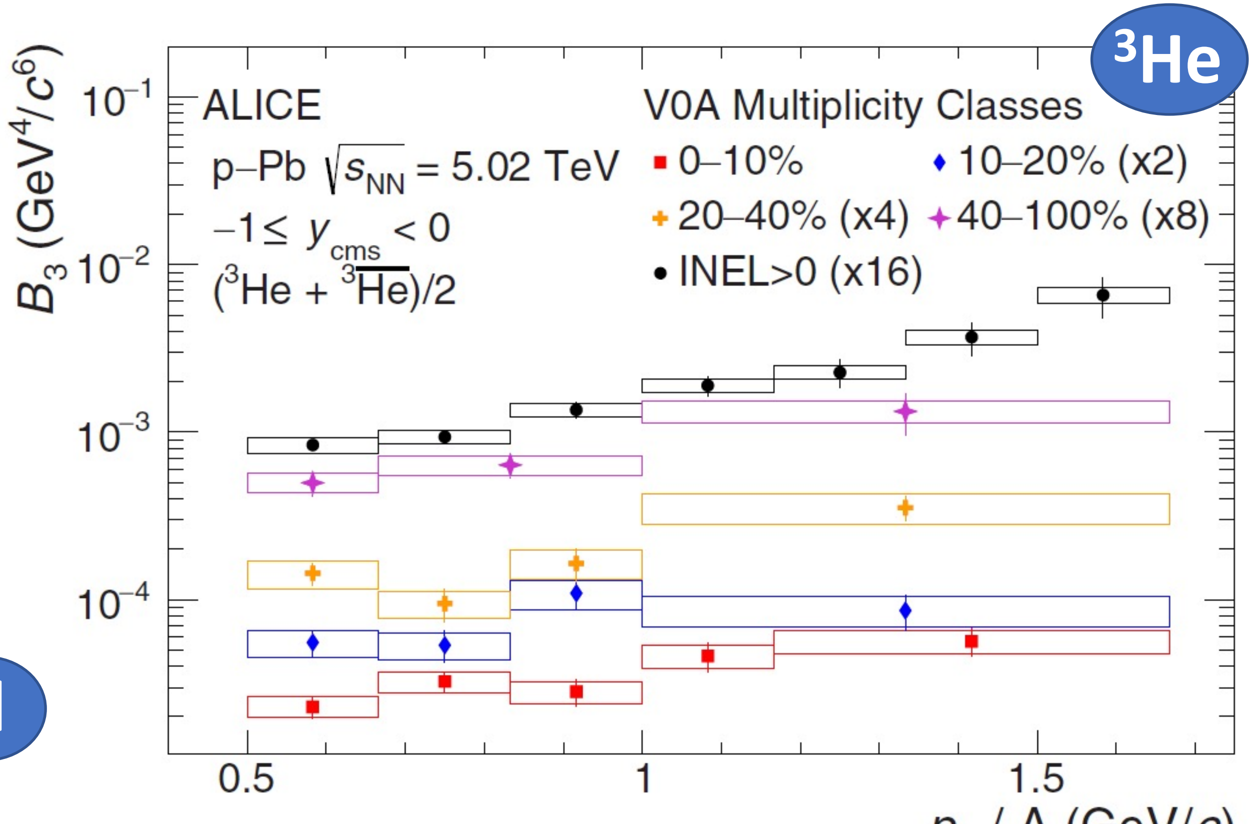
- Smooth transition across different collision systems and energies
- Light nuclei production seems to depend only on multiplicity
- Results challenge the models for A=3 nuclei

Coalescence parameters VS p_T/A

- B_A is rather flat in multiplicity classes, but increases at high p_T/A in the MB class



Eur. Phys. J. C (2020) 80:889

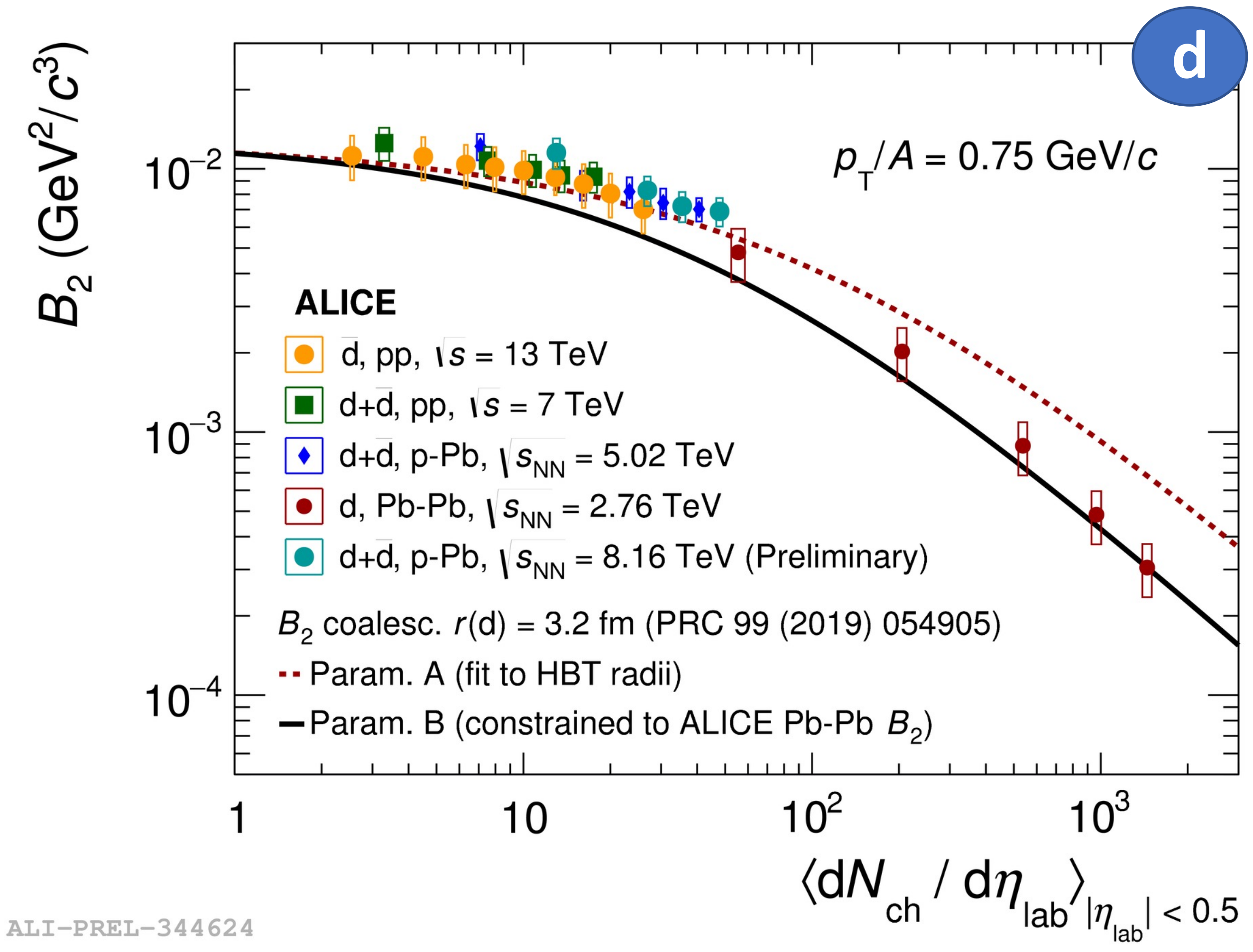


Phys. Rev. C 101, 044906 (2020)

pp @ 13 TeV

p–Pb @ 5.02 TeV

Coalescence parameter B_2



Strong dependence of B_2 on collision system size

Continuous evolution of B_2 with multiplicity

- Smooth transition from small to large system size
- Single underlying production mechanism?

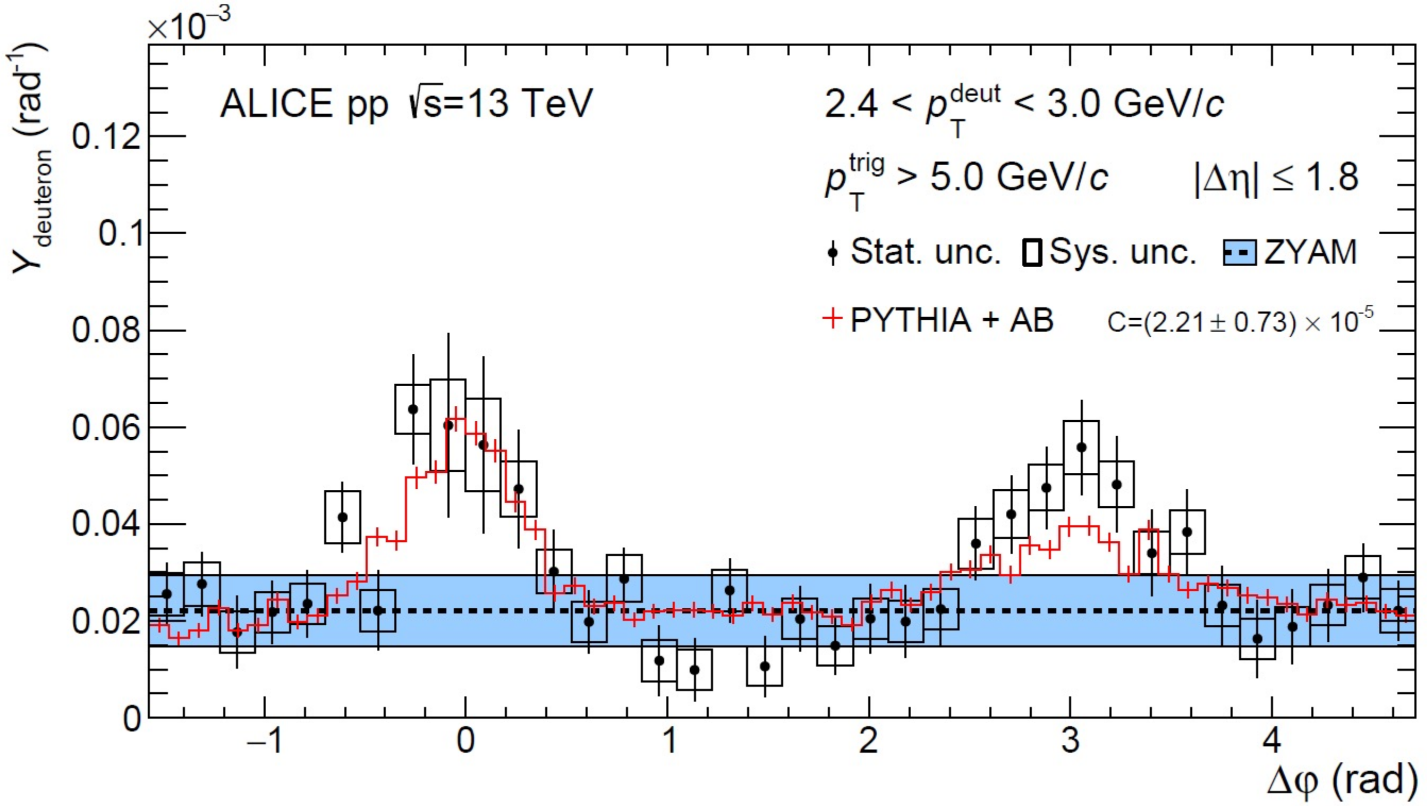
Similar conclusions apply also for B_3

Advanced coalescence models taking into account the size of the nucleus and of the emitting source predict similar trend

The evolution with multiplicity is explained as an increase in the source size R in coalescence models (e.g. *Scheibl, Heinz PRC 59 (1999) 1585*)

d production in jets (II)

- Insight on (anti)d production in smaller phase space available in jet fragmentation
- High-p_T (> 5 GeV/c) trigger particle used as jet proxy
- Measurement of (anti)d yields within $|\Delta\phi| < 0.7$ rad
  - Uncorrelated contribution subtracted with ZYAM (zero yield at minimum)
- (Anti)d yields is found to be 2.4–4.8 standard deviations above uncorrelated background ($p_T^d > 1.35$ GeV/c)
- Good agreement with PYTHIA calculation + coalescence afterburner



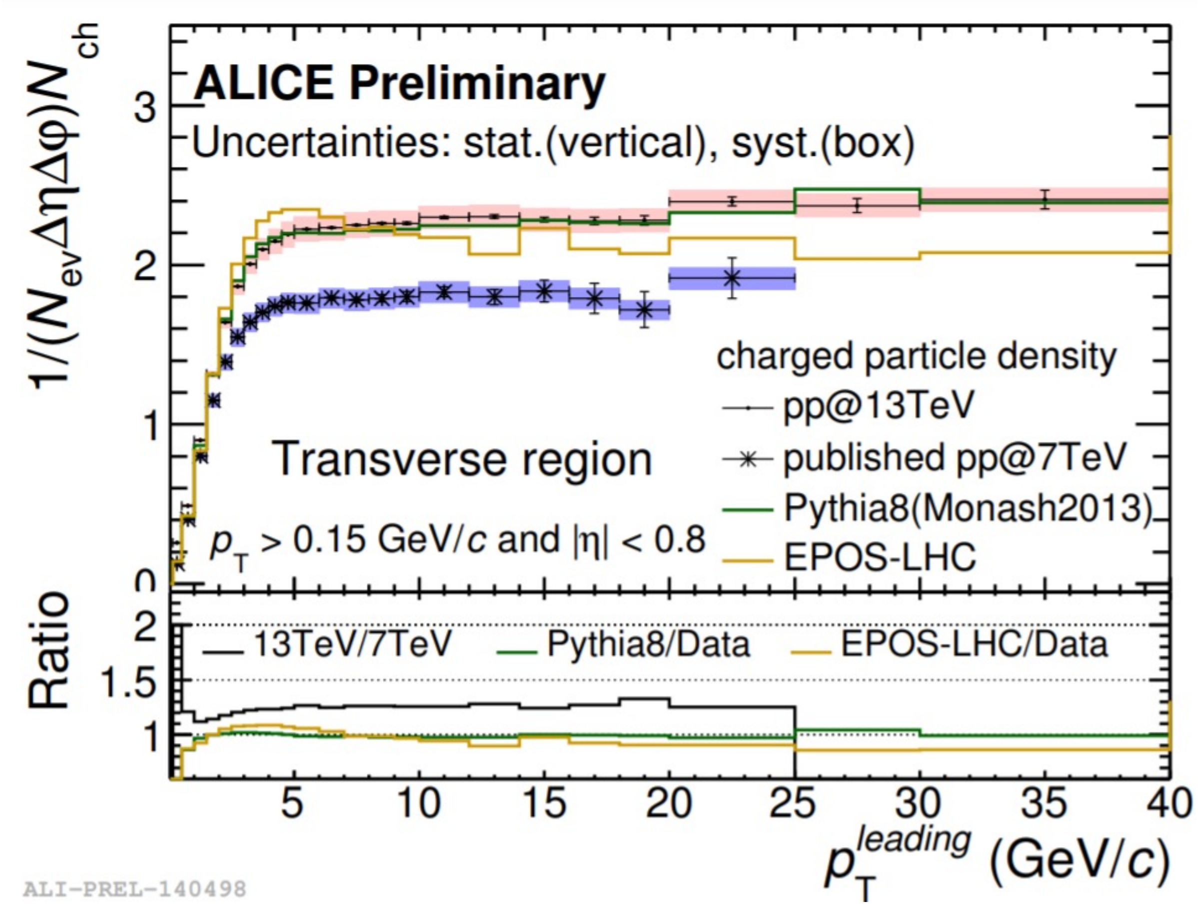
pp @ 13 TeV

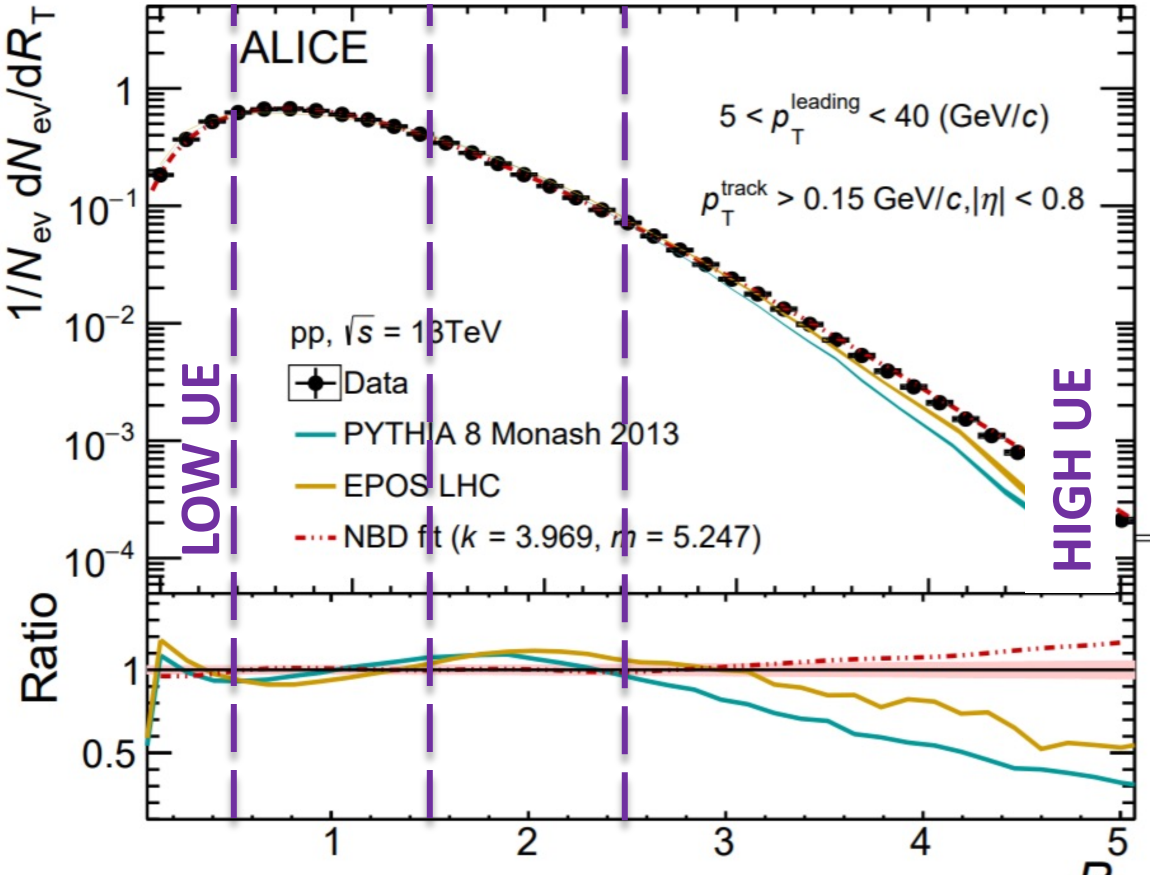
arXiv:2011.05898 [nucl-ex]

Characterize the UE

- Plateau region (jet pedestal): $5 < p_T^{leading} < 40$ GeV/c

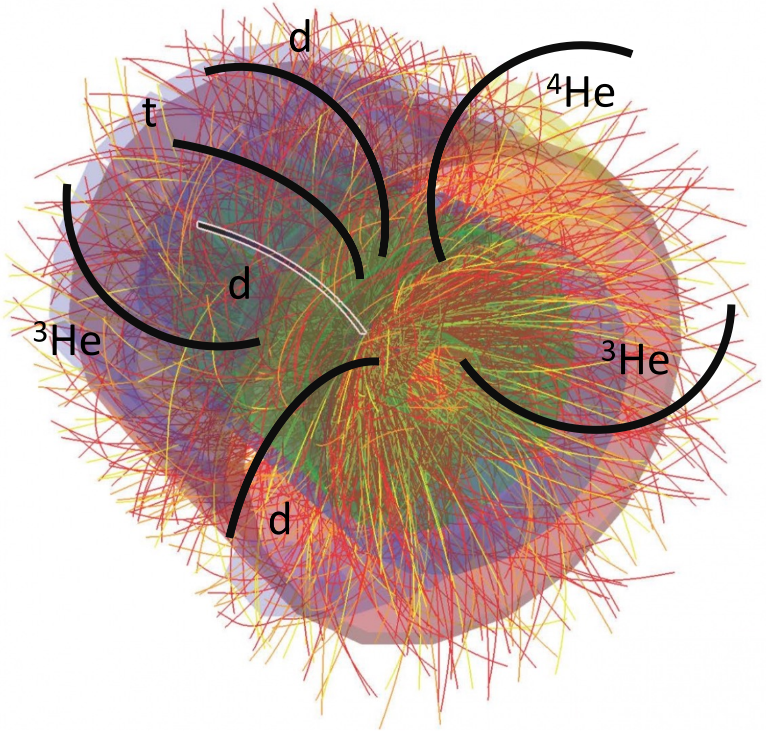
- Several intervals of R_T are selected in order to distinguish between low and high UE activity





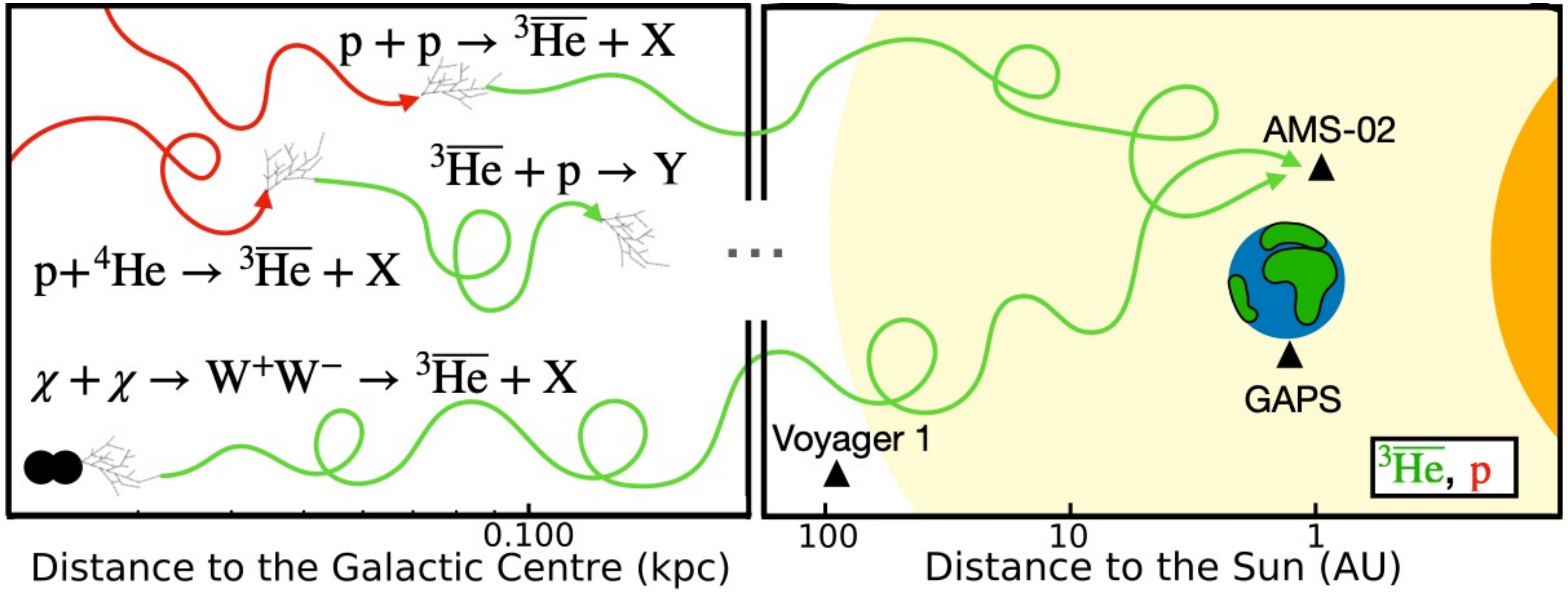
10.1007/JHEP04(2020)192

Physics motivation



- Multi-baryon states are produced in high energy hadronic collisions at the LHC
- (Anti)nuclei measurement studies are crucial
  - microscopic production mechanism
  - *input in the indirect dark matter searches through antinuclei probe*

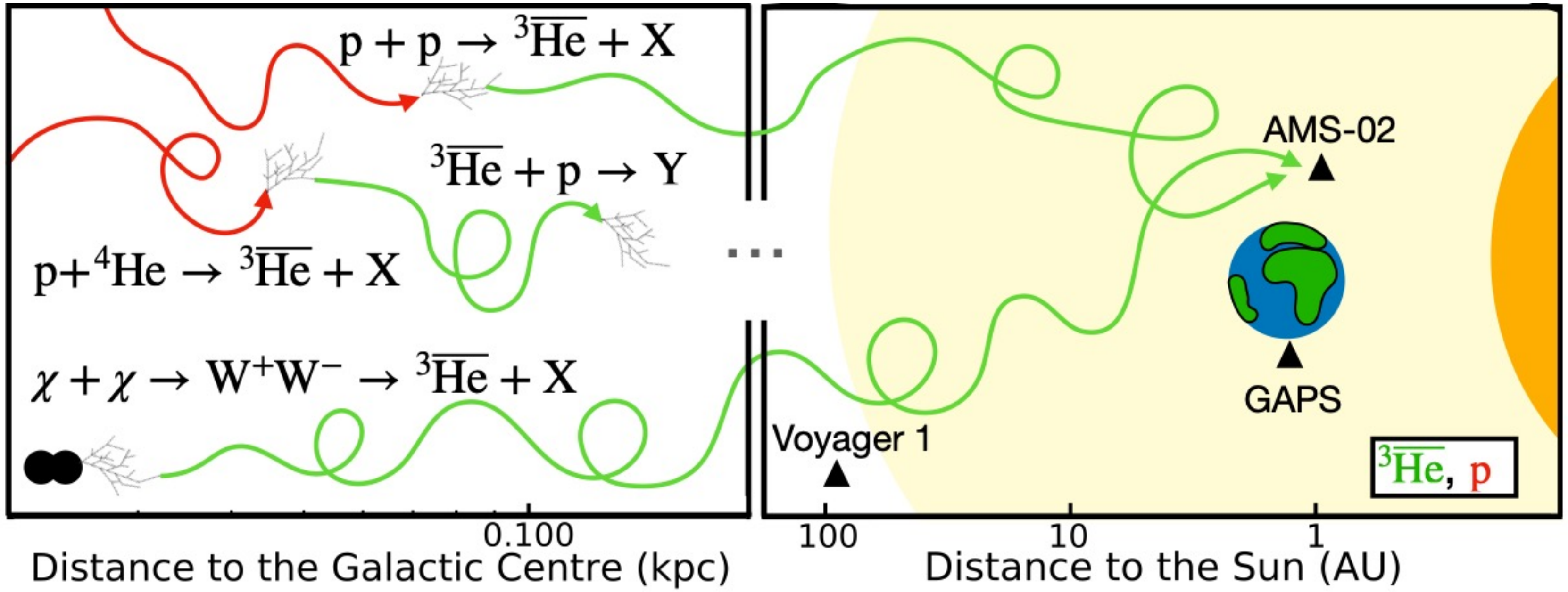
Antinuclei as dark matter probe

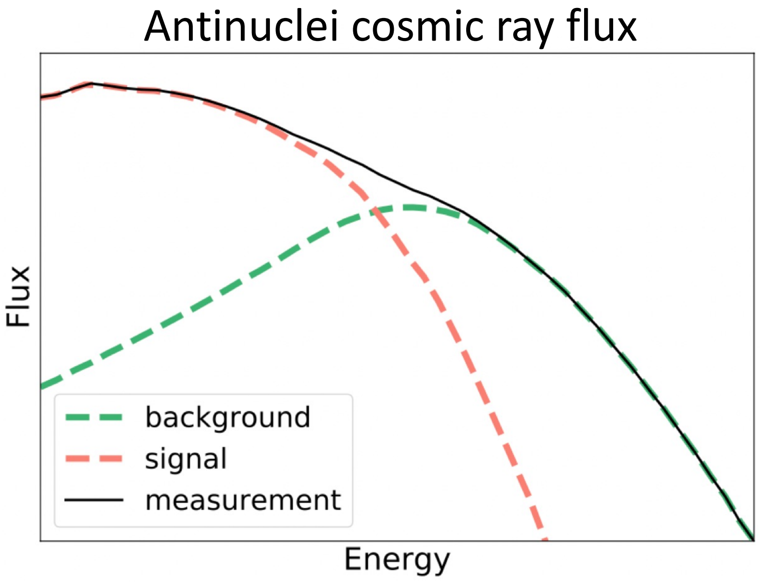


Antinuclei production:

- pp, p–A and (few) A–A reactions between primary **cosmic rays** and the interstellar medium
- **dark-matter** annihilation processes

Antinuclei as dark matter probe



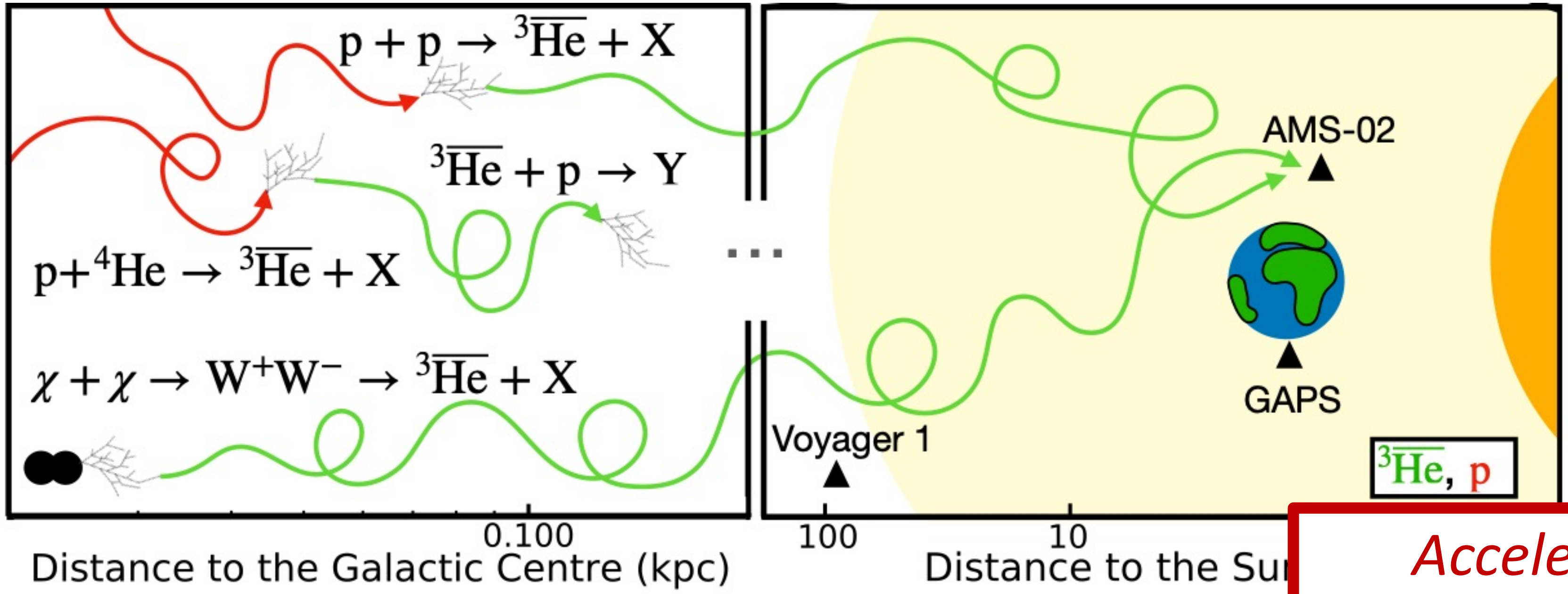


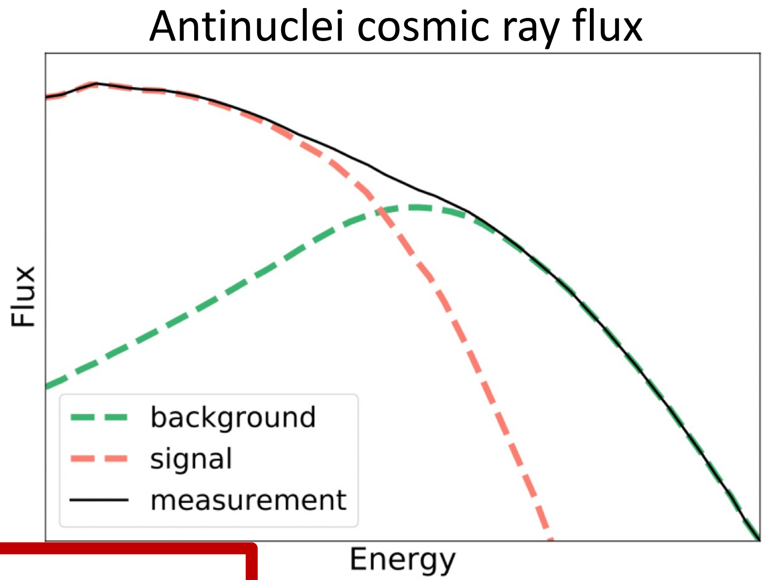
To determine exact primary and secondary fluxes → precise knowledge of antinuclei production, propagation and annihilation is needed

Transport equation: $$\frac{\partial \psi}{\partial t} = q(\mathbf{r}, p) + \mathbf{div}(D_{xx}\mathbf{grad}\psi - \mathbf{V}\psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{\psi}{p^2} - \frac{\partial}{\partial p}\left[\psi \frac{dp}{dt} - \frac{p}{3}(\mathbf{div} \cdot \mathbf{V})\psi\right] - \frac{\psi}{\tau_f} - \frac{\psi}{\tau_r}$$

Source Function | **Propagation: diffusion, convection…** | **Fragmentation, annihilation**

Antinuclei as dark matter probe





Accelerator experiments

To determine exact primary and secondary fluxes → prec … clei production, propagation and annihilation is needed

Transport equation:

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

Source Function

Propagation: diffusion, convection…

Fragmentation, annihilation