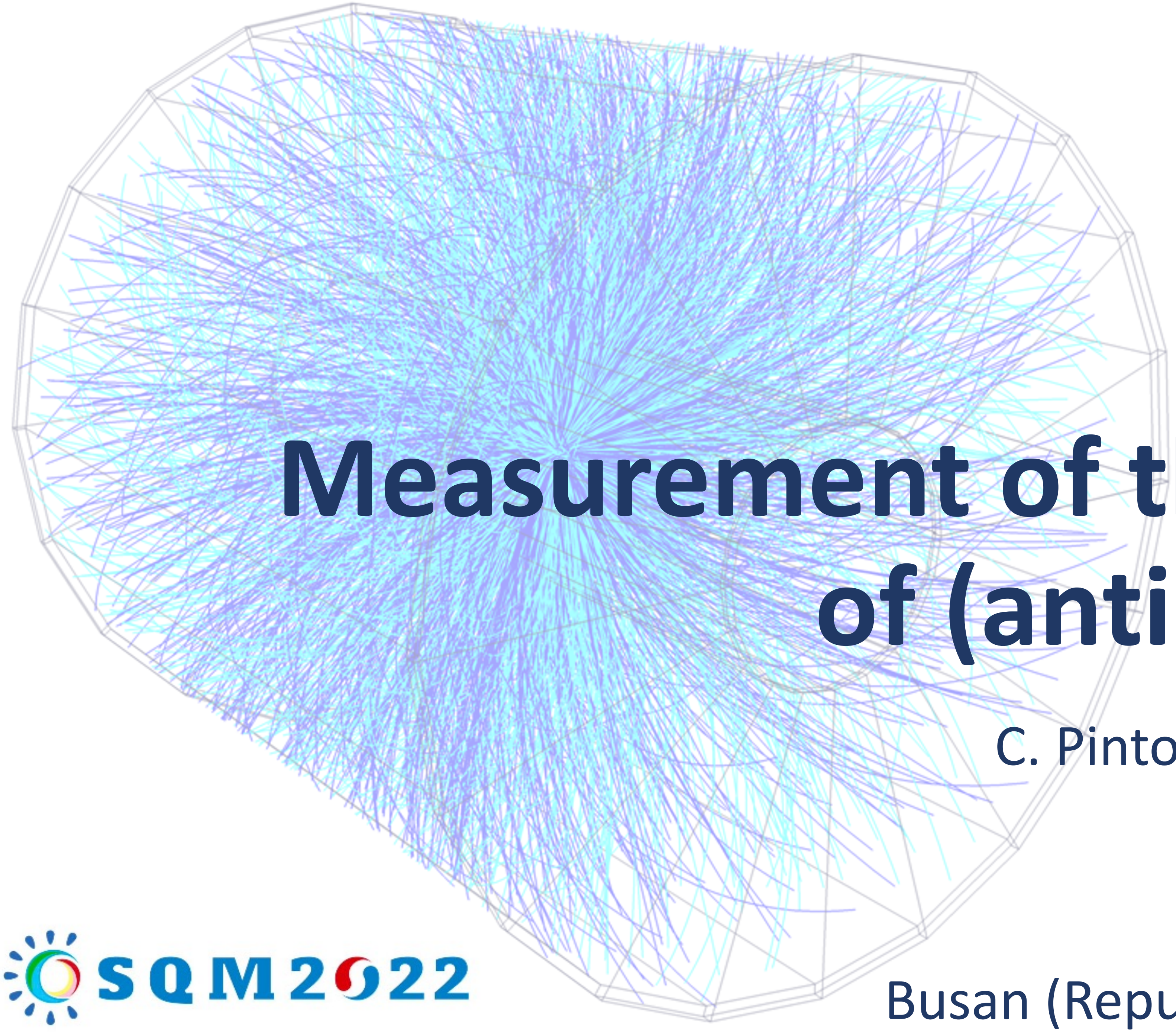


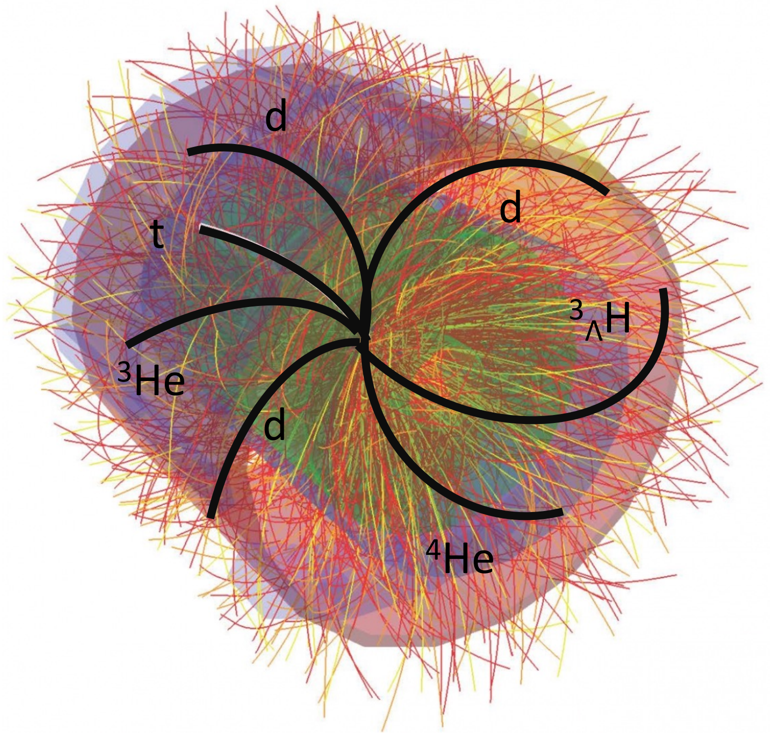
Measurement of the production of (anti)(hyper)nuclei

C. Pinto[1] for the ALICE Collaboration

[1] Technische Universität München

Busan (Republic of Korea) – 14 Jun. 2022

(Anti)(hyper)nuclei production



*See talk by M. Ciacco on Tue. 14/06
**See talk by P. Larionov on Wed. 15/06

- At LHC energies same amount of matter and antimatter is expected ($\mu_B \sim 0$)*
- (Anti)(hyper)nuclei measurement studies are crucial
  - *microscopic production mechanism*
  - input for indirect dark matter searches**
- Production mechanism usually described with two classes of phenomenological models:
  - statistical hadronization
  - coalescence
- Focus on production in small collision systems:
  - deuteron (minimum bias, jets & underlying event)
  - hypertriton ($^{3}_{\Lambda}H$)

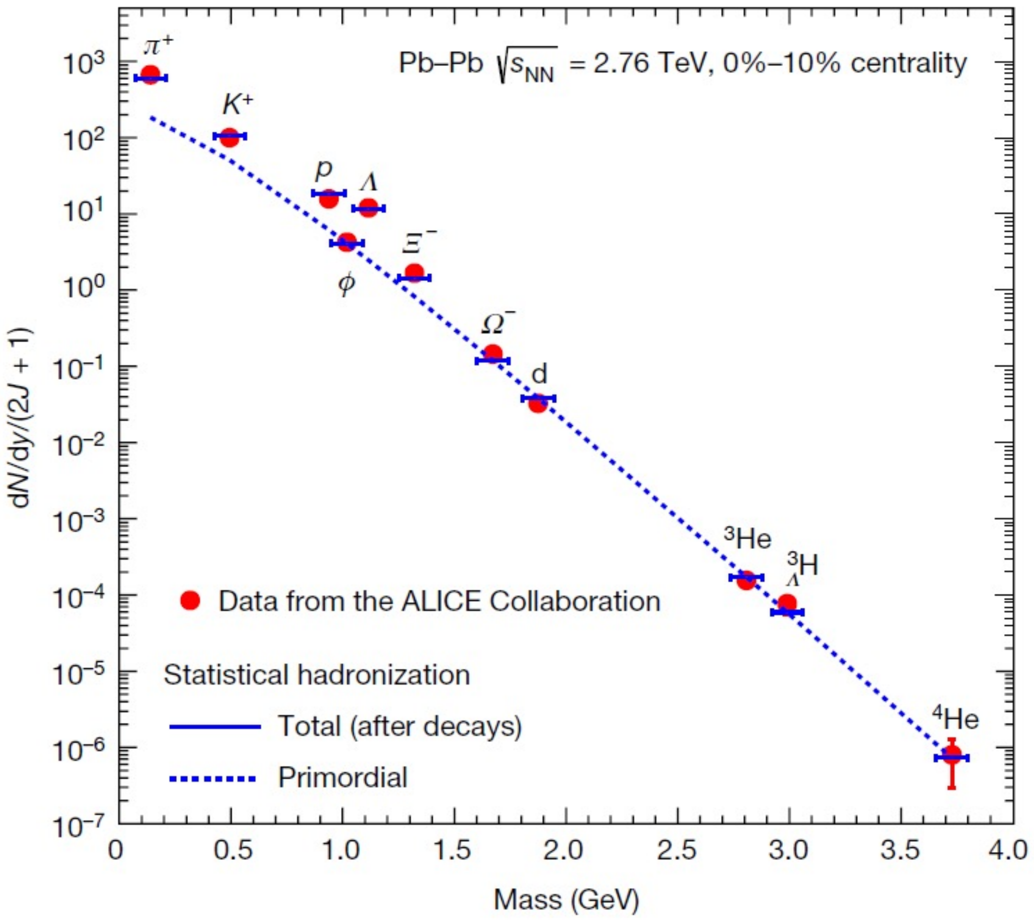
Statistical models

- 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 ($E_B \sim 2$ MeV for d)

⇒ how can they survive the hadronic phase environment?

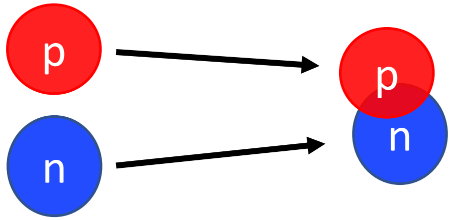


Particle yields of light-flavour hadrons described over 9 orders of magnitude with a **common $T_{chem} \approx 156$ MeV**

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

Coalescence models

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 observable

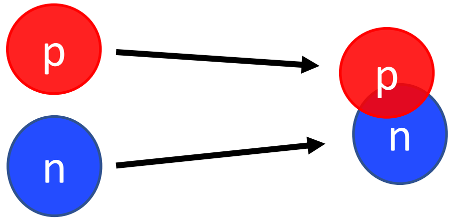
$$B_A(p_T^p) = E_A \frac{d^3 N_A}{d\,p_A^3} \Bigg/ \left(E_p \frac{d^3 N_p}{d\,p_p^3} \right)^A \Bigg|_{p_T^p = p_T^A / A}$$

- Experimental observable tightly connected to the coalescence probability

Larger B_A ⟺ Larger coalescence probability

Coalescence models

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



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[1]PRC 99 (2019) 024001
[2]PRL 123 (2019) 112002

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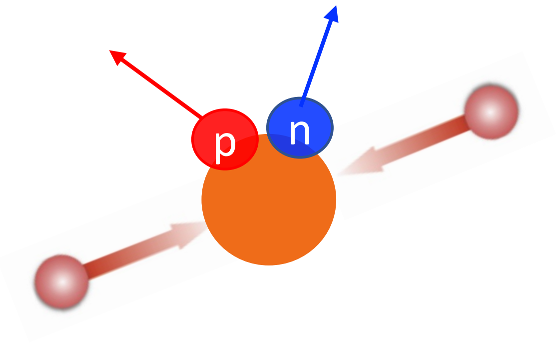
Larger B_A ⟺ Larger coalescence probability

- Coalescence probability depends on the system size



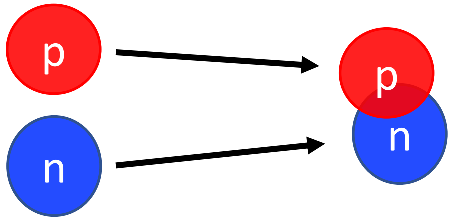
pp[1], p—Pb[2]: r_0 = 1–1.5 fm

Small distance in space
(Only momentum correlations matter)

⟺ large B_A

Coalescence models

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



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

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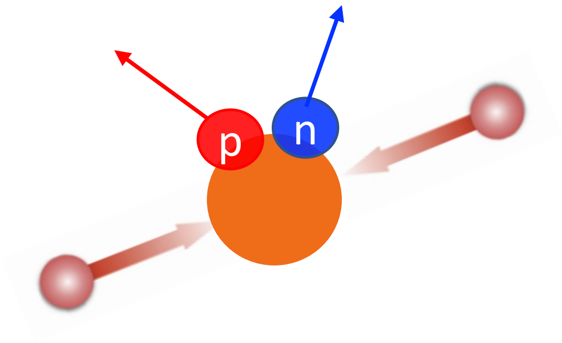
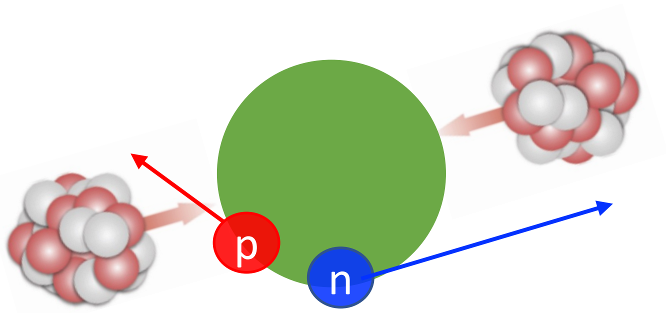


pp[1], p—Pb[2]: r₀ = 1–1.5 fm

Small distance in space
(Only momentum correlations matter)

⟺ large B_A



Pb—Pb[3]: r₀ = 3–6 fm

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

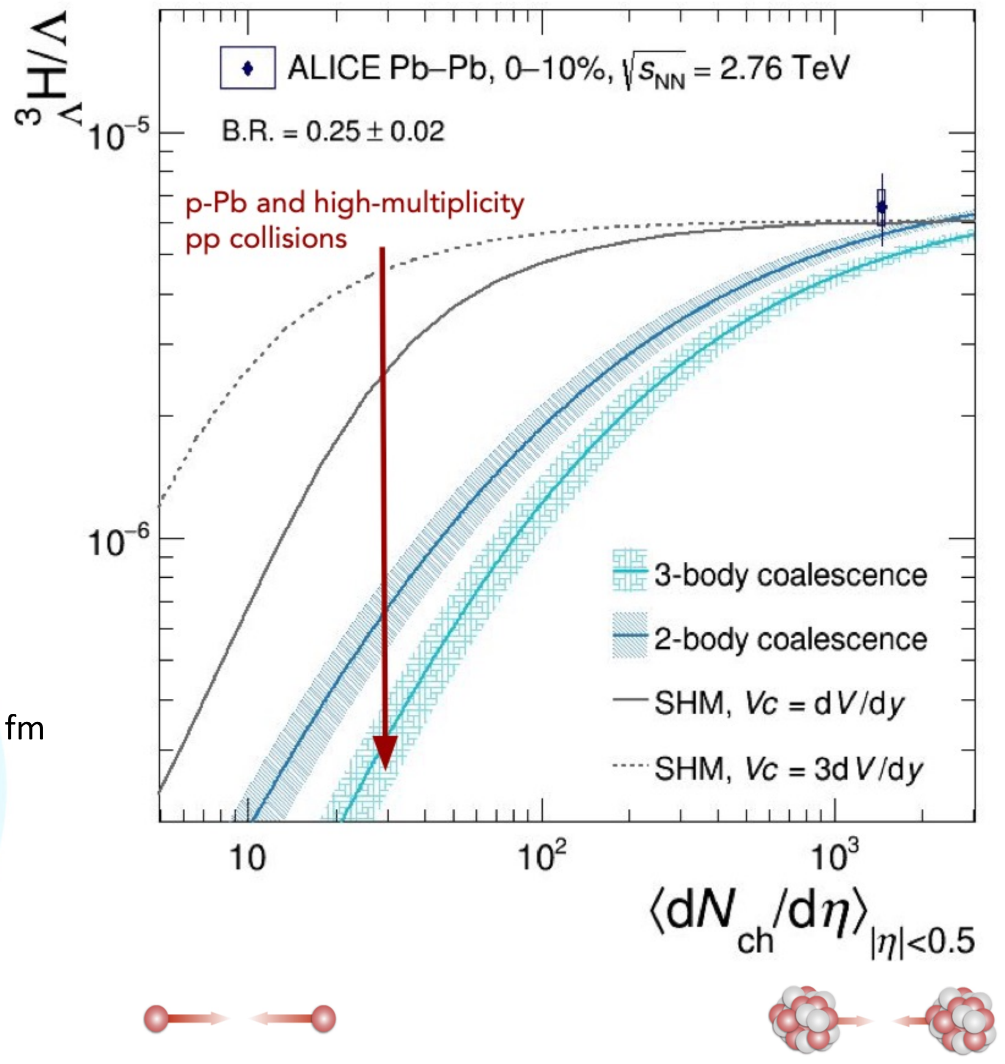
⟺ small B_A

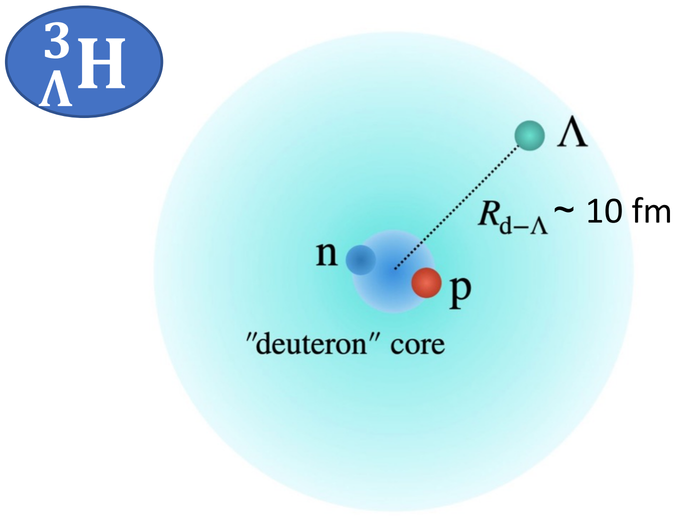
Small collision systems

Small collision systems (as pp) are particularly interesting:

- system created in the collision has a size smaller or equal to that of the nucleus under study
- allows for the study of coalescence since nucleons are created close to each other
- for small systems model predictions are quite different

PLB 754 (2016) 360–372





System size in pp and p—Pb collisions: 1–1.5 fm

r_d : 1.96 fm

r_{3He}: 1.76 fm

$r_{{}^{3}_{\Lambda}H\,(np\Lambda)}$: 4.9 fm ($B_\Lambda$= 2.35 MeV)

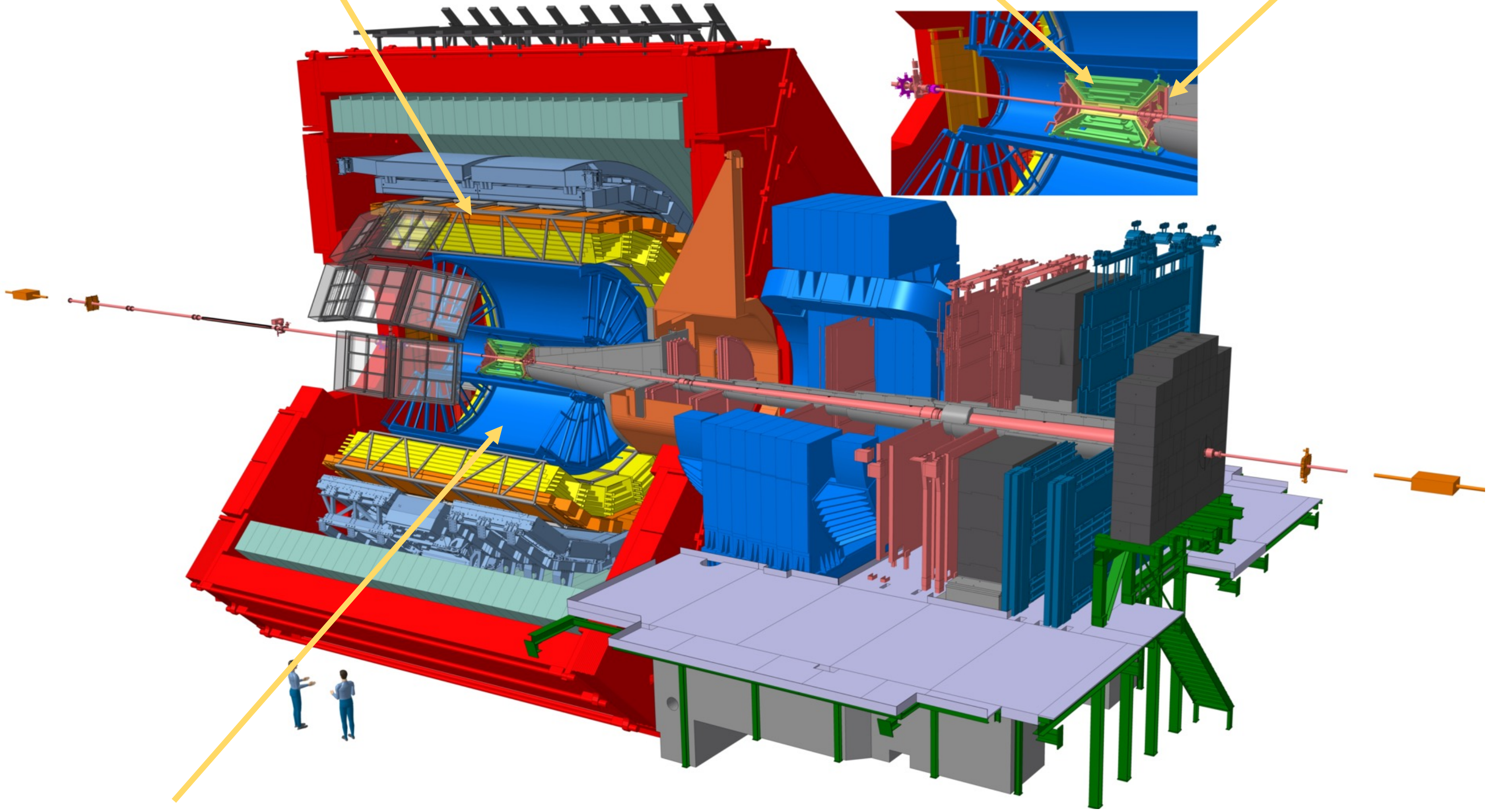
$r_{{}^{3}_{\Lambda}H\,(d\Lambda)}$: 10 fm ($B_\Lambda \sim$ 0.13 MeV)

The ALICE detector

Time Of Flight
PID via β

Inner Tracking System
tracking, vertex, PID at low p

V0 trigger, multiplicity estimators
(Minimum Bias: 0 – 100%, High Multiplicity: 0 – 0.1%)



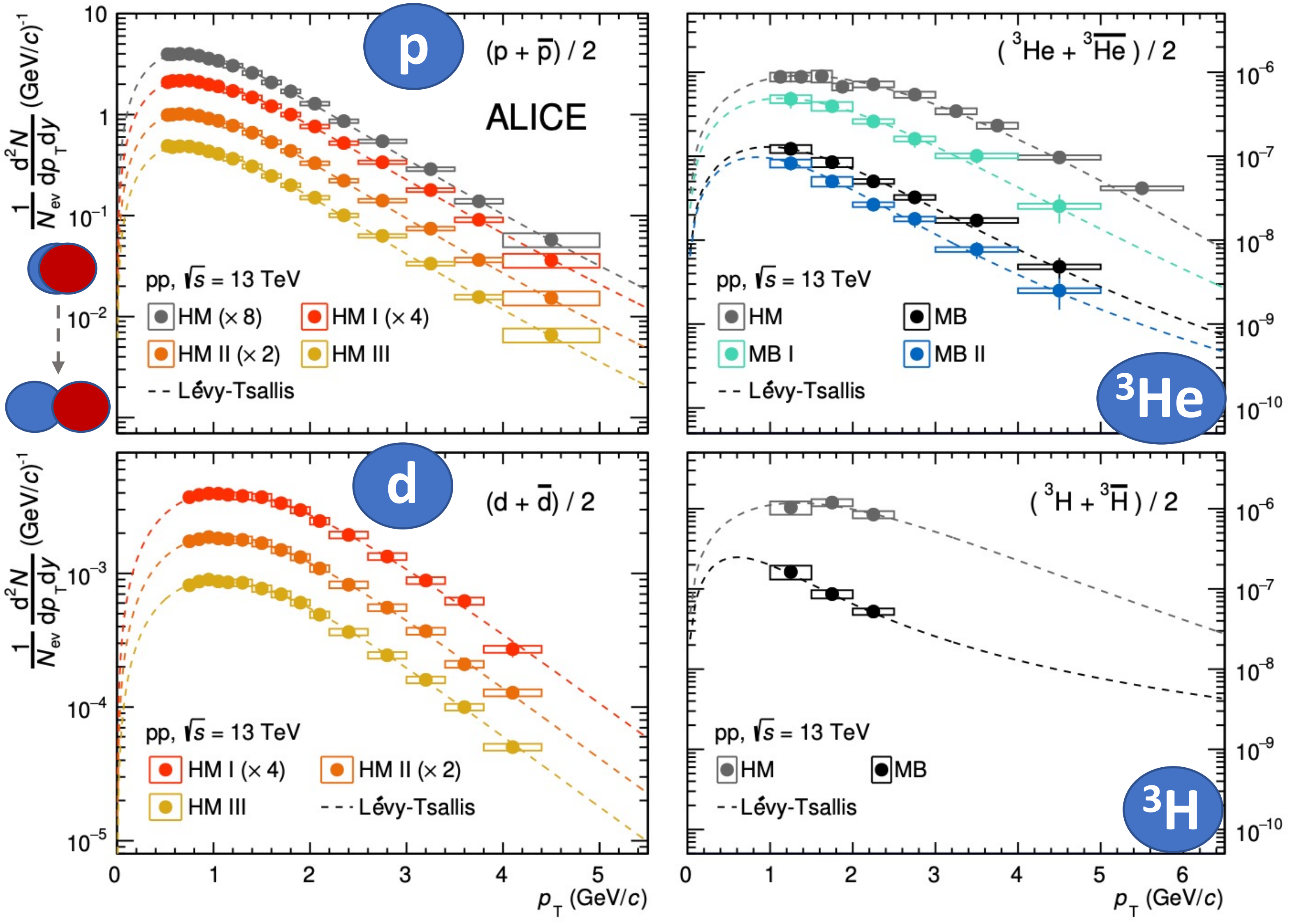
Time Projection Chamber
tracking, PID via dE/dx

- pp, p—Pb, Pb—Pb collisions at various centre-of-mass energies
- excellent tracking and PID capabilities over a broad momentum range
  - TPC: $\sigma_{\mathrm{d}E/\mathrm{d}x} \sim$ 5.5% for pp
    $\sigma_{\mathrm{d}E/\mathrm{d}x} \sim$ 7% for Pb—Pb
  - TOF: $\sigma_{\mathrm{PID}} \sim$ 70 ps for pp
    $\sigma_{\mathrm{PID}} \sim$ 60 ps for Pb–Pb
- low material budget

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

Light (anti)nuclei in small systems

JHEP 01 (2022) 106

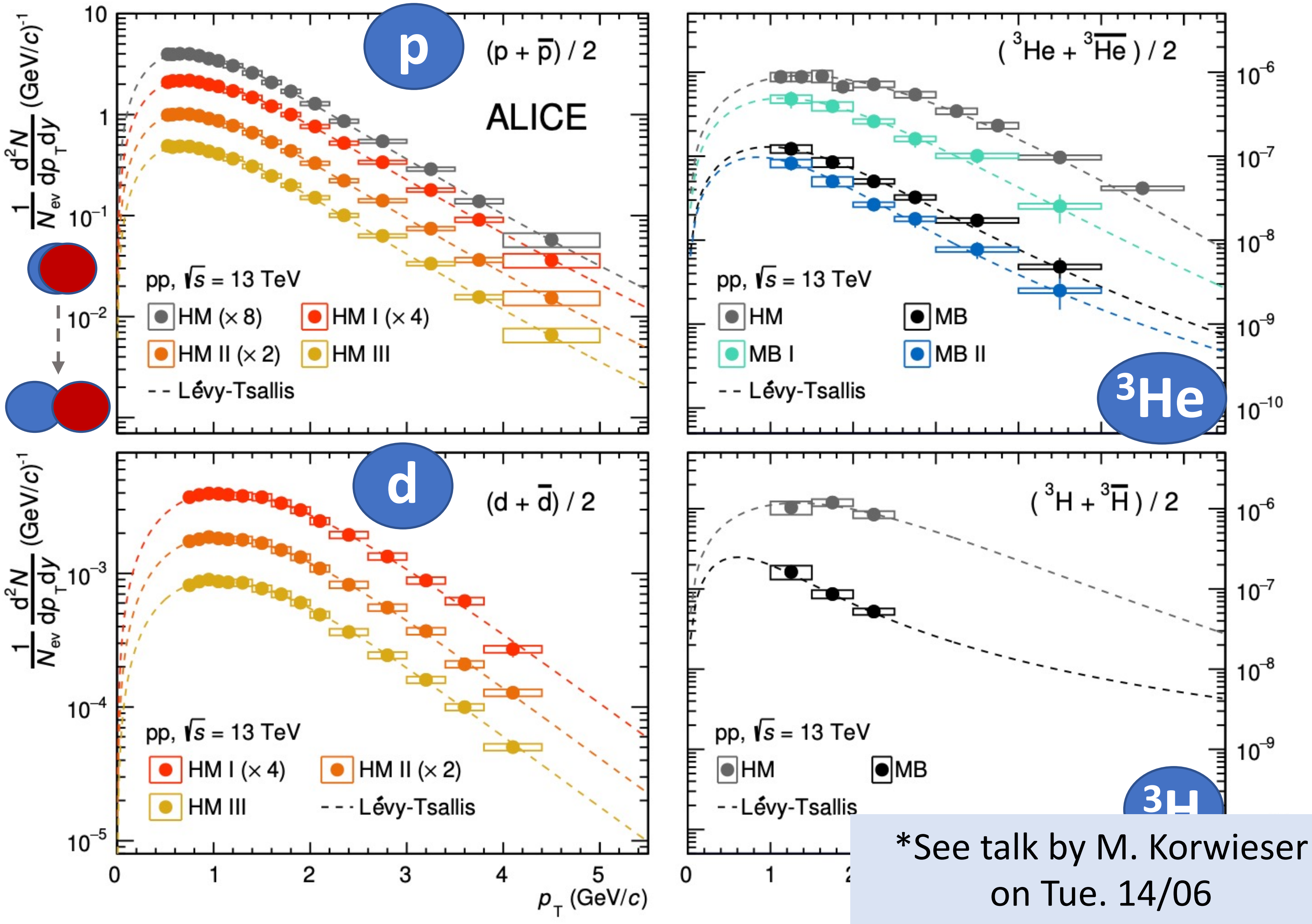


HM pp @ 13 TeV

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

Light (anti)nuclei in small systems

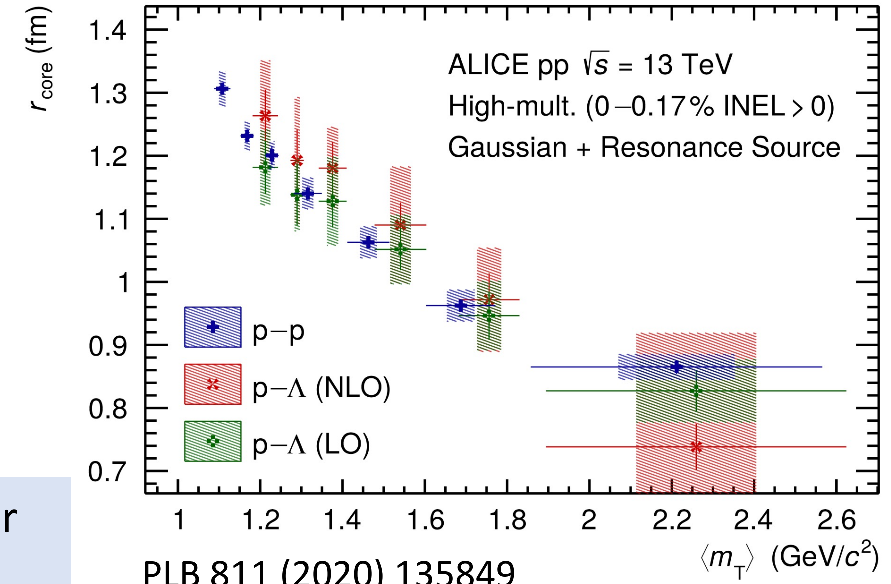
JHEP 01 (2022) 106



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

$\propto p_T$

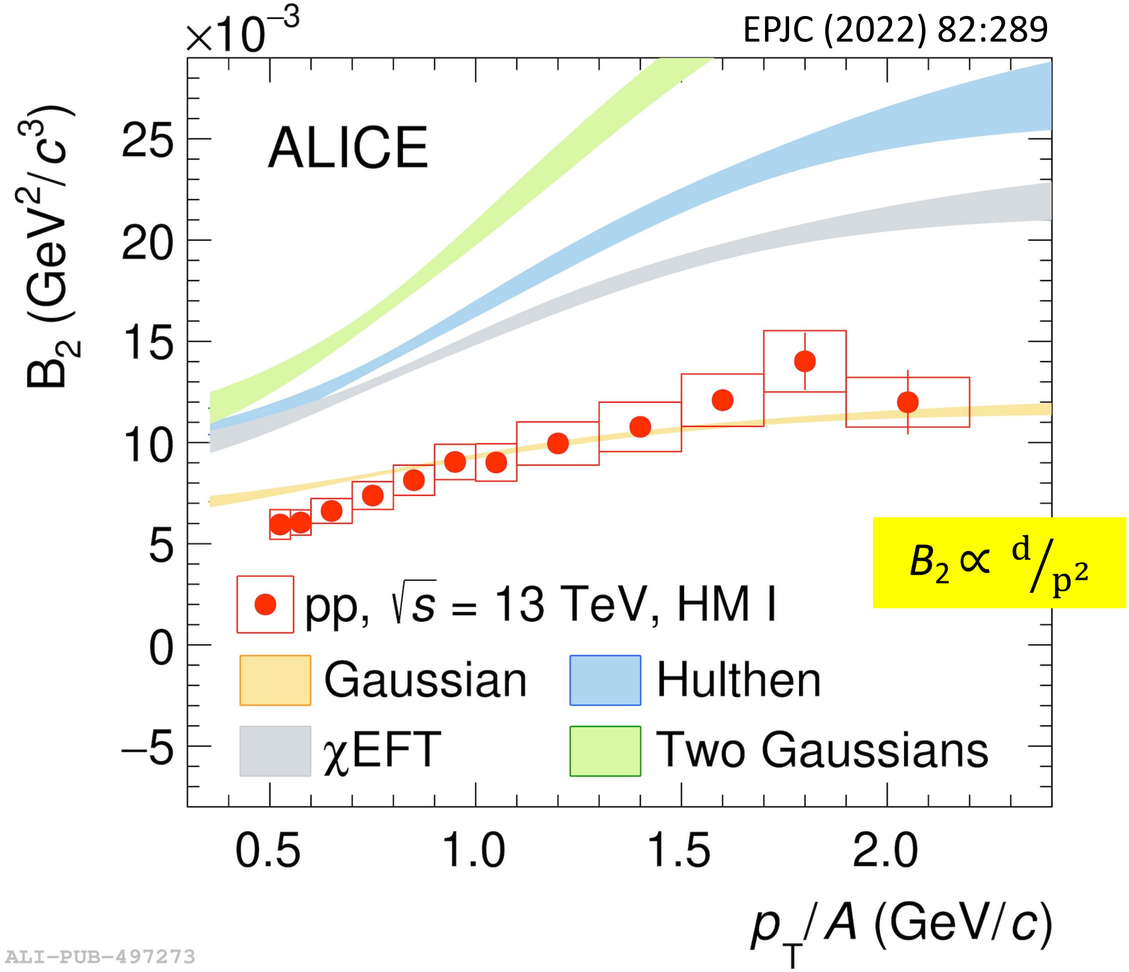
*See talk by M. Korwieser on Tue. 14/06

Testing coalescence model

HM pp @ 13 TeV

B_A measurements sensitive to the nuclear wave function

- HM data sample also used for the precise measurement of the source radii



emission source size

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

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

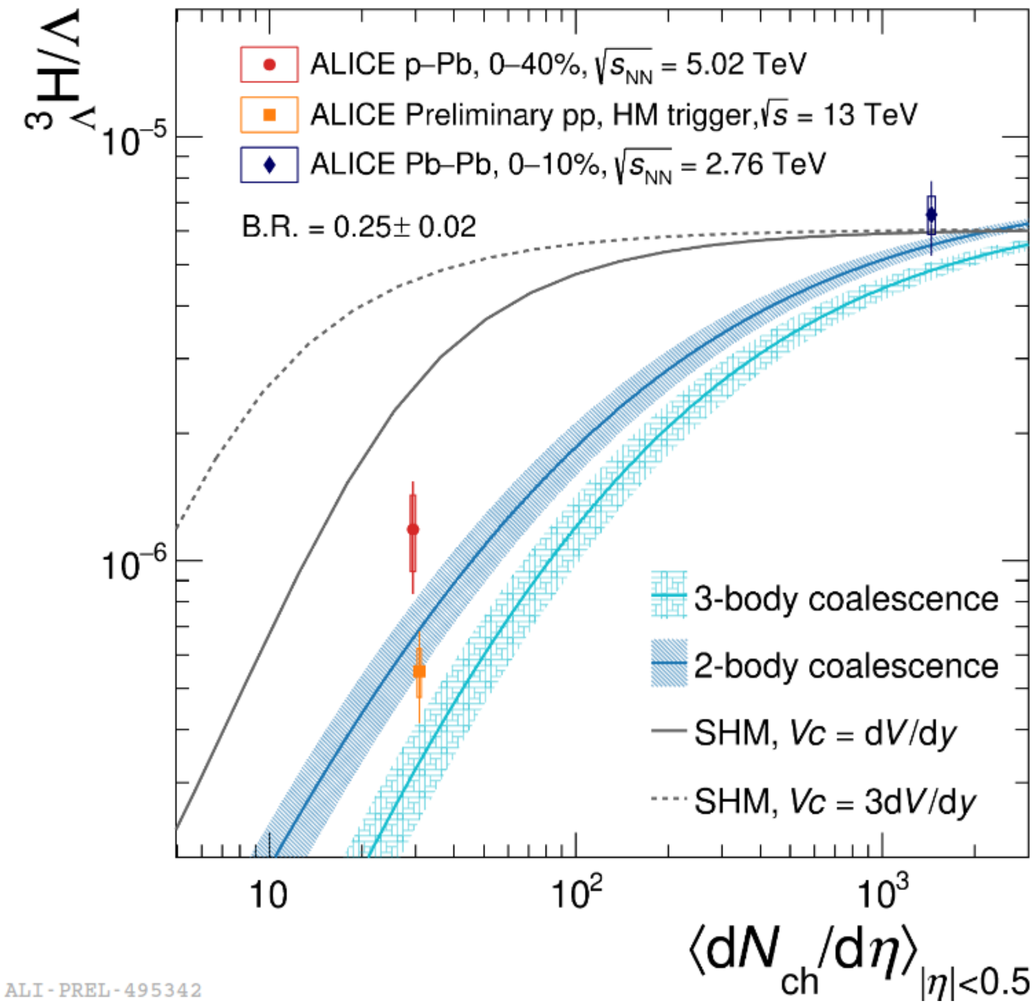
deuteron wave function (*size d = 3.2* fm)

Different wave functions are tested:

- **Hulthen**: favoured by low-energy scattering experiments
- **Gaussian**: best description of currently available ALICE data

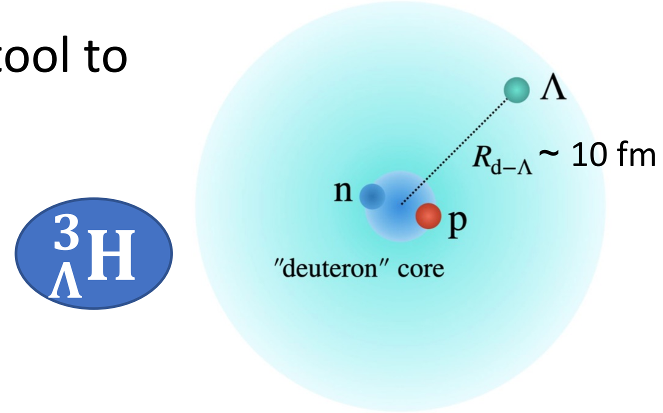
Blum, Takimoto, PRC 99 (2019) 044913
Scheibl, Heinz, PRC 59 (1999) 1585-1602
Kachelrieß et al., EPJA 1 (2020) 4

Hypertriton production



p—Pb: arXiv:2107.10627 (accepted by PRL)
Pb—Pb: PLB 754 (2016) 360-372

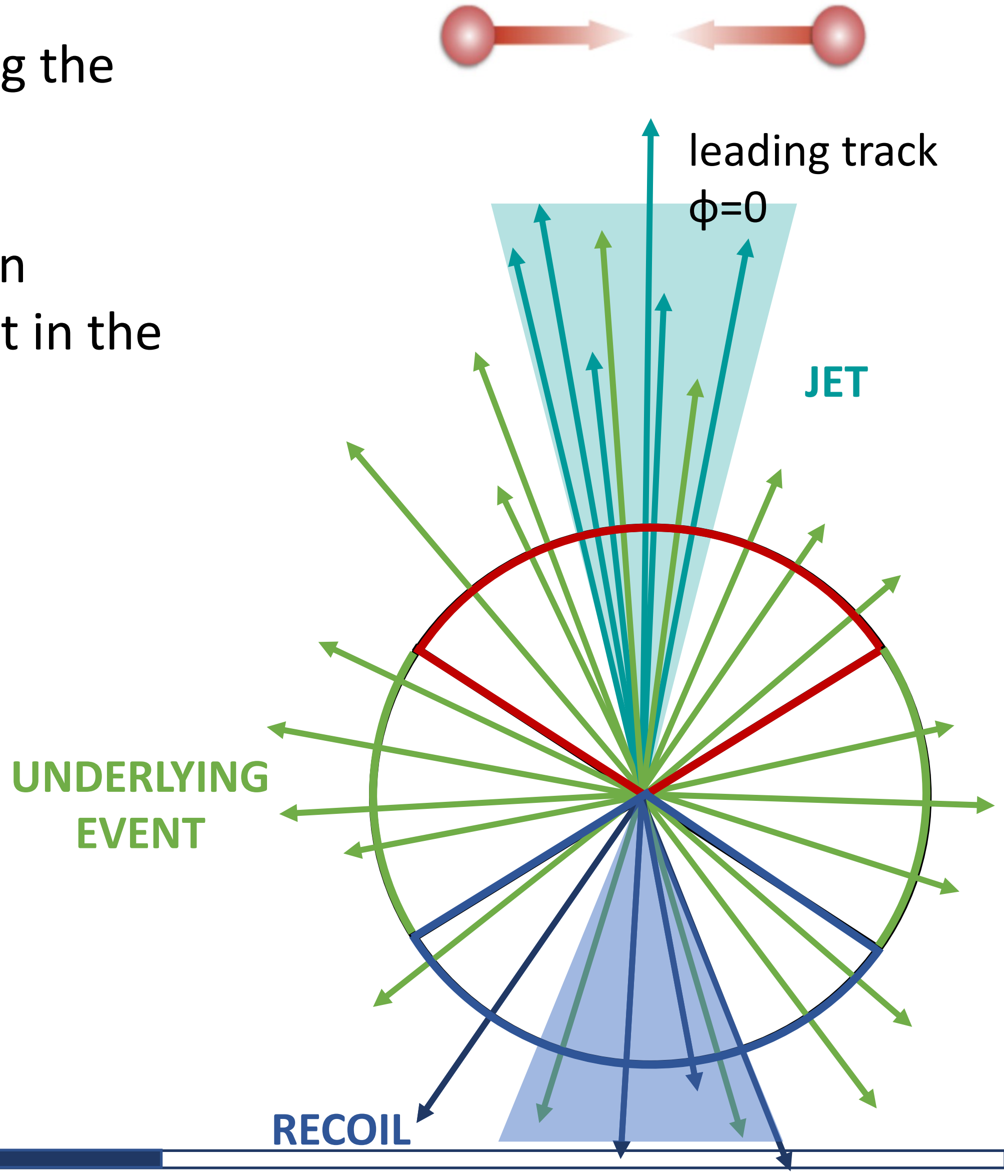
$^{3}_{\Lambda}$H/Λ ratio provides a powerful tool to investigate nuclear production mechanism



- **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

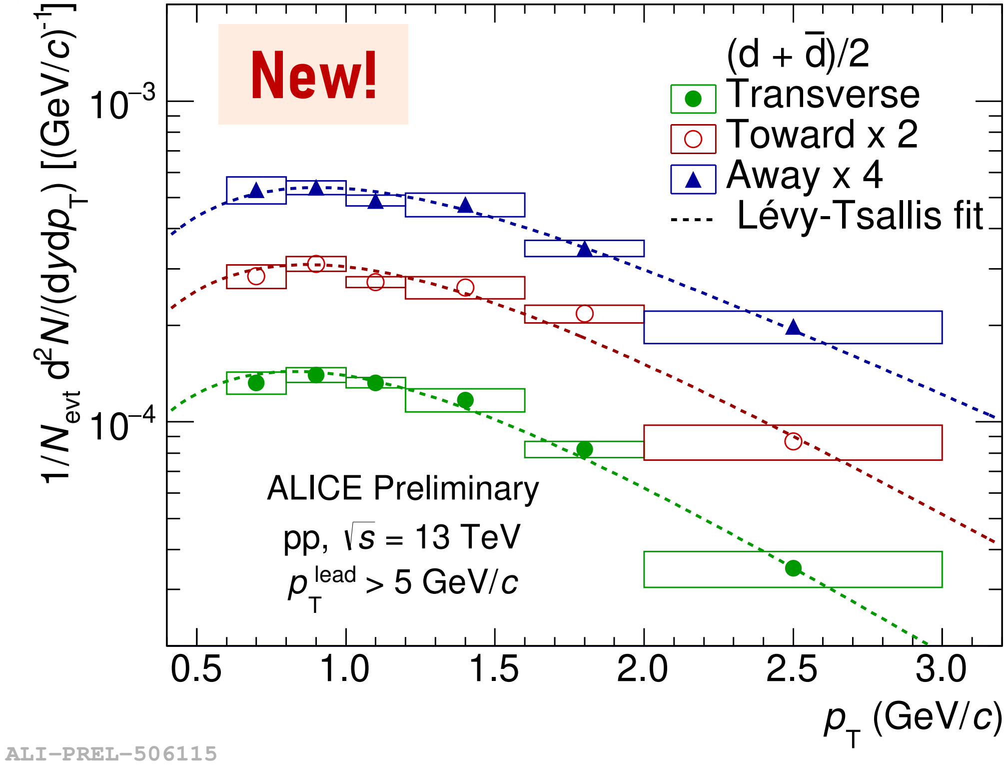
Underlying event activity

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

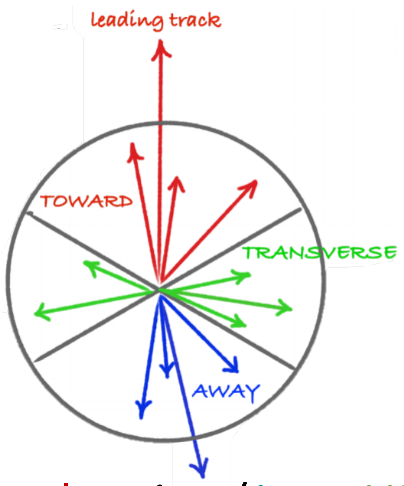


Martin et al., EPJC (2016) 76: 299

Deuteron spectra vs azimuthal regions

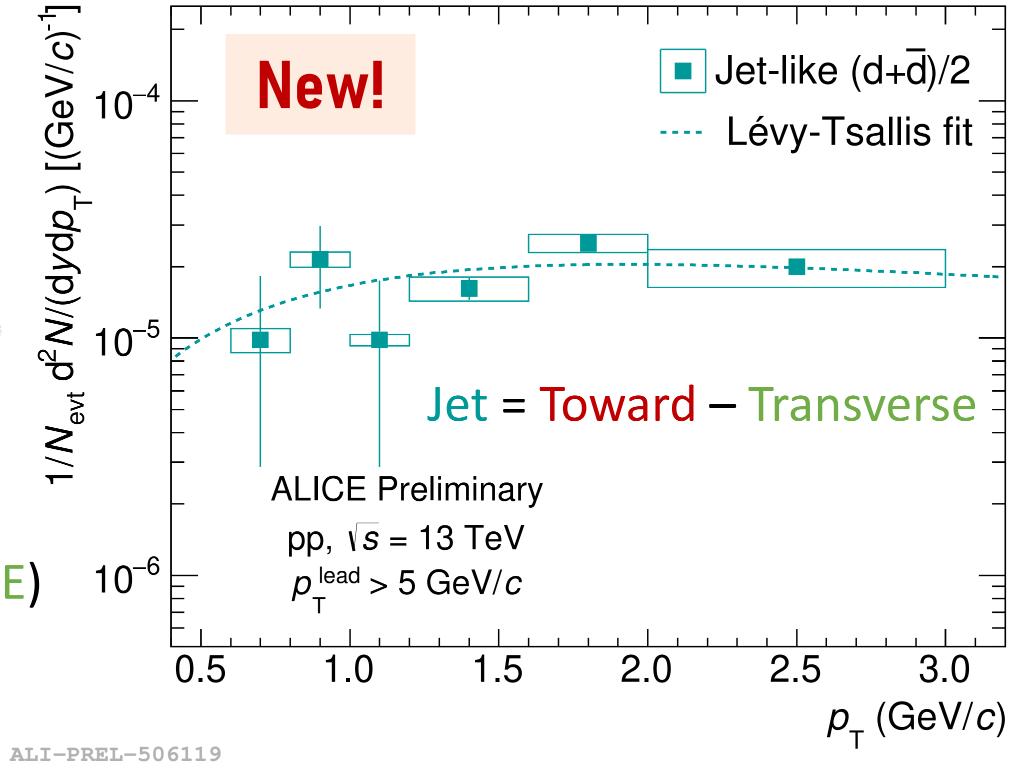


pp @ 13 TeV



Toward region (Jet + UE)

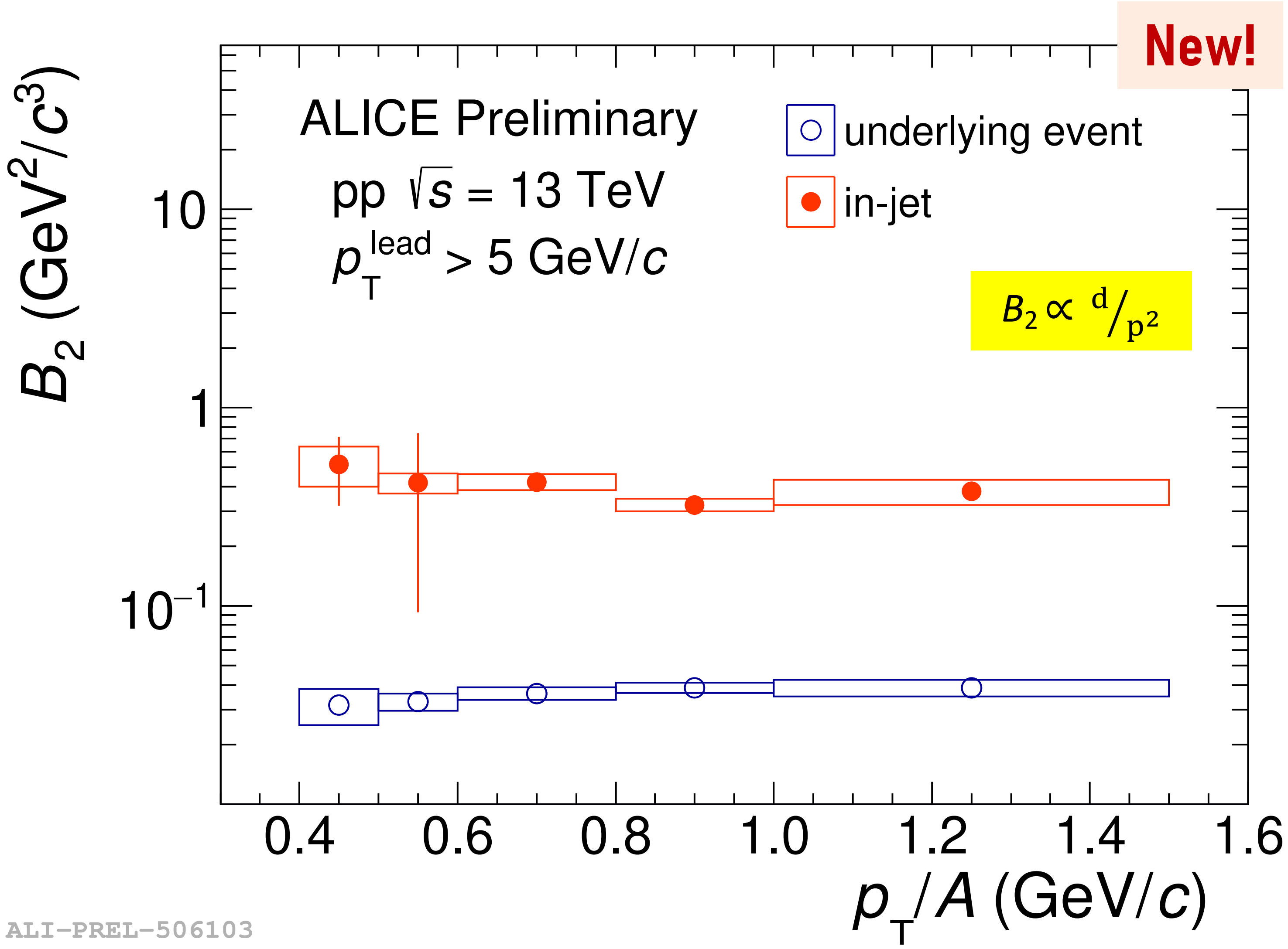
Transverse region (UE)



- Deuteron production from events with a jet: $p_T^{lead} > 5$ GeV/c
- Jet: ~10% of total production

→ The majority of deuterons is produced in the underlying event

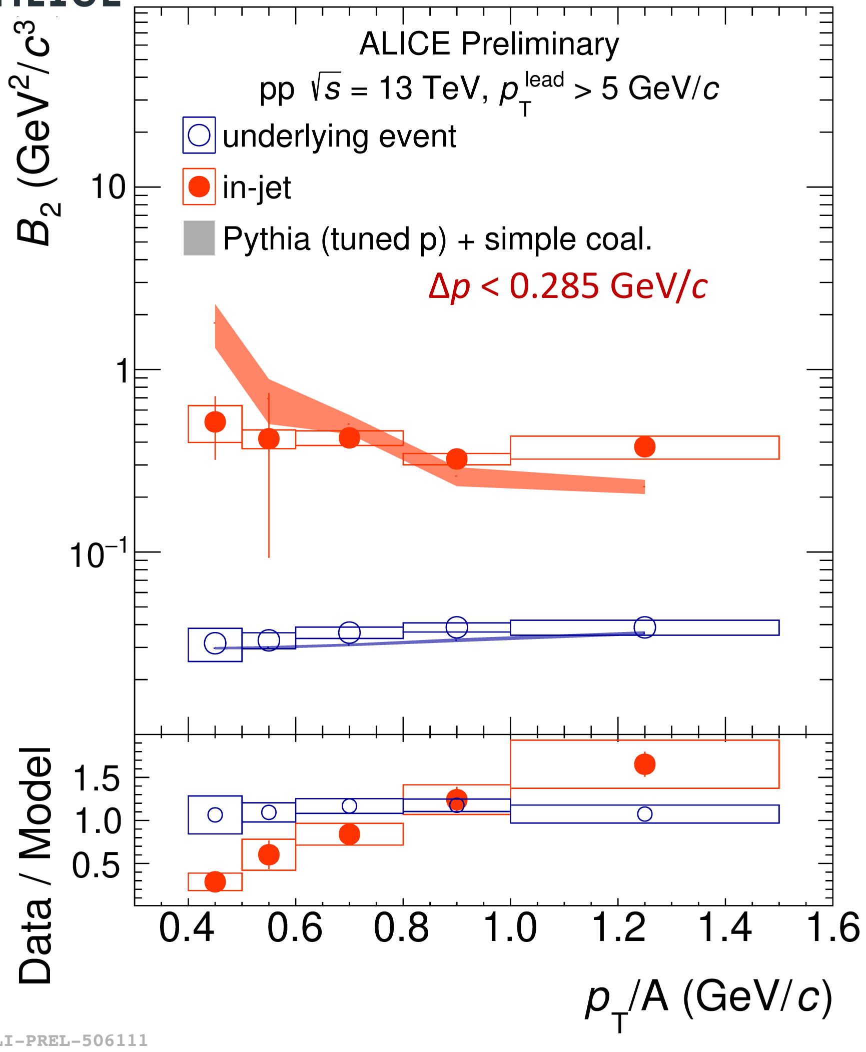
Deuteron coalescence in and out of jets



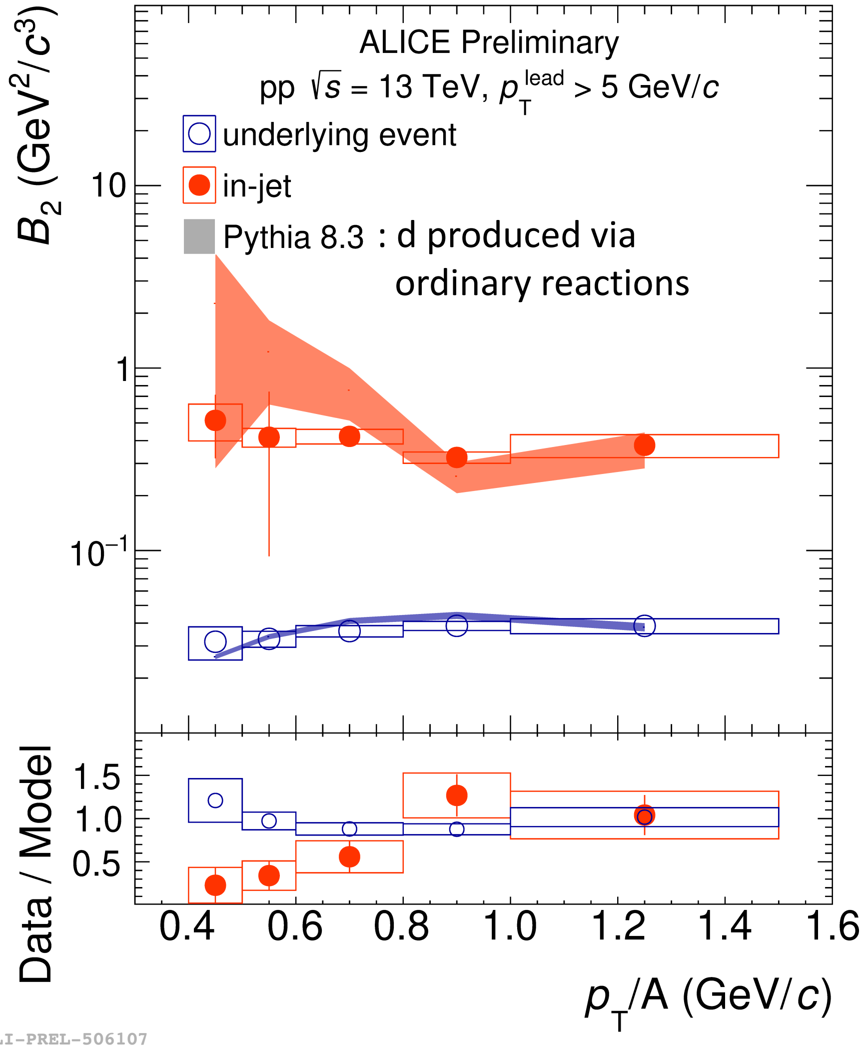
- B_2 parameter flat vs p_T/A → in agreement with simple coalescence
- B_2 in-jet ~ 15 times larger than B_2 in UE

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

Comparison with PYTHIA simulations



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

New!

PYTHIA 8: Skands et al., EPJC 74 (2014) 8, 3024
PYTHIA 8.3: Bierlich et al., arXiv:2203.11601

Summary

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

- Deuteron coalescence probability $\boldsymbol{B_2}$ **in HM pp collisions**
  - test coalescence model using several wave functions

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

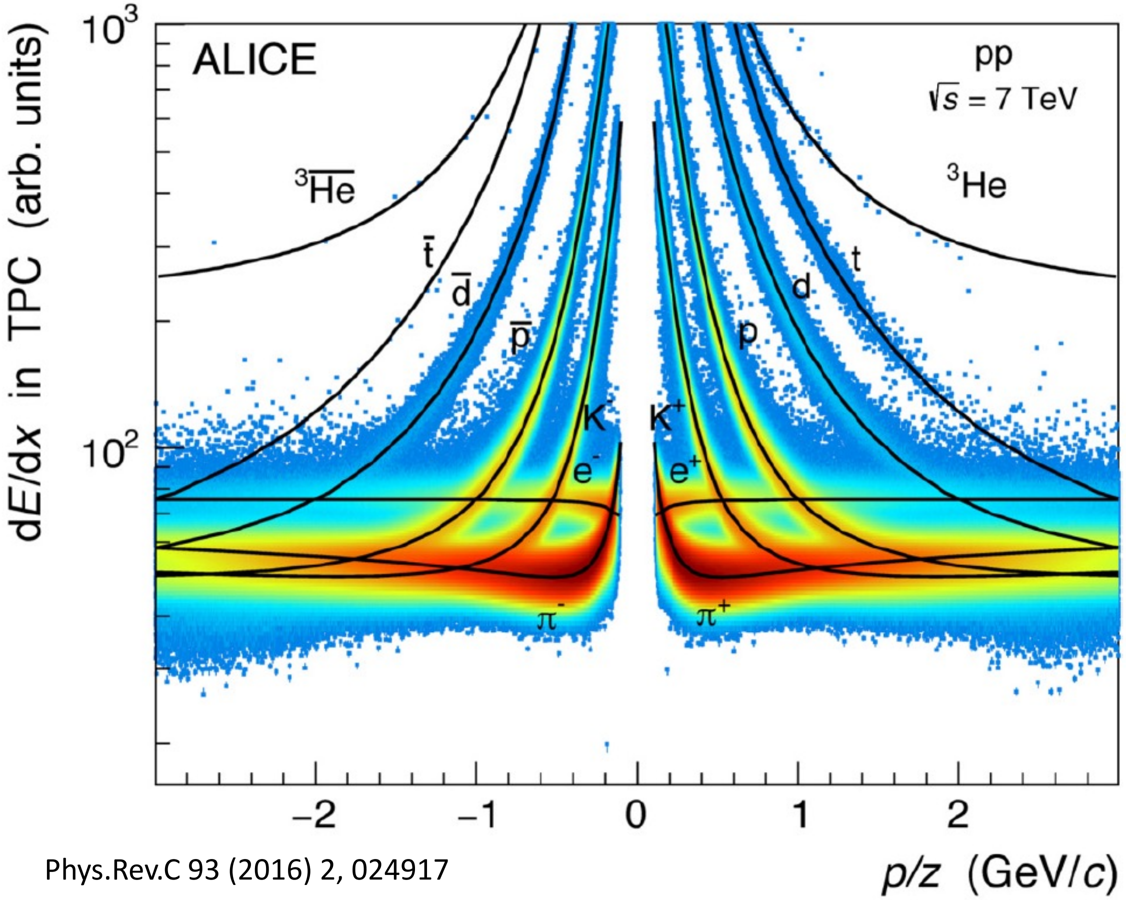
- Deuteron coalescence probability $\boldsymbol{B_2}$ **in and out of jets**
  - enhanced coalescence probability in the jet wrt UE by one order of magnitude is observed
  - agreement with coalescence picture

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

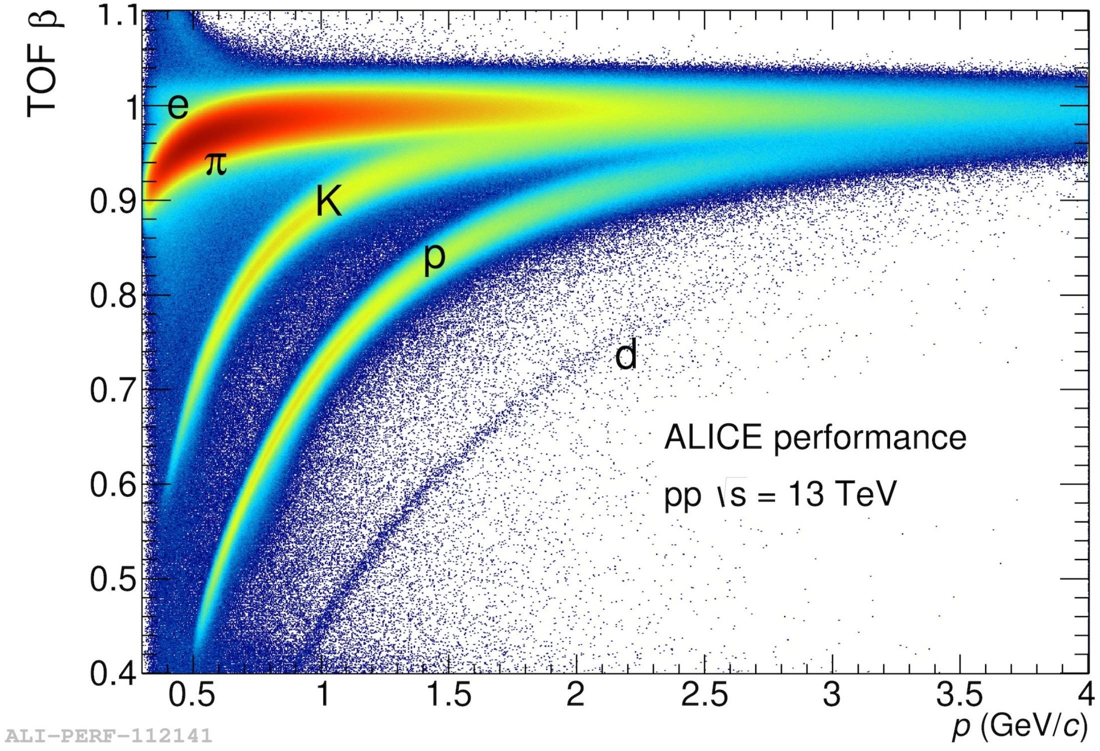
Backup

Nuclei identification

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



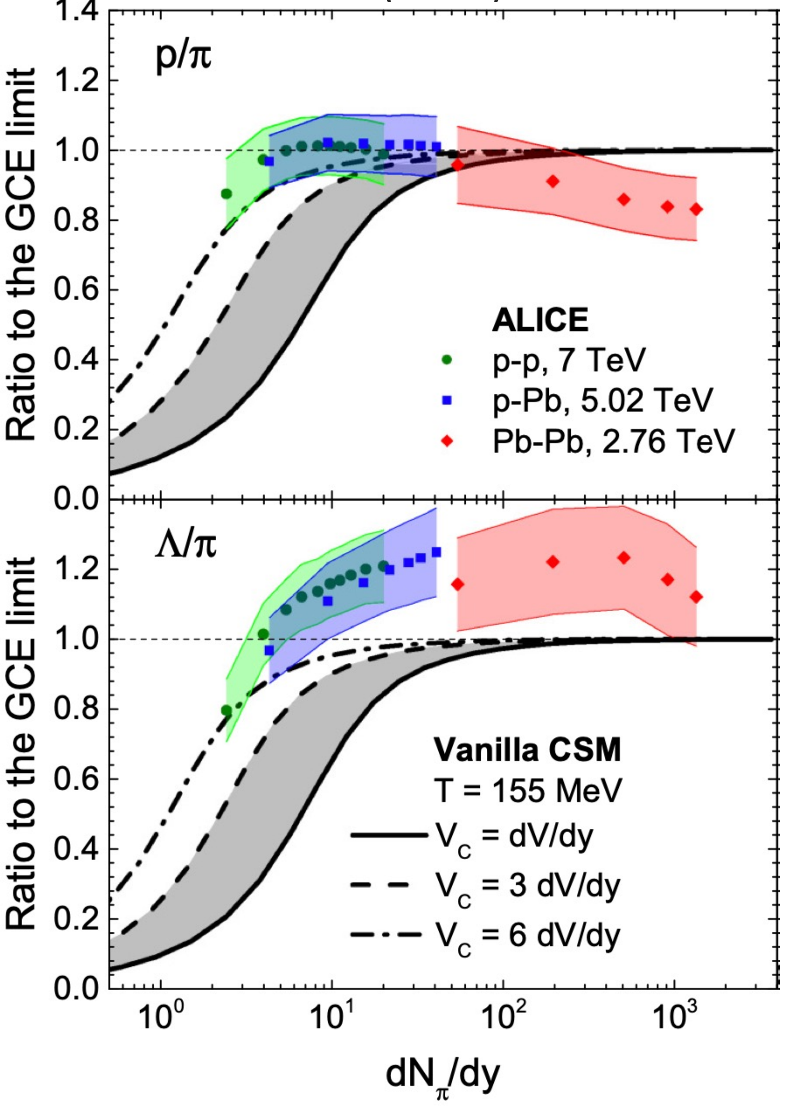
Phys.Rev.C 93 (2016) 2, 024917



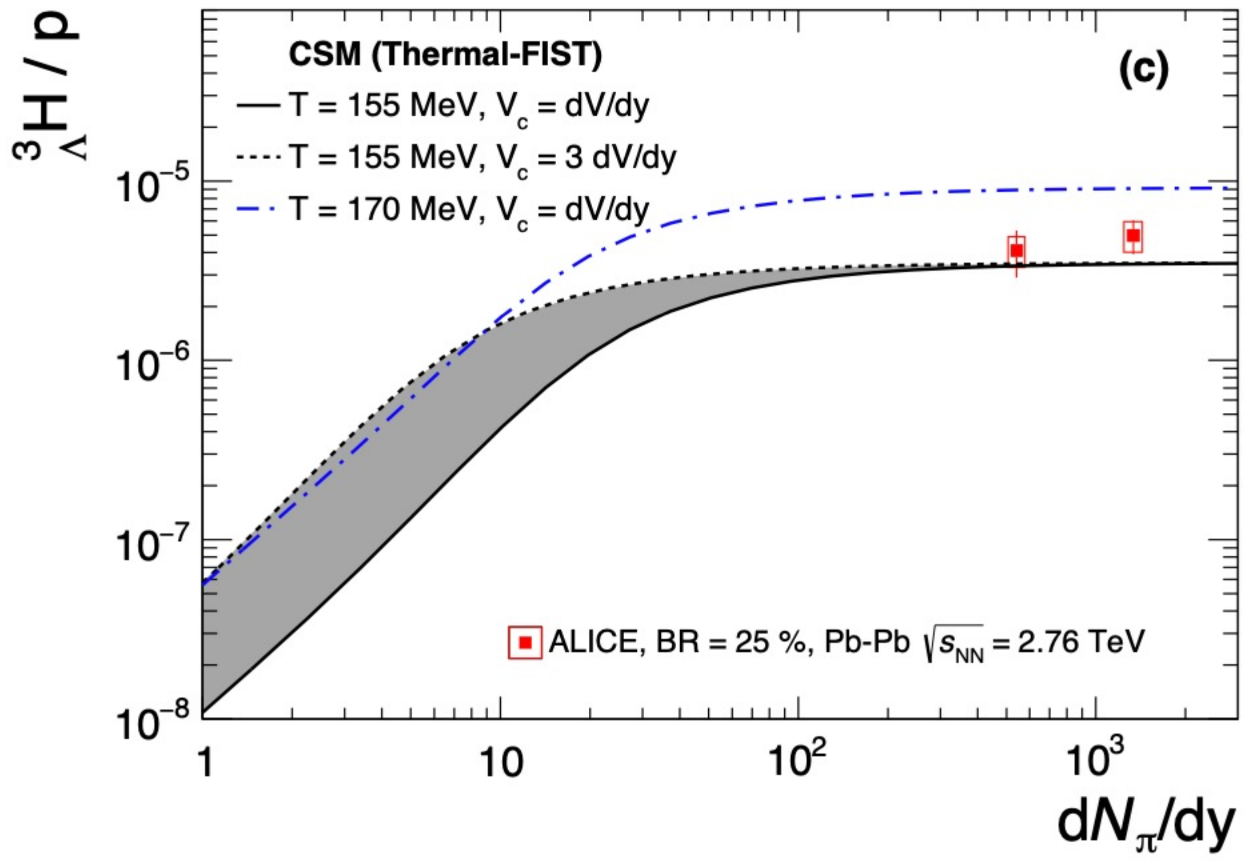
Higher *p* region (above 1 GeV/*c*) → PID via velocity β measurements in TOF

SHM predictions for particle yields

PRC 100 (2019) 054906



Vanilla SHM predicts the yield of hypertriton but underestimates the yield of Lambdas



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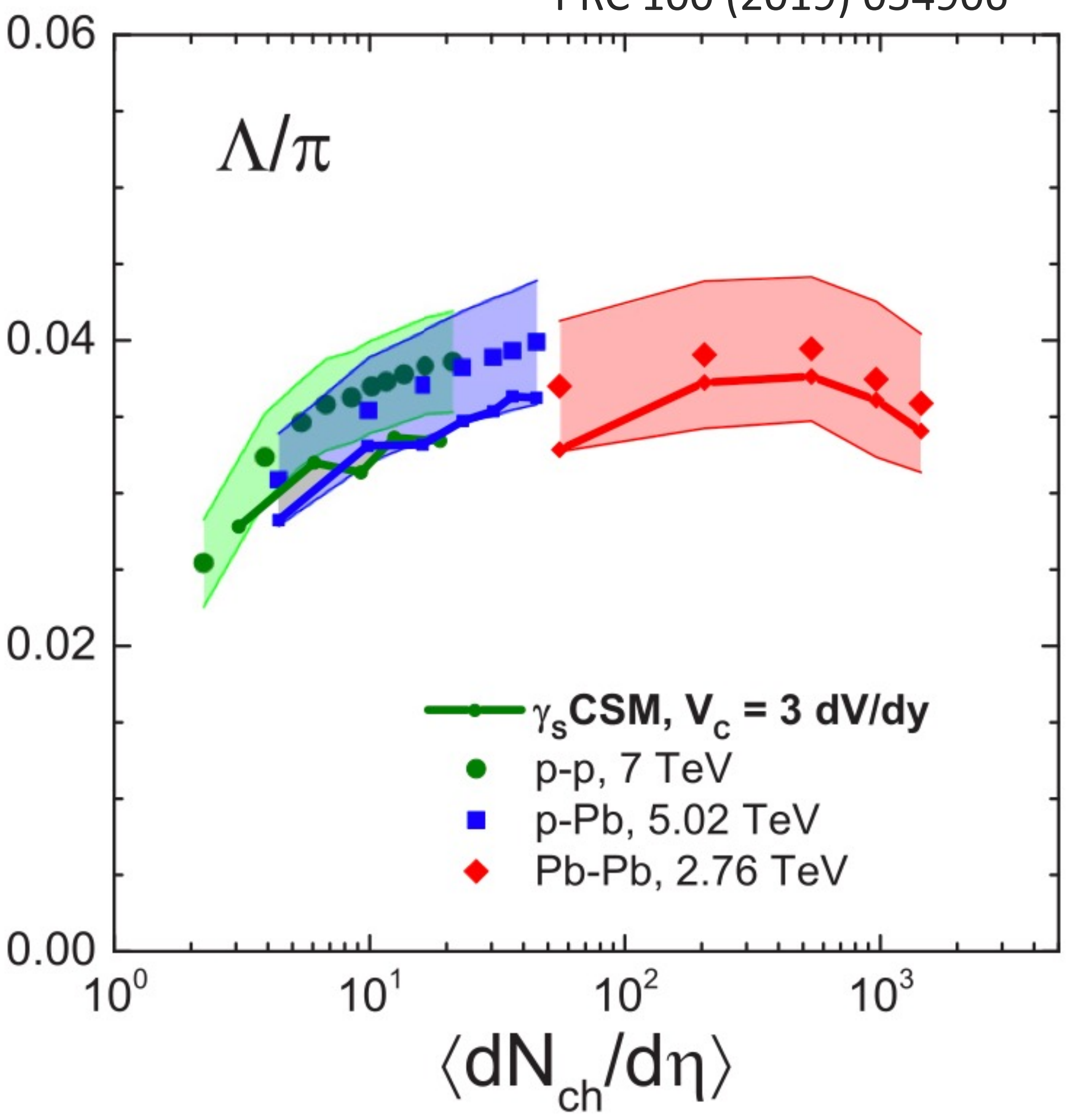
SHM predictions for particle yields

gammaS*-implementation of SHM predicts also the yield of Lambdas, for all systems

This implementation of SHM:

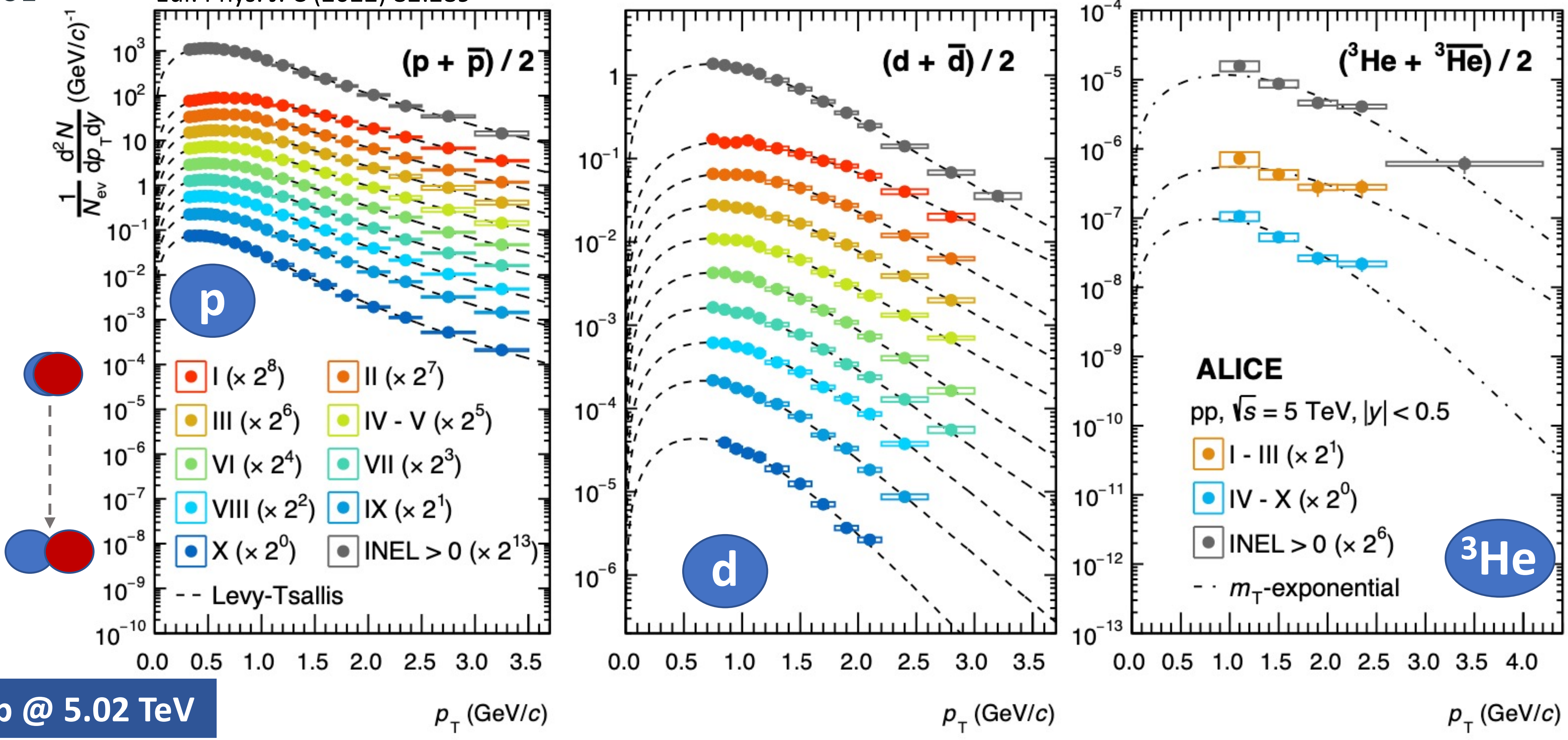
- incorporates the incomplete equilibration of strangeness by introducing the strangeness saturation factor gammaS
- accounts for the multiplicity-dependent chemical freezeout temperature

PRC 100 (2019) 054906



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

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

$p + n \rightarrow \gamma + d$

$p + n \rightarrow \pi^0 + d$

$p + n \rightarrow \pi^0 + \pi^0 + d$

$p + n \rightarrow \pi^+ + \pi^- + d$

$p + p \rightarrow \pi^+ + d$

$p + p \rightarrow \pi^+ + \pi^0 + d$

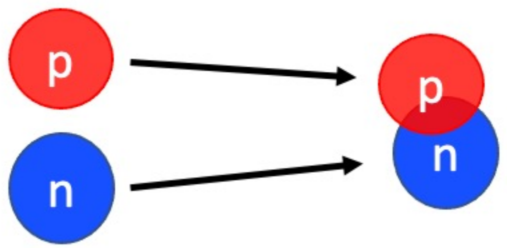
$n + n \rightarrow \pi^- + d$

$n + n \rightarrow \pi^- + \pi^0 + d$

2. Pythia 8 + simple coalescence

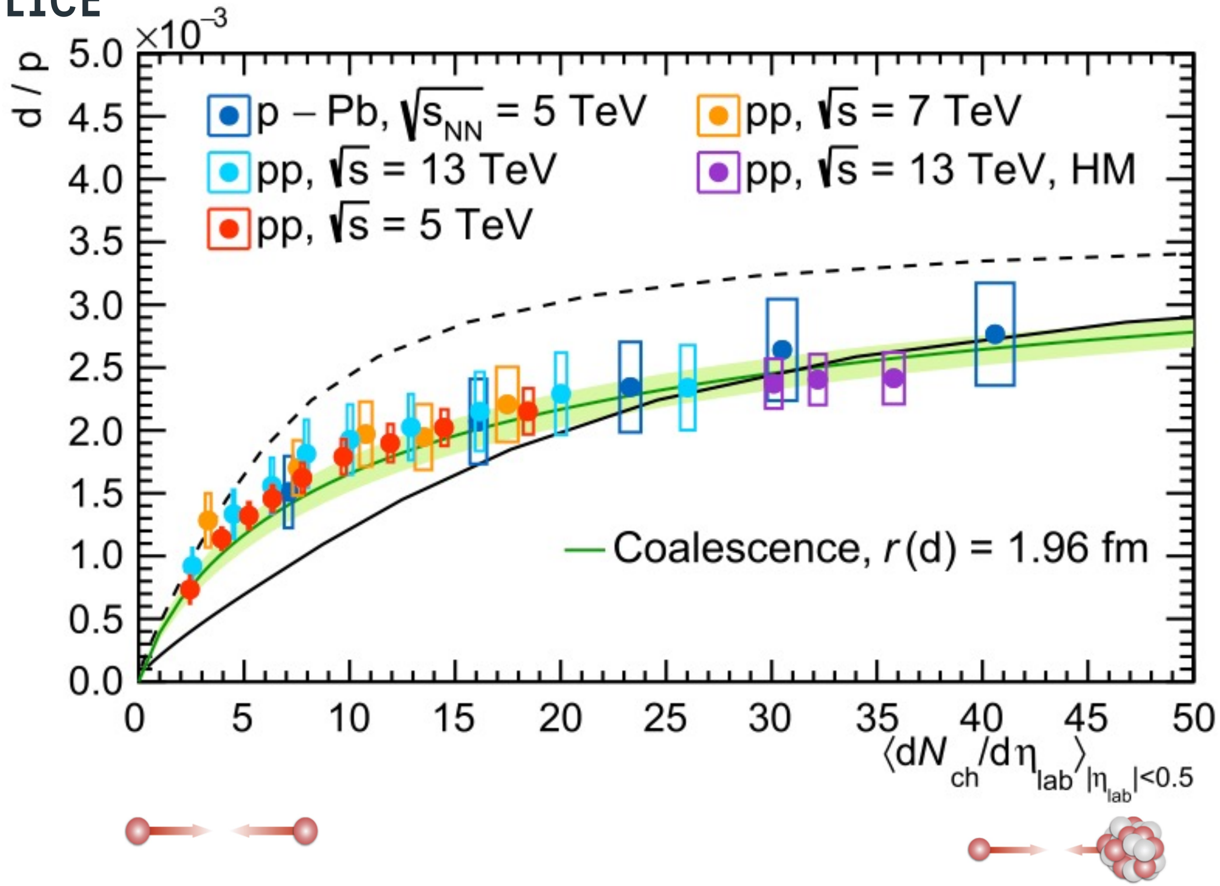
- $\Delta p < p_0$

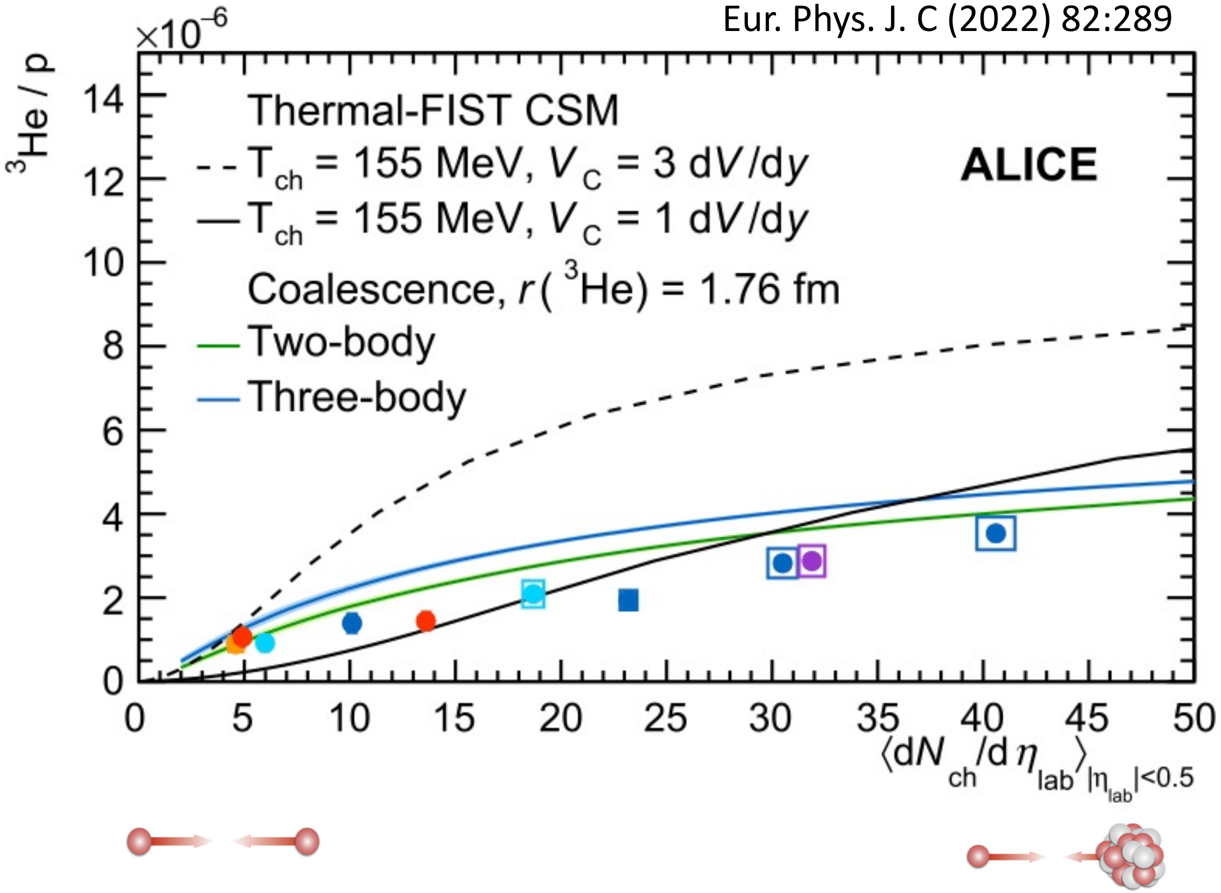
Skands et al., EPJC 74 (2014) 8, 3024



Model comparisons in small systems

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

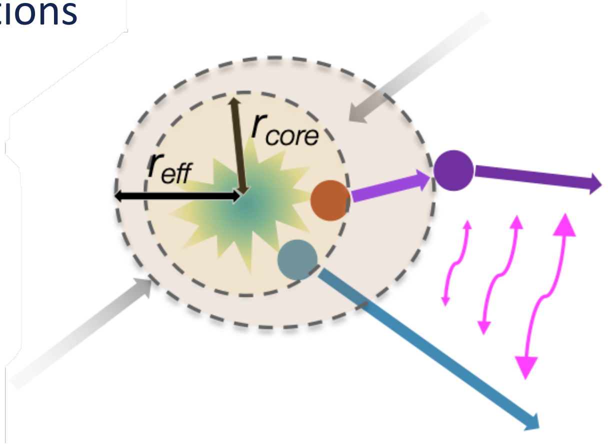


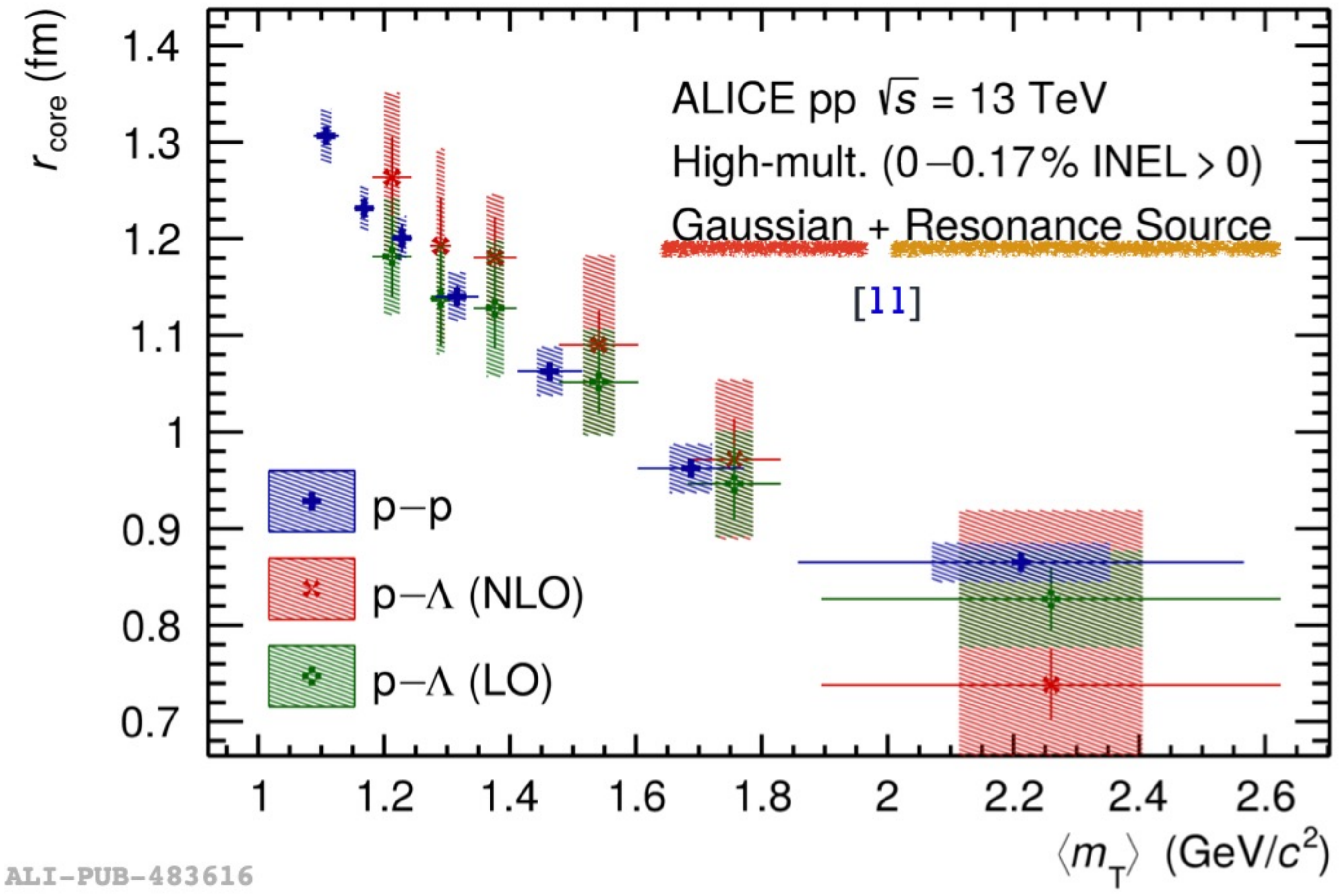


- Light nuclei production seems to depend only on multiplicity → smooth transition across different collision systems and energies
- Coalescence favored in d/p integrated yield ratios
- Results challenge the models for A=3 nuclei

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



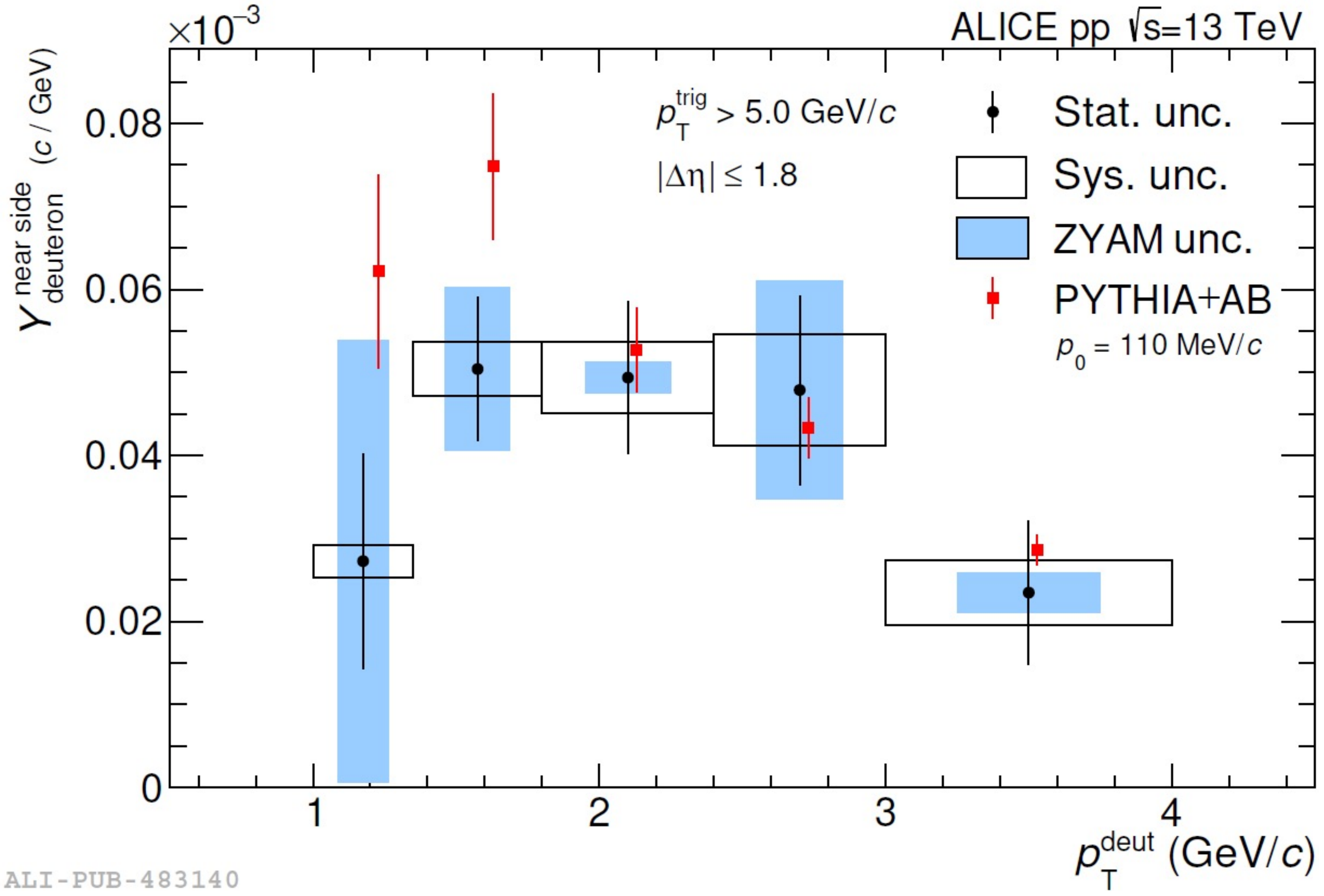


PLB 811 (2020) 135849

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

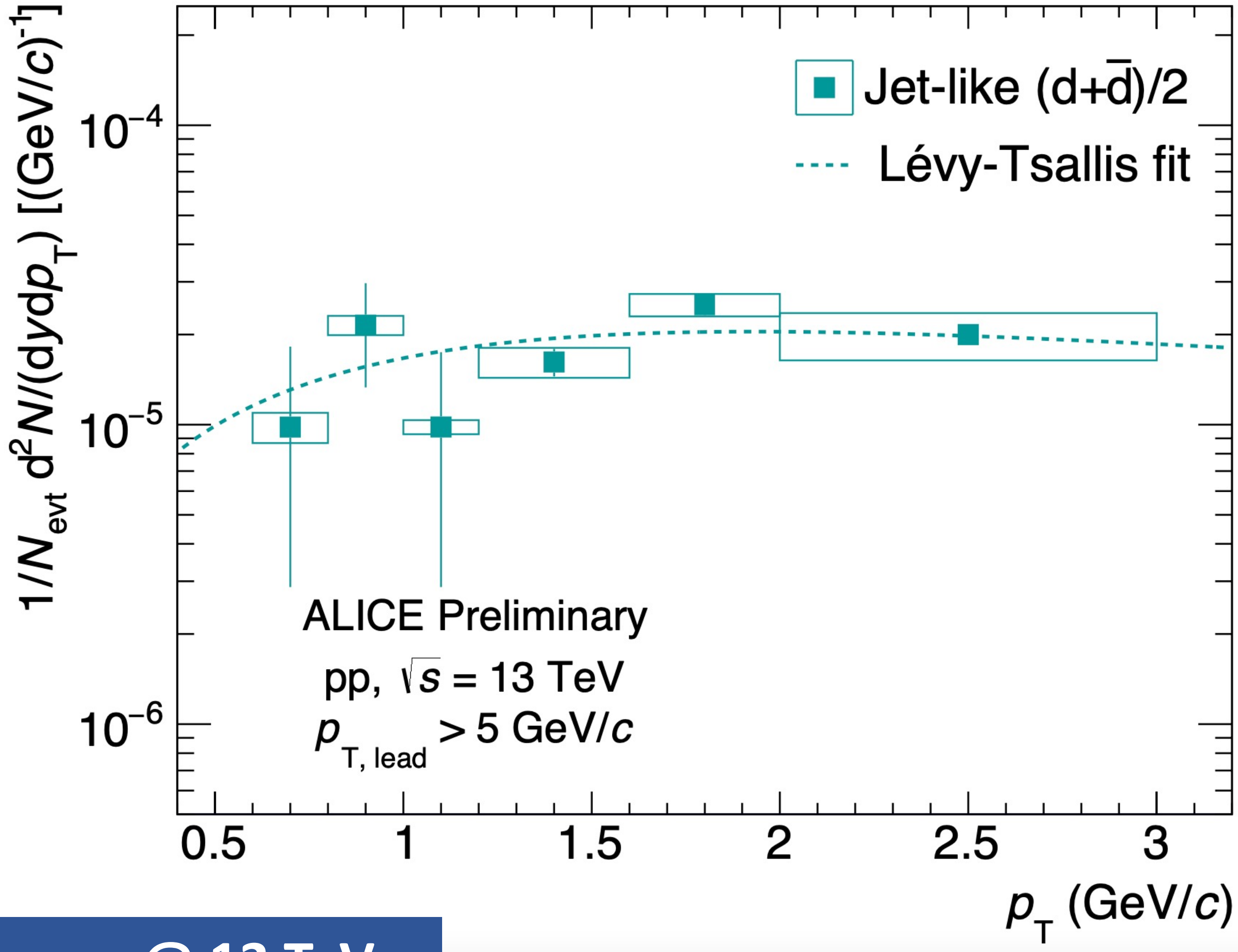
→ Towards region contains a large contribution from UE



pp @ 13 TeV

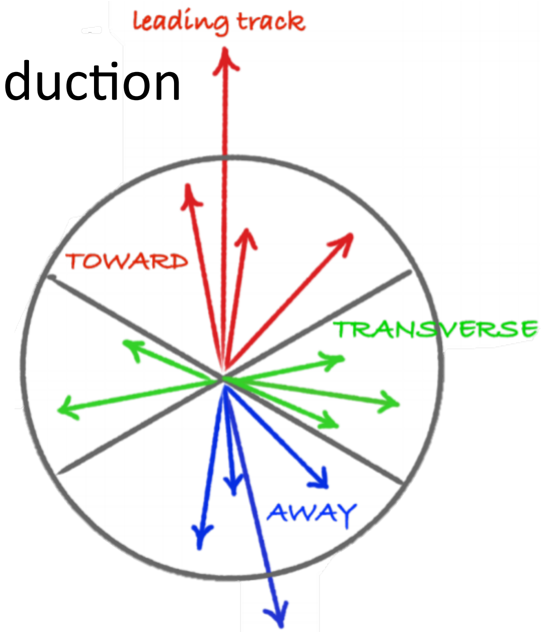
Phys.Lett.B 819 (2021) 136440

Jet-like deuteron spectrum



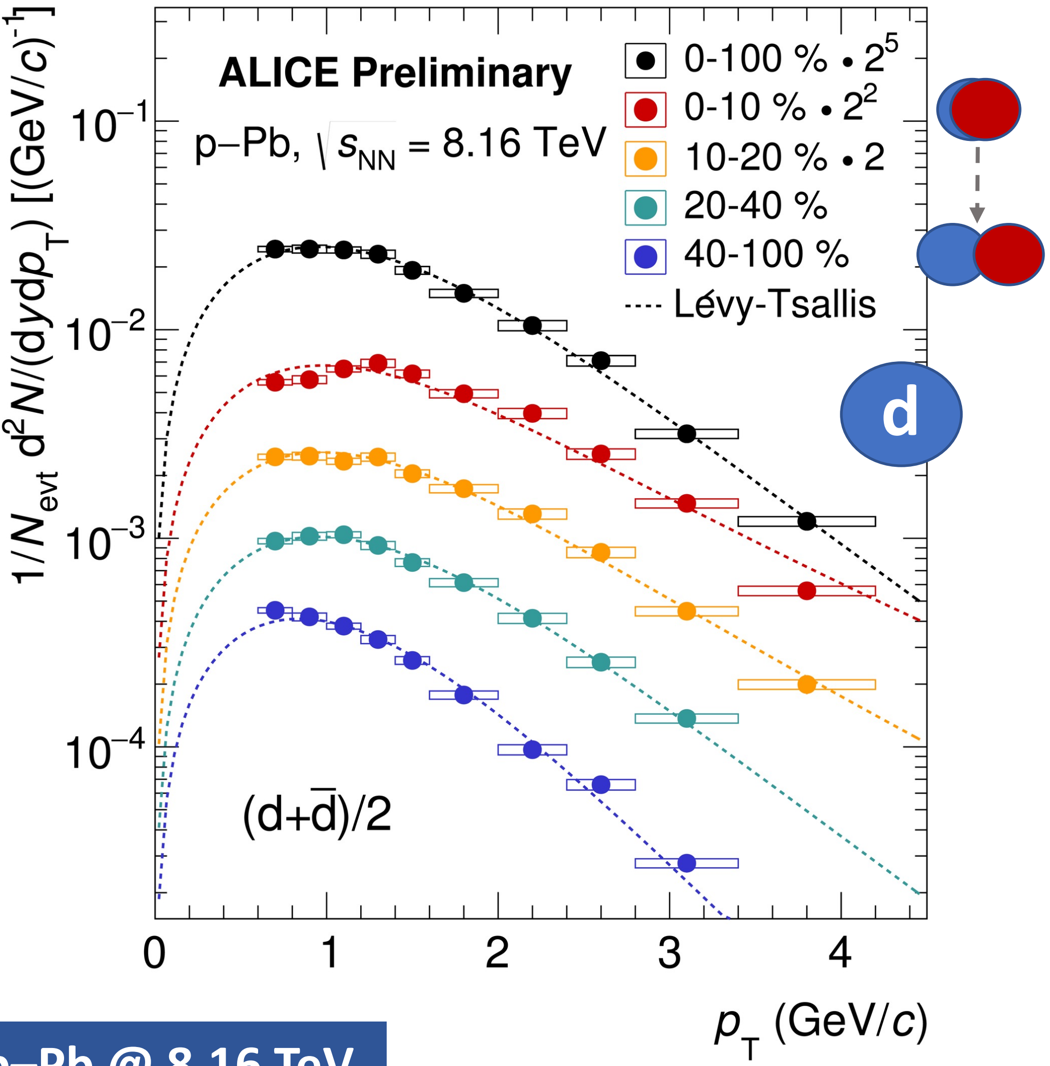
- Jet-like spectrum can be easily obtained by subtracting the UE from the Toward region (Jet + UE)
- Results consistent with the the two-particle correlation method [Phys.Lett.B 819 (2021) 136440]
- Jet: ∼10% of total production

Jet = Toward – Transverse

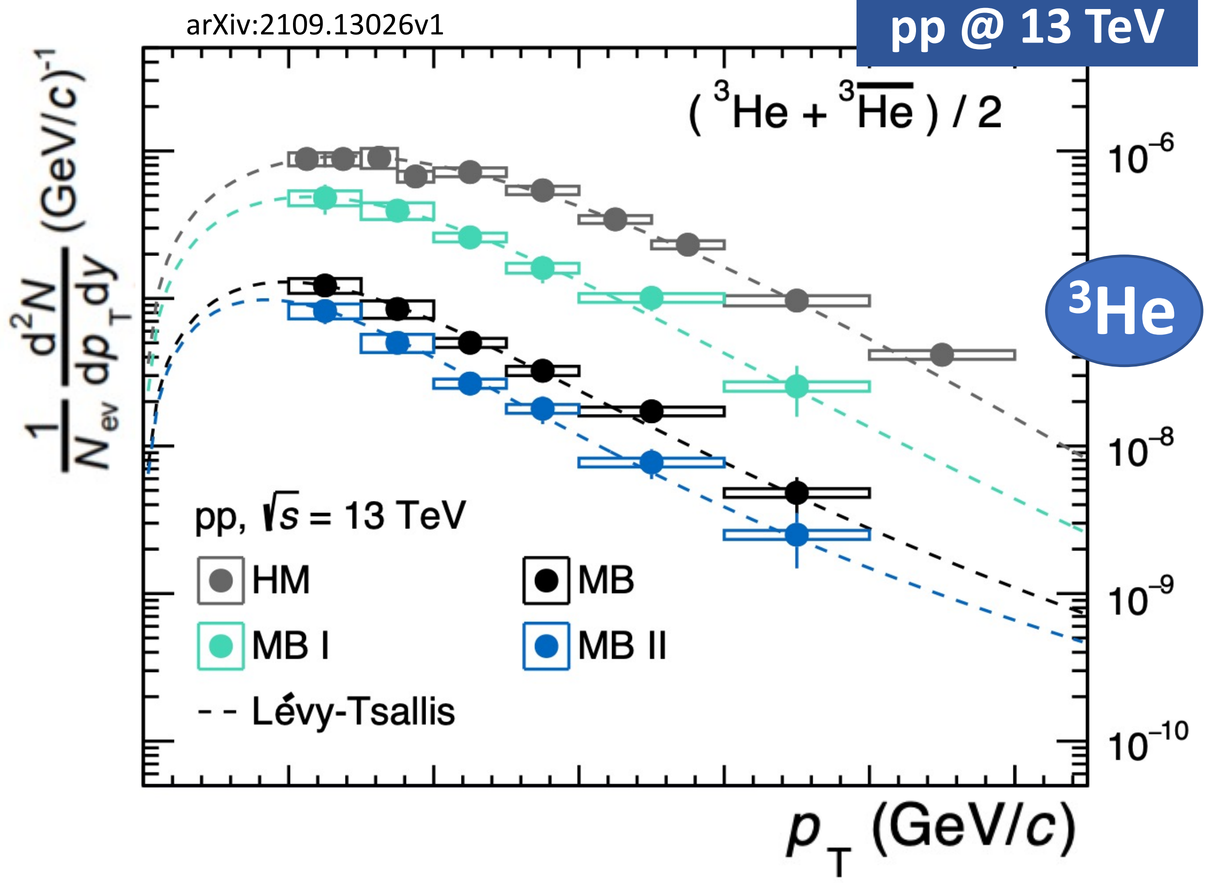


pp @ 13 TeV

Light (anti)nuclei in small systems

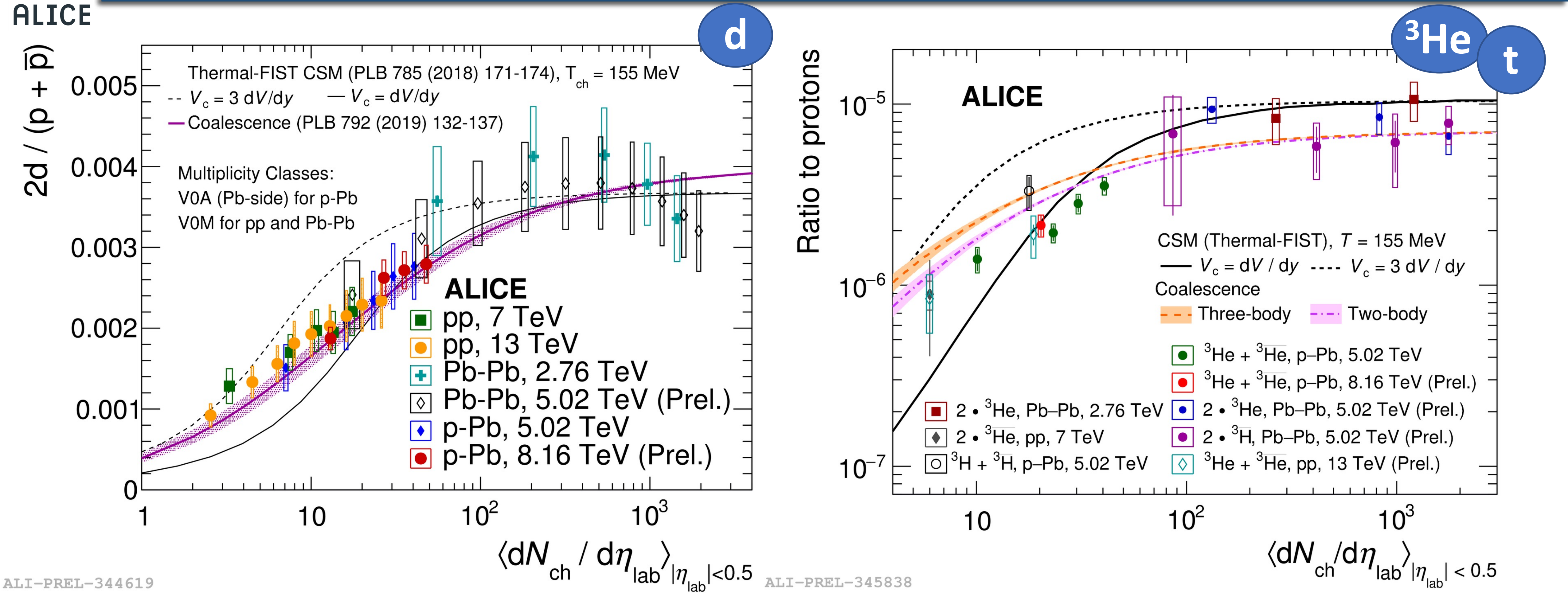


p–Pb @ 8.16 TeV



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

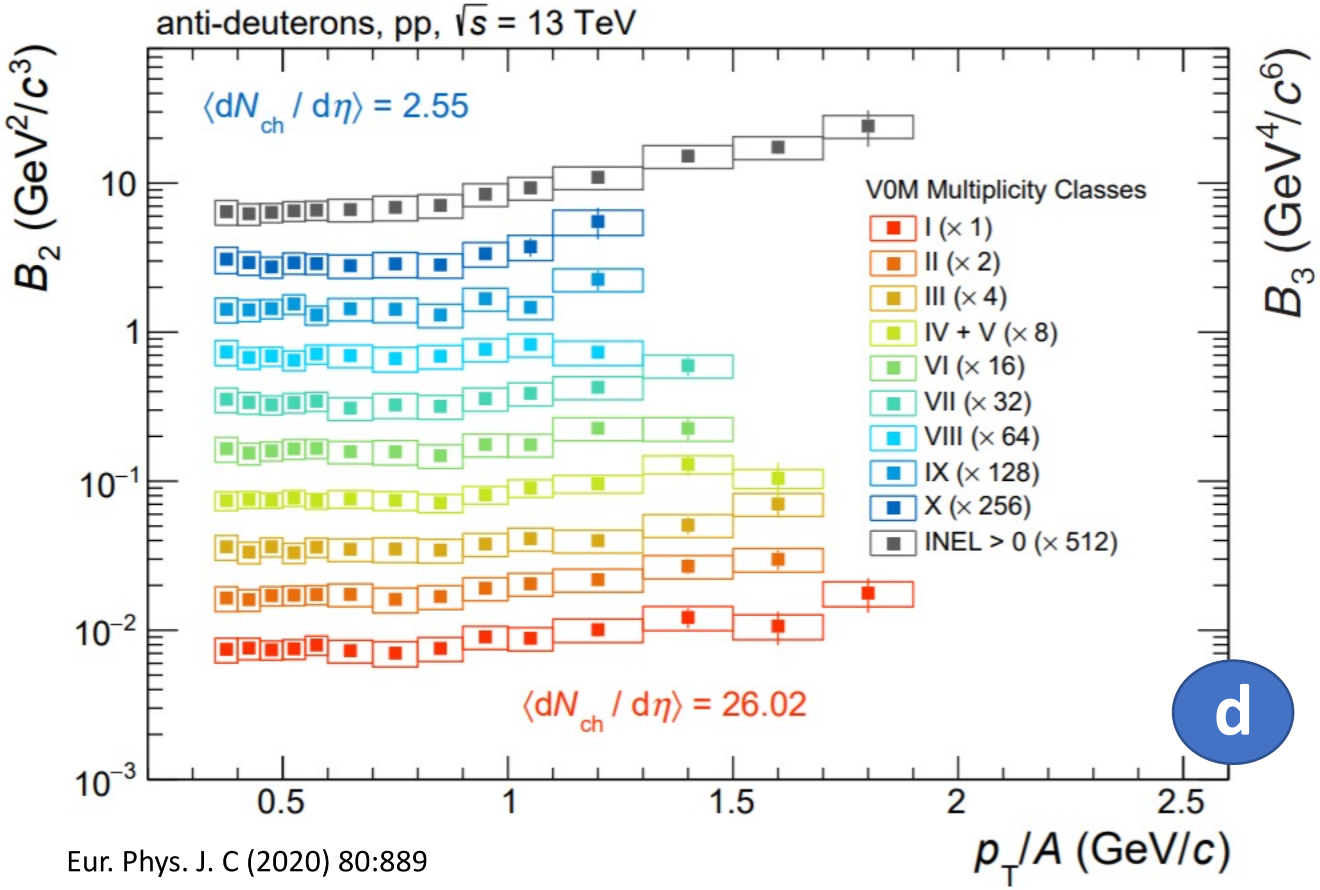
Ratio to protons – models comparison



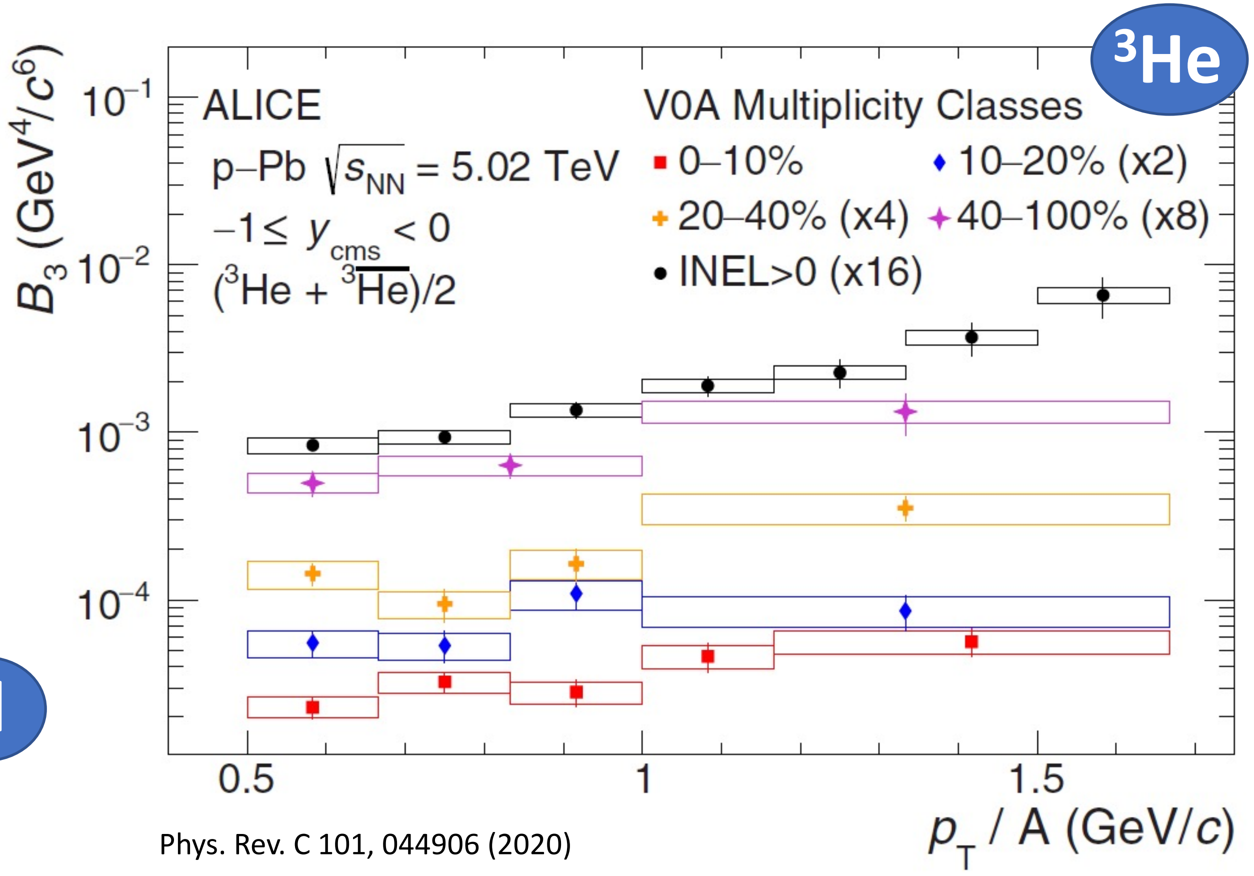
- Smooth transition across different collision systems and energies
- Light nuclei production seems to depend only on multiplicity
- Results challenge the models for A=3 nuclei

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

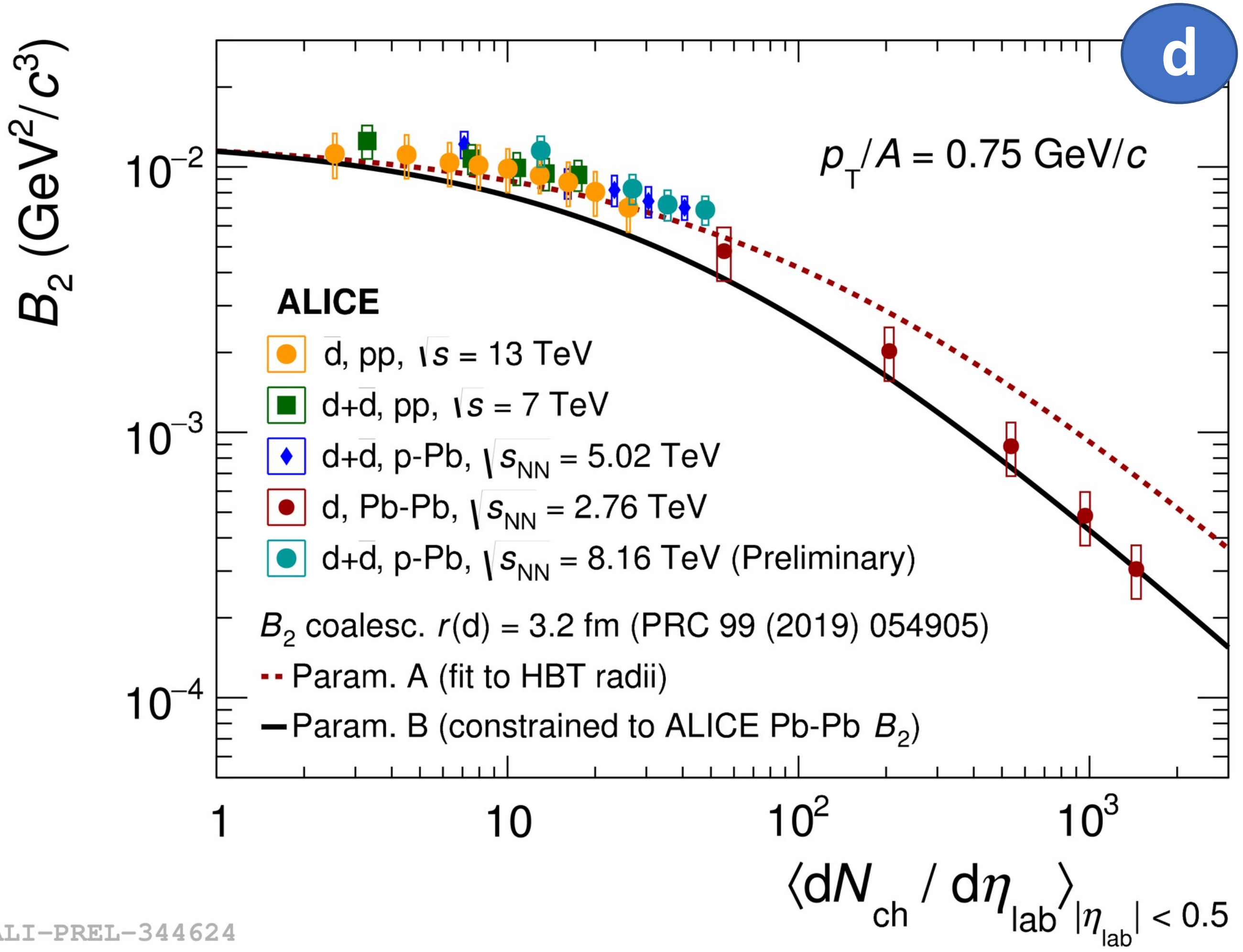


Phys. Rev. C 101, 044906 (2020)

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?

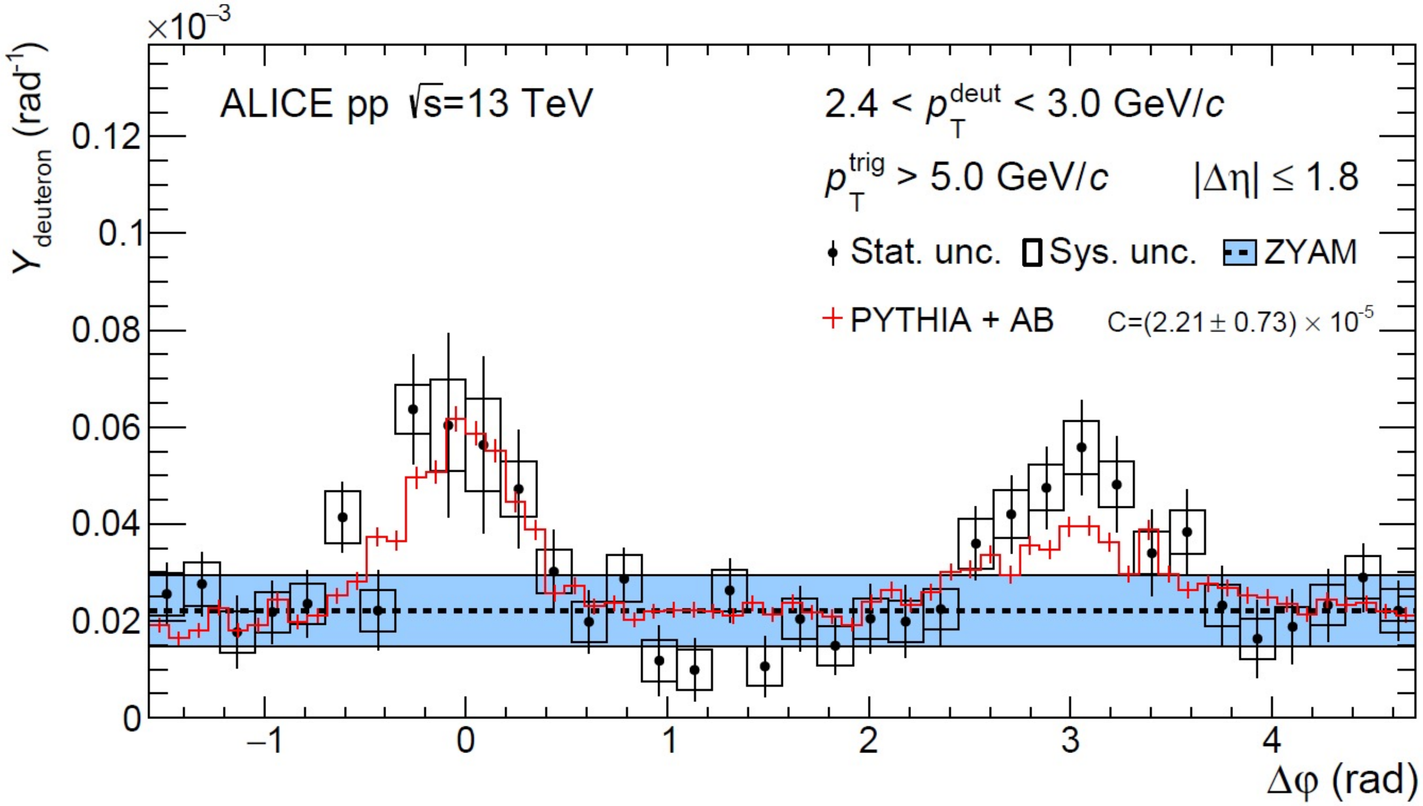
Similar conclusions apply also for B_3

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

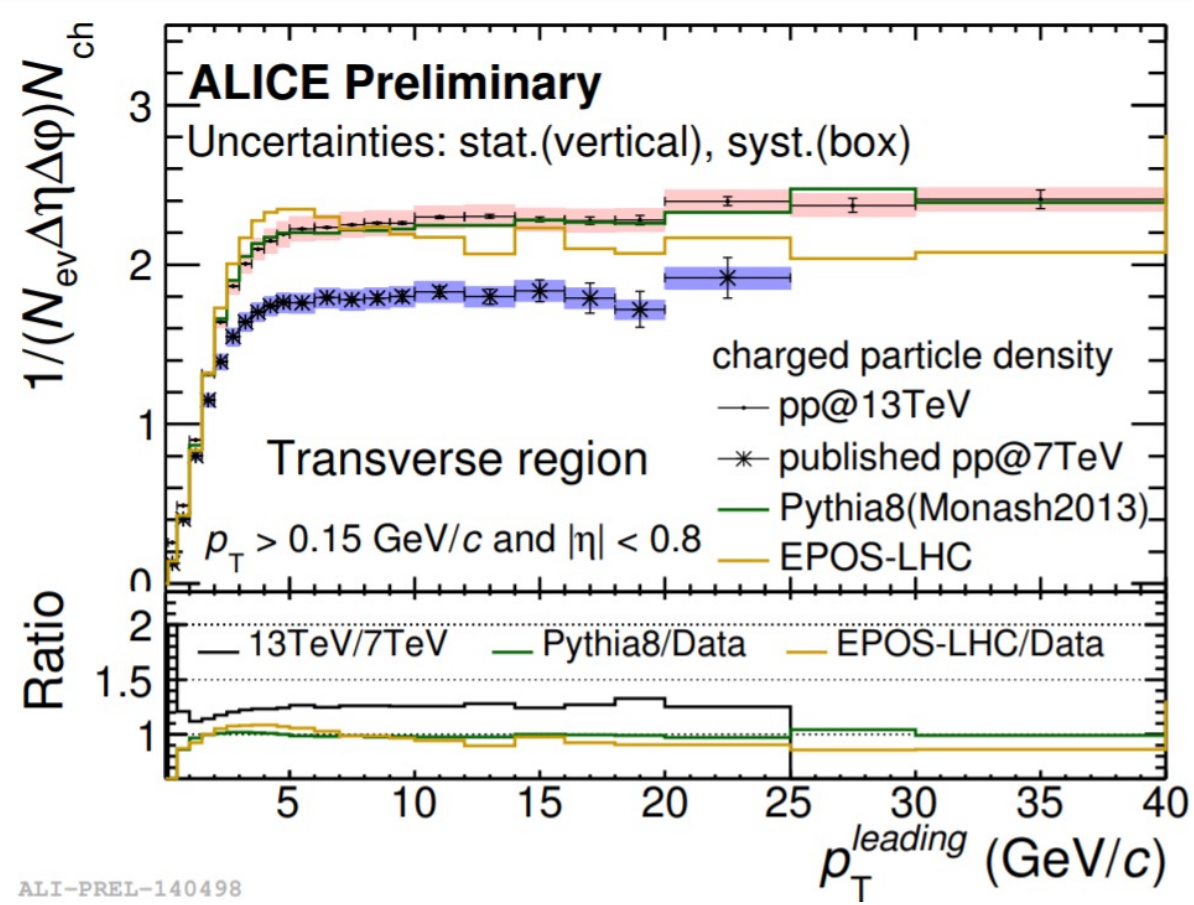


pp @ 13 TeV

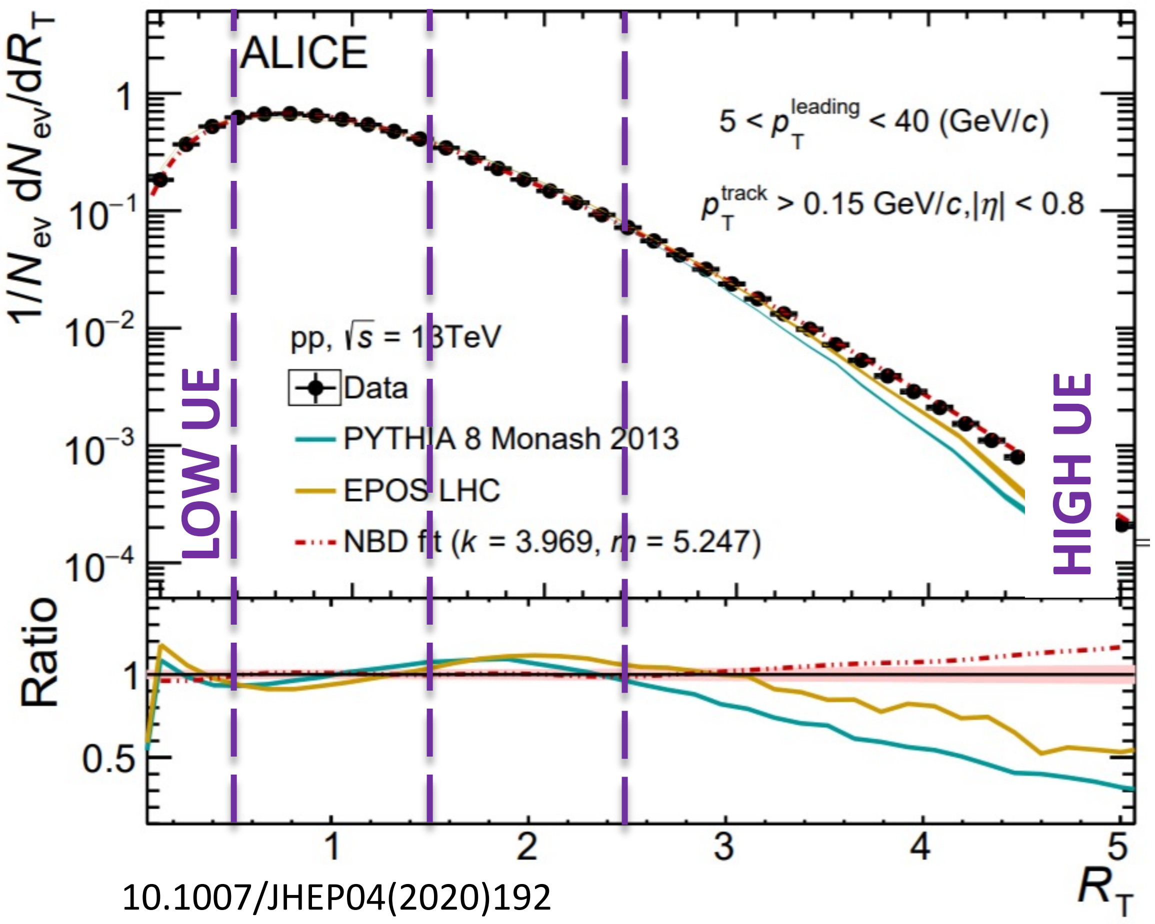
arXiv:2011.05898 [nucl-ex]

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

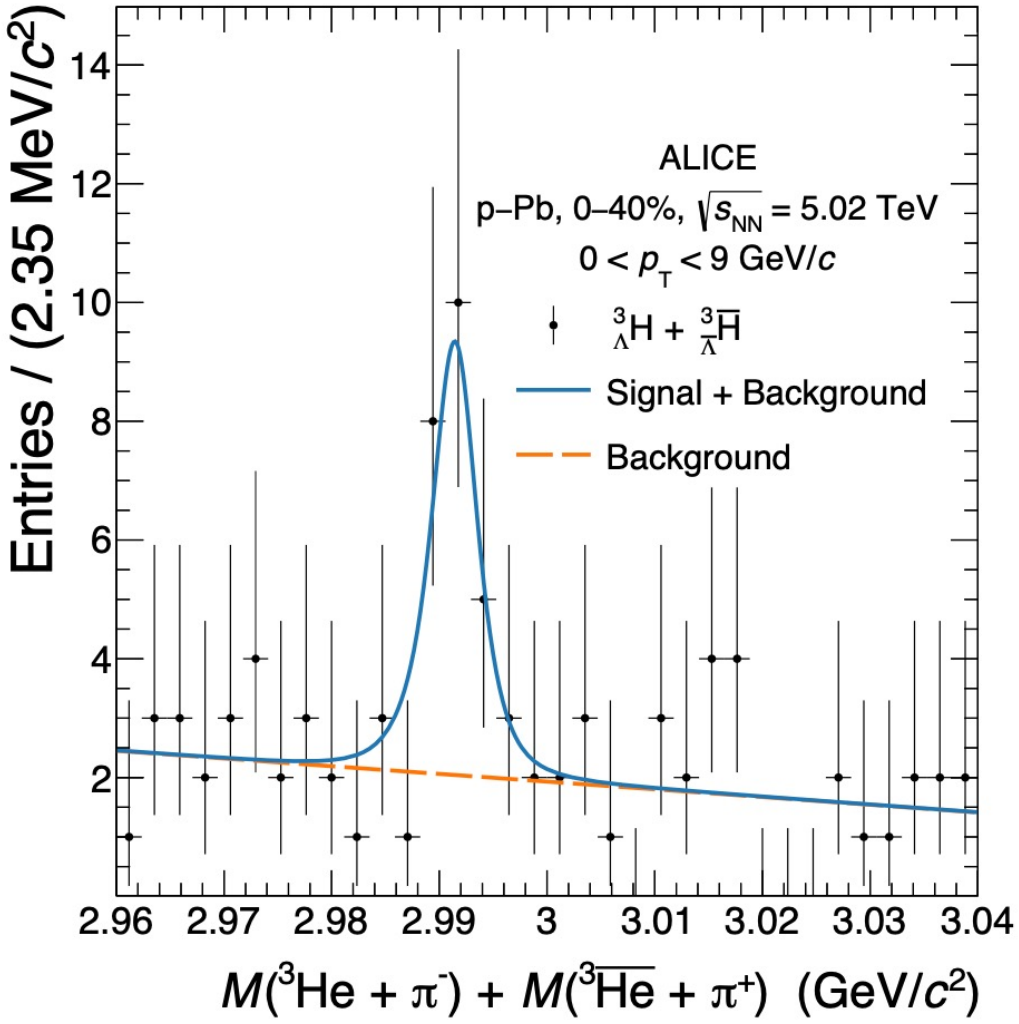


10.1007/JHEP04(2020)192

Hypertriton in small systems

- Data samples:
  - pp at √s = 13 TeV and p-Pb at 5.02 TeV collisions collected by ALICE during Run 2
- $^{3}_{\Lambda}H$ selection in pp: trigger on high multiplicity events using V0 detectors + topological cuts on triggered events
- $^{3}_{\Lambda}H$ selection in p-Pb: 40% most central collisions + BDT Classifier
- Significance > 4σ both in pp and p-Pb

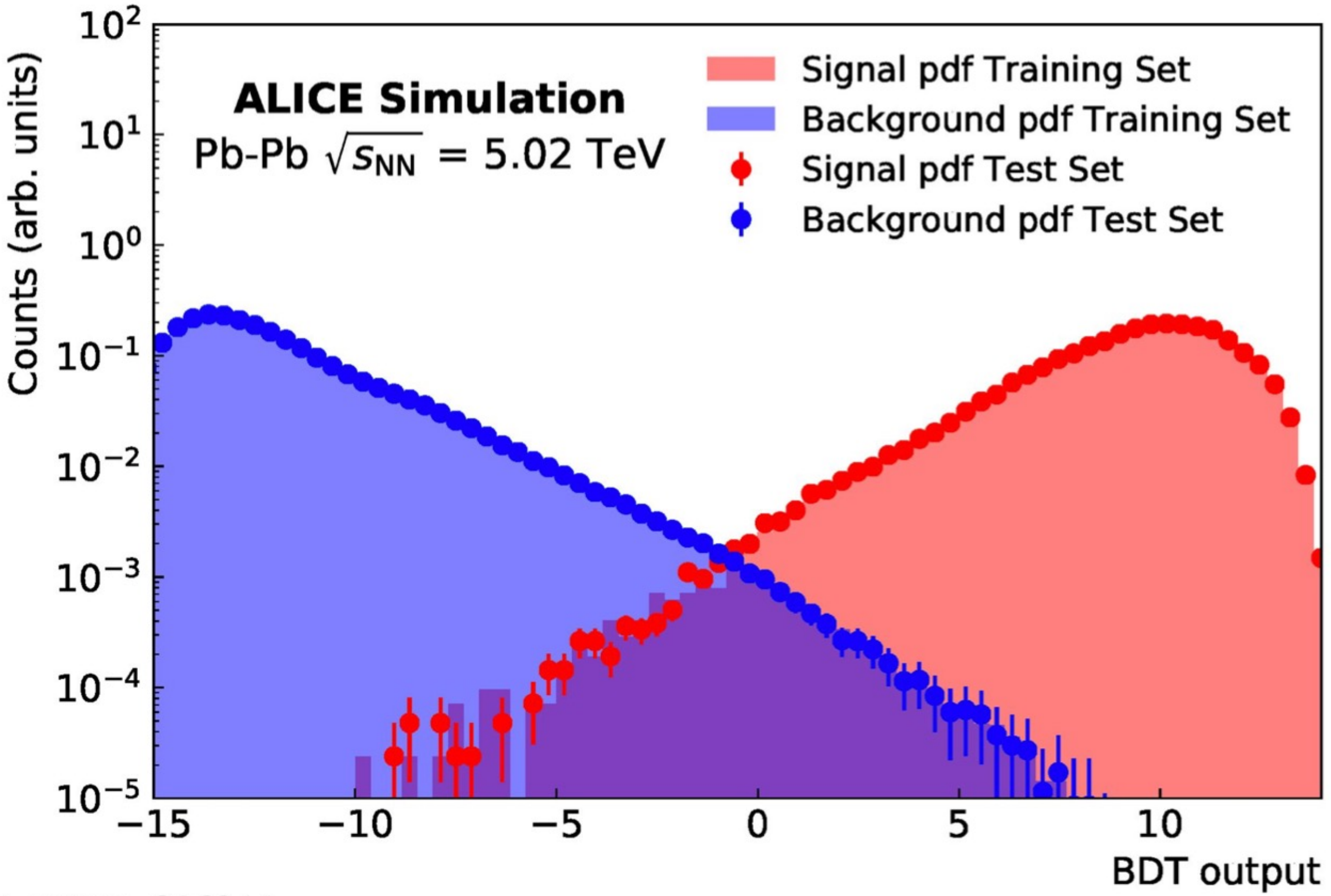
arXiv:2107.10627



Hypertriton selection: ML approach

- Boosted Decision Tree (BDT) classifier trained on a dedicated sample to discriminate between signal and background candidates

- BDT output (independent trainings for each bin):
  - Score related to the probability of the candidate to be signal or background
- Selection based on BDT score:
  - maximisation of the expected significance



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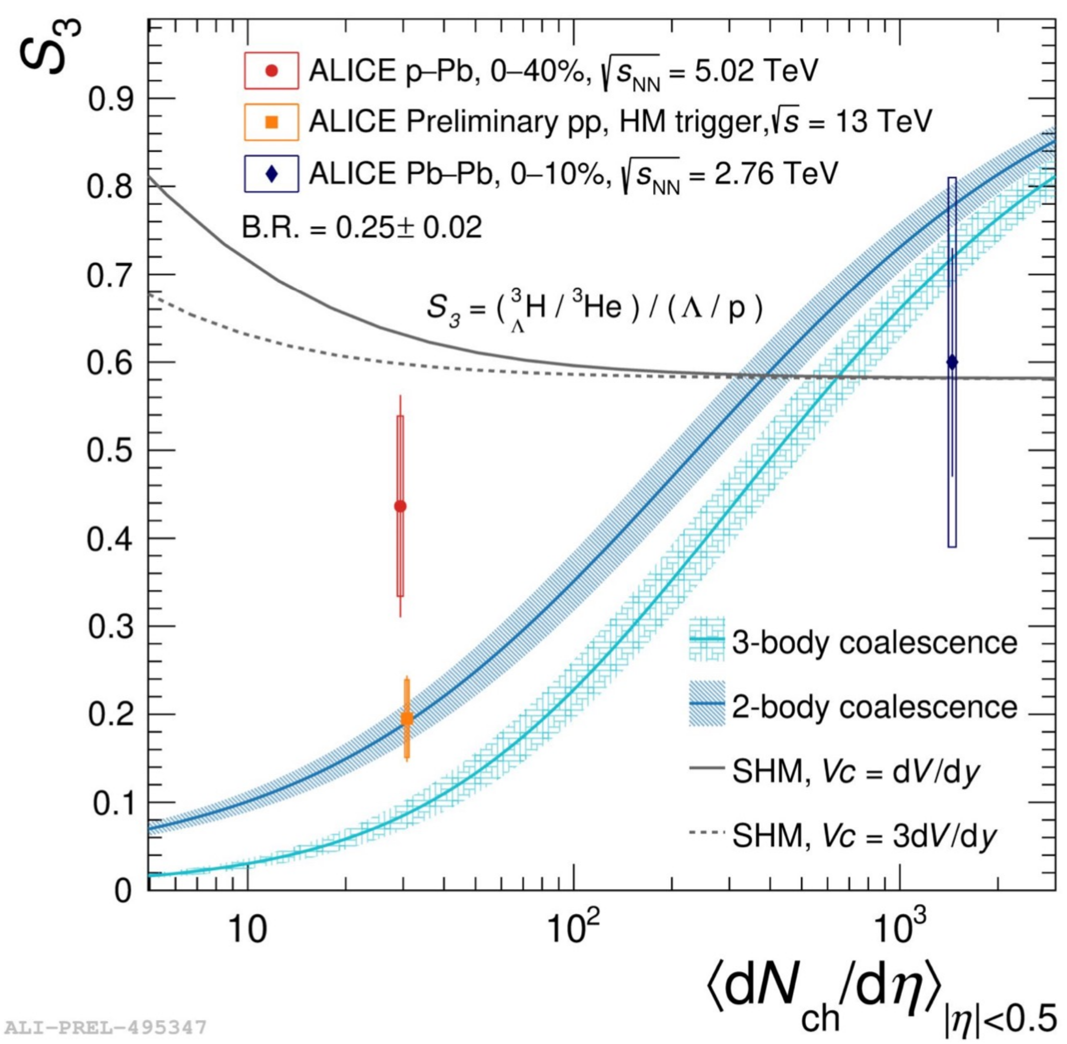
S_3 in small systems

- S_3 : strangeness population factor
  $({}^{3}_{\Lambda}H/{}^{3}He)/(\Lambda/p)$

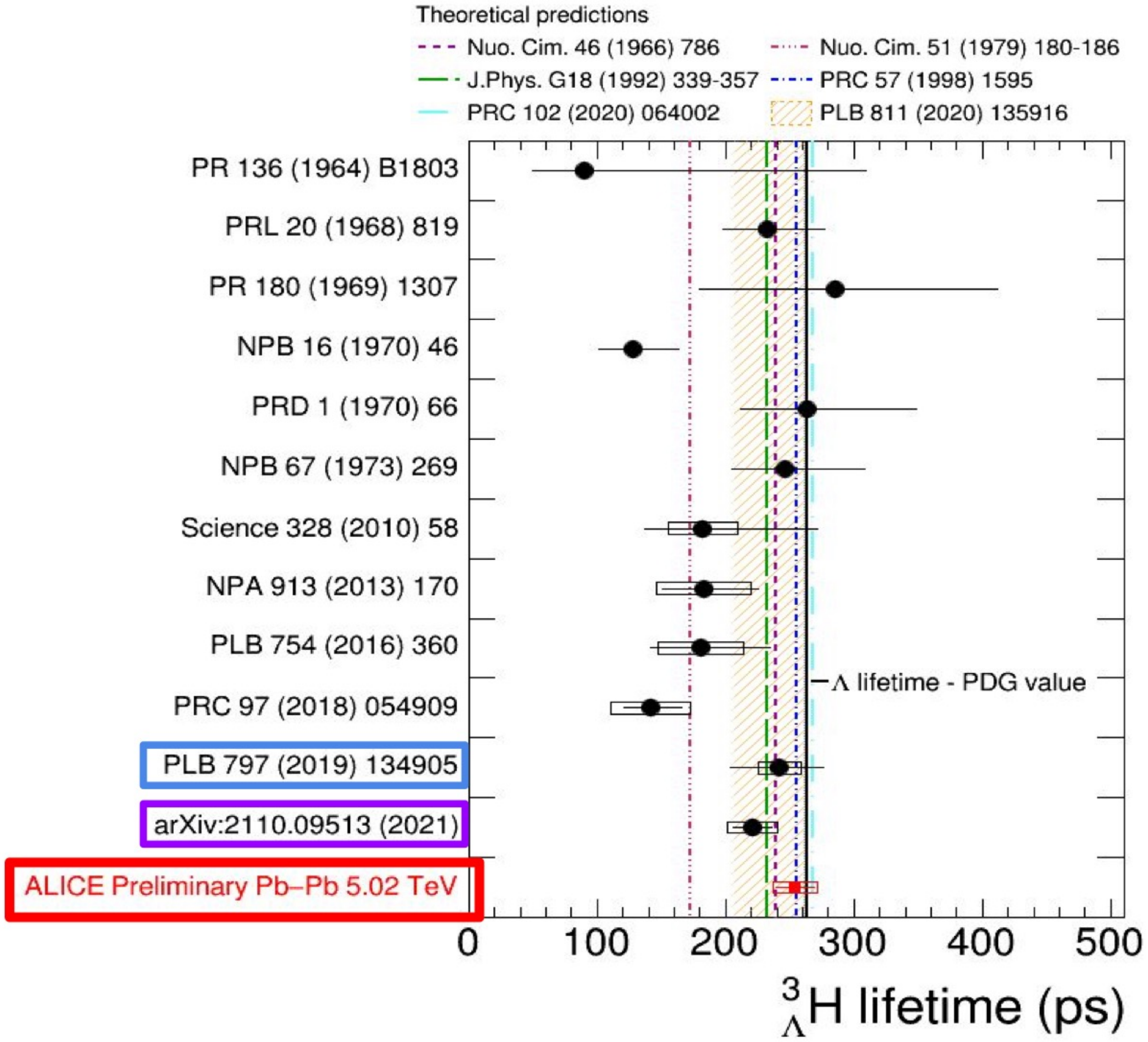
- S_3 in small systems:
  - same conclusions as for ${}^{3}_{\Lambda}H/\Lambda$ but with a lower sensitivity
  - LHC Run 3 will be crucial to finally distinguish between SHM and coalescence and explore the multiplicity dependence of S_3!



arXiv:2107.10627

Hypertriton lifetime

- Most precise measurement
- Compatible with latest ALICE and STAR measurements
- Models predicting a lifetime close to the free Λ one are favoured
- Strong hint that hypertriton is weakly bound, but B_Λ is still needed to solve the puzzle



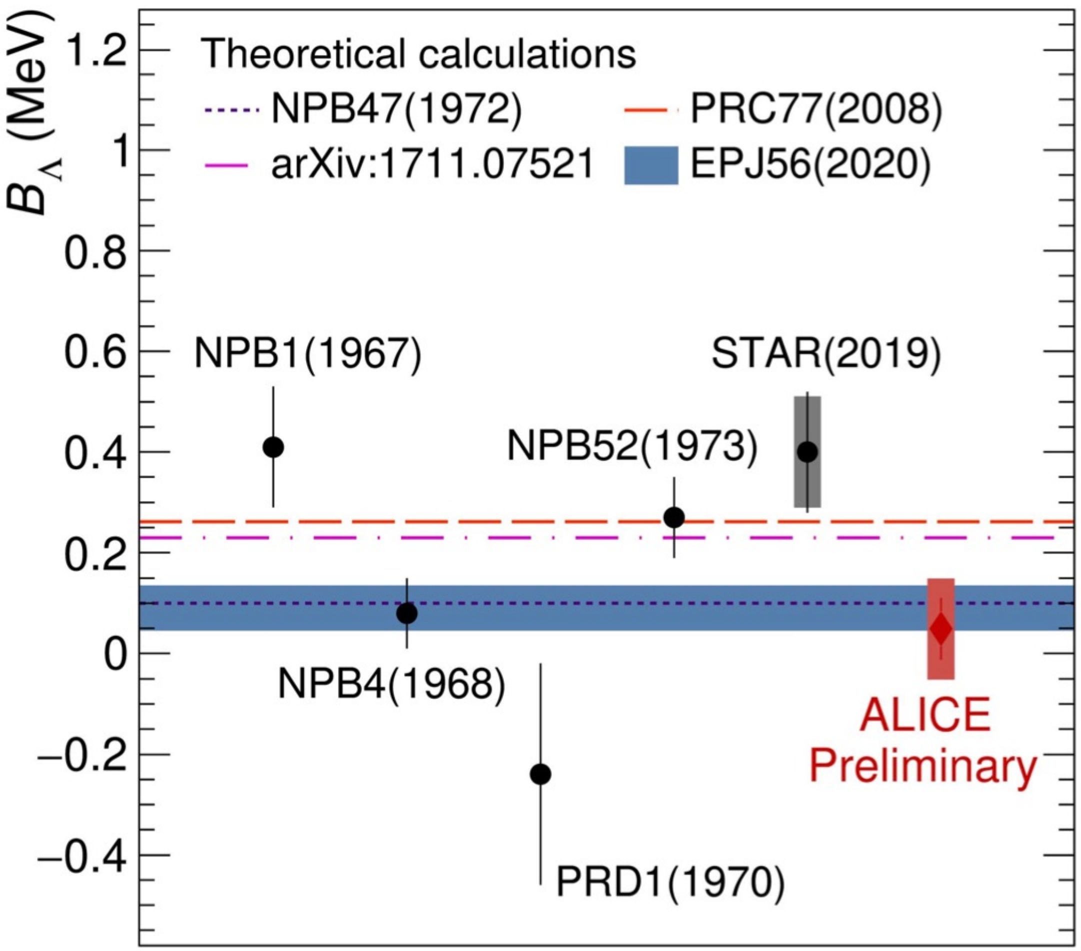
≥ 2020 models: assuming B_Λ = 70 keV
< 2020 models: assuming B_Λ = 130 keV

Hypertriton binding energy

- From the mass measurement to B_Λ

$$B_\Lambda = M_\Lambda + M_d - M_{^3_\Lambda H}$$

- Weakly bound nature of $^3_\Lambda$H is confirmed by the latest ALICE measurement
  - B_Λ compatible with zero
  - in agreement within 1σ with Dalitz and χEFT based predictions
  - fully consistent with the lifetime measurement according to recent theoretical calculations*



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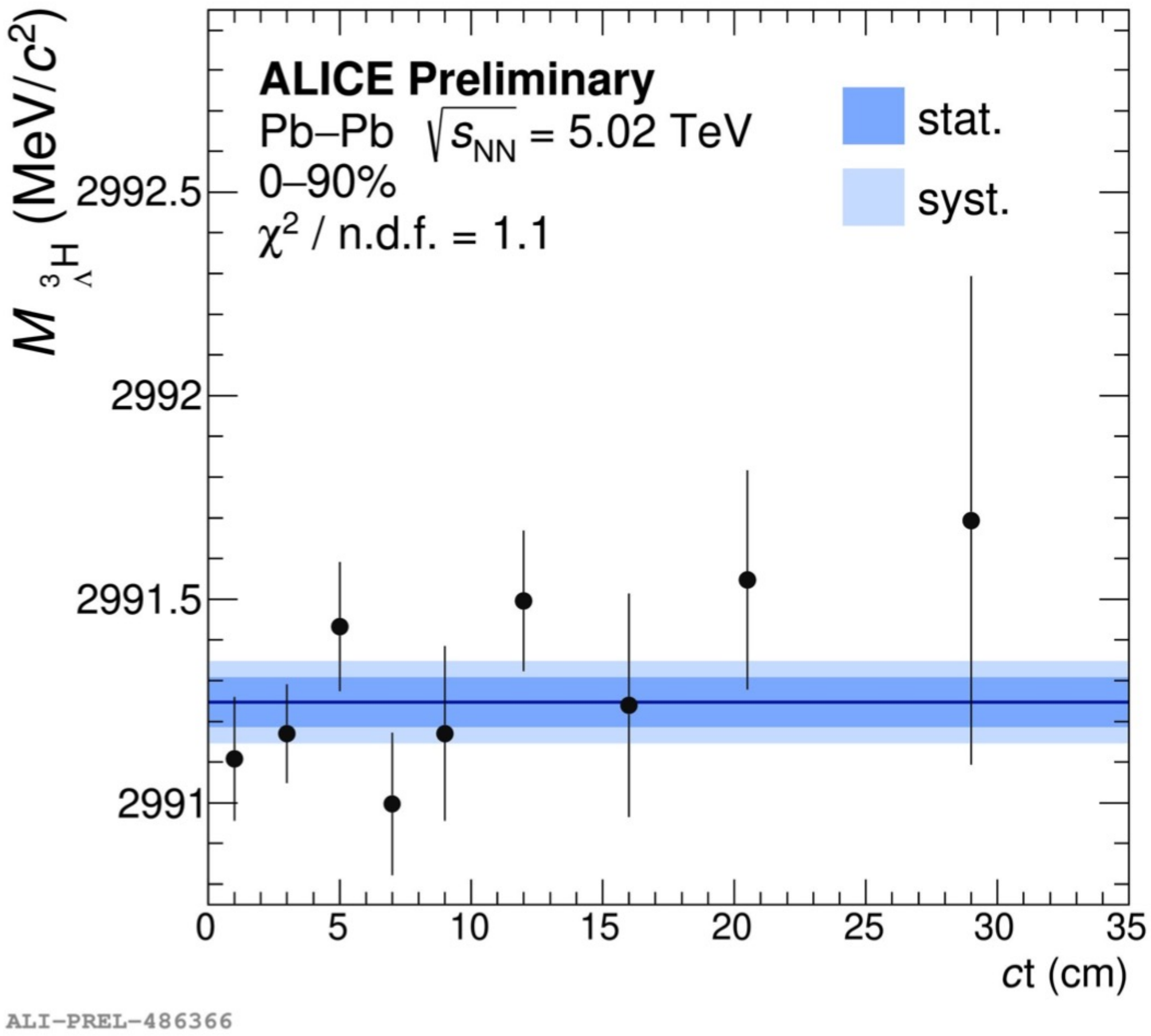
* Hildenbrand et al., PRC 102 (2020) 6; Pérez-Obiol et al., PLB (2020) 811

Hypertriton mass

Same signal extraction technique and *c*t bins used for the lifetime: precise mass measurement needed to obtain B_Λ

- Extremely precise measurement 0.0016% stat.
- Systematic uncertainty of ~100 keV (0.003%)



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