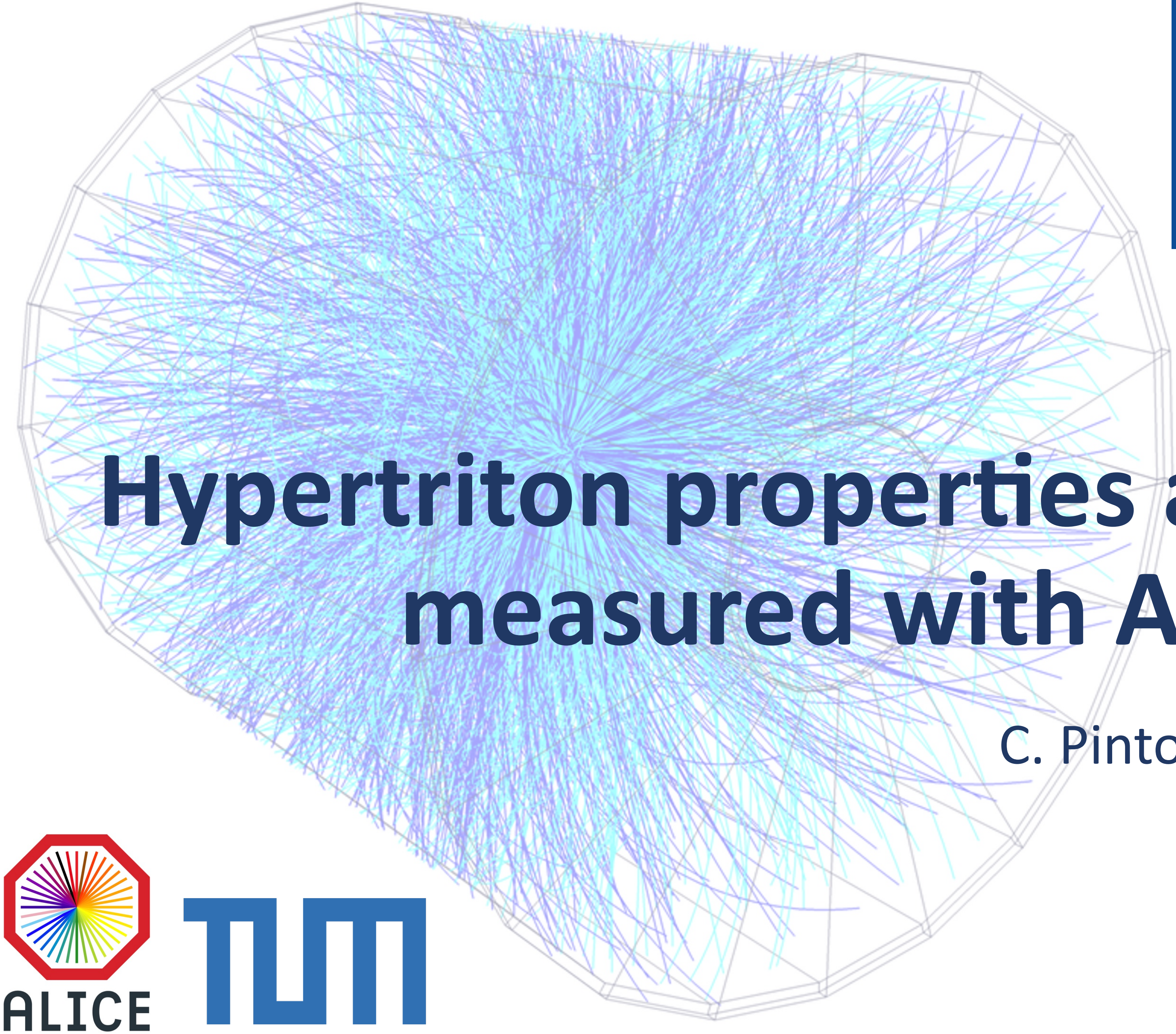
ExtreMe Matter Institute EMMI

EMMI Workshop

Meson and Hyperon Interactions
with Nuclei

Kitzbuehel, Austria, September 14 - 16, 2022



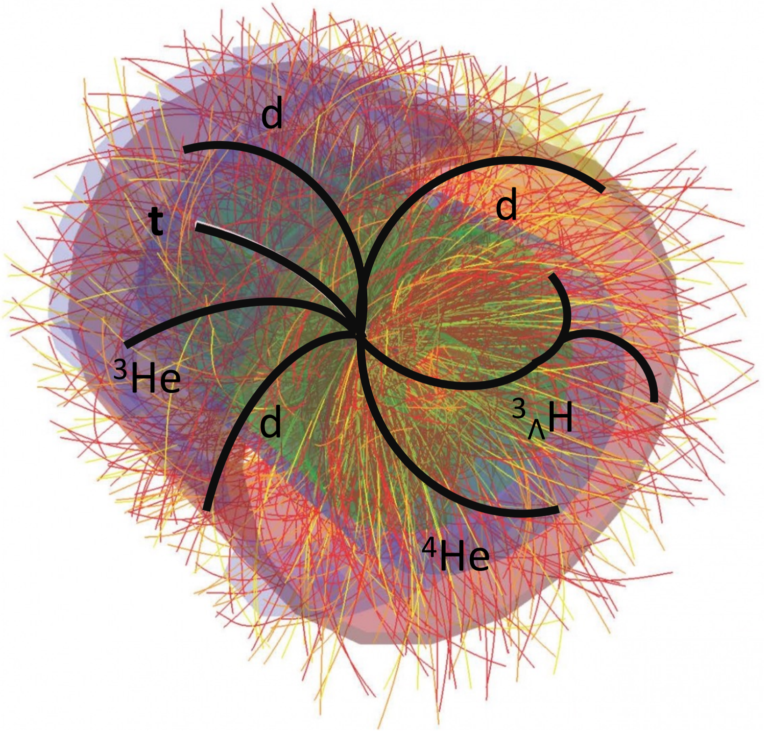
Hypertriton properties and production measured with ALICE at the LHC

C. Pinto[1] for the ALICE Collaboration

[1] Technische Universität München

Kitzbühel – 16 Sep. 2022

(Anti)(hyper)nuclei production



- 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
  - strong implications for astronuclear physics – hyperons expected to exist in the inner core of neutron stars
- Production mechanism usually described with two classes of phenomenological models:
  - statistical hadronization (SHM)
  - coalescence
- Focus on hypertriton ($^3_\Lambda$H) production and properties in
  - large collision systems (τ, mass, B_Λ)
  - small collision systems ($^3_\Lambda$H/ Λ)

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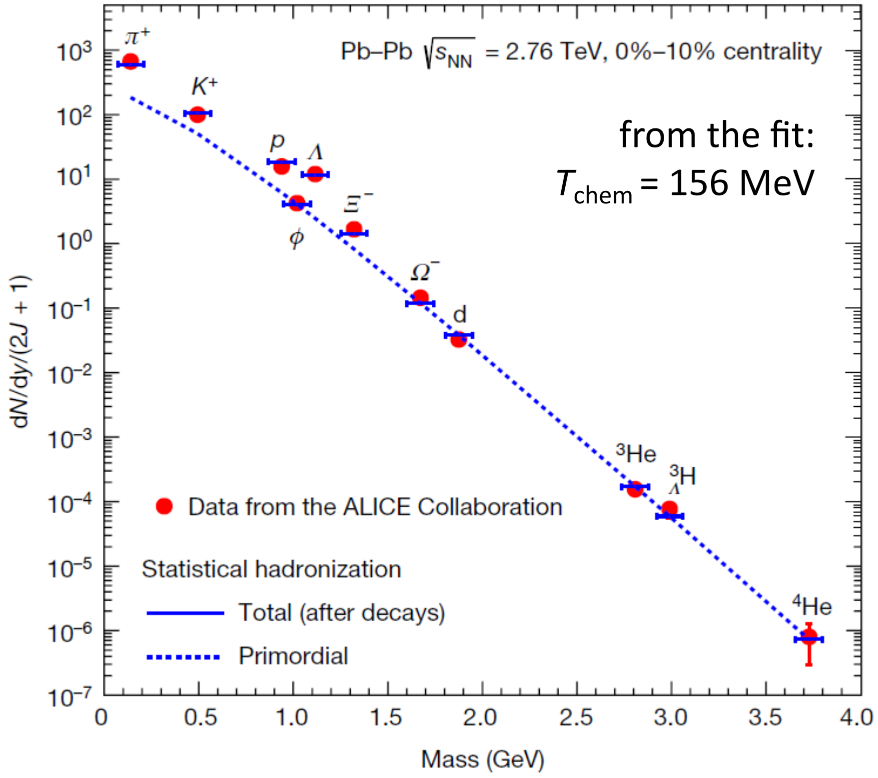
Modeling the production mechanisms

Statistical Hadronisation Model (SHM) [1]

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

  ⇒ (Hyper)Nuclei (large m): large sensitivity to T_{chem}
- Light nuclei are produced during phase transition (as other hadrons)



from the fit:
T_{chem} = 156 MeV

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

Modeling the production mechanisms

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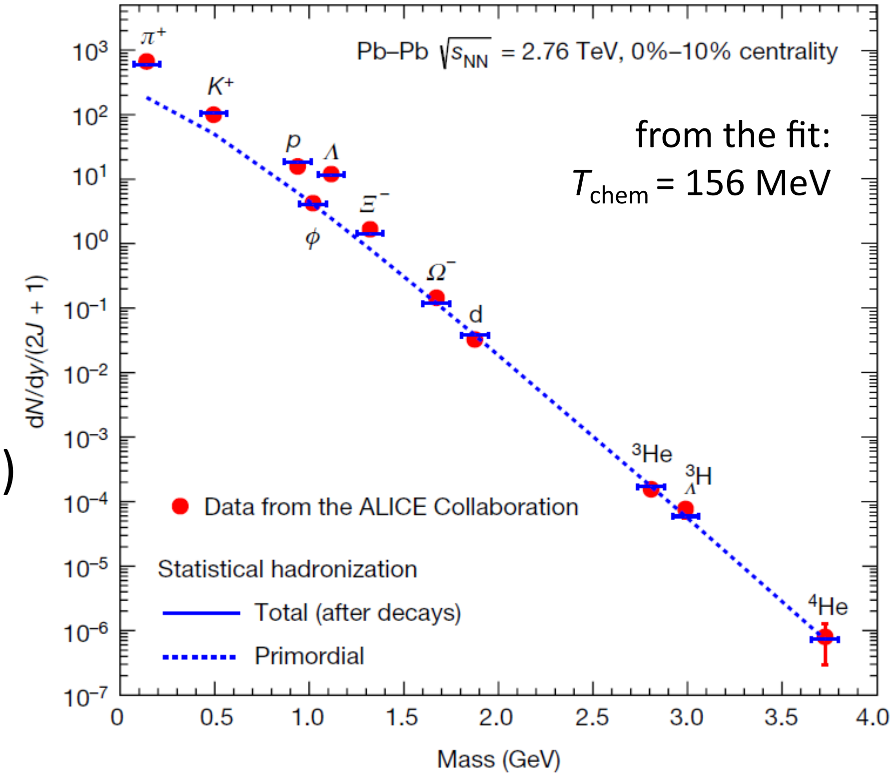
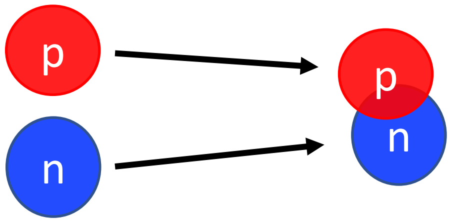


from the fit:
T_{chem} = 156 MeV

Coalescence models [2]

- (Anti)nucleons close in phase space ($\Delta \boldsymbol{p} < \boldsymbol{p}_0$) and matching the spin state can form a (anti)nucleus
- State-of-the-art coalescence models include nuclear quantum mechanical properties



[1] Andronic et al., Nature 561 (2018) 321–330
[2] Butler et al., Phys. Rev. 129 (1963) 836

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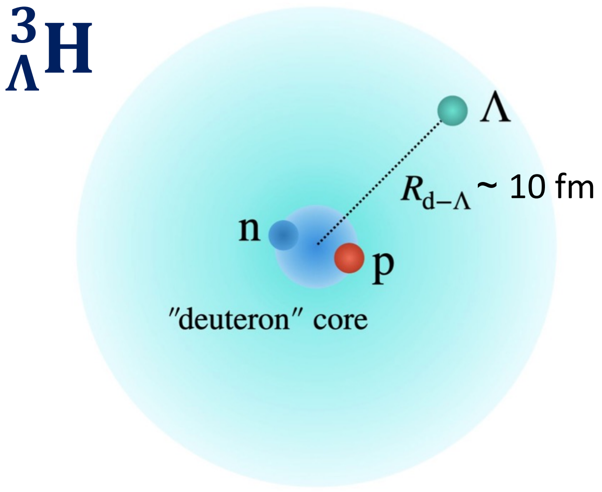
The hypertriton



r $_{^{3}_{\Lambda}\mathrm{H}\,(\mathrm{np}\Lambda)}$: 4.9 fm ($B_\Lambda$= 2.35 MeV)
r $_{^{3}_{\Lambda}\mathrm{H}\,(\mathrm{d}\Lambda)}$: ~10 fm ($B_\Lambda \sim$ 0.13 MeV)

- Lightest known hypernucleus
- Bound state of p + n + Λ
- Discovered in early 50s by M. Danysz and J. Pniewski [1]

- Two-body halo nucleus
- $^{3}_{\Lambda}\mathrm{H}$ approximated as a bound state of a deuteron and a Λ with an expected radius of ~ 10 fm [2]

- $^{3}_{\Lambda}\mathrm{H}$ lifetime and B_Λ reflect its structure
- Most of the theoretical models assume $B_\Lambda \sim$ 130 keV and predict lifetime close to the free Λ one
- Latest models based on EFT give lifetime predictions as a function of B_Λ [3, 4]

[1] M. Danysz, J. Pniewski, Philos. Mag. 44 348 (1953)
[2] Hildenbrand F. et al., PRC 100 (2019) 034002
[3] Hildenbrand F. et al., PRC 102 (2020) 064002
[4] Pérez-Obiol A., PLB 811 (2020)

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What can we study with ALICE?

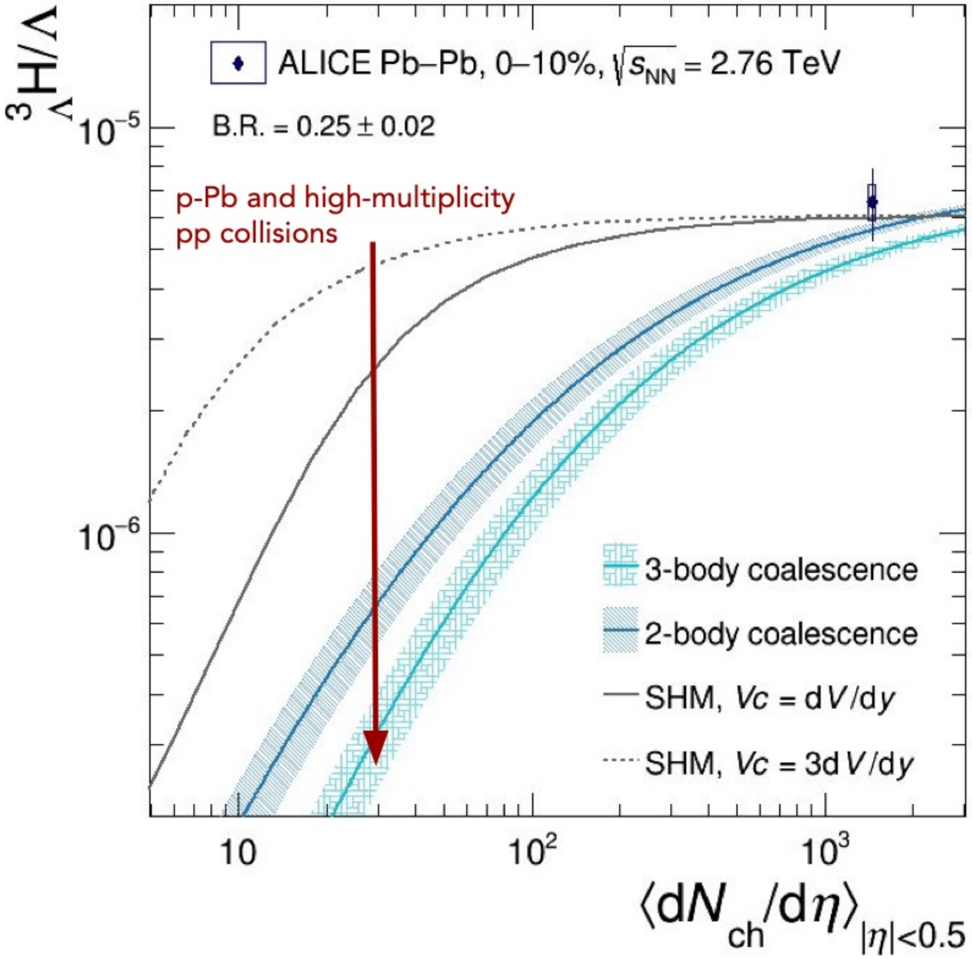
LARGE SYSTEMS

- recent results in heavy-ion collisions suggest that ${}^{3}_{\Lambda}\mathrm{H}$ could be more compact than expected [1, 2]
- precise measurements required to shed light on the ${}^{3}_{\Lambda}\mathrm{H}$ structure

SMALL SYSTEMS

- loosely bound nature of ${}^{3}_{\Lambda}\mathrm{H}$ has strong implications for its production mechanism
- SHM and coalescence predictions well separated at low charged-particle multiplicity density
- ${}^{3}_{\Lambda}\mathrm{H}$ production in pp and p–Pb is a key measurement to understand the nuclear production mechanisms in HIC

PLB 754 (2016) 360-372



p-Pb and high-multiplicity pp collisions

[1] STAR, PRC 97 (2018) 054909

[2] STAR, Nat. Phys. 16 (2020) 409-412

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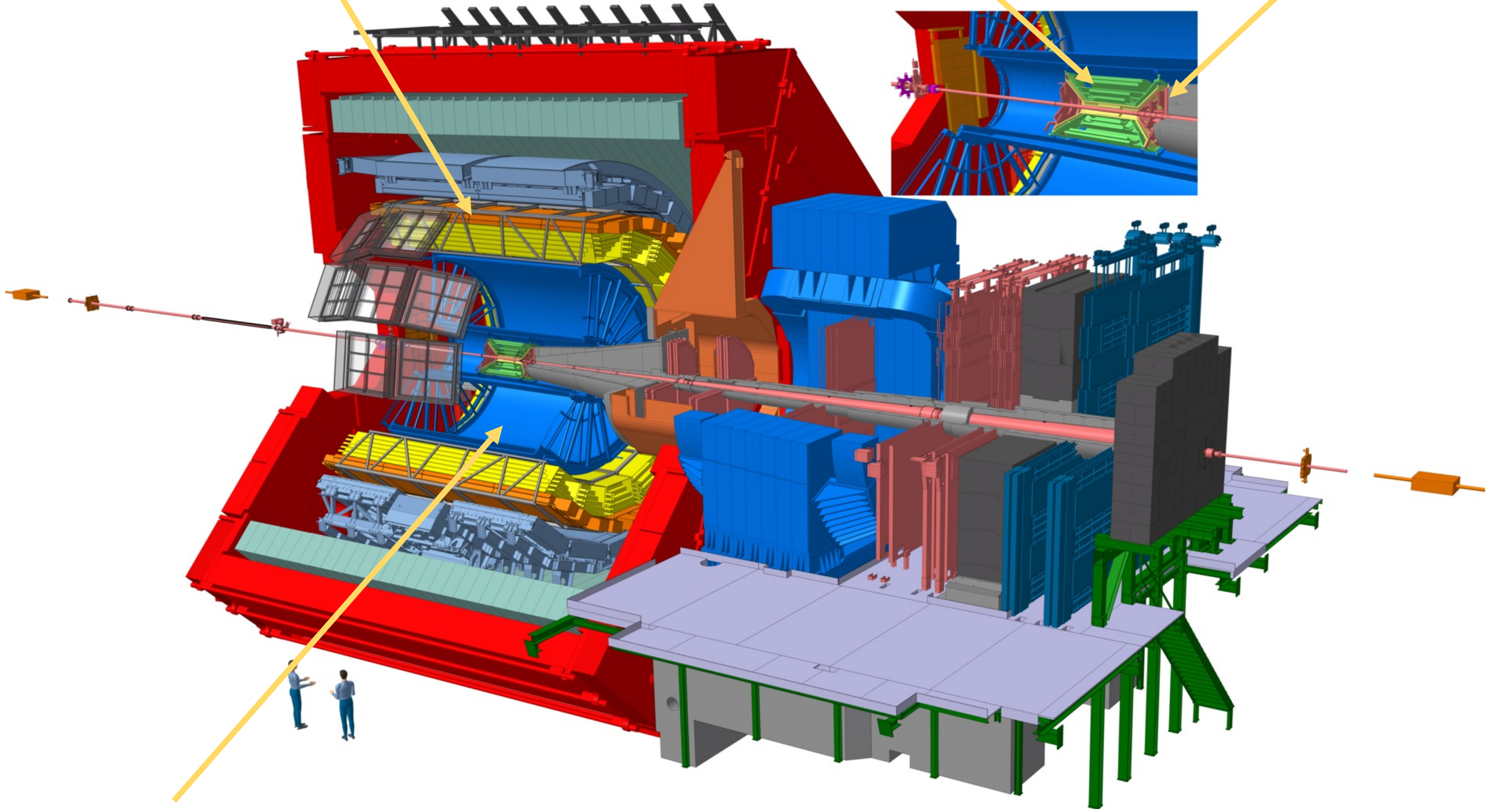
The ALICE detector



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

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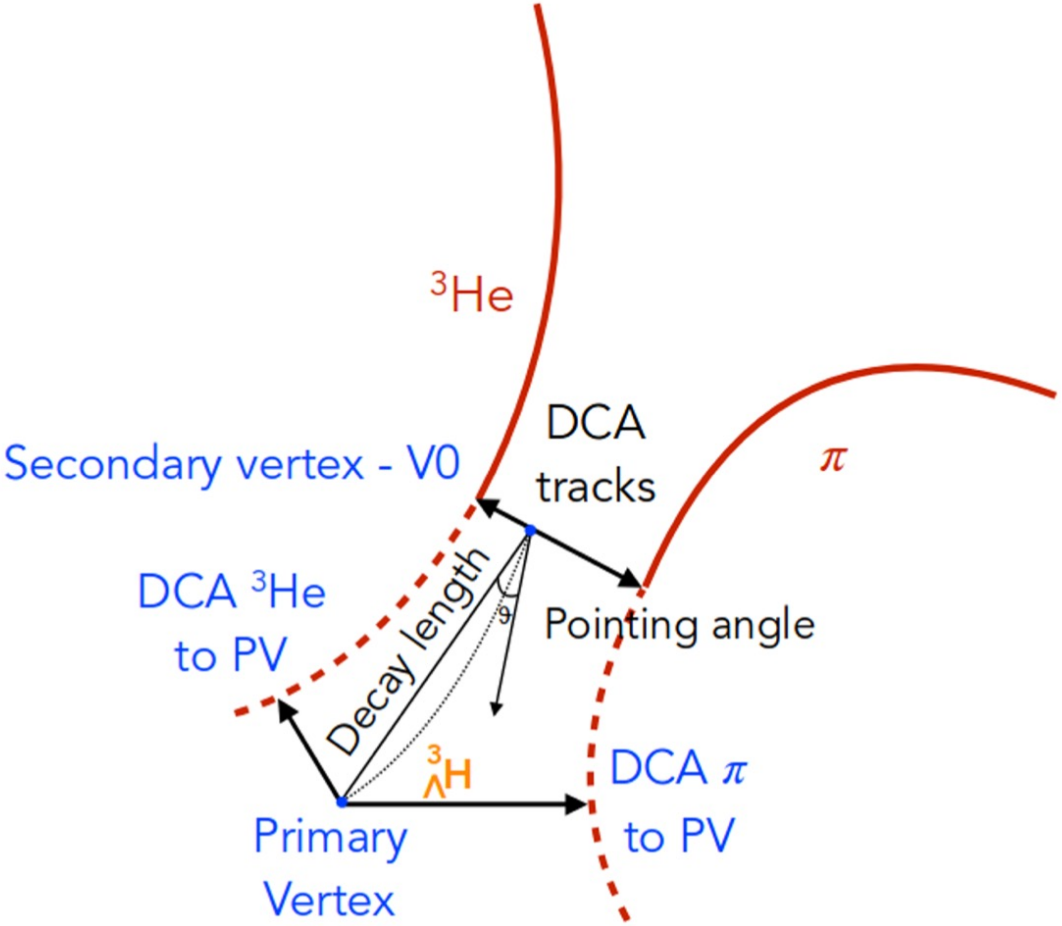
Hypertriton in large systems

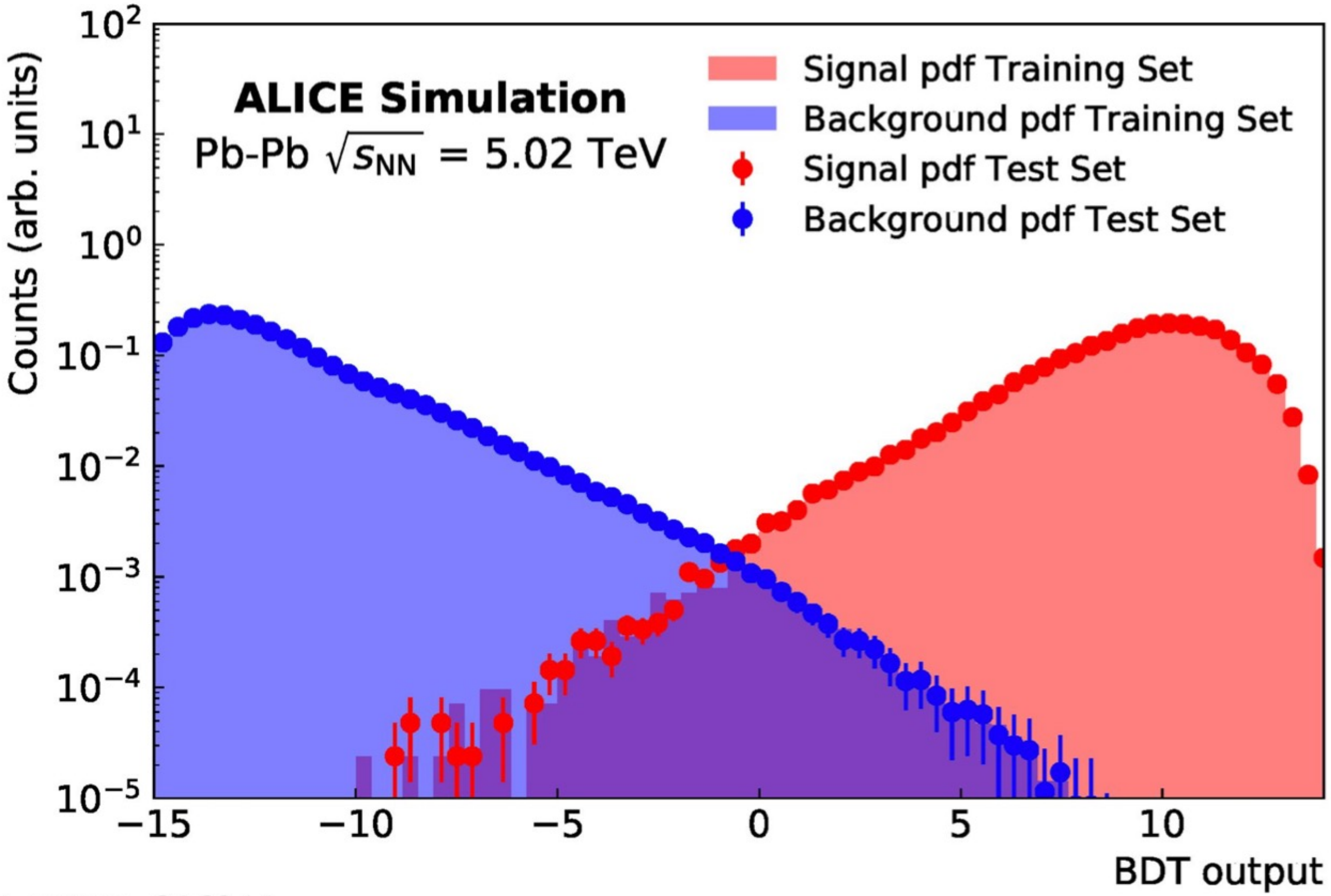
- Data sample:
  - Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV collected by ALICE during Run 2
- ${}^{3}_{\Lambda}$H candidate: ^{3}He + π^{-} pairs (and related charge conjugated states)
- Secondary vertex reconstruction
  - matching of ^{3}He + π^{-} tracks coming from a common vertex
- Huge combinatorial background
  - topological and kinematical cuts or Machine Learning (ML) approach



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



ALI-SIMUL-316844

Hypertriton signal extraction & lifetime

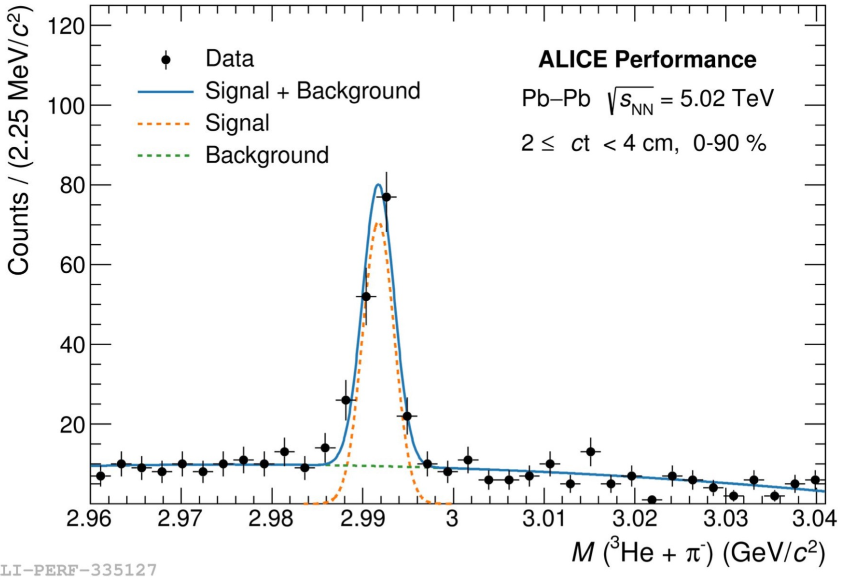
Signal extraction

- Signal extracted with a fit to the invariant mass spectrum of the selected candidates
- high significance over a wide range
- 9 *c*t bins from 1 to 35 cm

  (*c*t → *decay length of the candidate*)

Lifetime

- Corrected *c*t spectrum fitted with an exponential function
- Lifetime value from the fit
- Statistical uncertainty ~ 4%
- Systematic uncertainty ~ 3%
- *Most precise measurement of the lifetime ever done so far*



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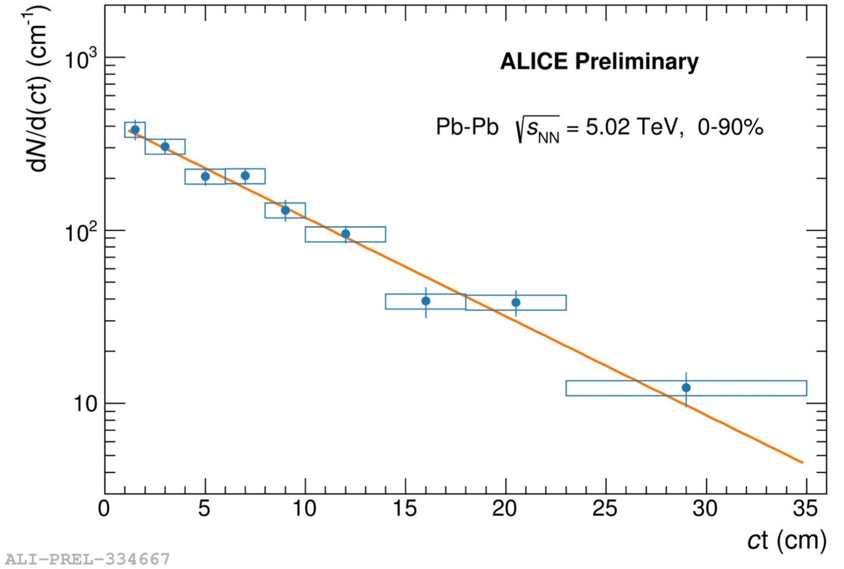
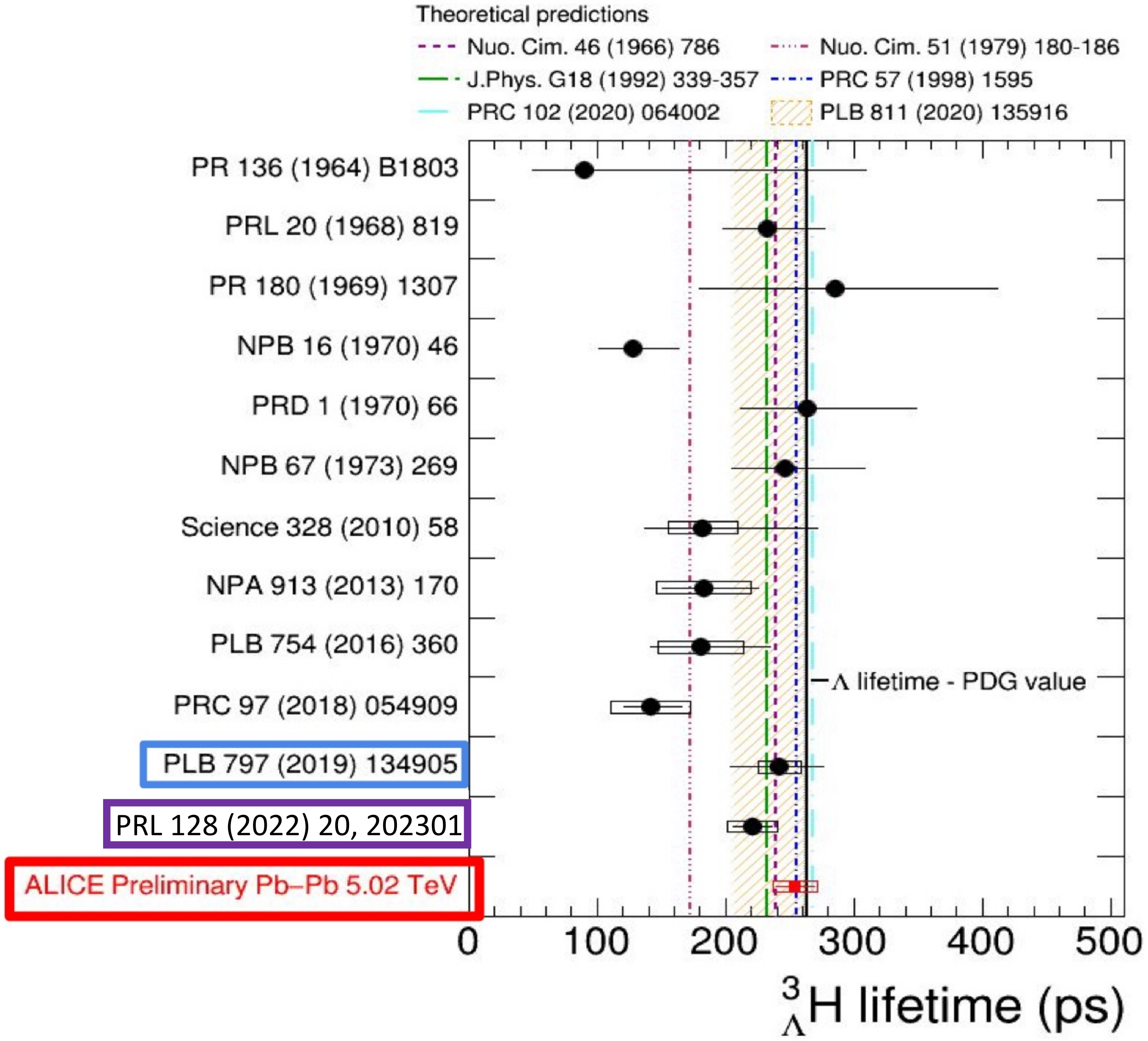


ALI-PREL-334667

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

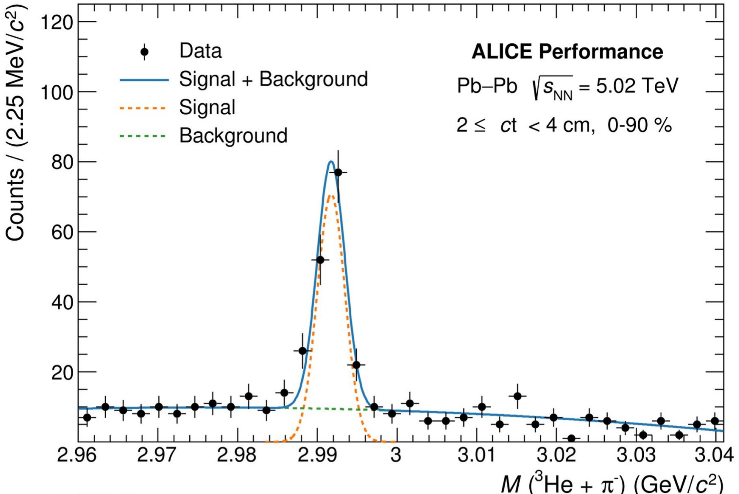
$$\tau = [253 \pm 11\ (\text{stat.}) \pm 6\ (\text{syst.})]\ \text{ps}$$



≥ 2020 models: assuming $B_\Lambda = 70$ keV
< 2020 models: assuming $B_\Lambda = 130$ keV

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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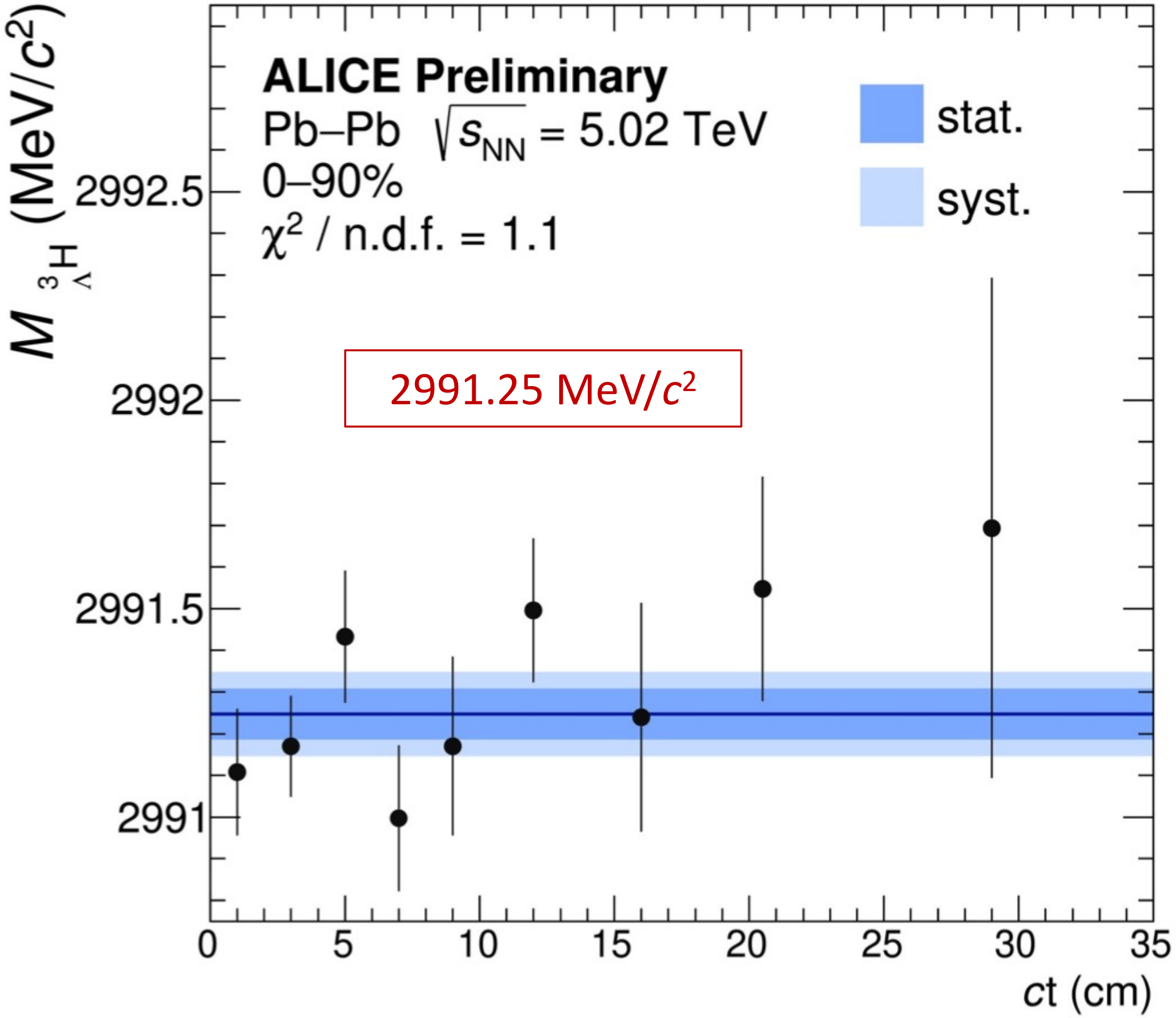


2991.25 MeV/c^2

ALI−PREL−486366

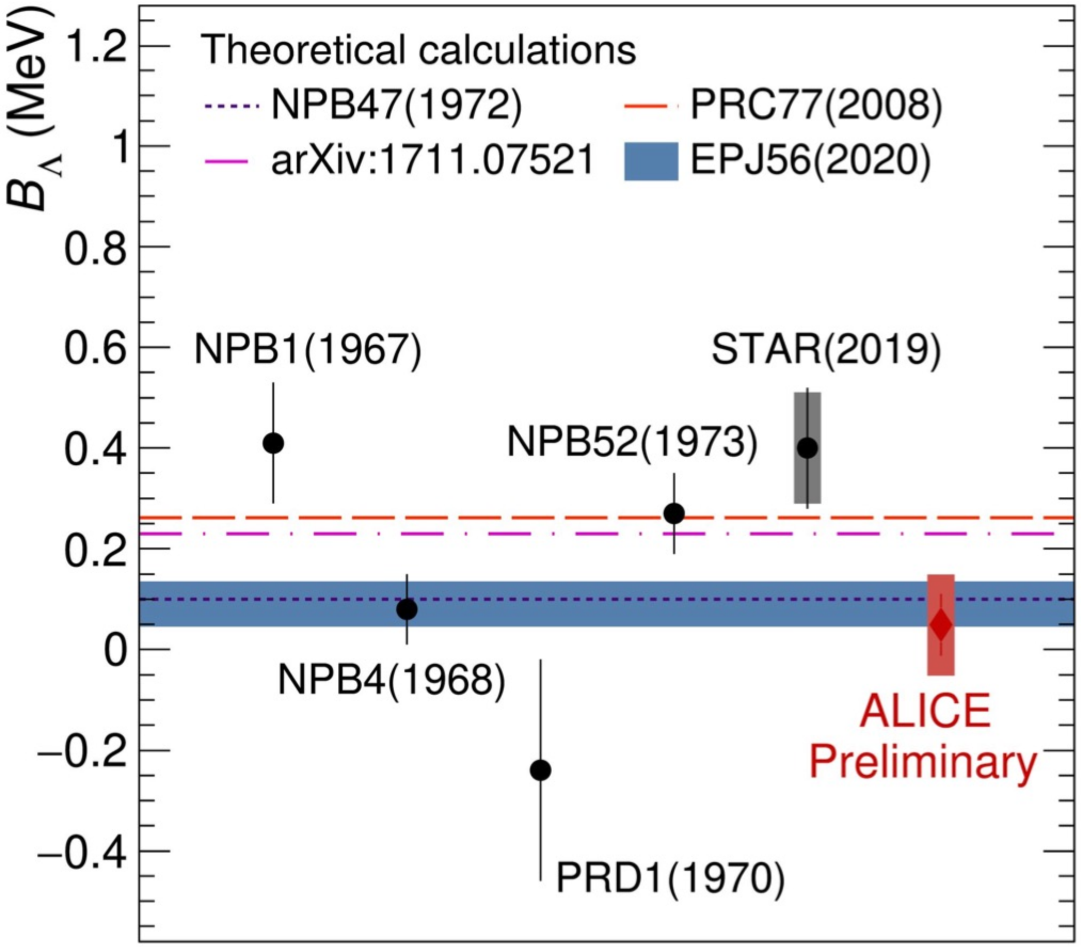
Hypertriton binding energy

- From the mass measurement to B_Λ

  $B_\Lambda = M_{\underline{\Lambda}} + M_{\underline{d}} - M_{^3_\Lambda\mathrm{H}}$

- 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 [1, 2]

$B_\Lambda = [72 \pm 63\ (\mathrm{stat.}) \pm 36\ (\mathrm{syst.})]\ \mathrm{keV}$



ALI-PREL-486370

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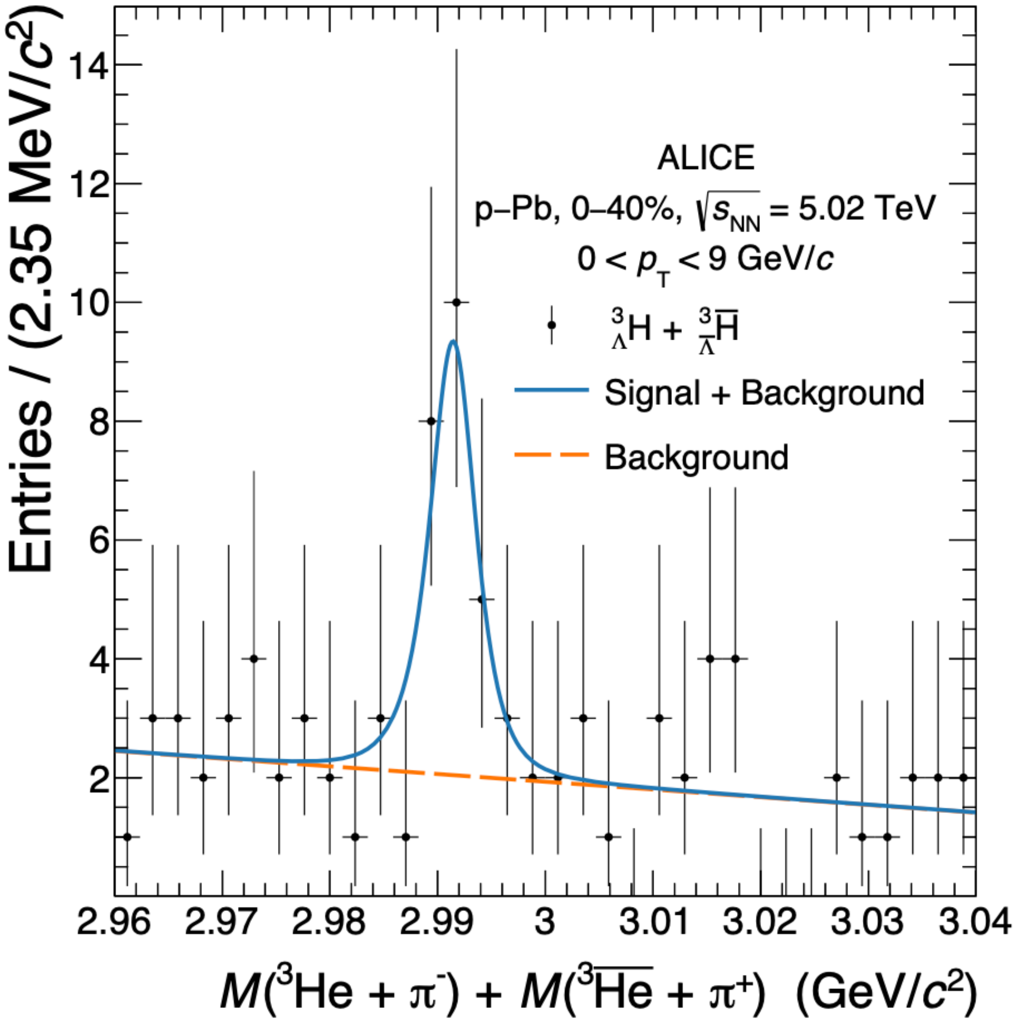
[1] Hildenbrand et al., PRC 102 (2020) 6

[2] Pérez-Obiol et al., PLB (2020) 811

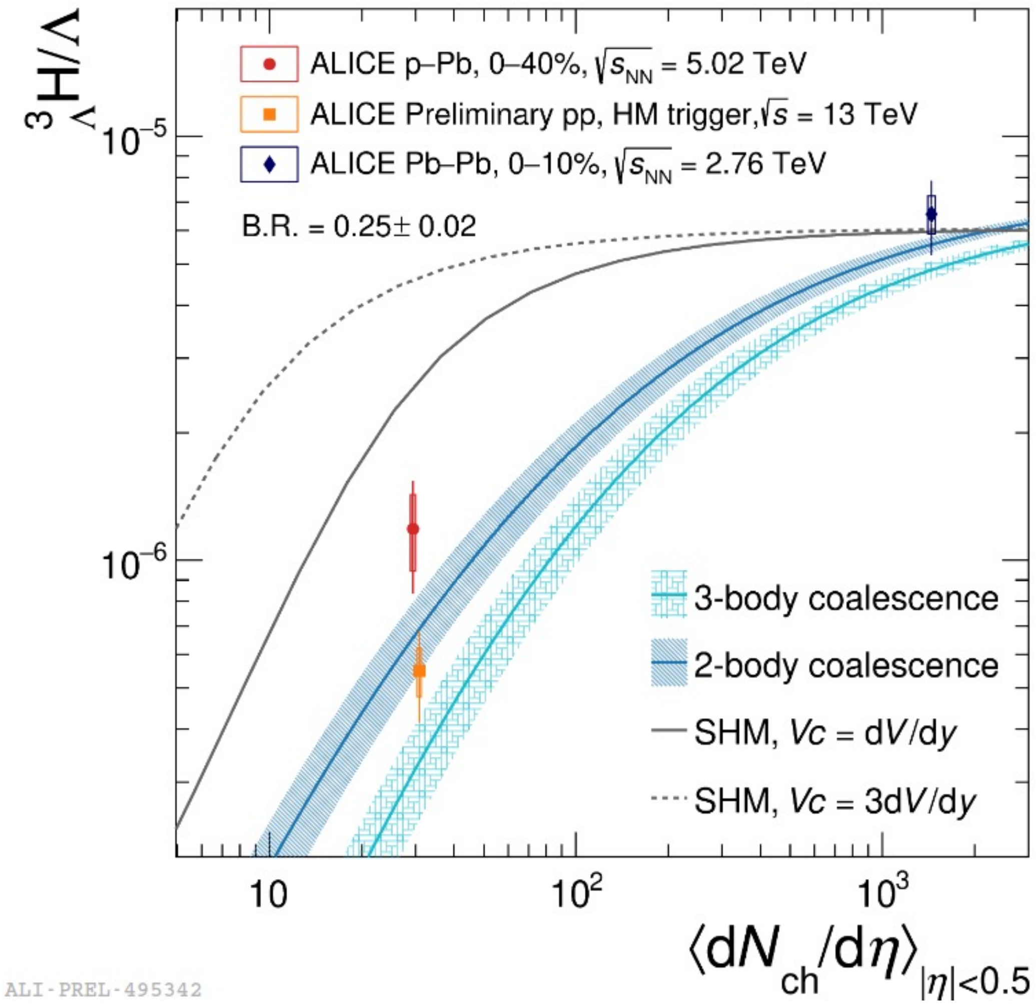
Hypertriton in small systems

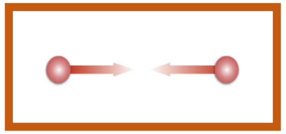
- Data samples:
  - pp at $\sqrt{s}$ = 13 TeV and p–Pb at 5.02 TeV collisions collected by ALICE during Run 2
- ${}^{3}_{\Lambda}$H selection in pp: trigger on high multiplicity events using V0 detectors + topological cuts on triggered events
- ${}^{3}_{\Lambda}$H selection in p–Pb: 40% most central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

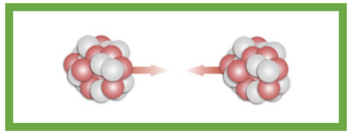
PRL 128 (2022) 25, 252003



Hypertriton production







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

- **Pb—Pb collisions:**
  - small difference between SHM and coalescence predictions
- **pp and p—Pb collisions:**
  - large separation between production models
  - 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

p—Pb: PRL 128 (2022) 25, 252003
Pb—Pb: PLB 754 (2016) 360-372

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Summary

- **$^{3}_{\Lambda}\mathrm{H}$ production in large collision systems**
  - precise measurements of lifetime and B_{Λ} in Pb–Pb collisions confirm the weakly bound nature of $^{3}_{\Lambda}\mathrm{H}$

- **$^{3}_{\Lambda}\mathrm{H}$ production in small collision systems**
  - powerful tool to distinguish with high significance between the two nucleosynthesis mechanisms: hint for coalescence
  - $^{3}_{\Lambda}\mathrm{H}/\Lambda$ ratio can be used to determine the radial extension of the hypertriton giving the source size as input of the coalescence model

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

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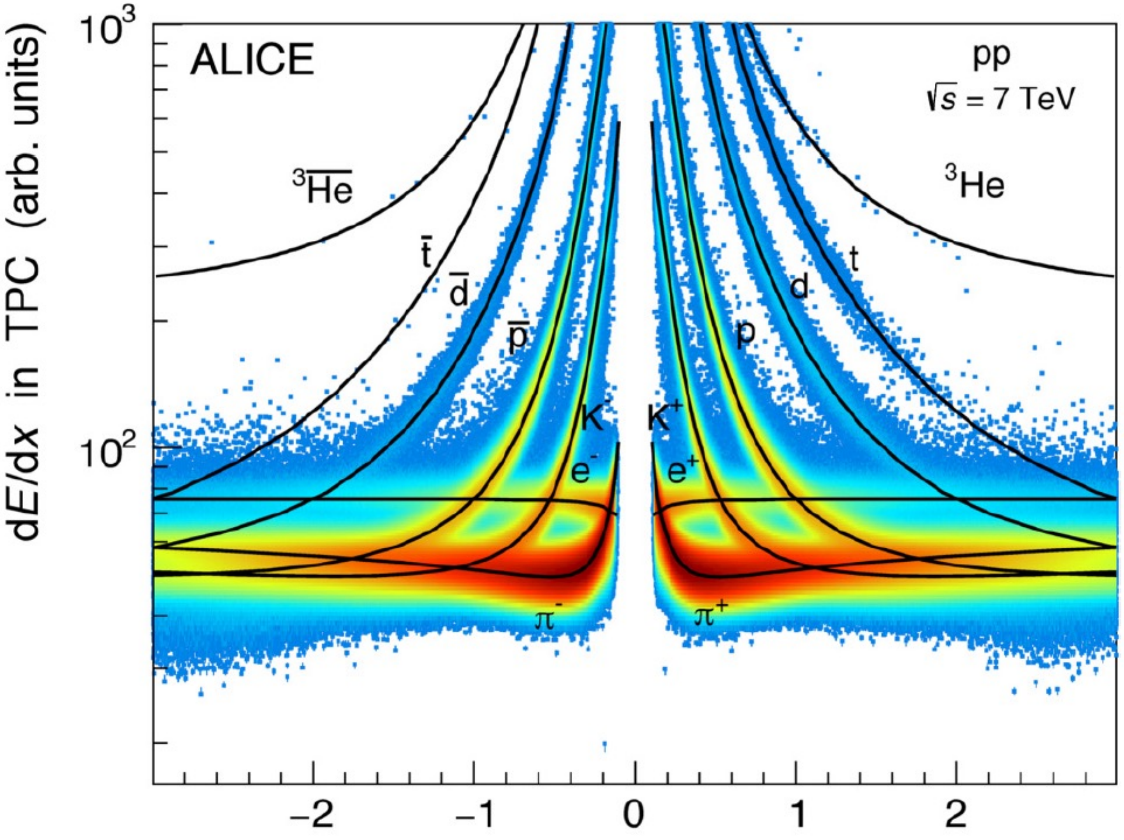
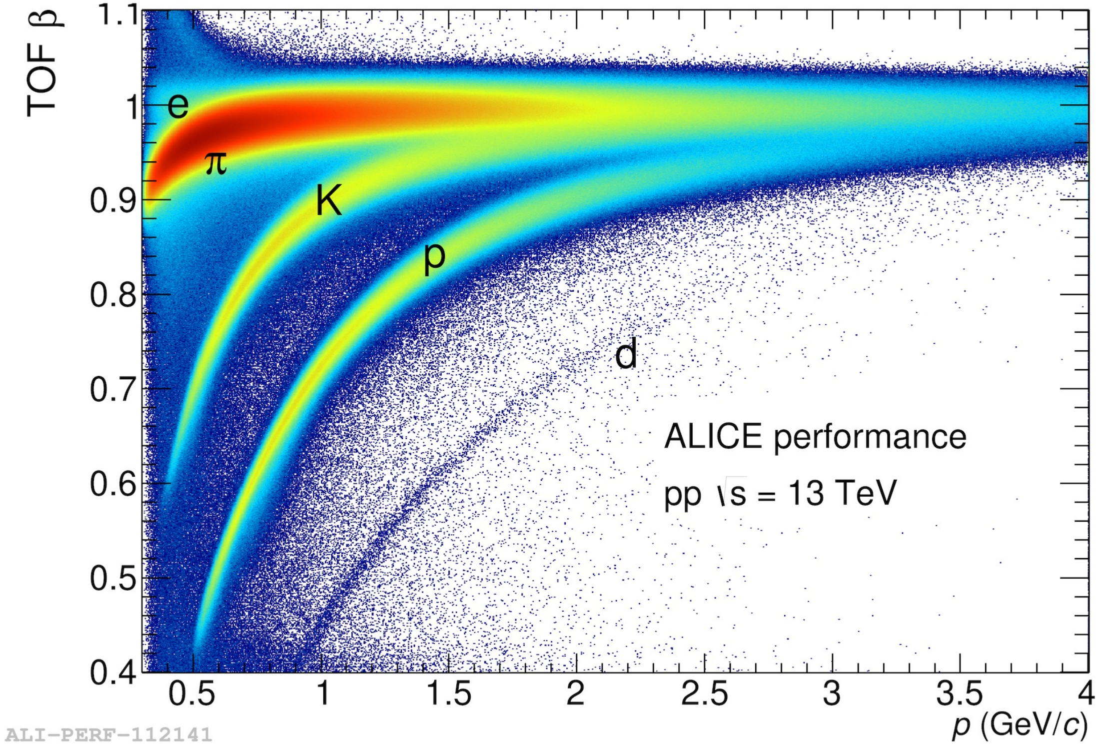
Backup

Nuclei identification

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

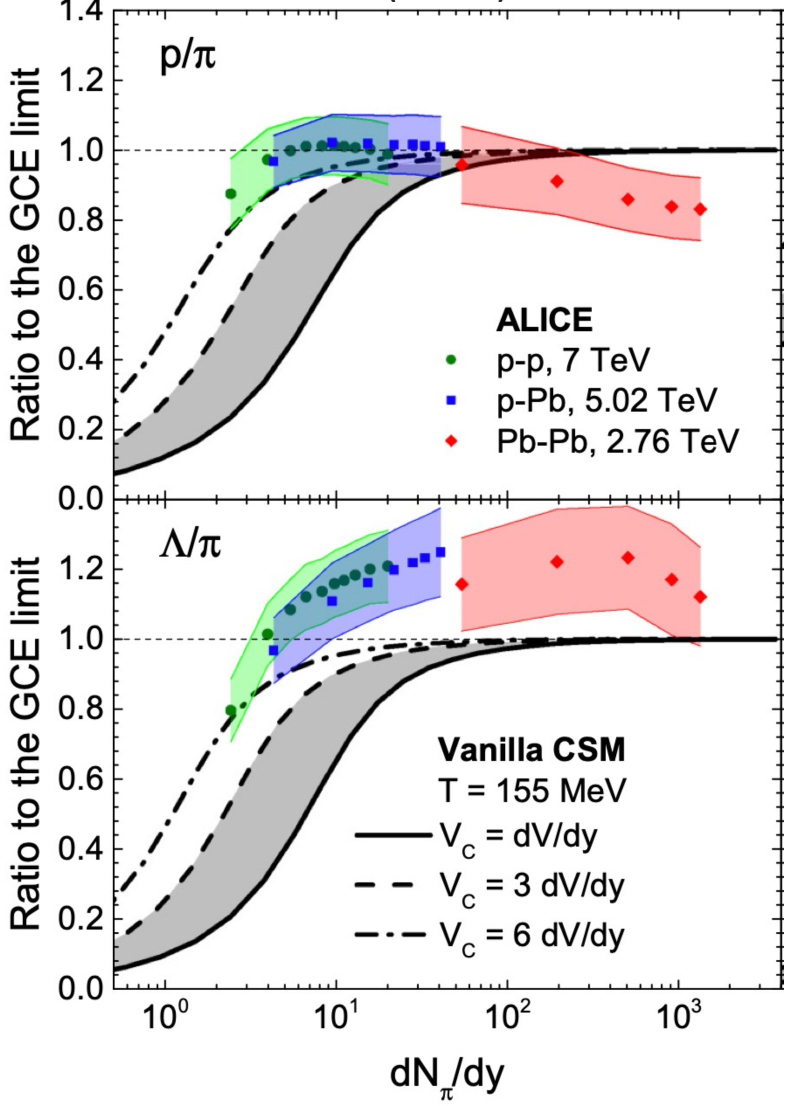


Phys.Rev.C 93 (2016) 2, 024917

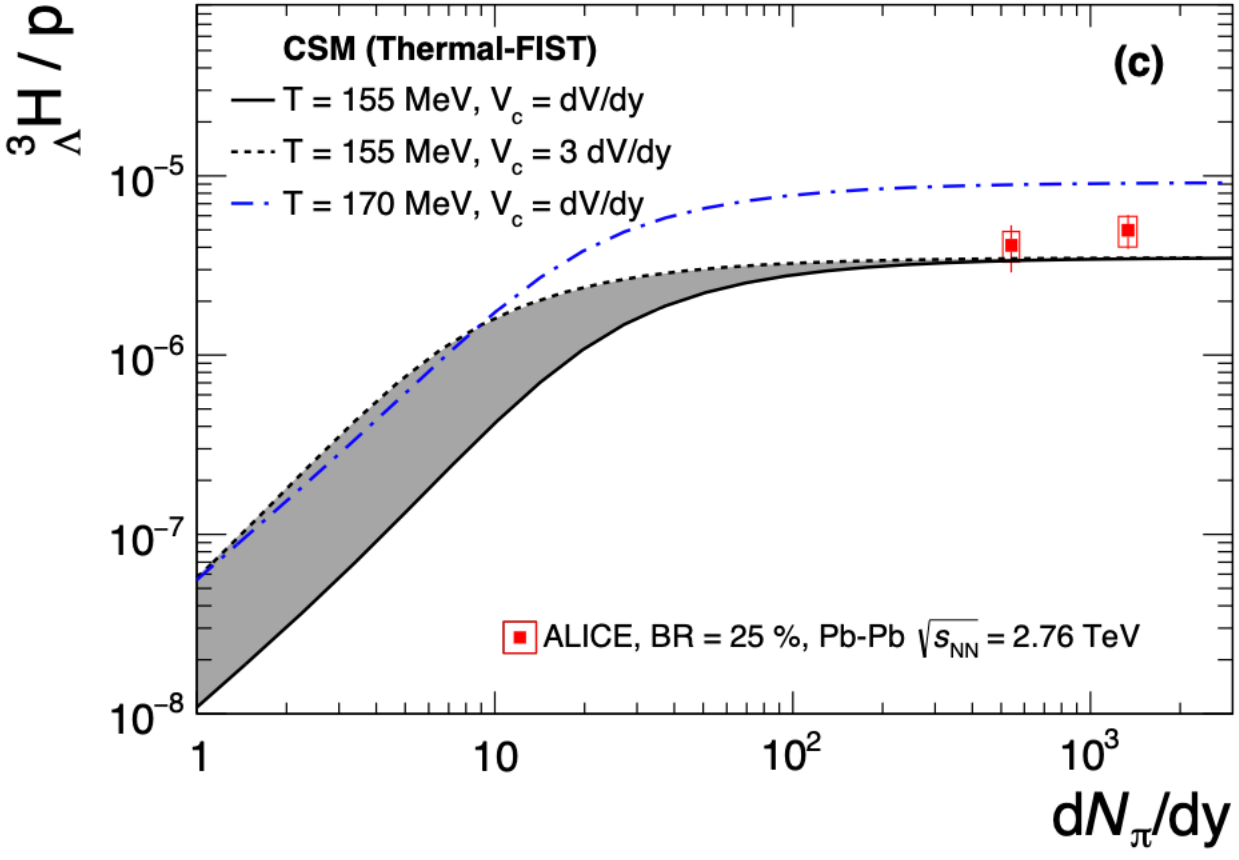


Higher *p* region (above 1 GeV/*c*) → PID via velocity β measurements in TOF

SHM predictions for particle yields


PRC 100 (2019) 054906

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



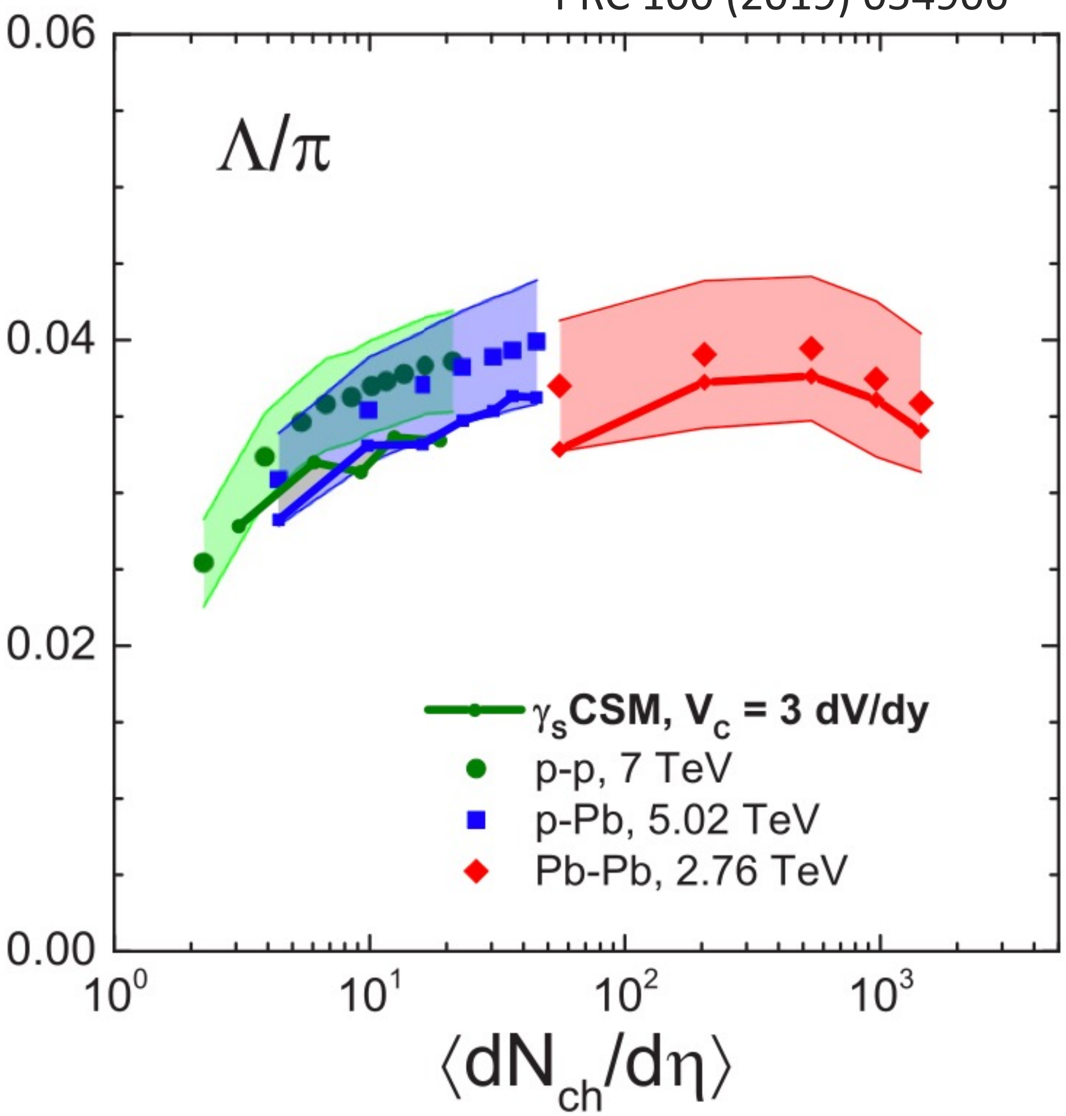
SHM predictions for particle yields

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

This implementation of SHM:

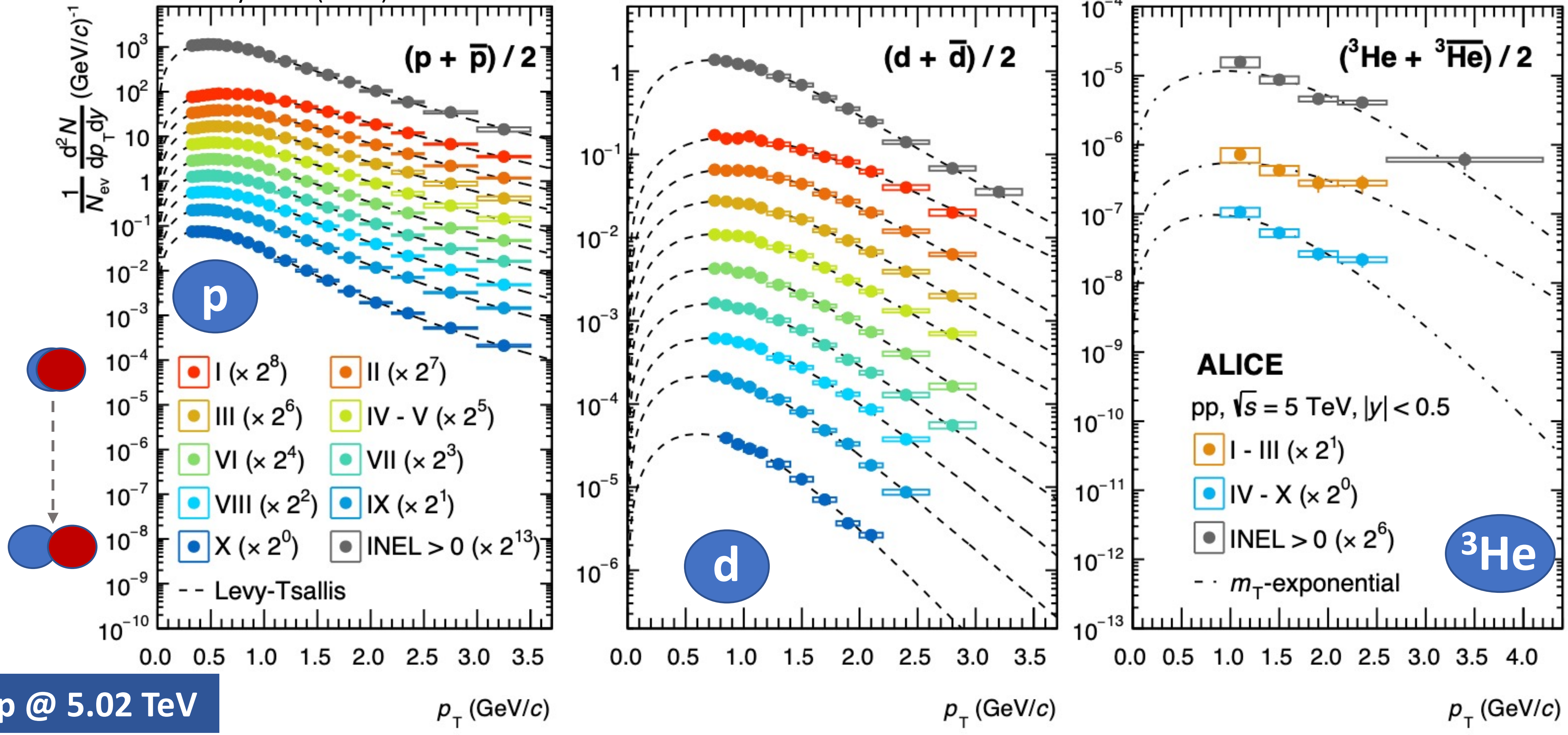
- incorporates the incomplete equilibration of strangeness by introducing the strangeness saturation factor gammaS
- accounts for the multiplicity-dependent chemical freezeout temperature

PRC 100 (2019) 054906



Light (anti)nuclei in small systems (I)

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

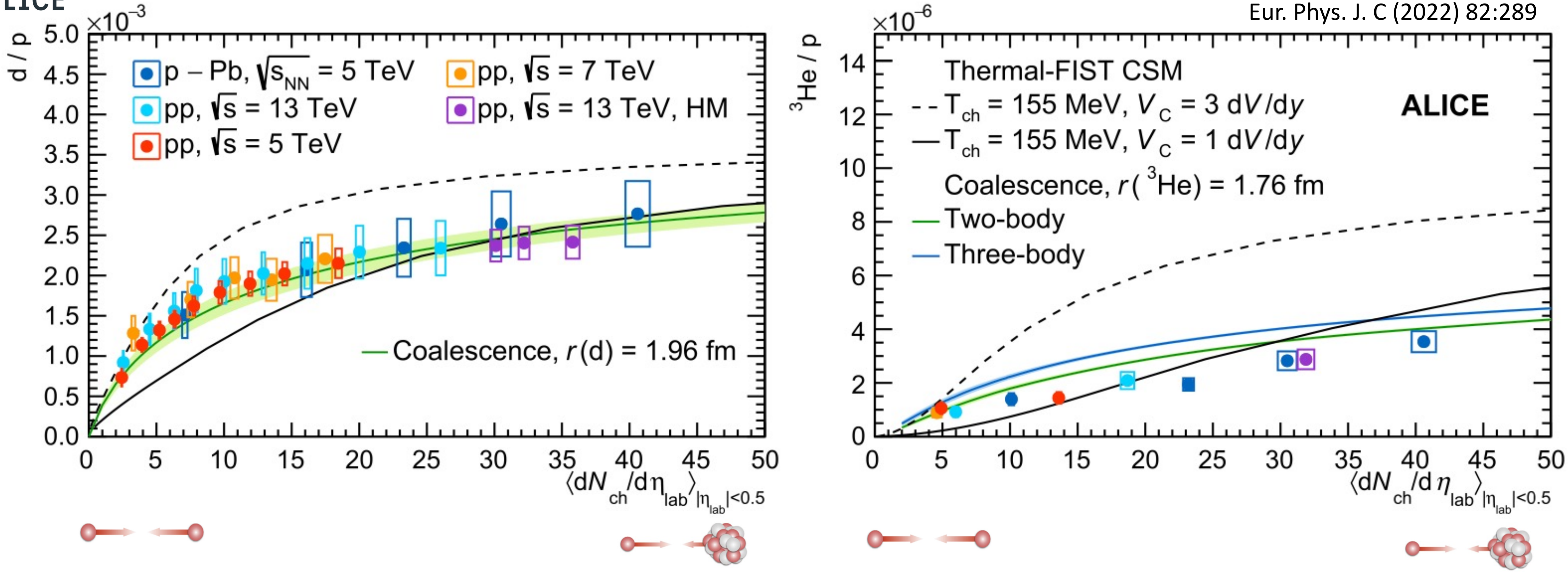


pp @ 5.02 TeV

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

ALICE

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

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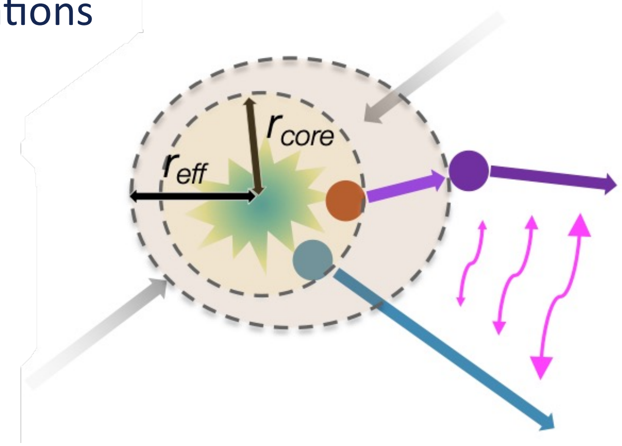
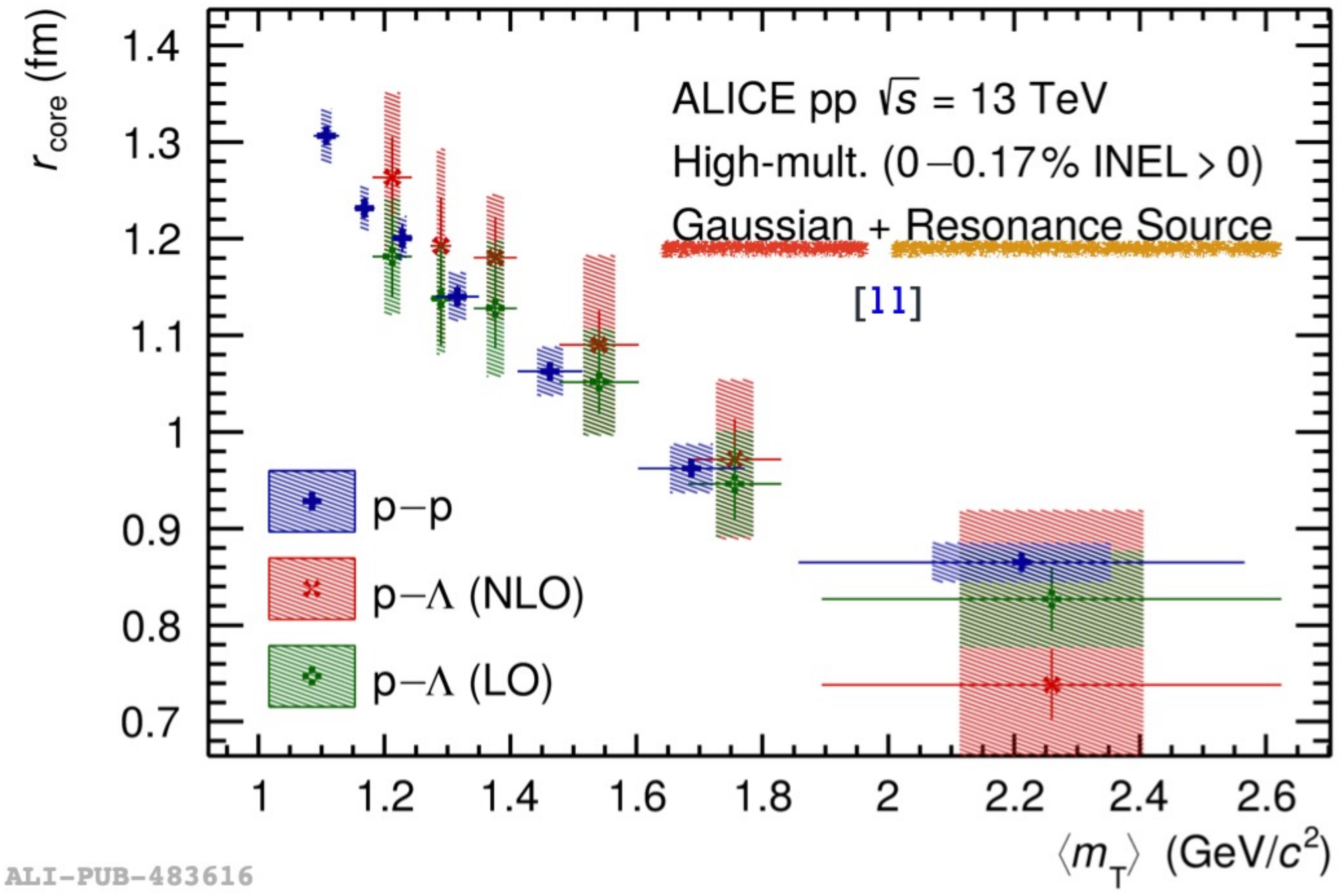
Characterization of emission source

- 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

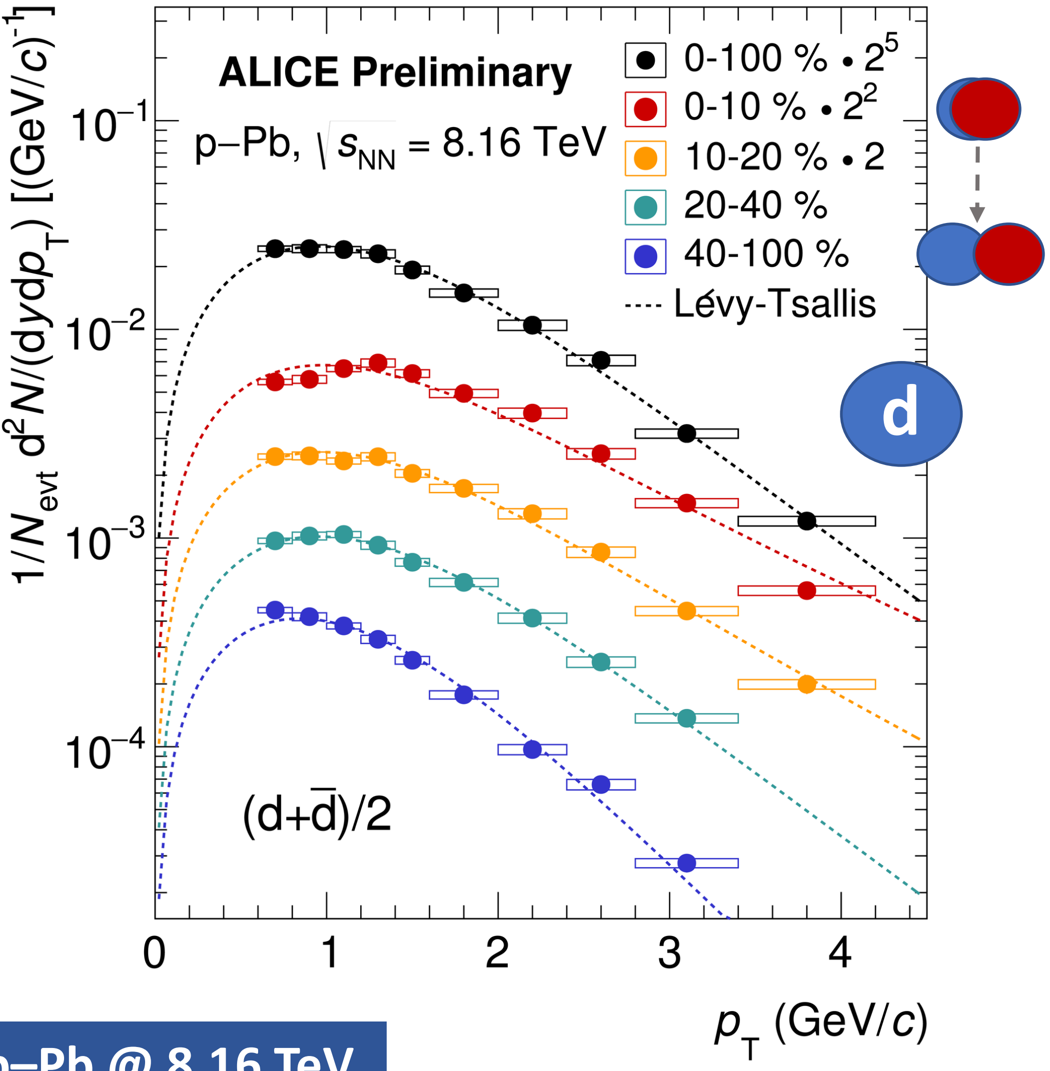




ALI-PUB-483616

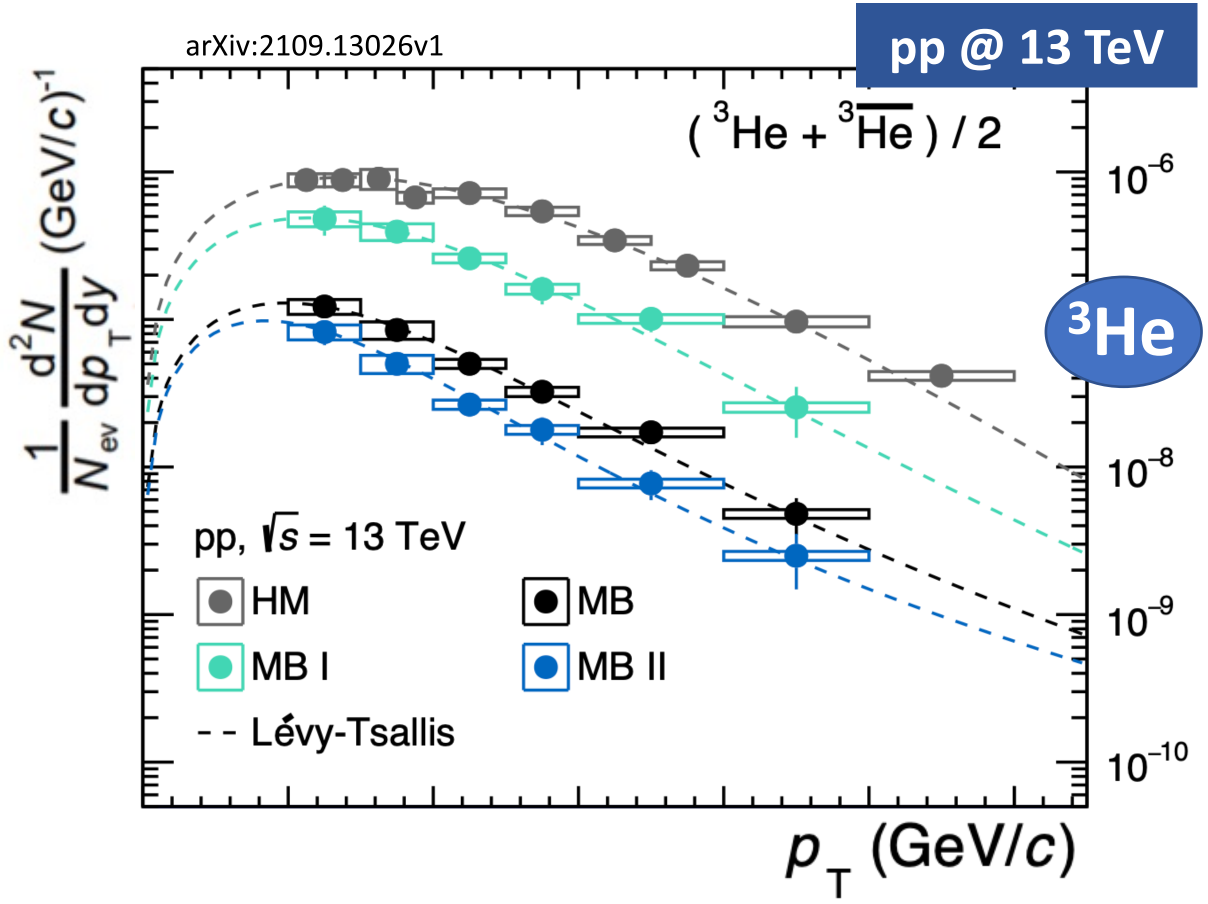
PLB 811 (2020) 135849

Light (anti)nuclei in small systems



p–Pb @ 8.16 TeV

pp @ 13 TeV



- $p_{\rm T}$ spectra fitted with Lévy-Tsallis function
  ⇒ Extrapolation to unmeasured regions

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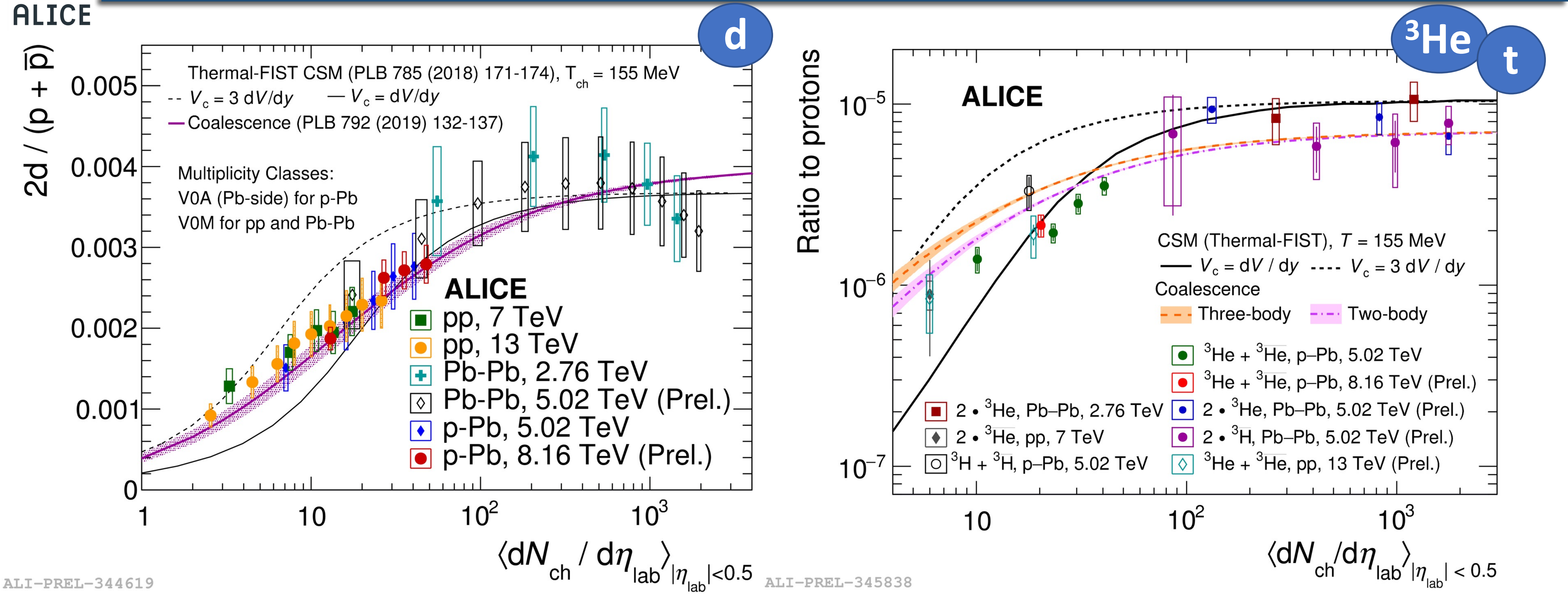
Ratio to protons – models comparison

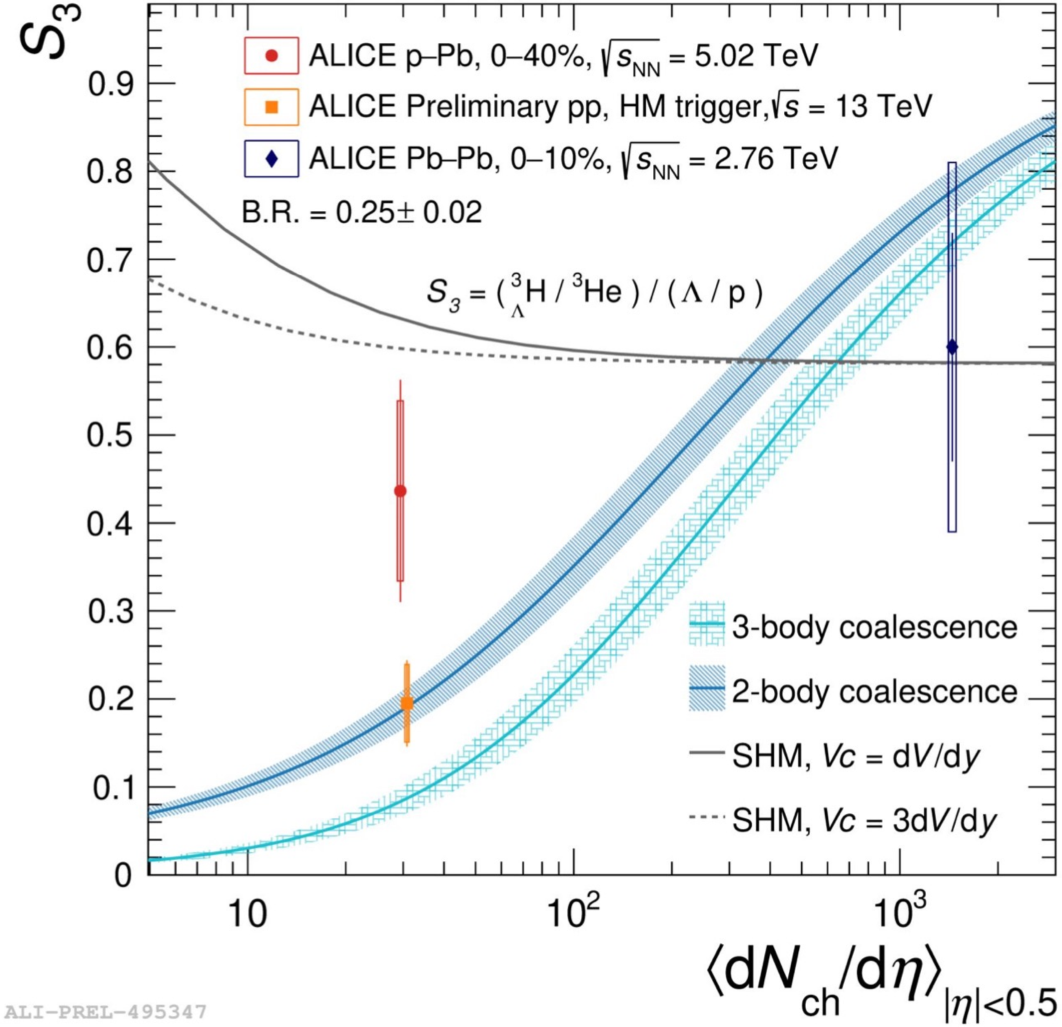


- Smooth transition across different collision systems and energies
- Light nuclei production seems to depend only on multiplicity
- Results challenge the models for A=3 nuclei

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!



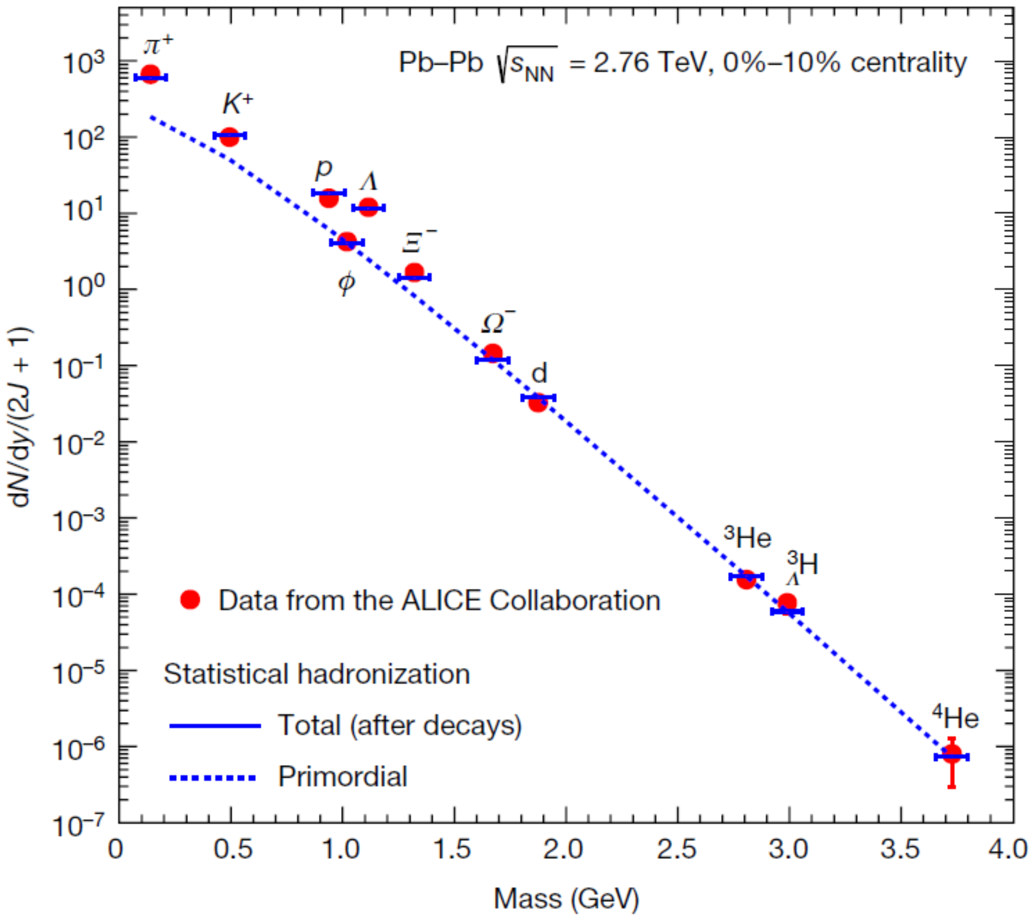
arXiv:2107.10627

Statistical models

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

  $\Rightarrow$ 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?

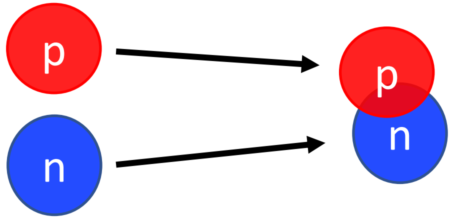


Particle yields of light-flavour hadrons described over 9 orders of magnitude with a **common $T_{\mathrm{chem}} \approx 156$ MeV**

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

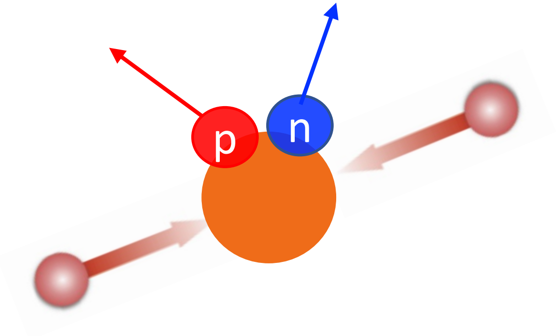
$$B_A(p_{\mathrm{T}}^{p}) = E_A \frac{\mathrm{d}^3 N_A}{\mathrm{d}\, p_A^3} \Big/ \left(E_p \frac{\mathrm{d}^3 N_p}{\mathrm{d}\, p_p^3} \right)^A \Bigg|_{p_{\mathrm{T}}^{p} = p_{\mathrm{T}}^{A}/A}$$

- Experimental observable tightly connected to the coalescence probability

Larger B_{A} ⟺ Larger coalescence probability

- Coalescence probability depends on the system size

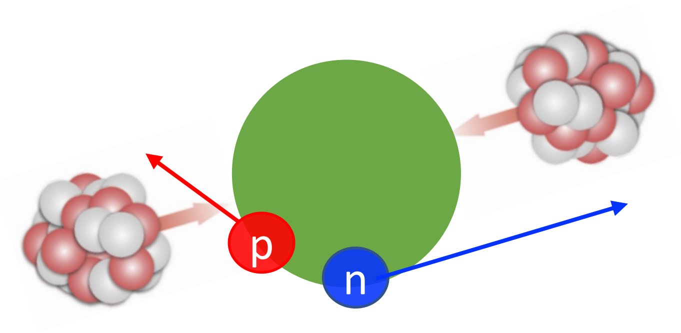
[1]PRC 99 (2019) 024001
[2]PRL 123 (2019) 112002
[3]PRC 96 (2017) 064613



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}