Recent results from ALICE (selection of hypernuclei & correlations)

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Trieste – 3 July 2023

Motivation

Particle production mechanism

Particle interactions

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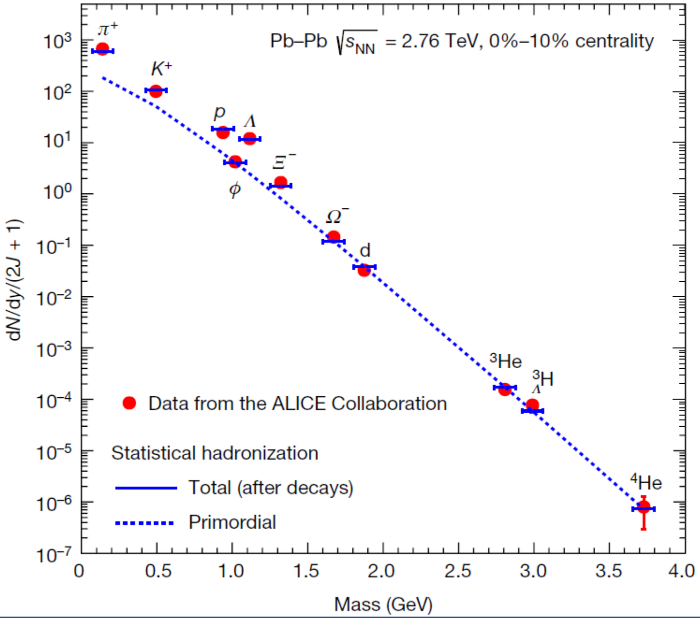
Statistical models (SHM)

- Hadrons emitted from a system in statistical and chemical equilibrium
- $dN/dy \propto \exp(-m/T_{chem})$
- $T_{chem} \approx 156$ MeV



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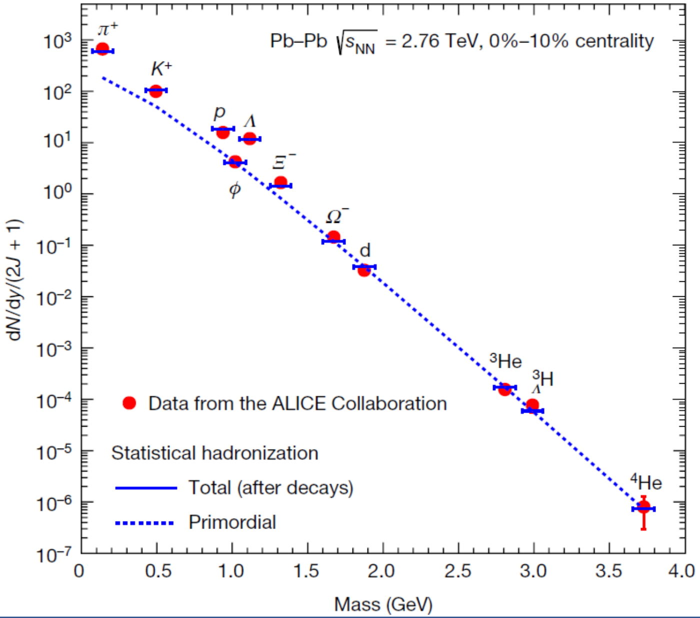
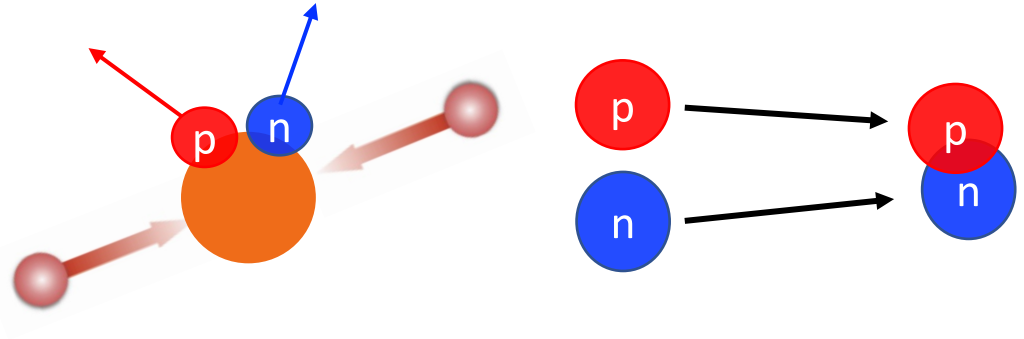


Particle interactions

Coalescence models

- (Anti)nuclei arise from the overlap of the (anti)nucleons phase-space distributions with the Wigner density of the bound state
- Microscopic description

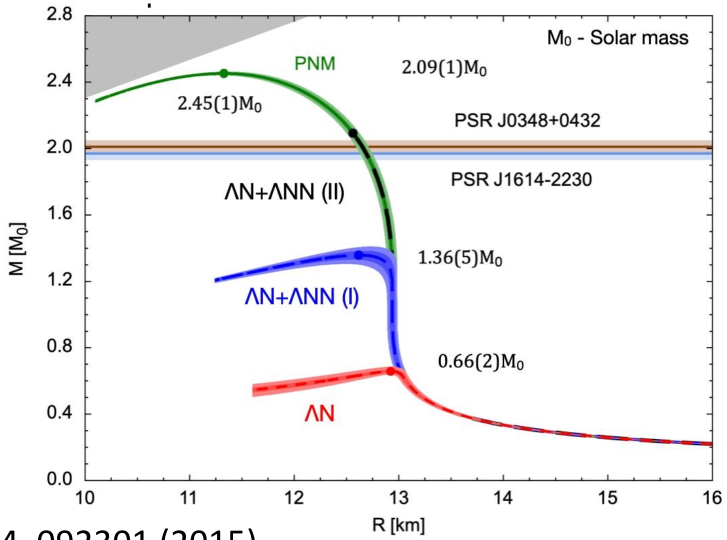


Motivation

Particle production mechanism

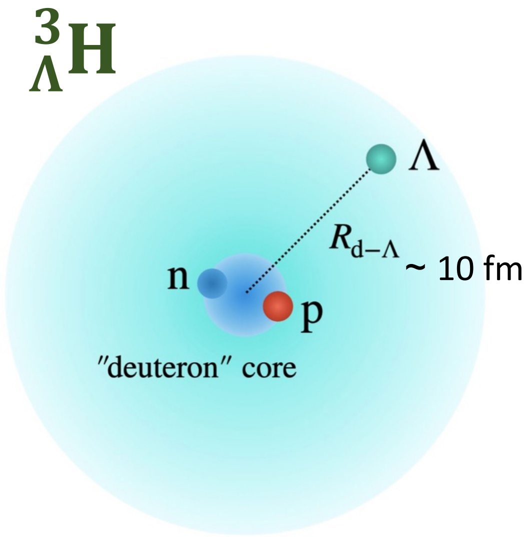
Particle interactions

- Equation of state
- Neutron stars
- Exotic states (bound states, molecular states, coupled channels, …)



D. Lonardoni et al., PRL 114, 092301 (2015)

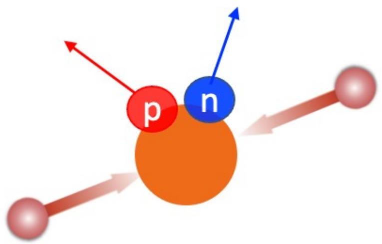
${}^{3}_{\Lambda}\mathrm{H}$ in small collision systems



${}^{3}_{\Lambda}\mathrm{H}$ in small collision systems

Small collision systems (as pp) are interesting:

- size of system created in the collision is smaller or equal to that of the nucleus under study



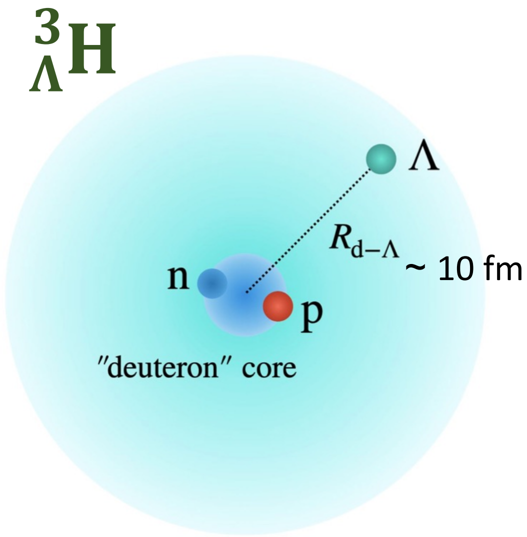
System size (pp, p—Pb): 1–1.5 fm

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)

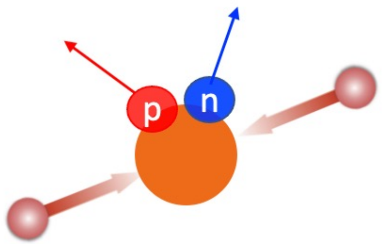


${}^{3}_{\Lambda}\mathrm{H}$ in small collision systems

Small collision systems (as pp) are interesting:

- size of system created in the collision is smaller or equal to that of the nucleus under study
- for small systems model predictions are quite different

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



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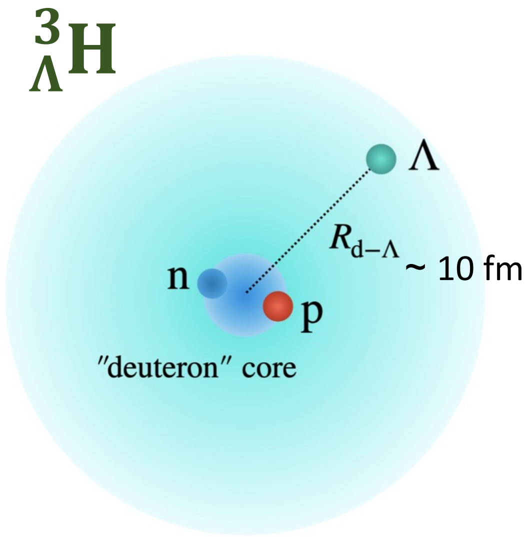
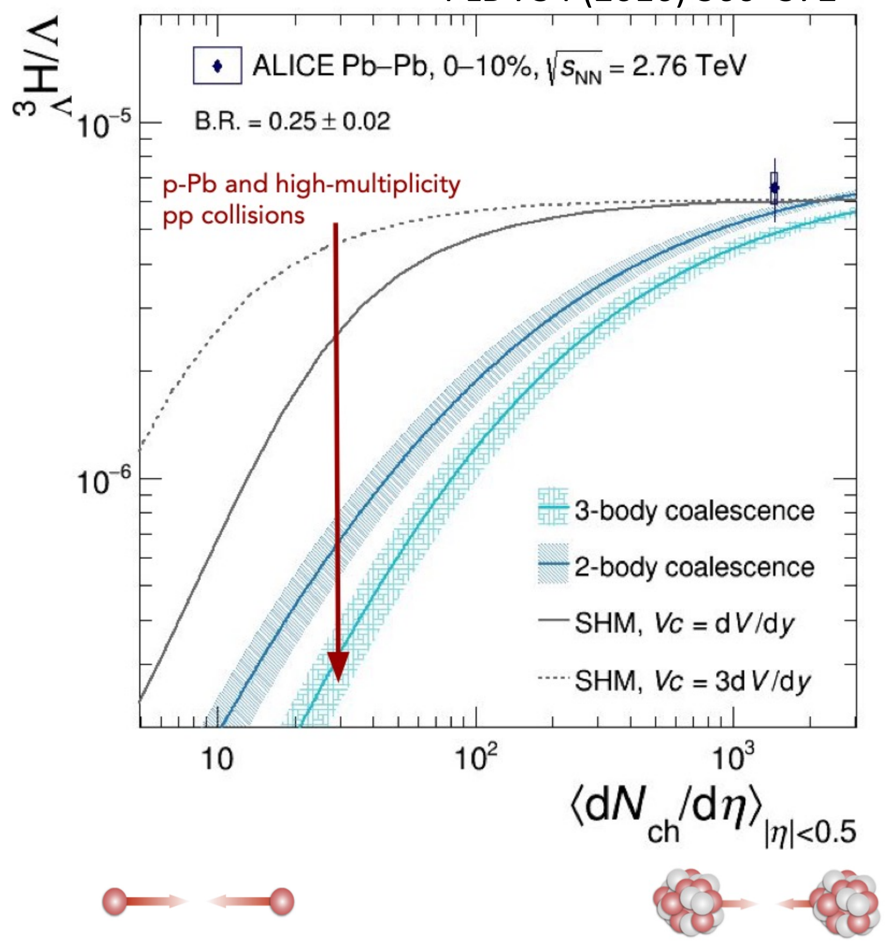


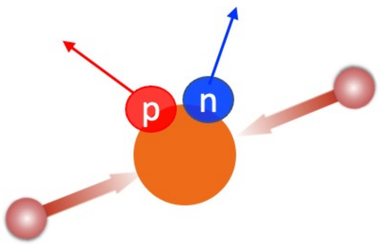
PLB 754 (2016) 360–372



${}^{3}_{\Lambda}$H in small collision systems

Small collision systems (as pp) are interesting:

- size of system created in the collision is smaller or equal to that of the nucleus under study
- for small systems model predictions are quite different
- coalescence is sensitive to the interplay between the size of the collision system and the spatial extension of the nucleus wave function



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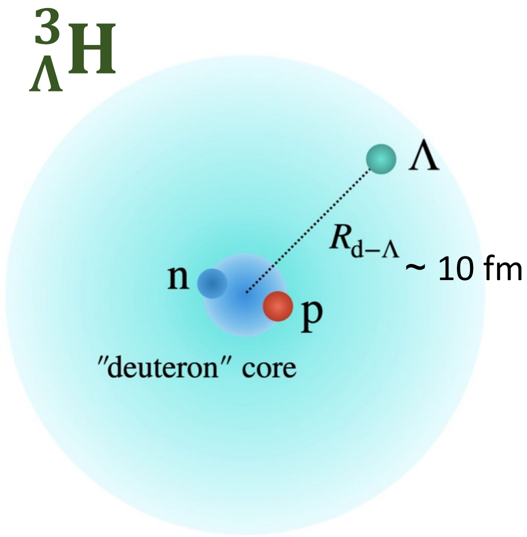
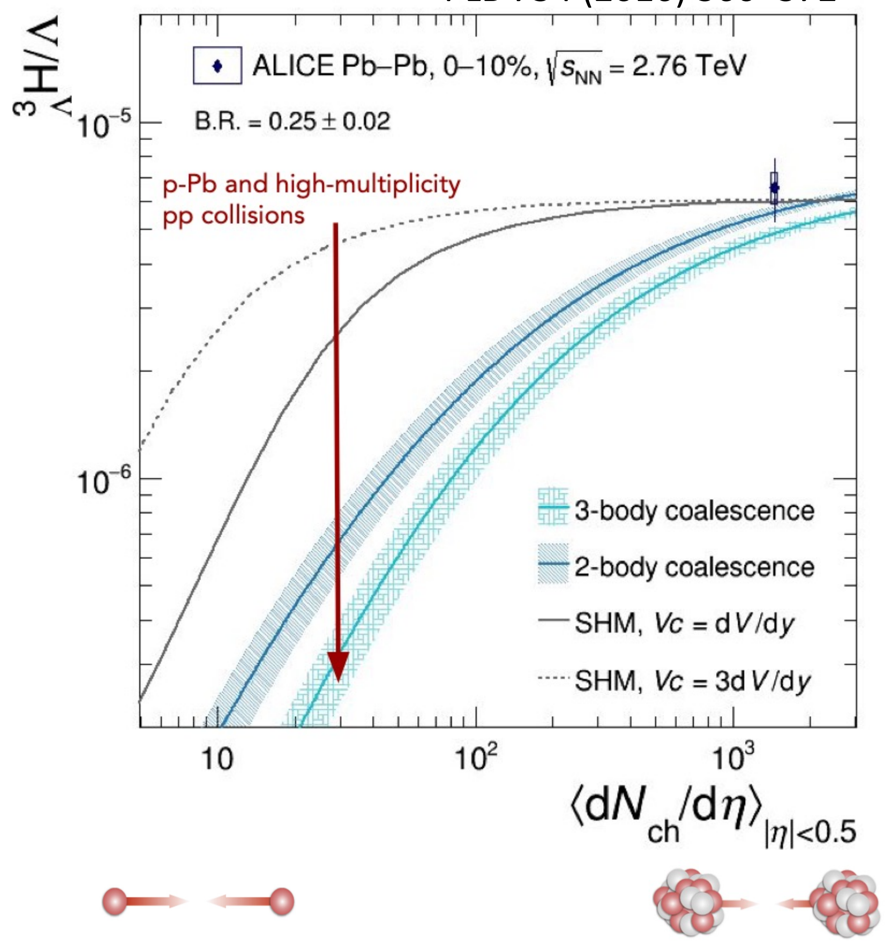


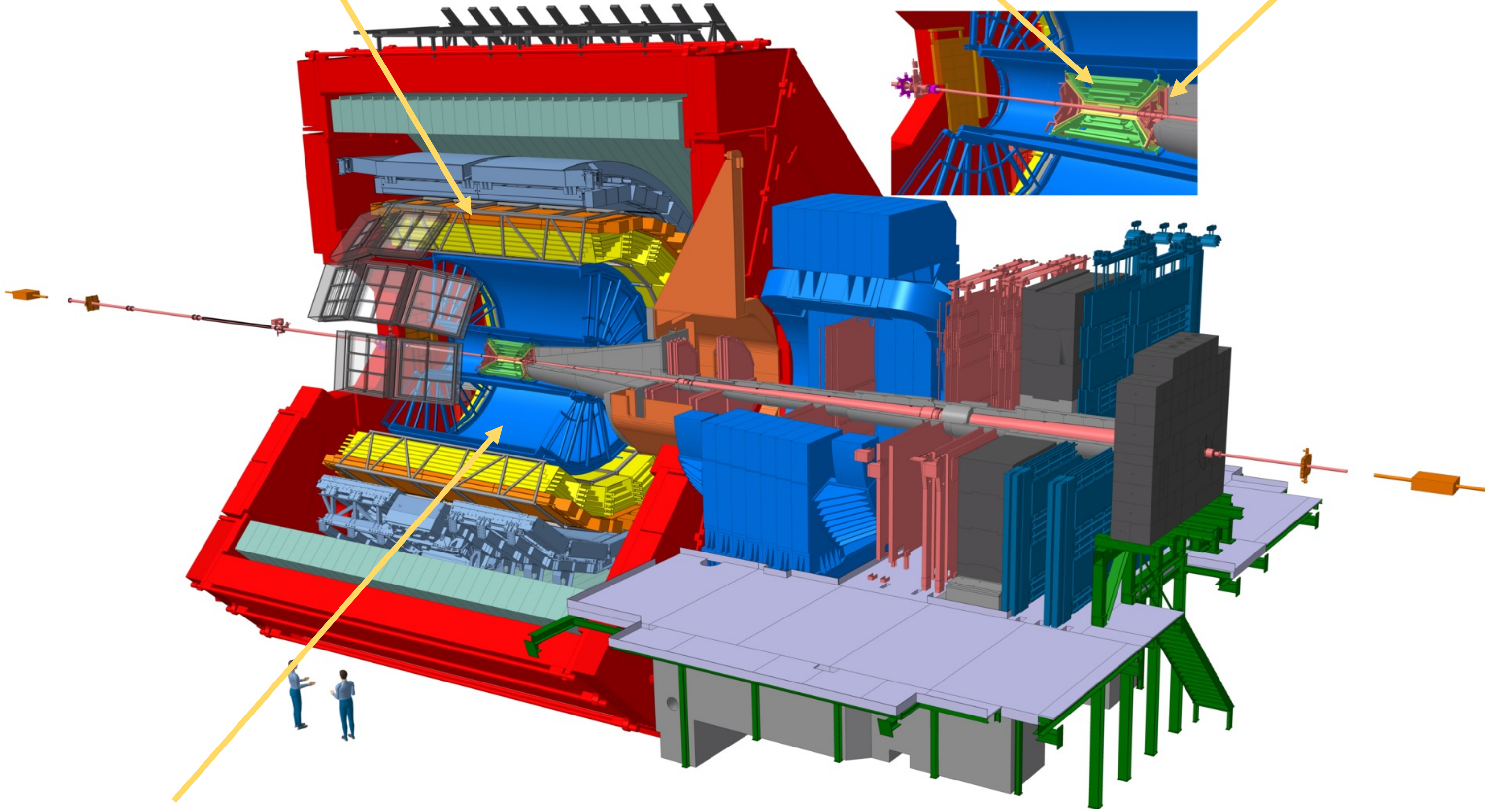
powerful probe for investigating the nucleon - Λ interaction

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

PLB 754 (2016) 360–372



The ALICE detector



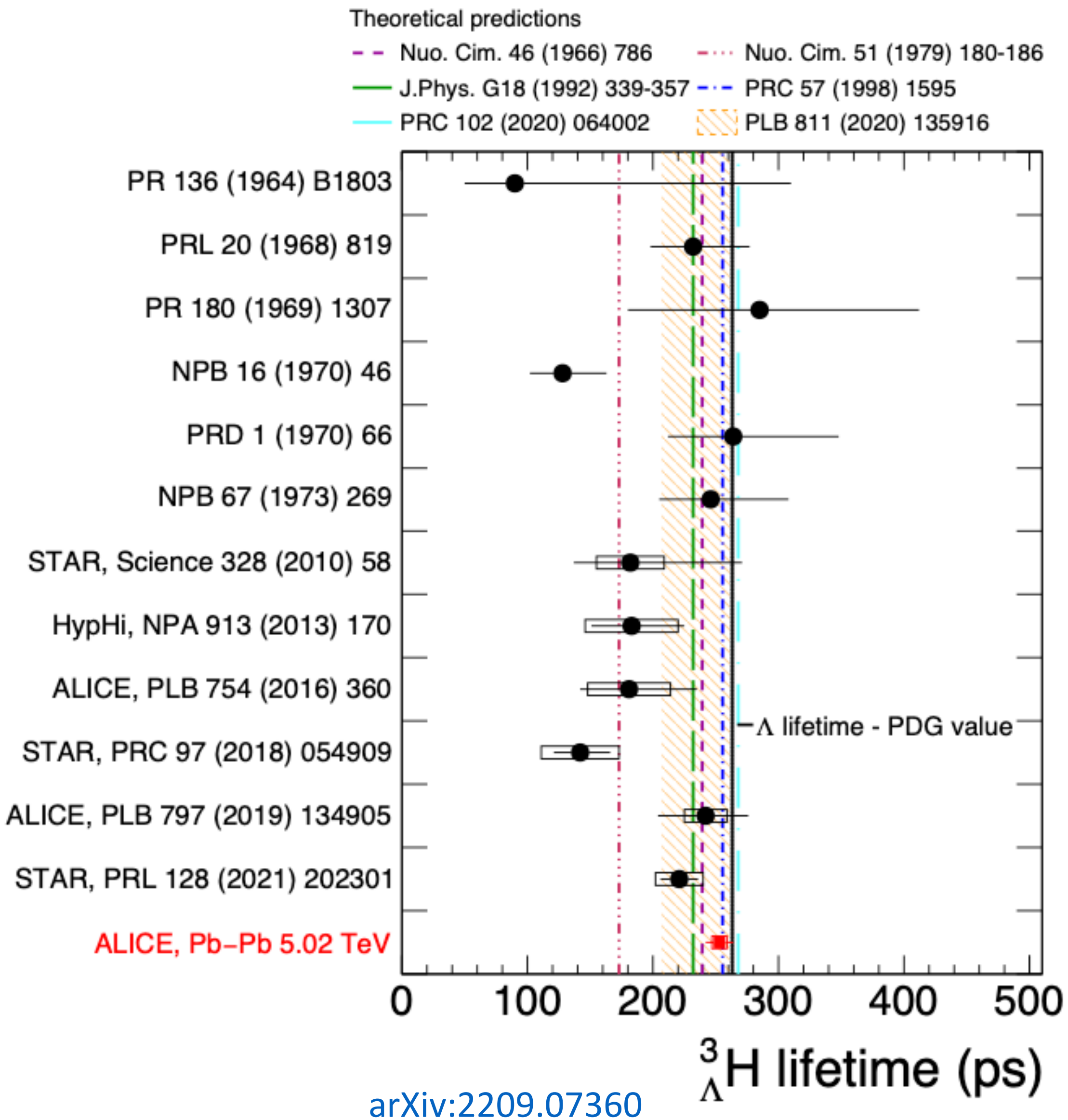
- pp, p—Pb, Pb—Pb collisions at various centre-of-mass energies
- excellent tracking and PID capabilities over a broad momentum range
  - TPC: $\sigma_{\mathrm{d}E/\mathrm{d}x} \sim$ 5.5% for pp
    $\sigma_{\mathrm{d}E/\mathrm{d}x} \sim$ 7% for Pb—Pb
  - TOF: $\sigma_{\mathrm{PID}} \sim$ 70 ps for pp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

→ most suited detector at the LHC for the study of (anti)(hyper)nuclei & hadron-hadron correlations

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

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



arXiv:2209.07360

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

Hypertriton binding energy

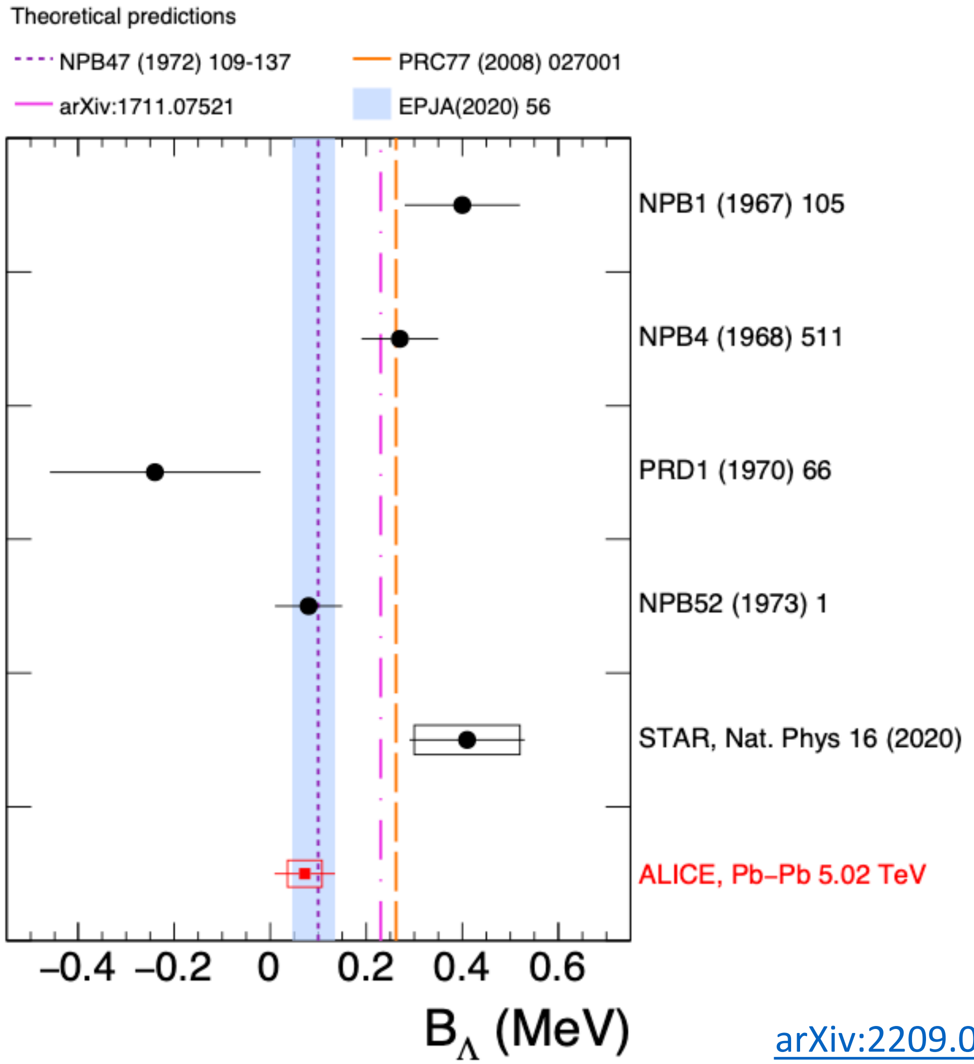
- From the mass measurement to B_Λ

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

- 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 [1, 2]

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

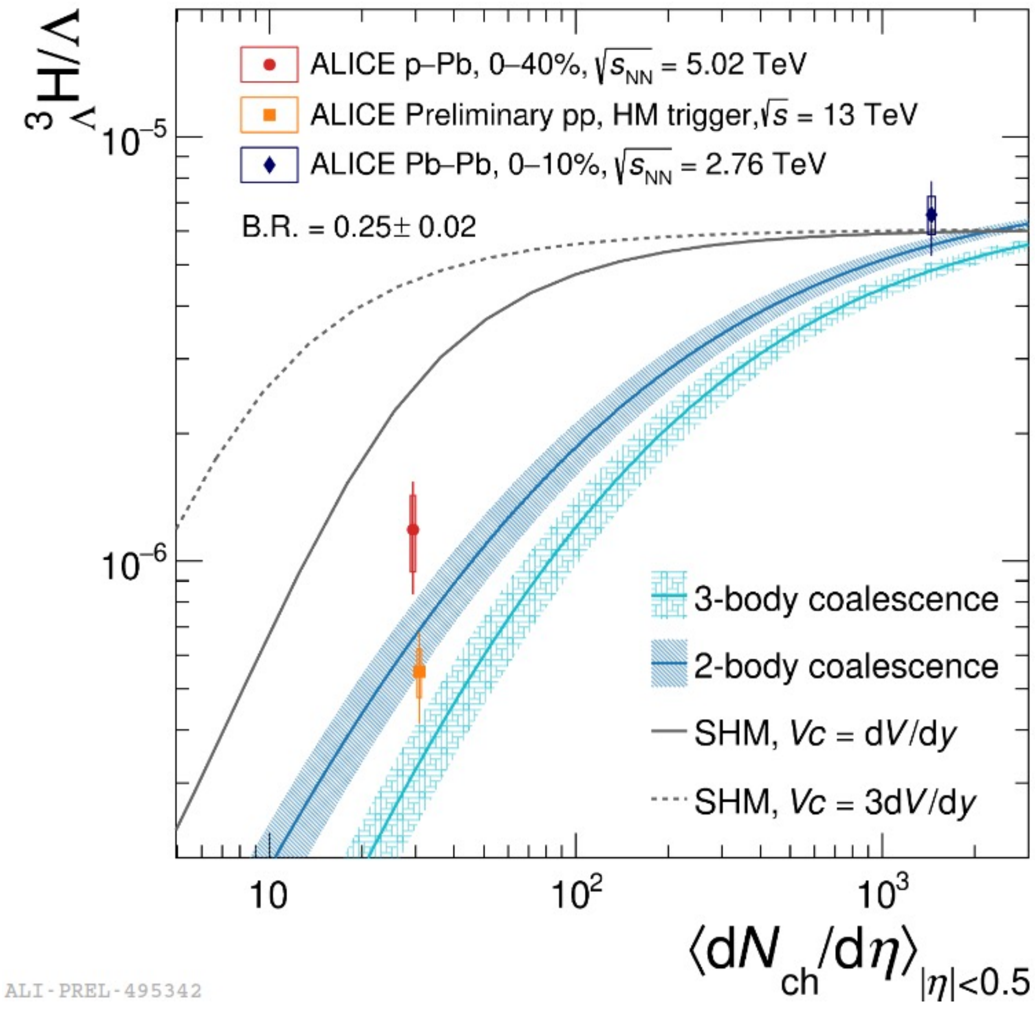
$$B_\Lambda = [72 \pm 63\ (\text{stat.}) \pm 36\ (\text{syst.})]\ \text{keV}$$



arXiv:2209.07360

[1] Hildenbrand et al., PRC 102 (2020) 6
[2] Pérez-Obiol et al., PLB (2020) 811

Hypertriton production



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

- **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

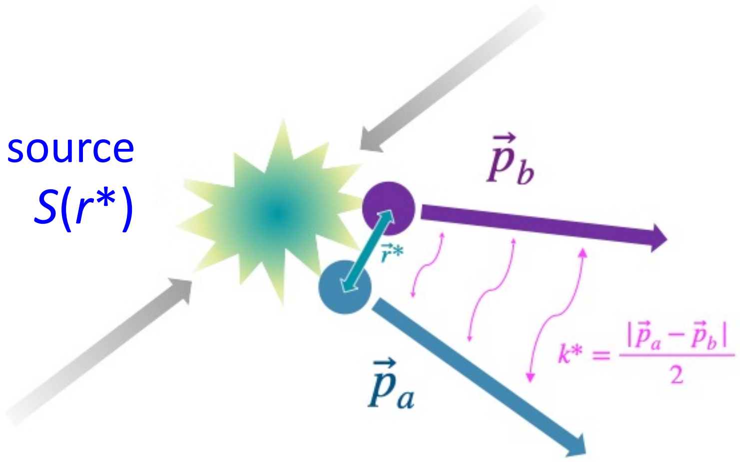
Coalescence quantitatively describes the $^{3}_{\Lambda}$H suppression in small systems
> the nuclear size matters at low charged-particle multiplicity

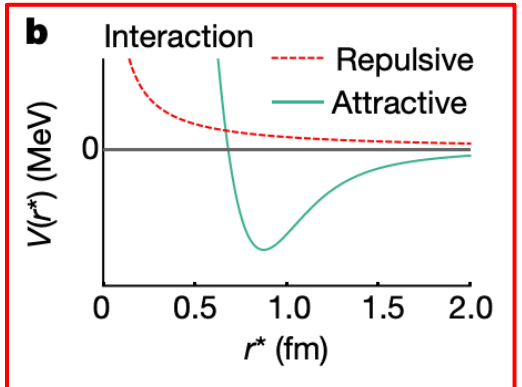
Nuclear interactions

- Femtoscopic measurement of the hadron - hadron interaction in pp collisions
  - Access to the strong interaction and short-range dynamics between hadrons (~ 1-2 fm)

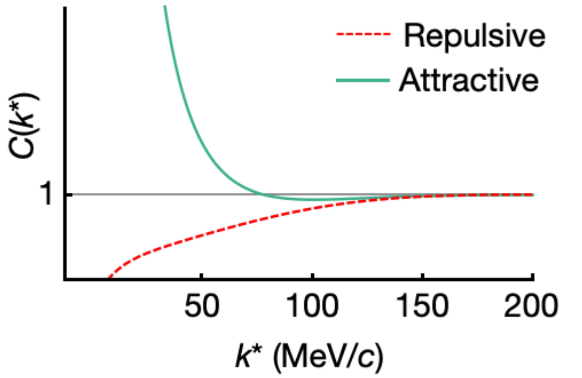
D. Mihaylov's talk
Mon. 14.30

Emission source
$S(r^*)$





Schrödinger equation



Correlation function

- Two particle correlation function: $C(k^*) = \int S(\vec{r}^*)\left|\psi(\vec{k}^*,\vec{r}^*)\right|^2 d^3\vec{r}^* = \mathcal{N}(k^*)\frac{N_{\mathrm{same}}(k^*)}{N_{\mathrm{mixed}}(k^*)}$
  - particle-emitting source (anchored to p-p correlation in ALICE data)
  - two-particle wave function

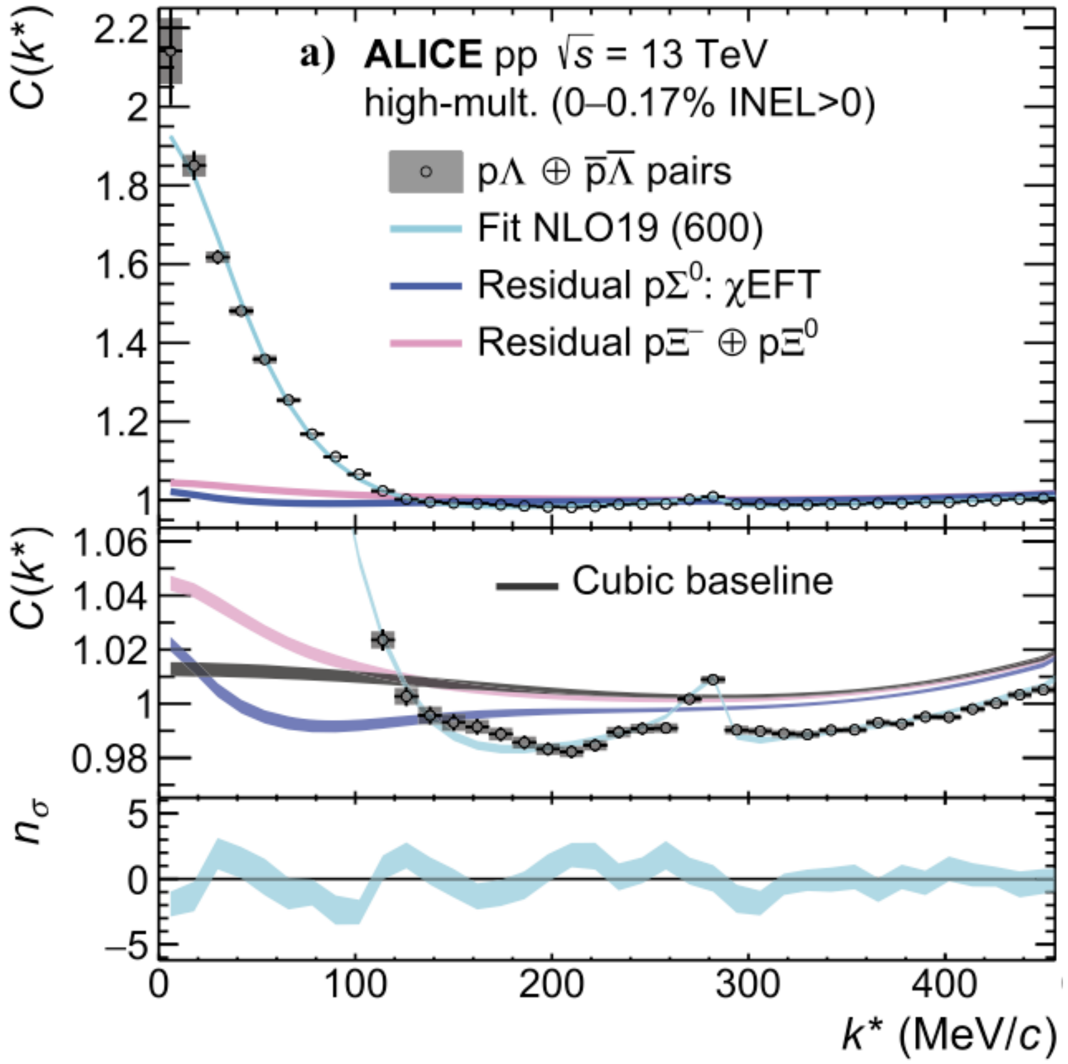
theoretical definition

measurement definition

M. Korwieser's talk
Mon. 15.00

PLB 811 (2020) 135849
Nature 588 (2020) 232-238
Koonin, Physics Letters B 70 (1977) 43-47

p-Λ correlations in pp collisions



- Test chiral effective field theories
- Small deviation k^* < 110 MeV of 3.2 sigmas → 2-body interactions are too attractive

D. Mihaylov's talk
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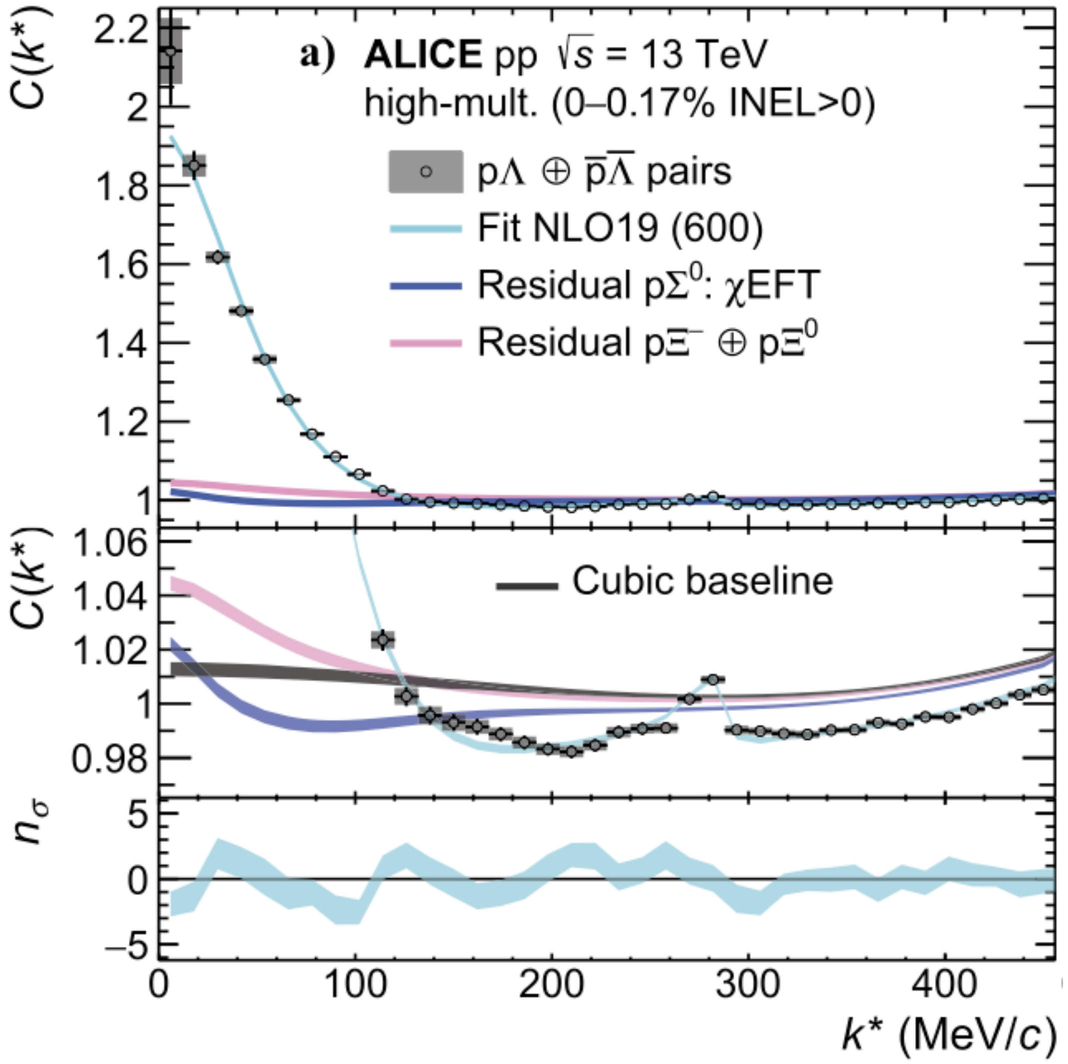
PLB 833 (2022) 137272

p-Λ correlations in pp collisions



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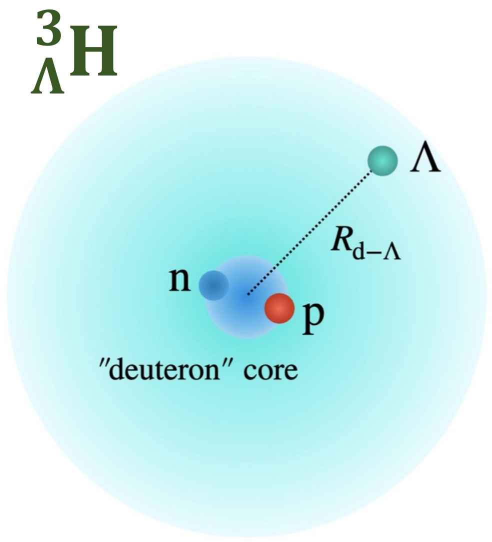
- Based on our knowledge of hypertriton binding energy the 3-body interaction could be less repulsive than expected



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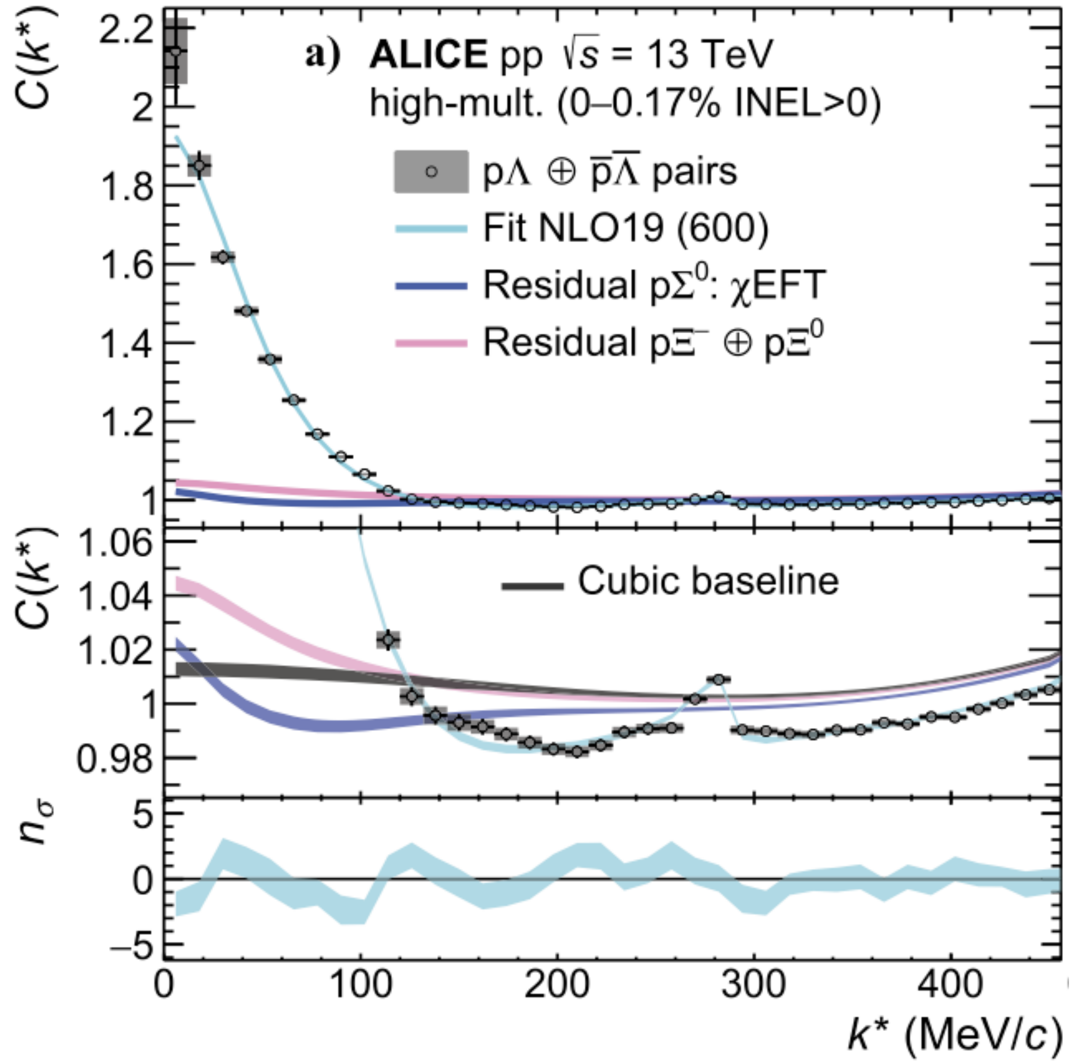

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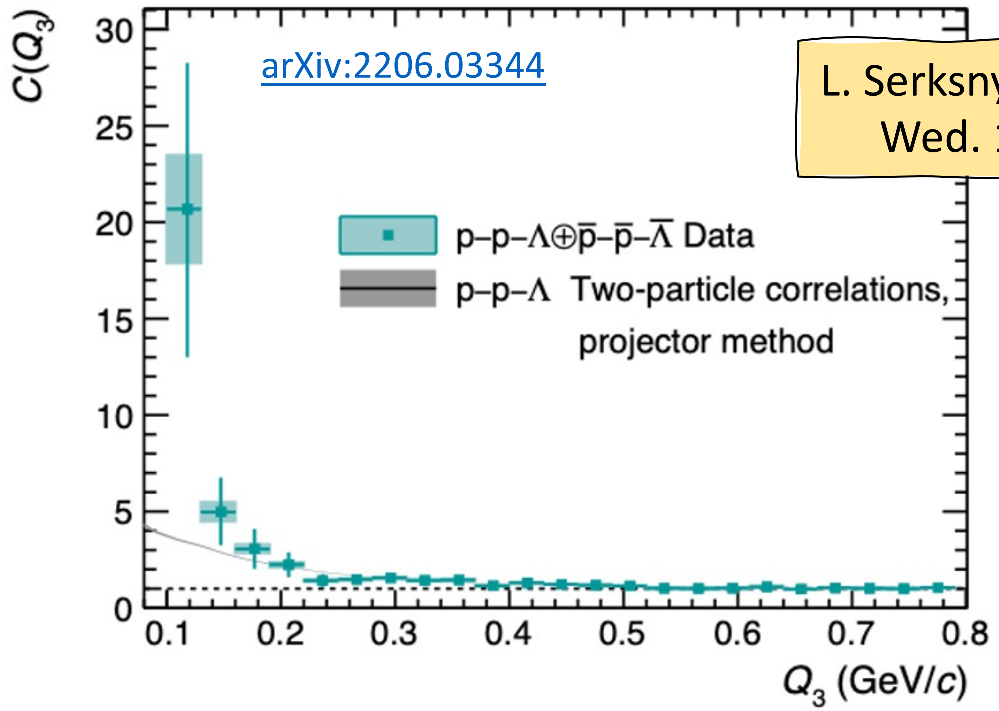
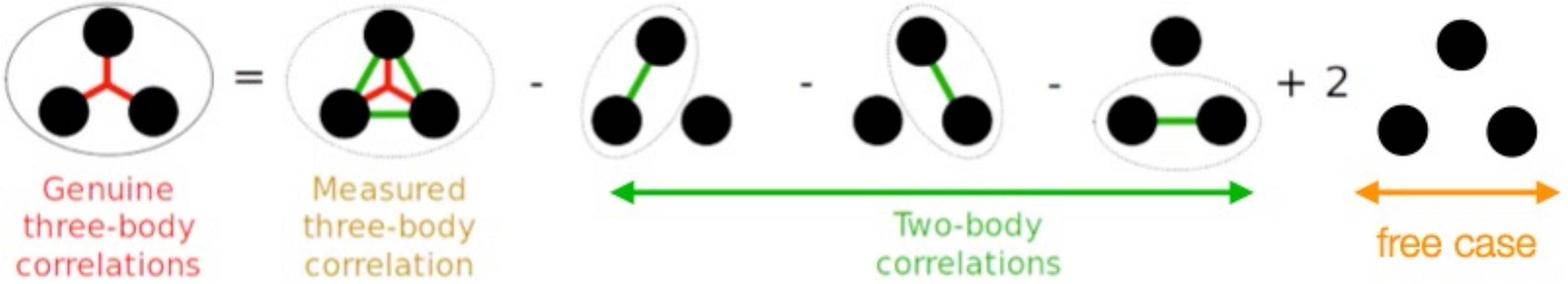


L. Serksnyte's talk
Wed. 15.00

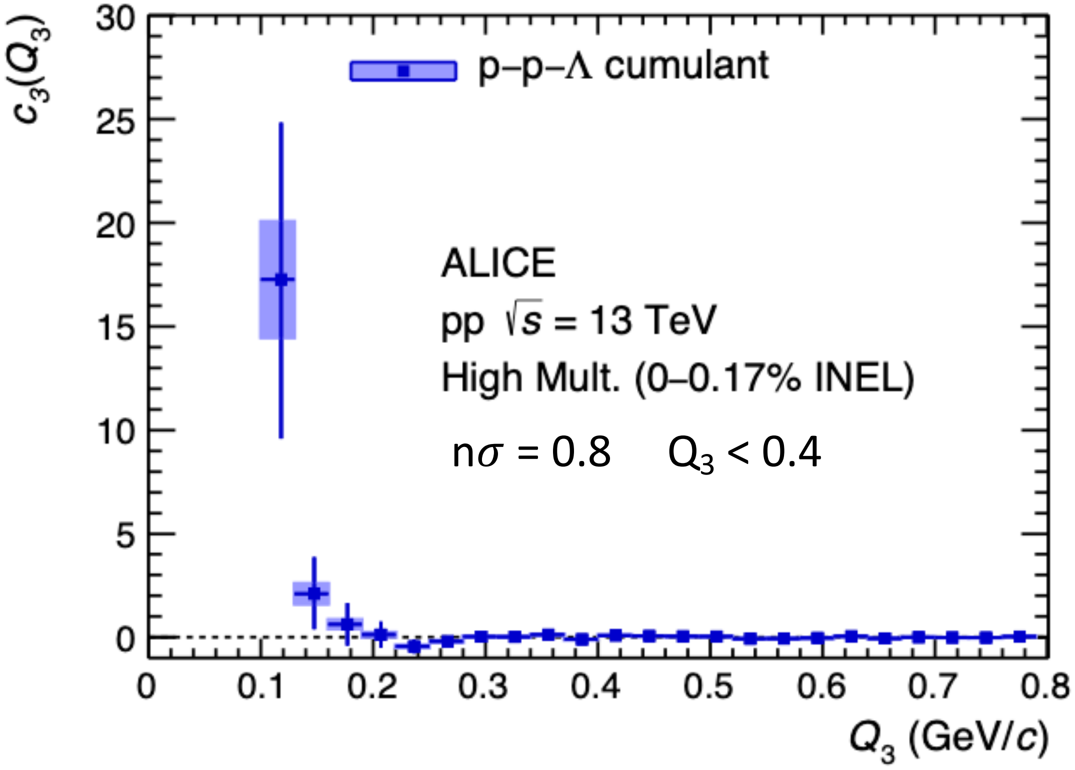
Accessing genuine 3-body interaction

c_3 (Q_3)



c_3 (Q_3) allows to isolate effects associated with the genuine three-body interaction

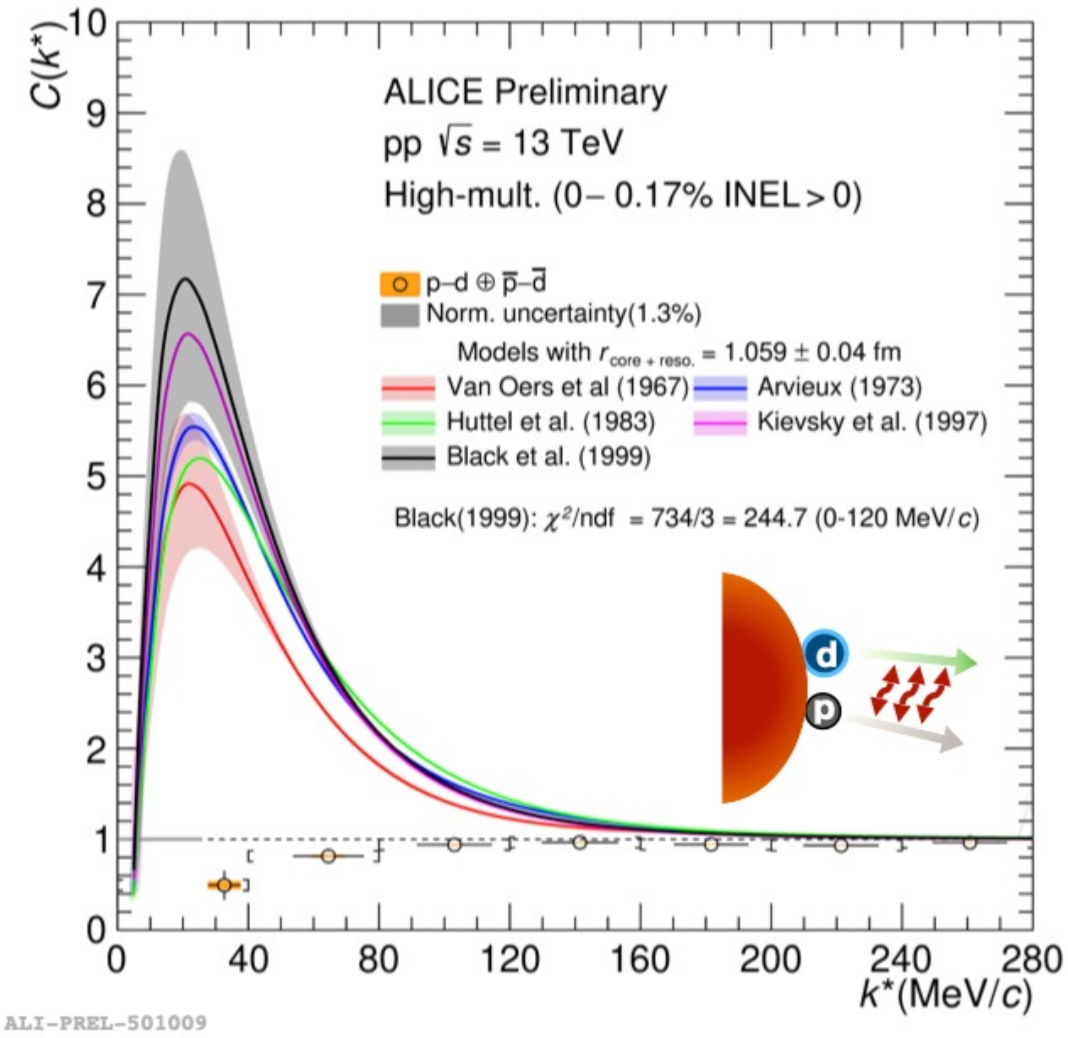
- p-p-Λ cumulants : consistent with null-hypothesis
  - No sign of a repulsion!
- Conclusions
  - Poses interesting questions for the equation of state
  - Need of more statistics → ALICE Run3 dedicated trigger!



L. Serksnyte's talk
Wed. 15.00

Kubo, J. Phys. Soc. Jpn. 177 (1962)
arXiv:2206.03344

p-d correlations in pp collisions



$$r_{\mathrm{eff}}^{\mathrm{pd}} = 1.08^{+0.06}_{-0.06}\ \mathrm{fm}$$

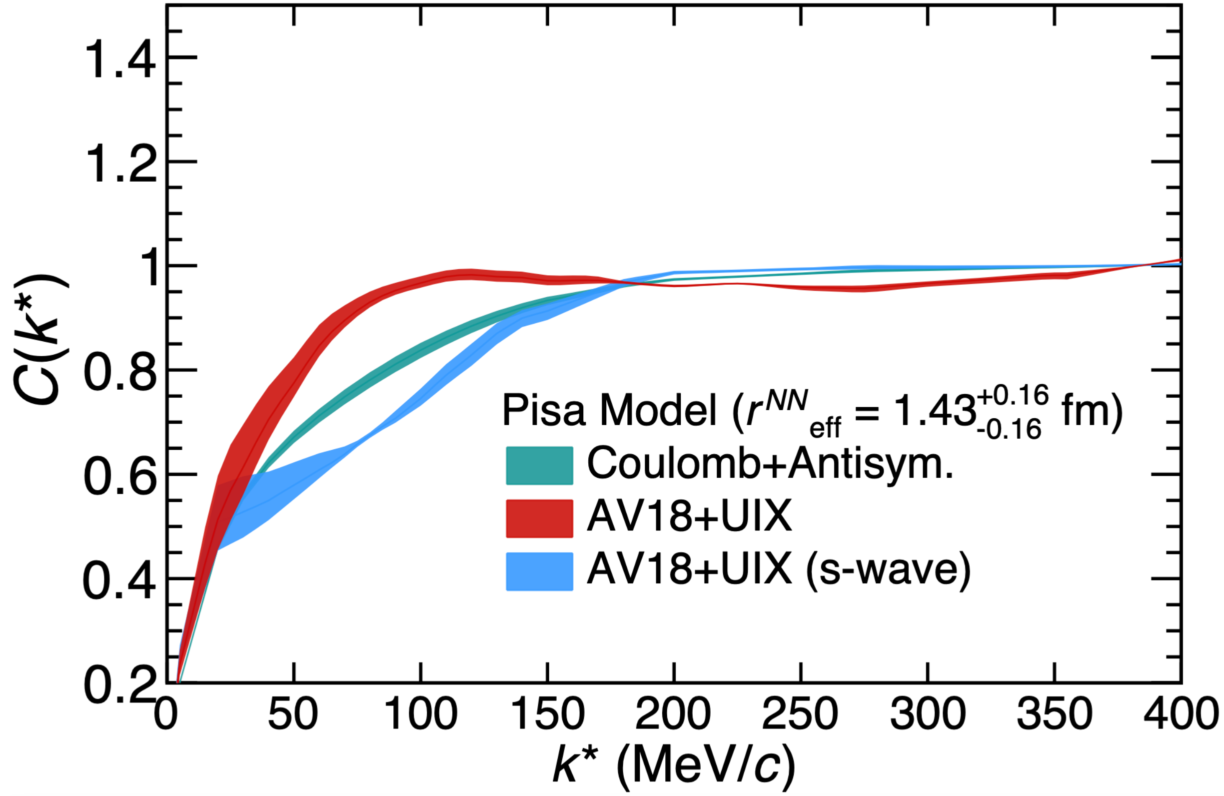
- Data compared with models that describe strong-interaction treating d as a point-like particle
- Models very different from the measurement at low k^*
    - the composite nature of d cannot be neglected
    - Short-range interaction must be treated properly

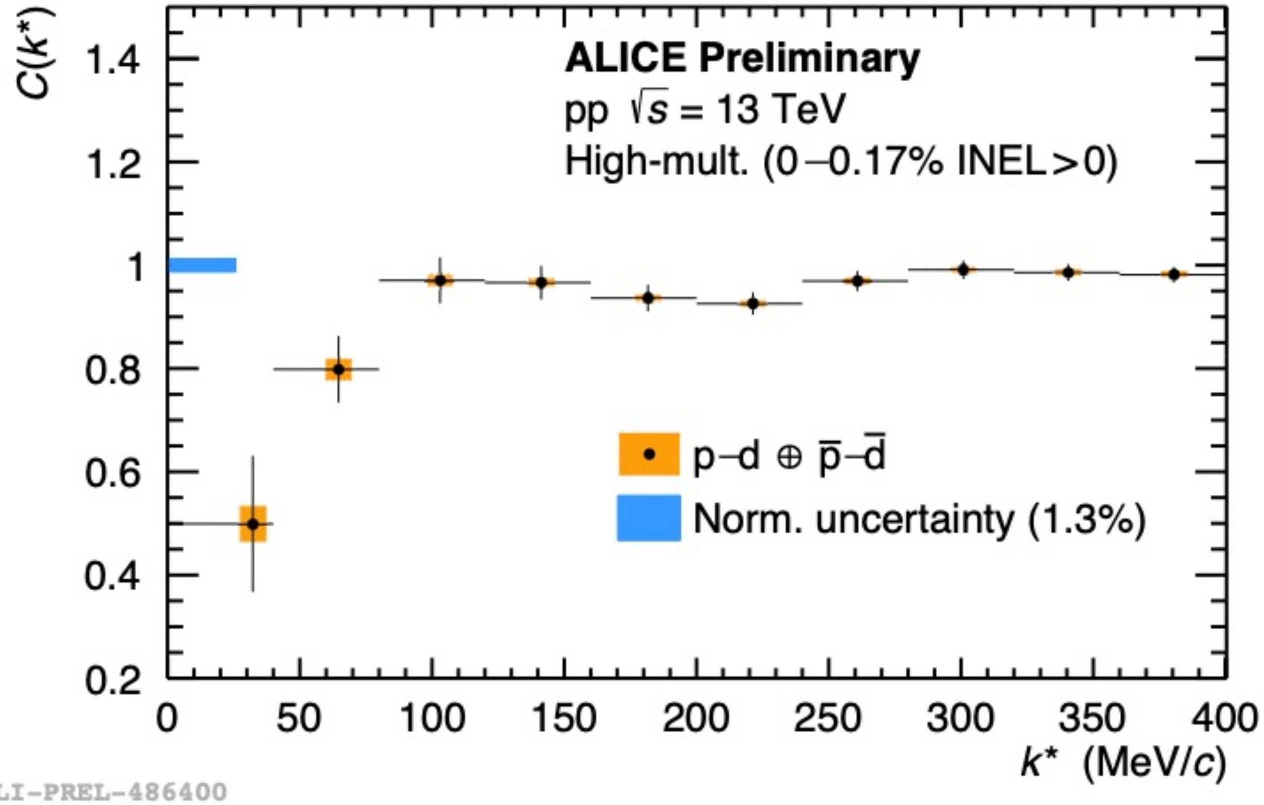
Sensitivity to the dynamics of the three-body p-(p-n) system

Lednicky et al., Phys. Part. Nuclei 40, 307–352 (2009)

p-d correlations in pp collisions

arXiv:2306.02478





3-body calculations done by PISA theory group: M. Viviani, A. Kievsky and L. Marcucci

→ Model calculation qualitatively reproduces the data

→ The p-d correlation is affected by two + three-body p-p-n interactions!

→ Data sensitive to the higher order partial waves

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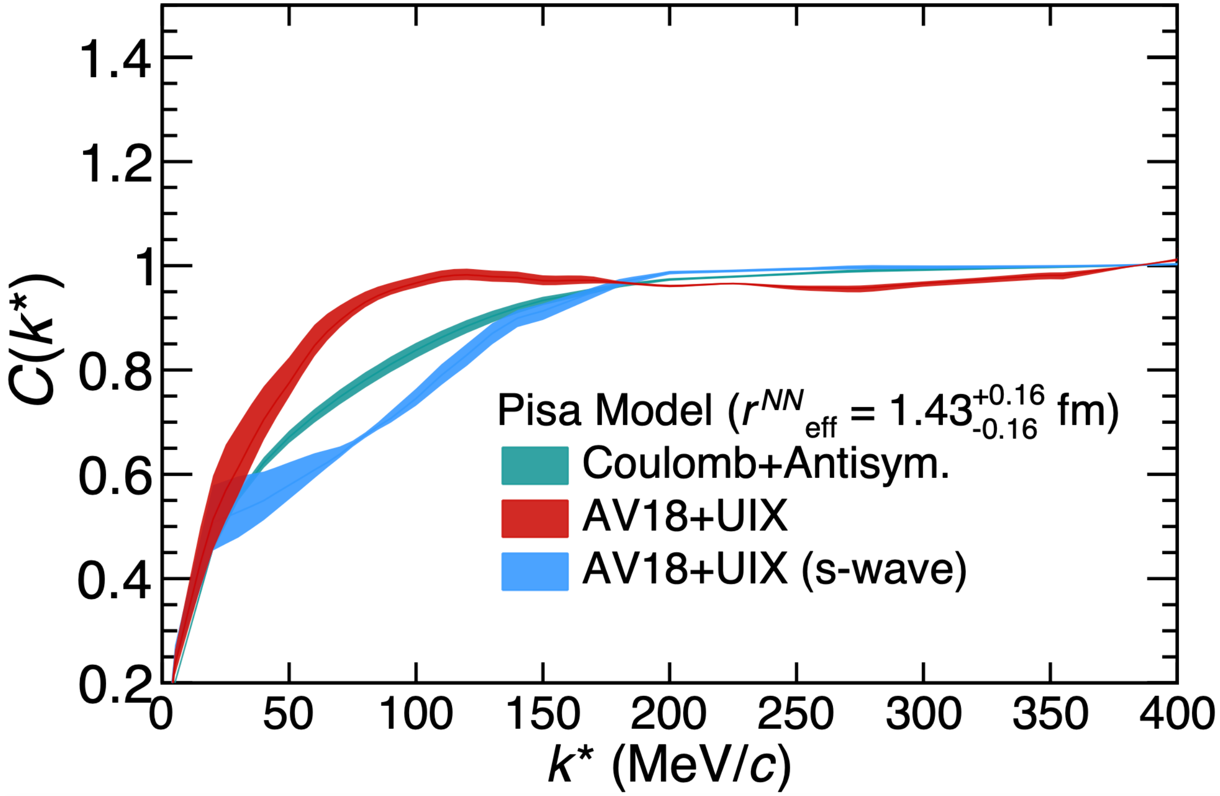

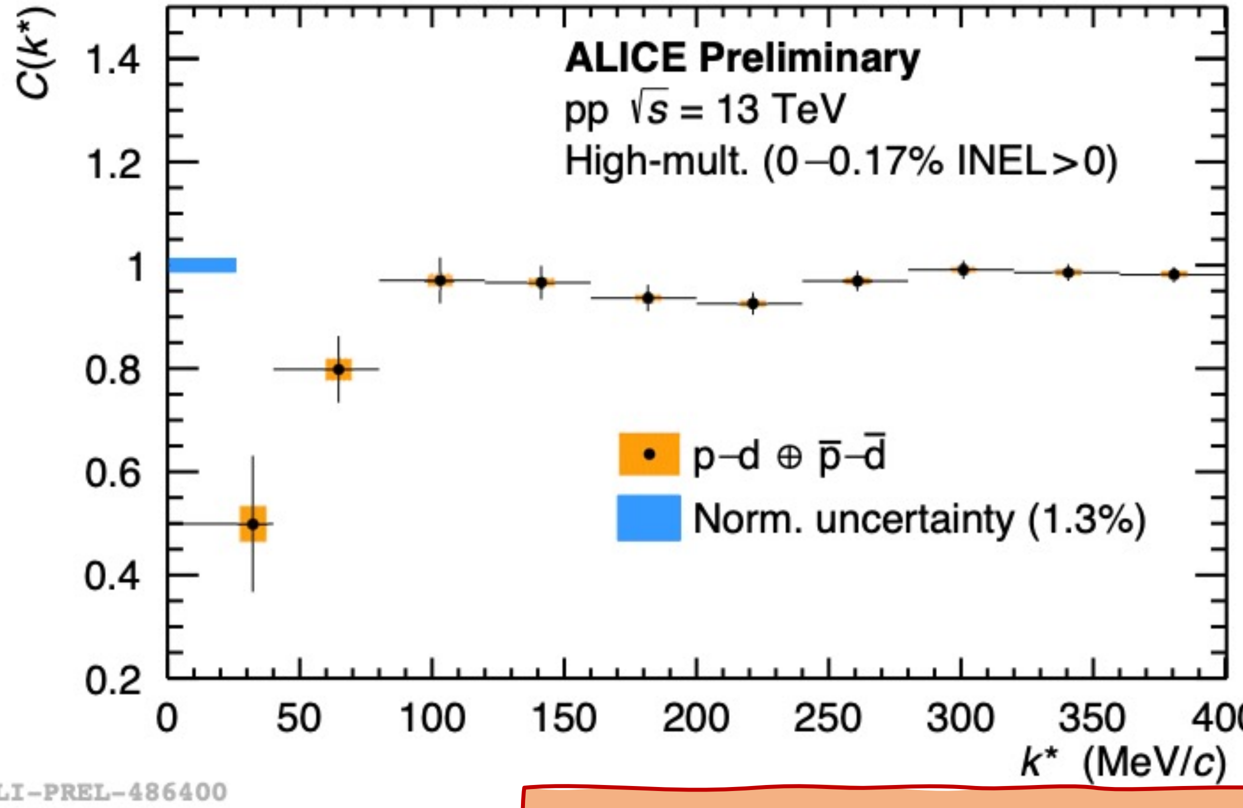

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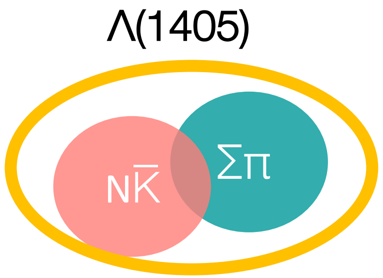
→ Data sensitive to the higher order partial waves

This paves the way to 3-body systems interactions measurements (hadron-deuteron systems)
→ Λ instead of p ($^{3}_{\Lambda}\mathrm{H}$)
→ ALICE Run3

Instead of an outlook…

- K^-p correlations measured by ALICE in different colliding systems [1]
  → Improve understanding on Λ(1405) molecular state [2]

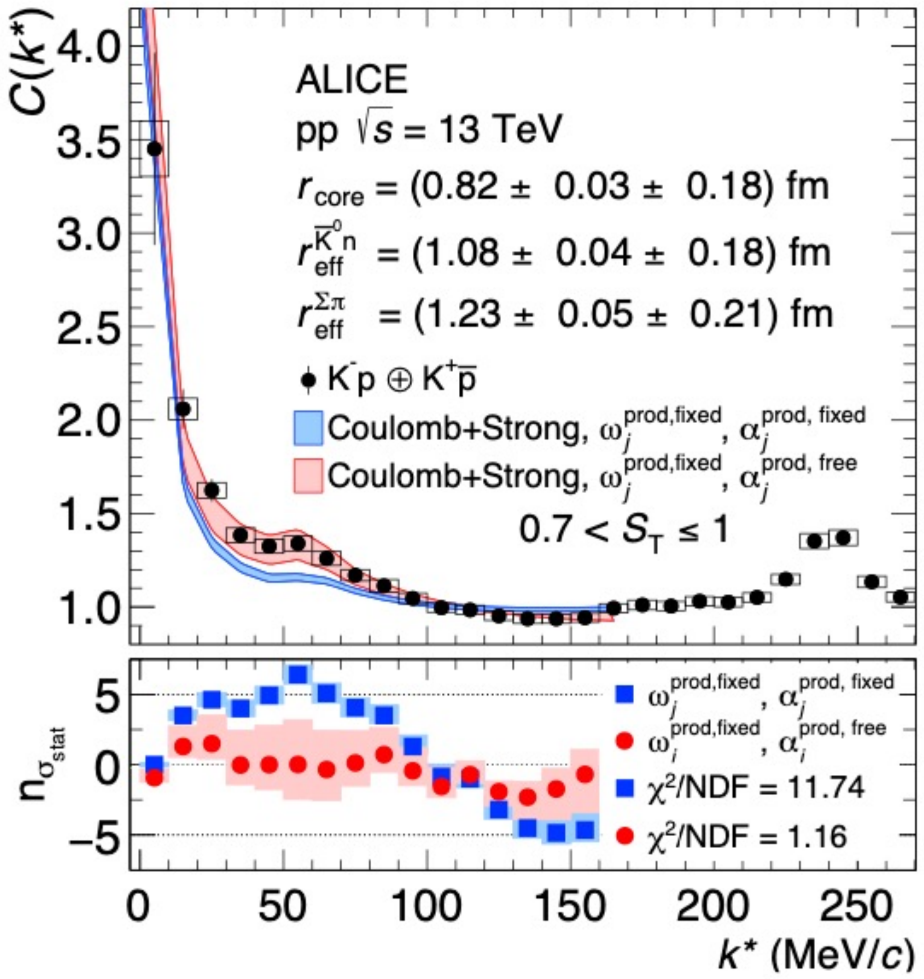


[1] PRL 124 (2020) 9, 092301, PLB 822 (2021), 136708, EPJC 83 (2023), 4, 340
[2] M. Mai EPJ.ST 230 (2021), 6, 1593-1607

O. Vazquez Doce's talk
Mon. 16.30

Instead of an outlook…

- K⁻p correlations measured by ALICE in different colliding systems [1]
  → Improve understanding on Λ(1405) molecular state [2]
- Cusp structure at $k^* \sim 59$ MeV/c is observed → due to opening of $\overline{\mathrm{K}}^0$n channel
- Studied also as a function of source sizes (in all available collision systems)



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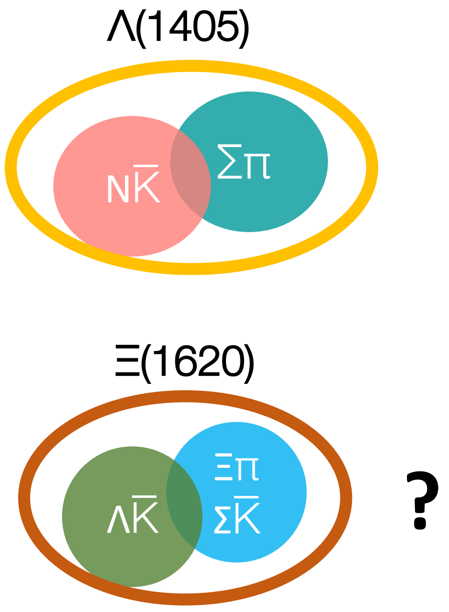
  → Shed light on the nature of Ξ(1620), observed by Belle in $\Xi^- \pi^+$ decay [3]



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[3] Belle coll. PRL 122 (2019), 7, 07250

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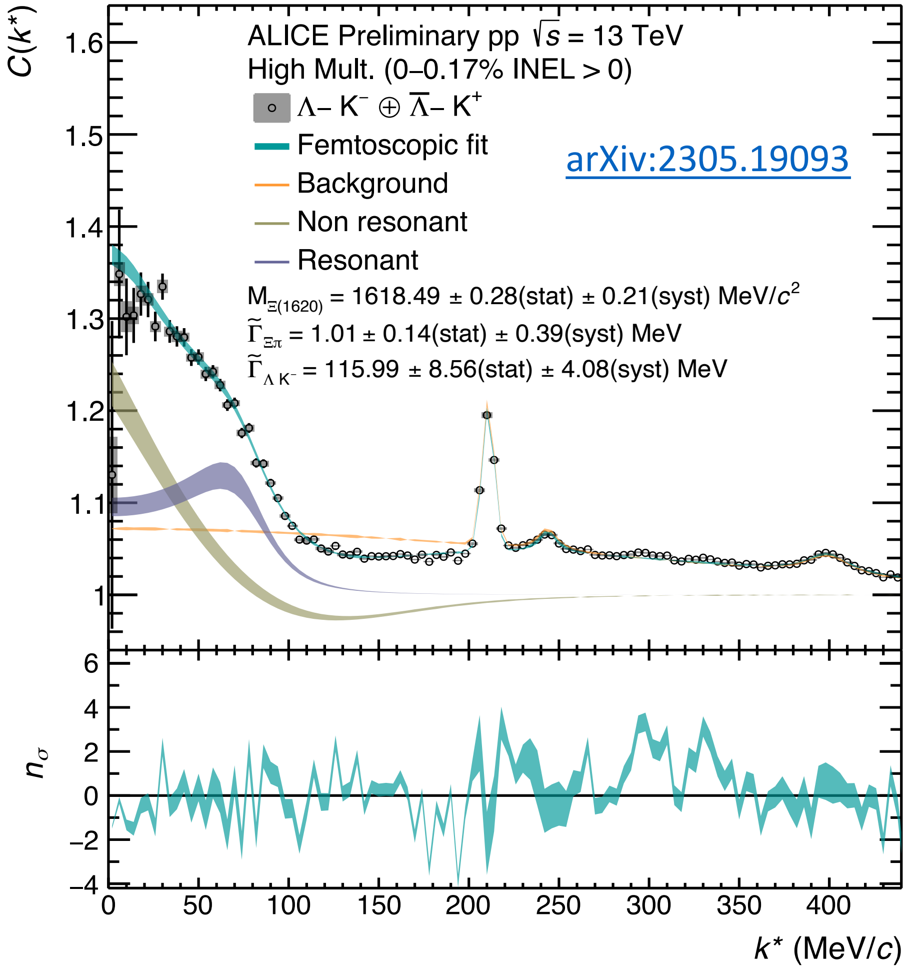
- Similar scenario in ΛK⁻ interaction with Ξ(1620) state?
  → Shed light on the nature of Ξ(1620), observed by Belle in $\Xi^- \pi^+$ decay [3]

- Invariant mass from same and mixed event distributions used to build the correlation
  - **Ξ(1620) just above the threshold**
    → First experimental evidence of decay into ΛK⁻
  - Mass in agreement with Belle

$$M_{\Xi(1620)} = 1618.49^{\pm 0.28(stat)}_{\pm 0.21(syst)}\ \text{MeV}/c^2$$



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Instead of an outlook…

- First measurement of the genuine correlation between protons and **D⁻** mesons
  → Important input in studies and searches for charm nuclear states [1]
- Comparison with available models
  → Indication of an attractive interaction
  → Compatible also with the formation of bound state

TABLE I. Scattering parameters of the different theoretical models for the $N\bar{D}$ interaction [22–25] and degree of consistency with the experimental data computed in the range $k^* < 200$ MeV/c.

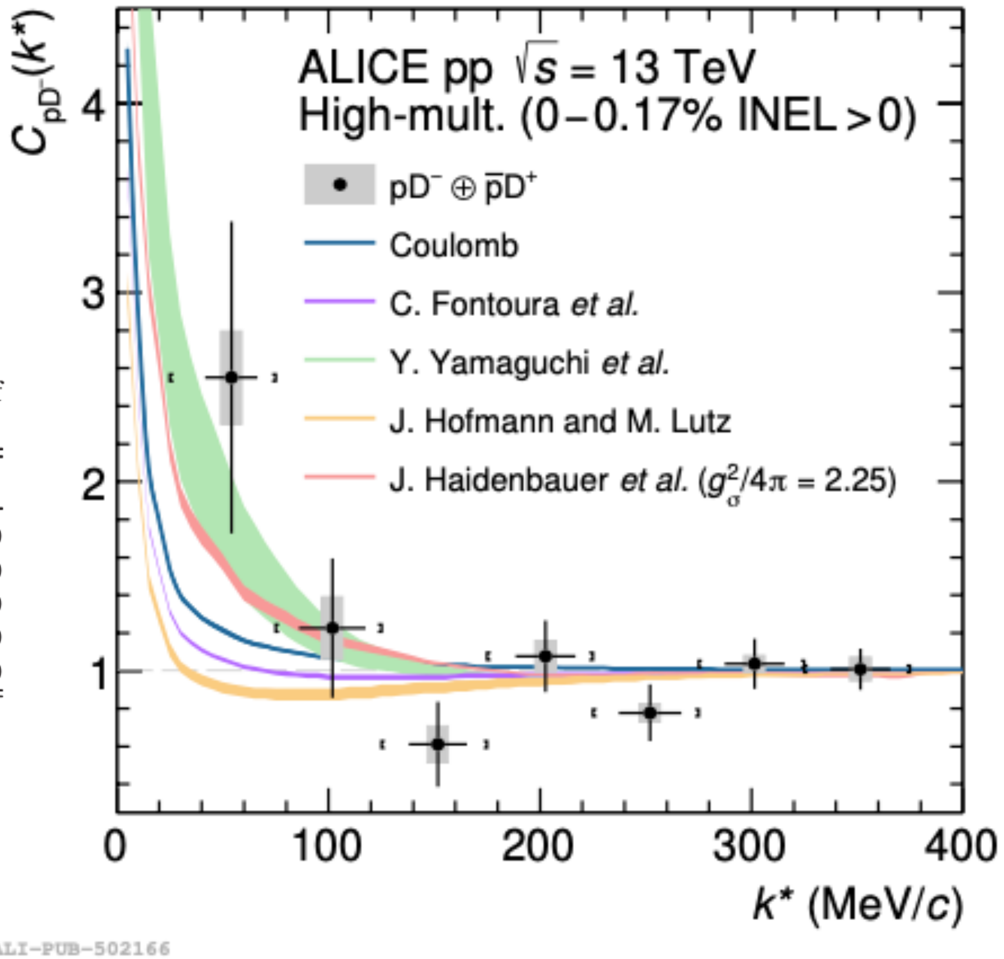
Model	$f_0(\mathrm{I}=0)$	$f_0(\mathrm{I}=1)$	n_σ
Coulomb			(1.1–1.5)
Haidenbauer *et al.* [22] ($g_\sigma^2/4\pi = 2.25$)	0.67	0.04	(0.8–1.3)
Hofmann and Lutz [23]	−0.16	−0.26	(1.3–1.6)
Yamaguchi *et al.* [25]	−4.38	−0.07	(0.6–1.1)
Fontoura *et al.* [24]	0.16	−0.25	(1.1–1.5)

- New results on Dπ and DK correlations measured by ALICE

(→ future will open way for T_{cc} measurements)

E. Chizzali's talk
Mon. 16.00

PRD 106 (2022), 5, 052010



[1] A. Hosaka et al. Prog. Part. Nucl. Phys. 96 (2017), 6, 062C01

Summary

- **${}^{3}_{\Lambda}\mathrm{H}$ measurements in small collision systems**
  - powerful tool to investigate **nuclear production mechanism**
  - powerful probe for investigating the **nucleon - Λ interaction**

- **${}^{3}_{\Lambda}\mathrm{H}$ lifetime and B_{Λ} measurements**
  - weakly bound state, compatible with calculations that assume a radius R~10 fm
  - from ${}^{3}_{\Lambda}\mathrm{H}/\Lambda$ concrete possibility to distinguish with high significance between the two nucleosynthesis mechanisms: hint for **coalescence**

- **N-Λ correlations**
  - p-Λ, p-p-Λ → interplay between 2-body and 3-body interactions is crucial

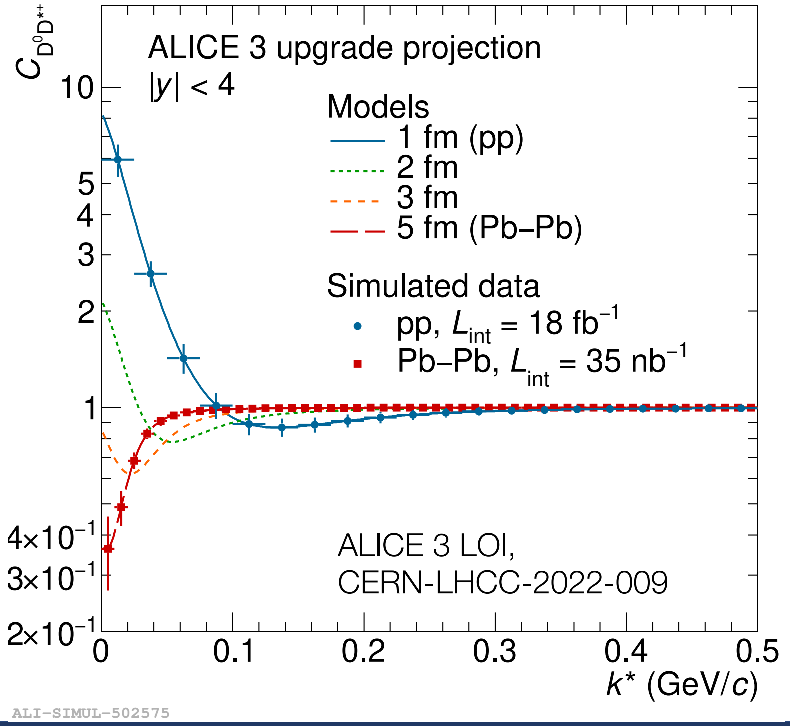
- **p-d correlations**
  - 2-body interactions insufficient to describe $C(k^*)$
  - 3-body calculations from Pisa group qualitatively describe the data
  - paves the way for measurements of correlations among hypertriton constituents (dΛ)

- Many more opportunities to be explored with femtoscopy in Run3!

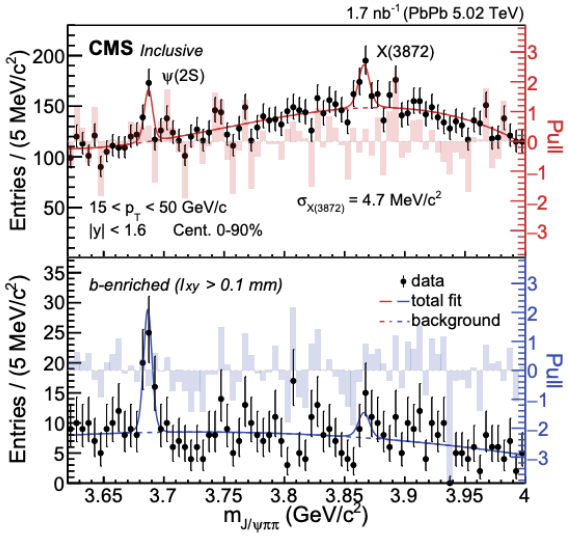
Spares

Correlations for a charming future

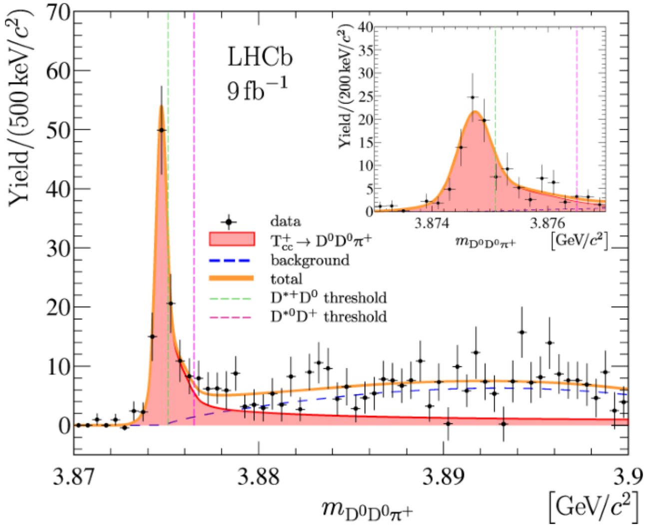
- Exotic charm states as T_{cc}^{+} or $\chi_{c1}(3872)$ investigated at LHCb and CMS
- Investigate its nature with **ALICE 3 in Run 5 and Run 6 via DD^* and $D\bar{D}^*$ correlations**
  → **Complementarity** between spectroscopy and femtoscopy



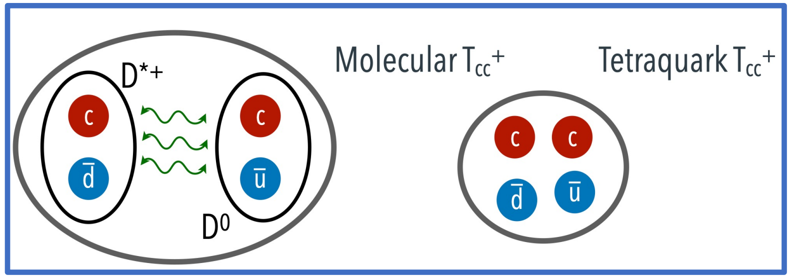
CMS, PRL 128 (2022) 032001



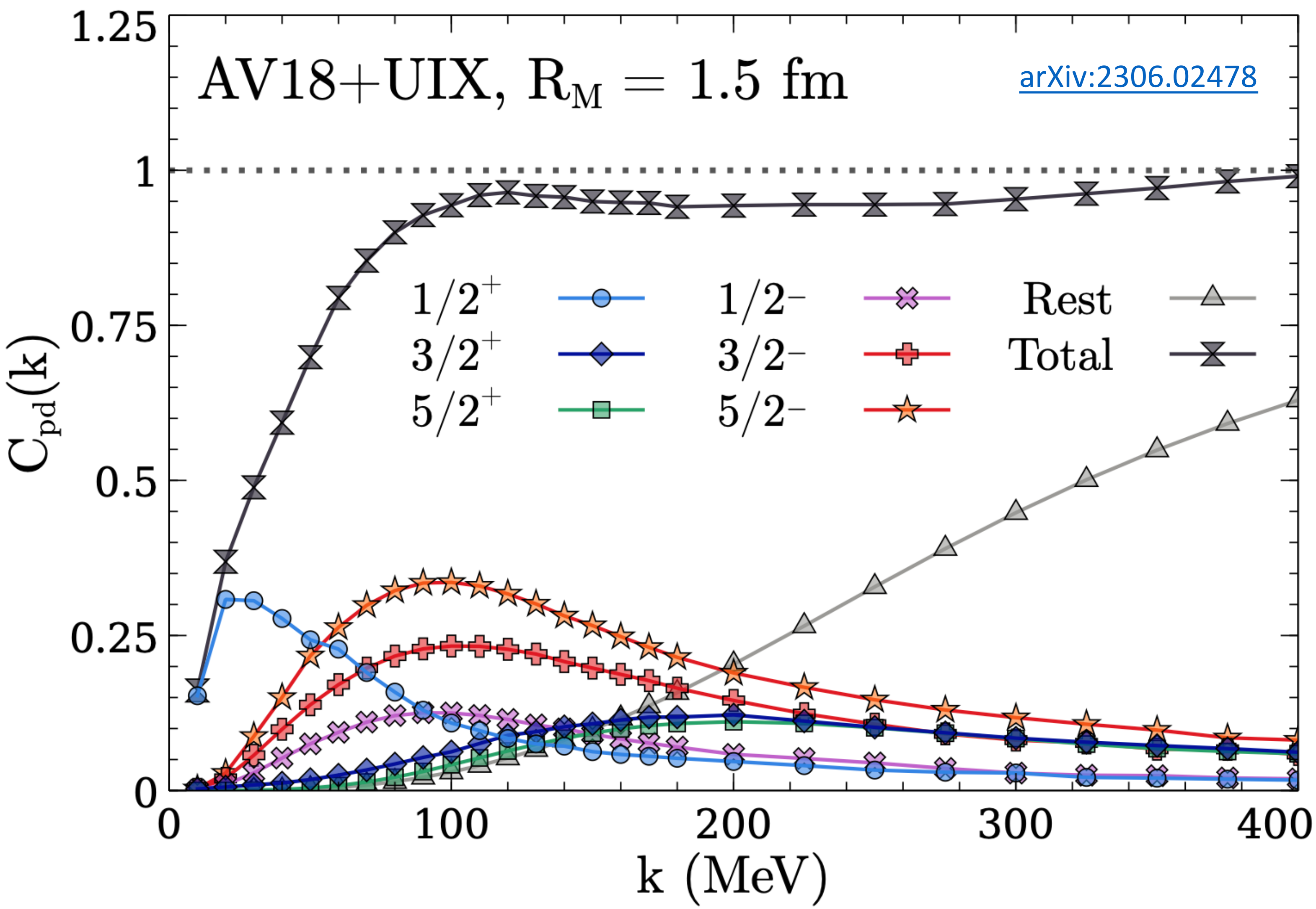
LHCb, Nature Physics 18 (2022)
LHCb, Nature Comm. 13 (2022)



- Interplay between source size and scattering length
  → Size-dependent modification on the $C(k^*)$ and insights into the nature of T_{cc}^{+}

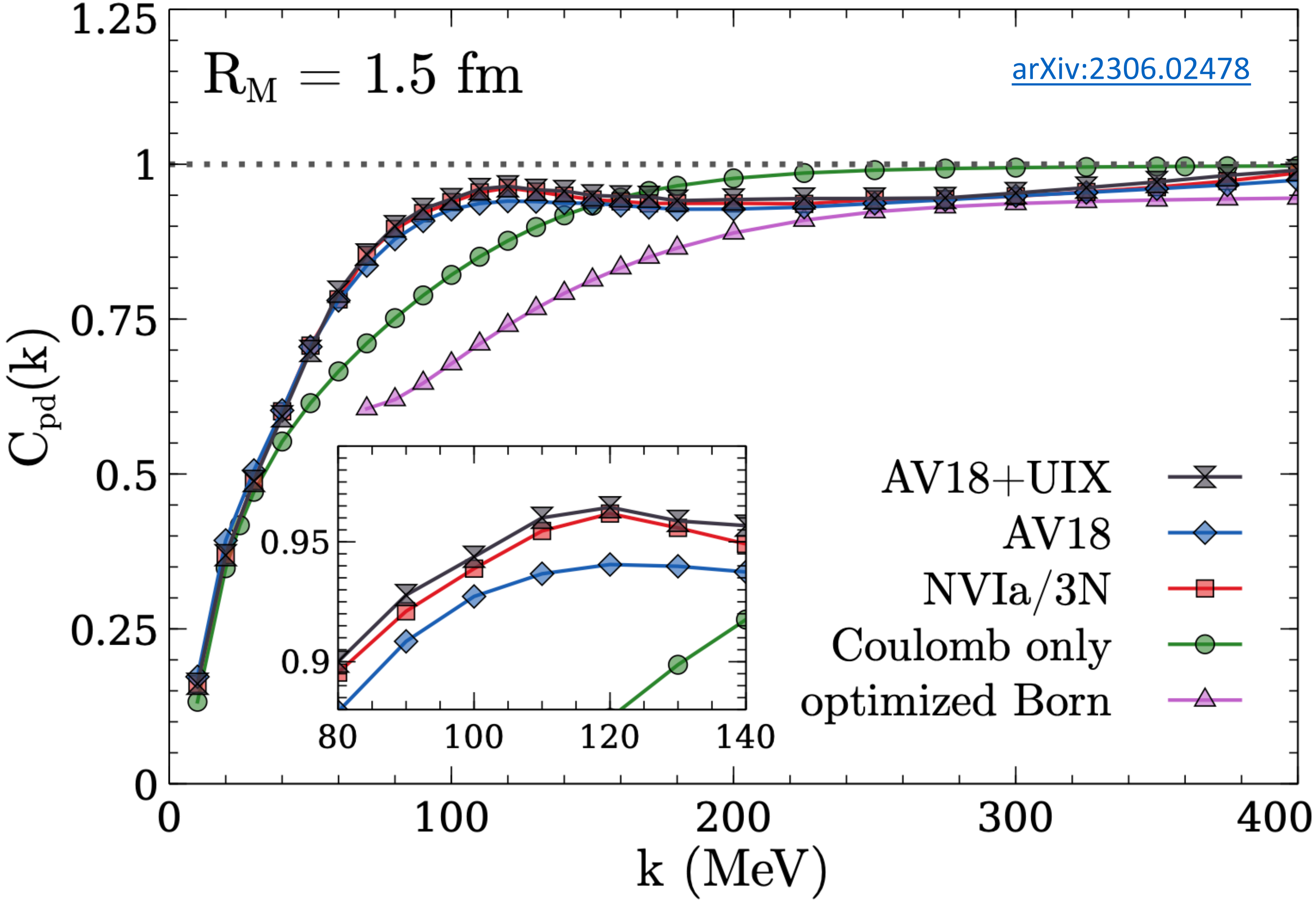


p-d calculations



Role of partial waves to the final $C(k^*)$

p-d calculations



Role of different potentials to the final $C(k^*)$

2-body + 3-body

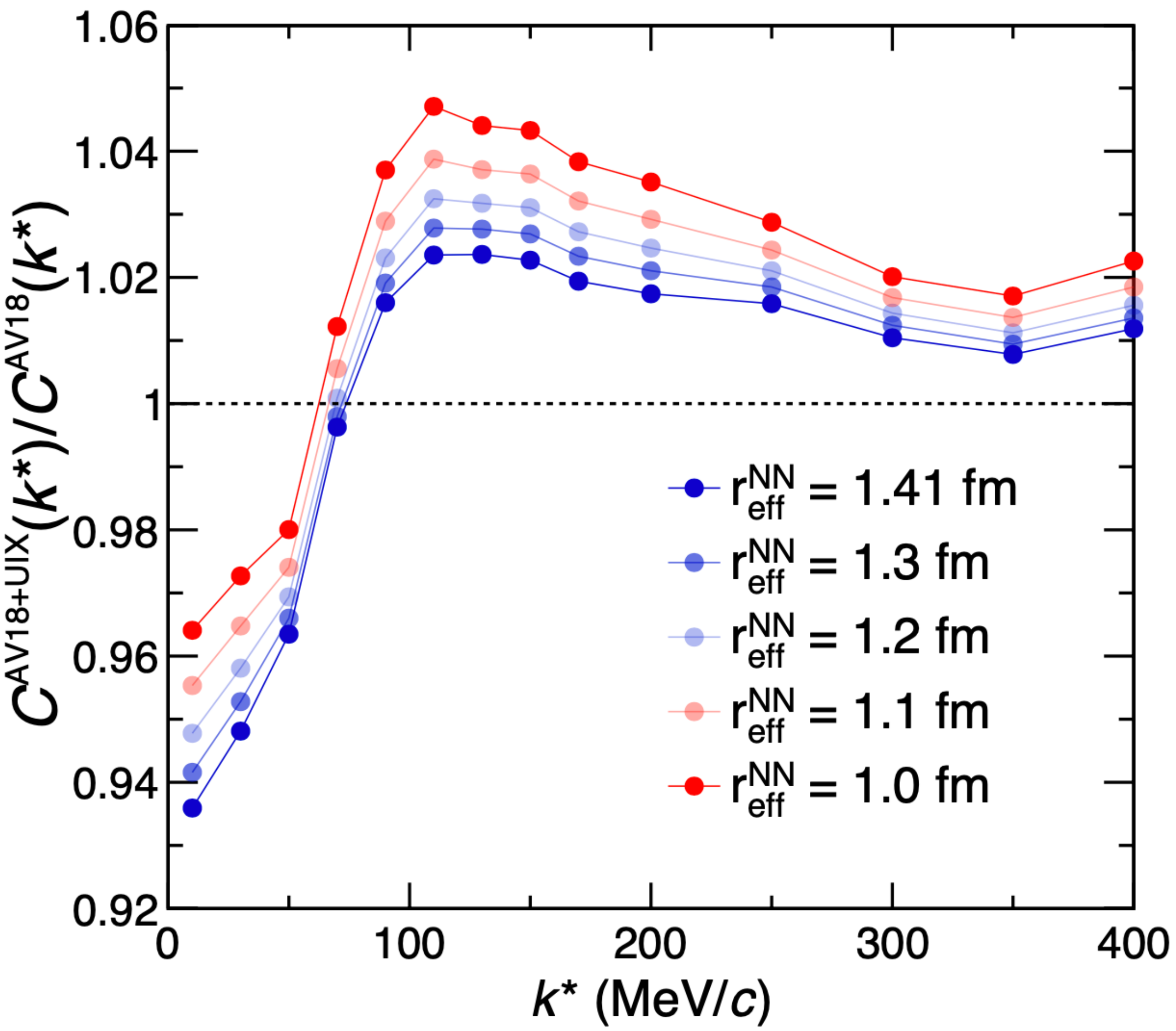
2-body

2-body + 3-body

asympthotic interaction + antisymm.

2-body interactions in a 3-body system!

p-d calculations



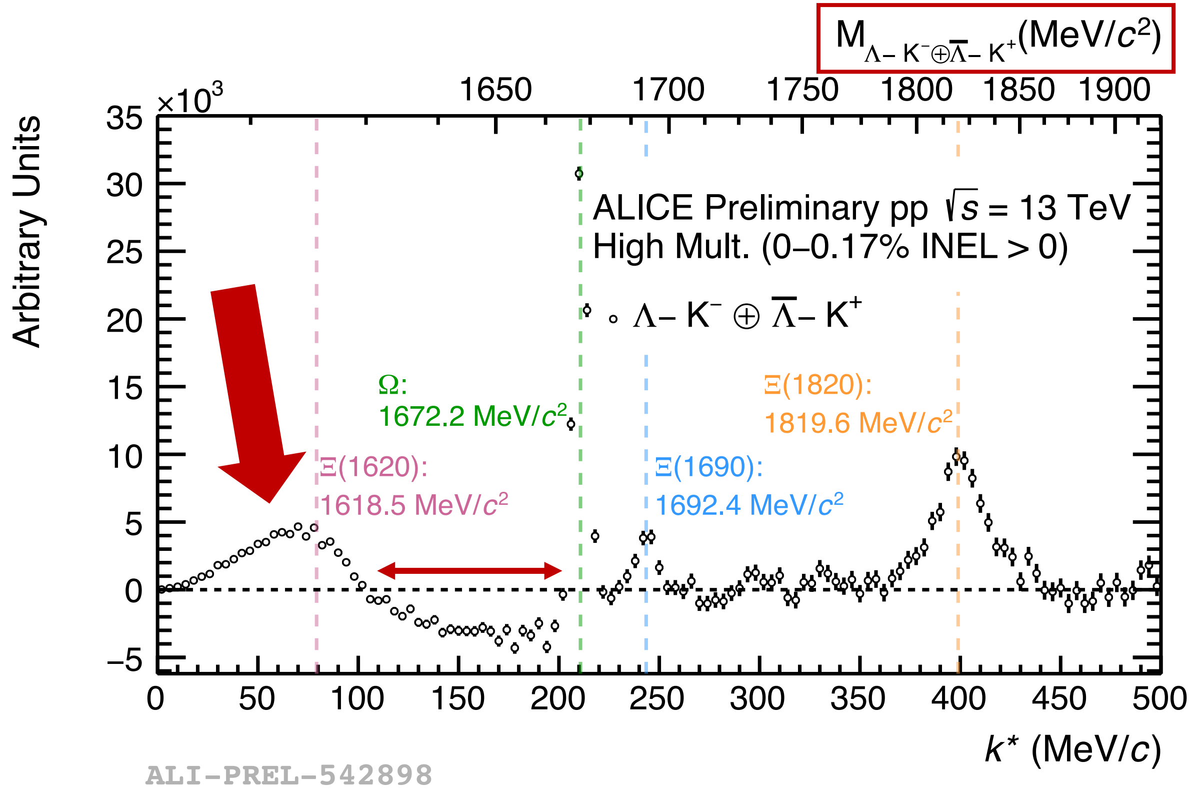
Contribution of the 3-body interactions over the 2-body ones, in a 3-body system

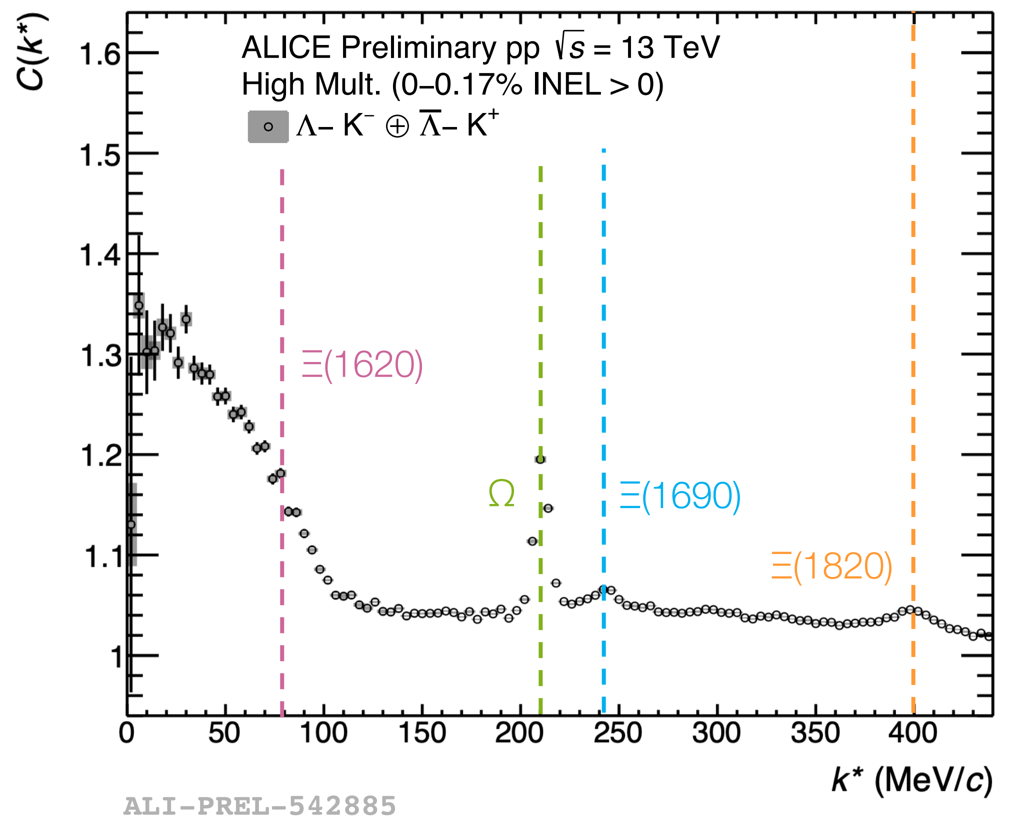
2-body interactions in a 3-body system!

arXiv:2306.02478

Λ-K⁻ → access Ξ(1620)

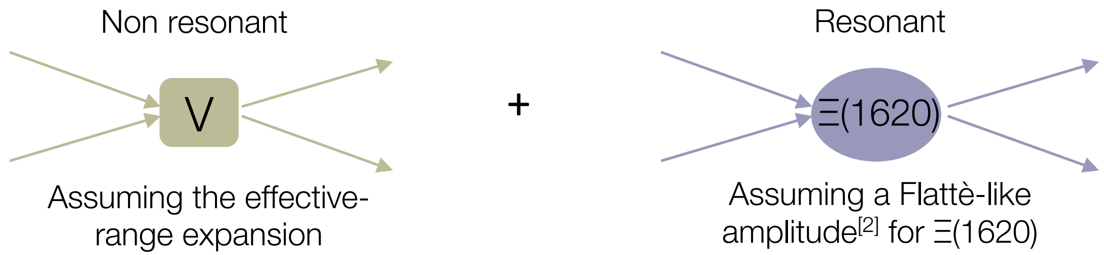
- Several peak structures in the measured correlation
- Invariant mass from same and mixed event distributions used to build the correlation
  - **Ξ(1620) just above the threshold**
    → First experimental evidence of decay into ΛK⁻





Λ-K⁻ correlation in pp collisions

- Data modeled with the Lednicky-Lyuboshits formula[1]

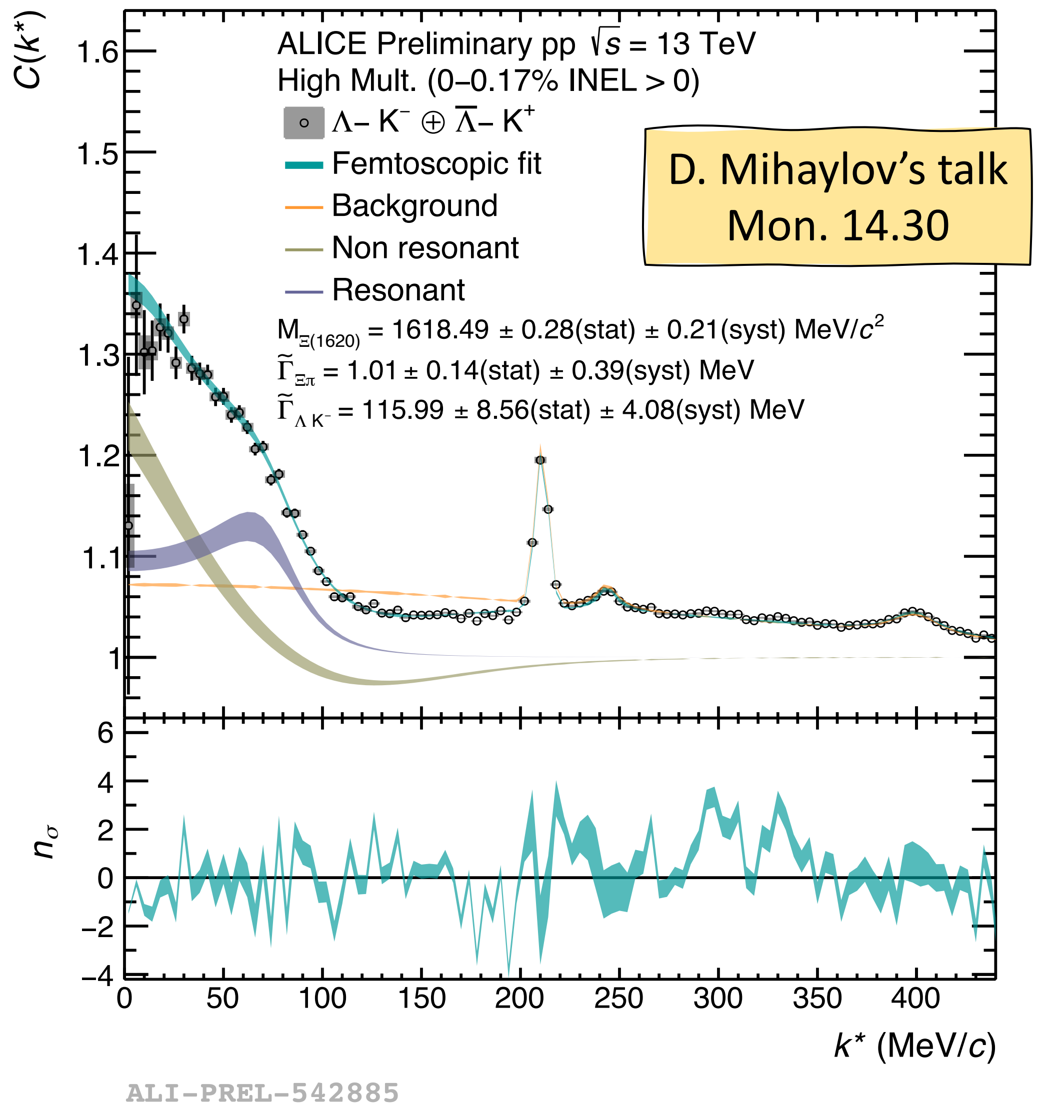


- Ξ(1620) properties and scattering parameters
  → Mass in agreement with Belle[3]

$$M_{\Xi(1620)} = 1618.49^{\pm 0.28(stat)}_{\pm 0.21(syst)}$$

→ Indication of a large coupling of Ξ(1620) to ΛK^-
→ Non-resonant scattering parameters in agreement with ALICE Pb-Pb results[4]

- High-precision data to constrain effective chiral theories and to understand the Ξ(1620) nature[5,6]

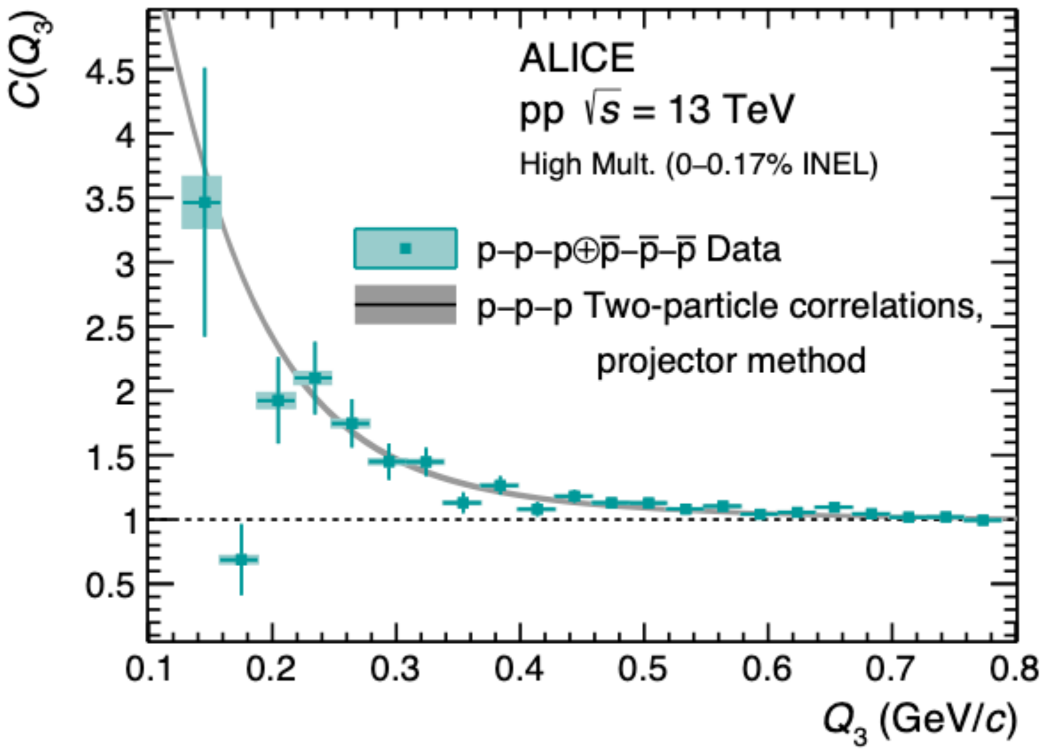


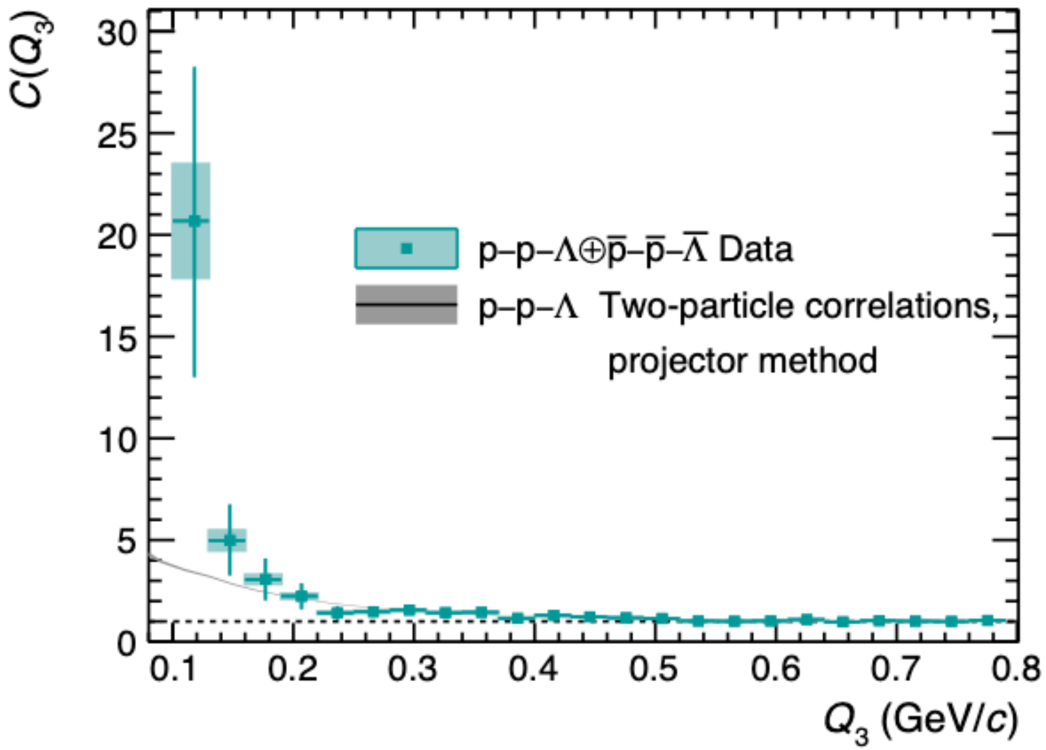
[1] R. Lednicky, V. Lyuboshits SJNP 35 (1982)
[2] F. Giacosa et al. EPJA 57 (2021), 12, 336
[3] Belle coll. PRL 122 (2019), 7, 07250
[4]ALICE coll. PRC 103 (2021)), 5, 055201
[5] A. Ramos et al. PRL 89 (2002), 252001
[6] A. Feijoo et al. PLB 841 (2023), 137927

Three-body femtoscopy

Extending femtoscopy to three-particle correlations: p-p-p and p-p-Λ
New way to study interaction in hadron-triplets

$$C(\mathbf{p_1}, \mathbf{p_2}, \mathbf{p_3}) = \frac{P(\mathbf{p_1}, \mathbf{p_2}, \mathbf{p_3})}{P(\mathbf{p_1})P(\mathbf{p_2})P(\mathbf{p_3})} = N\frac{N_{same}(Q_3)}{N_{mixed}(Q_3)} \qquad Q_3 = \sqrt{-q_{ij}^2 - q_{jk}^2 - q_{ki}^2}$$



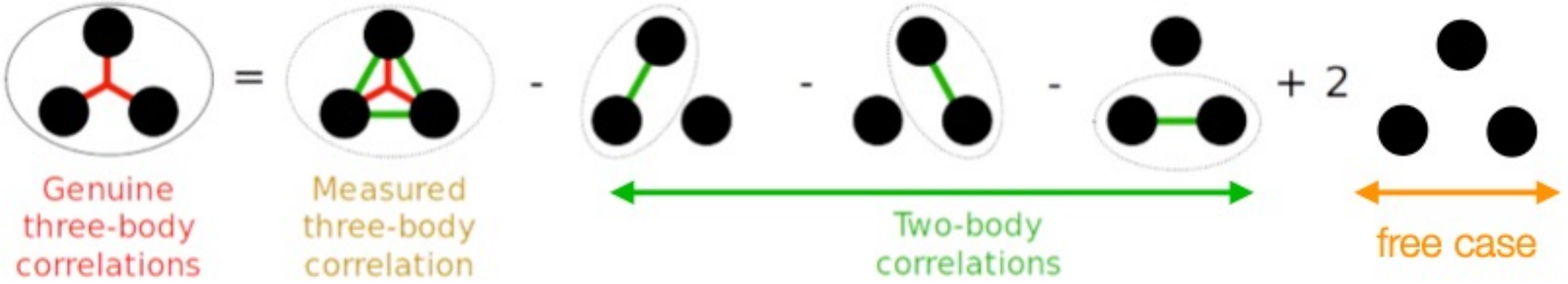


How to interpret the results? Interplay between 2-body and 3-body forces

arXiv:2206.03344

Accessing genuine 3-body interaction

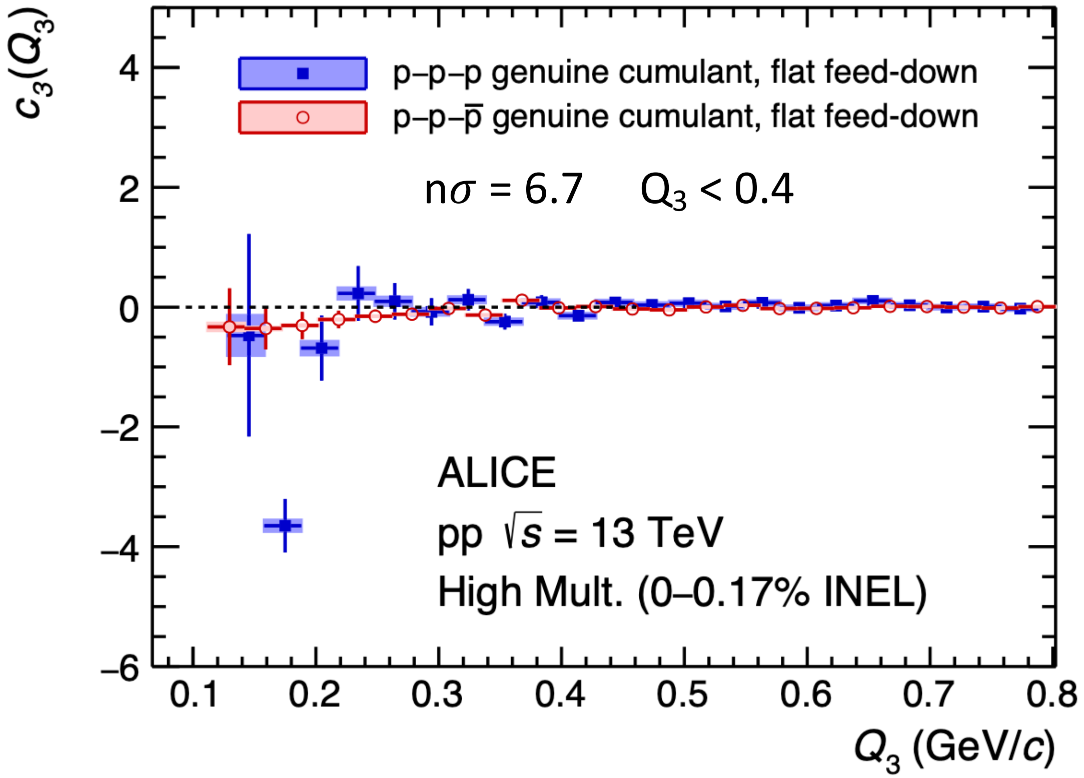
$c_3\ (Q_3)$



$c_3\ (Q_3)$ allows to isolate effects associated with the genuine three-body interaction

- p-p-p and p-p-p̄ cumulants : significant deviation from zero
  - Hint of a genuine three-body effect
- Possible interpretations
  - Pauli blocking at three-particle level
  - Three-body strong interaction

L. Serksnyte's talk
Wed. 15.00



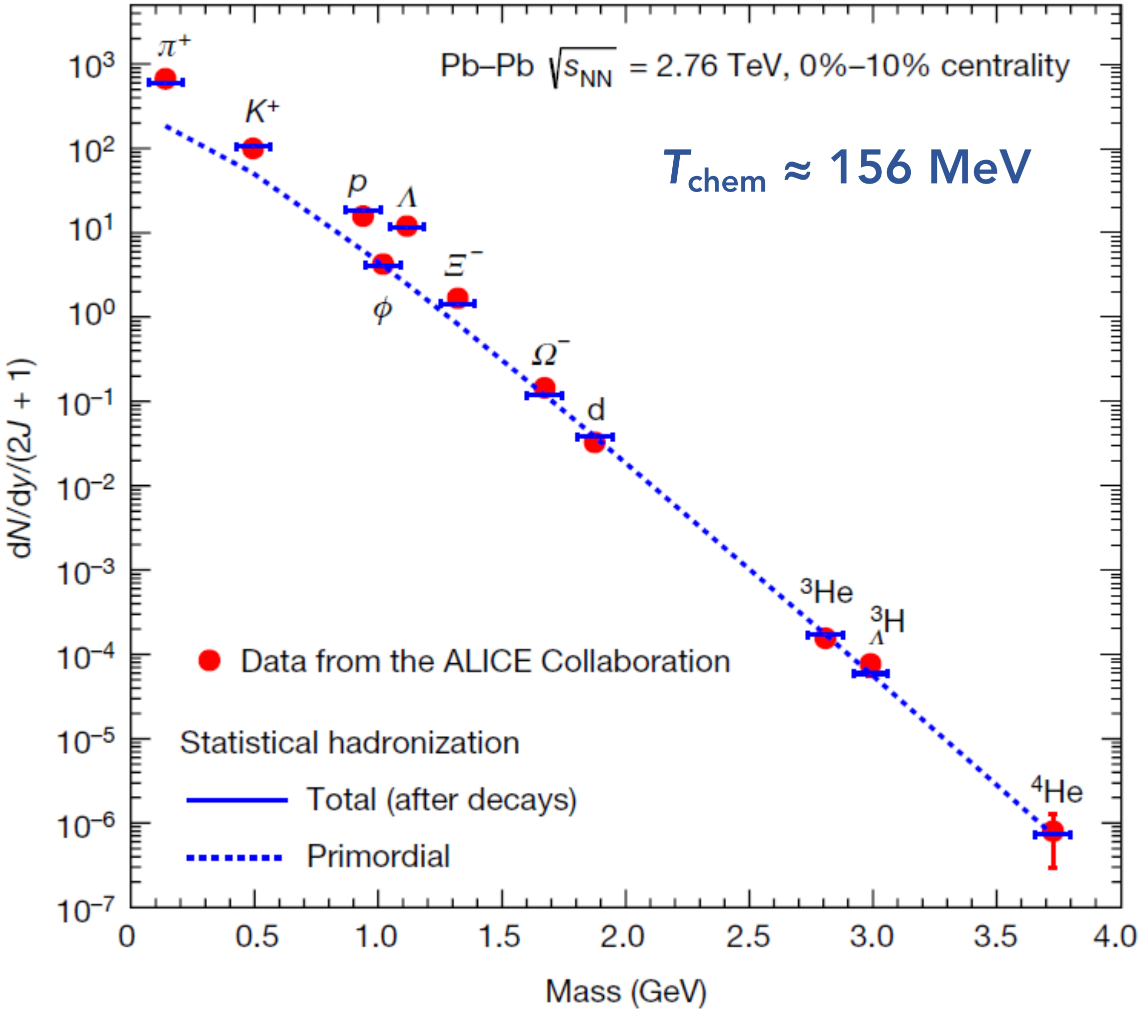
Kubo, J. Phys. Soc. Jpn. 177 (1962)
arXiv:2206.03344

Statistical models

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

  ⇒ 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)

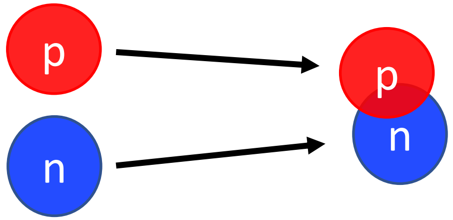
⇒ how can they survive the hadronic phase environment?



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

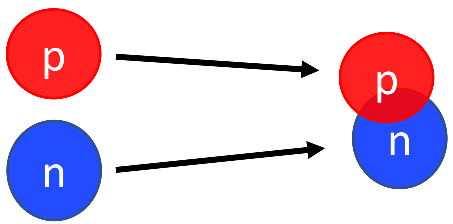
$$B_A(p_T^p) = E_A \frac{d^3 N_A}{d\, p_A^3} \bigg/ \left(E_p \frac{d^3 N_p}{d\, p_p^3} \right)^A \Bigg|_{p_T^p = p_T^A / A}$$

- Experimental observable tightly connected to the coalescence probability

Larger $B_A \Longleftrightarrow$ Larger coalescence probability

Coalescence models

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



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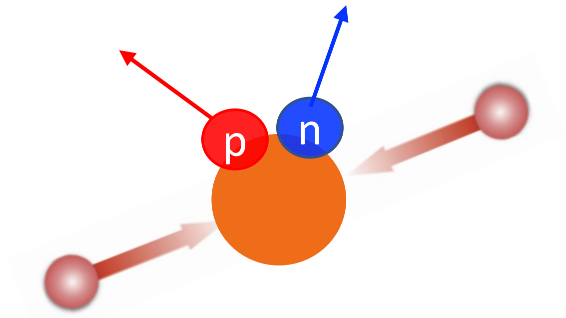
[1]PRC 99 (2019) 024001
[2]PRL 123 (2019) 112002

- Experimental observable tightly connected to the coalescence probability

Larger B_A $\Longleftrightarrow$ Larger coalescence probability

- Coalescence probability depends on the system size



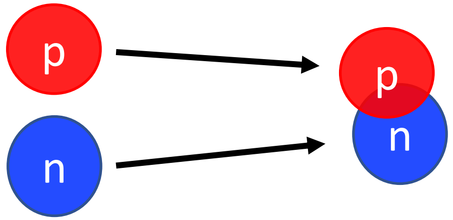
pp[1], p—Pb[2]: r_0 = 1–1.5 fm

Small distance in space
(Only momentum correlations matter)

$\Longleftrightarrow$ large B_A

Coalescence models

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



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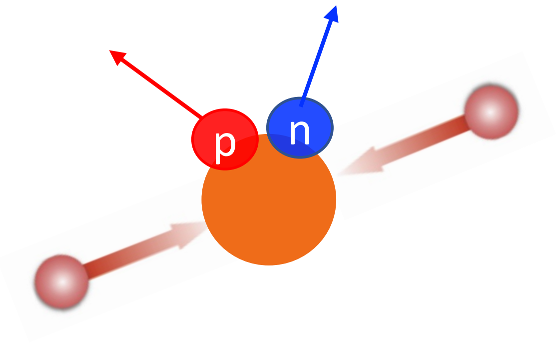
$$B_A(p_\mathrm{T}^p) = E_A \frac{\mathrm{d}^3 N_A}{\mathrm{d}\,p_A^3} \Bigg/ \left(E_p \frac{\mathrm{d}^3 N_p}{\mathrm{d}\,p_p^3} \right)^A \Bigg|_{p_\mathrm{T}^p = p_\mathrm{T}^A/A}$$

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

- Experimental observable tightly connected to the coalescence probability

Larger B_A ⟺ Larger coalescence probability

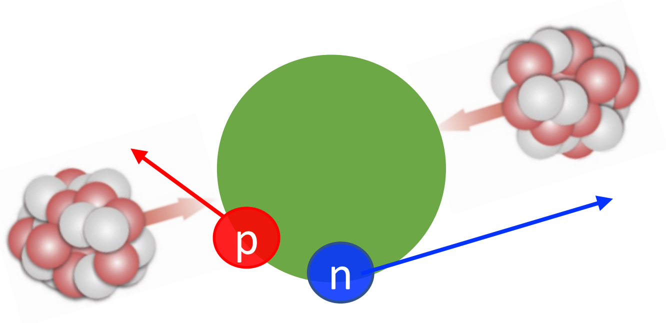
- Coalescence probability depends on the system size



pp[1], p—Pb[2]: r₀= 1–1.5 fm

Small distance in space
(Only momentum correlations matter)

⟺ large B_A



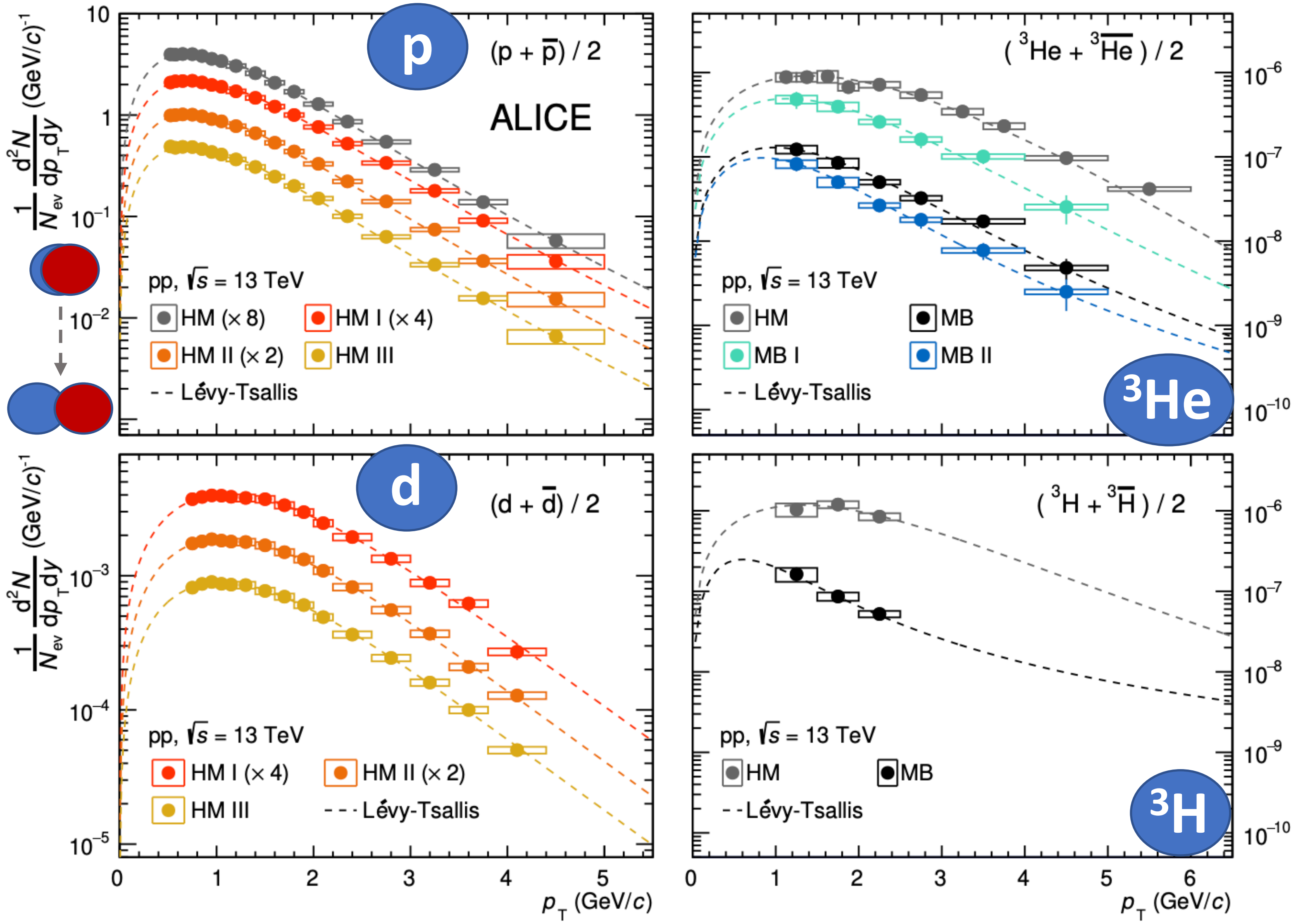
Pb—Pb[3]: r₀= 3–6 fm

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

⟺ small B_A

Light (anti)nuclei in small systems

JHEP 01 (2022) 106

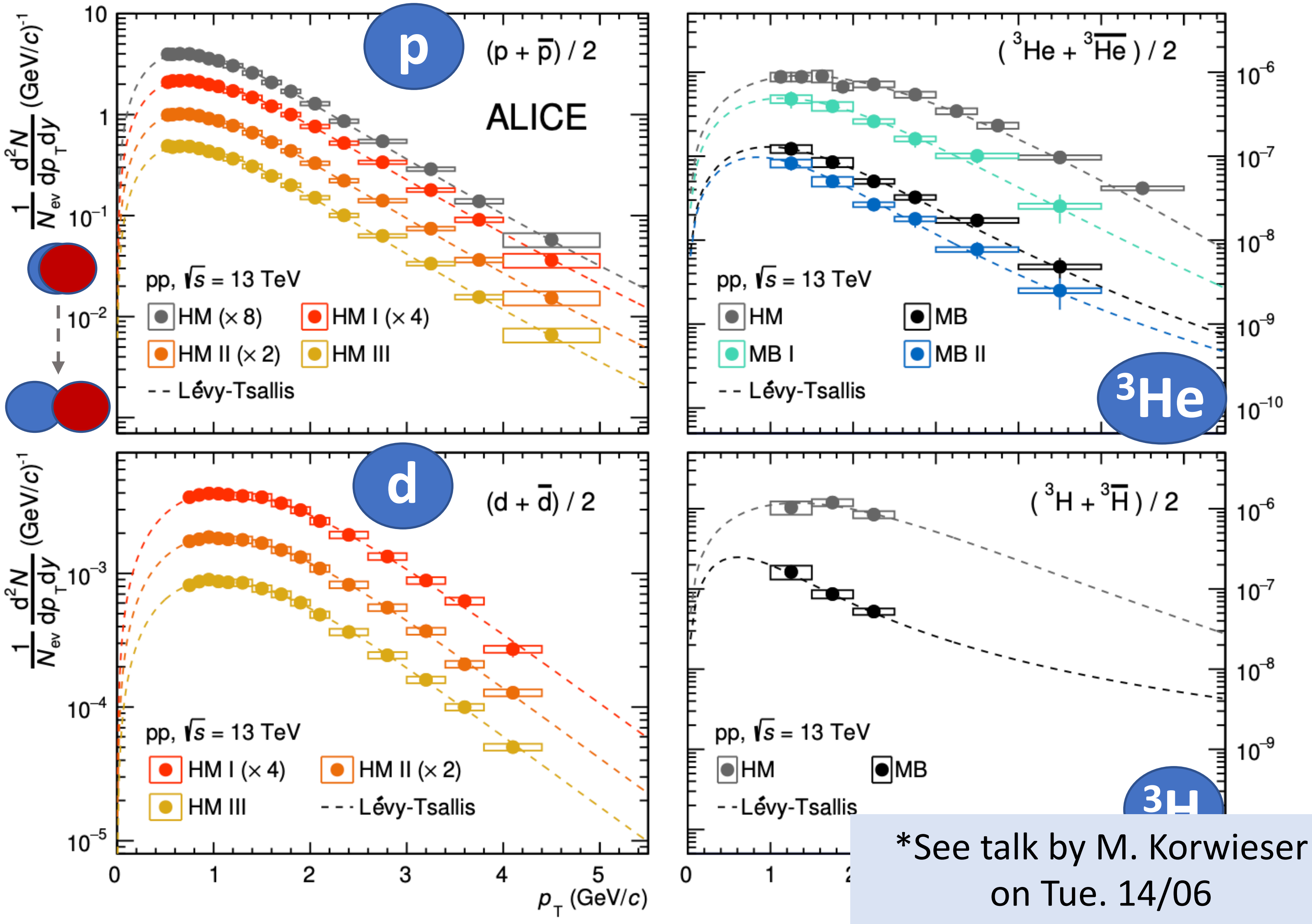


HM pp @ 13 TeV

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

Light (anti)nuclei in small systems

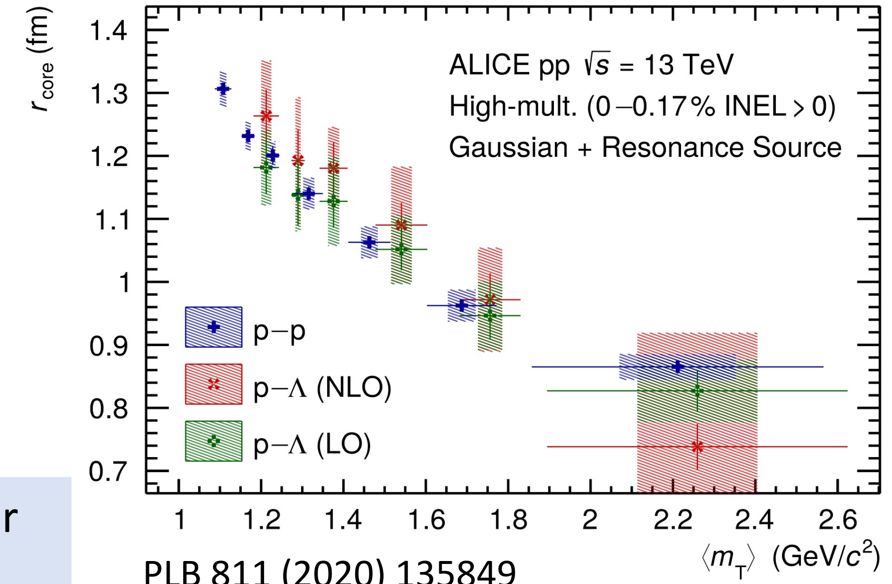
JHEP 01 (2022) 106



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

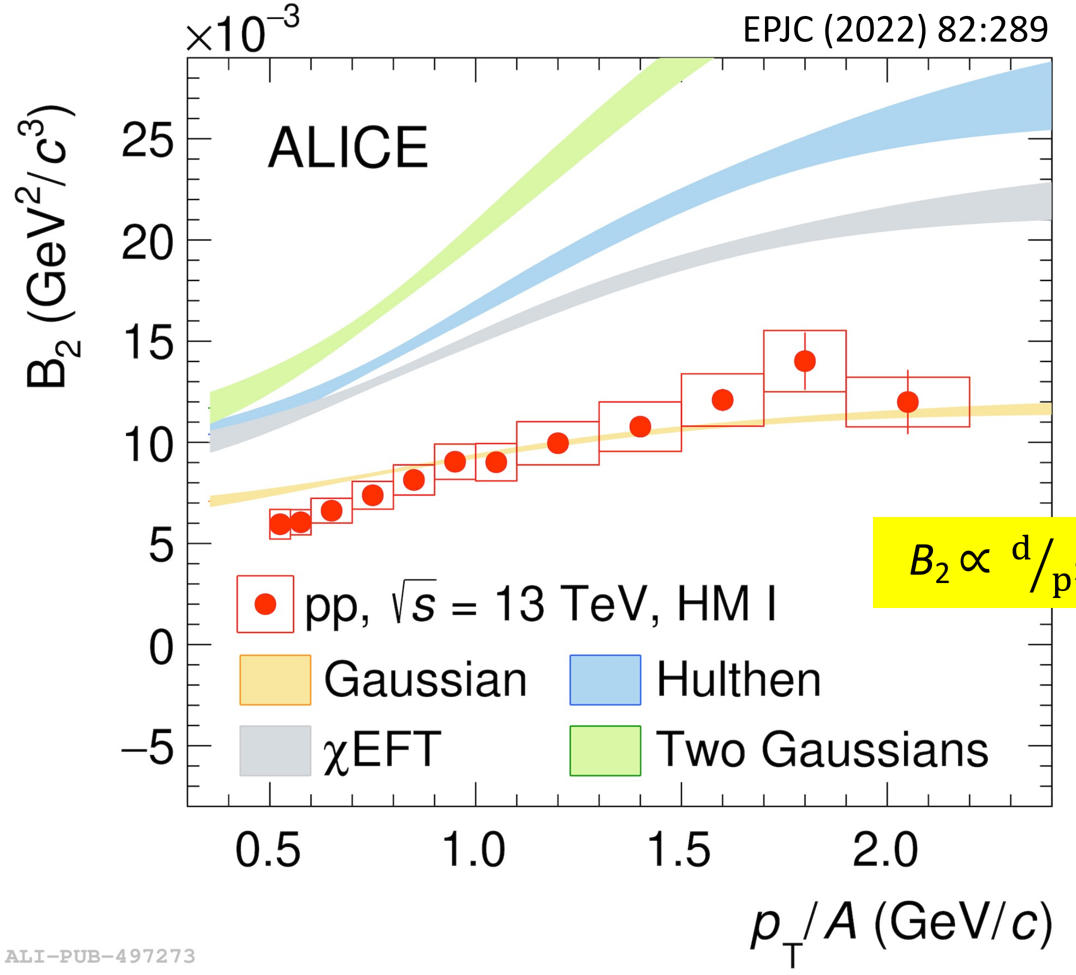
Testing coalescence model

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

EPJC (2022) 82:289



$B_2 \propto {}^{d}/_{p^2}$

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)

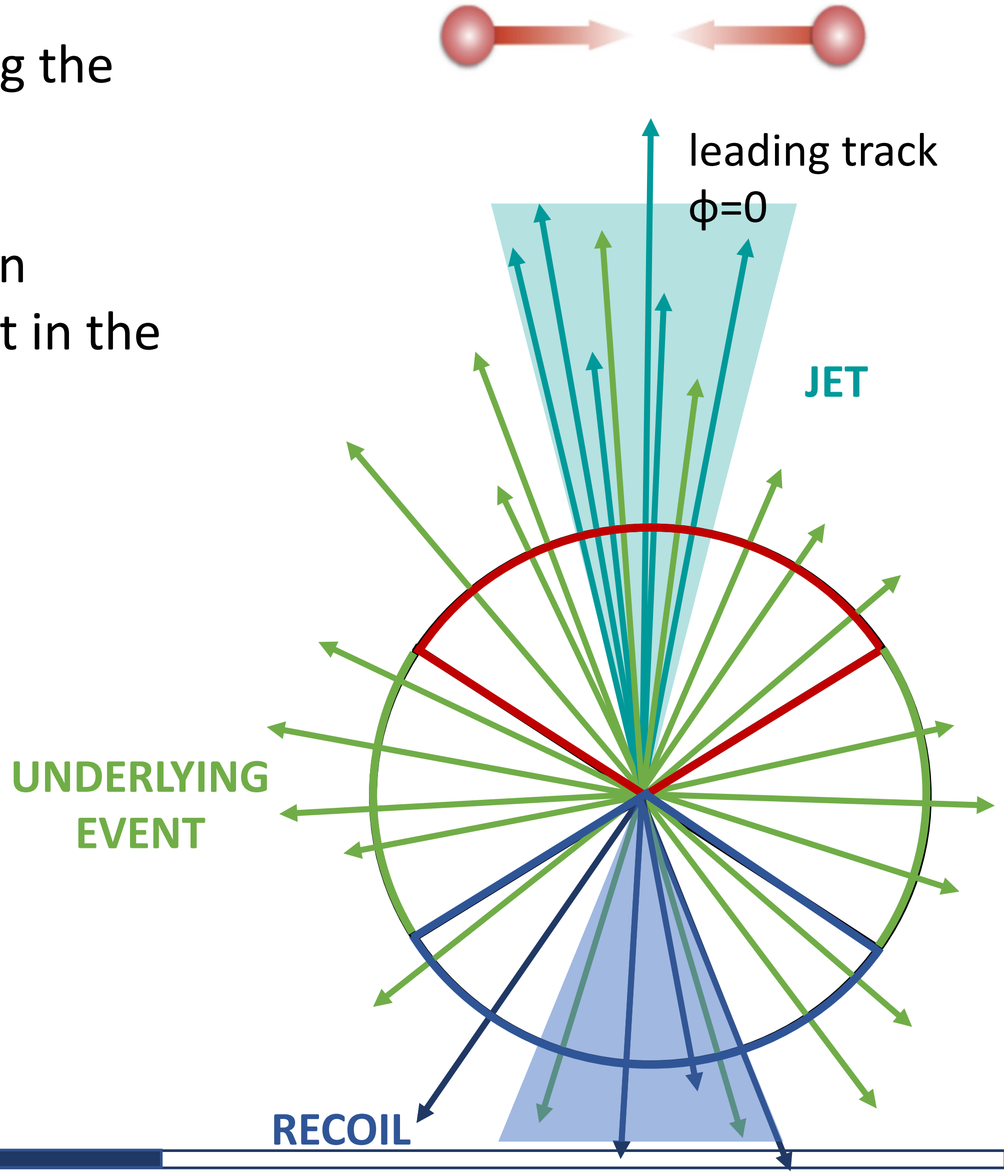
Different wave functions are tested:

- **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

Underlying event activity

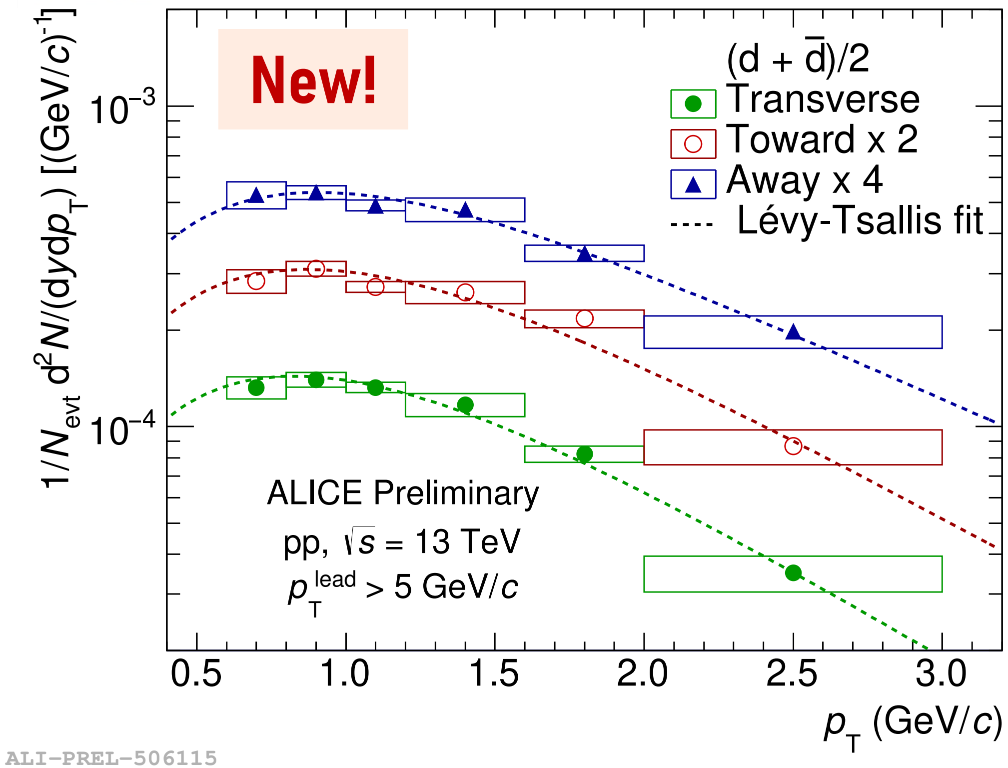
- Production in small collision systems can also be explored using the underlying event (UE) activity
- Coalescence mechanism can be tested comparing the deuteron production in jets, where nucleons are already closer, with that in the underlying event
- Highest p_T particle (p_T^{lead} > 5 GeV/c) used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

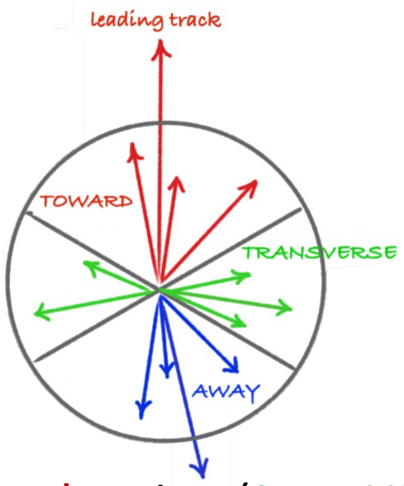


Martin et al., EPJC (2016) 76: 299

Deuteron spectra vs azimuthal regions

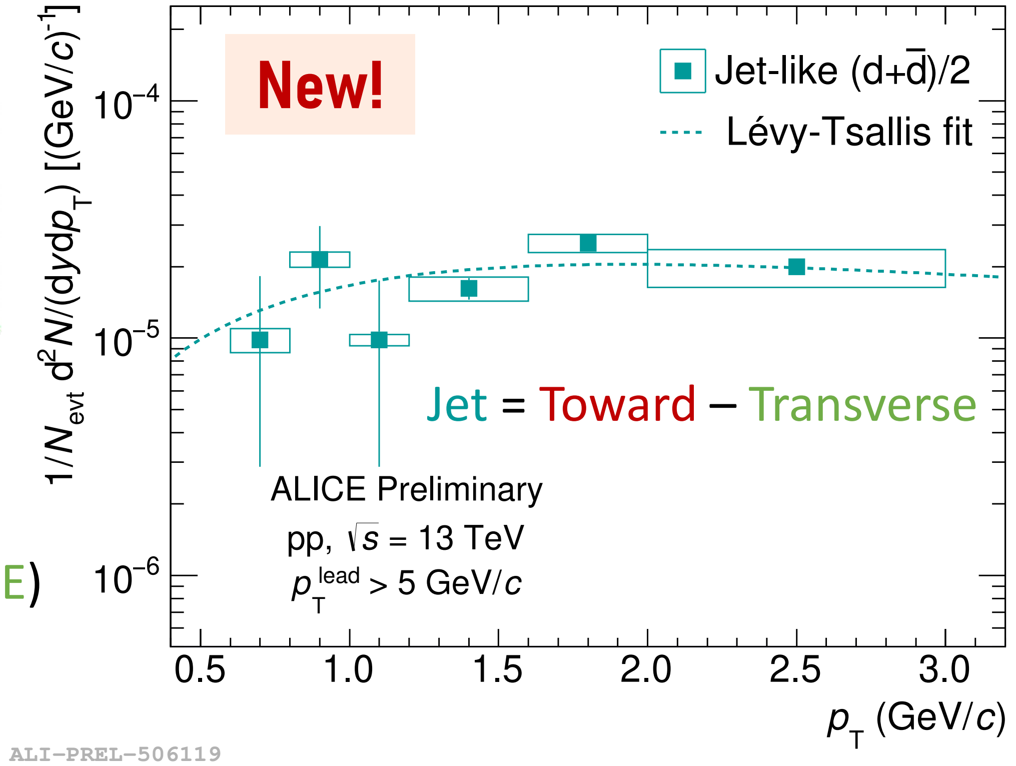
pp @ 13 TeV





Toward region (Jet + UE)

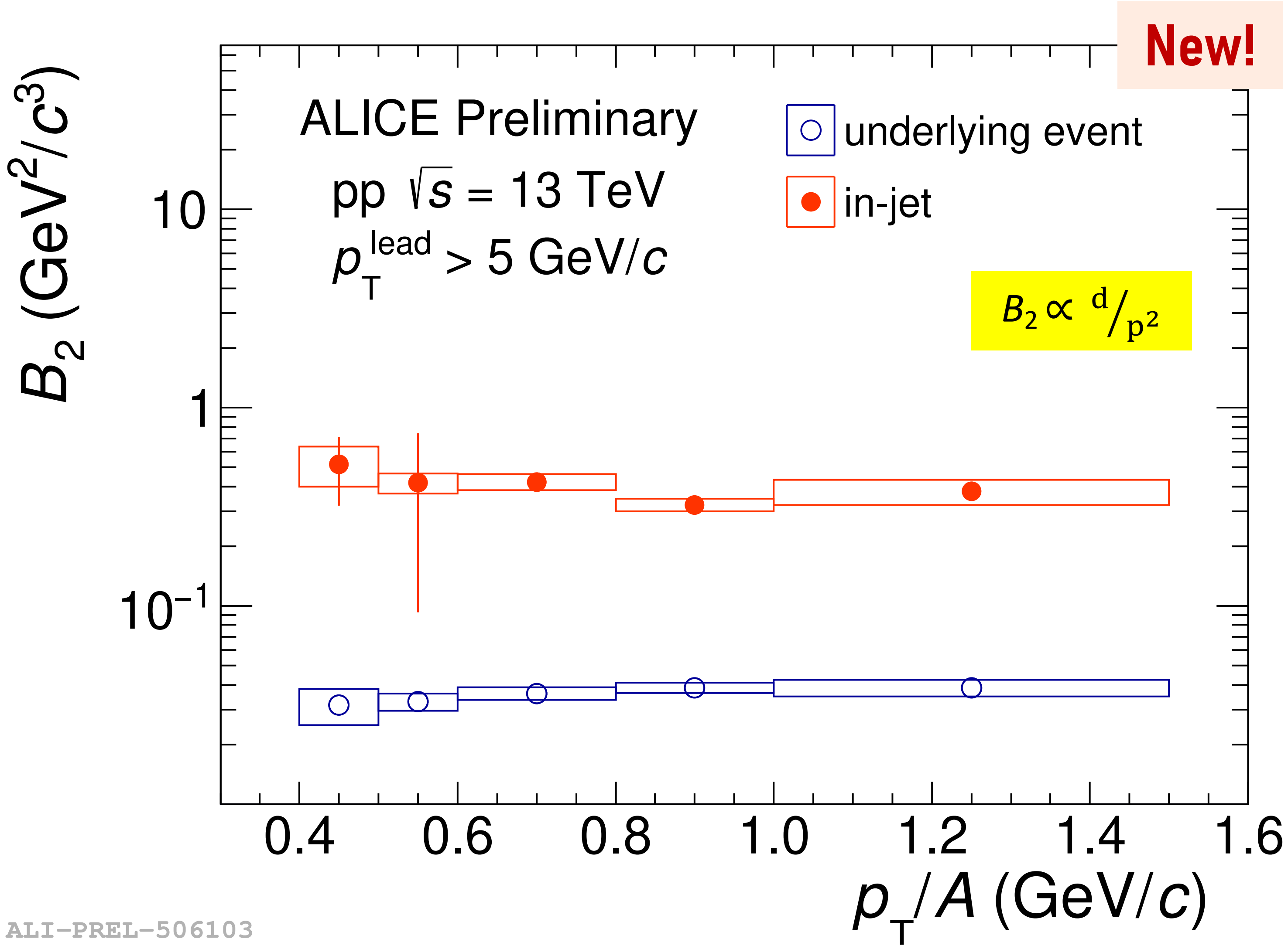
Transverse region (UE)



- 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

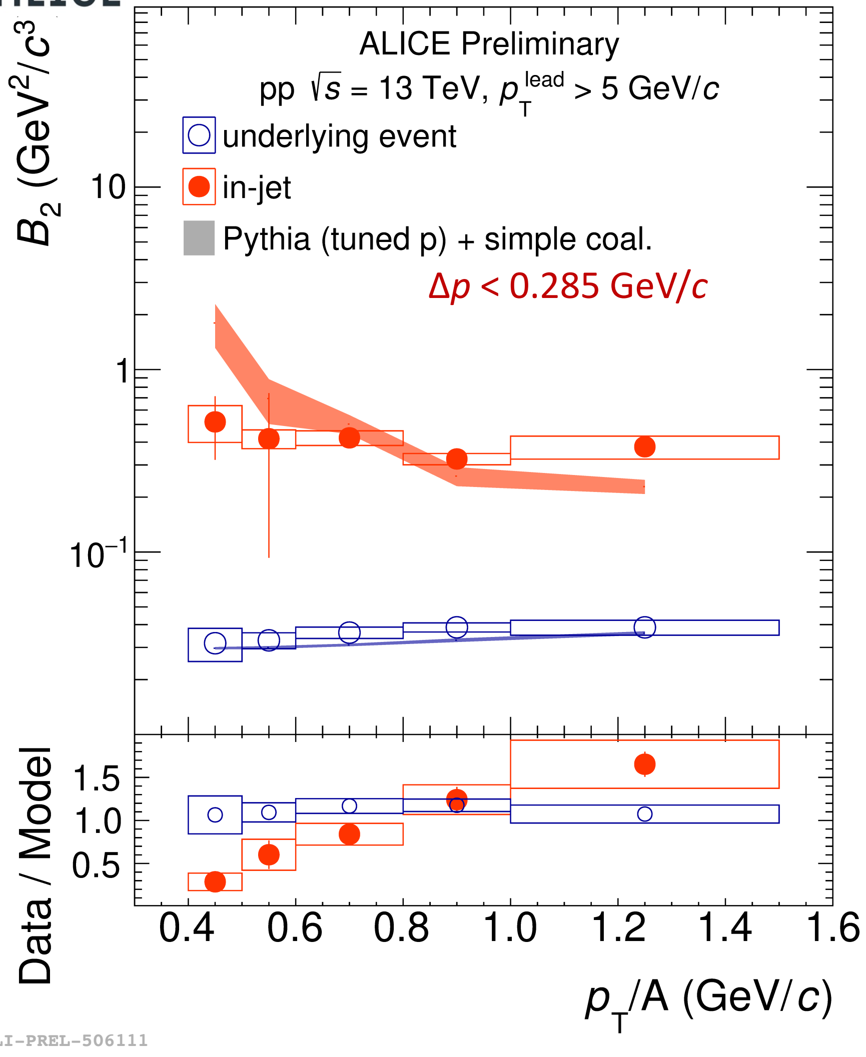
Deuteron coalescence in and out of jets

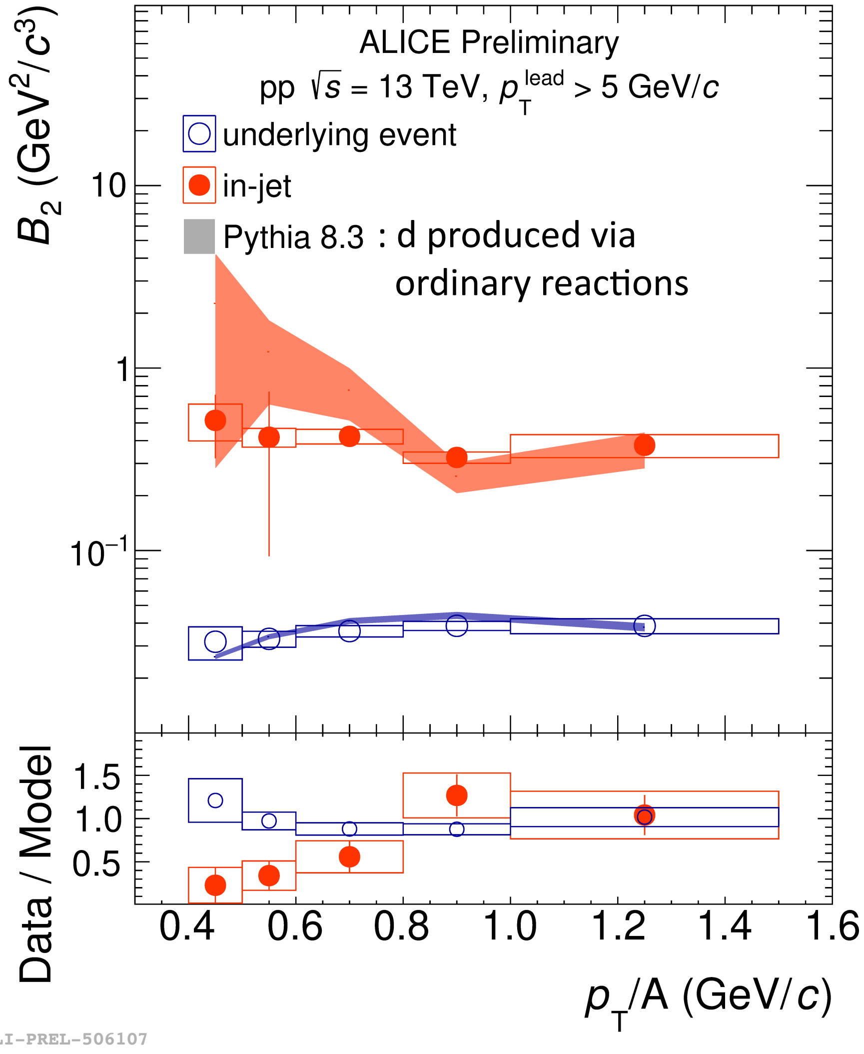


- B_2 parameter flat vs p_T/A → in agreement with simple coalescence
- B_2 in-jet ~ 15 times larger than B_2 in UE

→ ***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

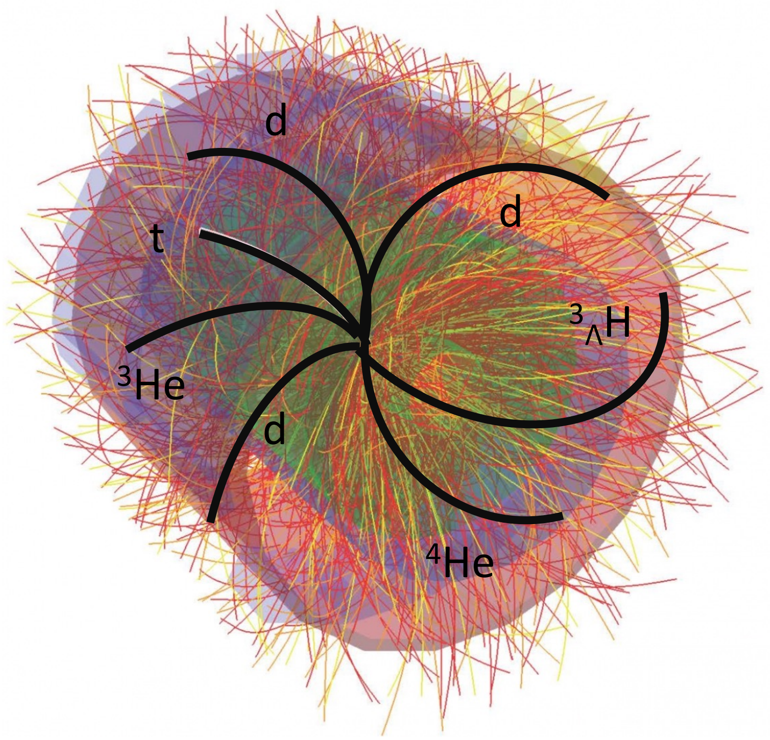
B_2 in-jet PYTHIA reproduces difference between UE and jet but shows a decreasing trend not observed in data

→ 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

(Anti)(hyper)nuclei production

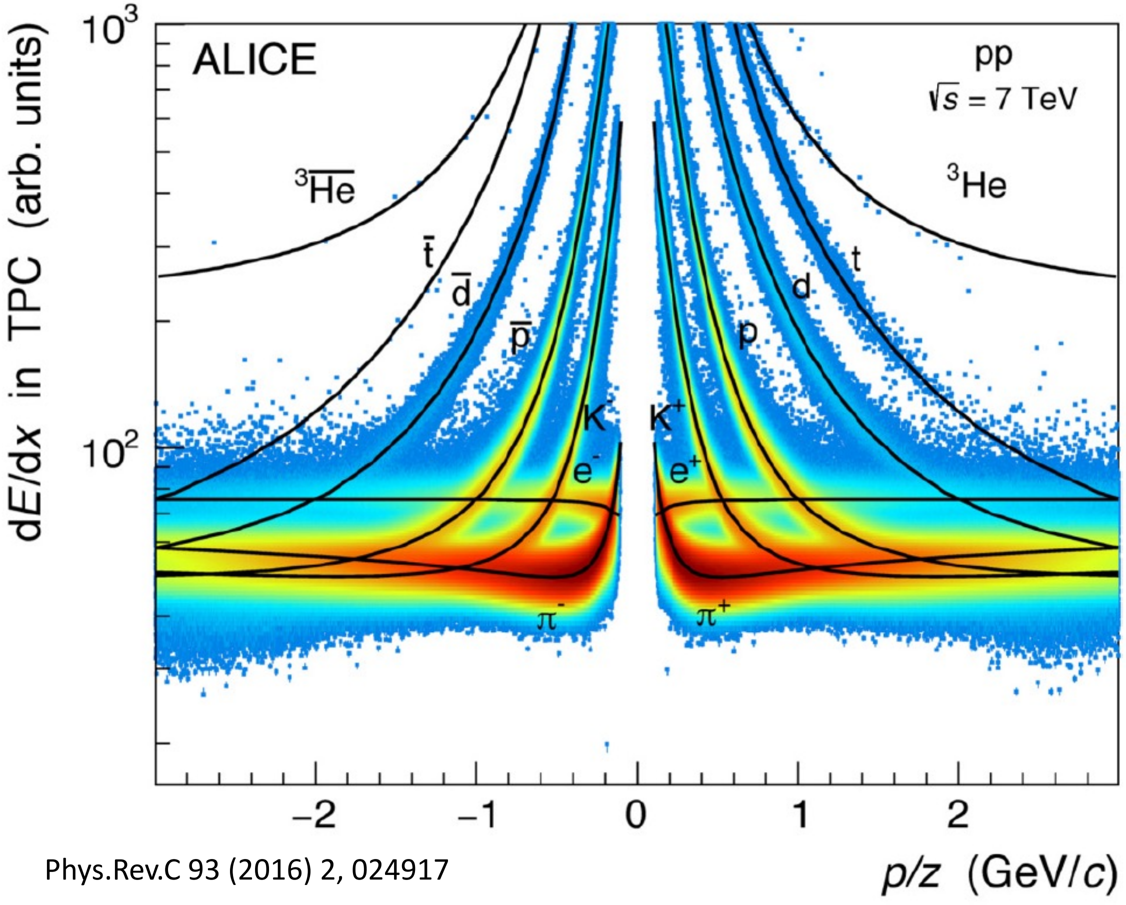


*See talk by M. Ciacco on Tue. 14/06
**See talk by P. Larionov on Wed. 15/06

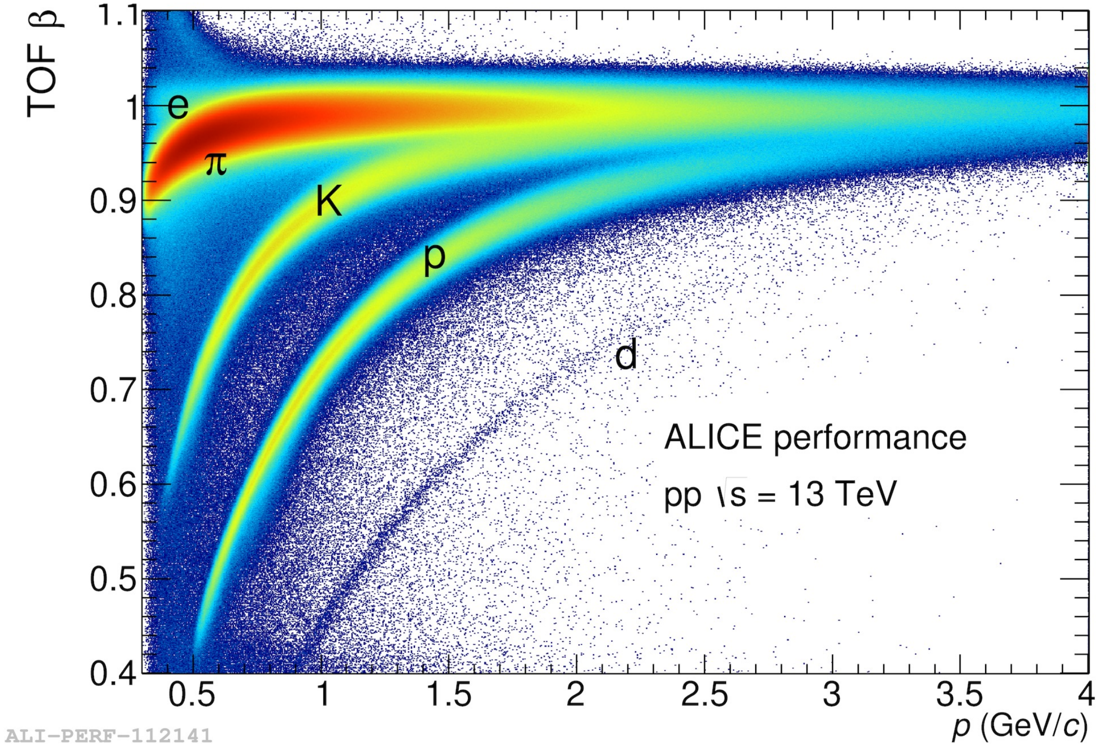
- At LHC energies same amount of matter and antimatter is expected ($\mu_B \sim 0$)*
- (Anti)(hyper)nuclei measurement studies are crucial
  - *microscopic production mechanism*
  - input for indirect dark matter searches**
- Production mechanism usually described with two classes of phenomenological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

Nuclei identification

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



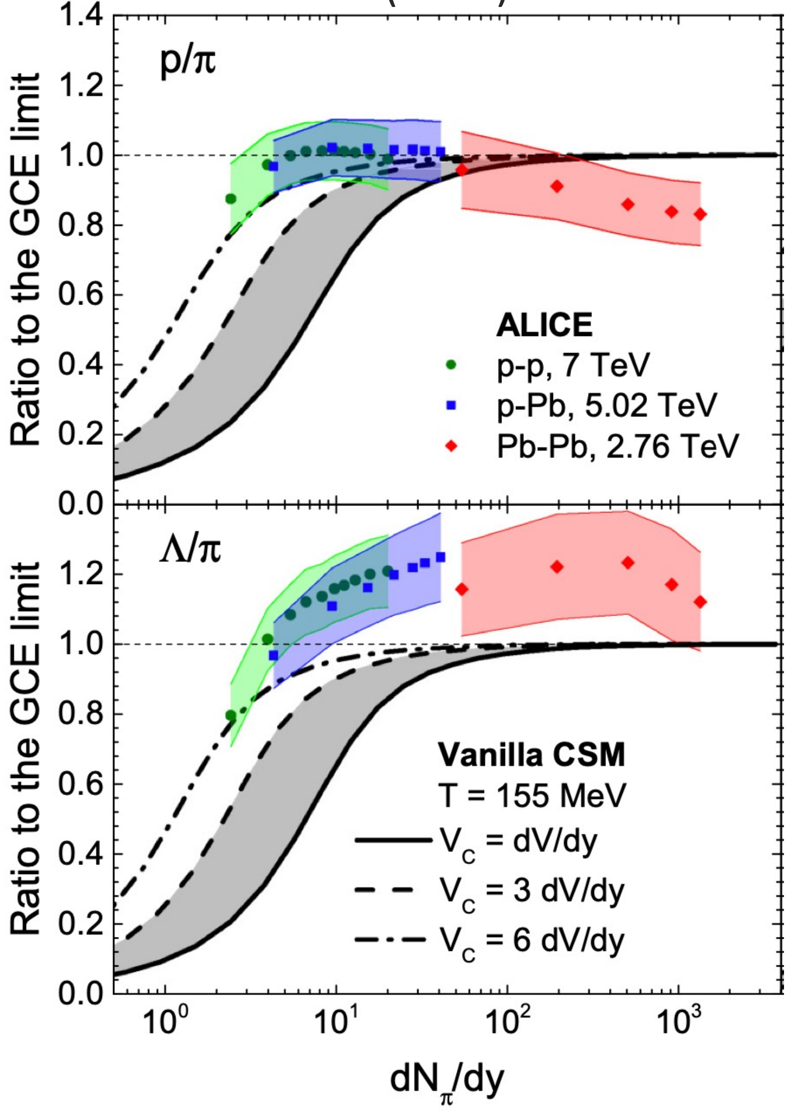
Phys.Rev.C 93 (2016) 2, 024917



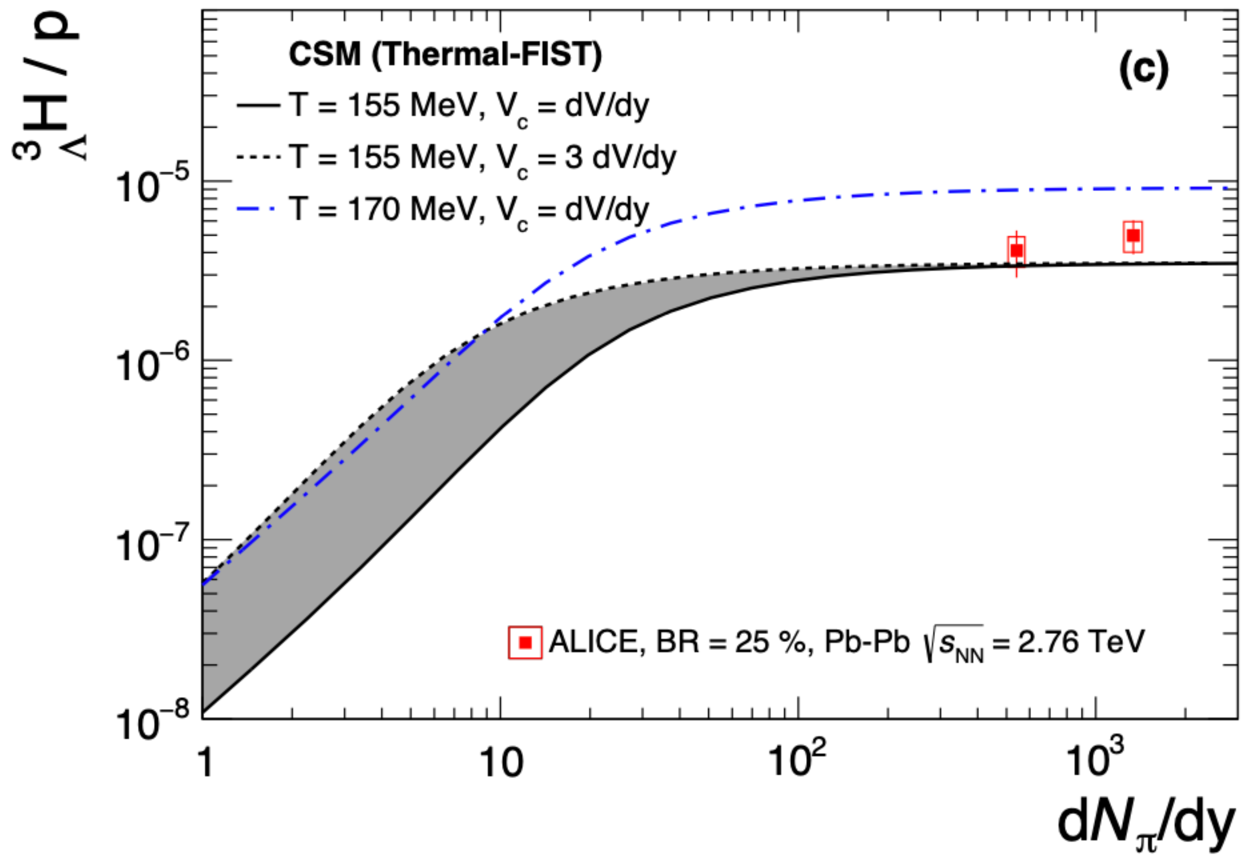
Higher p region (above 1 GeV/c) → PID via velocity β measurements in TOF

SHM predictions for particle yields

PRC 100 (2019) 054906



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

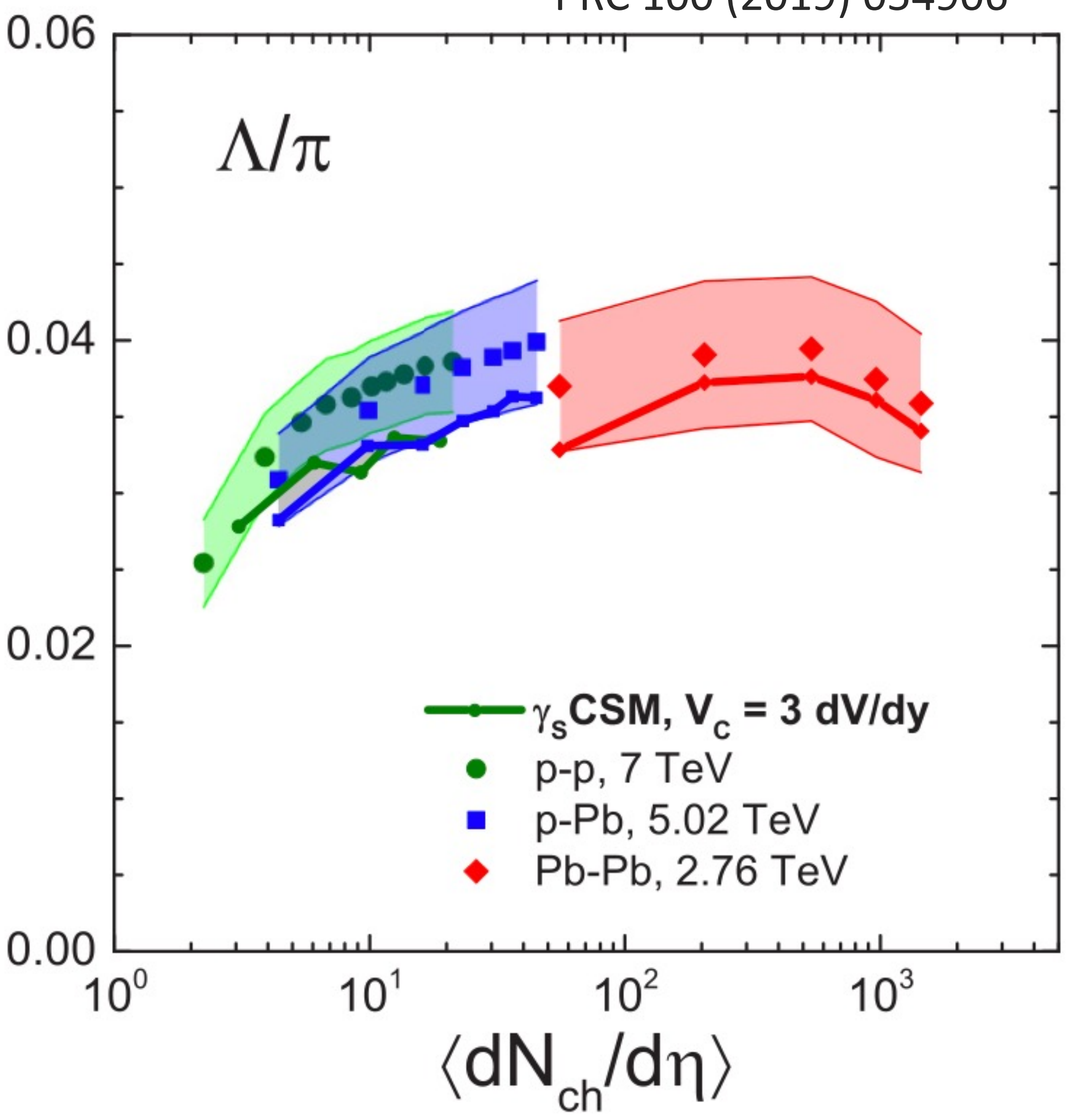


SHM predictions for particle yields

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

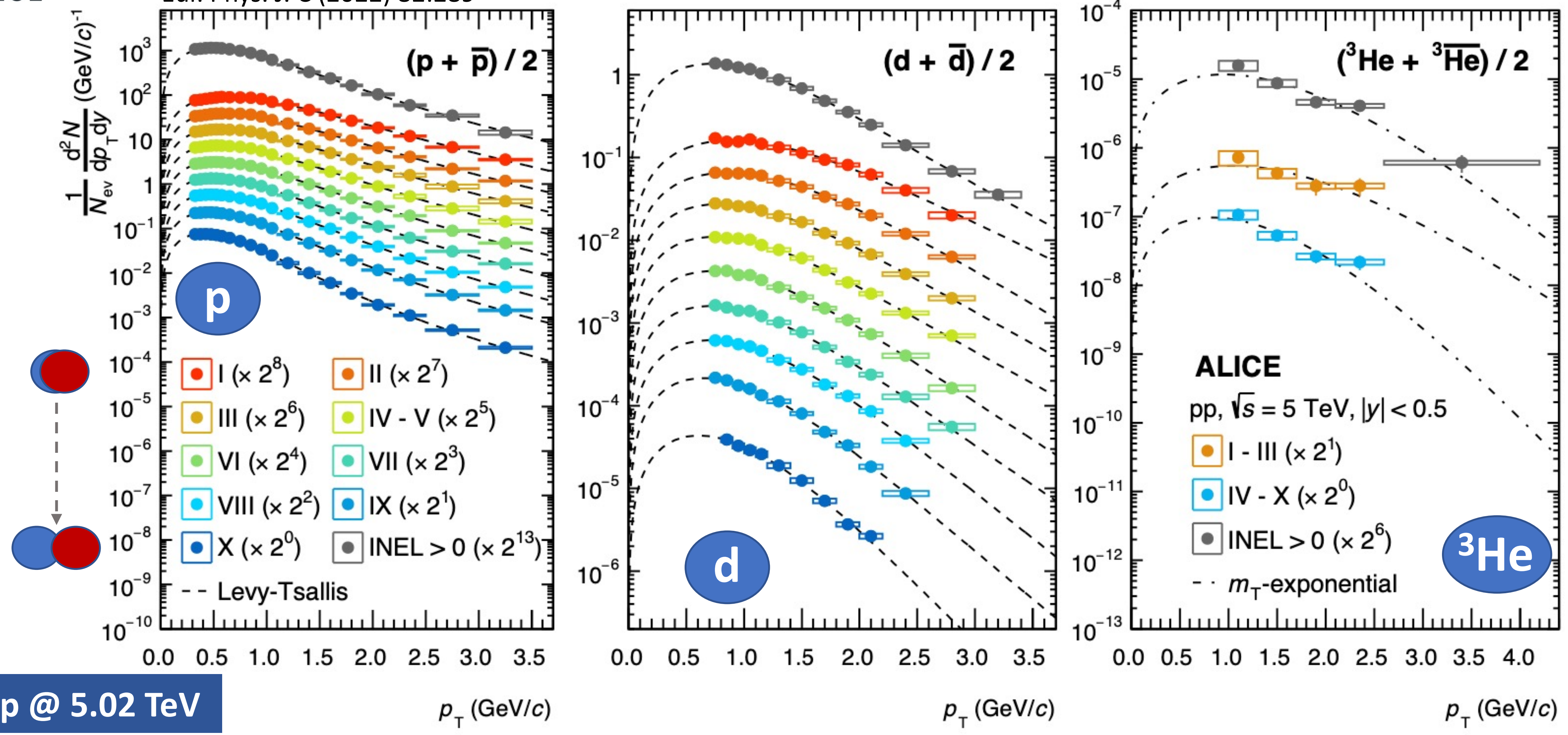
This implementation of SHM:
- incorporates the incomplete equilibration of strangeness by introducing the strangeness saturation factor gammaS
- accounts for the multiplicity-dependent chemical freezeout temperature

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

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

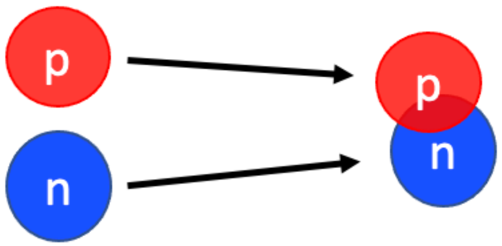
p+ n → γ + d
p+ n → π^0 + d
p+ n → π^0 + π^0 + d
p+ n → π^+ + π^- + d

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

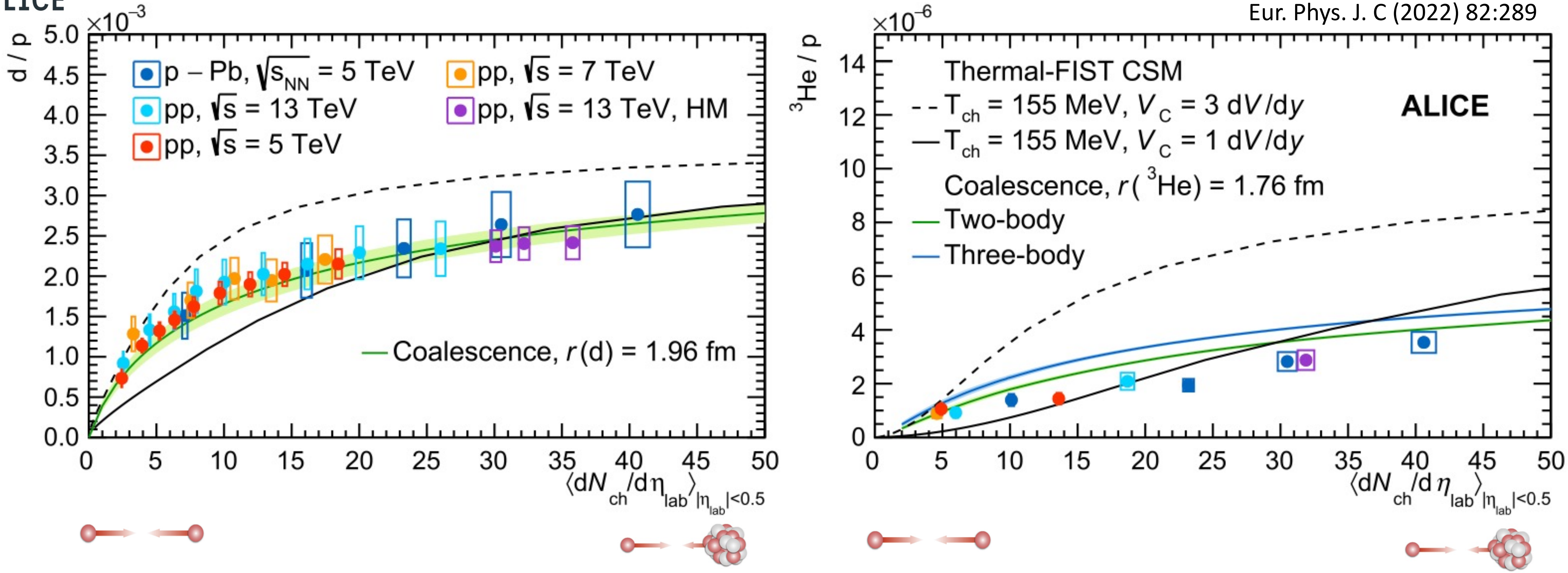
- $\Delta p < p_0$

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



Model comparisons in small systems

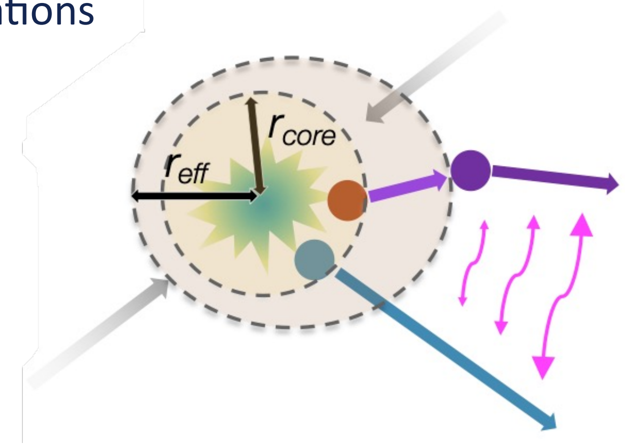
Eur. Phys. J. C (2022) 82:289

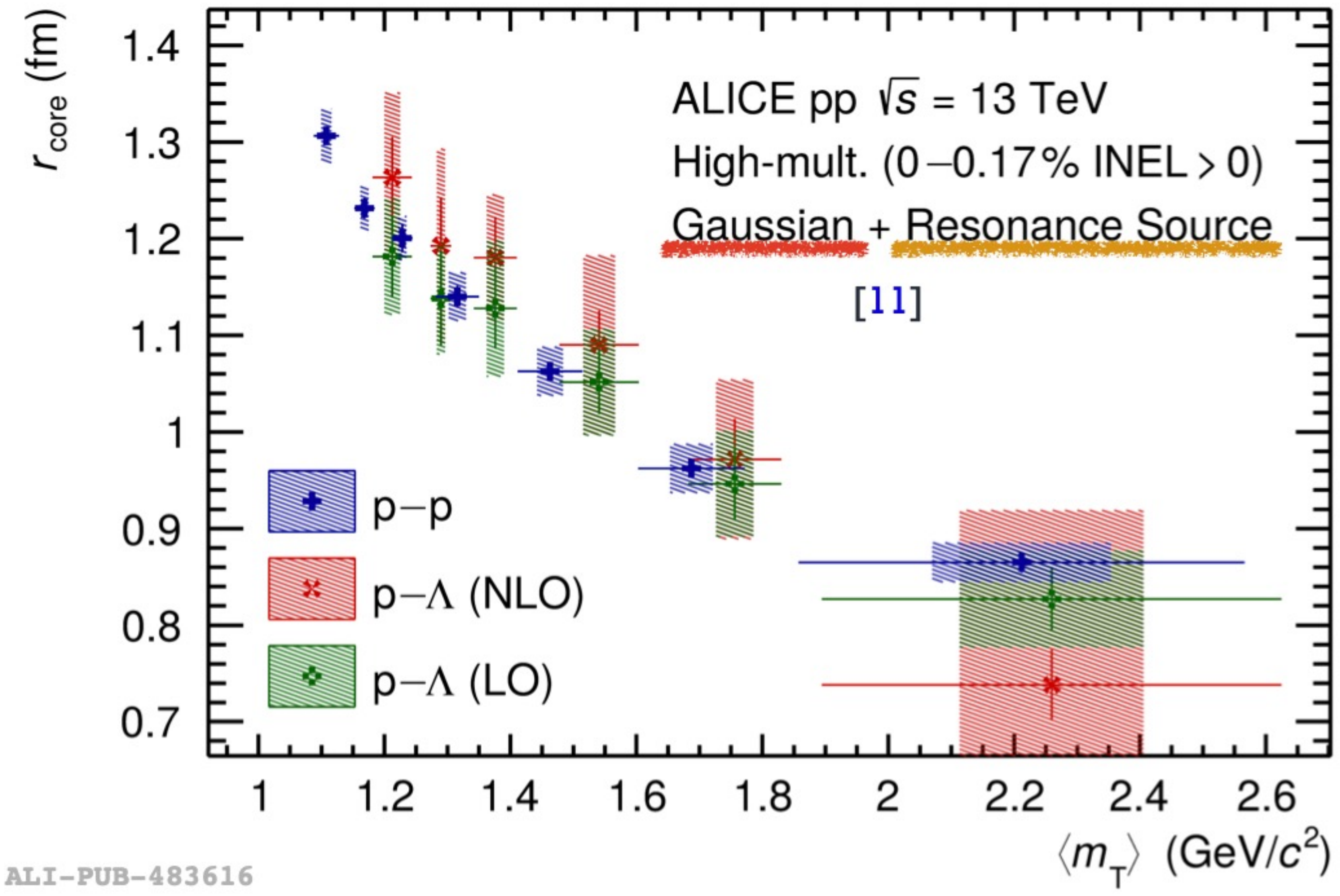


- Light nuclei production seems to depend only on multiplicity → smooth transition across different collision systems and energies
- Coalescence favored in d/p integrated yield ratios
- Results challenge the models for A=3 nuclei

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



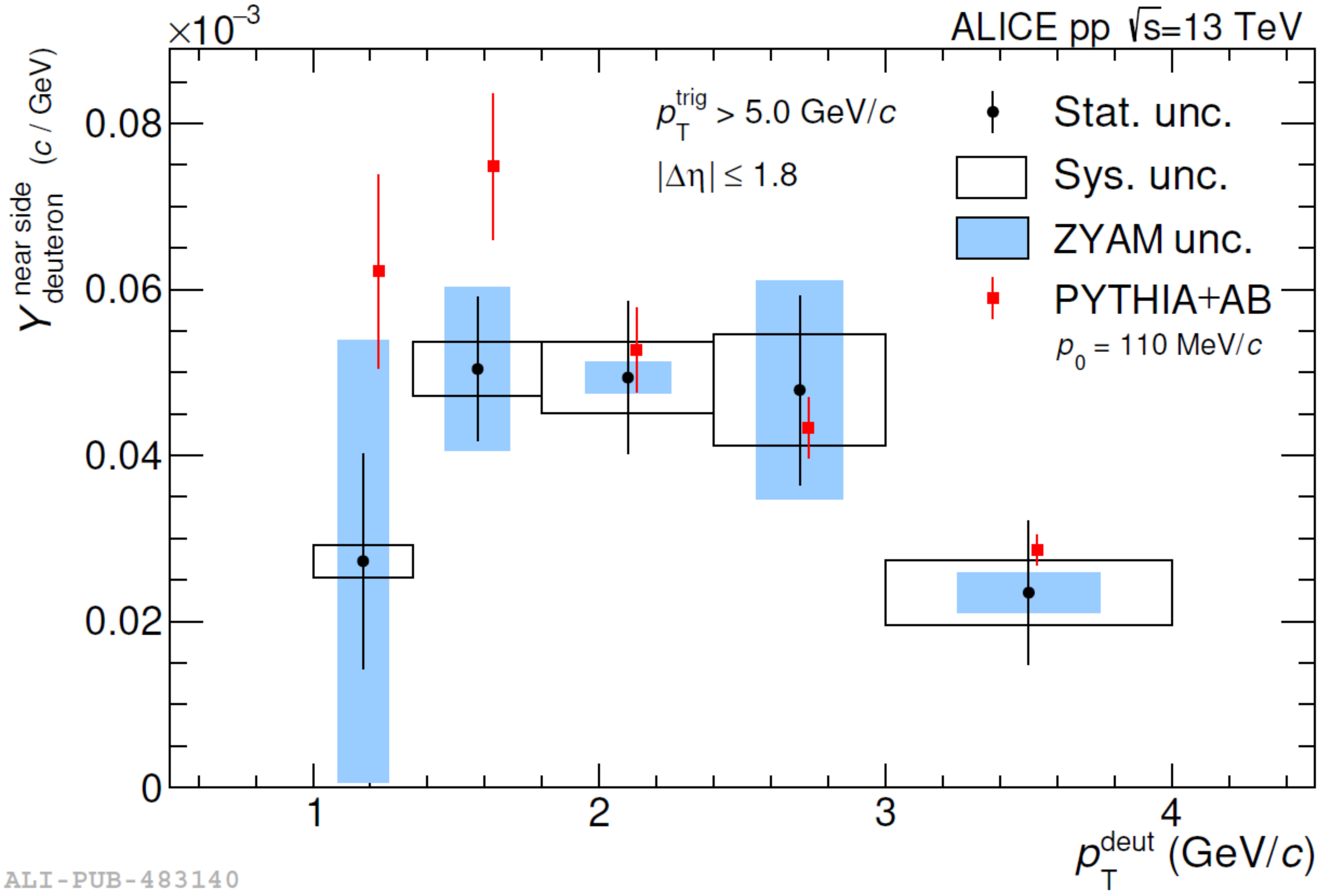


PLB 811 (2020) 135849

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

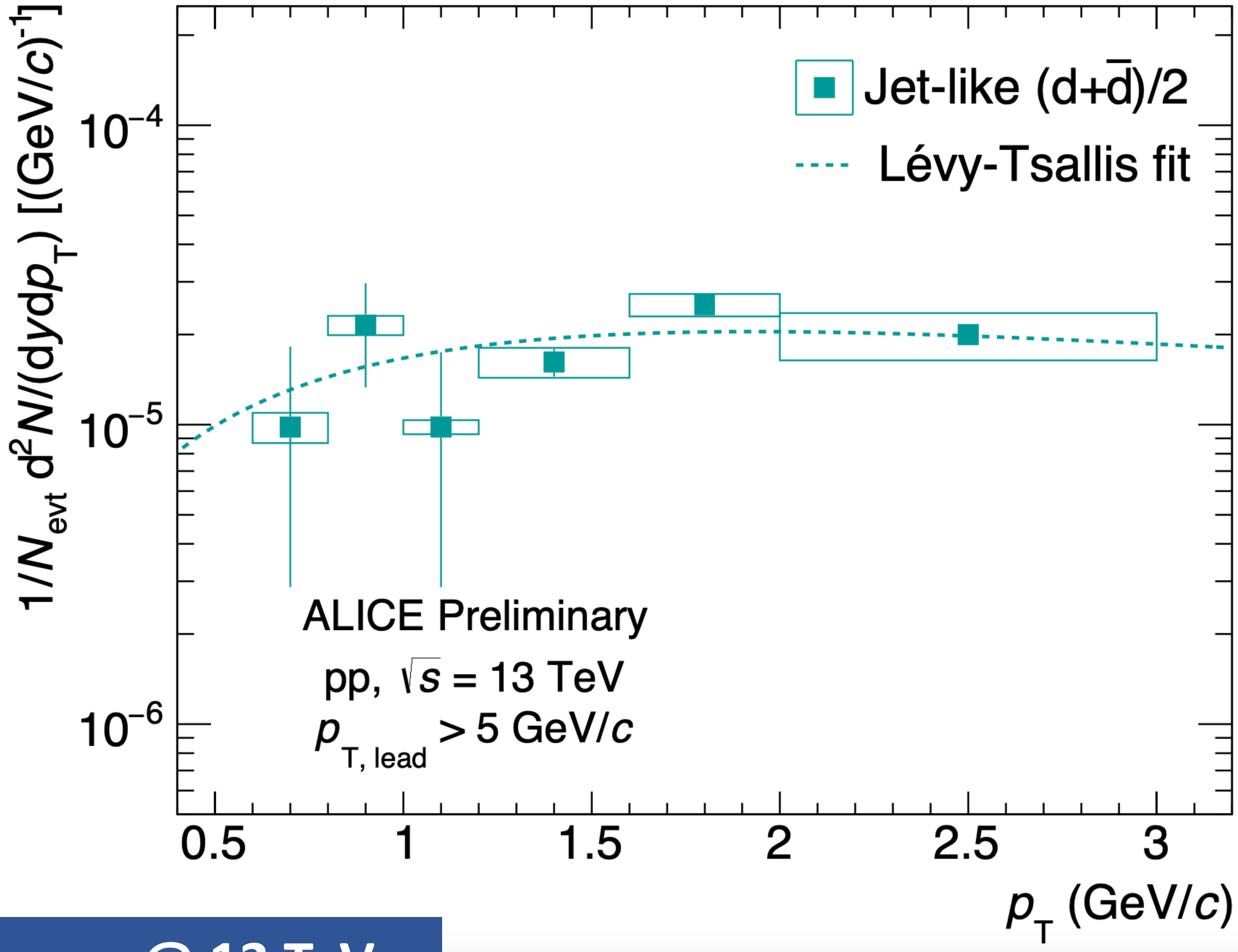
→ Towards region contains a large contribution from UE



pp @ 13 TeV

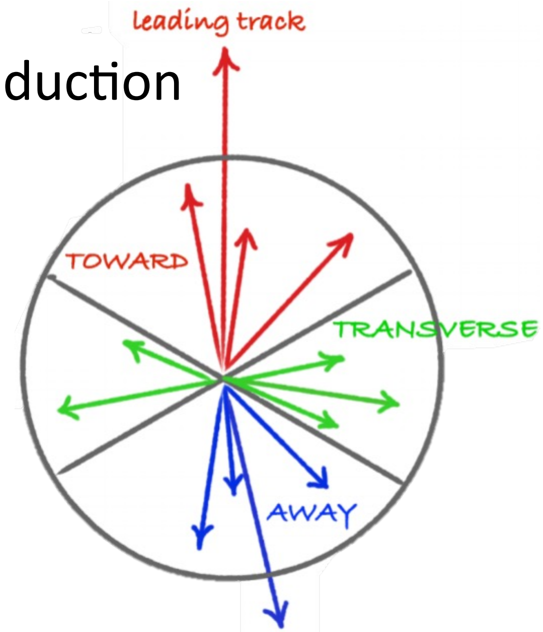
Phys.Lett.B 819 (2021) 136440

Jet-like deuteron spectrum



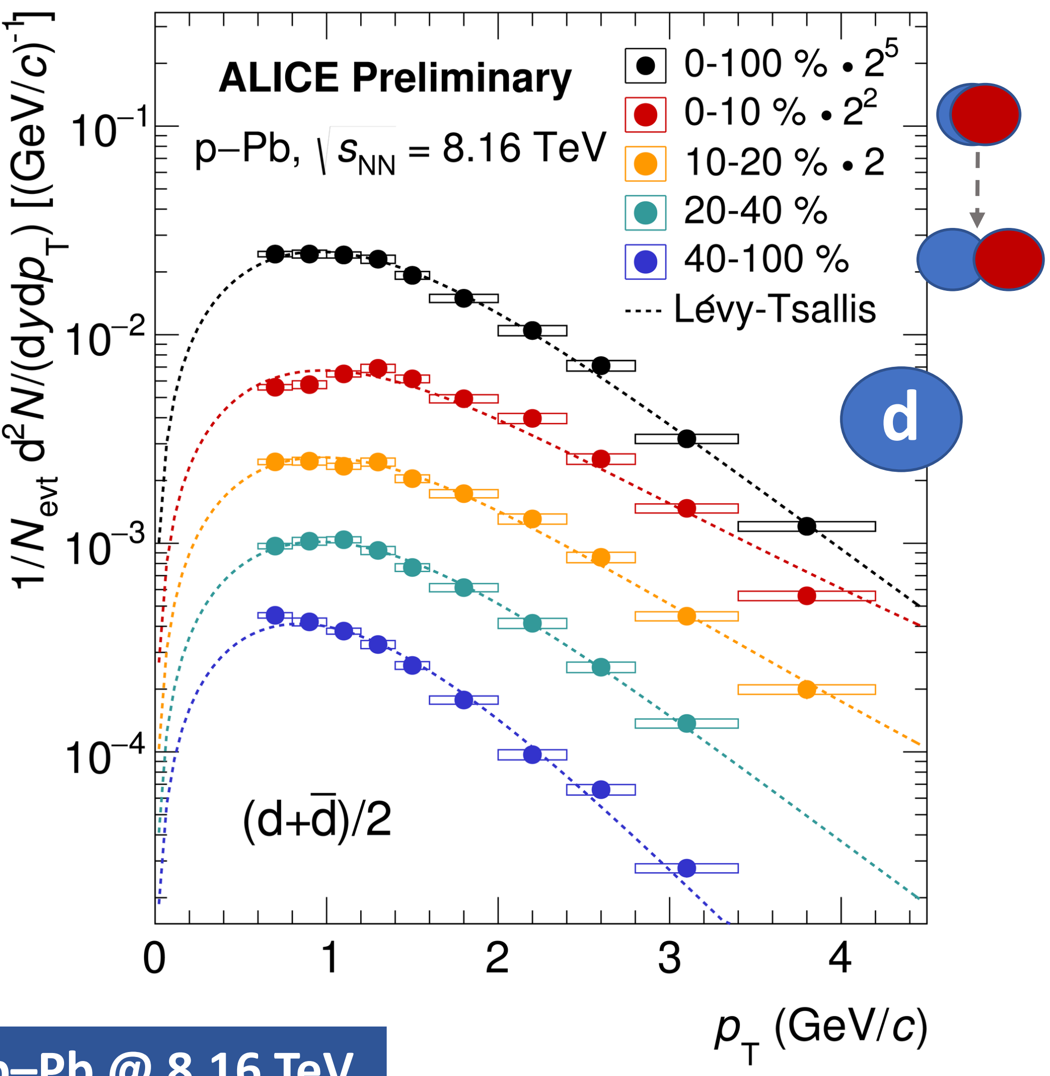
- Jet-like spectrum can be easily obtained by subtracting the UE from the Toward region (Jet + UE)
- Results consistent with the the two-particle correlation method [Phys.Lett.B 819 (2021) 136440]
- Jet: ∼10% of total production

Jet = Toward – Transverse

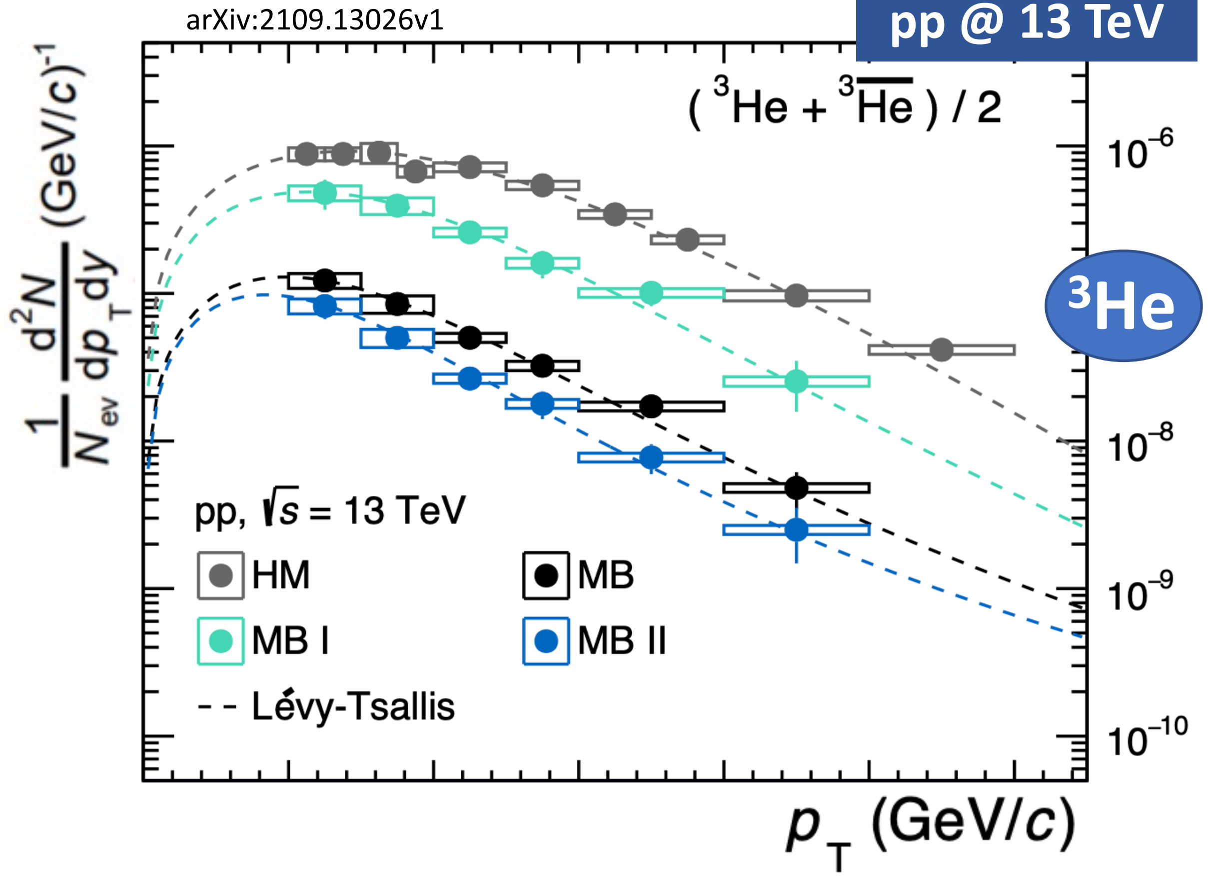


pp @ 13 TeV

Light (anti)nuclei in small systems



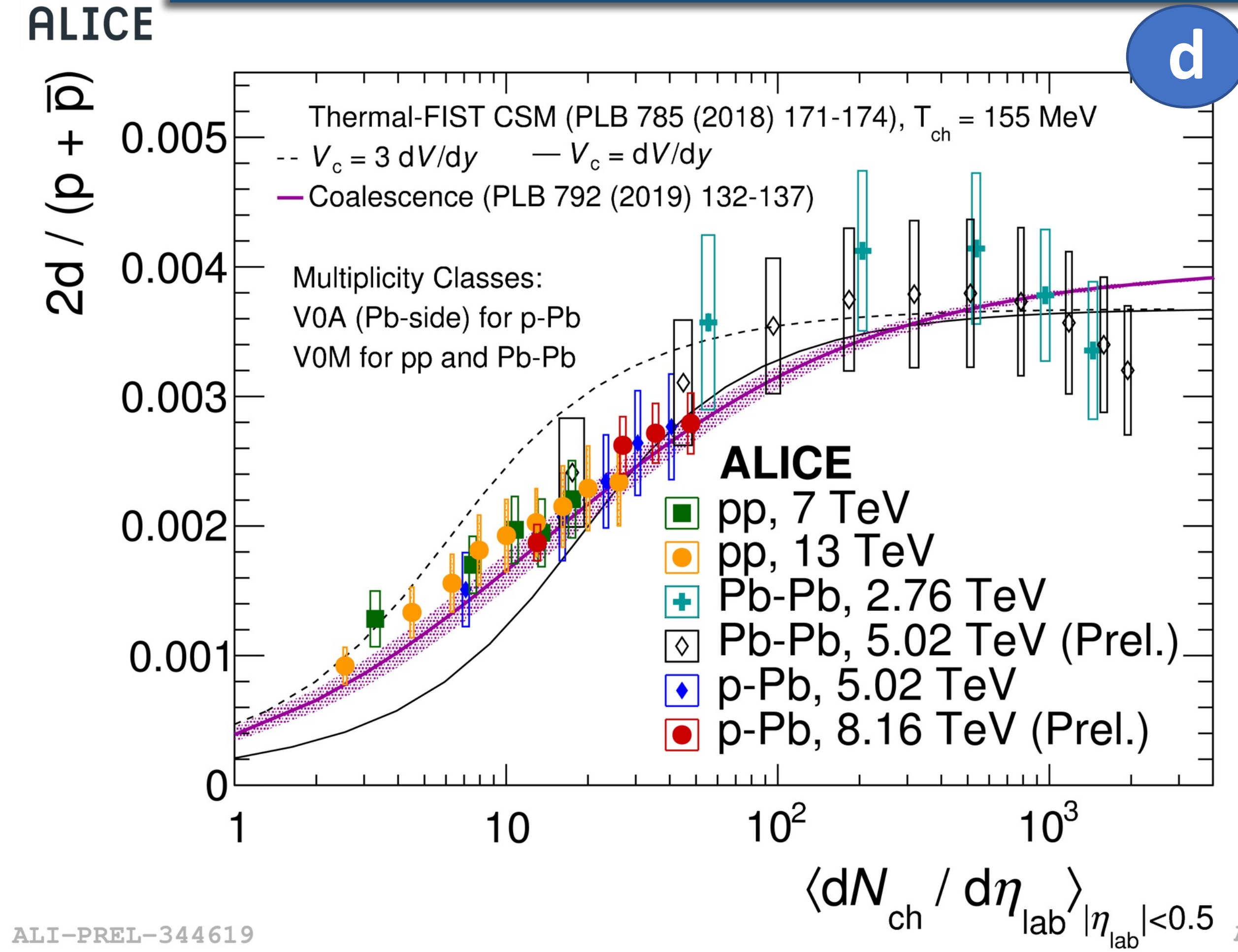
p–Pb @ 8.16 TeV

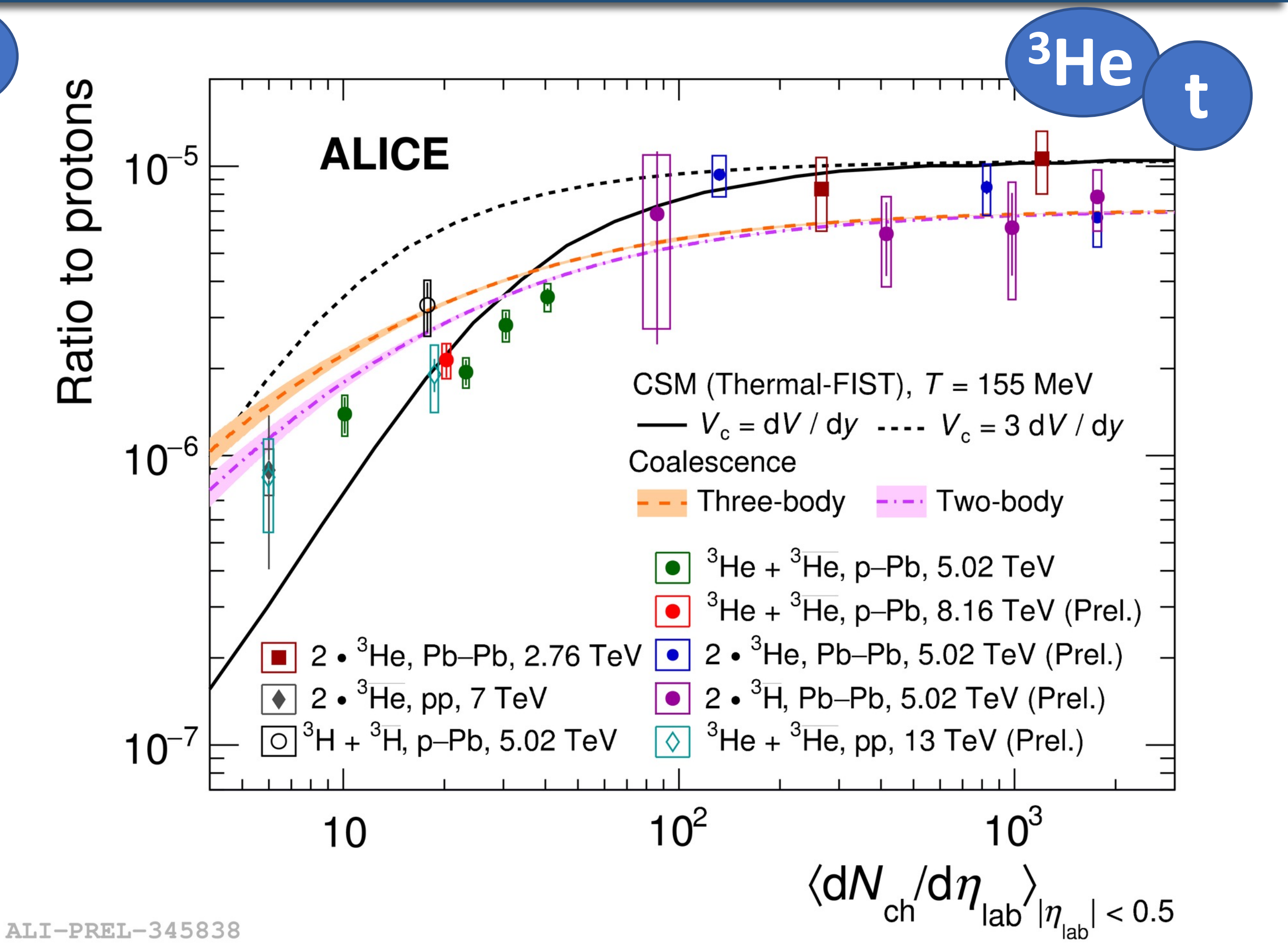


pp @ 13 TeV

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

Ratio to protons – models comparison

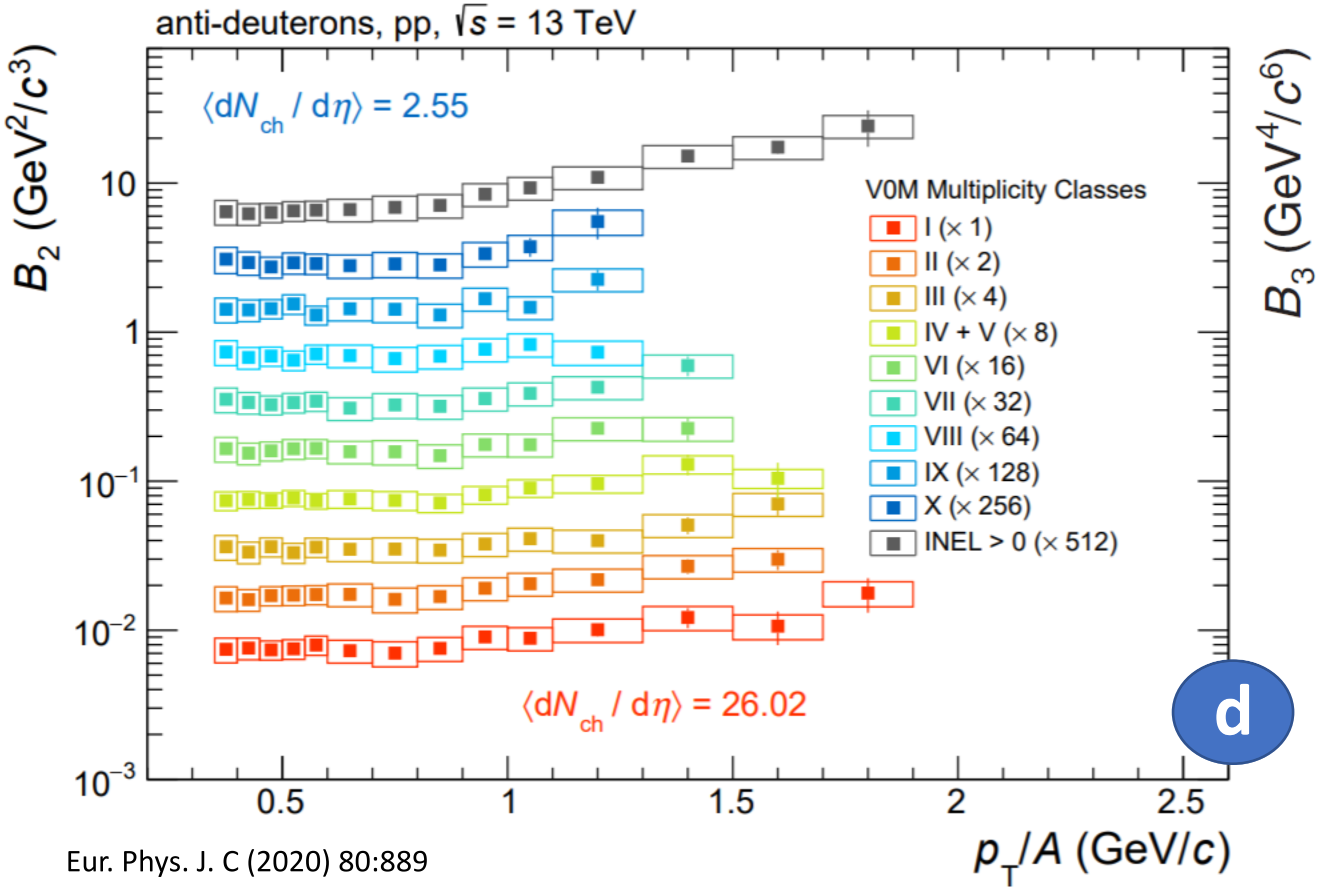




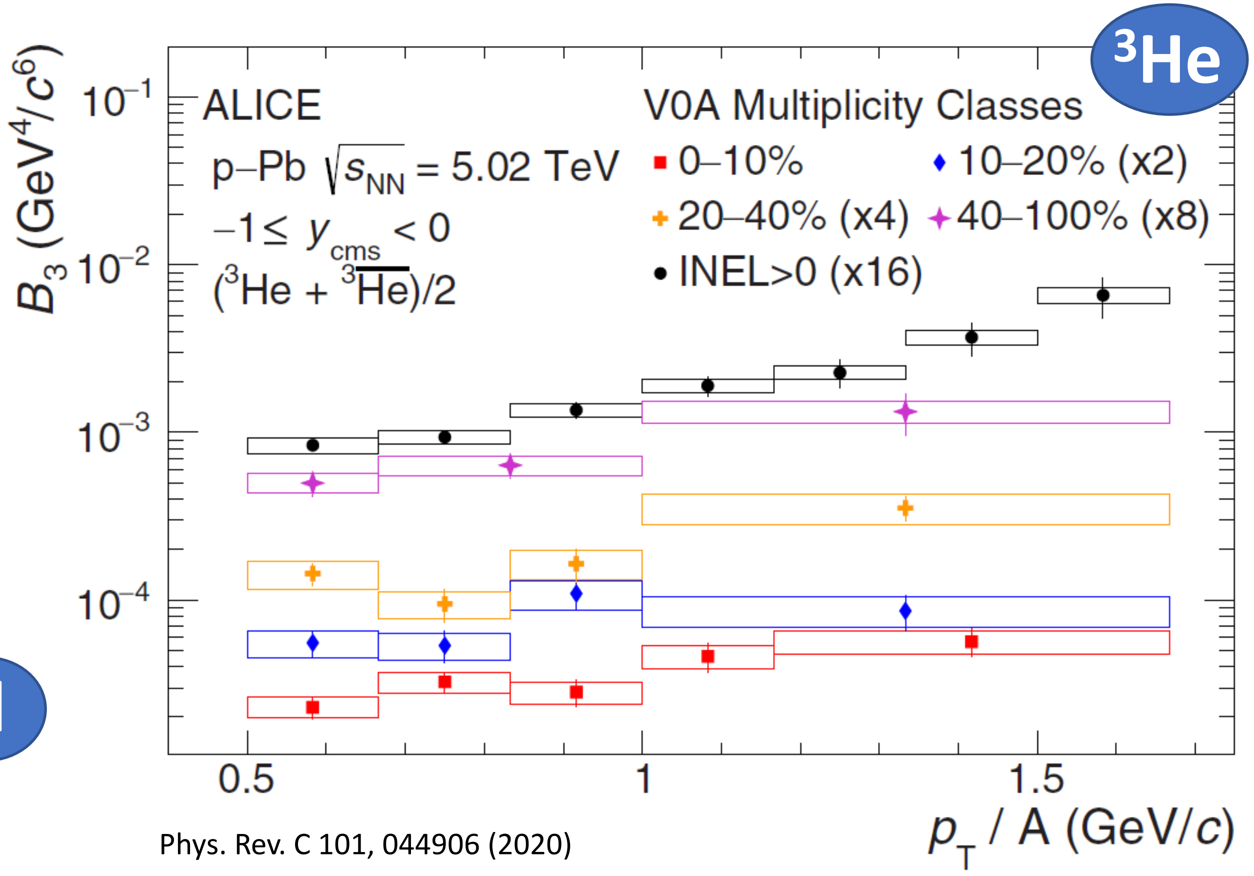
- Smooth transition across different collision systems and energies
- Light nuclei production seems to depend only on multiplicity
- Results challenge the models for A=3 nuclei

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

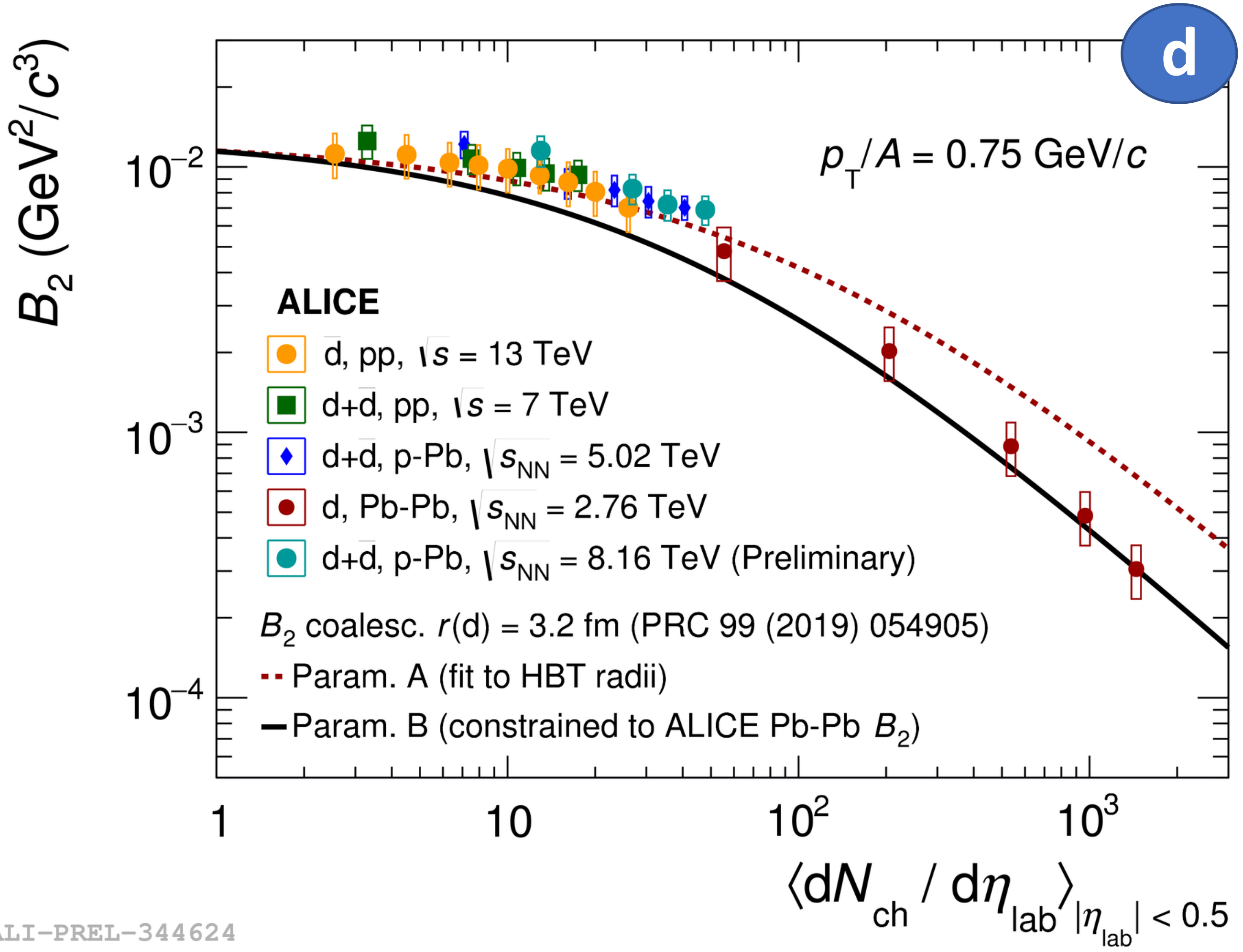


Phys. Rev. C 101, 044906 (2020)

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?

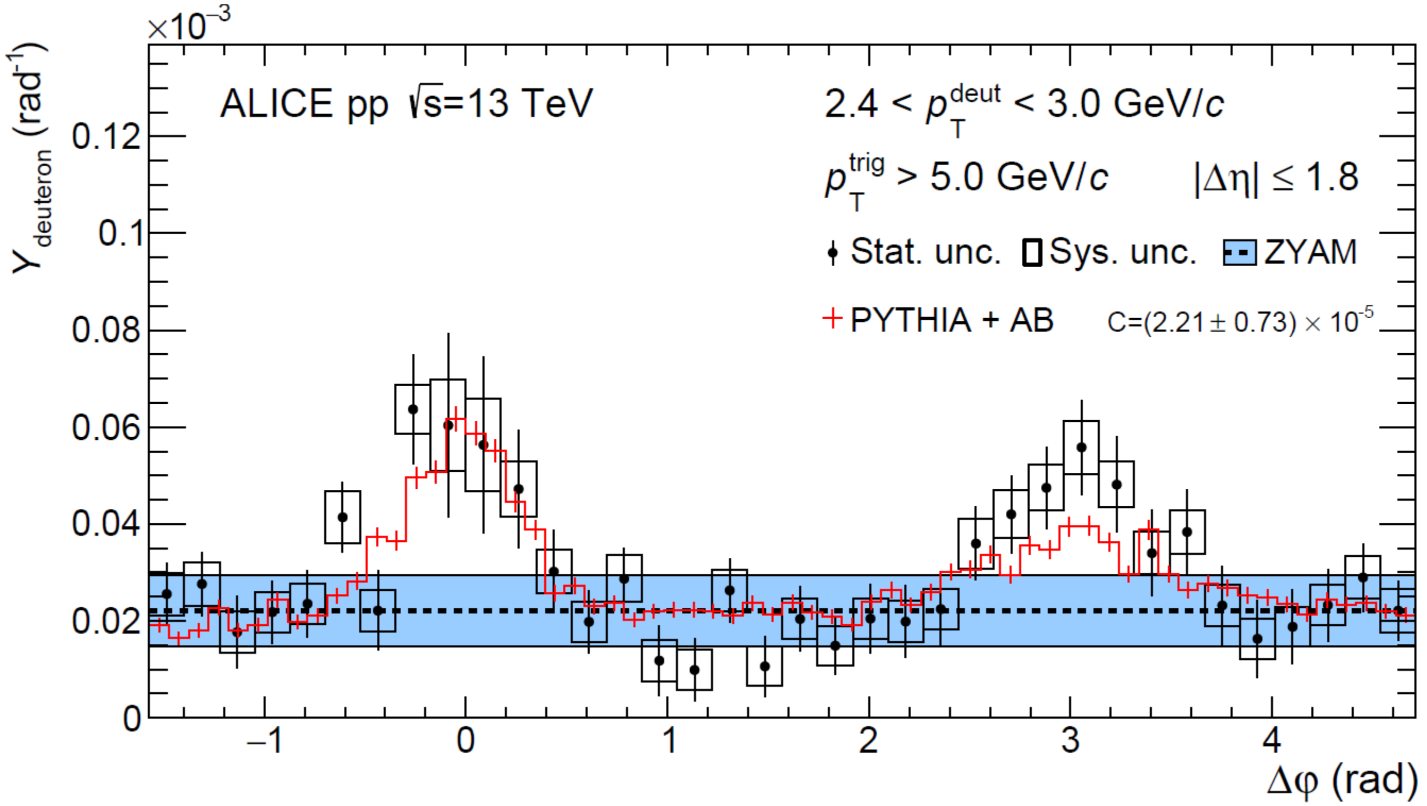
Similar conclusions apply also for B_3

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

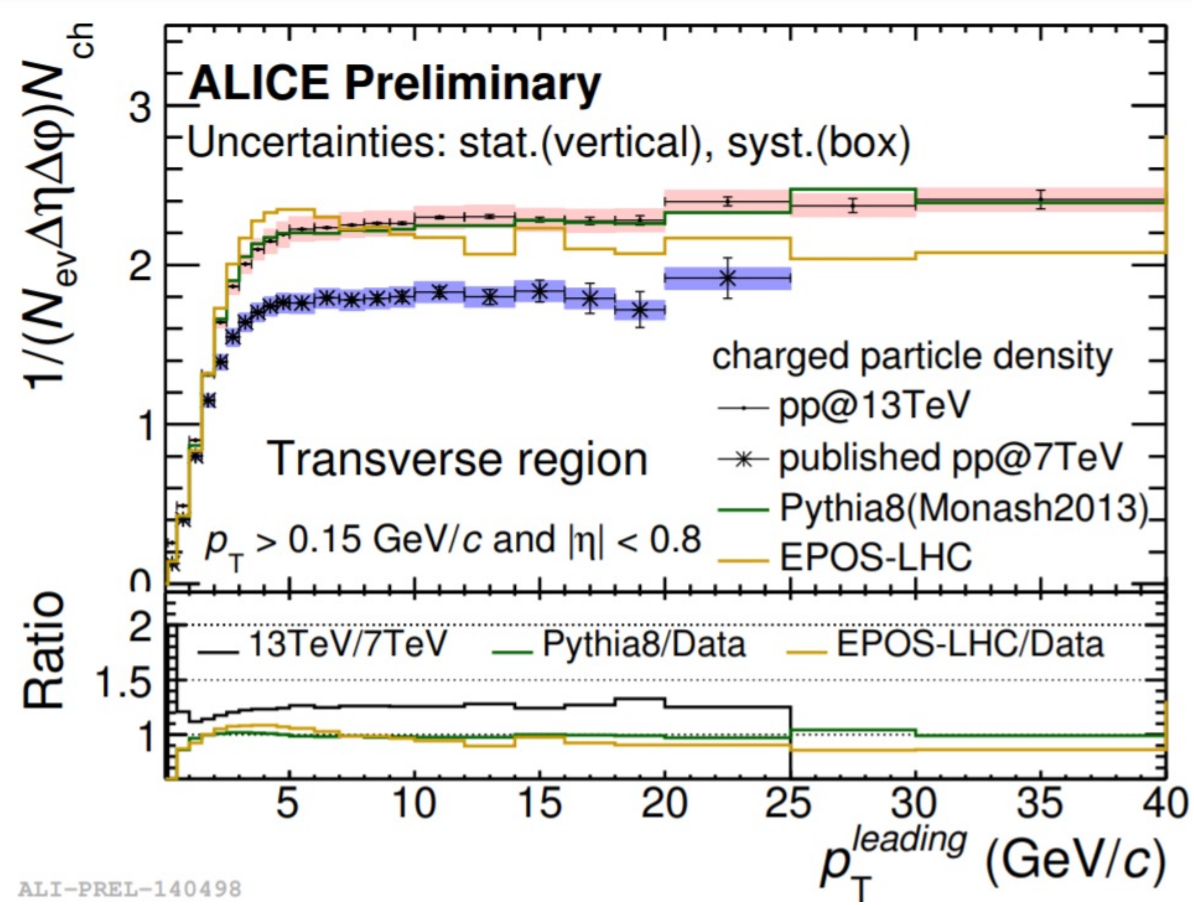
arXiv:2011.05898 [nucl-ex]

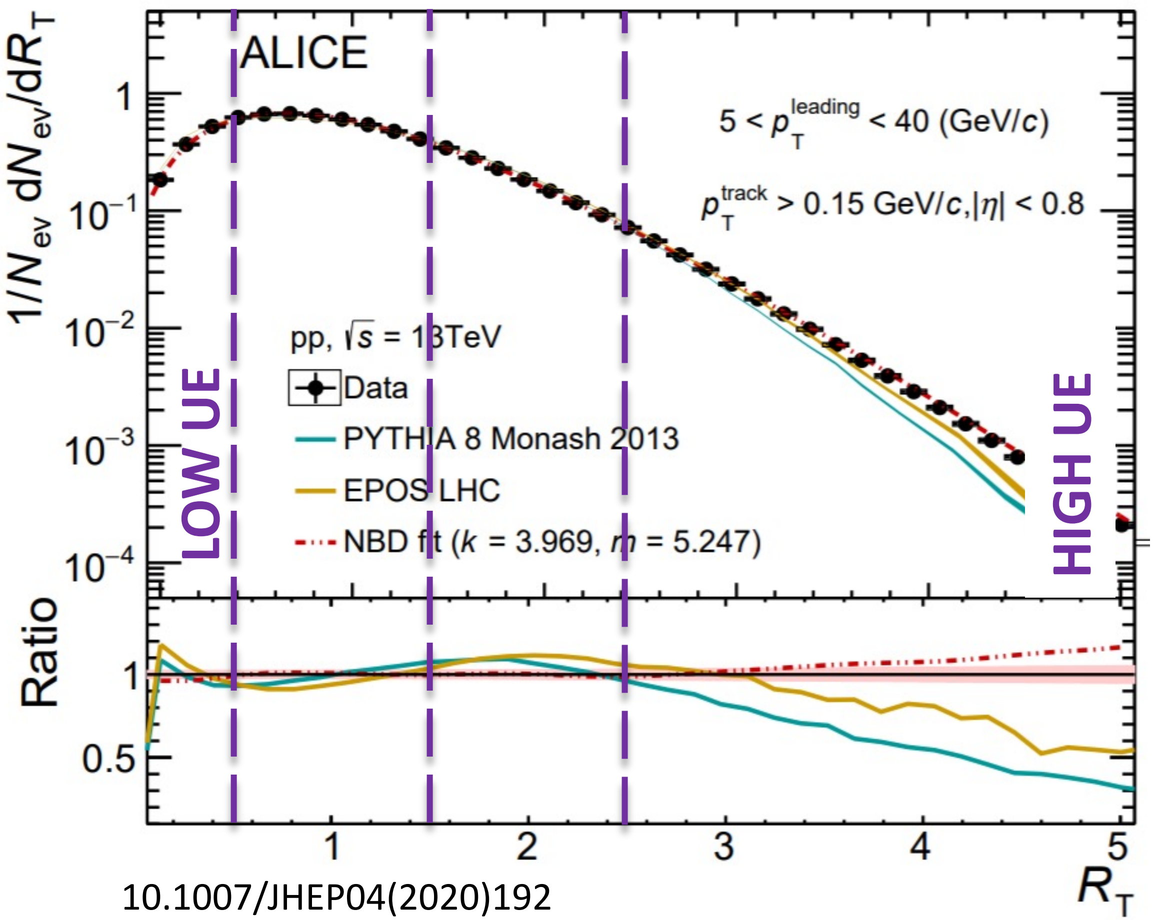
Characterize the UE

- 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



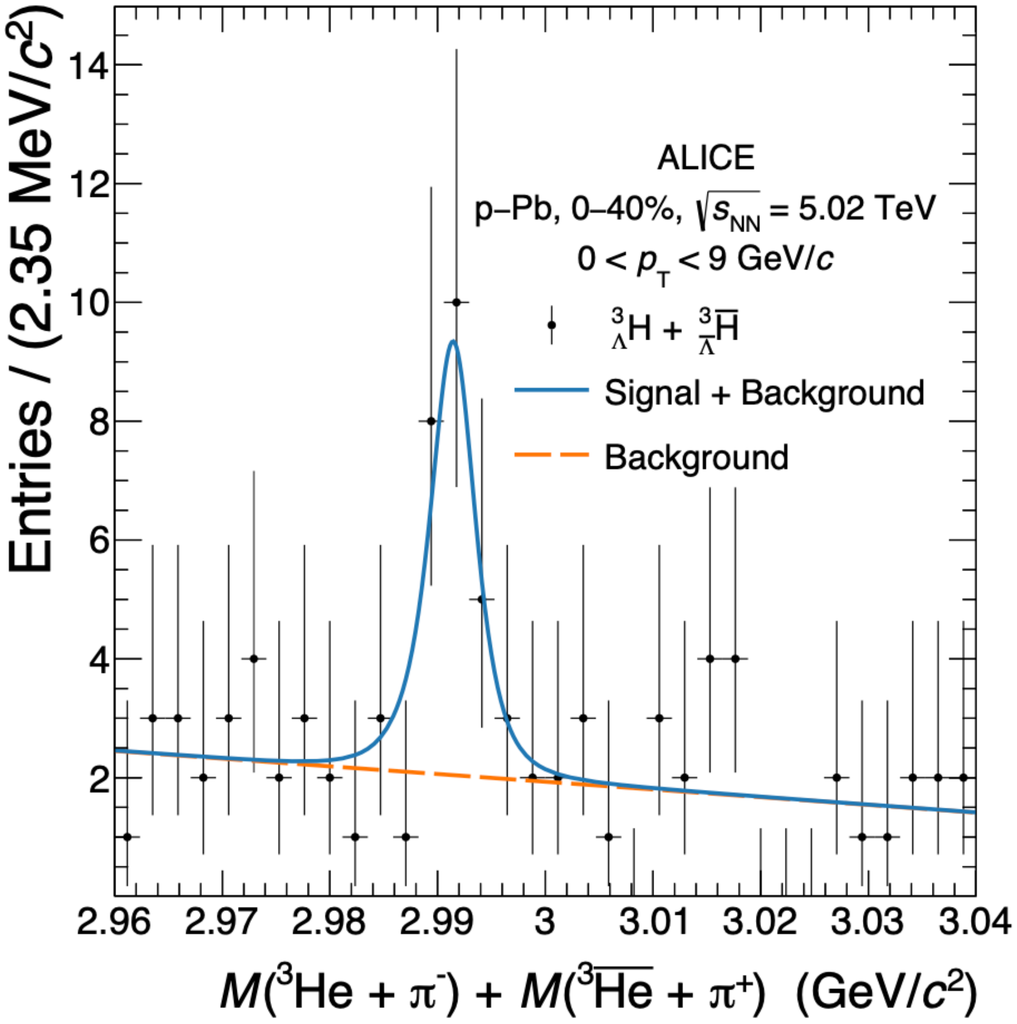


10.1007/JHEP04(2020)192

Hypertriton in small systems

arXiv:2107.10627

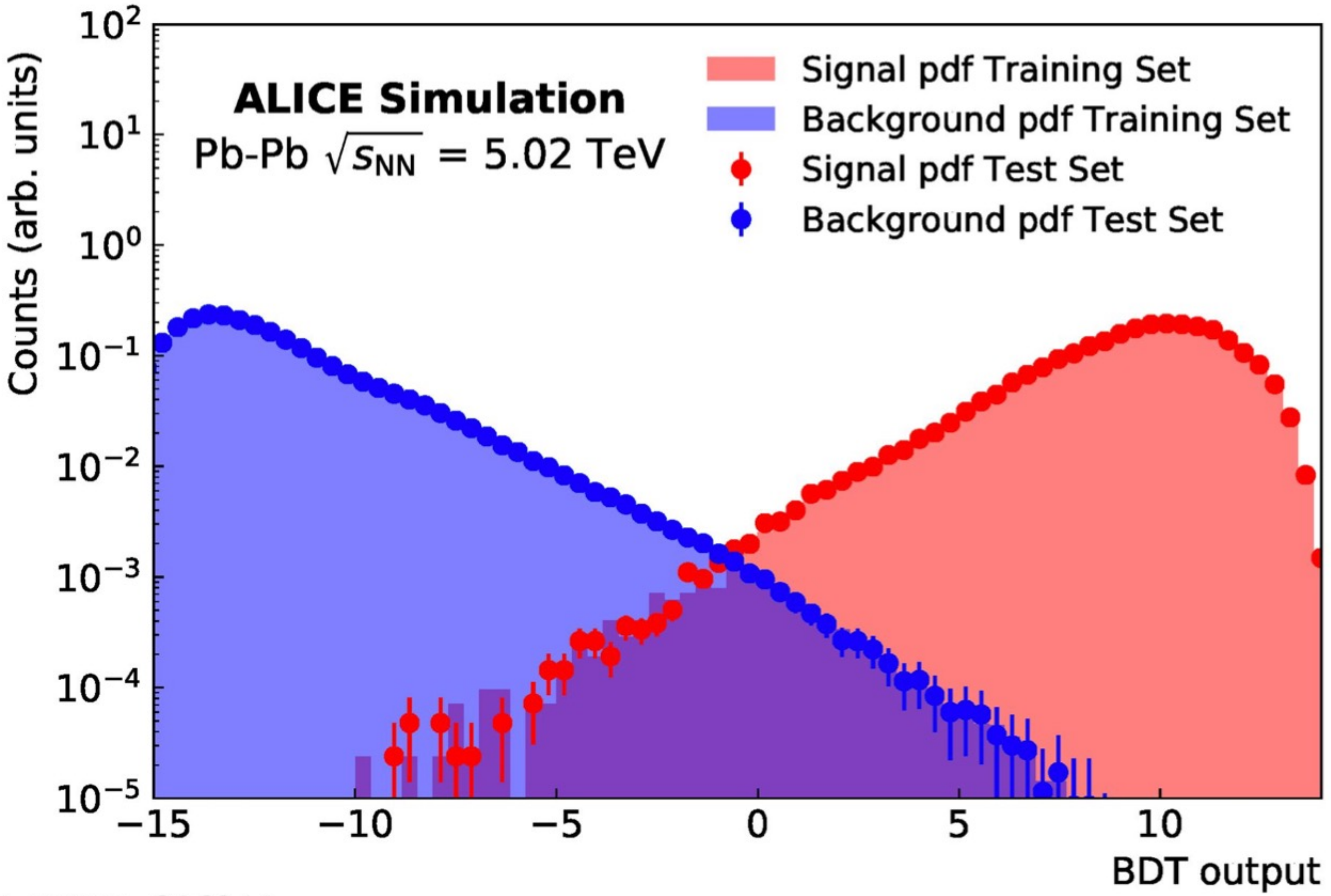
- Data samples:
  - pp at √s = 13 TeV and p-Pb at 5.02 TeV collisions collected by ALICE during Run 2
- ${}^{3}_{\Lambda}H$ selection in pp: trigger on high multiplicity events using V0 detectors + topological cuts on triggered events
- ${}^{3}_{\Lambda}H$ selection in p-Pb: 40% most central collisions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



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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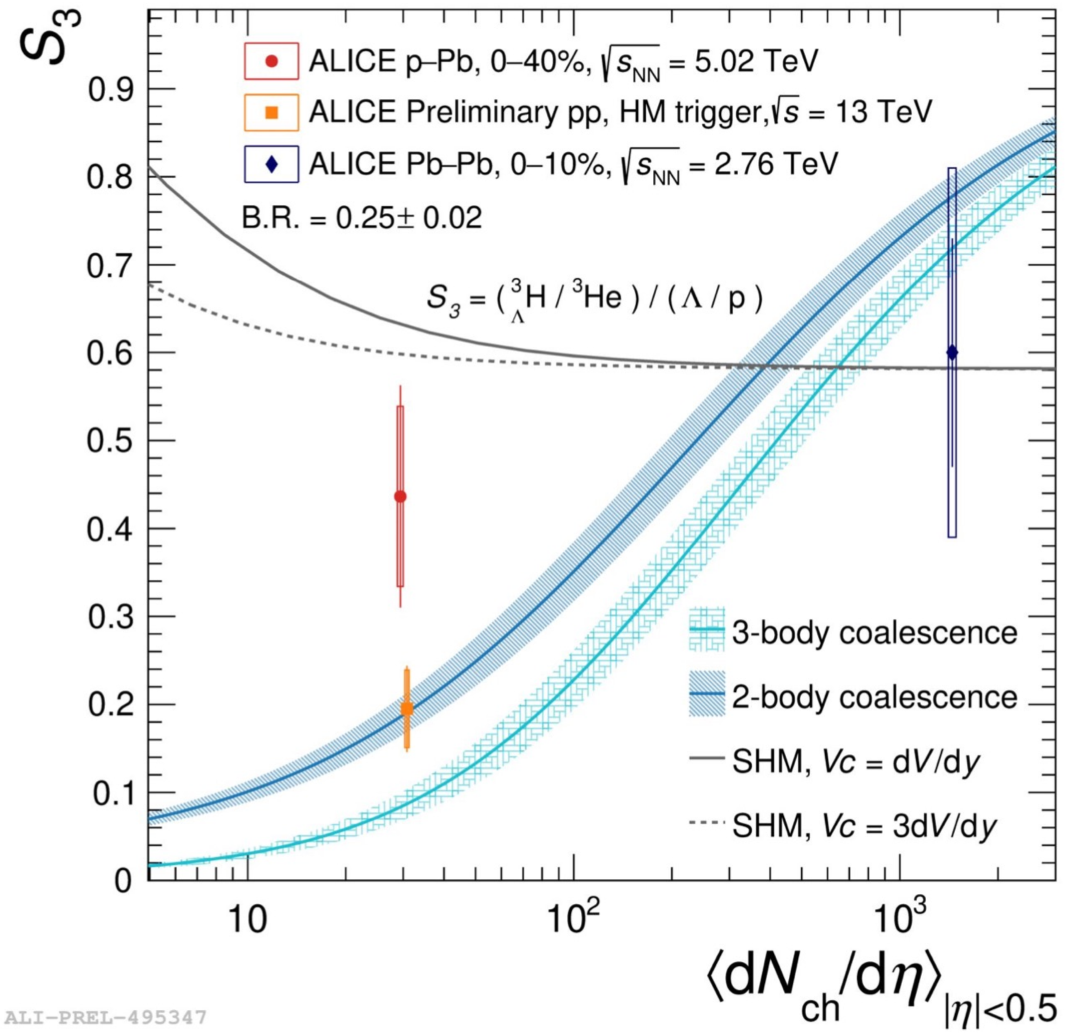
S_3 in small systems

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

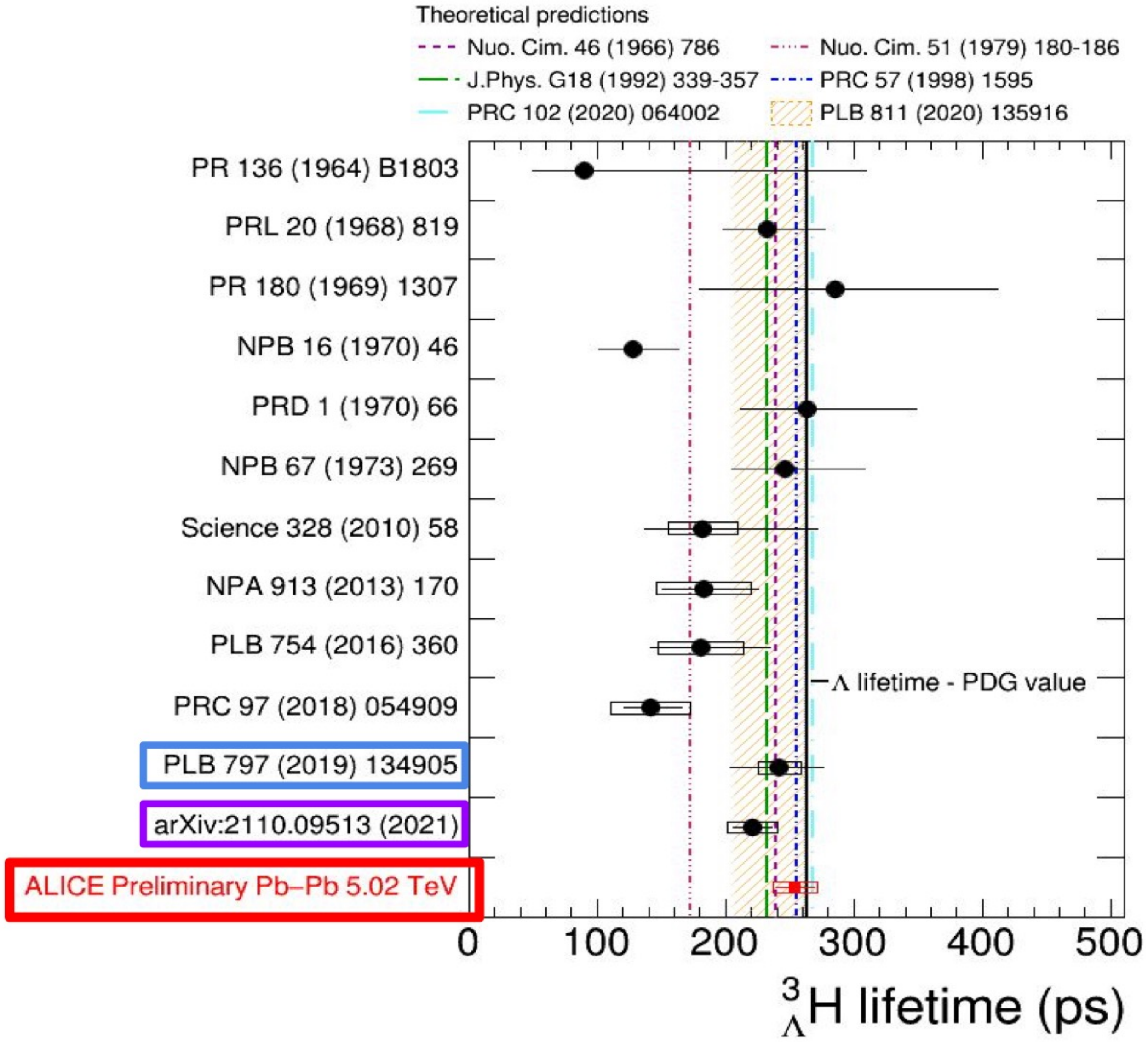
- S_3 in small systems:
  - same conclusions as for ${}^{3}_{\Lambda}H/\Lambda$ but with a lower sensitivity
  - LHC Run 3 will be crucial to finally distinguish between SHM and coalescence and explore the multiplicity dependence of S_3!



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



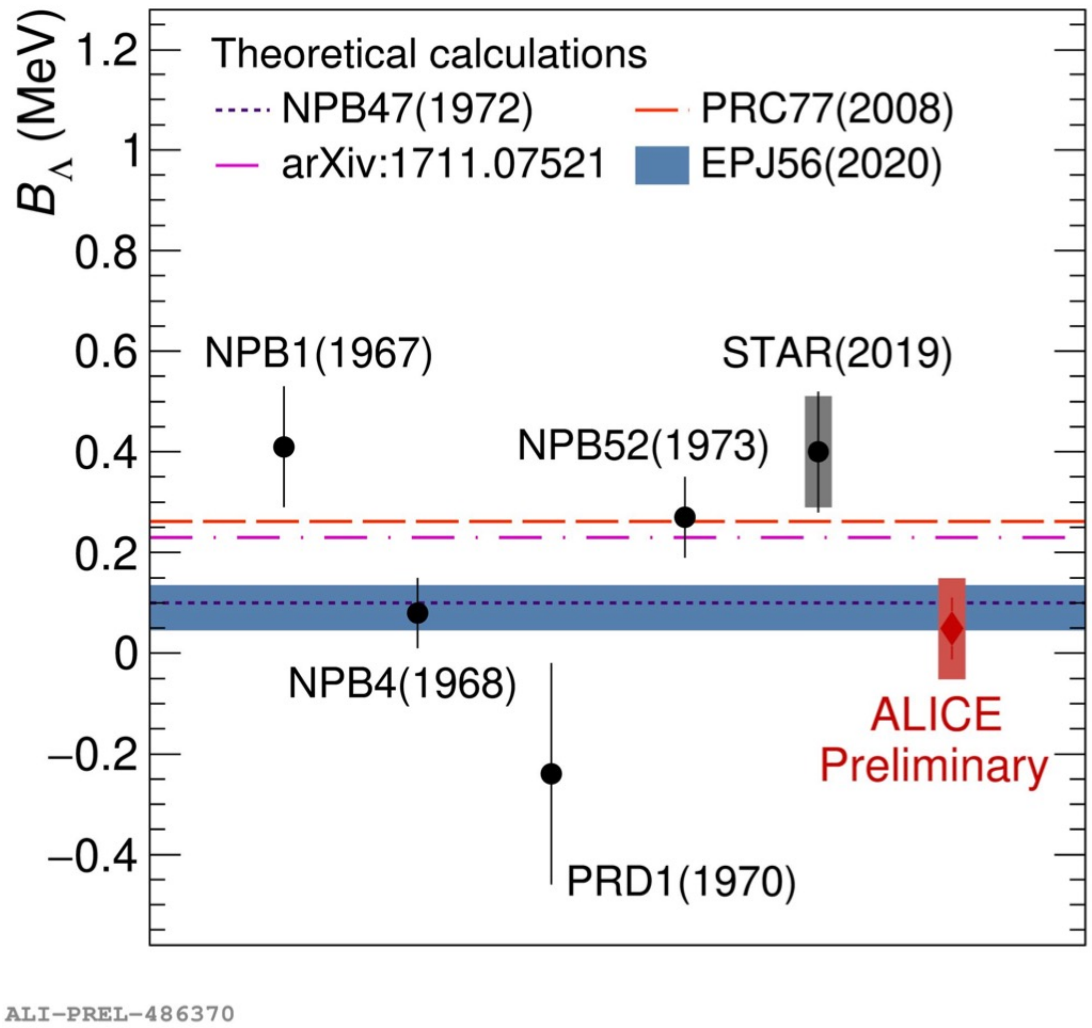
≥ 2020 models: assuming B_Λ = 70 keV
< 2020 models: assuming B_Λ = 130 keV

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*

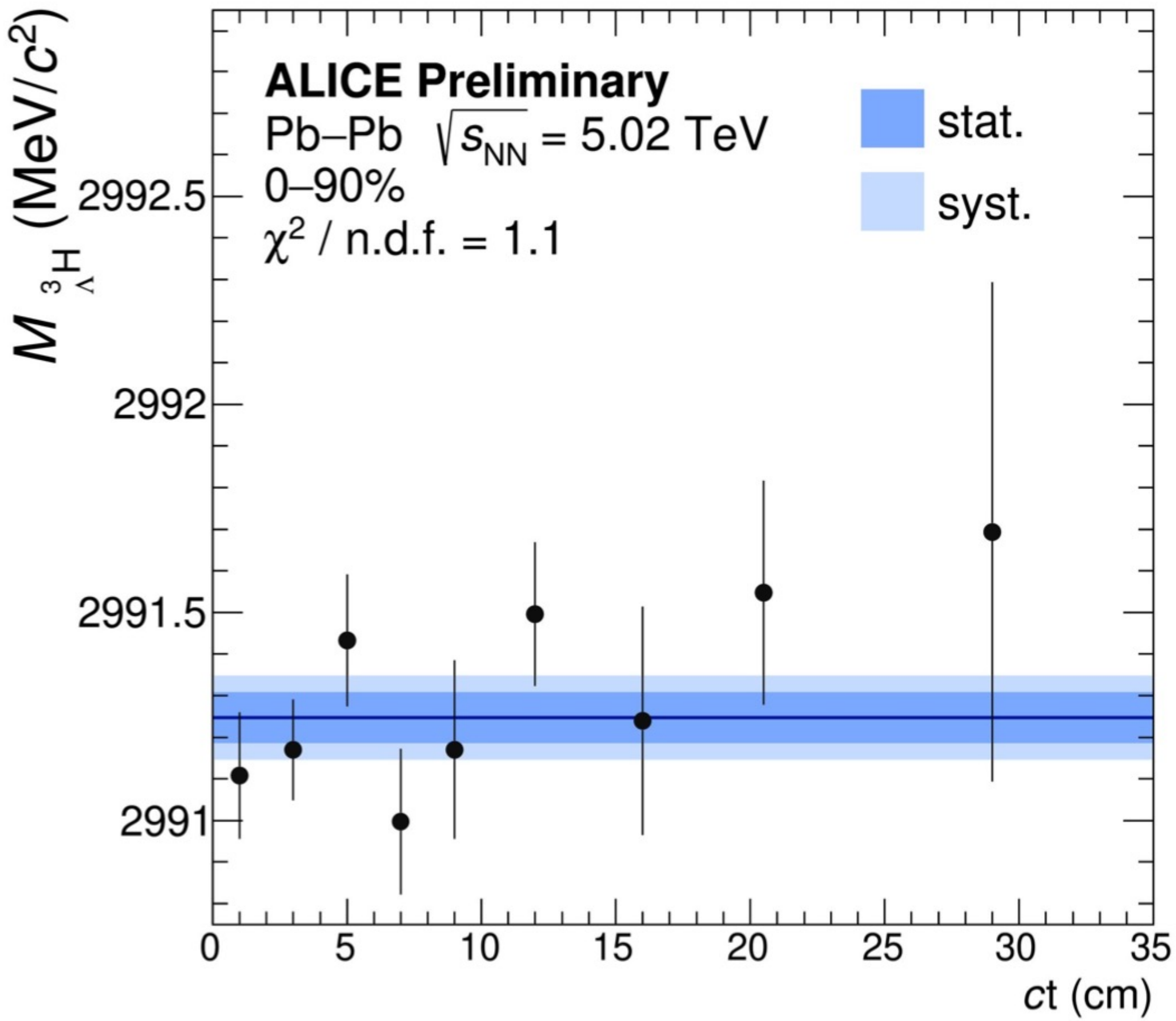


* Hildenbrand et al., PRC 102 (2020) 6; Pérez-Obiol et al., PLB (2020) 811

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%)



ALI-PREL-486366

Motivation

Particle production mechanism

Hypertriton
P-d
3 body (Ppp pplambda)

Bound states/resonance
Lambda-K- -> Xi 1620 [ppk 3 body - oton]
Charm-light hadrons -> p D- -> DPION DK
ALICE 3 -> Tcc