Results on light (anti)(hyper)nuclei production with ALICE at the LHC

ESTHER BARTSCH

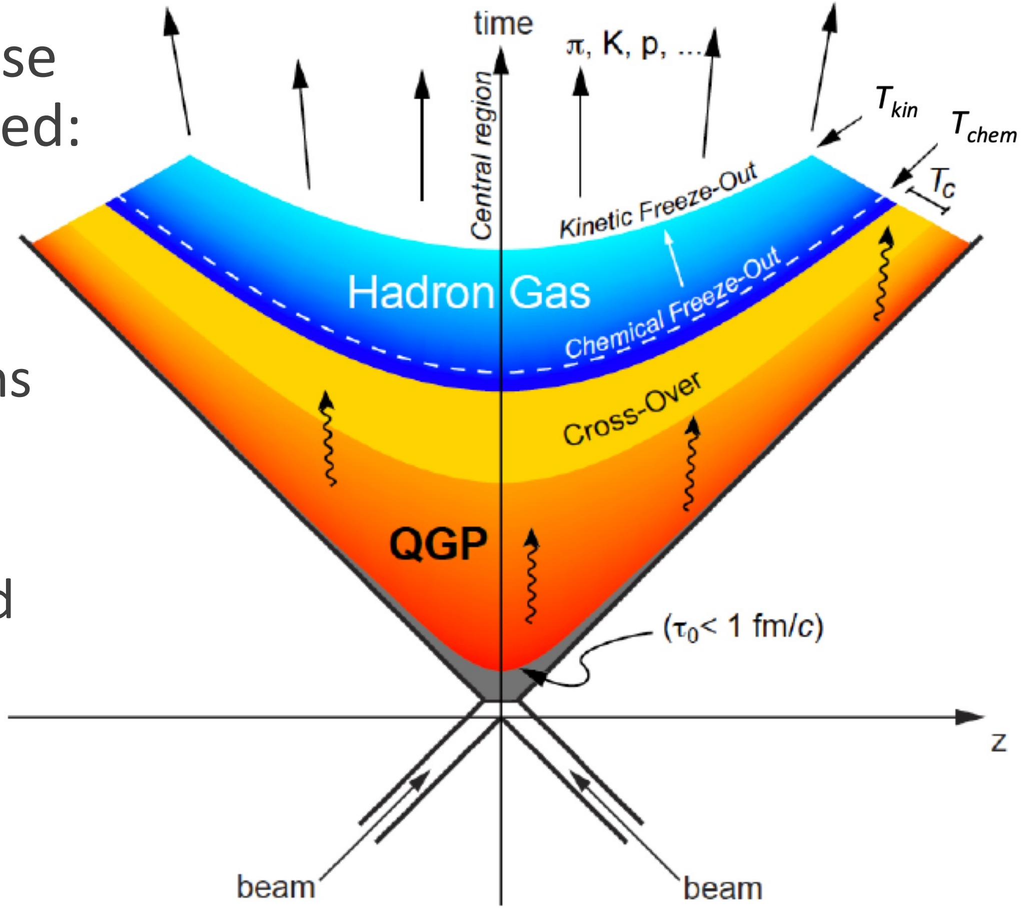
FOR THE ALICE COLLABORATION

GOETHE UNIVERSITY FRANKFURT

38TH WINTER WORKSHOP ON NUCLEAR DYNAMICS, PUERTO VALLARTA

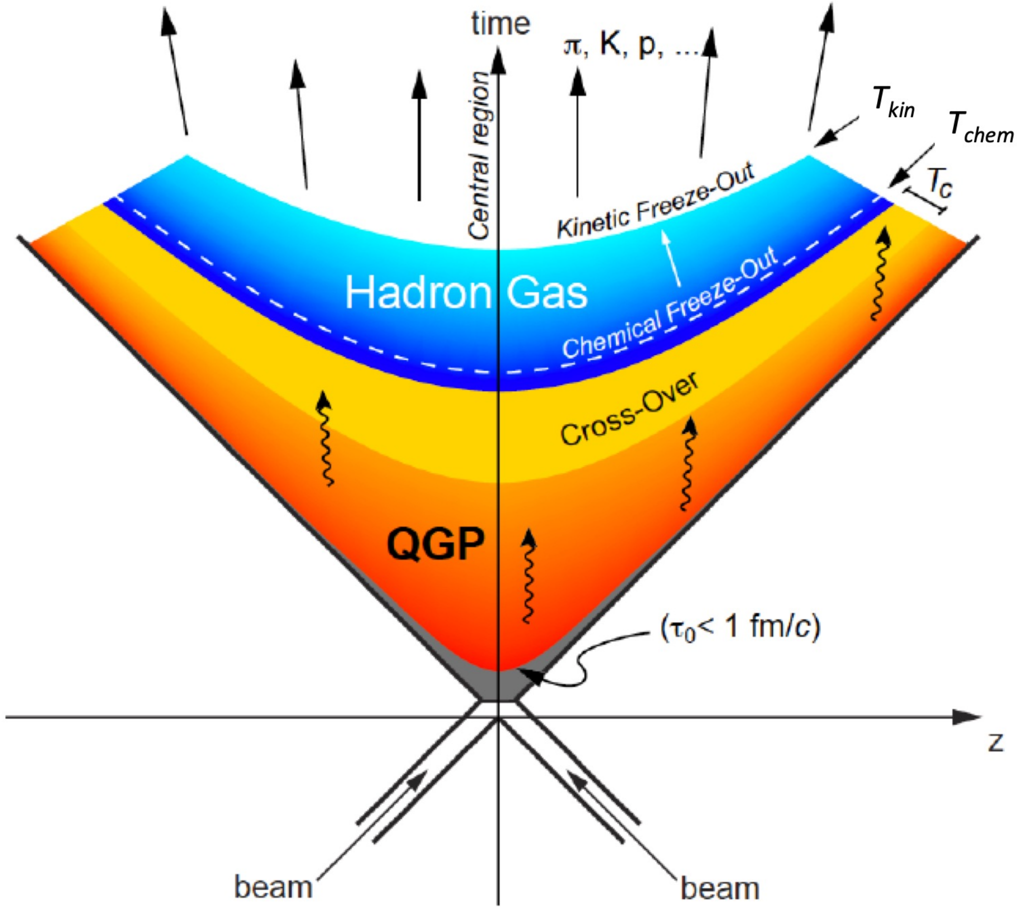
Nuclear matter production

- In high-energy hadronic collisions a deconfined phase of strongly interacting matter in equilibrium is created: quark-gluon plasma (QGP)
- The system expands and cools down
  - → When $T < T_C$: Transition to a gas of interacting hadrons and resonances
  - → Chemical freeze-out temperature T_{ch} (~155 MeV): Inelastic interactions stop and hadron yields are fixed
  - → Kinetic freeze-out temperature T_{kin} (~110 MeV): Elastic interactions stop and particle momentum distributions are fixed



Nuclear matter production

- Light (anti)(hyper)nuclei are abundantly produced at the LHC in pp, p—Pb and Pb—Pb collisions
- The production mechanism in high-energy physics is still not completely understood
- Two classes of models on the market to describe nuclei production:
  → Statistical hadronization model (SHM)
    T_{ch} relevant
    production scales with particle mass
  → Coalescence model (CM)
    production rates driven by the ratio between the particle radius and the system size

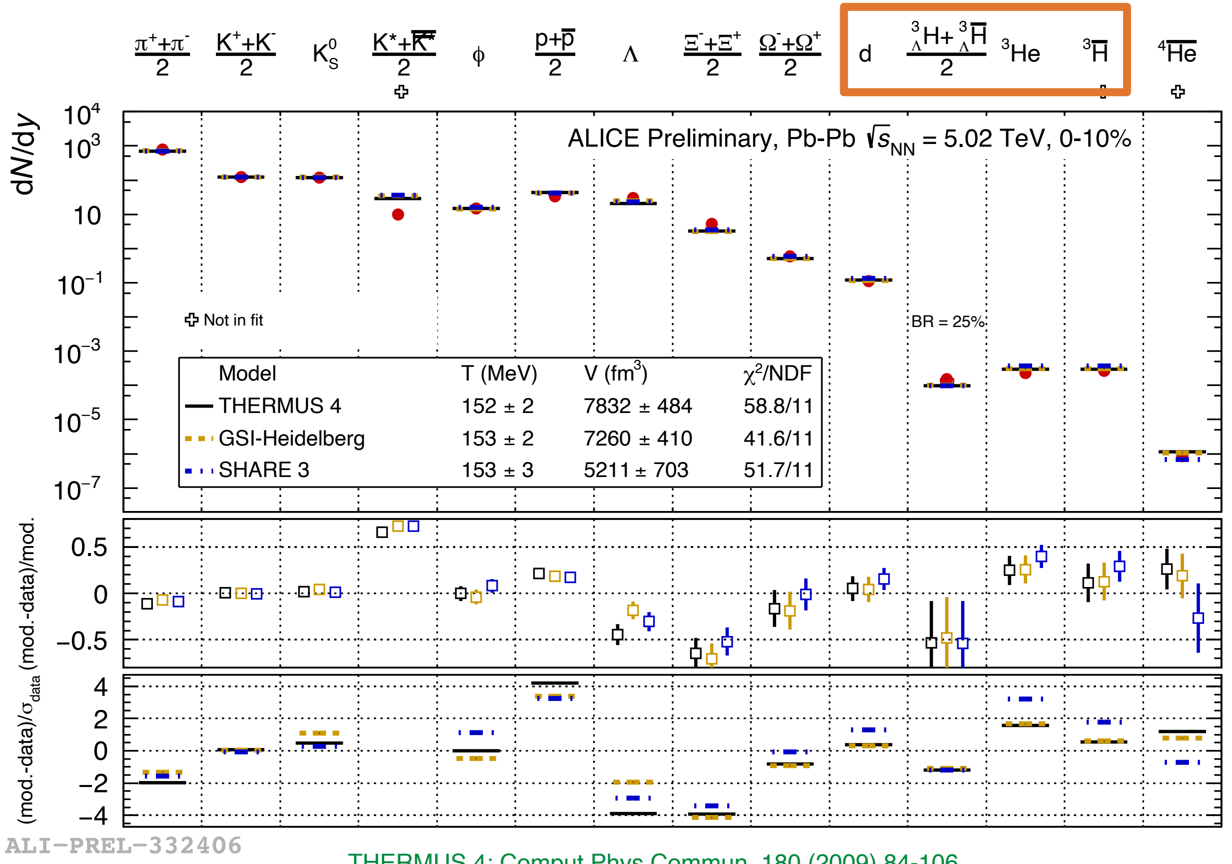


Statistical hadronization

- In Pb–Pb collisions the system can be described by a **grand canonical ensemble** with three free parameters (μ_B, V and T_{ch})
  - → Quantum numbers are conserved on average
- ALICE Pb–Pb data compared to Statistical Hadronization Model predictions
  - →Very good agreement
- In small systems a **canonical ensemble** (CSM) has to be applied (free parameters N, V, T_{ch})
  - → Quantum numbers are conserved exactly

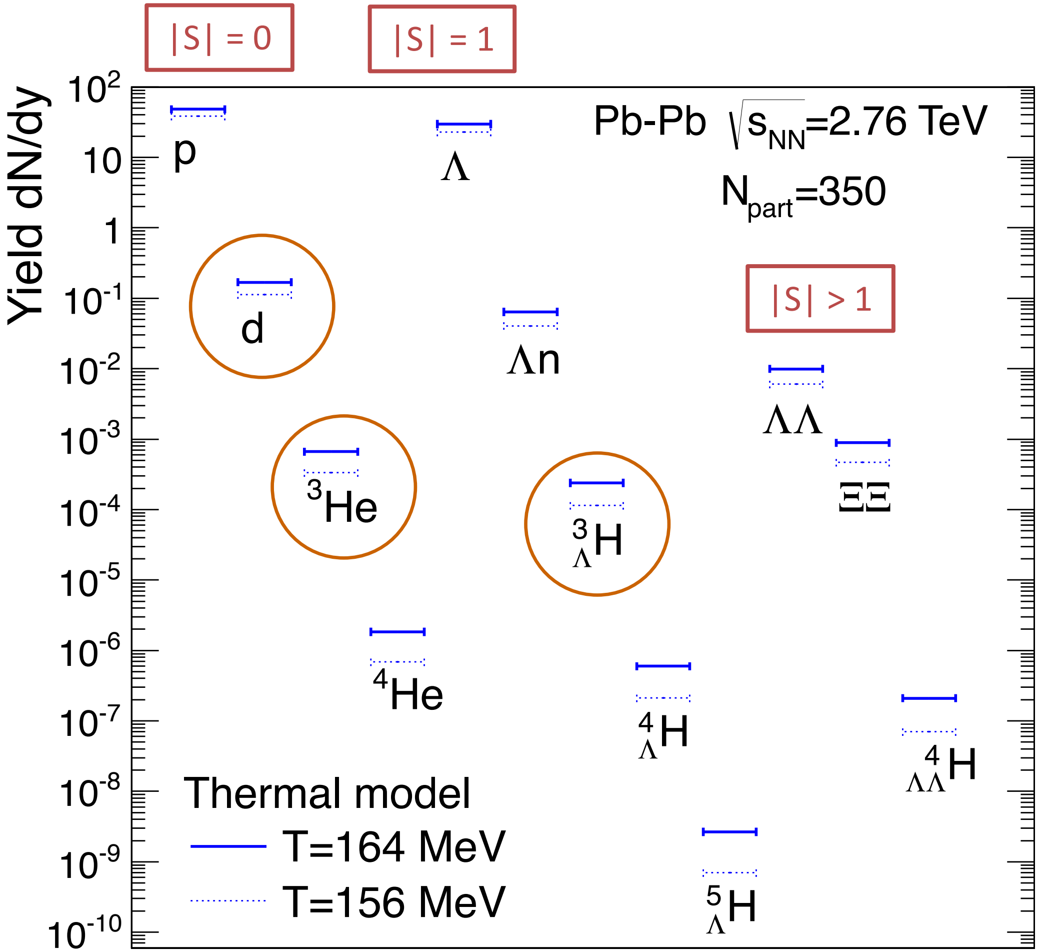
V. Vovchenko, B. Dönigus, and H. Stoecker, Phys. Rev. C 100 (2019) 054906

- Particles and antiparticles are produced equally at the LHC ($\mu_B \approx 0$)



THERMUS 4: Comput.Phys.Commun. 180 (2009) 84-106
GSI-Heidelberg: Nucl.Phys. A (2006) 167-199
SHARE 3: Comput.Phys.Commun. 167 (2005) 229-251

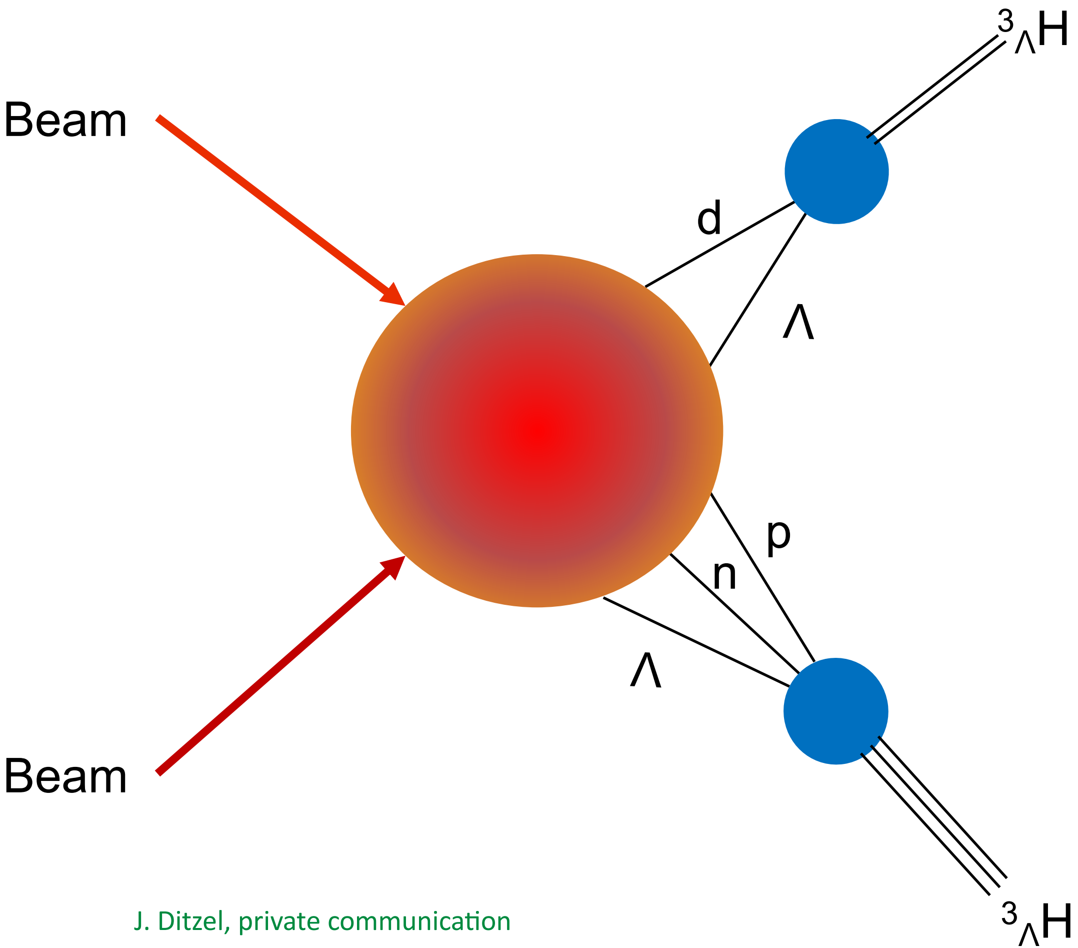
Production of light (hyper)nuclei



A. Andronic, private communication, model based on:
Phys. Lett. B 697 (2011) 203

- Abundance of nuclei strongly sensitive to chemical freeze-out temperature T_{ch}, due to
  - → Large mass
  - → Exponential dependence of the yield ~ $e^{(-m/T_{ch})}$
- Note: Binding energy of nuclei (few MeV) small compared to T_{ch}

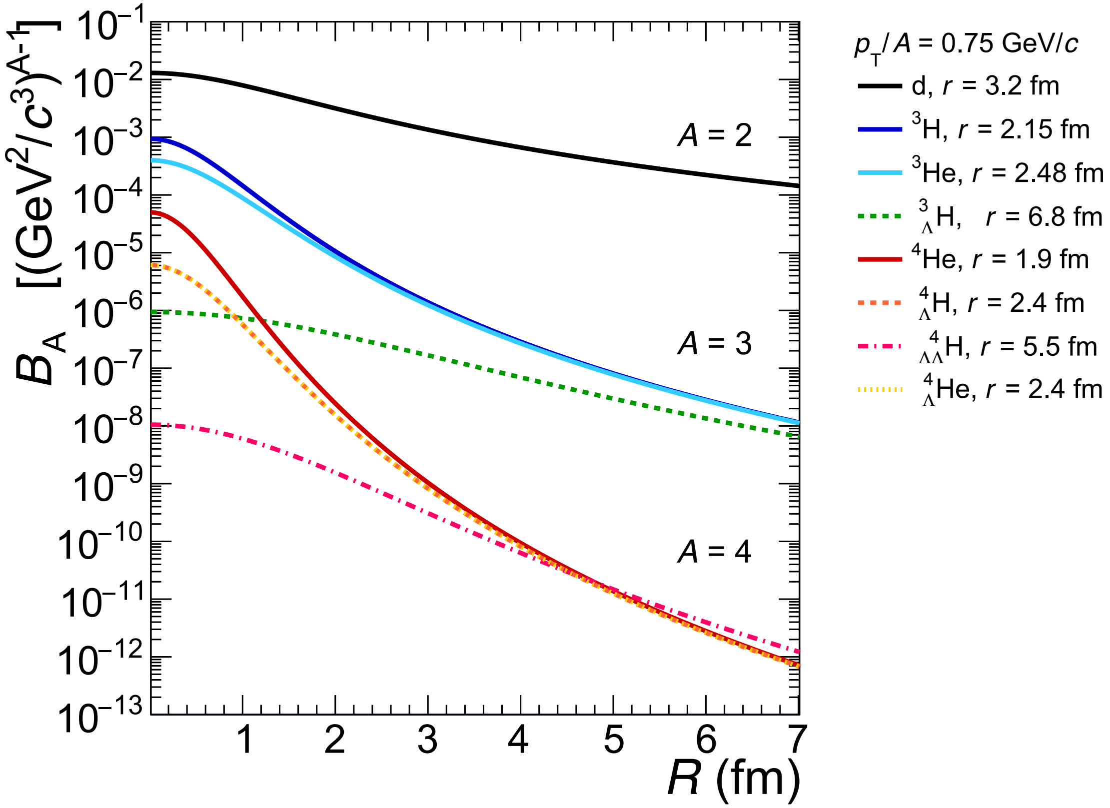
Coalescence model



J. Ditzel, private communication

- Nuclei are formed after kinetic freeze-out by protons and neutrons which are nearby in space and have similar velocities
  → Production rate is connected to the size of the bound state relative to the system size
- Advanced models use quantum mechanics
  → Wave functions of the constituents have to overlap with the nuclear wave function
  → Wigner formalism is used
- Differentiation between two-body and three-body coalescence

Coalescence parameter



F. Bellini, and A. Kalweit, Acta Phys. Pol. B 50 (2019) 991

- Main parameter of the coalescence model B_A:

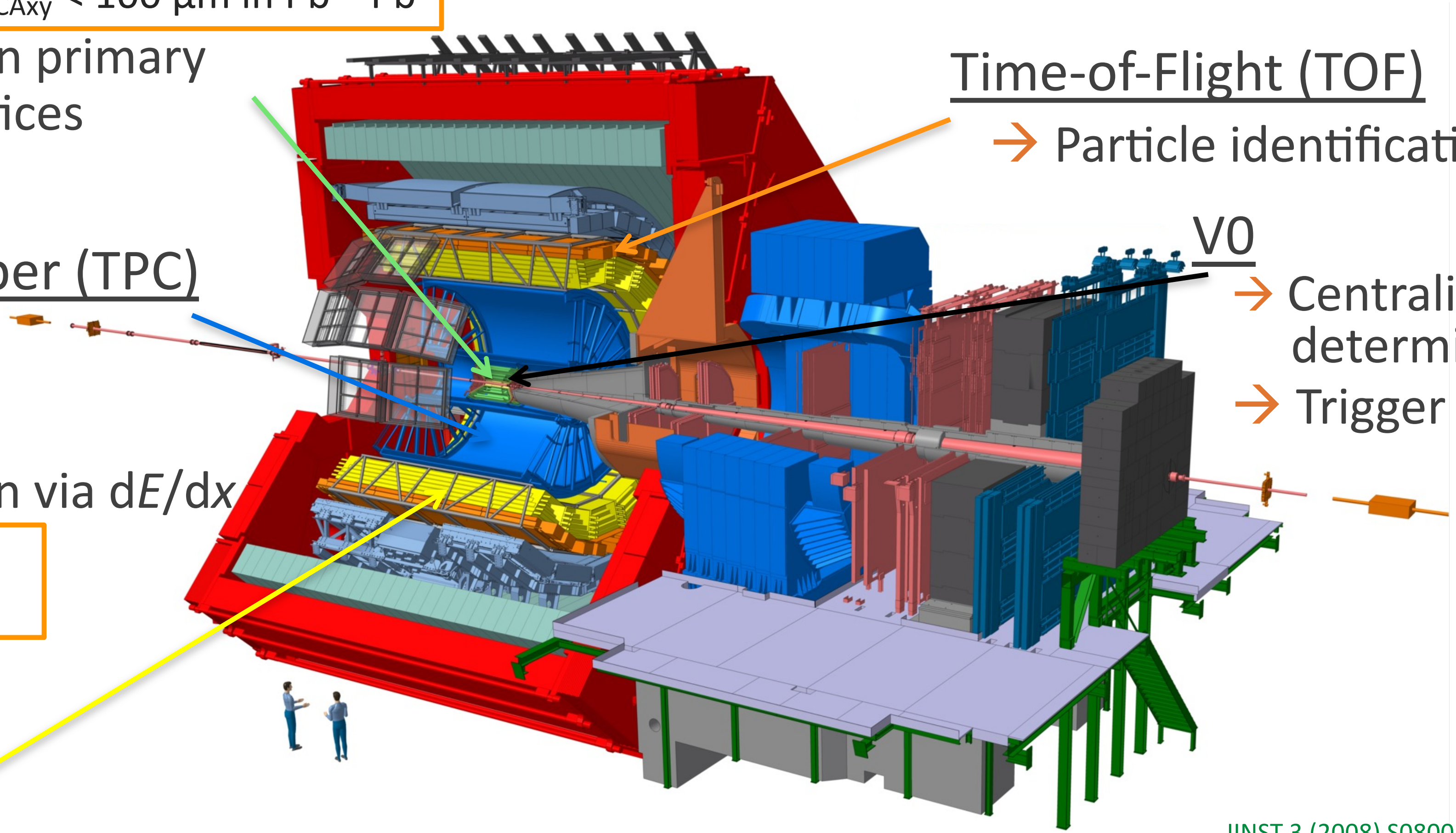
$$B_A = \frac{E_A \frac{d^3N_A}{d^3p_A}}{\left(E_p \frac{d^3N_p}{d^3p_p}\right)^A}$$

A: mass number of nucleus

$p_p = p_A/A$

- B_A is related to the probability to form a nucleus via coalescence

ALICE detector setup



Inner Tracking System (ITS)

- → Vertexing
- → Separation between primary and secondary vertices
- → Tracking

$\sigma_{\mathrm{DCA}xy} < 100\ \mu\mathrm{m}$ in Pb—Pb

Time Projection Chamber (TPC)

- → Tracking
- → Vertexing
- → Particle identification via dE/dx

$$\frac{\sigma(\mathrm{d}E/\mathrm{d}x)}{\mathrm{d}E/\mathrm{d}x} \approx 6\ \%$$

Transition Radiation Detector (TRD)

- → Tracking

Time-of-Flight (TOF)

- → Particle identification

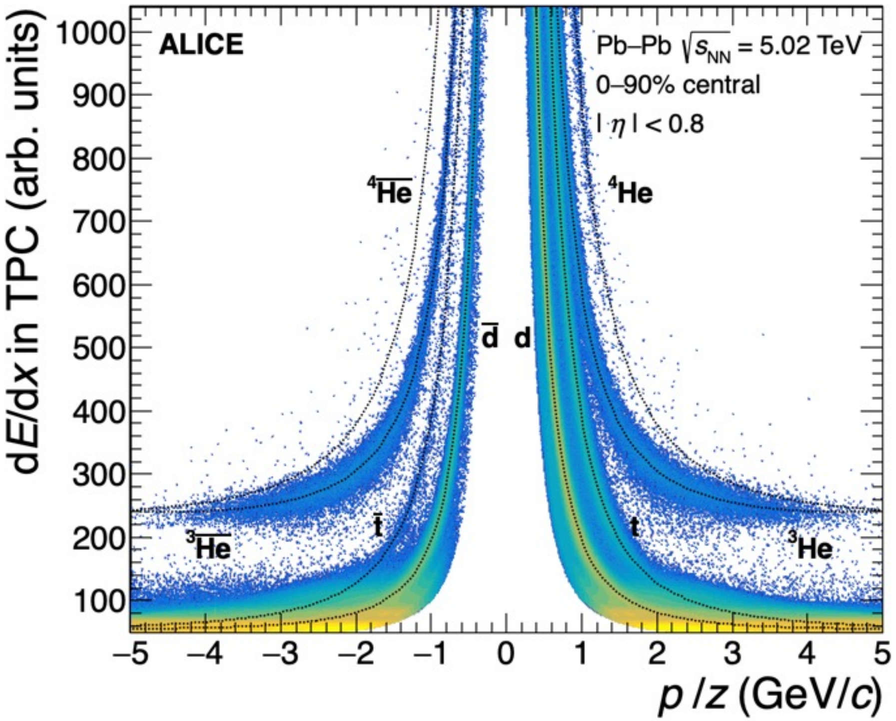
$\sigma_{\mathrm{TOF}} \approx 60$ ps in Pb—Pb

V0

- → Centrality/multiplicity determination
- → Trigger

JINST 3 (2008) S08002

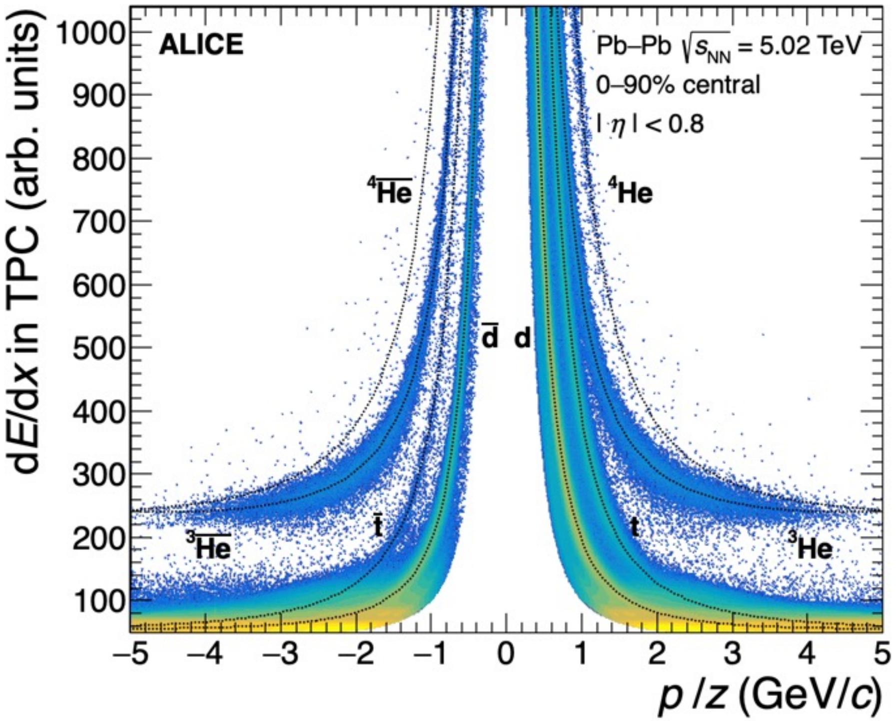
Nuclei identification



ALICE Collaboration, arXiv:2211.14015 [nucl-ex]

- Low momenta: TPC
  → Nuclei identified using the energy loss measurement

Nuclei identification



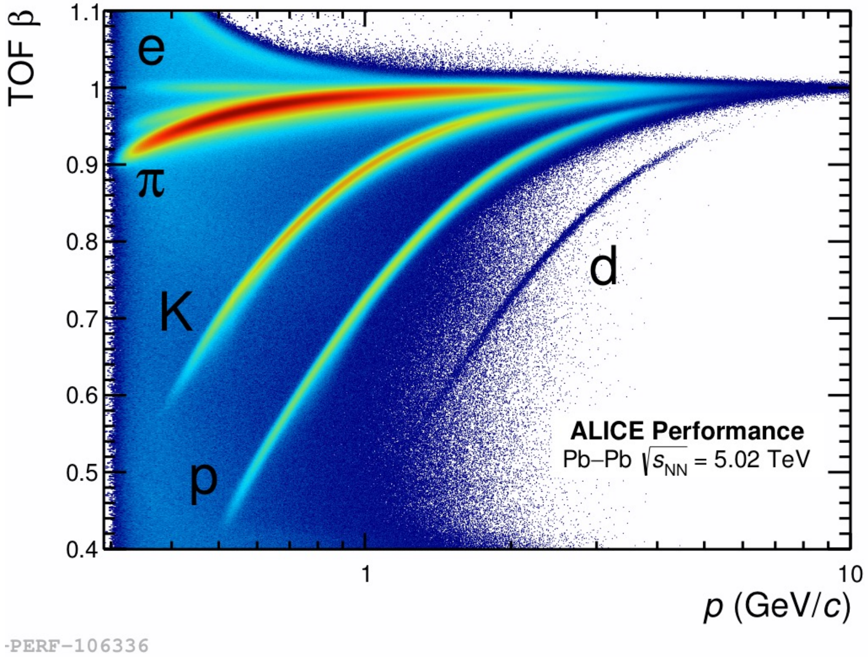
ALICE Collaboration, arXiv:2211.14015 [nucl-ex]

- Low momenta: TPC
  → Nuclei identified using the energy loss measurement
- Momentum determined from track curvature

$$\frac{p}{z} = r\,B$$

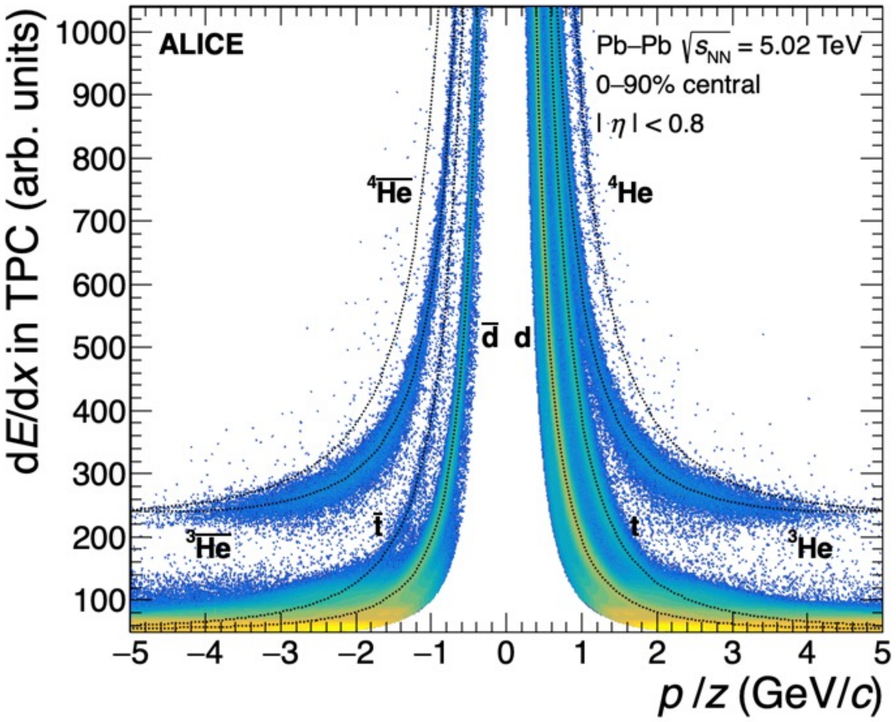
- High momenta: TOF

$$\beta = \frac{L}{t_{TOF}\,c}$$



Int. J. Mod. Phys. A 29 (2014) 1430044

Nuclei identification



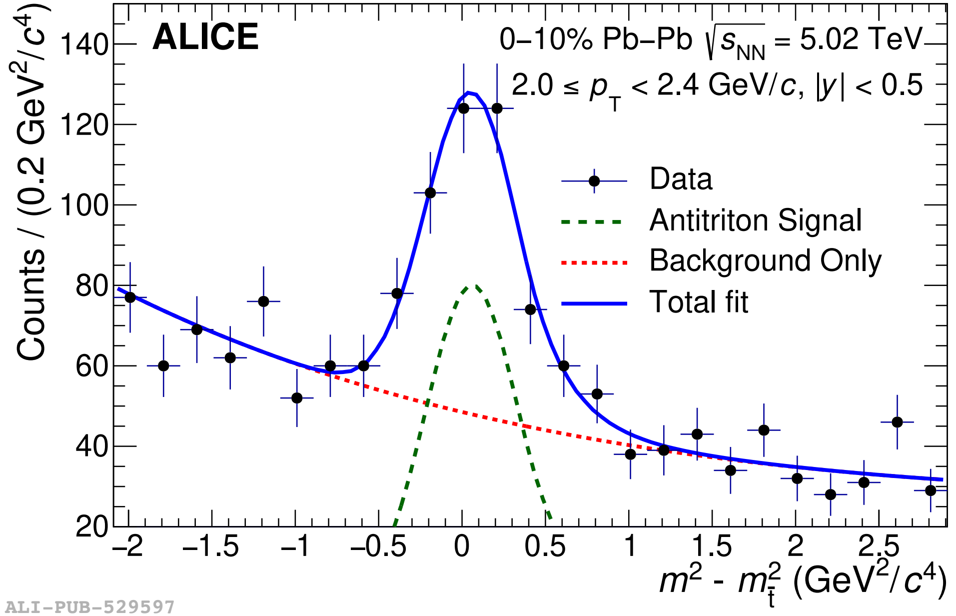
ALICE Collaboration, arXiv:2211.14015 [nucl-ex]

- Low momenta: TPC
  → Nuclei identified using the energy loss measurement
- Momentum determined from track curvature

$$\frac{p}{z} = rB$$

- High momenta: TOF
  → m^2 distribution is calculated from the time-of-flight measurement

$$m^2 = \frac{(1-\beta^2)}{\beta^2}p^2$$



ALICE Collaboration, arXiv:2211.14015 [nucl-ex]

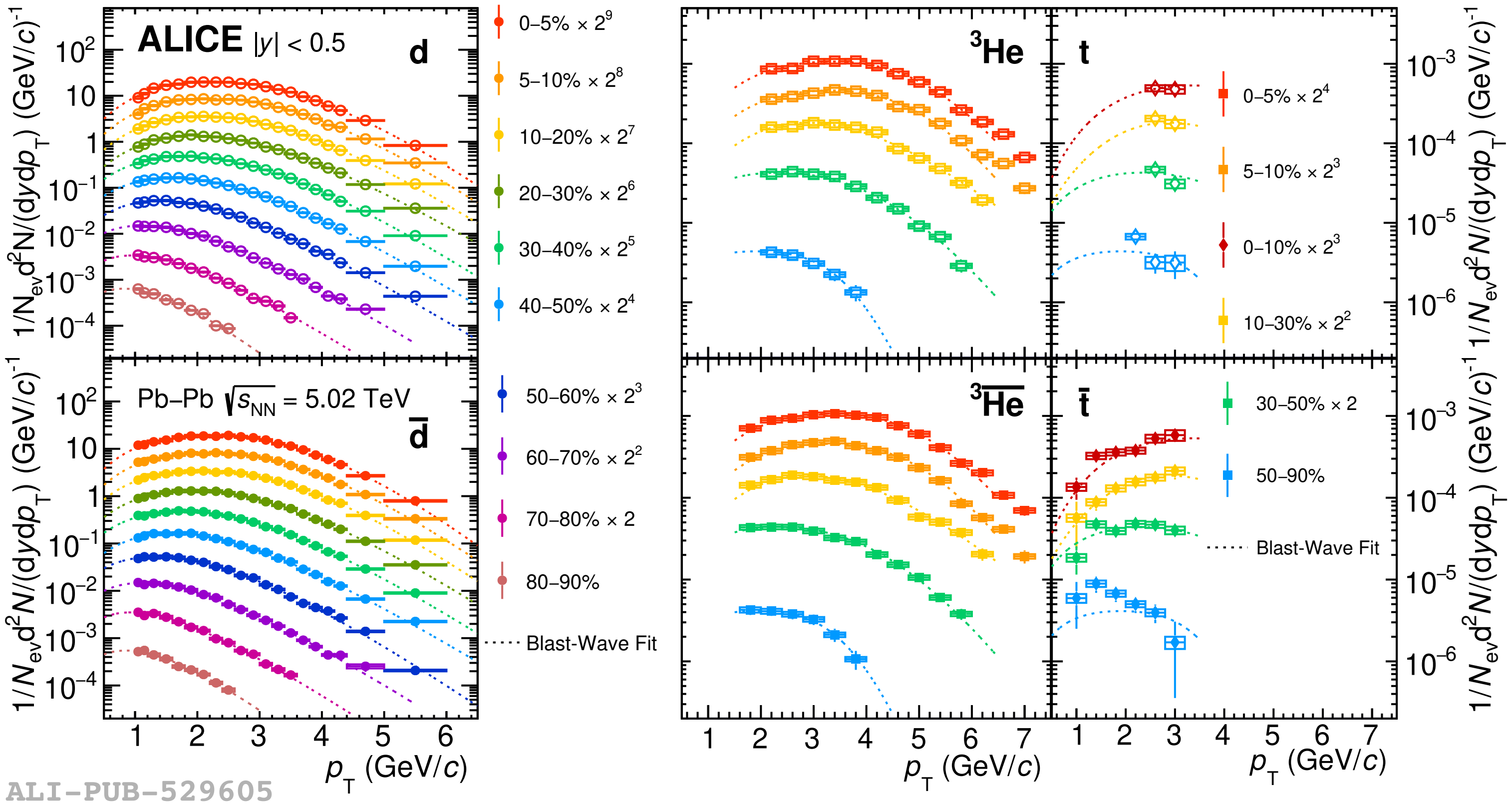
Nuclei p_{T} spectra in Pb—Pb at $\sqrt{s_{\mathrm{NN}}}$=5 TeV

A=2

A=3

nuclei

antinuclei

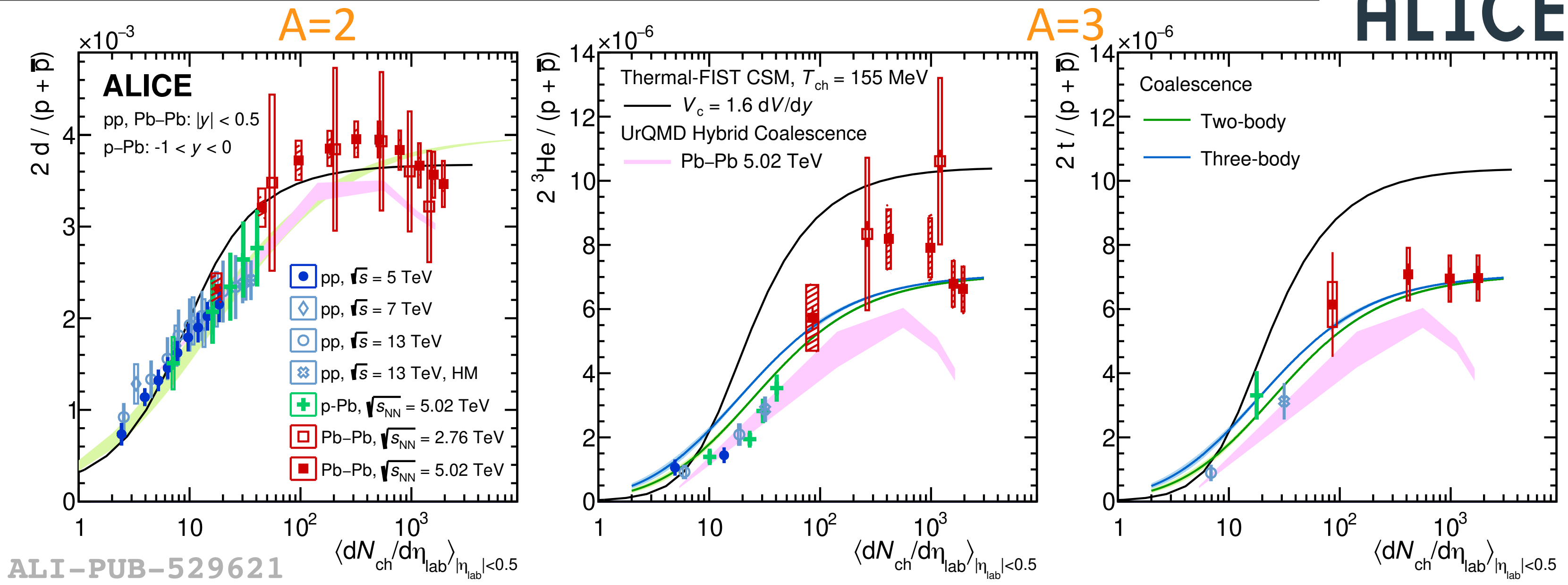


ALICE Collaboration, arXiv:2211.14015 [nucl-ex]

- A=2 and A=3 (anti)nuclei measured in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5 TeV in different centrality intervals.
- Nuclei and antinuclei compatible
- Hardening of the spectra
  →Average p_{T} nearly doubling going from peripheral to central collisions
- Production yields (dN/dy) extracted by integrating the spectra and extrapolating to zero and high p_{T} through a fit with a Blast-Wave function

Nuclei over proton ratio

- Clear increasing trend from pp to p–Pb and saturation in Pb–Pb collisions can be observed
- Data compared to CSM, Coalescence and UrQMD Hybrid Coalescence models
- All three models describe the data qualitatively but have problems describing it quantitatively



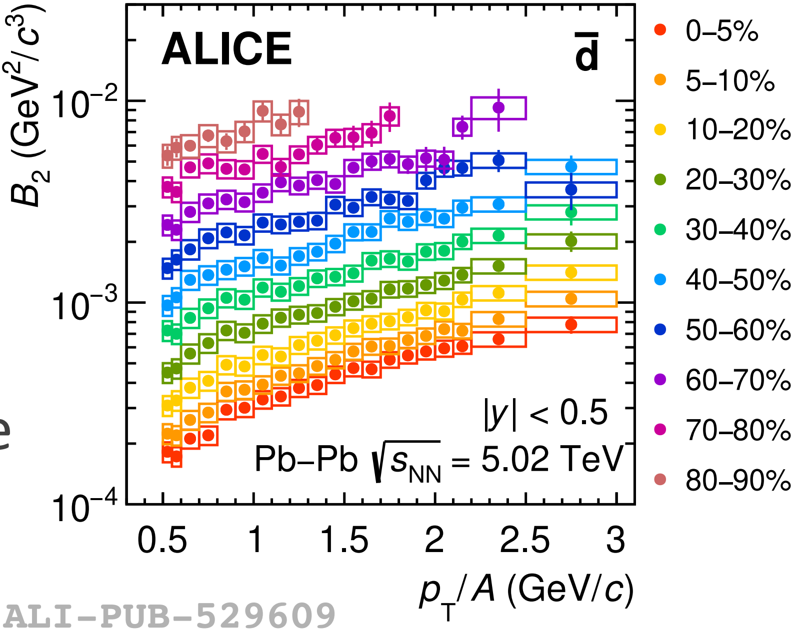
ALICE Collaboration, arXiv:2211.14015 [nucl-ex]
CSM: V. Vovchenko, B. Dönigus, and H. Stoecker, Phys. Lett. B 785 (2018) 171–174, arXiv:1808.05245 [hep-ph]
Coalescence: K.-J. Sun, C. M. Ko, and B. Dönigus, , Phys. Lett. B 792 (2019) 132–137, arXiv:1812.05175 [nucl-th]
UrQMD: T. Reichert, J. Steinheimer, V. Vovchenko, B. Dönigus, and M. Bleicher, Phys. Rev. C 107 (2023) 014912, arXiv:2210.11876 [nucl-th]

- For deuterons all models do rather good, for A=3 (in particular for tritons) coalescence is closer to the data with respect to the SHM

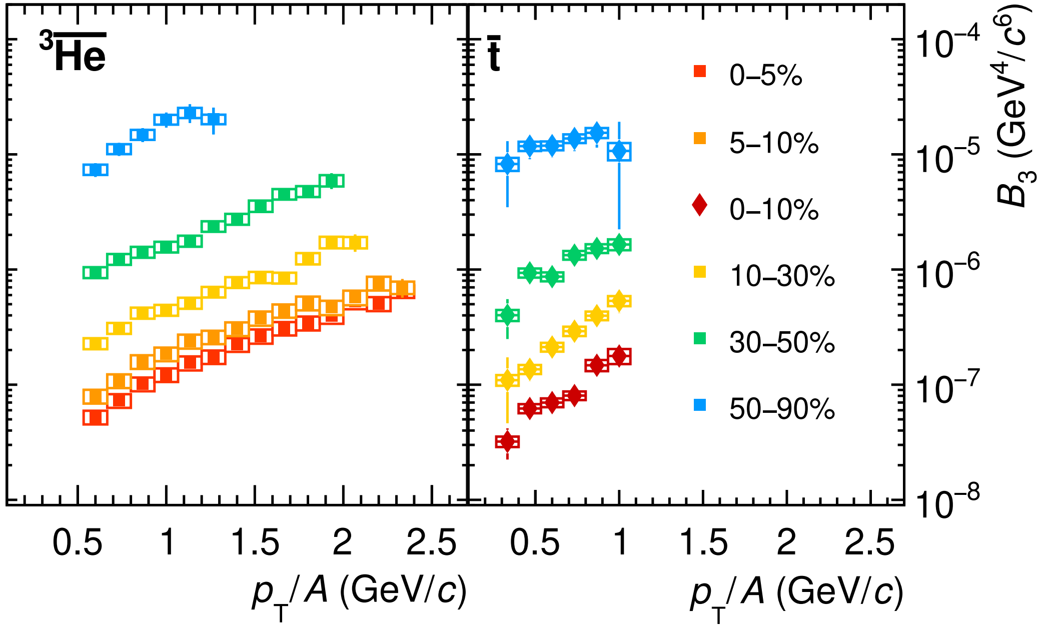
Coalescence parameters B_2 and B_3

- B_A is larger for peripheral collisions where the system size and thus the configuration space is smaller
- In Pb–Pb collisions a rise of B_A with p_T is observed
  → For high p_T particles the configuration space becomes smaller

A=2



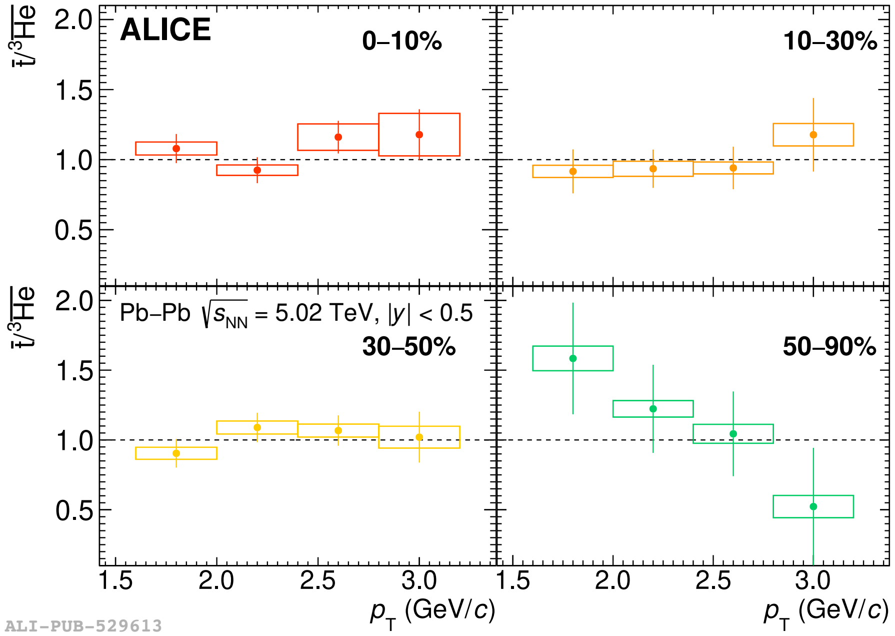
A=3



ALICE Collaboration, arXiv:2211.14015 [nucl-ex]

- Moving from central to more peripheral collisions (i.e. towards lower multiplicities) the rise in p_T becomes milder

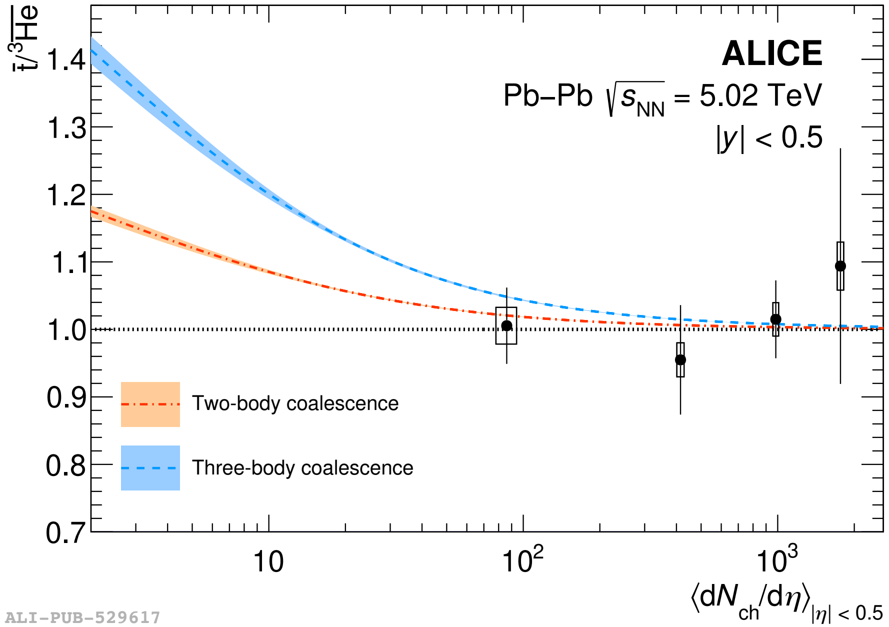
$\bar{t}$ over $^3\overline{\text{He}}$ ratio



ALICE Collaboration, arXiv:2211.14015 [nucl-ex]

Coalescence: K.-J. Sun, C. M. Ko, and B. Dönigus, Phys. Lett. B 792 (2019) 132–137, arXiv:1812.05175 [nucl-th]

- Ratio of transverse momentum spectra of $\bar{t}$ and $^3\overline{\text{He}}$ in different centrality intervals in Pb—Pb collisions
- Flat in p_T and within uncertainties compatible with unity



- Average $\bar{t}$ over $^3\overline{\text{He}}$ ratio versus multiplicity compared to two-body and three-body coal.
- SHM expectation of this ratio is close to unity, while CM expects a ratio larger than one at low multiplicities due to the different nuclei radii
  → will be addressed with high precision in Run 3

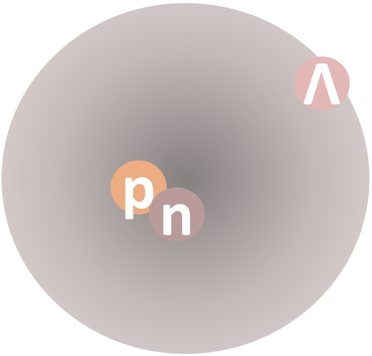
Hypertriton

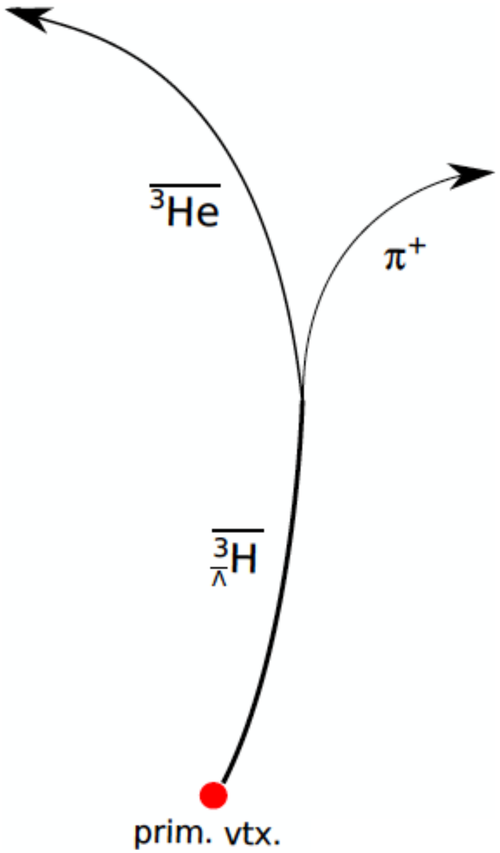
- Bound state of Λ, p and n
- Lightest bound hypernucleus ($m \approx 2.991$ GeV/c^2) and very low Λ separation energy (≈ 130 keV)
- Recent calculations predict a large radius for the hypertriton wave function $r_{\Lambda\text{-d}} = 10.79^{+3.04}_{-1.53}$ fm

F. Hildebrand, H.-W. Hammer, Phys. Rev. C 100 (2019) 034002 , arXiv:1904.05818[nucl-th]

- Hypertriton decays weakly after a few cm
- Decay modes:

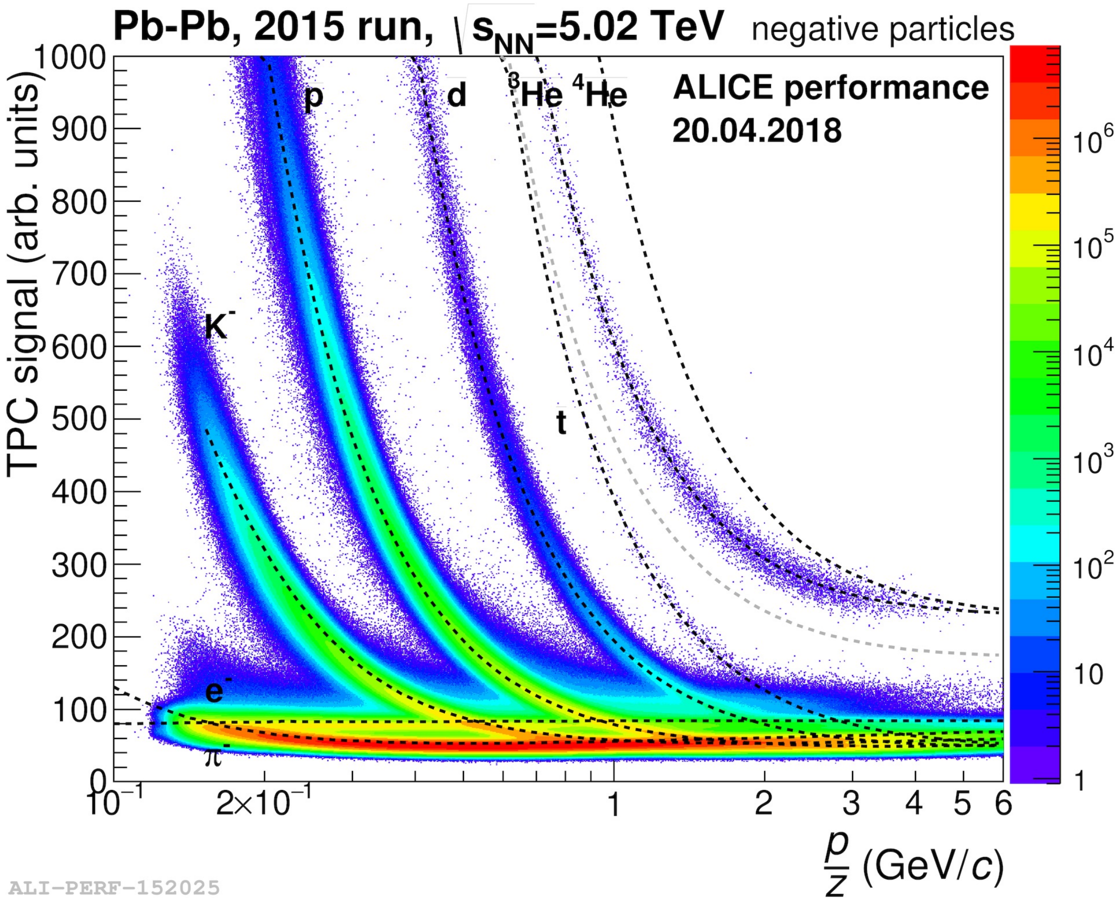
${}^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi^{-}$ ${}^{3}_{\Lambda}\mathrm{H} \rightarrow d + p + \pi^{-}$ ${}^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{H} + \pi^{0}$ ${}^{3}_{\Lambda}\mathrm{H} \rightarrow d + n + \pi^{0}$





Hypertriton reconstruction

- Step 1: find and identify the daughter particle tracks
  - →Using TPC PID via the specific energy loss
  - →Excellent separation of different particle species



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Hypertriton reconstruction

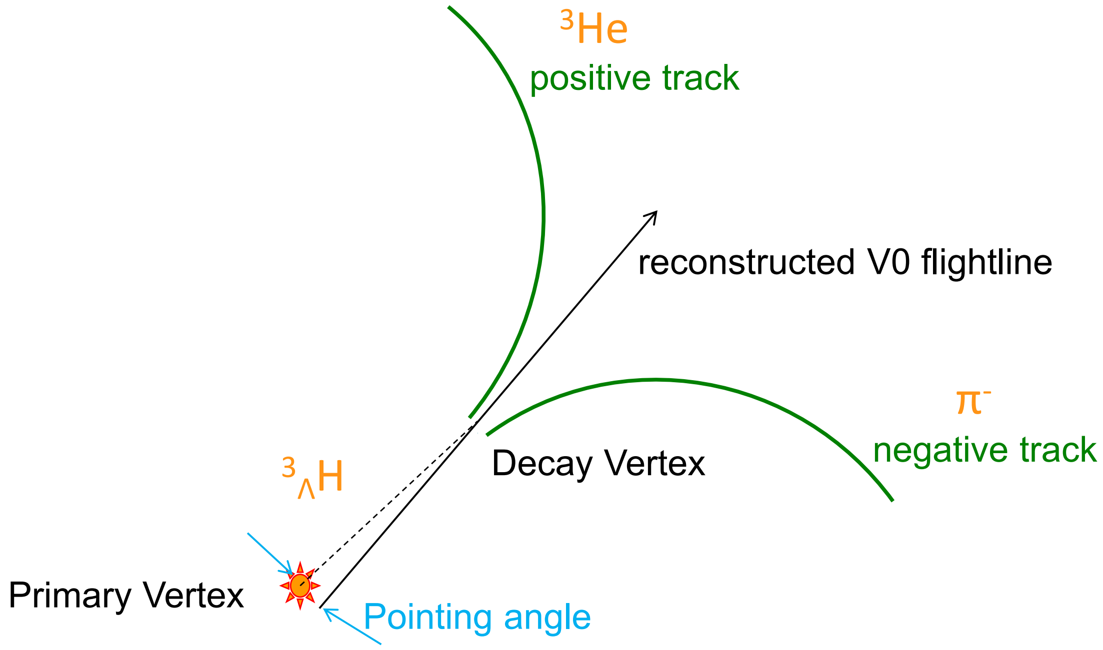
- Step 1: find and identify the daughter
  particle tracks
- Step 2: reconstruct the decay vertex
  of the hypertriton

→ The identified daughters are assumed to come from a common vertex

→ Their tracks are matched by algorithms to find the best possible decay vertex

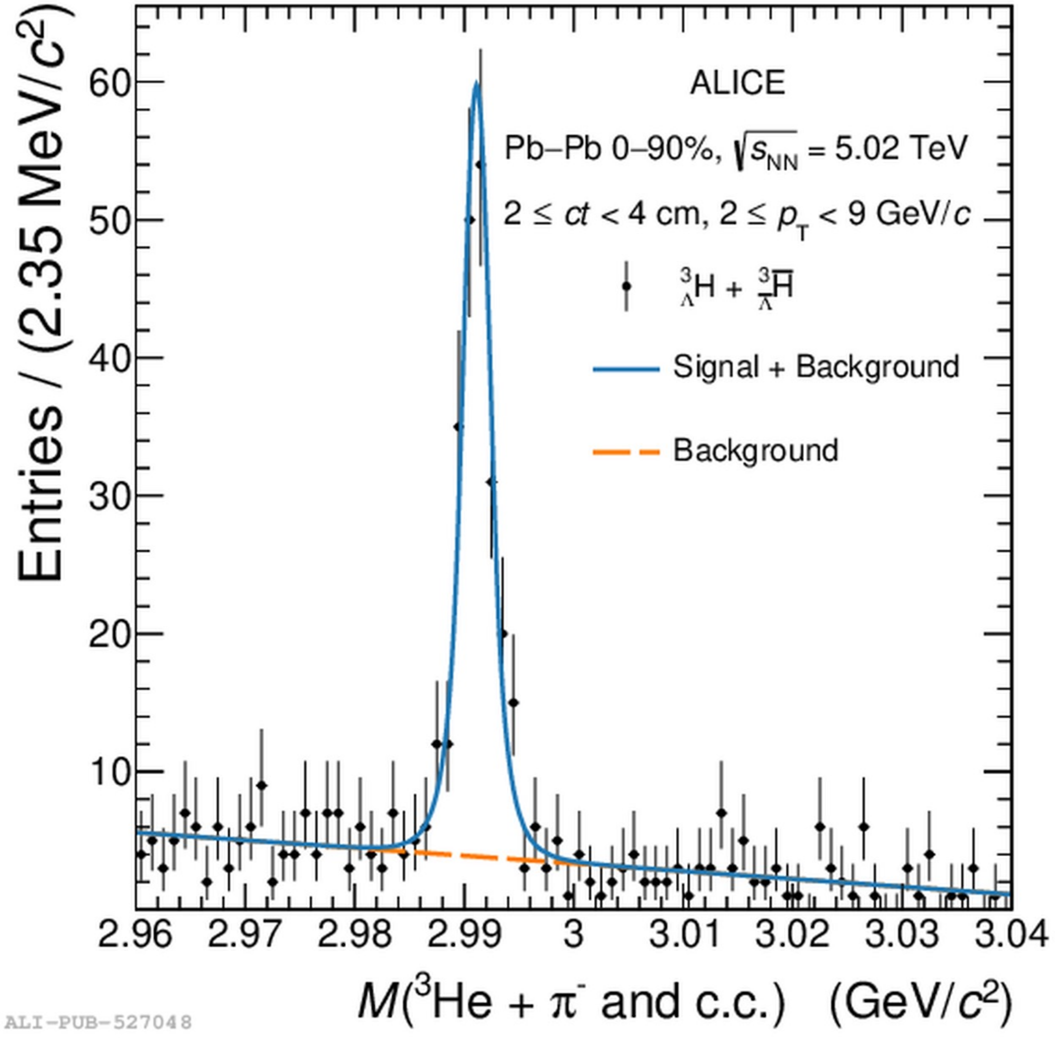
→ Problem: huge combinatorial background

→ Solution: topological and kinematical cuts
or machine learning approach



Hypertriton in Pb—Pb collisions

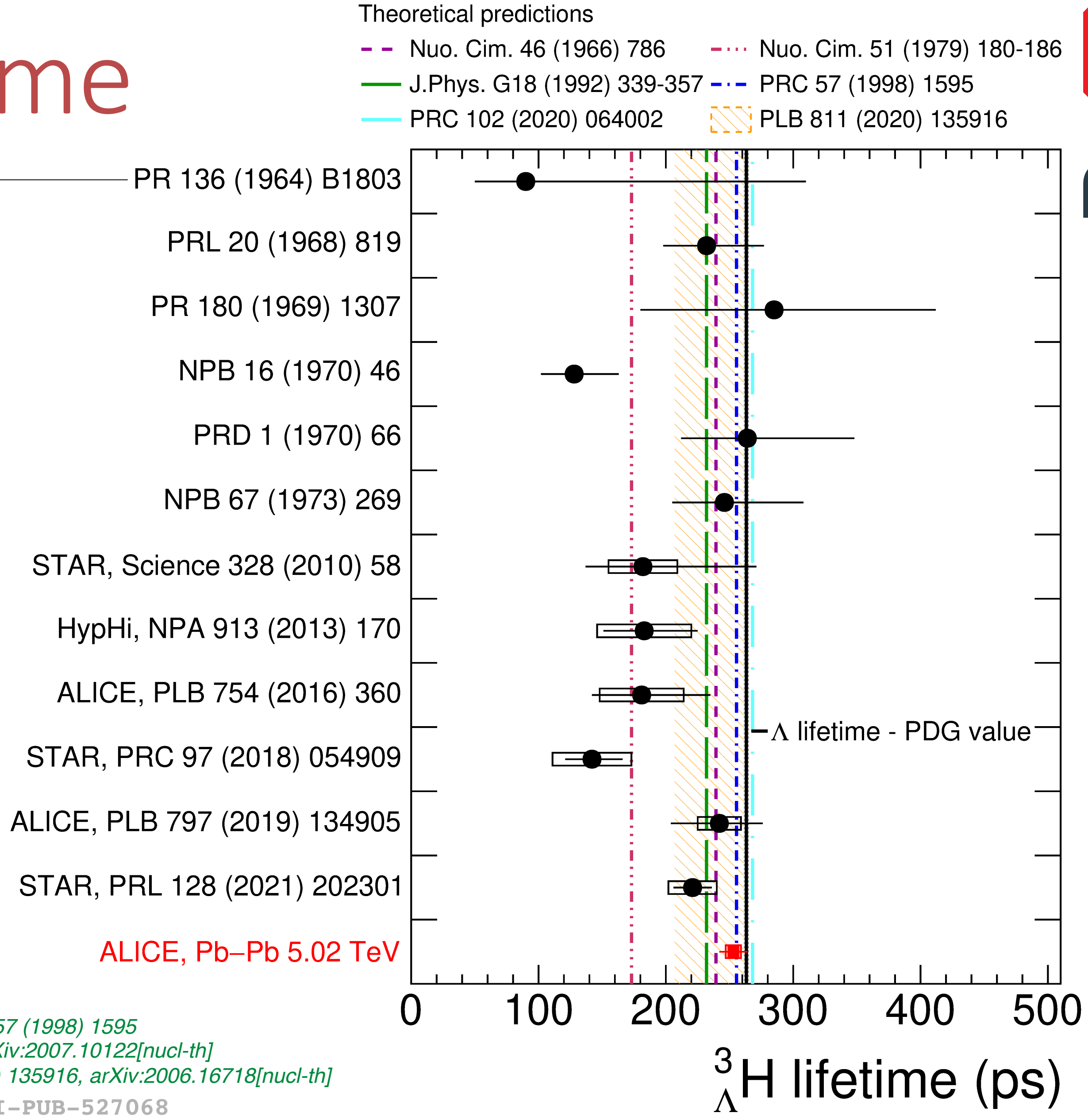
- Recent measurement in Run 2 Pb—Pb collisions at 5.02 TeV
- Signal extraction by using a machine learning approach
- Using a boosted decision tree (BDT) and hyper parameter optimisation



ALICE Collaboration, arXiv:2209.07360 [nucl-ex]

Hypertriton lifetime

- Hypertriton lifetime is compatible with the free Λ lifetime within its uncertainties
  - → Supports a very loosely-bound state
- New result increased the world average lifetime value

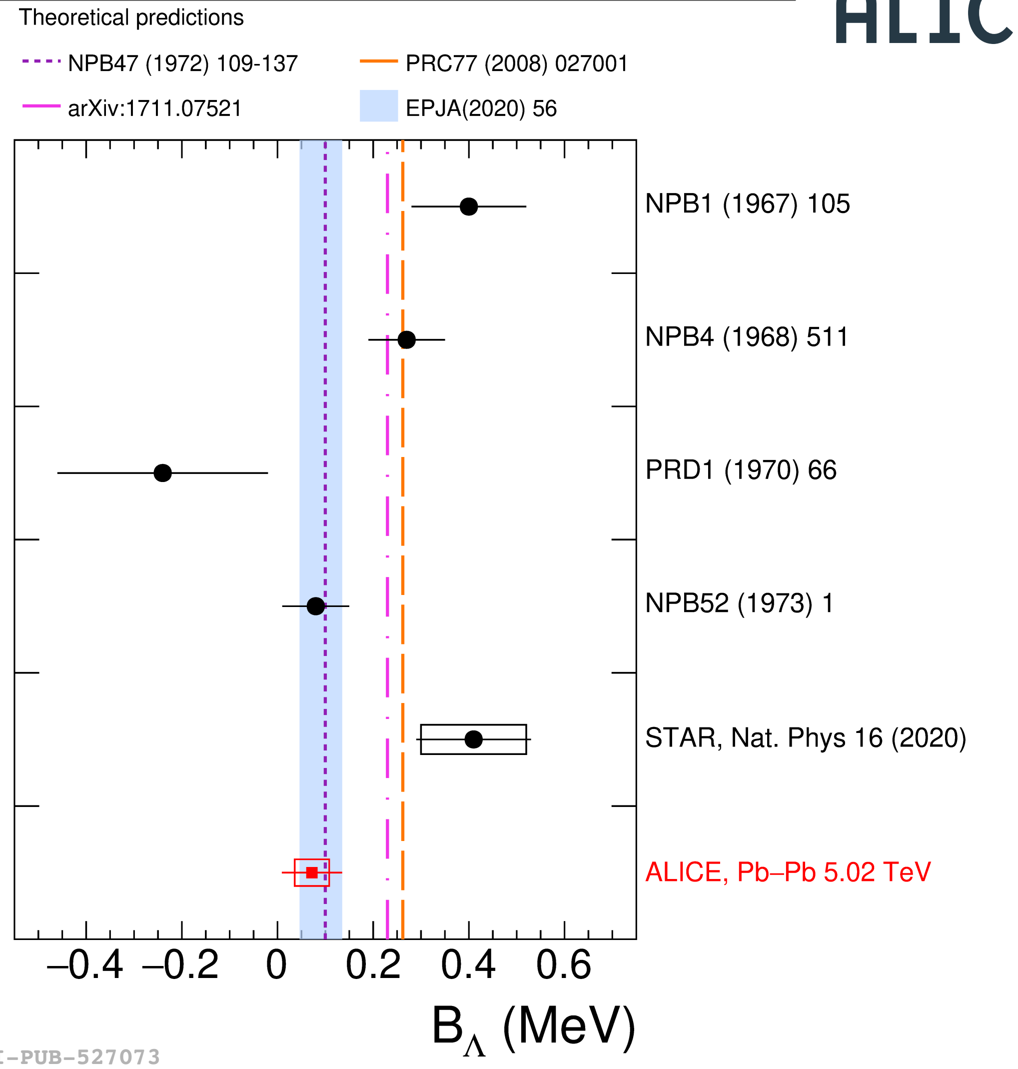


ALI-PUB-527068

ALICE Collaboration, arXiv:2209.07360 [nucl-ex]
[Nuo. Cim. 46 (1966) 786] *M. Rayet, and R. H. Dalitz, Nuovo Cim. A46 (1966) 786-794*
[Nuo. Cim. 51 (1979) 180-186] *H. M. M. Mansour, and K. Higgins, Nuovo Cim. A51 (1979) 180-186*
[J.Phys G18 (1992) 339-357] *J. G. Congleton, J. Phys. G 18 (1992) 339-357*
[PRC 57(1998) 1595] *H. Kamada, J. Golak, K. Miyagawa, H. Witała, and W. Glöckle, Phys. Rev. C 57 (1998) 1595*
[PRC 102 (2020) 064002] *F. Hildenbrand and H.-W. Hammer, Phys. Rev. C 102 (2020) 064002, arXiv:2007.10122[nucl-th]*
[PLB 811 (2020) 135916] *A.Pérez-Obiol, D.Gazda, E.Friedman, and A Gal, Phys. Lett. B 811 (2020) 135916, arXiv:2006.16718[nucl-th]*

Hypertriton binding energy

- ALICE measurement of the hypertriton binding energy is compatible with the latest theoretical predictions.



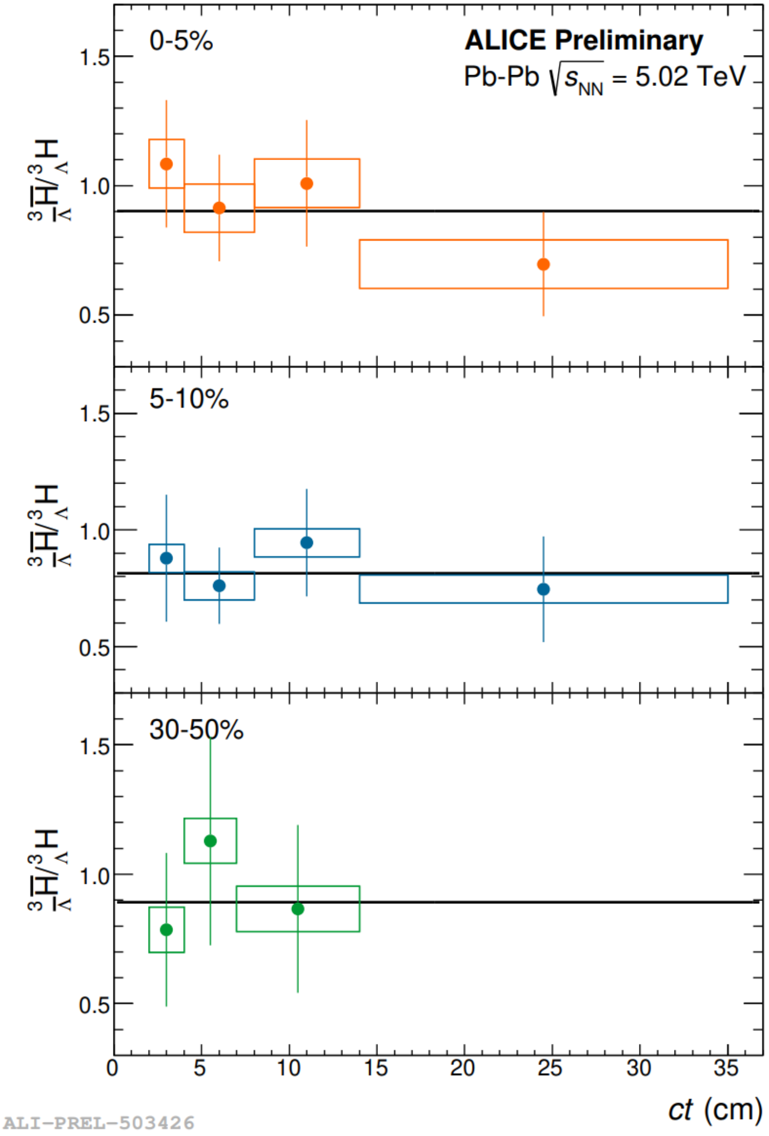
ALICE Collaboration, arXiv:2209.07360 [nucl-ex]
[NPB47(1972)] *R.H. Dalitz, R.C. Herndon, Y.C. Tang, Nuclear Physics B 47 (1972) 109-137*
[arXiv:1711.07521] *D. Lonardoni, and F. Pederiva, arXiv:1711.07521 [nucl-th]*
[PRC77(2008)] *Y. Fujiwara, Y. Suzuki, M. Kohno, and K. Miyagawa., Phys. Rev. C 77 (2008) 027001*
[EPJA(2020) 56] *F. Hildenbrand and H.-W. Hammer, Phys. Rev. C 100 (2019) 034002, arXiv:1904.05818[nucl-th]*

Hypertriton production

- Determination of the baryochemical potential including the hypertriton in different centrality intervals
- Using antiparticle to particle ratios as input
- Nuclei lead to higher sensitivity due to larger amount of baryons

$$\overline{h}/h \propto \exp\left[-2\left(B+\frac{S}{3}\right)\frac{\mu_B}{T} - 2I_3\frac{\mu_{I_3}}{T}\right]$$

Pb—Pb
$\sqrt{s_{NN}}$ = 5.02 TeV



0-5%

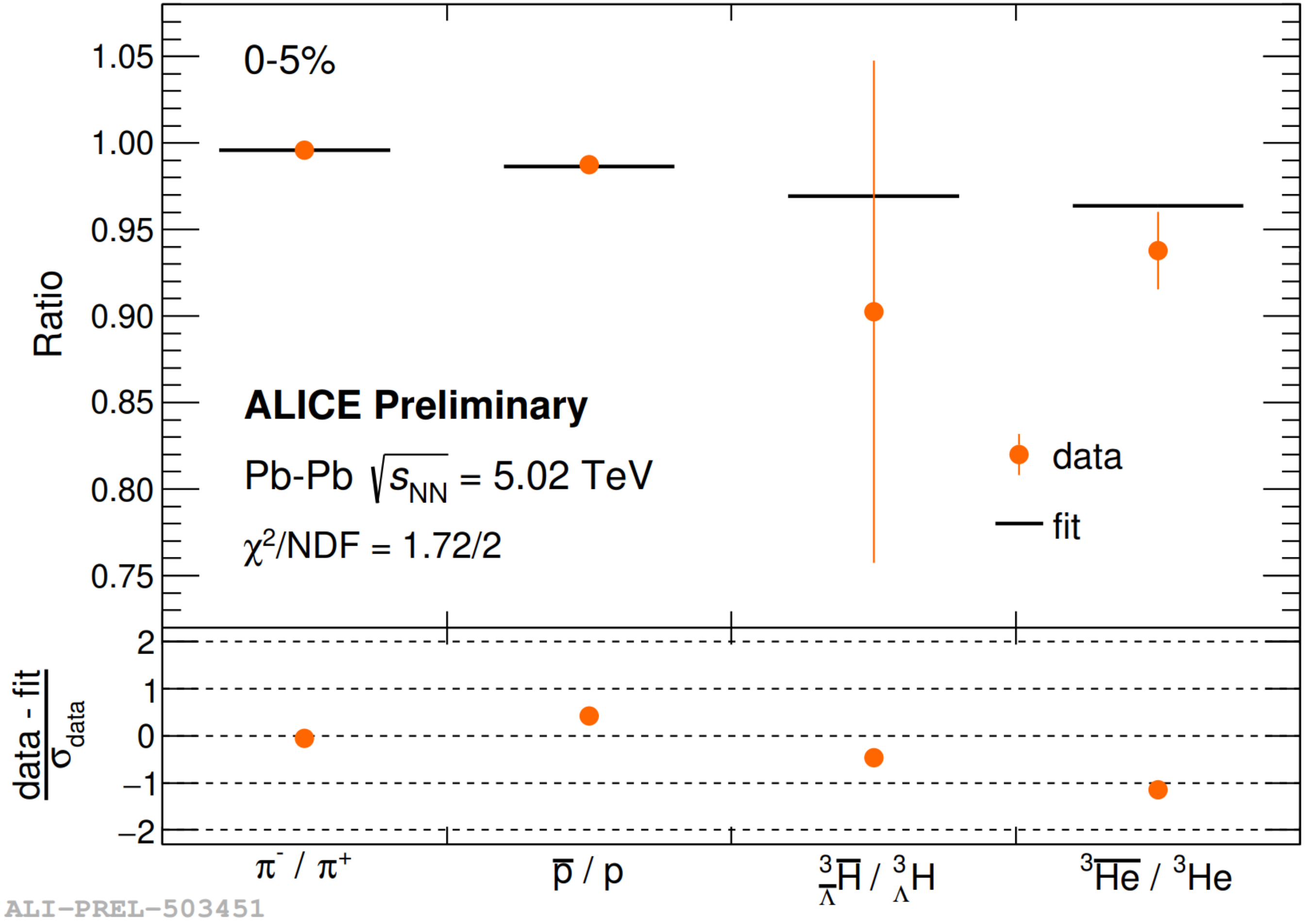
5-10%

30-50%

Hypertriton production

- Fit to the data provides a value of μ_B close to zero in the most central collisions
- Antiparticle-to-particle ratio compared to SHM predictions at T_{ch} = 155 ± 2 MeV and using the obtained μ_B
- Very precise result even with large uncertainties for the hypertriton and a small overestimation for the ^{3}He

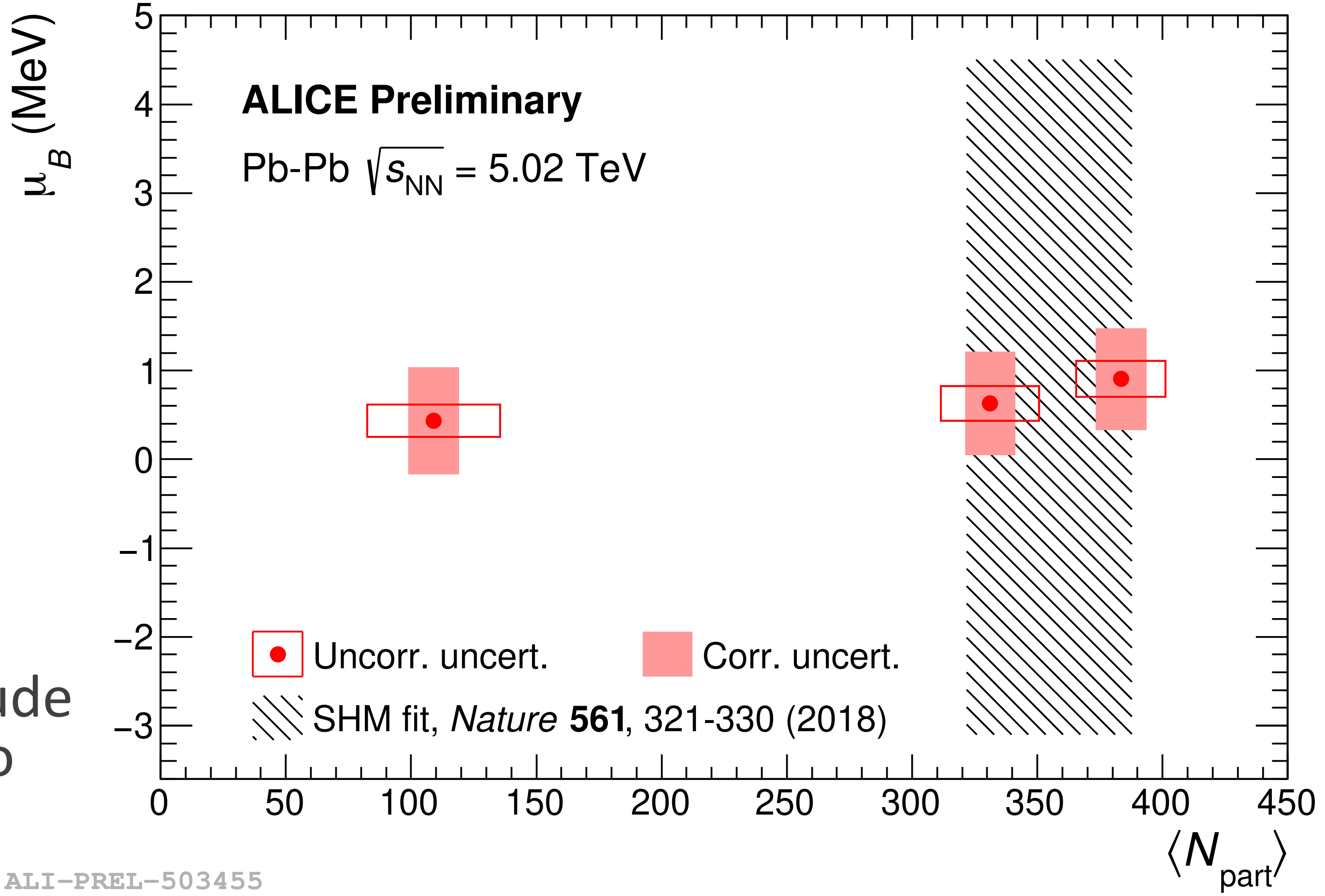
Pb—Pb
$\sqrt{s_{NN}}$ = 5.02 TeV



Hypertriton production

- Fit to the data provides a value of μ_B close to zero in the most central collisions
- Antiparticle-to-particle ratio compared to SHM predictions at T_{ch} = 155 ± 2 MeV and using the obtained μ_B
- Very precise result even with large uncertainties for the hypertriton and a small overestimation for the ^{3}He
- Measurement of μ_B in different centralities nearly one order of magnitude more precise than the SHM fit thanks to cancellation of correlated uncertainties

Pb—Pb
$\sqrt{s_{NN}}$ = 5.02 TeV



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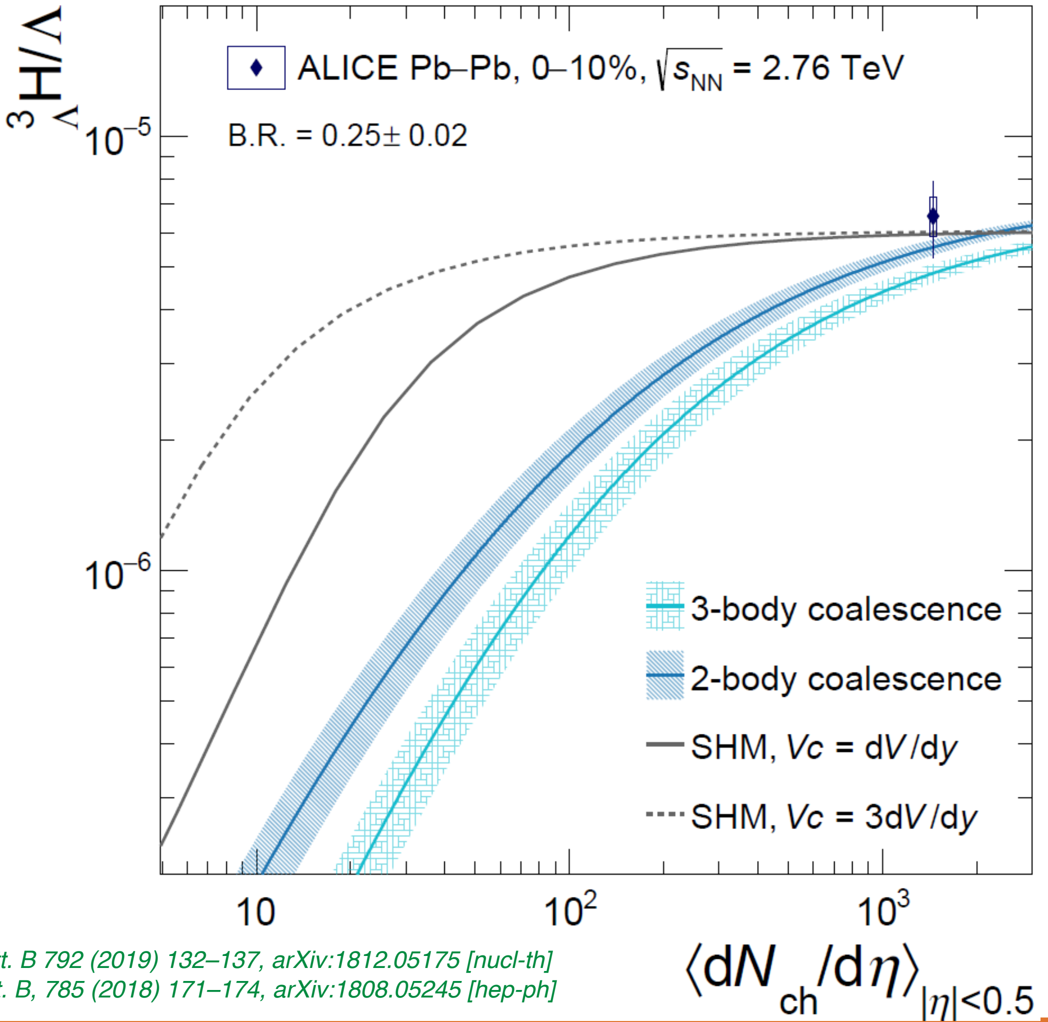
Hypertriton production vs. multiplicity

- ${}^{3}_{\Lambda}$H / Λ ratio vs. multiplicity
- Perfect candidate to distinguish between coalescence and statistical hadronization models
- Extremely sensitive to the nuclei production mechanism:
  - → For statistical hadronization models (SHM) the object size is not relevant
  - → In a coalescence picture large suppression of the production in small systems expected due to the object size

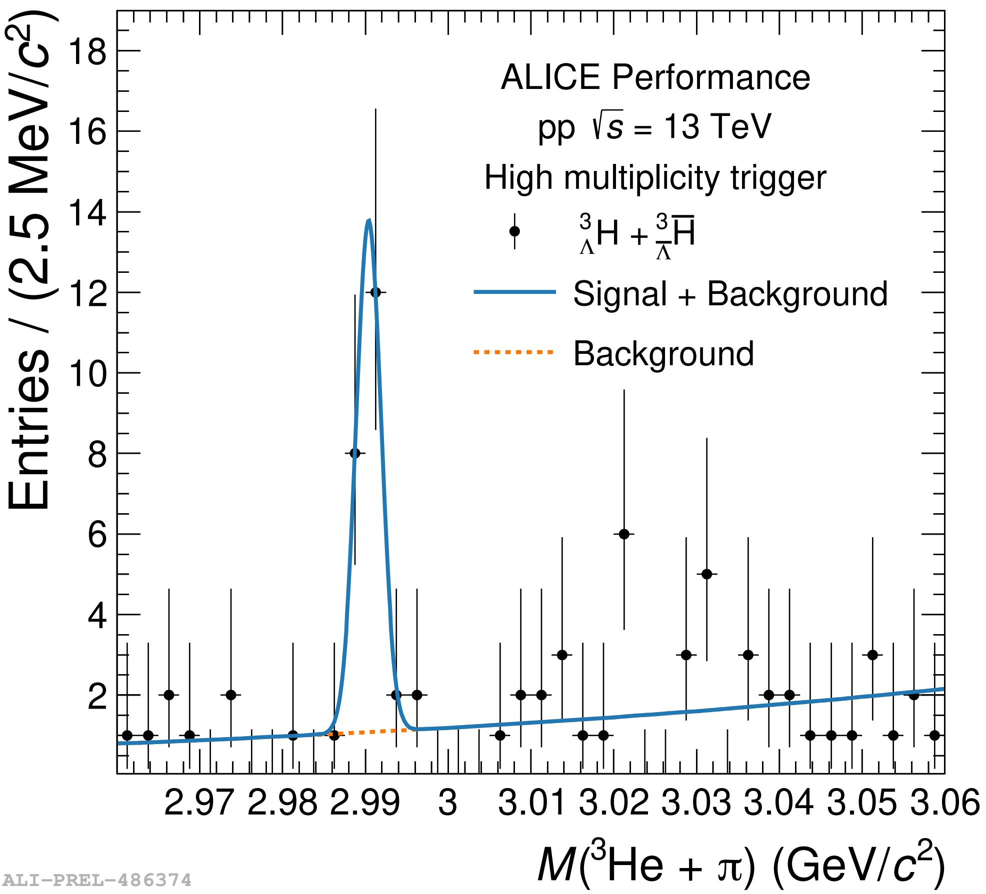


Coalescence: K.-J. Sun, C.-M. Ko and B. Dönigus, Phys. Lett. B 792 (2019) 132–137, arXiv:1812.05175 [nucl-th]
SHM: V. Vovchenko, B. Dönigus and H. Stoecker, Phys. Lett. B, 785 (2018) 171–174, arXiv:1808.05245 [hep-ph]

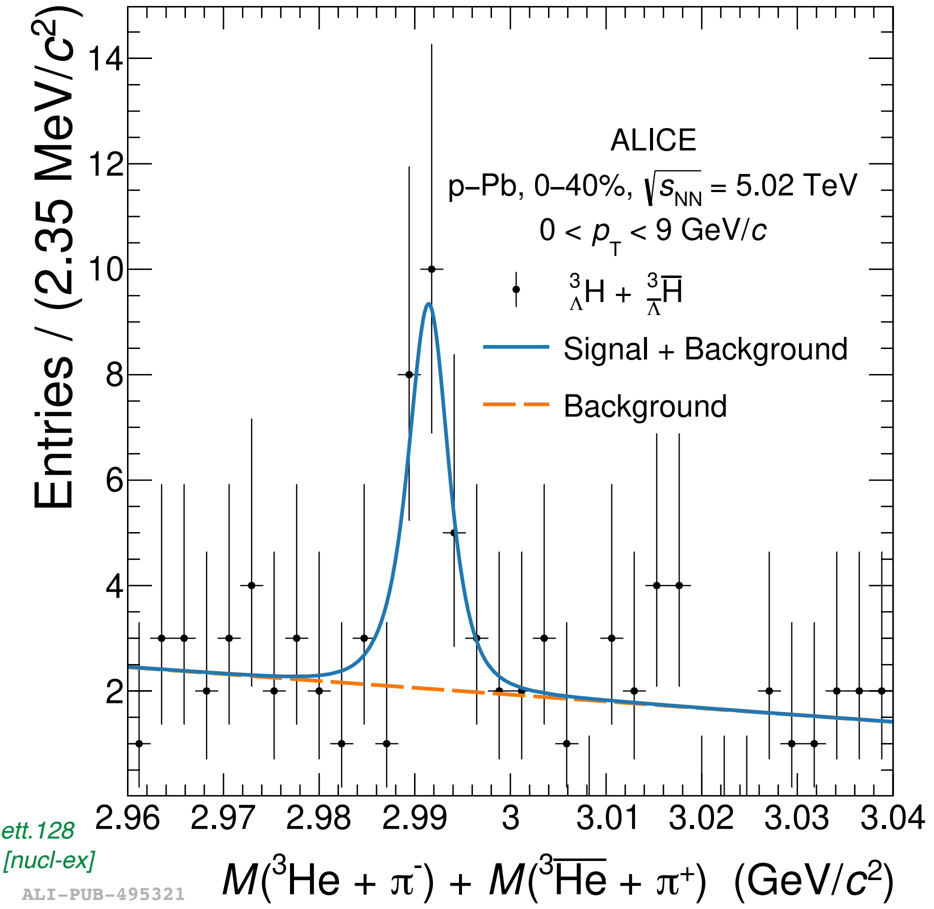
Hypertriton in small systems

pp

p—Pb



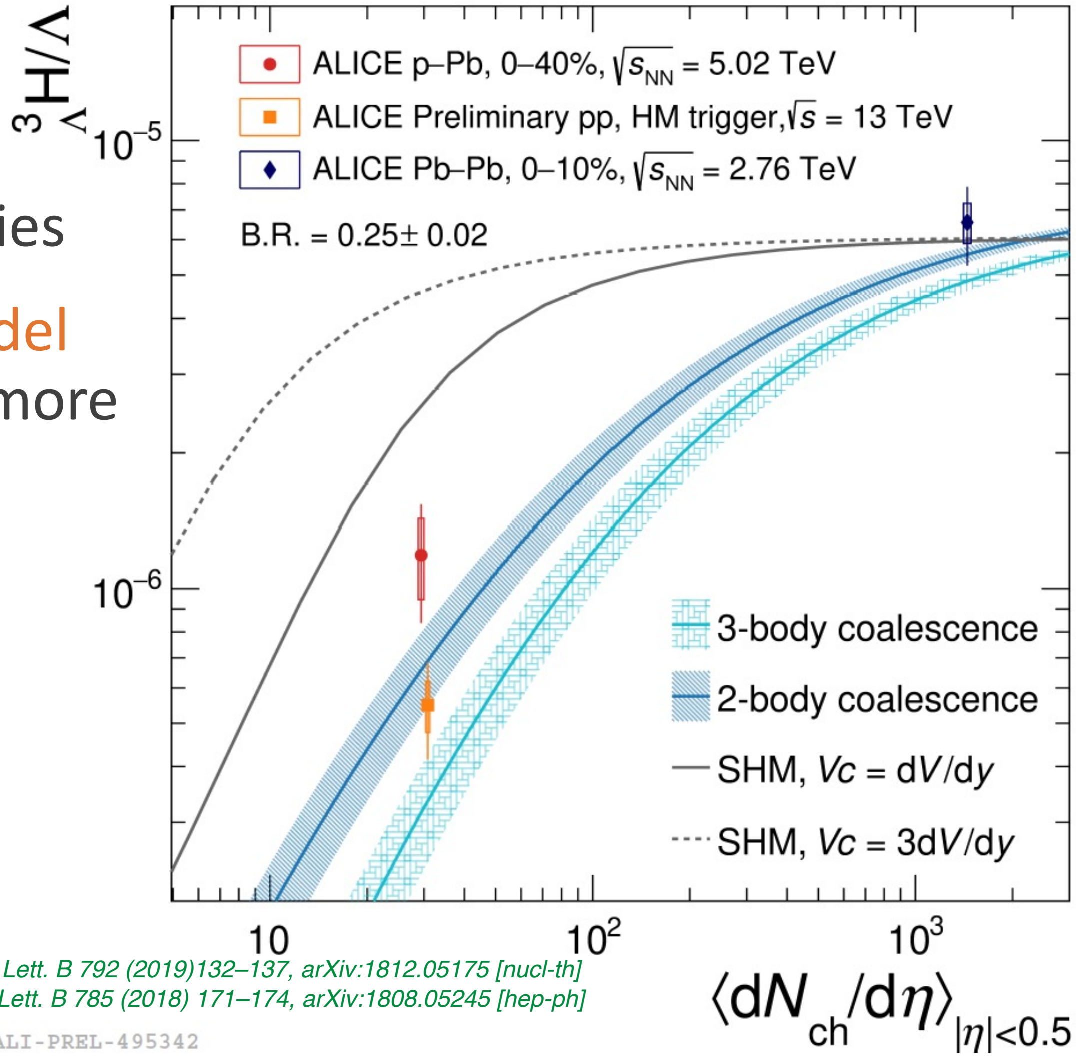
- First measurement of the hypertriton in pp (13 TeV) and p—Pb (5.02 TeV) collisions
- Signal extraction using topological and kinematic cuts (pp) or machine learning approach (p—Pb)



ALICE collaboration, Phys. Rev. Lett.128 (2022) 252003, arXiv:2107.10627 [nucl-ex]

$^{3}_{\Lambda}$H / Λ ratio

- Measurements in pp and p—Pb: Two new points at different multiplicities
- Leads to the exclusion of the SHM model implementation with V_C = 3 dV/dy by more than 6 σ
- Data slightly favours the two-body coalescence
- But does not exclude three-body coalescence



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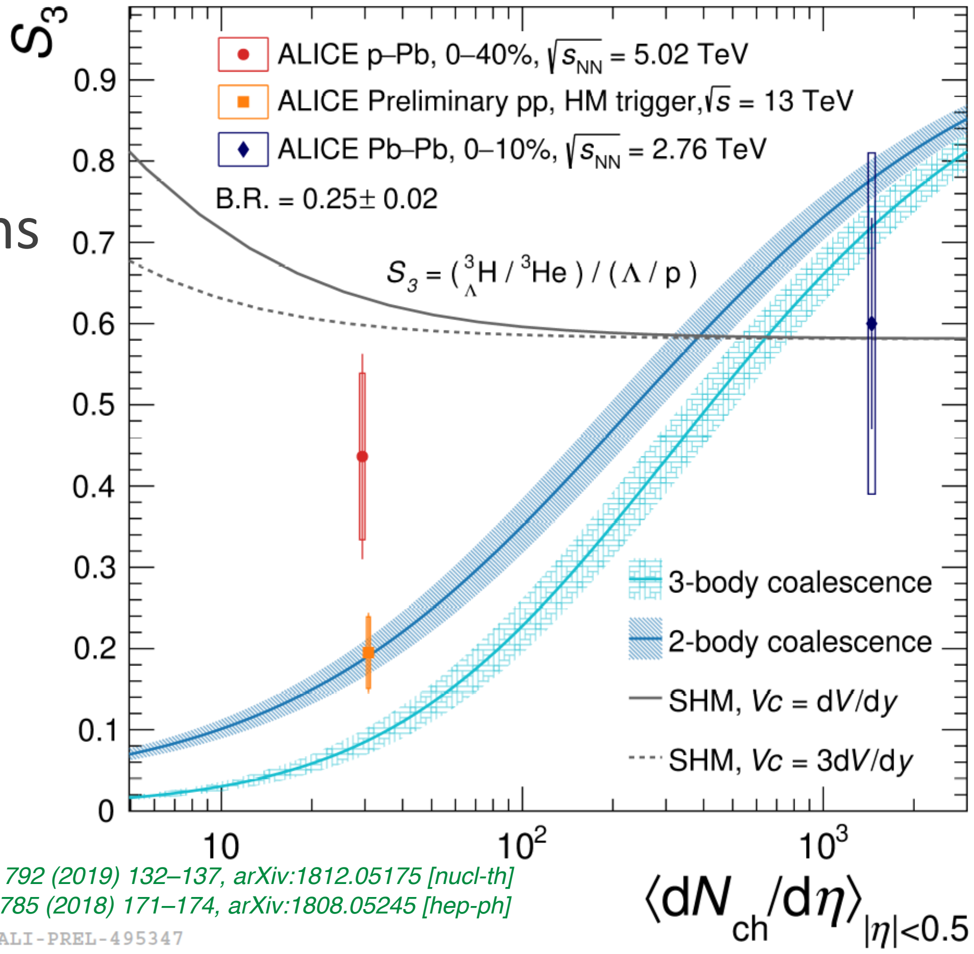
SHM: V. Vovchenko, B. Dönigus and H. Stoecker, Phys. Lett. B 785 (2018) 171–174, arXiv:1808.05245 [hep-ph]

ALI-PREL-495342

S_3

- $S_3 = ({}^{3}_{\Lambda}H \,/\, {}^{3}He) \,/\, (\Lambda \,/\, p)$ vs. multiplicity
- Strangeness population factor for the measurement of baryon-strangeness correlations
- Penalty factor due to mass difference cancels and size effects can be studied
- Measurements in pp and p—Pb:
  two new points at different multiplicities
- Data slightly favours the two-body coalescence
- But does not exclude three-body coalescence



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SHM: V. Vovchenko, B. Dönigus and H. Stoecker, Phys. Lett. B 785 (2018) 171–174, arXiv:1808.05245 [hep-ph]

Summary

- ALICE is the ideal experiment to study the production and properties of light (anti)(hyper)nuclei in all collision systems
- The latest results, even though more precise than previous data, still do not allow for a strong conclusion about the dominant production mechanism
- The presented experimental results on mass and binding energy of the hypertriton support its loosely-bound structure
- The upcoming Run 3 and Run 4 will add more statistics for the measurement of light (anti)(hyper)nuclei
- This may also give the possibility of a more conclusive answer to the question of the production mechanism

Backup

Free Λ lifetime

- New, extremely precise measurement of the free Λ lifetime as reference for the hypertriton lifetime
- About a factor 3 more precise than the PDG value