Measurements of (anti)(hyper)nuclei with ALICE

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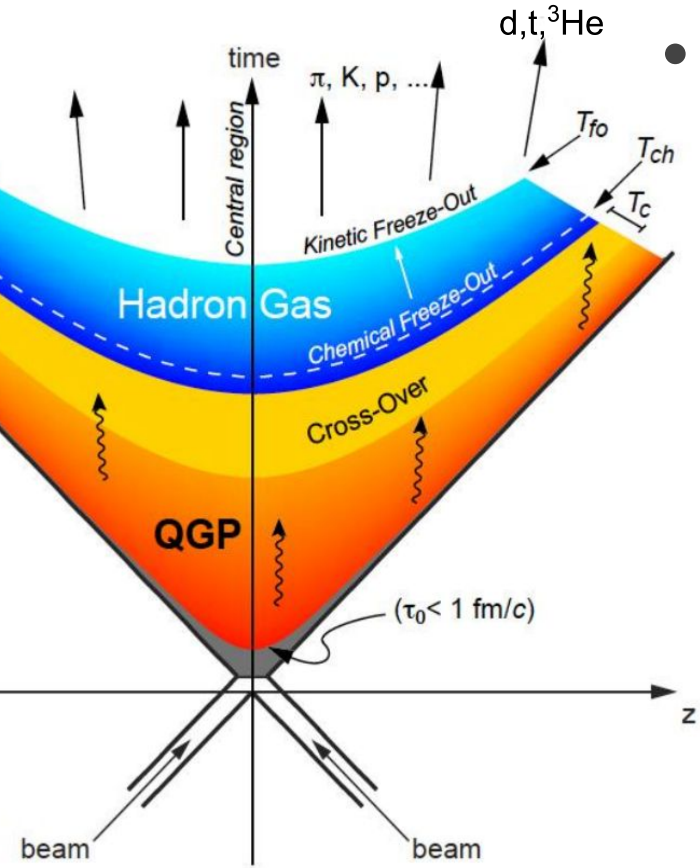
17th edition of the Workshop on Particle Correlations and Femtoscopy (WPCF 2024)

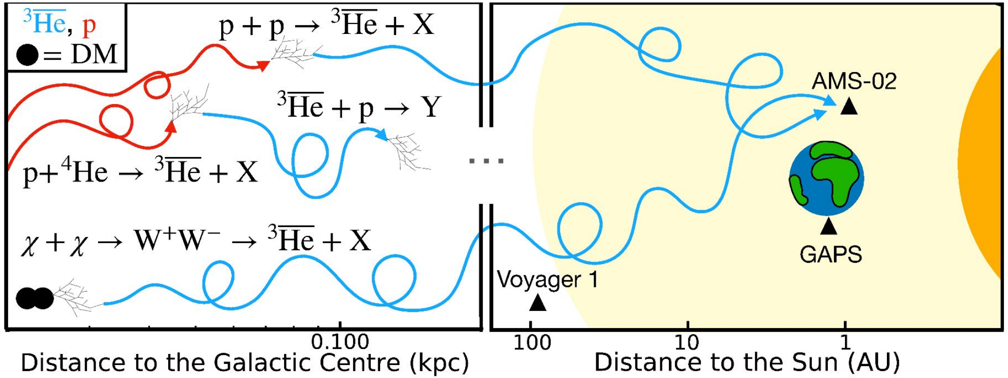
Light nuclei in heavy-ion collisions



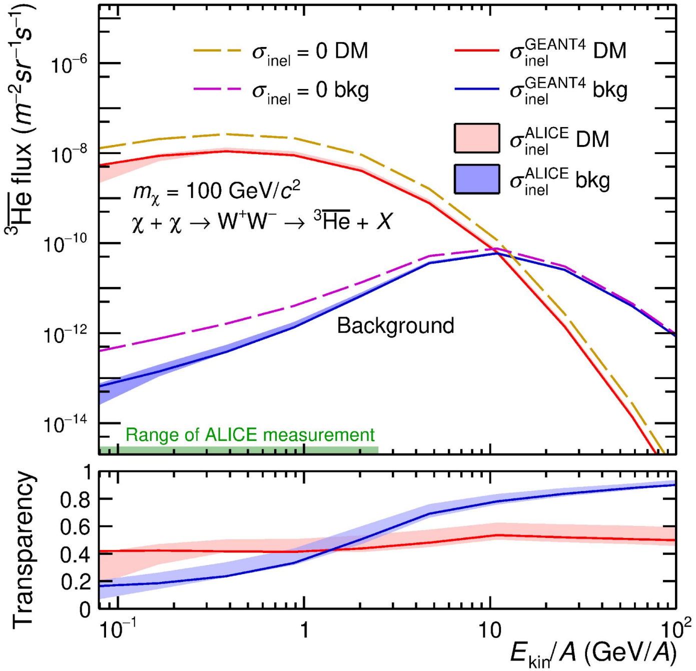
- The study of light (anti)(hyper)nuclei is very important:
  - Production mechanism is not well understood
    - How/when do they form?
      - “early” at chemical freeze-out (thermal production)
      - or “late” at kinetic freeze-out (coalescence)?
    - Do they suffer for the dissociation by rescattering?
  - Low binding energy (few MeV) "Snowballs in hell": nuclei formation is very sensitive to chemical freeze-out conditions and to the dynamics of the emitting source
  - Baseline for exotic bound state searches
  - Light nuclei measurements in high energy physics can be used to estimate the background of secondary anti-nuclei in dark matter search

Antinuclei production

- Antinuclei can be a sign of Dark Matter annihilation:
  - Background: production in the collisions between cosmic rays (CR) and the interstellar medium (ISM) (pp and p-A collisions)
    - Nuclei production must be known very well!



ALI-PUB-532052



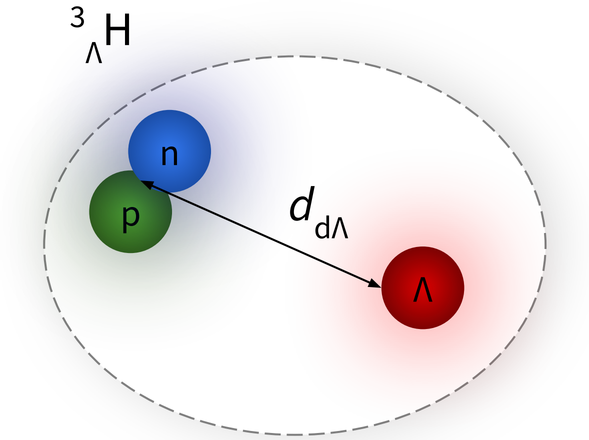
ALI-PUB-532056

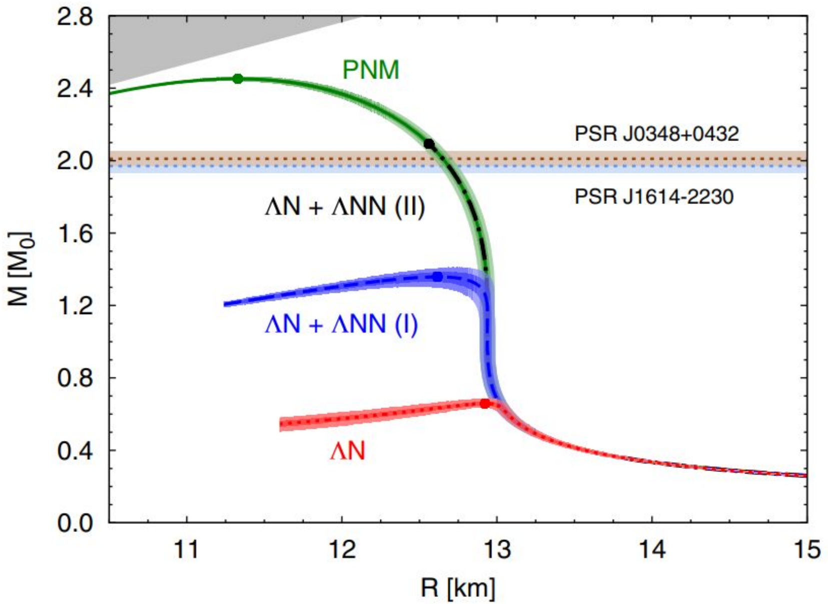
M. Korsmeier et al, Phys. Rev. D 97, 103011

Nature Phys. 19 (2023) 1, 61-71

Hypernuclei production

- Hypernuclei can be used to study nucleon-hyperon (N-Y) interaction
  - Production of exotic bound states
  - Determination of the equation of state
    - Application to neutron stars



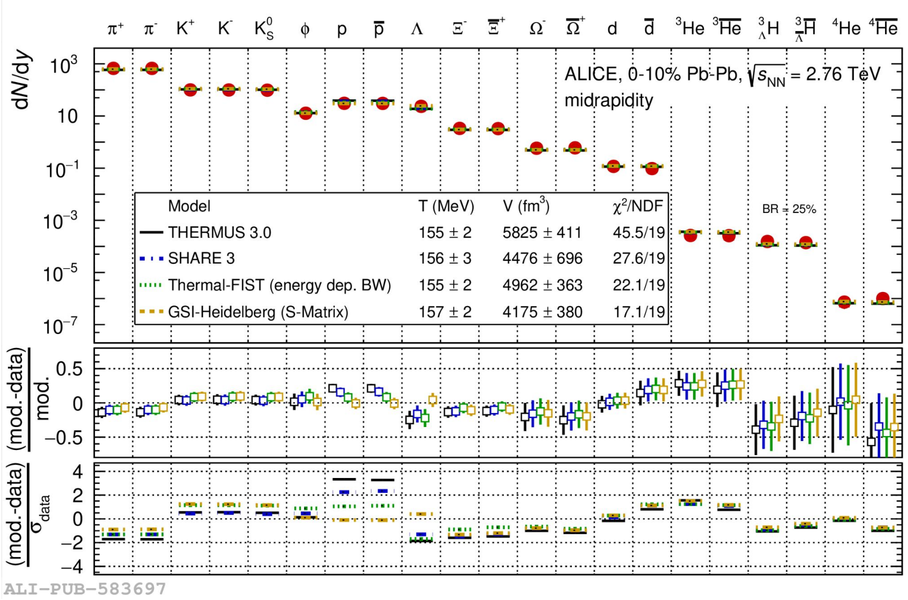


D. Lonardoni et al., PRL 114, 092301 (2015)

D. Logoteta et al., EPJA 55 (2019) 11, 207

Production models

- Statistical hadronization models (SHMs)
  - describe the yields of light- flavoured hadrons by requiring thermal and hadron-chemical equilibrium
    - Parameters: (T, V, μ_B)
  - light (anti)(hyper)**nuclei** are treated as **point-like objects**



Eur. Phys. J. C 84 (2024) 813

Production models: Statistical hadronization models

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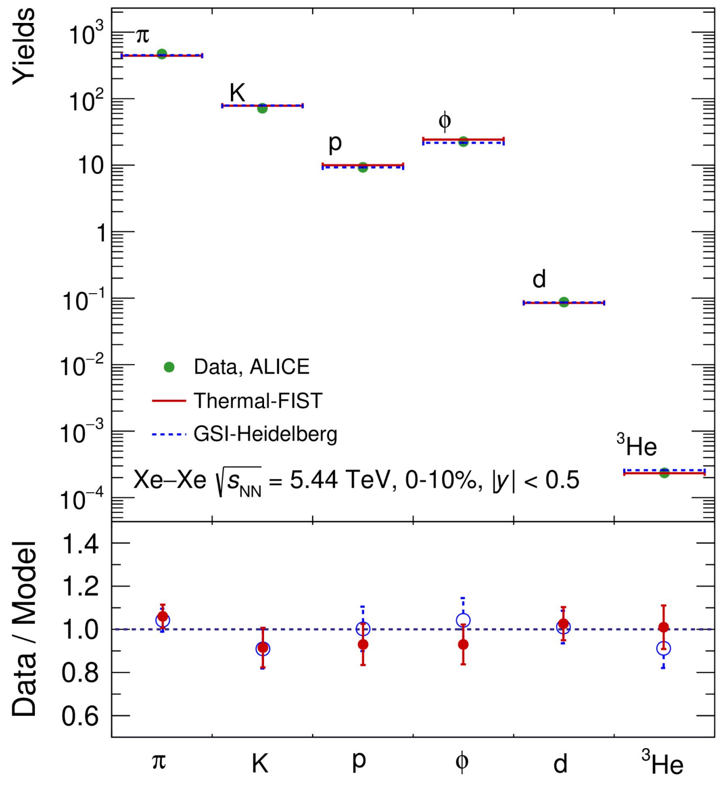
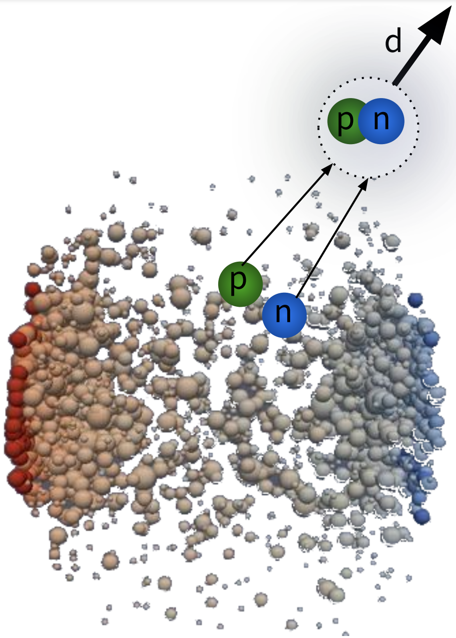
  - describe the yields of light- flavoured hadrons by requiring thermal and hadron-chemical equilibrium
    - Parameters: (T, V, μ_B)
  - light (anti)(hyper)**nuclei** are treated as **point-like objects**
  - Canonical ensemble (CSM): local conservation of quantum numbers (S, Q and B)
- Central Xe–Xe collisions: π, K, ϕ, p, d, ^{3}He
  - T_{chem} = (154.2 ± 1.1) MeV (Similar to the one obtained in Pb–Pb collision)
  - V = (3626 ± 298) fm^3
  - χ^2/NDF = 0.83



arXiv:2405.19826

Production models: Coalescence

- **Coalescence**
  - Nuclei are formed by nucleons emitted at freeze-out hypersurface
  - Coalescence calculations incorporate the **size of nuclei**
    - convolution between nucleon phase-space distribution and Wigner function of the nucleus



J. I. Kapusta, PRC 21, 1301 (1980)

Mahlein et al., EPJC 83 (2023) 9, 804

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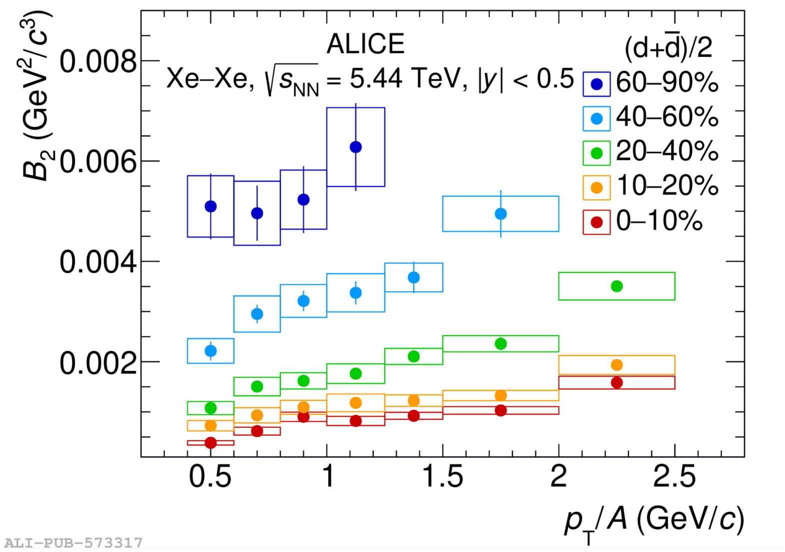
- Coalescence parameter B_A, related to formation probability via coalescence:



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

J. I. Kapusta, PRC 21, 1301 (1980)

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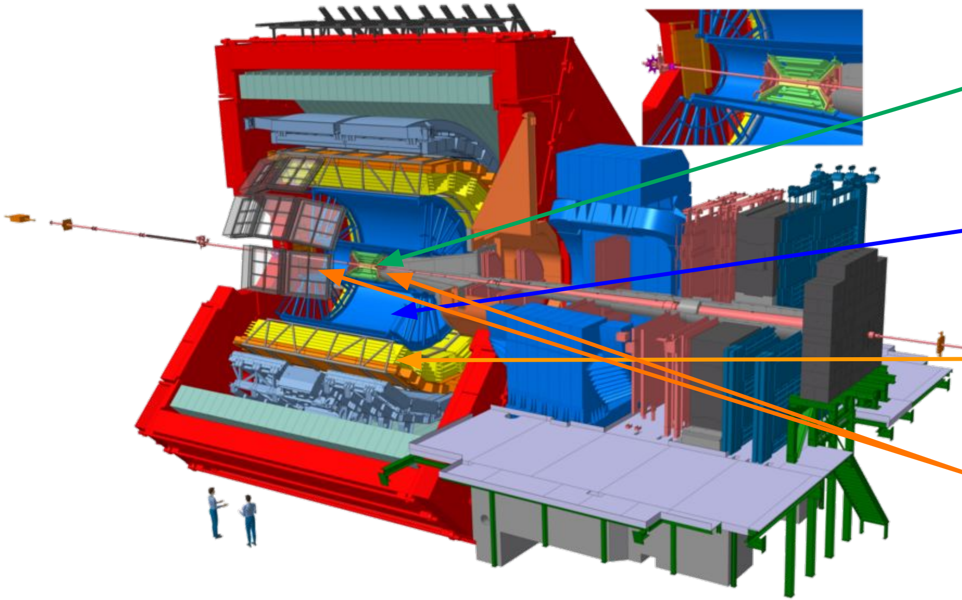
ALICE

ALICE particle identification capabilities are unique. Almost all known techniques are exploited: specific energy loss (dE/dx), time of flight, transition radiation, Cherenkov radiation, calorimetry and decay topology (V0, cascade).



Inner Tracking System (ITS) :
- Primary vertex
- Tracking
- Particle identification via dE/dx

Time Projection Chamber (TPC):
- Global tracking
- Particle identification via dE/dx

Time Of Flight (TOF):
- Particle identification via velocity measurement

V0 (A-C): Trigger, beam-gas event rejection, centrality, multiplicity classes

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

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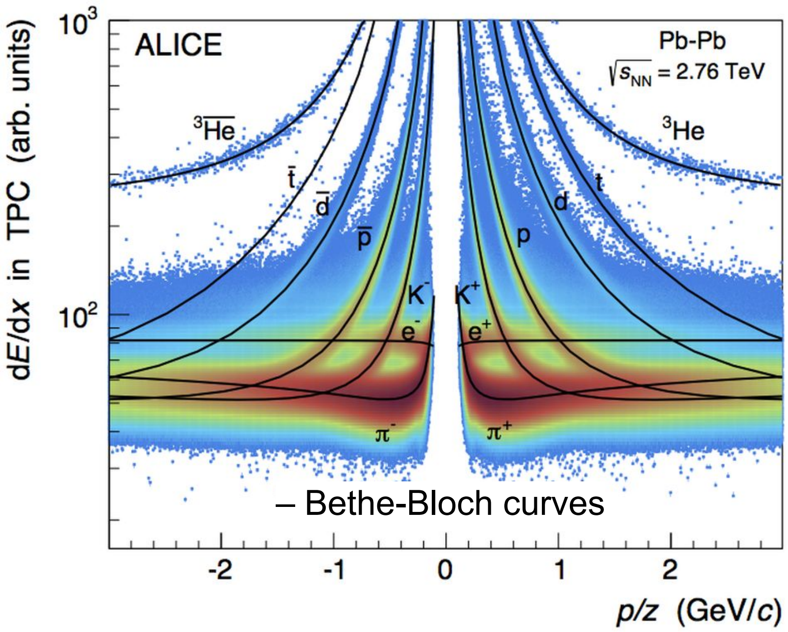
TPC: d*E*/dx in gas

- Separation of (anti)nuclei thanks to their large mass (and charge)



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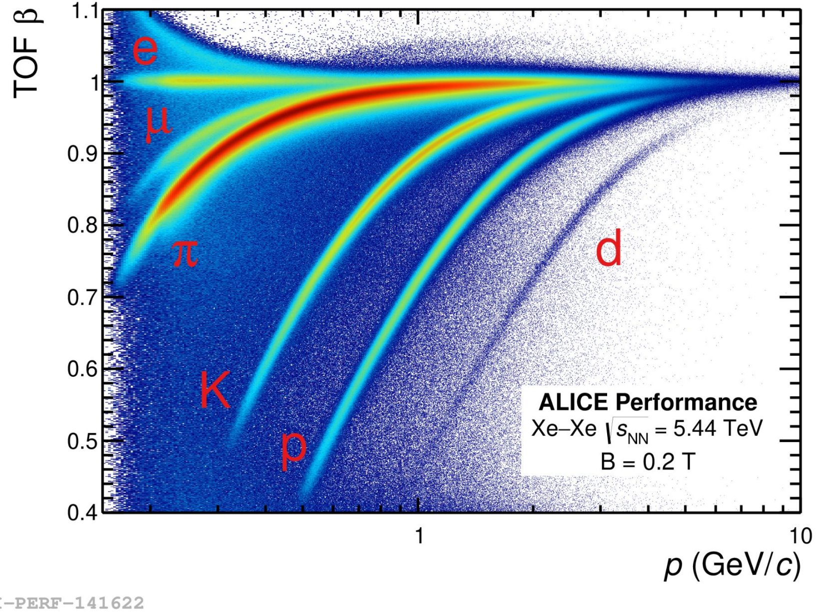
- $p = \gamma\beta m \rightarrow$ mass



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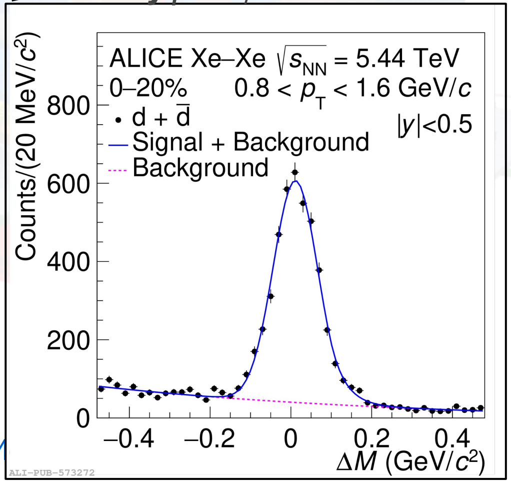
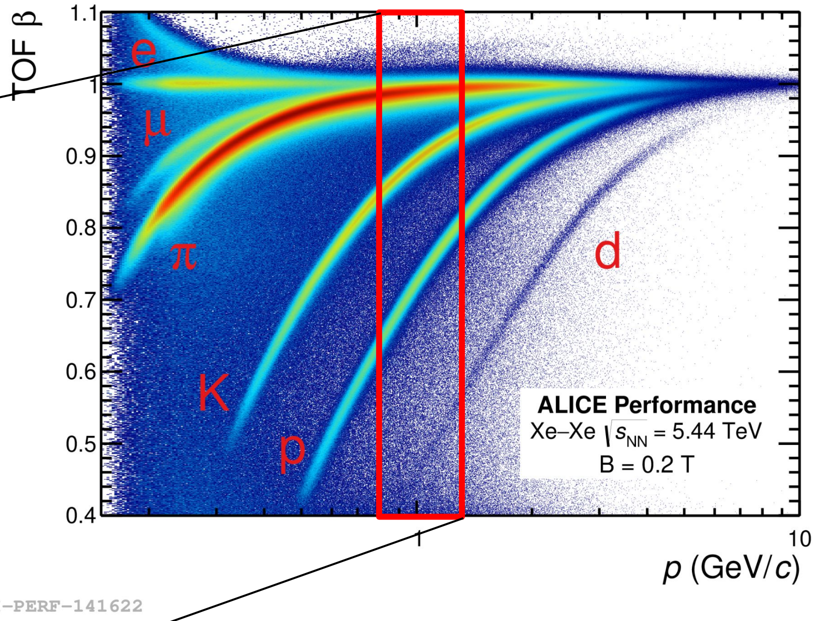




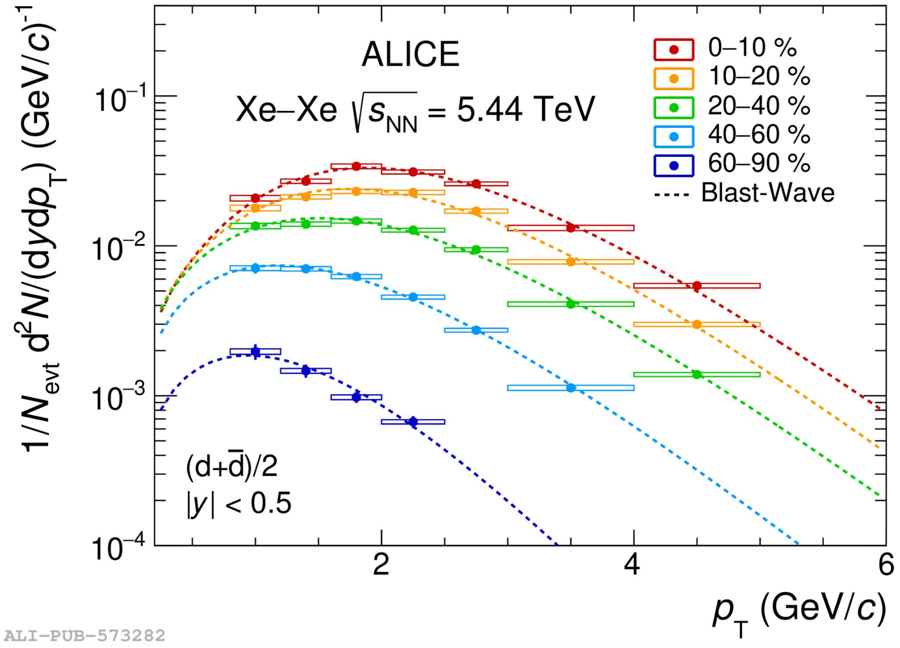
ALICE Collaboration Int. J. M

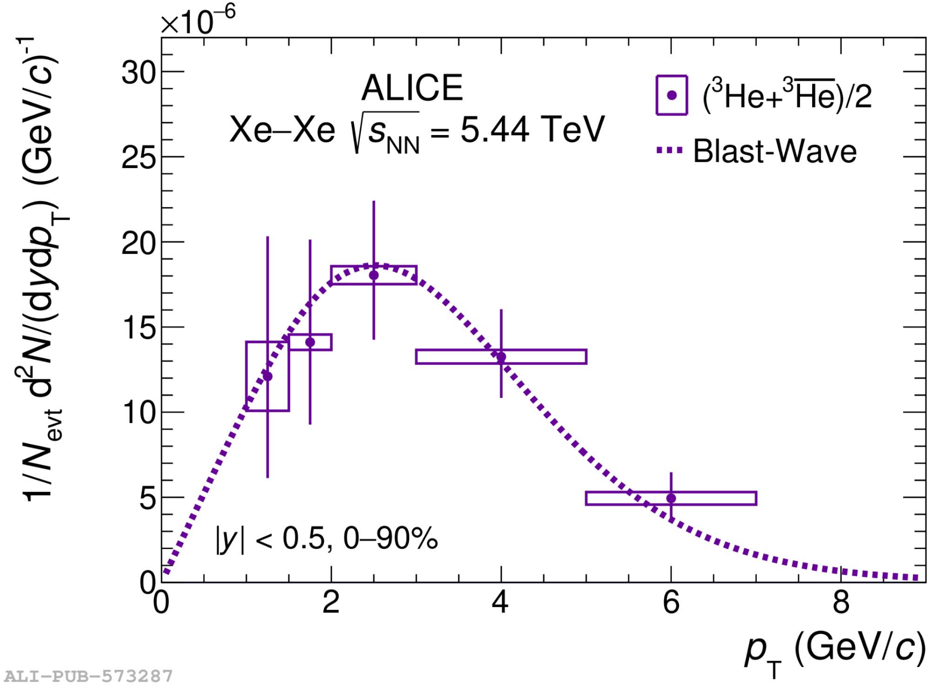
arXiv:2405.19826

Production spectra of nuclei

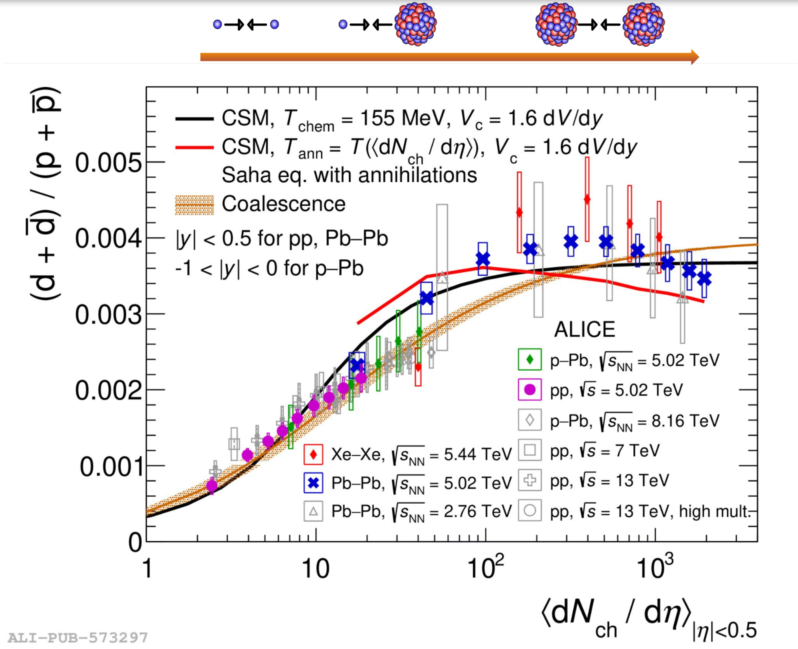
- ALICE measured production spectra of nuclei in pp, p–Pb, Xe–Xe and Pb–Pb collisions at mid-rapidity
- Measurements in classes of multiplicity or centrality
    - related to system size

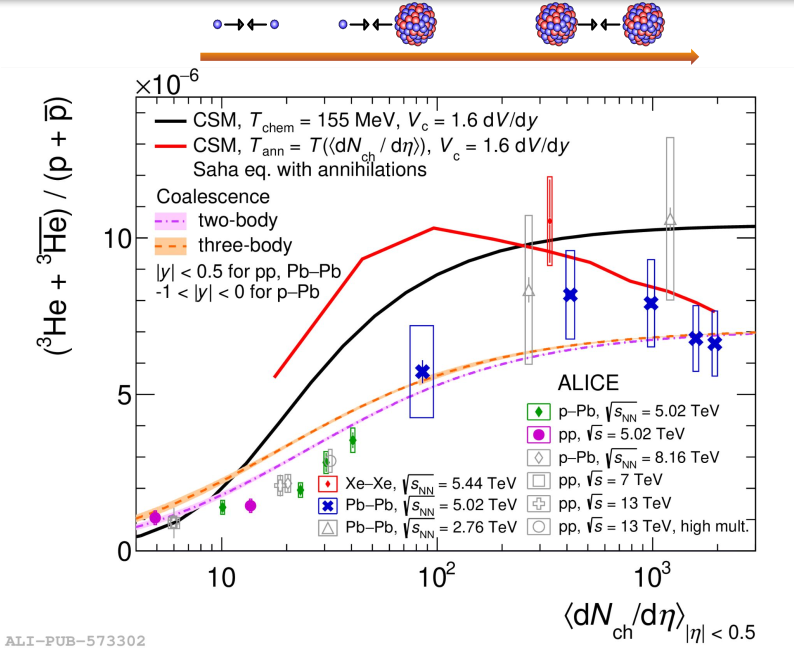
arXiv:2405.19826





Nucleon-to-proton ratio



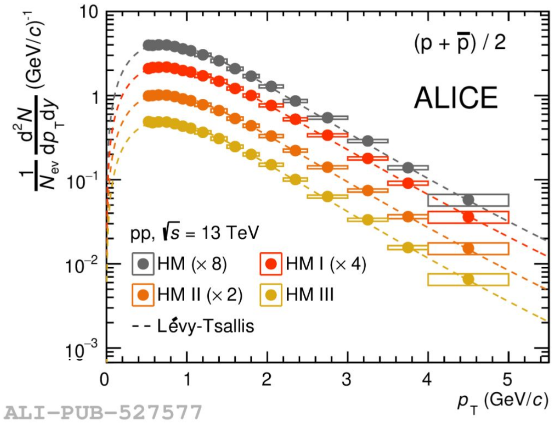


arXiv:2405.19826

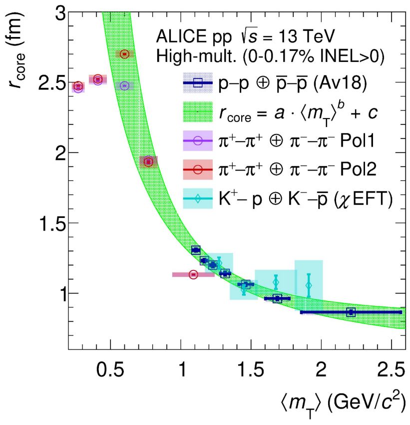
- Smooth evolution of d/p and 3He/p ratios with the system size
  - A=2 : multiplicity dependence is well reproduced by both **CSM** and **coalescence**
  - A=3 : ratio fairly described by the **coalescence** approach at low and high charged-particle multiplicity densities. Tension at intermediate multiplicities (10-40 charged particles)

Constraining nuclei wave function

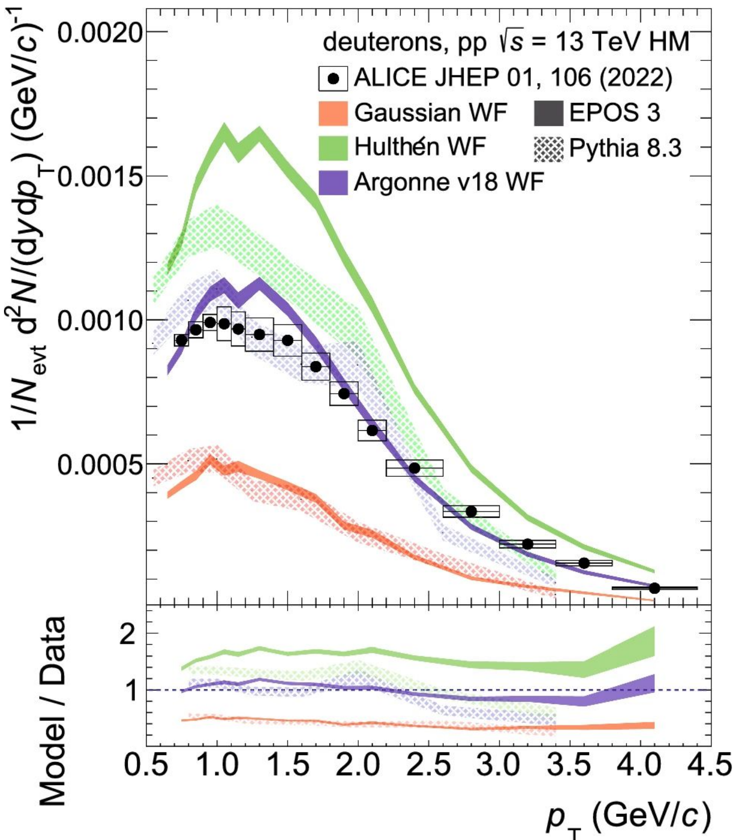
- A recent study shows that ALICE measurements in HM collisions of:
  - proton production yields
  - proton source radius
    - allow for the prediction of the deuteron spectrum via event-by-event coalescence with no free parameters!



JHEP 01 (2022) 106



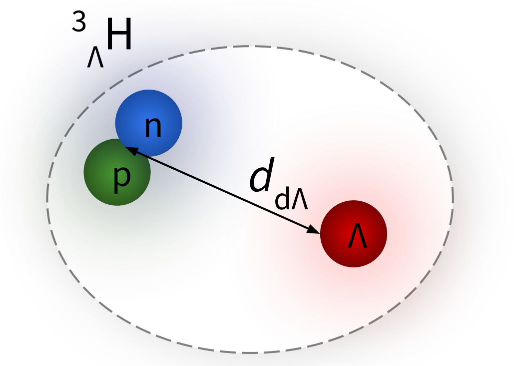
arXiv:2311.14527



Mahlein et al., EPJC 83 (2023) 9, 804

Hypertriton production

- Lightest known hypernucleus consisting of (p, n, Λ)
- Mass = 2.991 GeV/c^2
- B_Λ = 0.13 ± 0.05 MeV (B_d = 2.2 MeV, B_t = 8.5 MeV, B_{3He} = 7.7 MeV)
- $^3_\Lambda$H has a large size:
  - $d_{d-\Lambda}$ = 10.79 fm, r (d) = 1.96 fm

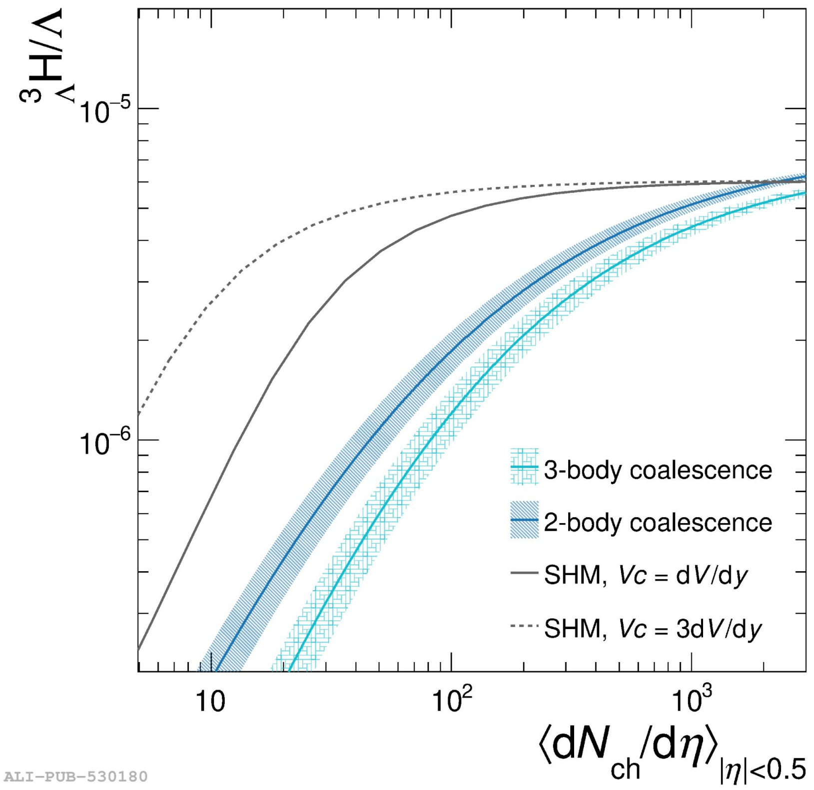


https://hypernuclei.kph.uni-mainz.de/

F. Hildenbrand and H.-W. Hammer, Phys. Rev. C 100, 034002

Hypertriton production in pp

- **SHM** and **coalescence** predictions for $^{3}_{\Lambda}$H are very different at low multiplicity



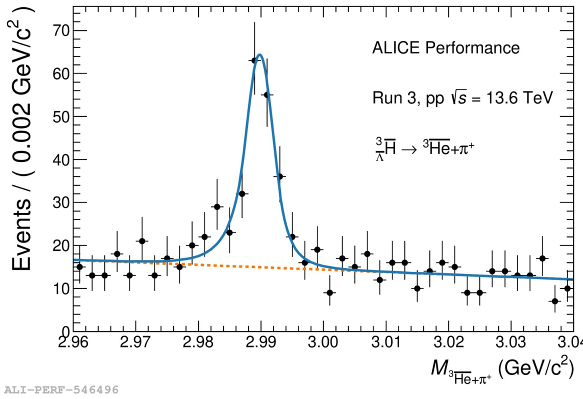
Phys. Rev. Lett. 128 (2022) 252003

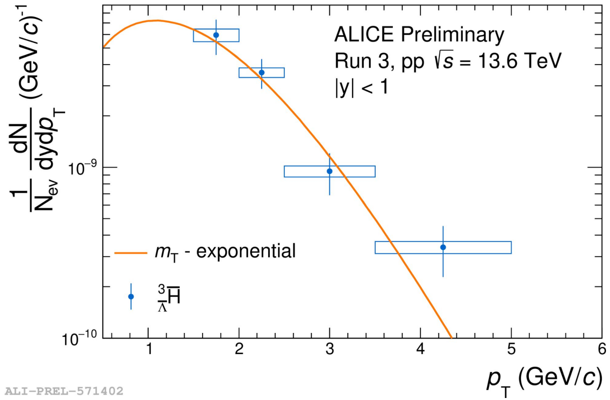
K.-J. Sun, et al. Phys. Lett. B 792, 132 (2019)

V. Vovchenko, et al. Phys. Lett. B 785, 171 (2018).

Hypertriton production in pp

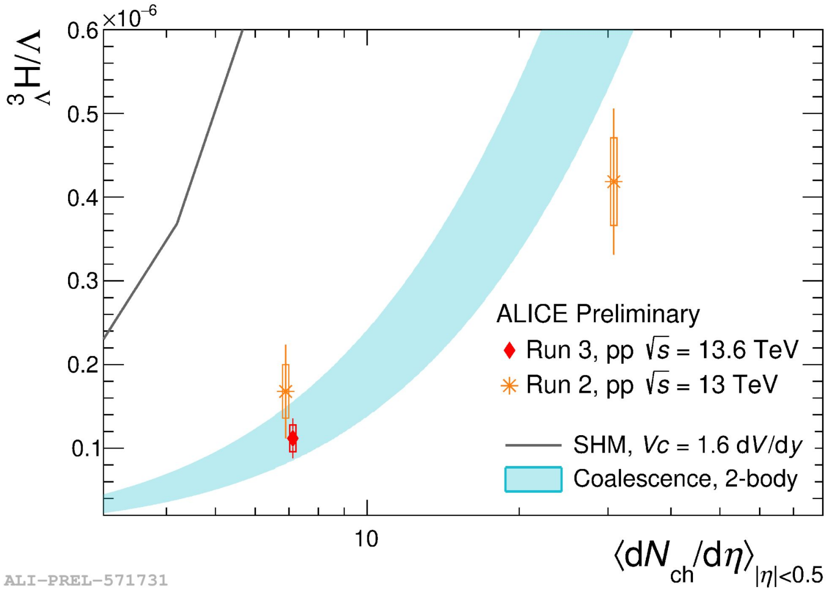
- **SHM** and **coalescence** predictions for $^{3}_{\Lambda}$H are very different at low multiplicity
- $^{3}_{\Lambda}$H measured in Run 3 by ALICE with good precision





Hypertriton production in pp

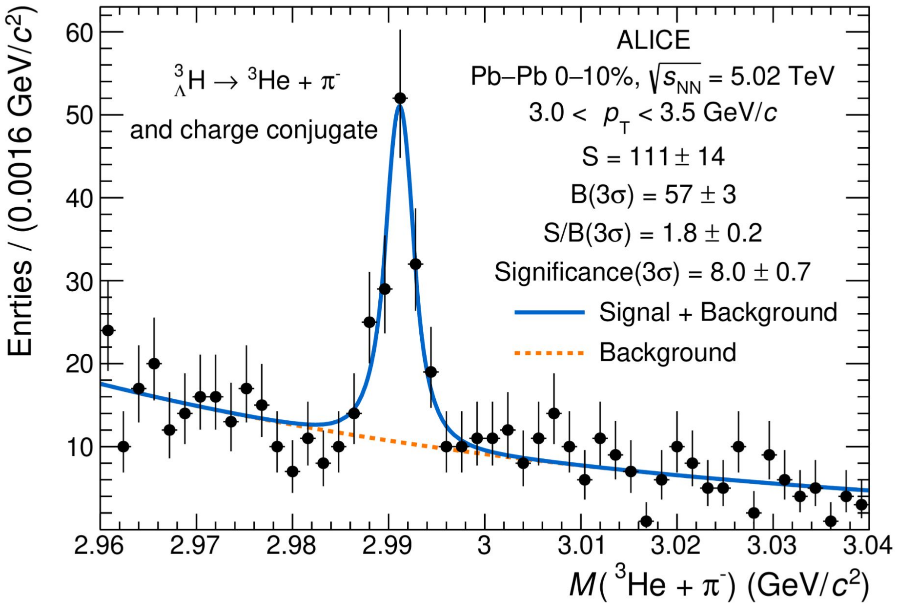
- **SHM** and **coalescence** predictions for $^{3}_{\Lambda}$H are very different at low multiplicity
- $^{3}_{\Lambda}$H measured in Run 3 by ALICE with good precision
- $^{3}_{\Lambda}$H/Λ is compared with the prediction of CSM and coalescence model
  - Two-body coalescence model provides the best description of data



➤ **Hypertriton in pp clearly favours coalescence**

Hypertriton production in Pb–Pb

- $^{3}_{\Lambda}$H has also been recently measured in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV



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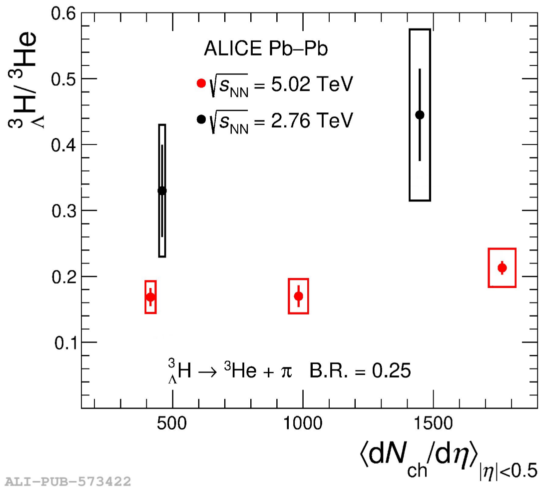

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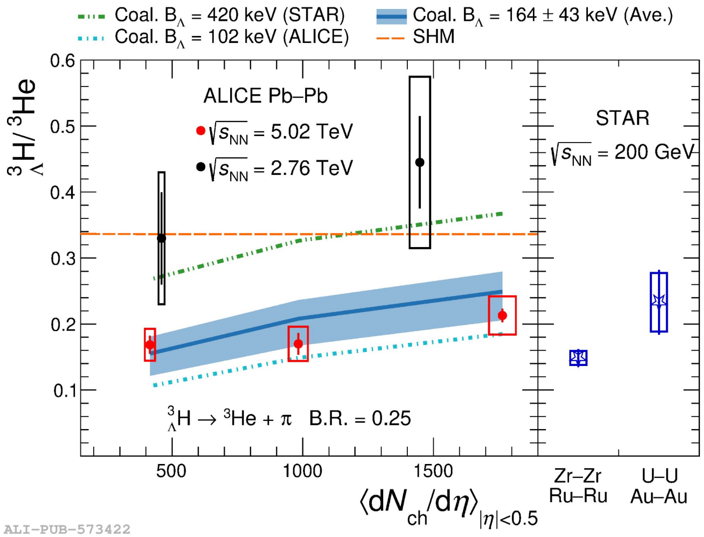

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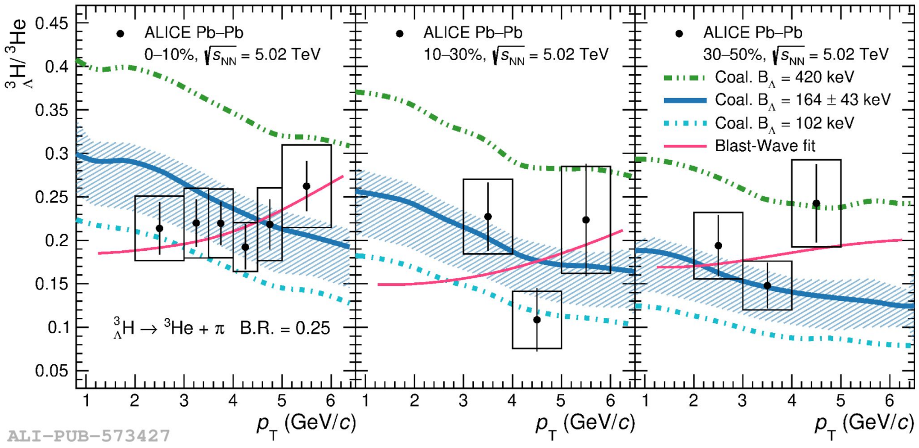
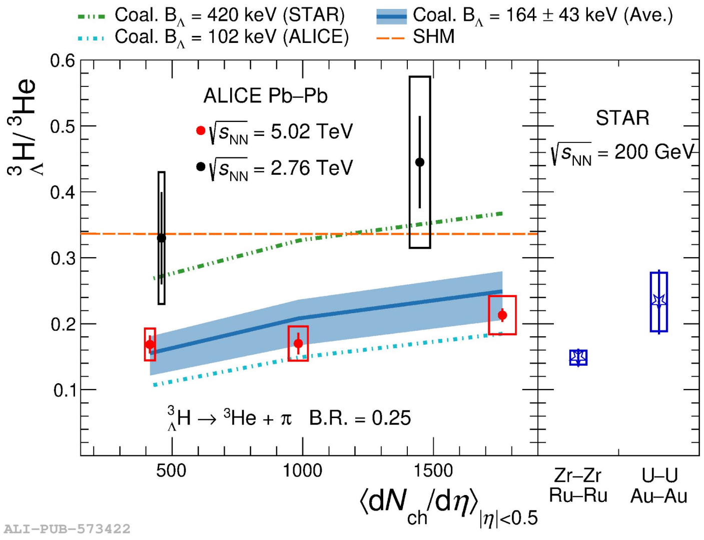


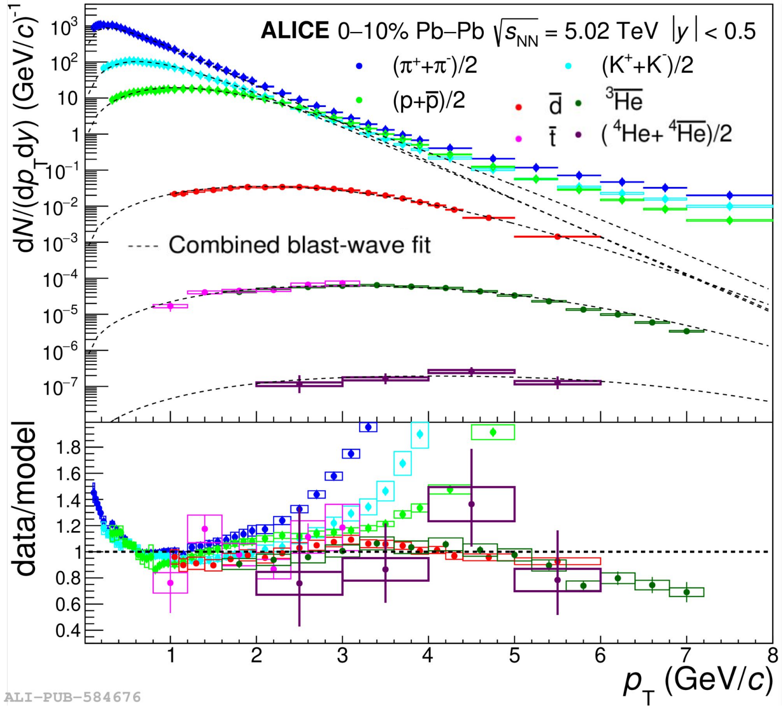


- p_T-differential measurement is also in agreement with **blast-wave** with common parameters with other nuclei
  - Large statistical uncertainties → Ongoing p_T-differential analyses with Run 3 data are fundamental to disentangle the two models

arXiv:2405.19839

^{4}He in Pb–Pb collisions

- ALICE has measured the production spectra for (anti) ^{4}He in Pb–Pb
- ^{4}He is more bound and compact than lighter nuclei:
  - E_B (^{4}He) ~ 28 MeV, r(^{4}He) ~ 1.7 fm
- p_T spectra are well reproduced by a blast-wave function, using common parameters with the other nuclei



Phys. Lett. B 858 (2024) 138943

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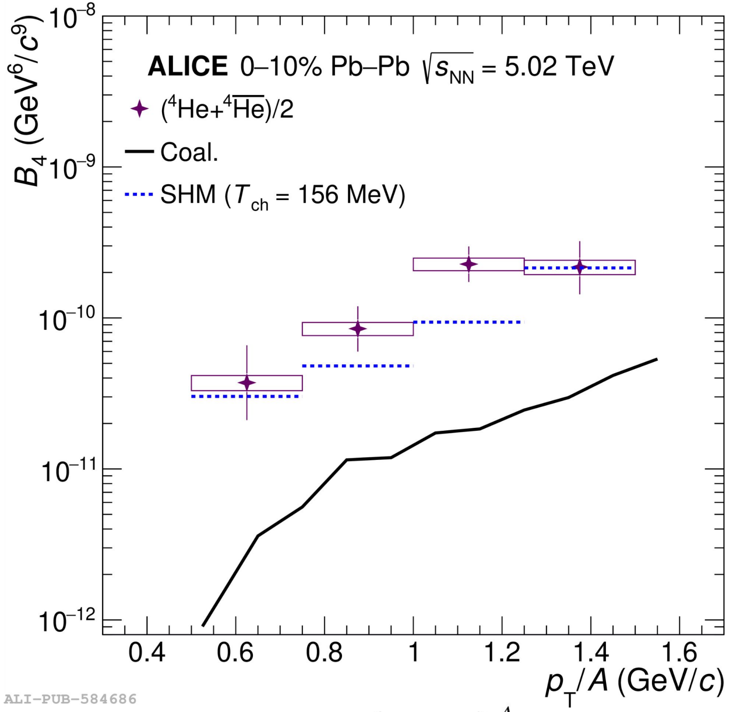
- The parameter B_4 is compared with **SHM+blast wave** and **coalescence** predictions

➢ **SHM describes nuclei with A = 4 better**



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

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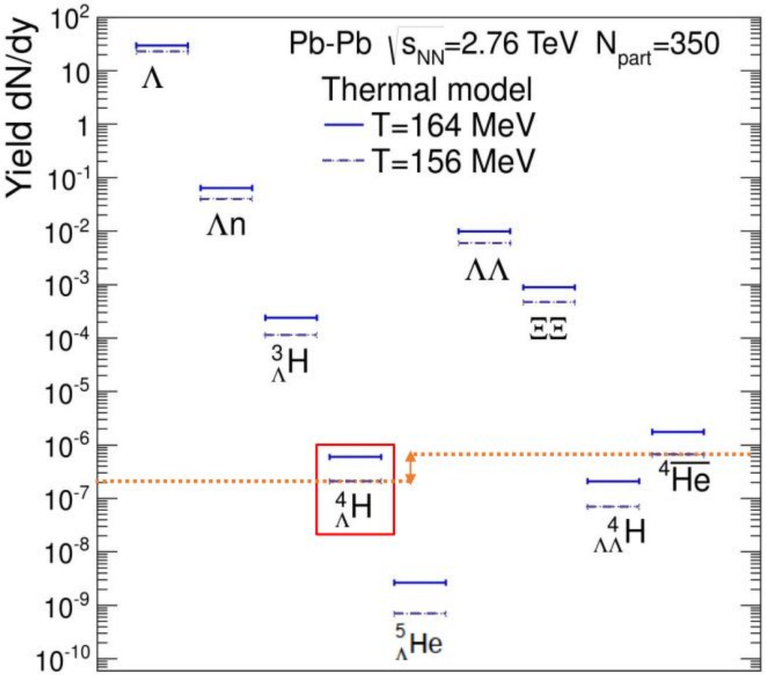
Hypernuclei with A = 4

- **SHM** predicts hypernuclei with A = 4 in Pb–Pb collisions
  - they are rare:
    - penalty factor for increasing A: ~ 300
    - suppression due to strangeness content



A. Adronic, private communication, based on
A. Andronic et al., PLB 697 (2011) 203-207

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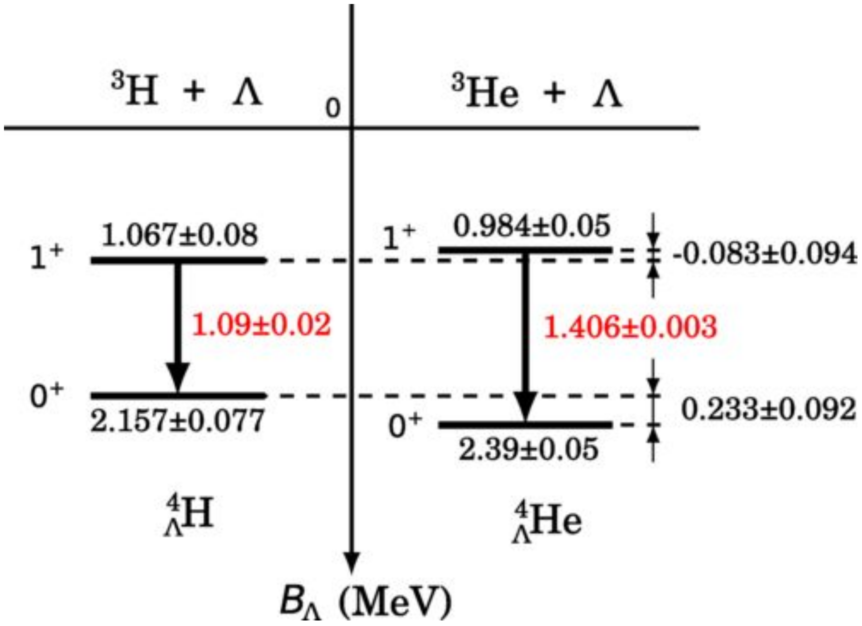
  - larger binding energy wrt A = 3
  - existence of excited states
  - spin degeneracy $\frac{dN}{dy} \propto 2J + 1$



M. Schäfer et al., PRC 106, L031001 (2022)

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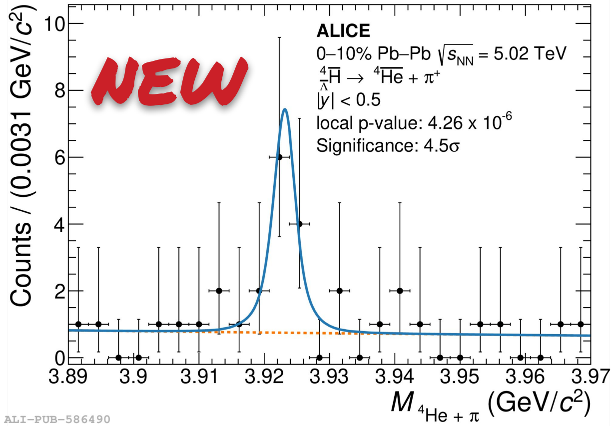
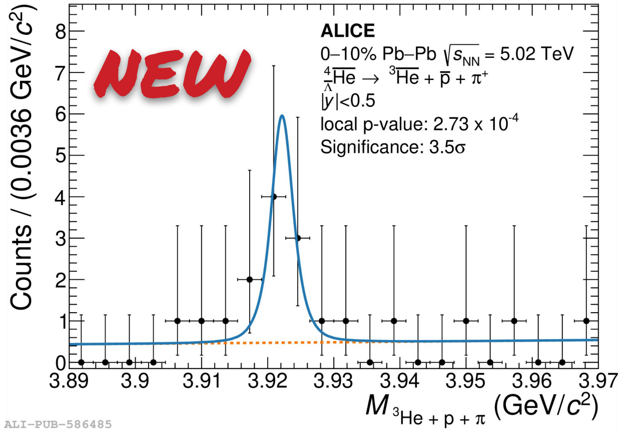
- In Pb–Pb at $\sqrt{s_{NN}}$ = 5.02 TeV, ALICE has observed:
  - ${}^{4}_{\Lambda}H \rightarrow {}^{4}He + \pi^{-}$
  - ${}^{4}_{\Lambda}He \rightarrow {}^{4}He + p + \pi^{-}$





arXiv:2410.17769

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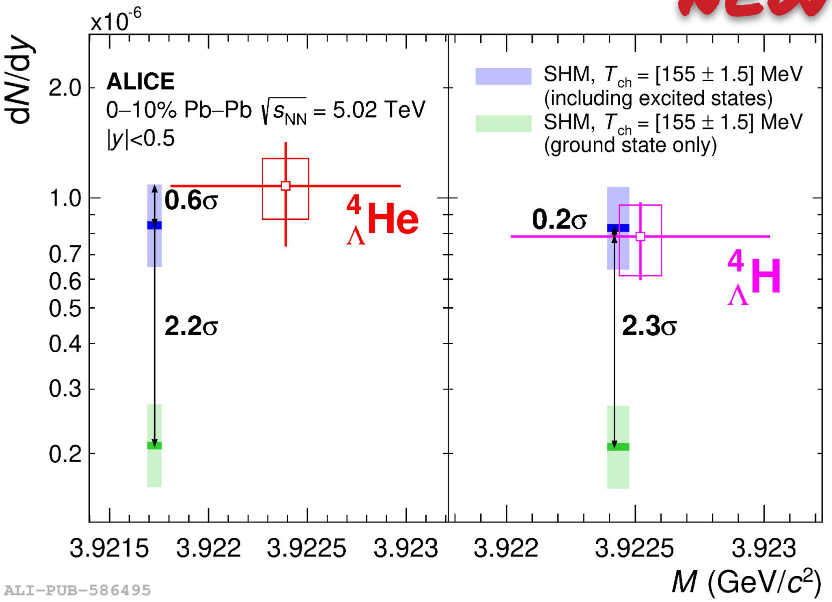
  - ${}^{4}_{\Lambda}H \rightarrow {}^{4}He + \pi^{-}$
  - ${}^{4}_{\Lambda}He \rightarrow {}^{4}He + p + \pi^{-}$
- Yields in agreement with **SHM** prediction that includes feed-down from excited states

➢ **SHM describes hypernuclei with A = 4 well**

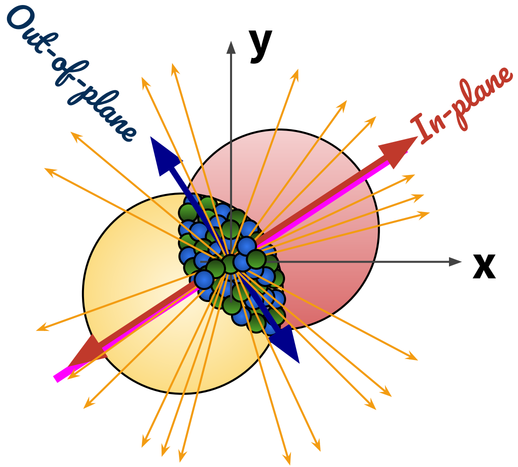
NEW



arXiv:2410.17769

Flow as a probe for nuclear production

- Anisotropic flow measures the momentum anisotropy of final-state particles
  - It is sensitive to a different production in-plane and out-of-plane
  - Can be used to test production mechanisms



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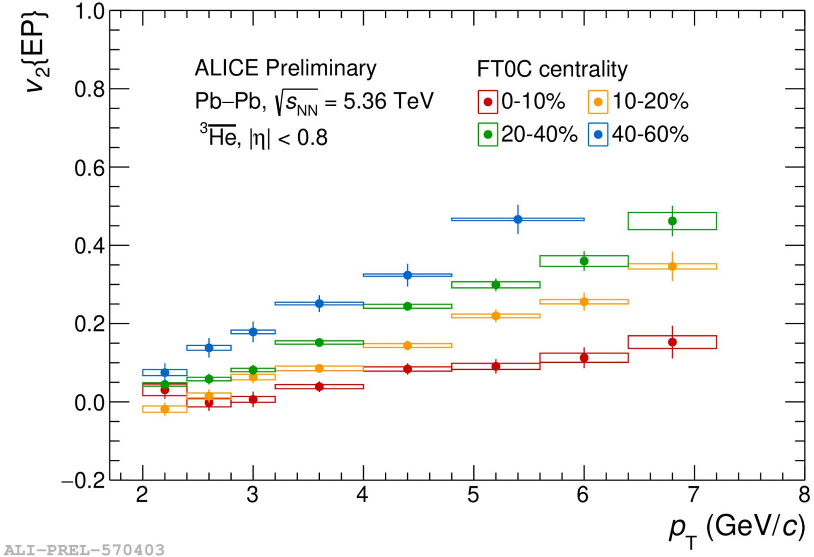
  - more differential both in p_T and centrality, more precise than in Run 2



ALI-PREL-570403

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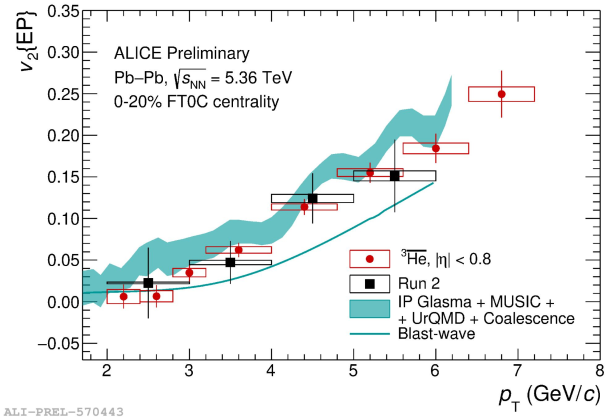
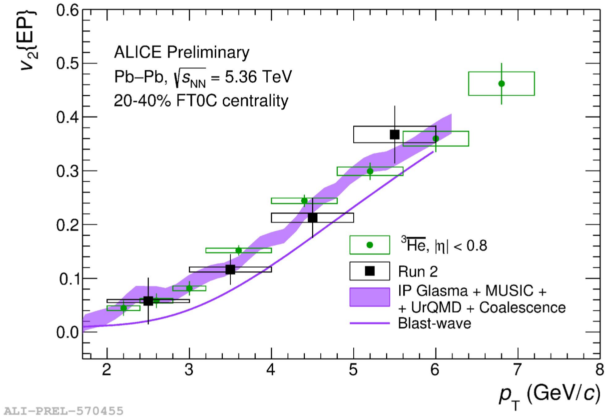
- Data are compared with the predictions of blast-wave and **coalescence** model

➤ **coalescence is favoured**



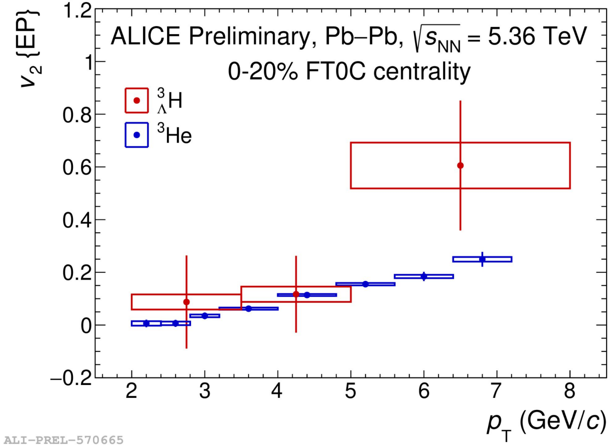
ALI-PREL-570443

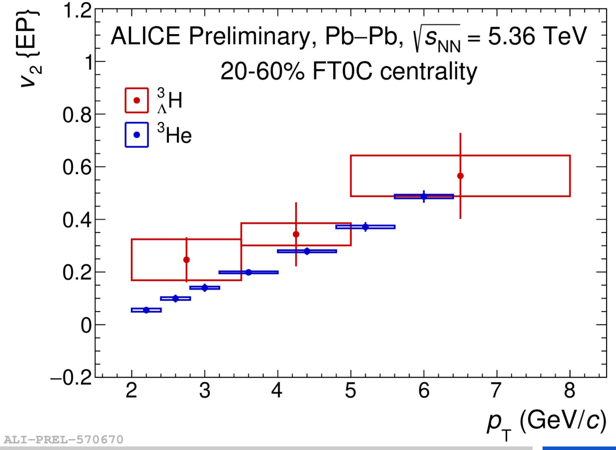


ALI-PREL-570455

Flow as a probe for nuclear production

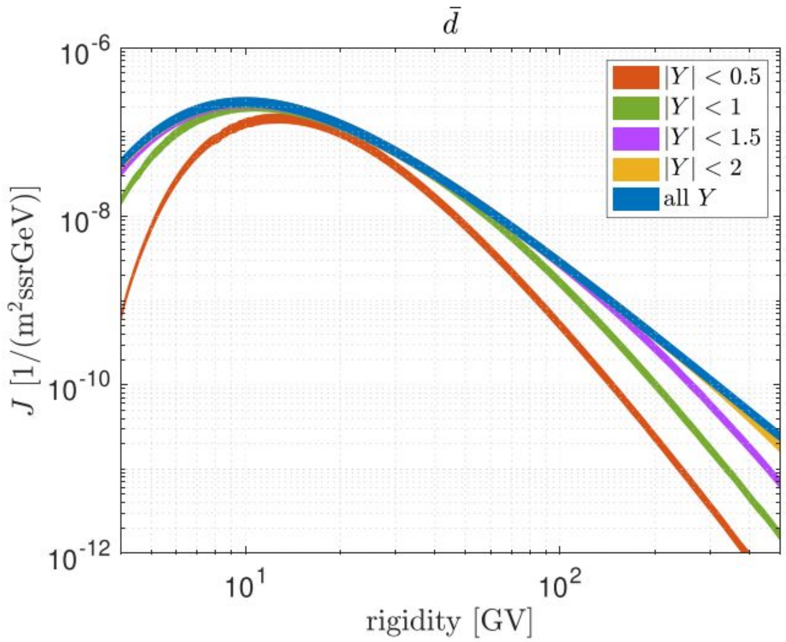
- Anisotropic flow measures the momentum anisotropy of final-state particles
  - It is sensitive to a different production in-plane and out-of-plane
  - Can be used to test production mechanisms
- ALICE has measured v_2 for (anti-)^{3}He in Run3 Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.36 TeV
  - more differential both in p_T and centrality, more precise than in Run 2
- Data are compared with the predictions of blast wave and coalescence model
  - ➤ **coalescence is favoured**
- Flow of hypertriton has been measured for the first time:
  - **compatible with ^{3}He, but large uncertainties currently**





Deuteron production vs rapidity

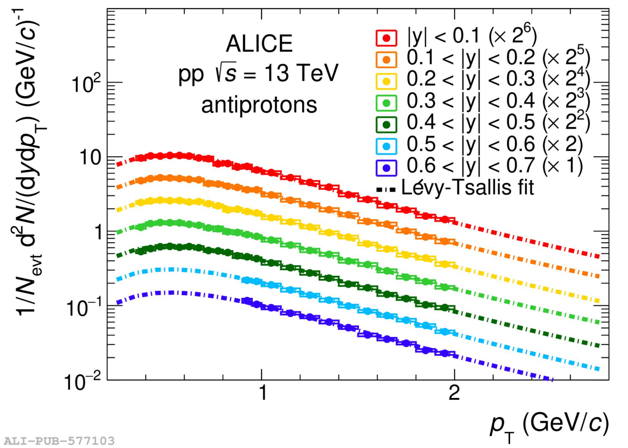
- In cosmic rays - interstellar medium collisions (anti)nuclei are mainly produced at forward rapidity:
  - important to study nuclear production vs rapidity

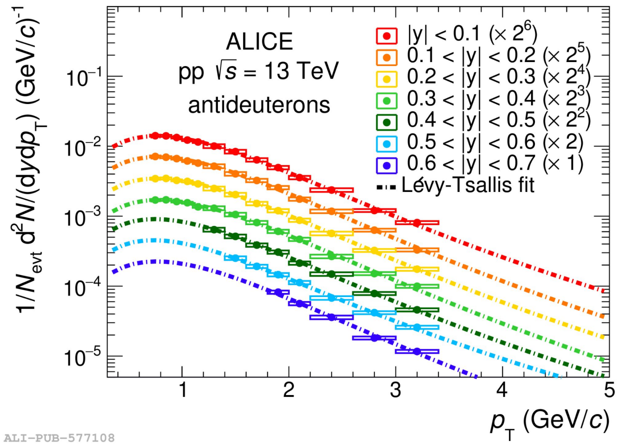


K.Blum Phys. Rev. C 109, L031904

Deuteron production vs rapidity

- In cosmic rays - interstellar medium collisions (anti)nuclei are mainly produced at forward rapidity:
  - important to study nuclear production vs rapidity
- Measurement of p and d production in rapidity intervals (|y|<0.7)

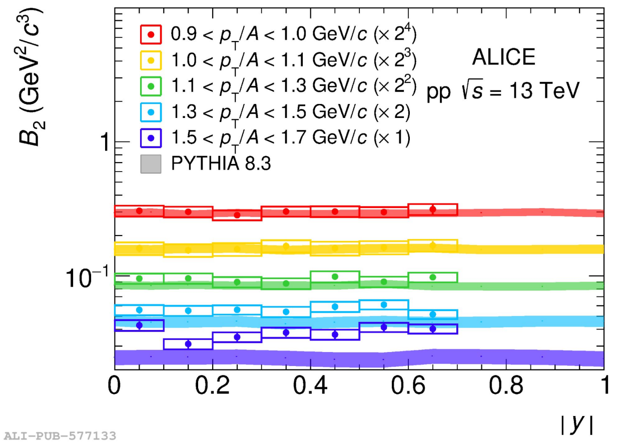


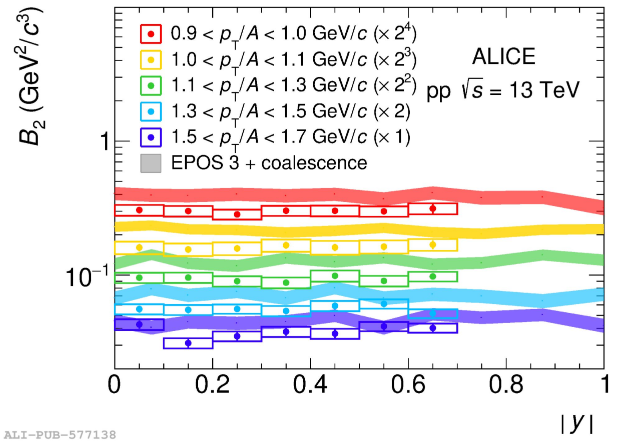


arXiv:2407.10527

Deuteron production vs rapidity

- In cosmic rays - interstellar medium collisions (anti)nuclei are mainly produced at forward rapidity:
  - important to study nuclear production vs rapidity
- Measurement of p and d production in rapidity intervals ($|y|<0.7$)
- B_2 is measured as a function of p_T and y:
  - data are compared with predictions from coalescence (PYTHIA and EPOS+**Coalescence**)
  - ➤ the shape is correctly reproduced, the magnitude not





arXiv:2407.10527

Summary

- Production of (anti)(hyper)nuclei measured at mid-rapidity in pp, p–Pb, Xe–Xe and Pb–Pb
  - light nuclei (E_B ~ MeV) are reproduced by both **SHM** and **coalescence**
  - loosely bound objects such $^{3}_{\Lambda}$H (B_{Λ} ~ 100 keV) are described better by **coalescence** as it includes nuclei size in the estimation

- With Run 3, some measurements that were possible only in Pb–Pb collisions will be accessible also in small systems

  - Measurements will help to disentangle the different production models providing a clearer understanding of the dynamics underlying nuclei formation dynamics

Backup slides

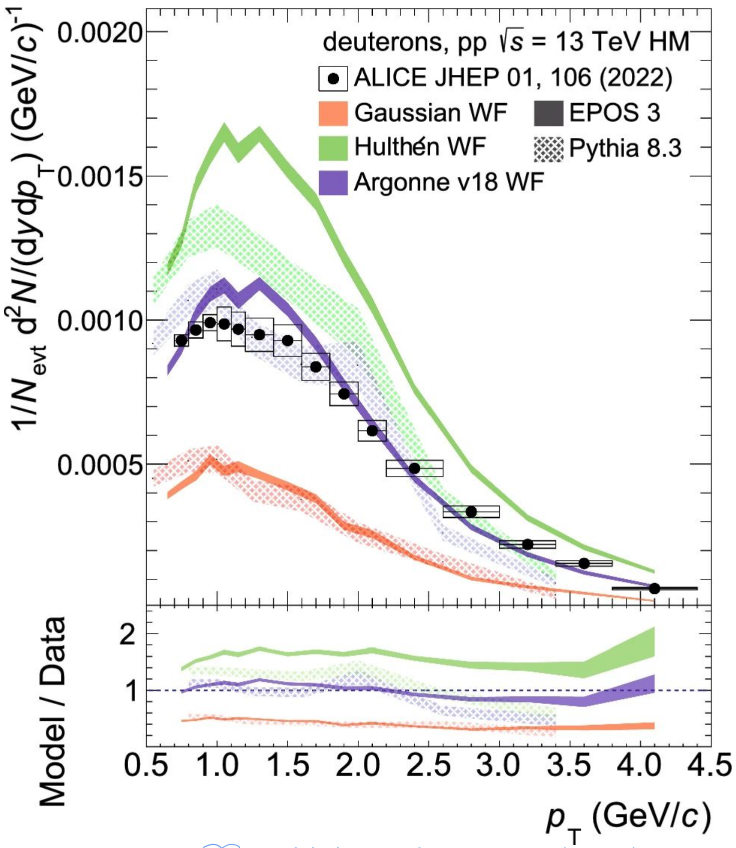
Event-by-event coalescence

- Possible to implement event-by-event coalescence, with probability:

$$\mathcal{P}(r_0, q) = \int d^3r_{\mathrm{d}} \int d^3r \, H_{\mathrm{pn}}(\vec{r}, \vec{r}_{\mathrm{d}}; r_0) \mathcal{D}(\vec{q}, \vec{r})$$

  - r_0 is the size of the emitting source
  - q is the relative p-n momentum
  - Two-particle emitting source: average two-particle distance
  - Wigner transform of the deuteron wavefunction

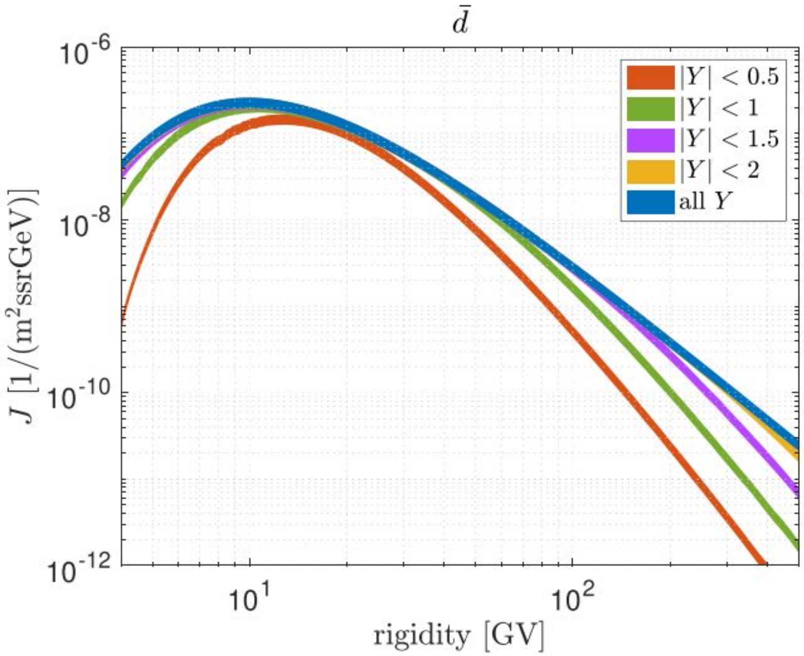
- production measurements to constrain the nuclear wave function



Mahlein et al., EPJC 83 (2023) 9, 804

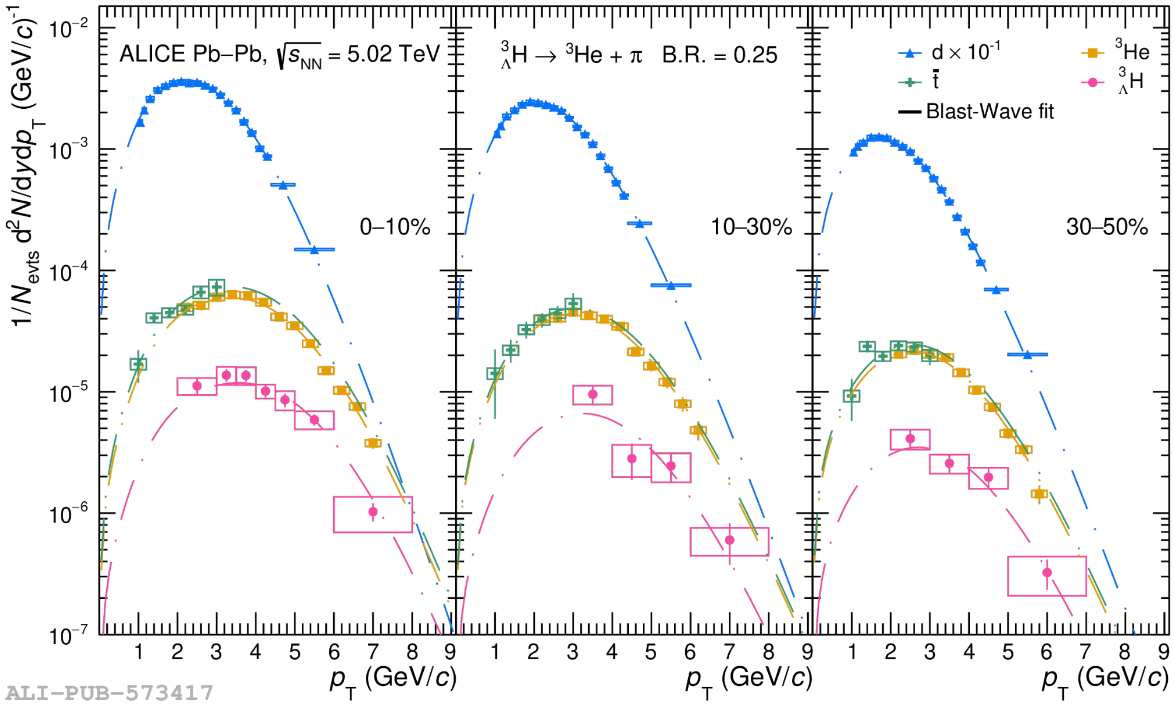
Rapidity dependence of coalescence

- Model predictions based on ALICE measurements are used as input to calculate antideuteron flux from cosmic rays
- But typically ALICE measurements cover midrapidity (|y|<0.5) while astrophysical models extrapolate to the forward region



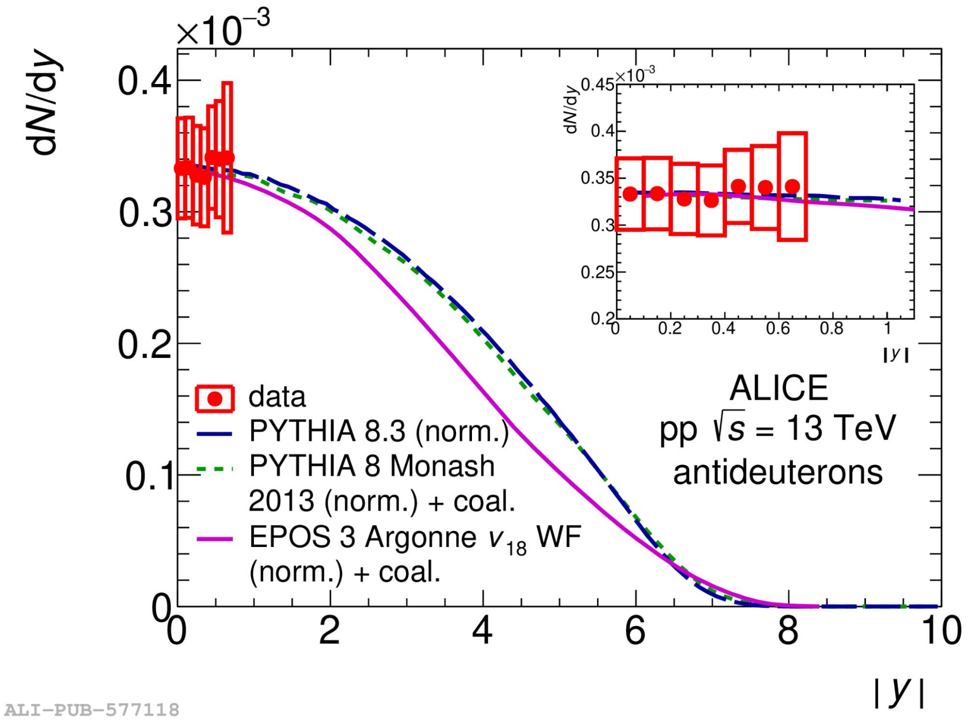
Kfir Blum Phys. Rev. C 109, L031904

$^{3}_{\Lambda}H$ p_T spectra in Pb–Pb



arXiv:2405.19839

Deuteron production vs rapidity



arXiv:2407.10527

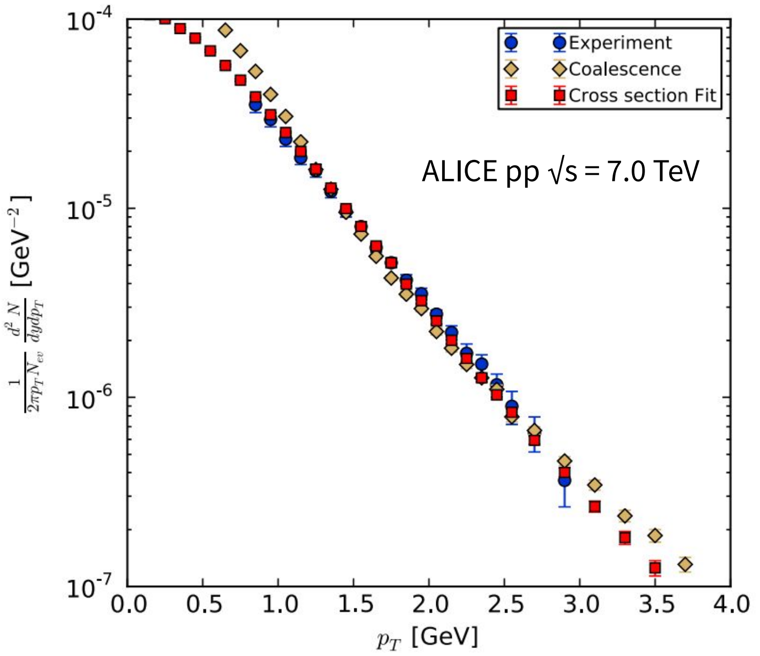
Deuteron production in PYTHIA

- PYTHIA 8.3:
  - d production via ordinary reactions
  - Energy dependent cross sections parameterized based on data

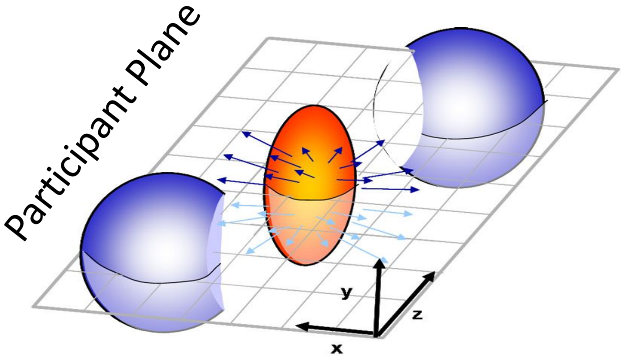
L.A. Dal, A.R. Raklev, Phys. Rev. D91 (2015) 123536

Reactions:

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



Light nuclei flow measurement



Angular distribution of reconstructed charged particles can be expanded into a Fourier series w.r.t. symmetry plane ψ_n:

$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos\left(n\left(\phi - \psi_n\right)\right)\right)$$

$$v_n = \langle \cos\left(n\left(\phi - \psi_n\right)\right)\rangle$$

- Elliptic flow (v_2) is sensitive to the system evolution:
  - It probes initial conditions and constraints particle production mechanisms

- The measurement of light nuclei v_n will help in the understanding of particle production mechanisms
  - Do light nuclei follow the mass ordering observed for lighter particles?
  - Do light nuclei follow a quark/baryon number scaling (coalescence) or follow mass scaling (hydro)?

Flow analysis method

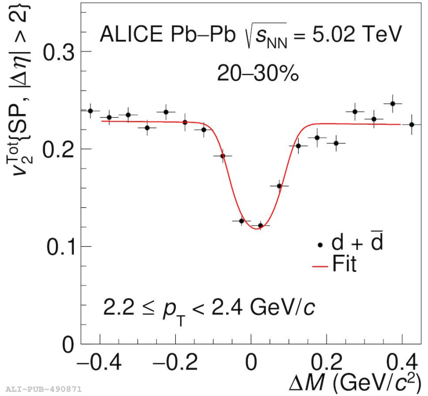
ALICE

- v_2 is measured using the scalar product method
  - Hits measured by V0A ($2.8 < \eta < 5.1$) and V0C ($-3.7 < \eta < -1.7$) are used as reference particles
  - Deuteron candidates are the particles of interest ($|\eta|<0.8$)

$$v_n\{SP\} = \frac{\left\langle u_{n,i}(p_T,\eta)\cdot \frac{Q_n^*}{M} \right\rangle}{\sqrt{\left\langle \frac{Q_{n,A}^*}{M_A}\cdot\frac{Q_{n,B}^*}{M_B}\right\rangle}}$$

- The contribution to the measured elliptic flow (v_2^{Tot}) due to misidentified deuterons (v_2^{Bkg}) was removed by studying the azimuthal correlations versus ΔM ($\Delta M = m_{TOF} - m_d$)

$$v_n(\Delta M) = v_n^{sig}\frac{N^{sig}}{N^{tot}}(\Delta M) + v_n^{bkg}(\Delta M)\frac{N^{bkg}}{N^{tot}}(\Delta M)$$



- The yields N^{Sig} and N^{Bkg} are extracted from fits of the invariant mass distribution obtained with the TOF detector

Phys. Rev. C 102 (2020) 055203