(Anti-)nuclei production and flow in pp, p–Pb and Pb–Pb collisions with ALICE

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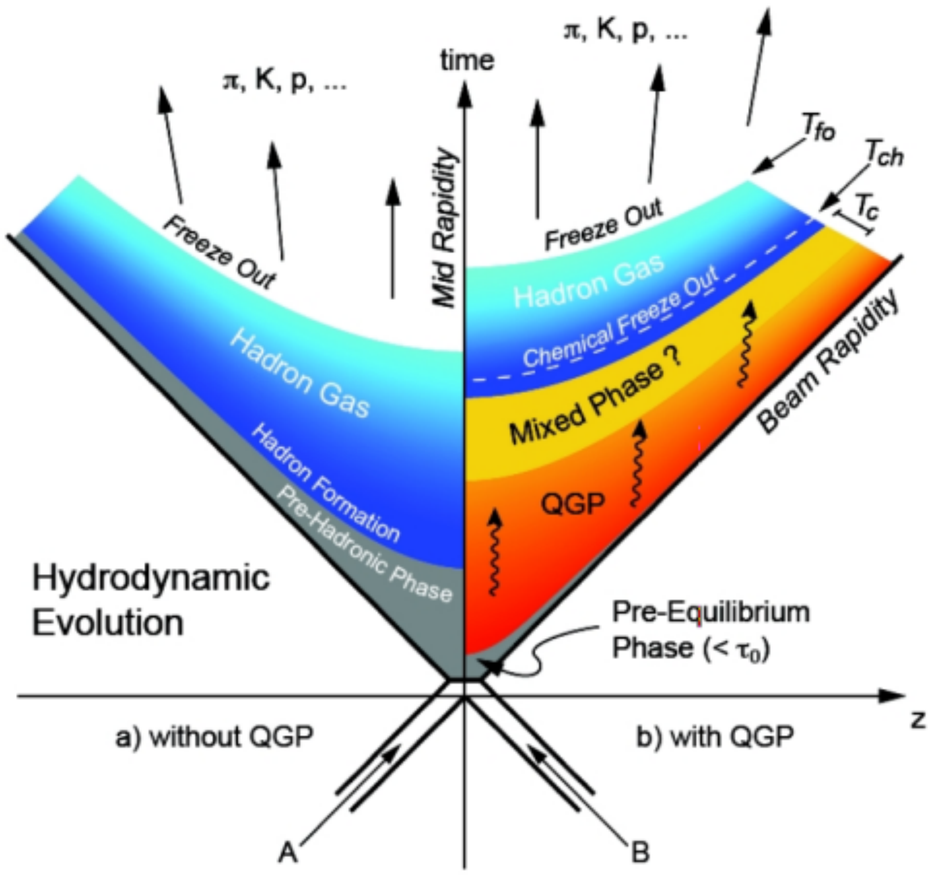
Helmholtz Graduate School for Hadron and Ion Research

EUROPEAN PHYSICAL SOCIETY EPS HEP2019

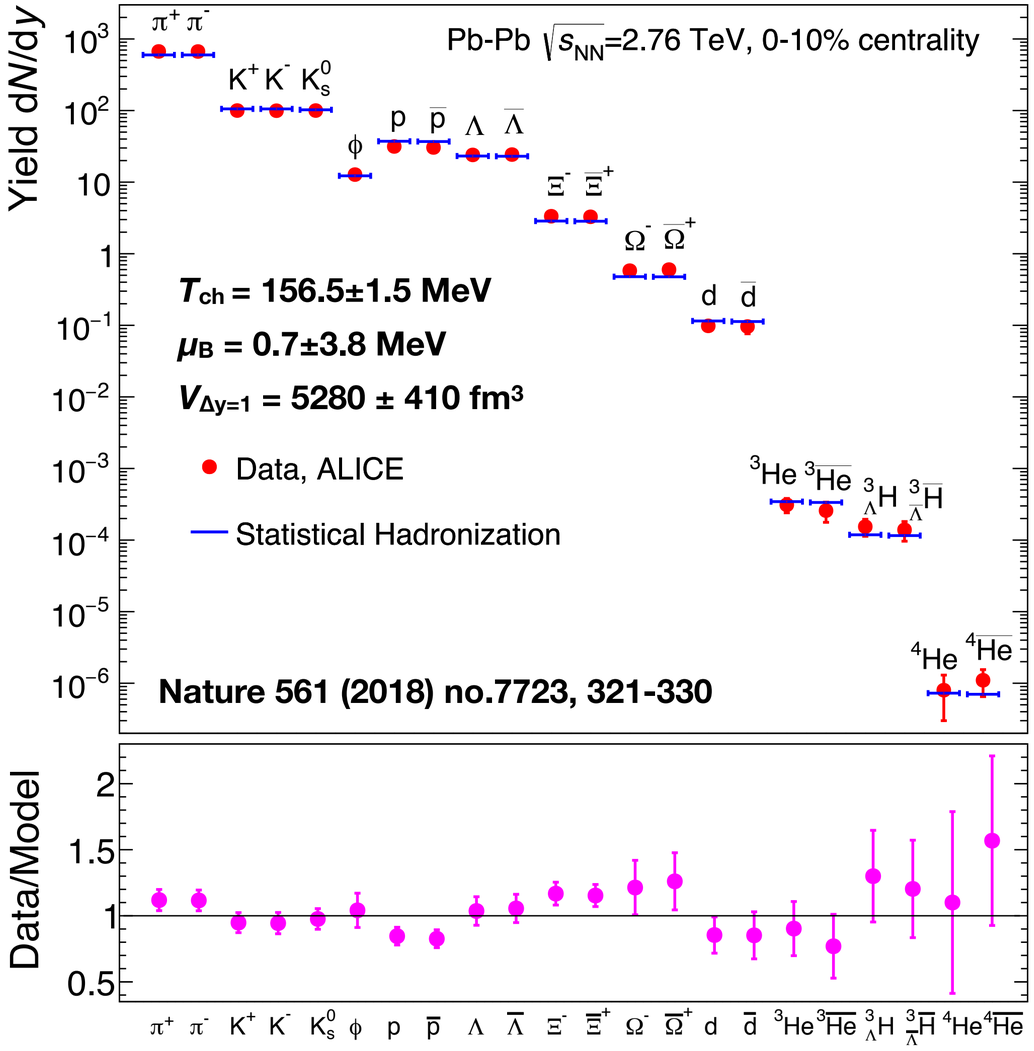
BMBF Forschungsschwerpunkt
ALICE Experiment 202
ALICE

Production of nuclei



- Significant amount of light (anti-)nuclei is produced in pp, p–Pb and Pb–Pb collisions at the LHC
- Production mechanism not completely understood
  - Separation energy E_S = O(1 MeV) small compared to the kinetic freeze-out temperature (T_{fo} ~ 100 MeV)
  - No first principle calculation possible
- Two classes of phenomenological models
  - Statistical Hadronization Model (SHM)
  - Coalescence model

Statistical Hadronisation Model



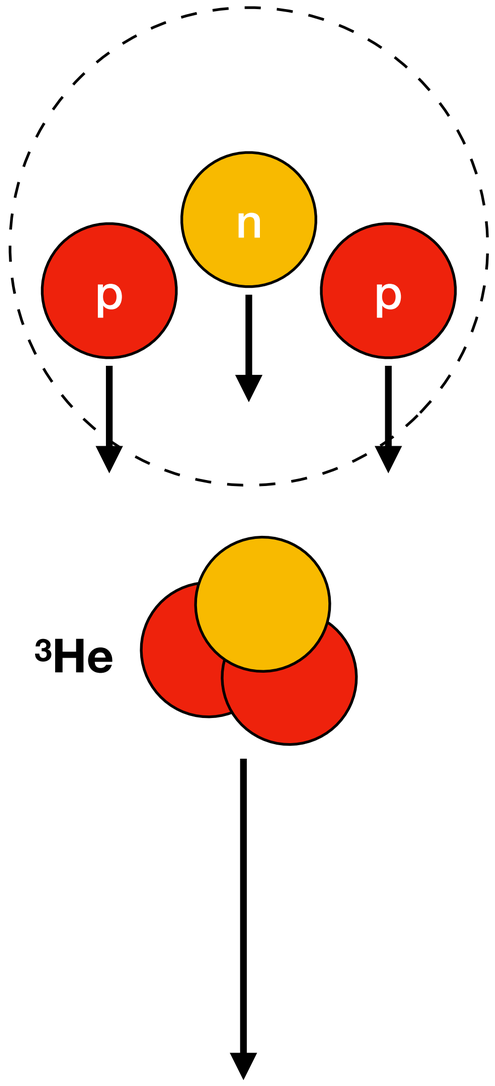
- Hadrons are emitted from a medium in statistical equilibrium at chemical freeze-out
- $dN/dy \propto \exp(-m/T_{ch})$

⇒ Strong dependence on T_{ch} for nuclei

- Pb–Pb: grand canonical ensemble
- Small systems: local conservation of quantum numbers is necessary

  ⇒ Canonical ensemble

Coalescence approach

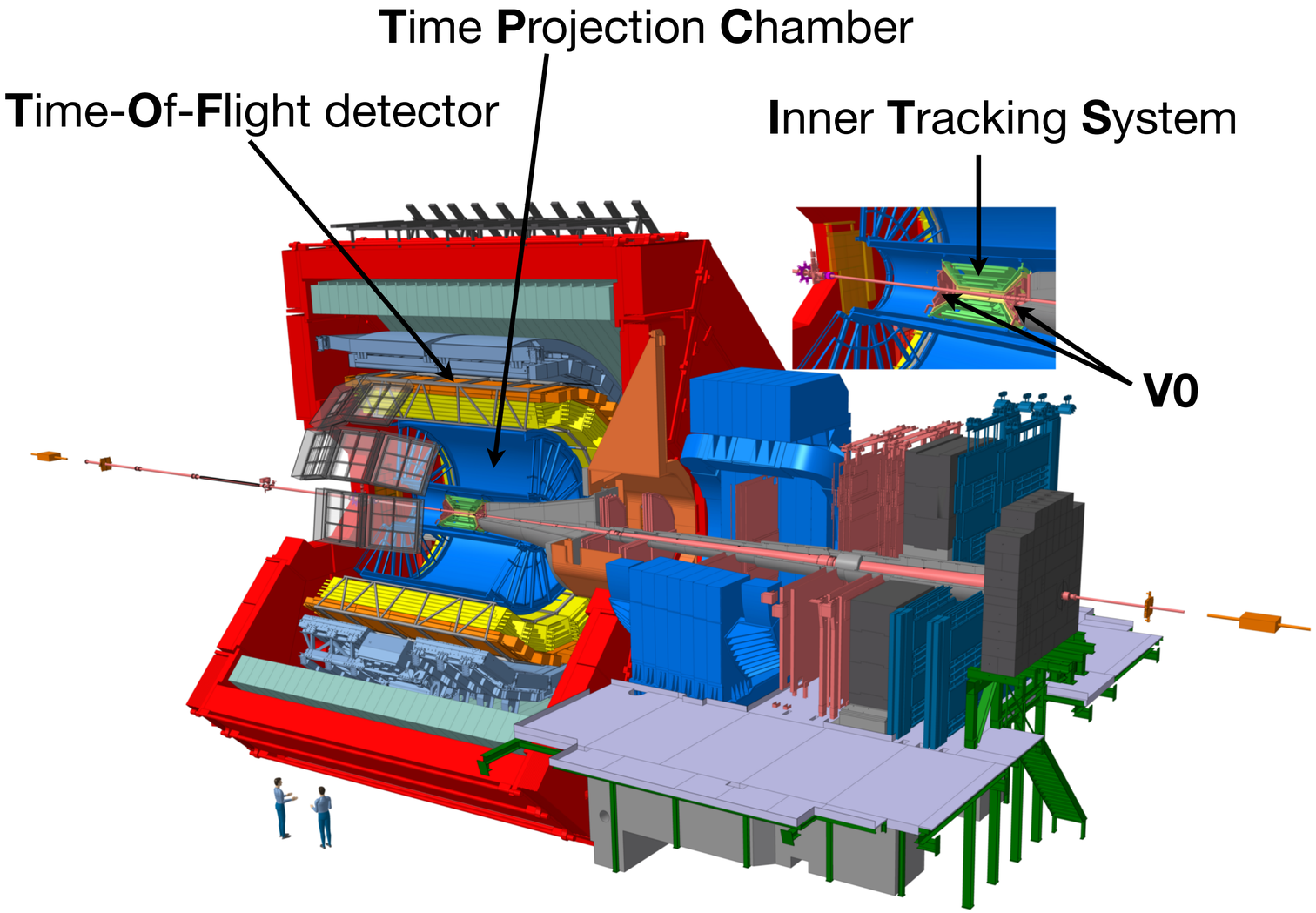


- At the kinetic freeze-out, baryons close by in phase space can form a nucleus
- Coalescence parameter B_A is the key parameter

$$E_A \frac{d^3N_A}{dp_A^3} = B_A \left(E_p \frac{d^3N_p}{dp_p^3} \right)^A \Bigg|_{\vec{p}_p = \vec{p}_A/A}$$

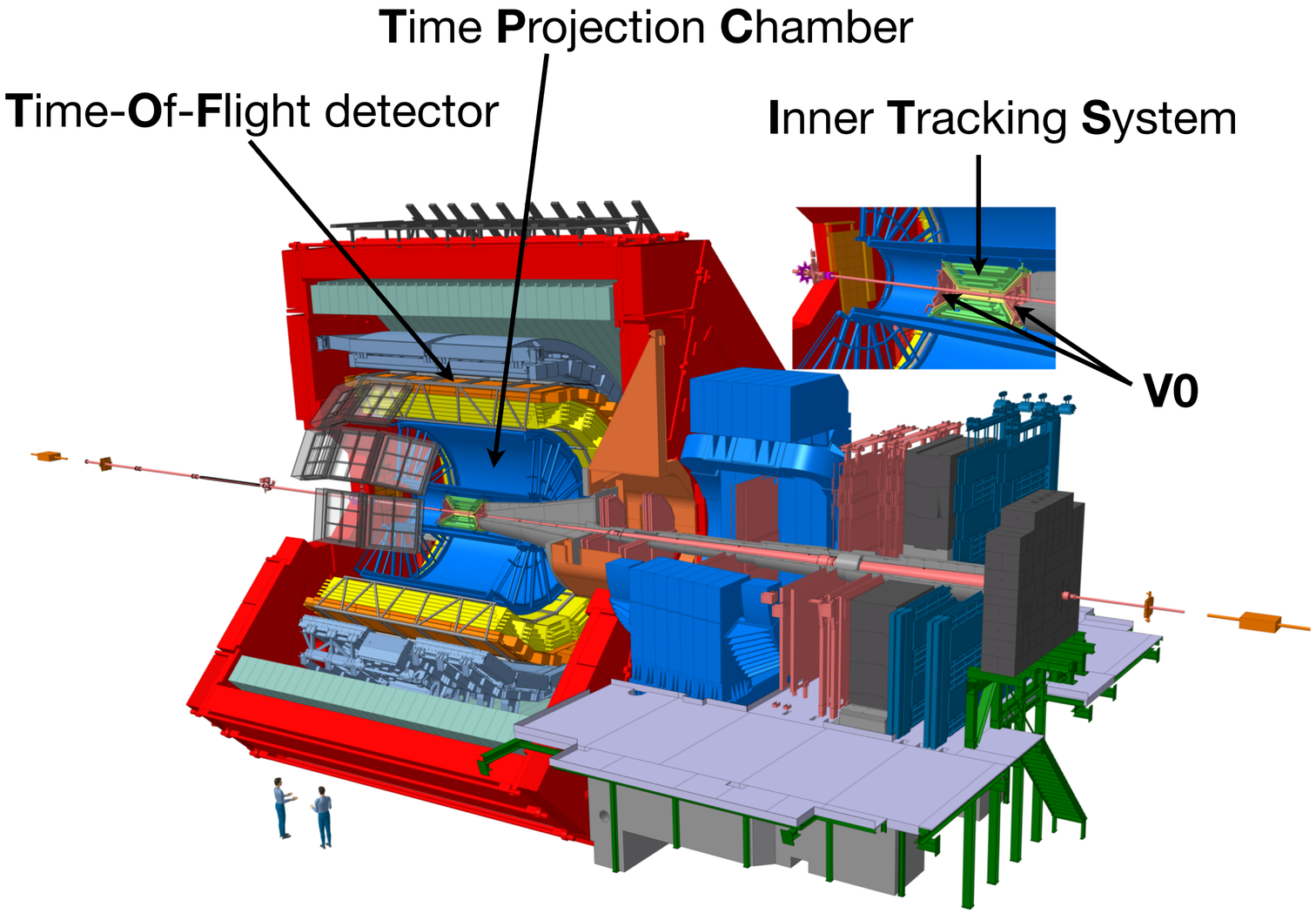
- B_A is related to the production probability
- B_A is calculable via the Wigner formalism without free parameters

The ALICE detector



- General purpose heavy-ion experiment
- Excellent tracking and particle identification (PID) capabilities
- Low material budget
- Best suited detector for studies of (anti-)nuclei production at the LHC

The ALICE detector



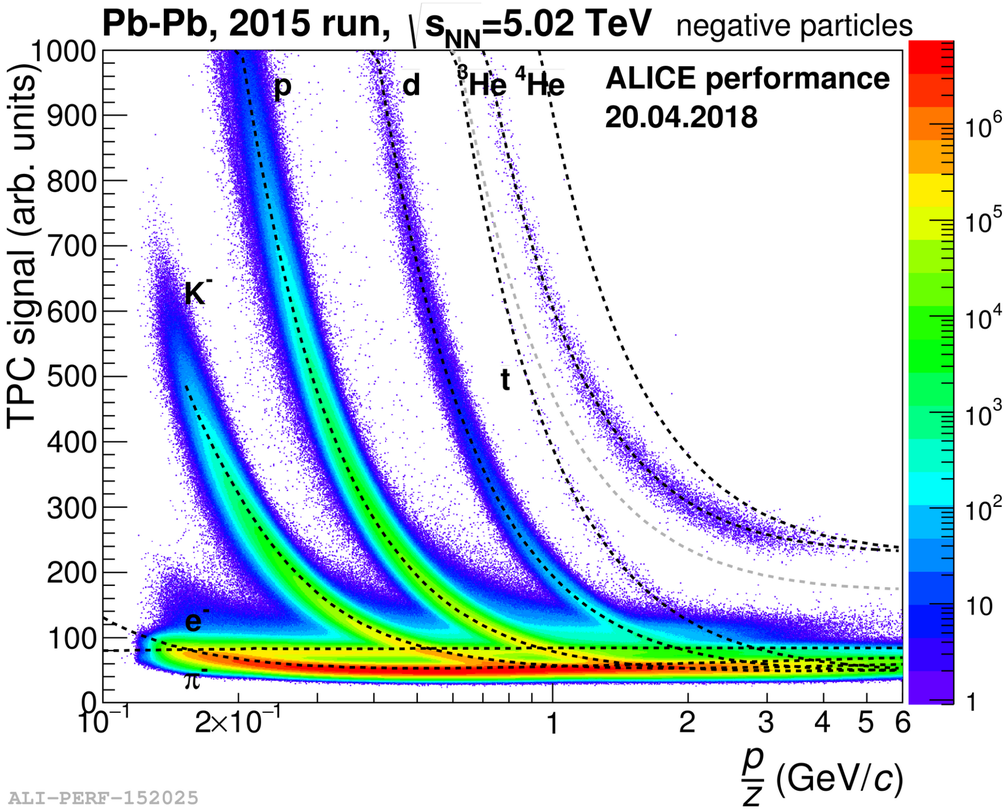
V0

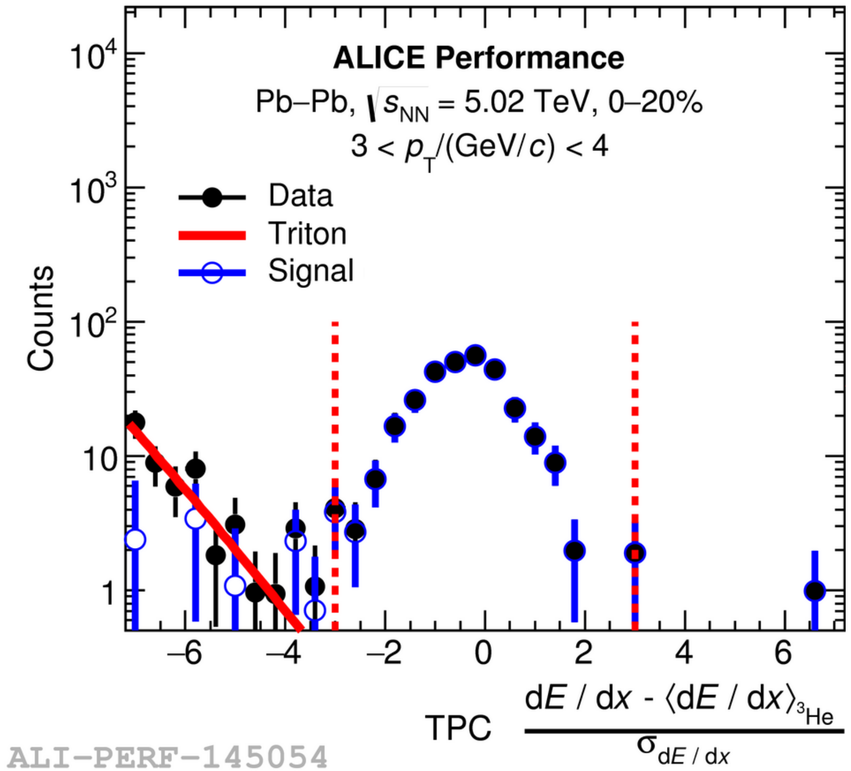
- Multiplicity / centrality estimation

Inner Tracking System

- Tracking and Vertex reconstruction
- Separation of primary and secondary vertices
- Separation of secondary nuclei (from spallation reactions)

Particle identification





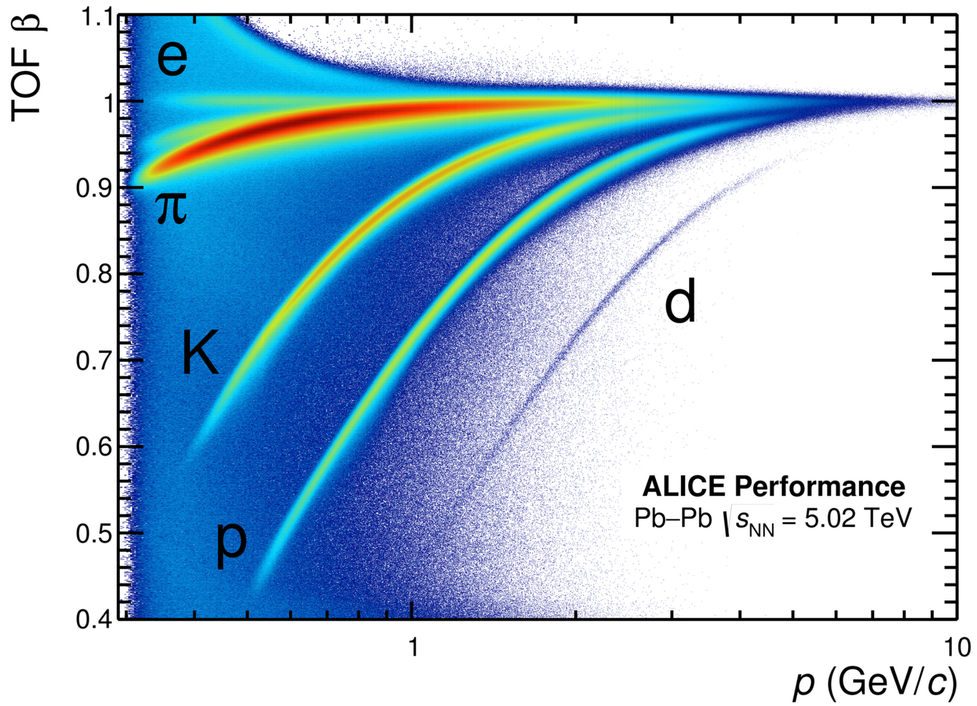
Time **P**rojection **C**hamber

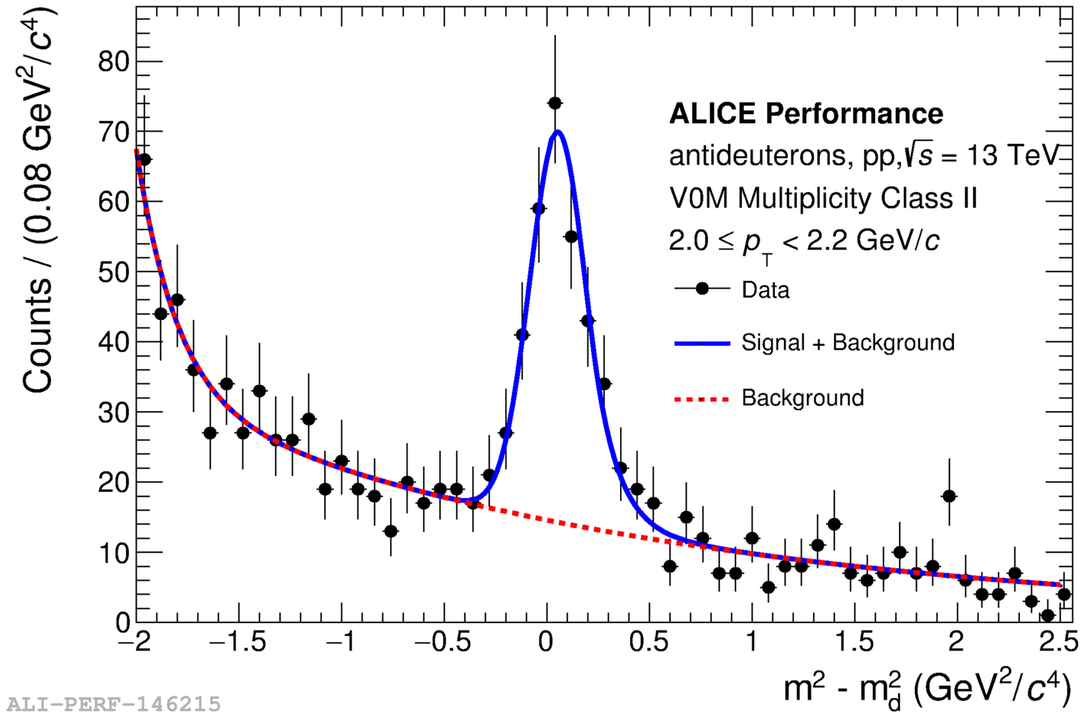
- Tracking
- PID via d*E*/d*x* measurement

Raw yield extraction

- From nσ distribution for each p_T interval

Particle identification





Time **O**f **F**light

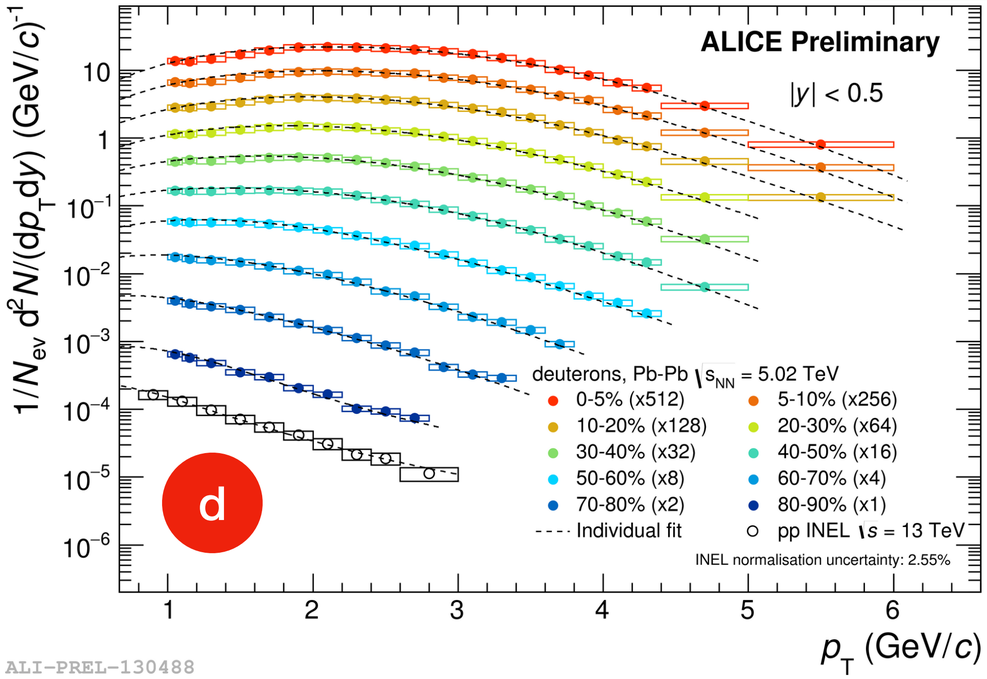
- PID via β measurement

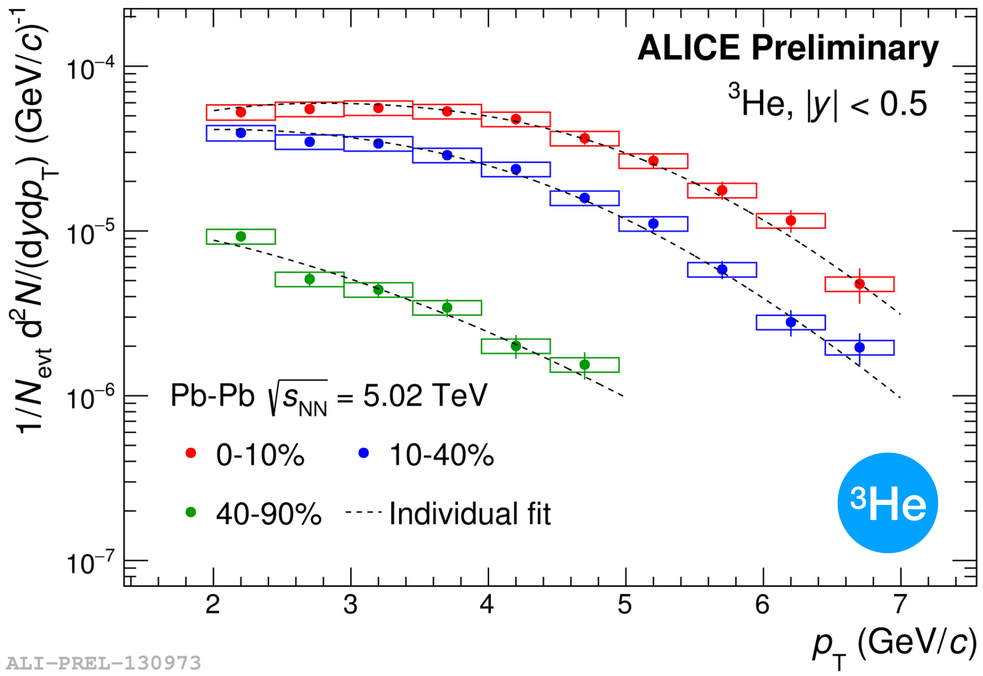
Raw yield extraction

- From TOF m^2 distribution for each p_T interval

Deuteron and ^{3}He spectra in Pb–Pb

Pb–Pb, $\sqrt{s_{NN}}$ = 5 TeV

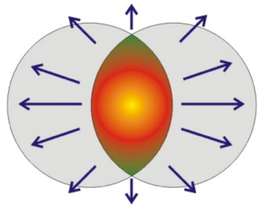




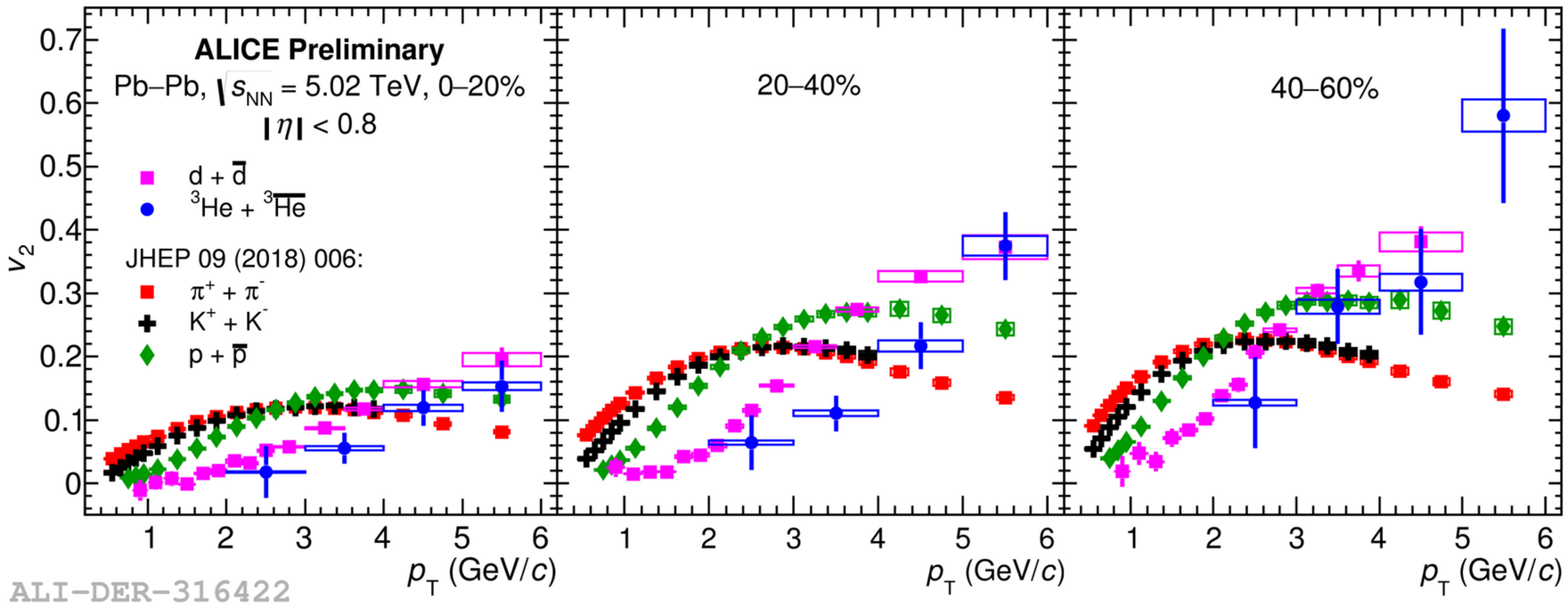
- p_T spectra fitted with Blast-Wave function ⇒ Extrapolation to unmeasured regions
- Hardening with increasing centrality ⇒ Collective motion (radial flow)
  - Consistent with both coalescence and SHM (hydrodynamics + hadron resonance gas model)

Deuteron and ^{3}He elliptic flow v_2

$$\frac{d^3N}{dp^3} \propto (1 + 2\sum_{n=1}^{\infty} v_n \cos(n(\phi - \Psi_n)))$$



Pb–Pb, $\sqrt{s_{NN}}$ = 5 TeV



- Mass ordering at low p_T, increasing trend with p_T and for more peripheral events
  - Expectations from relativistic hydrodynamics are fulfilled

Comparison to simplified models

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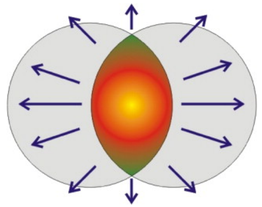

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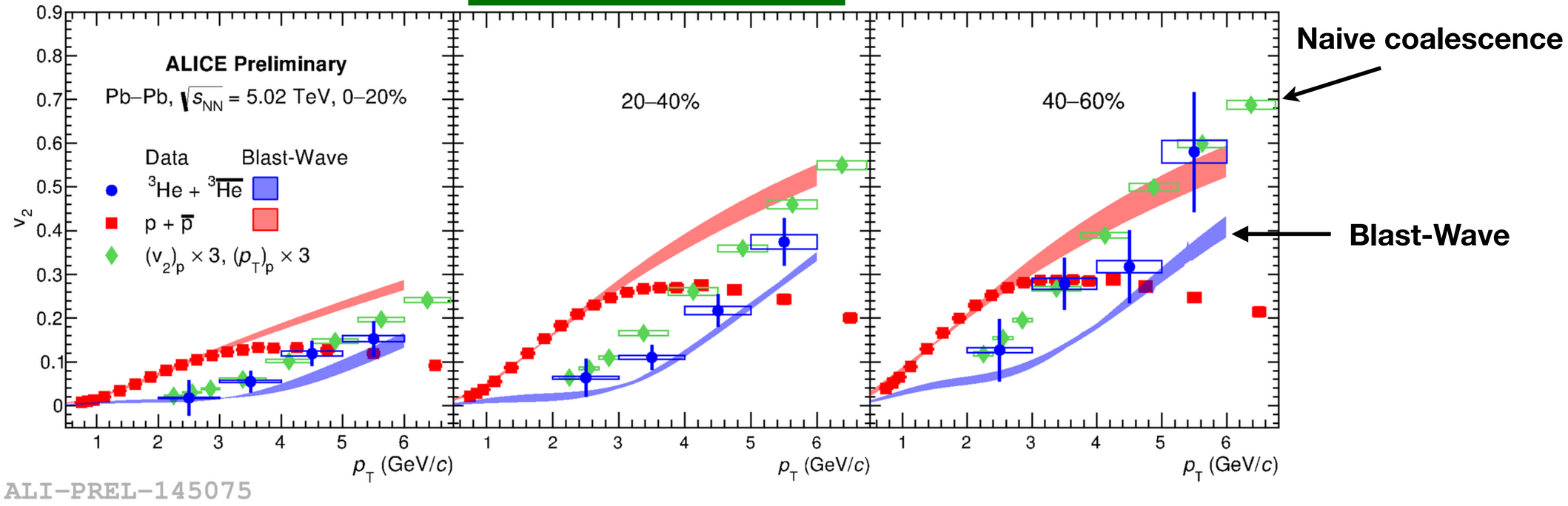
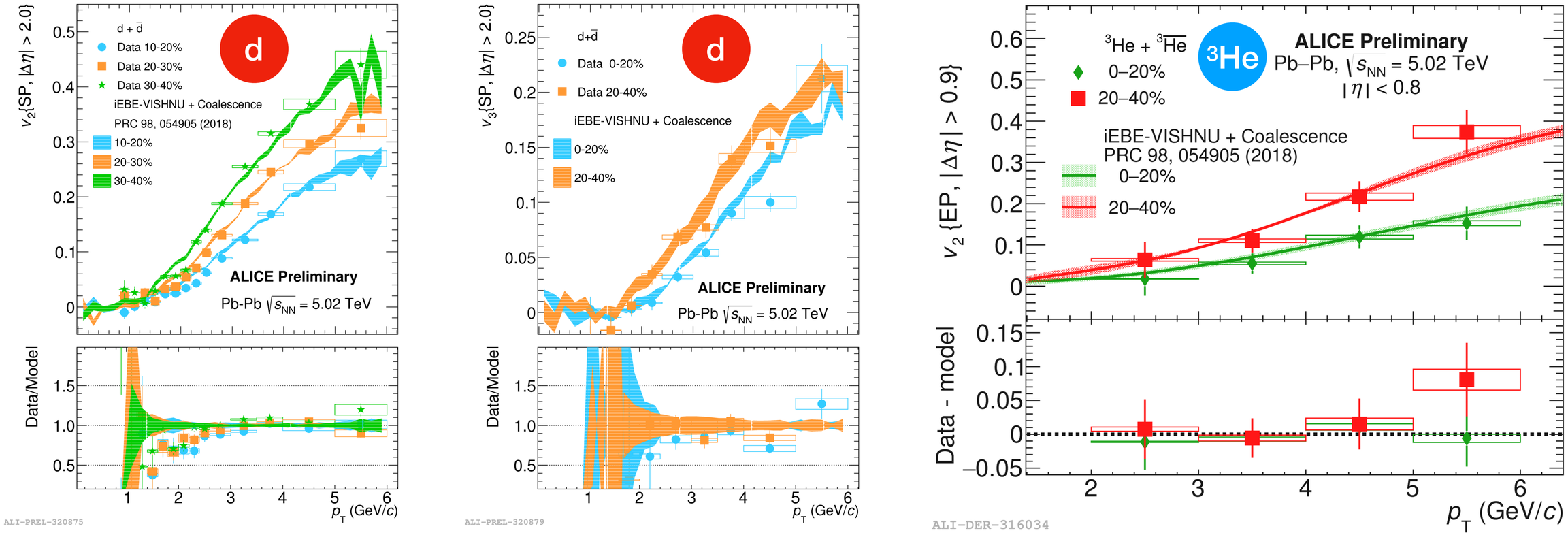


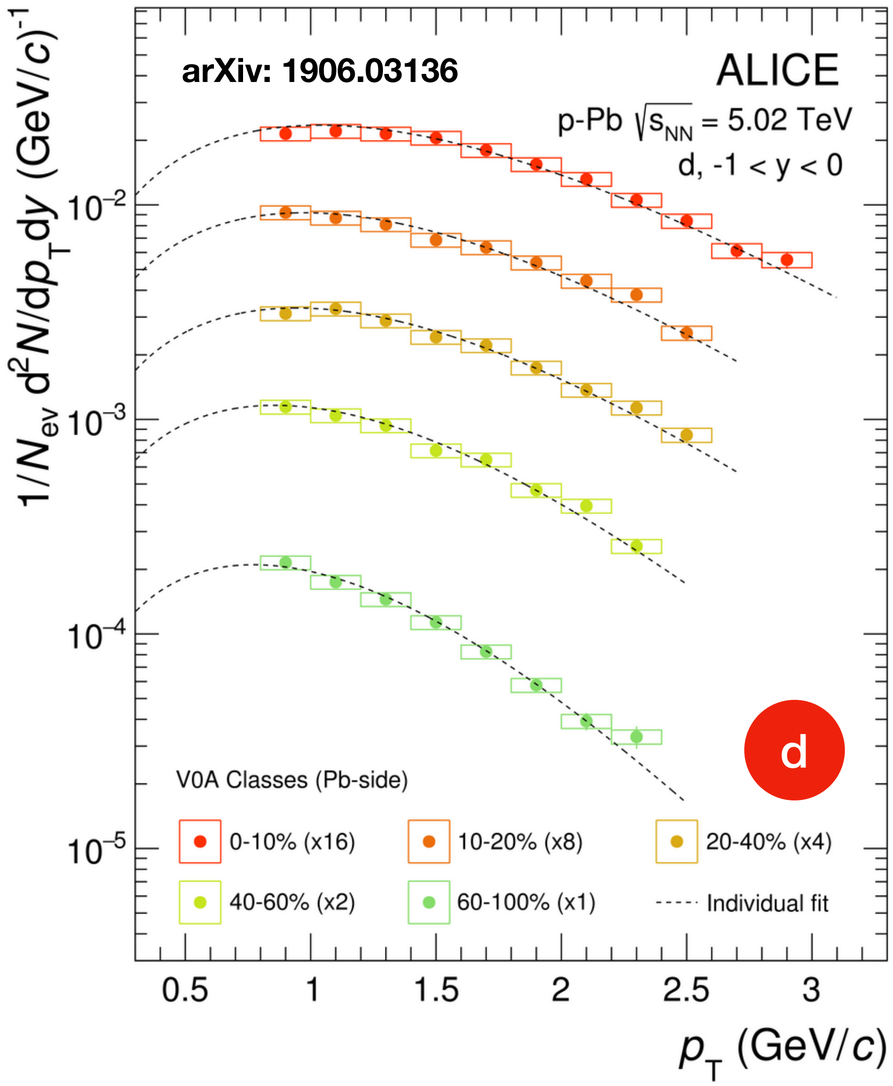
- v_2 of (anti-)^{3}He lies in between Blast-Wave and naive coalescence
  - Simplified hydrodynamic and coalescence models do not describe the data

Comparison to state-of-the-art coalescence



- Hydrodynamical simulation (iEBE-VISHNU) + coalescence (**Wenbin, PRC 98, 054905 (2018)**)
  - Good description of the deuteron v_2 and v_3 as well as the ^{3}He v_2 in 0-40%
- No predictions available for more peripheral collisions or SHM

Deuteron spectra in p–Pb

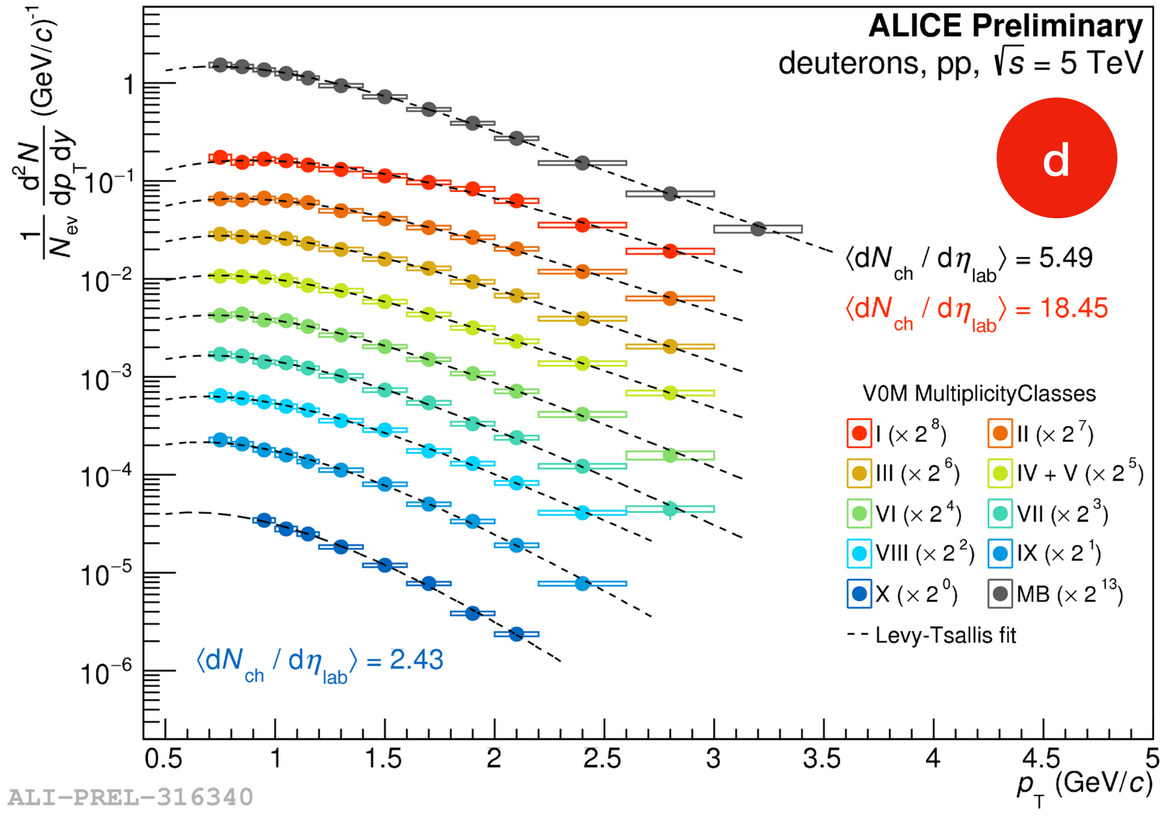


p–Pb, $\sqrt{s_{NN}}$ = 5 TeV

- Fit with Blast-Wave function unstable
- p_T spectra fitted with m_T-exponential function
- Hardening less pronounced than in Pb–Pb

Deuteron spectra in pp

pp, $\sqrt{s}$ = 5 TeV

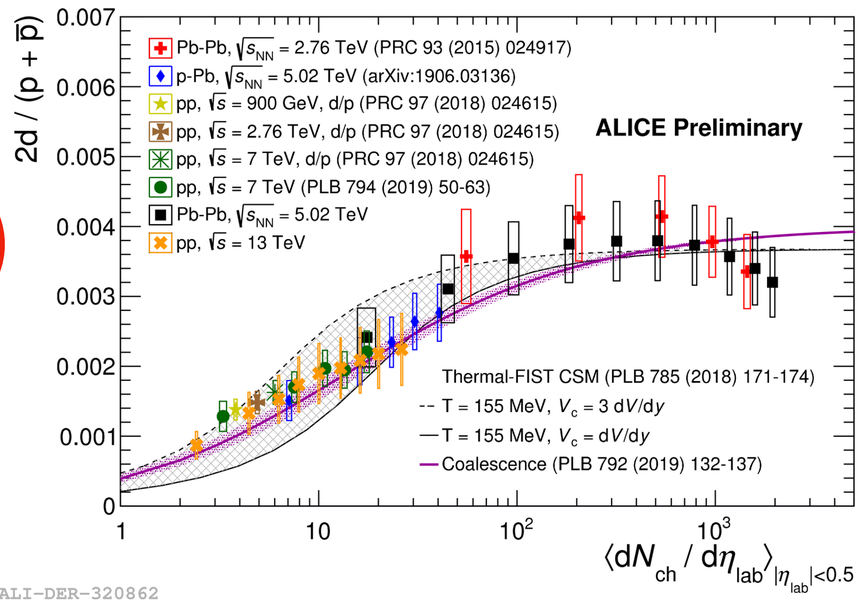


- p_T spectra fitted with Lévy-Tsallis[1] function
  ⇒ Extrapolation to unmeasured regions
- Hardening less pronounced than in Pb–Pb

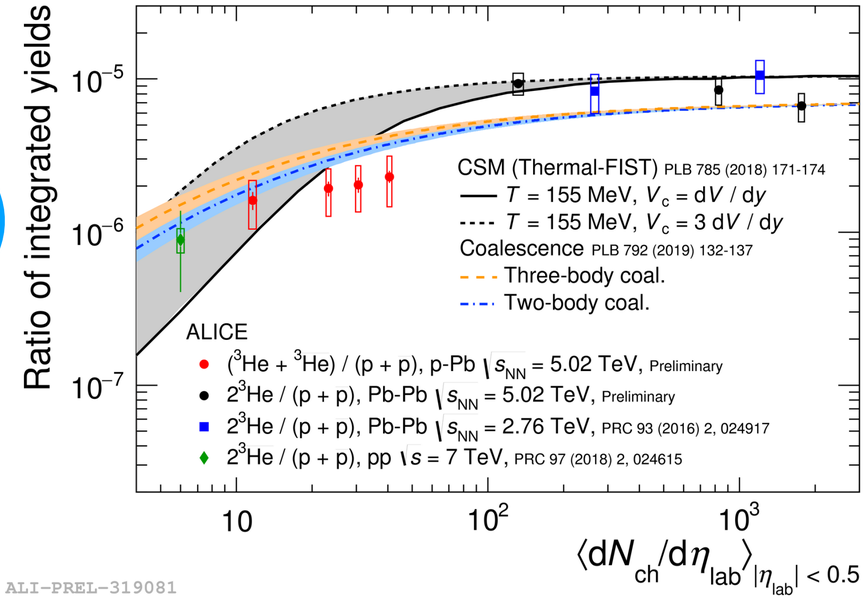
$$^{1}: \frac{d^2N}{dp_T dy} \propto \frac{(n-1)(n-2)}{nC[nC + m(n-2)]} \left(1 + \frac{m_T - m}{nC}\right)^{-n}$$

Ratio to protons

d/p



^{3}He/p



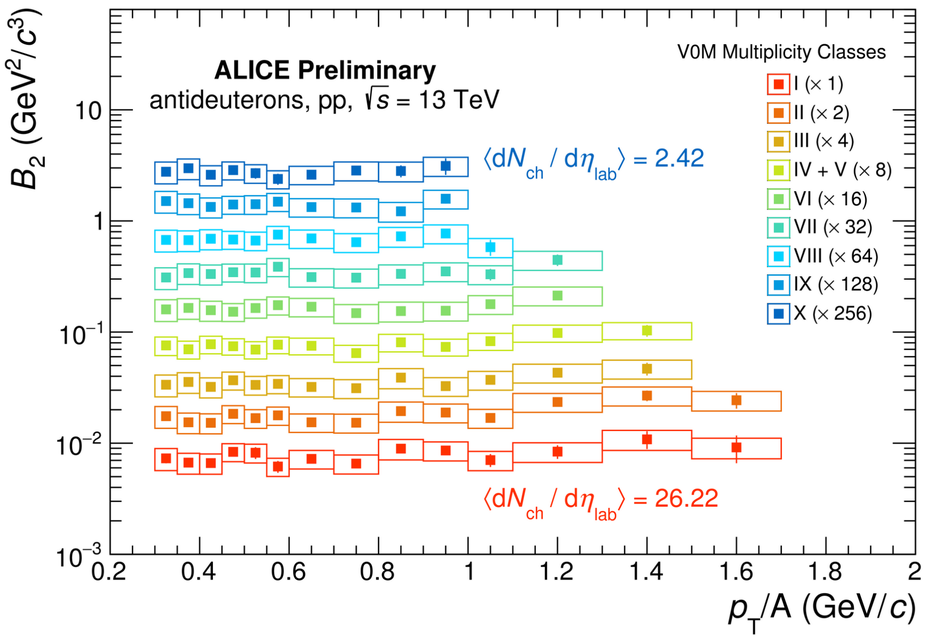
- Continuous evolution with multiplicity
  - ⇒ Smooth transition from small to large system size
  - ⇒ Single underlying production mechanism?
- Increasing trend at low and intermediate multiplicities
  - SHM: Canonical suppression ⇔ Tension[1] for ALICE p/π
  - Coalescence: increasing phase space
- No dependence of the ratio on multiplicity for high multiplicities
  - In agreement with both SHM and coalescence
  - Coalescence prediction below data for ^{3}He

[1]**Vovchenko, arXiv: 1906.03145**

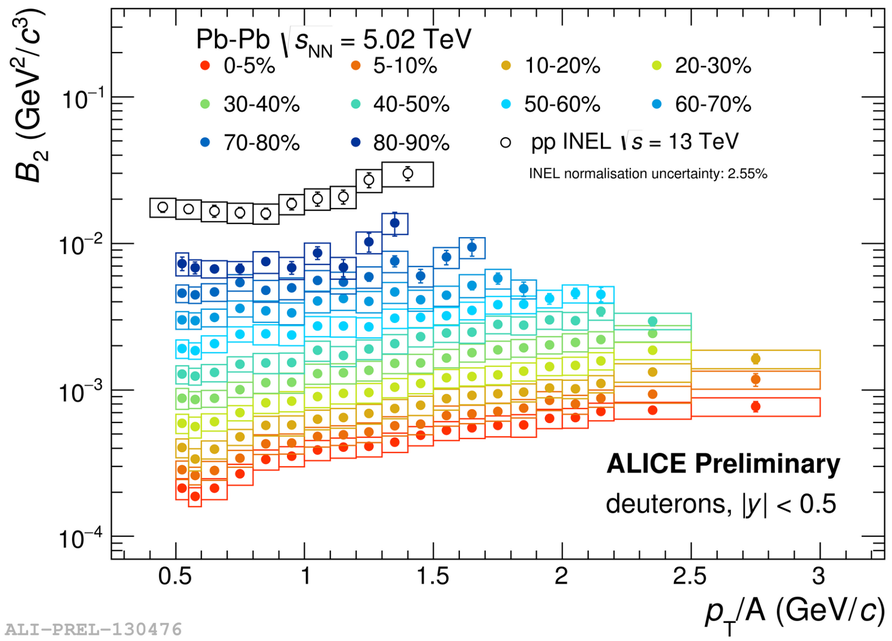
Coalescence parameter B_A

$$E_A \frac{d^3N_A}{dp_A^3} = B_A \left(E_p \frac{d^3N_p}{dp_p^3} \right)^A \Bigg|_{\vec{p}_p = \vec{p}_A/A}$$

pp, $\sqrt{s}$ = 13 TeV



Pb–Pb, $\sqrt{s_{NN}}$ = 5 TeV



- Measurements in pp are compatible with a flat B_A predicted by naive coalescence
- Trend with p_T/A in p–Pb and Pb–Pb collisions described by recent hydrodynamic calculations with afterburner (**Oliinychenko, PRC 99, 044907 (2019)**)

Coalescence parameter B_A

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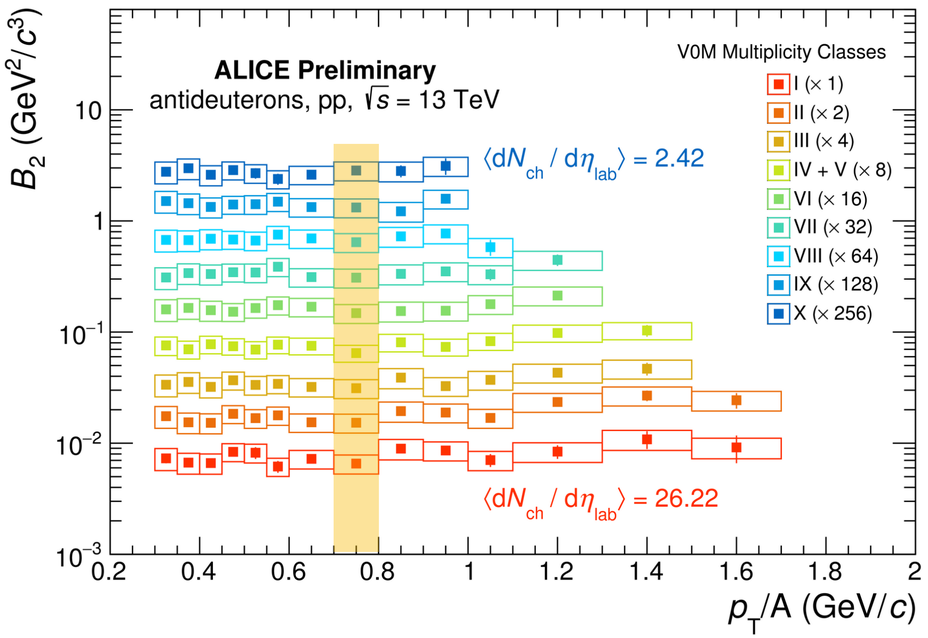

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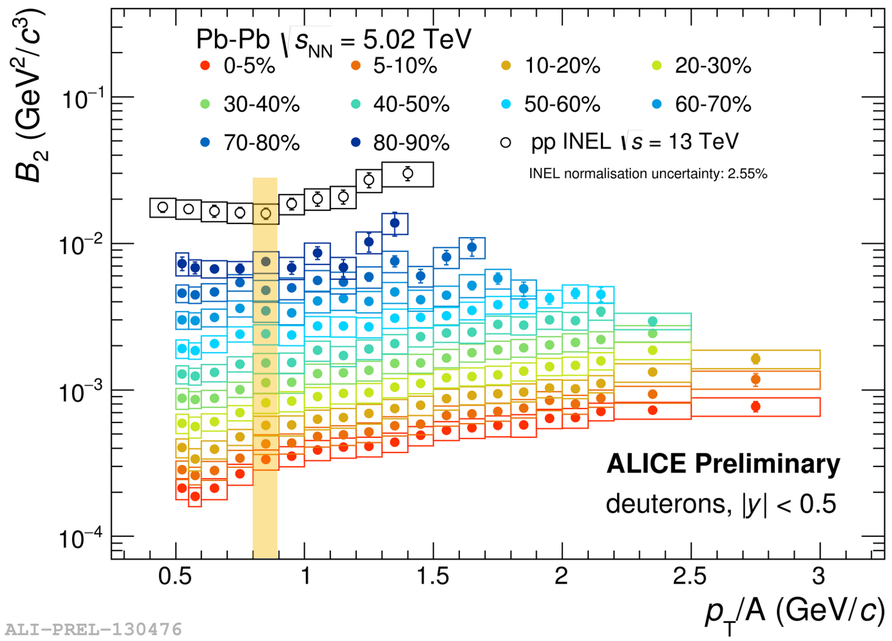

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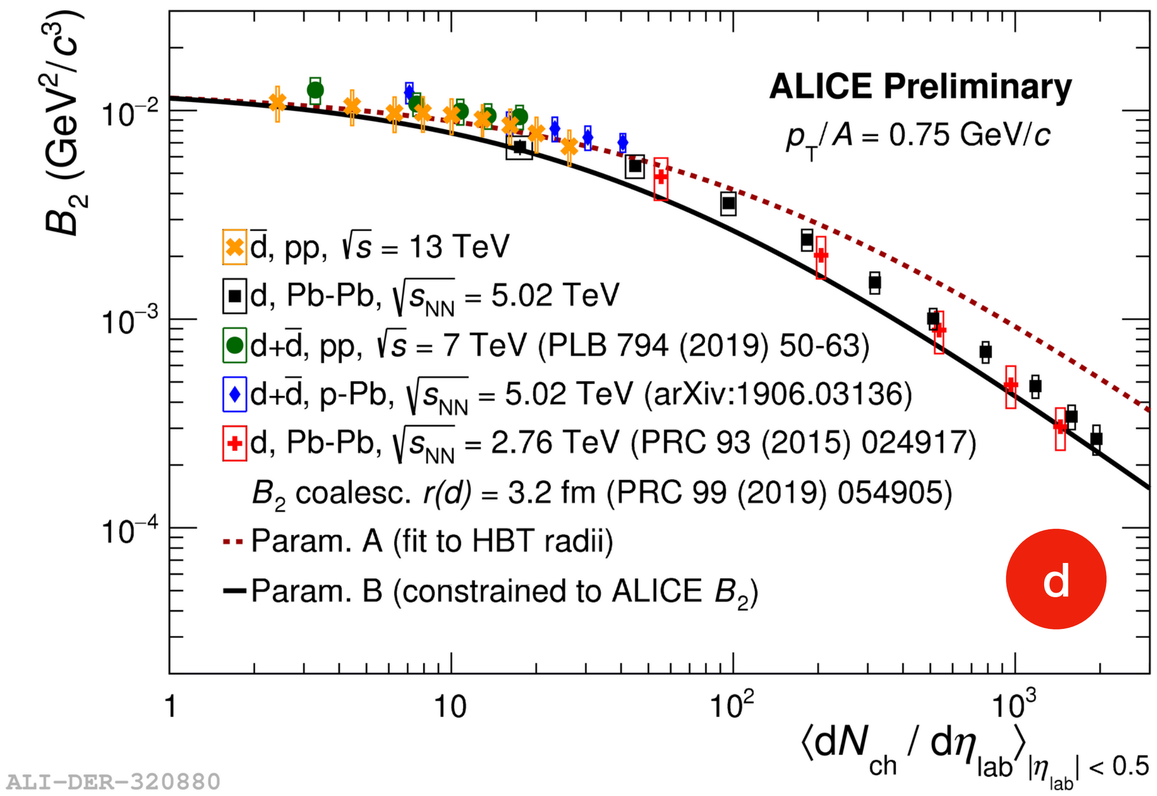
Coalescence parameter B_A



- Continuous evolution of B_A with multiplicity
  - ⇒ Smooth transition from small to large system size
  - ⇒ Single underlying production mechanism?
- Advanced coalescence taking the size of the nucleus and the emitting source into account predicts a similar trend

Conclusions

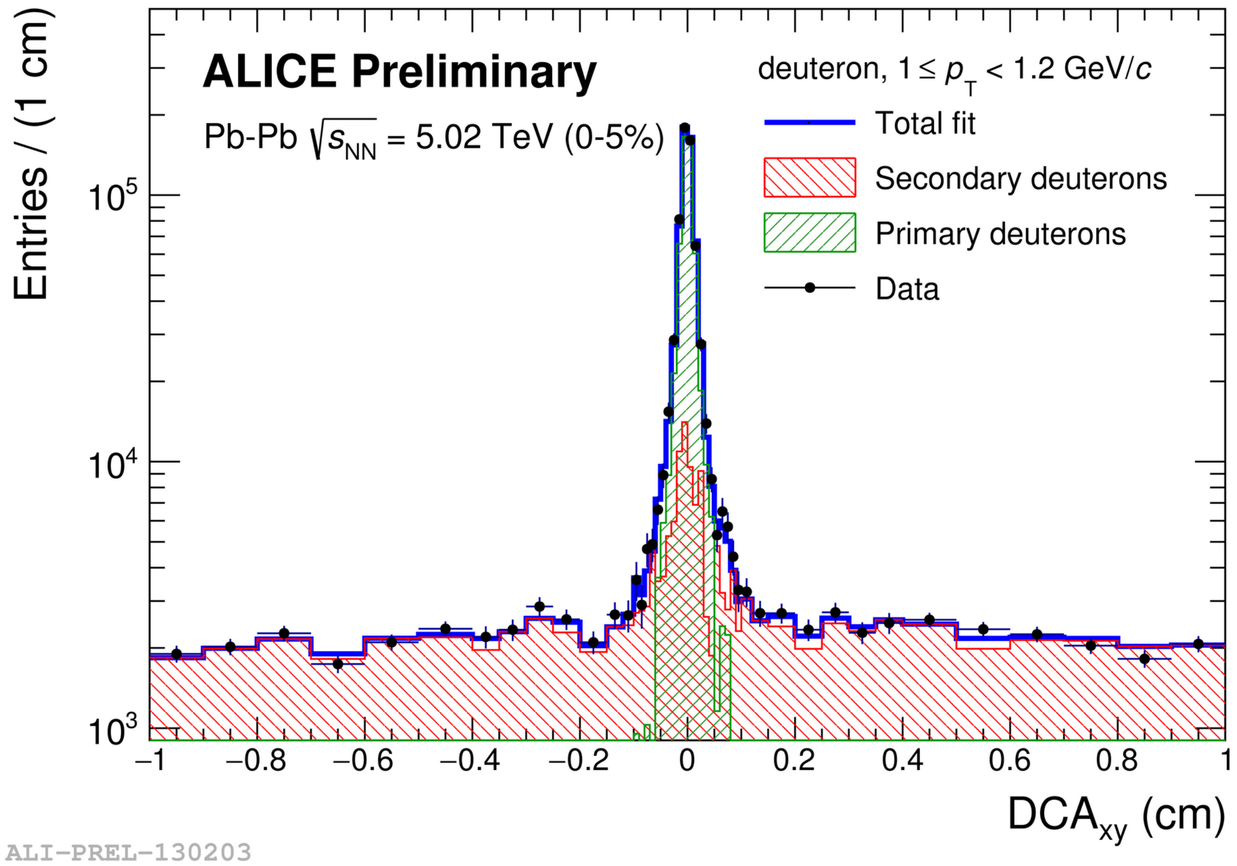
- ALICE has measured the production of light (anti-)nuclei in different collision systems and at different energies
- Measurements of the ratio-to-protons as well as the coalescence parameter as a function of the multiplicity show a smooth transition from small to large system size
  - Canonical Statistical Model can describe the evolution of the ratio-to-protons but there is some tension with the measured p/π ratio
  - Coalescence has difficulties to describe the data at high multiplicities
- State-of-the-art coalescence describes the flow of deuterons and ^{3}He
  - SHM predictions (hydrodynamics + hadron resonance gas model) are not available

⇒ More precise data and models are needed to clarify the production mechanism of light (anti-)nuclei

Thank you for your attention!

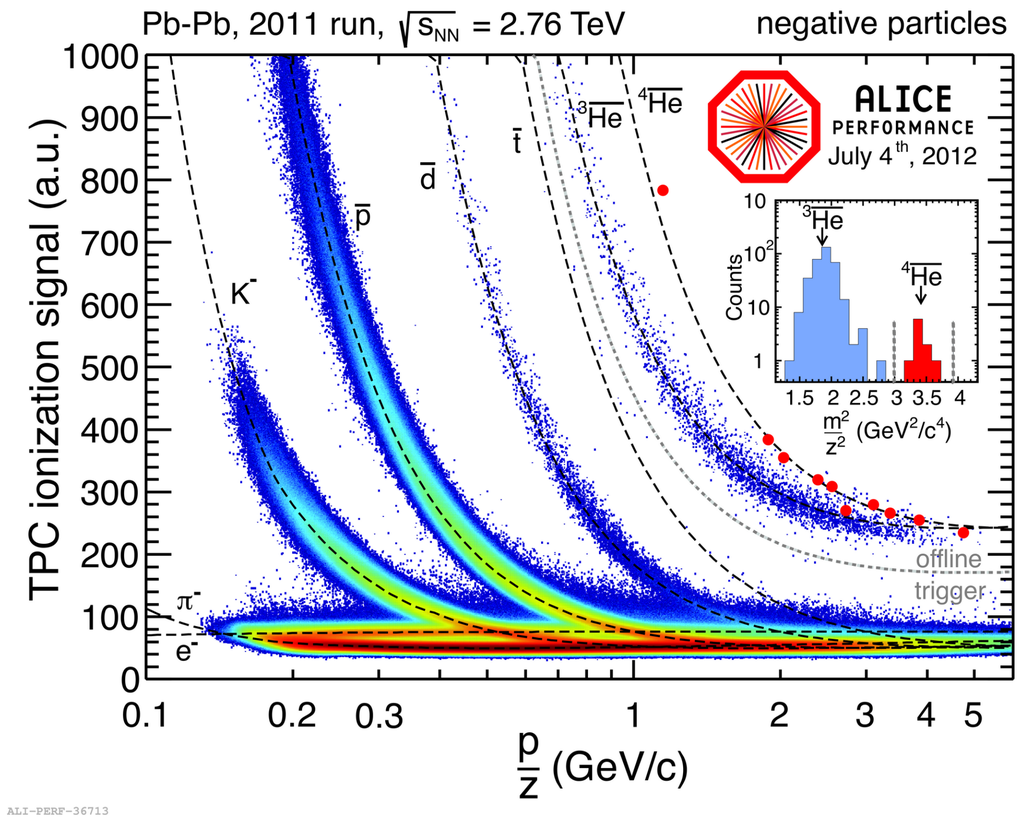
Back-up

Removal of secondary nuclei



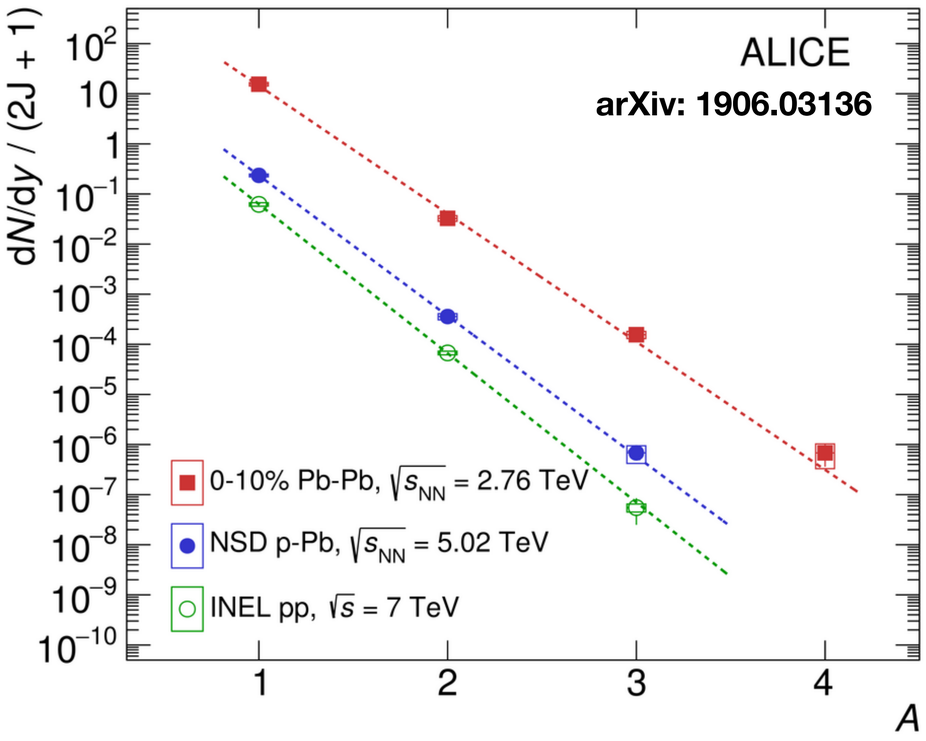
- Secondary nuclei from spallation affect the signal at low p_T
  - Distance-of-closest approach to the primary vertex distribution should be flat
  - Peak around zero due to wrong assignment of ITS cluster
- Fraction of primary nuclei obtained via fits of MC templates

Anti-^{4}He production in Pb–Pb



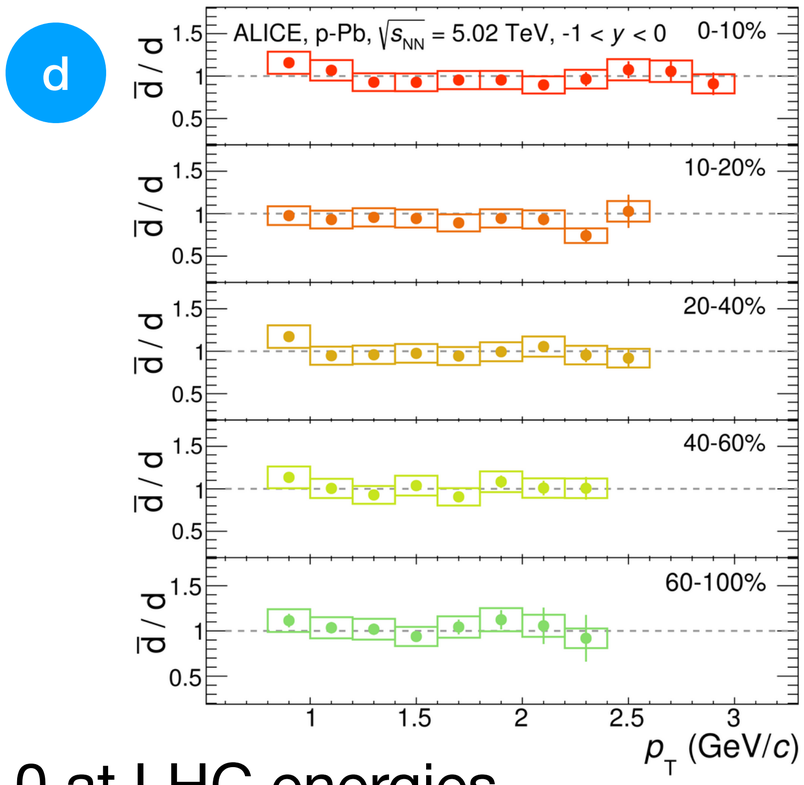
- Anti-^{4}He yield has been measured in Pb–Pb collisions

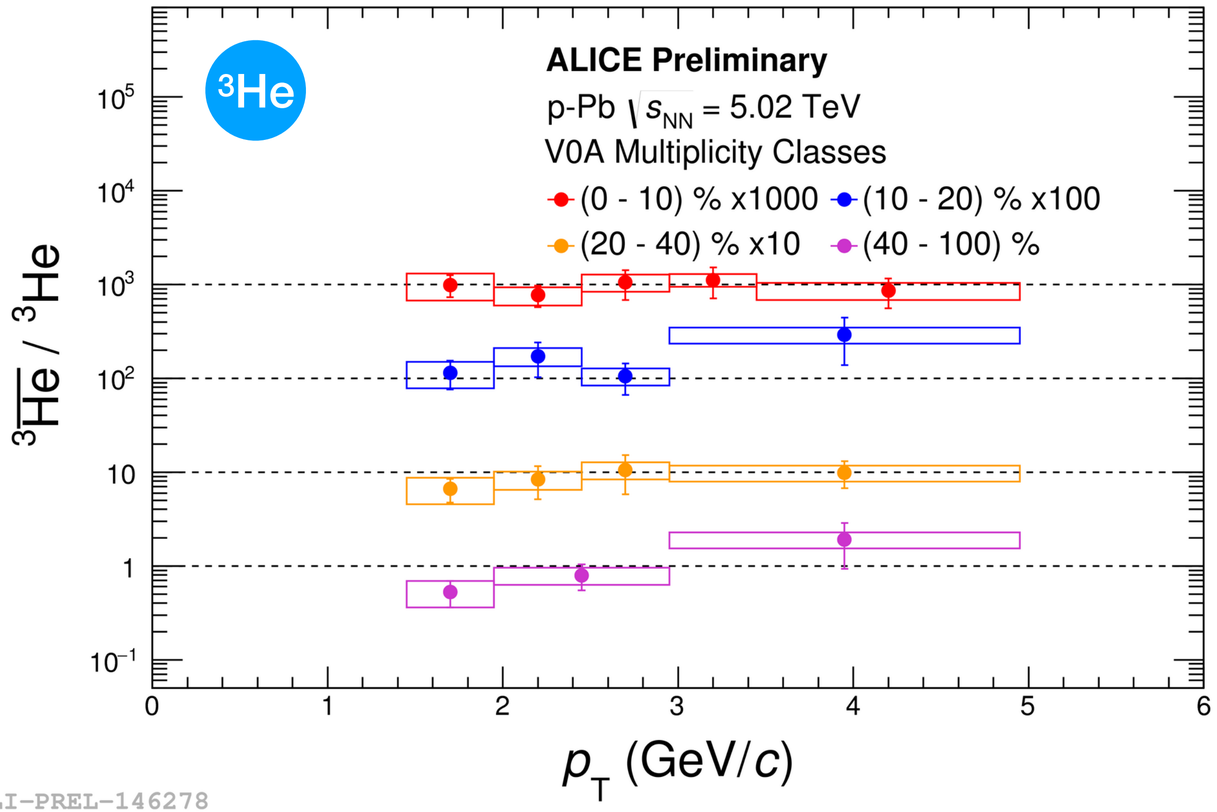
Anti-^{4}He production in Pb–Pb



- Anti-^{4}He yield has been measured in Pb–Pb collisions
- Exponential decrease in particle rate predicted by thermal model is confirmed
- Penalty factor:
  - Pb–Pb collisions: ~300
  - p–Pb collisions: ~600
  - pp collisions: ~1000

Anti-Nuclei / nuclei ratio





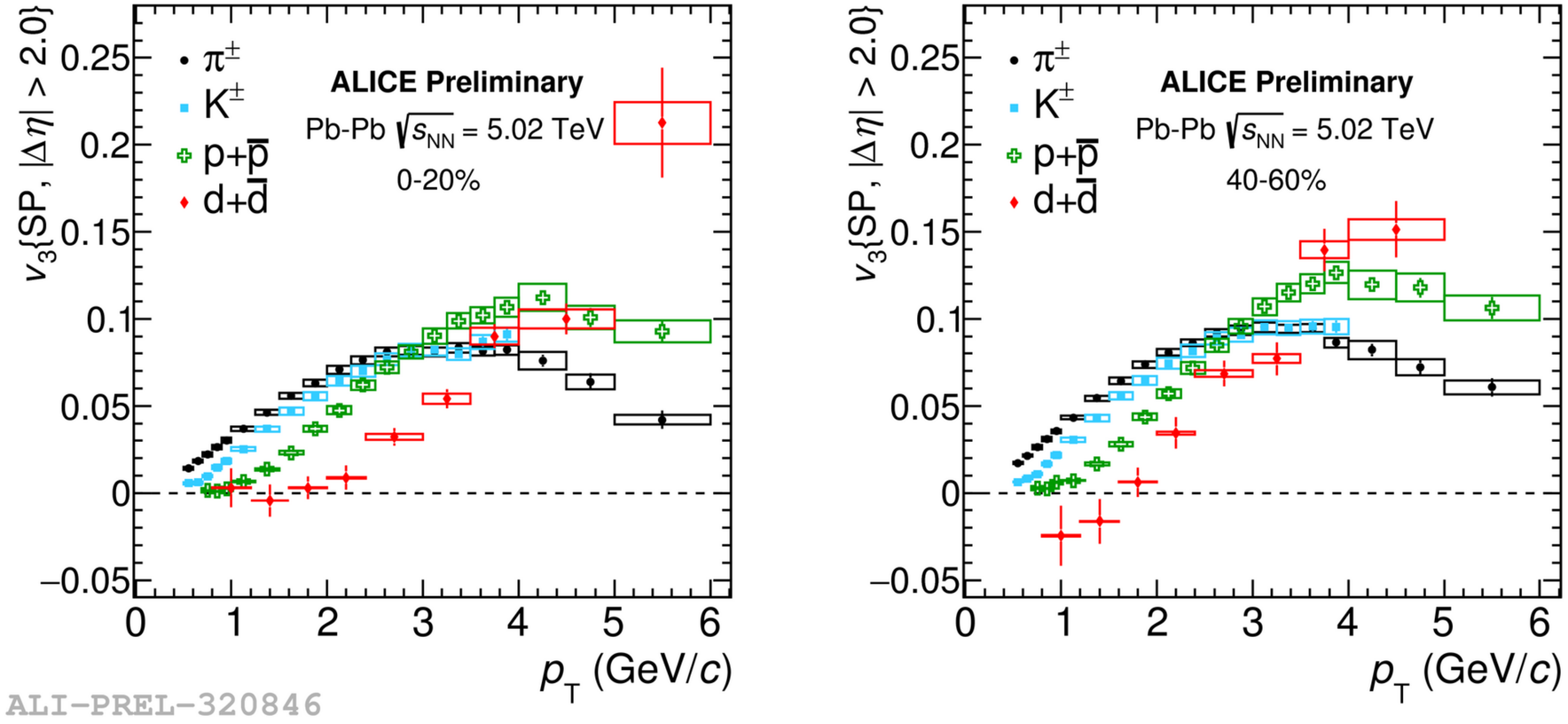
- μ_B ~ 0 at LHC energies

  ⇒ Anti-nucleus/nucleus ratio is expected to be compatible with unity

- Measured $\bar{d}$/d and $^3\overline{He}$/^{3}He in Pb–Pb, p–Pb and pp collisions confirm this prediction

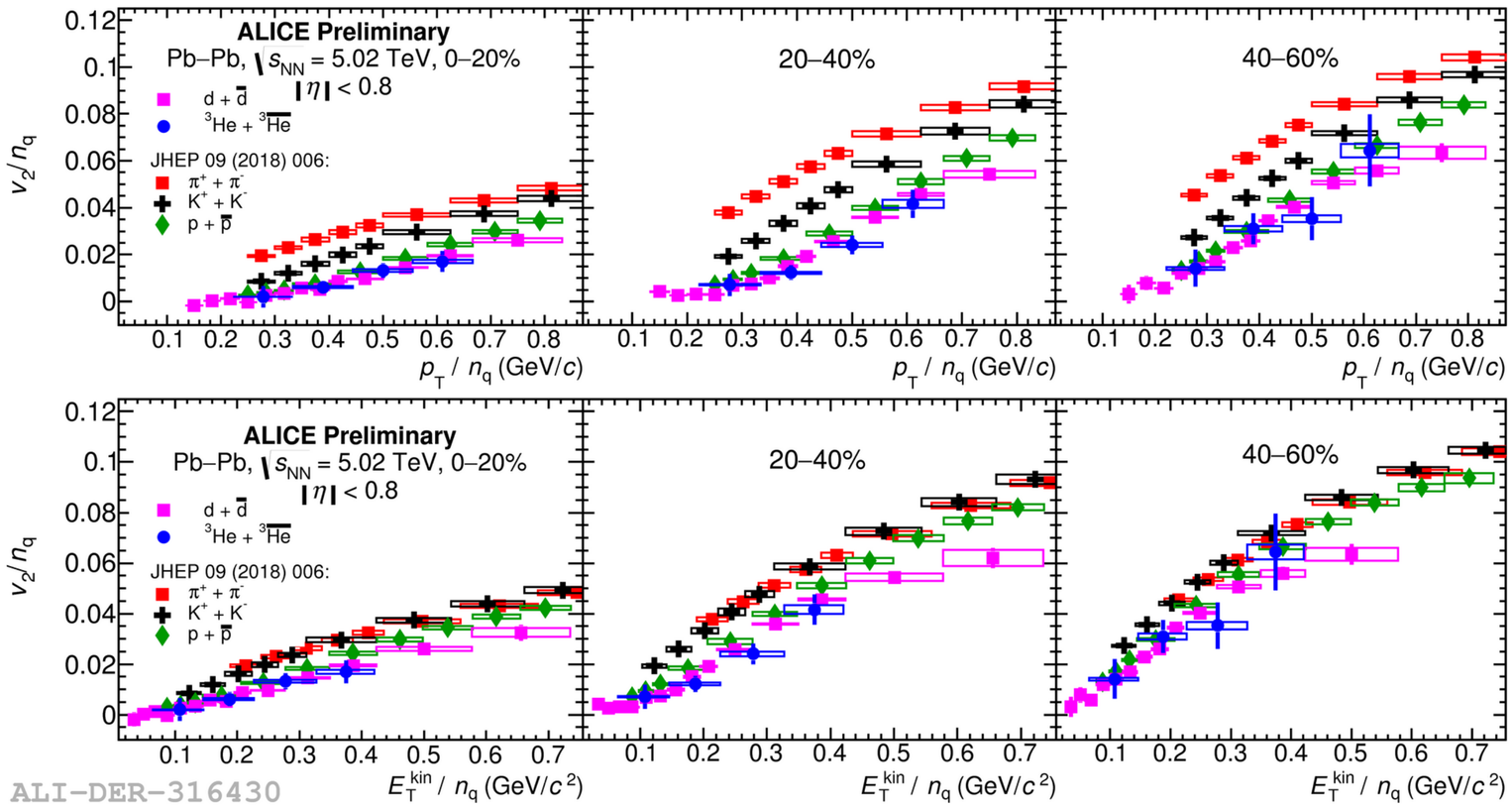
  ⇒ Matter and anti-matter is produced in the same amount

Deuteron v_3



- Both expectations from relativistic hydrodynamics are fulfilled
  - Mass ordering at low p_T
  - Slower rise for heavier particles

n_q-scaling of light (anti-)nuclei v_2



- Baryons follow an approximate scaling vs $p_{\mathrm{T}}/n_{\mathrm{q}}$
- Baryons and mesons show an approximate scaling vs $E_{\mathrm{T}}^{\mathrm{kin}}/n_{\mathrm{q}}$