Latest results on light (anti)nuclei production in Pb-Pb collisions with ALICE at the LHC

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ALICE

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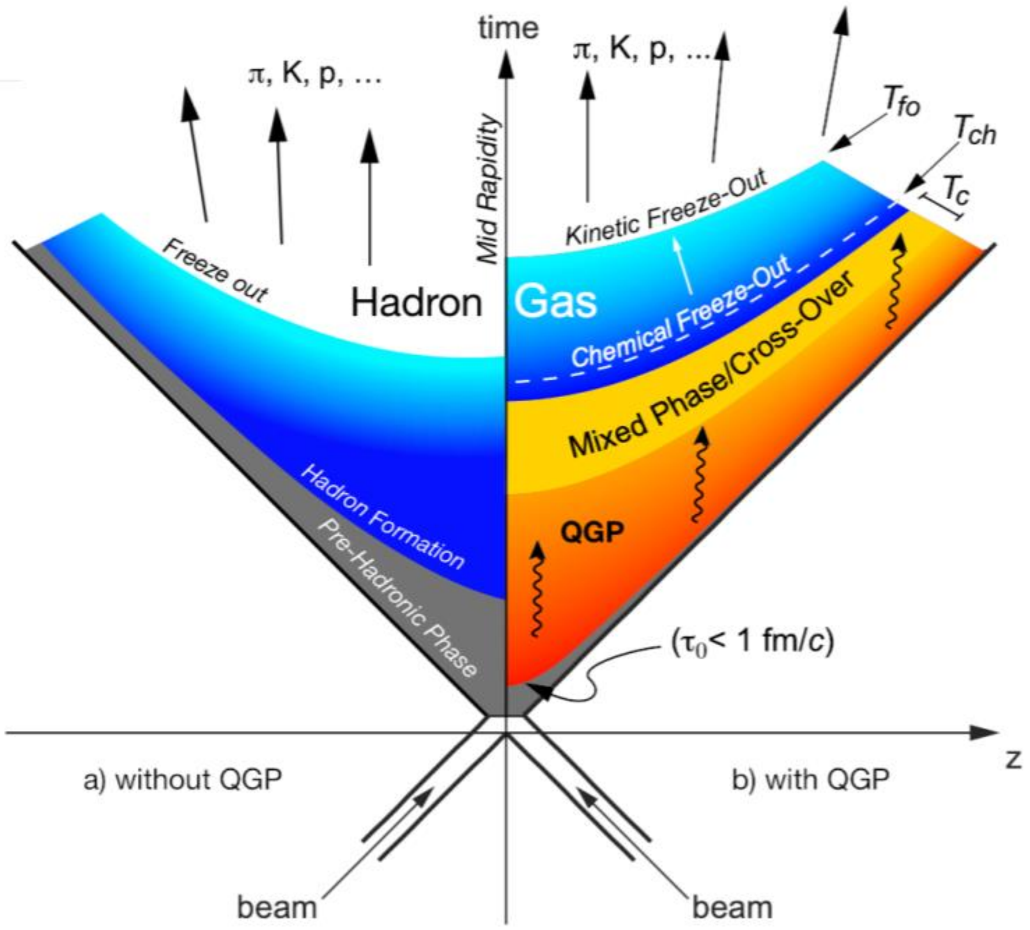
UNIVERSITÀ degli STUDI di CATANIA

INFN Catania Istituto Nazionale di Fisica Nucleare

Physics motivation



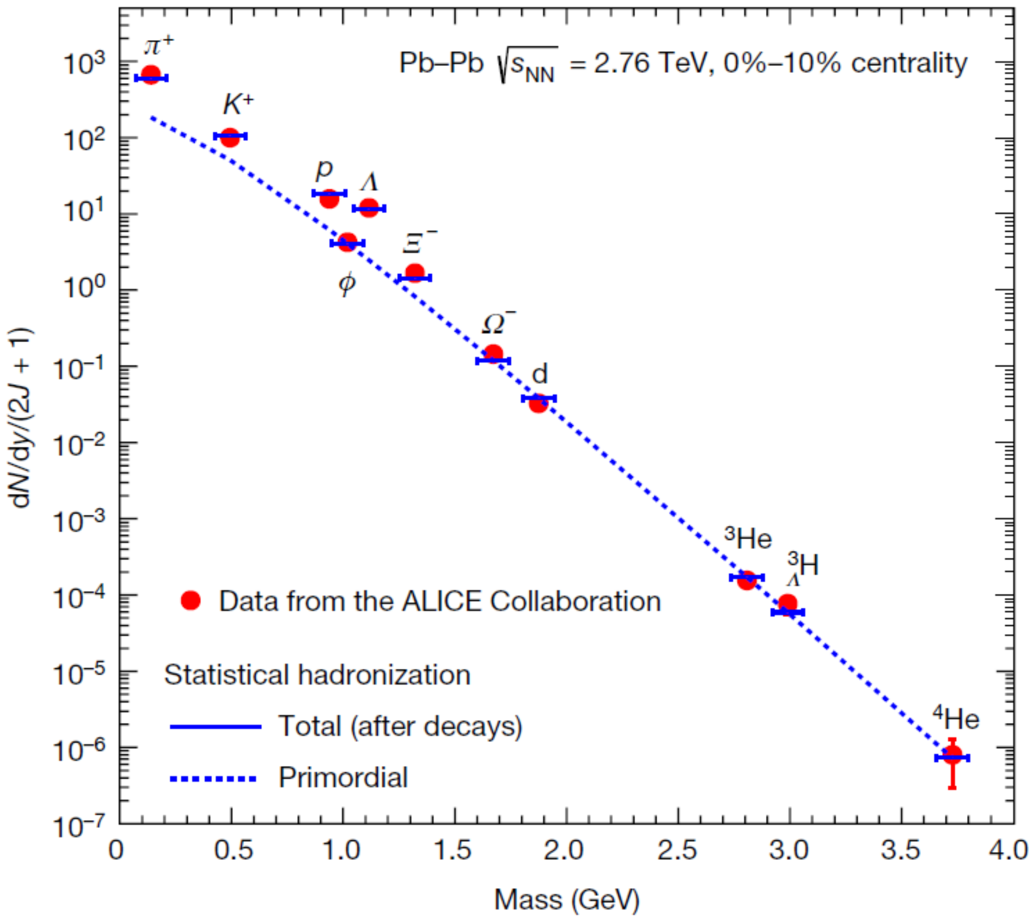
- Multi-baryon states are produced in high energy hadronic collisions at the LHC
- Their production mechanism is still under debate
- Two classes of phenomenological models:
  - Statistical hadronisation
  - Coalescence

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 (T_{chem} ~ 156 MeV)?

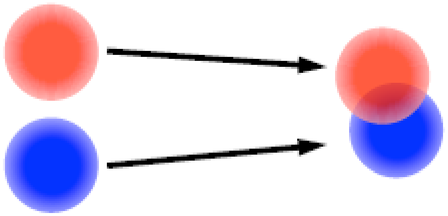


→ In Pb-Pb collisions, particle yields of light flavor hadrons are described over 9 orders of magnitude with a common chemical freeze-out temperature of T_{chem} ≈ 156 MeV.

Nature vol. 561, 321–330 (2018)

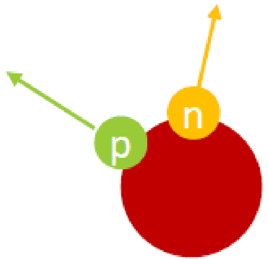
Coalescence models

[Phys. Rev. 129 (1963) 836]



- If (anti)baryons are close in phase space and match the spin state, they can form a (anti)nucleus
- Coalescence parameter B_A is the key parameter

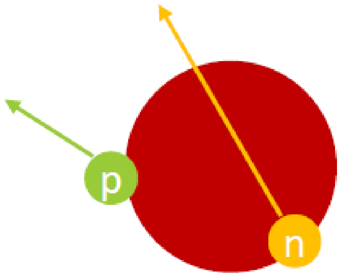
$$E_A \frac{d^3N_A}{dp_A^3} = B_A \left(E_p \frac{d^3N_p}{dp_p^3} \right)^A \Bigg|_{\vec{p}_p=\vec{p}_A/A}$$



- Experimental parameter tightly connected to the coalescence probability

Larger B_A ⟺Larger coalescence probability

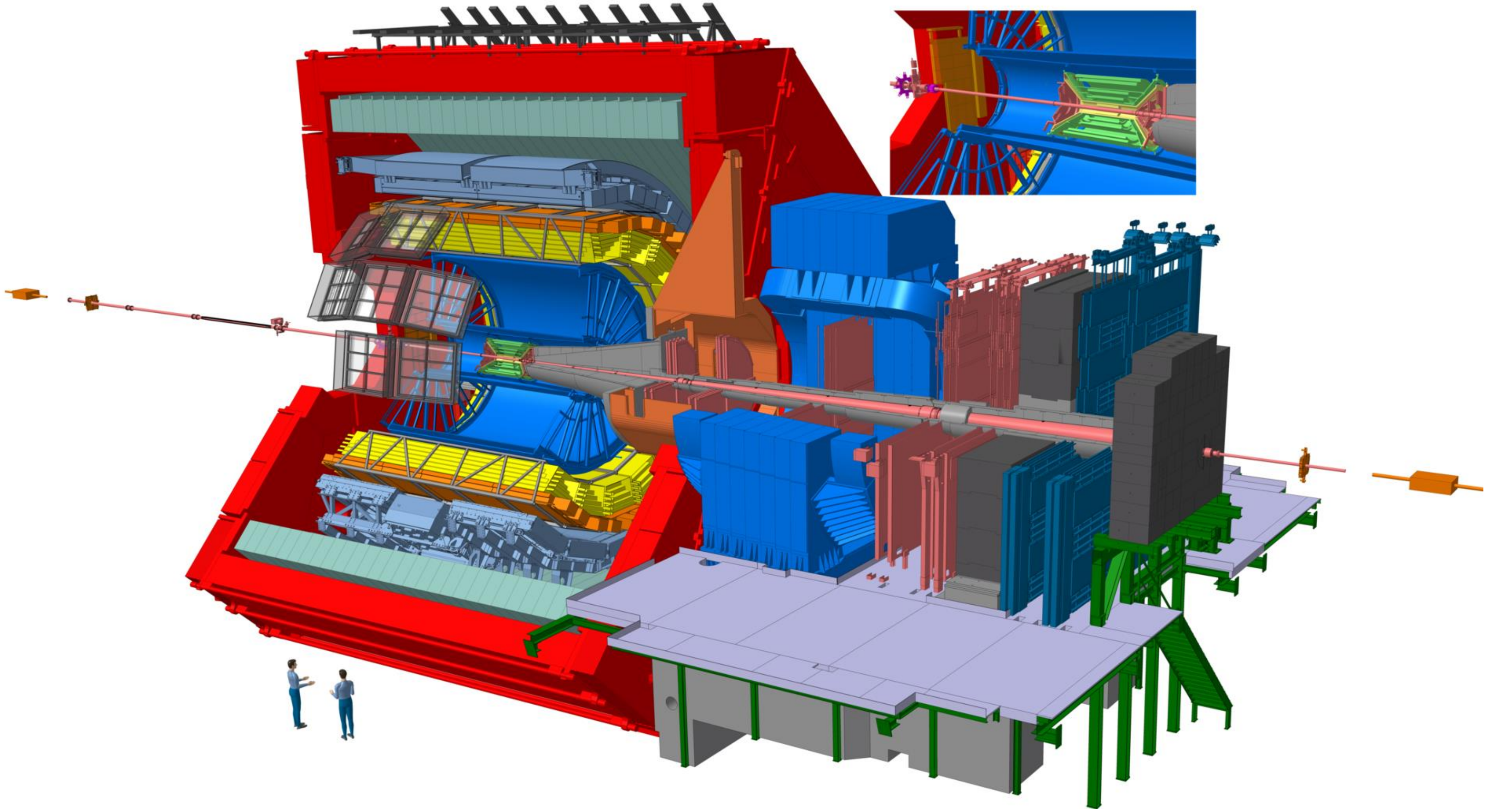
- Coalescence probability depends on the system size



Small distance in space
(Only momentum correlations matter)
⟺ large B_A

Large distance in space
(Both momentum and space correlations matter)
⟺ small B_A

The ALICE detector



- General purpose experiment
- Excellent tracking and PID capabilities over a broad momentum range
- Low material budget

→ Most suited detector at the LHC for the study of (anti)nuclei produced in HI collisions

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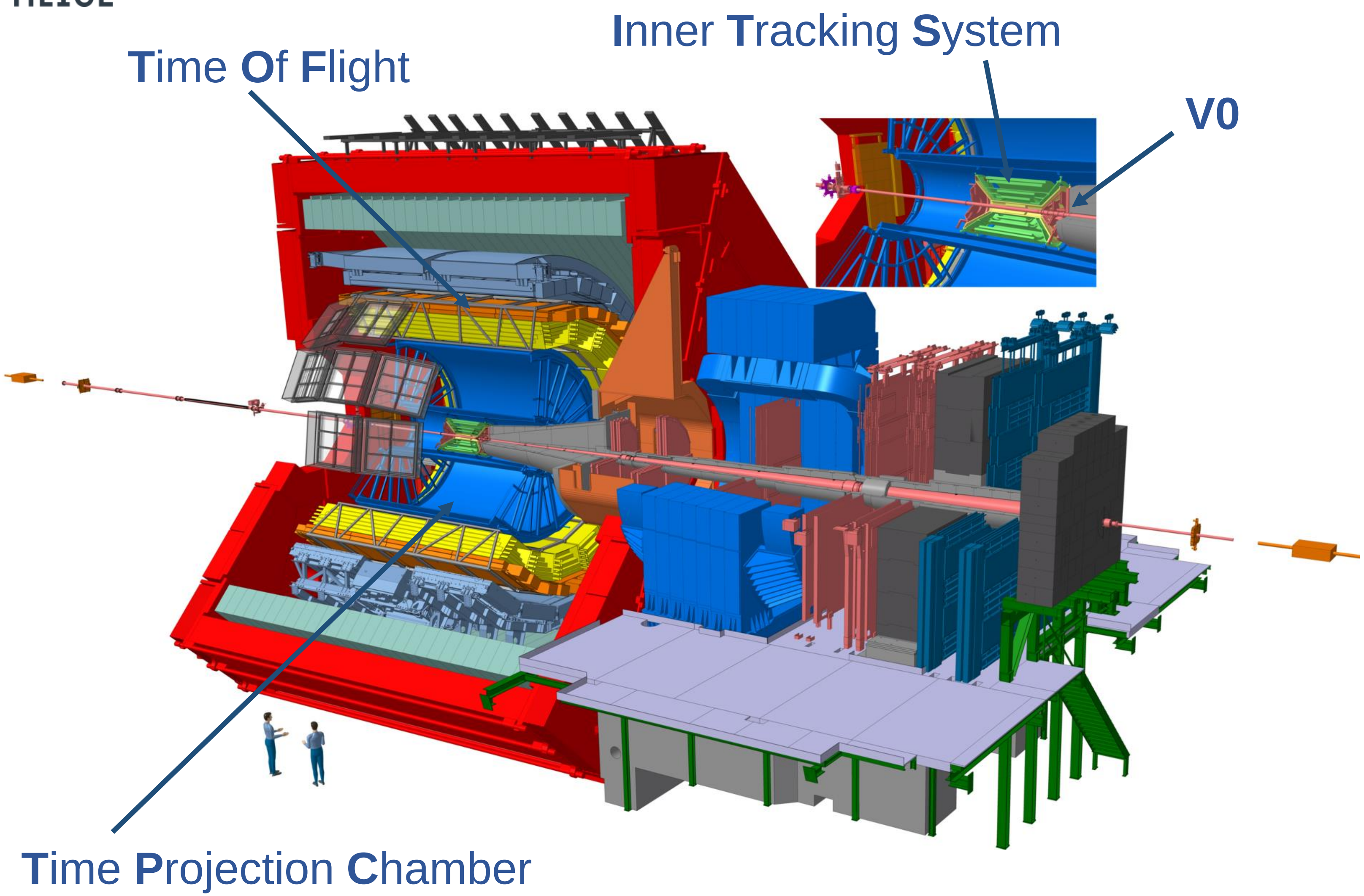

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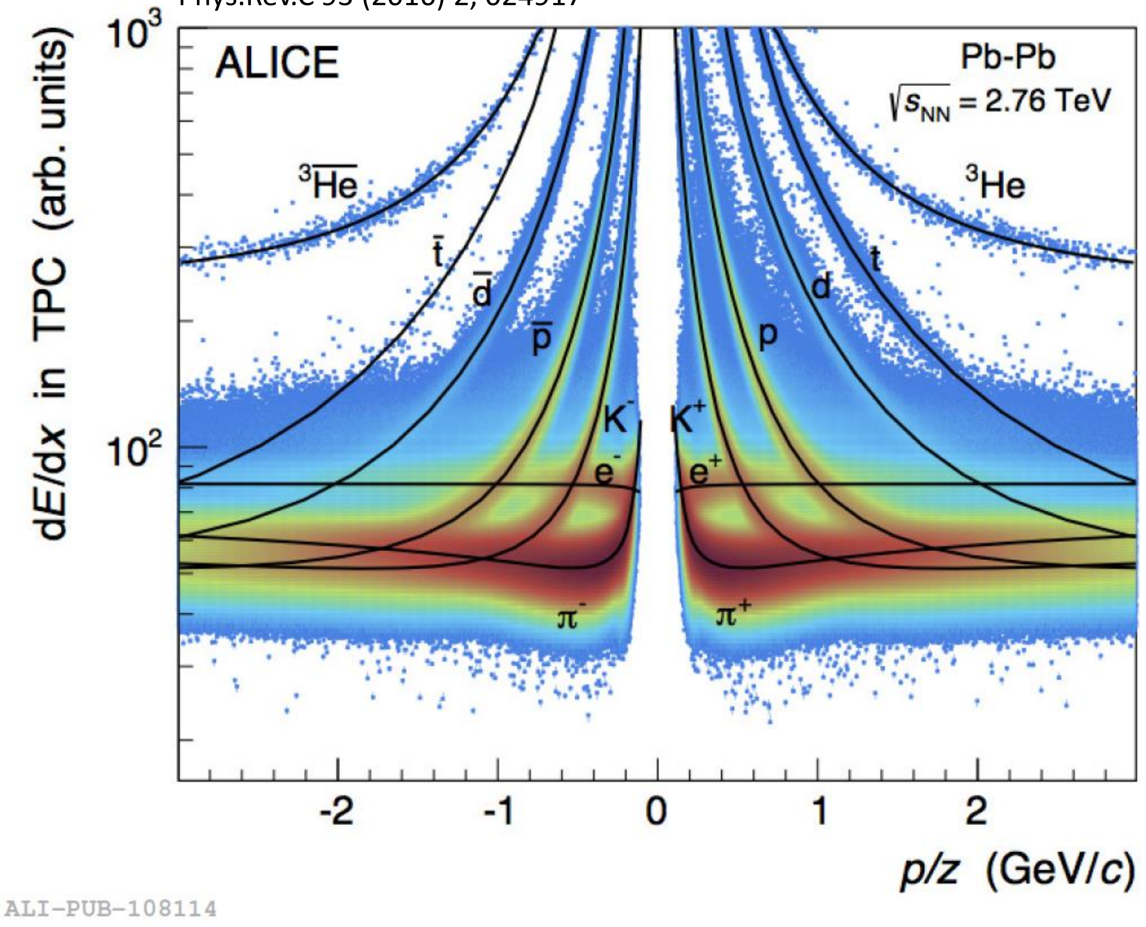
Low *p* nuclei identification

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

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



- Excellent PID for deuterons $\sigma_{dE/dx}$ ~ 6.5% (in Pb-Pb collisions)
- (anti)^{3}He well separated from the other particle species over the full momentum range

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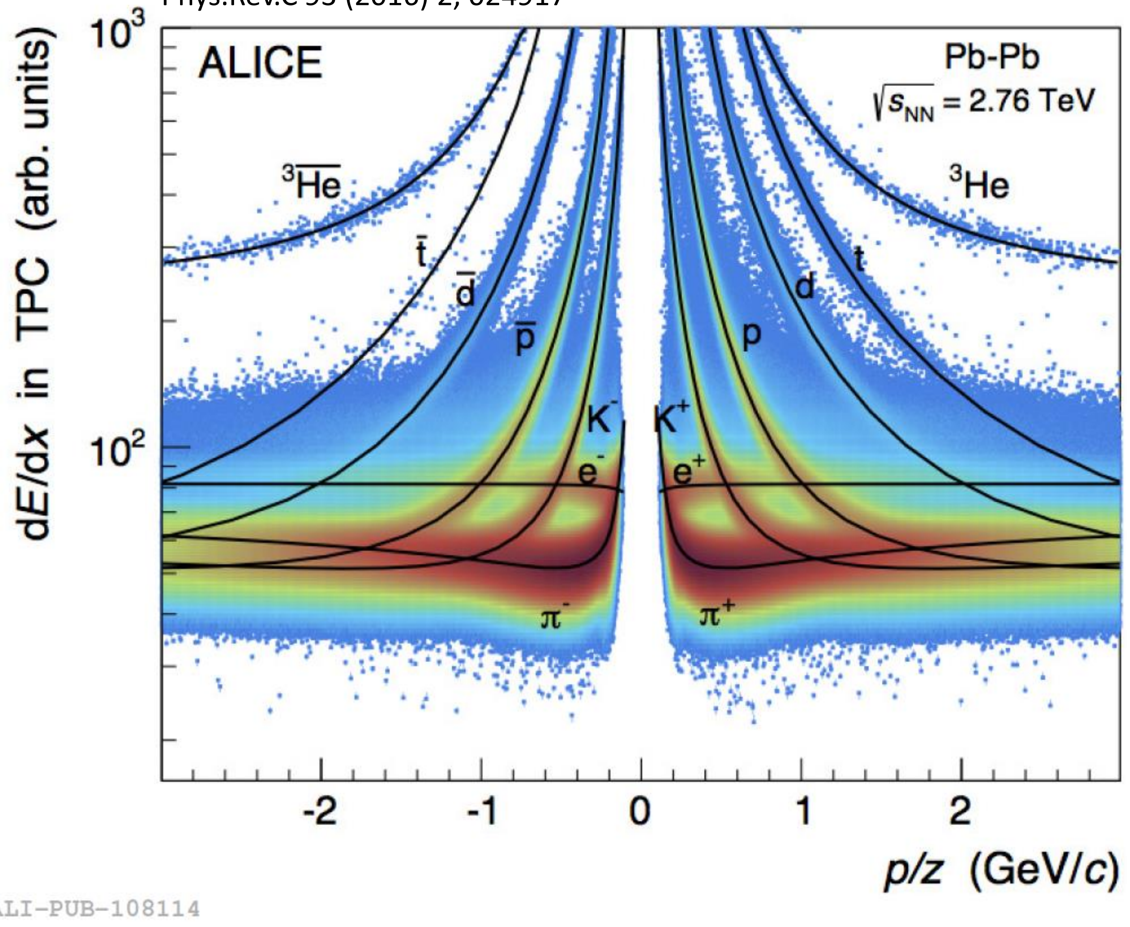

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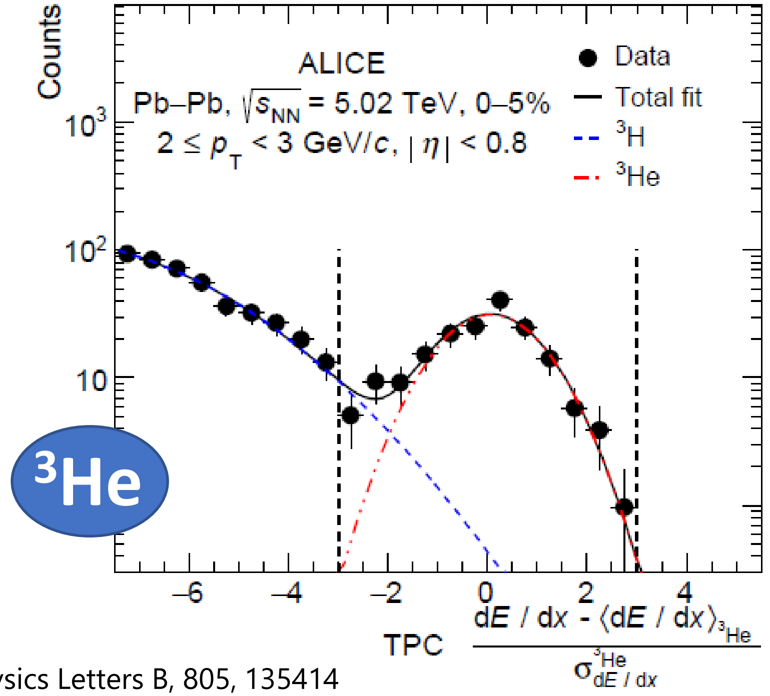


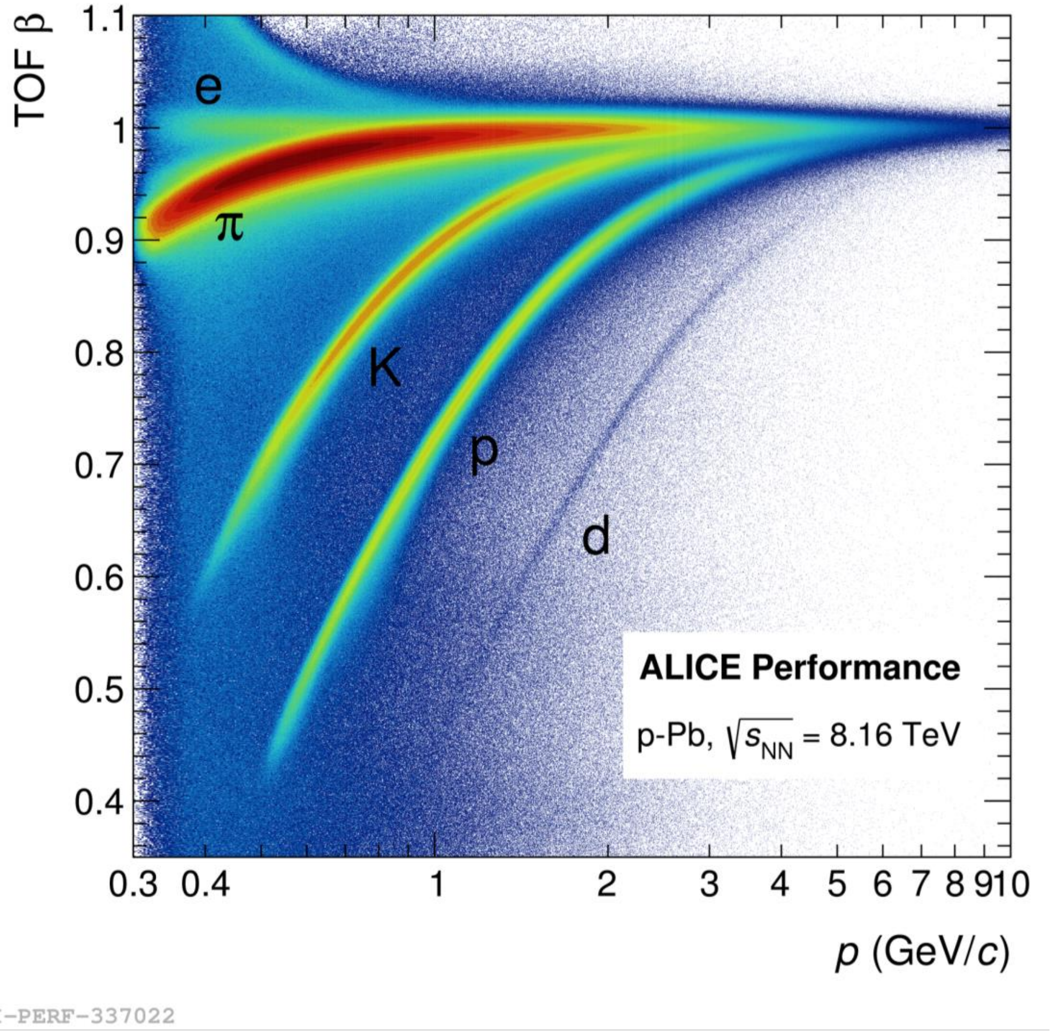
Physics Letters B, 805, 135414

RAW YIELD EXTRACTION

From nσ distribution for each p_T interval

High p nuclei identification

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



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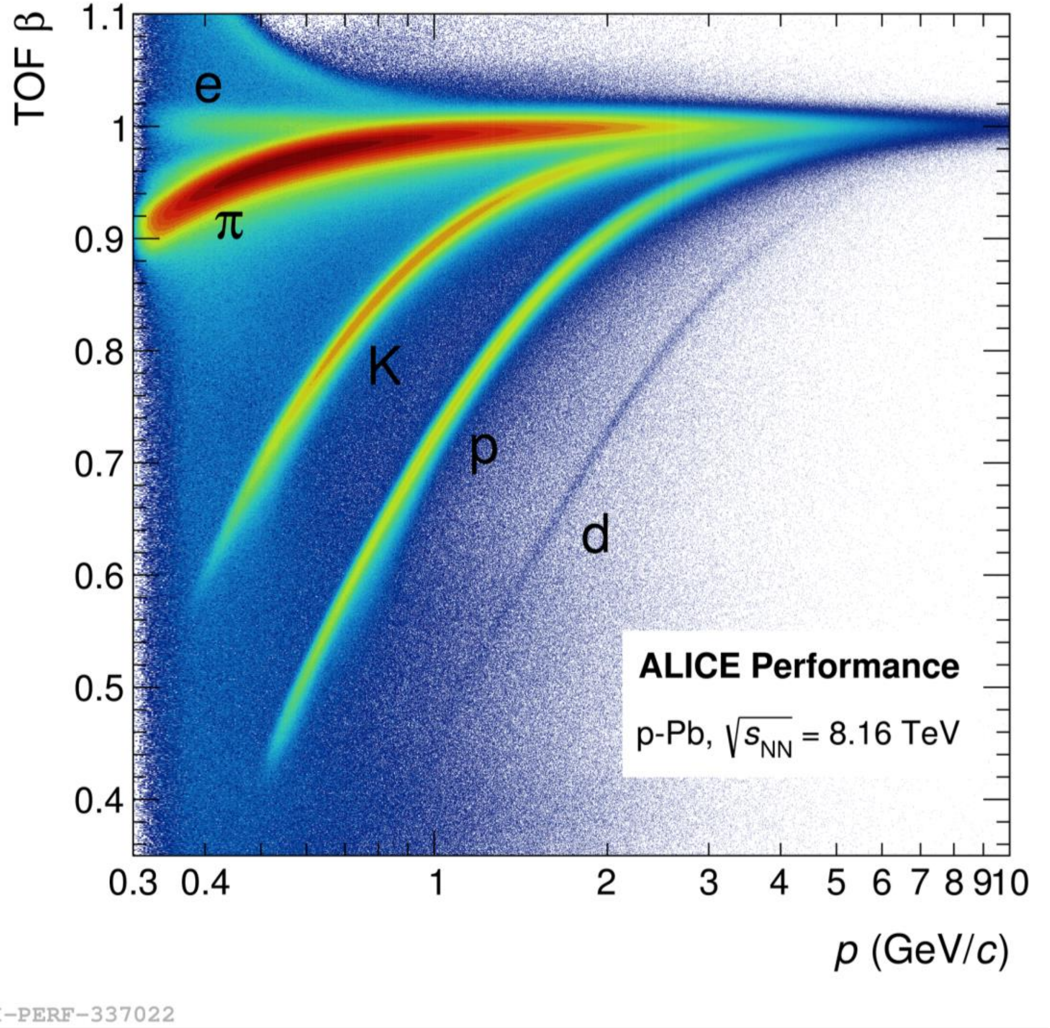

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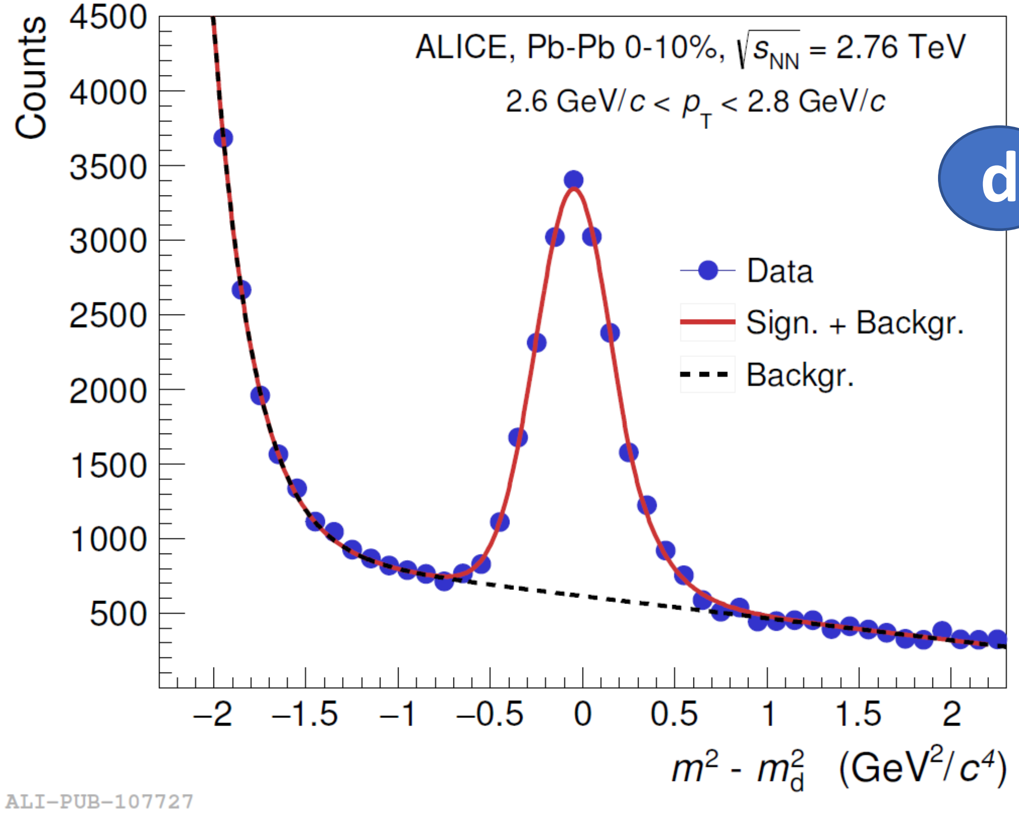
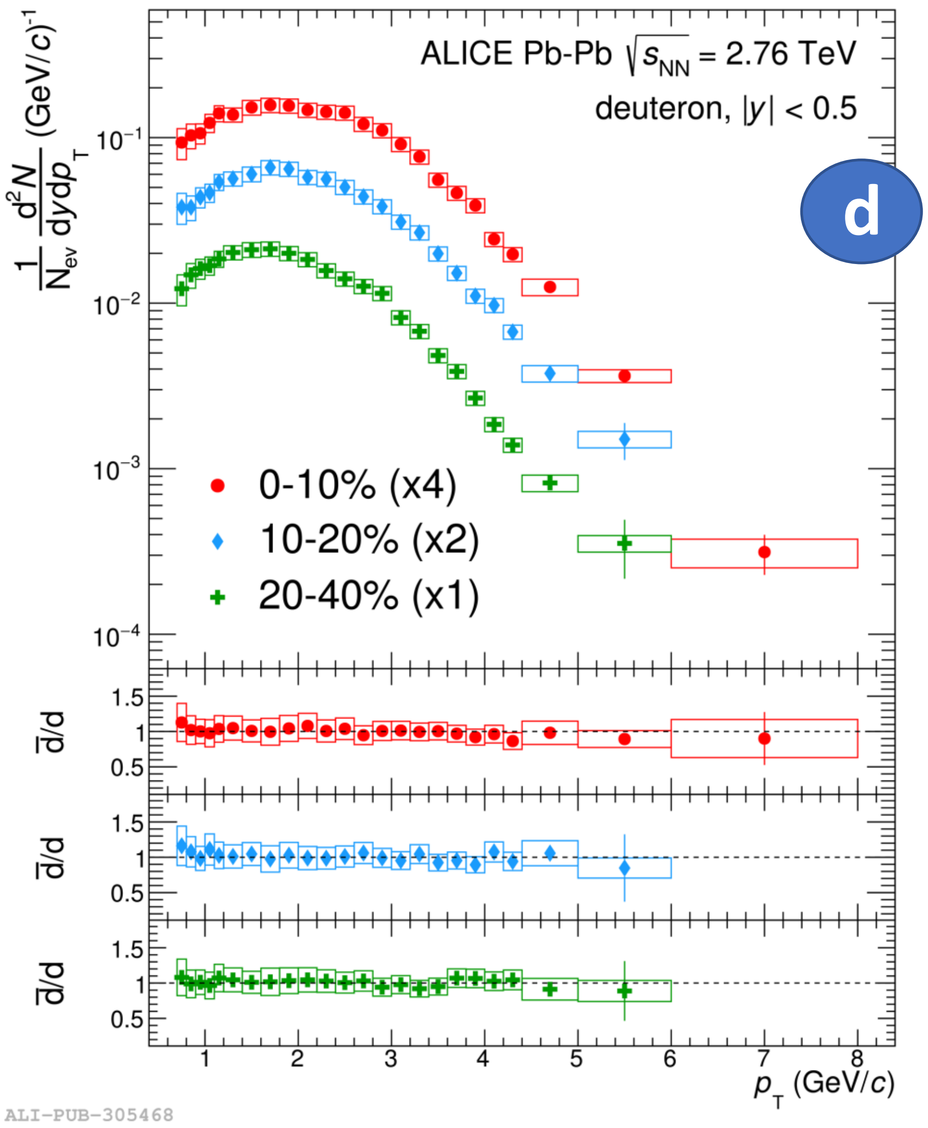


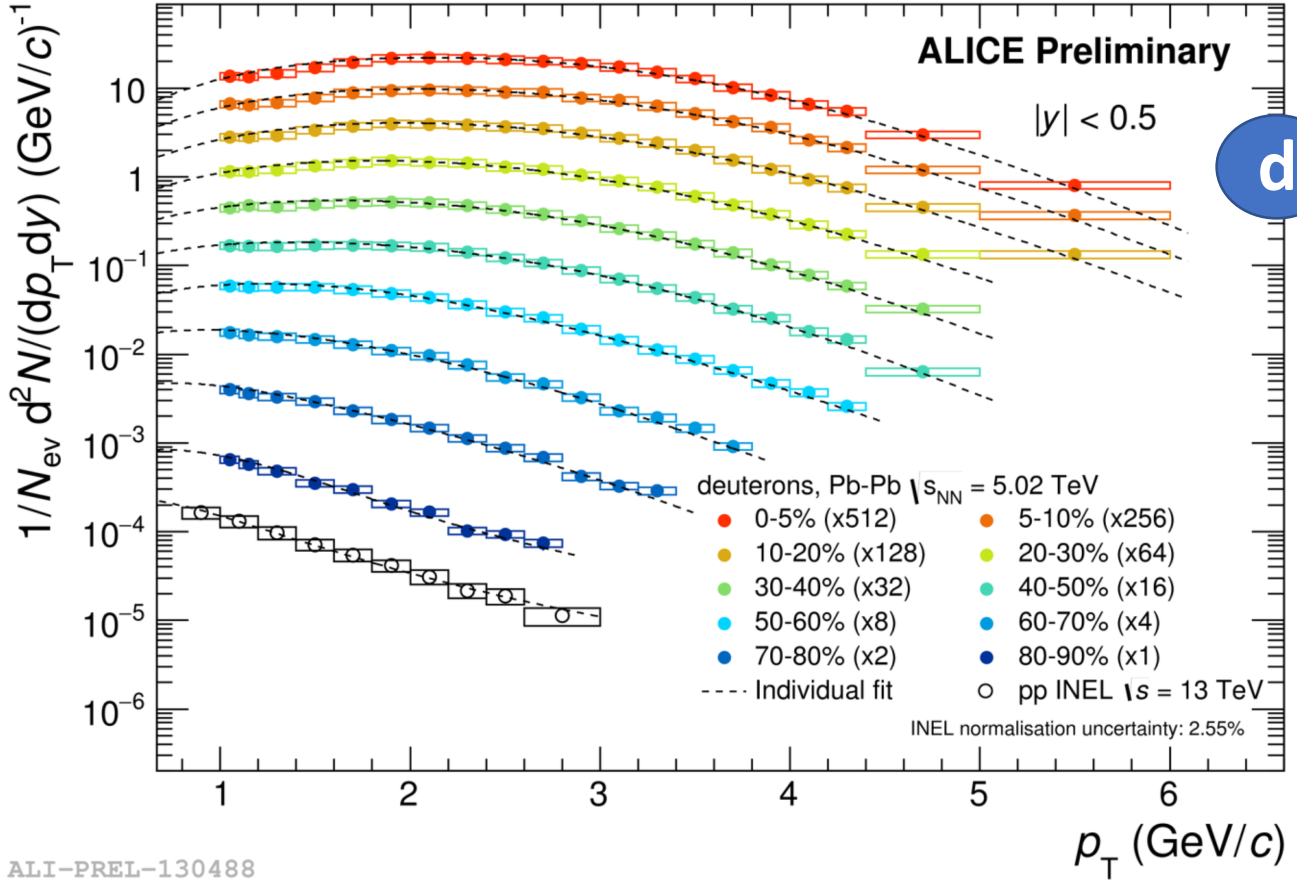
RAW YIELD EXTRACTION

From TOF m^2 distribution for each p_T interval

Light (anti)nuclei in Pb-Pb

Eur.Phys.J.C 77 (2017) 10, 658





- p_T spectra fitted with Blast-Wave function ⇒ Extrapolation to unmeasured regions
- Hardening with increasing centrality – as seen for other light-flavour hadrons ⇒ Collective motion (radial flow)

Light (anti)nuclei in Pb-Pb

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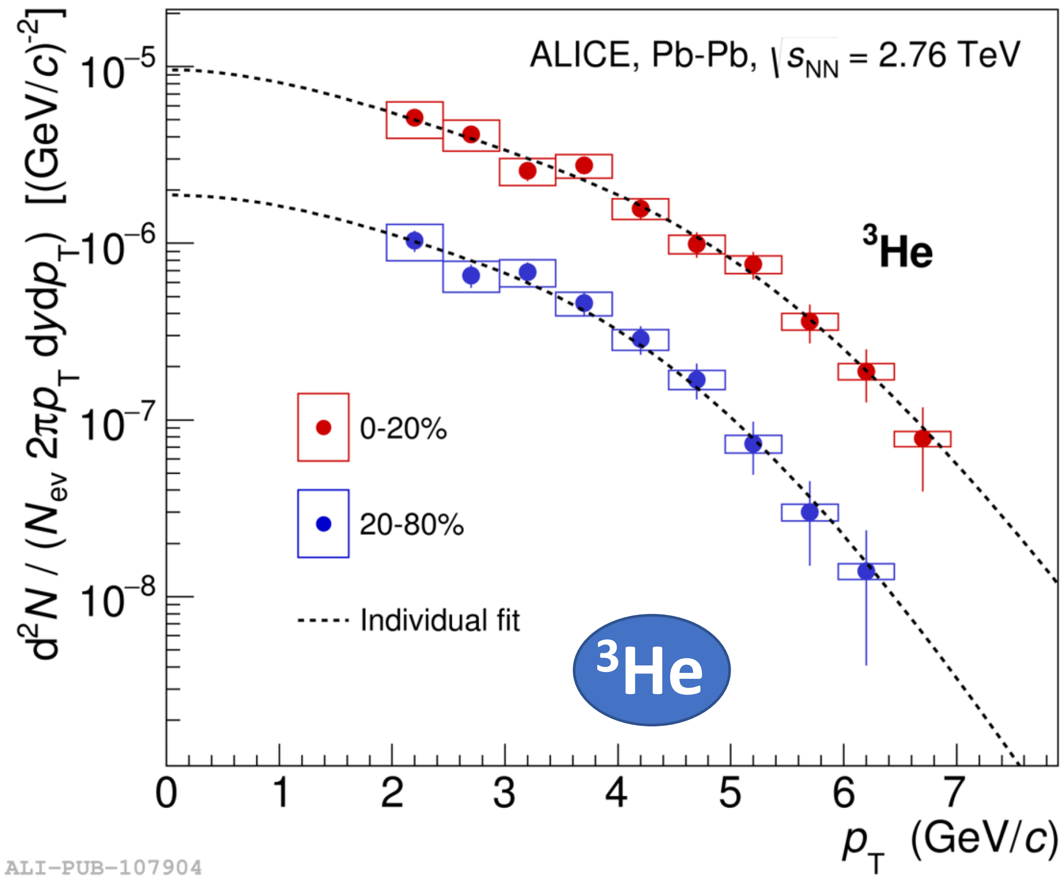
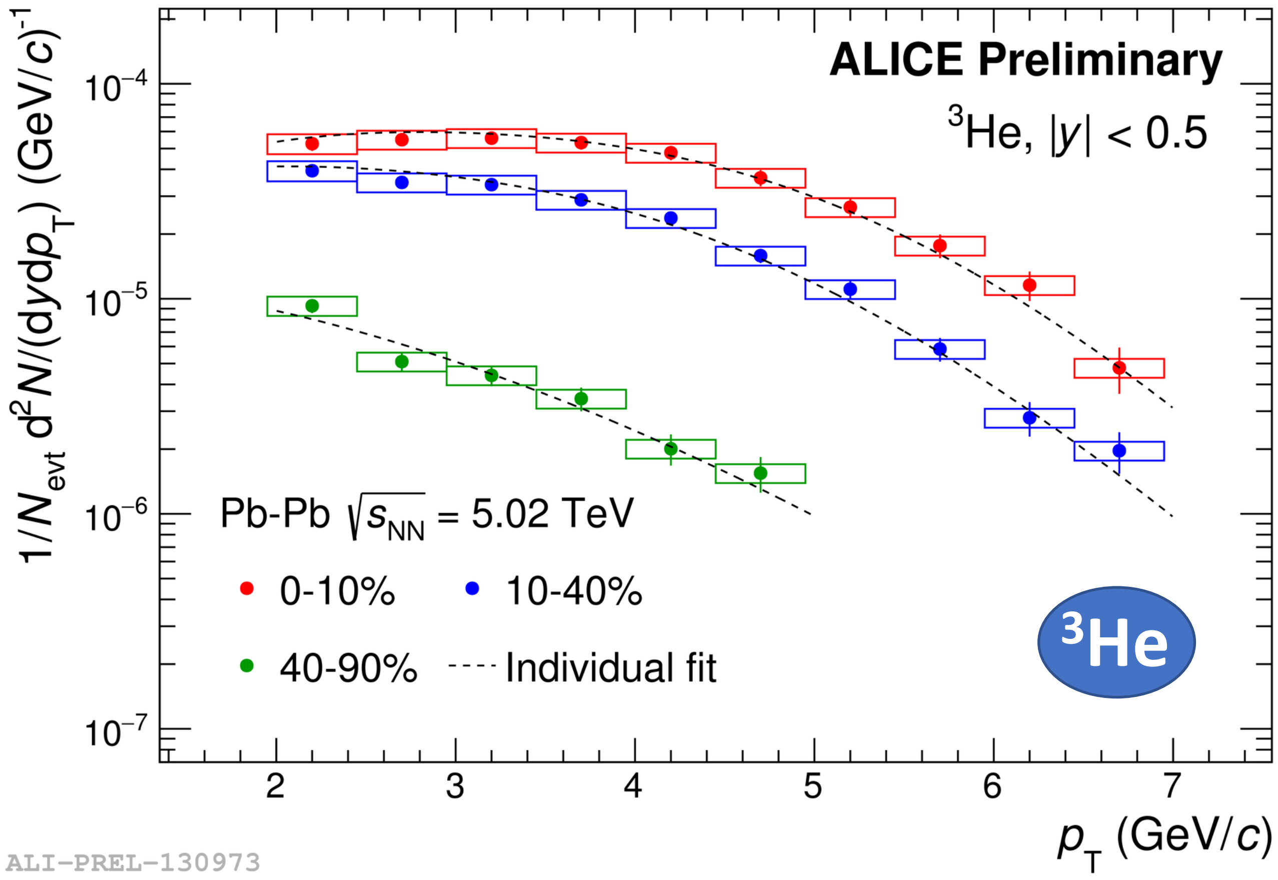
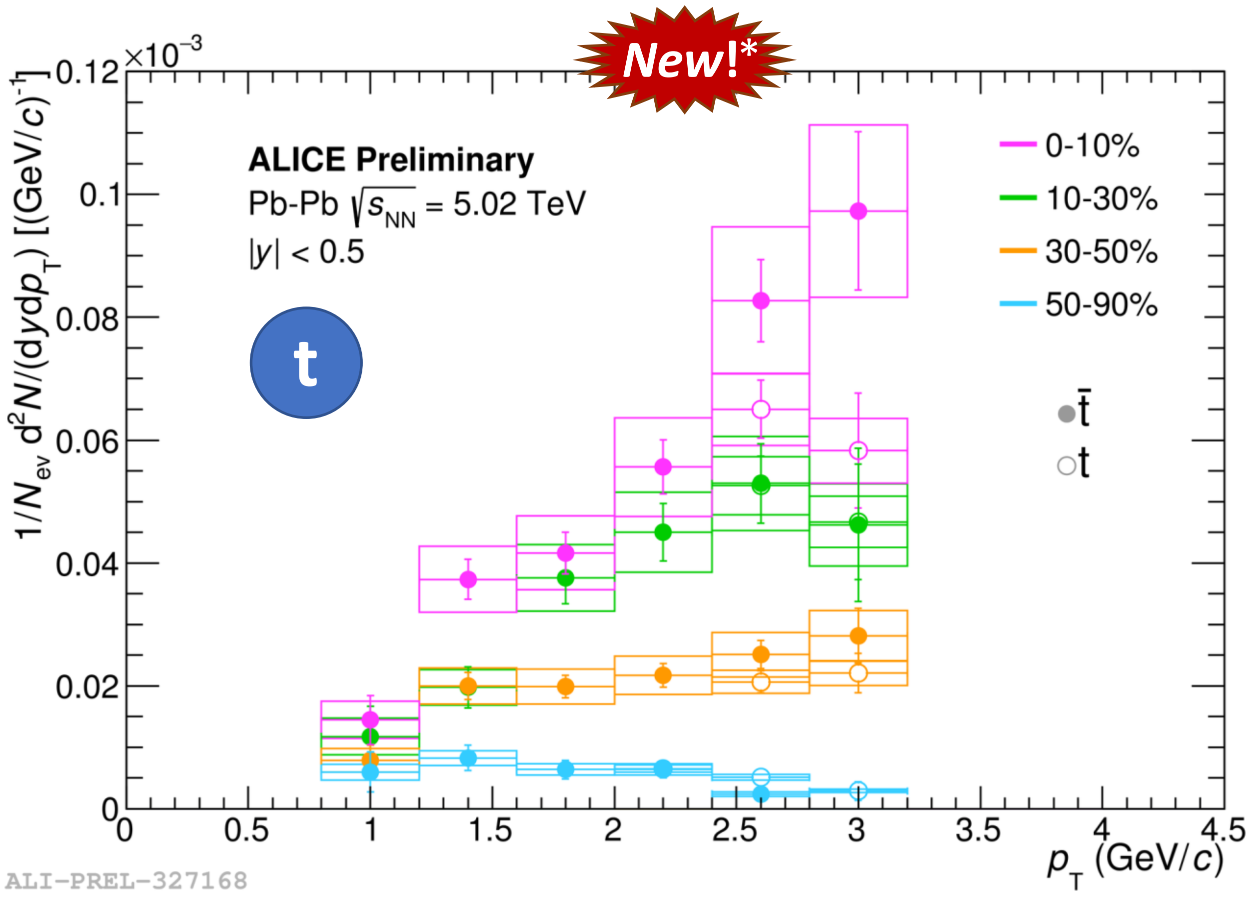
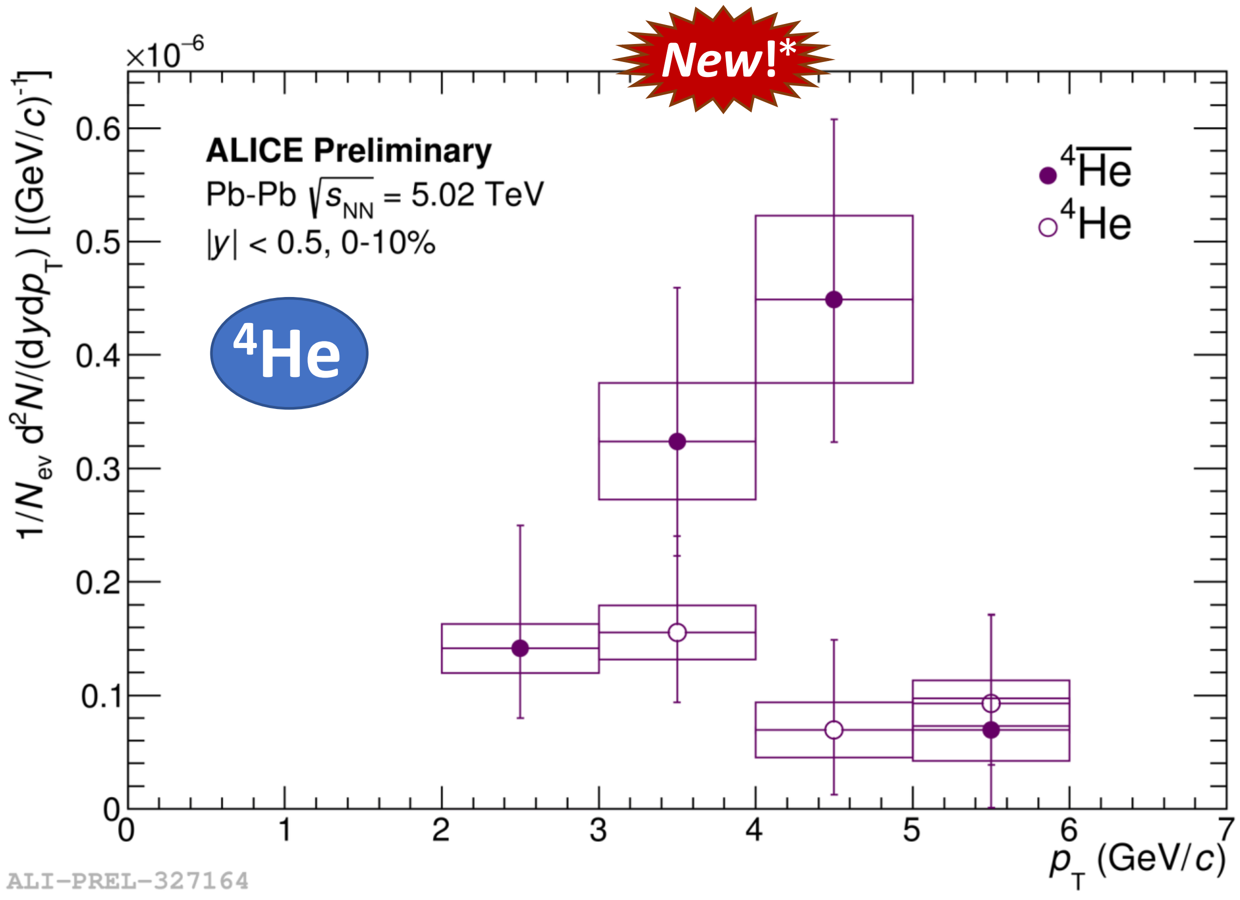




- Similar behaviour observed also in ^{3}He spectra
- Hardening with increasing centrality – as seen for other light-flavour hadrons ⇒ Collective motion (radial flow)

Light (anti)nuclei in Pb-Pb

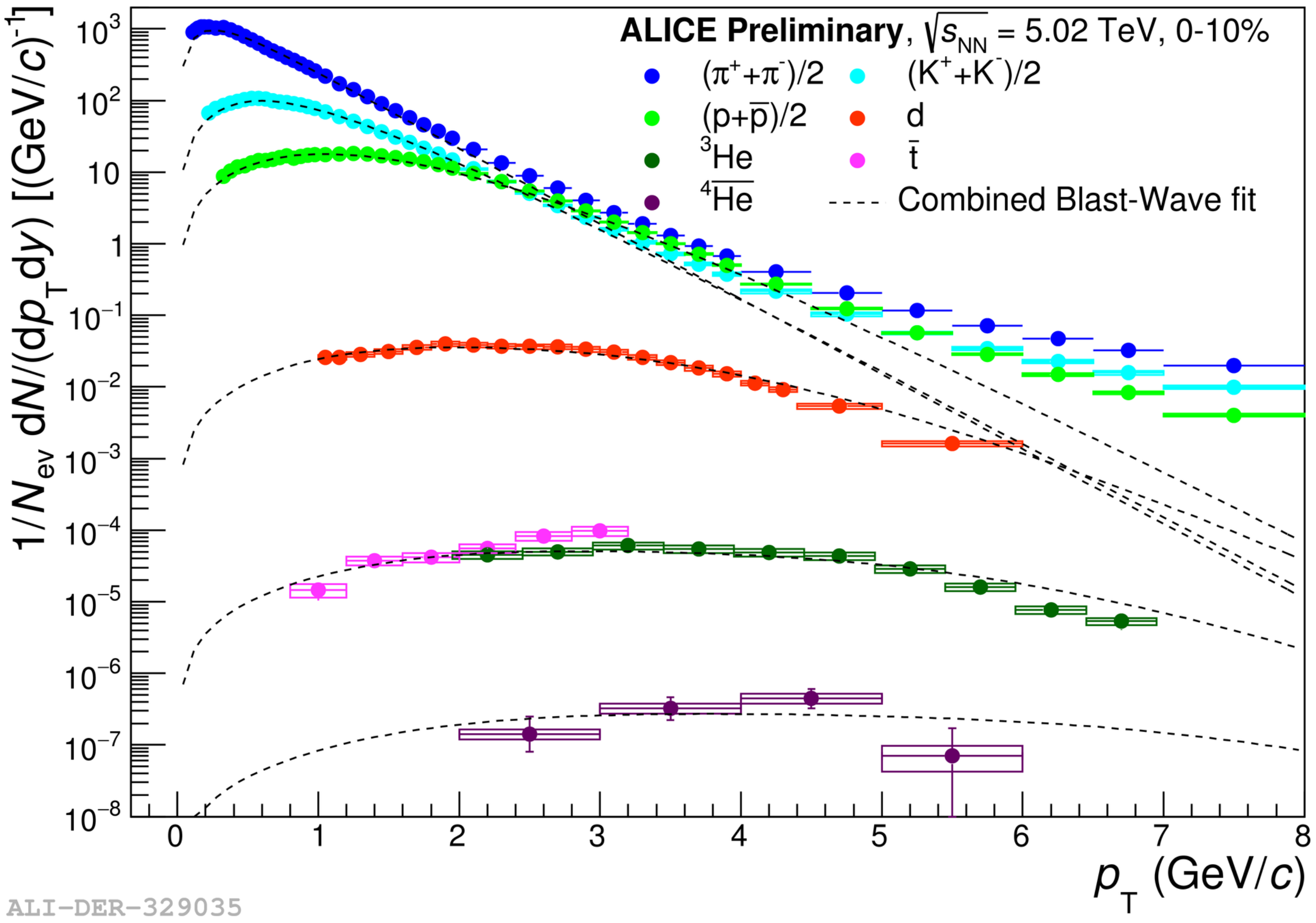




- Light (anti)nuclei up to ^{4}He have been measured

** released in summer 2020*

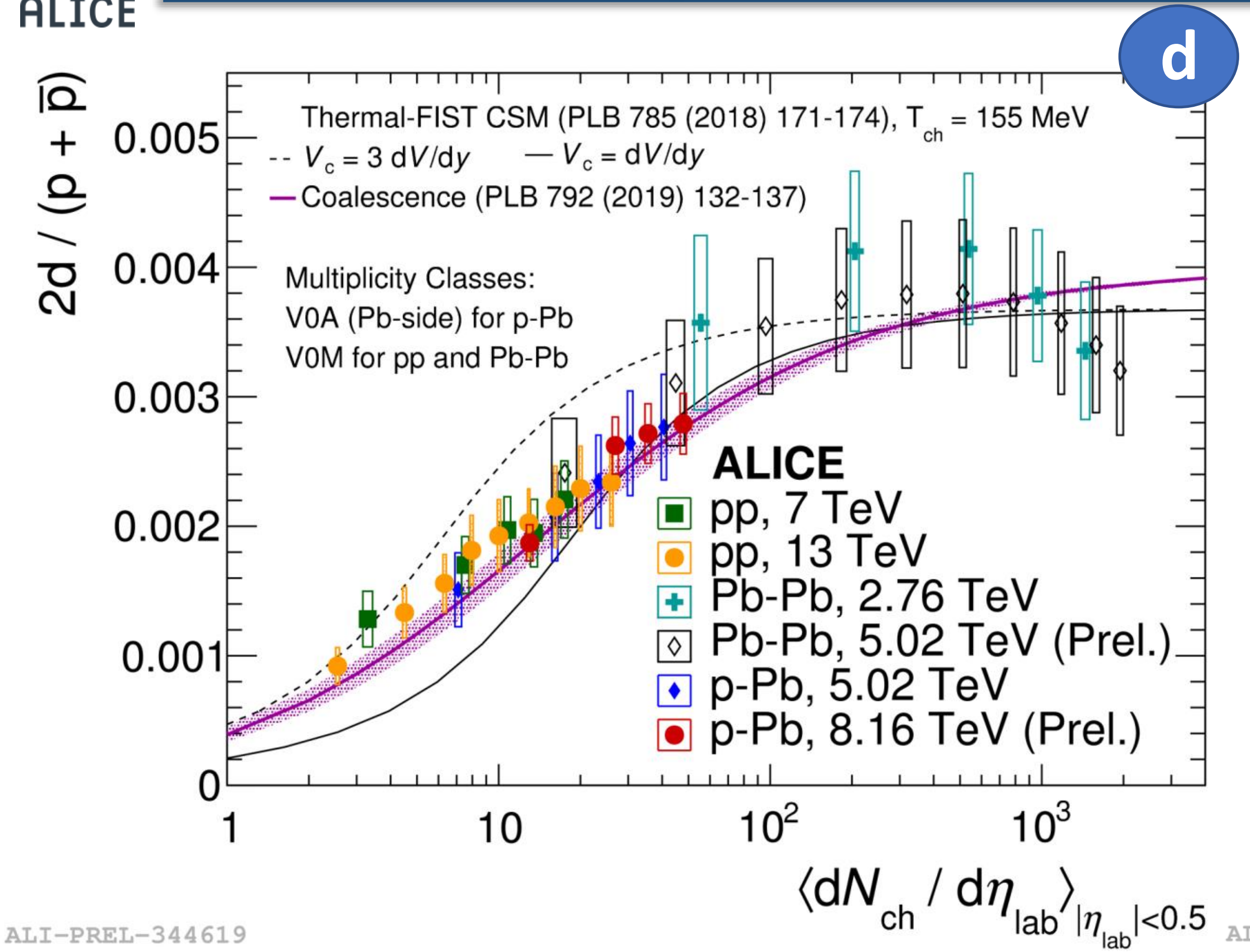
Blast-Wave fit of p_T spectra

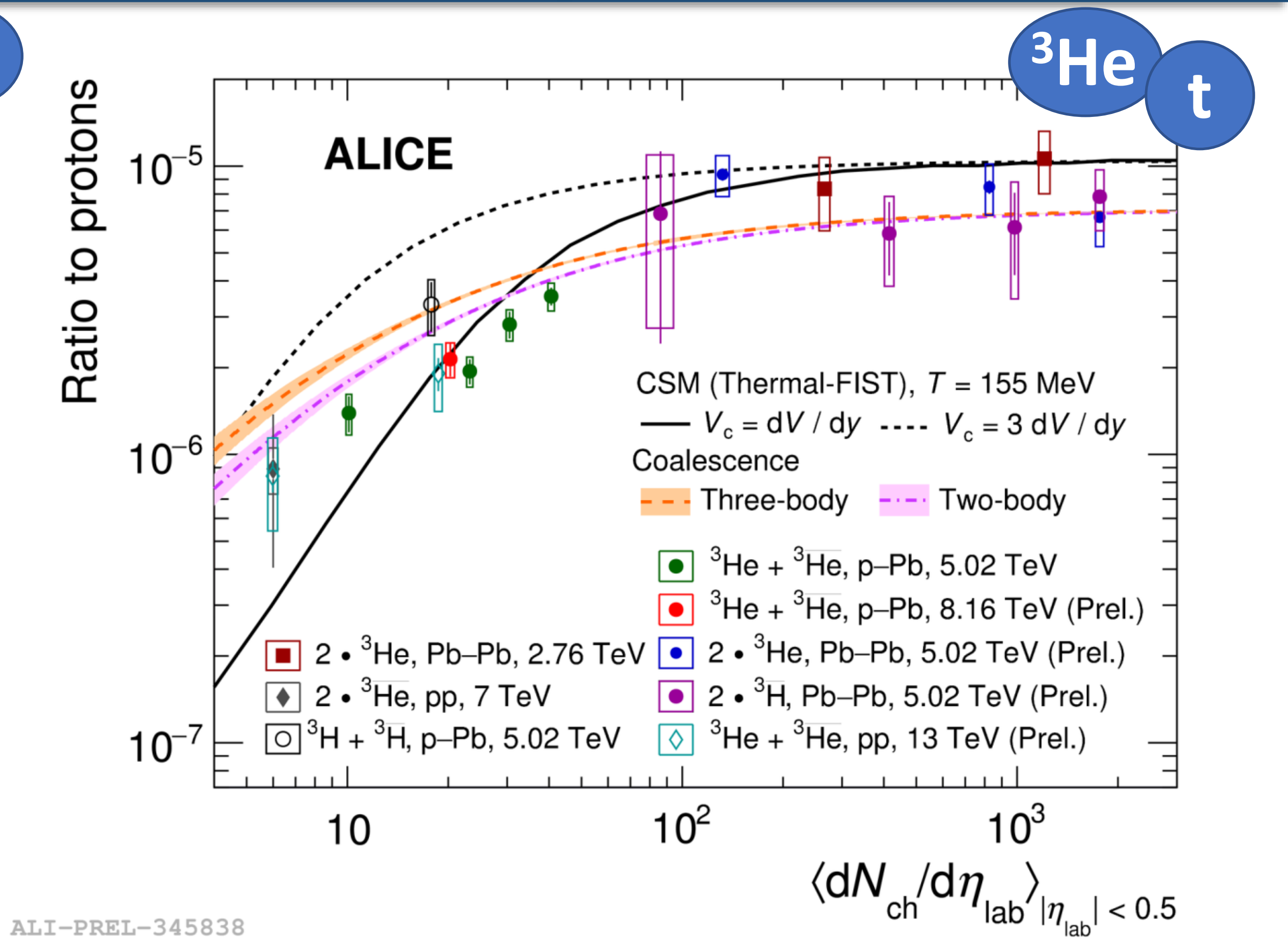


Pb-Pb @ 5.02 TeV

- Blast-Wave fit of light flavour hadrons – from π to α
- ^{3}H and ^{3}He p_T spectra are of the same order of magnitude ⇒ Considered comparable for the ratio-to-protons

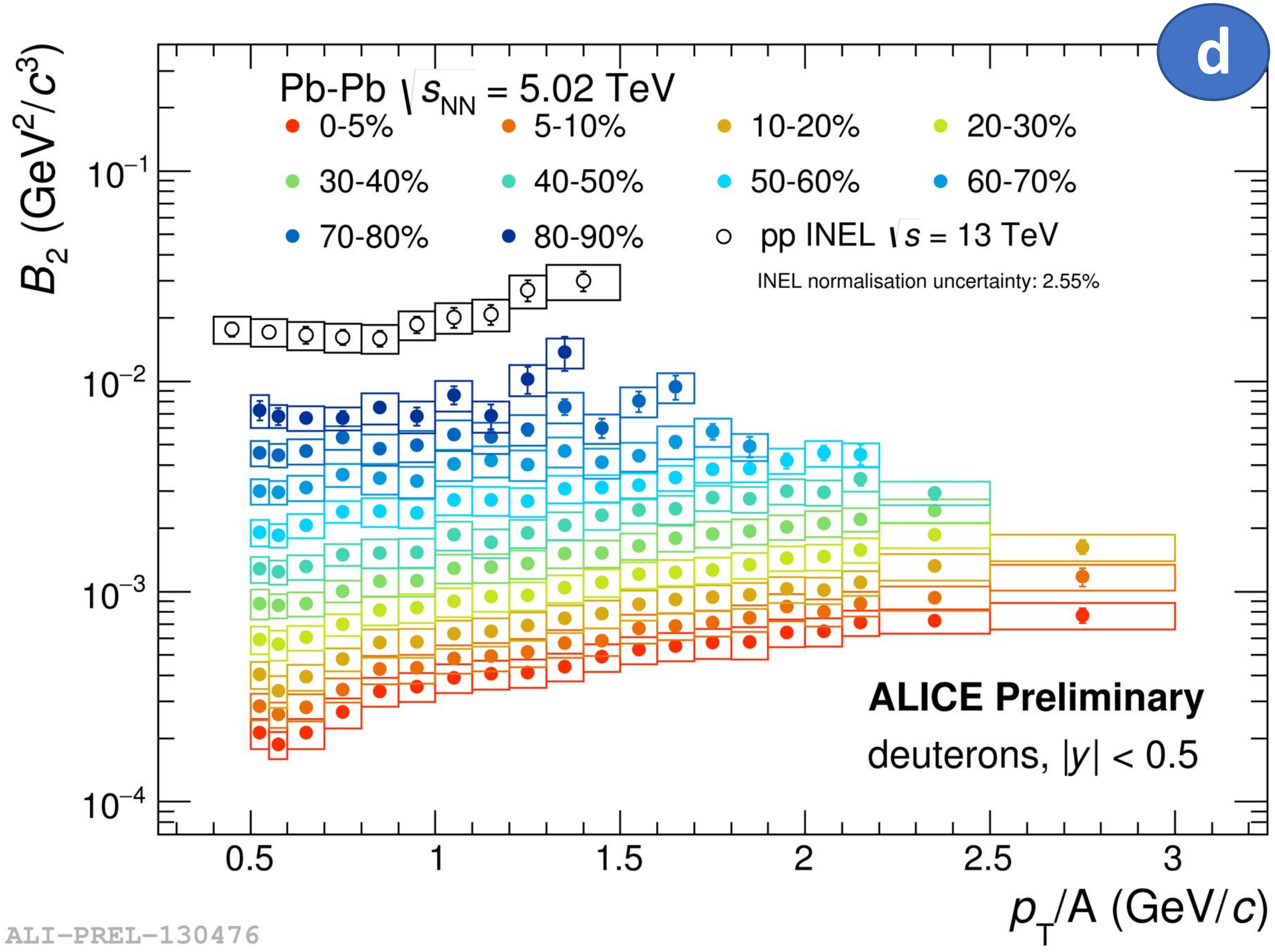
Ratio to protons – model comparison





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

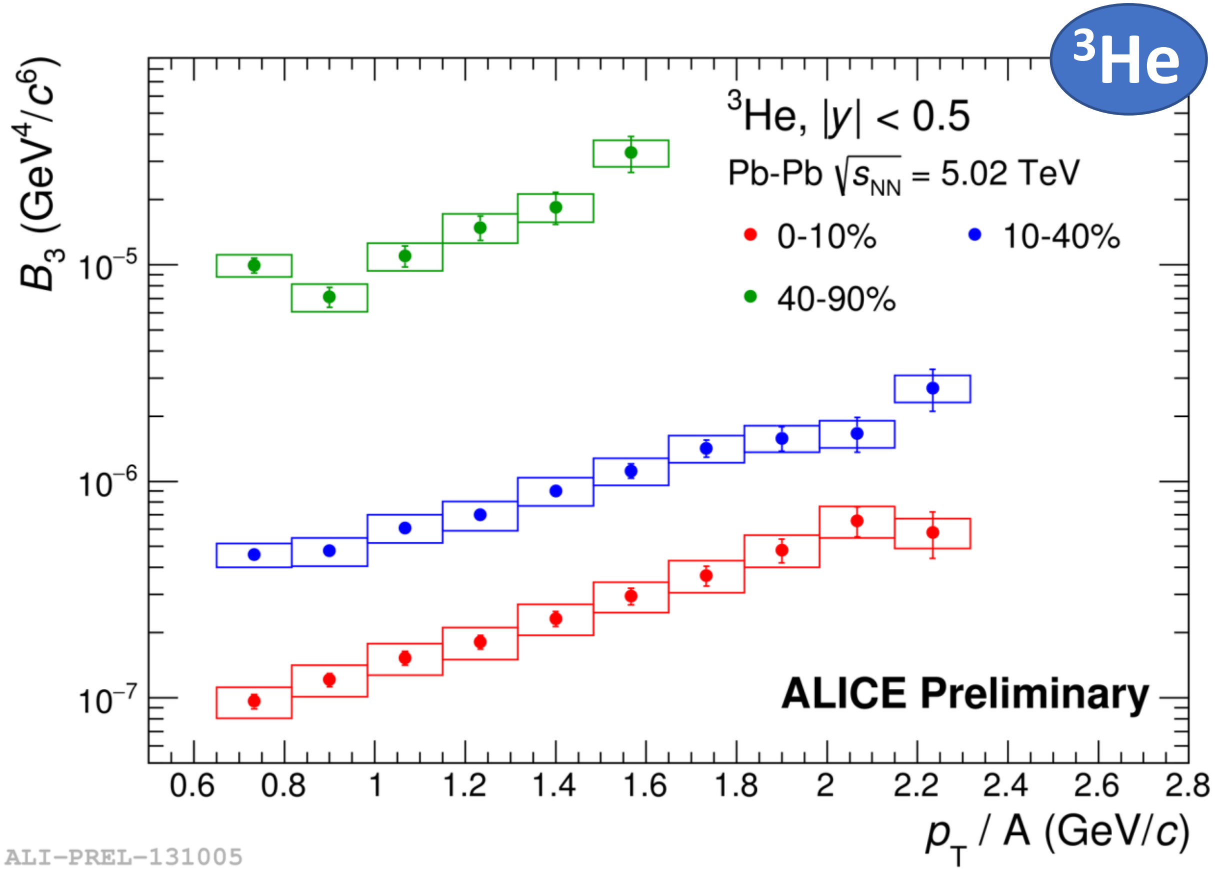
Coalescence parameters VS p_T/A

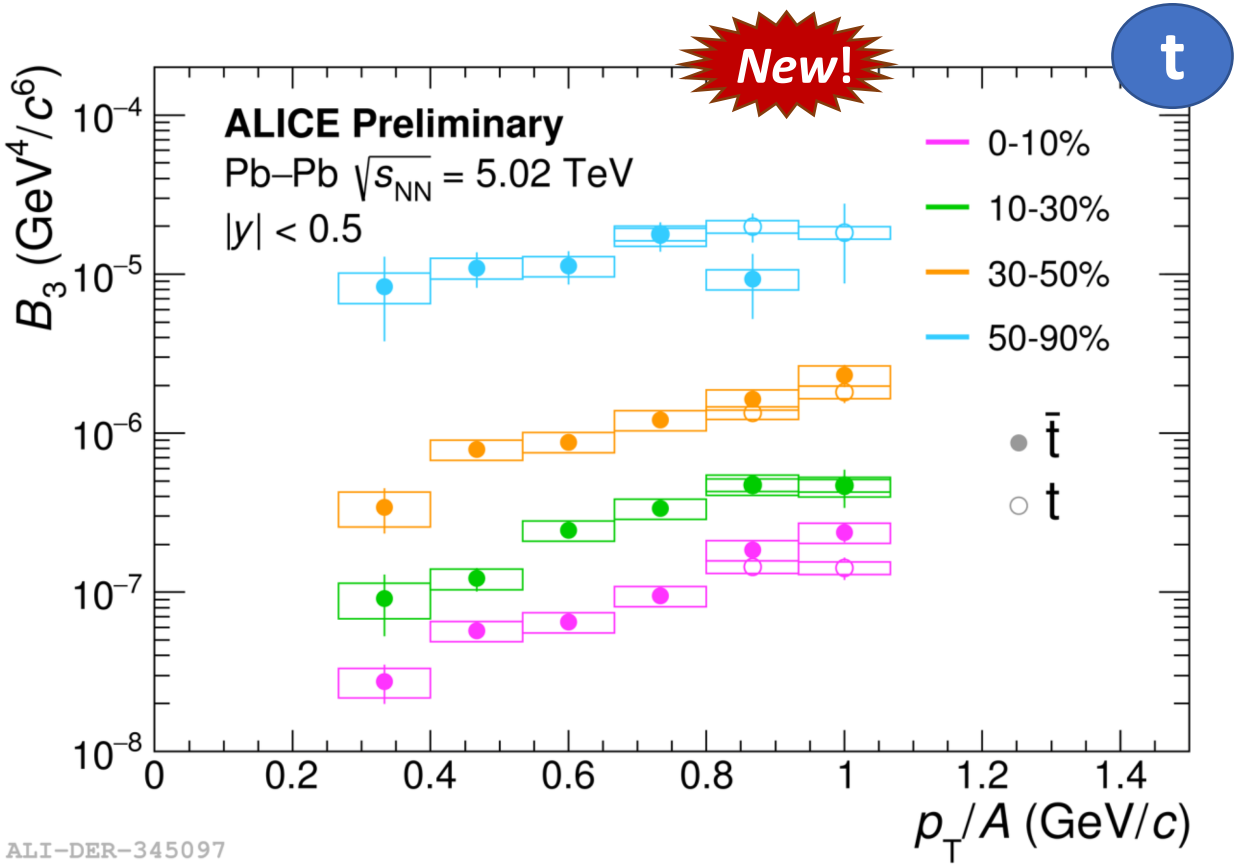


Pb-Pb @ 5.02 TeV

- Rise with increasing p_T/A (especially at higher multiplicities)
- Trend with p_T/A in Pb–Pb collisions described by hydrodynamic calculations with afterburner
  (Oliinychenko, PRC 99, 044907 (2019))

Coalescence parameters VS p_T/A

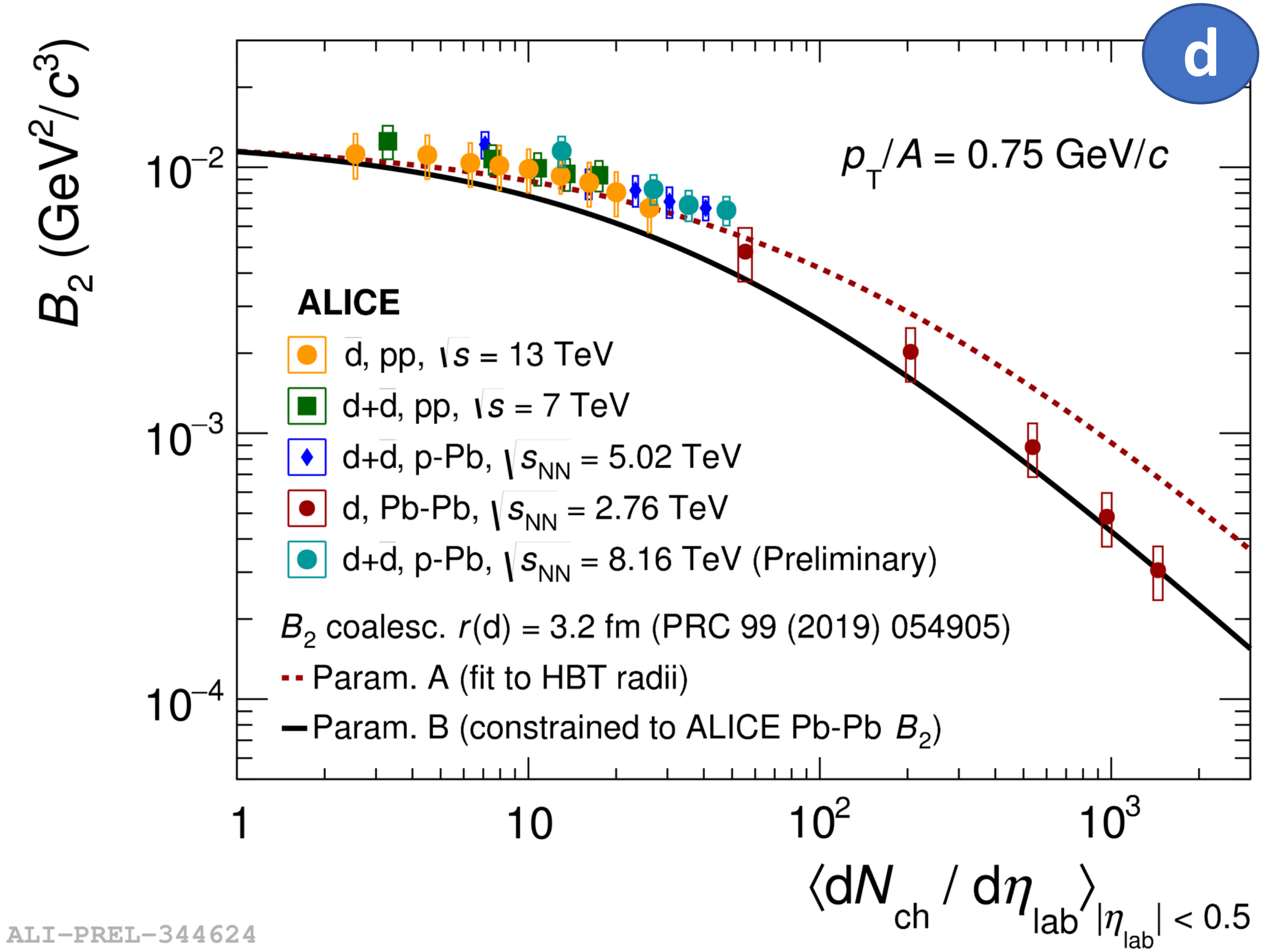




- Also for B_3 observed a rise with increasing p_T/A (especially at higher multiplicities)

Pb-Pb @ 5.02 TeV

Coalescence parameter B_2



Strong dependence of B_2 on collision geometry

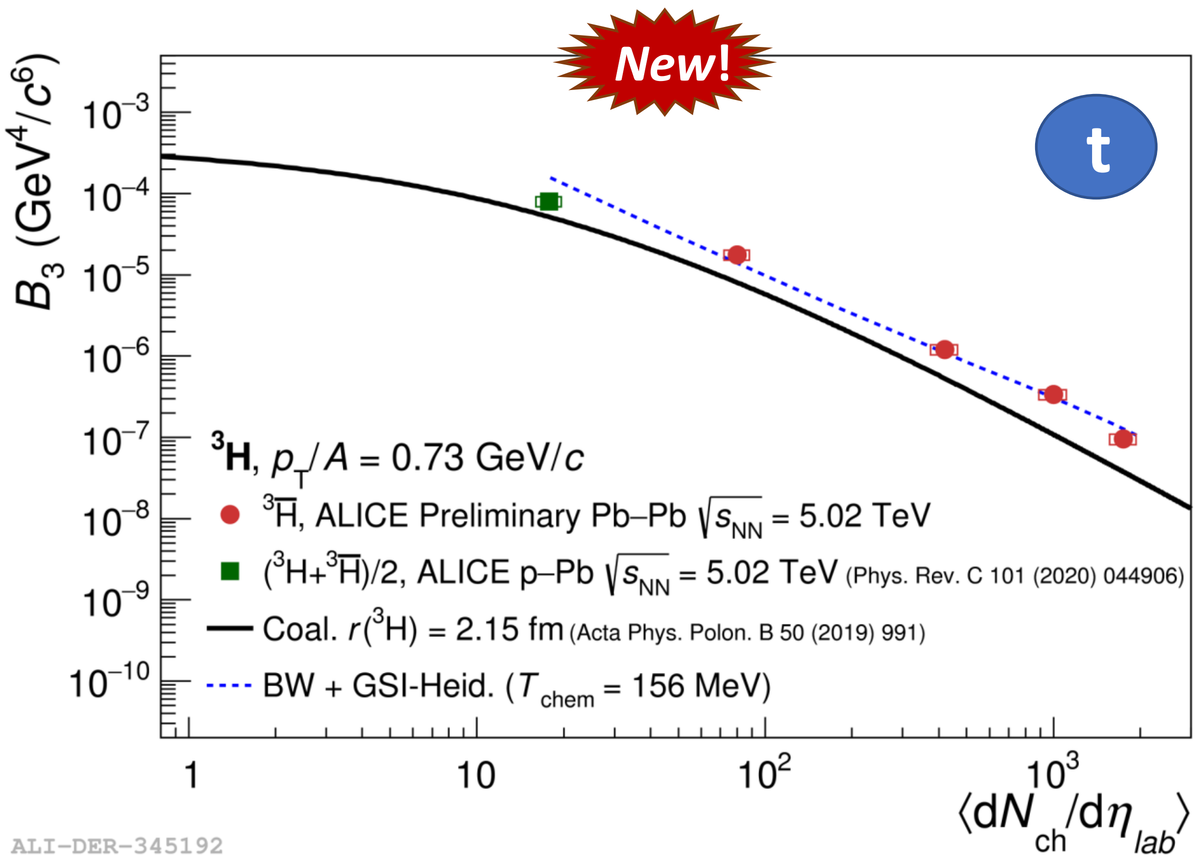
Continuous evolution of B_2 with multiplicity

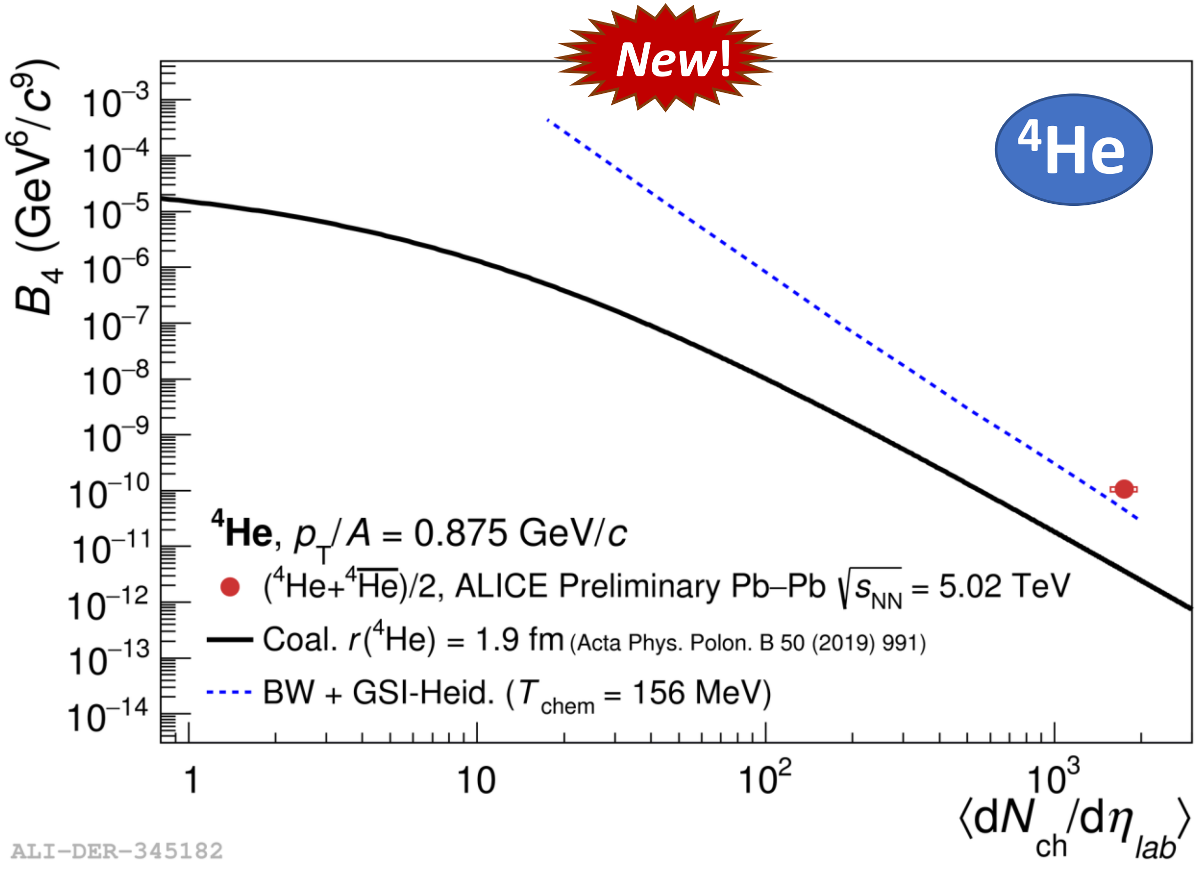
- Smooth transition from small to large system size
- Single underlying production mechanism?

Advanced coalescence taking the size of the nucleus and the emitting source into account predicts a similar trend

The trend with multiplicity is explained as an increase in the source size *R* in coalescence models
(e.g. *Scheibl, Heinz PRC 59 (1999) 1585*).

Coalescence parameters B_3 and B_4

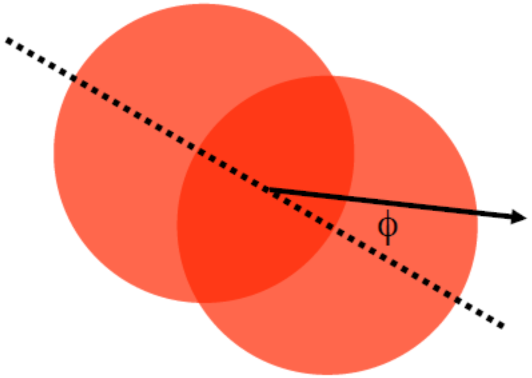




- Similar trend with multiplicity observed also in B_3
- Continuous evolution of B_3 with multiplicity

Models struggle to quantitatively describe the measured B_3 (and B_4)

Elliptic and triangular flow



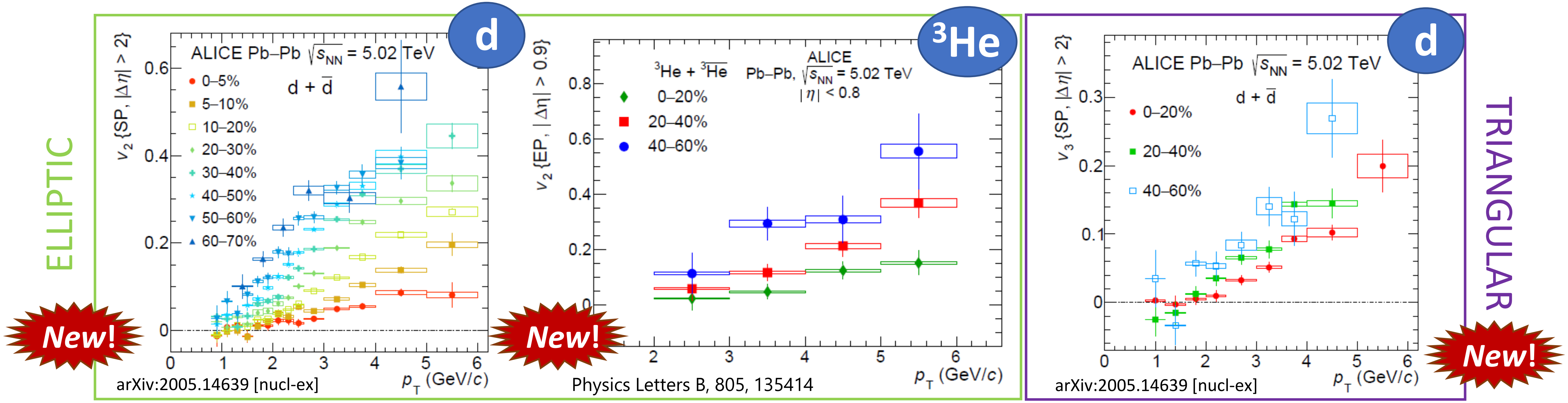
Initial space anisotropy in non-central A-A collisions

- ➢ azimuthal anisotropy of particle emission wrt symmetry plane

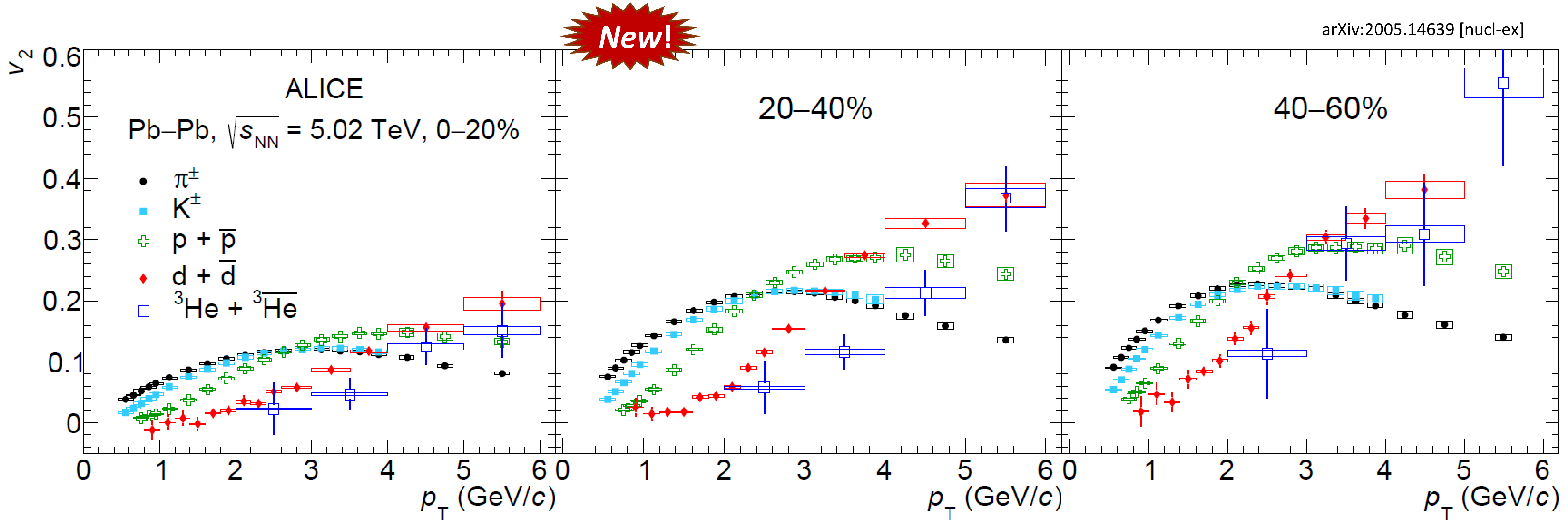
Particle azimuthal distribution can be espressed as a Fourier series

$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n\geq 1} v_n \cos\left(n\left(\varphi - \Psi_n\right)\right)$$

$$\begin{cases} \Psi_n = n^{th} \text{ symmetry plane} \\ \varphi = \text{azimuthal angle} \\ v_n = \text{flow coefficients} \end{cases}$$

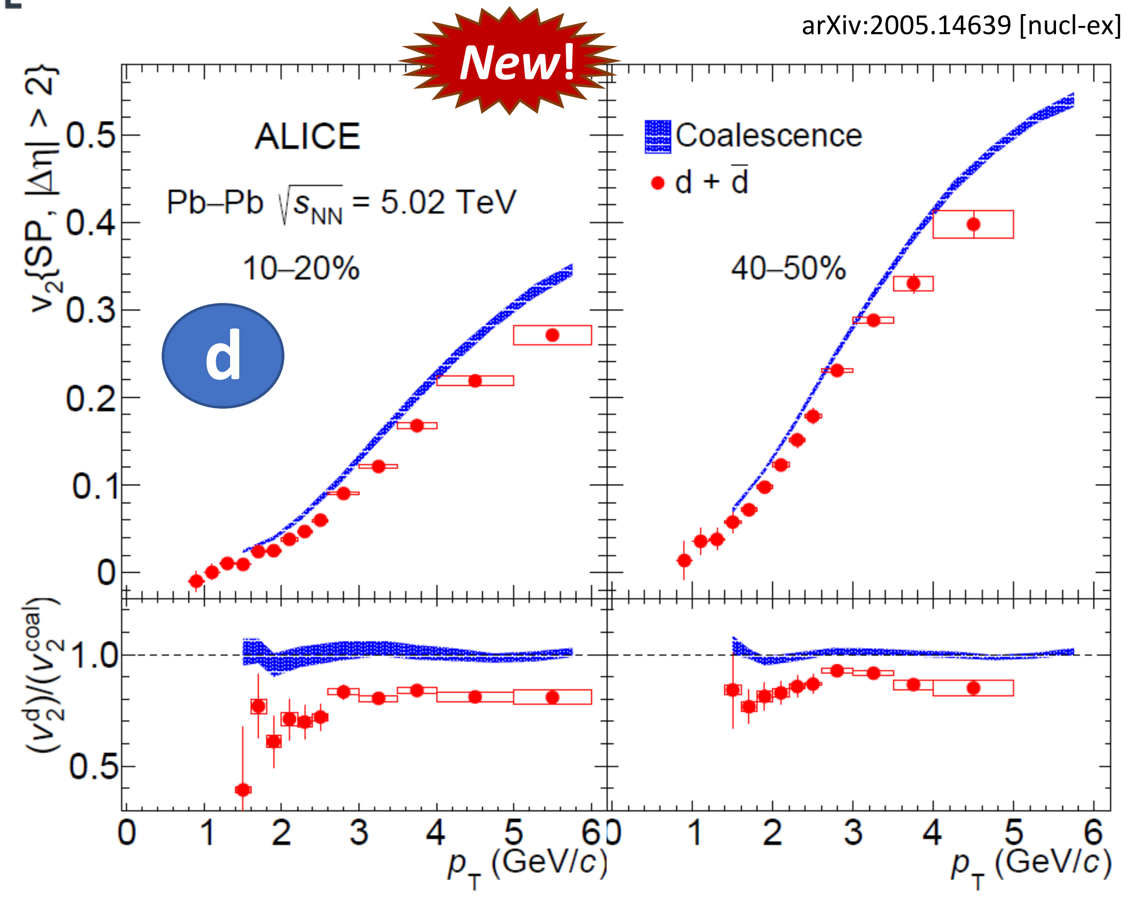


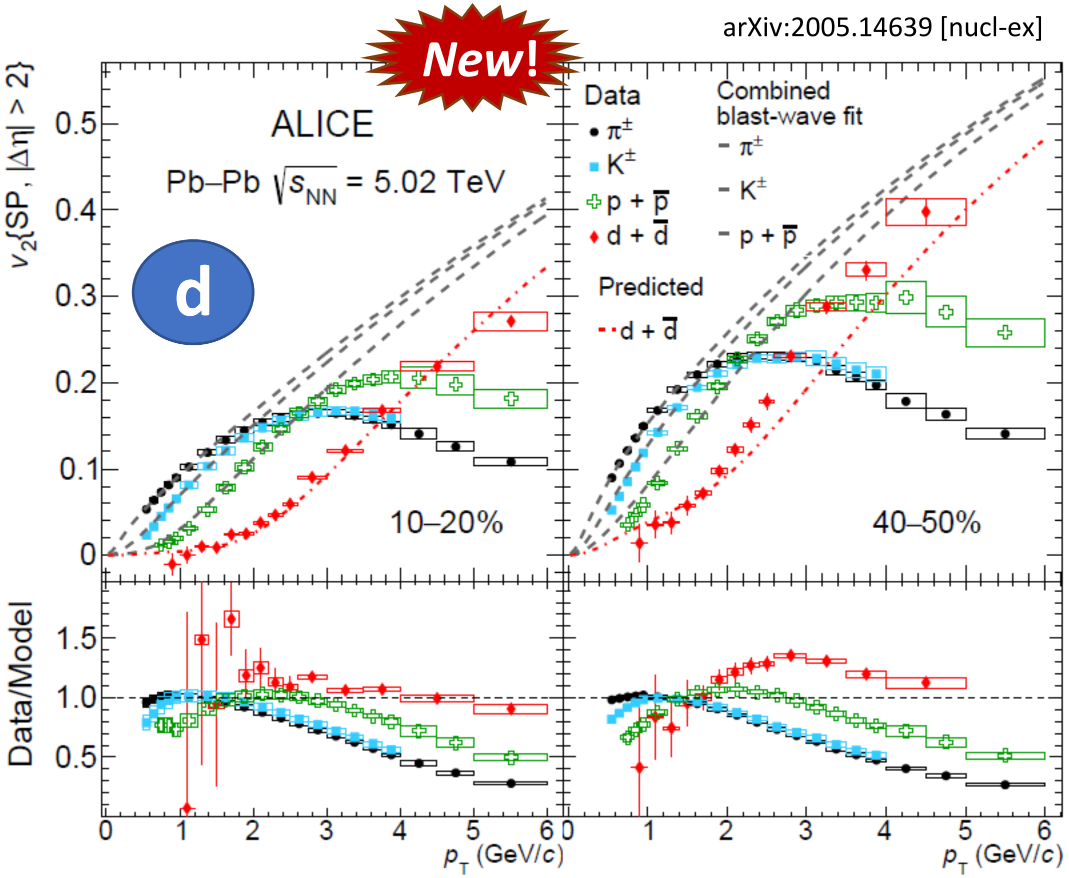
Elliptic flow v_2



- 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



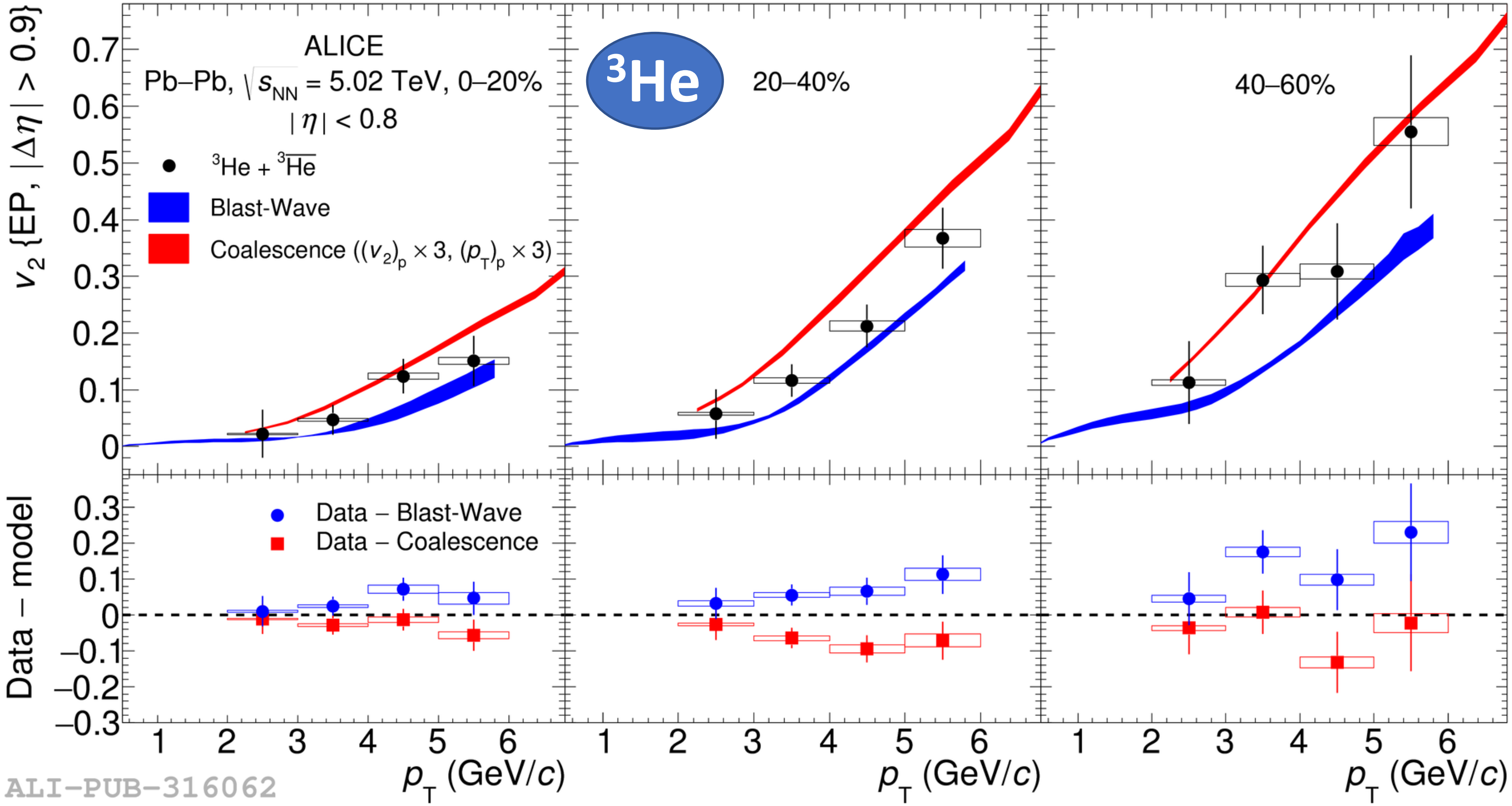


SIMPLE COALESCENCE	*SIMPLIFIED HYDRODYNAMICS*
Overestimate of data	Underestimate of data
Works better for more peripheral collisions	Works better for more central collisions

Comparison to simplified models

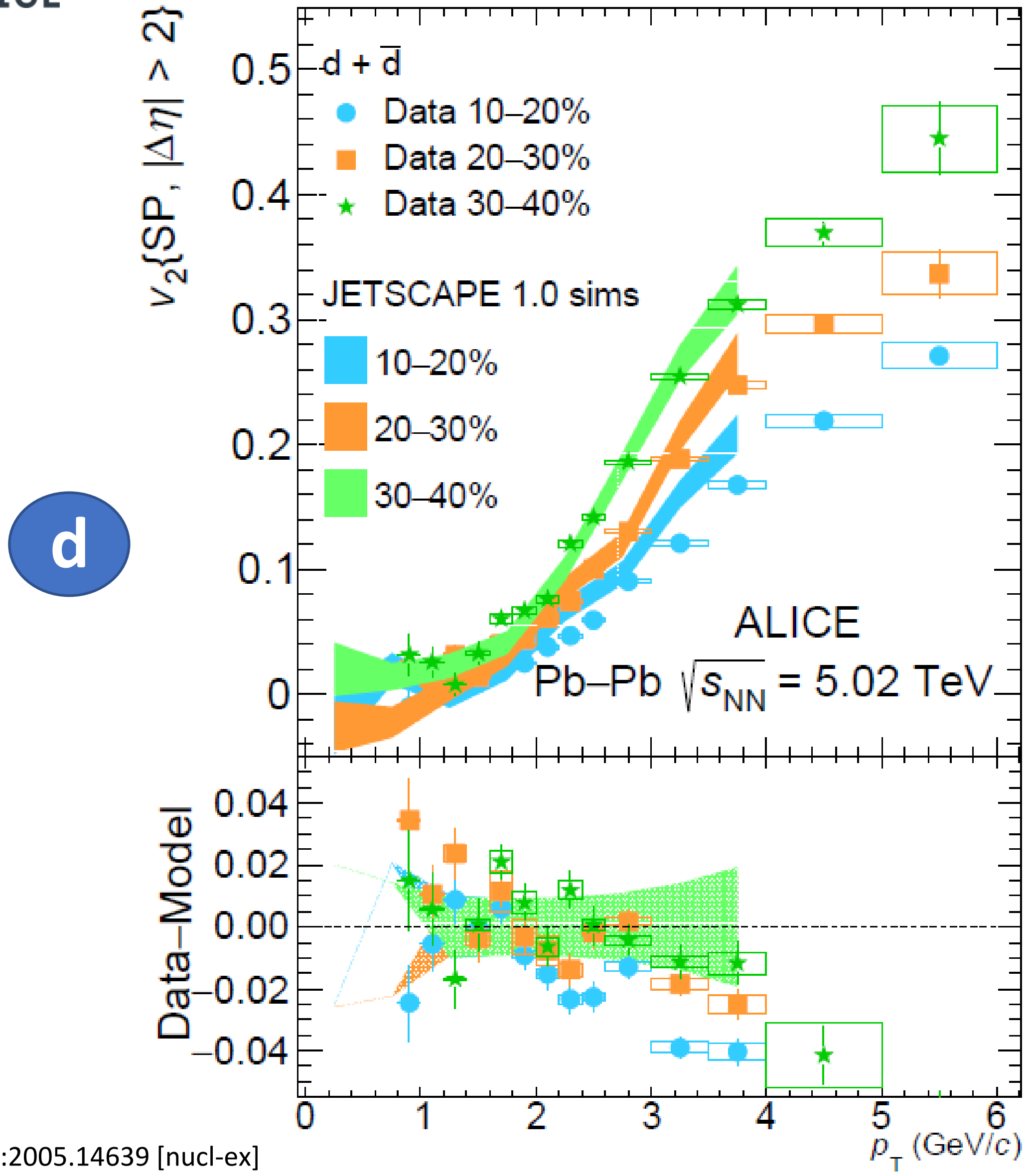
New!

Physics Letters B, 805, 135414



- Similar behaviour also for ^{3}He flow
- v_2 of (anti)^{3}He lies between Blast-Wave and naive coalescence
- Models partially describe the data – depending on centrality regions

Comparison to more sophisticated models

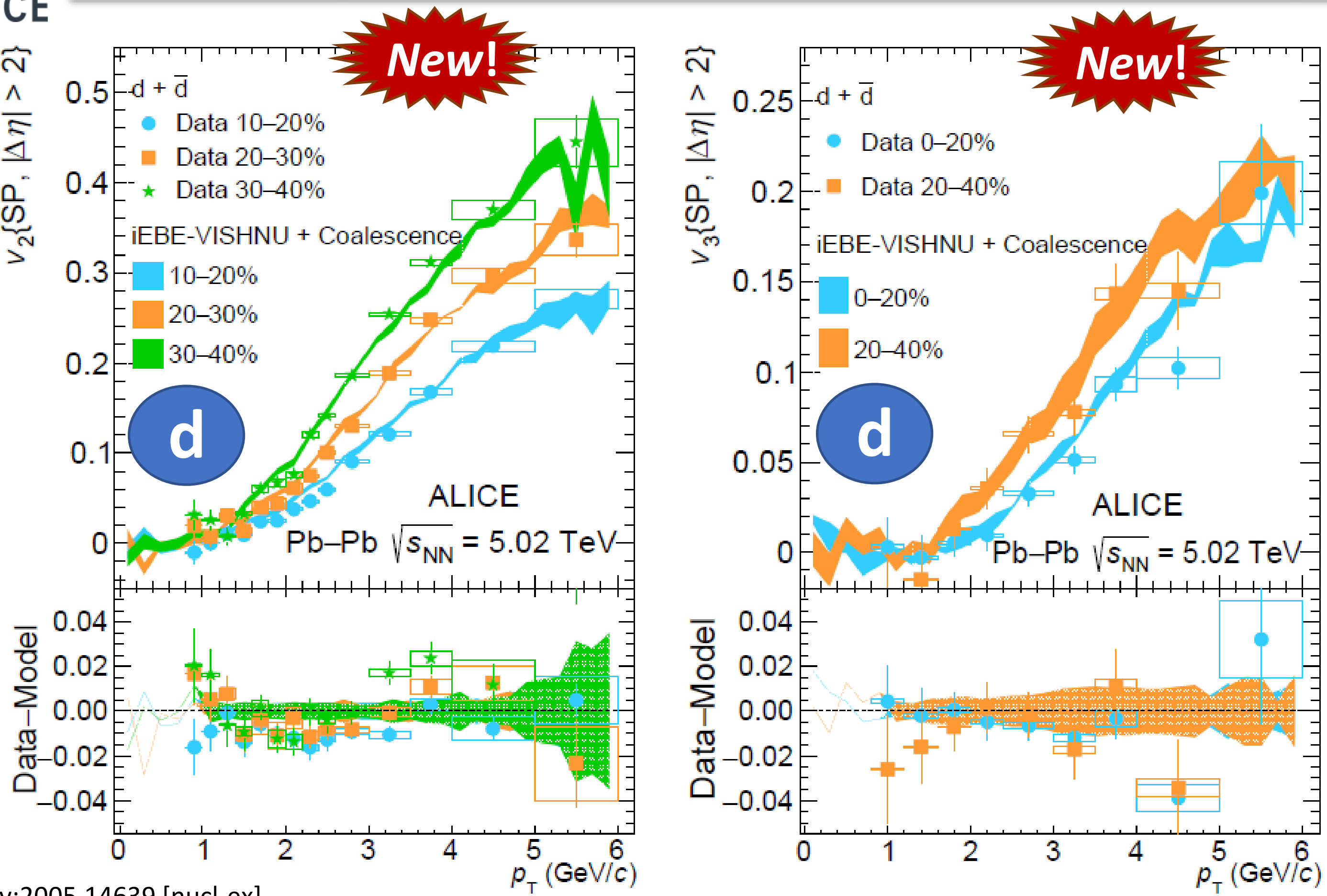


arXiv:2005.14639 [nucl-ex]

New!

- Comparison with predictions of a hybrid model based on relativistic viscous hydrodynamics (JETSCAPE 1.0) – no coalescence in the final state
- Good description of the deuteron v_2 20-30% and 30-40% collisions

Comparison to more sophisticated models



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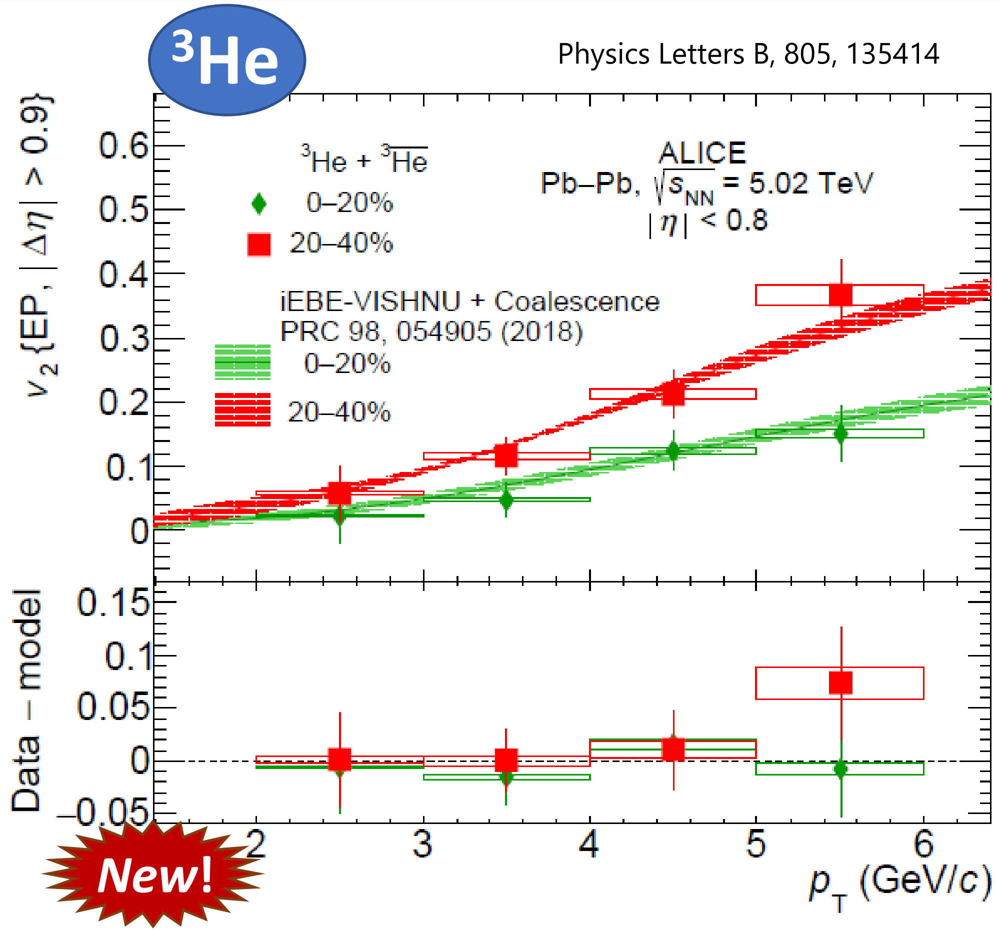


Hydrodynamical simulation (iEBE-VISHNU) + Coalescence (Wenbin, PRC 98, 054905 (2018))

- 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

Conclusions

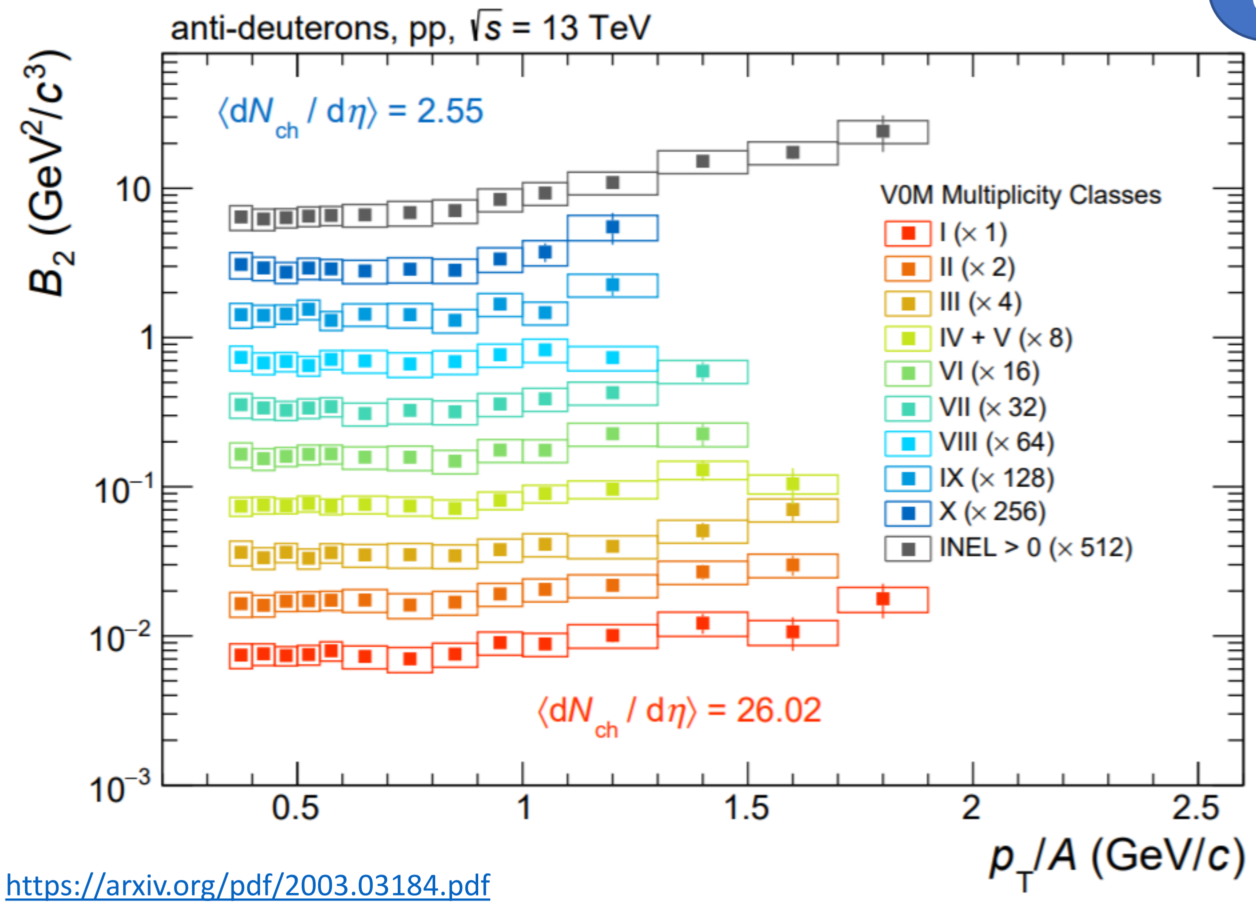
- Light (anti)nuclei up to ^{4}He are measured with ALICE
- Production mechanism evolves smoothly with multiplicity
- Statistical and Coalescence models describe different aspects of light (anti)nuclei production
- Experimental results challenge the models

Thank you for the attention!

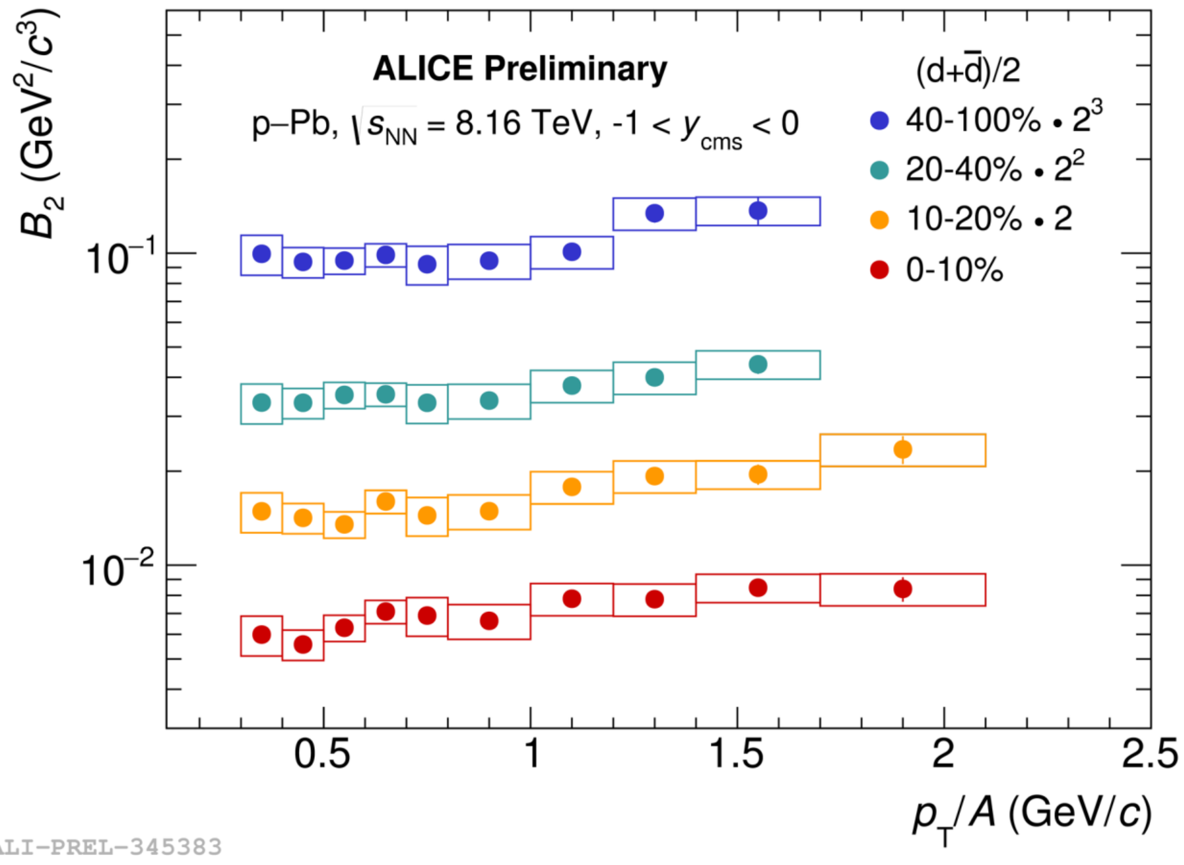
Backup

Coalescence parameters VS p_T/A

d



https://arxiv.org/pdf/2003.03184.pdf

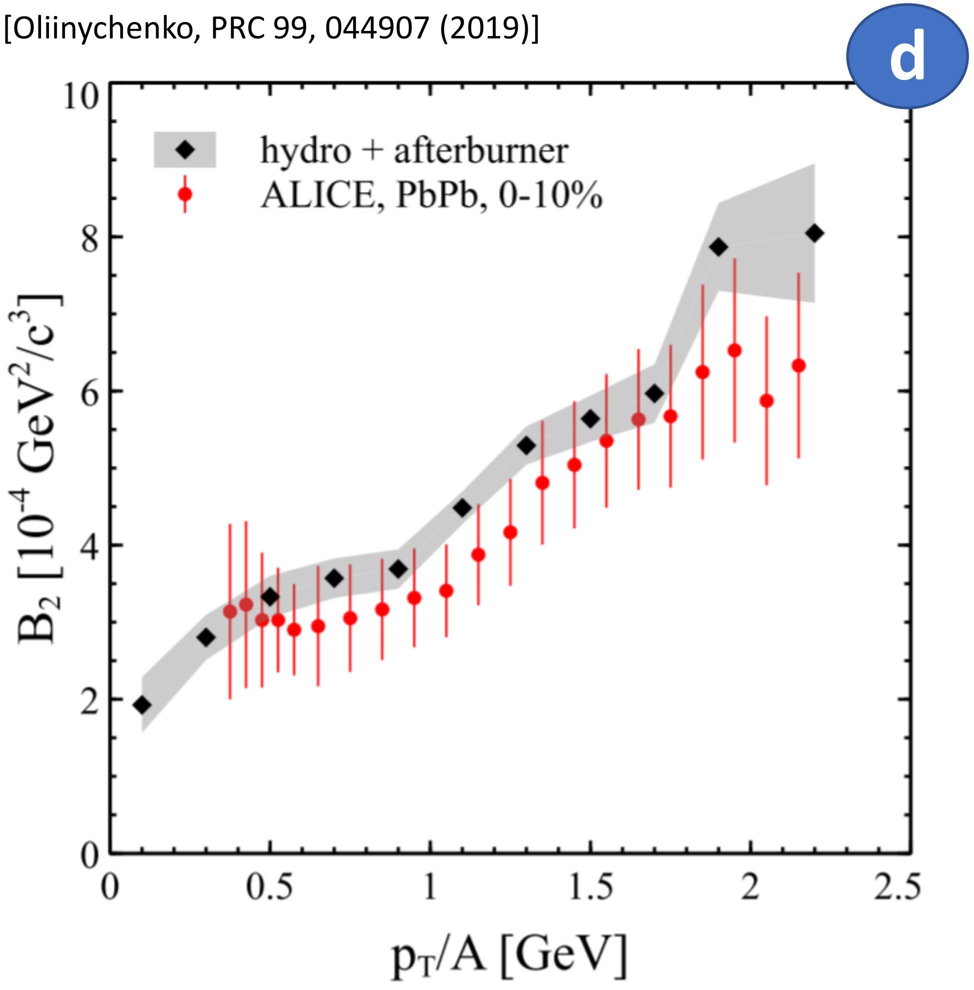


pp @ 13 TeV

p-Pb @ 8.16 TeV

Coalescence parameters VS p_T/A

[Oliinychenko, PRC 99, 044907 (2019)]



(central) Pb-Pb @ 2.76 TeV

- Trend with p_T/A in Pb–Pb collisions described by hydrodynamic calculations with afterburner

→ Deuteron B_2 from the hydro + SMASH simulation (no coalescence, only collisions with experimentally known deuteron cross sections) compared to ALICE measurements in Pb-Pb at 2.76 TeV

Also p_T spectra are reproduced by the model, but p & d spectra are slightly overestimated