Measurement of elliptic and triangular flow of light (anti-)nuclei with ALICE at the LHC

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Introduction & motivation

Production mechanism of light (anti-)nuclei in high-energy heavy-ion collisions is still not understood

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- **Statistical hadronization** model
- **Coalescence** approach

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Azimuthal flow of light (anti-)nuclei is a key observable to study their production mechanism

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- Mass number scaling (simplistic picture)
- Phase-space distributions of nucleons used to calculate flow of (anti-)nuclei in a more sophisticated approach

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Flow of light (anti-)nuclei could be described by **hydrodynamics**

- ➢ Only simplified approach (Blast-Wave) is available

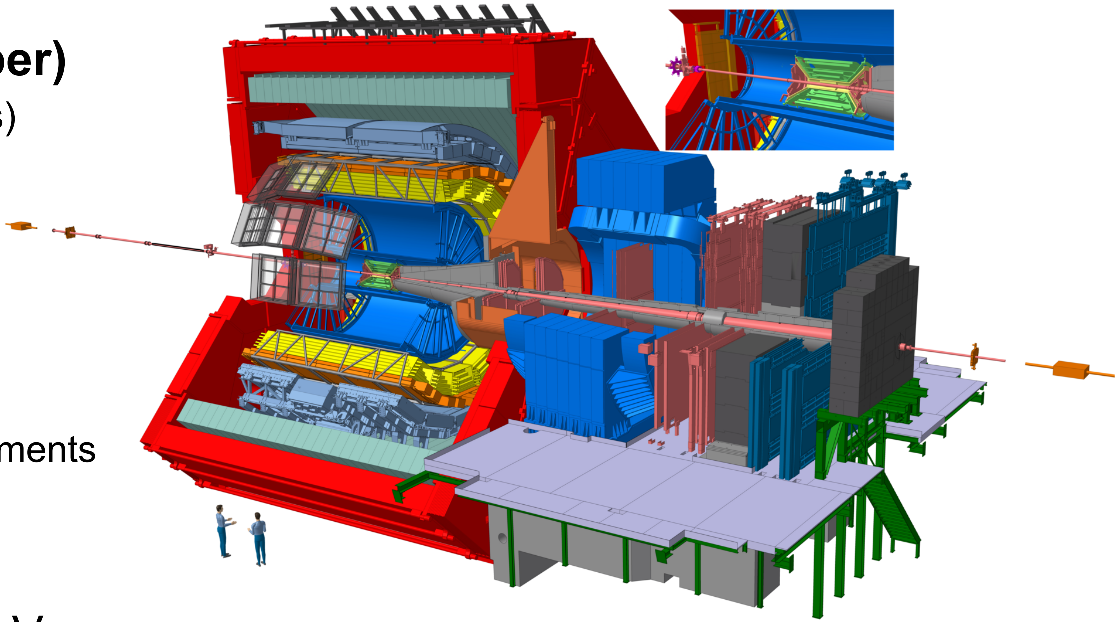
The ALICE setup and data sample

ITS (Inner Tracking System)
- Tracking, vertexing & PID (via dE/dx in silicon)

TPC (Time Projection Chamber)
- Tracking & PID (via dE/dx in the gas)

TOF (Time Of Flight)
- PID (via TOF measurement)

V0
- Centrality and event plane measurements

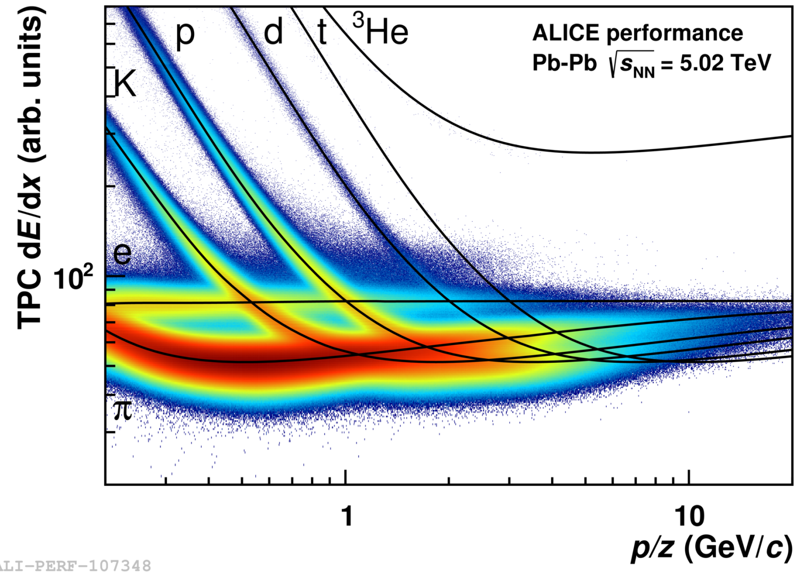


Data set:

Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

Number of events (×10^6)	Observable
56	v_2 of (anti-)deuterons
48	v_3 of (anti-)deuterons
60	v_2 of (anti-)^{3}He

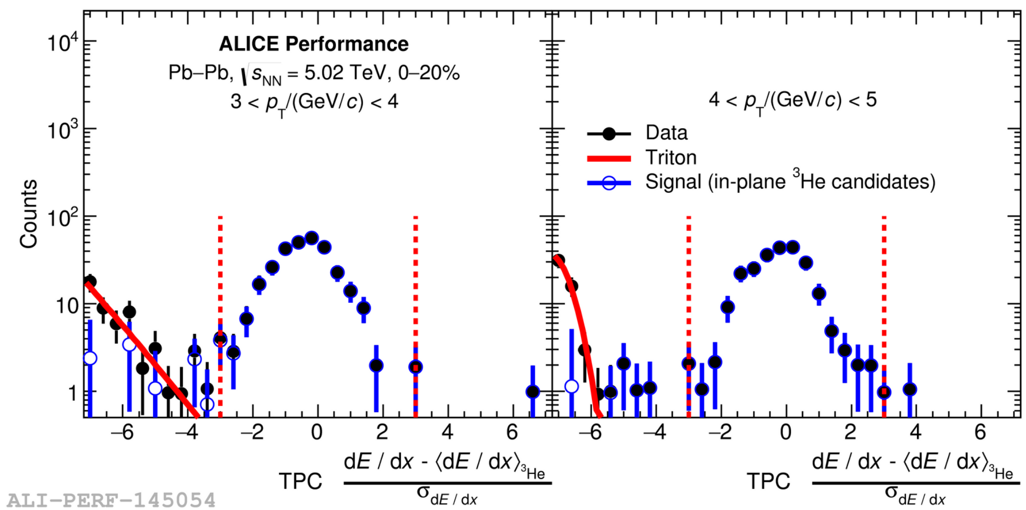
(Anti-)^{3}He identification



(anti-)^{3}He identification based on the dE/dx measured by the TPC

Negligible contamination from (anti-)^{4}He

- ^{4}He/^{3}He ~1/300 in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV (**NPA 971 (2018) 1-20**)
- Similar suppression is expected in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

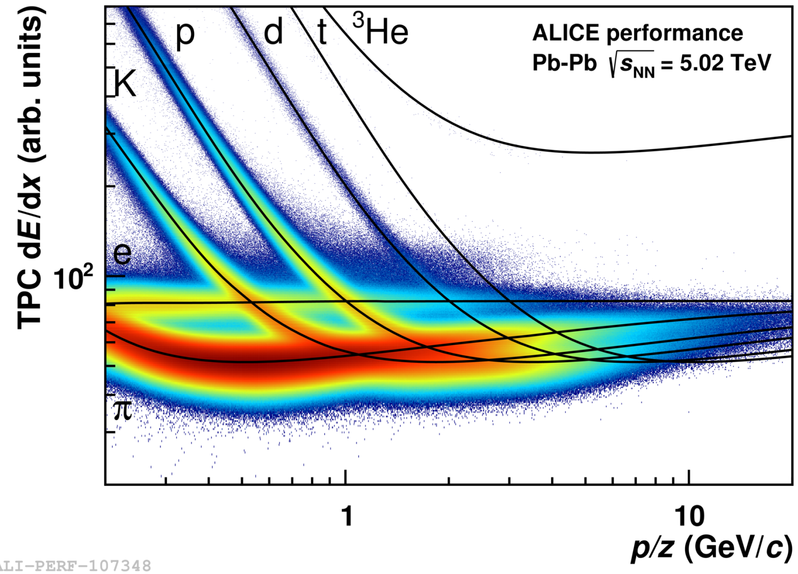


(anti-)^{3}H contamination relevant only for p_T < 3 GeV/c

(anti-)^{3}H contribution estimated using a Gaussian fit

Signal extraction in the range $|dE/dx - \langle dE/dx\rangle_{^3He}| < 3\sigma$

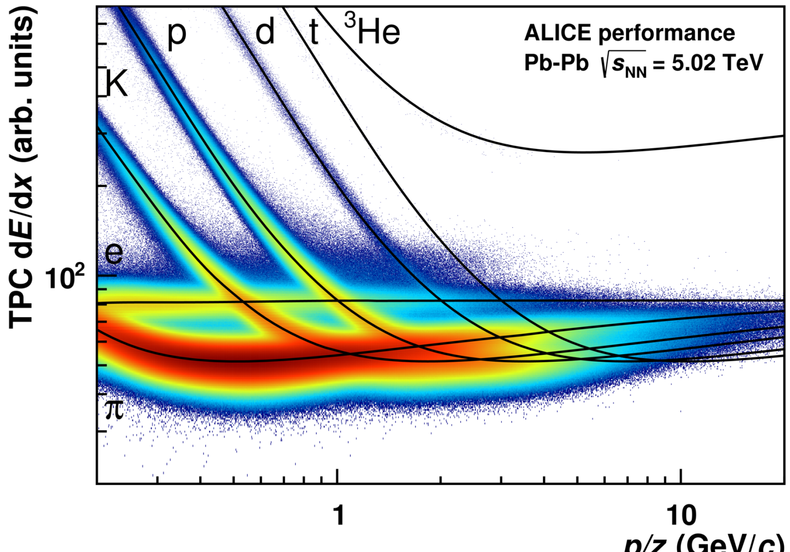
(Anti-)deuteron identification



p_T < 1 GeV/c:

The dE/dx measured by the TPC is used requiring $|dE/dx - \langle dE/dx \rangle_d| < 3\sigma$

(Anti-)deuteron identification



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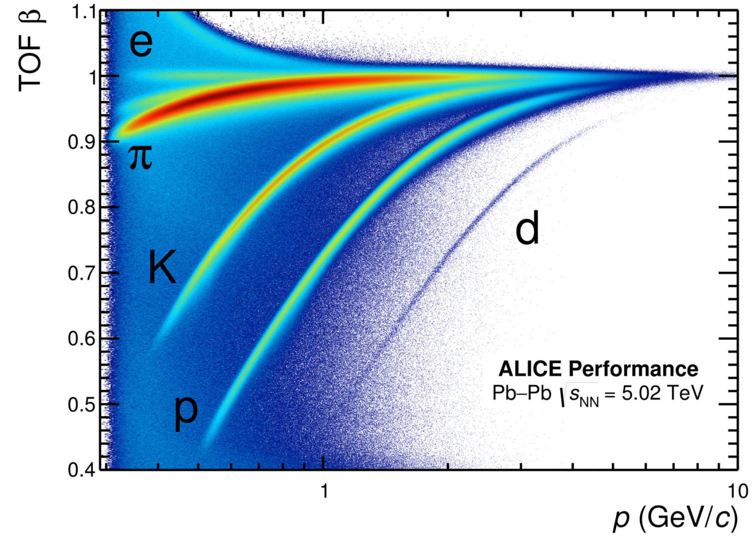

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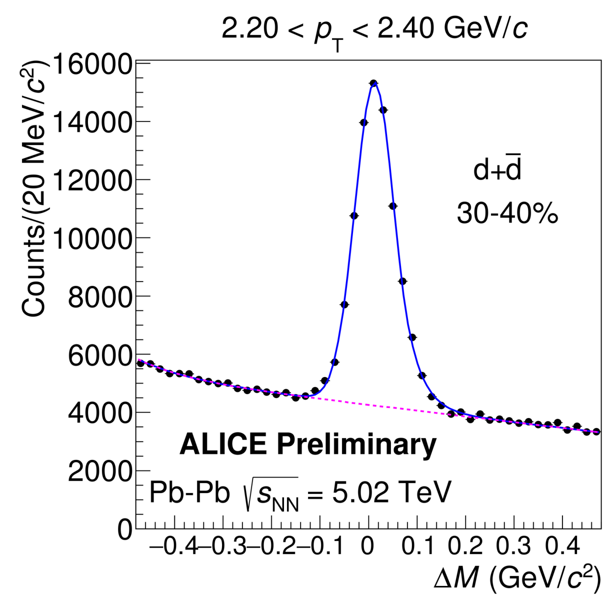

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p_T < 1 GeV/c:

The dE/dx measured by the TPC is used requiring $|dE/dx - \langle dE/dx \rangle_d| < 3\sigma$

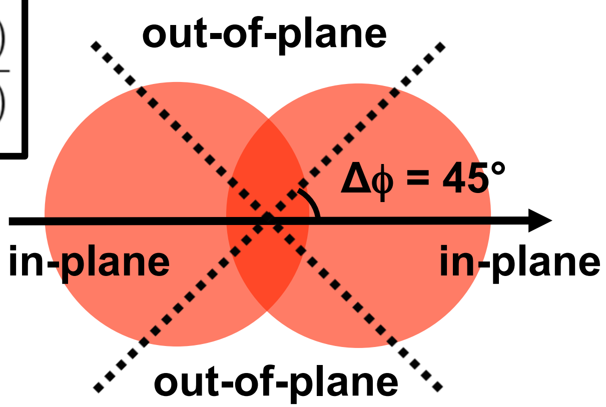
p_T > 1 GeV/c:

- TPC pre-selection ($|dE/dx - \langle dE/dx \rangle_d| < 3\sigma$)
- Signal extraction using the $\Delta M = M - M_d$ measured by TOF (background from TPC-TOF mismatch)

Analysis technique for the (anti-)^{3}He v_2

Elliptic flow of ^{3}He measured using the **Event Plane** (EP) method

$$v_2\{\mathrm{EP}, |\Delta\eta| > 0.9\}(p_\mathrm{T}) = \frac{\pi}{4R_{\Psi_2}} \frac{N_{\text{in-plane}}(p_\mathrm{T}) - N_{\text{out-of-plane}}(p_\mathrm{T})}{N_{\text{in-plane}}(p_\mathrm{T}) + N_{\text{out-of-plane}}(p_\mathrm{T})}$$



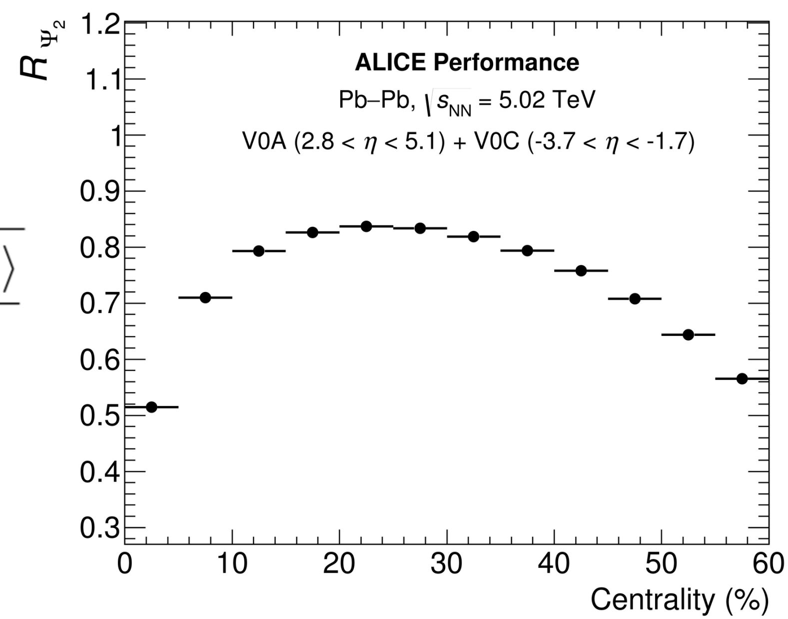
The symmetry plane of the collision is measured using the V0 detectors:

- V0A: $-3.7 < \eta < -1.7$
- V0C: $2.8 < \eta < 5.1$

Event plane resolution of the 2nd harmonic measured using the three sub-events method

$$R_{\Psi_2} = \sqrt{\frac{\langle \cos(2(\Psi_2^A - \Psi_2^B))\rangle \cdot \langle \cos(2(\Psi_2^A - \Psi_2^C))\rangle}{\langle \cos(2(\Psi_2^B - \Psi_2^C))\rangle}}$$

$$\begin{cases} A = \mathrm{V0} \\ B = \mathrm{TPC}\ (\eta > 0) \\ C = \mathrm{TPC}\ (\eta < 0) \end{cases}$$



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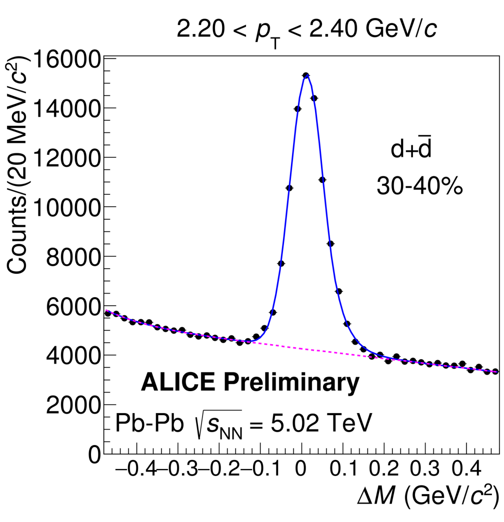
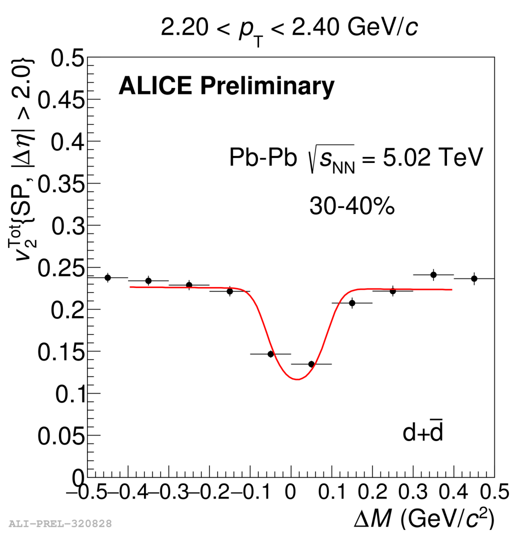
Analysis technique for the (anti-)d v_2 & v_3

Elliptic and triangular flow of (anti-)deuterons measured using the **Scalar Product** (SP) method

$$v_n\{\mathrm{SP}\} = \frac{\langle\langle \mathbf{u}_{n,\mathrm{k}} \mathbf{Q}_n^{*} \rangle\rangle}{\sqrt{\frac{\langle \mathbf{Q}_n \mathbf{Q}_n^{\mathrm{A}*} \rangle \langle \mathbf{Q}_n \mathbf{Q}_n^{\mathrm{B}*} \rangle}{\langle \mathbf{Q}_n^{\mathrm{A}} \mathbf{Q}_n^{\mathrm{B}*} \rangle}}}$$

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

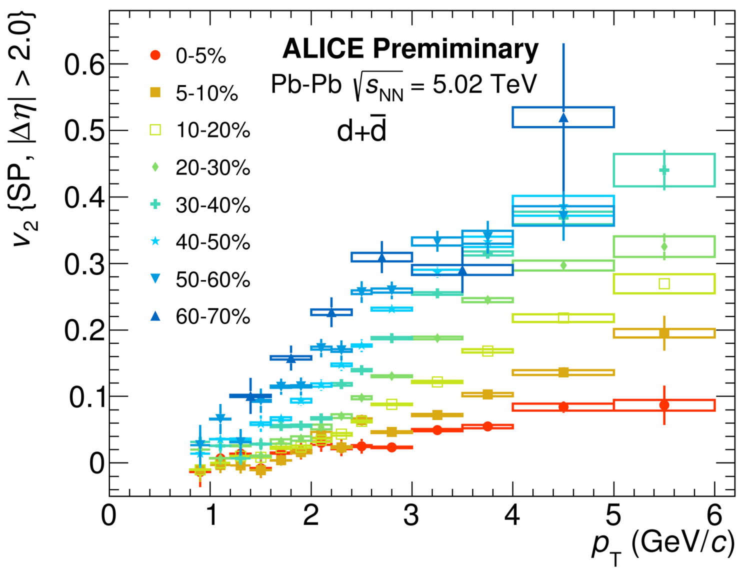




Signal extraction:

- N_{sig} and N_{bkg} extracted from the fit of (anti-)deuteron yield vs. $\Delta M = M - M_d$
- v_n^{bkg} described using a linear function
  - v_n^{sig} extracted from the fit of v_n^{tot}

Centrality & p_T dependence of v_2 and v_3



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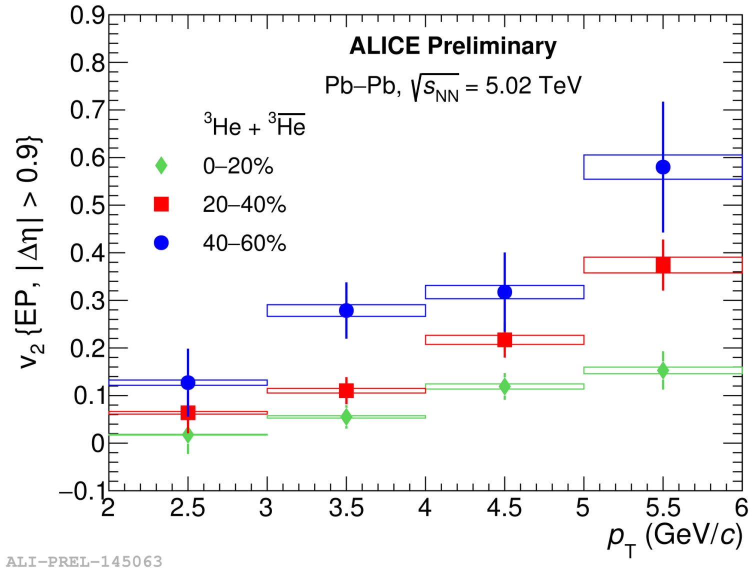

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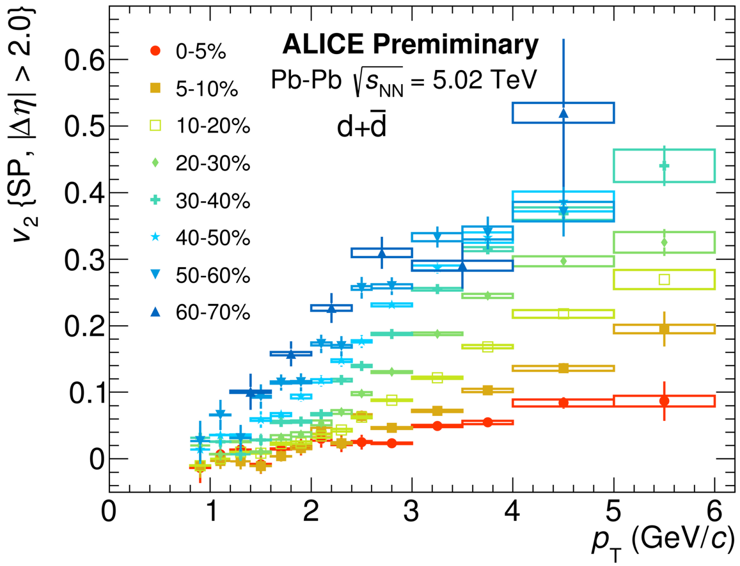
v_2 of (anti-)deuterons and (anti-)^{3}He:

- Centrality & p_T dependence as expected from relativistic hydrodynamics

Centrality & p_T dependence of v_2 and v_3



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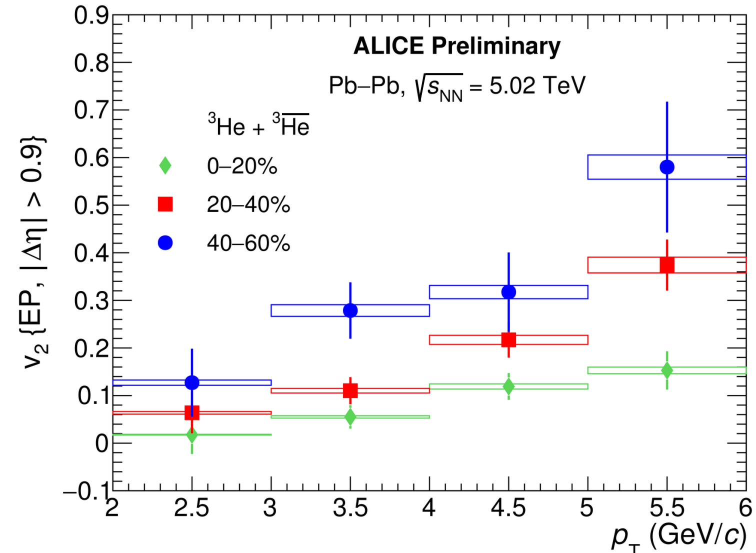

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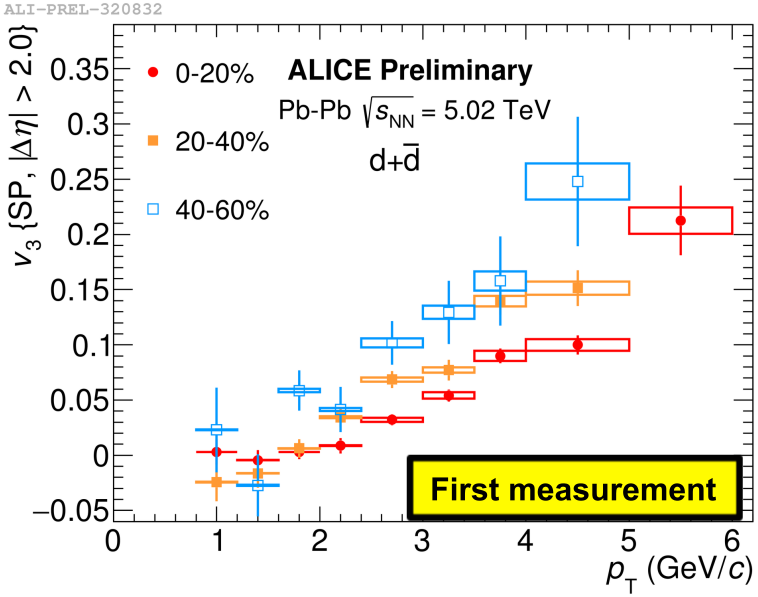

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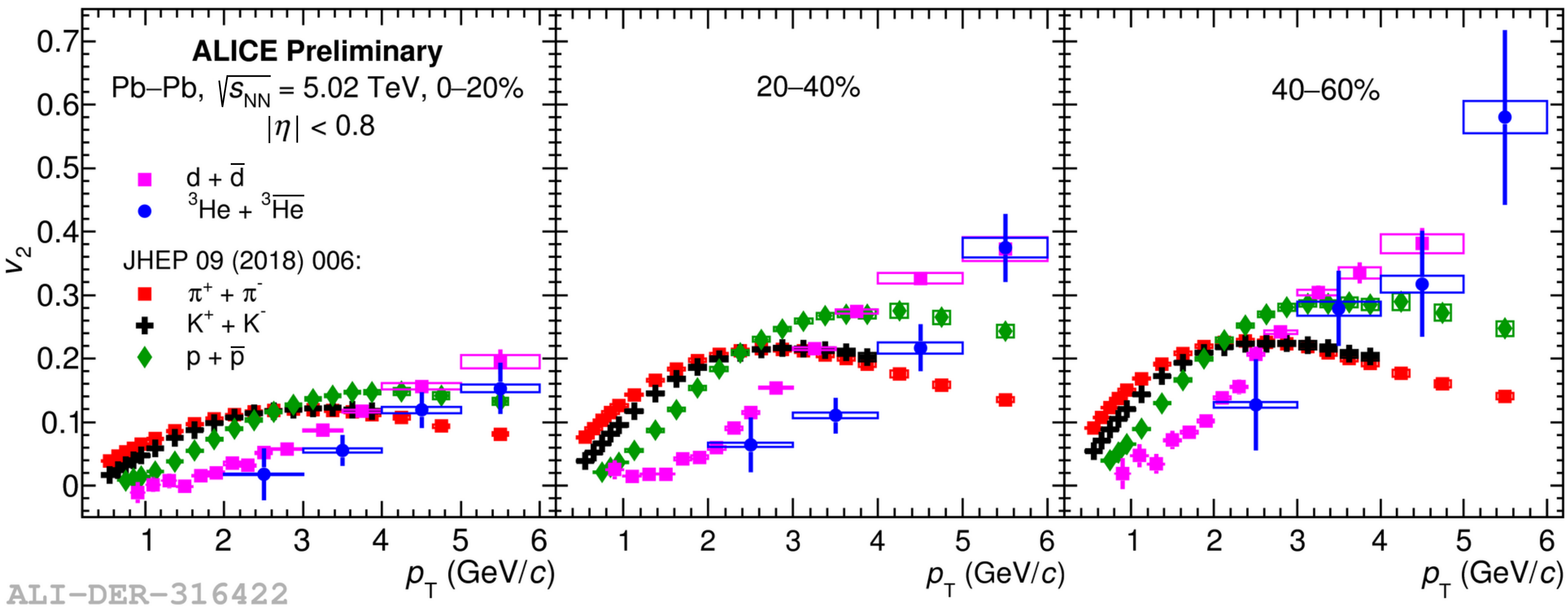
v_2 of (anti-)deuterons and (anti-)^{3}He:

- Centrality & p_T dependence as expected from relativistic hydrodynamics

v_3 of (anti-)deuterons:

- First measurement
- Effects of initial state fluctuations of energy density in the colliding nuclei visible also for (anti-)deuterons

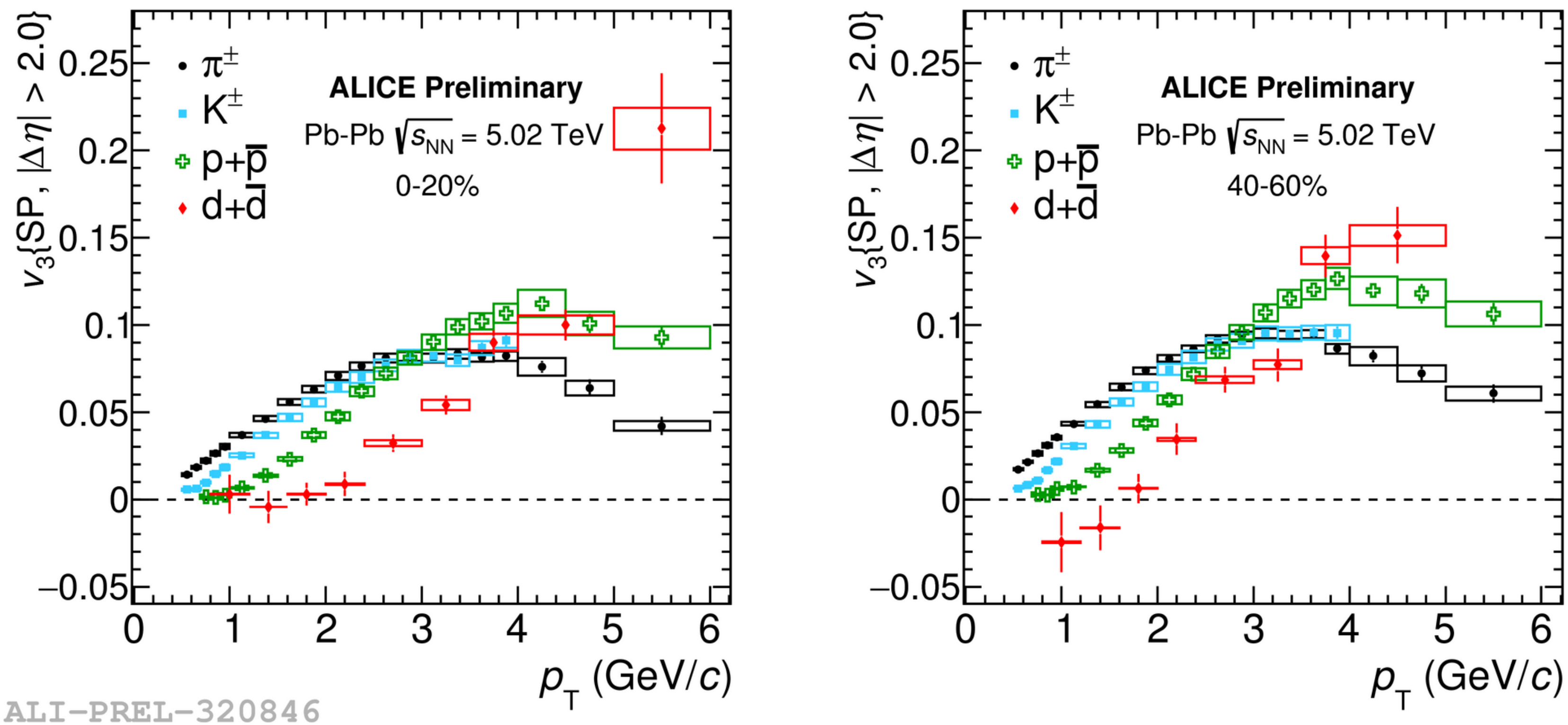
v_2 of light (anti-)nuclei vs. v_2 of π, K and p



Mass ordering at low p_T & slower rise for heavier particles

➢ as expected from relativistic hydrodynamics

v_3 of (anti-)deuterons vs. v_3 of π, K and p

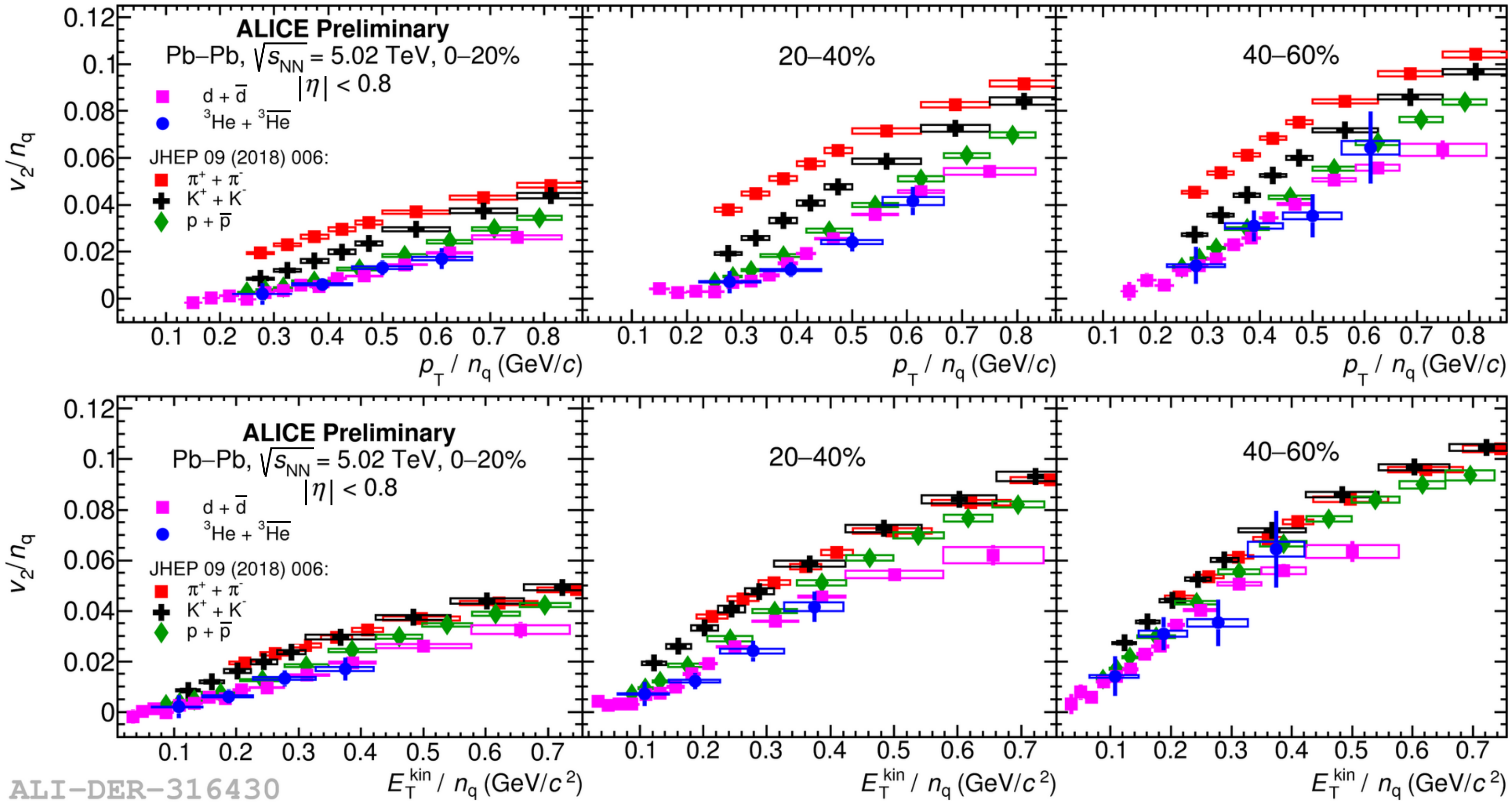


(Anti-)deuteron v_3 increases with p_T and going from central to peripheral collisions

Centrality & p_T dependence of the (anti-)deuteron v_3 consistent with expectations based on the v_3 of identified hadrons

- Mass ordering is observed at low p_T

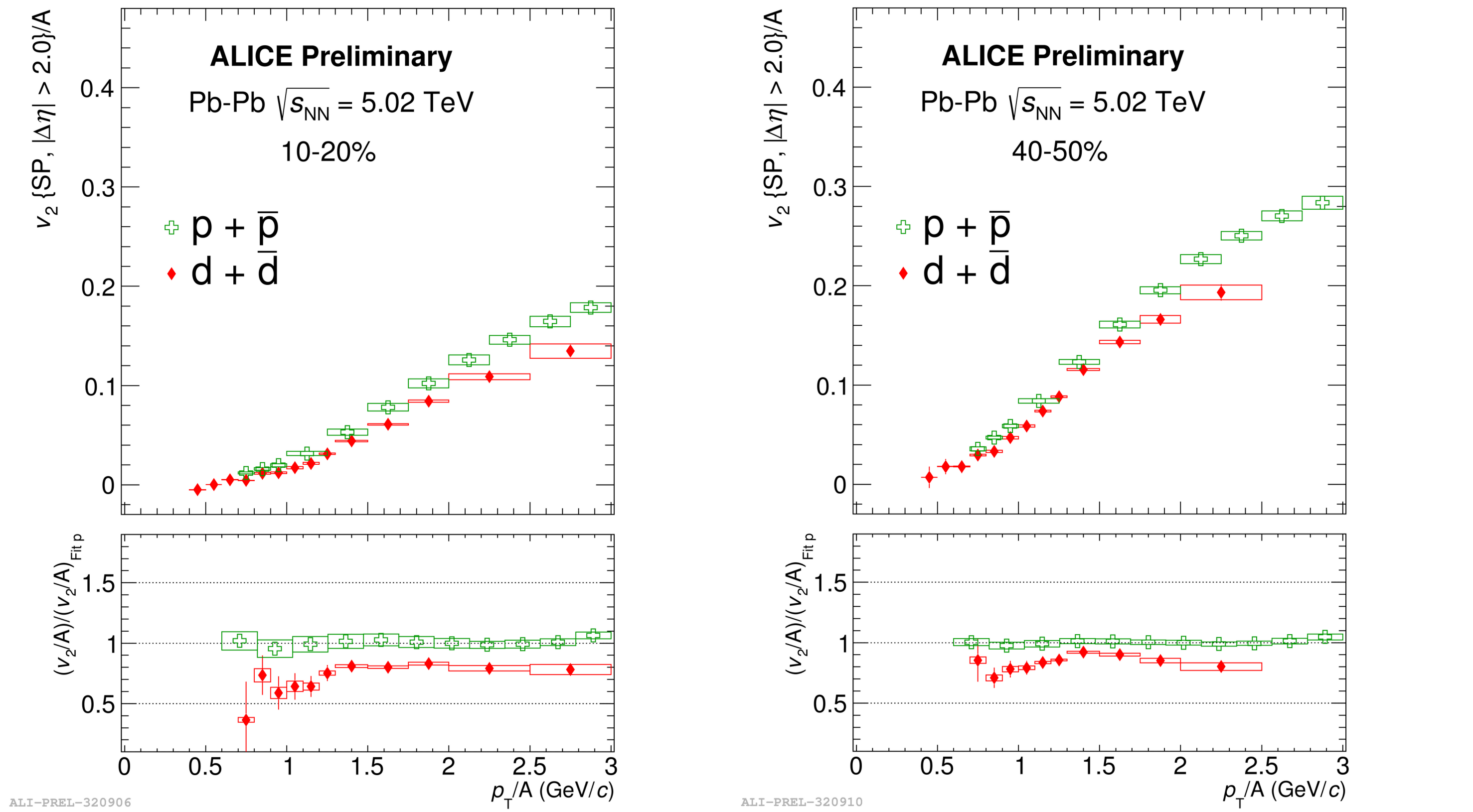
n_q-scaling of v_2 of light (anti-)nuclei



Scaling of v_2 with the number of constituent quarks (n_q):

- Baryons show an approximate scaling vs. p_T/n_q
  - However, deviations up to 50% are observed
- Mesons and baryons show approximate scaling vs. E_T^{kin}/n_q

A-scaling of v_2 of (anti-)deuterons

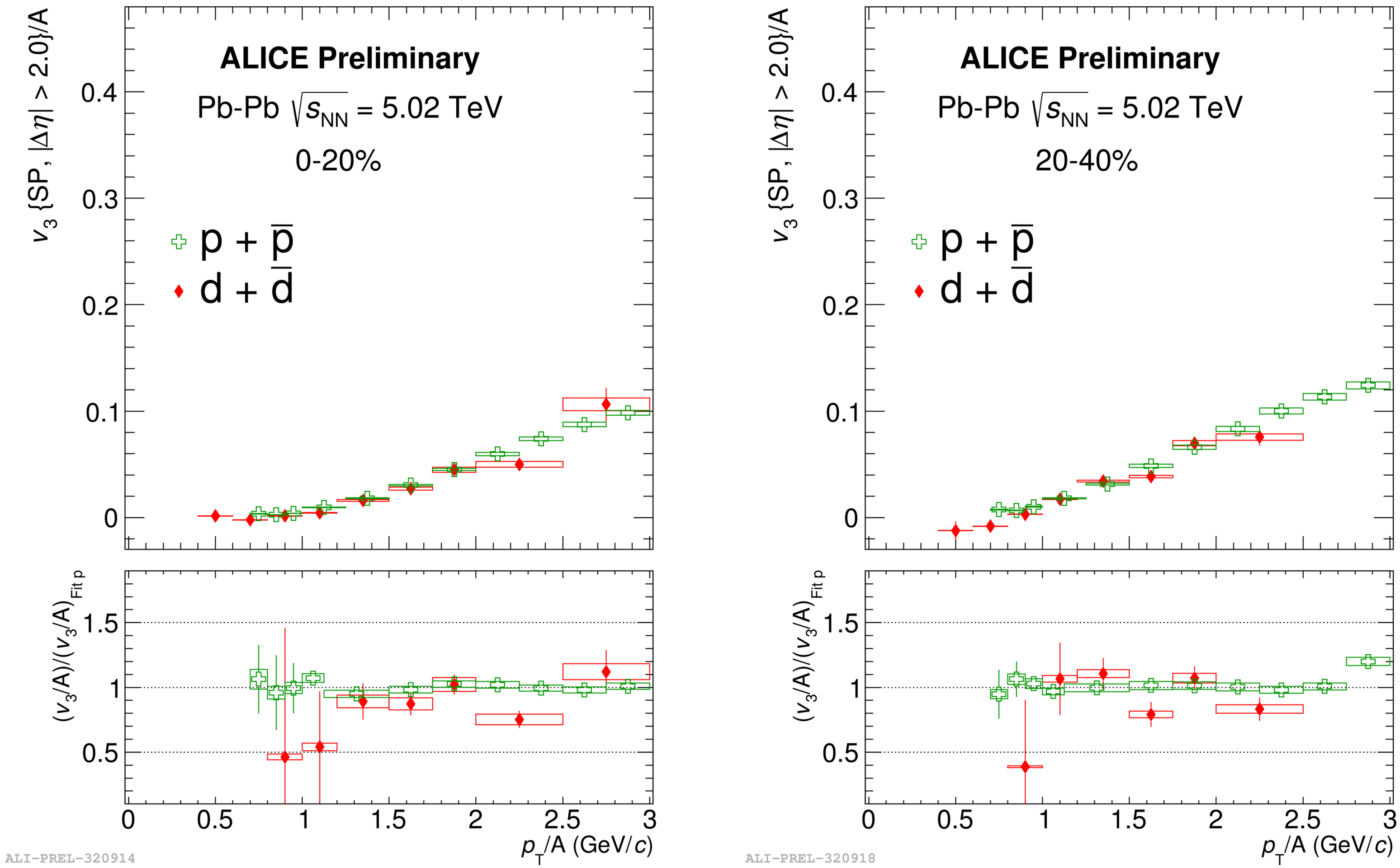


Scaling of v_2 with the mass number A (**simple coalescence approach**) is violated in all centrality ranges

The measured v_2 is overestimated by the predictions from simple coalescence

- ➢ smaller deviations in more peripheral collisions

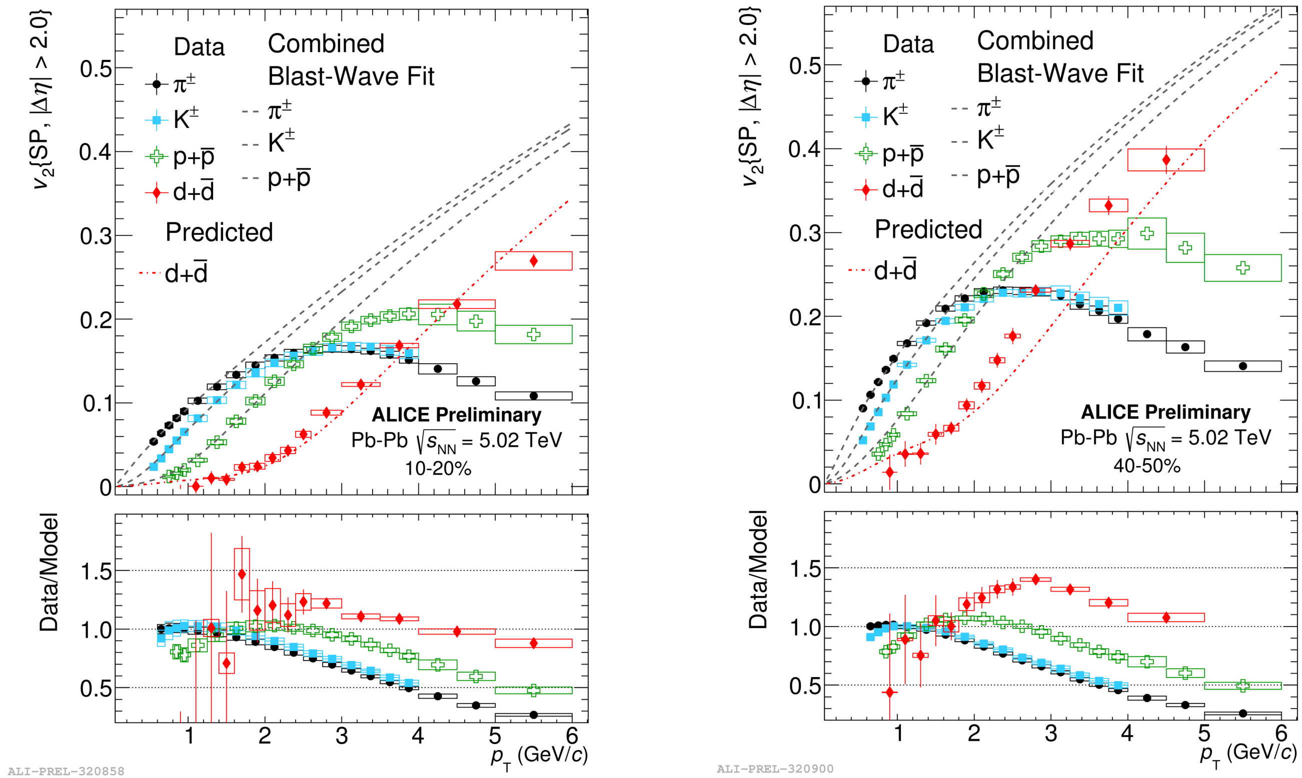
A-scaling of v_3 of (anti-)deuterons



Mass number scaling seems to be approximately valid for v_3

The uncertainties are larger however …

v_2 of (anti-)deuterons vs. Blast-Wave

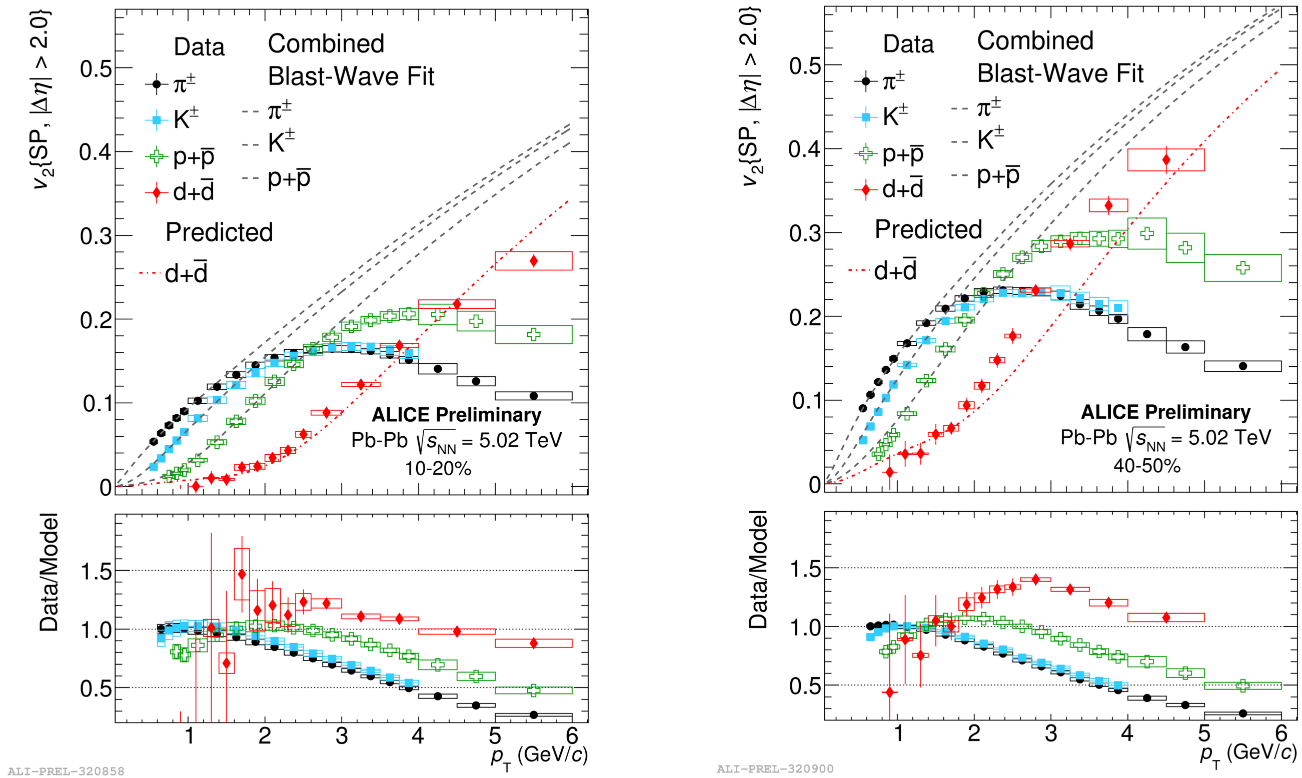


Blast-Wave (BW) predictions for the (anti-)deuteron v_2 from combined fits of v_2 and p_T-spectra of π,K,p in the p_T ranges:

$$\begin{cases} \pi\text{: } p_T \in [0.7, 1.5]\ \text{GeV}/c \\ \text{K: } p_T \in [0.7, 2.0]\ \text{GeV}/c \\ \text{p: } p_T \in [1.0, 2.5]\ \text{GeV}/c \end{cases}$$

- Closer to the data in more central collisions
- Deviations in more peripheral collisions

v_2 of (anti-)deuterons vs. Blast-Wave



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BW describes (anti-)deuteron v_2 in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV in 0-40%

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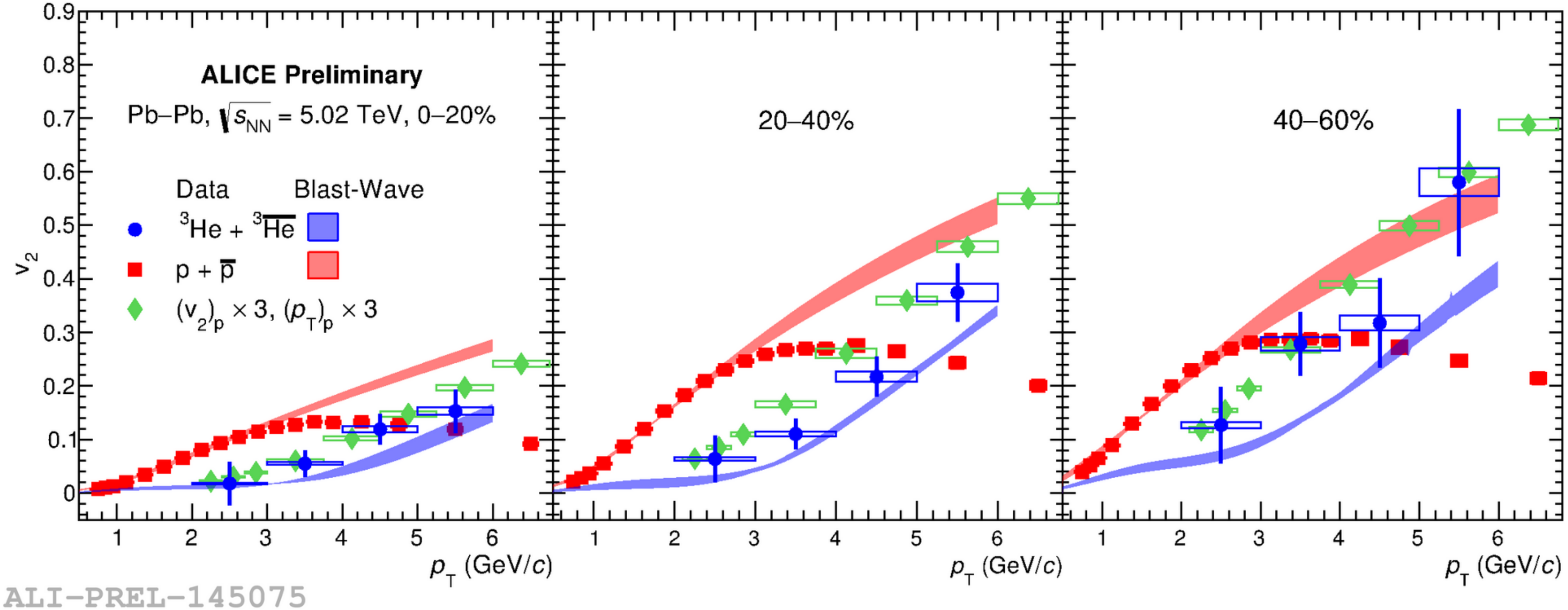
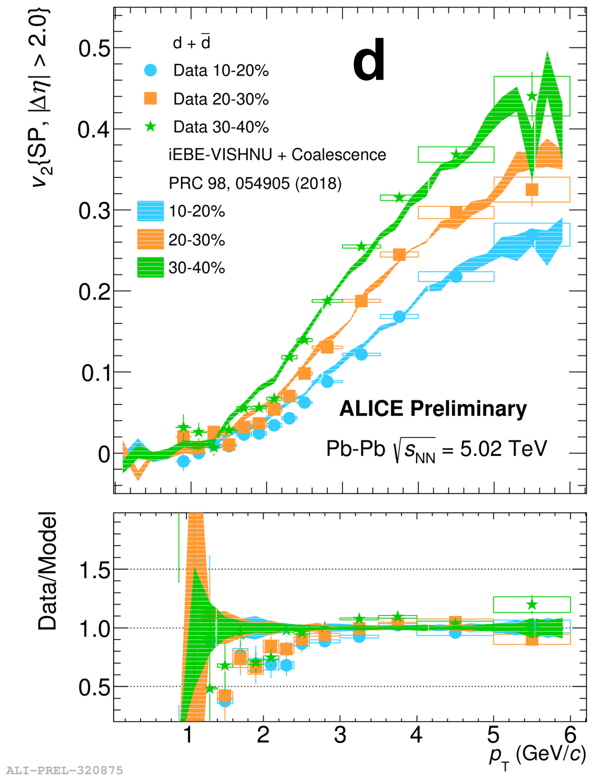
v_2 of (anti-)^{3}He vs. Blast-Wave & Coalescence

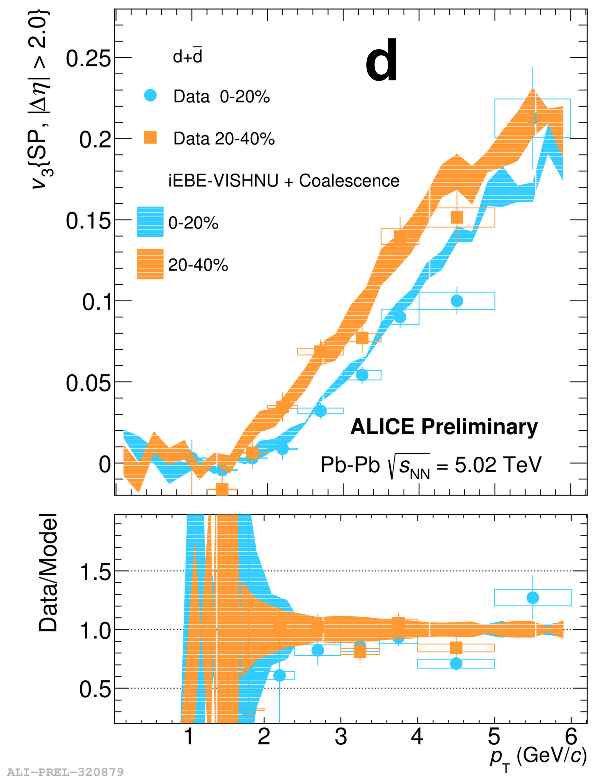


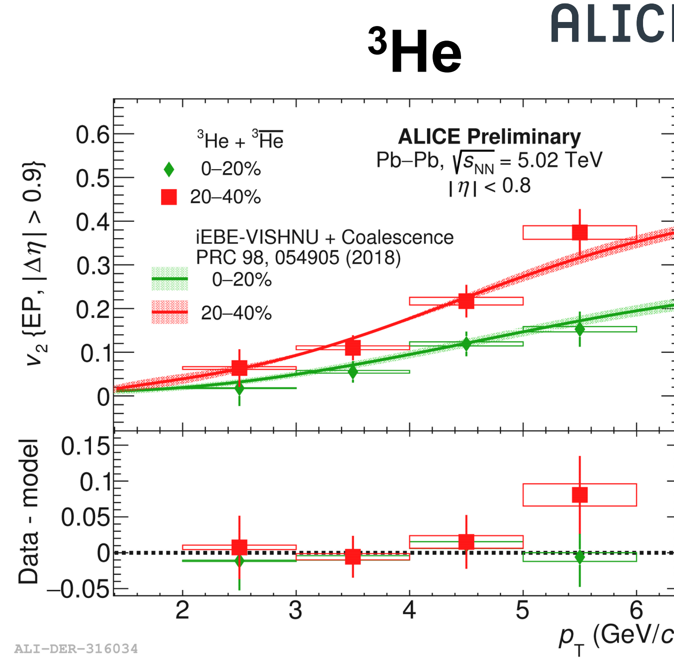
v_2 of (anti-)^{3}He lies between the Blast-Wave and simple coalescence predictions in all centrality ranges

- ➢ Consistent with the deuteron v_2 measurement and RHIC results

v_2 & v_3 vs. iEBE-VISHNU + Coalescence







Coalescence model with phase space distributions of nucleons generated by iEBE-VISHNU (**PRC 98, 054905 (2018)**):

- AMPT initial conditions
- (1+2)d hydro (VISHNU) + UrQMD

- good description of the data in 0-40%
- no predictions for more peripheral collisions

Summary

First measurement of the (anti-)deuteron v_3

- Effects of initial-state fluctuations seen for (anti-)deuterons
- p_T & centrality dependence consistent with identified hadrons

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- Simplified hydro (BW) underestimates v_2 of (anti-)deuterons and (anti-)^{3}He
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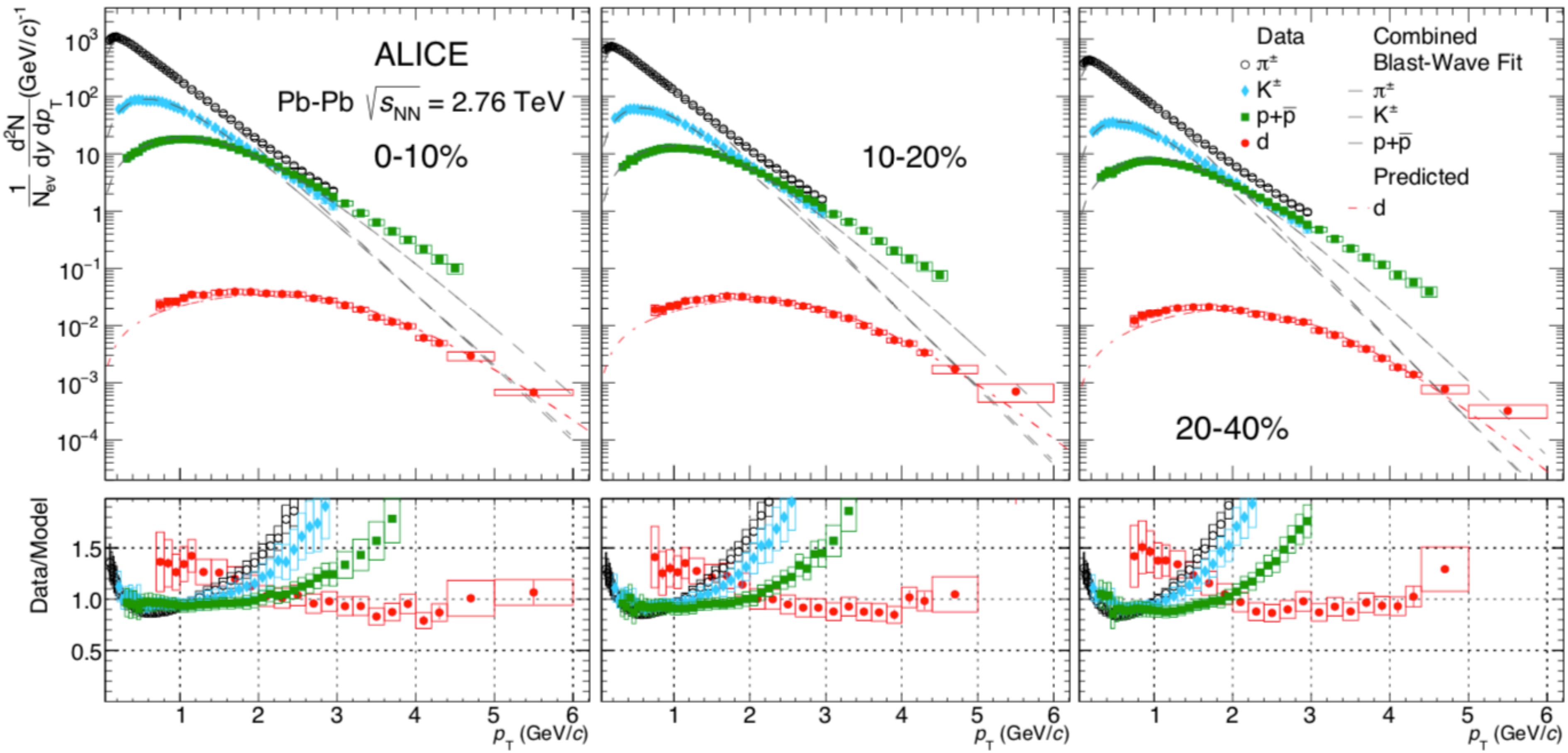
Thank you for your attention !

Backup slides

Blast-wave predictions of the (anti-)deuteron p_T-spectra



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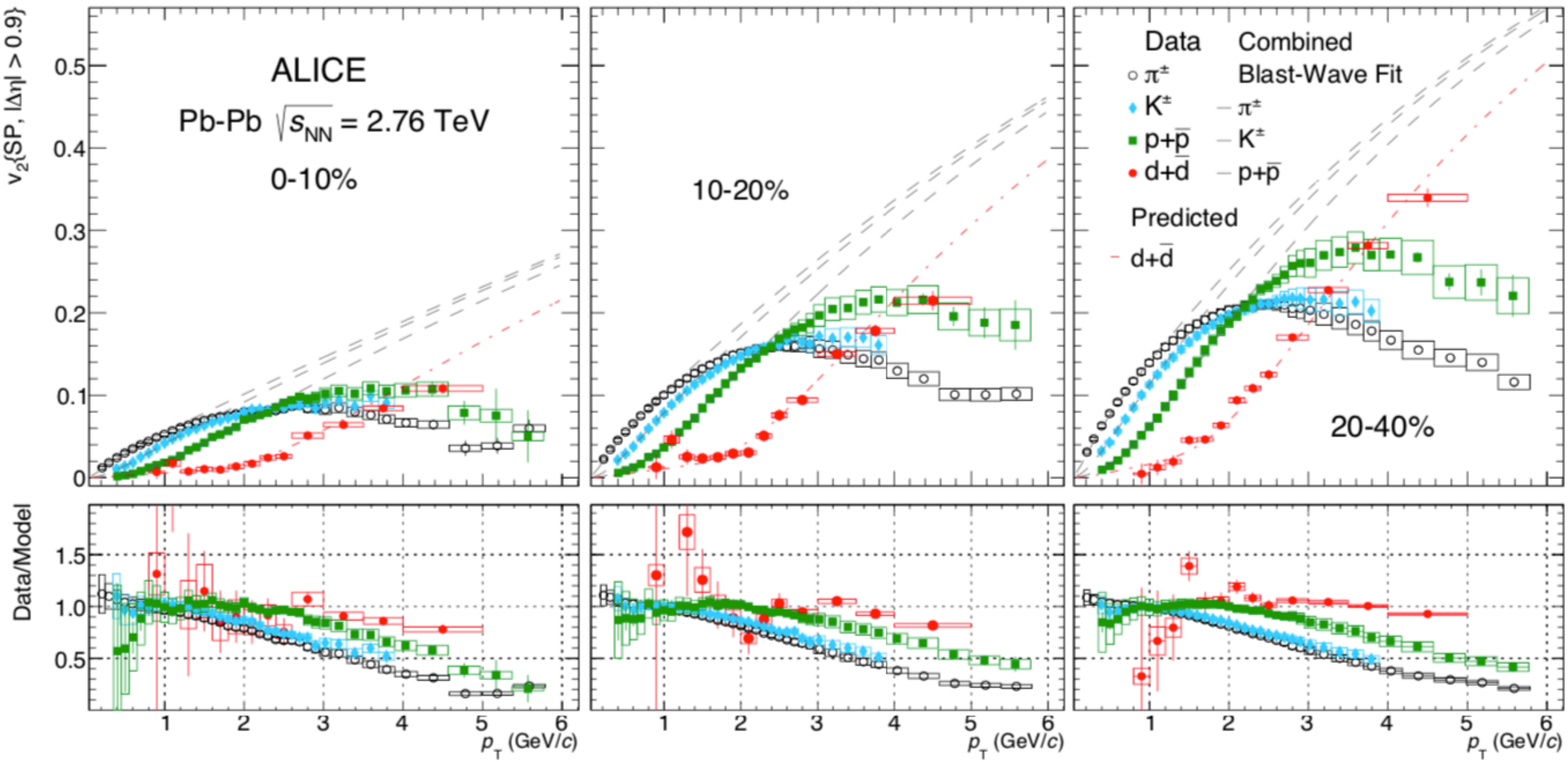
Blast-wave predictions of the (anti-)deuteron v_2



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