Azimuthal correlations in Pb-Pb and Xe-Xe collisions with ALICE

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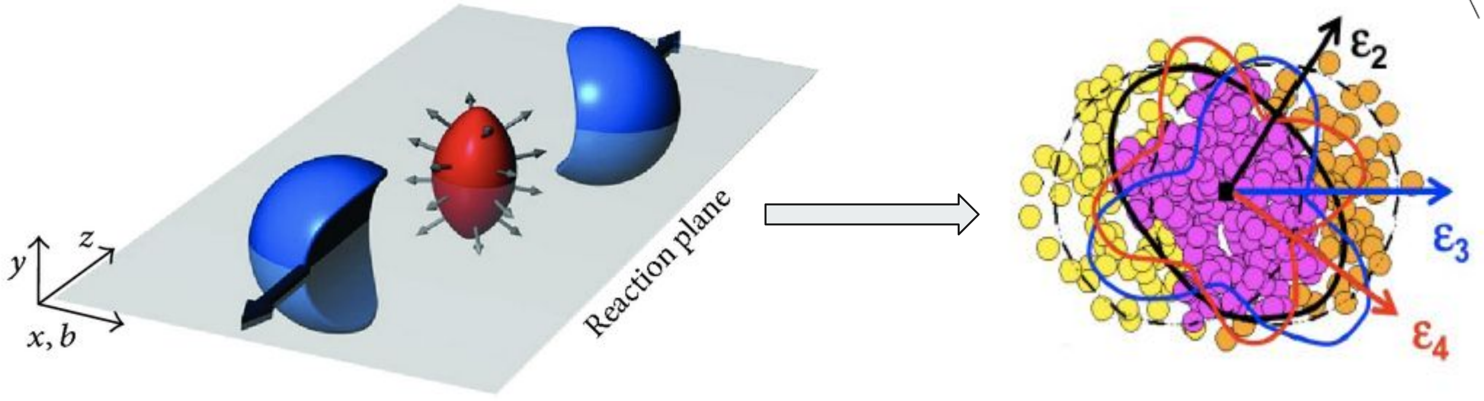
On behalf of the ALICE Collaboration

8th September 2021

Anisotropic flow

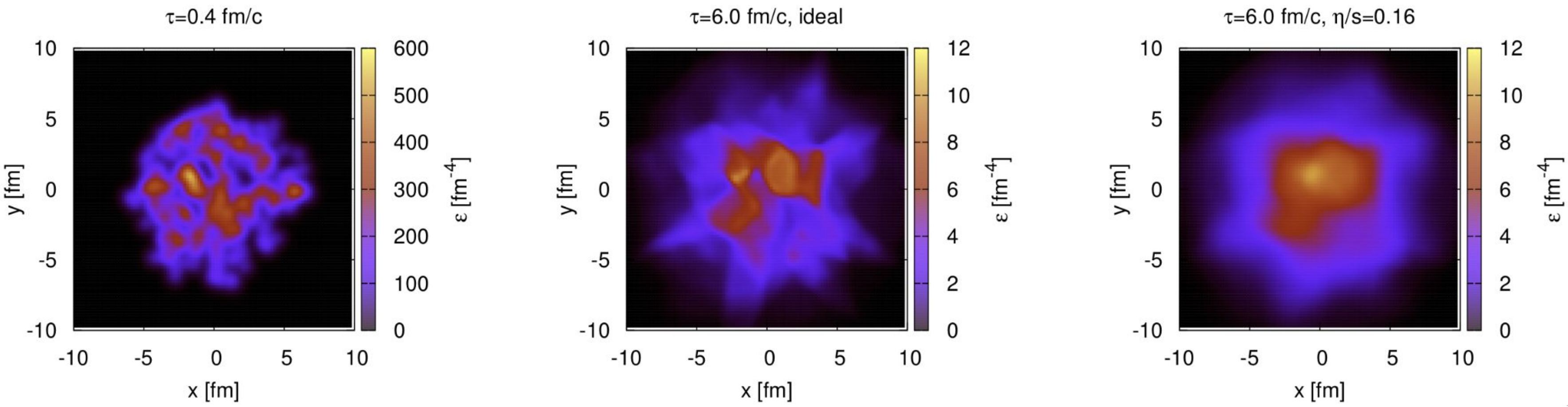
Eccentricity: $\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$



Anisotropic flow: the transfer of initial spatial anisotropy into the final anisotropy in momentum space via collective interactions

Most central collision: fluctuations of participating nucleons

Anisotropic flow



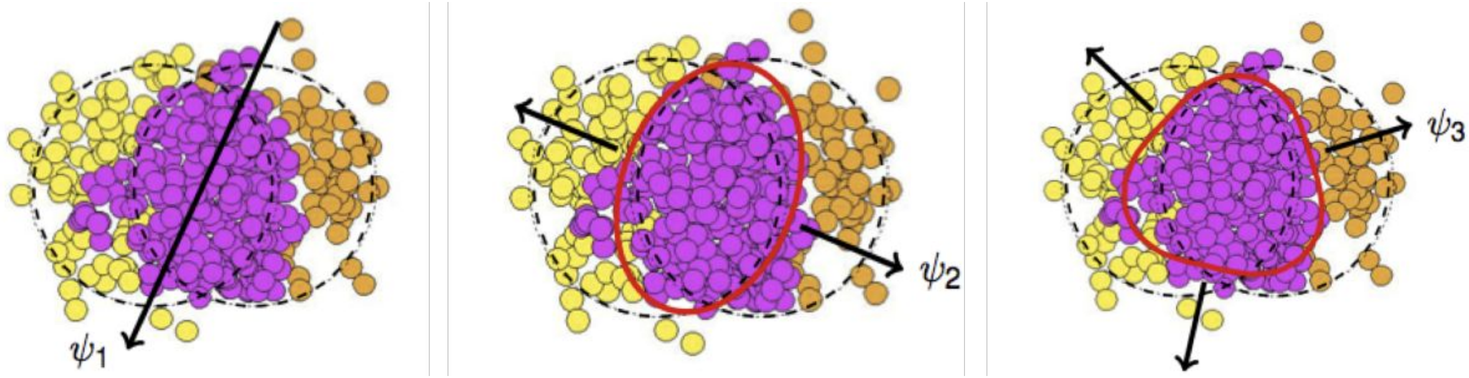
Anisotropic flow: the transfer of initial spatial anisotropy into the final anisotropy in momentum space via collective interactions

Most central collision: fluctuations of participating nucleons

Sensitive to the system evolution

- Constrain initial conditions, equation-of-state (EOS), transport properties
- Stronger constraints are obtained from measurements of identified particles

Anisotropic flow



M. Luzum, J. Phys. G: Nucl. Part. Phys. 38 (2011) 124026

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

Particle azimuthal distribution measured with respect to the symmetry plane is not isotropic → Fourier series

v_n quantify the event anisotropy

- v_2 elliptic flow → reflects the almond-shaped **geometry** of the interaction volume
- v_3 triangular flow → originates from event-by-event **fluctuations** of nucleon positions

Scalar product method

STAR Coll, Phys. Rev. C66 (2002) 034904
N. Borghini, Phys. Lett. B642 (2006) 227–231
ALICE, arXiv:2107.10592

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

$\mathbf{u}_{\mathrm{n,k}} = e^{in\varphi_{\mathrm{k}}}$ unit vector of particle of interest (POI) k
$\mathbf{Q}_{\mathrm{n}}$ the **Q** vector from reference particles (RPs)

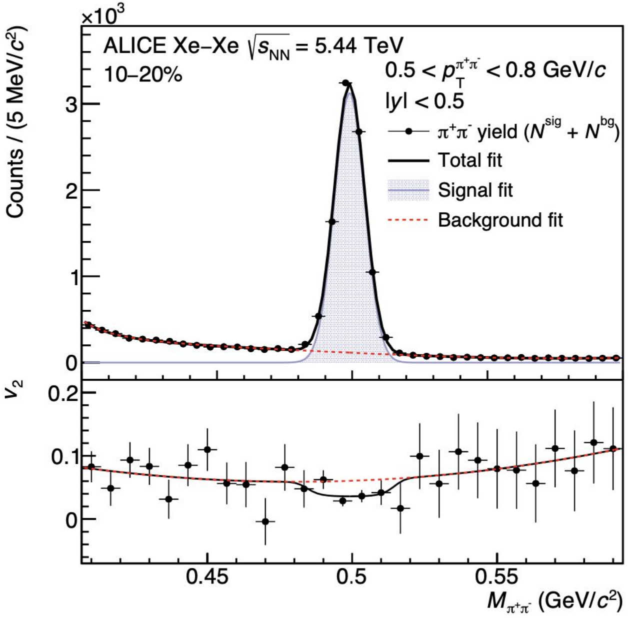
$$Q_{\mathrm{n,x}} = \sum_{\mathrm{j}} w_{\mathrm{j}} \cos(\mathrm{n}\varphi_{\mathrm{j}}),\ Q_{\mathrm{n,y}} = \sum_{\mathrm{j}} w_{\mathrm{j}} \sin(\mathrm{n}\varphi_{\mathrm{j}})$$

u_n, Q_n from the same or different detectors

- a pseudorapidity gap $|\Delta\eta|$ between POI and RPs

v_n of K^0_S, Λ, Ξ is determined using the v_n vs invariant mass method
N^{Sgn} and N^{Bg} are extracted from fits of the invariant mass distribution
$v_n^{\mathrm{Tot}}(m_{\mathrm{inv}})$ is measured using the scalar product method

$$v_{\mathrm{n}}^{\mathrm{Tot}}(m_{\mathrm{inv}}) = v_{\mathrm{n}}^{\mathrm{Sgn}} \frac{N^{\mathrm{Sgn}}}{N^{\mathrm{Tot}}}(m_{\mathrm{inv}}) + v_{\mathrm{n}}^{\mathrm{Bg}}(m_{\mathrm{inv}}) \frac{N^{\mathrm{Bg}}}{N^{\mathrm{Tot}}}(m_{\mathrm{inv}})$$



Cumulants method

Ollitrault & Borghini

Two- and four-particle azimuthal correlations, average over one event

$$\langle 2 \rangle \equiv \langle \cos(n(\varphi_i - \varphi_j)) \rangle, i \neq j$$

$$\langle 4 \rangle \equiv \langle \cos(n(\varphi_i + \varphi_j - \varphi_k - \varphi_l)) \rangle, i \neq j \neq k \neq l$$

Cumulants of 2th, 4th and 6th order, average over all events

$$c_n\{2\} \equiv \langle\langle 2 \rangle\rangle = v_n^2$$

$$c_n\{4\} \equiv \langle\langle 4 \rangle\rangle - 2\langle\langle 2 \rangle\rangle^2 = -v_n^4$$

$$c_n\{6\} \equiv \langle\langle 6 \rangle\rangle - 9\langle\langle 4 \rangle\rangle\langle\langle 2 \rangle\rangle + 12\langle\langle 2 \rangle\rangle^3 = 4v_n^6$$

$$\ldots$$

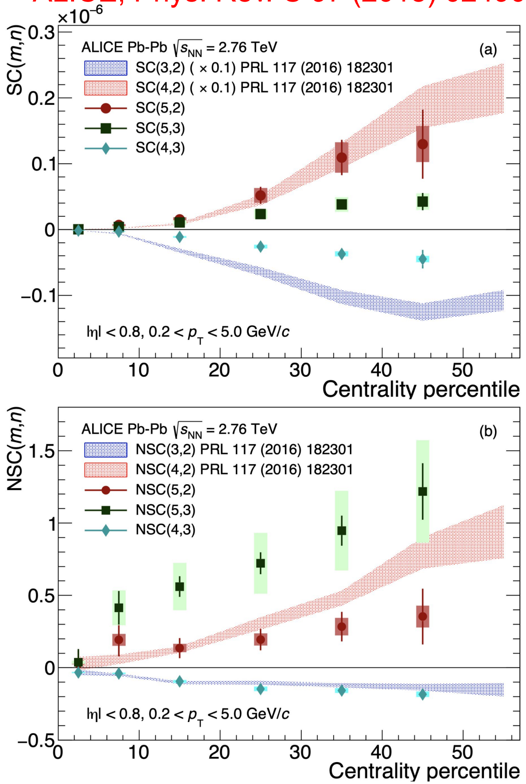
Symmetric Cumulants SC(m, n)

$$SC(m,n) = \langle v_m^2 v_n^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle$$

$$NSC(m,n) = SC(m,n)/\langle v_m^2 \rangle \langle v_n^2 \rangle$$

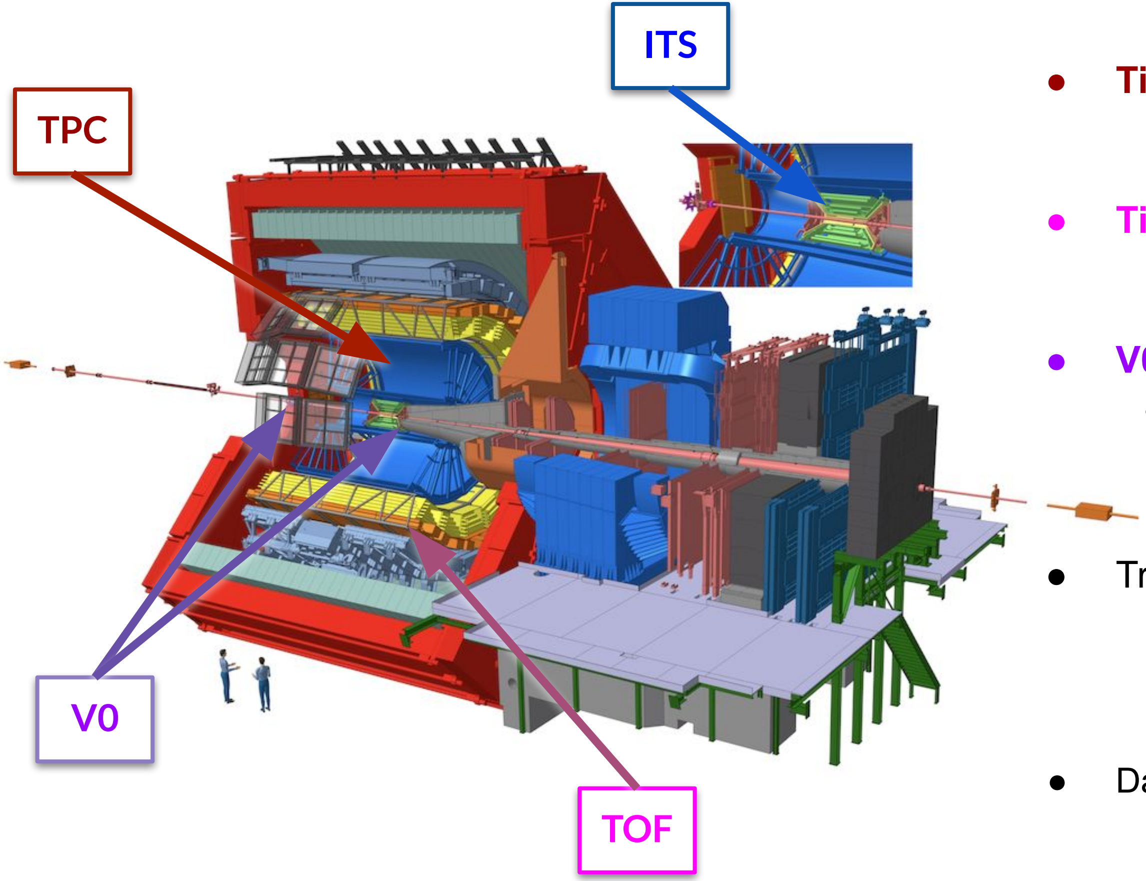
SC/NSC > 0 → correlation, SC/NSC < 0 → anti-correlation

ALICE, Phys. Rev. C 97 (2018) 024906



A. Bilandzic et al, Phys. Rev. C 89, 064904 (2014)
Phys. Rev. C 103, 024913 (2021)

ALICE@Run2



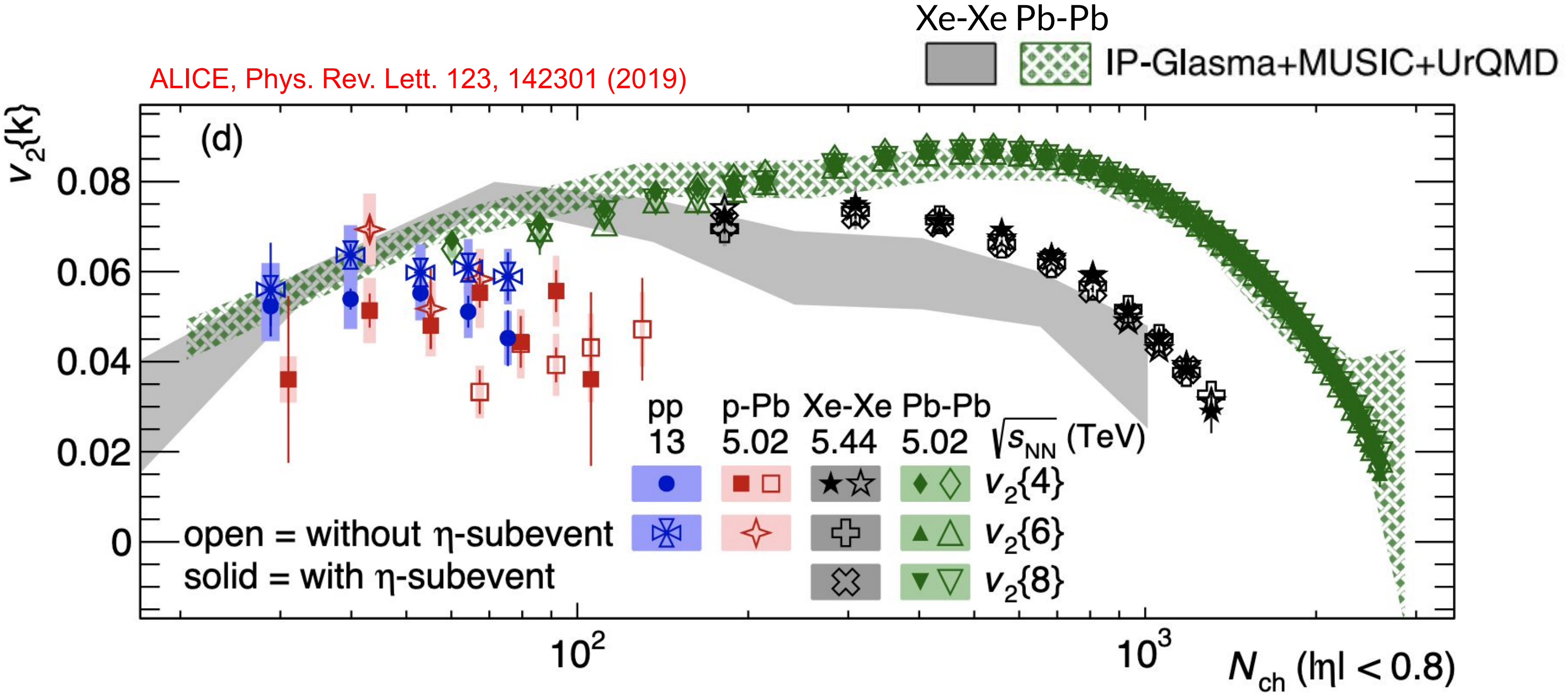
- **Inner Tracking System (ITS)**
  - Tracking, triggering, vertexing
- **Time Projection Chamber (TPC)**
  - Tracking, vertexing, particle identification based on specific energy loss
- **Time-of-Flight (TOF)**
  - Particle identification based on the flight time
- **V0 detector (forward region)**
  - Triggering, centrality determination, Q-vector, event-shape selection

- Track selection
  - $|\eta| < 0.8$ (unidentified)
  - $|y| < 0.5$ (π, K, p, K^0_S , Λ, Ξ)

- Data sample
  - Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV ~320M events
  - Xe-Xe at $\sqrt{s_{NN}}$ = 5.44 TeV ~1.3M events

ALICE v_2 measurements

ALICE, Phys. Rev. Lett. 123, 142301 (2019)



$v_2\{n\}$ (n=4,6,8) measured in various collision systems over a broad multiplicity range

- Long-range multiparticle correlations in pp and p–Pb collisions at multiplicities $N_{ch} \geq 30$
- Good agreement of $v_2\{4\}$ between data and calculations from IP-Glasma+MUSIC+UrQMD

SC/NSC

ALICE, Phys. Rev. Lett. 127, 092302 (2021)

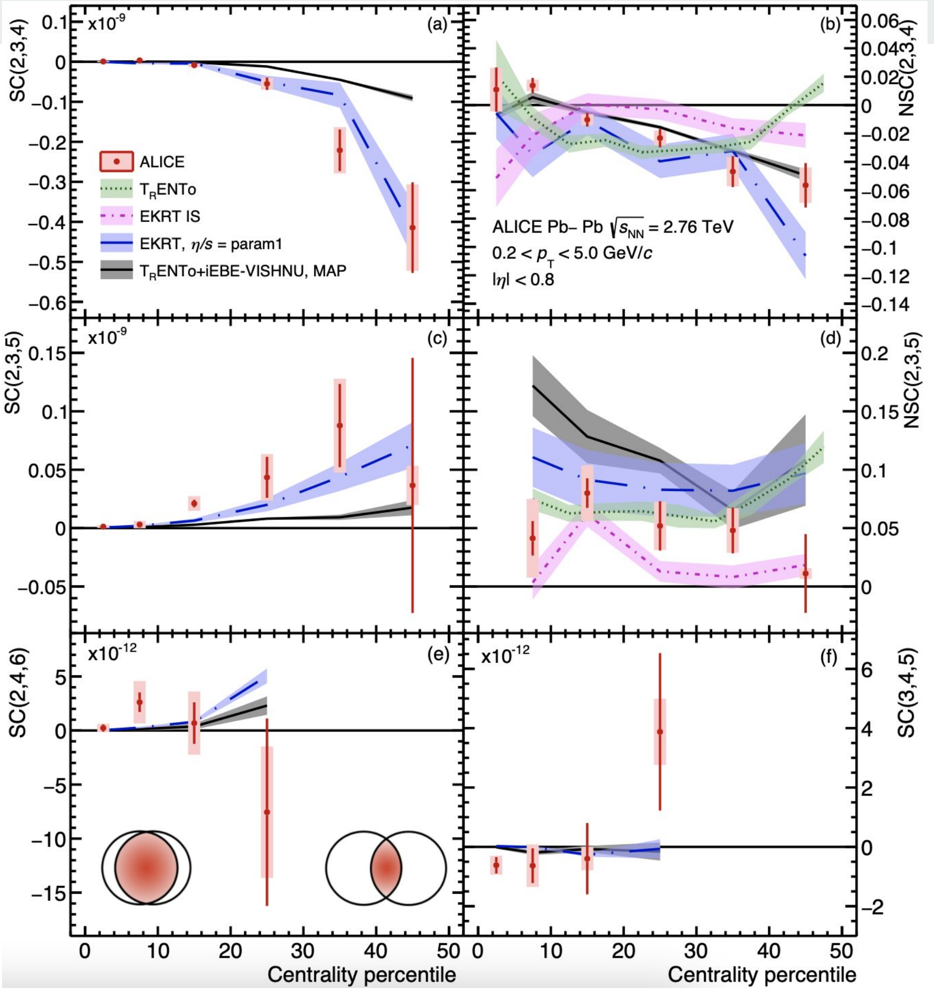
First measurements of higher order Symmetric Cumulants (SC) → independent constraints

$$\mathrm{SC}(k,l,m) = \langle v_k^2 v_l^2 v_m^2 \rangle - \langle v_k^2 v_l^2 \rangle \langle v_m^2 \rangle - \langle v_k^2 v_m^2 \rangle \langle v_l^2 \rangle - \langle v_l^2 v_m^2 \rangle \langle v_k^2 \rangle + 2 \langle v_k^2 \rangle \langle v_l^2 \rangle \langle v_m^2 \rangle$$

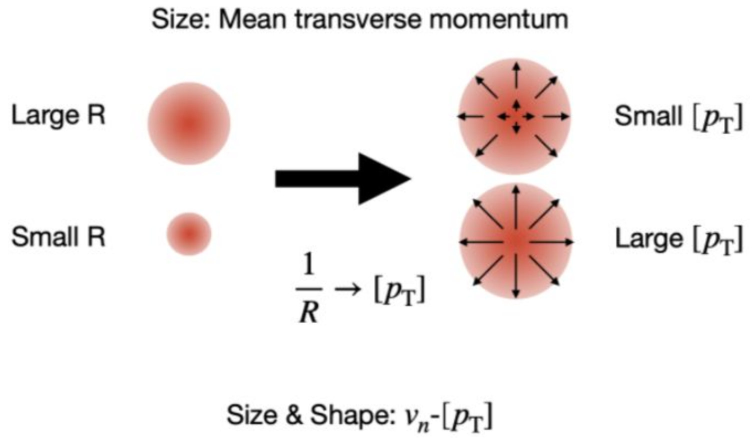
$$\mathrm{NSC}(k,l,m) = \frac{\mathrm{SC}(k,l,m)}{\langle v_k^2 \rangle \langle v_l^2 \rangle \langle v_m^2 \rangle}$$

SC(2,3,4) non-zero in mid-central collisions ➔ presence of genuine correlations between the flow amplitudes v_2, v_3 and v_4

- Both T$_R$ENTo+*hydro* and **EKRT-hydro** → hint for correlations developed in the hydrodynamic evolution of the system
- Further constraints to the models

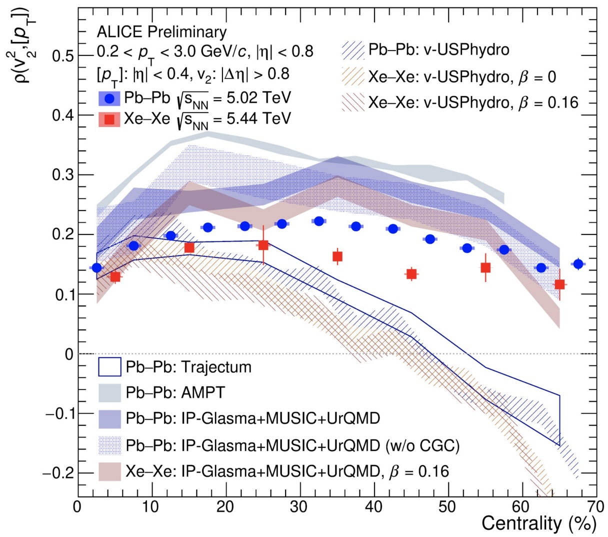


$\rho(v_n, [p_T])$ correlations



Pearson corr. coeff. $$\rho(v_n^2, [p_T]) = \frac{cov(v_n^2, [p_T])}{\sqrt{var(v_n^2)}\sqrt{var([p_T])}}$$

- Positive $\rho(v_2, [p_T])$ for all centralities - $\rho^{Pb-Pb} > \rho^{Xe-Xe}$
  - Weak centrality dependence
- Strong constraints to initial state models
  - Data favour IP-Glasma initial state
- Constrain deformation of Xe-nucleus



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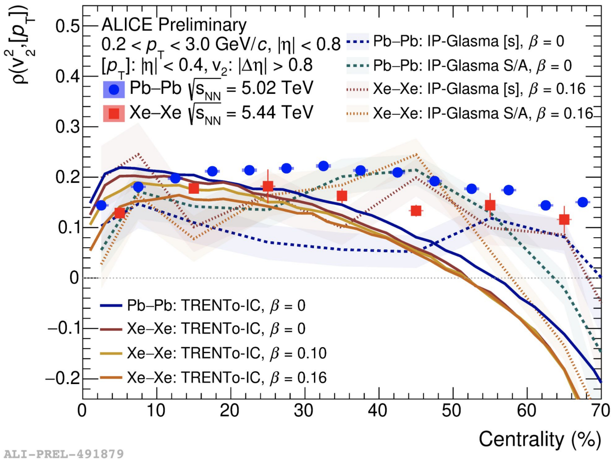

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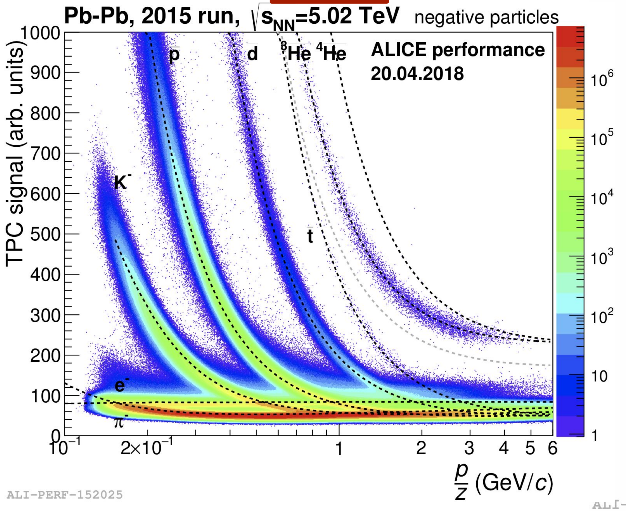
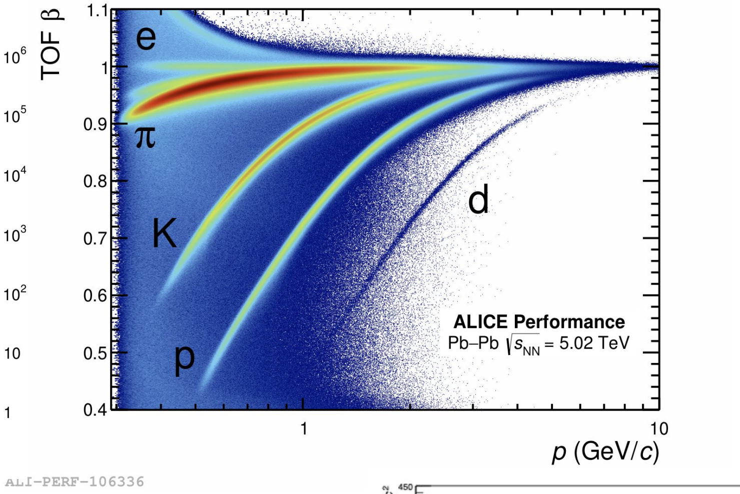
Particle identification (PID)

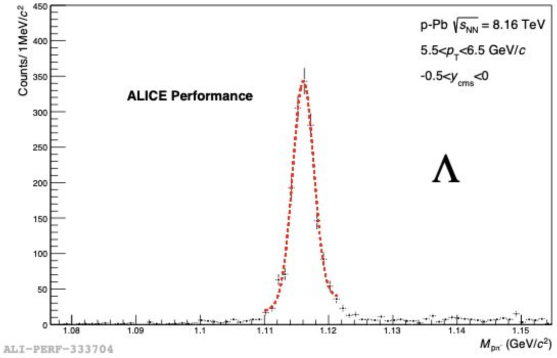
TPC



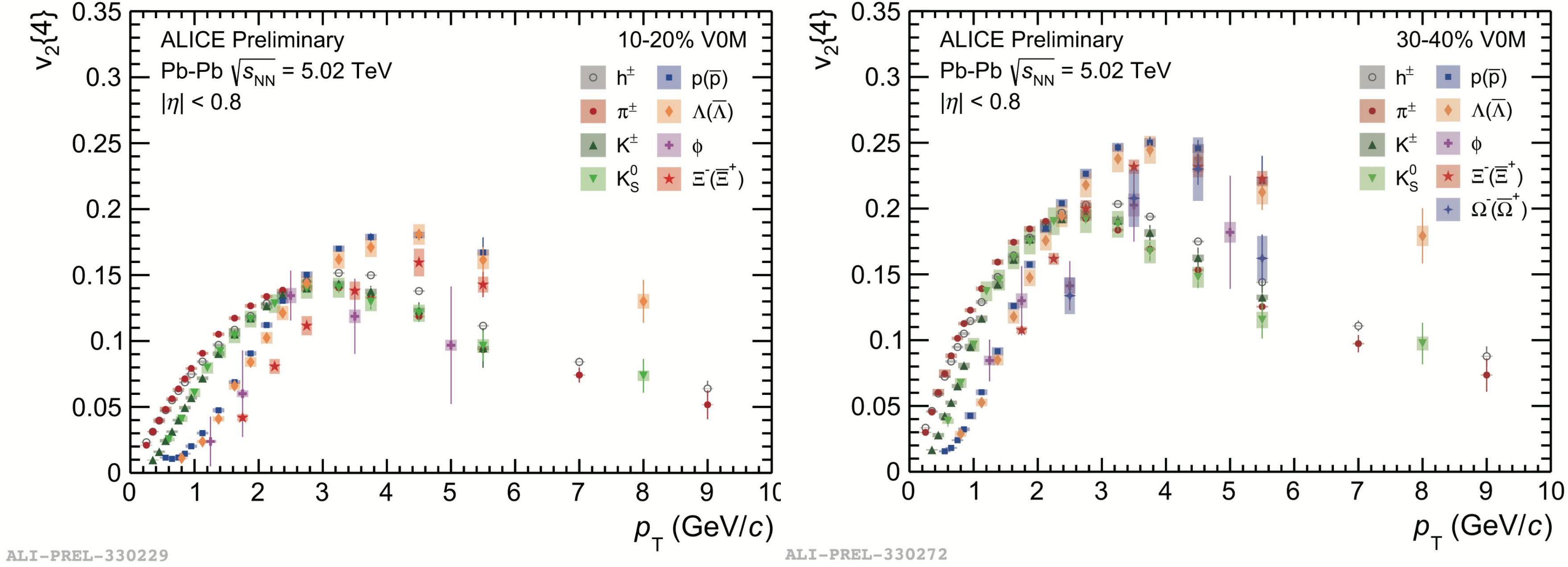
TOF



- PID @ p_T < 4 GeV/c
  - π, K, p identified using TPC and TOF (purity >90%)
- PID @ p_T > 4 GeV/c
  - π and p identified using TPC (purity >80%)
- Topological reconstruction for K^0_S, Λ and Ξ



$v_2\{4\}$ for identified hadrons



- For p_T<2 GeV/c: v_2 of lighter particles is larger than heavier ones → mass ordering
  - Interplay between elliptic and radial flow
    - Radial flow (isotropic expansion) pushes particles to higher p_T
- For 3<p_T<10 GeV/c: particles tend to group into mesons and baryons

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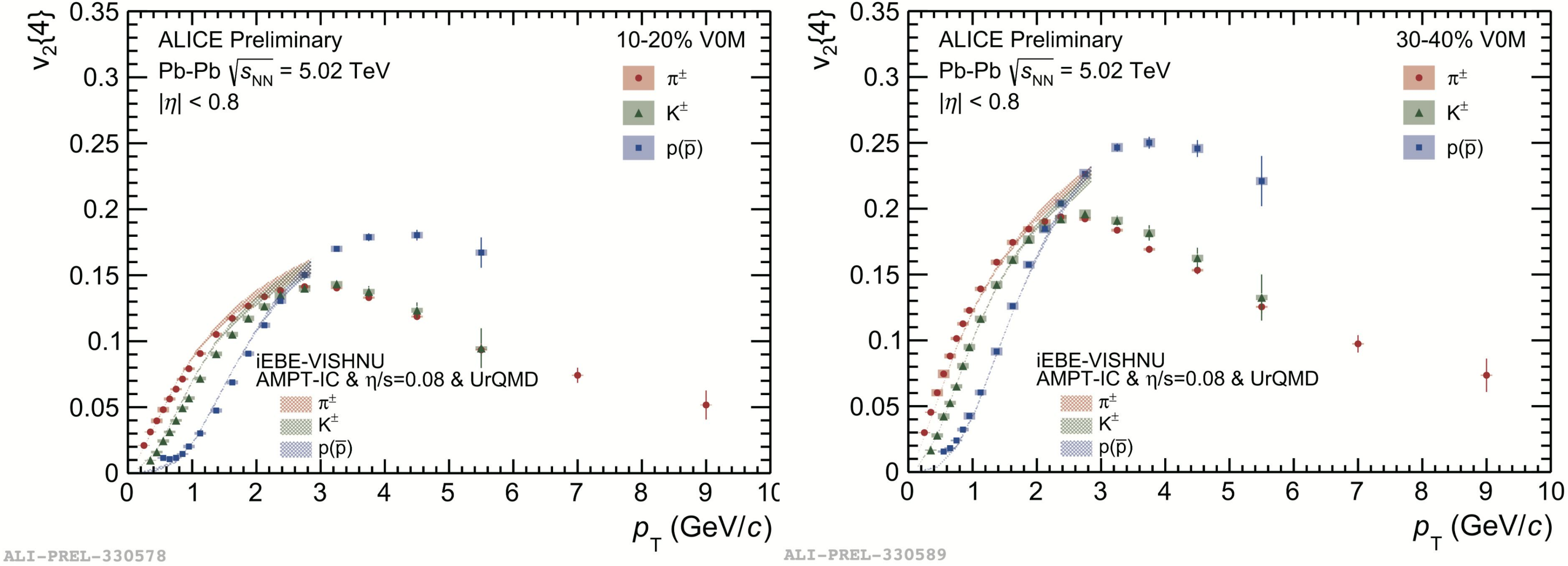

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- For 3<p_T<10 GeV/c: particles tend to group into mesons and baryons
- Hydrodynamics calculations describe $v_2\{4\}$ of π, K, p well

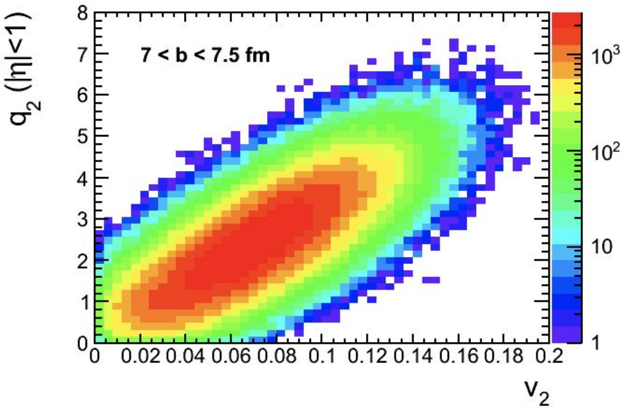
Event Shape Engineering (ESE)

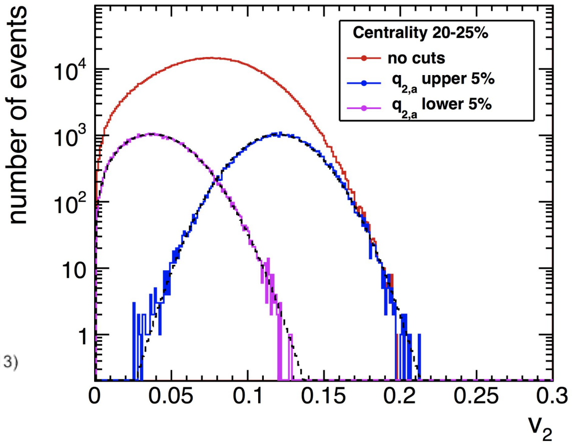
Select events with similar centralities and different shapes based on the event-by-event flow/eccentricity fluctuations

Flow vector $\rightarrow$ q_n distribution

$$Q_{n,x}=\sum_i \cos(n\varphi_i)$$
$$Q_{n,y}=\sum_i \cos(n\varphi_i)$$

$$Q_n=\{Q_{n,x}, iQ_{n,y}\}$$
$$q_n=|Q_n|/\sqrt{M}$$





J. Schukraft *et al*, PLB 719, 394 (2013)
H. Petersen *et al*, PRC 88, 044918 (2013)
P. Huo *et al*, PRC 90, 024910 (2014)

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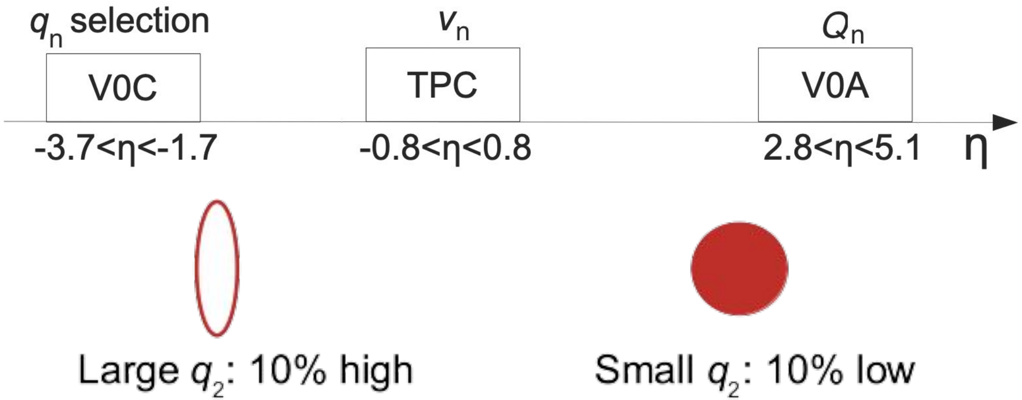

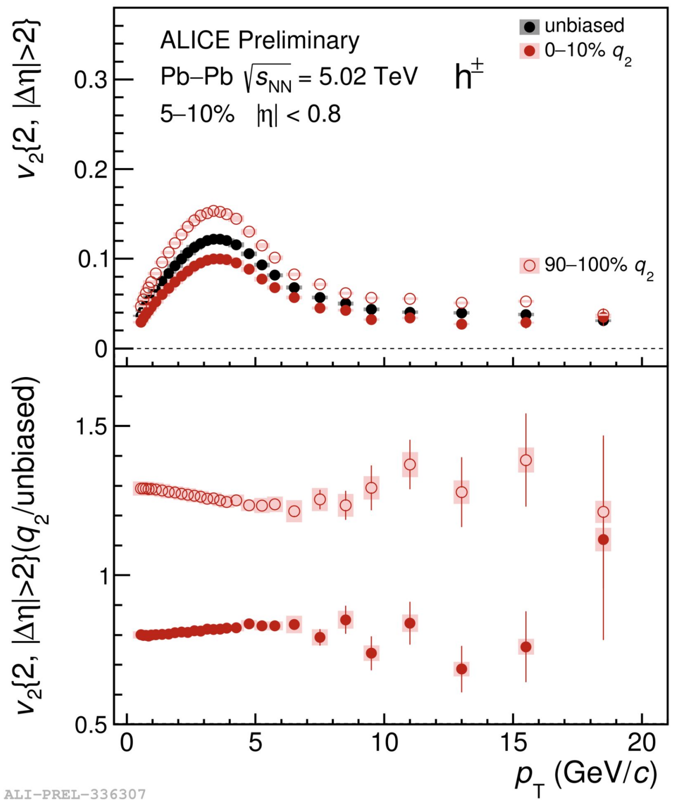

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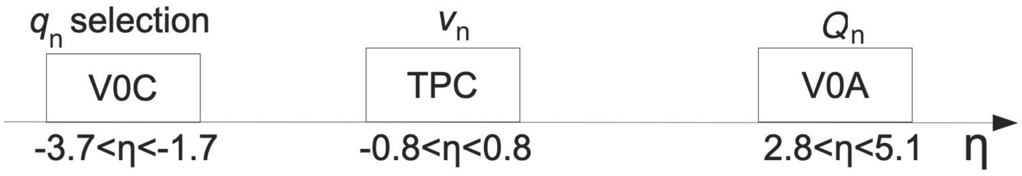
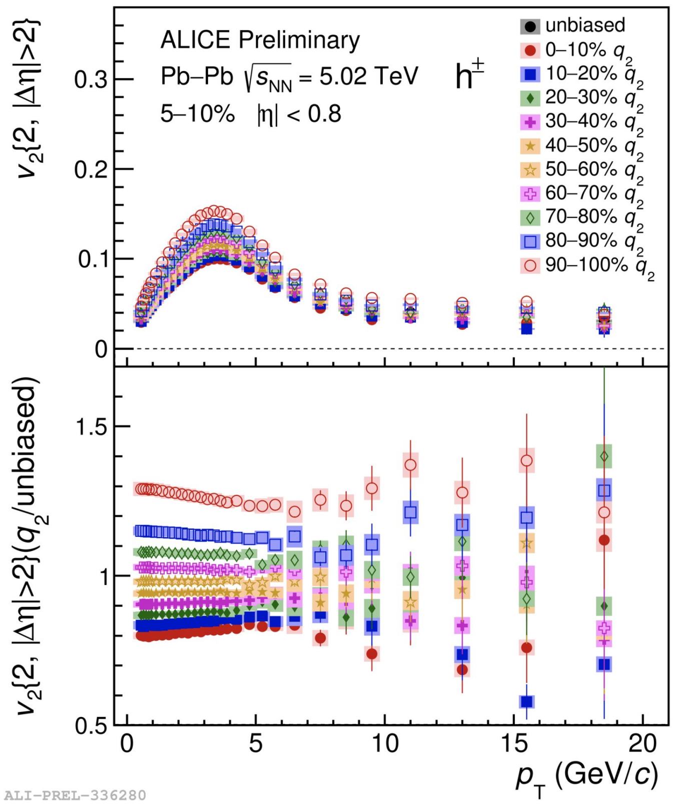
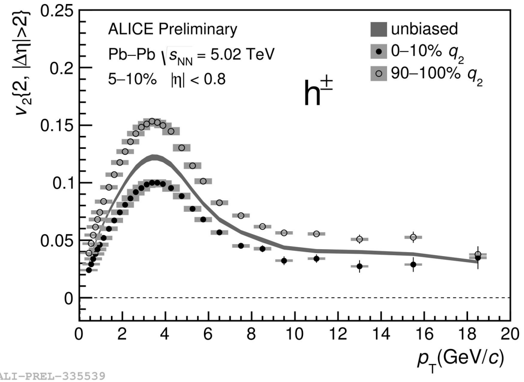


- q_2 V0C selects events up to 30% larger or smaller v_2 than the average
- p_T > 3 GeV/c: ratios almost flat → same source of flow fluctuations
- p_T < 3 GeV/c: weak p_T dependence



PID $v_2(p_T)$ with q_2 selection: 5-10% centrality



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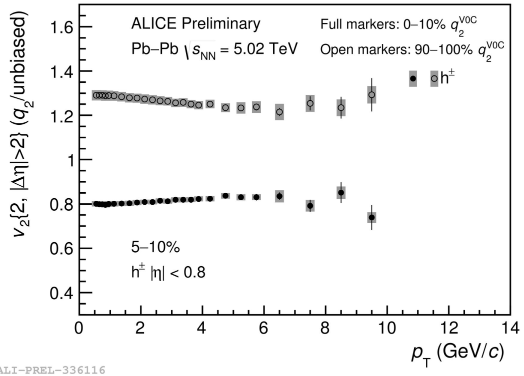
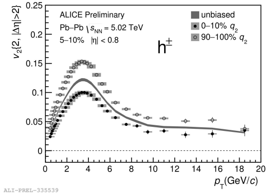
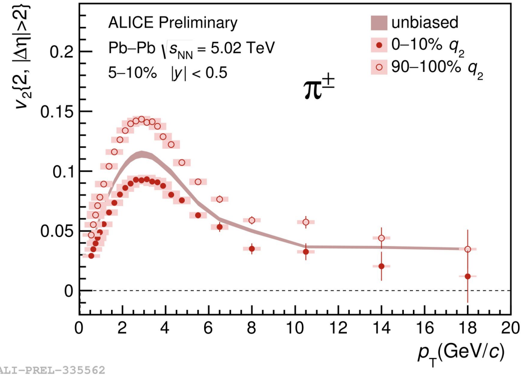


ALI-PREL-336116

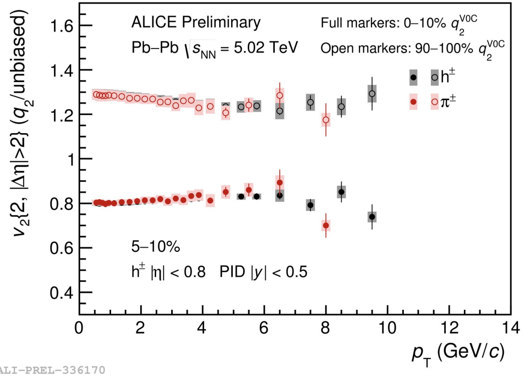
PID $v_2(p_T)$ with q_2 selection: 5-10% centrality



ALI-PREL-335539

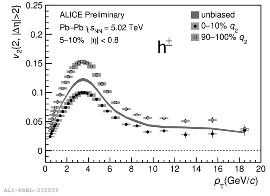


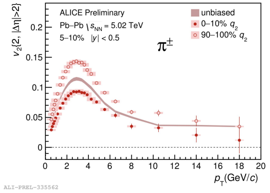
ALI-PREL-335562

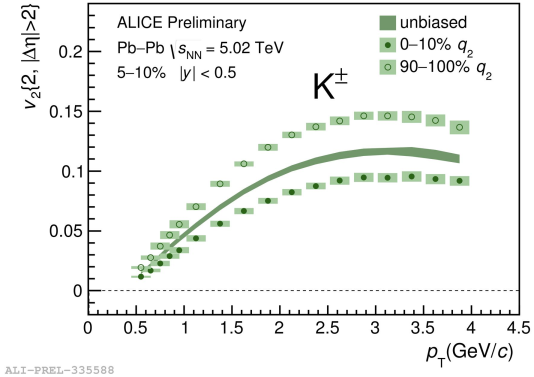


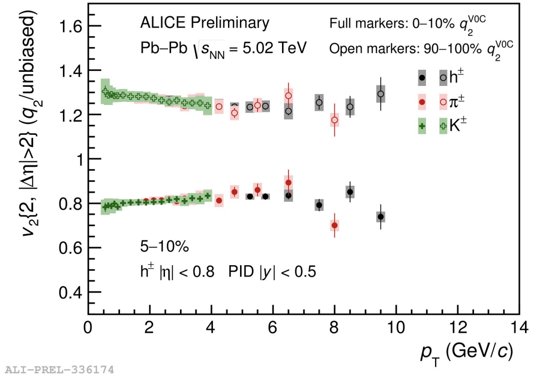
ALI-PREL-336170

PID $v_2(p_T)$ with q_2 selection: 5-10% centrality









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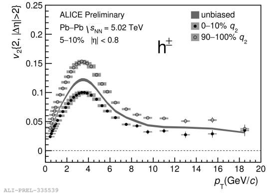

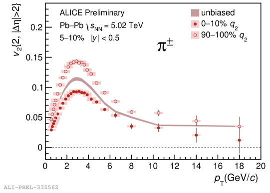

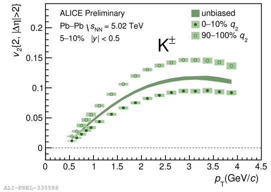

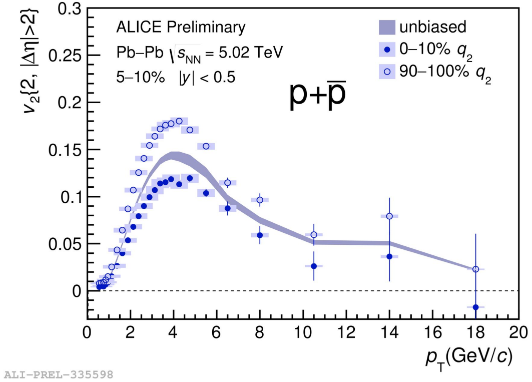

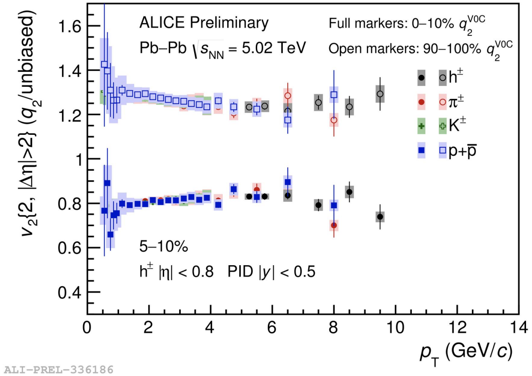

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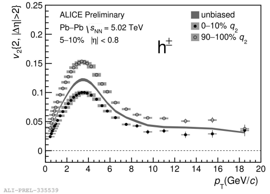

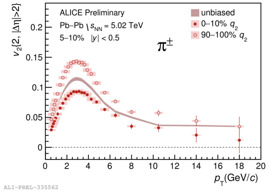

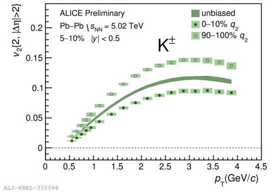

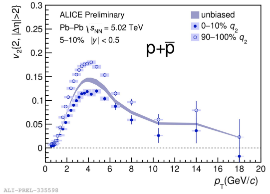

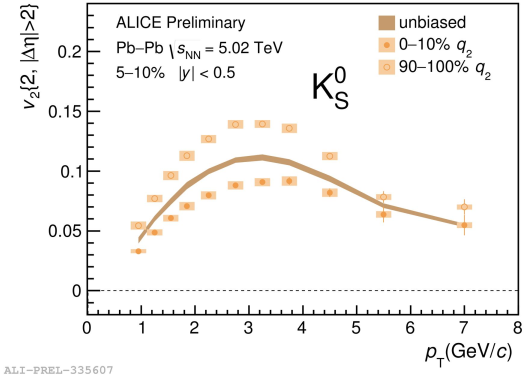

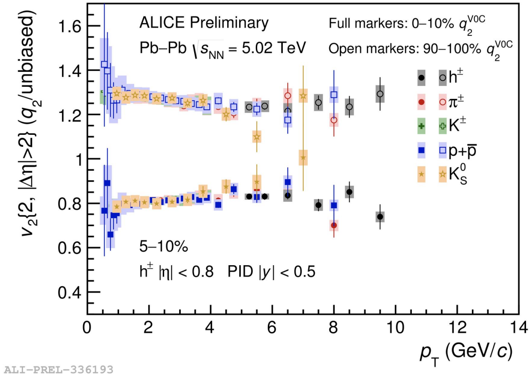

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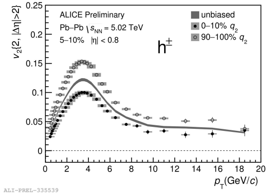
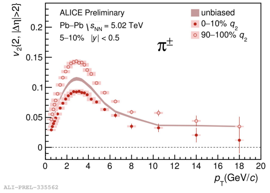
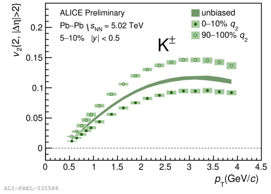
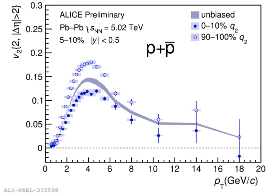
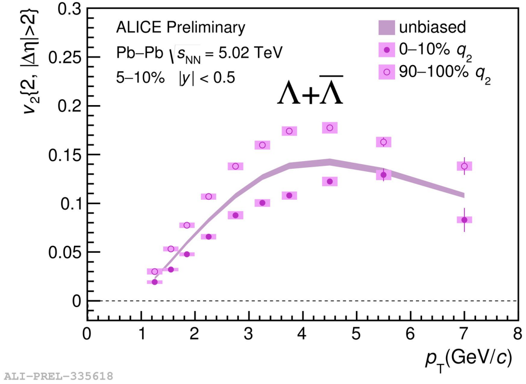
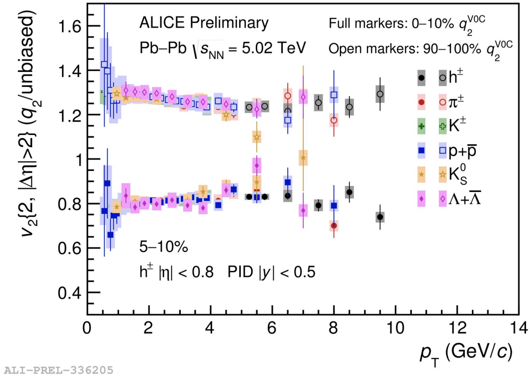


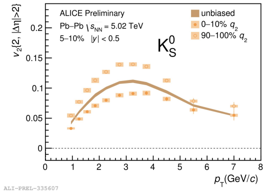




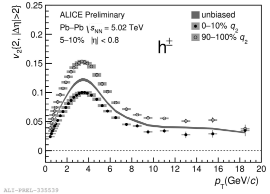


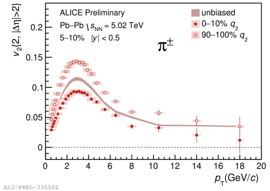


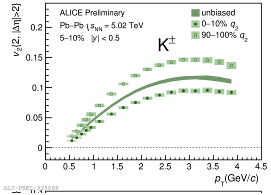


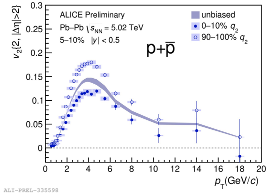


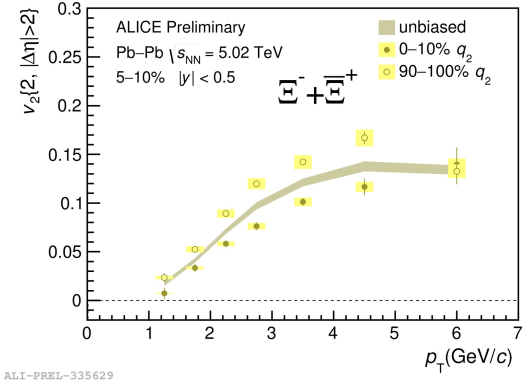
PID $v_2(p_T)$ with q_2 selection: 5-10% centrality

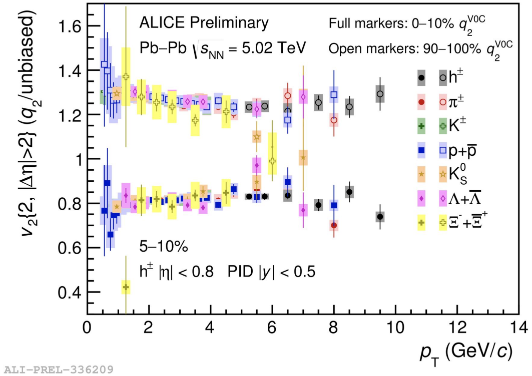


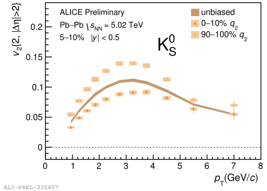


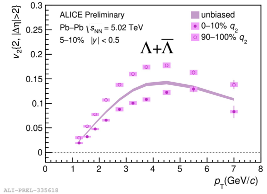




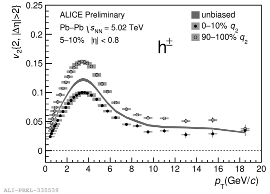


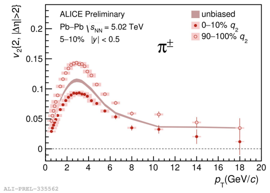


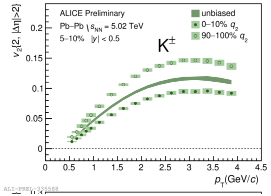


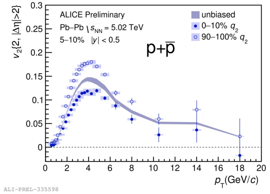


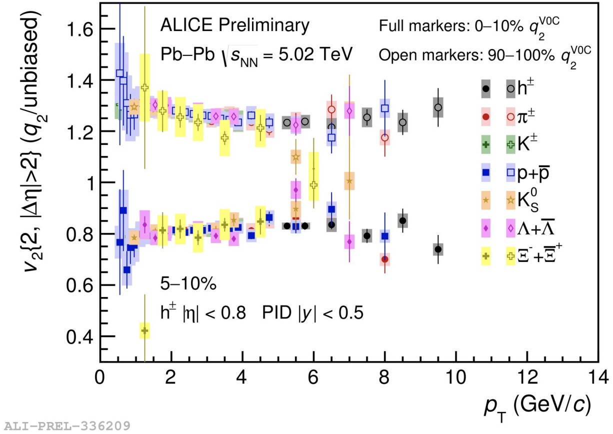
PID $v_2(p_T)$ with q_2 selection: 5-10% centrality

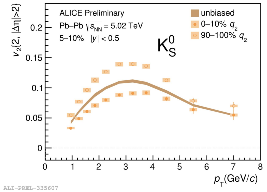


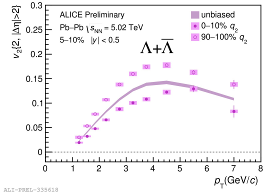


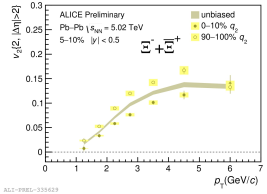






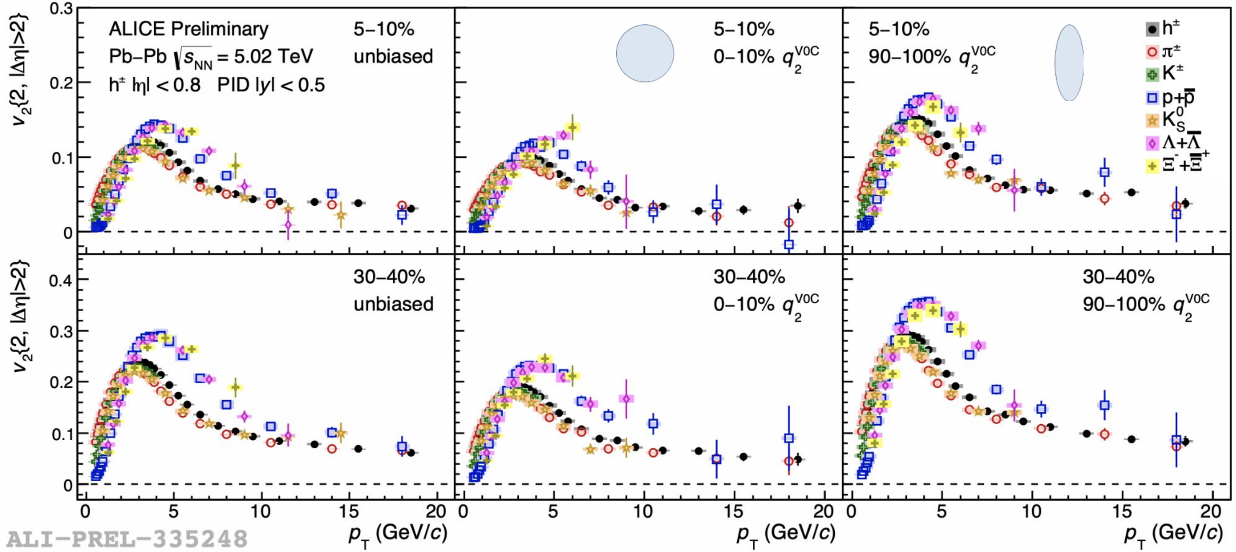


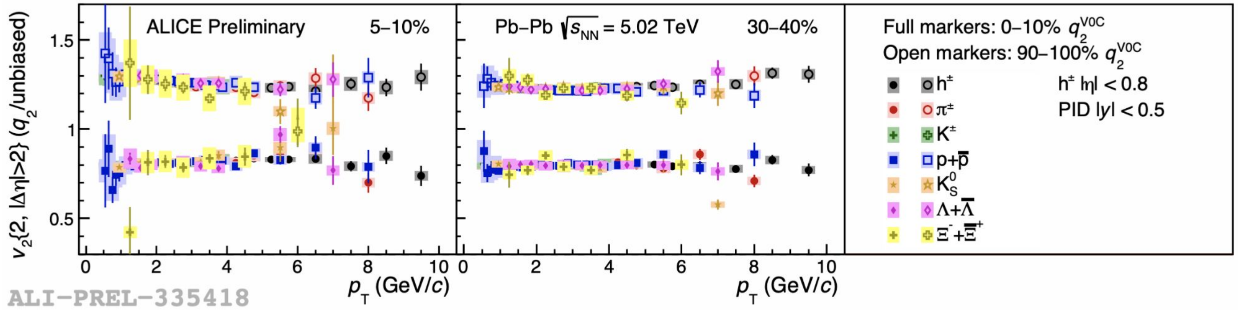




- p_T > 3 GeV/*c*: ratios almost flat → same source of flow fluctuations
- p_T < 3 GeV/*c*: weak p_T dependence → different ellipticity for q_2 classes
- Same values for inclusive and identified hadrons
  - No dependence on particle species

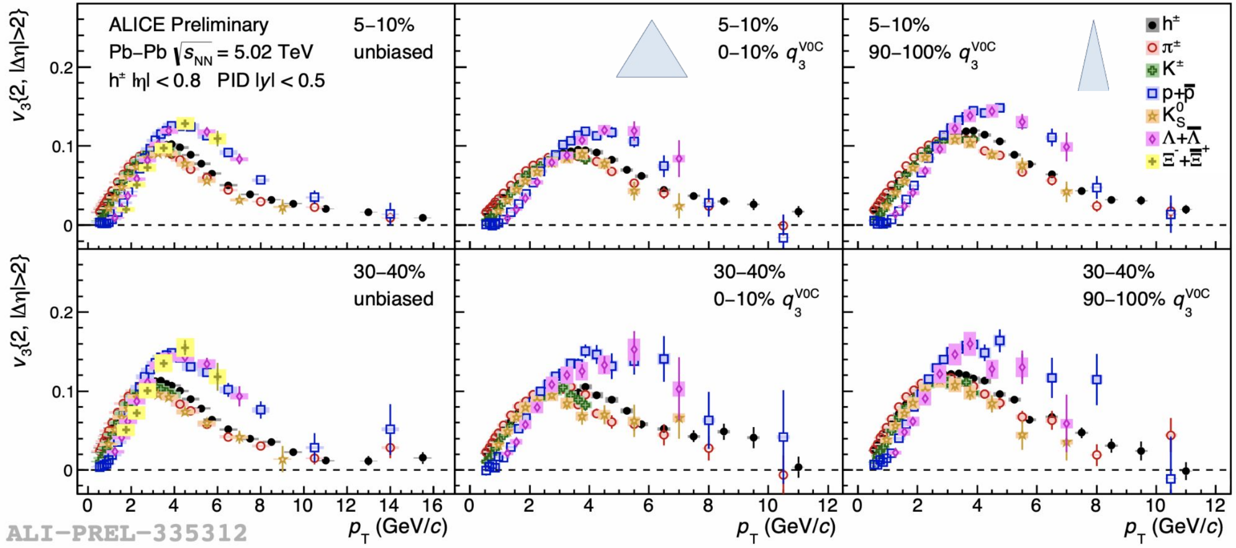
$v_2(p_T)$ with q_2: 5-10%, 30-40% centrality

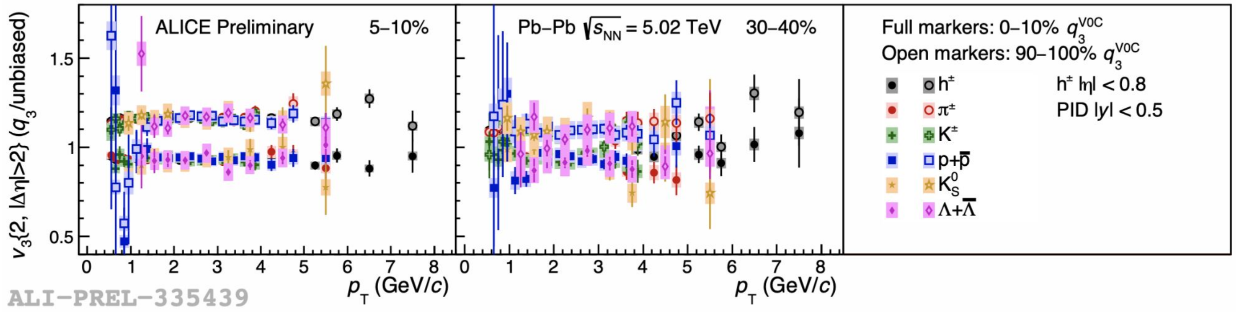




- p_T < 2 GeV/c: mass ordering → interplay between radial and elliptic flow
- p_T ~ 2-3 GeV/c: crossing between v_2 of mesons and baryons
- 3 < p_T < 10 GeV/c: v_2(baryons) > v_2(mesons)
- Particles grouping according to their type (mesons and baryons)
- p_T > 10 GeV/c: no particle type dependence within uncertainties
- Same source of flow fluctuations
  - No dependence on particle species

$v_3(p_T)$ with q_3: 5-10%, 30-40% centrality

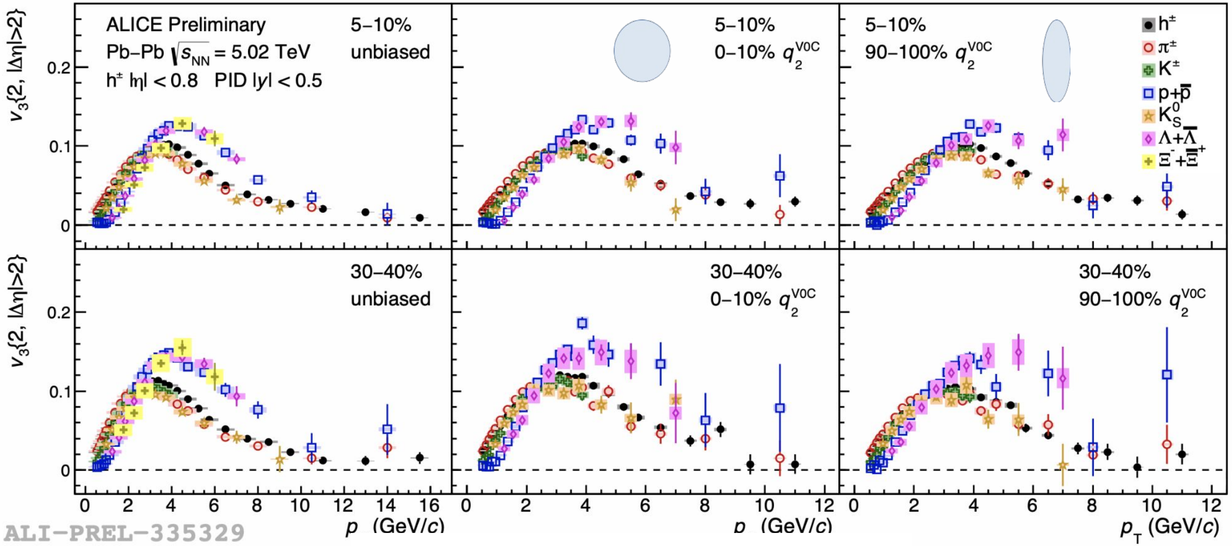




- Mass ordering at low p_T, baryon-meson grouping at intermediate p_T

- Same source of flow fluctuations
  - No dependence on particle species

$v_3(p_T)$ with q_2: 5-10%, 30-40% centrality



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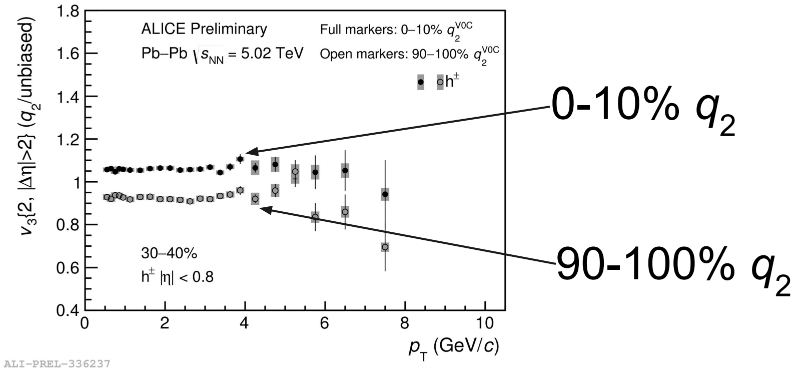
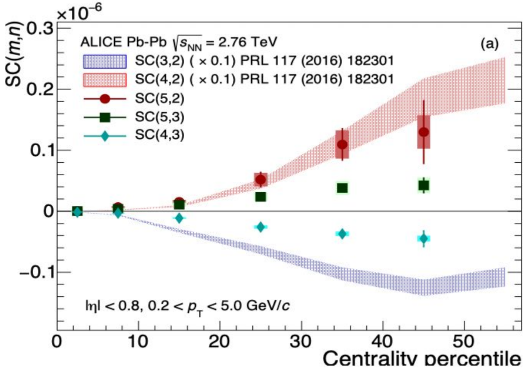
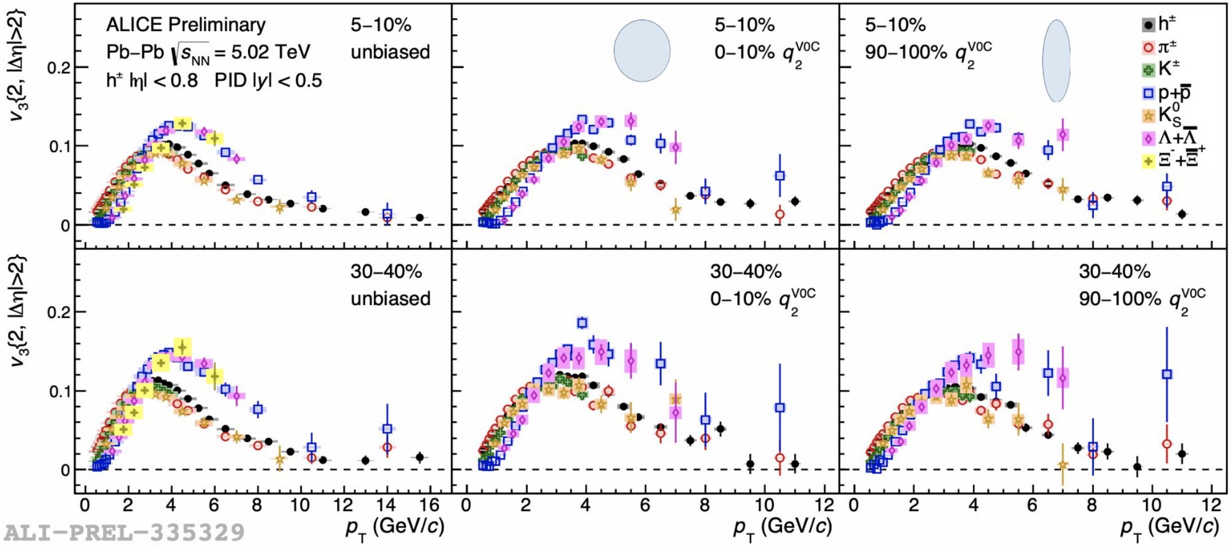


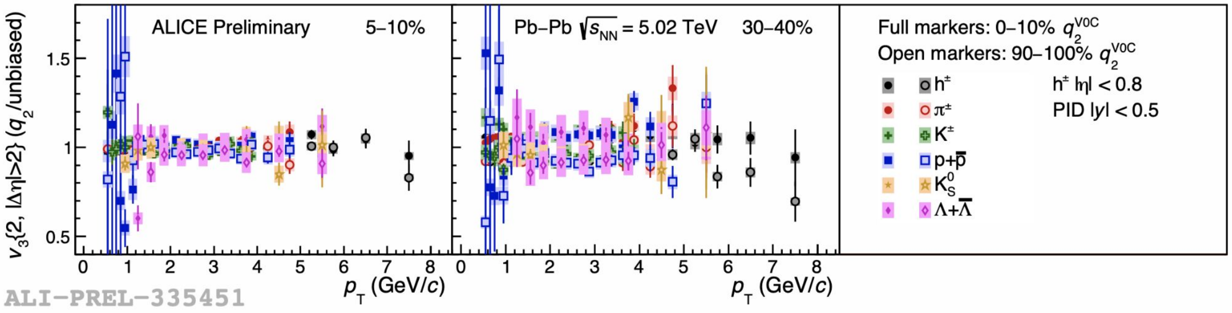
- v_3 anti-correlated with q_2

ALICE, Phys. Rev. C 97 (2018) 024906



$v_3(p_T)$ with q_2: 5-10%, 30-40% centrality

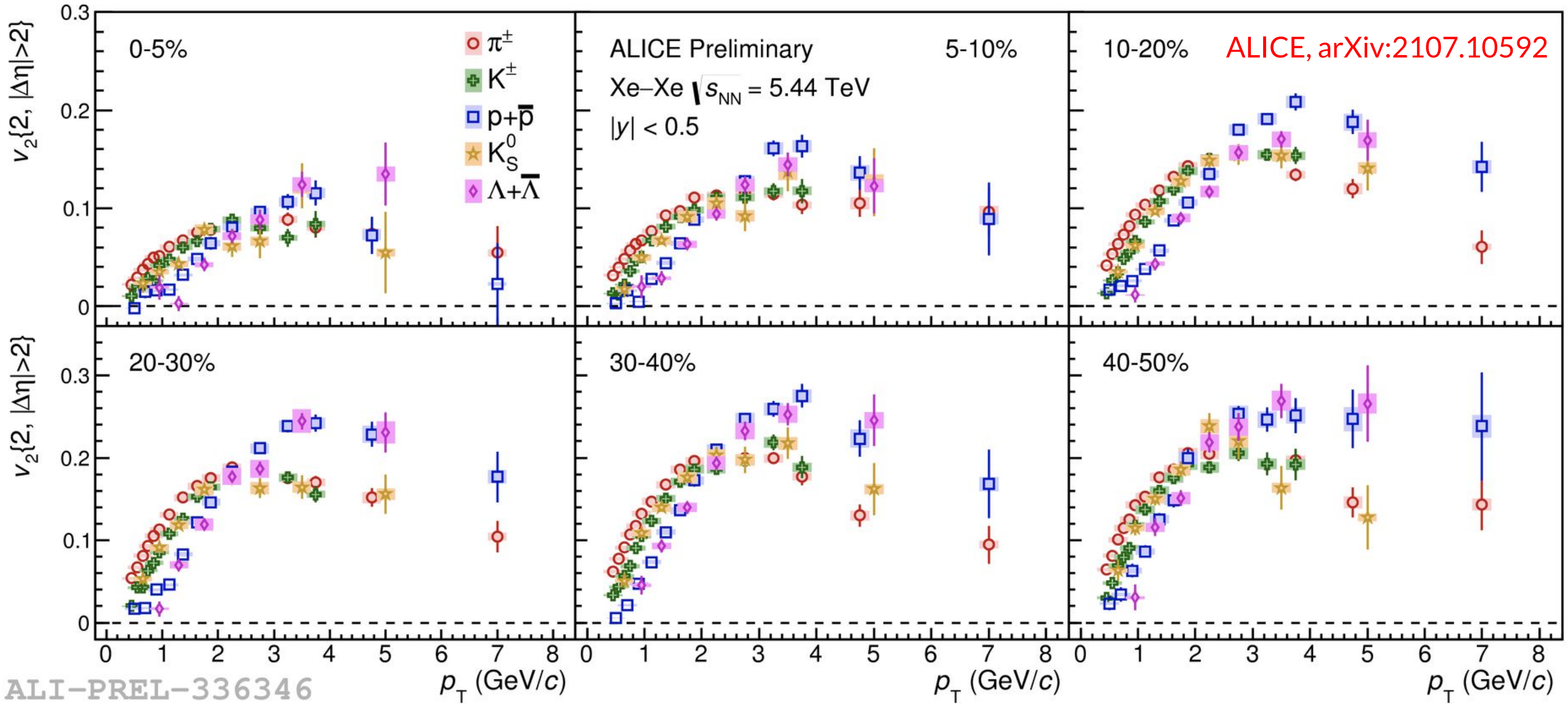




- Mass ordering at low p_T, baryon-meson grouping at intermediate p_T

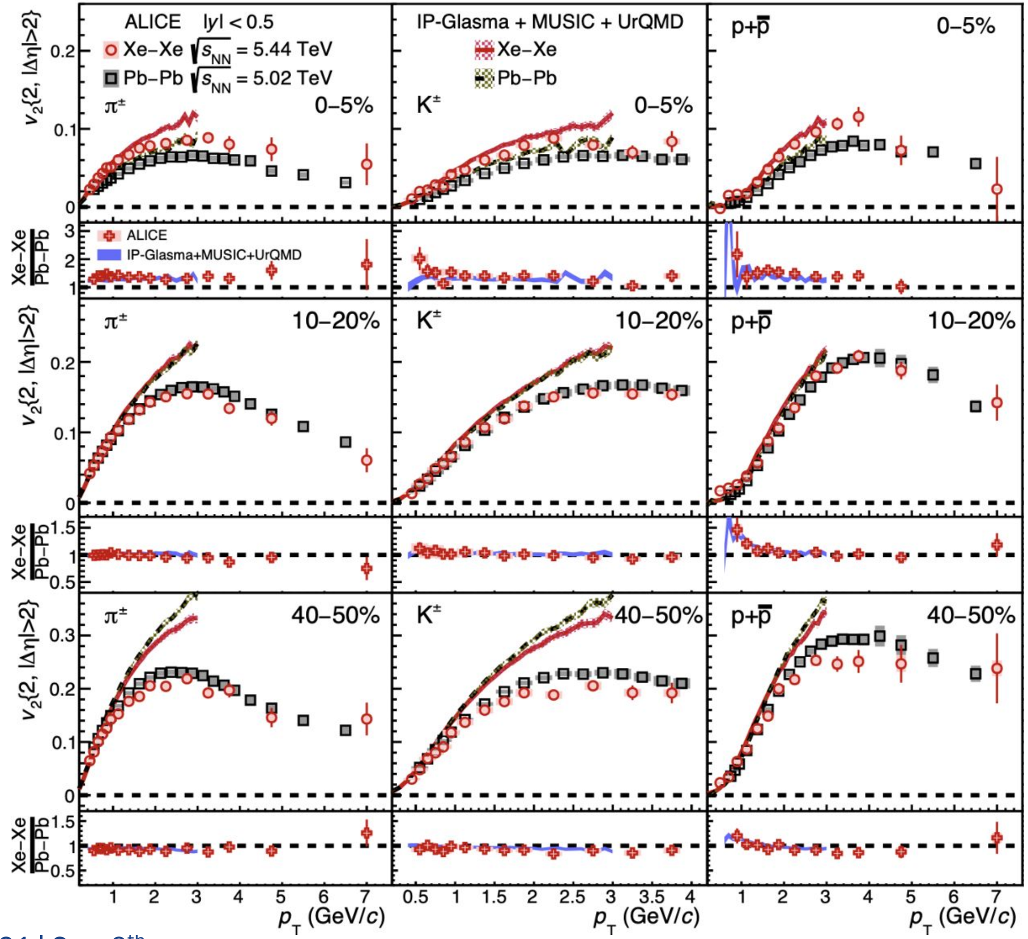
- v_3 anti-correlated with q_2
- Same source of flow fluctuations
  - No dependence on particle species

Xe-Xe: v_2 for identified hadrons



- p_T < 2 GeV/c: mass ordering due to interplay between radial flow and anisotropic geometry
- p_T ~ 2-3 GeV/c: crossing between v_n of mesons and baryons
- p_T > 3 GeV/c: particles grouping according to their type ($v_n^{baryons} > v_n^{mesons}$)

System size dependence, v_2



Constrain initial geometry and transport coefficients (e.g. η/s)

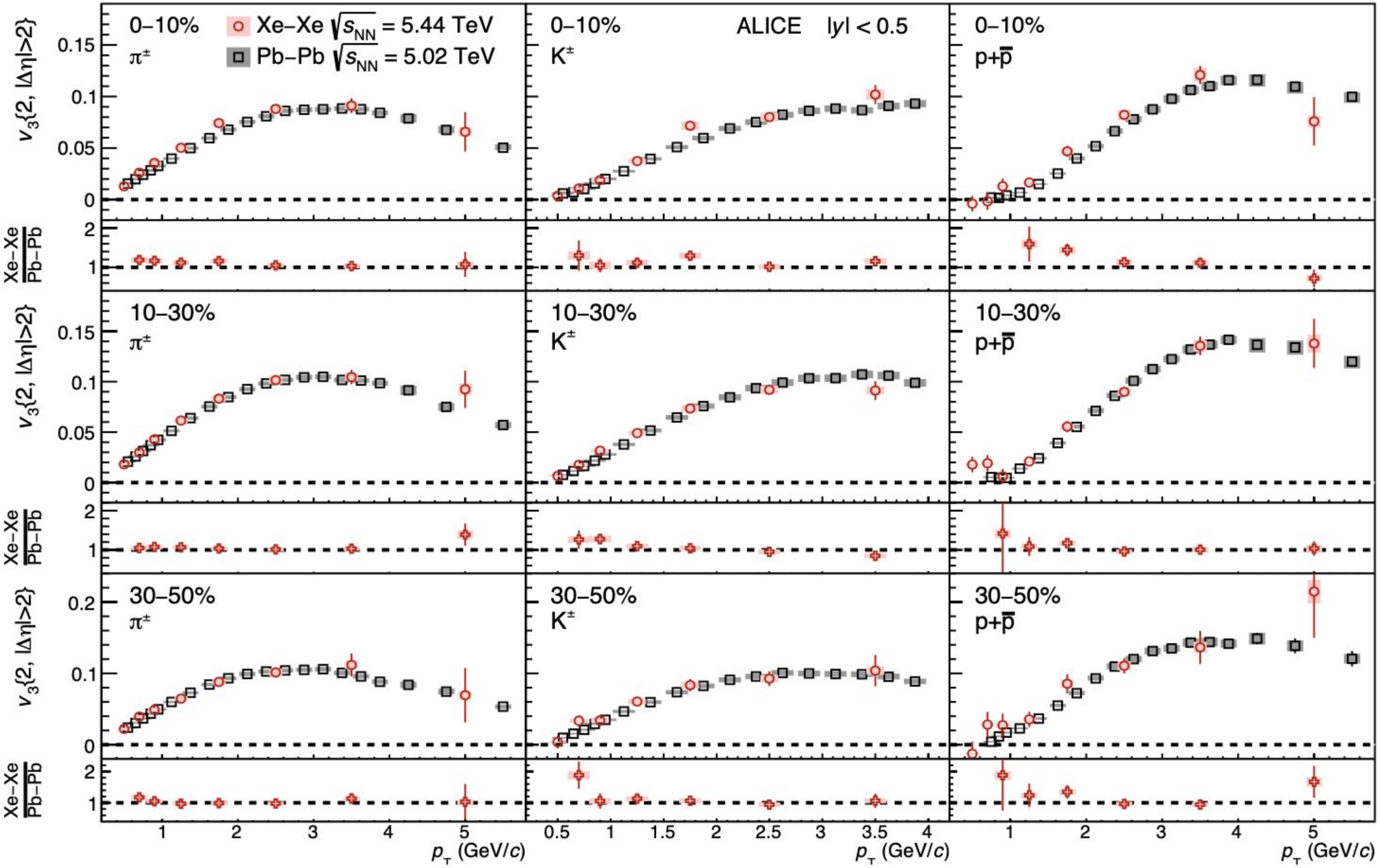
- 0-5%: $v_2^{Xe} > v_2^{Pb}$ → Xe deformation
- 10-20%: $v_2^{Xe} \sim v_2^{Pb}$
- 40-50%: $v_2^{Pb} > v_2^{Xe}$

IP-Glasma+MUSIC+UrQMD

- Reproduces data for p_T < 1 GeV/c for all centralities
- Overestimates by same amount both Pb-Pb and Xe-Xe data for p_T > 1 GeV/c

ALICE, arXiv:2107.10592

System size dependence, v_3



$\varepsilon_3\{2\}$ Xe-Xe > $\varepsilon_3\{2\}$ Pb-Pb, but v_3 Xe-Xe ~ v_3 Pb-Pb

No significant p_T dependence, except for π and p v_3 for p_T < 2 GeV/c in the 0–10% centrality class

ALICE, arXiv:2107.10592

Summary

Plethora of azimuthal correlations measurements by ALICE

First measurements of higher order SC in Pb-Pb collisions

- Presence of genuine correlations between flow amplitudes

First measurement of centrality dependence of $\rho(v_2, [p_T])$, $\rho(v_3, [p_T])$ and $\rho(v_2, v_3, [p_T])$

- Models reproduce the trend within errors

v_n coefficients measured with ESE technique in Pb-Pb collisions

- v_n larger or smaller than the average
- v_3 is anti-correlated with q_2 classes
- Same source of flow fluctuations up to 10 GeV/*c*
    - No dependence on particle species

v_n coefficients of identified hadrons measured in Pb-Pb and Xe-Xe collisions

- Mass ordering for $p_T < 2$ GeV/*c*
- Crossing between mesons and baryons for $p_T \sim 2$-3 GeV/*c*
- Particle type dependence for $p_T > 3$ GeV/*c*

Summary

Plethora of azimuthal correlations measurements by ALICE

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v_n coefficients of identified hadrons measured in Pb-Pb and Xe-Xe collisions
- Mass ordering for p_T < 2 GeV/c
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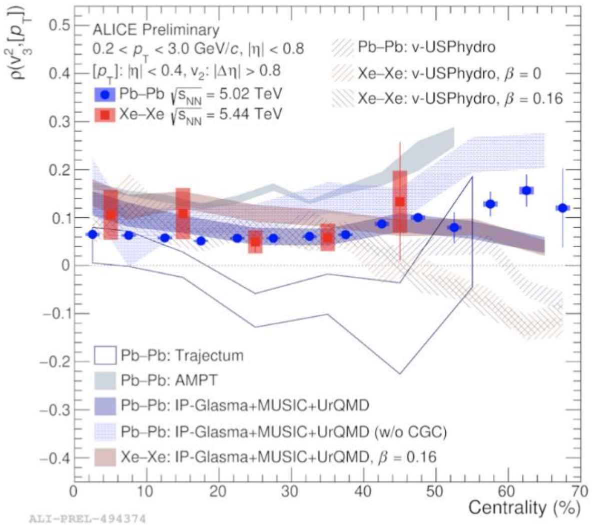
- Particle type dependence for p_T > 3 GeV/c

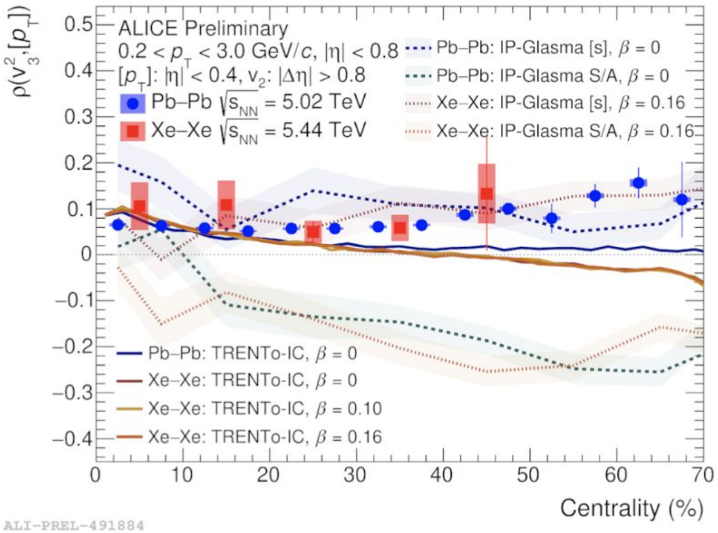
BACKUP

ρ(v3, [pt])

HYDRO



INITIAL STATE



- ❖ ρ_3 Pb−Pb and Xe−Xe results are compatible
- ❖ ρ_3 results are positive and have a modest centrality dependence for the presented centralities
- ❖ Comparison to hydro models:
  - Better described by IP-Glasma
  - TRENTo predicts negative ρ_3 in peripheral collisions which is not seen in data

- ❖ ρ_3 comparison to initial state calculations:
  - IP-Glasma with [s] estimator works best
  - Choice of estimator for [p_T] matters

    → S/A has anti-correlation of ϵ_2 and ϵ_3 - leading to negative ρ_3
  - Negative values predicted by TRENTo in non-central collisions - not seen in data
  - ρ_3 not sensitive to deformation parameter β

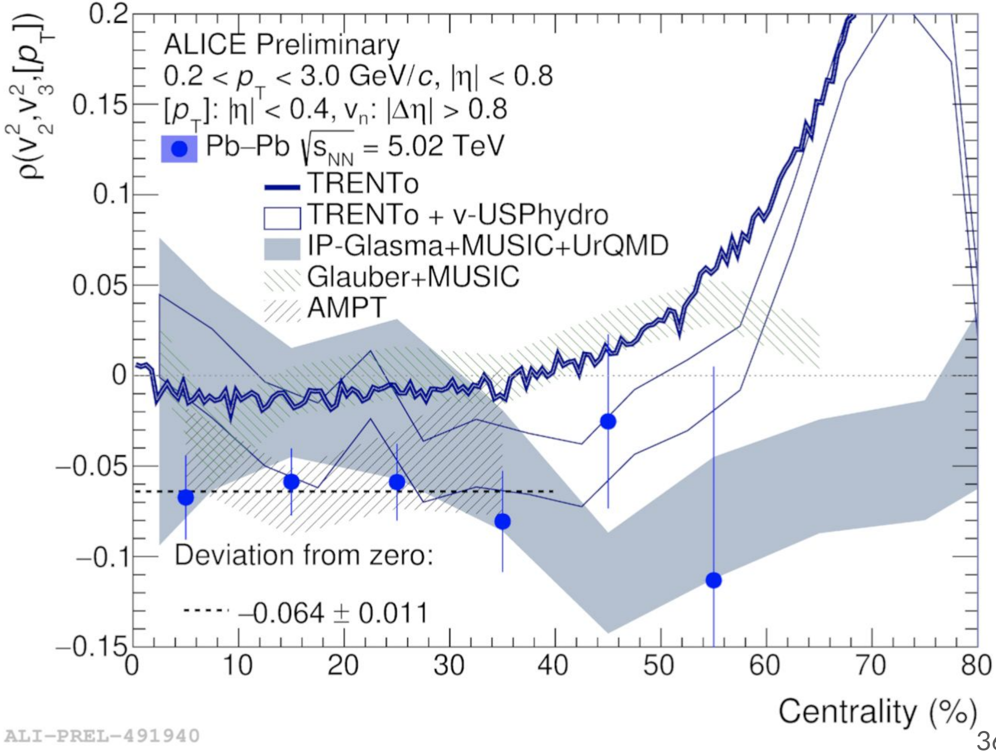
$\rho(v_2, v_3, [p_T])$ correlations

$$\rho(v_2^2, v_3^2, [p_T]) = \frac{\langle v_2^2, v_3^2, [p_T]\rangle - \langle v_2^2\rangle\langle v_3^2, [p_T]\rangle - \langle v_3^2\rangle\langle v_2^2, [p_T]\rangle - \langle [p_T]\rangle\langle v_2^2, v_3^2\rangle + 2\langle [p_T]\rangle\langle v_2^2\rangle\langle v_3^2\rangle}{\sqrt{var(v_2^2)}\sqrt{var(v_3^2)}\sqrt{c_k}}$$

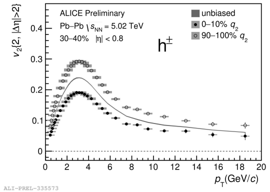
Genuine correlation of v_2 , v_3 and $[p_T]$

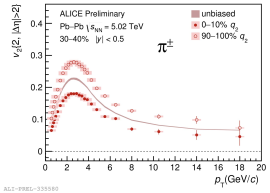
First measurement performed in Pb-Pb collisions

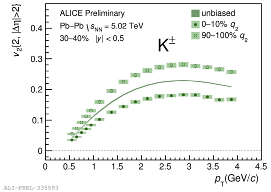
- Non-zero for all centralities
- ~ 3σ effect in 0-40% centrality
- Models reproduce the trend within uncertainties
  - Measurement will benefit from increased statistics in Run 3

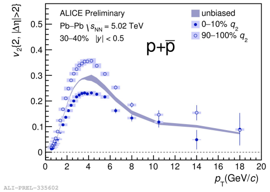


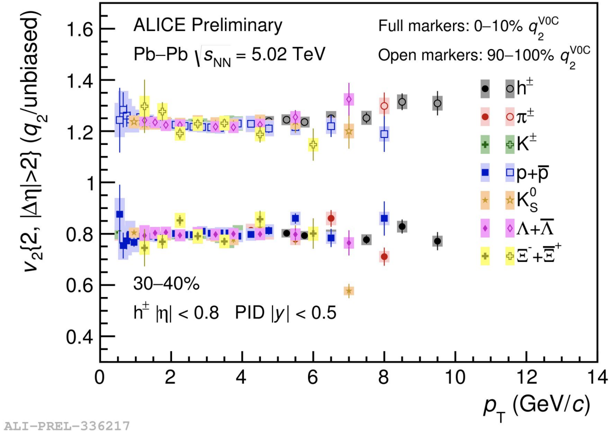
PID $v_2(p_T)$ with q_2 selection: 30-40% centrality

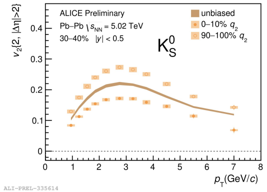


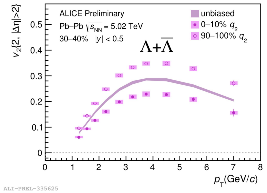


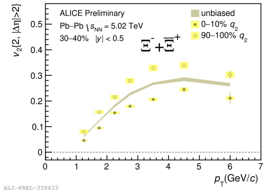












- p_T > 3 GeV/c: ratios almost flat → same source of flow fluctuations
- p_T < 3 GeV/c: almost no p_T dependence in contrast to central collisions
- Same values for inclusive and identified hadrons
- No dependence on particle species