Shaping the quark-gluon plasma using measurements of anisotropic flow in Pb–Pb and Xe–Xe collisions with ALICE

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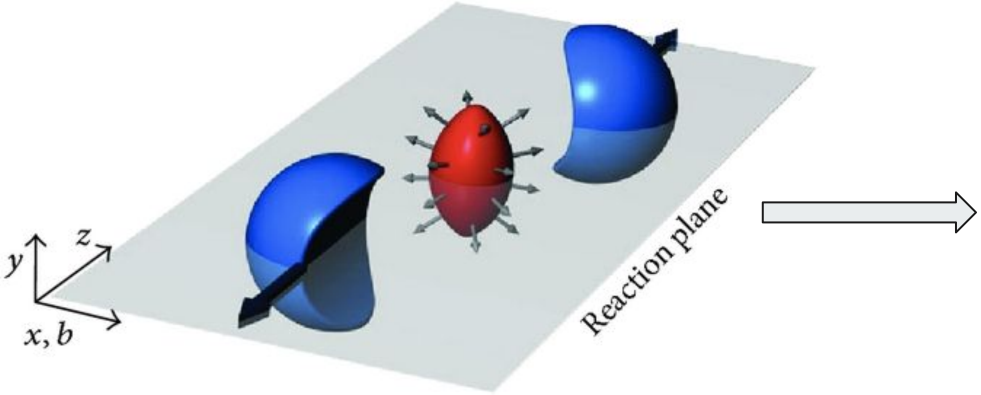
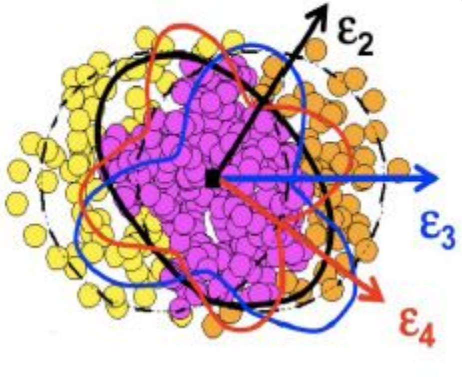
On behalf of the ALICE Collaboration

Anisotropic flow

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

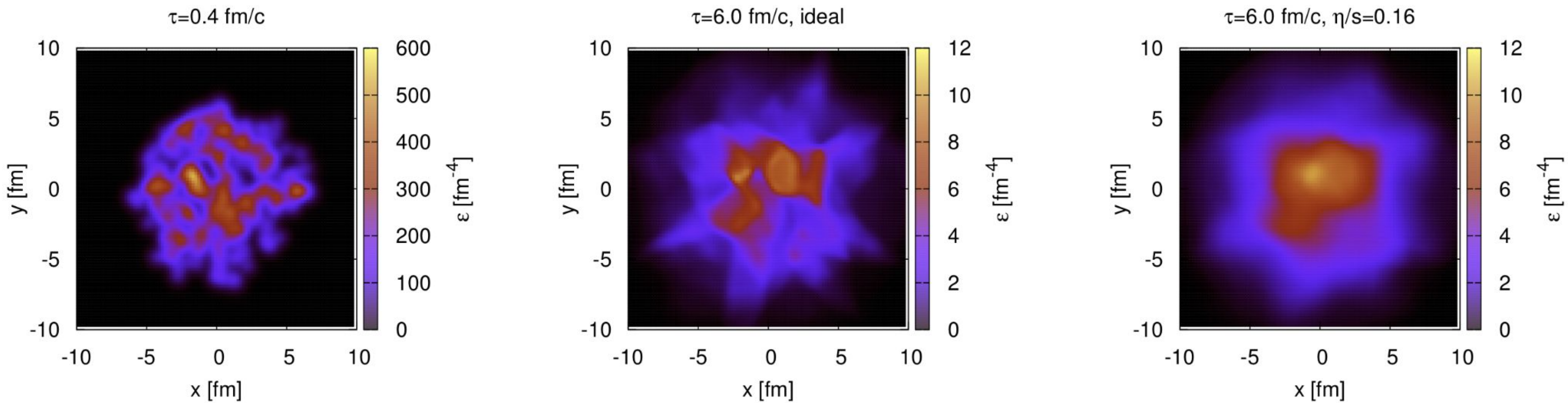




Anisotropic flow: the transfer of initial spatial anisotropy into the final anisotropy in momentum space via collective interactions

Most central collision: fluctuations of participating nucleons

Anisotropic flow



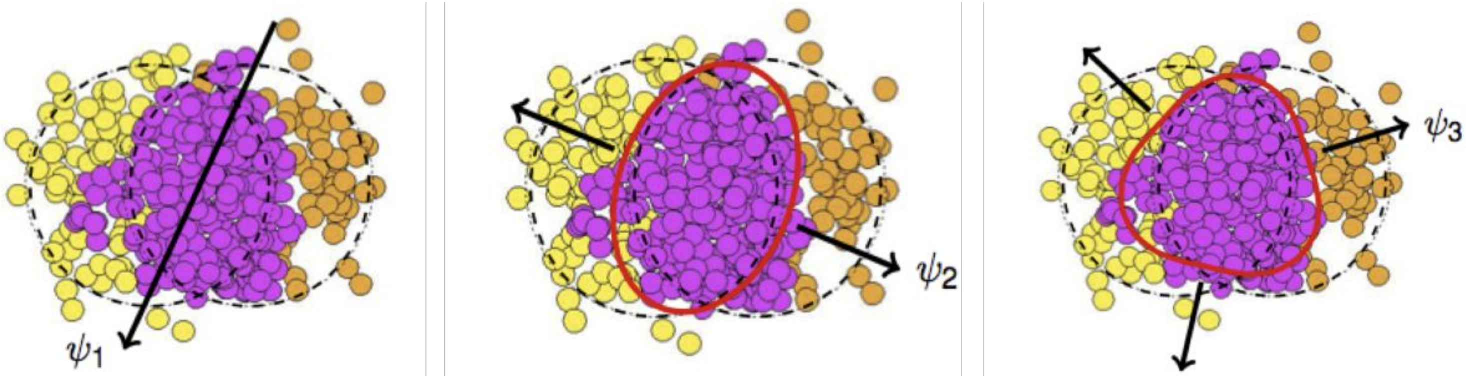
Anisotropic flow: the transfer of initial spatial anisotropy into the final anisotropy in momentum space via collective interactions

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 (SP) method

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

$\mathbf{u}_{n,k} = e^{in\varphi_k}$: unit vector of particle of interest (POI) k

$\mathbf{Q}_n$: the event flow vector from reference particles (RPs)

$$Q_{n,x} = \sum_j w_j \cos(n\varphi_j),\ Q_{n,y} = \sum_j w_j \sin(n\varphi_j)$$

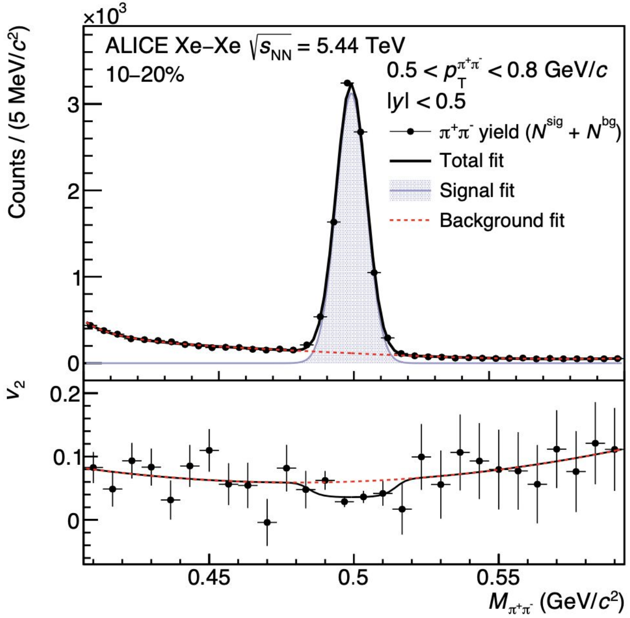
- Pseudorapidity gap $|\Delta\eta| > 2$ between POI and RPs

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

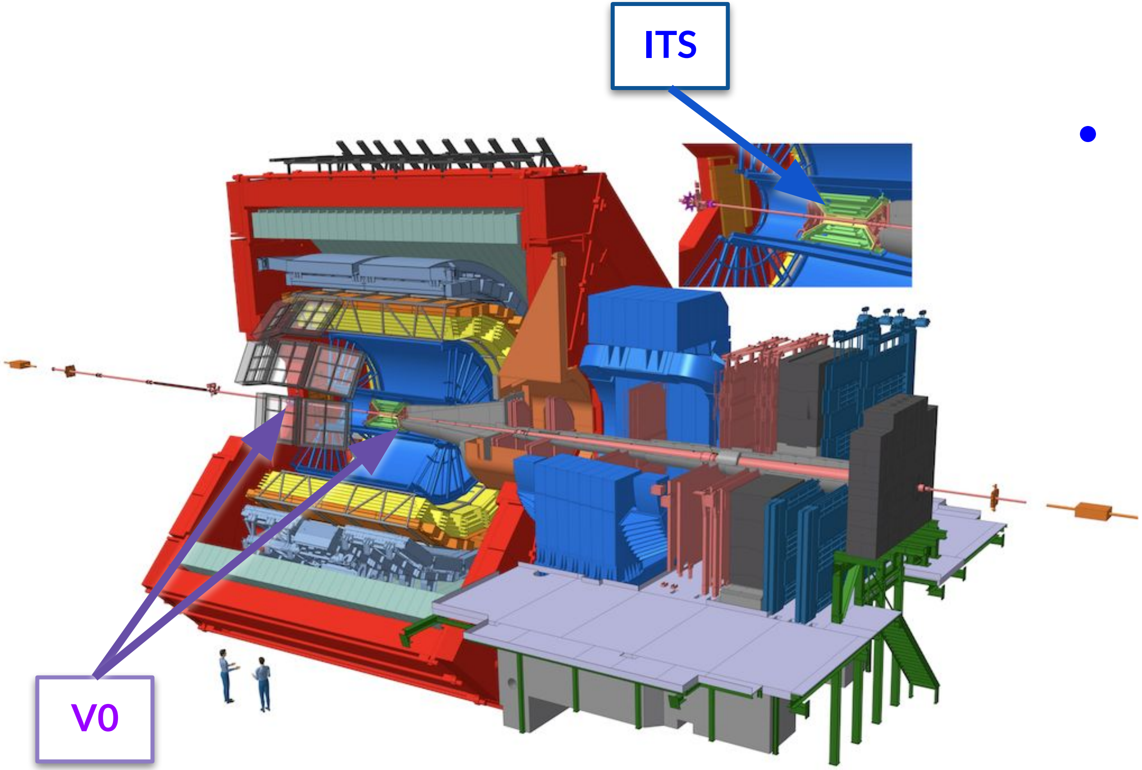
- v_n of π, K, p is determined using directly the SP method
- v_n of K^0_S, Λ, Ξ is determined using the v_n vs invariant mass method

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

- N^{Sgn} and N^{Bg} are extracted from fits of the invariant mass distribution
- $v_n^{Tot}(m_{inv})$ is measured using the SP method

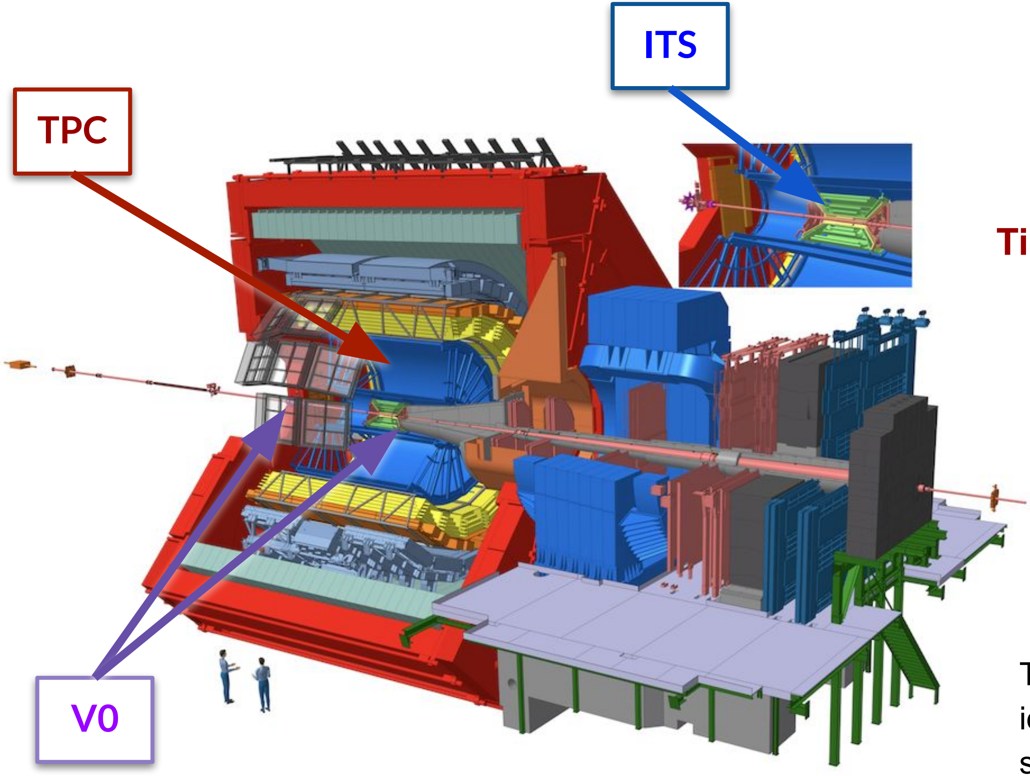


ALICE@Run2



- **V0 detector (forward region)**
  - Triggering, centrality determination, Q-vector, event-shape selection
- **Inner Tracking System (ITS)**
  - Tracking, triggering, vertexing

ALICE@Run2



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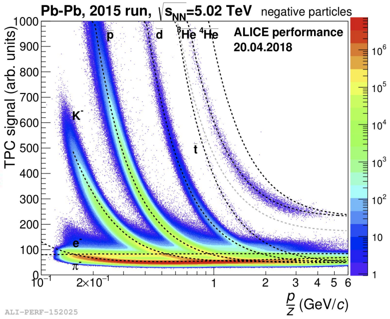
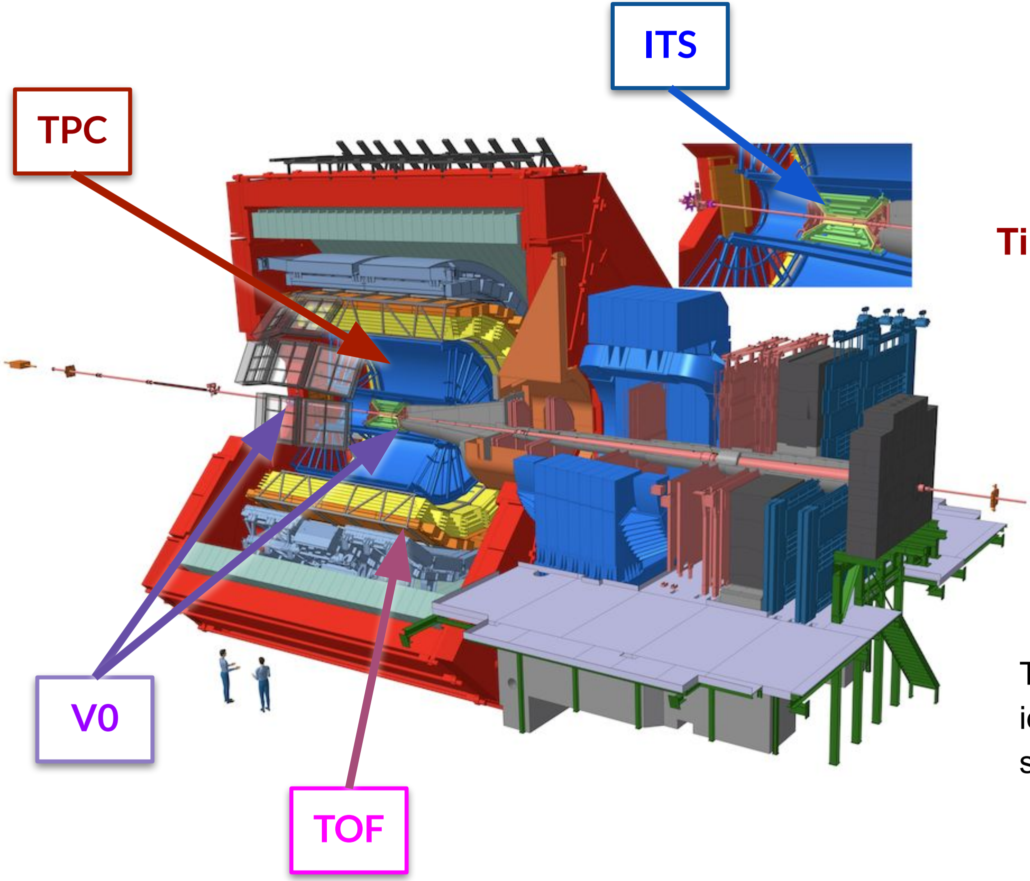
Time Projection Chamber (TPC)



Tracking, vertexing, particle identification based on specific energy loss

ALICE@Run2



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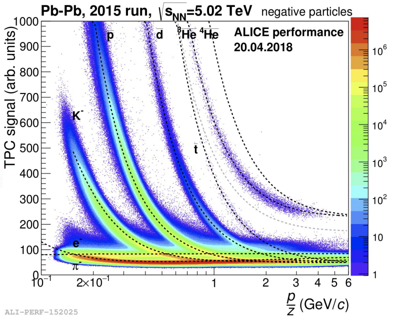
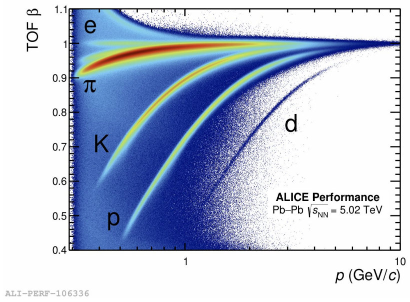


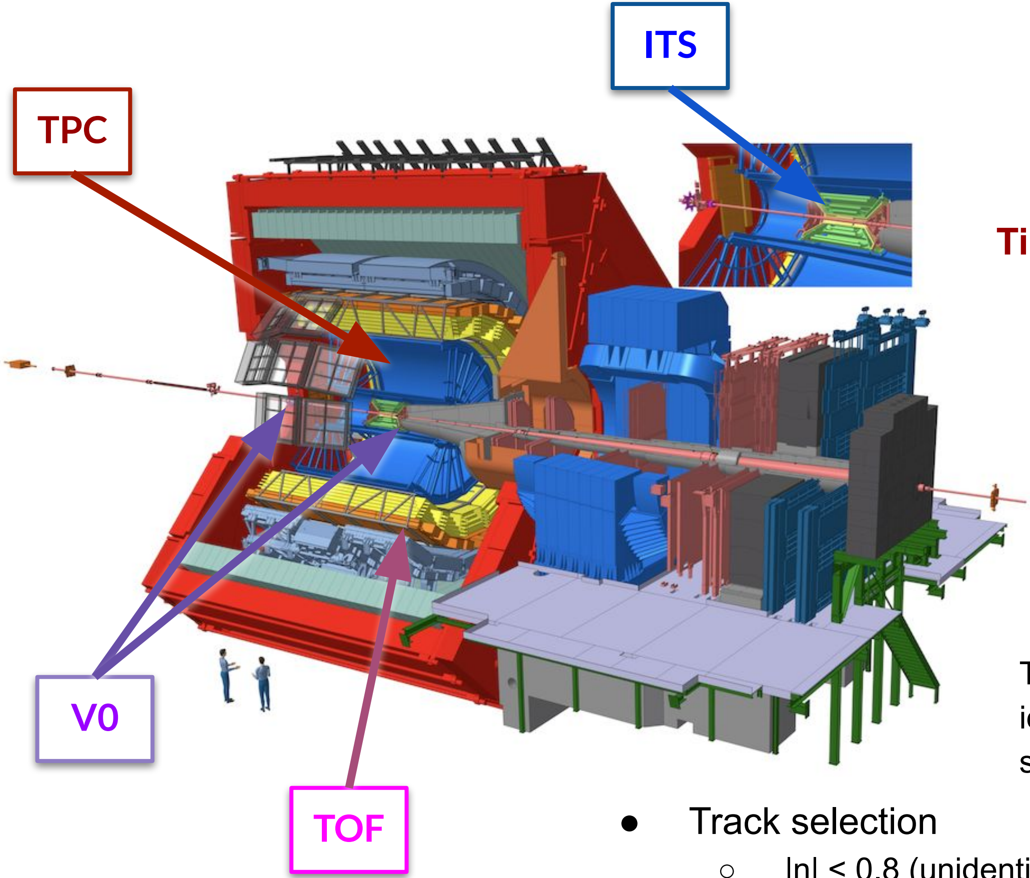
Tracking, vertexing, particle identification based on specific energy loss

Time-of-Flight (TOF)



Particle identification based on the flight time

ALICE@Run2



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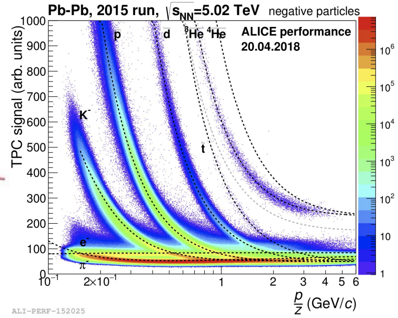

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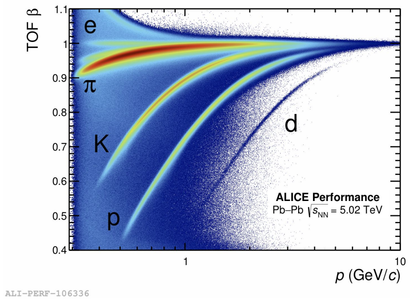


Particle identification based on the flight time

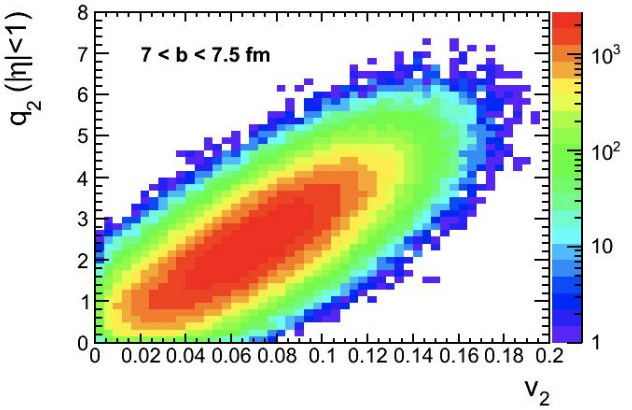
- Track selection
  - $|\eta| < 0.8$ (unidentified)
  - $|y| < 0.5$ (π, K, p, K^0_S, Λ, Ξ)
- Data sample
  - Pb–Pb at $\sqrt{s_{NN}}$ = 5.02 TeV ~320M events
  - Xe–Xe at $\sqrt{s_{NN}}$ = 5.44 TeV ~1.3M events

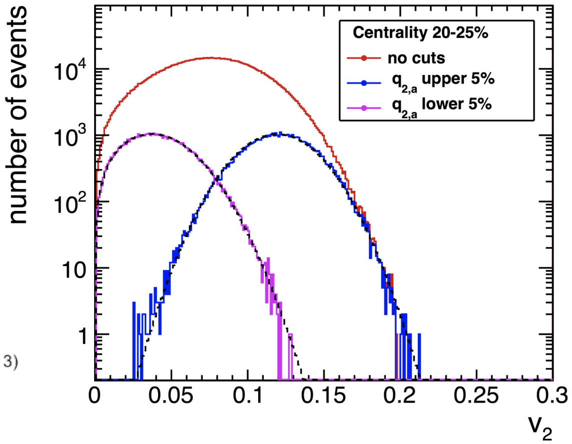
Event Shape Engineering (ESE)

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

Flow vector $\qquad\qquad$ q_n distribution

$$Q_{n,x}=\sum_i \cos(n\varphi_i) \quad \rightarrow \quad Q_n=\{Q_{n,x}, iQ_{n,y}\}$$
$$Q_{n,y}=\sum_i \cos(n\varphi_i) \qquad\quad q_n=|Q_n|/\sqrt{M}$$





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

Event Shape Engineering (ESE)

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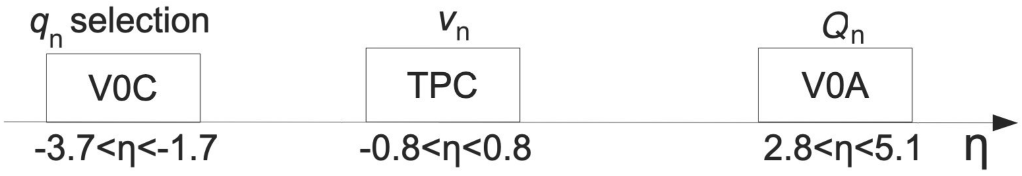
Flow vector

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

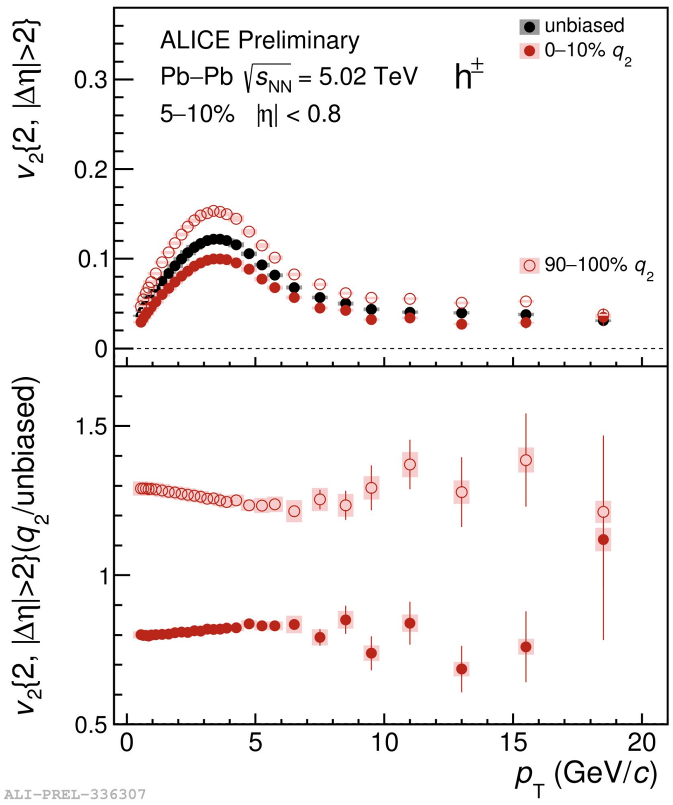
q_n distribution

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



Large q_2: 10% high

Small q_2: 10% low



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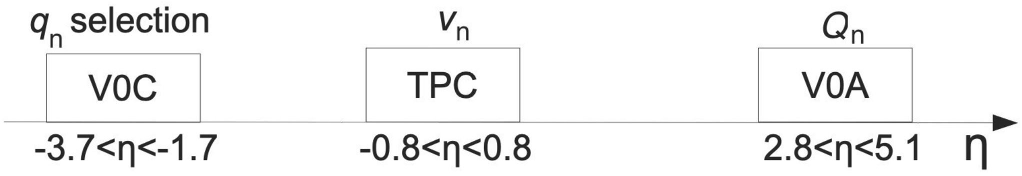
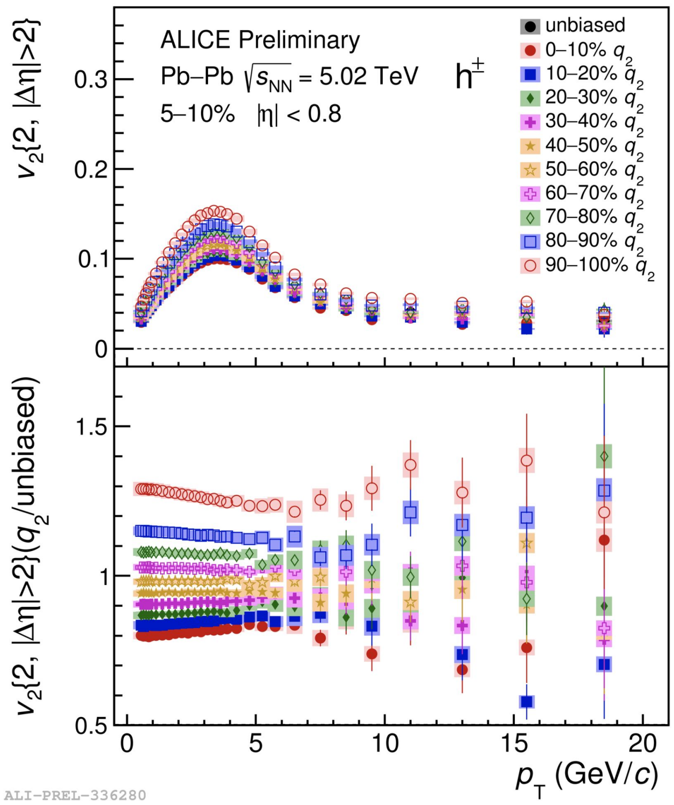
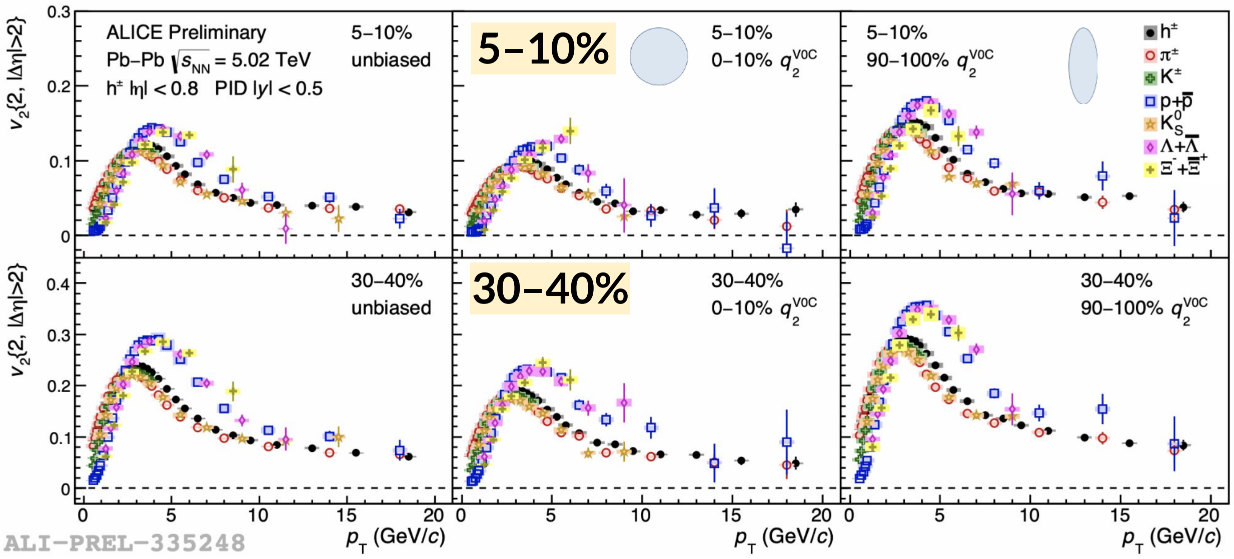


- q_2^{V0C} selects events up to 30% larger or smaller v_2 than the average
- p_T > 3 GeV/c: ratios almost flat → same source of flow fluctuations
- p_T < 3 GeV/c: weak p_T dependence



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



- p_T < 2 GeV/c: mass ordering
  - Radial and elliptic flow interplay
- p_T ~ 2–3 GeV/c: crossing between mesons and baryons
- p_T ~ 3–10 GeV/c: particles grouping according to their type
  - v_2(baryons) > v_2(mesons)
- p_T > 10 GeV/c: no particle type dependence within uncertainties

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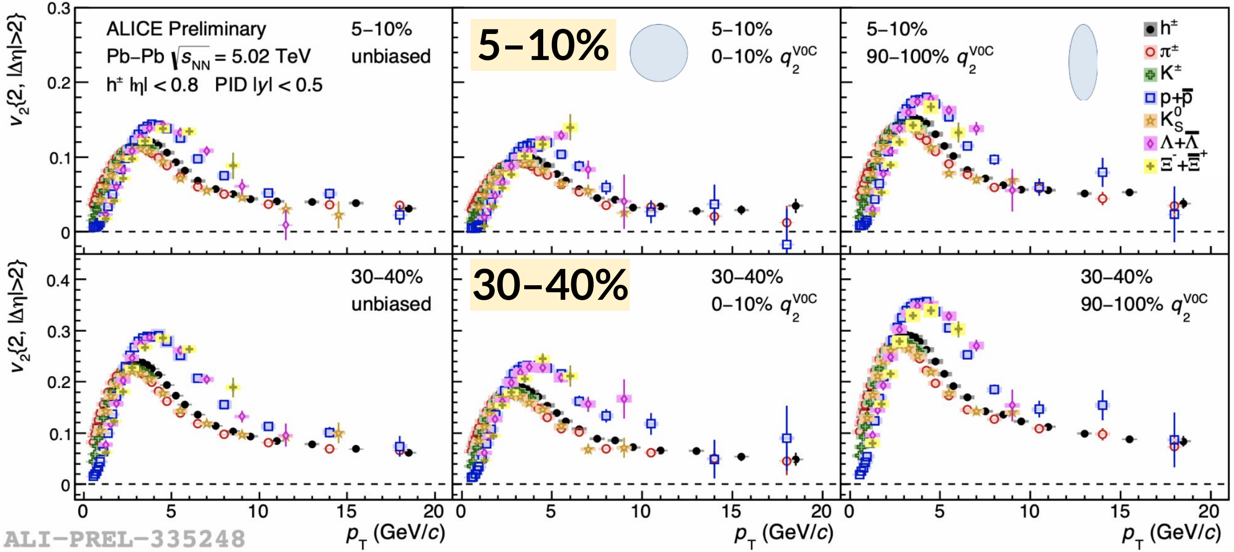

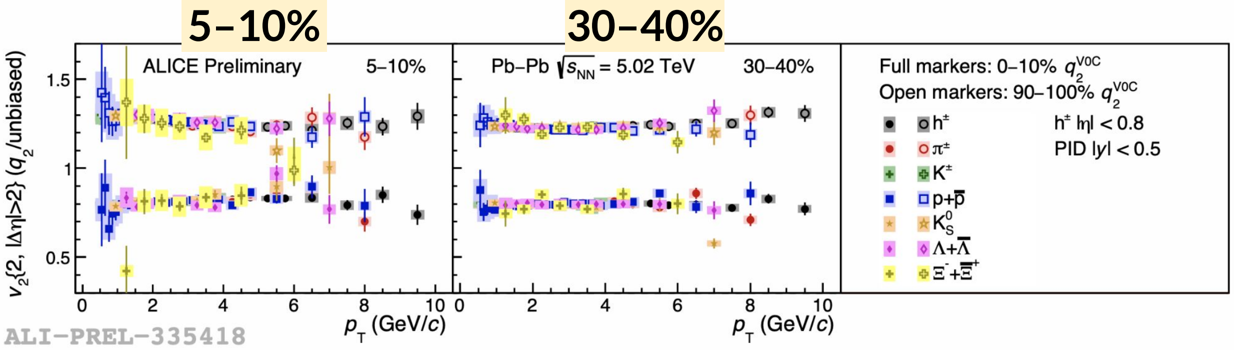

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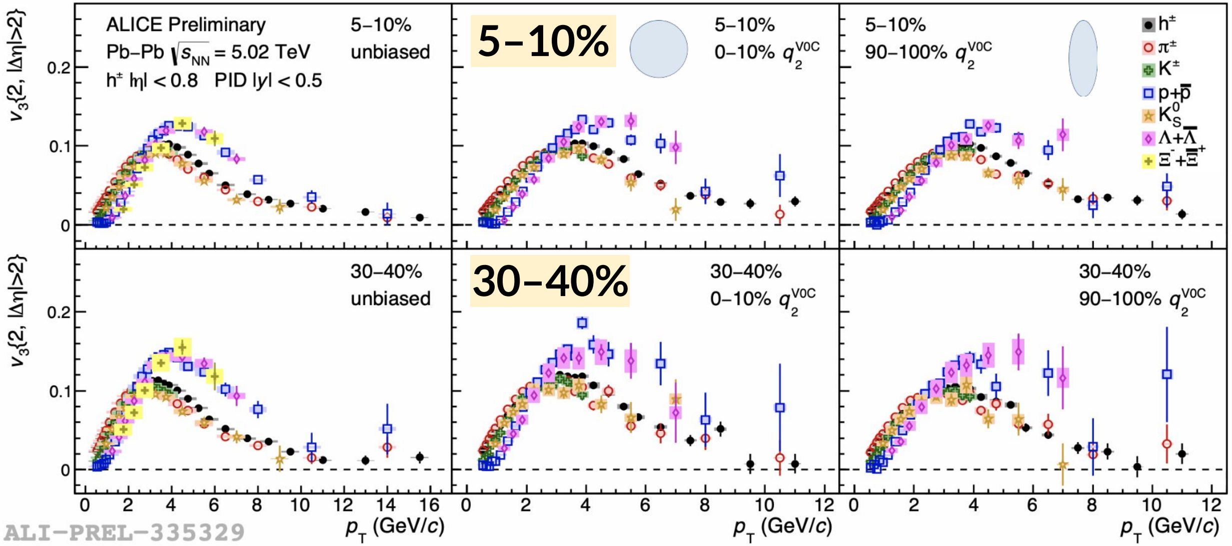
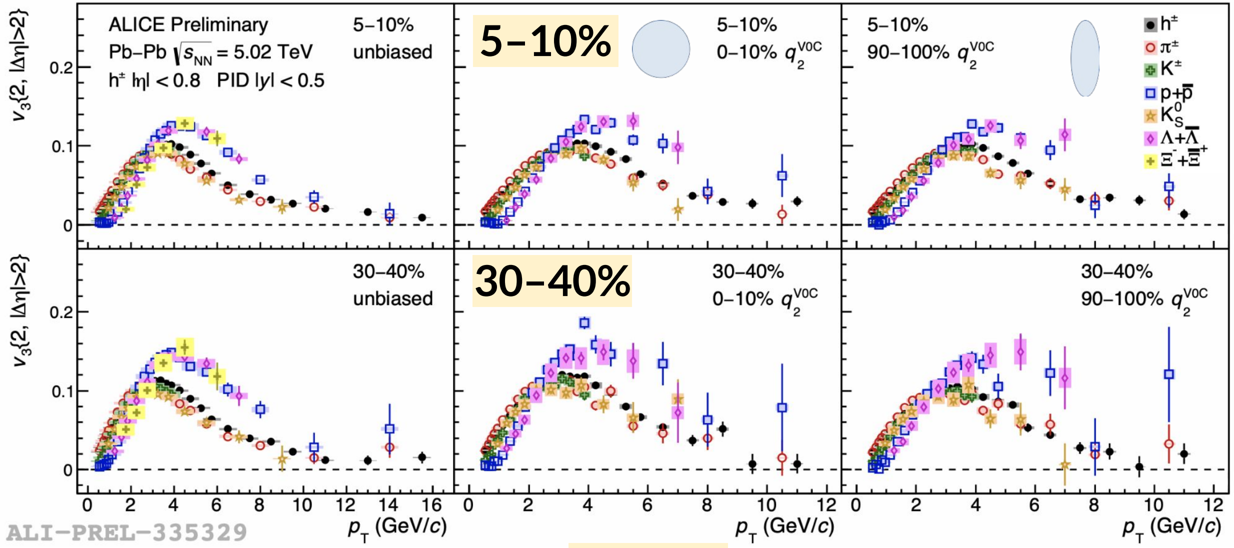
- Same source of flow fluctuations
  - No dependence on particle species

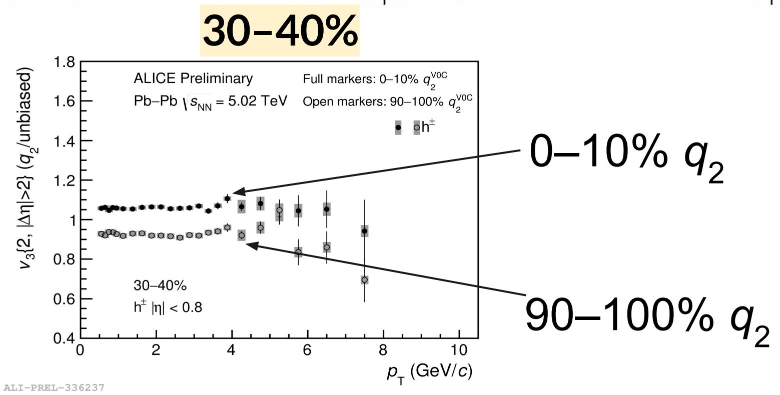
$v_3(p_T)$ with q_2: 5–10%, 30–40% centrality



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

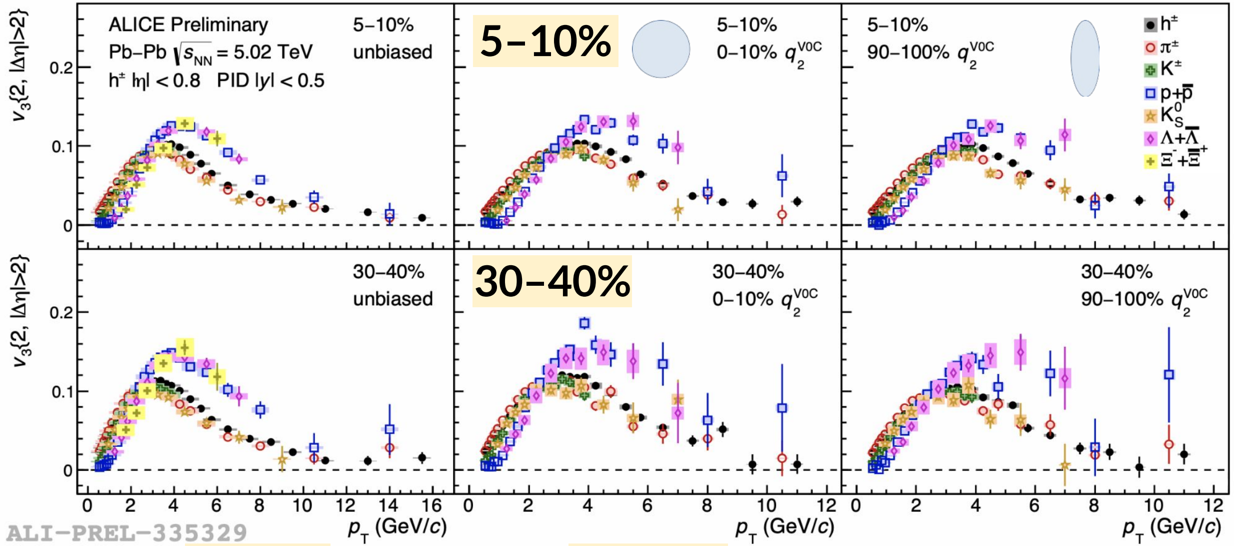
$v_3(p_T)$ with q_2: 5–10%, 30–40% centrality





- Mass ordering at low p_T, baryon-meson grouping at intermediate p_T
- v_3 anti-correlated with q_2

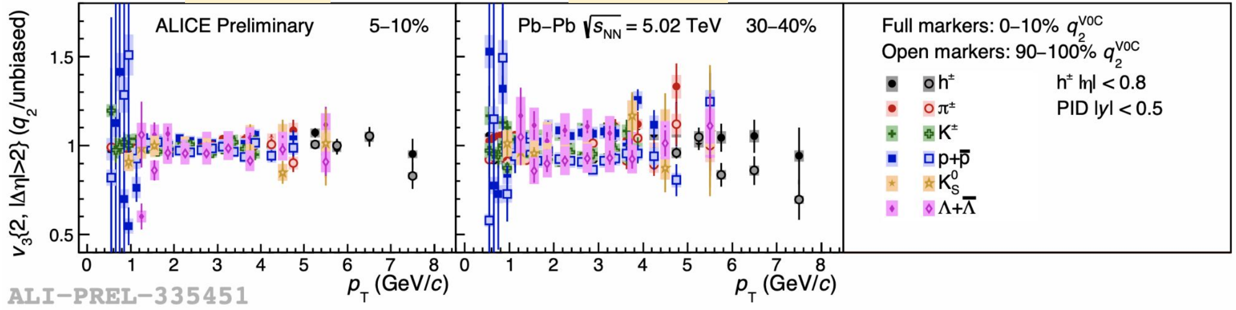
$v_3(p_T)$ with q_2: 5–10%, 30–40% centrality



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

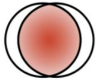
5–10%

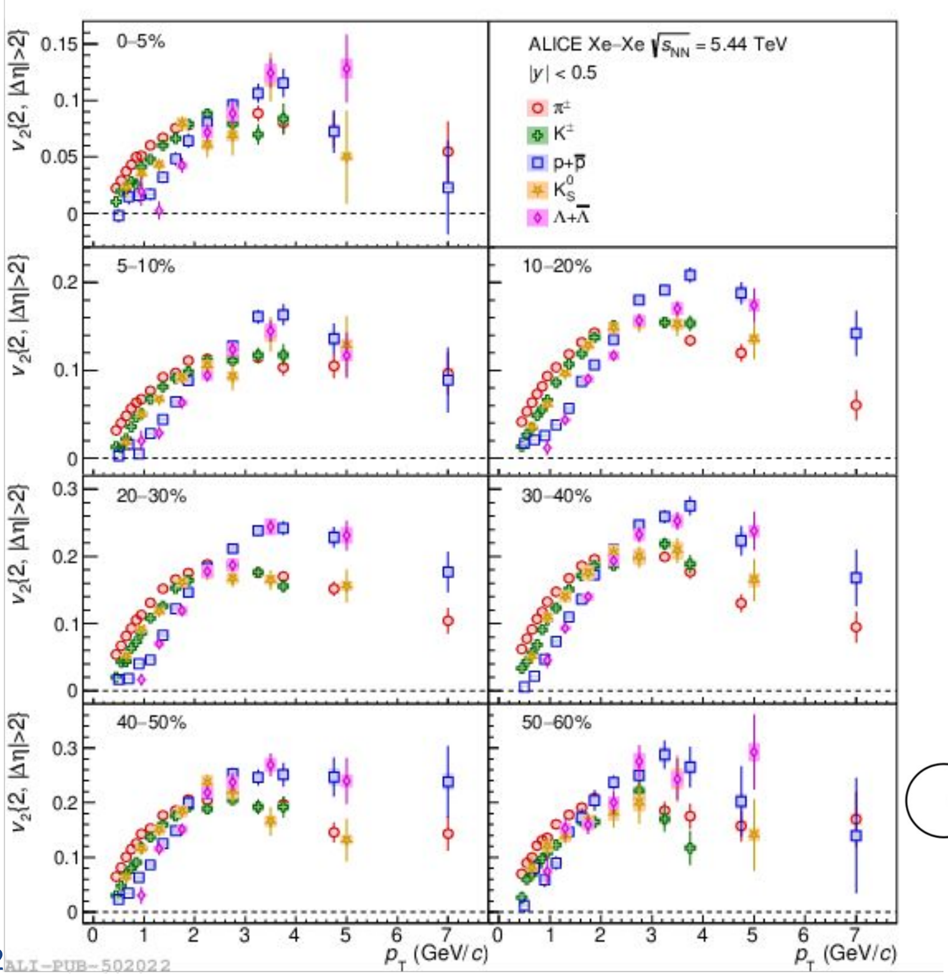
30–40%

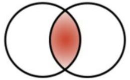


- v_3 anti-correlated with q_2
- Same source of flow fluctuations
  - No dependence on particle species

Xe–Xe: v_2 for identified hadrons



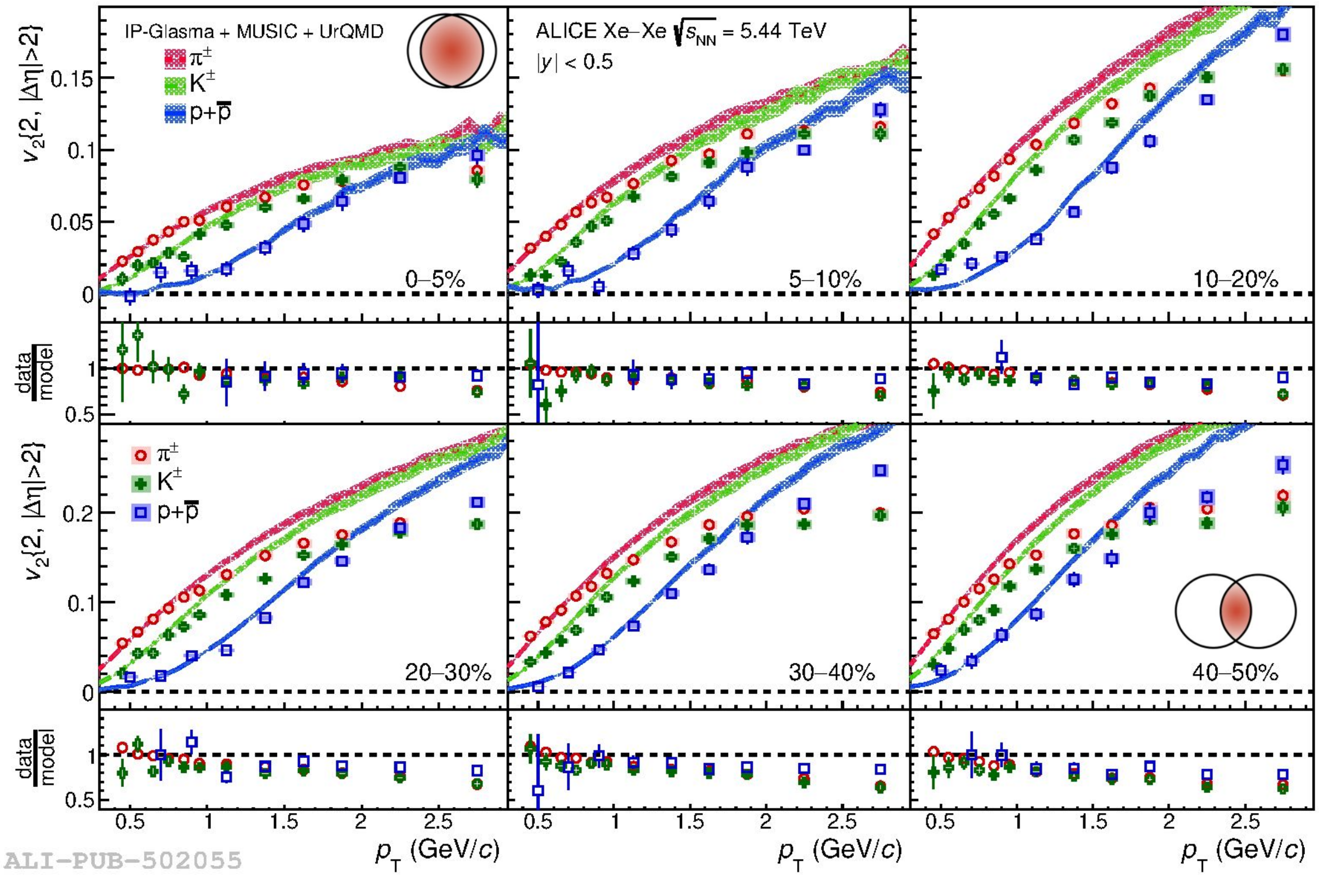




ALICE, JHEP (10), 152 (2021)

- 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_2 of mesons and baryons
- p_T > 3 GeV/c: particles grouping according to their type → v_2(baryons) > v_2(mesons)

Comparison to model, Xe–Xe v_2



IP-Glasma+MUSIC+UrQMD

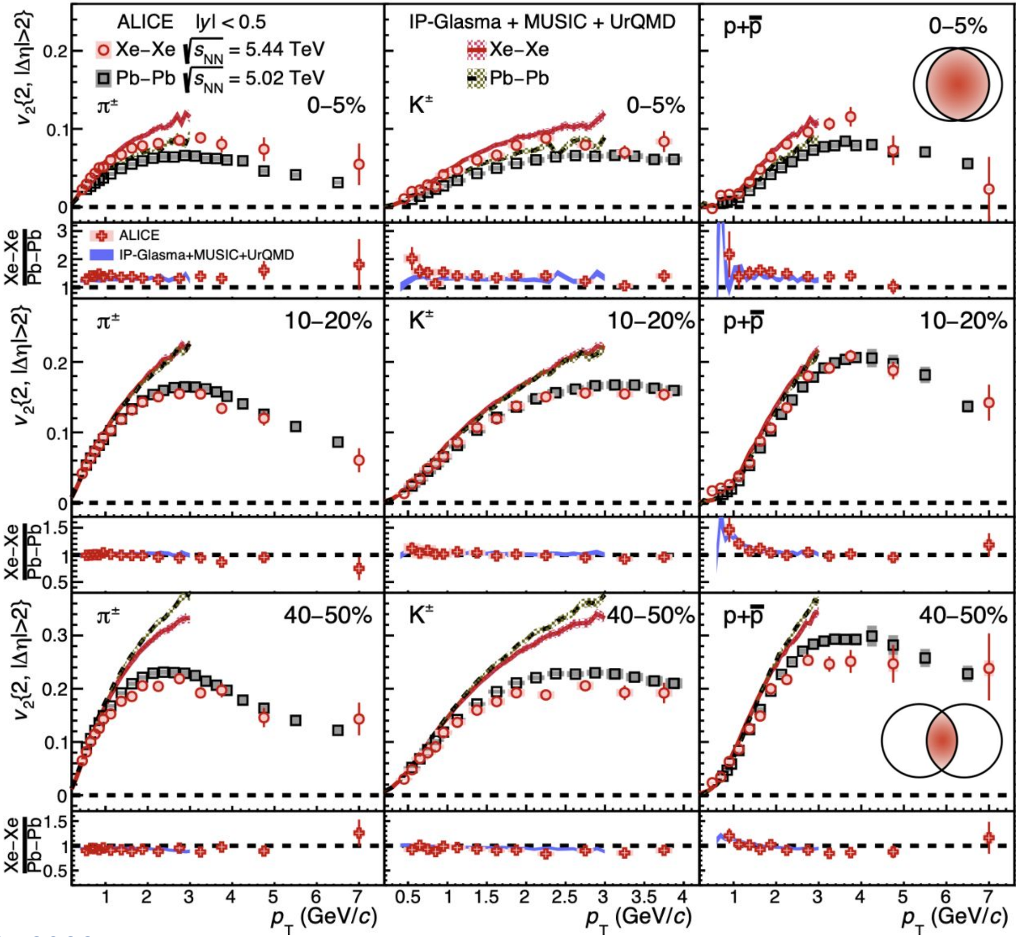
(B. Schenke et al.: PRC 102, 044905 (2020))

- Reproduces data for $p_T < 1$ GeV/c
- Overestimates data for $p_T > 1$ GeV/c
  - Better agreement for protons than for mesons

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

ALICE, JHEP (10), 152 (2021)

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

(B. Schenke et al.: PRC 102, 044905 (2020))

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

ALICE, JHEP (10), 152 (2021)

Summary

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_2 coefficient of identified hadrons measured in 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

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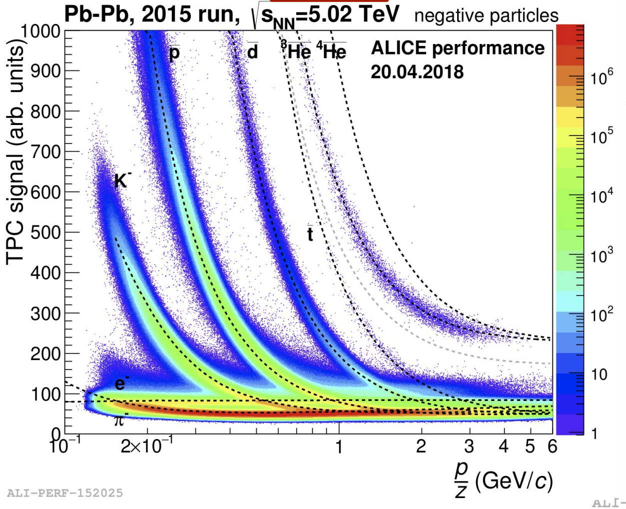
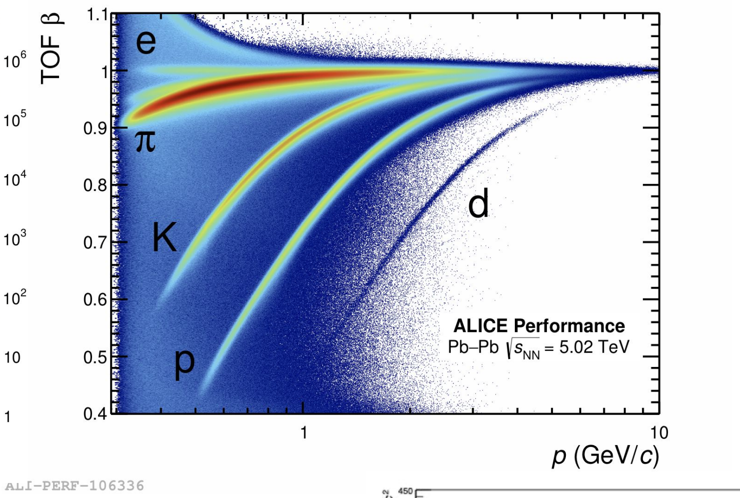
BACKUP

Particle identification (PID)

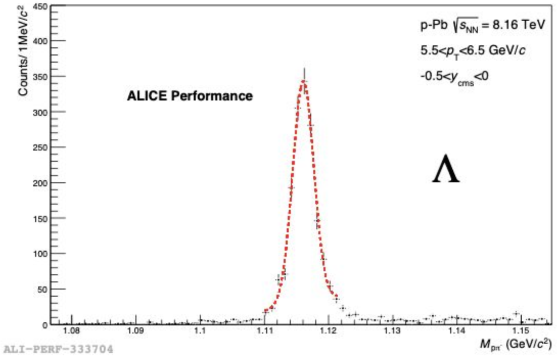
TPC



TOF

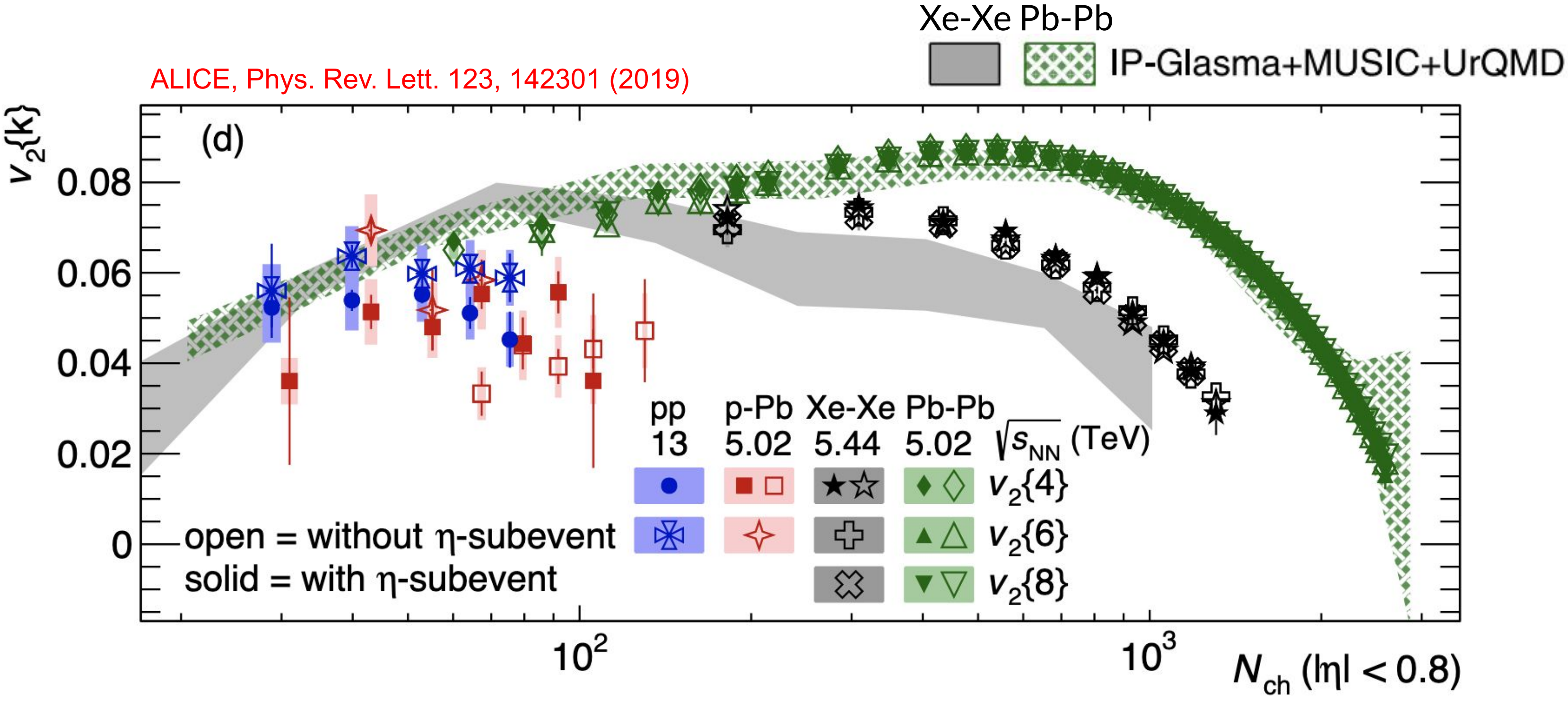


- PID @ p_T < 4 GeV/c
  - π, K, p identified using TPC and TOF (purity >90%)
- PID @ p_T > 4 GeV/c
  - π and p identified using TPC (purity >80%)
- Topological reconstruction for K^0_S, Λ and Ξ



ALICE v_2 measurements

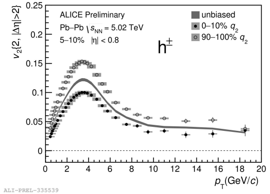
ALICE, Phys. Rev. Lett. 123, 142301 (2019)

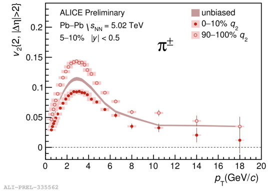


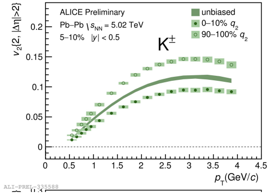
$v_2\{n\}$ (n=4,6,8) measured in various collision systems over a broad multiplicity range

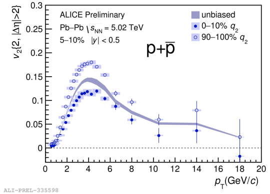
- Long-range multiparticle correlations in pp and p–Pb collisions at multiplicities $N_{ch} \geq 30$
- Good agreement of $v_2\{4\}$ between data and calculations from IP-Glasma+MUSIC+UrQMD

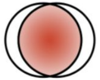
PID $v_2(p_T)$ with q_2 selection: 5–10% centrality

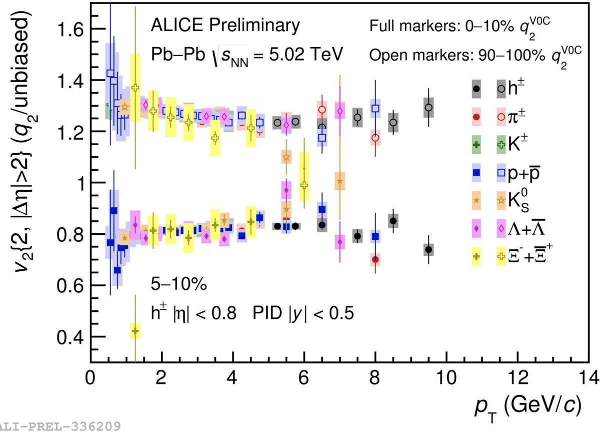


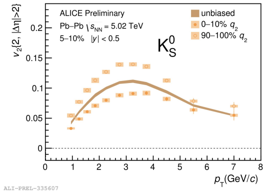


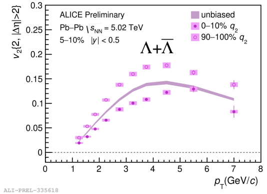


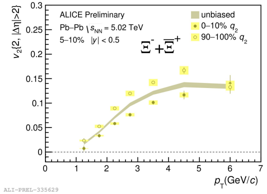






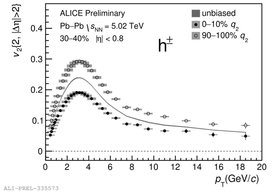


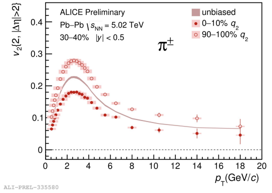


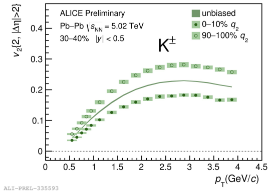


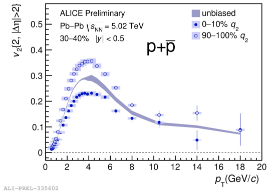
- p_T > 3 GeV/c: ratios almost flat → same source of flow fluctuations
- p_T < 3 GeV/c: weak p_T dependence → different ellipticity for q_2 classes
- Same values for inclusive and identified hadrons
    - No dependence on particle species

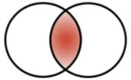
PID $v_2(p_T)$ with q_2 selection: 30–40% centrality

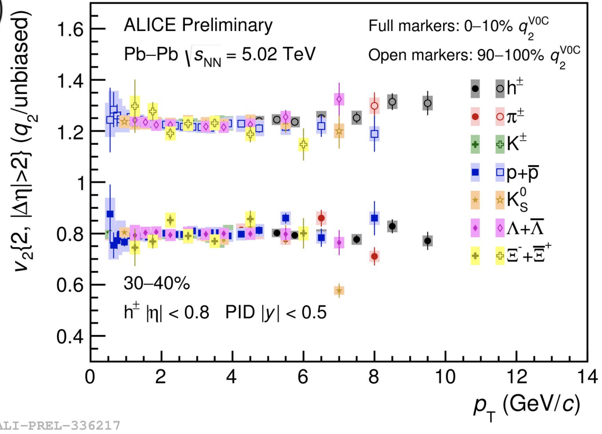


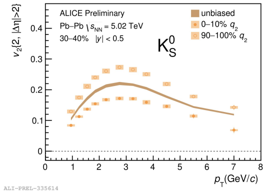


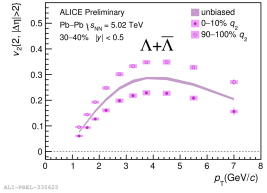


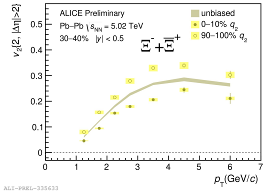






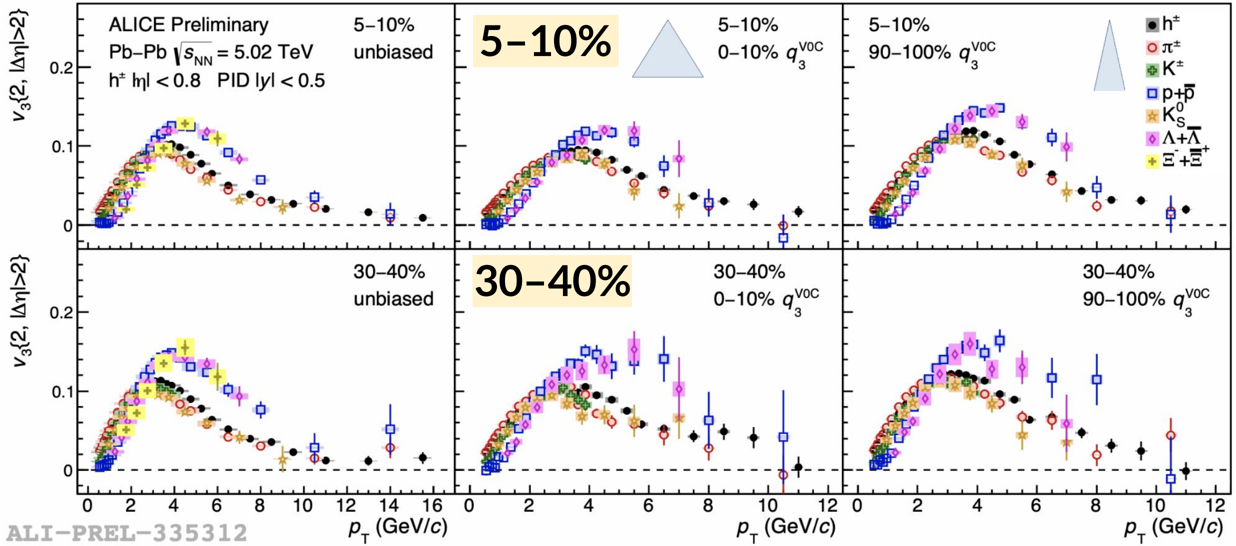


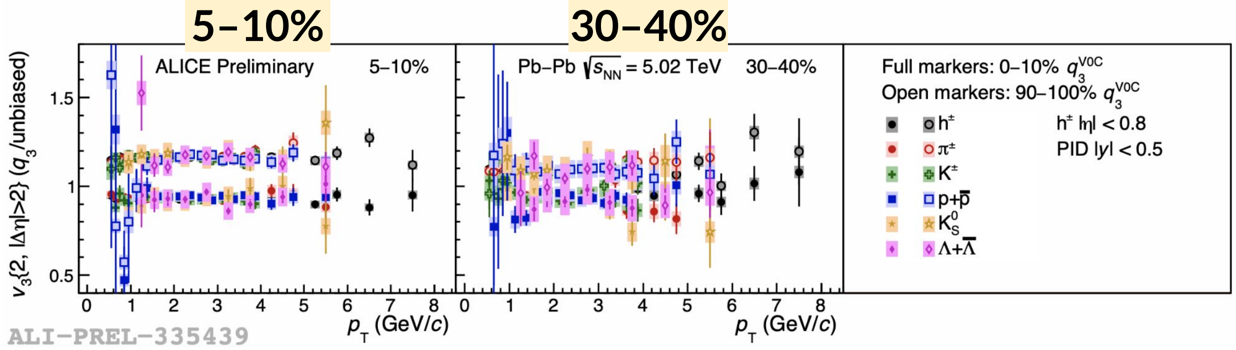




- p_T > 3 GeV/*c*: ratios almost flat → same source of flow fluctuations
- p_T < 3 GeV/*c*: almost no p_T dependence in contrast to central collisions
- Same values for inclusive and identified hadrons
- No dependence on particle species

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

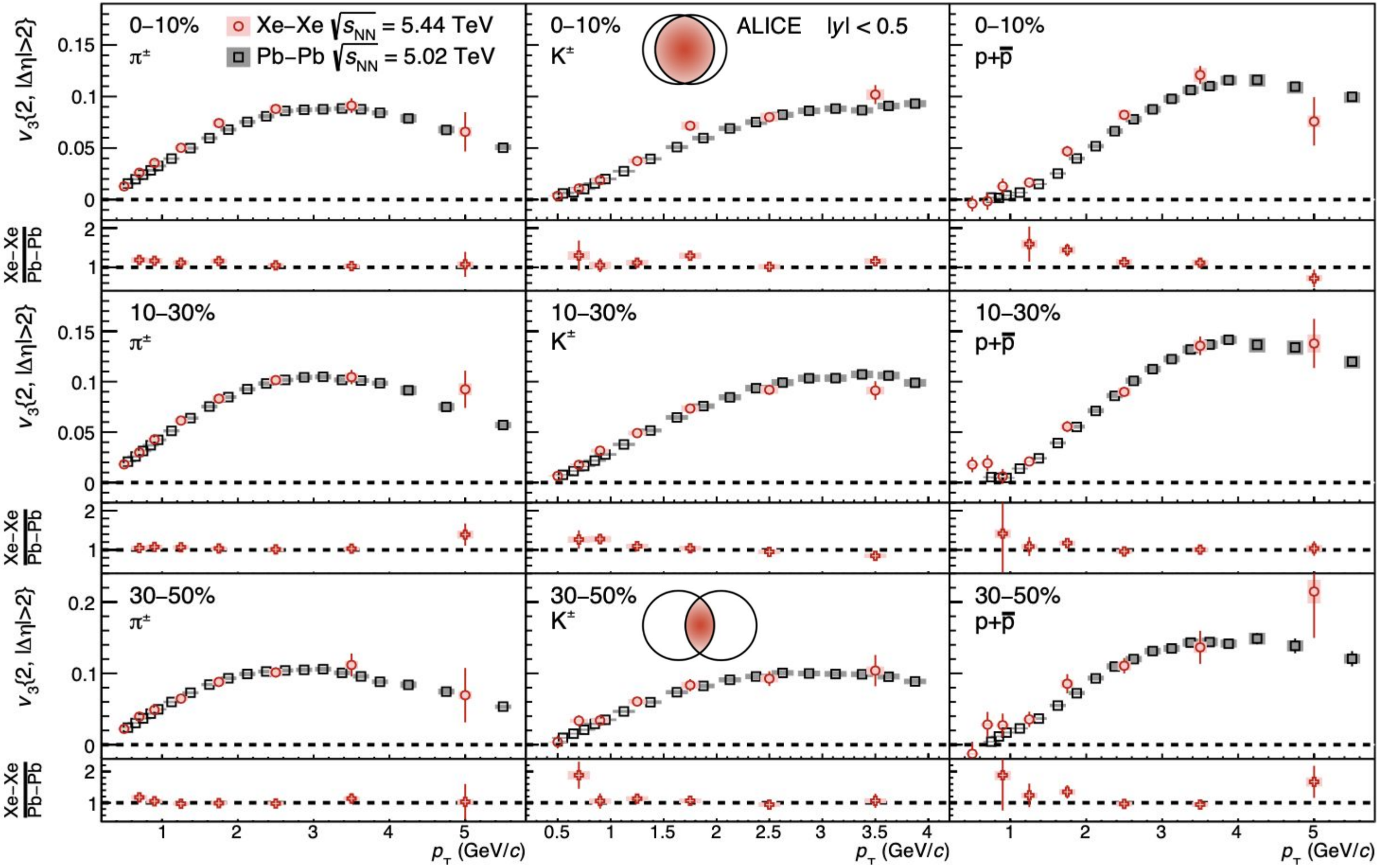




- Mass ordering at low p_T, baryon-meson grouping at intermediate p_T

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

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, JHEP (10), 152 (2021)