Elliptic flow fluctuations of charged and identified hadrons relative to the participant and spectator planes in heavy-ion collisions with ALICE

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for the ALICE collaboration

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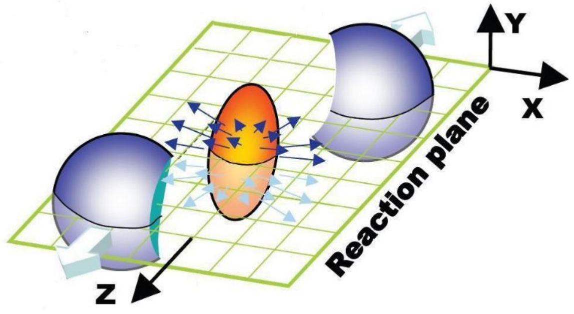
ALICE

UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

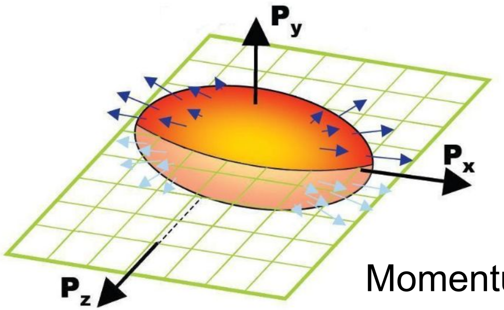
GSI

FSP ALICE
Erforschung von Universum und Materie

Collective flow in heavy-ion collisions



Initial spatial anisotropy



Momentum anisotropy

- Anisotropies of final-state particles with respect to the reaction plane Ψ_{RP} described by:

$$\frac{dN}{d\phi} = 1 + \sum_{n=1}^{\infty} v_n cos(n(\phi - \Psi_{\mathrm{RP}})$$

- Flow coefficients v_n sensitive to the initial state and QGP properties.

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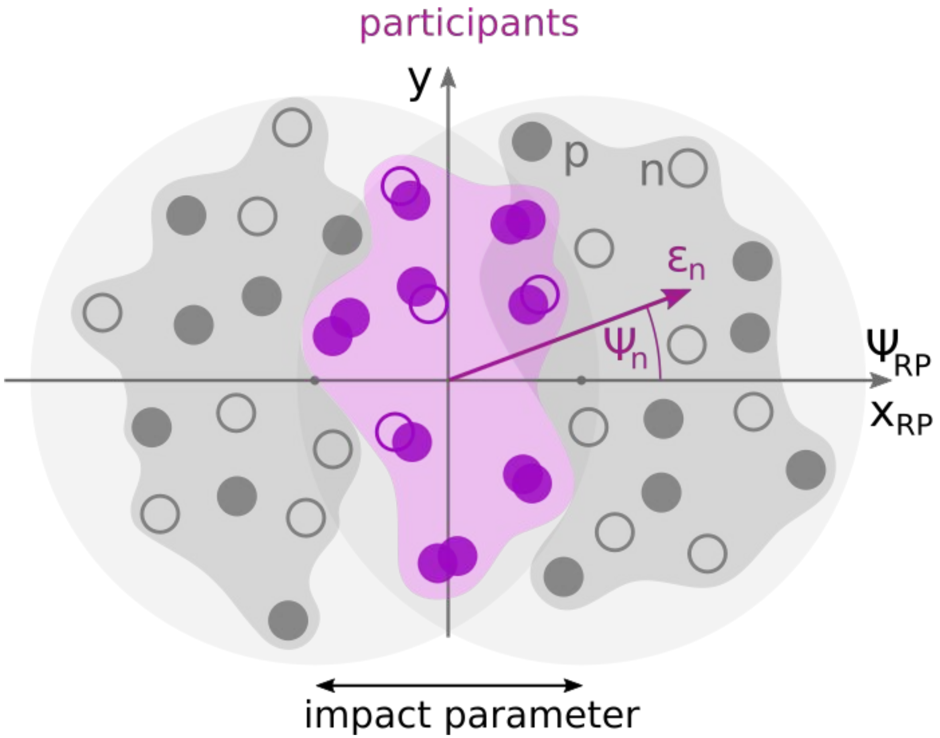
Initial state fluctuations in the participant zone



- Anisotropies of final-state particles with respect to the reaction plane Ψ_{RP} described by:

$$\frac{dN}{d\phi} = 1 + \sum_{n=1}^{\infty} v_n cos(n(\phi - \Psi_{\mathrm{RP}}))$$

- Flow coefficients v_n sensitive to the initial state and QGP properties.

- Event-by-Event fluctuations of the initial state quantified by eccentricities (ε_n) and symmetry planes (Ψ_n)

$$\epsilon_n = \frac{\int r^n e^{in\Phi} \rho(r,\Phi) r\mathrm{d}r\mathrm{d}\Phi}{\int r^n \rho(r,\Phi) r\mathrm{d}r\mathrm{d}\Phi}$$

Flow fluctuations with respect to participant plane for charged hadrons

- Elliptic flow using multi-particle cumulant:

$$c_2\{2\} = \langle\langle 2 \rangle\rangle \qquad v_2\{2\} = \sqrt{c_2\{2\}}$$

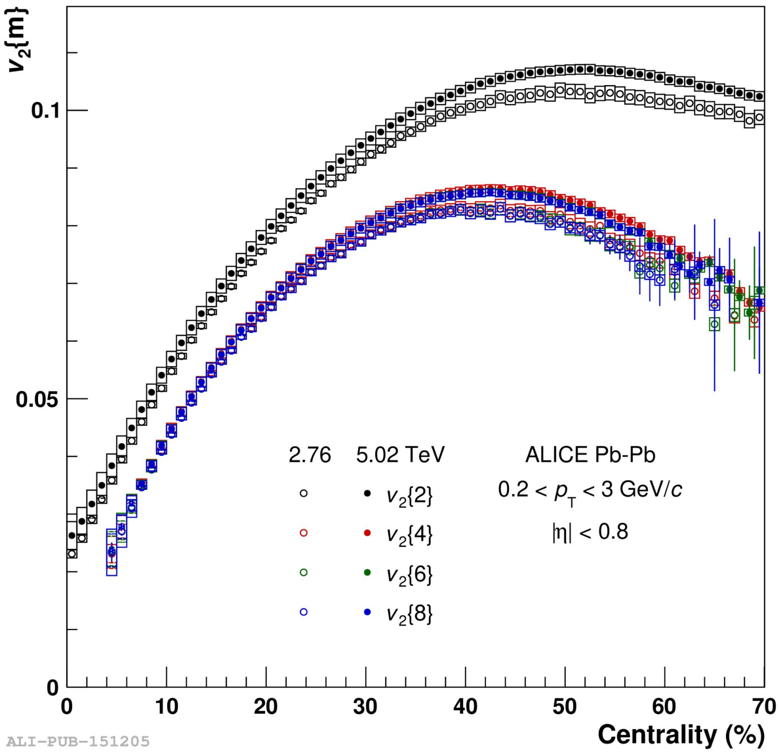
$$c_2\{4\} = \langle\langle 4 \rangle\rangle - 2\langle\langle 2 \rangle\rangle^2 \qquad v_2\{4\} = \sqrt[4]{-c_2\{4\}}$$

$$\langle 2 \rangle = \langle \cos(2(\phi_1 - \phi_2)) \rangle$$

$$\langle 4 \rangle = \langle \cos(2(\phi_1 + \phi_2 - \phi_3 - \phi_4)) \rangle$$

direct cumulants: A. Bilandzic, et al., PRC 83 (2011) 044913

ALICE, JHEP 07 (2018) 103



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$$\langle 2\rangle = \langle \cos(2(\phi_1 - \phi_2))\rangle$$

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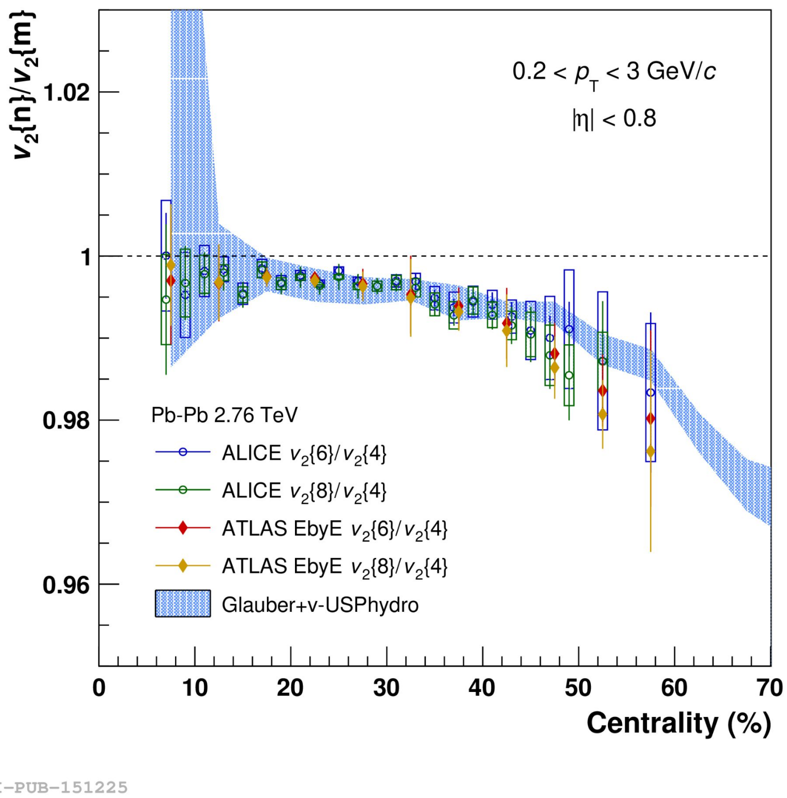
- Shape of flow fluctuations:
  - Bessel-Gaussian model (BGM)[1]:

$$v_2\{2\} > v_2\{4\} = v_2\{6\} = v_2\{8\}$$

  - Elliptic power model (EPM)[2]:

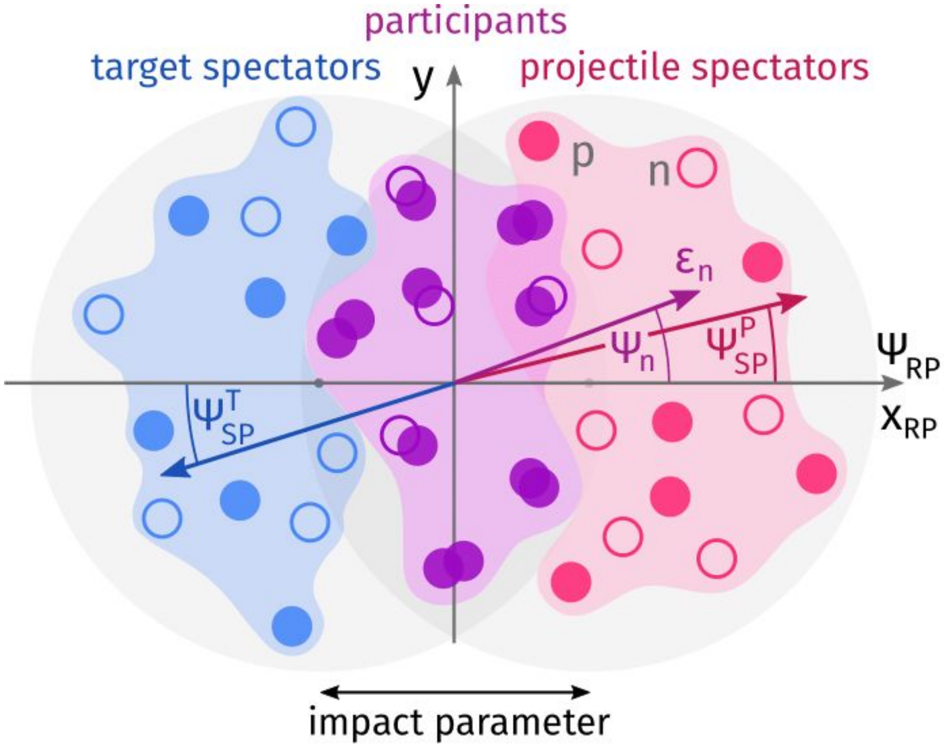
$$v_2\{2\} > v_2\{4\} > v_2\{6\} > v_2\{8\}$$

ALICE, JHEP 07 (2018) 103



[1] S. Voloshin, et al., PLB 659 (2008) 537
[2] L. Yan, et al., PRC 90 (2014) 024903

Initial state fluctuations and spectators

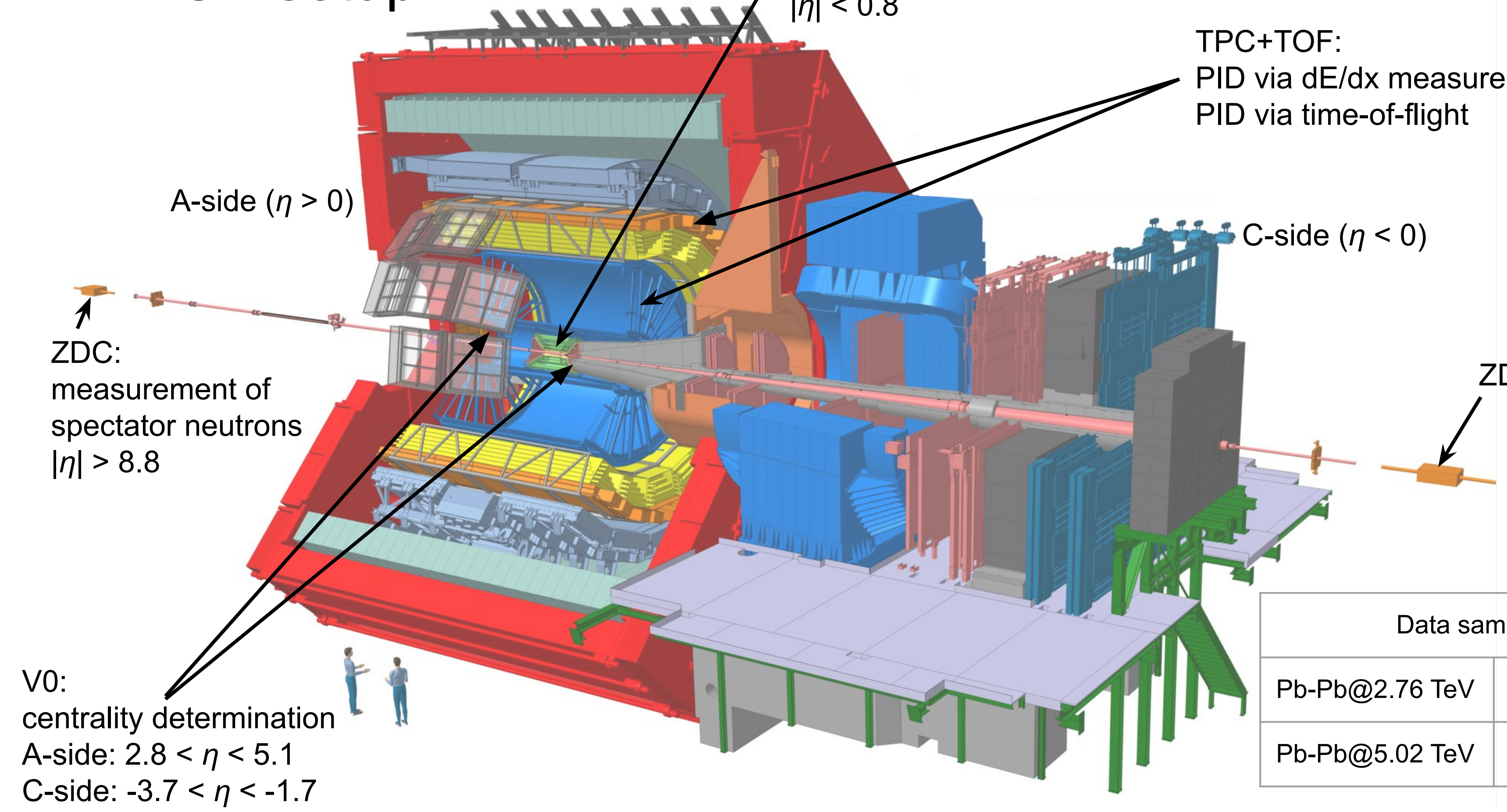


- Spectators decouple very early from participants before QGP formation
- Proxy for the collision geometry

$$\Psi^{P}_{SP} \approx \Psi^{T}_{SP} \approx \Psi_{SP} \approx \Psi_{RP}$$

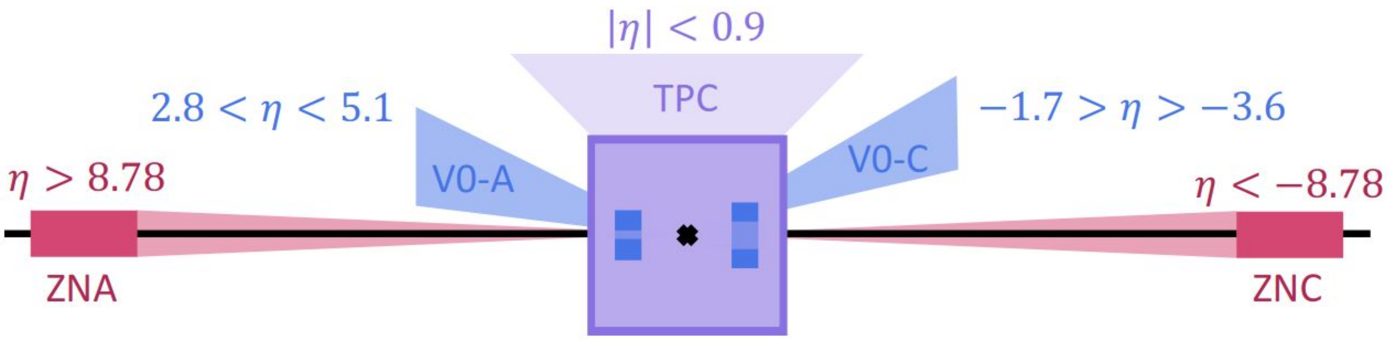
- Elliptic flow wrt to Ψ_{SP} allows to study:
  - Initial state models
  - $v_2\{2\} > v_2\{4\} \stackrel{?}{=} v_2\{\Psi_{SP}\} \stackrel{?}{=} v_2\{\Psi_{RP}\}$

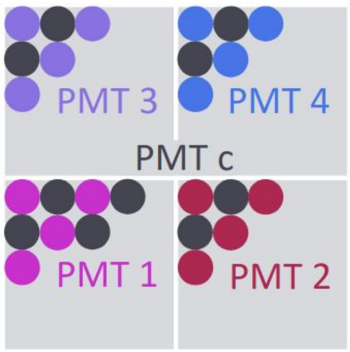
ALICE setup



Data sample	
Pb-Pb@2.76 TeV	~ 10 million
Pb-Pb@5.02 TeV	~ 245 million

Spectator measurements in ALICE: neutron ZDCs[1]

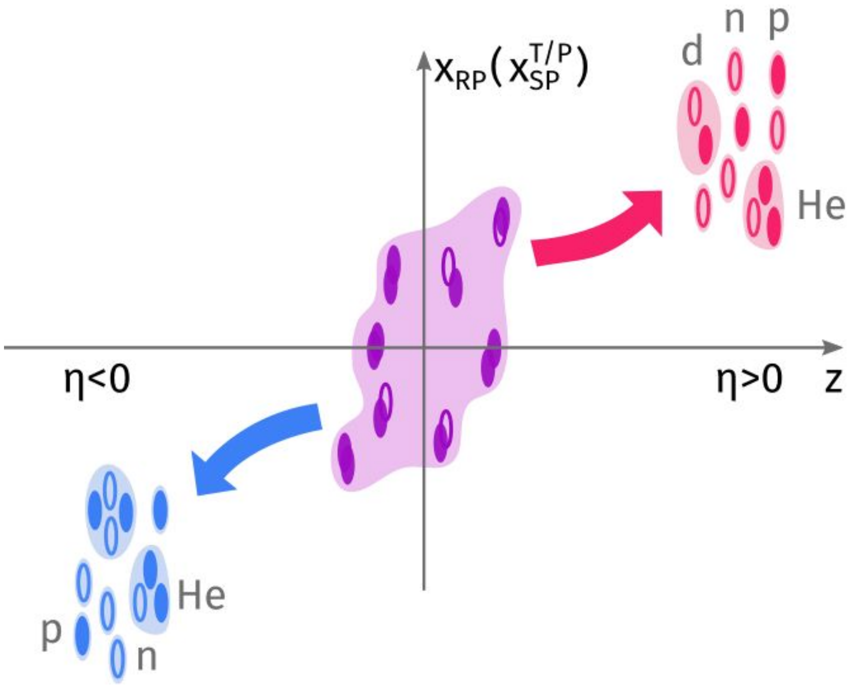




- Measurement of energy deposition by the spectator neutrons using the four ZDC channels
- Proton ZDCs are not used for the analysis
- Charged fragments with Z>1 are deflected in the LHC
  →Decorrelation between Ψ_{RP} and Ψ_{SP}

[1] *J. Phys.: Conf. Ser.* **1162** 012006

Elliptic flow with respect to the spectator plane $v_2\{\Psi_{SP}\}$



- Ψ_{SP} estimated from the outward deflection of neutron spectators (directed flow)[1]

- $v_2\{\Psi_{SP}\}$ mixed harmonic method[1,2]

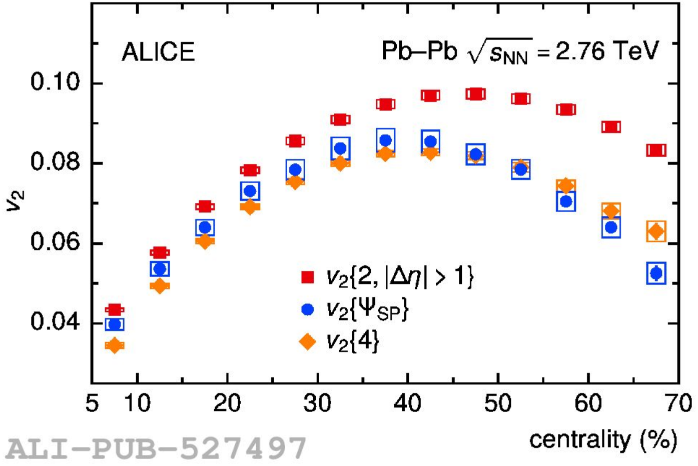
$$v_2\{\Psi_{\mathrm{SP}}\} = \frac{2}{3}\left(\frac{\langle xXX\rangle}{\langle XX\rangle} - \frac{\langle xYY\rangle}{\langle YY\rangle} + \sqrt{\left|\frac{\langle yYX\rangle\langle yXY\rangle}{\langle XX\rangle\langle YY\rangle}\right|}\right)$$

Notations: $\langle xXX\rangle = \langle q_{2,x}^{\mathrm{TPC}} Q_{1,x}^{\mathrm{ZNA}} Q_{1,x}^{\mathrm{ZNC}}\rangle$

[1] ALICE, Phys. Rev. Lett. 111, 232302
[2] ALICE, Phys. Lett. B 137453 (2022)

v_2 fluctuations wrt. spectators for charged hadrons

ALICE, Phys. Lett. B 137453 (2022)



- In a leading order: $v_2\{\Psi_{SP}\} \approx v_2\{\Psi_{RP}\} \approx v_2\{4\}$
  - Close to the Bessel-Gaussian shape of flow fluctuations

v_2 fluctuations wrt. spectators for charged hadrons

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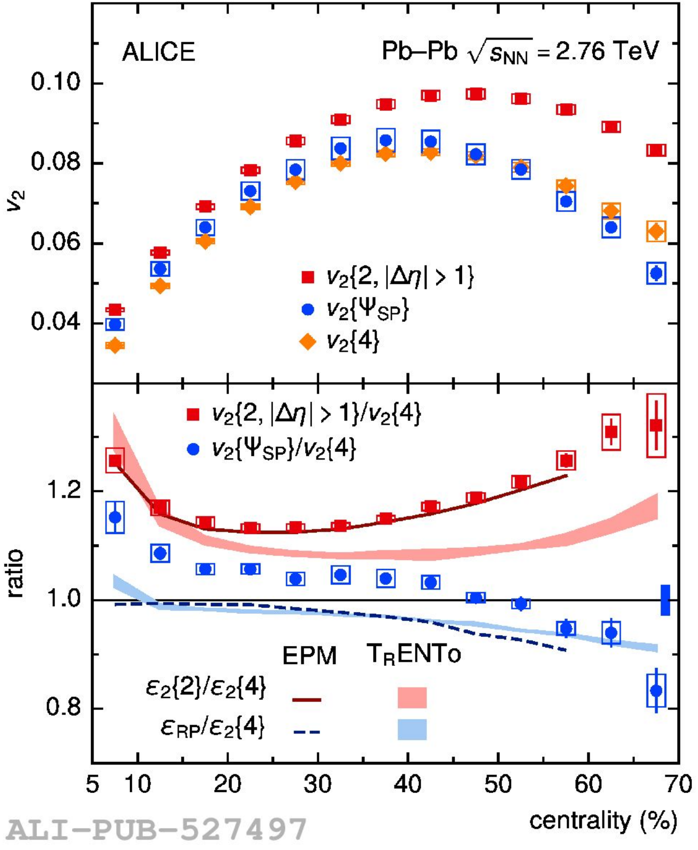
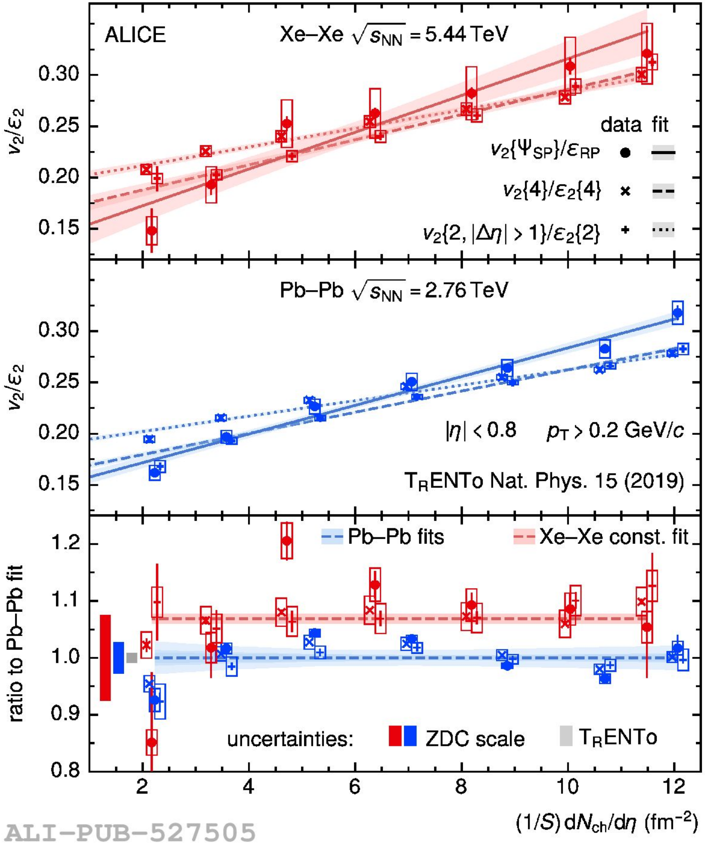


- In a leading order: $v_2\{\Psi_{SP}\} \approx v_2\{\Psi_{RP}\} \approx v_2\{4\}$
  - Close to the Bessel-Gaussian shape of flow fluctuations
- $v_2\{\Psi_{SP}\}/v_2\{4\}$ ratio for charged hadrons deviates from eccentricity ratios predicted by the initial state models:
  - Effects of hydrodynamic evolution
  - Incomplete initial state model
  - Decorrelation between spectator (Ψ_{SP}) and reaction (Ψ_{RP}) planes

System size dependence of v_2/ε_2 scaling

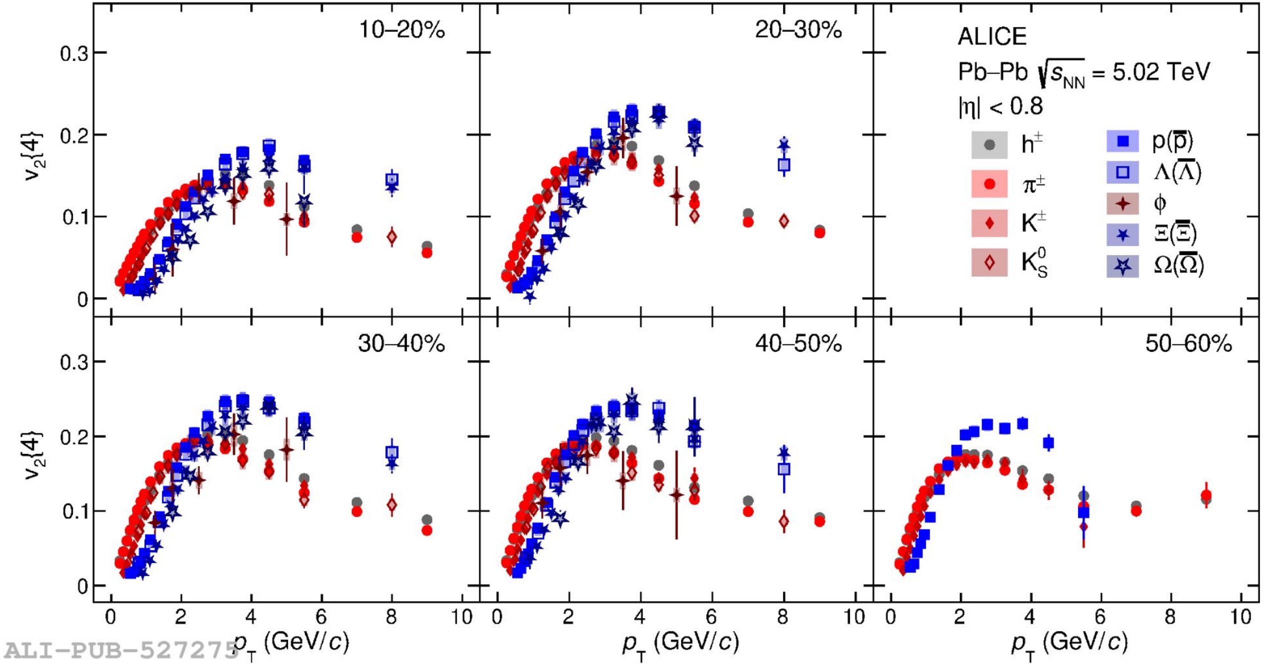
ALICE, Phys. Lett. B 137453 (2022)



- Individual fit to each v_2/ε_2 ratio for participant and spectator planes
  - Scaling well described by a linear fit
- Difference of (7.0 ± 0.9)% observed between Pb–Pb and Xe–Xe
  - Sensitive to details of the initial state and QGP viscosity

Particle-type dependence flow fluctuations with respect to the participant plane

ALICE, JHEP 05 (2023) 243

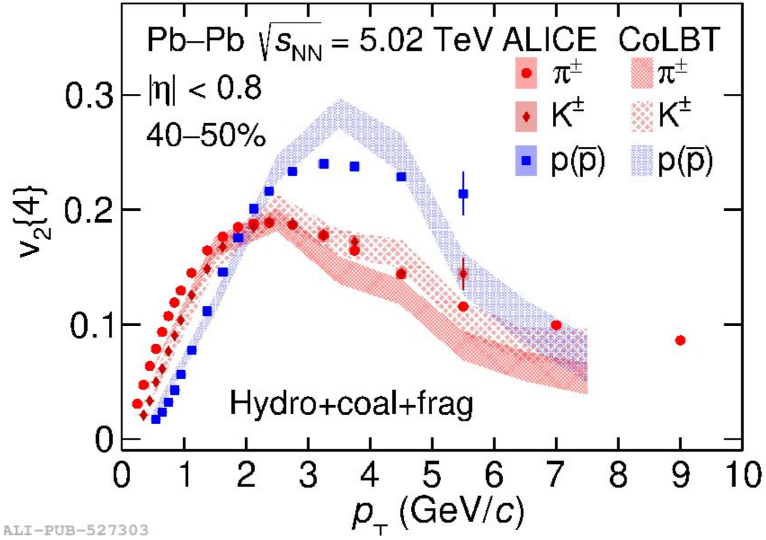


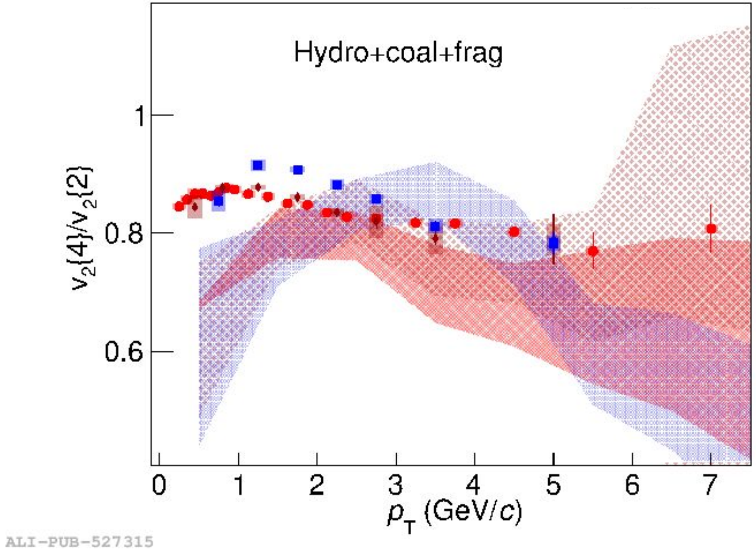
Particle-type dependence sensitive to hydrodynamical evolution of QGP and hadronization:

- Low p_T region: mass ordering
- Intermediate p_T region: baryon-meson ordering

Particle-type dependence of flow fluctuations with respect to the participant plane

ALICE, JHEP 05 (2023) 243





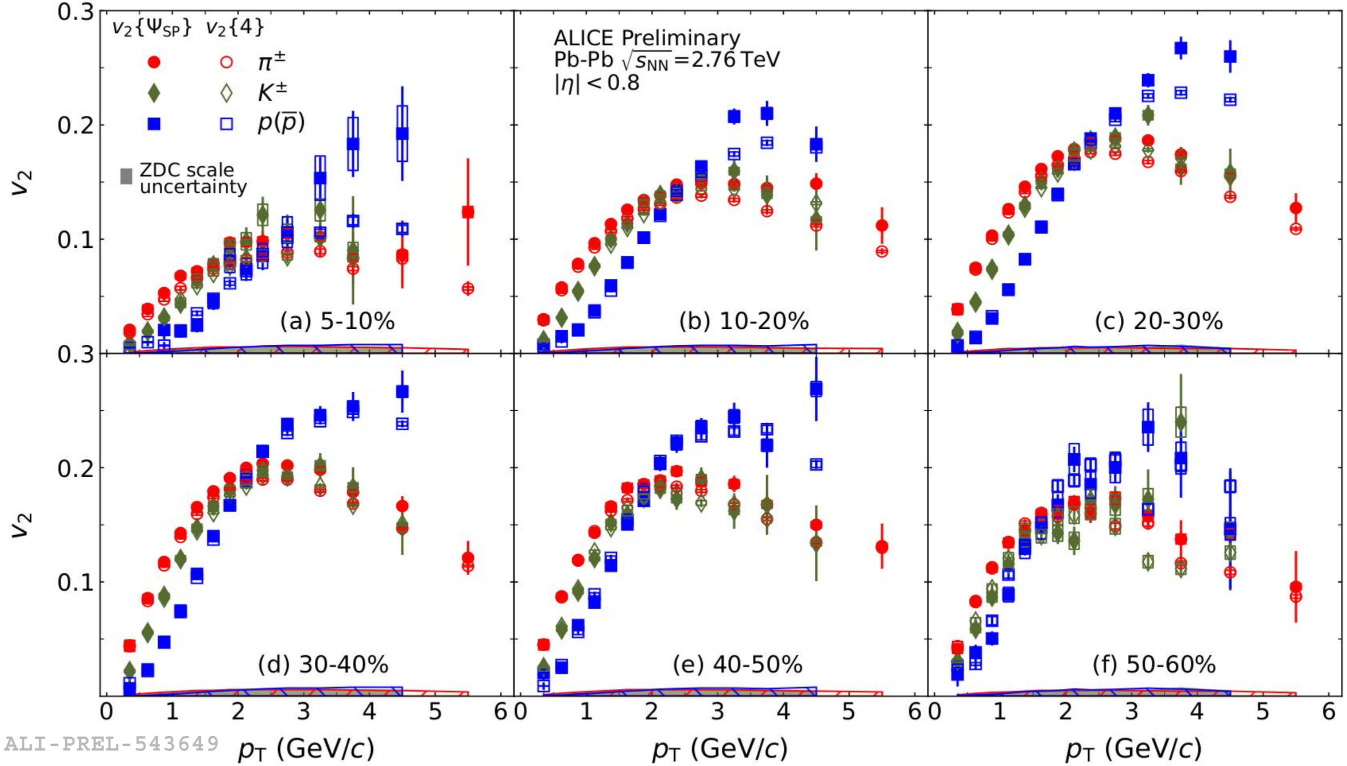
- $v_2\{4\}$ and $v_2\{4\}/v_2\{2\}$ compared with predictions of CoLBT[1] which combines:
  - Hydrodynamic expansion of QGP
  - Hadron production via quark coalescence and fragmentation

- Model comparison shows the importance of final-state effects for both $v_2\{4\}$ and $v_2\{4\}/v_2\{2\}$

[1] W. Chen, et al., Phys. Lett. B 810 (2020) 135783

Particle-type dependence of elliptic flow with respect to spectator plane

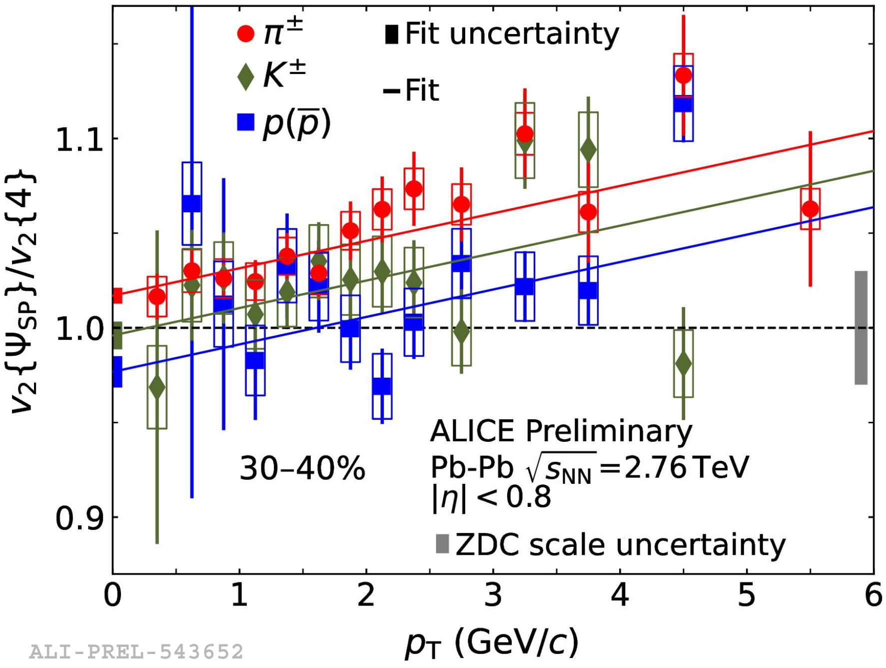
new



- Elliptic flow wrt to spectator plane $v_2\{\Psi_{SP}\}$ exhibits similar features as $v_2\{4\}$
- In a leading order:
  $v_2\{4\} \approx v_2\{\Psi_{SP}\}$ for all particle types similar as for charged hadrons

Particle-type dependence of elliptic flow with respect to spectator plane

new

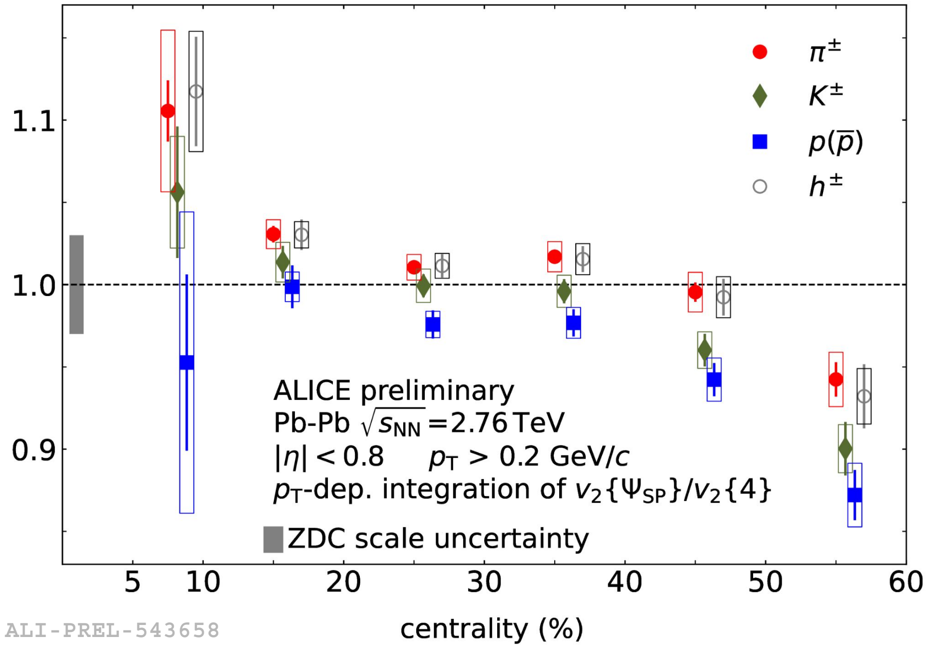


Fit procedure used to extract particle-type dependence as a function of centrality:

- Linear fit ($p_0 + p_1 \cdot p_T$) in the range of p_T = (0.2, 3.0) GeV/c
- Slope parameter (p_1) is fixed by the linear fit to the charged hadrons (reduces stat. uncertainties)
- p_0 parameter is the intercept of $v_2\{\Psi_{SP}\}/v_2\{4\}$ at p_T = 0
- Extracted for all centrality classes

Intercept of $v_2\{\Psi_{SP}\}/v_2\{4\}$ at $p_T = 0$ as function of centrality

new



- Intercept show similar shape as a function of centrality for all particle species:
  → Initial state fluctuation
- Particle type dependent splitting:
  → Hydrodynamic evolution
  → Hadronization

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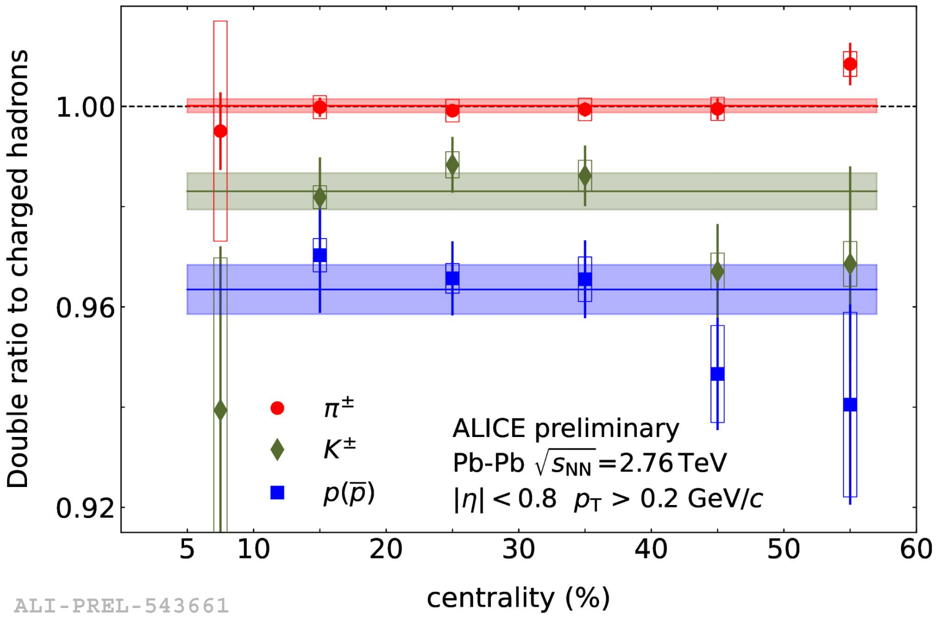
Double ratio of intercept as function of centrality

new



Splitting quantified by double ratio to that of charged hadrons via a constant fit vs p_T:

- Particle-type splitting found to be 3.6% (1.6%) between pions and protons (kaons)
- Initial state effects should cancel in the double ratio

Non-zero contribution from the QGP evolution & hadronization to the measured $v_2\{\Psi_{SP}\}/v_2\{4\}$ double ratio. Important for quantifying effects of the initial state when comparing eccentricity and v_2 ratios

Summary

Collective flow measurements with respect to the spectator plane provide new insights on initial stage models and set new constraints on QGP evolution and hadronization processes!

- Charged hadrons:
  - Deviations of measurements to model prediction may indicate an incomplete description of initial state fluctuations
  - Difference of v_2/ε_2 between Pb–Pb and Xe–Xe sensitive to details of the initial state and QGP viscosity

- Identified hadrons:
  - Particle-type dependence sensitive to QGP evolution and final state effects
    as shown by comparison of $v_2\{2\}/v_2\{4\}$ with model (CoLBT)

  - Observation of a particle-type dependent splitting in $v_2\{\Psi_{SP}\}/v_2\{4\}$ suggest a non-zero contribution from QGP evolution & hadronization processes and is important for understanding deviation between eccentricity and flow ratios

new