Anisotropic flow fluctuations relative to participant and spectator planes in heavy-ion collisions with ALICE

Lukas Kreis (Universität Heidelberg)
for the ALICE collaboration

6.4.2022

Quark Matter 2022 Kraków

new: ALICE-PUBLIC-2022-008

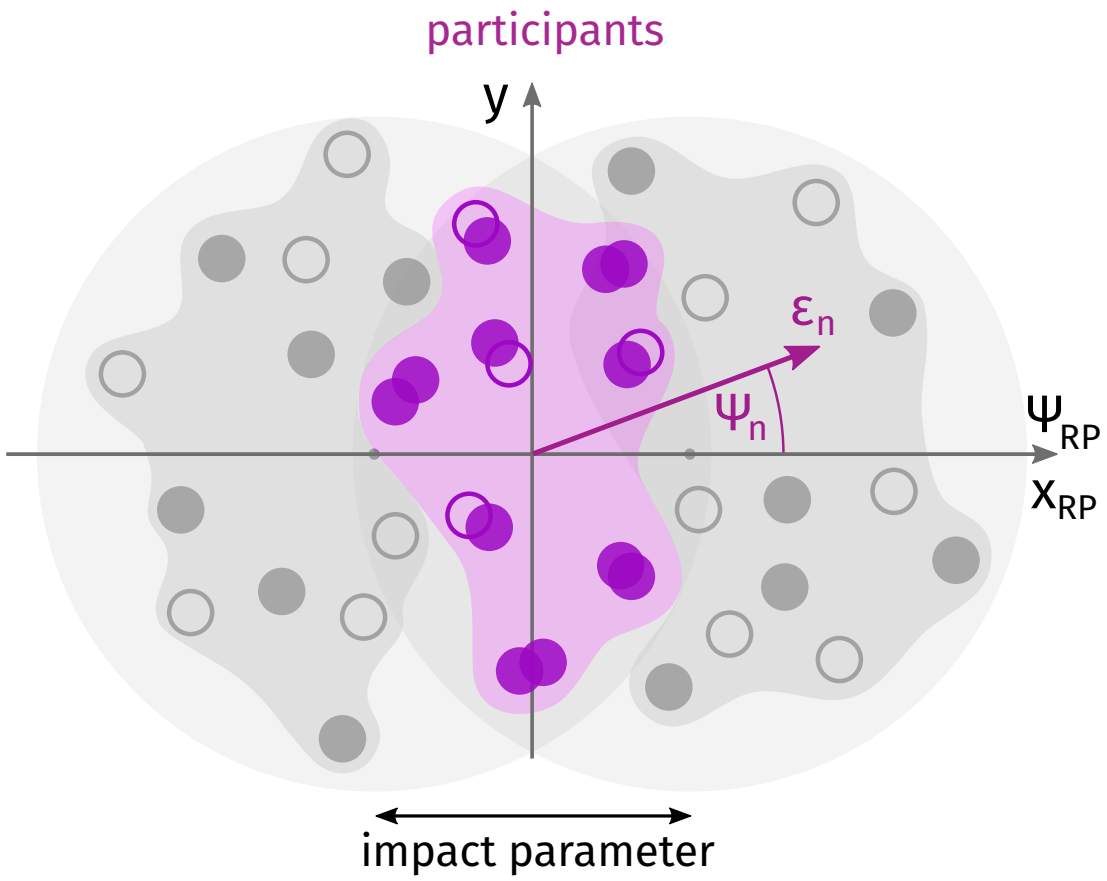
UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

GSI

FSP ALICE
Erforschung von Universum und Materie

ALICE

Initial state fluctuations in the participant region



Knowledge of initial state important to extract QGP properties based on final state observables

Event-by-event fluctuations quantified by participant eccentricities ε_n and symmetry planes Ψ_n

Detailed studies of QGP need experimental constraints of the initial state

Studying participant plane fluctuations

JHEP 07 (2018) 103

Elliptic flow using multi-particle cumulants

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

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

$\langle\langle m \rangle\rangle$: particle and event averaged m-particle correlation

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

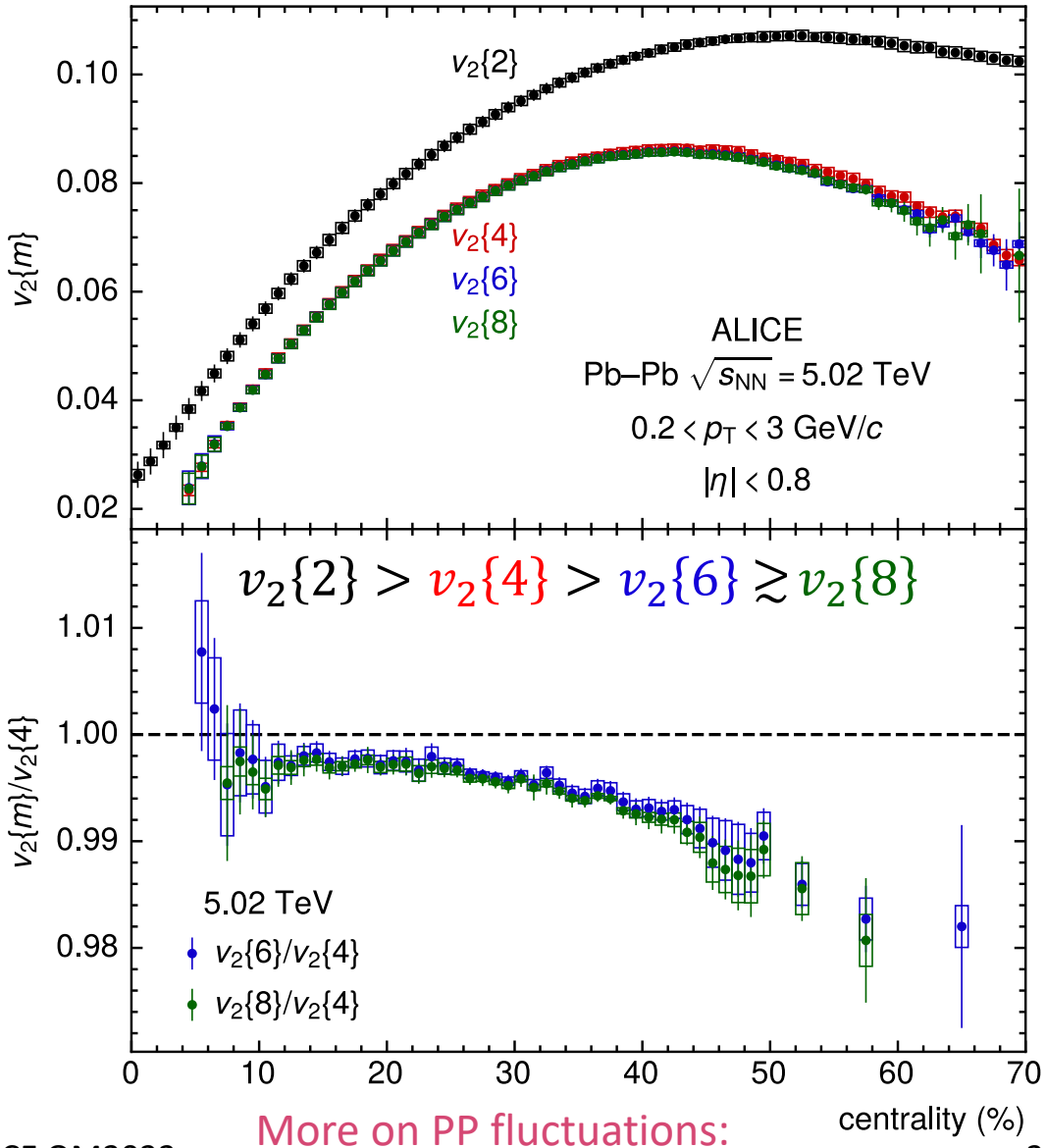
Shape of elliptic flow fluctuations

- Bessel-Gaussian model (BGM)[1]

$$v_2\{2\} \neq v_2\{4\} = v_2\{2m\} = v_2\{\Psi_{\mathrm{RP}}\}$$

- Elliptic-Power model (EPM)[2]

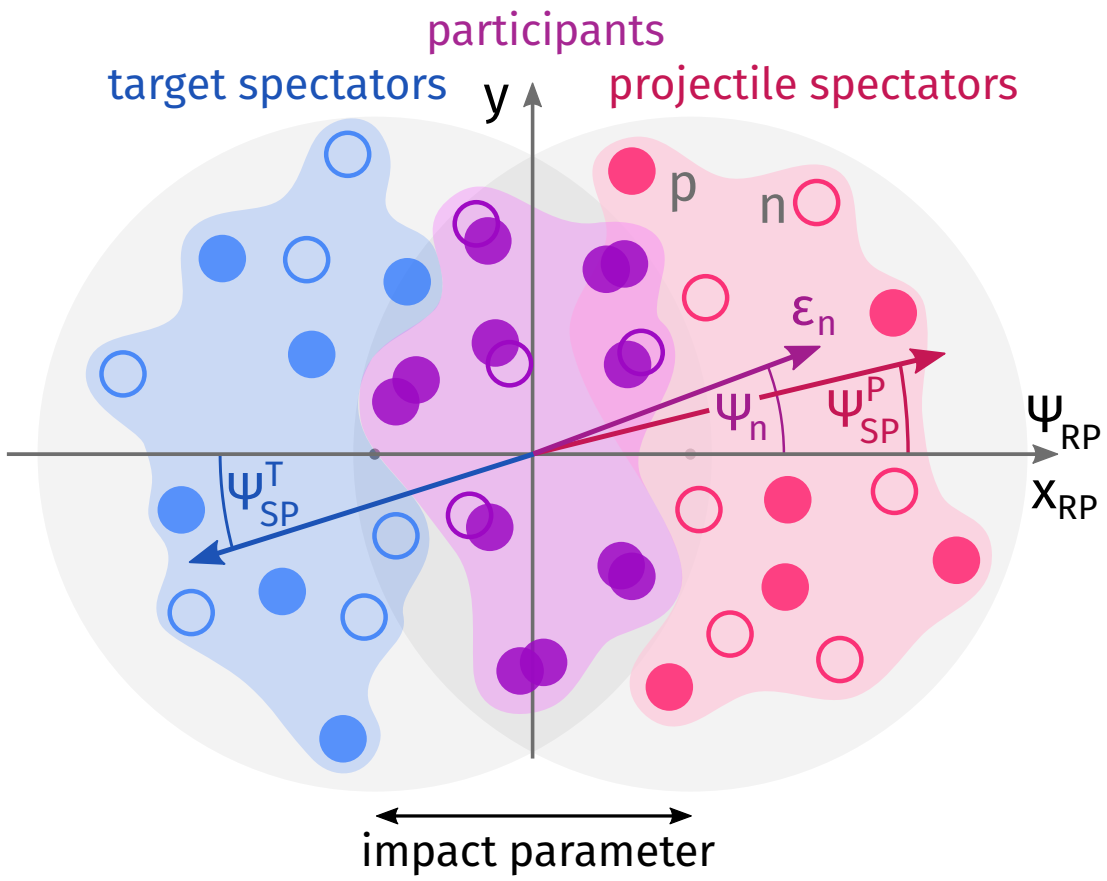
$$v_2\{2\} > v_2\{4\} > v_2\{2m\} > v_2\{\Psi_{\mathrm{RP}}\}$$



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

More on PP fluctuations:
V. Vislavicius T07 07.04@12:15

Spectators and initial state fluctuations



Spectators quickly decouple from participants before QGP formation

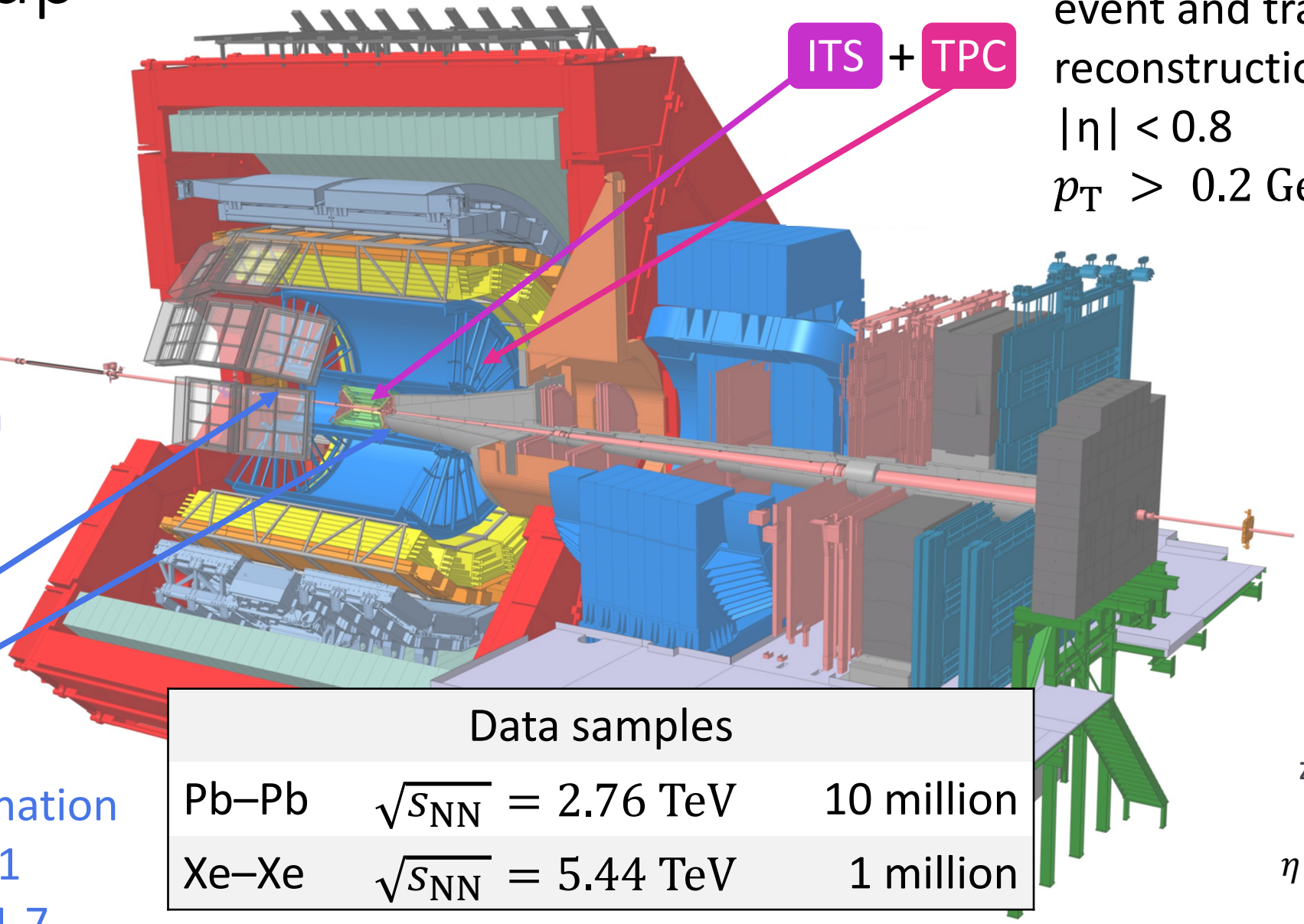
In case of small fluctuations of spectator planes

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

Elliptic flow relative to Ψ_{SP} allows to study:

- $v_2\{2\} > v_2\{4\} \overset{?}{\approx} v_2\{\Psi_{\mathrm{SP}}\} \overset{?}{\approx} v_2\{\Psi_{\mathrm{RP}}\}$
- Initial state models

ALICE setup

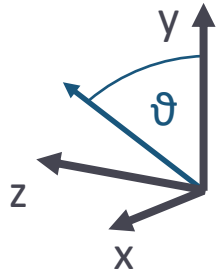


event and track reconstruction
$|\eta| < 0.8$
$p_T > 0.2\ \mathrm{GeV}/c$

spectator neutron measurement
$|\eta| > 8.8$

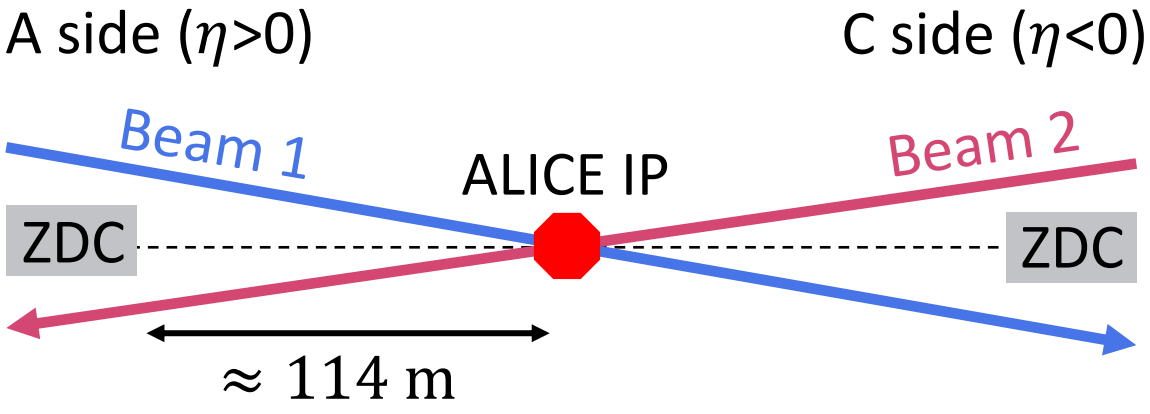
centrality determination
A side: $2.8 < \eta < 5.1$
C side: $-3.7 < \eta < -1.7$

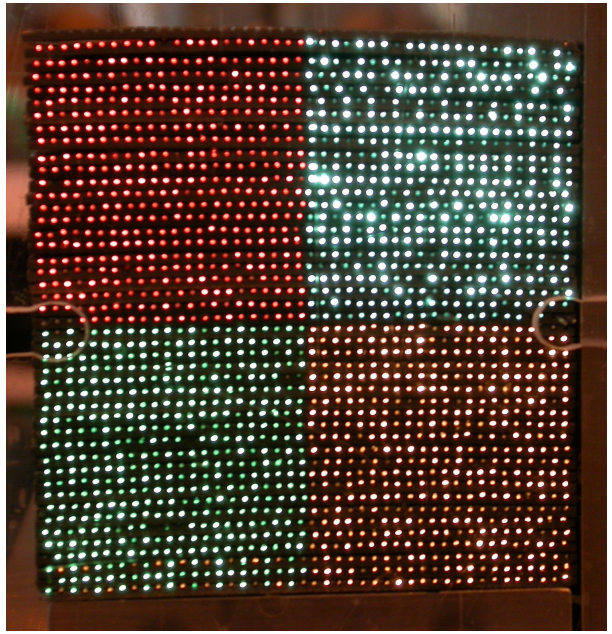
Data samples		
Pb–Pb	$\sqrt{s_{NN}} = 2.76$ TeV	10 million
Xe–Xe	$\sqrt{s_{NN}} = 5.44$ TeV	1 million



$$\eta = -\ln\tan\frac{\vartheta}{2}$$

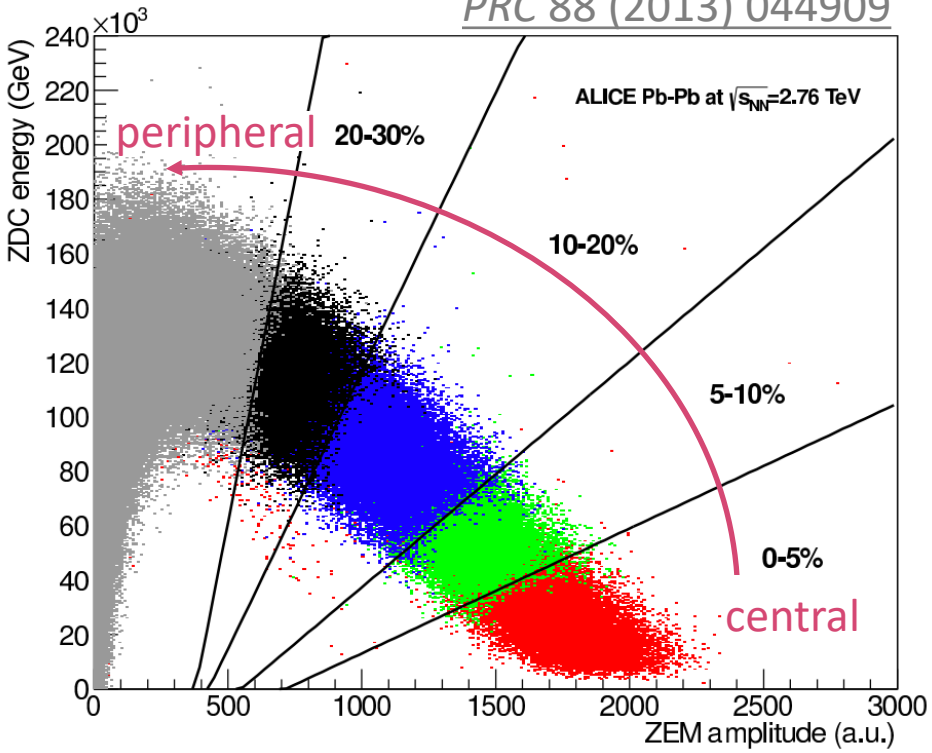
Spectator measurement with the neutron ZDC





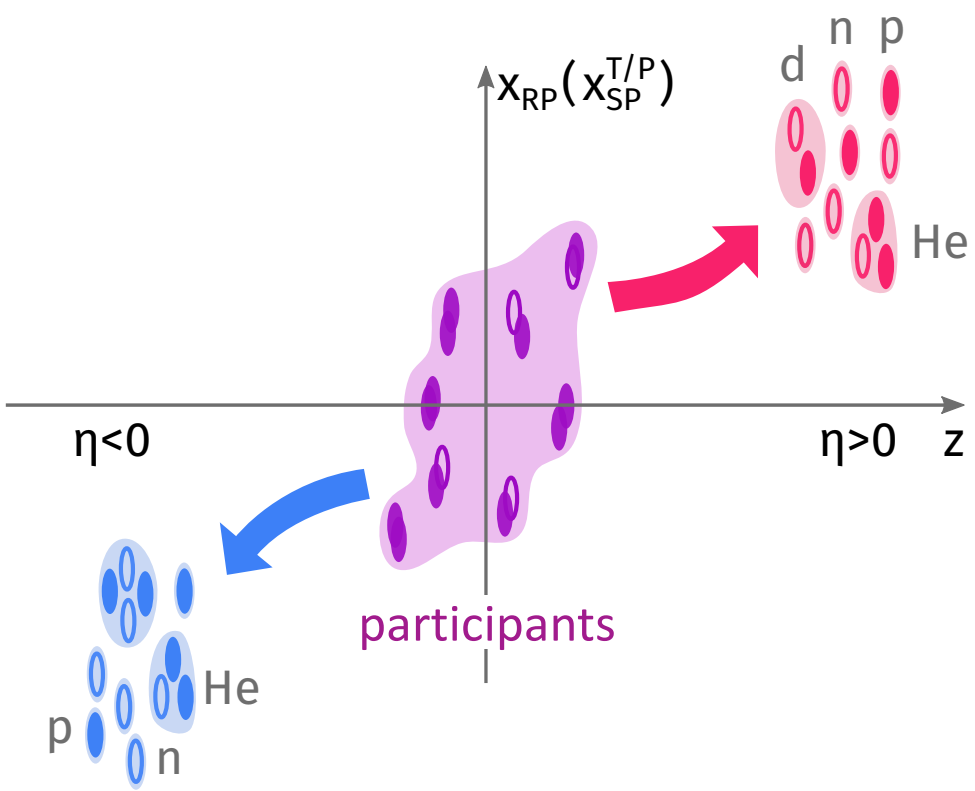
Picture of the front face of ZDC

PRC 88 (2013) 044909



Transverse energy distribution of neutrons reconstructed on each side event-by-event using the 4 ZDC Channels.

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



Ψ_{SP} estimated from outward deflection of neutron spectators (directed flow) *PRL* 111 (2013) 232302

Decorrelated from plane of all spectators & Ψ_{RP} because nuclear recoils release

- Neutrons
- Protons
- Nuclear fragments (deflected in LHC)

Mixed harmonic[1] observable $v_2\{\Psi_{SP}\} = \frac{1}{3}\left(\frac{\langle x_2^T x_1^C x_1^A\rangle}{\langle x_1^C x_1^A\rangle} + \frac{\langle x_2^T y_1^C y_1^A\rangle}{\langle y_1^C y_1^A\rangle} + \sqrt{\left|\frac{\langle y_2^T y_1^C x_1^A\rangle\langle y_2^T x_1^C y_1^A\rangle}{\langle x_1^C x_1^A\rangle\langle y_1^C y_1^A\rangle}\right|}\,\mathrm{sgn}(\dots)\right)$

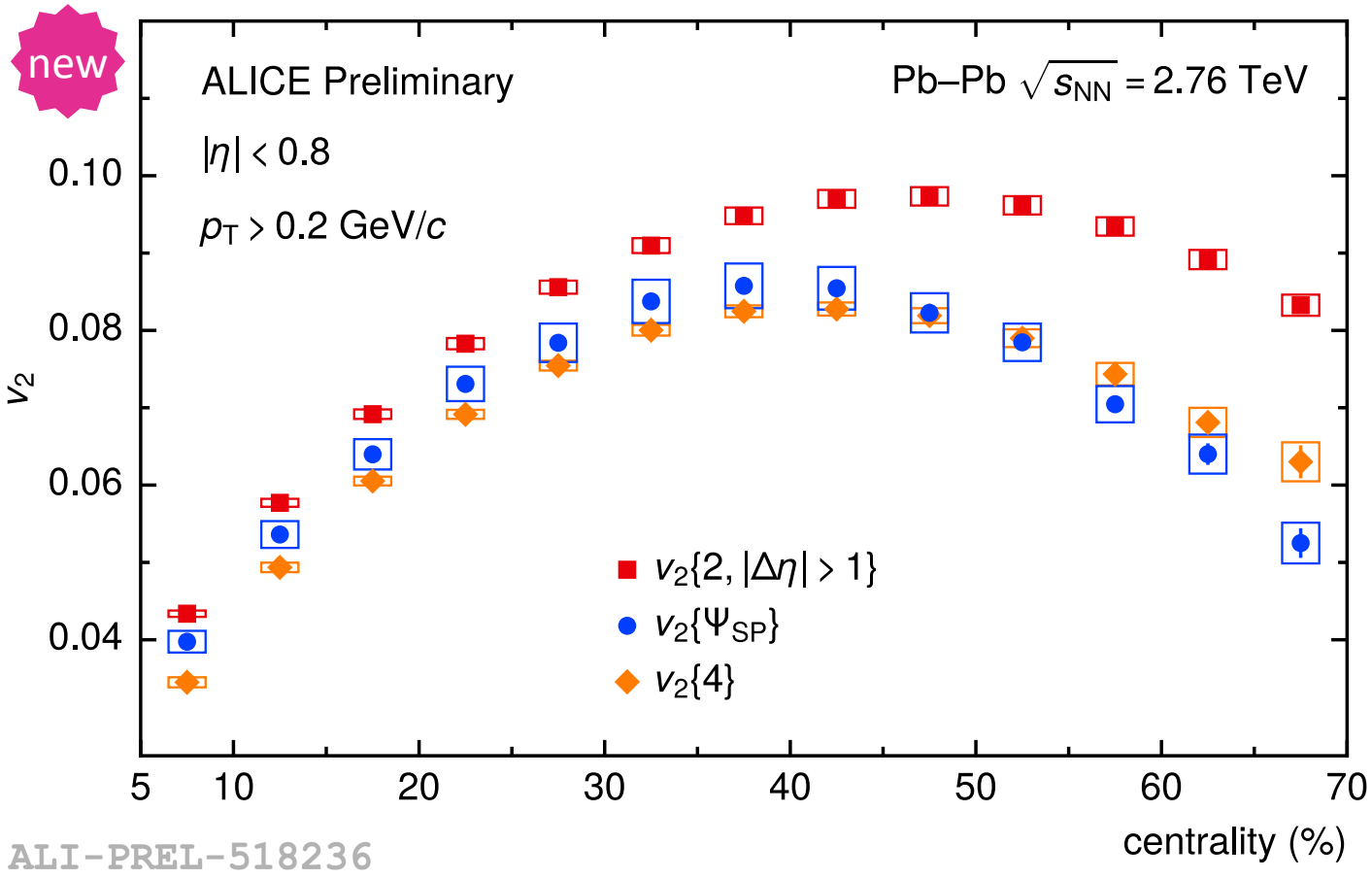
$q_n = x_n + iy_n = \sum w_j \exp in\varphi_j$

$\langle\dots\rangle$ = event average

$T \coloneqq$ tracks ($|\eta| < 0.8$) $C \coloneqq$ ZDC ($\eta < -8.8$) $A \coloneqq$ ZDC ($\eta > 8.8$)

[1] *Selyuzhenkov et al. PRC* 77 (2008) 034904

Elliptic flow: participant vs. spectator plane



$$v_2\{2, |\Delta\eta| > 1\} = \sqrt{\langle\langle \cos 2(\varphi_1 - \varphi_2)\rangle\rangle}$$

$$v_2\{\Psi_{SP}\} = \langle\langle \cos 2(\varphi - \Psi_{SP})\rangle\rangle$$

$$v_2\{4\} = \left[2\langle\langle \cos 2(\varphi_1 - \varphi_2)\rangle\rangle^2 - \langle\langle \cos 2(\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4)\rangle\rangle\right]^{\frac{1}{4}}$$

Close to Bessel-Gaussian Model (BGM) $v_2\{2\} \neq v_2\{4\} = v_2\{\Psi_{SP}\}$

But splitting between $v_2\{\Psi_{SP}\}$ and $v_2\{4\}$ observed

ALICE-PUBLIC-2022-008

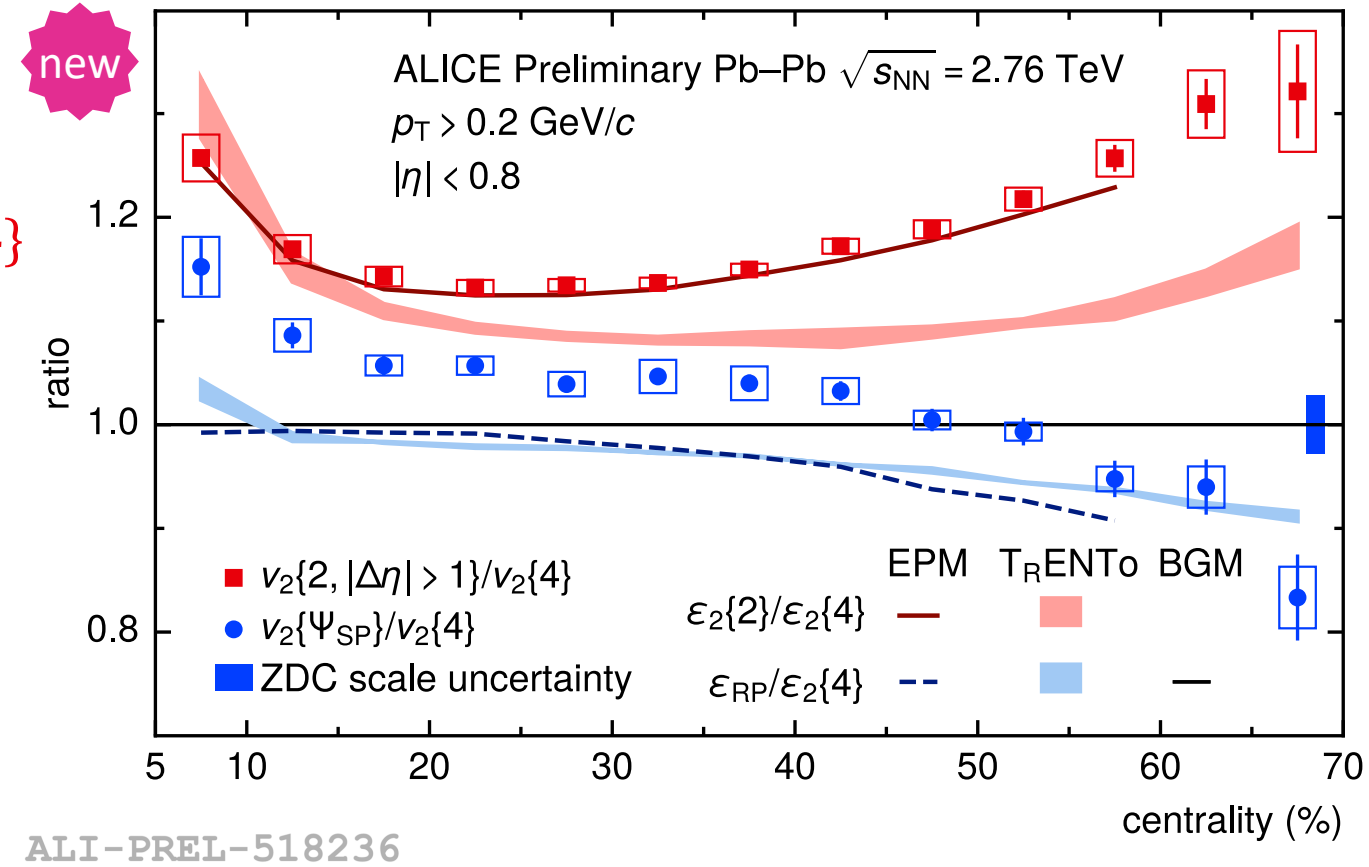
Participant vs. spectator plane fluctuations

ALICE-PUBLIC-2022-008

new

$v_2\{2, |\Delta\eta| > 1\}/v_2\{4\}$

$v_2\{\Psi_{SP}\}/v_2\{4\}$



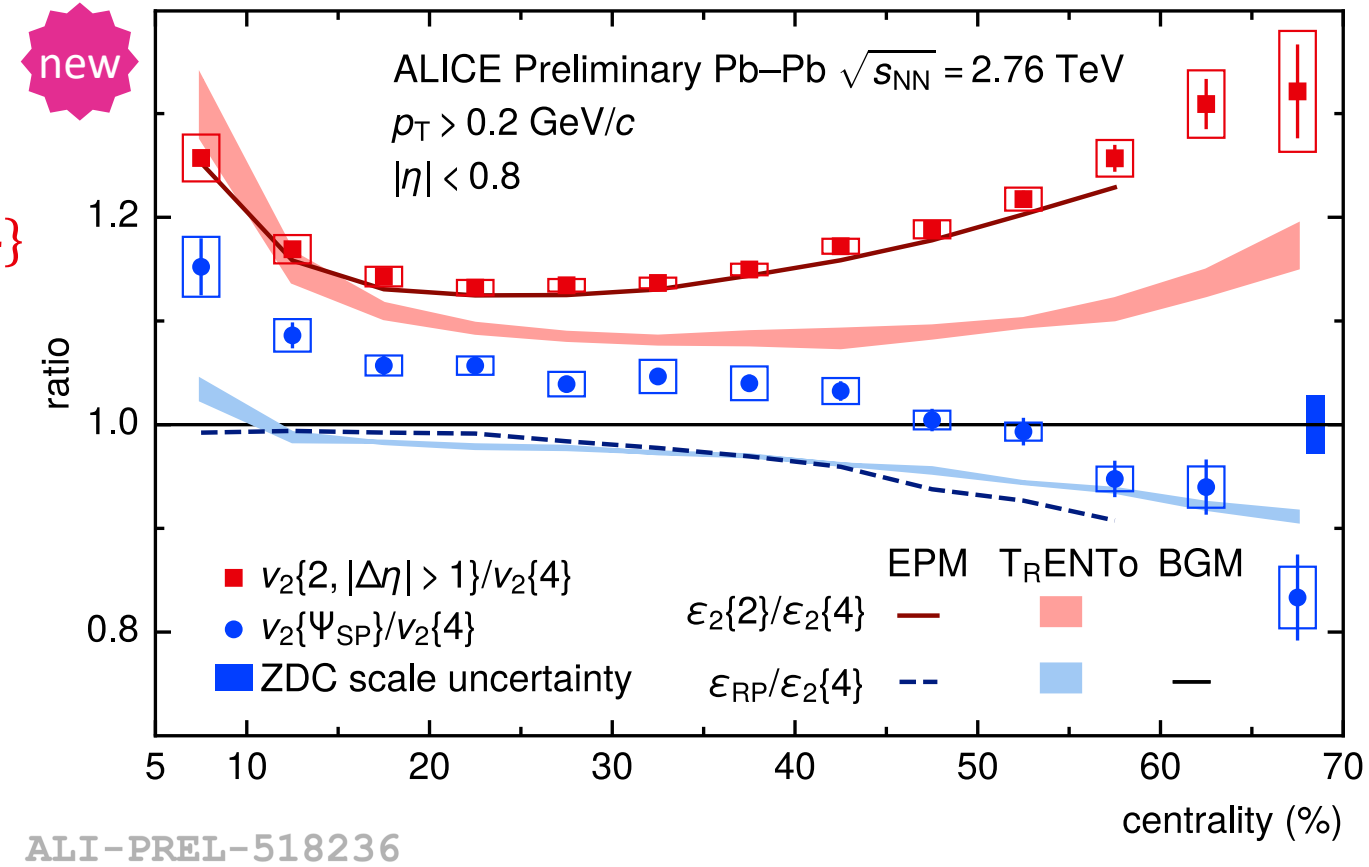
Participant vs. spectator plane fluctuations

ALICE-PUBLIC-2022-008

new

$v_2\{2, |\Delta\eta| > 1\}/v_2\{4\}$

$v_2\{\Psi_{SP}\}/v_2\{4\}$



Central: ratio > 1

- Fewer spectator neutrons
- Correlation of Ψ_{SP} & Ψ_2
- Correlated local particle production reducing $v_2\{4\}$

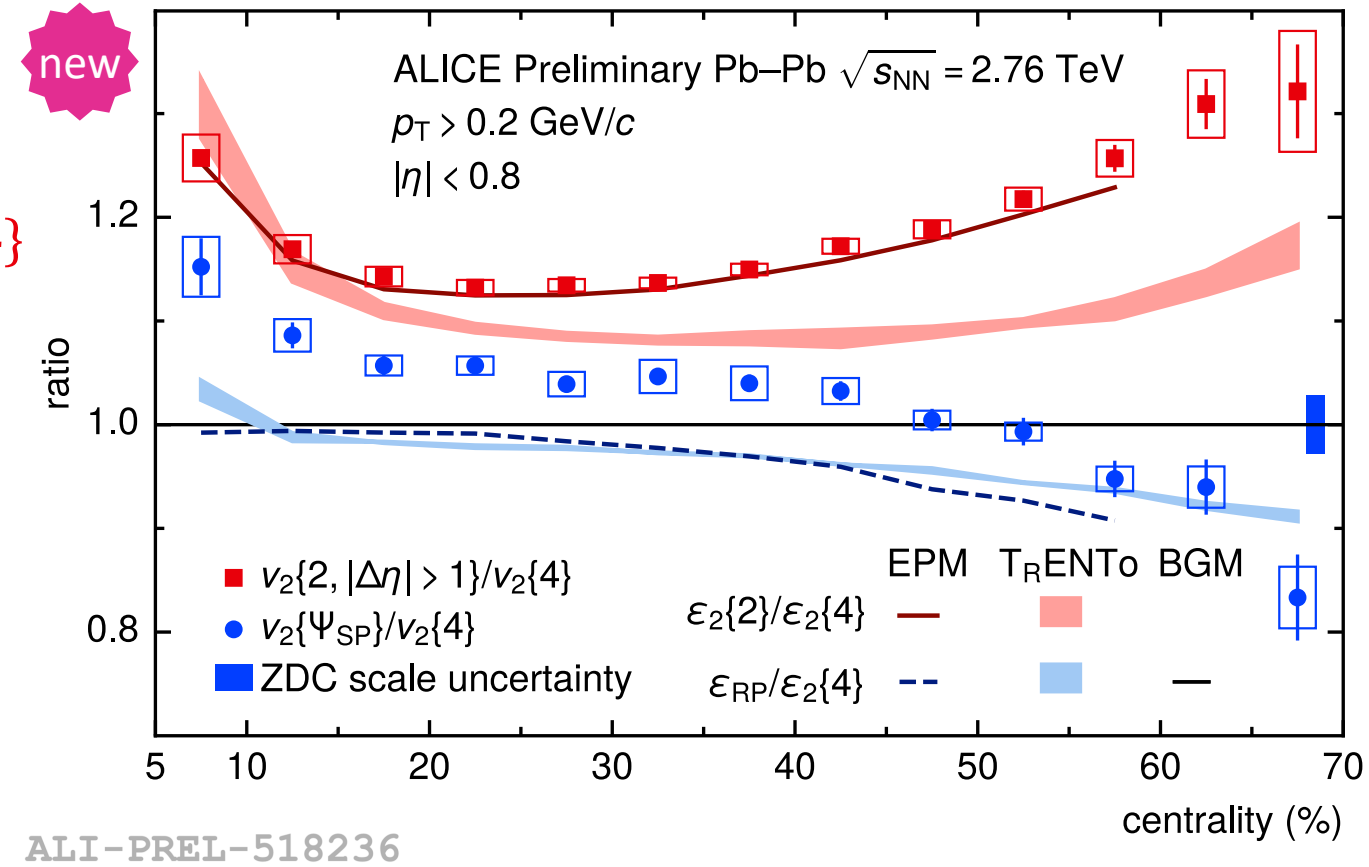
Participant vs. spectator plane fluctuations

ALICE-PUBLIC-2022-008

new

$v_2\{2, |\Delta\eta| > 1\}/v_2\{4\}$

$v_2\{\Psi_{SP}\}/v_2\{4\}$



Central: ratio > 1

- Fewer spectator neutrons
- Correlation of Ψ_{SP} & Ψ_2
- Correlated local particle production reducing $v_2\{4\}$

Midcentral: ratio ≥ 1

- $\Psi_{SP} \neq \Psi_{RP}$: non-trivial decorrelaton due to loss of fragments and protons

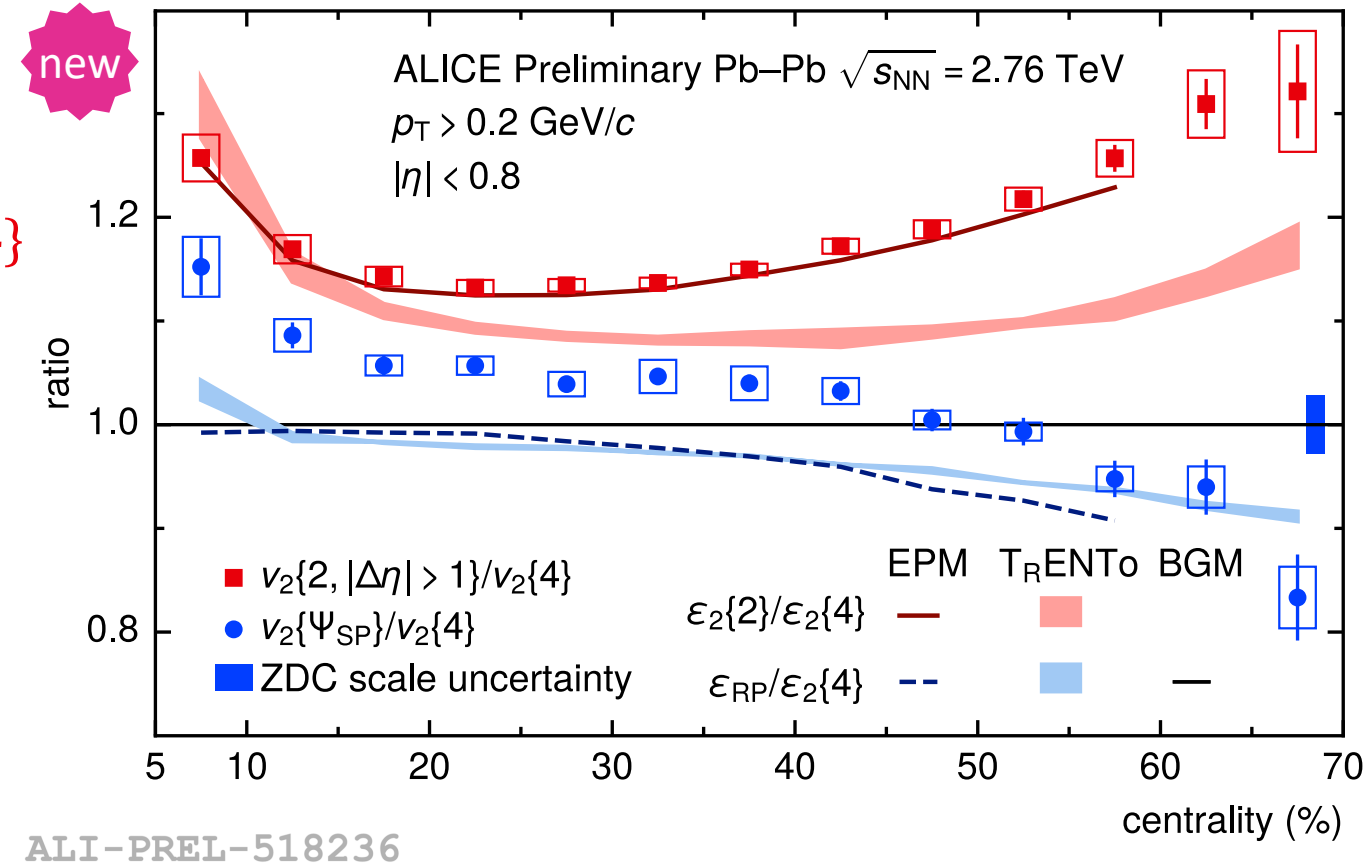
Participant vs. spectator plane fluctuations

ALICE-PUBLIC-2022-008

new

$v_2\{2, |\Delta\eta| > 1\}/v_2\{4\}$

$v_2\{\Psi_{SP}\}/v_2\{4\}$



ALI-PREL-518236

Central: ratio > 1

- Fewer spectator neutrons
- Correlation of Ψ_{SP} & Ψ_2
- Correlated local particle production reducing $v_2\{4\}$

Midcentral: ratio ≥ 1

- $\Psi_{SP} \neq \Psi_{RP}$: non-trivial decorrelaton due to loss of fragments and protons

Peripheral: ratio ≤ 1

- Fewer spectator neutrons (bound into fragments)
- Fewer participants: deviations from BGM

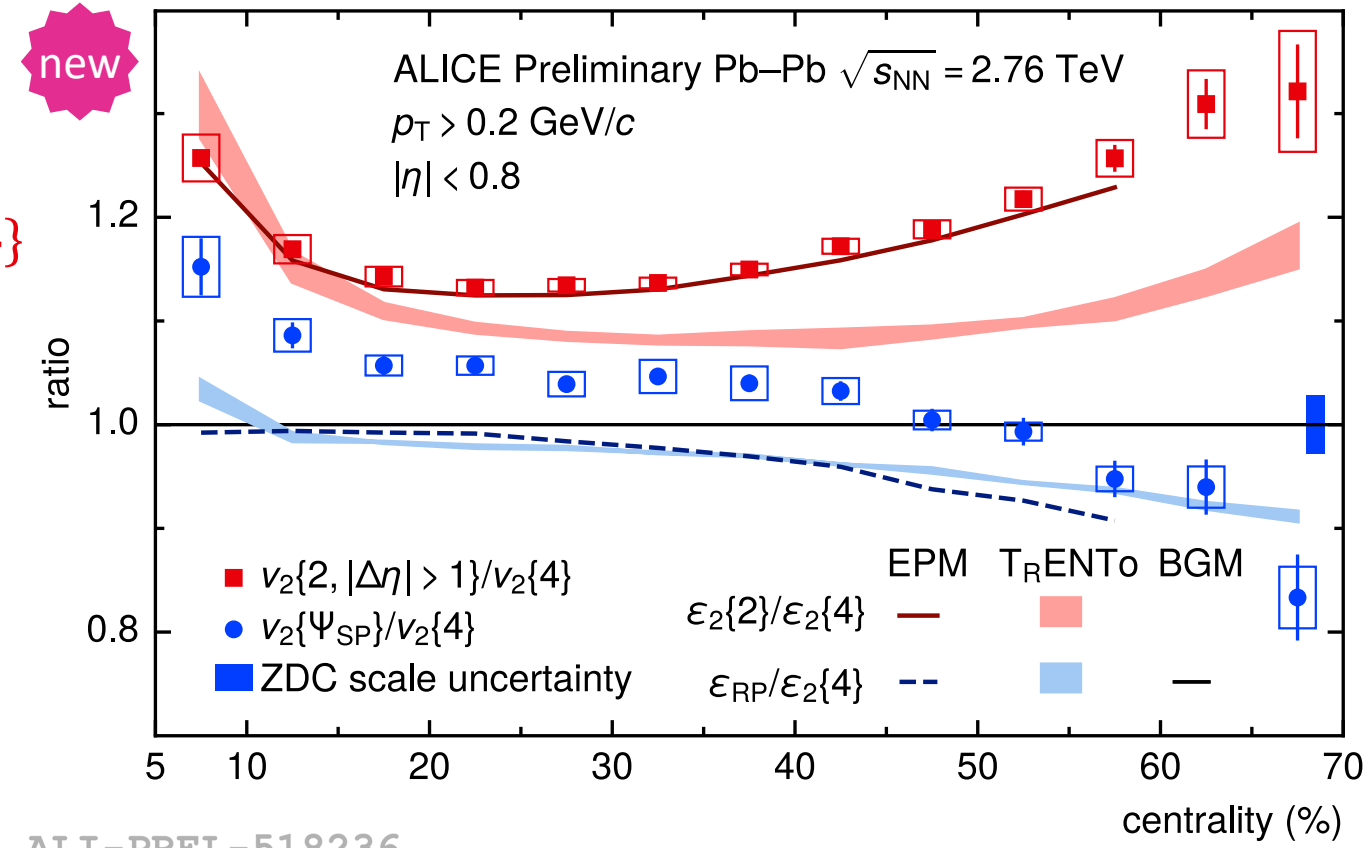
Participant vs. spectator plane fluctuations

ALICE-PUBLIC-2022-008

new

$v_2\{2, |\Delta\eta| > 1\}/v_2\{4\}$

$v_2\{\Psi_{SP}\}/v_2\{4\}$



ALI-PREL-518236

Comparison to Models

- Incomplete initial state description
- Effects of QGP evolution

Central: ratio > 1

- Fewer spectator neutrons
- Correlation of Ψ_{SP} & Ψ_2
- Correlated local particle production reducing $v_2\{4\}$

Midcentral: ratio ≥ 1

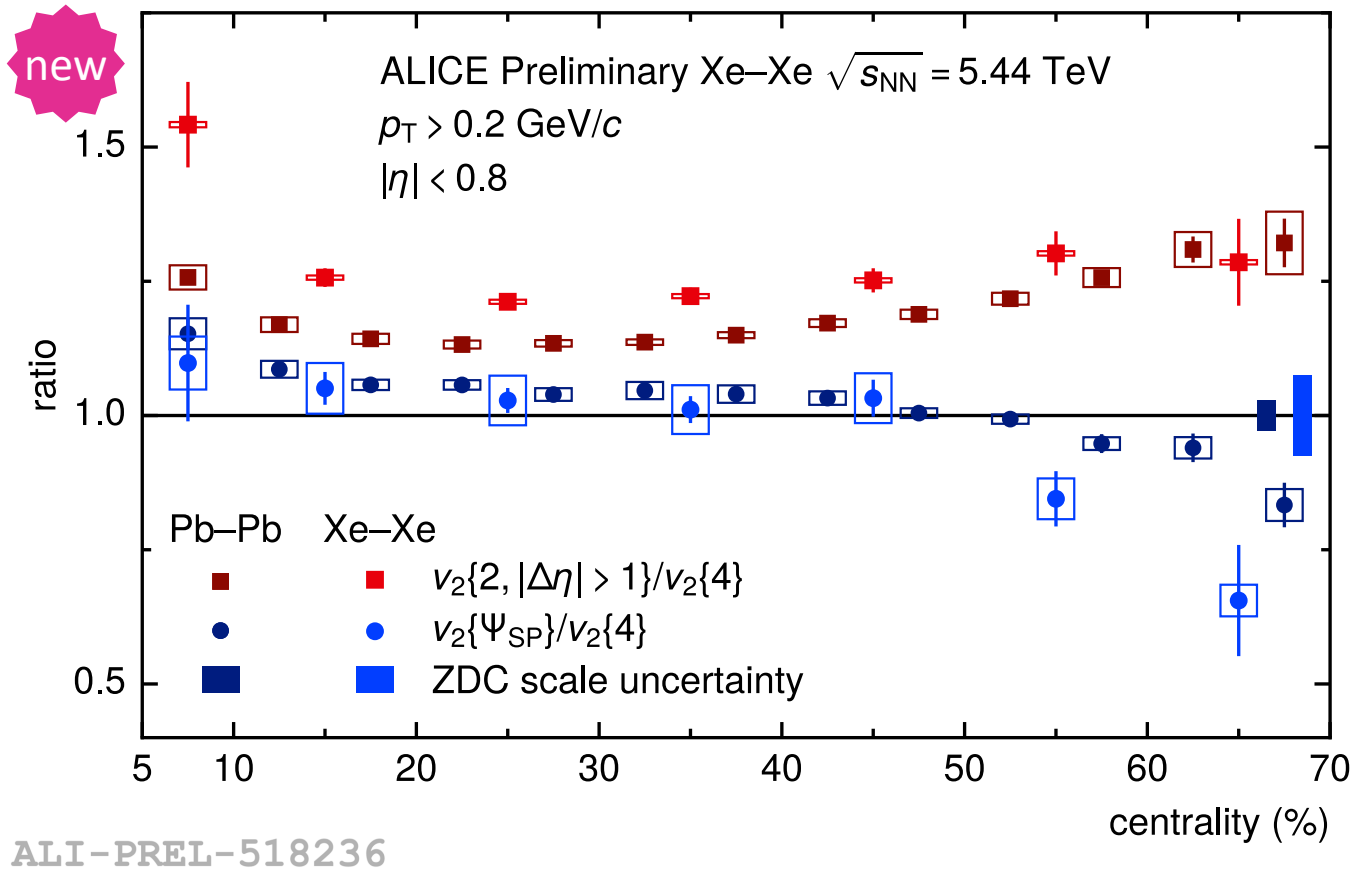
- $\Psi_{SP} \neq \Psi_{RP}$: non-trivial decorrelaton due to loss of fragments and protons

Peripheral: ratio ≤ 1

- Fewer spectator neutrons (bound into fragments)
- Fewer participants: deviations from BGM

System size dependence of Ψ_2 & Ψ_{SP} fluctuations

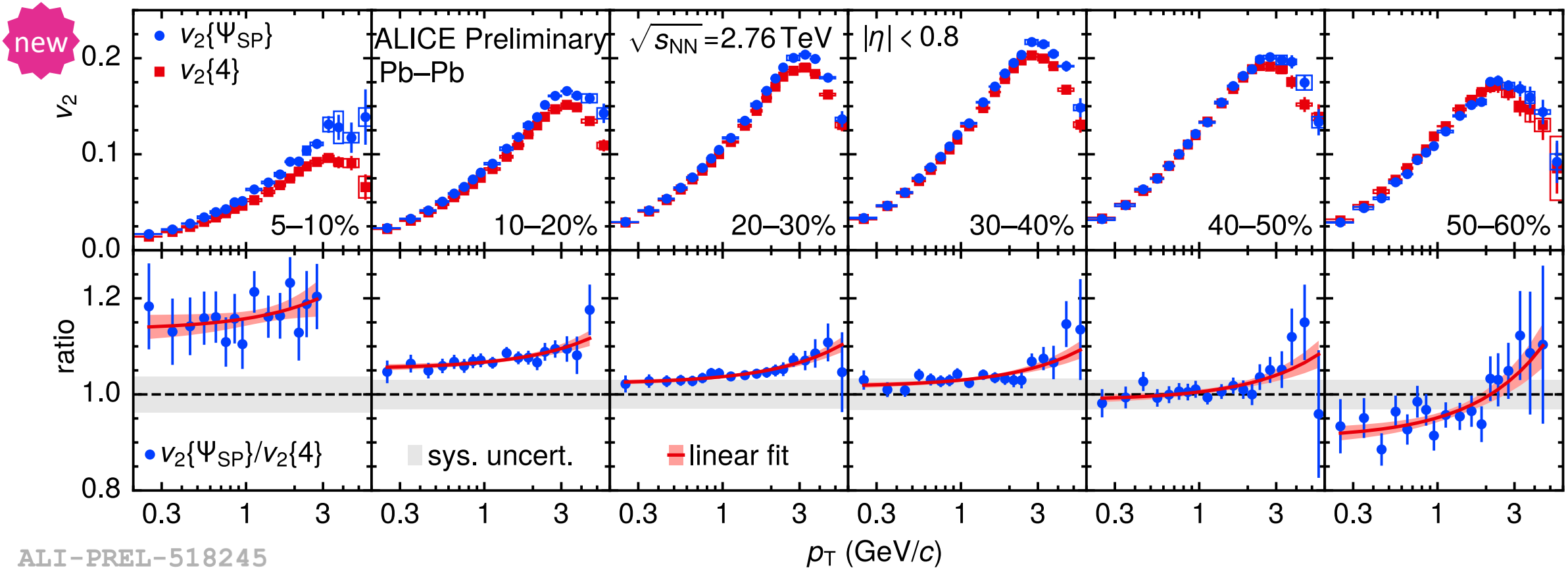
ALICE-PUBLIC-2022-008



Similar trends in Pb–Pb and Xe–Xe

Xe–Xe: statistics limits significance of $v_2\{\Psi_{SP}\}/v_2\{4\}$ deviation from unity

p_T-dependence of elliptic flow fluctuations



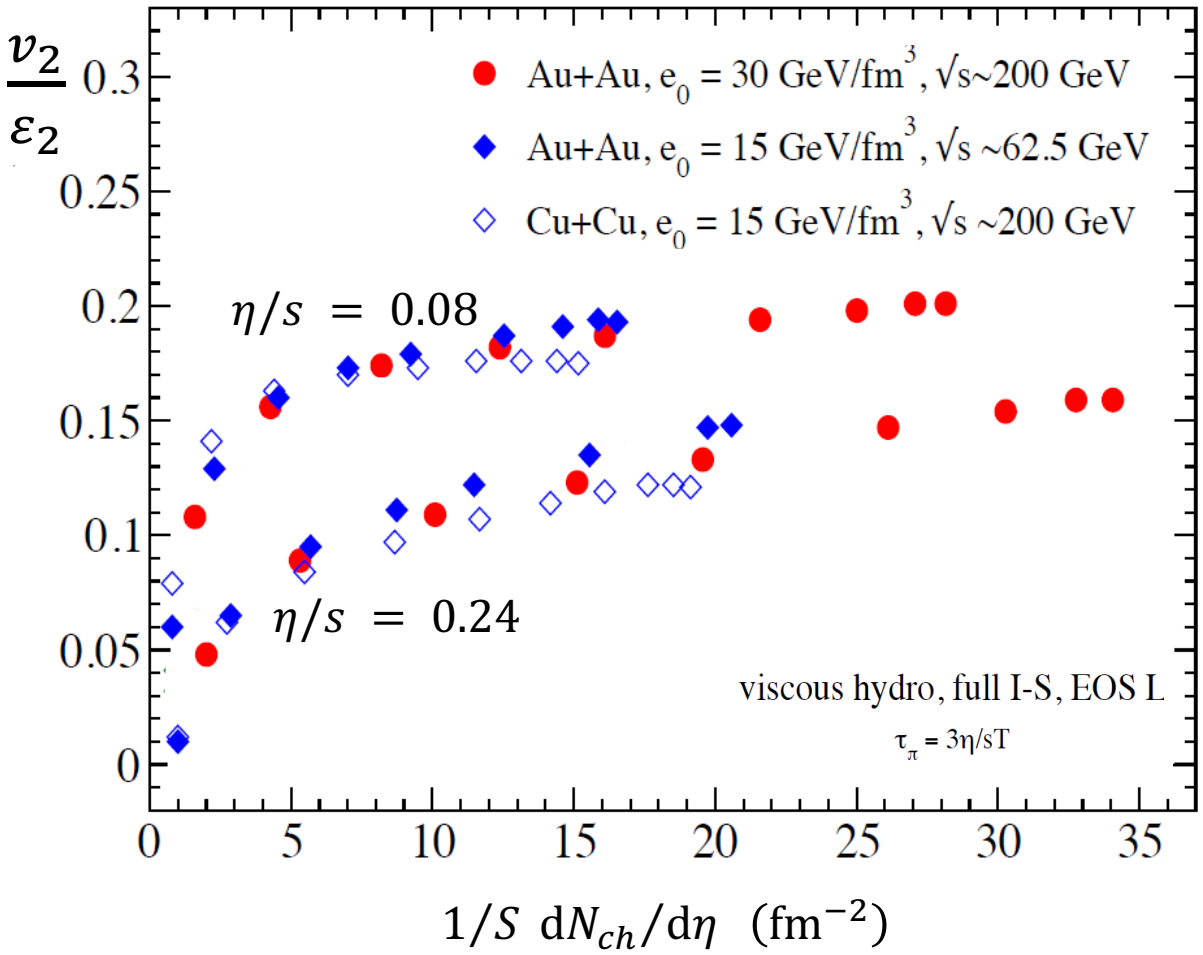
slope × 100: 2.31 ± 2.17 1.41 ± 0.48 1.48 ± 0.36 1.40 ± 0.42 1.74 ± 0.65 4.29 ± 1.34

Weak p_T-dependence suggests common origin of fluctuations at low and intermediate p_T

Slopes ($2 - 4\sigma$ significance) indicate p_T-dependent decorrelation of flow magnitude & angles

v_2/ε_2 scaling in hydrodynamics

Song et al. PRC 78 (2008) 024902



peripheral ⟷ central

Ideal fluid evolution $v_2 \propto \kappa\varepsilon_2$

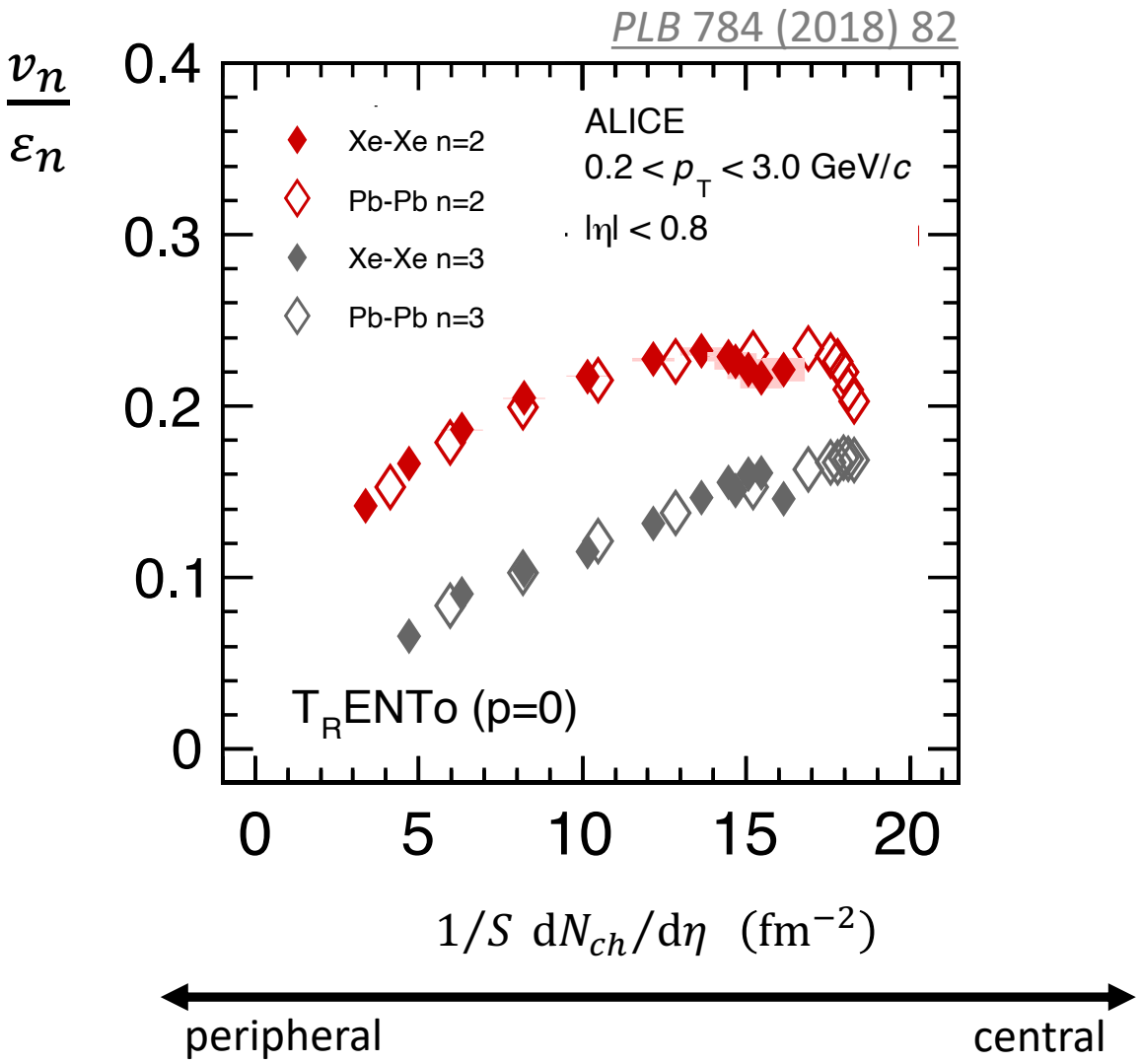
κ hydrodynamic response of QGP

- $\frac{v_2}{\varepsilon_2} \propto$ initial energy density $\approx \frac{1}{S}\frac{dN_{ch}}{d\eta}$
- Deviation from scaling due to
  - Later stages of evolution: freeze-out
  - Viscosities

In viscous hydrodynamics v_2/ε_2 depends on

- Centrality: sensitive due to lifetime of QGP
- Viscosity: strong sensitivity
- Colliding system: weak dependence

v_2/ε_2 scaling with ALICE at the LHC



Ideal fluid evolution $v_2 \propto \kappa\varepsilon_2$

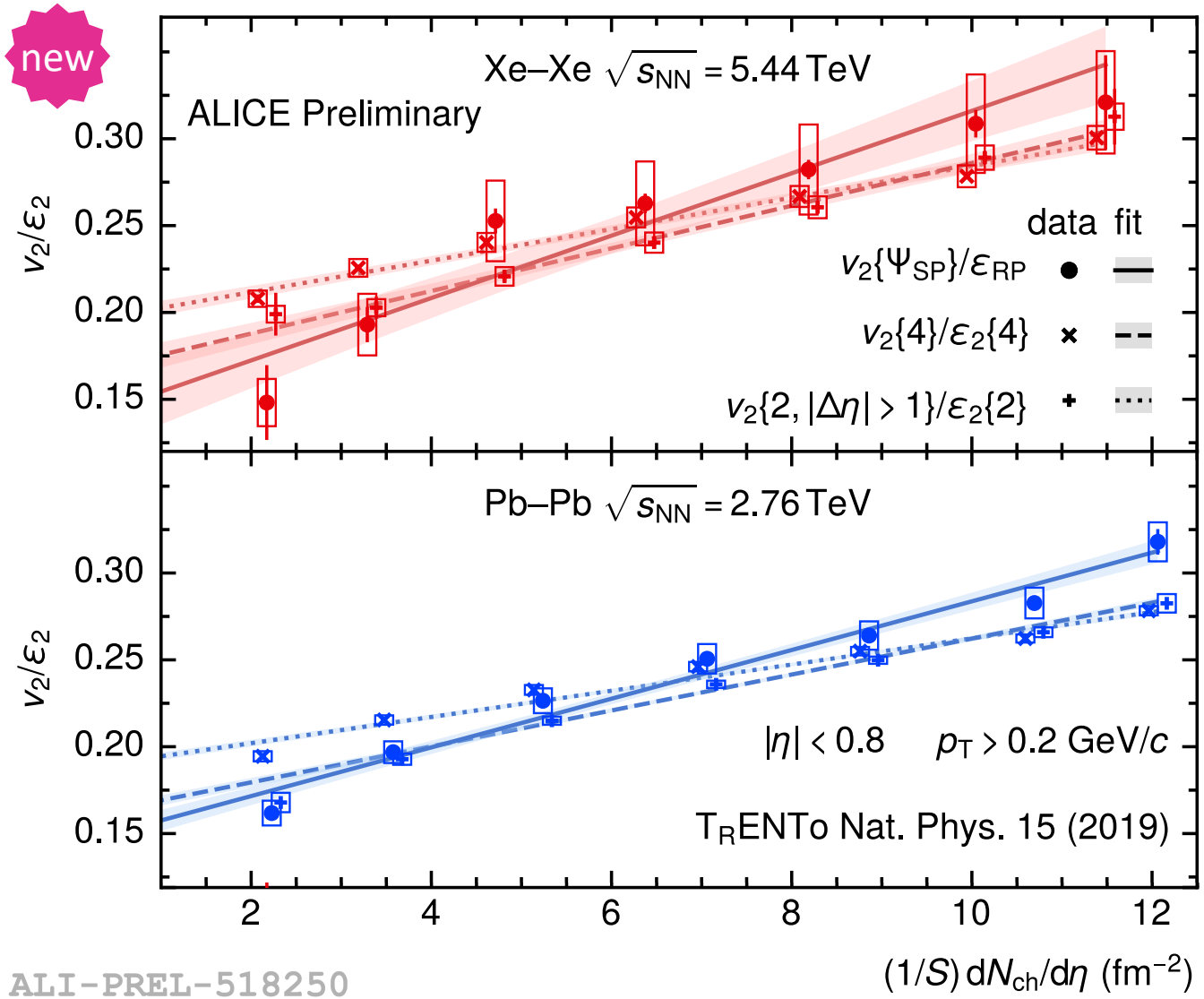
κ hydrodynamic response of QGP

- $\frac{v_2}{\varepsilon_2} \propto$ initial energy density $\approx \frac{1}{S}\frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}\eta}$
- Deviation from scaling due to
  - Later stages of evolution: freeze-out
  - Viscosities

In viscous hydrodynamics v_2/ε_2 depends on

- Centrality: sensitive due to lifetime of QGP
- Viscosity: strong sensitivity
- Colliding system: weak dependence

System size dependence of v_2/ε_2 scaling



- ε_2 and transverse area (S) from T_RENTo: *Bernhard et. al. Nat. Phys.* 15 (2019) 1113
- $dN_{ch}/d\eta$ from ALICE:
  Xe-Xe *PLB* 790 (2019) 35
  Pb-Pb *PRL* 106 (2011) 032301

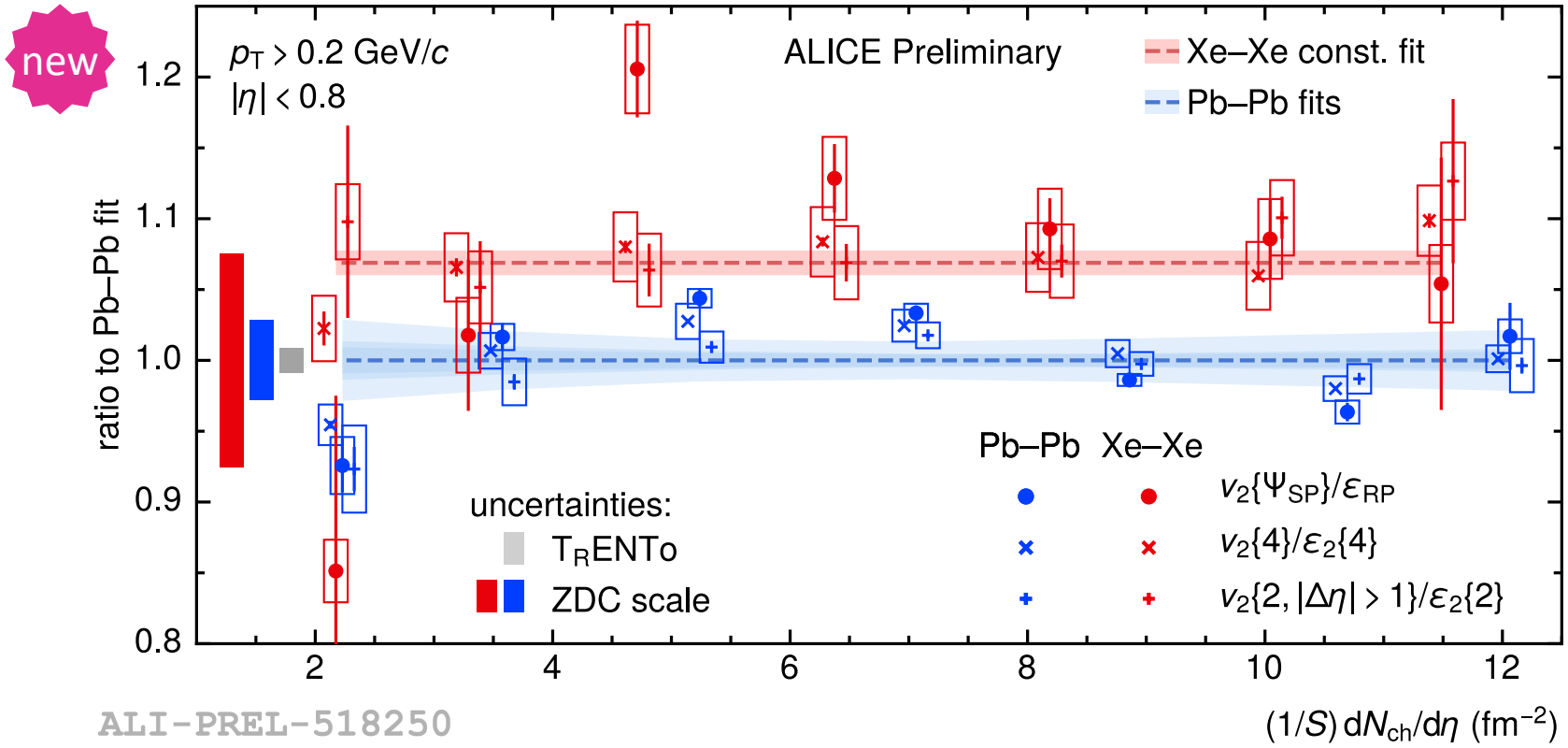
Individual fits to each v_2/ε_2 ratio for participant and spectator planes

- Scaling well described by linear function
- Each v_2/ε_2 has a different slope

ALI-PREL-518250

ALICE-PUBLIC-2022-008

System size dependence of v_2/ε_2 scaling



Difference of (7.0 ± 0.9)% observed between Pb-Pb and Xe-Xe collisions

- Additional +1.8 % from choice of T_RENTo tune: LHC data[1] versus LHC+RHIC data[2]

Sensitive to details of initial state and QGP viscosity

[1] *Bernhard et al. Nat. Phys.* 15 (2019) 1113

[2] *JETSCAPE collaboration PRC* 103 (2021) 054904

Summary

first measurement of $v_2\{\Psi_{\mathrm{SP}}\}$ at the LHC

$v_2\{\Psi_{\mathrm{SP}}\}/v_2\{4\}$

- Large deviations of models indicate an incomplete description of fluctuations
- Weak p_{T}-dependence suggests common origin of fluctuations
- Small non-zero slopes indicate p_{T}-dependent flow vector decorrelation

v_2/ε_2 in Pb–Pb and Xe–Xe collisions

- Observed difference is sensitive to details of initial state and QGP viscosity