# Studying the nuclear structures with high-energy collisions of light and heavy ions at the LHC

**Maxim Virta**[1]

1. Niels Bohr Institute, Denmark

1. July 2026

5th International Workshop on Emergent QCD Collectivity Across Scales:
From Small System Collisions to Jets

European Research Council
Established by the European Commission

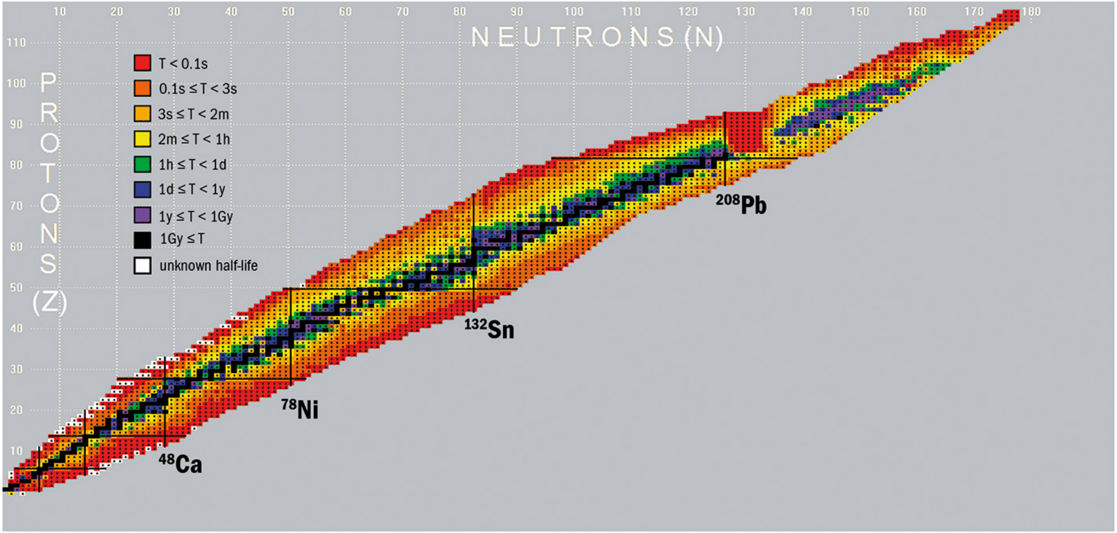
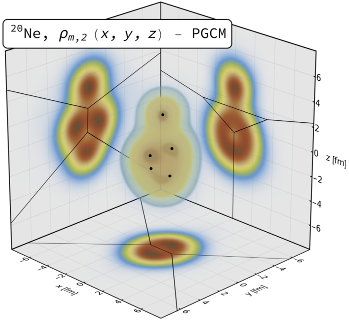


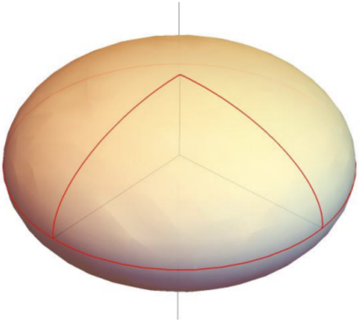

Figure from CERN Courier: https://cerncourier.com/a/exploring-nuclei-at-the-limits/

## Light ions

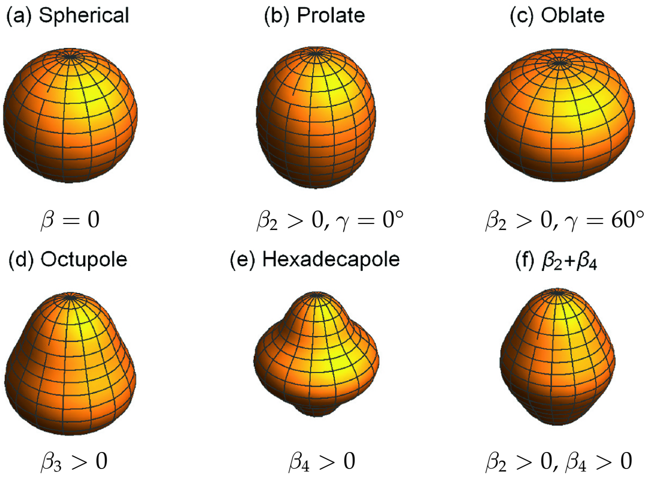



Based on *ab-initio* calculations

## Heavy ions

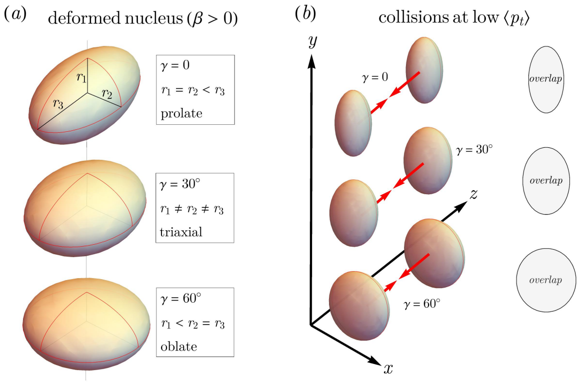


Based on the Woods-Saxon distribution




$$\boxed{R(\theta, \phi) = R_0 \left(1 + \sum_{l,m} \beta_{l,m} Y_{l,m}\right)}$$

Figure from: Kota, V.K.B. (2020). Introduction. In: SU(3) Symmetry in Atomic Nuclei. Springer

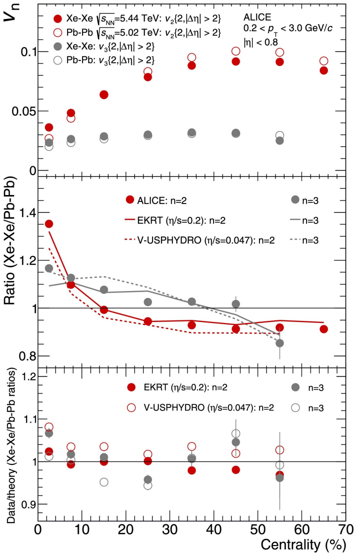



B. Bally *et al.*, *Phys. Rev. Lett.* 128 (2022), 082301

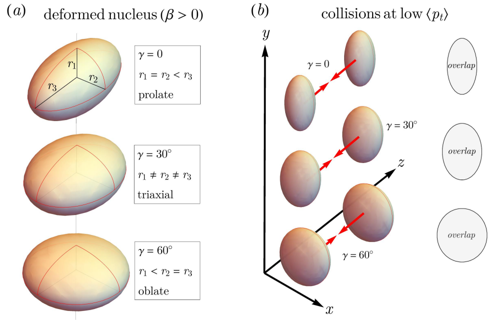
$$R(\theta, \phi) = R_0 \left[1 + \beta_2 \left(\cos\gamma Y_{2,0} + \sin\gamma Y_{2,2}\right)\right]$$

- Xenon nucleus has mostly quadrupole deformation
- Probe the nuclear structure, quadrupole deformation magnitude $\beta_2$ and triaxiality angle $\gamma$

$$\beta_2 = \sqrt{\beta_{2,0}^2 + 2\beta_{2,2}^2},\ \gamma = \mathrm{atan}(\sqrt{2}\beta_{2,2}/\beta_{2,0})$$



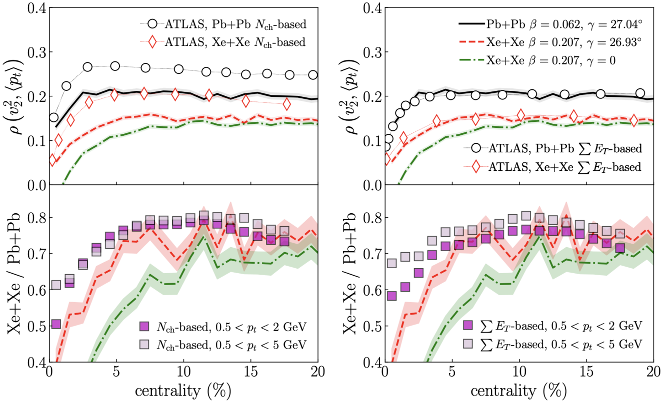

ALICE, *Phys. Lett. B* 784 (2018), 82-95




- Deformation of the nucleus affects the collision geometry
- $v_2$ can be traced back to eccentricities
- $\langle v_2^2 \rangle \propto \langle \varepsilon_2^2 \rangle \propto \beta_2^2$

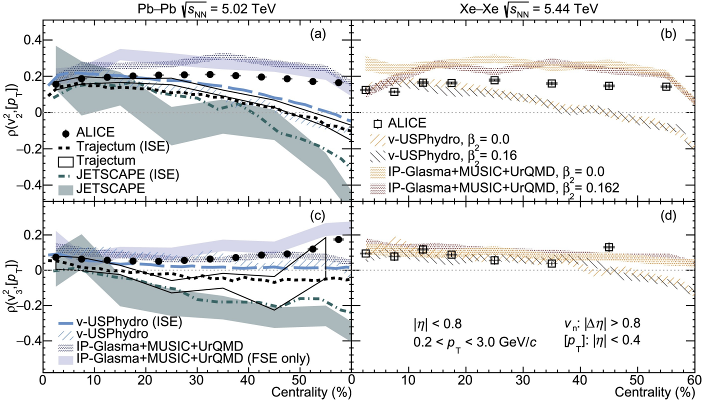
- Deformation of the nucleus affects the collision geometry
- $\beta_2$ requires two-particle correlation, while $\gamma$ needs three-particle correlation
- $\rho(v_2^2, \delta p_\mathrm{T})$ is defined as the Pearson correlation between $v_2^2$ and $\delta p_\mathrm{T}$
- $\langle v_2^2 \delta p_\mathrm{T} \rangle \propto \langle \varepsilon_2^2 \delta d_\perp \rangle \propto \beta_2^3 \cos(3\gamma)$

Bally *et al.*, *Phys. Rev. Lett* 128 (2022), 082301

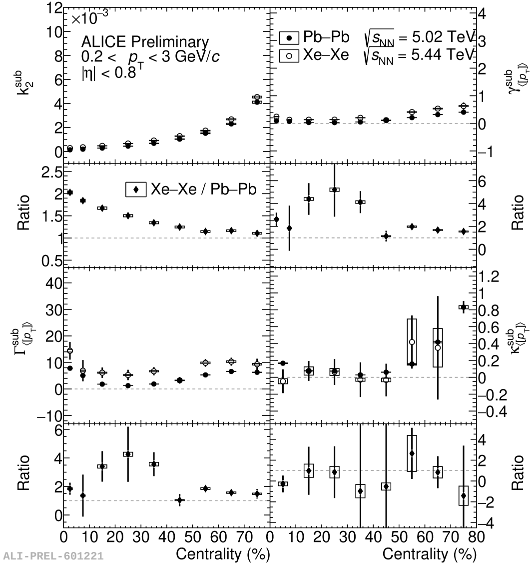


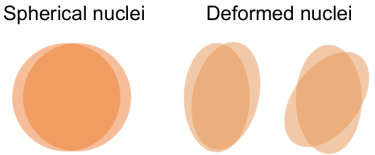
ALICE, *Phys. Lett. B* 834 (2022), 137393

- Deformation of the nucleus affects the collision geometry
- $\beta_2$ requires two-particle correlation, while $\gamma$ needs three-particle correlation
- $\rho(v_2^2, \delta p_\mathrm{T})$ is defined as the Pearson correlation between $v_2^2$ and $\delta p_\mathrm{T}$
- $\langle v_2^2 \delta p_\mathrm{T} \rangle \propto \langle \varepsilon_2^2 \delta d_\perp \rangle \propto -\beta_2^3 \cos(3\gamma)$



# Moments of $\delta p_{\mathrm{T}}^2$

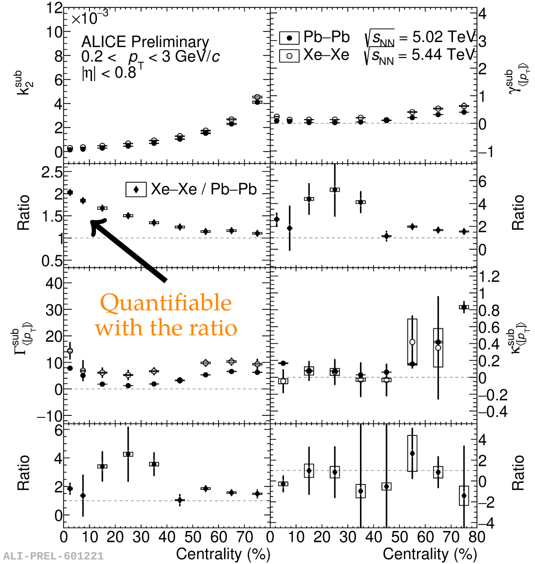


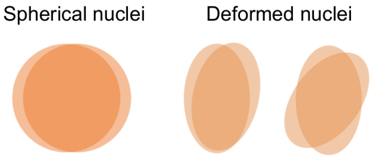




$$k_2^{\mathrm{sub}} = \frac{c_2^{\mathrm{sub}}}{[p_{\mathrm{T}}]_A [p_{\mathrm{T}}]_B} \qquad \gamma^{\mathrm{sub}}_{[p_{\mathrm{T}}]} = \frac{c_3^{\mathrm{sub}}}{(c_2^{\mathrm{sub}})^{\frac{3}{2}}}$$

$$\Gamma^{\mathrm{sub}}_{[p_{\mathrm{T}}]} = \frac{[p_{\mathrm{T}}] c_3^{\mathrm{sub}}}{(c_2^{\mathrm{sub}})^2} \qquad \kappa^{\mathrm{sub}}_{[p_{\mathrm{T}}]} = \frac{c_4^{\mathrm{sub}}}{(c_2^{\mathrm{sub}})^2}$$

- Event-by-event meant-$p_{\mathrm{T}}$ fluctuations are measured
- Larger fluctuations for deformed nuclei
- Additional constraints for the initial conditions



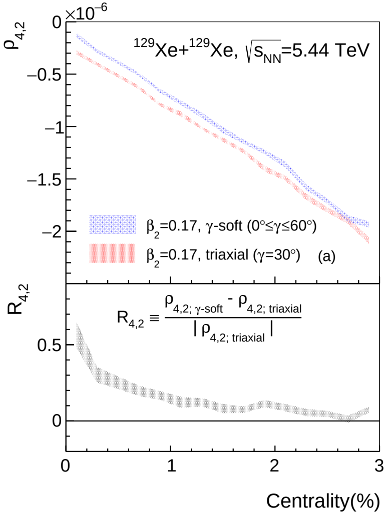




$$k_2^{sub} = \frac{c_2^{sub}}{[p_T]_A [p_T]_B} \qquad \gamma_{[p_T]}^{sub} = \frac{c_3^{sub}}{(c_2^{sub})^{\frac{3}{2}}}$$

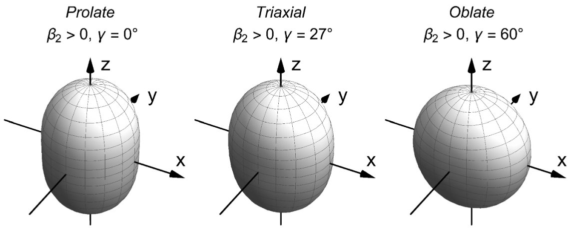
$$\Gamma_{[p_T]}^{sub} = \frac{[p_T] c_3^{sub}}{(c_2^{sub})^2} \qquad \kappa_{[p_T]}^{sub} = \frac{c_4^{sub}}{(c_2^{sub})^2}$$

- Event-by-event meant-$p_T$ fluctuations are measured
- Larger fluctuations for deformed nuclei
- Additional constraints for the initial conditions

S. Zhao *et al.*, *Phys. Rev. Lett.* 133 (2024), 192301

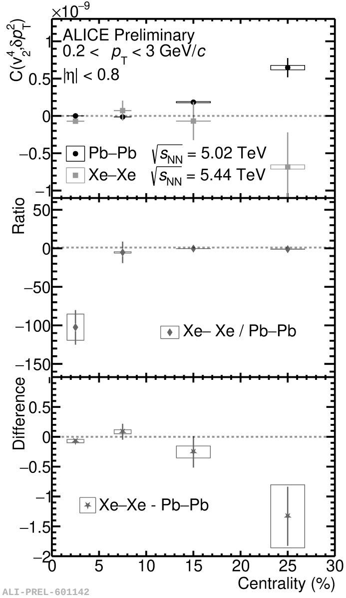



E. Nielsen *et al.*, *Eur.Phys.J.A* 60 (2024) 2, 38

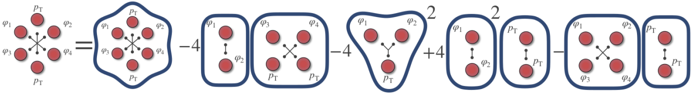



- $\gamma$ requires a three-particle correlation
  $\rightarrow \gamma$ fluctuations need six-particle correlation
- New 6-particle correlation between flow harmonics and mean-$p_{\mathrm{T}}$, $C(v_2^4, \delta p_{\mathrm{T}}^2)$
- $\rho_{4,2}$ is the corresponding initial-state observable

# The six-particle correlation $C(v_2^4, \delta p_\mathrm{T}^2)$

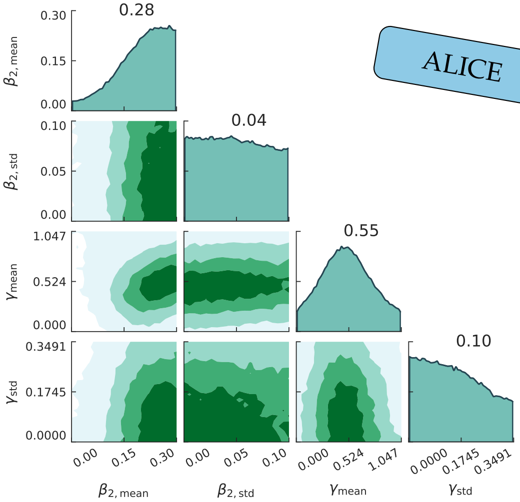



$$C(v_2^4, \delta p_\mathrm{T}^2) = \langle v_2^4 \delta p_\mathrm{T}^2 \rangle - 4\langle v_2^2\rangle\langle v_2^2 \delta p_\mathrm{T}^2 \rangle - 4\langle v_2^2 \delta p_\mathrm{T} \rangle^2 + 4\langle v_2^2\rangle^2\langle \delta p_\mathrm{T}^2 \rangle - \langle v_2^4\rangle\langle \delta p_\mathrm{T}^2 \rangle$$



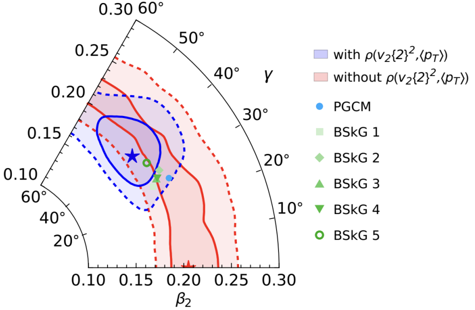
- Measured for the first time in Pb–Pb and Xe–Xe collisions
- The difference between the systems is used due to fluctuations around zero

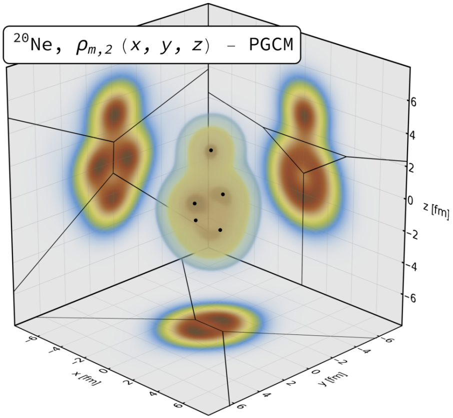
One can utilise Bayesian inference to extract nuclear structure parameters

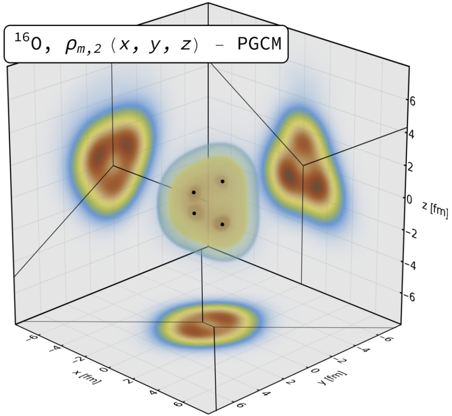



ALICE

Trajectum, *arXiv* 2606.03993

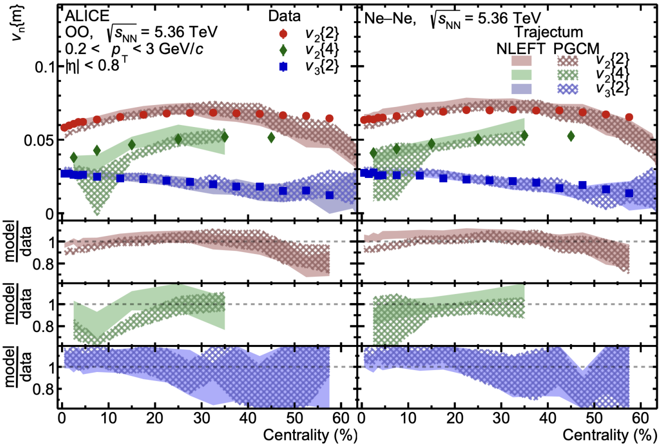



$^{20}$Ne, $\rho_{m,2}(x, y, z)$ – PGCM
z [fm]
x [fm]
y [fm]

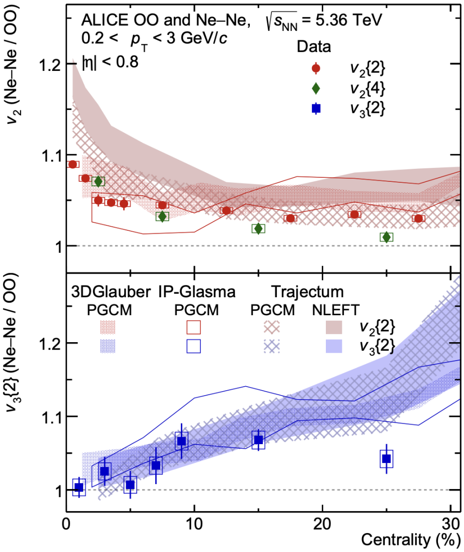

$^{16}$O, $\rho_{m,2}(x, y, z)$ – PGCM
z [fm]
x [fm]
y [fm]

ALICE, *arXiv* 2509.06428

- Latest $v_n$ measurements in OO and Ne–Ne collisions
- Flow is driven by collision anisotropy and fluctuations
- Nuclear structure effects become visible in the central collisions



- Nuclear structure effects become visible in the central collisions
- Extracting the ratio gets rid of final-state effects
- Ne exhibits stronger $v_2$ due to bowling-pin shape
- Models with lower subnucleon width ($v_q = 0.11$) agree better with the data

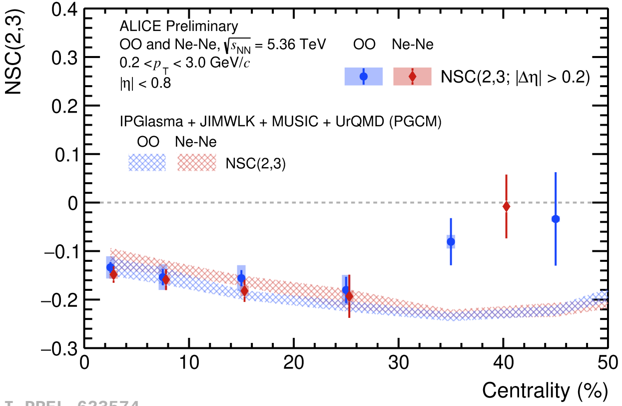



ALICE, *arXiv* 2509.06428

Vojtech Machacek, SQM2026

$$NSC(n,m) = \frac{\langle v_n^2 v_m^2\rangle - \langle v_n^2\rangle\langle v_m^2\rangle}{\langle v_n^2\rangle\langle v_m^2\rangle}$$
$$\propto \frac{\langle \varepsilon_n^2 \varepsilon_m^2\rangle - \langle \varepsilon_n^2\rangle\langle \varepsilon_m^2\rangle}{\langle \varepsilon_n^2\rangle\langle \varepsilon_m^2\rangle}$$

- Correlations between flow harmonics relate to the initial eccentricity correlations
- Very similar between OO and Ne–Ne
- Sensitivity to the nuclear structure

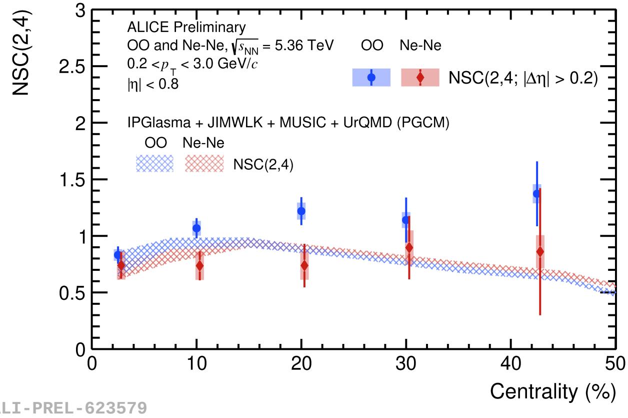


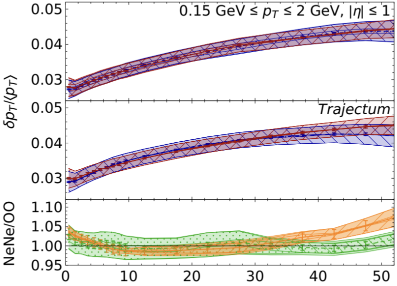

ALI-PREL-623574

Vojtech Machacek, SQM2026

$$NSC(n,m) = \frac{\langle v_n^2 v_m^2 \rangle - \langle v_n^2 \rangle \langle v_m^2 \rangle}{\langle v_n^2 \rangle \langle v_m^2 \rangle} \propto \frac{\langle \varepsilon_n^2 \varepsilon_m^2 \rangle - \langle \varepsilon_n^2 \rangle \langle \varepsilon_m^2 \rangle}{\langle \varepsilon_n^2 \rangle \langle \varepsilon_m^2 \rangle}$$

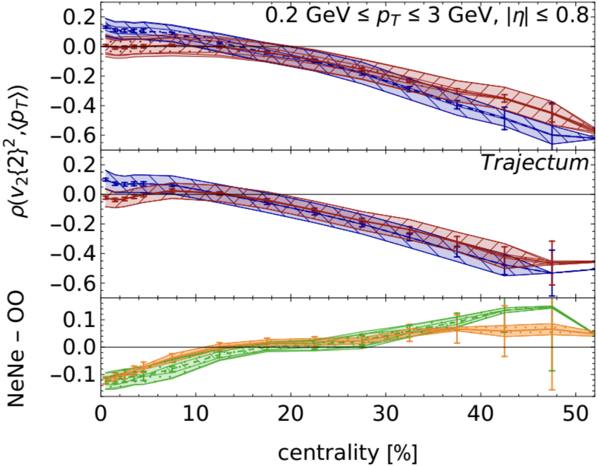
- Correlations between flow harmonics relate to the initial eccentricity correlations
- Very similar between OO and Ne–Ne
- Sensitivity to the nuclear structure





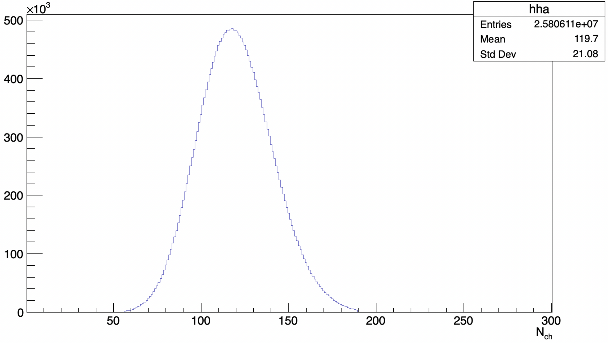

- $\delta p_{\mathrm{T}}$-fluctuations dependent on the nucleon positions
- $\rho(v_2^2, [p_{\mathrm{T}}])$ shows a stronger correlation for Oxygen due to the bowling-pin shape of Ne
- $\langle v_2^2 \delta p_{\mathrm{T}} \rangle \propto \langle \varepsilon_2^2 \delta d_\perp \rangle \propto -\beta_2^3 \cos(3\gamma)$

Giacalone *et al.*, *arXiv* 2402.05995



# CHALLENGES

- Light-ion collisions are affected more by fluctuations than heavier ions
- Multiplicities change a lot for a given centrality bin
- Results from the same centrality, e.g. 0-1%, may have hugely different statistics
- Importance of multiplicity weighting and narrow binning



Without weights (or unit weights) gives the regular event average

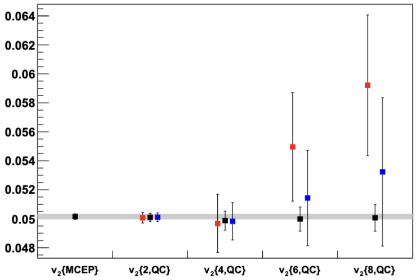
$$\langle\langle 2\rangle\rangle = \sum_{l}^{N} \frac{\sum_{a\neq b}^{M_l} e^{in(\phi_{l,a}-\phi_{l,b})}}{M_l(M_l-1)} \Big/ N$$

Applying pair-weights gives a multiplicity-weighted average

$$\langle\langle 2\rangle\rangle_{\text{weight}} = \sum_{l}^{N} M_l(M_l-1)\frac{\sum_{a\neq b}^{M_l} e^{in(\phi_{l,a}-\phi_{l,b})}}{M_l(M_l-1)} \Big/ \sum_{l}^{N} M_l(M_l-1)$$

$$= \sum_{l}^{N} \sum_{a\neq b}^{M_l} e^{in(\phi_{l,a}-\phi_{l,b})} \Big/ \sum_{l}^{N} M_l(M_l-1)$$

Ante Bilandzic's thesis



Generalises to multiparticle correlations

$$\langle v_n^2 \delta p_{\mathrm{T}} \rangle = \langle v_n^2 [p_{\mathrm{T}}] - v_n^2 \langle [p_{\mathrm{T}}] \rangle \rangle$$
$$= \frac{\sum_l^N M_l^a M_l^b M_l^c v_n\{2\}[p_{\mathrm{T}}]}{\sum_l^N M_l^a M_l^b M_l^c} - \frac{\sum_l^N M_l^a M_l^b M_l^c v_n\{2\}}{\sum_l^N M_l^a M_l^b M_l^c} \frac{\sum_l^N [p_{\mathrm{T}}]}{N}$$

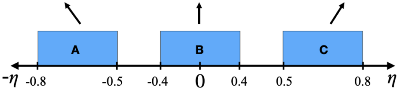
Similarly to $\delta p_{\mathrm{T}}$ cumulants

$$c_k = \mathrm{var}([p_{\mathrm{T}}]) = \langle \delta p_{\mathrm{T}}^2 \rangle$$
$$= \frac{\sum_l^N M_l(M_l - 1)\delta p_{\mathrm{T}}^2}{\sum_l^N M_l(M_l - 1)}$$

Three-particle correlations are evaluated with 3-sub event

Example $\langle v_2^2 \delta p_{\mathrm{T}} \rangle$

- Flow taken from sections A and C
- Mean transverse momentum from section B

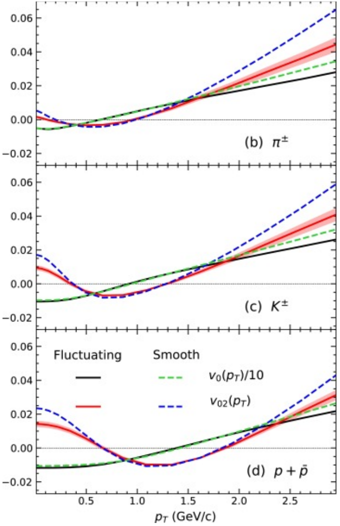


$$n(p_\mathrm{T}) = \frac{N(p_\mathrm{T})}{N_\mathrm{ch}} \Rightarrow \int_{p_\mathrm{T}} n(p_\mathrm{T}) = 1$$

$$v_{02}(p_\mathrm{T}) = \frac{\langle \delta n(p_\mathrm{T}) v_2^2 \rangle}{\langle n(p_\mathrm{T}) \rangle \langle v_2^2 \rangle} = \frac{\langle n(p_\mathrm{T}) - \langle n(p_\mathrm{T}) \rangle v_2^2 \rangle}{\langle n(p_\mathrm{T}) \rangle \langle v_2^2 \rangle}$$

$$v_{02} = \frac{1}{\langle [p_\mathrm{T}] \rangle} \int_{p_\mathrm{T}} p_\mathrm{T} \langle n(p_\mathrm{T}) \rangle v_{02}(p_\mathrm{T})$$

- Where should the weight be applied?
- We argue that it should be applied for $v_2^2$ only as $n(p_\mathrm{T})$ is a ratio, not a proper particle correlation




Parida et al., Phys. Lett. B 868 (2025) 139729

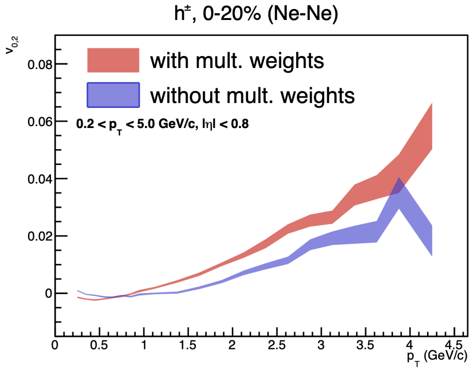
$$n(p_\mathrm{T}) = \frac{N(p_\mathrm{T})}{N_\mathrm{ch}} \Rightarrow \int_{p_\mathrm{T}} n(p_\mathrm{T}) = 1$$

$$v_{02}(p_\mathrm{T}) = \frac{\langle \delta n(p_\mathrm{T}) v_2^2 \rangle}{\langle n(p_\mathrm{T}) \rangle \langle v_2^2 \rangle}$$

$$= \frac{\langle n(p_\mathrm{T}) - \langle n(p_\mathrm{T}) \rangle v_2^2 \rangle}{\langle n(p_\mathrm{T}) \rangle \langle v_2^2 \rangle}$$

$$v_{02} = \frac{1}{\langle [p_\mathrm{T}] \rangle} \int_{p_\mathrm{T}} p_\mathrm{T} \langle n(p_\mathrm{T}) \rangle v_{02}(p_\mathrm{T})$$

- Where should the weight be applied?
- We argue that it should be applied for $v_2^2$ only as $n(p_\mathrm{T})$ is a ratio, not a proper particle correlation

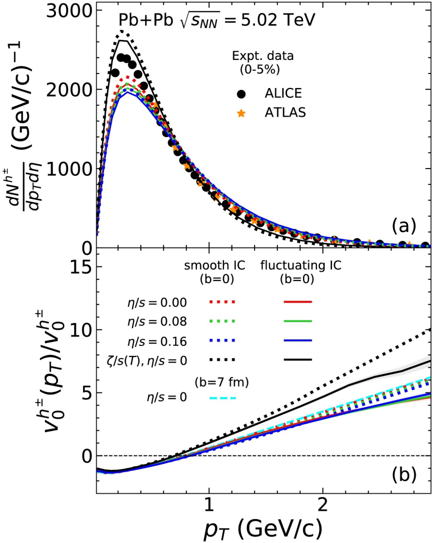


$$n(p_{\mathrm{T}}) = \frac{N(p_{\mathrm{T}})}{N_{\mathrm{ch}}} \Rightarrow \int_{p_{\mathrm{T}}} n(p_{\mathrm{T}}) = 1$$

$$v_0(p_{\mathrm{T}}) = \frac{\langle \delta n(p_{\mathrm{T}}) \delta p_{\mathrm{T}} \rangle}{\langle n(p_{\mathrm{T}}) \rangle \sigma_{[p_{\mathrm{T}}]}}$$

$$v_0 = \frac{1}{\langle [p_{\mathrm{T}}] \rangle} \int_{p_{\mathrm{T}}} p_{\mathrm{T}} \langle n(p_{\mathrm{T}}) \rangle v_0(p_{\mathrm{T}})$$

- Where should the weight be applied here?
- Should both of the terms in the numerator be weighted, neither of them, or only one of them; which one?




Parida *et al.*, *Phys. Lett. B* 857 (2024) 138985

# THANK YOU!