

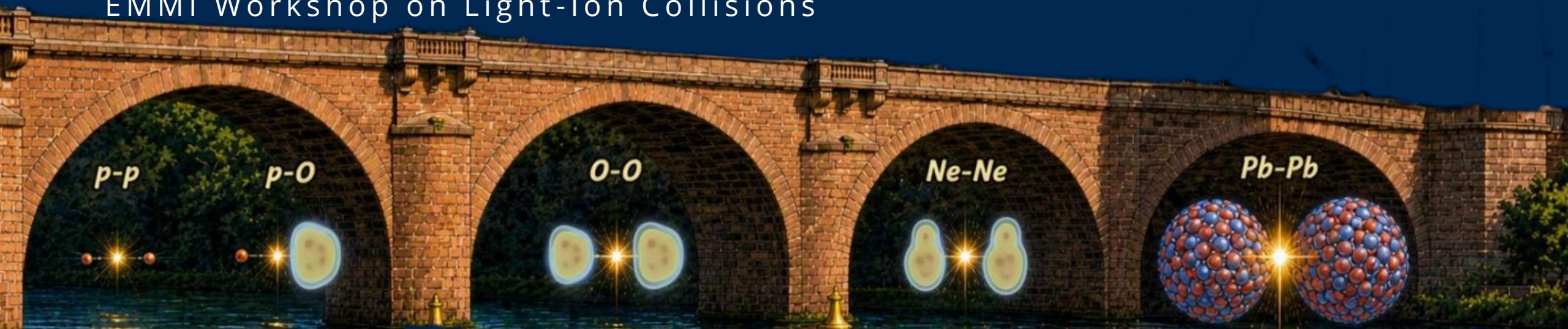


EÖTVÖS LORÁND
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Femtoscopic signatures of unique nuclear structures in
relativistic collisions, arXiv:???? (coming soon)
(follow up to [Phys. Rev. Research 7, L042028](#))

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Barnabás Pórfy, Máté Csanád, Márton Nagy)

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EMMI Workshop on Light-Ion Collisions



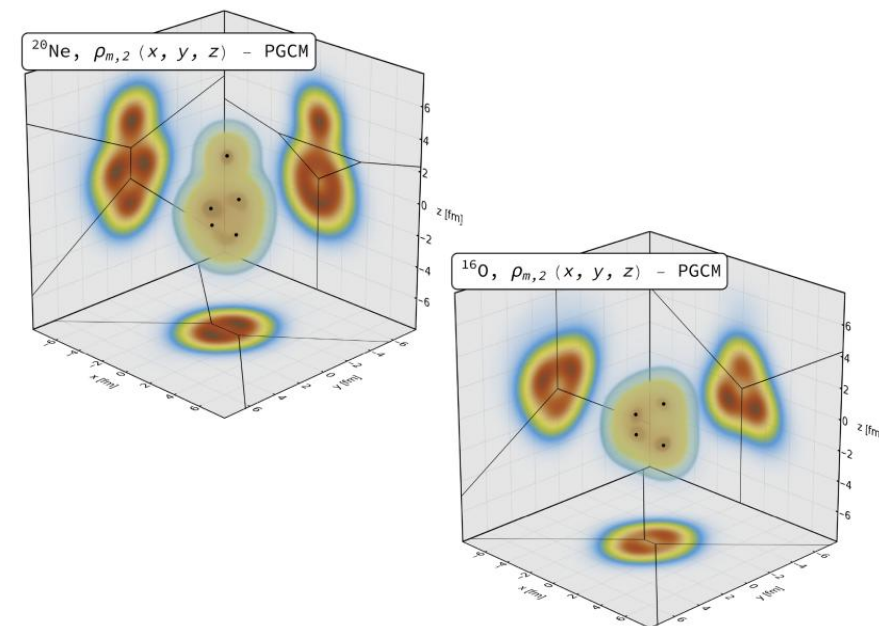
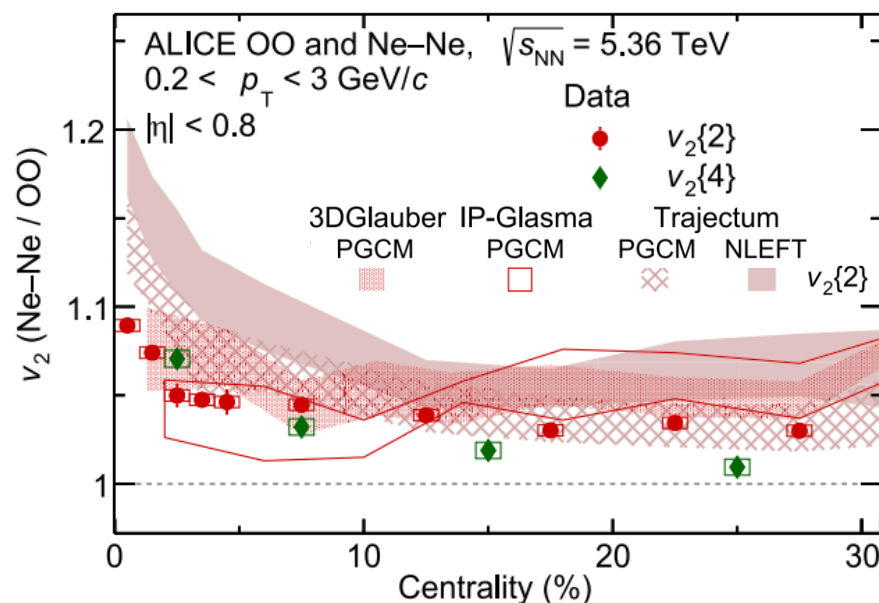
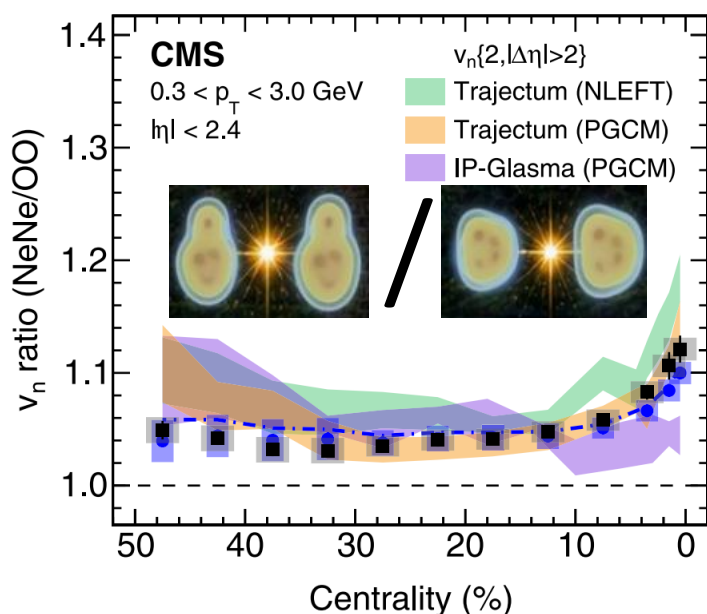
Motivation

ALICE, [Phys.Rev.Lett. 137 \(2026\) 8, 082301](#)

CMS, [Phys.Rev.Lett. 137 \(2026\) 8, 082302](#)

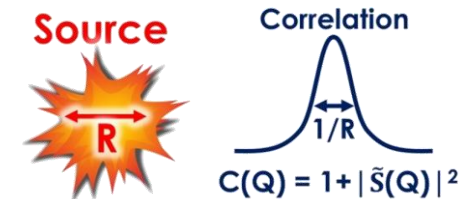
G. Giacalone et al., [Phys.Rev.Lett. 135 \(2025\) 1, 012302](#)

- **Nuclear structure imaging in high-energy collisions** – hot topic, many interesting new results
 - Sensitivity of anisotropic flow to ^{20}Ne bowling-pin shape deformation demonstrated
 - Deformed nuclear geometry $\rightarrow$ imprint on initial state ellipticity $\rightarrow$ NeNe/OO increase for central events



- Could there be other important observables? **What about femtoscopic freeze-out eccentricity?**

Femtoscscopy with Lévy sources



- Shape of **pair distance distribution** for identical pions → **elliptically contoured 3D Lévy-stable distr.:**

$$D(\vec{\rho}) = \mathcal{L}(\alpha, R^2, \vec{\rho}) = \frac{1}{(2\pi)^3} \int d^3 y e^{i\vec{\rho} \cdot \vec{y}} e^{-\frac{1}{2} |\vec{y}^T R^2 \vec{y}|^{\frac{\alpha}{2}}}, \quad R^2 = \begin{pmatrix} R_{\text{out}}^2 & R_{\text{out-side}}^2 & R_{\text{out-long}}^2 \\ R_{\text{out-side}}^2 & R_{\text{side}}^2 & R_{\text{side-long}}^2 \\ R_{\text{out-long}}^2 & R_{\text{side-long}}^2 & R_{\text{long}}^2 \end{pmatrix}$$

- **Lévy exponent α :** describes the asymptotic behavior, $\alpha = 2$ Gaussian, $\alpha < 2$ power-law
- **Lévy scale matrix R^2 :** usually diagonal, but in an azimuthally sensitive analysis cross-terms matter!
- Coordinate system: based on the $\vec{k}_T$ average transverse momentum of the pion pair
 - „**out**” is the direction of $\vec{k}_T$, „**long**” is the beam direction, „**side**” is perpendicular to the others
- **Momentum correlation C** related to pair-distance distribution D through pair wave function ψ :

$$C_2(\vec{q}, \vec{K}) = \int d^3 \vec{\rho} D_{\vec{K}}(\vec{\rho}) |\psi_{\vec{q}}(\vec{\rho})|^2 \xrightarrow{\text{no FSI}} 1 + \lambda e^{-|\vec{q}^T R^2 \vec{q}|^{\alpha/2}}$$

- Origin of Lévy source in high-energy collisions: Lévy-walk of pions (hadronic rescattering, decays)
- D. Kincses et al., <https://www.nature.com/articles/s42005-025-01973-x>

Azimuthally sensitive femtoscopy

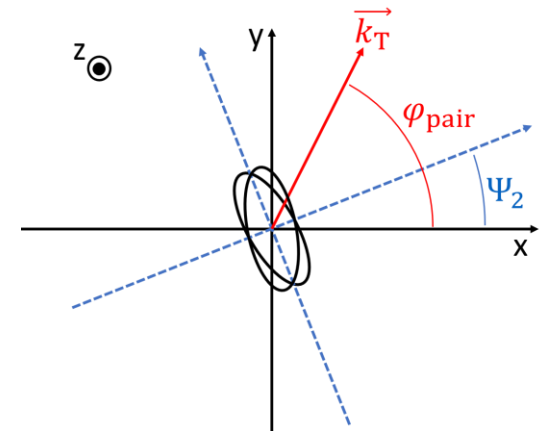
- Azimuthal analysis: pair average azimuthal angle φ_{pair} relative to the second order event plane Ψ_2
- For symmetric collisions (NeNe, OO) at midrapidity, out-long and side-long terms are zero
- **Radii oscillations → freeze-out shape!**

$$\begin{aligned} \bullet R_{\mu}^2(\varphi_{\text{pair}} - \Psi_2) &= R_{\mu,0}^2 \left(1 + \varepsilon_{\mu} \cos \left(2(\varphi_{\text{pair}} - \Psi_2) \right) \right), \varepsilon_{\mu} = 2 \frac{R_{\mu,2}^2}{R_{\mu,0}^2}, \text{ if } \mu = \text{out, side, long} \\ \bullet R_{\mu}^2(\varphi_{\text{pair}} - \Psi_2) &= R_{\mu,0}^2 + 2R_{\mu,2}^2 \sin \left(2(\varphi_{\text{pair}} - \Psi_2) \right), \text{ if } \mu = \text{out} - \text{side} \end{aligned}$$

- Relative oscillation in the side direction → **femtoscopic ellipticity parameter** (freeze-out eccentricity)

$$\bullet \varepsilon_{\text{side}} = 2 \frac{R_{\text{side},2}^2}{R_{\text{side},0}^2}$$

- Can the initial ellipticity remain through the medium evolution, and leave an imprint on the freeze-out shape?

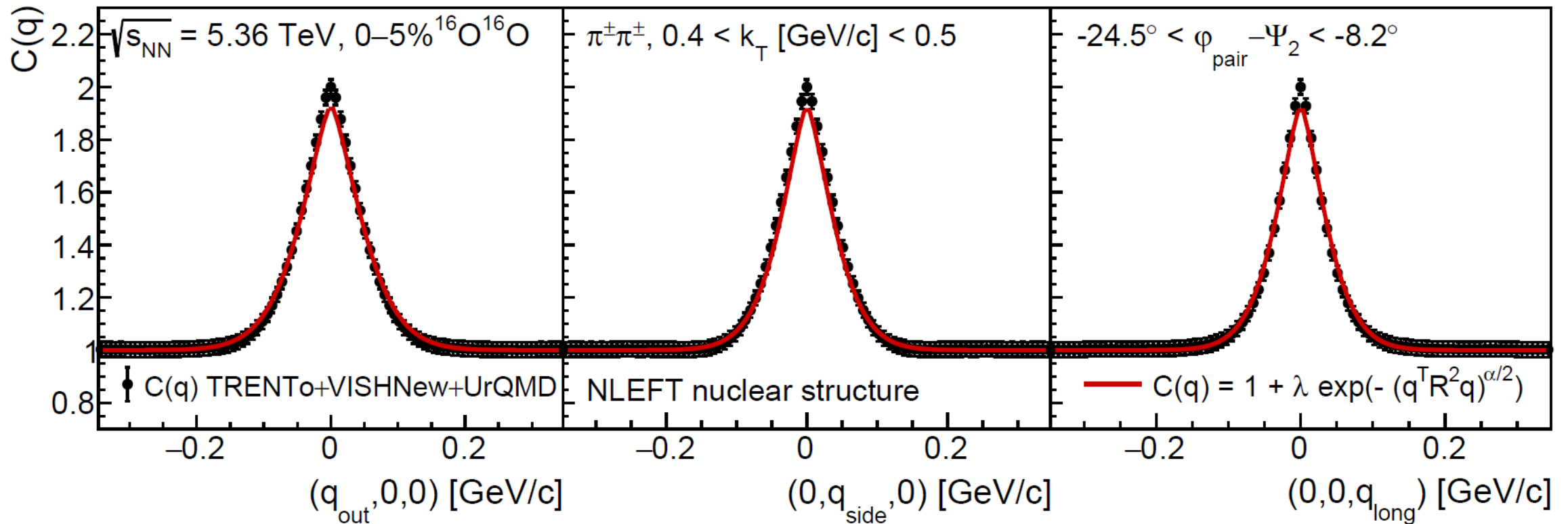


Hydrodynamical simulations

- $\sqrt{s_{NN}} = 5.36$ TeV $^{20}\text{Ne} + ^{20}\text{Ne}$ and $^{16}\text{O} + ^{16}\text{O}$ collisions simulated with **TRENTo+VISHNew+UrQMD**
- Three initial nucleon configuration studied:
 - **Wood-Saxon** $\rightarrow$ spherically symmetric
 - **Nuclear Lattice Effective Field Theory (NLEFT)** $\rightarrow$ resemble α -clusters
 - **Projected Generator Coordinate Method (PGCM)**
- 100,000 min.bias hydro events simulated for each setting, with 50 UrQMD oversampling per hydro event
- Second order event plane angle determined similarly to STAR Coll., [Phys. Rev. C 92, 014904 \(2015\)](#):
- $\Psi_2 = \frac{1}{2} \arctan(Q_y/Q_x)$, $Q_x = \frac{1}{N} \sum_i p_{T,i} \cos(2\phi_i)$, $Q_y = \frac{1}{N} \sum_i p_{T,i} \sin(2\phi_i)$, N : total number of particles, p_T : transverse momentum, ϕ : azimuthal angle
- Single particle selection criteria: $|\eta| < 0.5$, p_T [GeV/c] = 0.15 – 1.5
- **3D pion pair distance distribution $D(\vec{\rho})$ constructed** in 6 centrality classes from 0—30%, 3 average transverse momentum k_T ranges, 15 different ranges of pair azimuthal angle relative to Ψ_2
- **$C(\vec{q})$ constructed from $D(\vec{\rho})$ via Fast Fourier Transform**

Fits to the constructed $C(\vec{q})$ correlation functions

- In case of a given cent., k_T and $\varphi_{\text{pair}} - \Psi_2$ range, **fully 3D fits** with the formula: $C(\vec{q}) = 1 + \lambda e^{-|\vec{q}^T R^2 \vec{q}|^{\alpha/2}}$
- Uncertainties on $C(\vec{q})$ are unphysical and uniform due to FFT, so rescaled with $\sqrt{\chi^2/\text{NDF}}$



Extracting azimuthal oscillations

- The PGCM configuration was studied without pre-equilibrium free streaming as well (★)
- Free streaming clearly has a significant effect on the radii magnitudes
- Azimuthal angle dependence parametrized as:

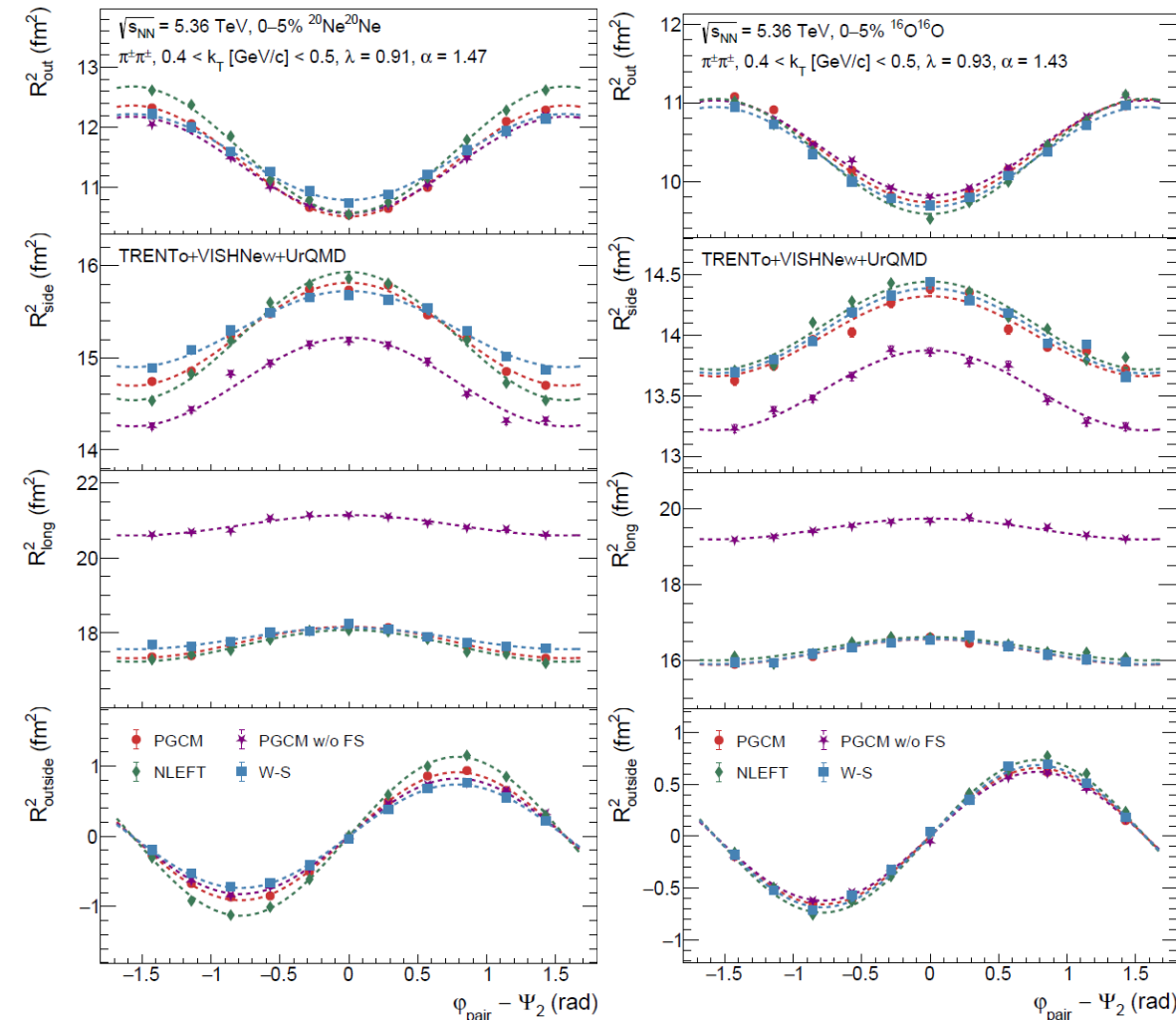
$$R_{\mu}^2(\varphi_{\text{pair}} - \Psi_2) = R_{\mu,0}^2 \left(1 + \varepsilon_{\mu} \cos \left(2(\varphi_{\text{pair}} - \Psi_2) \right) \right),$$

if $\mu = \text{out, side, long}$

$$R_{\mu}^2(\varphi_{\text{pair}} - \Psi_2) = R_{\mu,0}^2 + 2R_{\mu,2}^2 \sin \left(2(\varphi_{\text{pair}} - \Psi_2) \right),$$

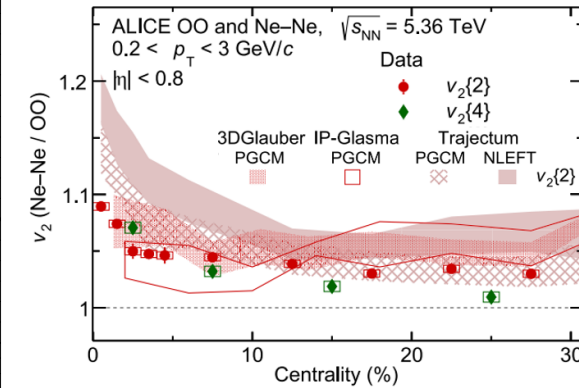
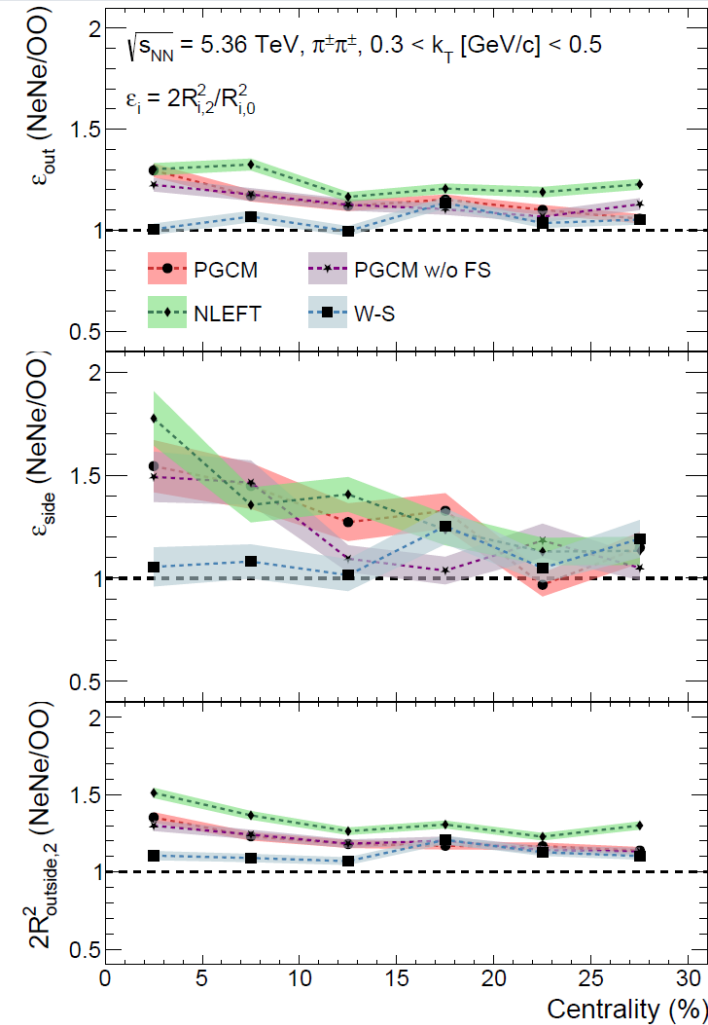
if $\mu = \text{out} - \text{side}$

- Fourier terms extracted as a function of centrality, and $m_T = \sqrt{k_T^2 + m_{\pi}^2}$
- NeNe/OO ratios of the parameters investigated



Femtoscopic freeze-out ellipticity ratios (NeNe/OO) centrality dependence

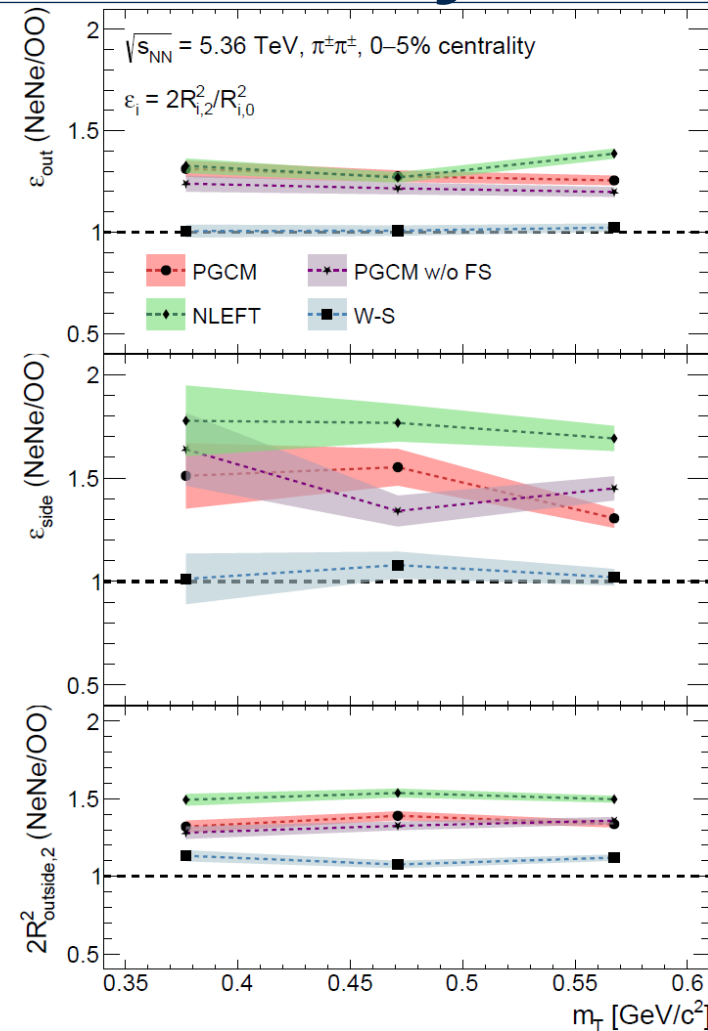
- Freeze-out eccentricity ratios shows the **same centrality trend as v_2 ratio**
- Ratios **unaffected by free streaming, the increase in central events is purely due to nuclear geometry**
- $\varepsilon_{\text{side}}$ shows no clear PGCM/NLEFT difference, **purely spatial observable**
- $\varepsilon_{\text{side}}$ central ratio **> 1.5, larger signal than v_2 !**
- $R_{\text{outside},2}^2$ cross-term amplitude shows significant NLEFT/PGCM differences



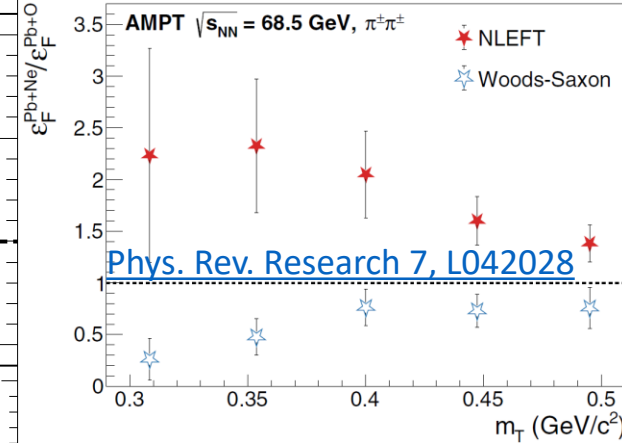
Femtoscopic freeze-out ellipticity ratios (NeNe/00) m_T dependence for 0–5% centrality

- Woods-Saxon baseline around unity
- No dependence on free streaming
- $\varepsilon_{\text{side}}$ ratio shows largest signal, > 1.5
- NLEFT $>$ PGCM in general

Such femtoscopic measurements could provide important additional constraints on nuclear geometry!

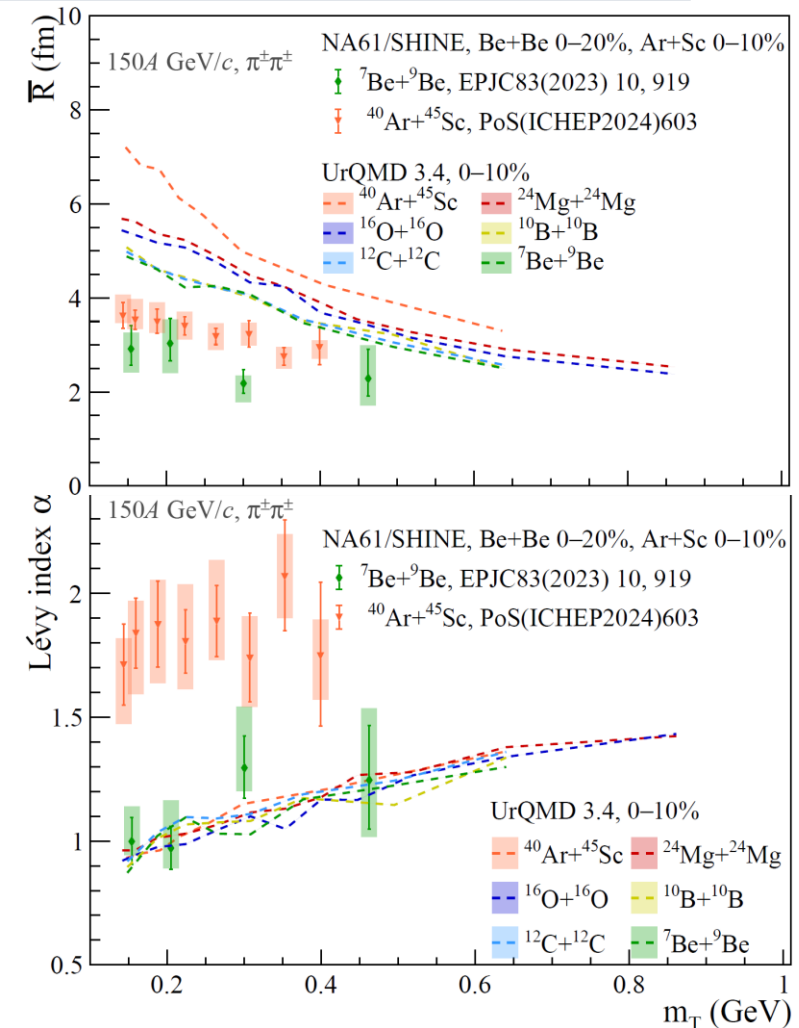


Similar to PbNe/PbO, AMPT



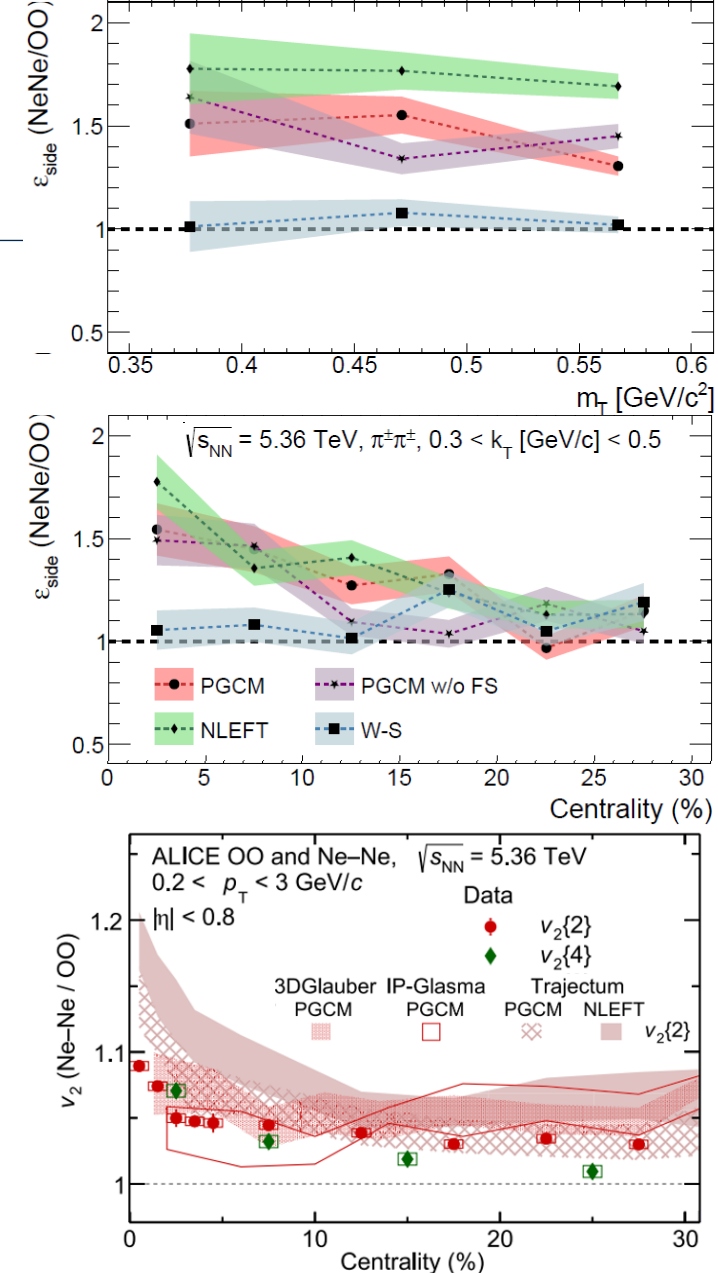
+1 topic: azimuthally integrated light-ion femtoscopy

- Pion femtoscopy measurements ongoing at NA61/SHINE
B. Pórfy, M. Csanád, [Phys.Lett.B 877 \(2026\) 140446](#)
B. Pórfy, [PoS ICHEP2024 \(2025\) 603](#),
NA61/SHINE, [Eur.Phys.J.C 83 \(2023\) 10, 919](#)
- Lévy scales show clear geometric system-size dependence, experimental data overestimated by UrQMD transport simulations
- **Lévy index α shows large system size dependence in experiment, but not in UrQMD transport simulations!**
- **Difference due to onset of hydrodynamics in Ar+Sc collisions?**
- **Collectivity in light-ion collisions could be studied at NA61/SHINE**

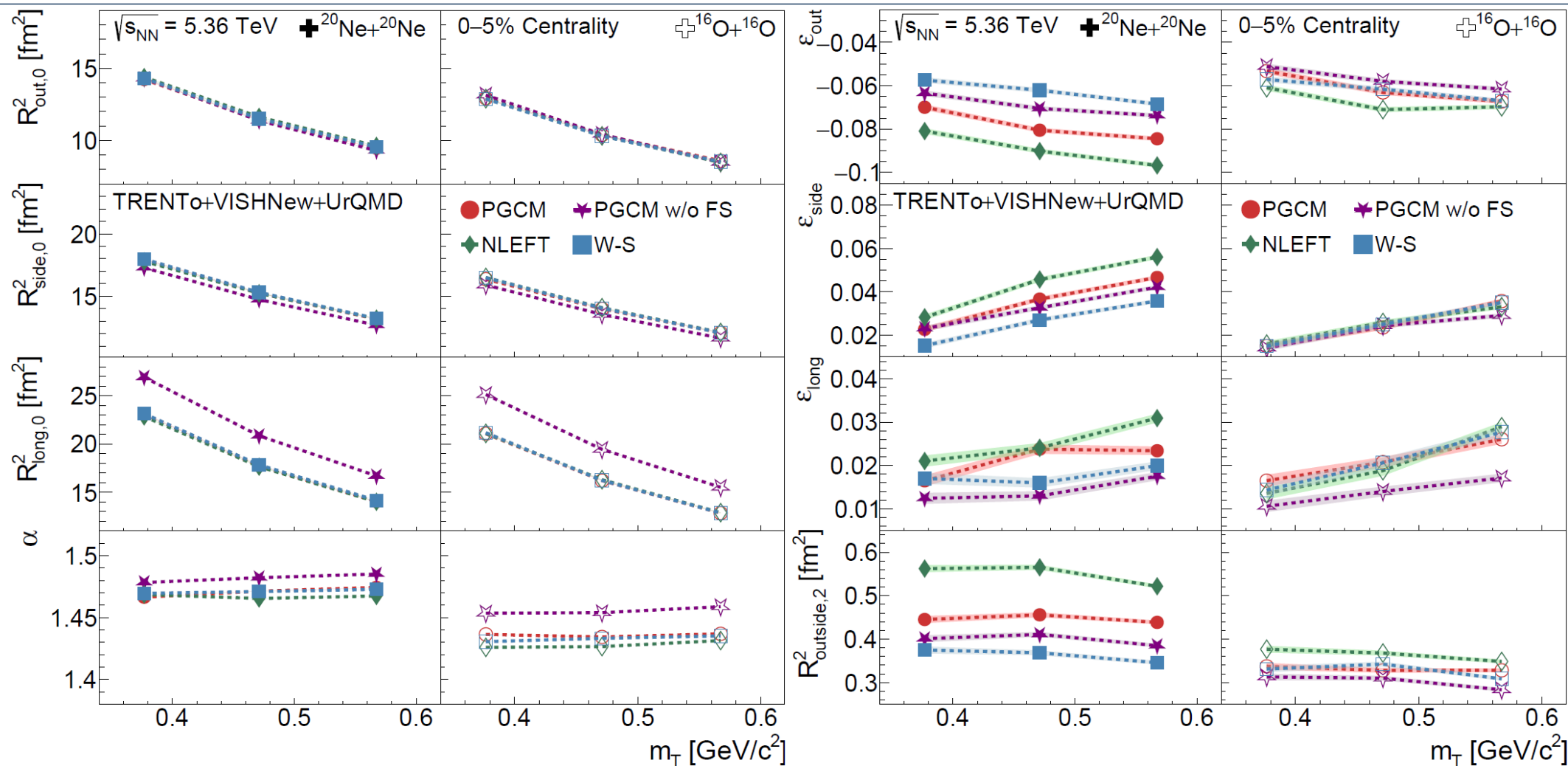


Summary and outlook

- Nuclear structure studies in high-energy collisions so far focused on anisotropic flow observables
- A proposed new observable: **freeze-out eccentricity ε** , determined from azimuthally sensitive pion femtoscopy with Lévy-stable source assumption
- The NeNe/OO ratio in central events is significantly larger than for v_2
- Ratio is robust against pre-equilibrium free streaming
- **New experimental measurements could provide important additional constraints on nuclear geometry calculations!**
- If you are interested in such topics: **come to the Zimányi School 2026!**



Further details – m_T dependence of the source parameters



Further details – centrality dep. of the source parameters

