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Femtoscopic signatures of unique nuclear structures in relativistic collisions

Phys. Rev. Research 7, L042028

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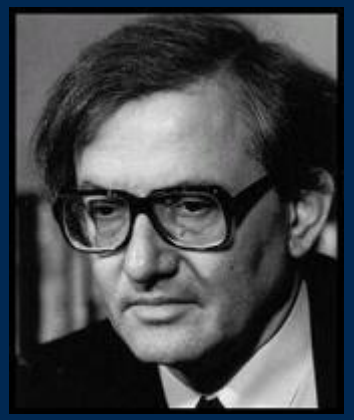
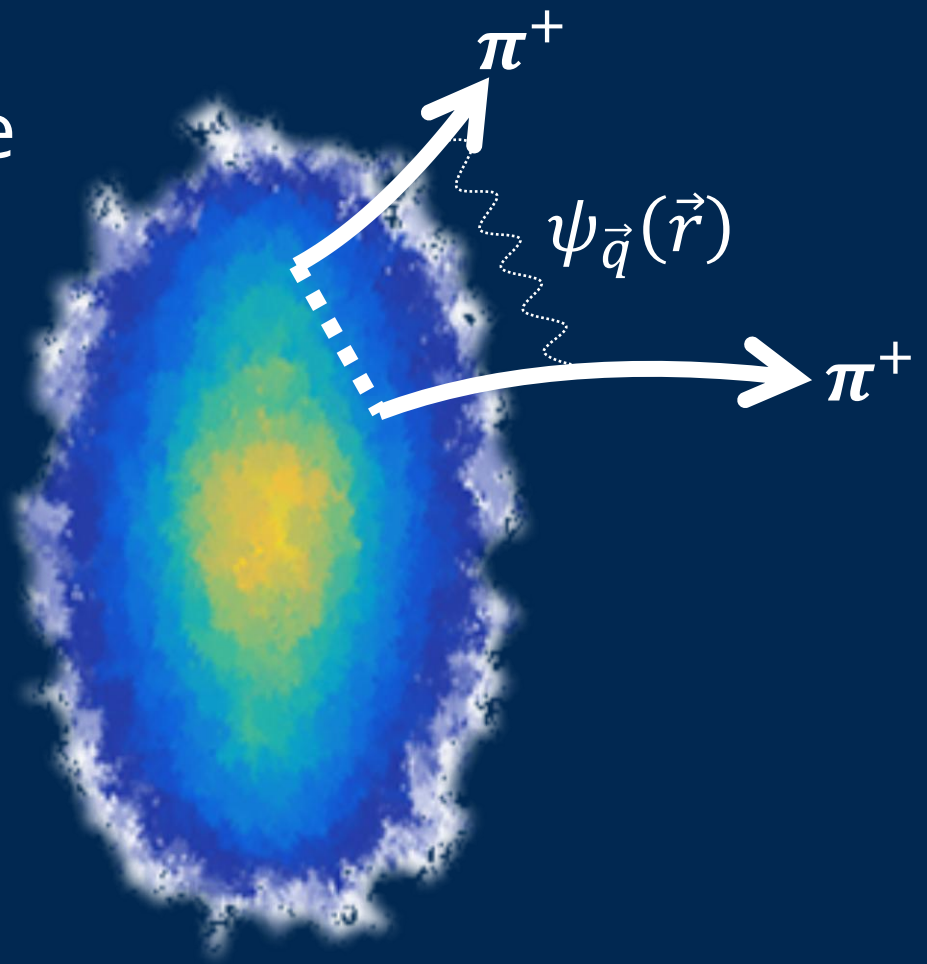
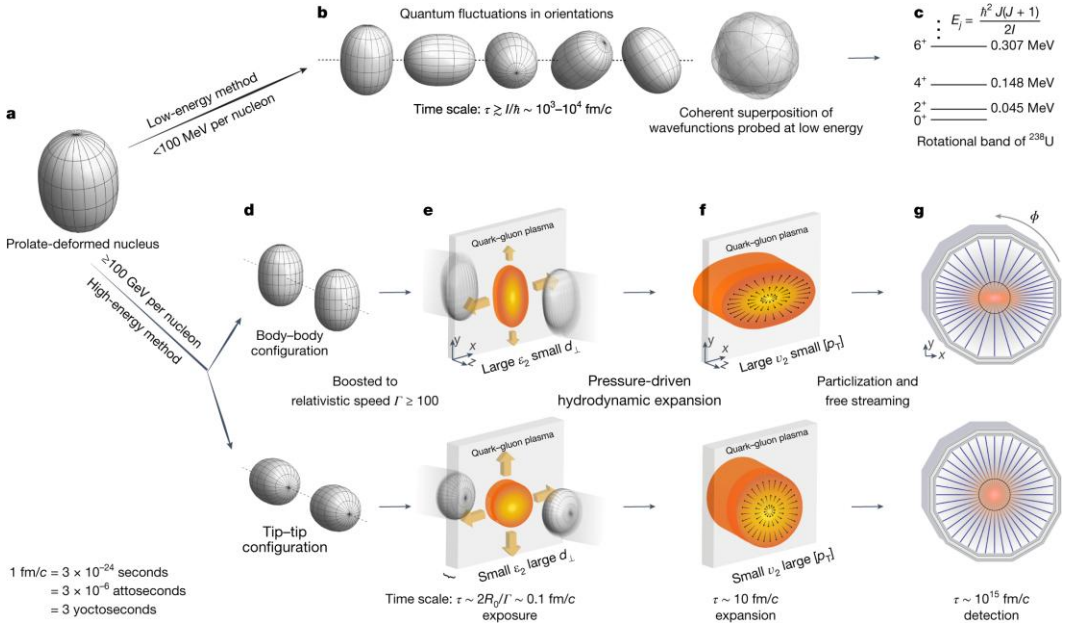
25th Zimányi School, Budapest



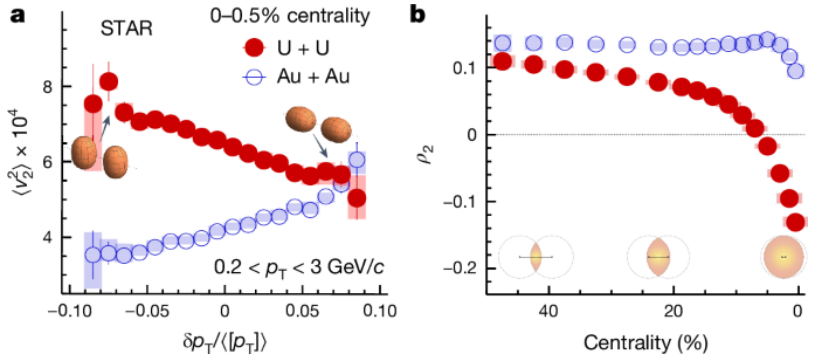


Motivation

- **Nuclear structure imaging in high-energy collisions** – hot topic, many interesting new results
  - Sensitivity of anisotropic flow and its correlations with transverse momentum demonstrated



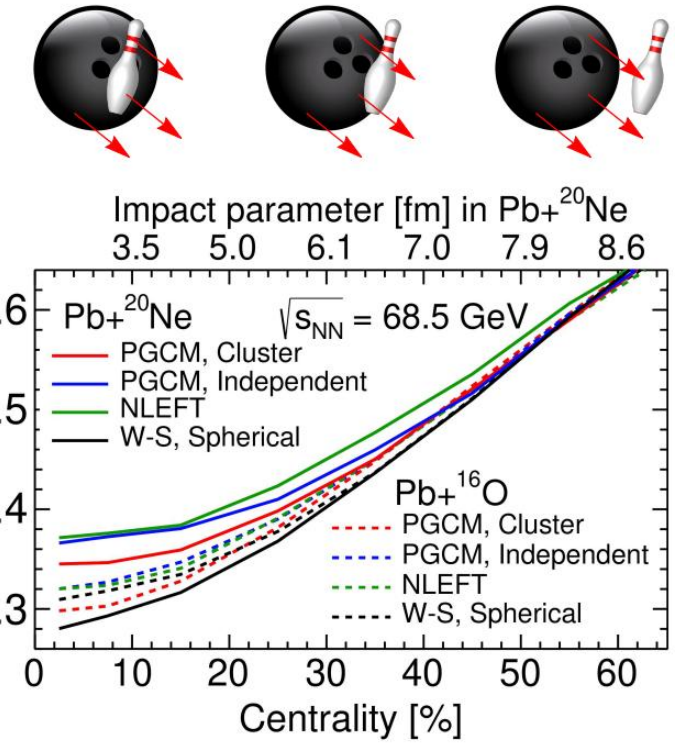
- STAR, Nature (London) **635**, 67 (2024)
- G. Giacalone et al., Phys. Rev. Lett. **127**, 242301 (2021)
- S. Zhao et al., Phys. Rev. Lett. **133**, 192301 (2024).
- For a more comprehensive list, see Phys. Rev. Research 7, L042028



- Could there be other important observables? **What about femtoscopy?**

Nuclear bowling alley

- **Goal:** investigate if femtoscopic observables can show sensitivity to nuclear structure
- **Choice of system to study:** $\sqrt{s_{NN}} = 68.5$ GeV ^{208}Pb+^{20}Ne and ^{208}Pb+^{16}O, relevant for LHCb SMOG2
- Anisotropic flow studies for this system have been published:
  - Z. Lu et al., Phys. Lett. B **868**, 139698 (2025) → AMPT
  - G. Giacalone *et al.,* Phys. Rev. Lett. **134**, 082301 (2025).
    → 3DGlauber+MUSIC+UrQMD
- Bowling-pin shape of Ne → imprint on initial state ellipticity
- **Ultra central case: large differences between PbNe and PbO**



- Spherical Woods-Saxon shape: $\varepsilon_2\{2\}\,(\mathrm{PbNe}) < \varepsilon_2\{2\}\,(\mathrm{PbO})$
- Bowling-pin shape: $\varepsilon_2\{2\}\,(\mathrm{PbNe}) > \varepsilon_2\{2\}\,(\mathrm{PbO})$

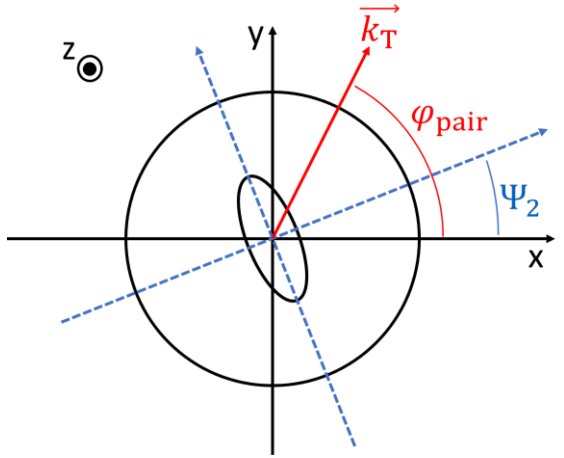
- **Can this ordering show up in the freeze-out eccentricity determined by femtoscopy?**

Femtoscopy with Lévy sources

- Momentum correlation C related to pair-distance distribution D through pair wave function ψ:
  - $C_2(\vec{q},\vec{K}) = \int d^3\vec{\rho} D_{\vec{K}}(\vec{\rho})\left|\psi_{\vec{q}}(\vec{\rho})\right|^2$
- Shape of **pair distance distribution** for identical pions → **elliptically contoured 3D Lévy-stable distr.**:
  - $D(\vec{\rho}) = \mathcal{L}(\alpha, R^2, \vec{\rho}) = \frac{1}{(2\pi)^3}\int d^3y e^{i\vec{\rho}\cdot\vec{y}} e^{-\frac{1}{2}\left|\vec{y}^T R^2 \vec{y}\right|^{\frac{\alpha}{2}}}, \quad R^2 = \begin{pmatrix} R^2_{\text{out}} & R^2_{\text{out-side}} & R^2_{\text{out-long}} \\ R^2_{\text{out-side}} & R^2_{\text{side}} & R^2_{\text{side-long}} \\ R^2_{\text{out-long}} & R^2_{\text{side-long}} & R^2_{\text{long}} \end{pmatrix}$
  - **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 $\vec{k}_{\text{T}}$ average transverse momentum of the pion pair
    - „**out**" is the direction of $\vec{k}_{\text{T}}$, „**long**" is the beam direction, „**side**" is perpendicular to the others
- 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
- **Radii oscillations → freeze-out shape!**
  - $R_\mu^2\left(\varphi_{\mathrm{pair}}-\Psi_2\right)=R_{\mu,0}^2+2R_{\mu,2}^2\cos\left(2\left(\varphi_{\mathrm{pair}}-\Psi_2\right)\right)$, if $\mu=\mathrm{out},\mathrm{side},\mathrm{long},\mathrm{out}-\mathrm{long}$
  - $R_\mu^2\left(\varphi_{\mathrm{pair}}-\Psi_2\right)=R_{\mu,0}^2+2R_{\mu,2}^2\sin\left(2\left(\varphi_{\mathrm{pair}}-\Psi_2\right)\right)$, if $\mu=\mathrm{out}-\mathrm{side},\mathrm{side}-\mathrm{long}$
- Relative oscillation in the side direction → **femtoscopic ellipticity parameter** (freeze-out eccentricity)
  - $\varepsilon_F=2\dfrac{R_{\mathrm{side},2}^2}{R_{\mathrm{side},0}^2}$
- Can the initial ellipticity remain through the medium evolution, and leave an imprint on the freeze-out shape?



AMPT simulations

- $\sqrt{s_{NN}} = 68.5$ GeV ^{208}Pb+^{20}Ne and ^{208}Pb+^{16}O collisions investigated with the **AMPT transport model**
- Two initial nucleon configuration studied:
  - **Wood-Saxon** → spherically symmetric
  - **Nuclear Lattice Effective Field Theory (NLEFT)** → resembles α-clusters (tetrahedron shape for O, bowling pin shape for Ne, configurations rotated randomly)
- 100,000 ultra central (b = 0) events simulated for each system, and for each nucleon configuration
- 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

- **Pion pair distance distribution $D(\vec{\rho})$ constructed** in 5 different average transverse momentum k_T ranges, and 15 different ranges of pair azimuthal angle relative to Ψ_2

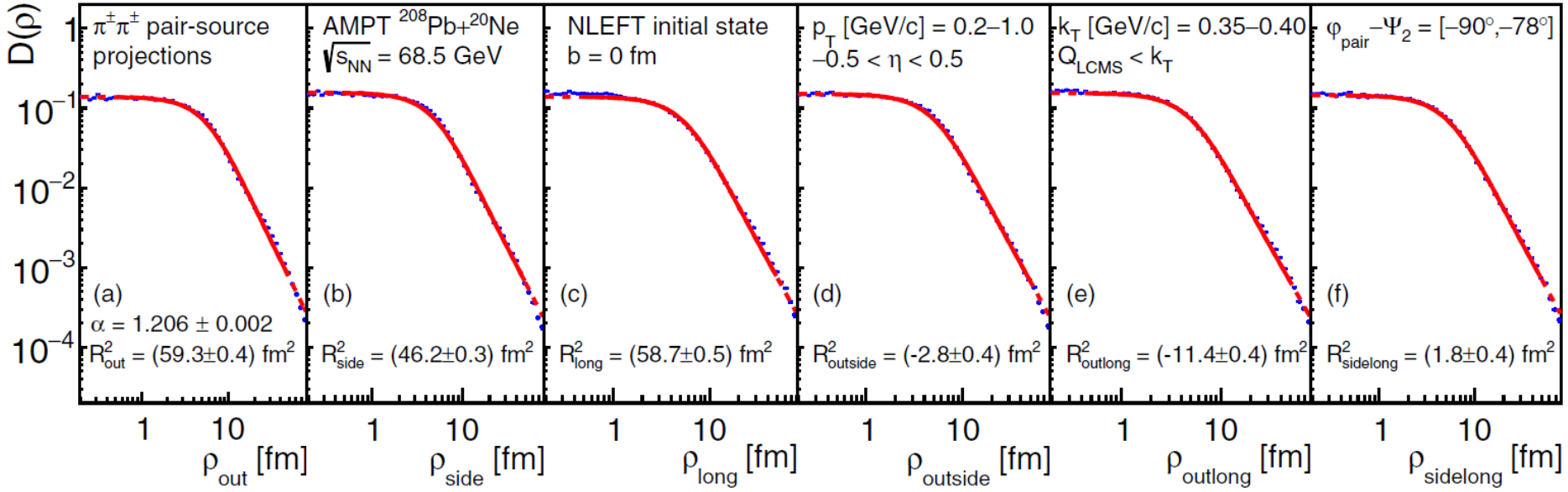
Fits to the constructed D(ρ) distributions

- One-dimensional projections of the 3D source distribution along six different directions:

$$\vec{e}^{(o)} = (1,0,0), \quad \vec{e}^{(os)} = \frac{1}{\sqrt{2}}(1,1,0),$$
$$\vec{e}^{(s)} = (0,1,0), \quad \vec{e}^{(ol)} = \frac{1}{\sqrt{2}}(1,0,1),$$
$$\vec{e}^{(l)} = (0,0,1), \quad \vec{e}^{(sl)} = \frac{1}{\sqrt{2}}(0,1,1).$$

$$\mathcal{L}^{1D}(\rho_\nu, \alpha, R_\nu) = \frac{1}{2\pi}\int dq\, e^{iq\rho_\nu} e^{-\frac{1}{2}|qR_\nu|^\alpha}, \text{ where}$$
$$\rho_\nu = \vec{e}^{(\nu)} \cdot \vec{\rho}, \quad R_\nu = \sqrt{\vec{e}^{(\nu),T} R^2 \vec{e}^{(\nu)}},$$
$$\nu = o, s, l, os, ol, sl.$$

- In case of a given k_T and $\varphi_{\text{pair}} - \Psi_2$ range, six projections are fitted simultaneously:



Extracting azimuthal oscillations

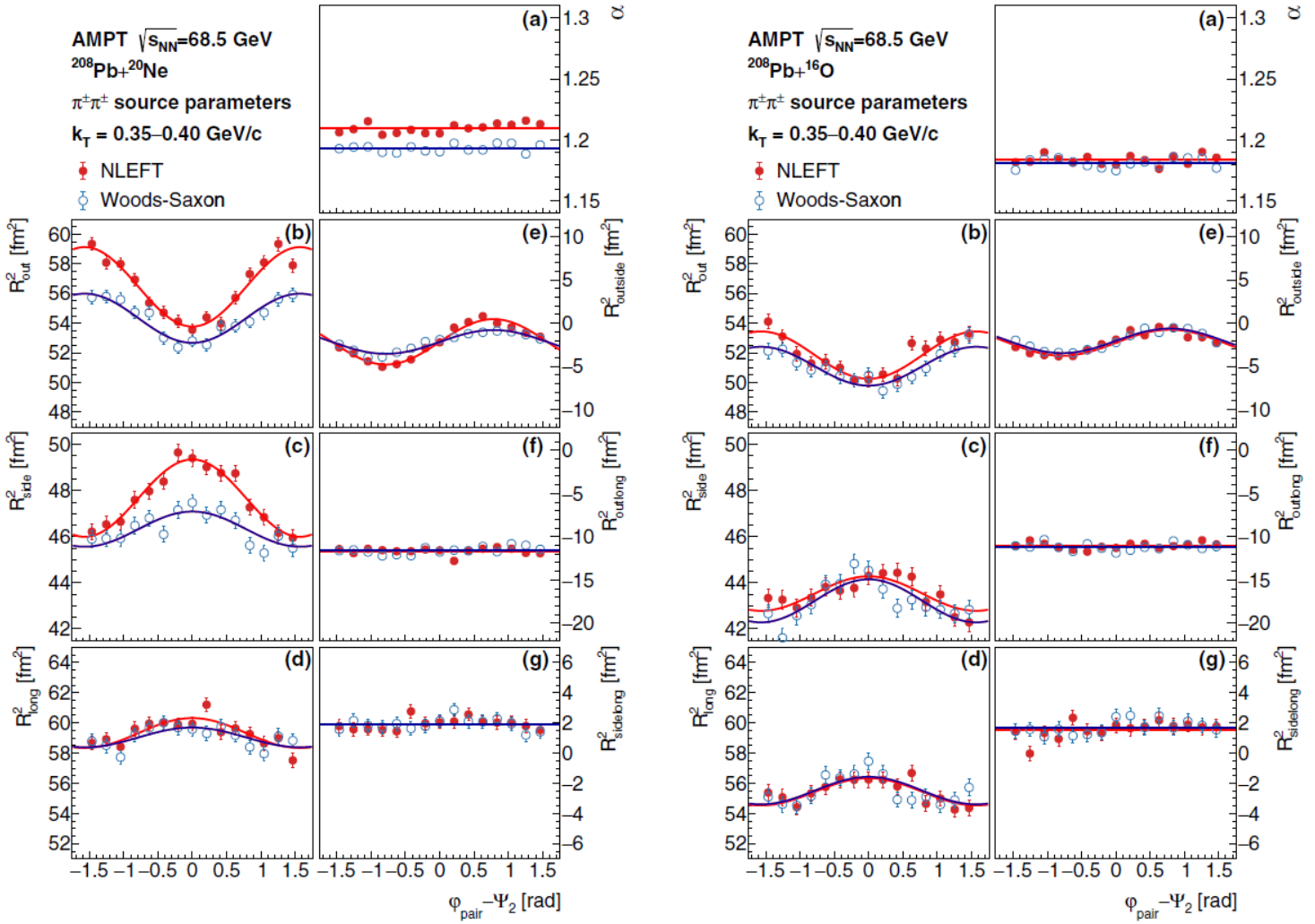
- At each k_T range, the azimuthal angle dependence is parametrized as:

$$R^2_\mu(\varphi_{\text{pair}} - \Psi_2) = R^2_{\mu,0} + 2R^2_{\mu,2}\cos(2(\varphi_{\text{pair}} - \Psi_2)),$$
$$\text{if } \mu = \text{out, side, long, out-long}$$

and

$$R^2_\mu(\varphi_{\text{pair}} - \Psi_2) = R^2_{\mu,0} + 2R^2_{\mu,2}\sin(2(\varphi_{\text{pair}} - \Psi_2)),$$
$$\text{if } \mu = \text{out-side, side-long.}$$

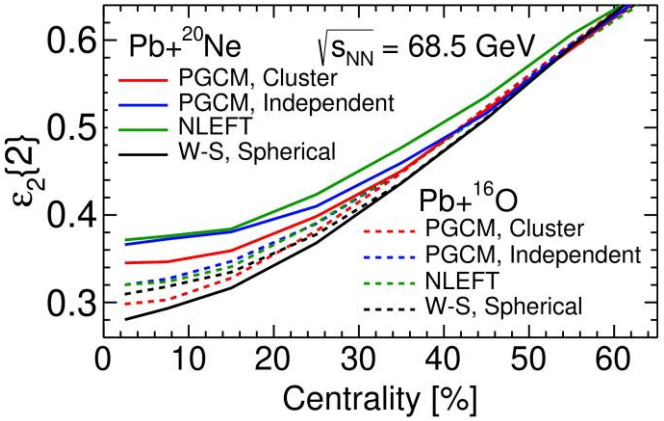
- Relative oscillation extracted as a function of $m_T = \sqrt{k_T^2 + m_\pi^2}$

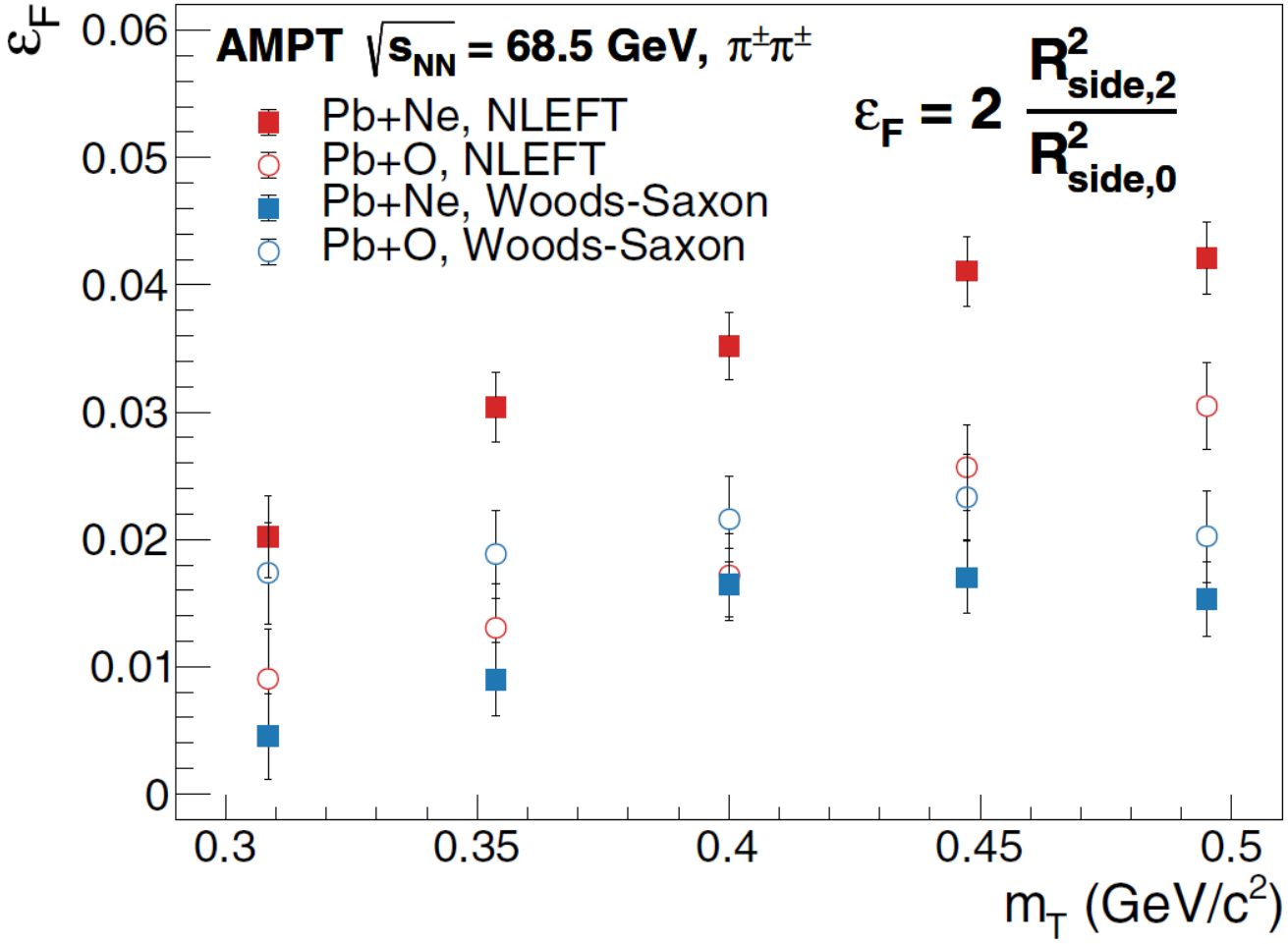


Femtoscopic freeze-out ellipticity

- **Freeze-out eccentricity shows the same ordering as initial state ellipticity!**

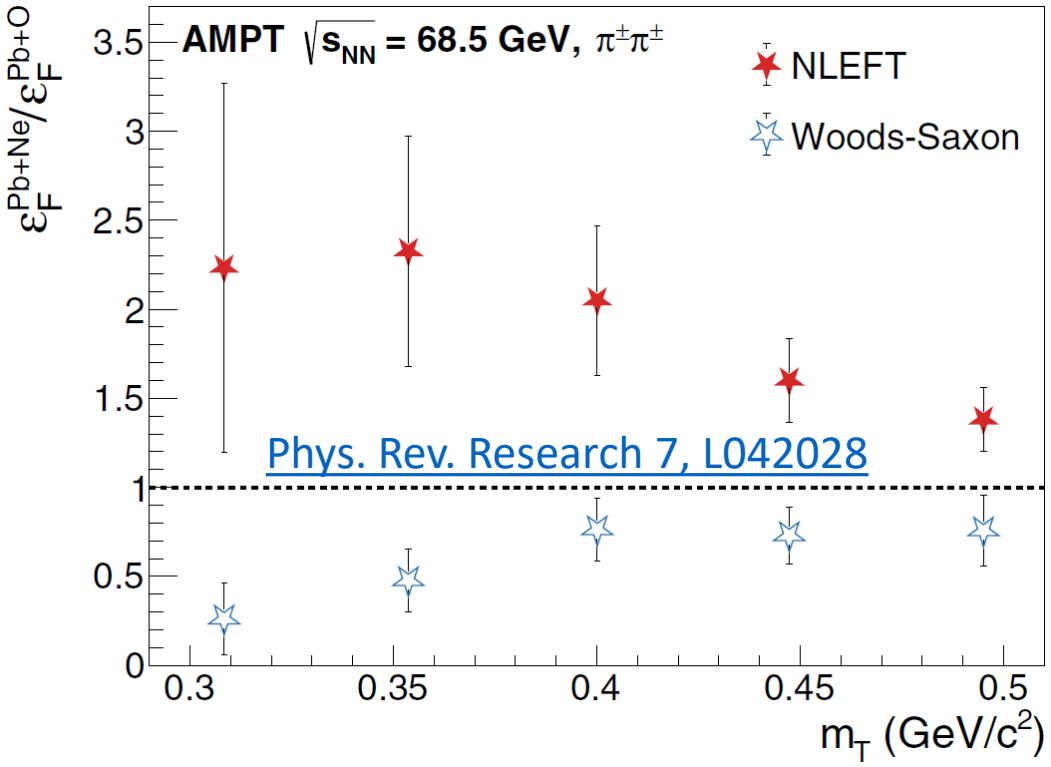
- Spherical Woods-Saxon shape:
  - ε_F (PbNe) $<$ ε_F (PbO)
- NLEFT bowling-pin shape:
  - ε_F (PbNe) $\gg$ ε_F (PbO)

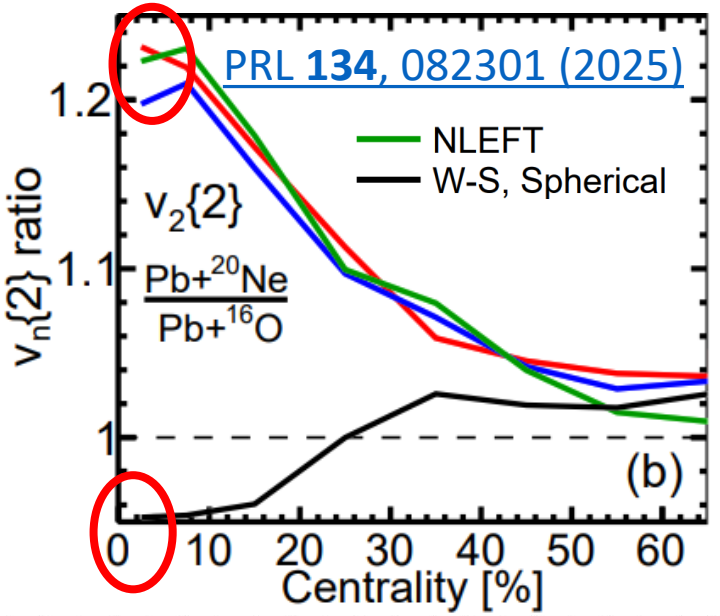


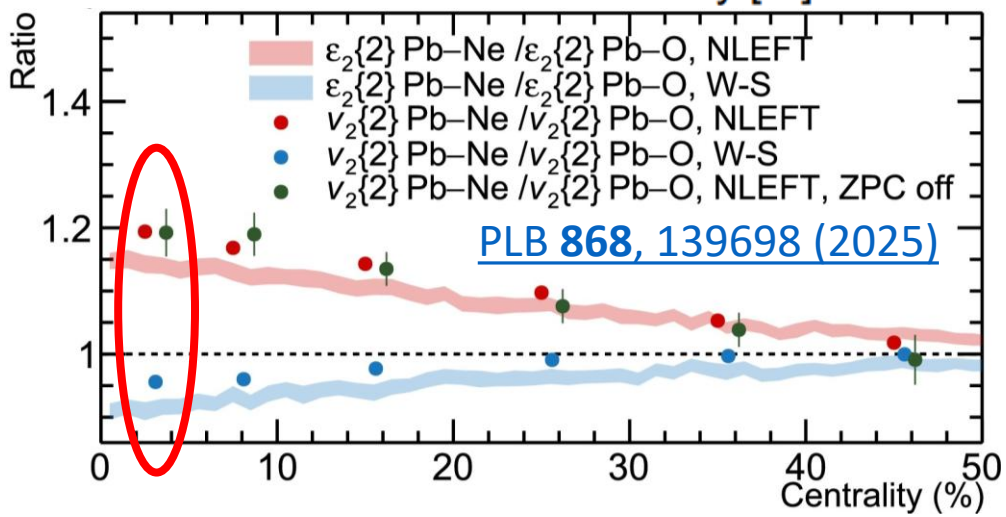


Pb+Ne / Pb+O ratios

- Ratio of observables provide better experimental distinction
- **Femtoscopic freeze-out eccentricity shows even larger differences between WS and NLEFT, than $v_2\{2\}$!**

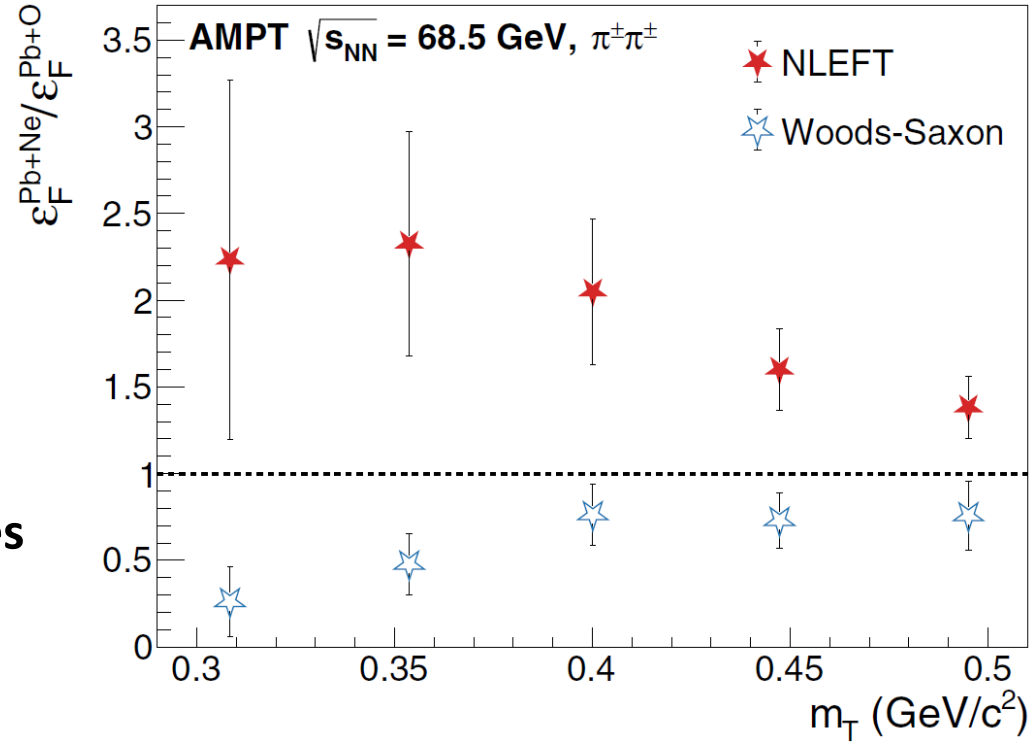






Summary

- Nuclear structure studies in high-energy collisions so far mostly focused on anisotropic flow observables
- A proposed new observable: **freeze-out eccentricity ε_F,** determined from azimuthally sensitive pion femtoscopy with a Lévy-stable source assumption
- **AMPT study of ultra-central Pb+Ne and Pb+O collisions**
  - ε_F determined for spherical Woods-Saxon and deformed NLEFT nucleon configurations
  - **Ratio of this observable provides a strong distinction between the spherical and the deformed initial states**
  - Next step: check what happens in hydro models!
- **This pilot study demonstrates that femtoscopic observables can be sensitive to nuclear structure as well**



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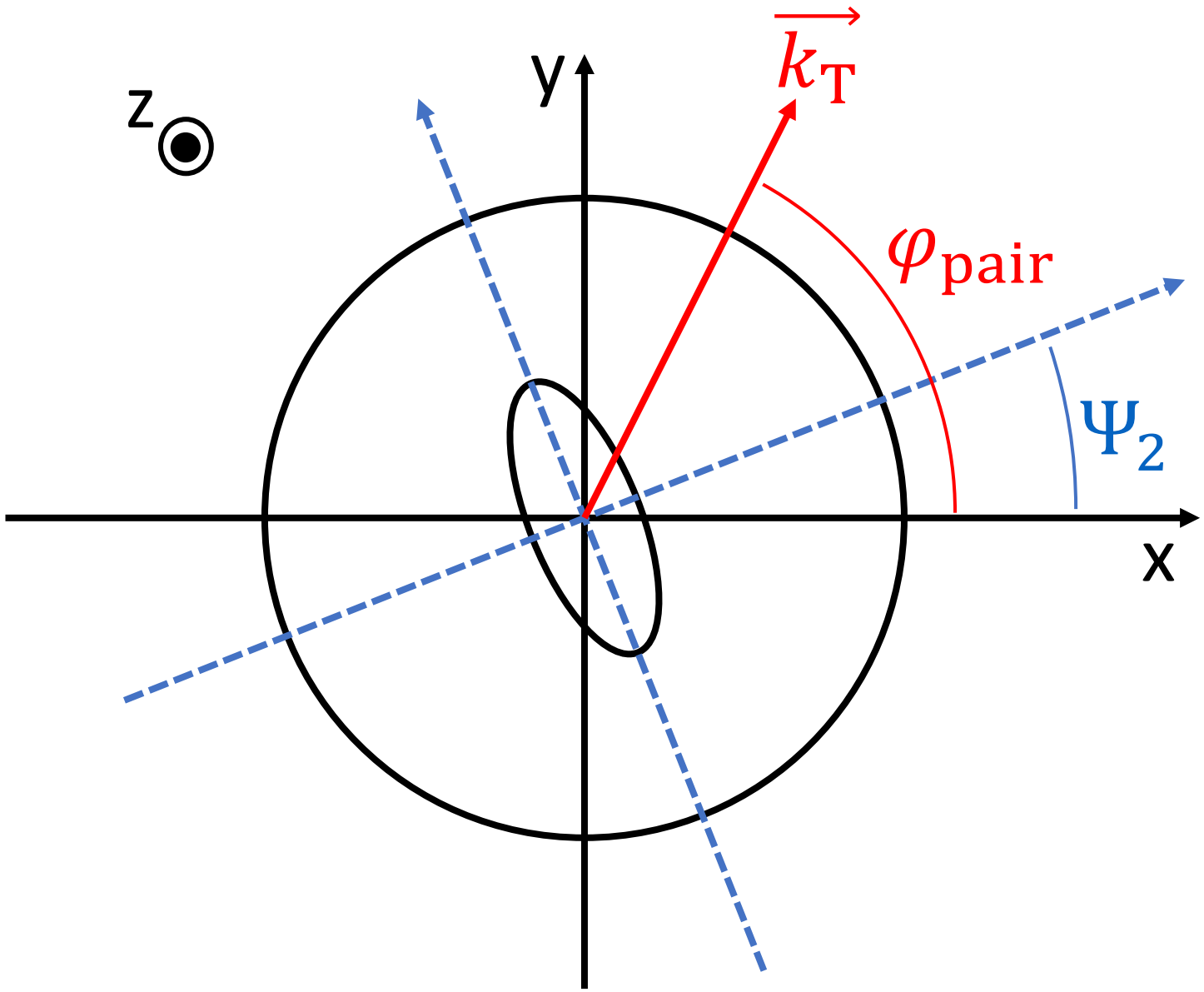
z
y
x
$\overrightarrow{k_T}$
φ_{pair}
Ψ_2