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Probing nuclear deformation in ultra-relativistic heavy-ion collisions with standardized cumulants of mean transverse momentum fluctuations

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Abstract

While most nuclei generally poses an intrinsic deformation, the most significant contribution is caused by the quadrupole moment characterized by strength β_2, and the axial structure γ. We present direct measurement of higher-order standardized cumulants of mean transverse momentum fluctuation as a fine probe for accessing initial conditions of AA collision of deformed nuclei due to sensitivity to strength β_2 and triaxiality γ.

Nuclear deformation

- Deformation caused by multipole moments of the nucleon density function.
- Low energy experiments mostly based on proton charge distribution
- Use high-energy physics to probe the complete nucleon distribution

Model the complete nucleon distribution by the *Wood-Saxon* potential

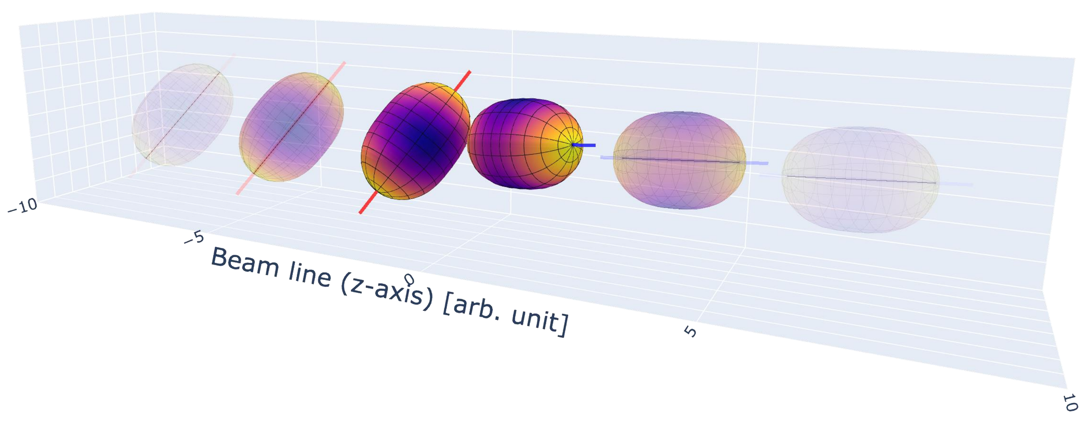
$$\rho(r,\theta,\varphi) = \frac{n_0}{1+\exp([r-R'(\theta,\varphi)]/a_0)}$$

Where n_0 is the nucleon density and a_0 is the surface diffusion. For deformed nuclei the nuclear surface $R'(\theta,\varphi)$ can be expressed by spherical harmonics parametrized by the strength β_2 and triaxiality γ

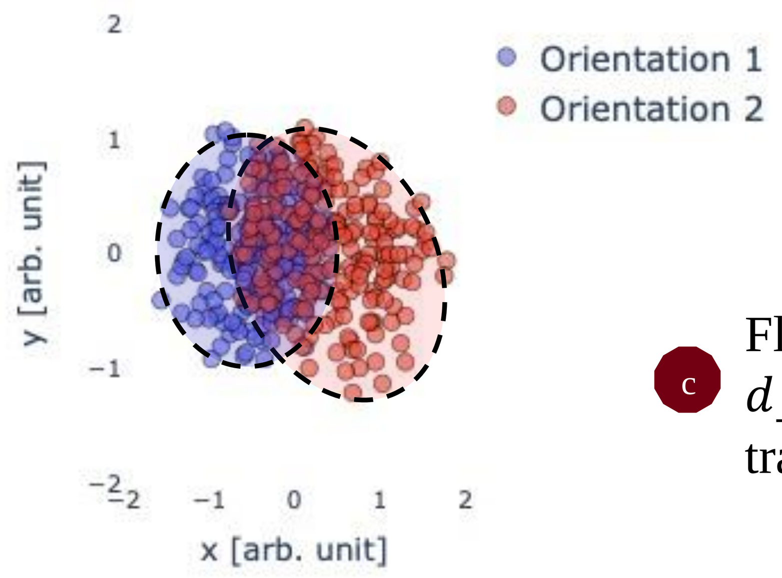
$$R'(\theta,\varphi) = R_0(1+\beta_2[\cos(\gamma)\,Y_{20}(\theta,\varphi)+\sin(\gamma)\,Y_{22}(\theta,\varphi)])$$

Effect of deformation in heavy-ion collision

a — Nuclei can collide with different orientations



b — Transverse nucleon density $d_\perp$ in the overlap region of the colliding nuclei fluctuates with the orientation



c — Fluctuation in transverse nucleon density $d_\perp$ causes final state fluctuation in the transverse momentum spectrum [1]

$$-k_0\frac{\delta R_\perp}{R_\perp} = k_0\frac{\delta d_\perp}{d_\perp} = \frac{\delta\langle p_T\rangle}{\langle p_T\rangle}$$

1. Unravelling nuclear shapes in heavy-ion collision with cumulants

- In the QGP stage, particles becomes correlated through their mutual energy distribution.
- Genuine m-particle correlation probes event-by-event fluctuation of the $\langle p_T\rangle$ distribution.

The experimental process is as follows

i. Probe the complete m-particle $\langle p_T\rangle$ distribution with intrinsic moments

$$\langle p_T'^{\,m}\rangle \equiv \frac{\sum_{i_1\neq\cdots\neq i_m}^{N_{ch}} w_{i_1}w_{i_2}\cdots w_{i_m}\,p_T^{(i_1)}\,p_T^{(i_2)}\cdots p_T^{(i_m)}}{\sum_{i_1\neq\cdots\neq i_m}^{N_{ch}} w_{i_1}w_{i_2}\cdots w_{i_m}}$$

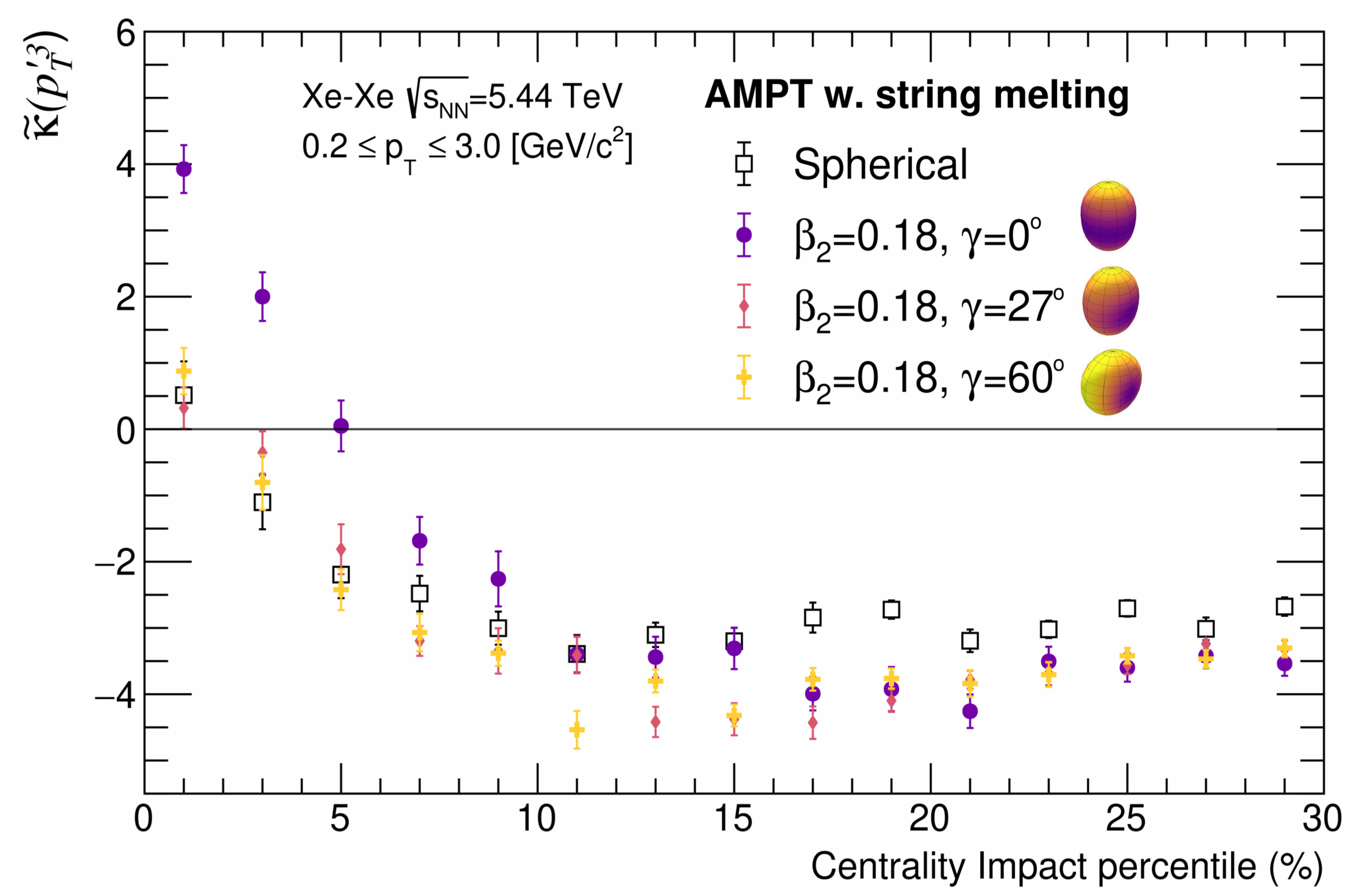
ii. Decompose distribution into a series of correlation functions[2]

iii. Isolate for the genuine correlation, denoted as the cumulant $\kappa(p_T'^m)$

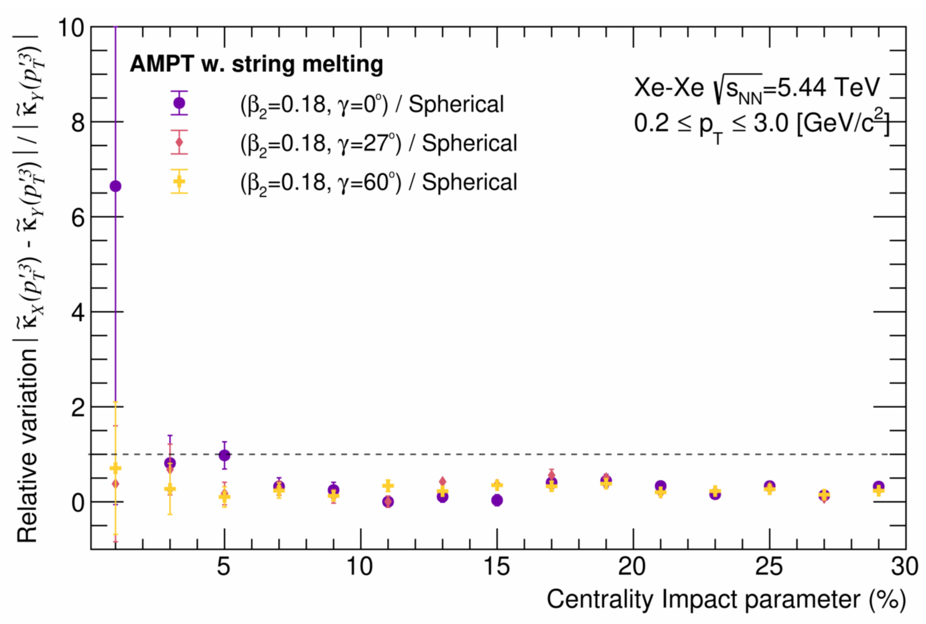
$$\kappa(p_T'^2) = \langle\langle p_T'^2\rangle\rangle - \langle\langle p_T'^1\rangle\rangle^2 \qquad \kappa(p_T'^3) = \langle\langle p_T'^3\rangle\rangle - 3\langle\langle p_T'^1\rangle\rangle\,\langle\langle p_T'^2\rangle\rangle + 2\,\langle\langle p_T'^3\rangle\rangle$$

Standardized scaling $\tilde{\kappa}(p_T'^3) = \kappa(p_T'^3)/\sqrt{\kappa(p_T'^2)^3}$

- Eliminate unknown transport properties
- Compare different collision system



2. Sensitivity to overall deformation β_2 and γ



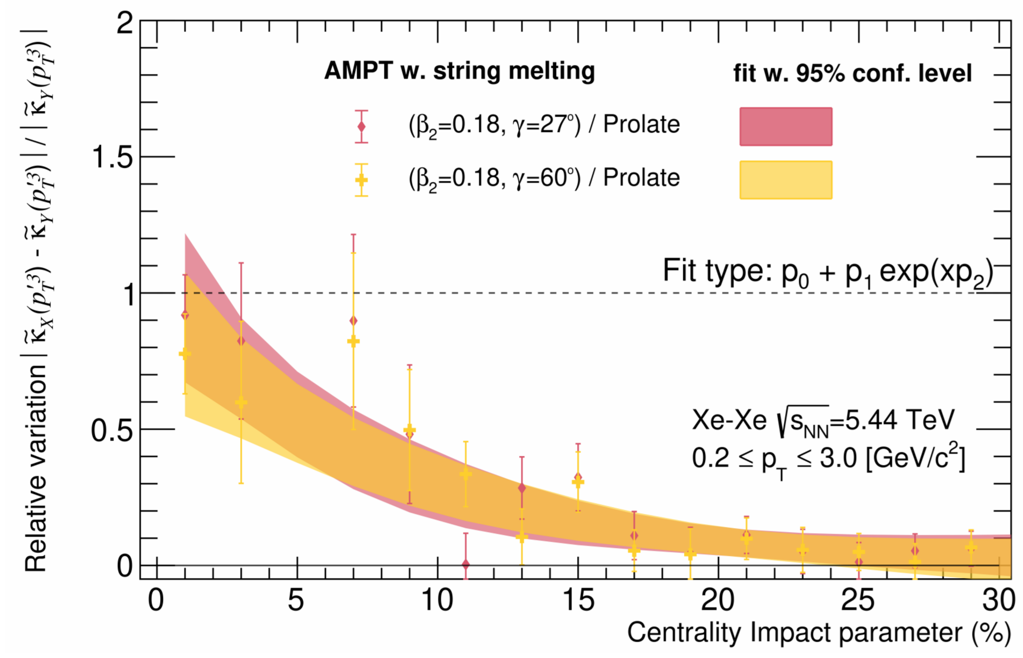
Motivation: While there are significant differences in AMPT calculations, the observables need to be accessible in experiments

Method: Deviation in the p_T spectrum is calculated with the relative variation between standardized cumulants.

$$\frac{|\tilde{\kappa}_X(p_T'^3) - \tilde{\kappa}_Y(p_T'^3)|}{|\tilde{\kappa}_Y(p_T'^3)|}$$

- Large variation w.r.t prolate nucleus
- Grouping between all quadrupole deformed nuclei for centrality > 15
- Similar trends for $\gamma = 27°$ and $\gamma = 60$
- No obvious trend that can be predicted with current statistic

3. Sensitivity to triaxiality γ



Motivation: Triaxiality is challenging to probe experimentally in low energy experiments.

Method: Deviation in the p_T spectrum is calculated with the relative variation between standardized cumulants.

- Trend persist over wide centrality range
- Diminishing variation for increased centrality:
  - Snap-Shot effect
- Small difference between $\gamma = 27°$ and $\gamma = 60°$

Fit to initial stage calculations

Motivated by initial stage calculation[1] the final state p_T fluctuations are fitted with a functional type on the form $a' + c'\cos(3\gamma)$, see fit statistic to the right, fit are plotted with 95% confidence level

$f(x) = p_0 + p_1 e^{x\cdot p_2}$	$f(0)$	$f(\infty)$	χ^2/NDF
Triaxial / Prolate	1.12	0.051	6.3 / 12
Oblate / Prolate	0.95	0.052	10.1 / 12

References and Acknowledgement

[1] Jiangyong Jia, "*Probing triaxial deformation of atomic nuclei in high-energy heavy ion collisions*" In: *Physical Review C* **105**. no. 4, (Apr. 2022)

[2] N.G. Van Kampen. "Chapter II - RANDOM EVENTS". In: Stochastic Processes in Physics and Chemistry. Third Edition. Amsterdam: Elsevier, 2007

The data presented in this document represents a portion of the research conducted during my master's thesis at the Niels Bohr Institute. While the work presented here reflects my own efforts, it is important to acknowledge the valuable contributions of others. I am grateful for the insightful discussions, feedback, and corrections provided by the brilliant individuals I have had the privilege to collaborate with. I extend my sincere appreciation to the HEHI group at NBI for their support and guidance throughout this project.

Conclusion

- $\tilde{\kappa}(p_T'^3)$ has shown to poses a sensitive to deformation, her both strength β_2 and γ.
- Diminishing difference in $\tilde{\kappa}(p_T'^3)$ calculation as the nuclei goes towards the peripheral range, snap-shot effect.
- Standardized ratios of $\tilde{\kappa}(p_T'^3)$ shows similar behaviour as in initial stage calculations.
- For nuclei with same quadrupole strength β_2, the observed effect w.r.t triaxiality γ is significant.