Transverse momentum dependent flow correlation in spherical and deformed nuclei collisions

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Motivation

- **Spatial anisotropy** at the initial state ⟶ **anisotropy in momentum distribution** of the final state particles ⟶ **flow harmonics** V_n

$$\frac{dN}{dp d\phi} = \frac{dN}{2\pi dp}\left(1 + 2\sum_{n=1}^{\infty} V_n(p) e^{in\phi}\right)$$

flow vector, $V_n(p) = |V_n(p)| e^{in\Psi_n(p)}$;
$|V_n(p)| \to$ flow magnitude
and $\Psi_n(p) \to$ flow angle ($p \equiv p_T$)

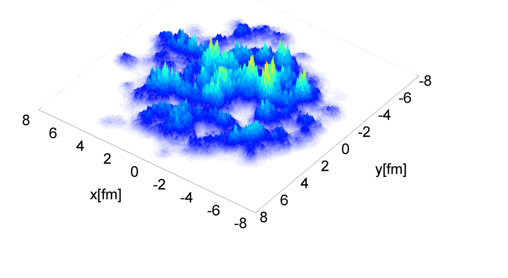

Fig. 1: Initial state fluctuation, arXiv: 1206.6805

- **Event-by-event fluctuation** of initial state ⟶ event-by-event fluctuation of V_n's ⟶ **decorrelations between the flow vectors** in two transverse momentum bins ⟹ **"factorization-breaking coefficients"** ⟶ **includes both flow magnitude and flow angle decorrelations.**

Model

- **Flow magnitude and flow angle decorrelation could not be measured with the first order correlation** ⟶ needs second order construction between the **squares of the flow** ⟶ $V_n(p)^2 - V_n^2$ correlations (one flow p-dependent and other p-averaged) ease measurement difficulty in experiment.
- The **flow vector square and flow magnitude square factorization coefficients** are constructed as,

$$r_{n;2}(p) = \frac{\langle V_n^2 V_n^*(p)^2 \rangle}{\sqrt{\langle |V_n|^4 \rangle \langle |V_n(p)|^4 \rangle}} \quad \text{and} \quad r_n^{v_n^2}(p) = \frac{\langle |V_n|^2 |V_n(p)|^2 \rangle}{\sqrt{\langle |V_n|^4 \rangle \langle |V_n(p)|^4 \rangle}}$$

- The **flow angle decorrelation** is obtained from the **ratio of the flow vector and flow magnitude** factorization coefficients,

$$F_n(p) = \frac{\langle V_n^2 V_n^*(p)^2 \rangle}{\langle |V_n|^2 |V_n(p)|^2 \rangle} = \frac{\langle |V_n|^2 |V_n(p)|^2 \cos[2n(\Psi_n - \Psi_n(p))] \rangle}{\langle |V_n|^2 |V_n(p)|^2 \rangle} \simeq \frac{\langle |V_n|^4 \cos[2n(\Psi_n - \Psi_n(p))] \rangle}{\langle |V_n|^4 \rangle}$$

Collision of deformed nuclei

- **Woods-Saxon density distribution** for the shape of atomic nucleus:

$$\rho(r,\theta,\phi) = \frac{\rho_0}{1 + e^{\frac{[r - R_0(1 + \beta_2 Y_2^0(\theta,\phi) + \beta_3 Y_3^0(\theta,\phi))]}{a_0}}}$$

$\beta_2 \longrightarrow$ **Quadrupole deformation**
$\beta_3 \longrightarrow$ **Octupole deformation**

- **Woods-Saxon parameters**:

Species	Type	R_0 (fm)	a_0 (fm)	β_2	β_3
^{208}Pb	Spherical	6.624	0.549	0	0
^{238}U	Deformed	6.86	0.42	0.265	0
^{96}Ru	Deformed	5.09	0.46	0.162	0
^{96}Zr	Deformed	5.02	0.52	0.06	0.20

$$v_n\{2\}^2 = a_n + b_n\beta_n^2 + \sum_{m \neq n} b_{n,m}\beta_m^2$$

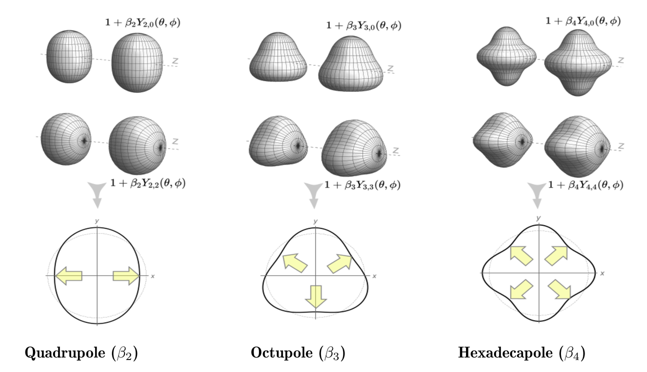

Fig. 2: Deformed structures of the nuclei, arXiv: 2106.08768

- Collision of deformed nuclei ⟶ **deformation affects the fluctuations of the flow vectors** ⟶ deformed structure could be probed by factorization-breaking coefficients; ^{238}U+^{238}U collision.
- **Isobar collision** between ^{96}Ru+^{96}Ru and ^{96}Zr+^{96}Zr ⟶ identical mass (same number of participants) but different deformed structures ⟶ **ideal candidates for the nuclear structure study !**

Conclusions and Outlook

- **Event-by-event flow fluctuations** in HI collision ⟶ **flow decorrelation in transverse momentum (p)** ⟶ **factorization-breaking coefficients**
- Extraction of flow magnitude and flow angle decorrelation ⟶ **correlators between the squares of flow** ⟶ one flow momentum dependent $V_n(p)$ and other flow momentum averaged V_n is **experimentally preferable**
- For spherical **Pb+Pb collision our model results reproduce the data** for factorization-breaking coefficients in central collision (0-5%)
- Factorization-breaking coefficients could be studied for **deformed nuclei collision (U+U)** ⟶ **deformation causes smaller decorrelation** ⟶ **a probe for nuclear deformation**
- Momentum dependent **mixed-flow correlation:** $V_2^2 - V_4(p)$ **and** $V_2V_3 - V_5(p)$ correlation ⟶ measure of **non-linear response** of the medium
- **Isobar collision (Ru+Ru and Zr+Zr)** ⟶ ideal candidates for nuclear structure study ⟶ **show difference in the mixed-flow correlator** due to different nuclear structures.

Model Results [PRC 105, 034904 (2022) and PRC 107, 054916 (2023)]

Factorization-breaking coefficients : Pb+Pb collision

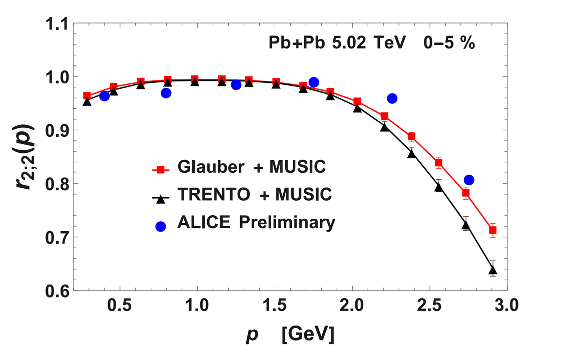

Fig. 3: Flow vector square factorization coefficient

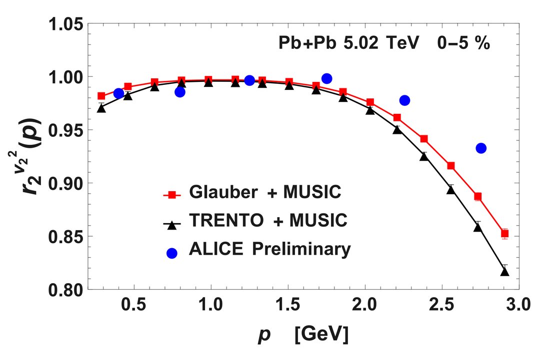

Fig. 4: Flow magnitude factorization coefficient

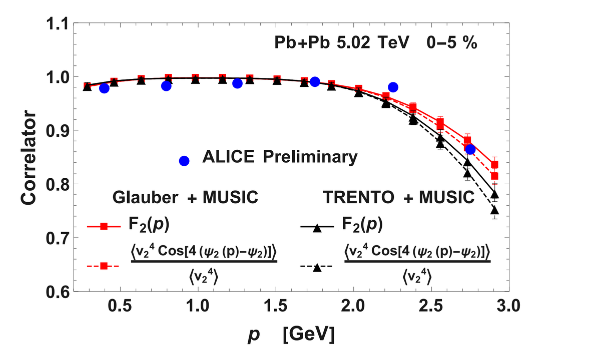

Fig. 5: Flow angle decorrelation

- For central collision (0-5 %) **our model results reproduce the data** for the elliptic flow.
- The flow magnitude and the flow angle decorrelation both are **approximately one half** of the flow vector decorrelation: $[1 - r_n^{v_n^2}(p)] \simeq \frac{1}{2}[1 - r_{n;2}(p)]$

Factorization-breaking coefficients : U+U collision

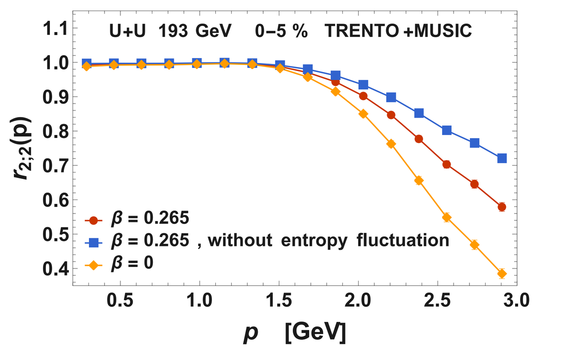

Fig. 6: Flow vector square factorization coefficient

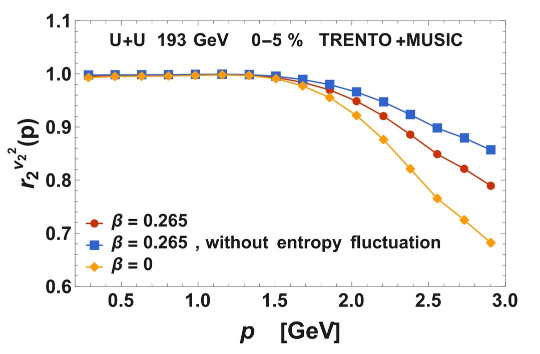

Fig. 7: Flow magnitude factorization coefficient

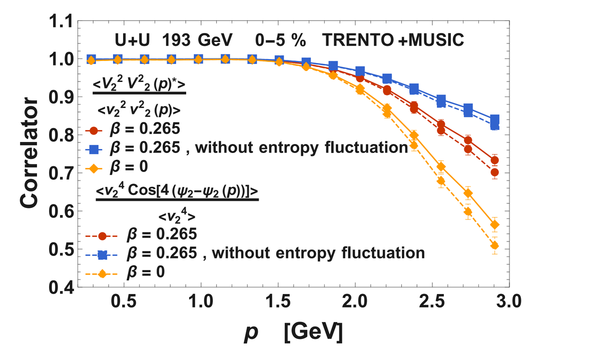

Fig. 8: Flow angle decorrelation

- **Significant difference in decorrelation** between the **spherical** ($\beta_2 = 0$) and **deformed** ($\beta_2 = 0.265$) U+U collision. Deformation **enhances** ϵ_2 in the initial state ⟶ **larger contribution of geometry to** v_2 ⟶ **lesser contribution of fluctuation** ⟶ **lesser decorrelation.**

Mixed-flow correlations: Ru+Ru and Zr+Zr isobar collision

- In isobar collision, **p-dependent mixed-flow correlations** between different orders of flow provide as **fine tool to probe nuclear structural difference** ⟶ also serves as a non-linear response of the medium e.g V_2^2-$V_4(p)$ and V_2V_3-$V_5(p)$ correlation:

$$\frac{\langle V_2^2 V_4^*(p) \rangle}{\sqrt{\langle |V_2|^4 \rangle \langle |V_4(p)|^2 \rangle}} \quad \text{and} \quad \frac{\langle V_2 V_3 V_5^*(p) \rangle}{\sqrt{\langle |V_2|^2 |V_3|^2 \rangle \langle |V_5(p)|^2 \rangle}}$$

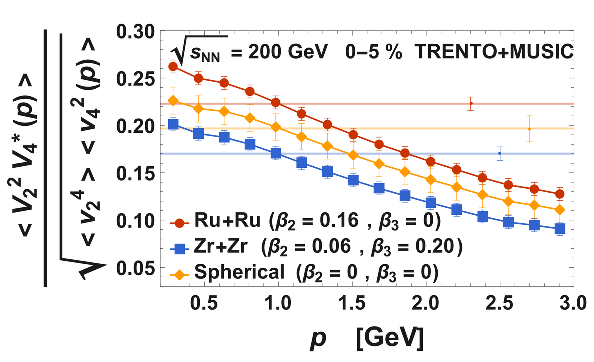

Fig. 9: V_2^2-$V_4(p)$ correlation for isobar collision

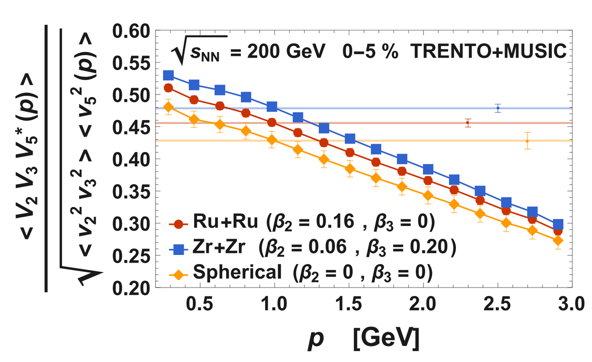

Fig. 10: V_2V_3-$V_5(p)$ correlation for isobar collision

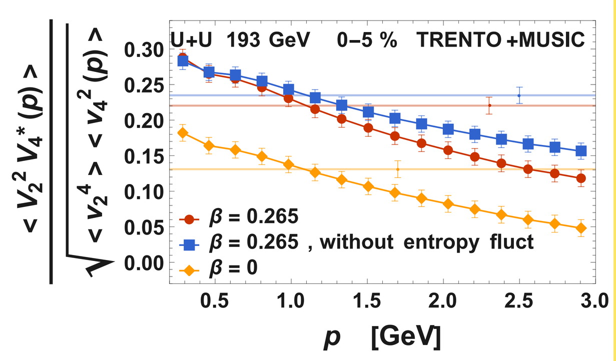

Fig. 11: V_2^2-$V_4(p)$ correlation for U+U collision

- **Structural difference** between Ru+Ru (*quadrupole* deformation) and Zr+Zr (*octupole* deformation) is **clearly reflected** in V_2^2-$V_4(p)$ and V_2V_3-$V_5(p)$ correlation. The horizontal lines being the correlation between the momentum averaged flows ⟶ **baselines**.
- Similar results for U+U collision. **The ratio of V_2^2-$V_4(p)$** between Ru+Ru and Zr+Zr **increases from central to (0-5 %) ultra-central (0-1 %)** collision.

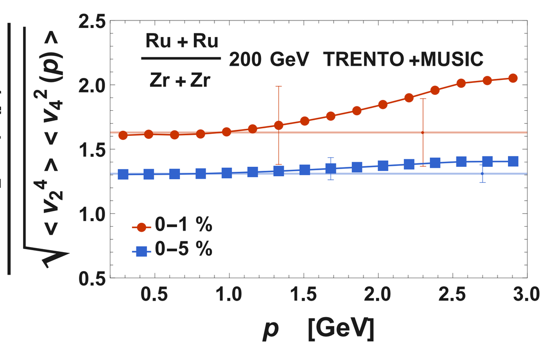

Fig. 12: V_2^2-$V_4(p)$ isobar-ratio in central collision

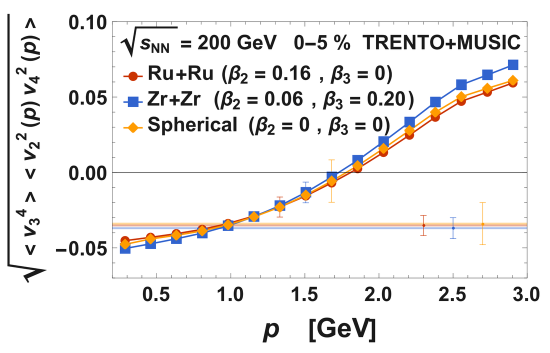

Fig. 13: $V_3^2 - V_2^*(p)V_4^*(p)$ correlation

- The correlator $V_3^2 - V_2^*(p)V_4^*(p)$ (related to subleading coupling of $V_3^2V_2^*$ to V_4) shows **completely opposite but interesting momentum dependence** ⟶ correlation **changes sign** as a function of momentum !

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