Study of Uranium nuclei deformation via flow and mean transverse momentum correlation at STAR

Supported in part by: U.S. DEPARTMENT OF ENERGY

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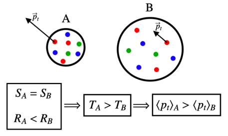
Motivations

※ Shape-flow transmutation in deformed nuclear collisions

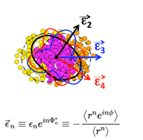
※ System size affect the p_T of particles

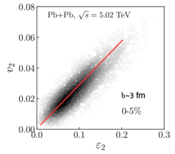


G. Giacalone, PRC102, 024901(2020)

$$\langle p_T \rangle \sim 1/R$$

※ Shape affect the v_n of particles

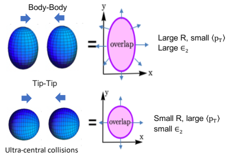




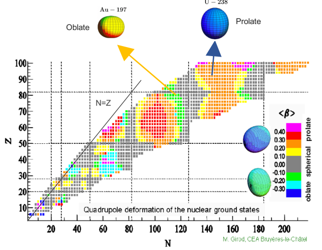
F.G. Gardim et al., arXiv:2002.07008v1

$$v_n \propto \epsilon_n$$

※ How the prolate nuclei affect the v_n and $\langle p_T \rangle$



※ Can we constrain quadrupole deformation β_2 in heavy-ion collider?



A. gorgen, Tech. Rep. 051, 019(2015); Moller et al., 1508.06294; BNL nuclear data center

For a deformed nucleus, the leading form of nuclear density becomes:

$$\rho(r,\theta) = \frac{\rho_0}{1 + e^{(r - R_0(1+\beta_2 Y_{20}(\theta))/a}}$$

Deformation is dominated by quadrupole component β_2

A few values based on the nuclear structure approximations

The β_2 of ^{238}U still have a large uncertainty:

reference	Raman et al.	Löbner et al.	Möller et al.	Möller et al.	CEA DAM	Bender et al.
method	exp	exp	FRDM	FRLDM	HFB	"beyond mean field"
β_2	0.286	0.281	0.215	0.236	0.30	0.29

[Raman et al., ADNDT78,1(2001)] [Möller et al., ADNDT59,185(1995)] [Hilaire & Girod, EPJA(2007)]
[Löbner et al., NDT A7, 495 (1970)] [Möller et al., 1508.06294] [Bender et al., nucl-th/0508052]

The β_2 of ^{179}Au is small and can be used as baseline

reference	Möller et al.	Möller et al.	CEA DAM
method	FRDM	FRLDM	HFB
β_2	−0.131	−0.125	−0.10

[Möller et al., 1508.06294]
[Möller et al., ADNDT59,185(1995)] [Hilaire & Girod, EPJA(2007)]

Observables

※ Pearson coefficient:

P. Bozek et al., PRC96, 014904(2017); ATLAS EPJC79, 985(2019); G. Giacalone, PRL124, 202301(2020); B.Shenke et al., PRC102,034905(2020)

$$\mathrm{cov}(v_n^2, [p_\mathrm{T}]) \equiv \left\langle \frac{\sum_{i\neq j\neq k} w_i w_j w_k e^{in\phi_i} e^{-in\phi_j} (p_{\mathrm{T},k} - \langle\langle p_\mathrm{T} \rangle\rangle)}{\sum_{i\neq j\neq k} w_i w_j w_k} \right\rangle_{\mathrm{evt}}$$

$$\rho(v_n^2, [p_T]) = \frac{\mathrm{cov}(v_n^2, [p_T])}{\sqrt{\mathrm{Var}(v_n^2)_{\mathrm{dyn}} \langle \delta p_T \delta p_T \rangle}}$$

$$[p_\mathrm{T}] \equiv \frac{\sum_i w_i p_{\mathrm{T},i}}{\sum_i w_i}, \langle\langle p_\mathrm{T} \rangle\rangle \equiv \langle [p_\mathrm{T}] \rangle_{\mathrm{evt}}$$

$$\mathrm{Var}(v_n^2)_{\mathrm{dyn}} = v_n\{2\}^4 - v_n\{4\}^4$$

$$\langle \delta p_\mathrm{T} \delta p_\mathrm{T} \rangle = \left\langle \frac{\sum_{i\neq j} w_i w_j (p_{\mathrm{T},i} - \langle\langle p_\mathrm{T}\rangle\rangle)(p_{\mathrm{T},j} - \langle\langle p_\mathrm{T}\rangle\rangle)}{\sum_{i\neq j} w_i w_j} \right\rangle_{\mathrm{evt}}$$

dynamical quantities with self-correlation removed

subevent method crucial for non-flow and detector systematics

Standard method	Two-subevent method		Three-subevent method		
$v_2, p_T \lvert\eta\rvert < 1.0$	$v_2^A, \eta < -0.1$	$v_2^B, \eta > 0.1$	$v_2^A, \eta < -0.35$	$v_2^B, \lvert\eta\rvert < 0.3$	$v_2^C, \eta > 0.35$

※ Mean p_T fluctuations:

Skewness:

$$\langle \delta p_\mathrm{T} \delta p_\mathrm{T} \delta p_\mathrm{T} \rangle = \left(\frac{\sum_{i\neq j\neq k} w_i w_j w_k (p_{\mathrm{T},i} - \langle\langle p_\mathrm{T}\rangle\rangle)(p_{\mathrm{T},j} - \langle\langle p_\mathrm{T}\rangle\rangle)(p_{\mathrm{T},k} - \langle\langle p_\mathrm{T}\rangle\rangle)}{\sum_{i\neq j\neq k} w_i w_j w_k} \right)_{\mathrm{evt}}$$

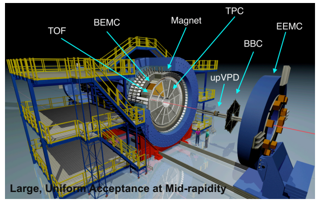
Standard skewness:

$$\gamma_{p_t} \equiv \frac{\langle \delta p_\mathrm{T} \delta p_\mathrm{T} \delta p_\mathrm{T} \rangle}{\langle \delta p_\mathrm{T} \delta p_\mathrm{T} \rangle}^{3/2}$$

Intensive skewness:

$$\Gamma_{p_t} \equiv \frac{\langle \Delta p_i \Delta p_j \Delta p_k \rangle \langle\langle p_t \rangle\rangle}{\langle \Delta p_i \Delta p_j \rangle^2}$$

STAR Detector



※ Datasets: Run11 Au+Au@200GeV; Run12 U+U@193GeV

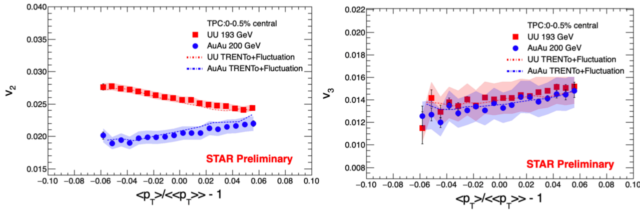
※ $\langle p_T \rangle$, v_n and N_{ch} are measured within:

$$0.2 < p_T < 2.0\ \mathrm{GeV/c}\ \text{and}\ 0.5 < p_T < 2.0\ \mathrm{GeV/c}$$
$$|\eta| < 1.0$$

※ Centrality is defined by N_{ch} ($|\eta|$<0.5)

Pearson coefficient

※ v_n - $\langle p_T \rangle$ correlation demonstrates shape-flow transmutation

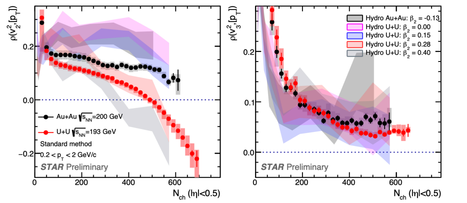


※ An anticorrelation is observed between v_2 and $\langle p_T \rangle$ in top 0.5% U+U collisions while not in Au+Au.

※ v_3 and $\langle p_T \rangle$ correlations are positive and similar for Au+Au and U+U collisions.

※ After adding the statistical fluctuations, TRENTo can reproduce data quantitatively.

※ $\rho(v_n^2, [p_T])$ compared with IP-Glasma+MUSIC+UrQMD

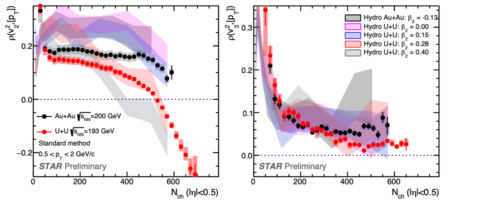


※ $\rho(v_2^2, [p_T])$ has a sign-change behavior in U+U central collisions.

※ IP-Glasma + Hydro shows the hierarchical β_2 dependence in $\rho(v_2^2, [p_T])$.

※ IP-Glasma + Hydro quantifies the β_2 value around 0.28 with large uncertainty.

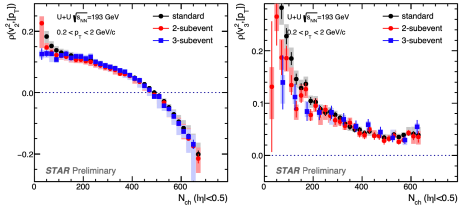
※ Main features are robust against p_T selection



※ Features are same for 0.5 < p_T < 2 GeV/c as 0.2 < p_T < 2 GeV/c.

IP-Glasma+MUSIC+UrQMD: *B. Schenke, C. Shen and P. Tribedy, PRC102, 044905(2020)*

※ Subevent methods suppress non-flow in peripheral collisions

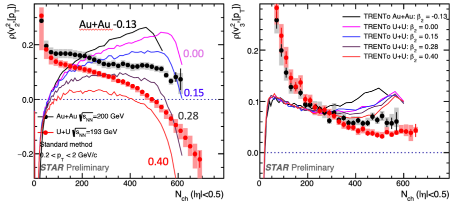


※ Standard method is consistent with subevent methods.

※ Subevent calculations indicate decrease non-flow contributions in peripheral collisions.

※ $\rho(v_n^2, [p_T])$ compared with TRENTo initial condition model

TRENTo: *G. Giacalone, PRC102, 104901(2020), PRL124,202301(2020)*

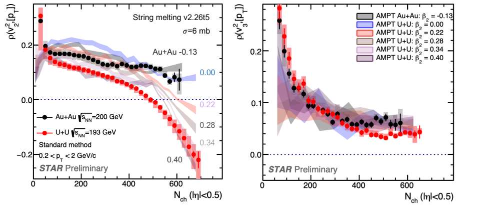


※ TRENTo fails to describe STAR data but show an hierarchical β_2 dependence in U+U.

※ TRENTo suggests this sign-change in the central collisions could be due to deformation effect.

※ $\rho(v_n^2, [p_T])$ compared with transport AMPT model

AMPT: *Chunjian Zhang and Jiangyong Jia et al., (In preparation)*

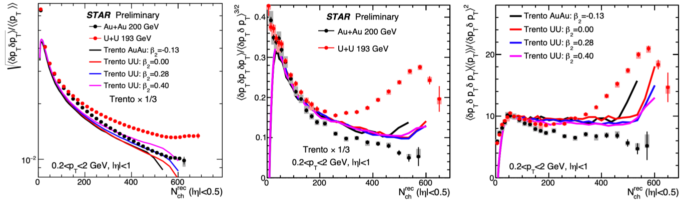


※ AMPT shows a clear β_2 dependence in uranium $\rho(v_2^2, [p_T])$.

※ AMPT also confirms the sign-change could due to deformation effect.

Mean p_T fluctuations

※ Standard variance, standard skewness and intensive skewness compared with TRENTo

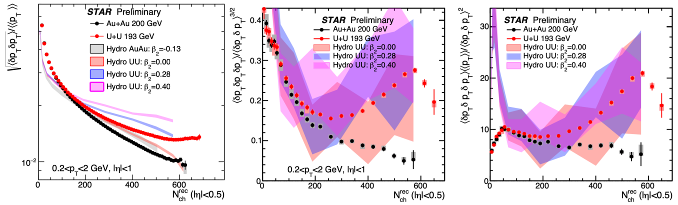


※ A Clear difference could be due to deformation effect.

※ Deformation also affect mid-central collisions.

※ TRENTo describe the trend qualitatively.

※ Standard variance, standard skewness and intensive skewness compared with IP-Glasma+MUSIC+UrQMD



※ TRENTo and IP-Glasma + Hydro all predict the size – $\langle p_T \rangle$ transmutation.

※ IP-Glasma + Hydro describes the data qualitatively while it still need more statistics in future.

※ High-order mean p_T fluctuation is also an important test on the thermal equilibrium, EoS and collision geometry.

Summary

※ We presented measurements from STAR that demonstrate a clear shape – flow transmutation.

※ The slope of v_2 vs $\langle p_T \rangle$ are different between Au+Au and U+U due to the deformation.

※ **The sign-change behavior in Pearson coefficient $\rho(v_2^2, [p_T])$ in central U+U collisions could be used to constrain quadrupole component β_2:**

- ※ Subevent methods could suppress nonflow contamination in peripheral collisions.
- ※ Main features are robust against p_T selection.

※ **Precise data-model comparison (IP-Glasma+Hydro, TRENTo, AMPT) could be helpful to constrain the initial conditions such as nuclear deformation parameters, shear/bulk viscosity and c_s in EoS.**

- ※ IP-Glasma + Hydro model partially reproduces the data with Uranium deformation parameter β_2 around 0.28 with large uncertainty.
- ※ TRENTo initial-state model shows an hierarchical β_2 dependence in U+U and prefers the β_2 value between 0.28 and 0.4.
- ※ AMPT model also confirms the sign-change could due to the deformation and prefers the β_2 value between 0.28 and 0.4.

※ **Mean p_T fluctuations (standard variance, standard skewness and intensive skewness) show a clear difference due to deformation effect.**

- ※ TRENTo and IP-Glasma + Hydro predict the clear size - $\langle p_T \rangle$ transmutation and describe the data qualitatively.

※ **These measurements provide novel ways to constrain nuclear deformation in heavy-ion collisions.**