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

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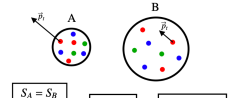
Motivations

Shape-flow transmutation in deformed nuclear collisions

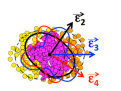
* System size affects the p_T of particles



G. Giacalone, PRC102, 024901(2020)

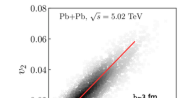
$$\langle p_T \rangle \sim 1/R$$

* Shape affects the v_n of particles

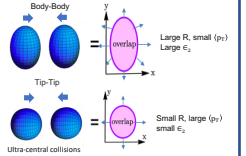


F.G. Gardim et al., arXiv:2002.07008v1

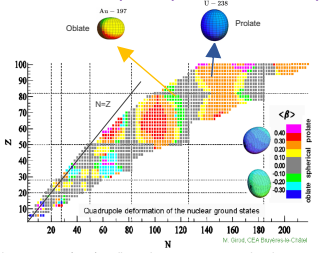
$$v_n \propto \epsilon_n$$



* How the prolate nuclei affects the v_n and $\langle p_T \rangle$



Can we constrain quadrupole deformation parameter β_2 in heavy-ion collisions?



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.	Lobner et al.	Moller et al.	Moller 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)] [Moller et al., ADNDT59,185(1995)] [Hilaire & Girod, EPJA(2007)]
[Lobner 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 a baseline

reference	Moller et al.	Moller et al.	CEA DAM
method	FRDM	FRLDM	HFB
β_2	−0.131	−0.135	−0.10

[Möller et al., 1508.06294]
[Moller 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)

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

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

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

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

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

dynamical quantities with self-correlation removed

subevent method is 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:

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

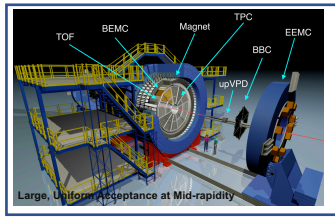
Standard skewness:

$$\gamma_{p_t} \equiv \frac{\langle \delta p_T \delta p_T \delta p_T \rangle}{\langle \delta p_T \delta p_T \rangle^{3/2}}$$

Intensive skewness:

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

STAR Detector

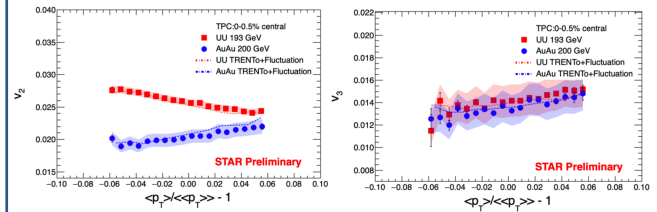


* Datasets: Run11 Au+Au@200GeV; Run12 U+U@193GeV
* Centrality is defined by the number of charged particles N_{ch} ($|\eta|<0.5$)
* $\langle p_T \rangle$, v_n and N_{ch} are measured within:

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

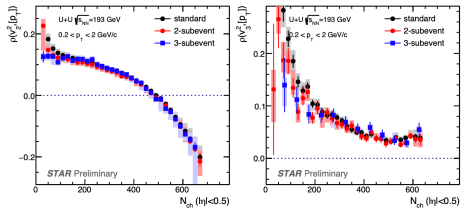
Pearson coefficient

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



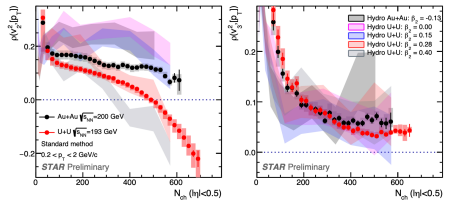
* An anticorrelation is observed between v_2 and $\langle p_T \rangle$ in top 0.5% U+U collisions while not in Au+Au.
* v_3 and $\langle p_T \rangle$ correlations are positive and similar for Au+Au and U+U collisions.
* After adding the statistical fluctuations, TRENTo can reproduce data quantitatively.

Subevent methods suppress non-flow in peripheral collisions



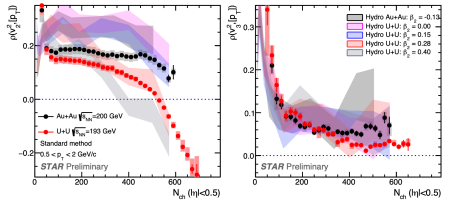
* Standard method is consistent with subevent methods.
* Subevent calculations indicate decrease of non-flow contributions in peripheral collisions.

$\rho(v_2^2, [p_T])$ 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 pT selection

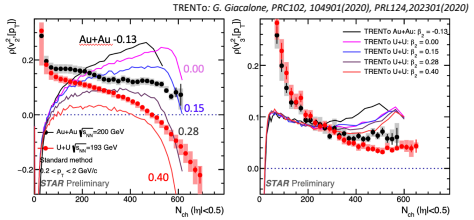


* Features are same for $0.5 < p_T < 2$ GeV/c as $0.2 < p_T < 2$ GeV/c.

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

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

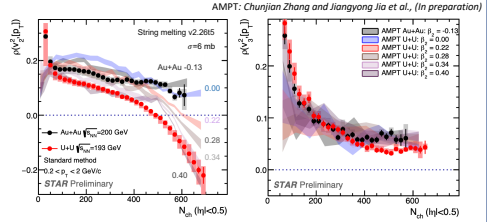
TRENTo: *G. Giacalone, PRC102, 104901(2020), PRL124,202301(2020)*



* 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

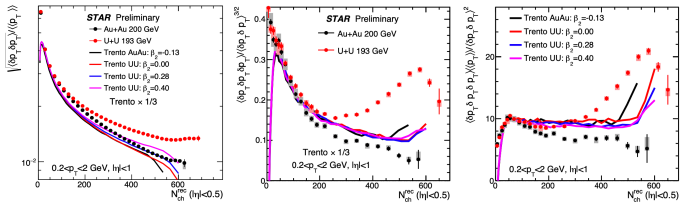
AMPT: *Chunjian Zhang and Jiangyong Jia et al., (In preparation)*



* AMPT shows a clear β_2 dependence in uranium $\rho(v_2^2, [p_T])$.
* AMPT also confirms the sign-change could be due to deformation effect.

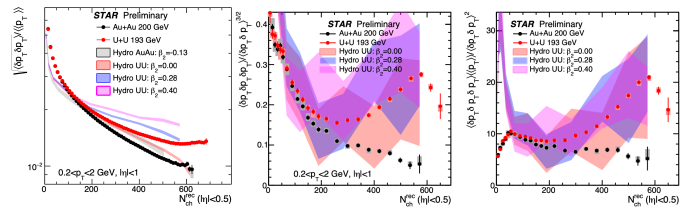
Mean p_T fluctuations

Standard variance, standard skewness and intensive skewness compared with TRENTo



* A Clear difference could be due to deformation effect.
* Deformation also affects mid-central collisions.
* TRENTo describes 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 needs 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.**