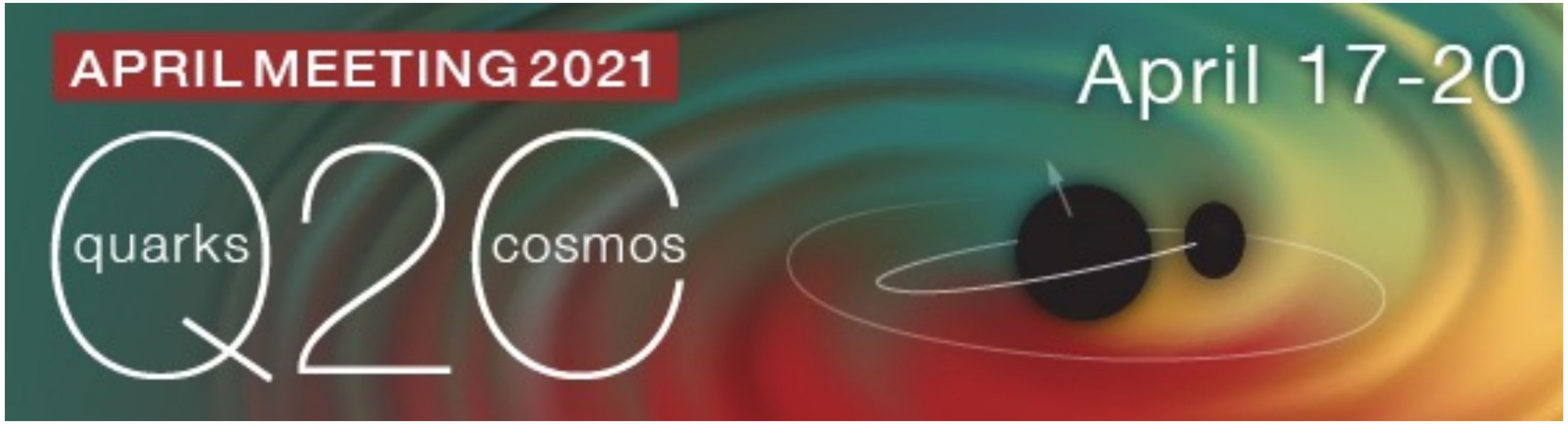


Study of uranium nuclei deformation at STAR

Chunjian Zhang

Session H14.00004

March 18, 2021

Supported in part by
U.S. DEPARTMENT OF ENERGY

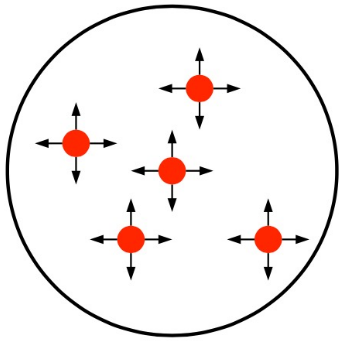
Stony Brook University

STAR

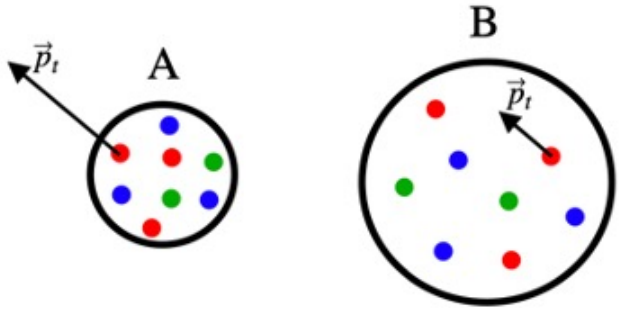
Connecting the initial state to the nuclear geometry

- System size affects the transverse momentum of particles

initial density profile



small R, large $\langle p_T \rangle$ large R, small $\langle p_T \rangle$



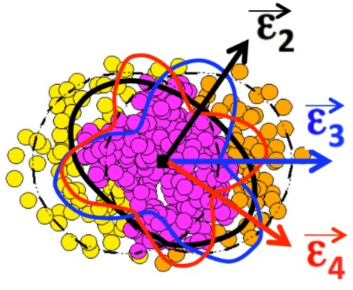
$$c_s^2 = \frac{dP}{d\epsilon} = \frac{d\ln T}{d\ln s} = \frac{d\ln\langle p_T\rangle}{d\ln N_{ch}}$$

$$\frac{d\langle p_t\rangle}{\langle\langle p_t\rangle\rangle} = -3c_s^2\frac{dR}{\langle R\rangle}$$

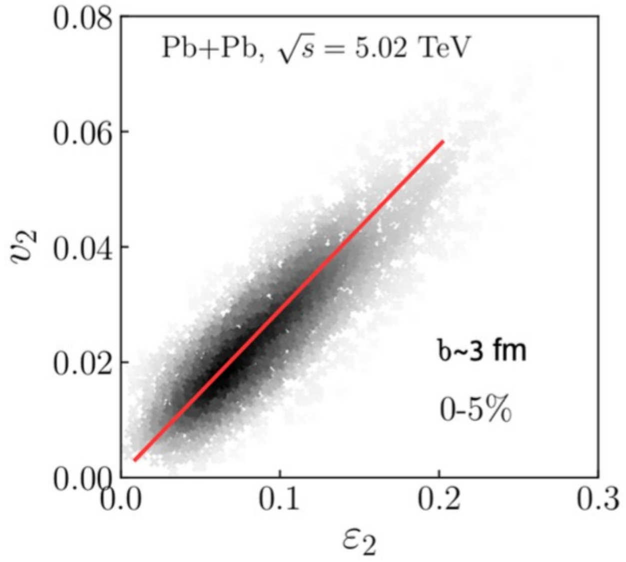
(Hydrodynamic approximation)

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

- Shape affects anisotropic flow of particles



$$\vec{\epsilon}_n \equiv \epsilon_n e^{in\Phi_n^*} \equiv -\frac{\langle r^n e^{in\phi}\rangle}{\langle r^n\rangle}$$

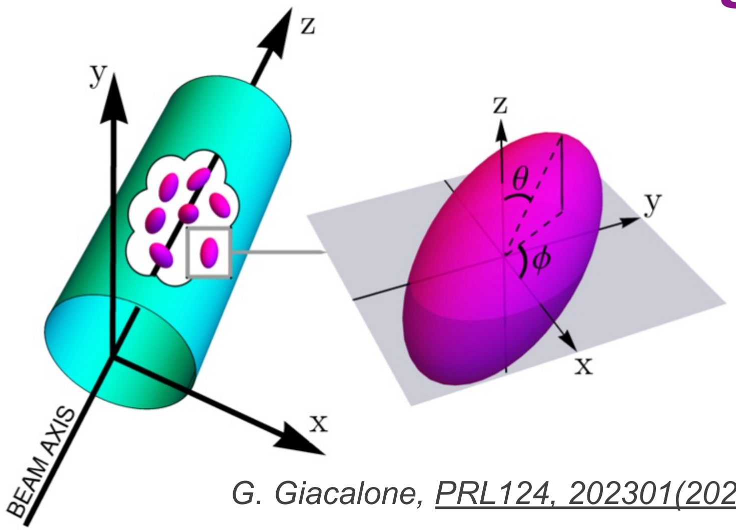


$$v_n \propto \epsilon_n, n = 2, 3$$

The fluctuation in size and shape are related to mean p_T fluctuation and v_n.

J. E. Bernhard et al., Nature Physics 15, 1113(2019); IS2021-Jiangyong Jia , M.A. Stephanov, PRL102, 032301(2009); S.A. Voloshin, PRC60, 024901(1999), F.G. Gardim et al., arXiv:2002.07008v1; G. Giacalone, PRC102, 024901(2020); W. Broniowski et al., PRC80, 051902(R)(2009).

Connecting the initial state to the nuclear geometry



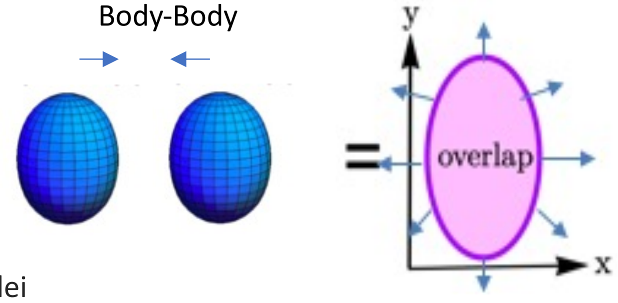
G. Giacalone, PRL124, 202301(2020)

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

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

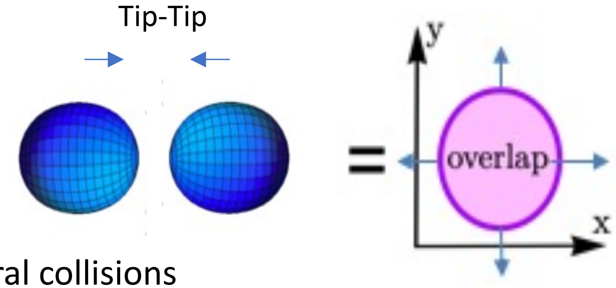
$$Y_{20} = \sqrt{\frac{5}{16\pi}}(3\cos^2\theta - 1)$$

Deformation is dominated by quadrupole component β_2



large *R*, small $\langle p_T \rangle$

large $\boldsymbol{\varepsilon}_2$



small *R*, large $\langle p_T \rangle$

small $\boldsymbol{\varepsilon}_2$

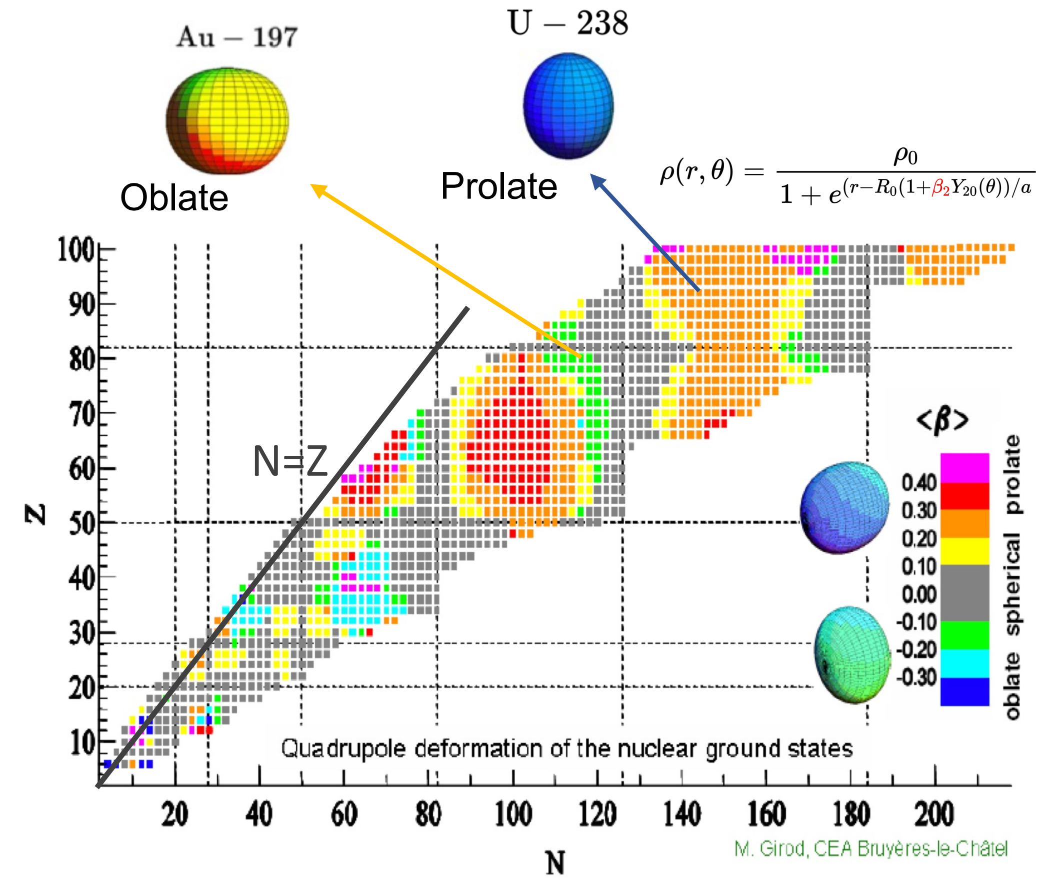
- $\boldsymbol{\varepsilon}_2$ and R are influenced by the quadrupole deformation β_2
- $\langle p_T \rangle \sim 1/R$ and $v_2 \propto \boldsymbol{\varepsilon}_2$:

deformation contributes to anticorrelation between v_2 and $\langle p_T \rangle$

Measuring the v_2 - $\langle p_T \rangle$ correlation could reveal the quadrupole deformation β_2 .

Quadrupole deformations β_2 of different nuclei

A. Gorgen, Tech. Rep. 051, 019(2015)



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

Hartree-Fock-Bogolyubov (Gogny D1S effective interaction)

A few values based on the nuclear structure approximations

The β_2 of ^{238}U has a large value:

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

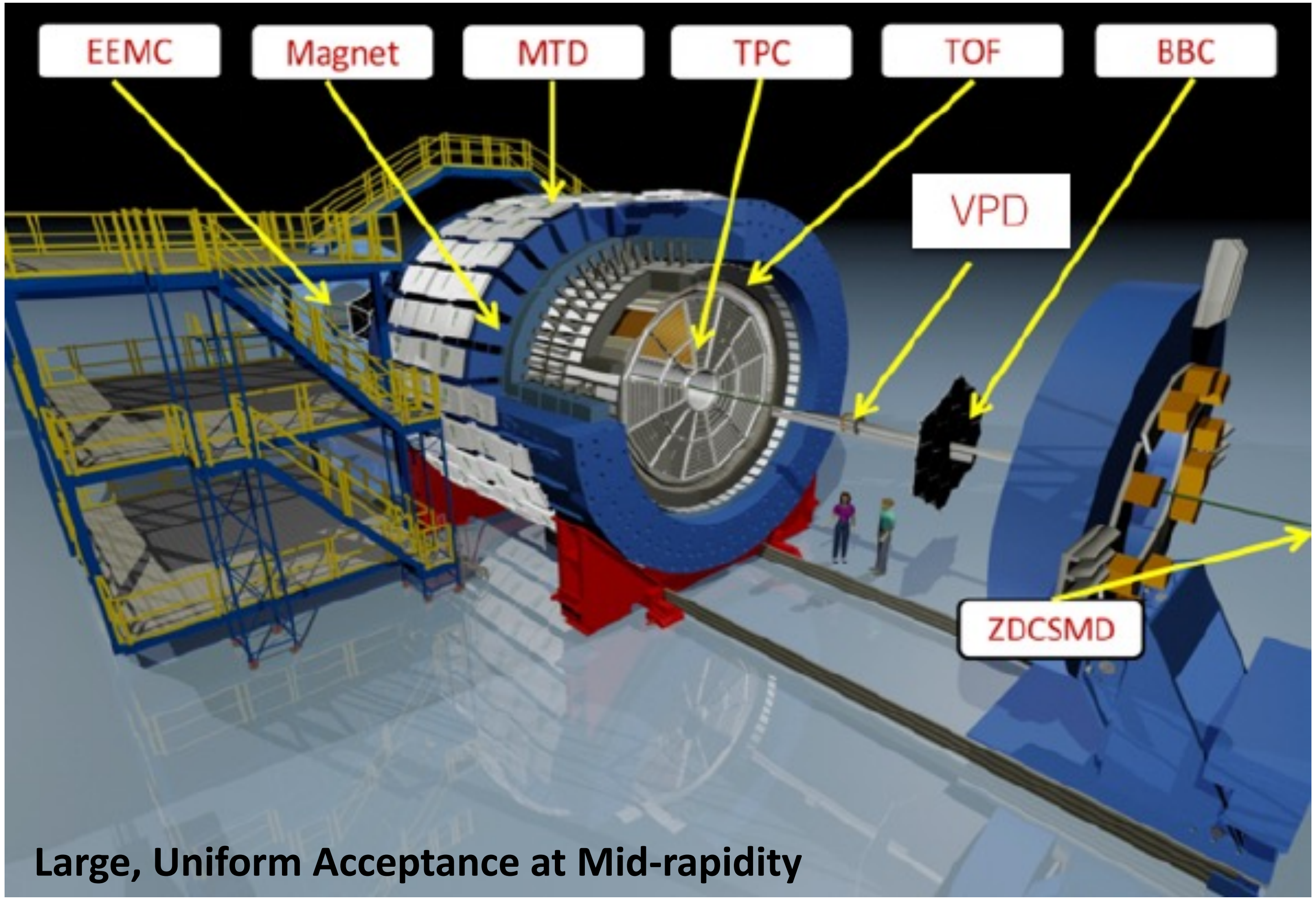
reference	Möller et al.	Möller et al.	CEA DAM
method	FRDM	FRLDM	HFB
β_2	−0.131	−0.125	−0.10

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

BNL nuclear data center

Heavy-ion collisions could perform a new experimental test of constraint on the uranium β_2 in such a short time-scale (~10^{-23}s).

STAR detector and datasets



- Dataset:

  Au+Au@200GeV

  U+U@193GeV

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

  $0.2 < p_T < 2.0$ GeV/c and $0.5 < p_T < 2.0$ GeV/c

  $|\eta| < 1.0$

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

Two topics are explored:

(I) Results for the size fluctuation

(II) Results for the v_n-$\langle p_T \rangle$ correlations

Observables for the size fluctuation

Mean p_T fluctuations

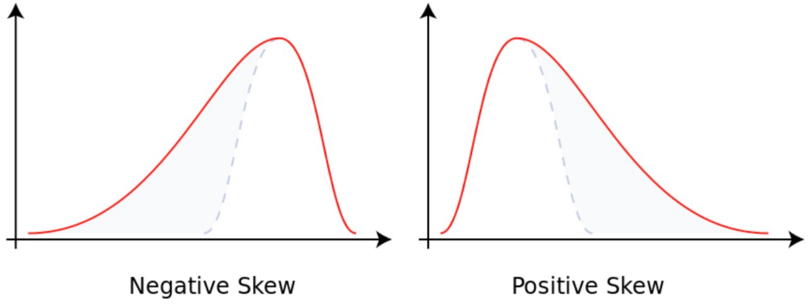
Mean $$[p_{\mathrm{T}}] \equiv \frac{\sum_i w_i p_{\mathrm{T},i}}{\sum_i w_i}, \langle\langle p_{\mathrm{T}}\rangle\rangle \equiv \langle [p_{\mathrm{T}}]\rangle_{\mathrm{evt}}$$

$$\delta p_T = p_{\mathrm{T}} - \langle\langle p_{\mathrm{T}}\rangle\rangle$$

Variance $$\langle(\delta p_{\mathrm{T}})^2\rangle = \left\langle \frac{\sum_{i\neq j} w_i w_j (p_{\mathrm{T},i} - \langle\langle p_{\mathrm{T}}\rangle\rangle)(p_{\mathrm{T},j} - \langle\langle p_{\mathrm{T}}\rangle\rangle)}{\sum_{i\neq j} w_i w_j} \right\rangle_{\mathrm{evt}}$$

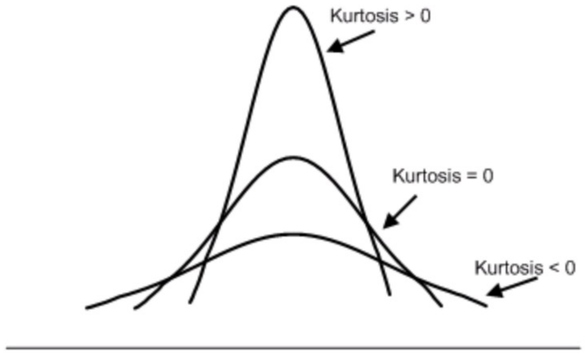
skewness $$\langle(\delta p_{\mathrm{T}})^3\rangle = \left\langle \frac{\sum_{i\neq j\neq k} w_i w_j w_k (p_{\mathrm{T},i} - \langle\langle p_{\mathrm{T}}\rangle\rangle)(p_{\mathrm{T},j} - \langle\langle p_{\mathrm{T}}\rangle\rangle)(p_{\mathrm{T},k} - \langle\langle p_{\mathrm{T}}\rangle\rangle)}{\sum_{i\neq j\neq k} w_i w_j w_k} \right\rangle_{\mathrm{evt}}$$

kurtosis $$\langle(\delta p_T)^4\rangle_c = \langle(\delta p_T)^4\rangle - 3 * \langle(\delta p_T)^2\rangle^2$$



Normalized cumulants:

$$\frac{\sqrt{\langle(\delta p_T)^2\rangle}}{\langle p_T\rangle}, \quad \frac{\langle(\delta p_T)^3\rangle}{\langle(\delta p_T)^2\rangle^{3/2}}, \quad \frac{\langle(\delta p_T)^3\rangle * \langle p_T\rangle}{\langle(\delta p_T)^2\rangle^2}, \quad \frac{\langle(\delta p_T)^4\rangle_c}{\langle(\delta p_T)^2\rangle^2}$$



P. Bozek, PRC93, 044908(2016), PRC96.014904(2017); B. Schenke et al., PRC102, 034905(2020); G. Giacalone et al., PRC103, 024910(2021), 2101.00168; F.G. Gardim et al., PLB809, 135749(2020) ; ATLAS EPJC79, 985(2019); J. E. Bernhard et al., Nature Physics 15, 1113(2019); ALICE EPJC 74, 3077(2014); thesis1_STAR;

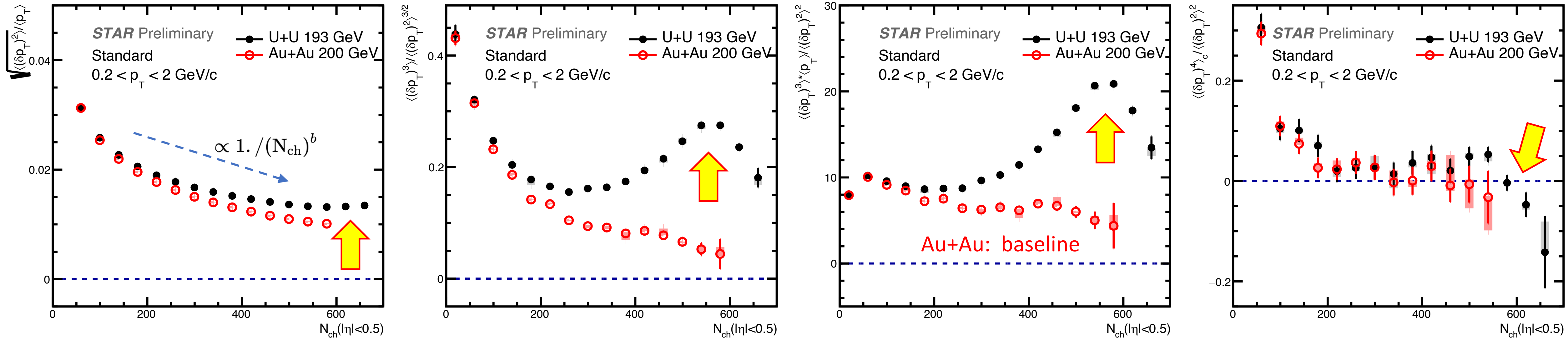
Mean p_T fluctuations

Normalized variance $\frac{\sqrt{\langle(\delta p_T)^2\rangle}}{\langle p_T\rangle}$

Normalized skewness $\frac{\langle(\delta p_T)^3\rangle}{\langle(\delta p_T)^2\rangle^{3/2}}$

Intensive skewness $\frac{\langle(\delta p_T)^3\rangle * \langle p_T\rangle}{\langle(\delta p_T)^2\rangle^2}$

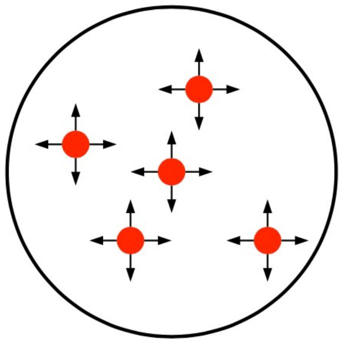
Normalized kurtosis $\frac{\langle(\delta p_T)^4\rangle_c}{\langle(\delta p_T)^2\rangle^2}$



Normalized variance and skewness in Au+Au roughly follow a power-law function of Nch.

U+U shows significant enhancement in central region in variance and skewness quantities
→ size fluctuation due to deformation effect.

U+U shows sign-change in normalized kurtosis → size fluctuation due to deformation effect

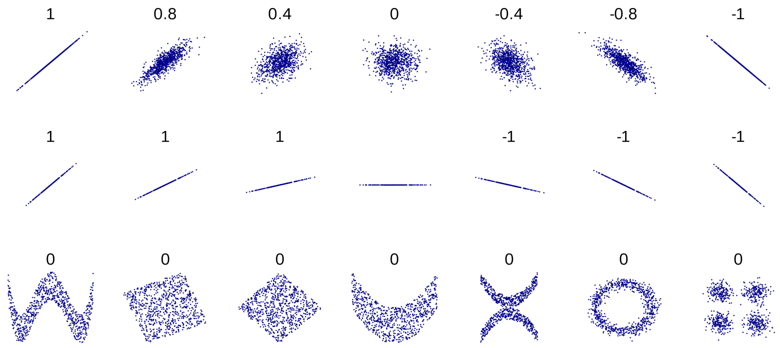


Independent source

Observables for the v_n-$\langle p_T \rangle$ correlations

Pearson correlation coefficient: measuring linear correlation between two variables *X* and *Y*.

$$\rho(X,Y) = \frac{\mathrm{cov}(X,Y)}{\sigma_X \sigma_Y}$$



Pearson coefficient: v_n-p_T three particle correlator

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

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

w_i is track weight

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

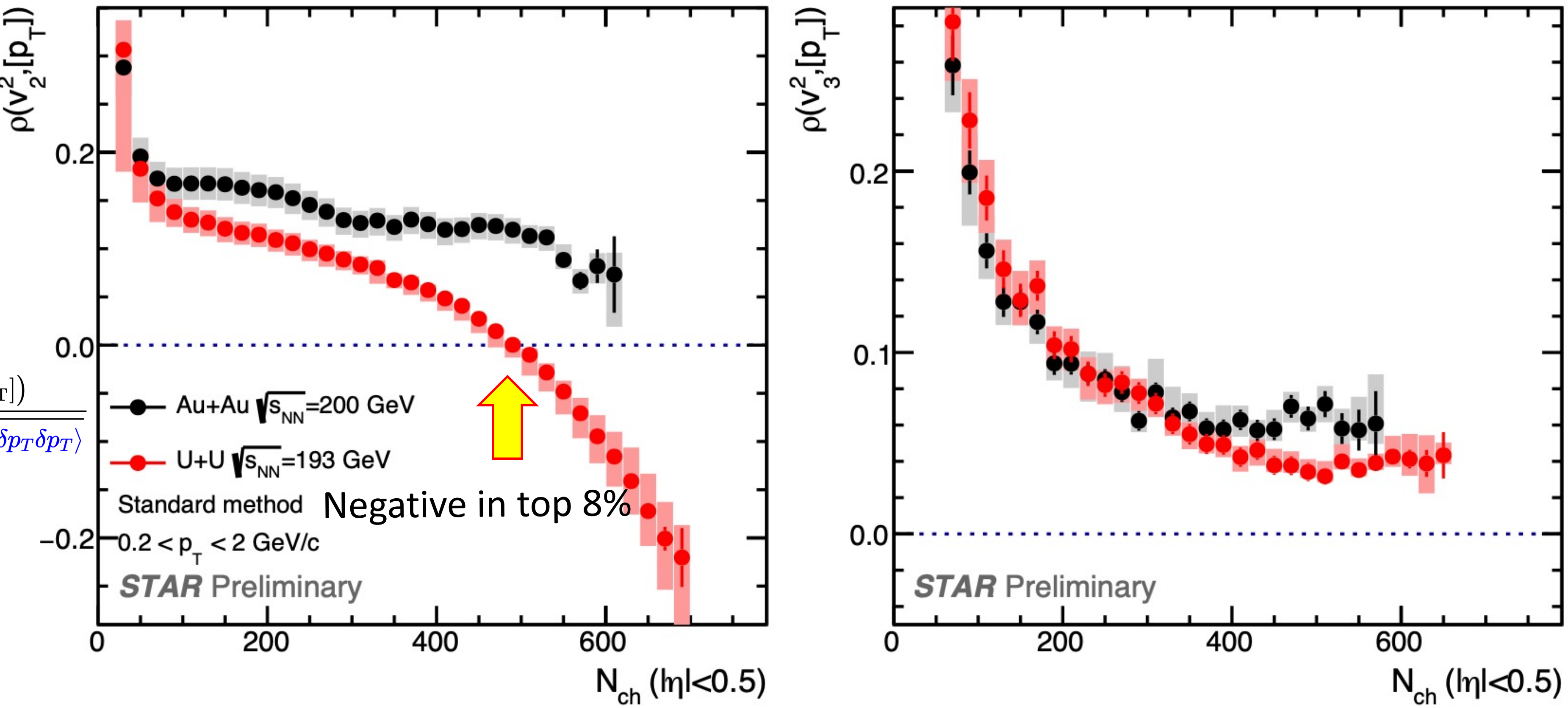
$$\mathrm{Var}\left(v_n^2\right)_\mathrm{dyn} = v_n\{2\}^4 - v_n\{4\}^4$$

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

P. Bozek, PRC93, 044908(2016), PRC96.014904(2017); B. Schenke et al., PRC102, 034905(2020); G. Giacalone et al., PRC103, 024910(2021), 2101.00168; F.G. Gardim et al., PLB809, 135749(2020) ; ATLAS EPJC79, 985(2019); J. E. Bernhard et al., Nature Physics 15, 1113(2019); ALICE EPJC 74, 3077(2014); thesis1_STAR;

Pearson coefficient $\rho(v_n^2, [p_T])$

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



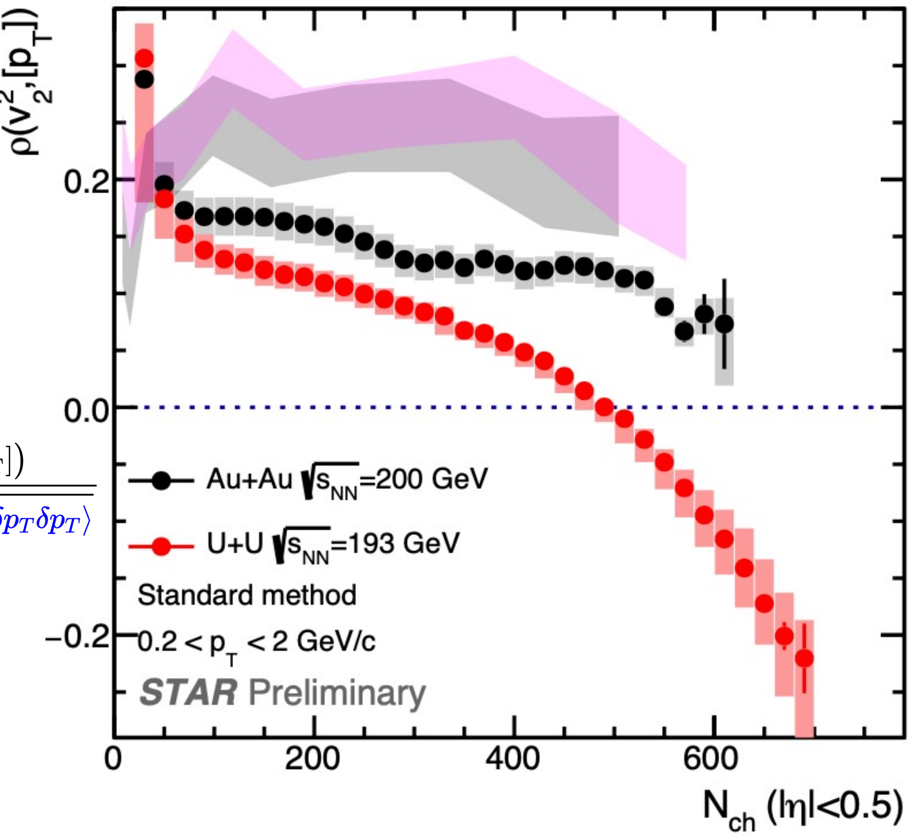
$\rho(v_2^2, [p_T])$ has a clear difference: **negative (anticorrelation)** in U+U central, **positive** in Au+Au central.

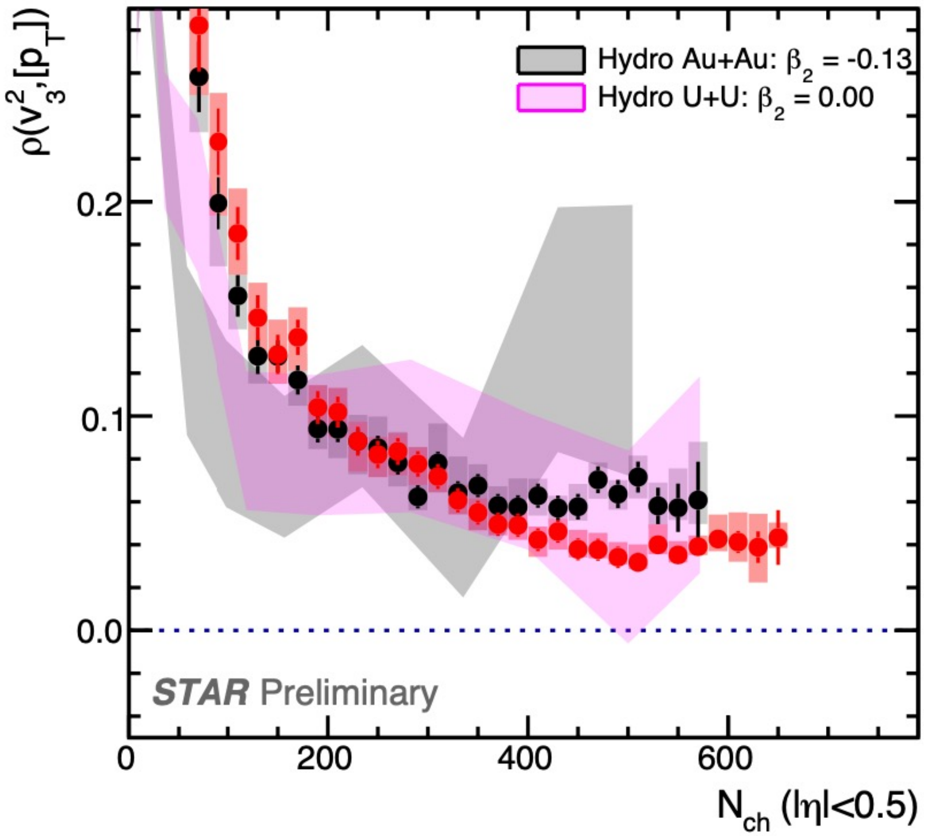
$\rho(v_3^2, [p_T])$ is **positive and consistent** in Au+Au and U+U collisions.

$\rho\left(v_n^2, [p_T]\right)$ compared to IP-Glasma+Hydro

IP-Glasma+Hydro: private calculation provided by Bjoern Schenke (based on B. Schenke, C. Shen, P. Tribedy, PRC102, 044905(2020))

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



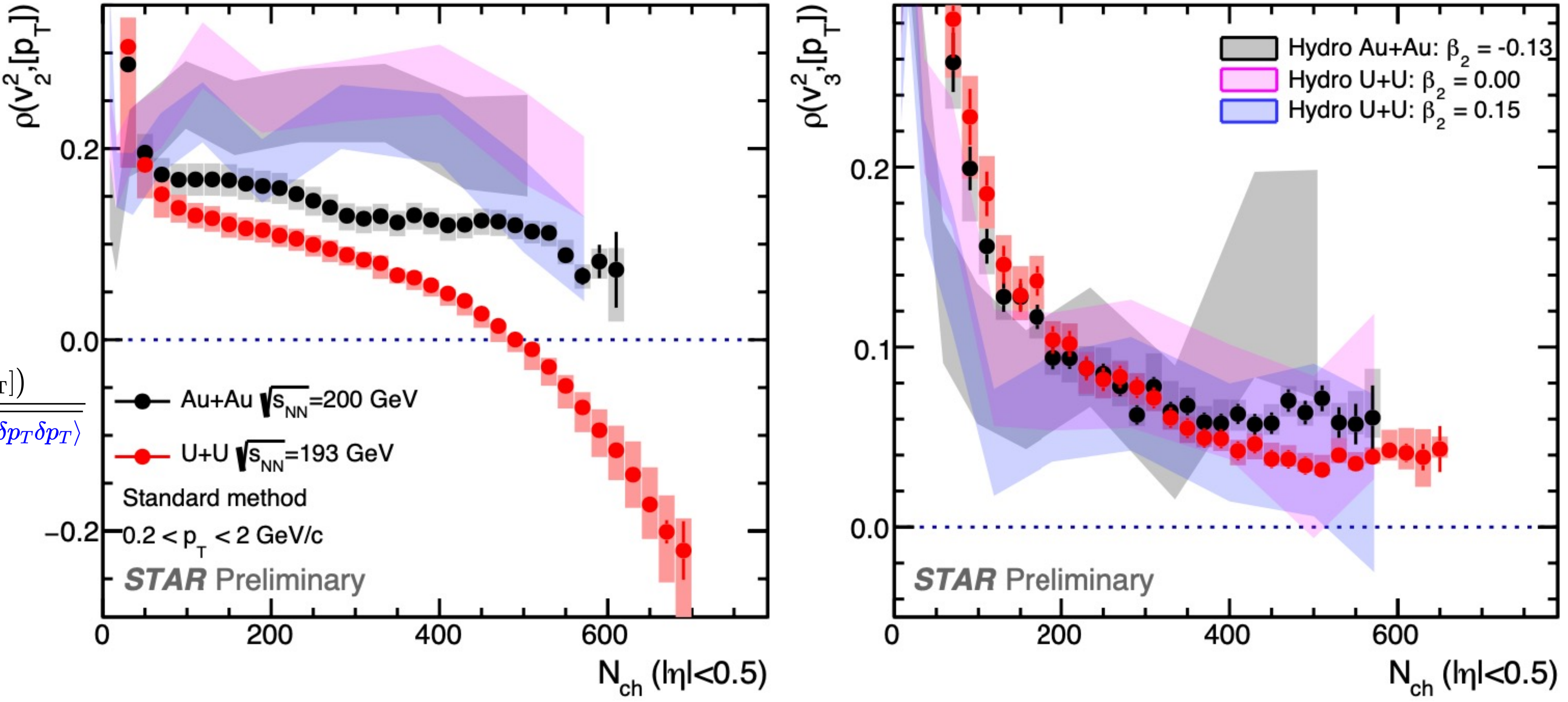


Without deformation, model over-predicts the values for $\rho(v_2^2, [p_T])$.

$\rho\left(v_n^2, [p_T]\right)$ compared to IP-Glasma+Hydro

IP-Glasma+Hydro: private calculation provided by Bjoern Schenke (based on B. Schenke, C. Shen, P. Tribedy, PRC102, 044905(2020))

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



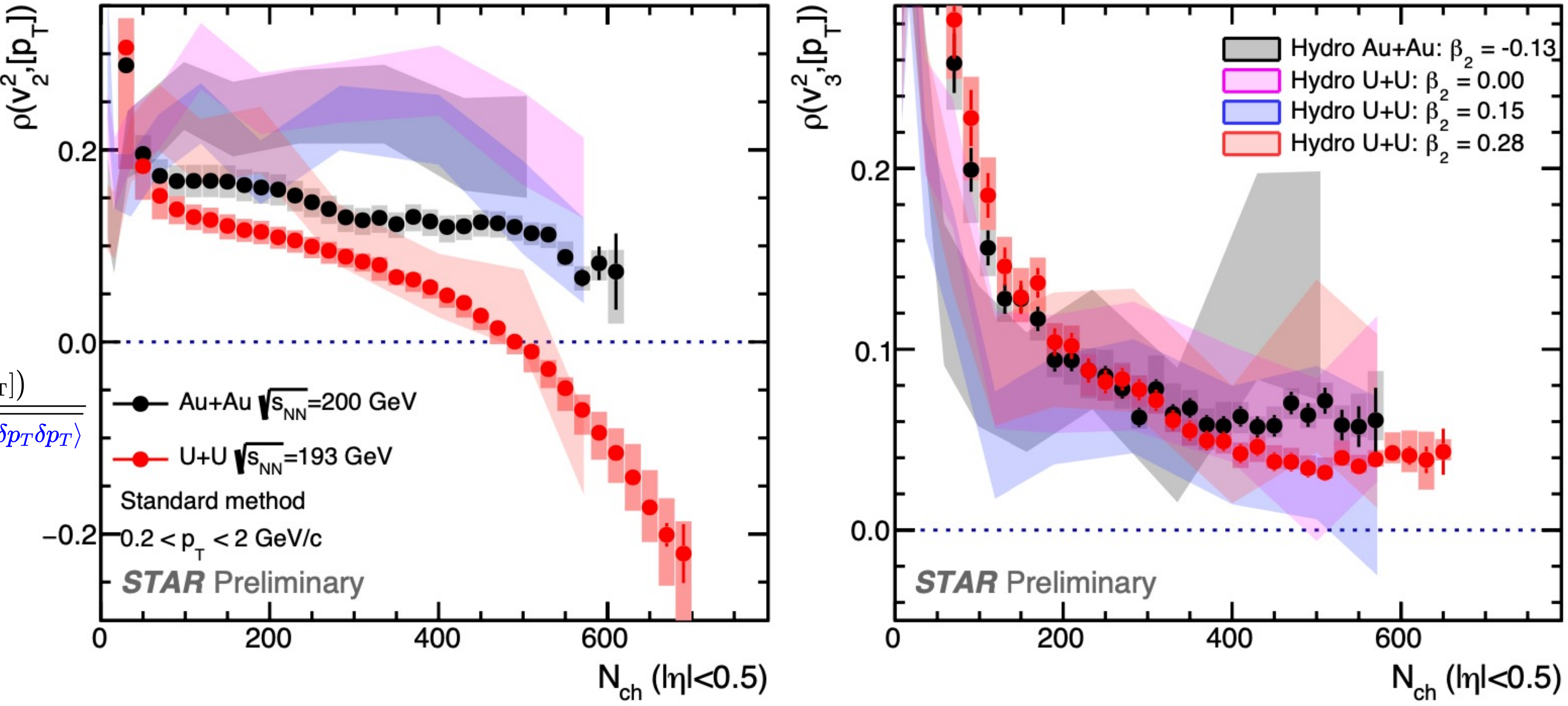
Without deformation, model over-predicts the values for $\rho(\mathrm{v}_2^2, [\mathrm{p_T}])$.

With increasing β_2, model roughly describes the trend of $\rho(\mathrm{v}_2^2, [\mathrm{p_T}])$.

$\rho\left(v_n^2, [p_T]\right)$ compared to IP-Glasma+Hydro

IP-Glasma+Hydro: private calculation provided by Bjoern Schenke (based on B. Schenke, C. Shen, P. Tribedy, PRC102, 044905(2020))

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



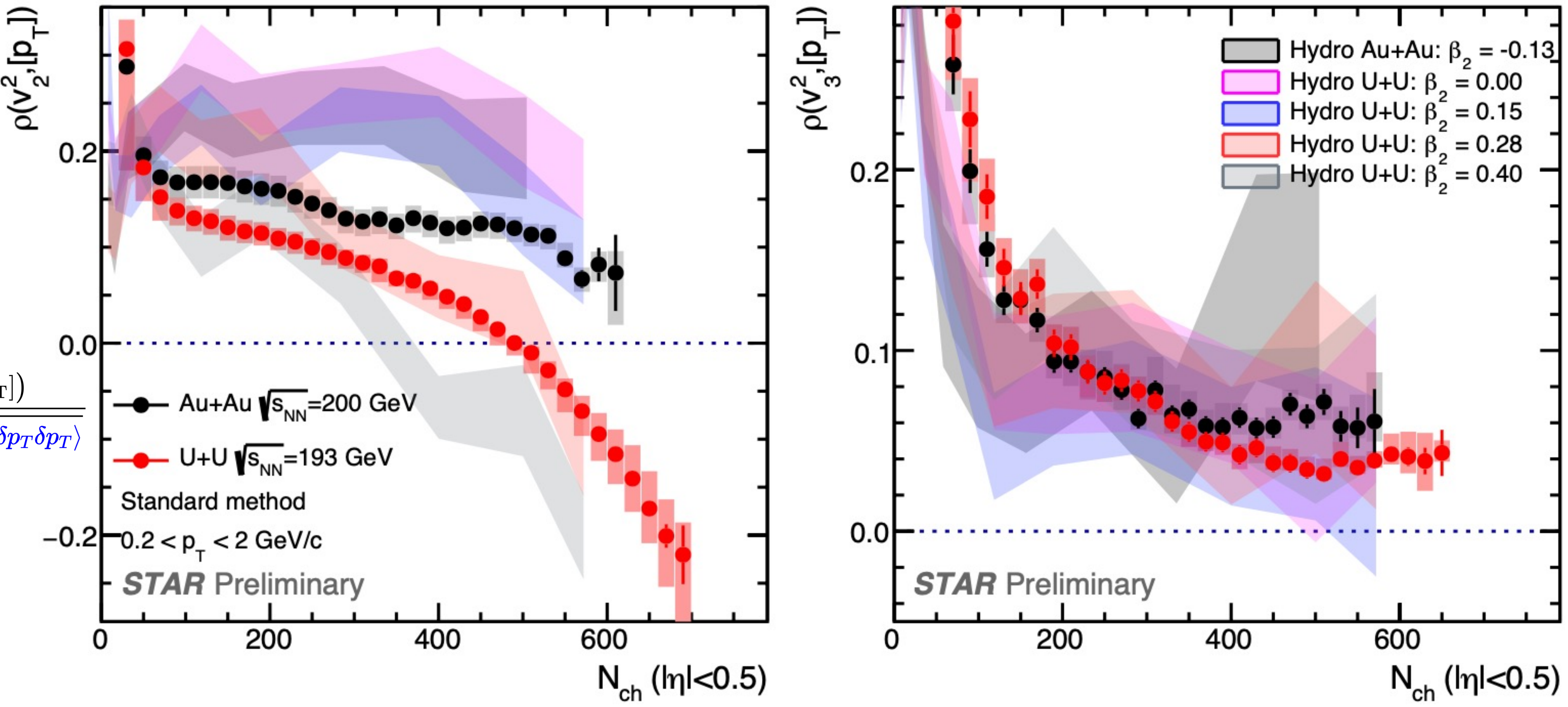
Without deformation, model over-predicts the values for $\rho(v_2^2, [p_T])$.

With increasing β_2, model roughly describes the trend of $\rho(v_2^2, [p_T])$.

$\rho\left(v_n^2, [p_T]\right)$ compared to IP-Glasma+Hydro

IP-Glasma+Hydro: private calculation provided by Bjoern Schenke (based on B. Schenke, C. Shen, P. Tribedy, PRC102, 044905(2020))

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



Without deformation, model over-predicts the values for $\rho\left(v_2^2, [p_T]\right)$.

With increasing β_2, model roughly describes the trend of $\rho\left(v_2^2, [p_T]\right)$.

Model shows that $\rho\left(v_3^2, [p_T]\right)$ are insensitive to β_2.

The sign-change is due to deformation effect and model quantifies the β_2 value around $0.28 < \beta_2 < 0.4$

Conclusions and outlooks

1. $[p_T]$ fluctuations:

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

- Show sensitivity to quadruple deformation β_2.
- Strong increase of variance, skewness and negative kurtosis towards central U+U.

2. $\mathbf{v_n}$- $[p_T]$ correlations:

- Strong suppression and sign-change for n=2 in U+U, but no difference for n=3 in Au+Au and U+U.
- Deformation influences collisions over a wide centrality range: mid-central to central.
- Subevent method could decrease non-flow contributions in peripheral collisions.
- Main features are robust against p_T selection.

3. Qualitatively described by IP-Glasma+MUSIC+UrQMD calculations:

- Prefer a quadrupole deformation of $0.28 \leq \beta_2 \leq 0.40$.
- Help model to constrain the initial conditions.
- Open up an avenue for studying nuclear shape in heavy-ion collisions.

4. Outlooks: isobar collisions and small system collisions could address two questions

- Could decipher the puzzle of nuclear deformation in Ru and Zr.
- Could study the initial state momentum anisotropy from the CGC prediction.

Many thanks to APS and also thank you for listening.

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

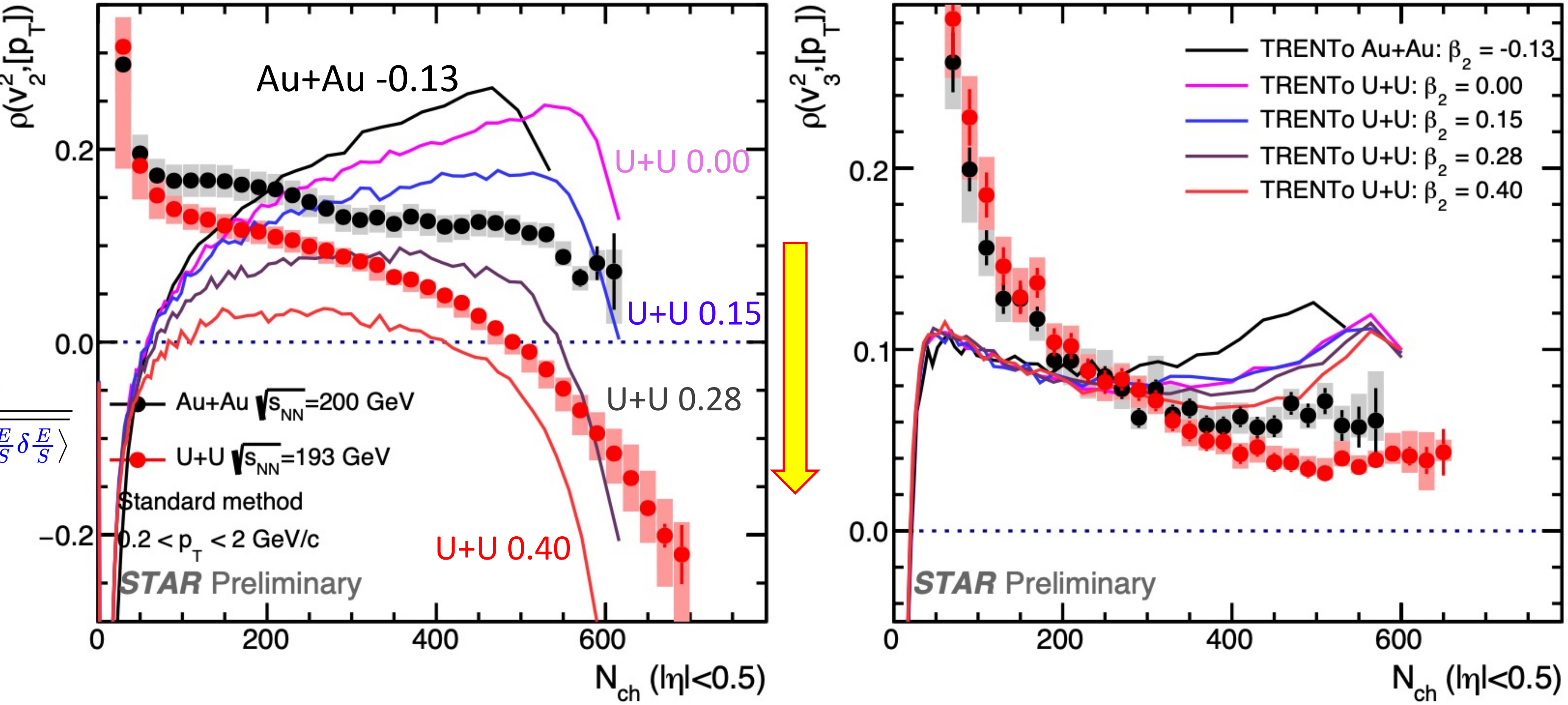
TRENTo: private calculation provided by Giuliano Giacalone (based on PRC102, 024901(2020),PRL124, 202301(2020))

TRENTo assumption:

$$v_n \propto \epsilon_n$$

$$[p_T] \propto \frac{E}{S}$$

$$\rho(v_n^2, [p_T]) \sim \frac{\langle \epsilon_n^2 \delta \frac{E}{S} \rangle}{\sqrt{\mathrm{var}(\epsilon_n^2) \langle \delta \frac{E}{S} \delta \frac{E}{S} \rangle}}$$



TRENTo fails to describe the STAR data but shows a hierarchical β_2 dependence in U+U collisions.

TRENTo suggests this sign-change in central U+U collisions due to deformation effect, and prefers $0.28 < \beta_2 < 0.4$

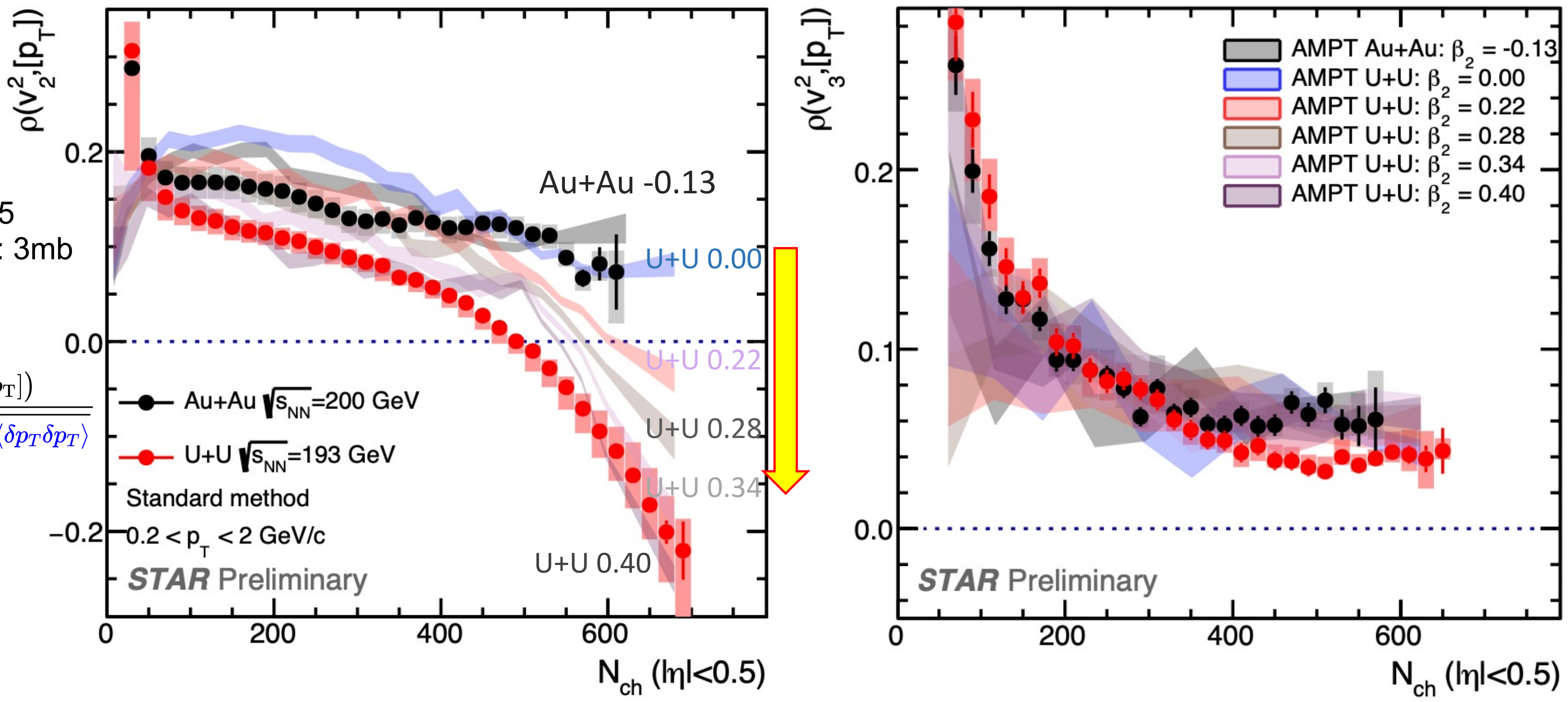
TRENTo shows that $\rho(v_3^2, [p_T])$ is insensitive to the nuclear deformation effects.

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

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

String melting v2.26t5
Parton cross section: 3mb

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



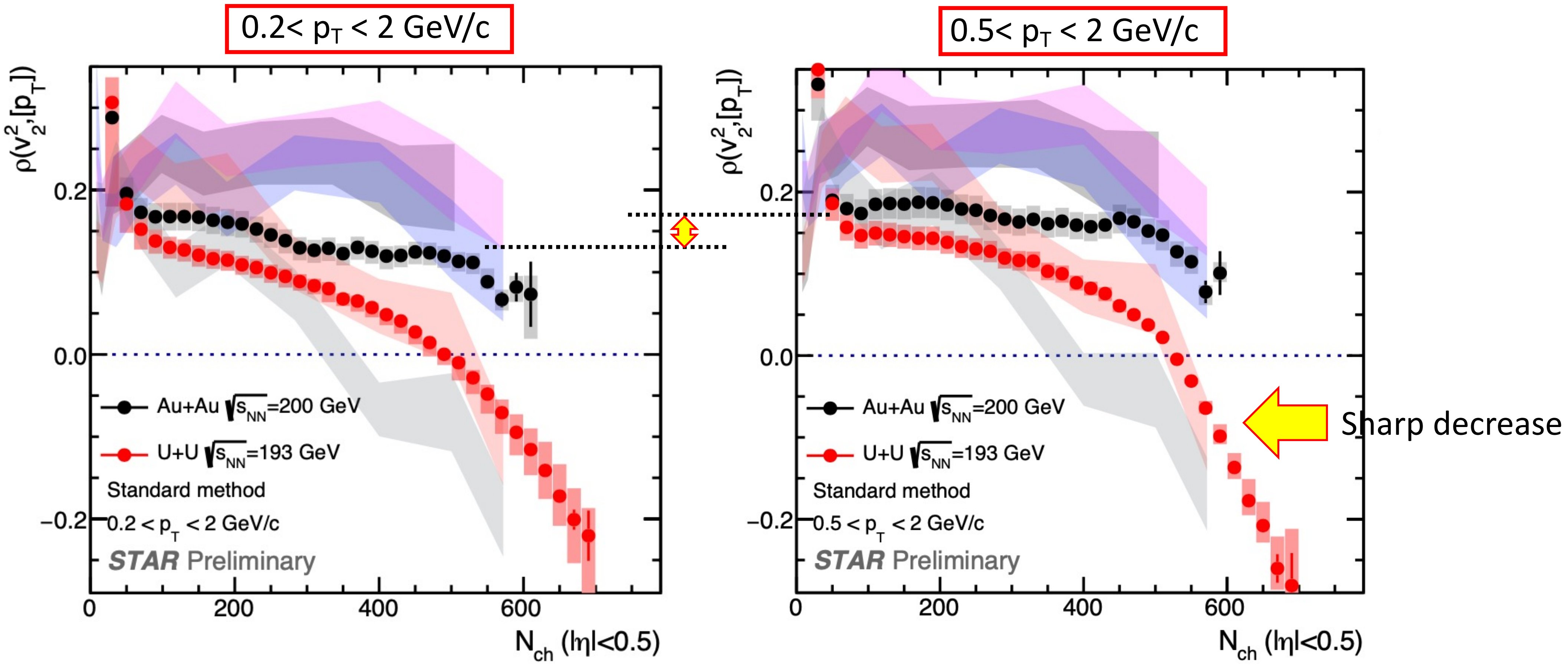
AMPT shows a clear β_2 dependence in Uranium $\rho(v_2^2, [p_T])$ while not in $\rho(v_3^2, [p_T])$.

AMPT also supports the sign-change of $\rho(v_2^2, [p_T])$ in U+U is due to deformation effect .

AMPT favors the β_2 value around 0.28< β_2<0.4 for uranium.

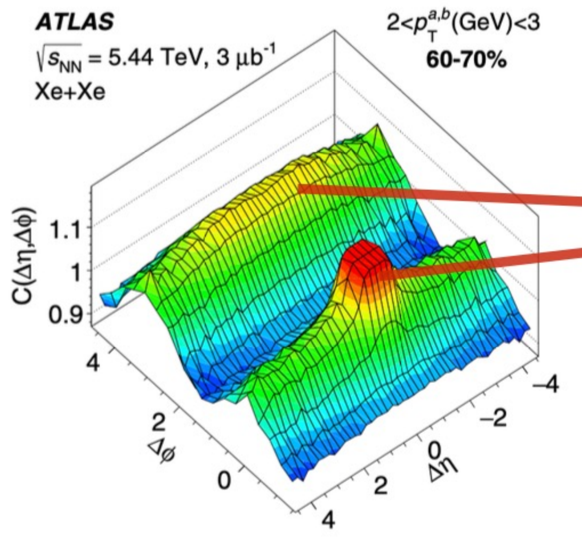
$\rho(v_n^2, [p_T])$ in different p_T selection

IP-Glasma+Hydro: private calculation provided by Bjoern Schenke (based on B. Schenke, C. Shen, P. Tribedy, PRC102, 044905(2020))

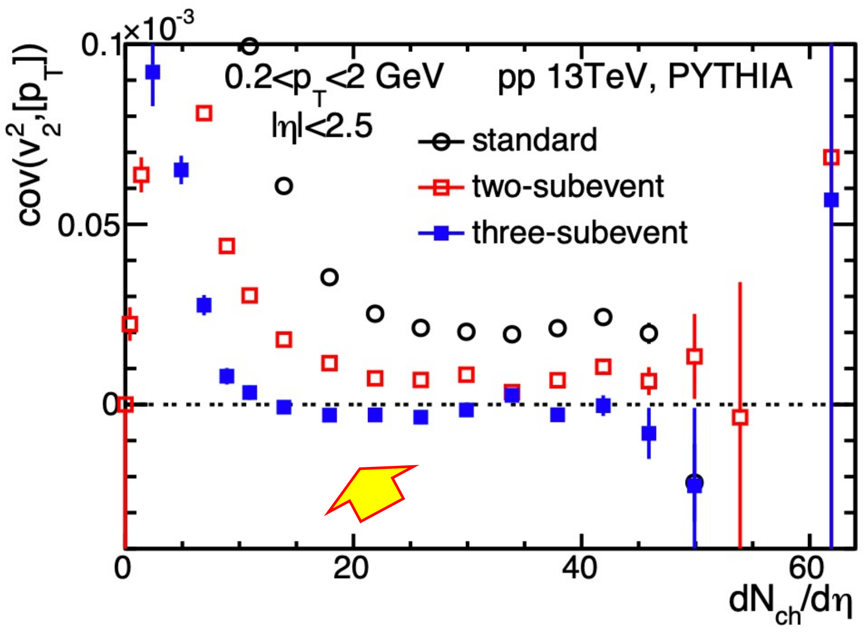


Features are same for 0.5<p_T<2 GeV/c as 0.2<p_T<2 GeV/c.

Non-flow suppression



Short range correlations:
jets, resonance decays, HBT, etc.



C.J. Zhang et al, arXiv:2102.05200

non-flow suppression via subevent methods by correlating particles from different η windows

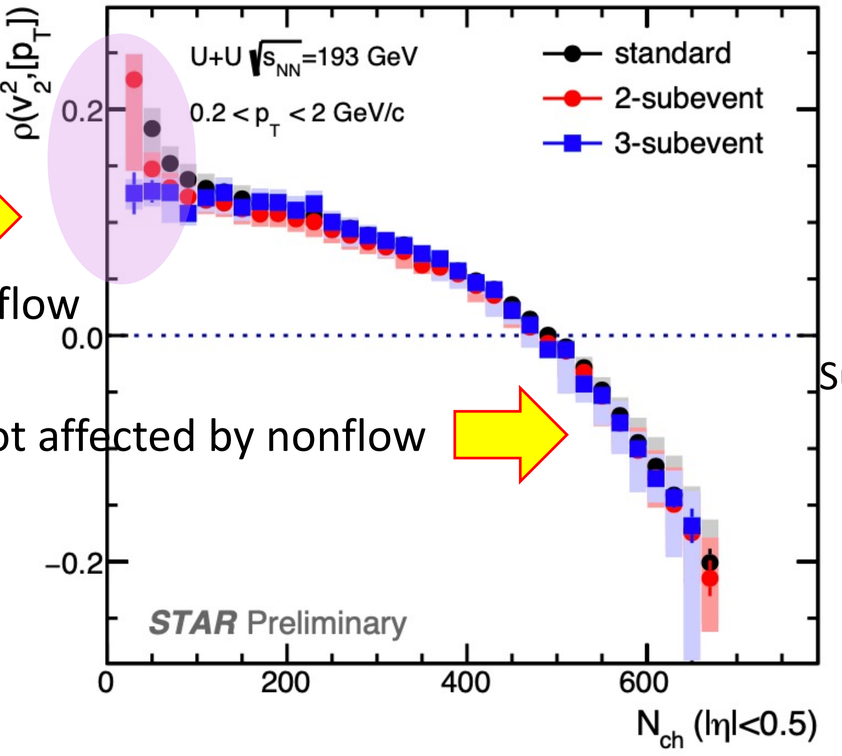
Full event	Two-subevent		Three-subevent		
$v_2, p_T\ \lvert\eta\rvert < 1.0$	$v_2^A\ \eta < -0.1$	$v_2^B\ \eta > 0.1$	$v_2^A\ \eta < -0.35$	$v_2^B \lvert\eta\rvert < 0.3$	$v_2^C \eta > 0.35$

Non-flow effect is important in peripheral region and they are greatly suppressed using subevent method.

P. Bozek, PRC93, 044908(2016), PRC96.014904(2017); B. Schenke et al., PRC102, 034905(2020); G. Giacalone et al., PRC103, 024910(2021), 2101.00168; F.G. Gardim et al., PLB809, 135749(2020) ; ATLAS EPJC79, 985(2019); J. E. Bernhard et al., Nature Physics 15, 1113(2019); ALICE EPJC 74, 3077(2014); thesis1_STAR;

The effects of non-flow in $\rho(v_n^2, [p_T])$

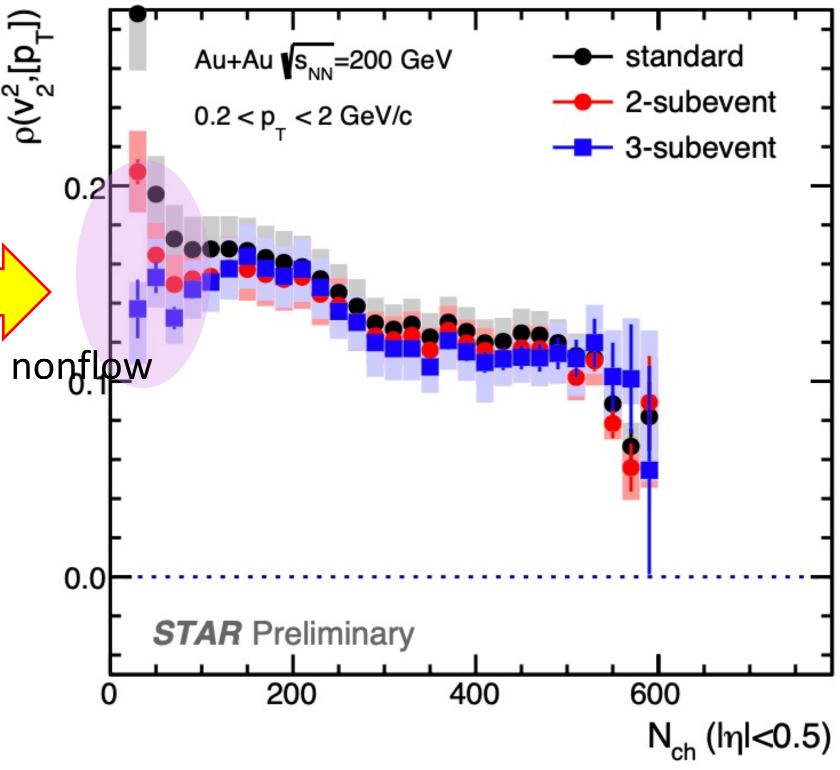
U+U collisions



Suppress nonflow

Not affected by nonflow

Au+Au collisions



Suppress nonflow

Standard method is consistent with subevent methods at high N_{ch}.

Subevent methods could decrease non-flow contributions in peripheral collisions.

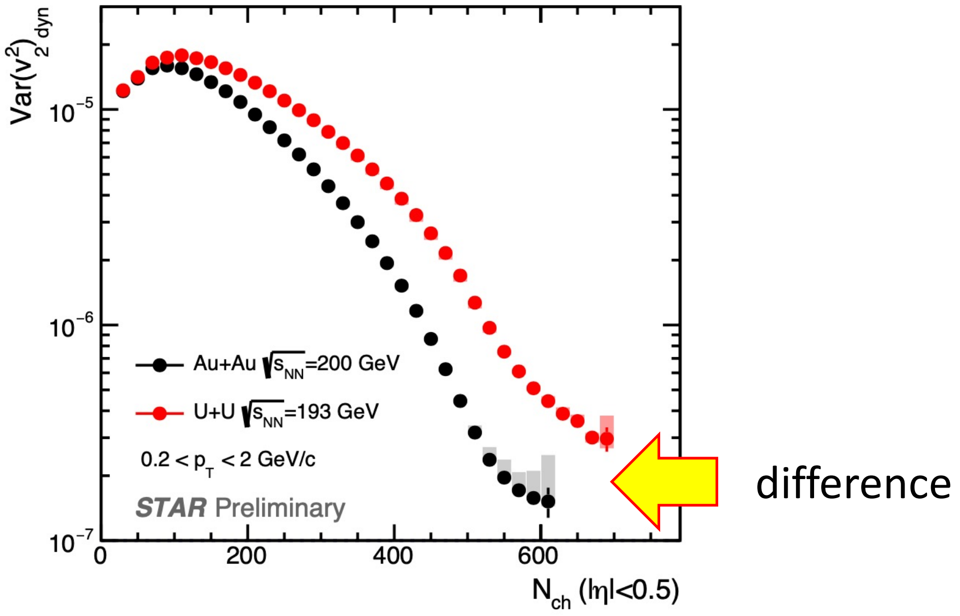
Non-flow effect is not responsible for the sign-change in U+U collisions.

Dynamical v_n^2 variance and $\langle p_T \rangle$ fluctuations

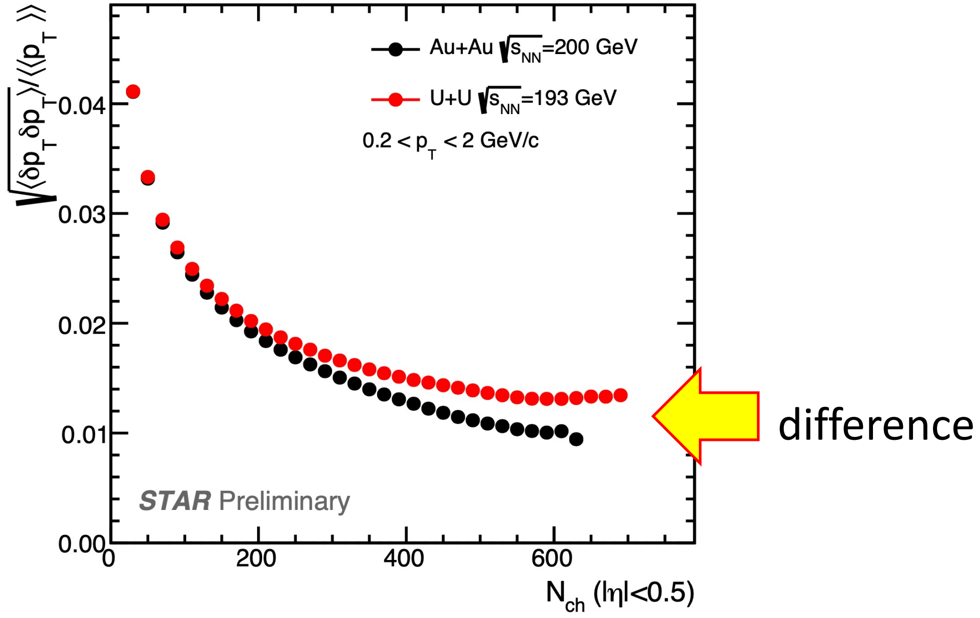
$$\rho(v_n^2, [p_T]) = \frac{\mathrm{cov}(v_n^2, [p_T])}{\sqrt{\mathrm{Var}\,(v_n^2)_{\mathrm{dyn}} \langle \delta p_T \delta p_T \rangle}}$$

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

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



difference of flow fluctuation due to deformation.



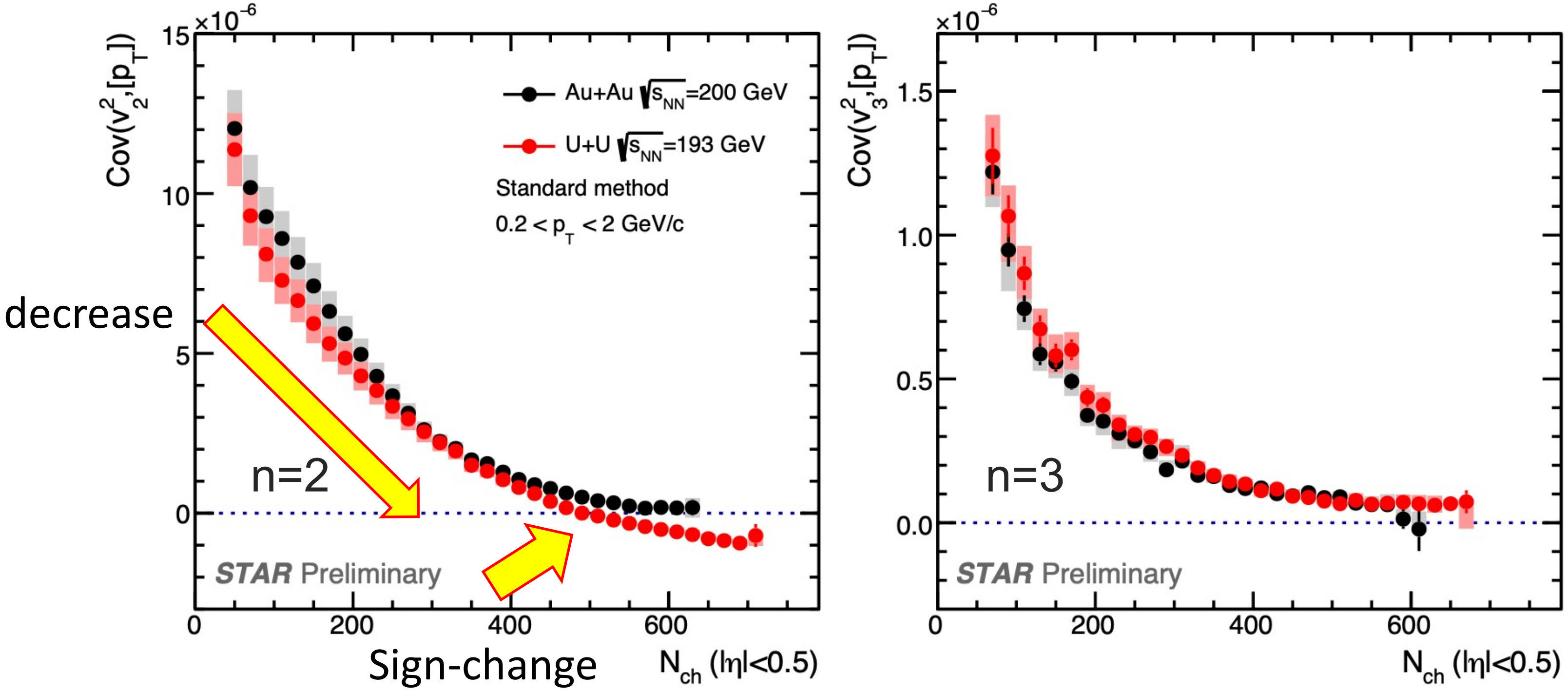
difference of $\langle p_T \rangle$ fluctuation due to deformation .

Nuclear deformation plays a role in flow and $\langle p_T \rangle$ fluctuations.

Covariance $\mathrm{Cov}(v_n^2, [p_T])$

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

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

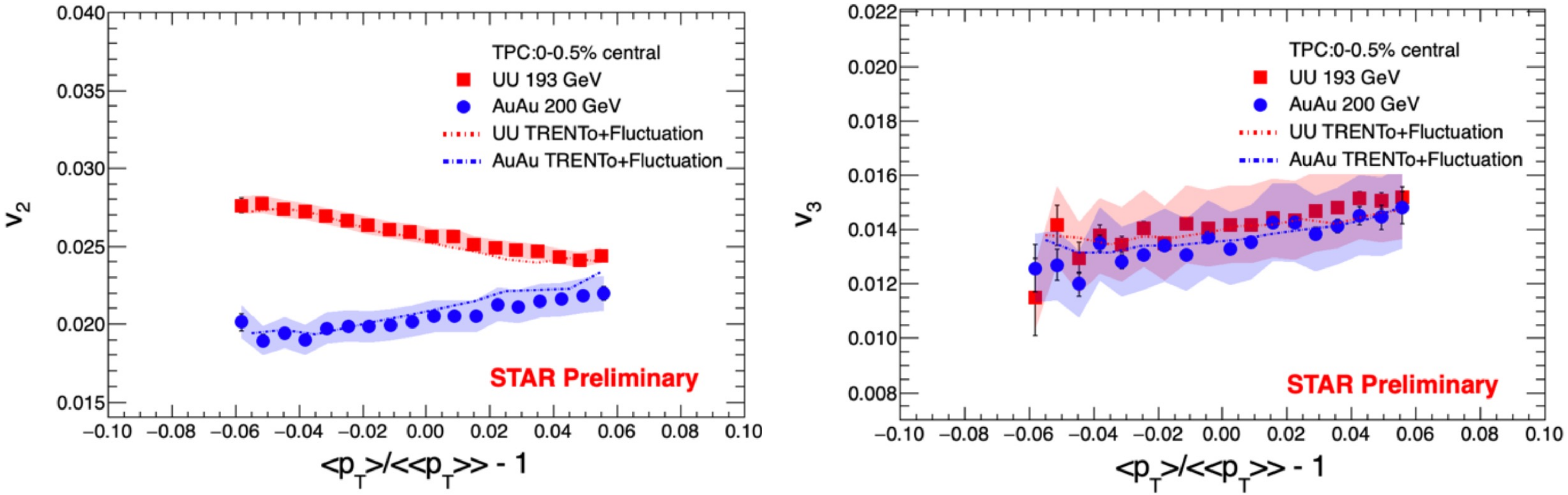


U+U collisions show a sign-change behavior in $\mathrm{Cov}(v_2^2, [p_T])$ while not in Au+Au. But they are consistent for $\mathrm{Cov}(v_3^2, [p_T])$.

This sign-change behavior indicates the effect of deformation.

Event-by-event v_n vs. $\langle p_T \rangle$ in ultra central (0-0.5%) collisions

WWND2020, Shengli Huang (STAR Collaboration)



v_n	System	slope
v_2	U + U	$-3.5\% \pm 0.1\%$
v_2	Au + Au	$2.6\% \pm 0.2\%$
v_3	U + U	$1.7\% \pm 0.2\%$
v_3	Au + Au	$1.9\% \pm 0.2\%$

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 incorporating the statistical fluctuation due to finite multiplicity, the TRENTo model can reproduce the data quantitively.

The anticorrelation in v_2 vs. $\langle p_T \rangle$ for U+U is due to deformation.