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Exploring the deformation of nuclei with v_n-$\langle p_T \rangle$ correlation from STAR

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Outline:

1. Physics motivations
2. Correlation between v_n and $\langle p_T \rangle$
3. Model comparisons
4. Summary

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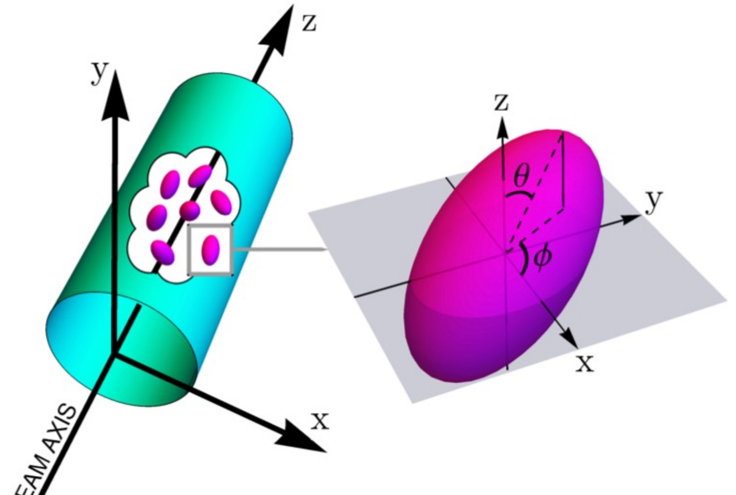
STAR

Deformation and v_2- $\langle p_T \rangle$ correlation



G. Giacalone, PRL124, 202301(2020)

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

β_2 of ^{238}U is large

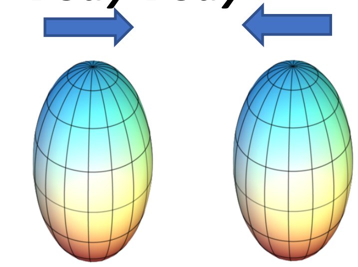
reference	Raman et al.	Löbner et al.	Möller et al.	Möller et al.
method	exp	exp	FRDM	FRLDM
β_2	0.286	0.281	0.215	0.236

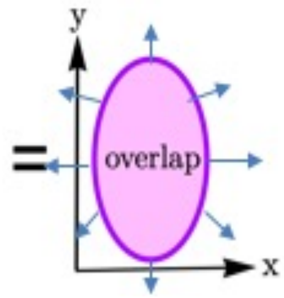
β_2 of ^{179}Au is small and can be used as baseline

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

- ✓ Deformation is dominated by quadrupole component β_2

Body-Body

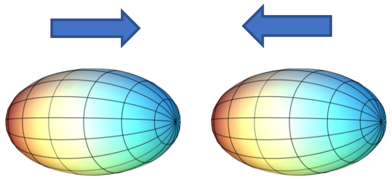


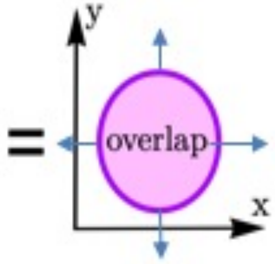


large *R*, small $\langle p_T \rangle$

large ε_2, large v_2

Tip-Tip



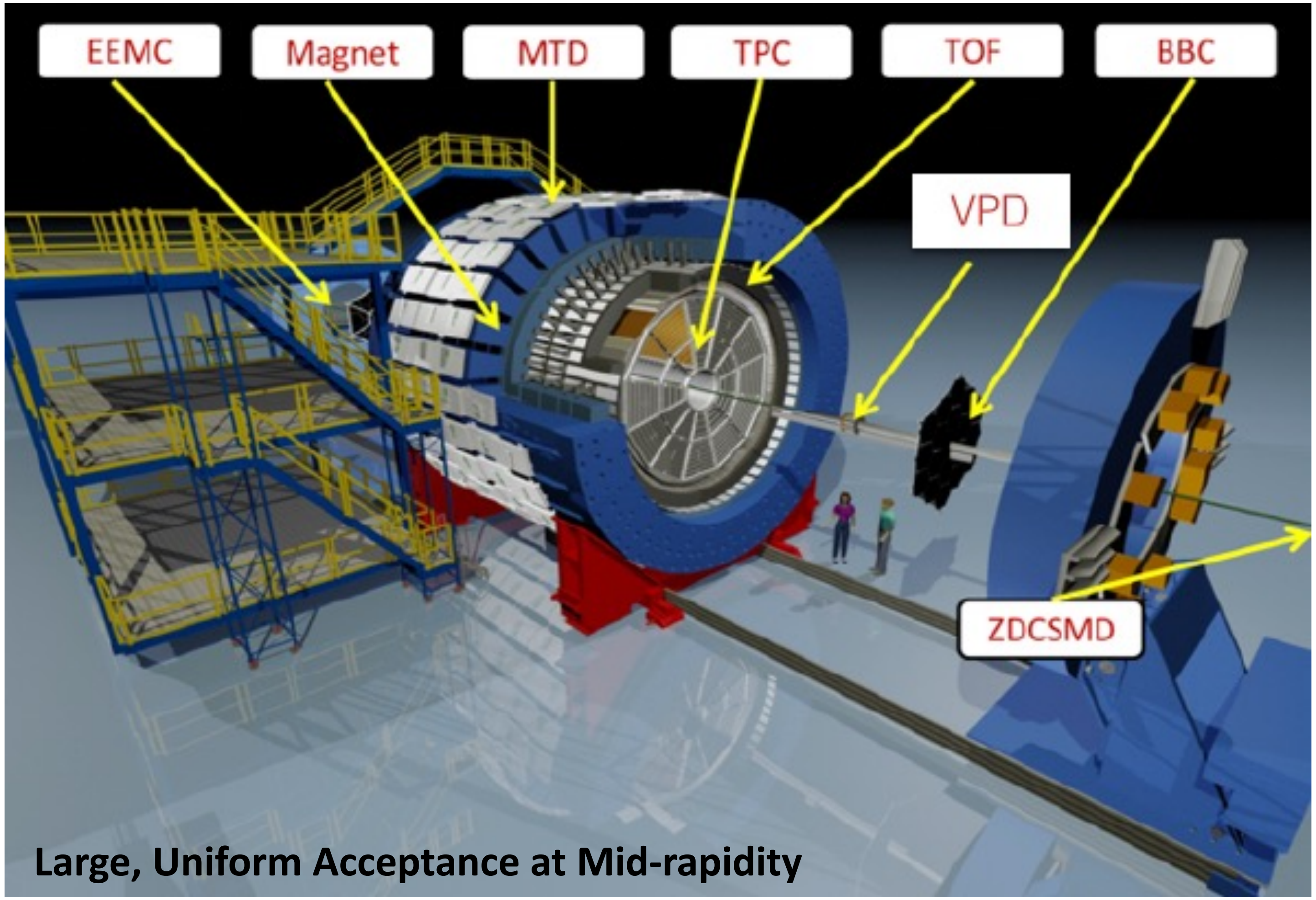


small *R*, large $\langle p_T \rangle$

small ε_2, small v_2

- ✓ Deformation has negative contribution on correlation between v_2 and $\langle p_T \rangle$
- ✓ v_2 - $\langle p_T \rangle$ correlation: A novel tool to reveal the quadrupole deformation at extremely short time scale ($< 10^{-24}$s).

The STAR detector



- $\langle p_T \rangle$ and v_n are measured within $0.2<p_T<2.0$ GeV/c and $|\eta|<1.0$
- Multiplicity are measured within $0.2<p_T<2.0$ GeV/c and $|\eta|<0.5$
- Track efficiency is corrected from embedding data

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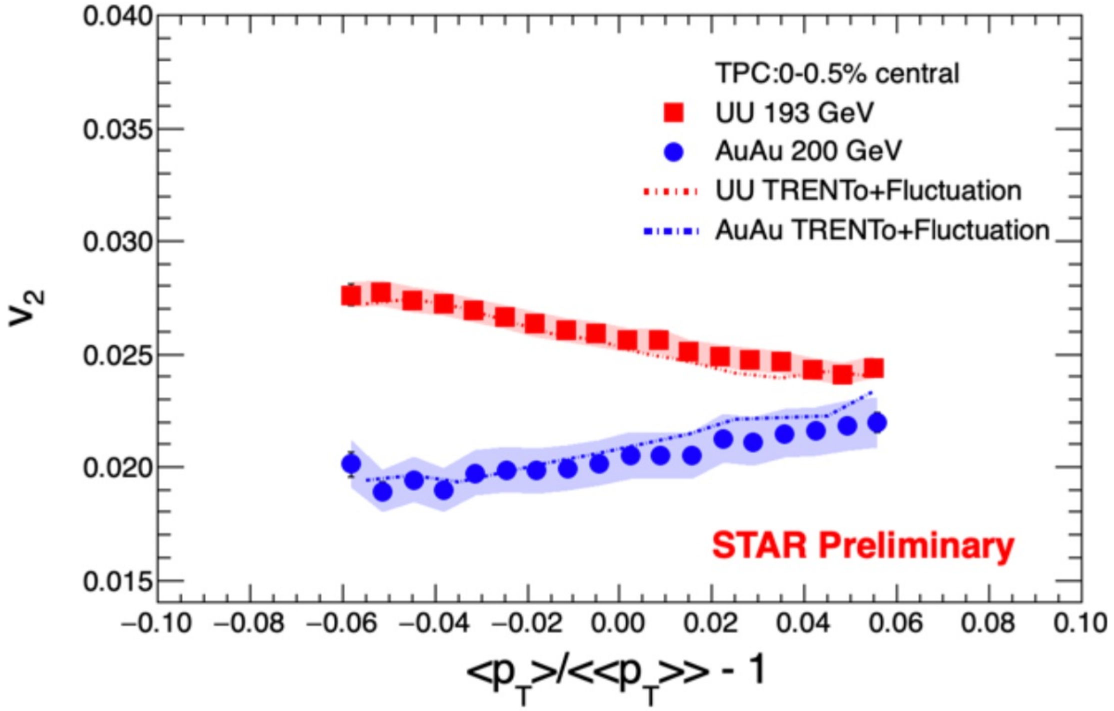
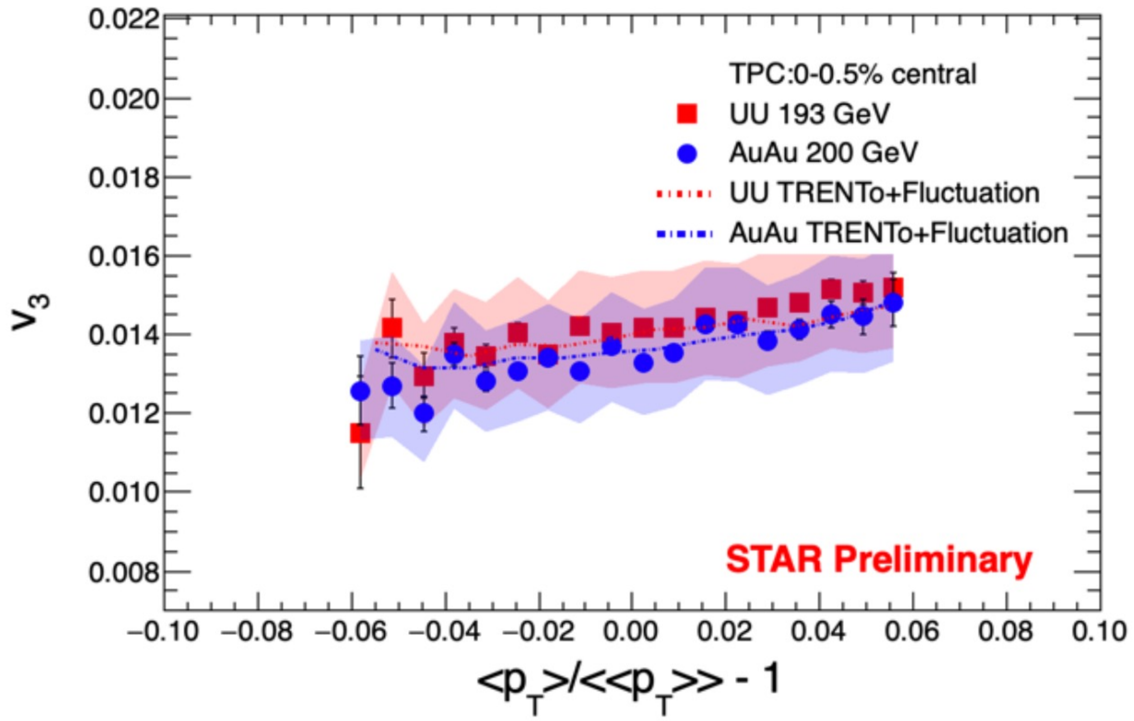
Event-by-event v_n vs. $\langle p_T \rangle$ in ultra central (0-0.5%) collisions





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	$1.9\% \pm 0.2\%$

- Negative correlation is observed between v_2 and $\langle p_T \rangle$ in central U+U collisions while not in Au+Au ⟶ ***large deformation in U+U***
- $v_3 - \langle p_T \rangle$ correlations are positive and similar between Au+Au and U+U
- After implementing the statistical fluctuation (due to finite multiplicity), TRENTo model can reproduce the data quantitatively.

Pearson coefficient

Pearson coefficient: designed to measure dynamical fluctuations

P. Bozek, PRC93, 044908(2016); B. Schenke et al., PRC102, 034905(2020); G. Giacalone, PRC102, 024901(2020), PRL124, 202301(2020), arXiv:2006.15721; F.G. Gardim et al., PLB809, 135749(2020) ; ATLAS EPJC79, 985(2019)

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

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

w_i is track weight

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

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

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

Nonflow effect: sub-event method

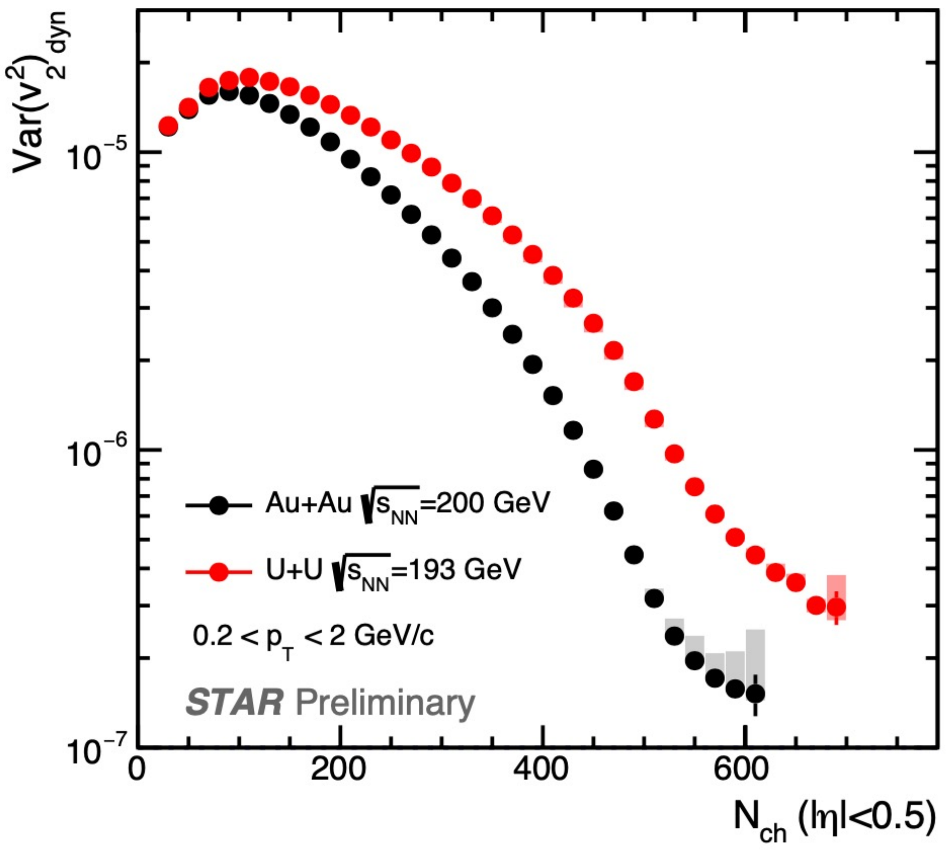
Standard	2-subevent	3-subevent
$v_2, p_T \ |\eta| < 1.0$	$v_2^\mathrm{A}\ \eta < -0.1$; $v_2^\mathrm{B}\ \eta > 0.1$; $\langle p_T \rangle\ |\eta| < 1.0$	$v_2^\mathrm{A}\ \eta < -0.35$; $\langle p_T \rangle\ |\eta| < 0.35$; $v_2^\mathrm{C}\ \eta > 0.35$

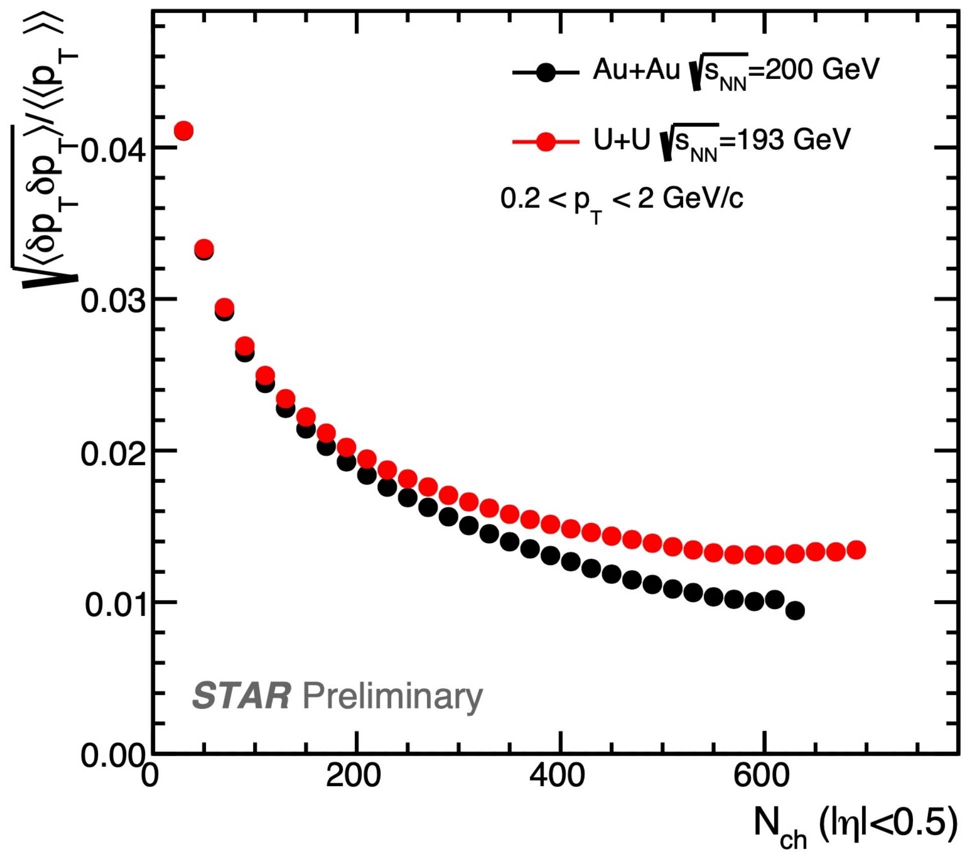
Dynamical v_n^2 variance and $\langle p_T \rangle$ fluctuations

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

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

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



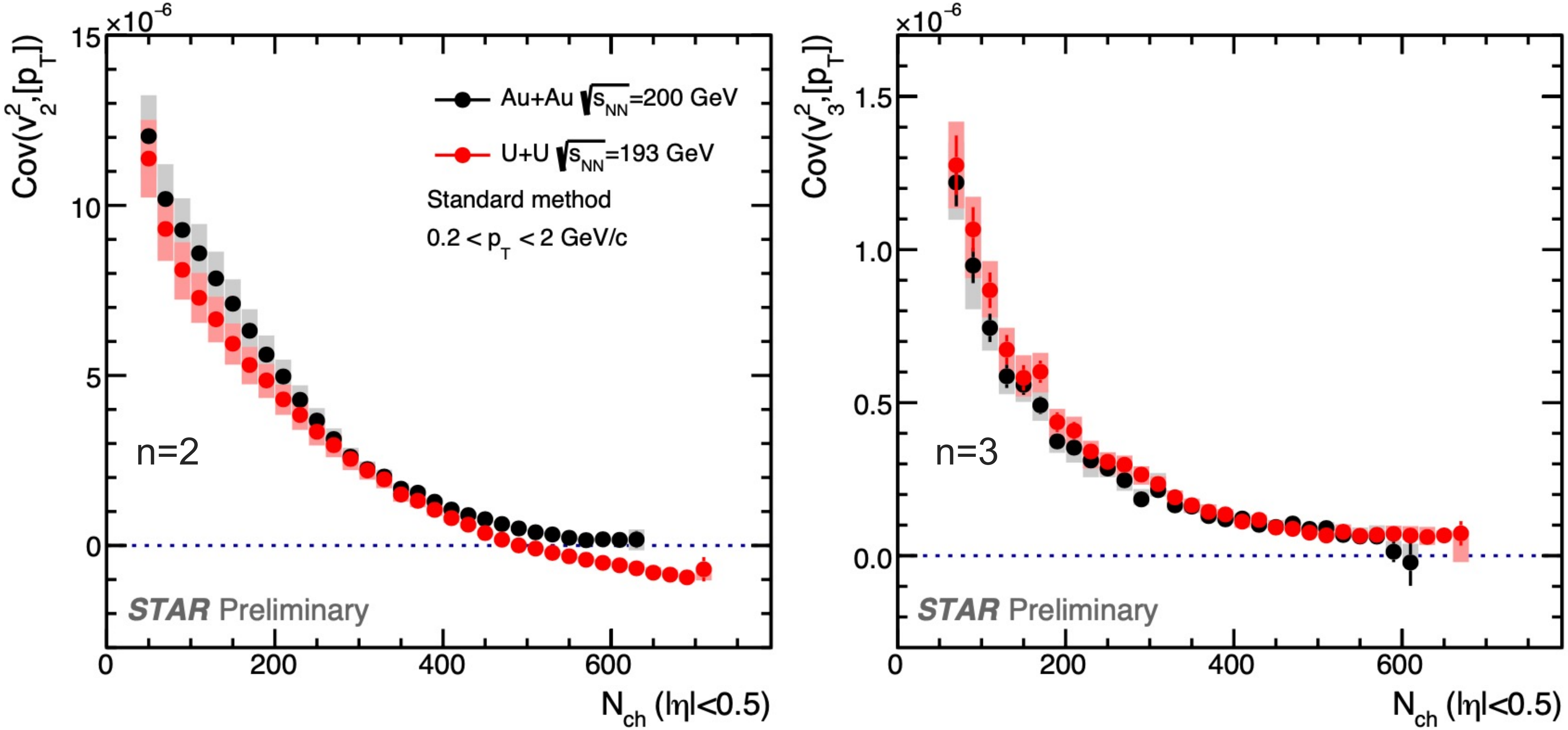


Both flow and $\langle p_T \rangle$ fluctuations affected by nuclear deformation

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

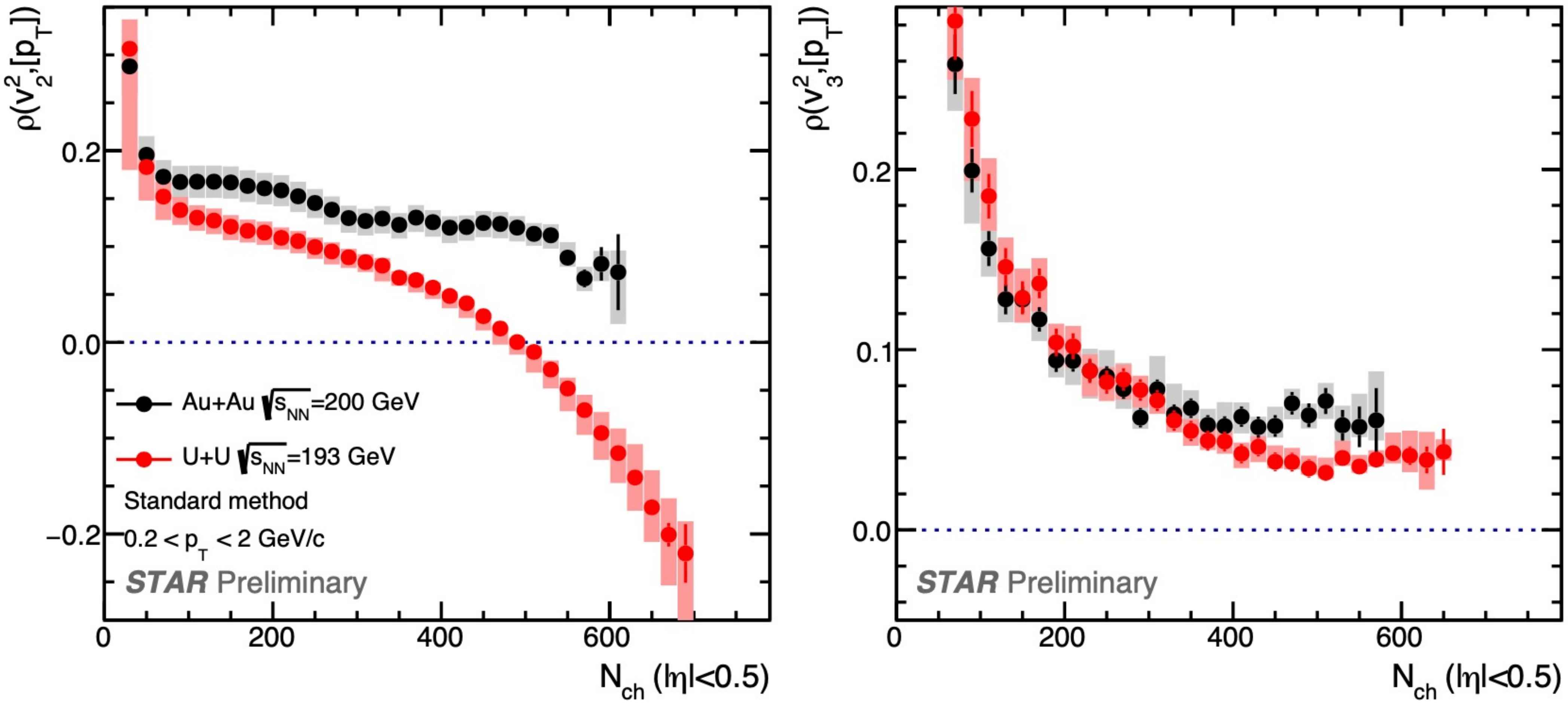
$$\rho(v_n^2, [p_T]) = \frac{\mathrm{cov}(v_n^2, [p_T])}{\sqrt{\mathrm{Var}\,(v_n^2)_{\mathrm{dyn}} \langle \delta p_T \delta p_T \rangle}}$$

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



Sign-change for $\mathrm{cov}(v_2^2, [p_T])$ in central U+U as expected from deformation

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



✓ $\rho(v_2^2, [p_T])$ is quite different between central U+U(negative) and Au+Au(positive)

✓ $\rho(v_3^2, [p_T])$ is similar and always positive in Au+Au and U+U collisions

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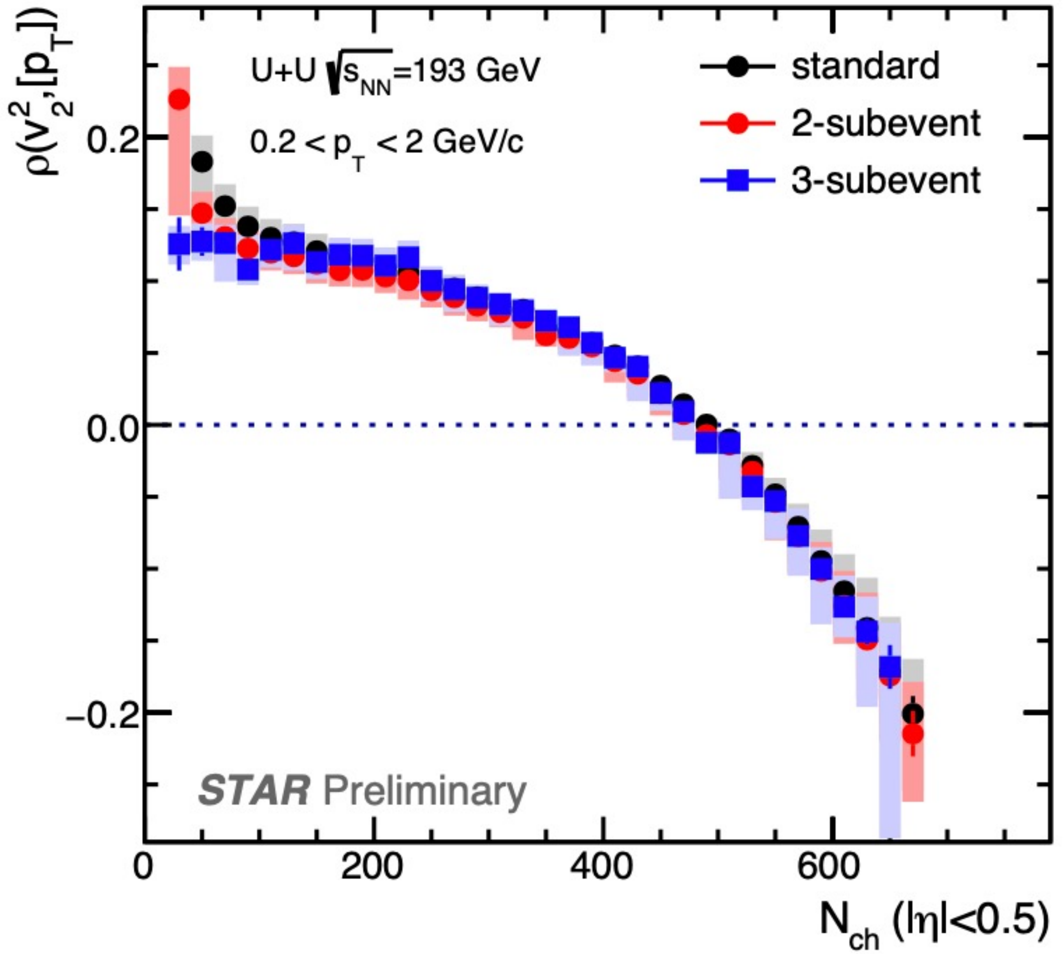
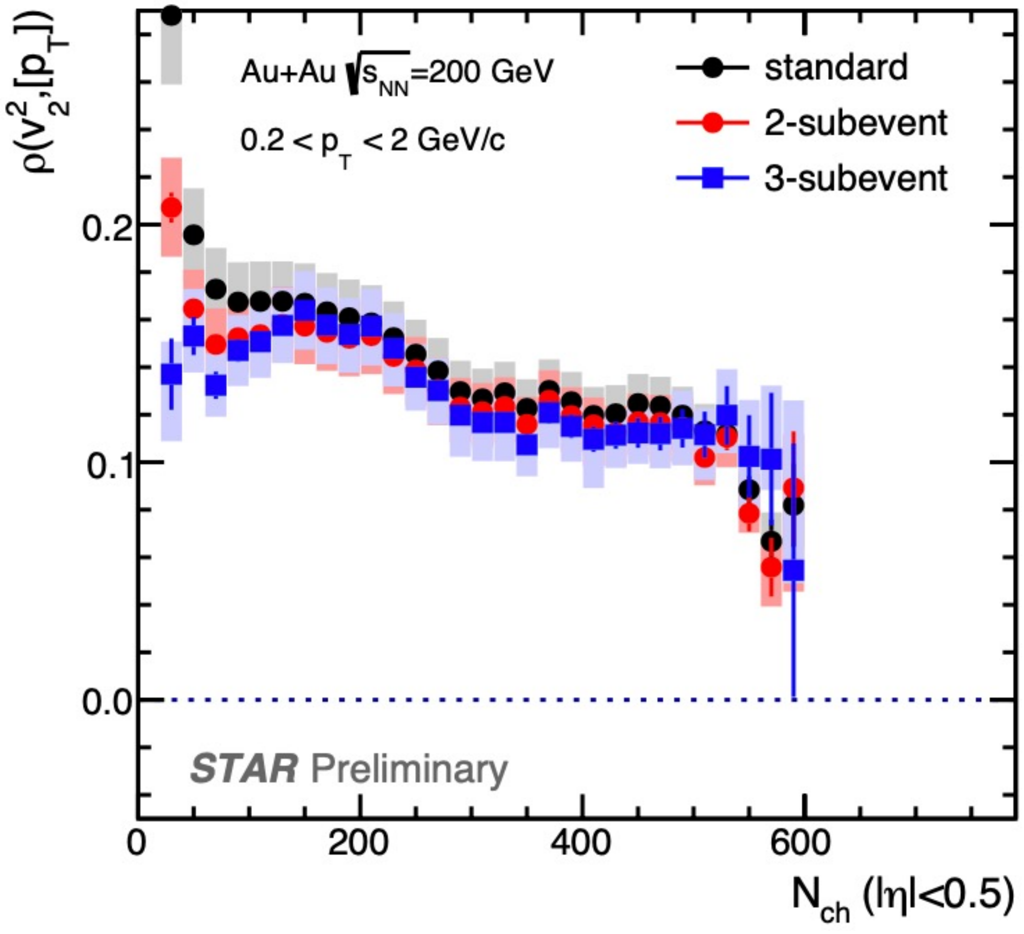
$\rho(v_n^2, [p_T])$ from Sub-Event Method



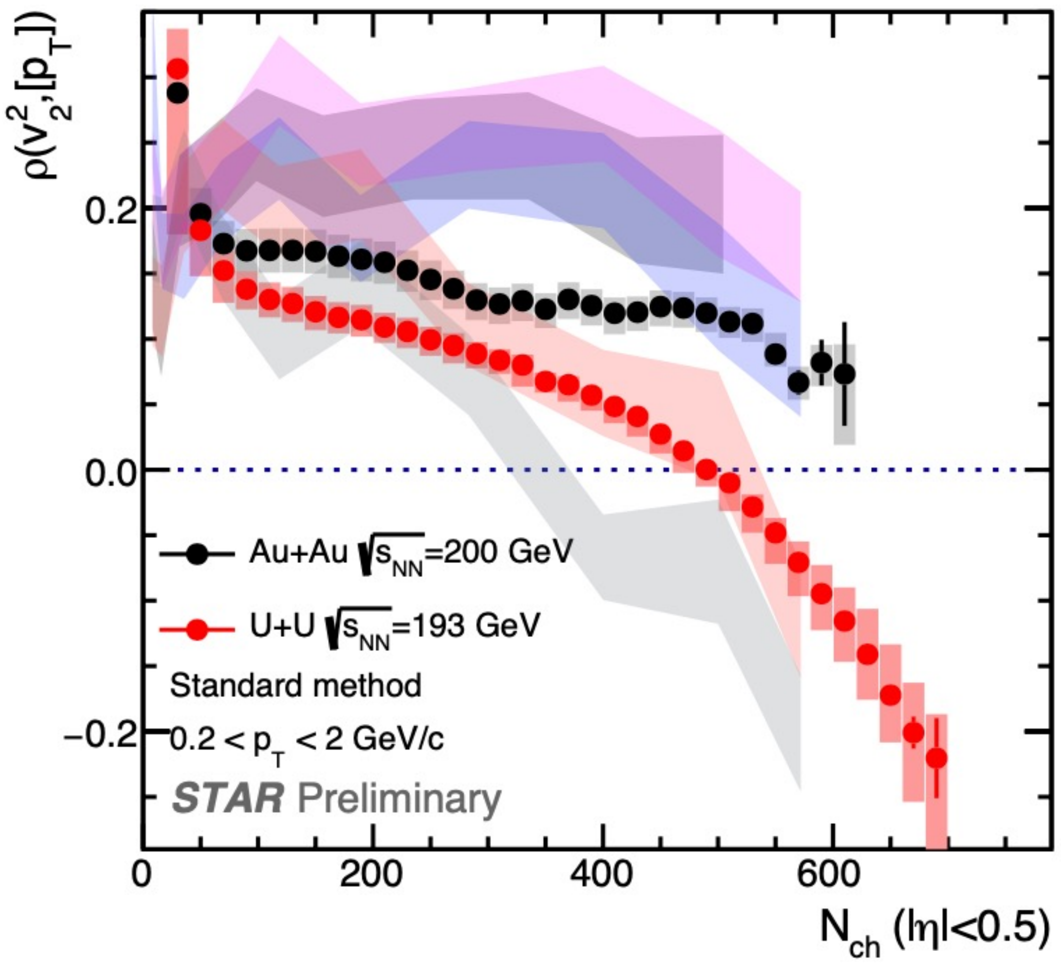


Sub-event methods indicate non-flow effect is negligible in central AA collisions

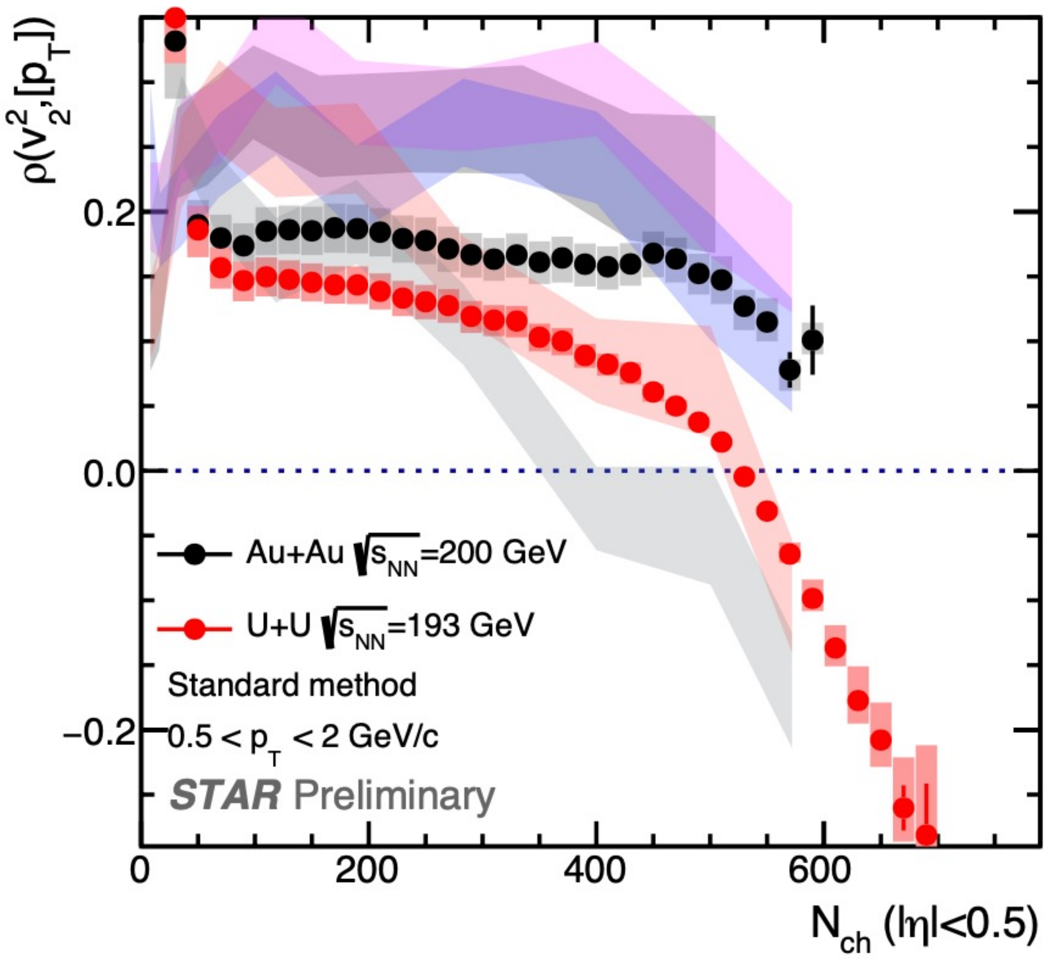
$\rho(v_n^2, [p_T])$ in Different P_T Selection

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

0.2< p_T < 2 GeV/c



0.5< p_T < 2 GeV/c



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

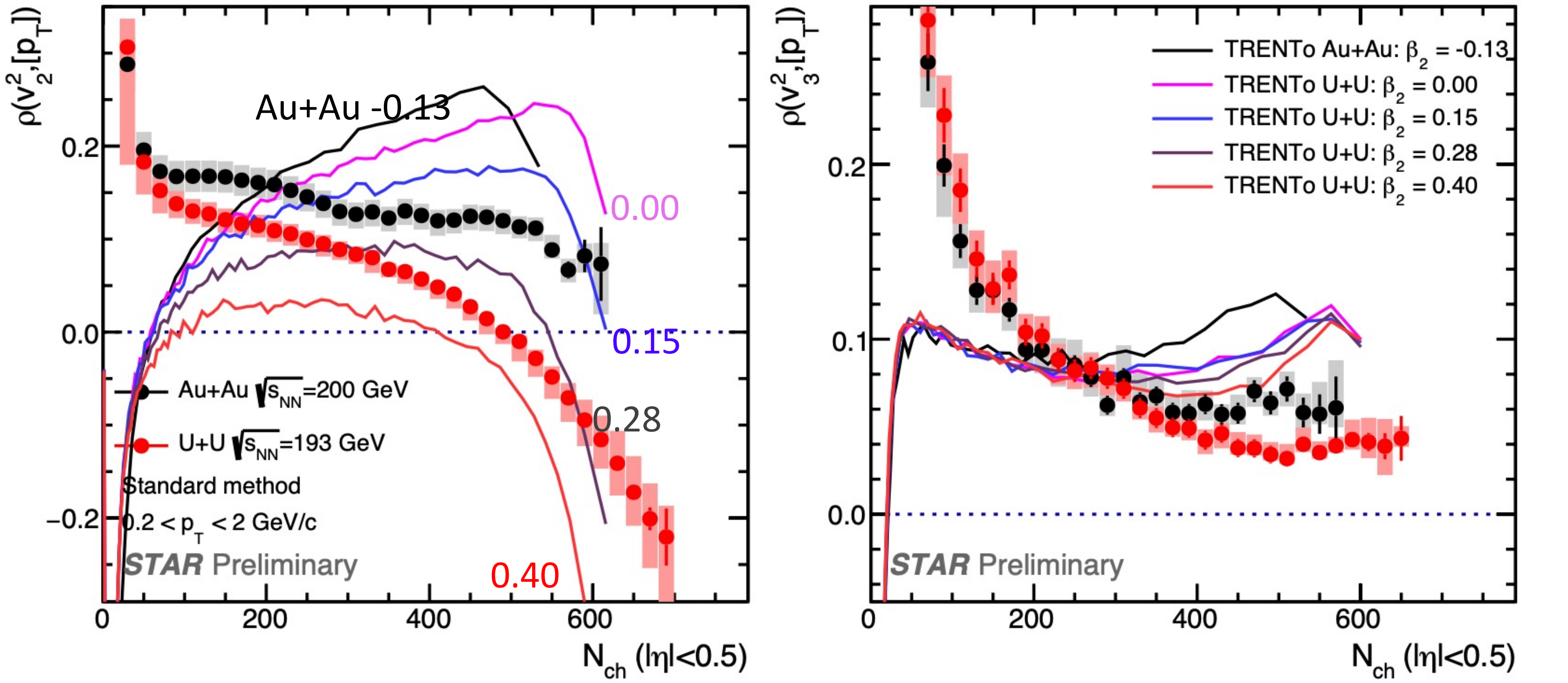
Comparison with TRENTo Model

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

TRENTo: assuming

$$v_n \propto \epsilon_n$$

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



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

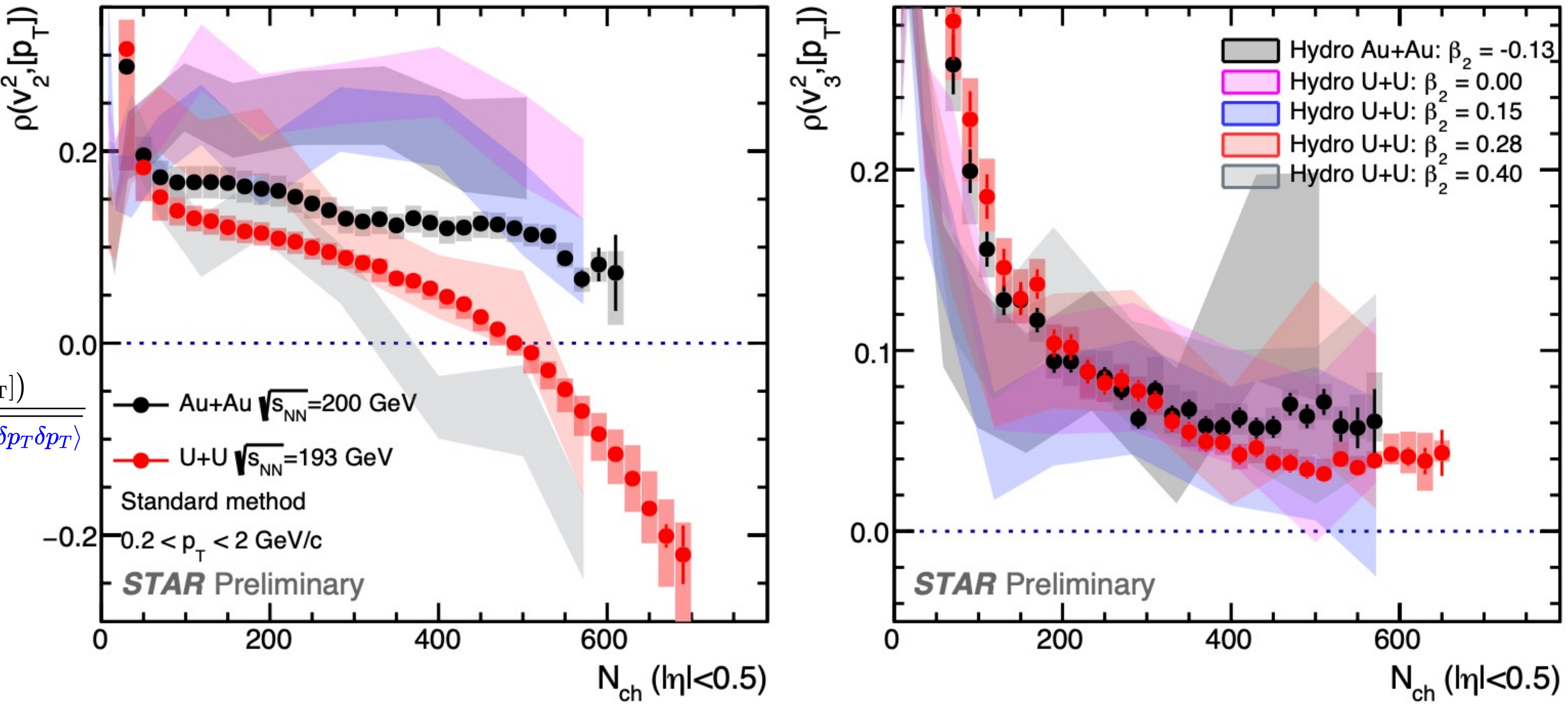
TRENTo suggests this sign-change in the central collisions could be due to deformation effect.

TRENTo prefers the β_2 value between 0.28 to 0.4 for Uranium

Comparison with IP-Glasma+Hydro

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

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



A hierarchical β_2 dependence for $\rho(\mathrm{v}_2^2, [\mathrm{p_T}])$ while not for $\rho(\mathrm{v}_3^2, [\mathrm{p_T}])$ in U+U in IP-Glasma

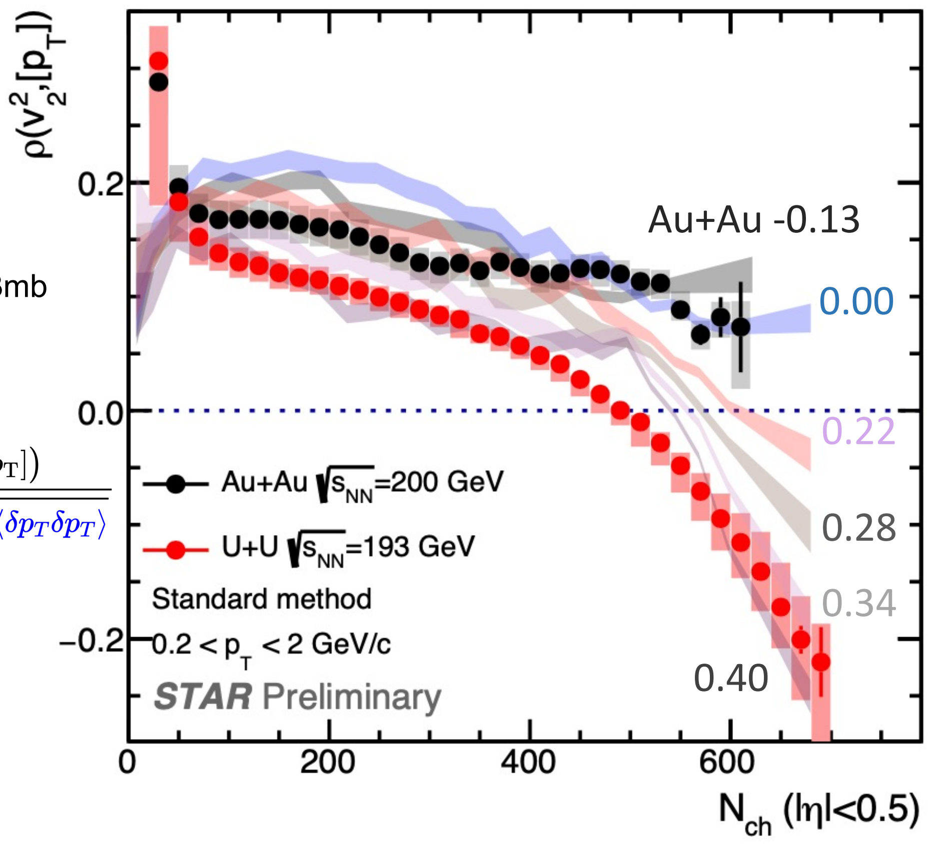
Data comparable to β_2~0.28 with IP-Glasma but with large uncertainty

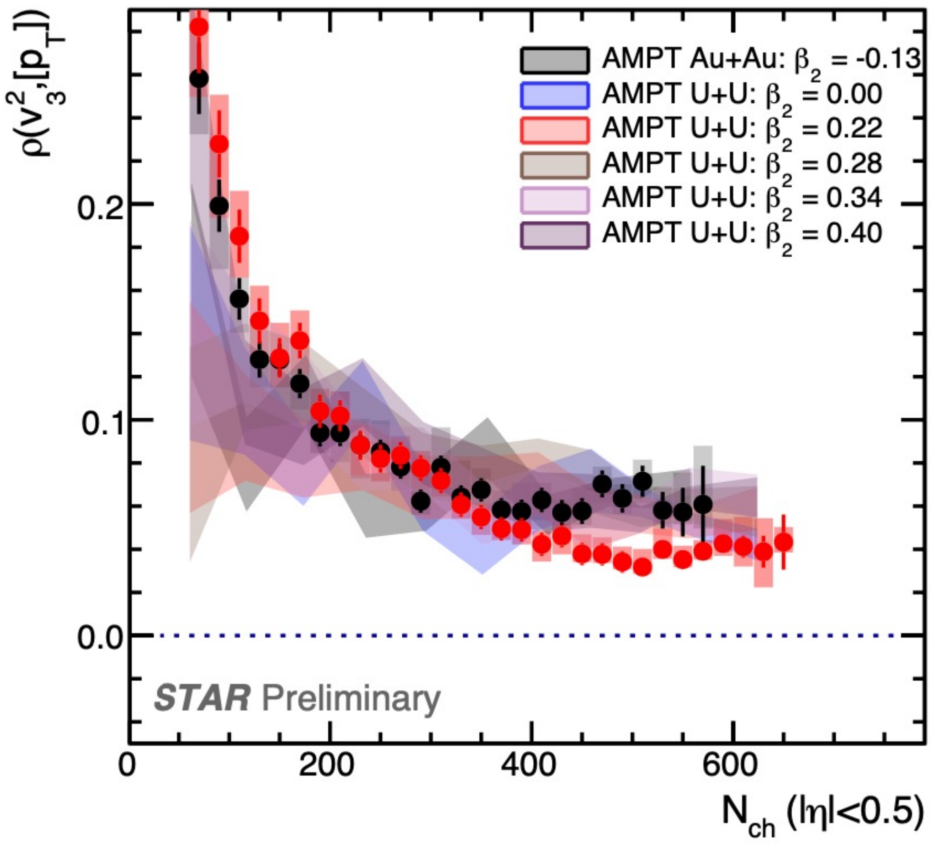
Comparison with AMPT Model

AMPT-SM: Chunjian Zhang, Jiangyong Jia et al., arXiv:2105.05713

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

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

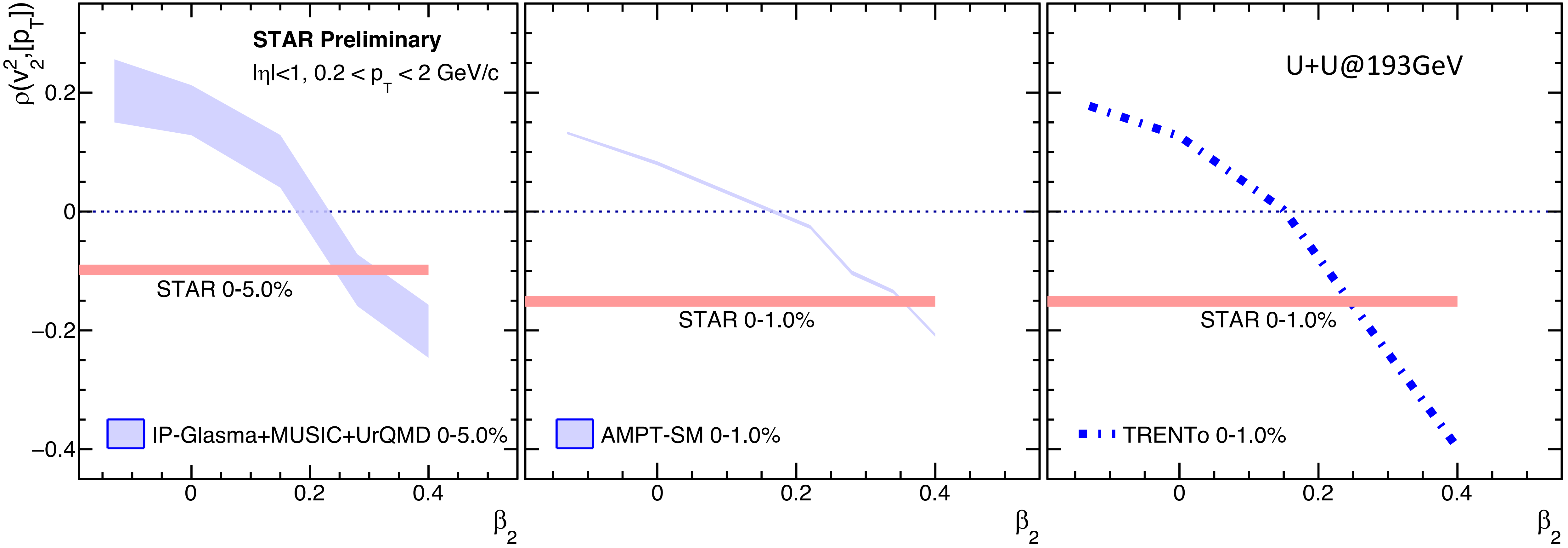




✓ AMPT allows more precise calculation due to large statistics

✓ β_2 value around 0.34-0.40 by comparing with AMPT

Comparison with Model in Central UU



- ✓ β_2 is around 0.2-0.4 for U+U by comparing with three models in central collisions
- ✓ First extraction of the quadrupole deformation at extremely short time scale (< 10^{-24}s) in heavy-ion collisions.

Summary

A sign change of v_2-p_T correlation is observed in central U+U while not in Au+Au collisions

Nonflow has been studied via sub-event methods and found to be negligible in central collisions

Comparison with several model calculations constrains β_2 in the range of 0.2-0.4 for Uranium

First constraints on quadrupole deformation at extremely short time scale (< 10^{-24}s) accessible through heavy-ion collisions.