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

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(For the STAR Collaboration)

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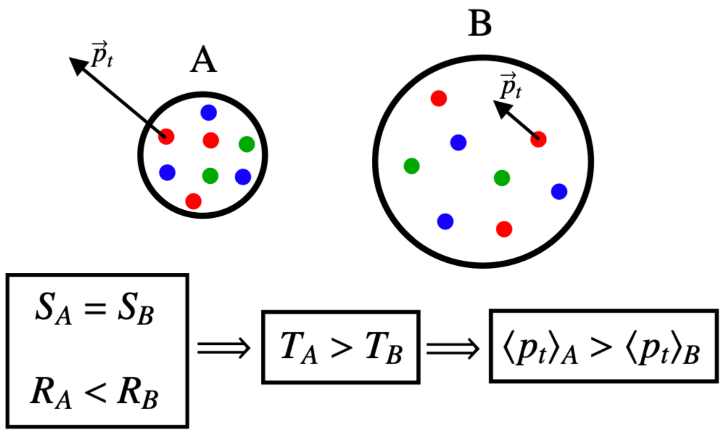
Stony Brook University

STAR

Shape-flow transmutation

Smaller R (fixed multiplicity, same N_{part}) ⇒ Larger pressure gradient higher collision rate of partons ⇒ Faster collective expansion Larger radial flow ⇒ Larger mean p_T

- System size affect the transverse momentum of particles



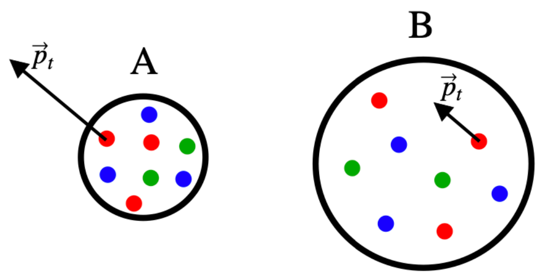
$$\langle p_T \rangle > \propto 1/R$$

G. Giacalone, PRC102, 024901(2020)

Shape-flow transmutation

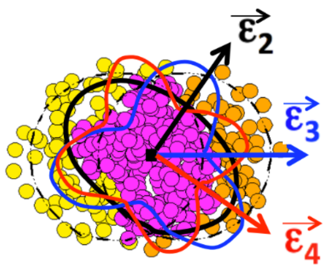
Smaller R (fixed multiplicity, same N_{part}) ➡ Larger pressure gradient higher collision rate of partons ➡ Faster collective expansion Larger radial flow ➡ Larger mean p_T

- System size affect the transverse momentum of particles
- Shape affect anisotropic flow of particles

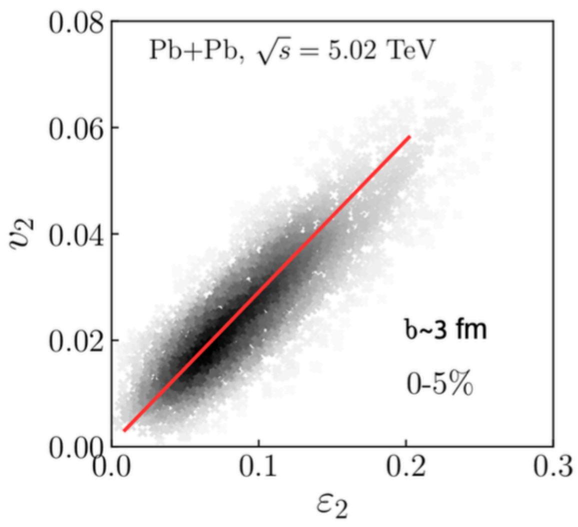


$$\begin{array}{c} S_A = S_B \\ R_A < R_B \end{array} \Longrightarrow T_A > T_B \Longrightarrow \langle p_t \rangle_A > \langle p_t \rangle_B$$

$$\langle p_T \rangle > \propto 1/R$$



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



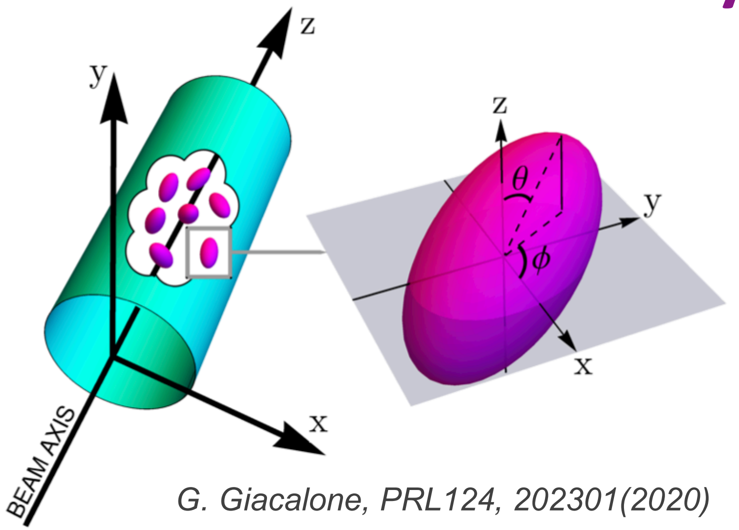
$$v_n \sim \epsilon_n$$

G. Giacalone, PRC102, 024901(2020)

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

The fluctuation in shape and size are converted into flow and mean p_T fluctuation.

Eccentricity and system size in deformed nuclei



G. Giacalone, PRL124, 202301(2020)

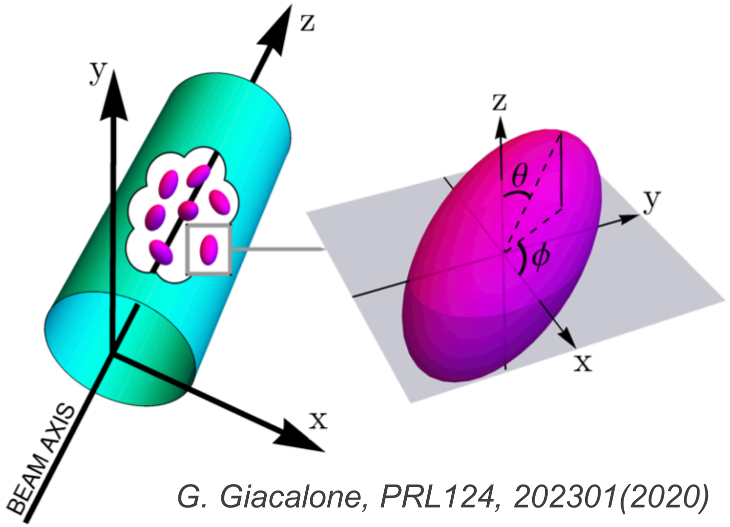
For a deformed nucleus, the leading form of nuclear density becomes:

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

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

Deformation is quantified by quadrupole β_2 parameter

Eccentricity and system size in deformed nuclei



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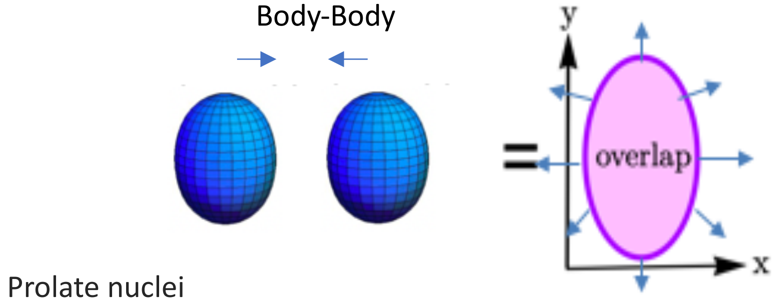
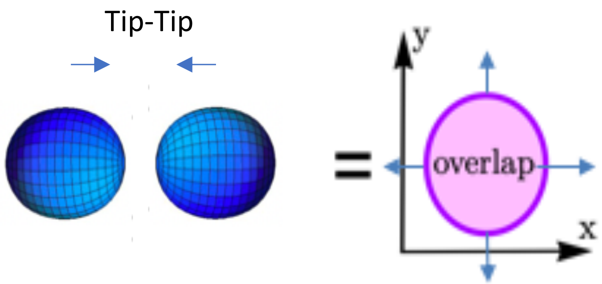


large *R,* small $\langle p_T \rangle$

large $\boldsymbol{\varepsilon}_2$



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

small $\boldsymbol{\varepsilon}_2$

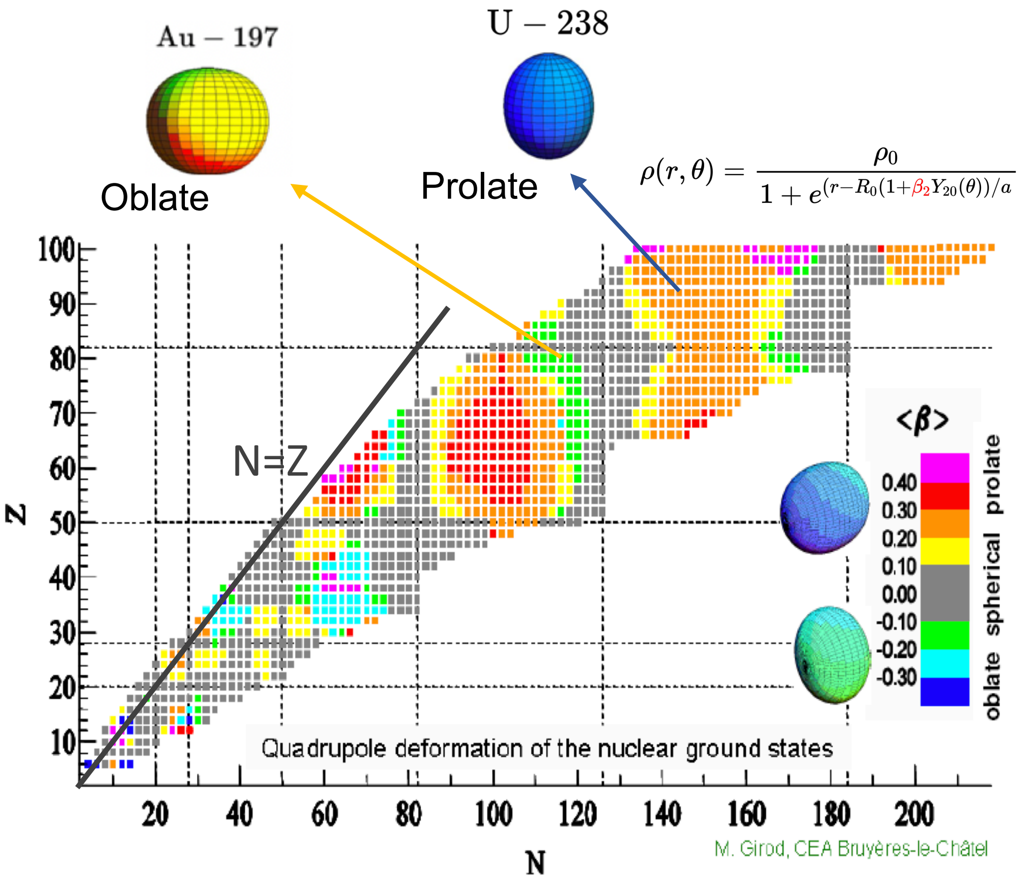
- $\boldsymbol{\varepsilon}_2$ and system size depend on the deformation factor
- $\langle p_T \rangle \propto 1/R$ and $v_n \propto \boldsymbol{\varepsilon}_n$:

  Anticorrelation between v_2 and $\langle p_T \rangle$ due to deformation

Measuring the flow - $\langle p_T \rangle$ correlation can be used to reveal the deformation factor.

Shape deformations in atomic nuclei

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

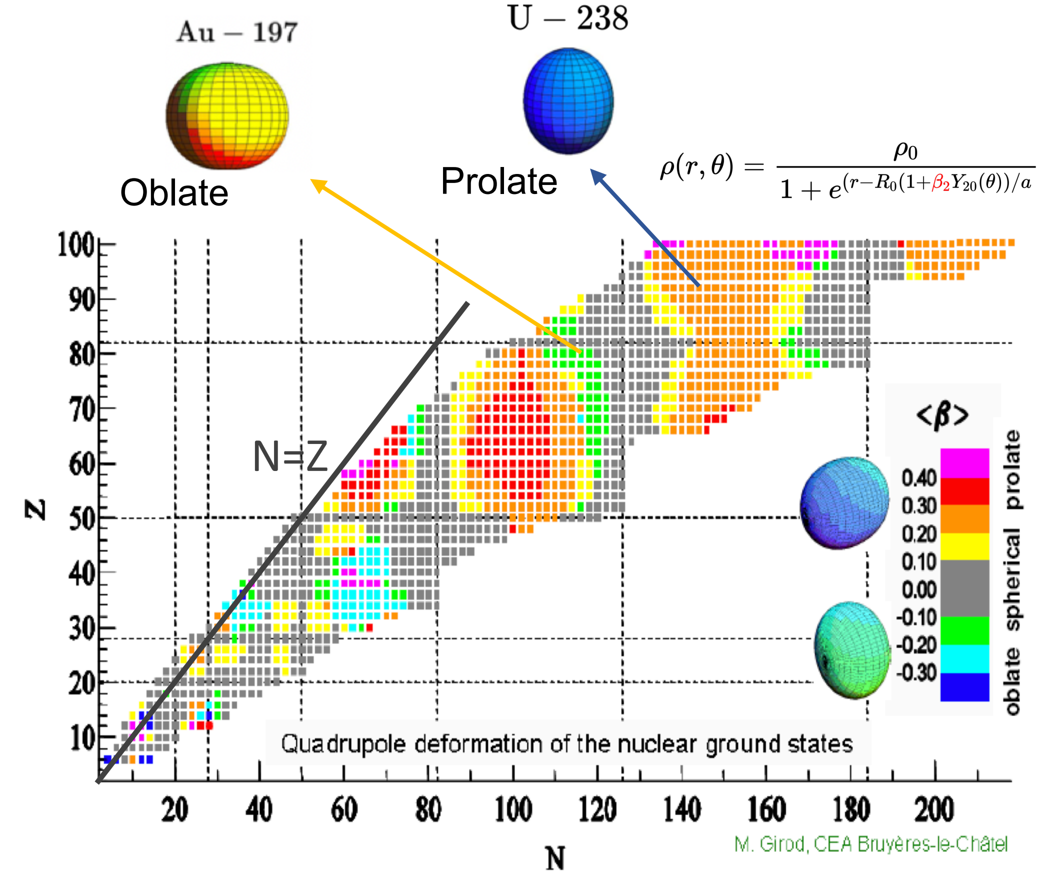


Hartree-Fock-Bogolyubov (Gogny D1S effective interaction)

Shape deformations in atomic nuclei

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

G. Giacalone, "Phenomenology of nuclear structure in HI"



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Hartree-Fock-Bogolyubov (Gogny D1S effective interaction)

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)]

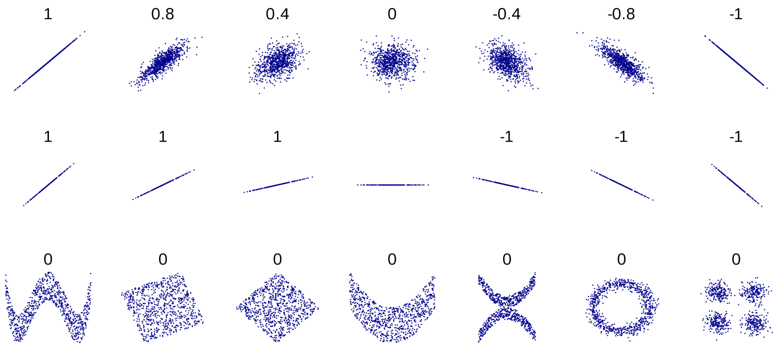
Or access BNL nuclear data center

Can we constrain Uranium deformation β_2 using flow-mean p_T correlations?

Observables

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

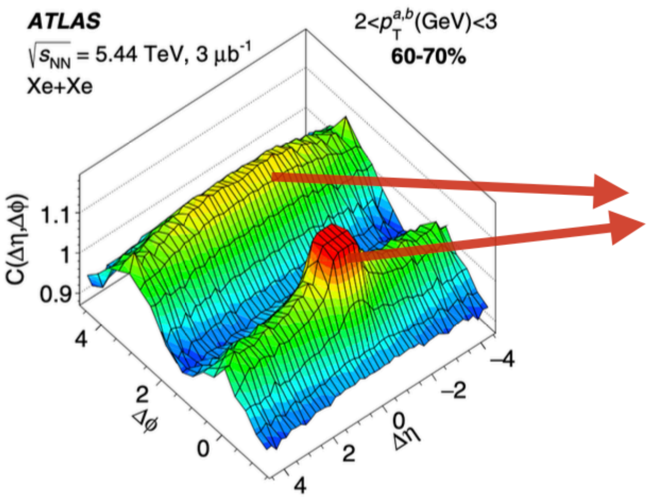
$$\rho\left(v_n^2, [p_T]\right) = \frac{\mathrm{cov}\left(v_n^2, [p_\mathrm{T}]\right)}{\sqrt{\mathrm{Var}\left(v_n^2\right)_\mathrm{dyn} \langle \delta p_T \delta p_T \rangle}}$$

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

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

P. Bozek, PRC93, 044908(2016); 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)

Non-flow suppression and self-correlation removal



Short range non-flow correlations: jets, resonance decays, HBT, etc.

Dynamical quantities with self-correlation removed:

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

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

Subevent method is crucial for non-flow suppression:

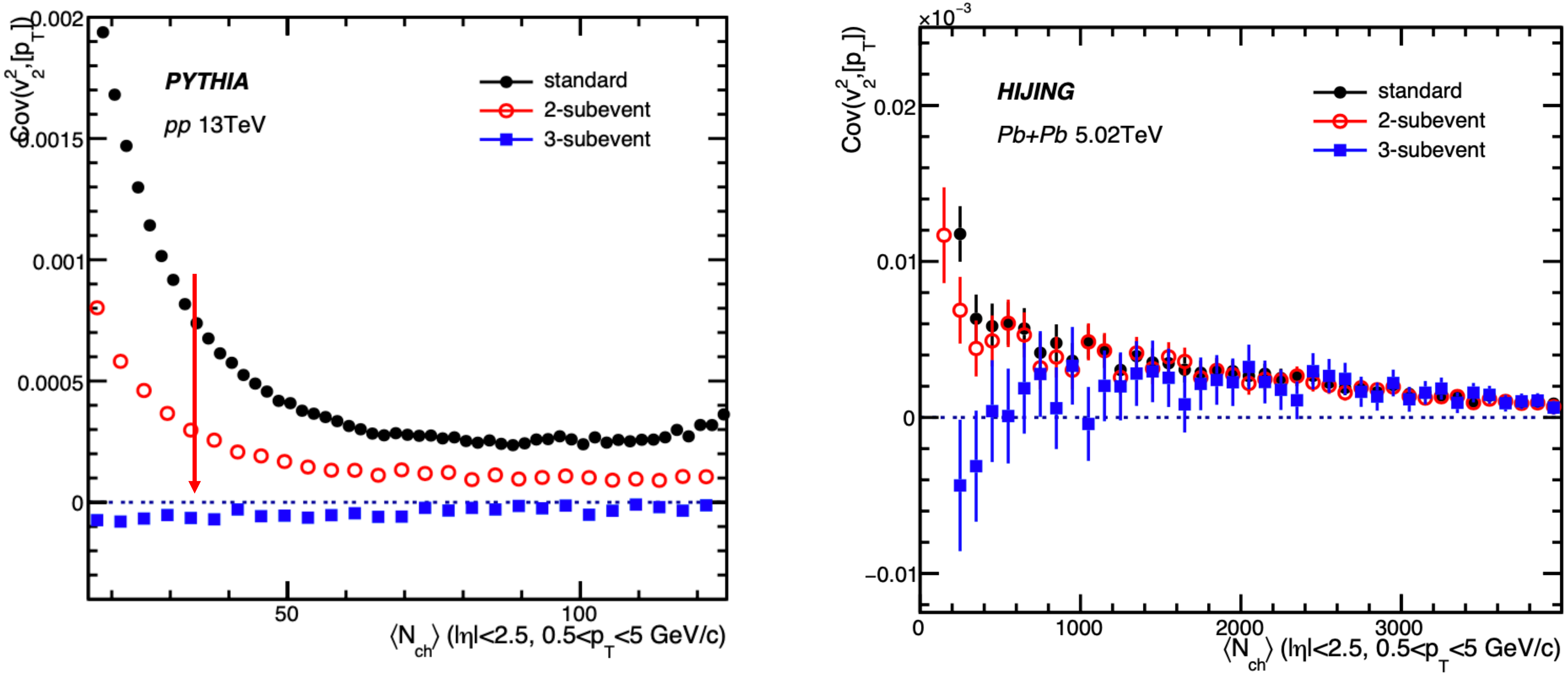
Full event	2-subevent		3-subevent		
$v_2, p_T \; \lvert\eta\rvert < 1.0$	$v_2^A \; \eta < -0.1$	$v_2^B \; \eta > 0.1$	$v_2^A \; \eta < -0.35$	$v_2^B \lvert\eta\rvert < 0.3$	$v_2^C \eta > 0.35$

Correlate particles from different rapidity windows with gap

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)

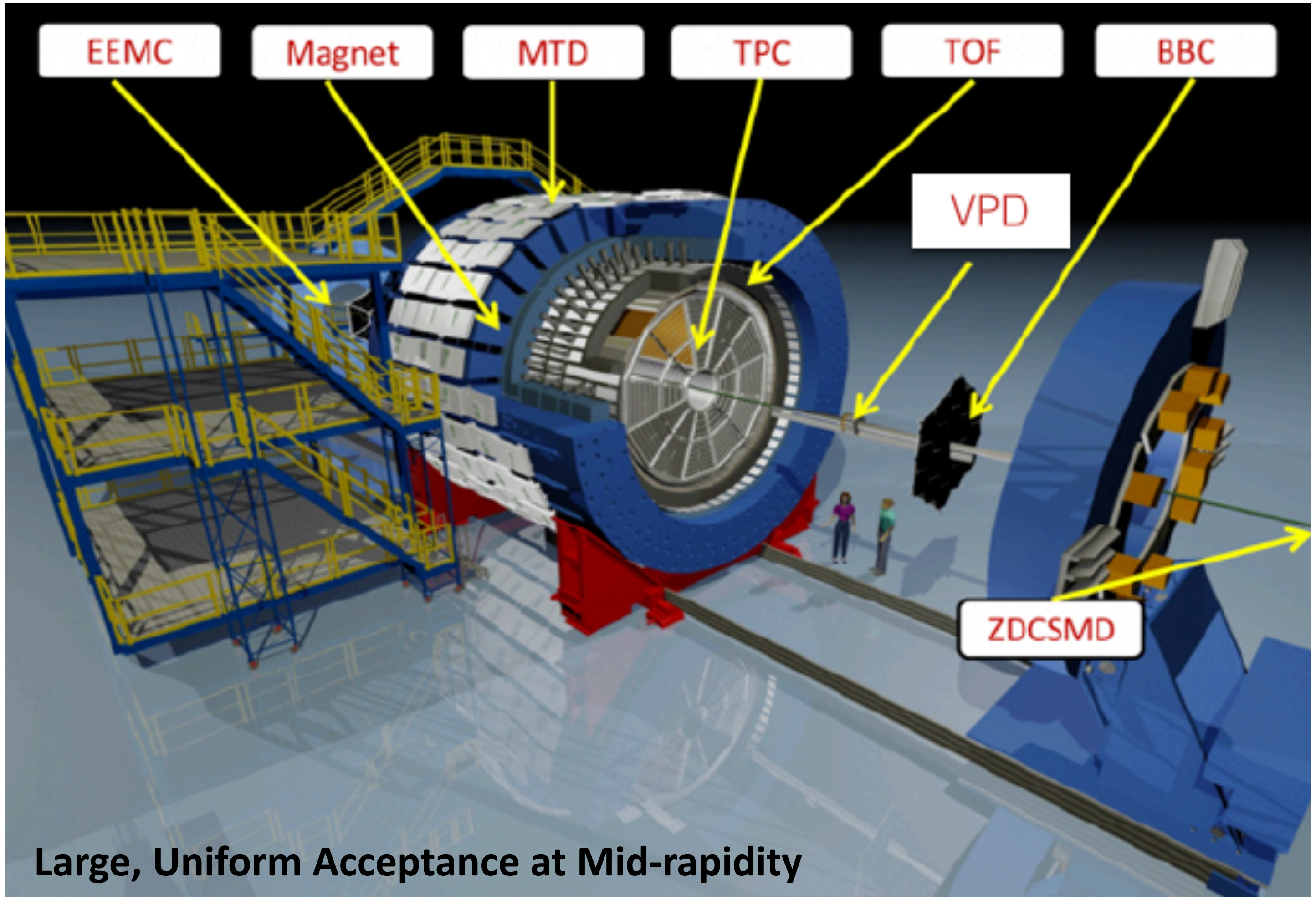
Non-flow contribution in PYTHIA and HIJING

PYTHIA and HIJING only have non-flow.



Subevent method suppress nonflow clearly.

The STAR detector



- Dataset:

  Au+Au@200GeV, year2011

  U+U@193GeV, year2012

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

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

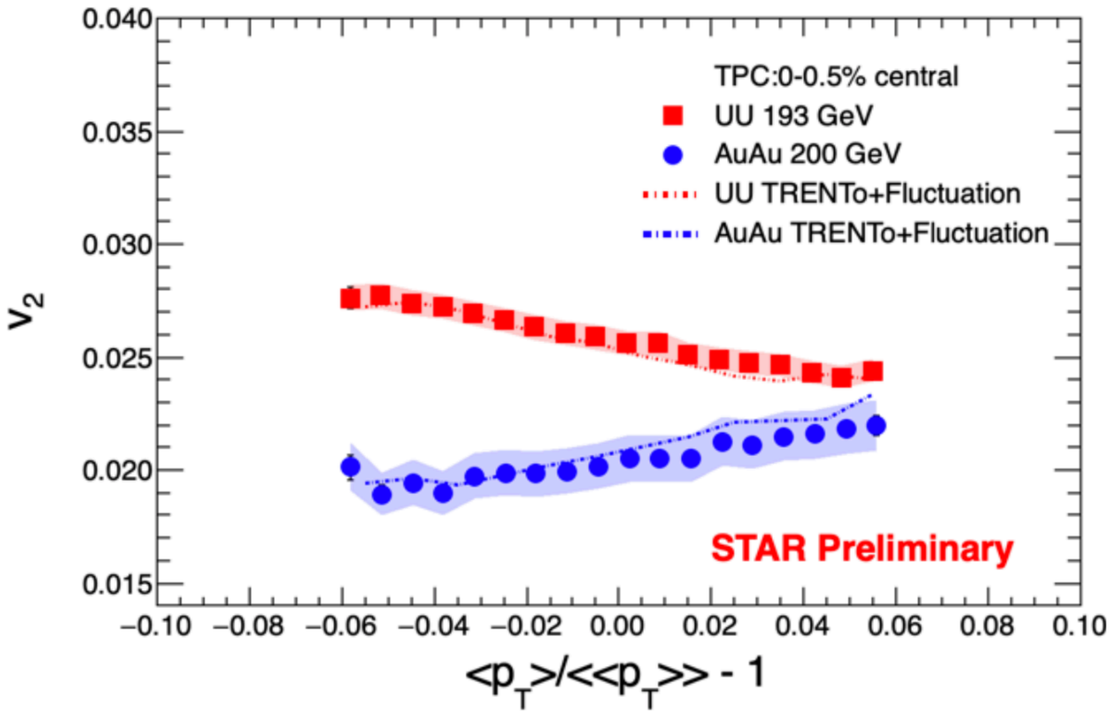
  $|\eta| < 1.0$

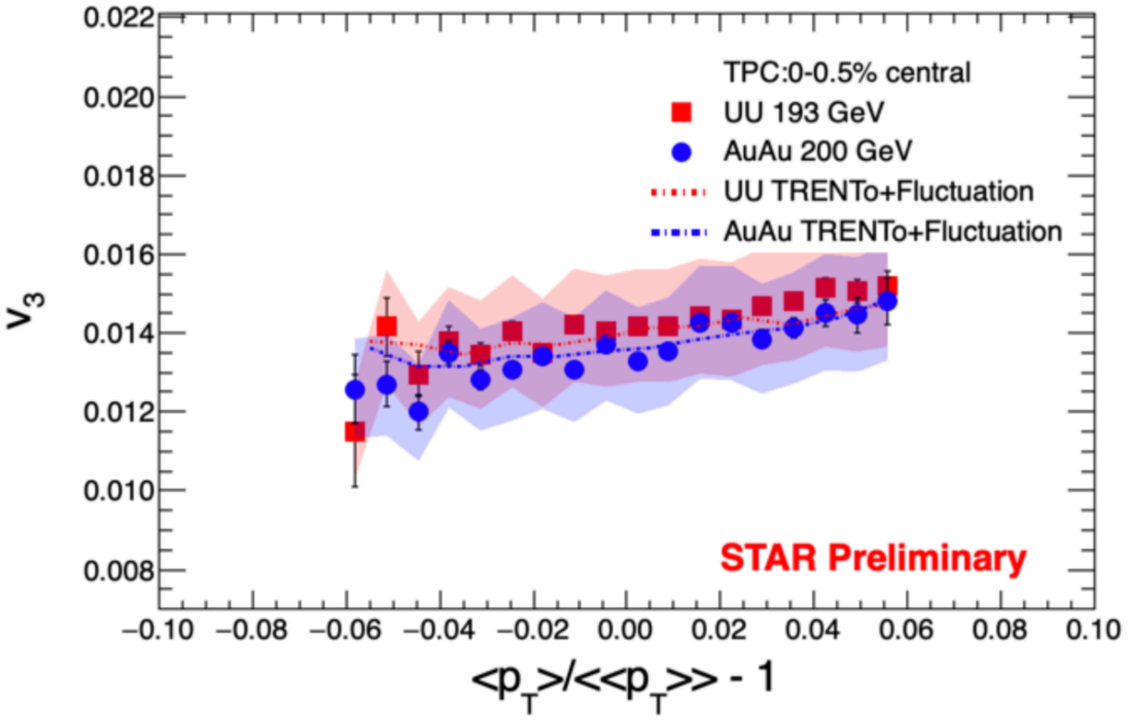
- Centrality is defined by N_{ch} ($|\eta|$<0.5).

- The track efficiency is estimated from embedding data

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

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 quantitatively.

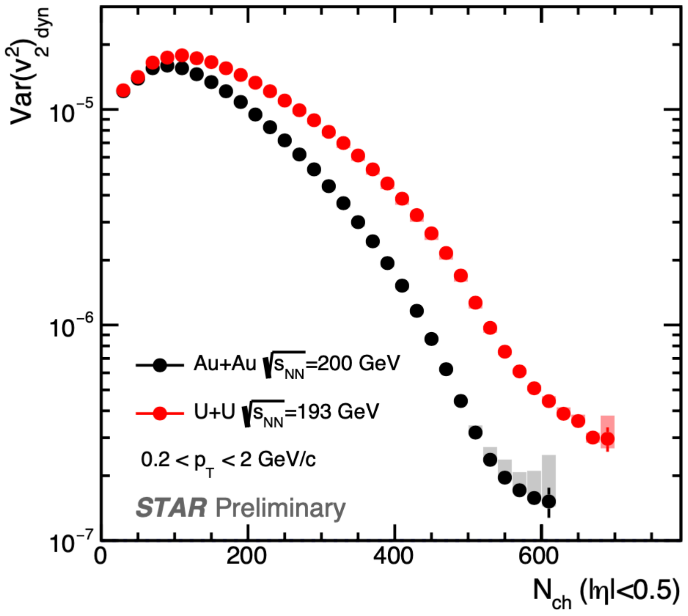
The anticorrelation in v_2 vs. $\langle p_T \rangle$ for U+U is due to deformation.

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

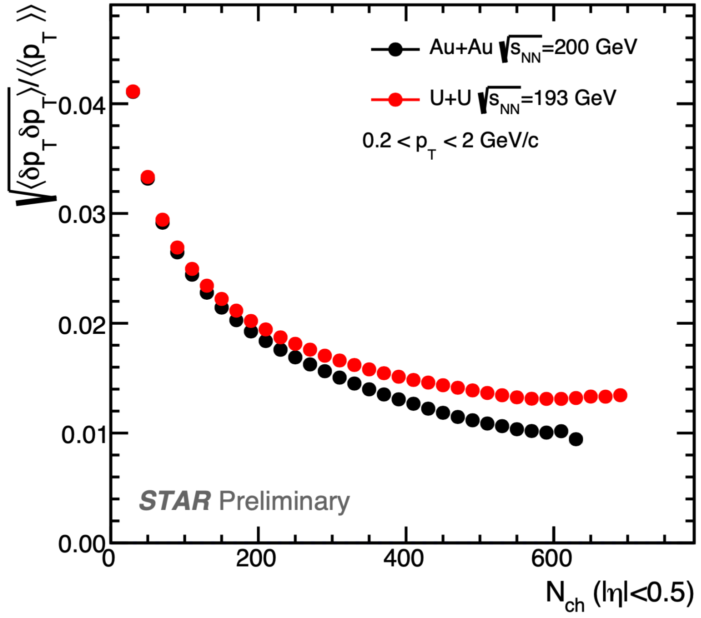
$$\rho(v_n^2, [p_T]) = \frac{\mathrm{cov}(v_n^2, [p_\mathrm{T}])}{\sqrt{\mathrm{Var}\,(v_n^2)_{\mathrm{dyn}} \langle \delta p_T \delta p_T \rangle}}$$

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

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



Clear difference due to flow fluctuation.



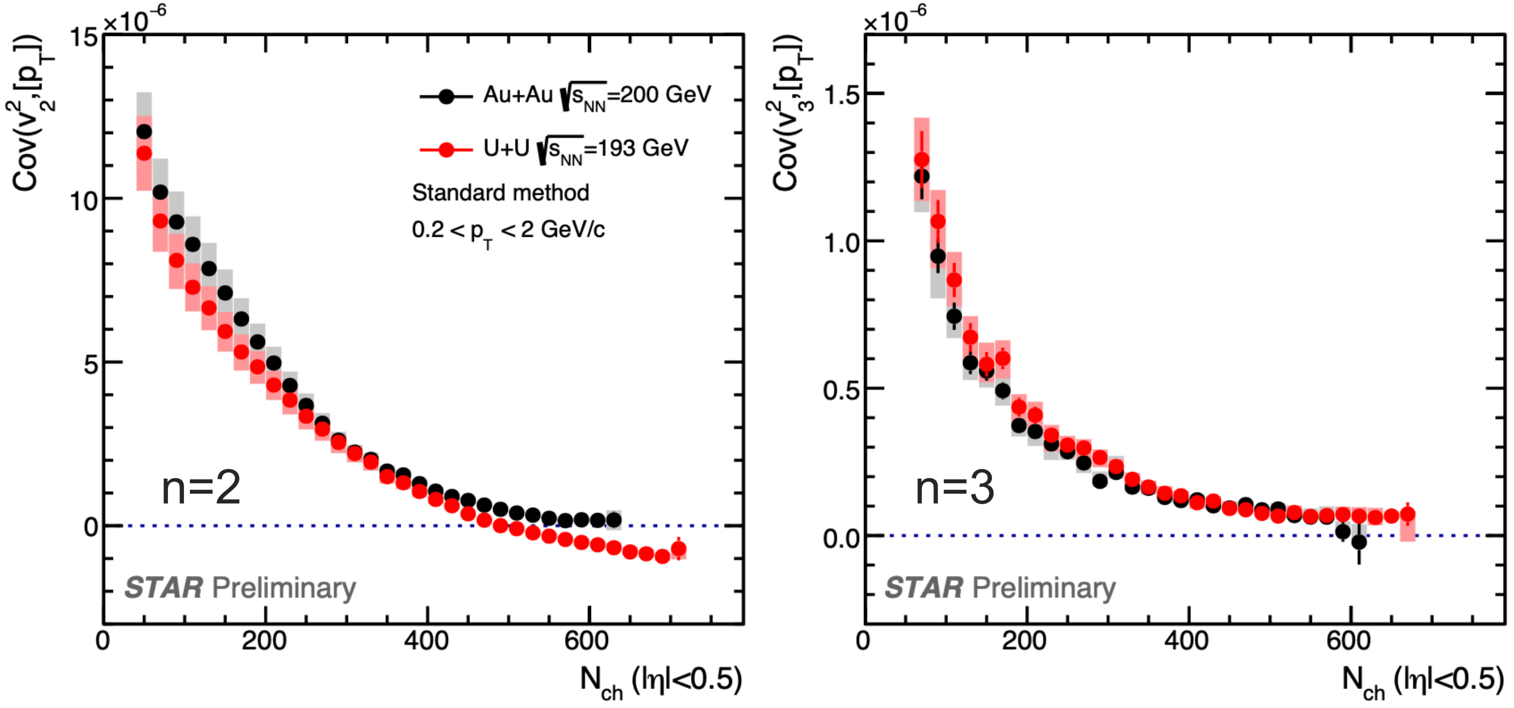
Clear difference due to size fluctuation.

Nuclear deformation play a role in flow and size fluctuations.

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

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

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

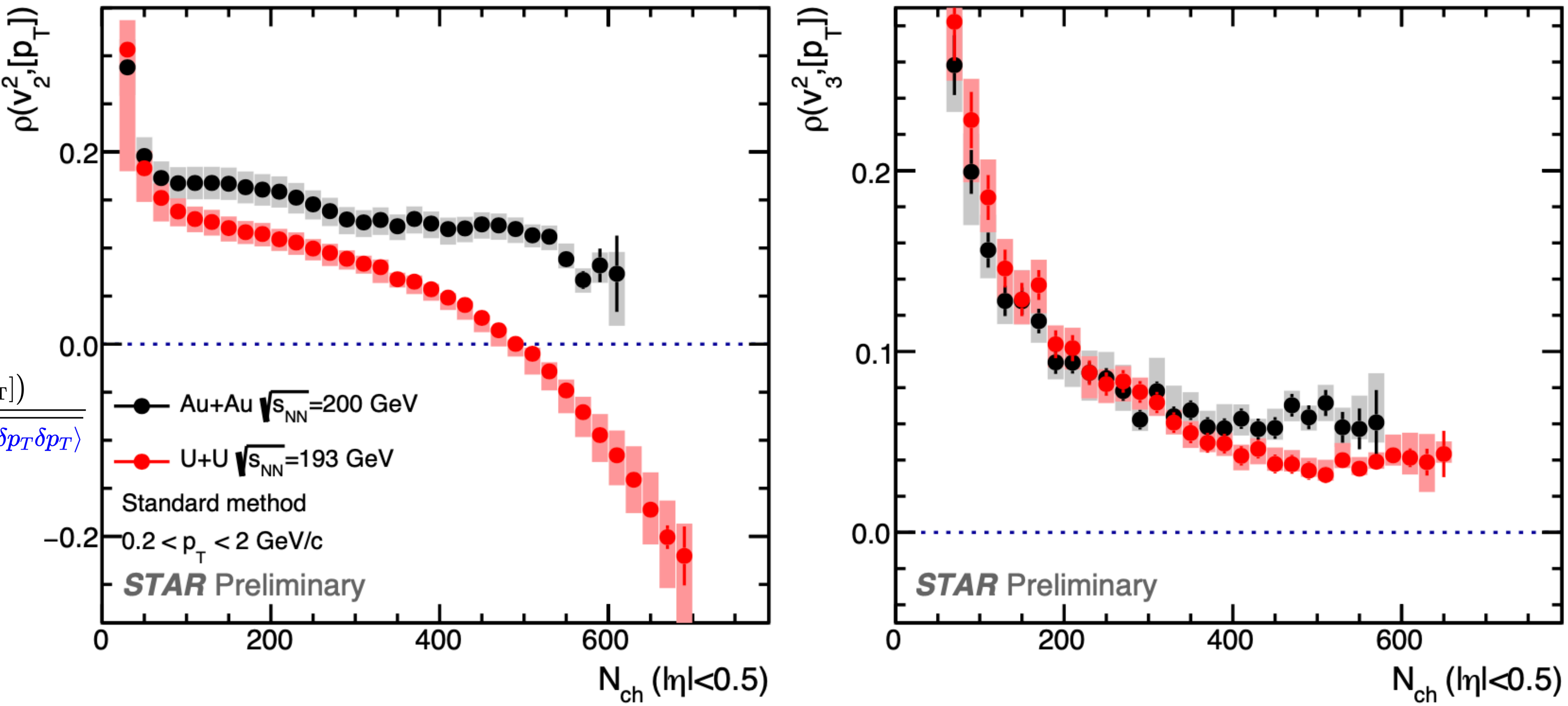


U+U collisions show a sign-change behavior in $\mathrm{Cov}(v_2^2, [p_T])$ while not in Au+Au. But they are consistent for $\mathrm{Cov}(v_3^2, [p_T])$.

This sign-change behavior indicates the effect of deformation.

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

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



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

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

Pearson coefficient $\rho(v_n^2, [p_T])$ comparing with IP-Glasma+Hydro

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

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

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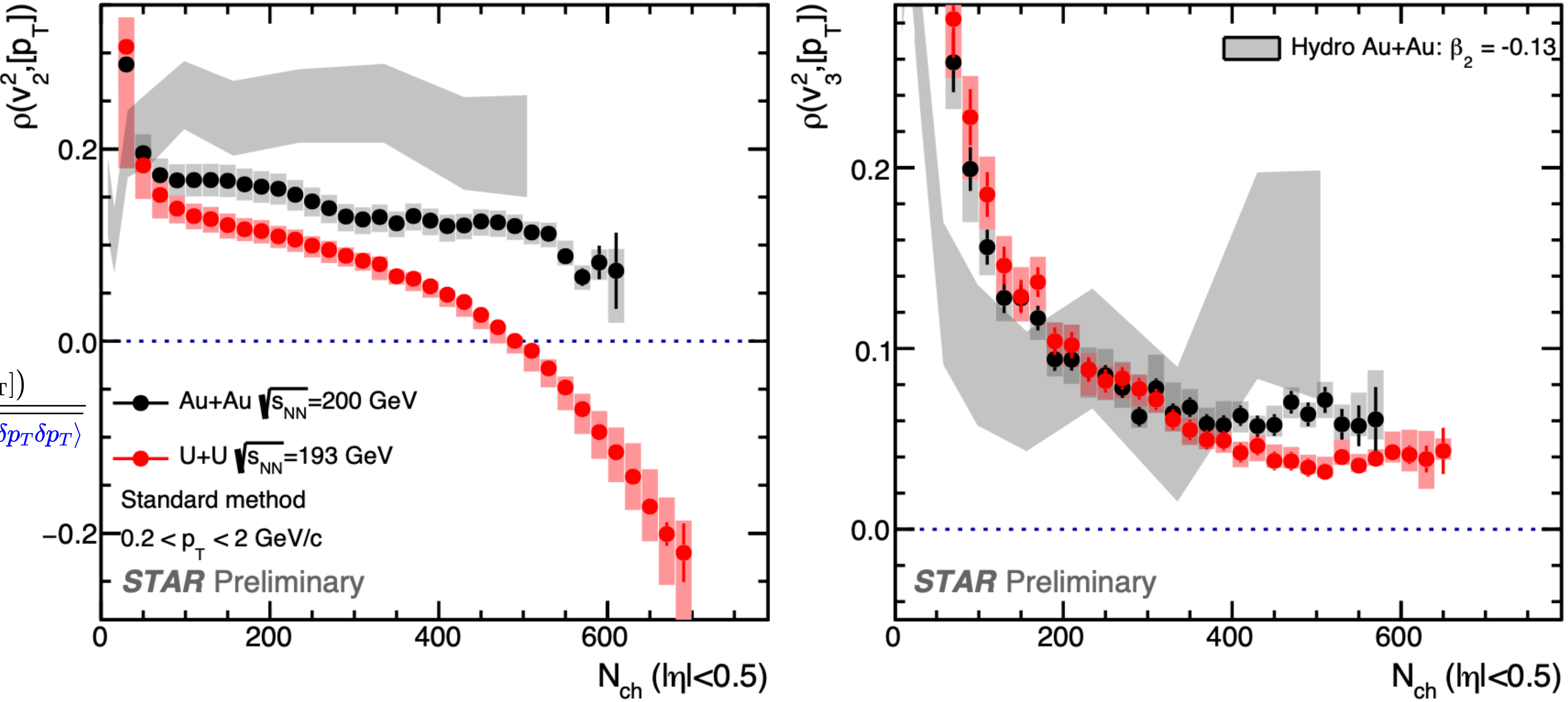

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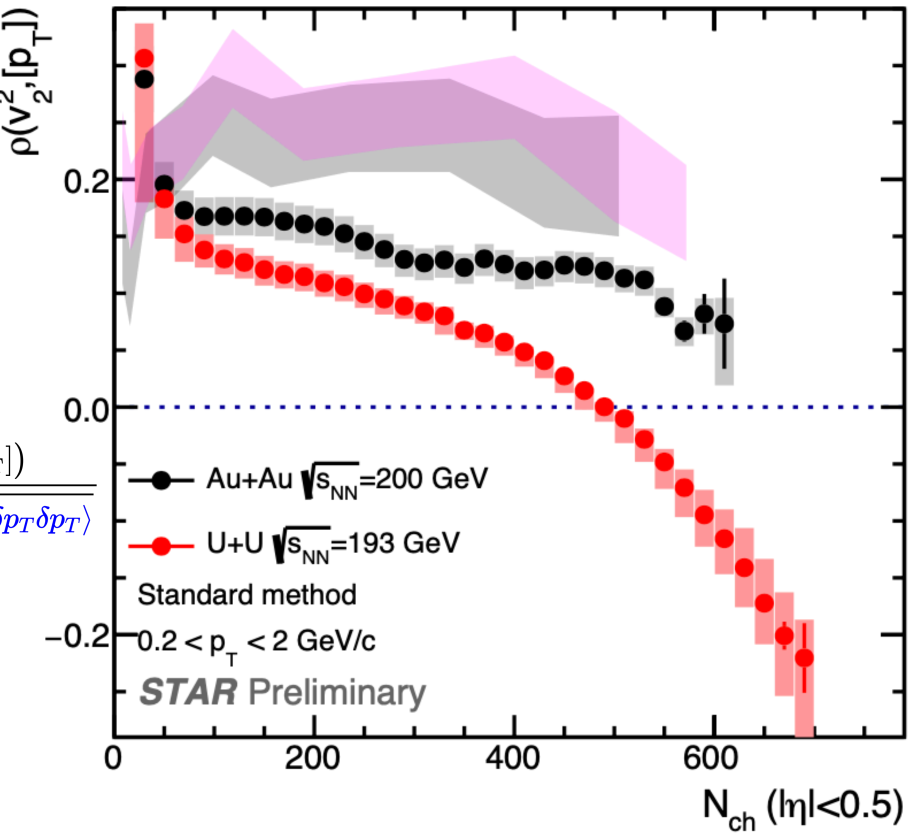

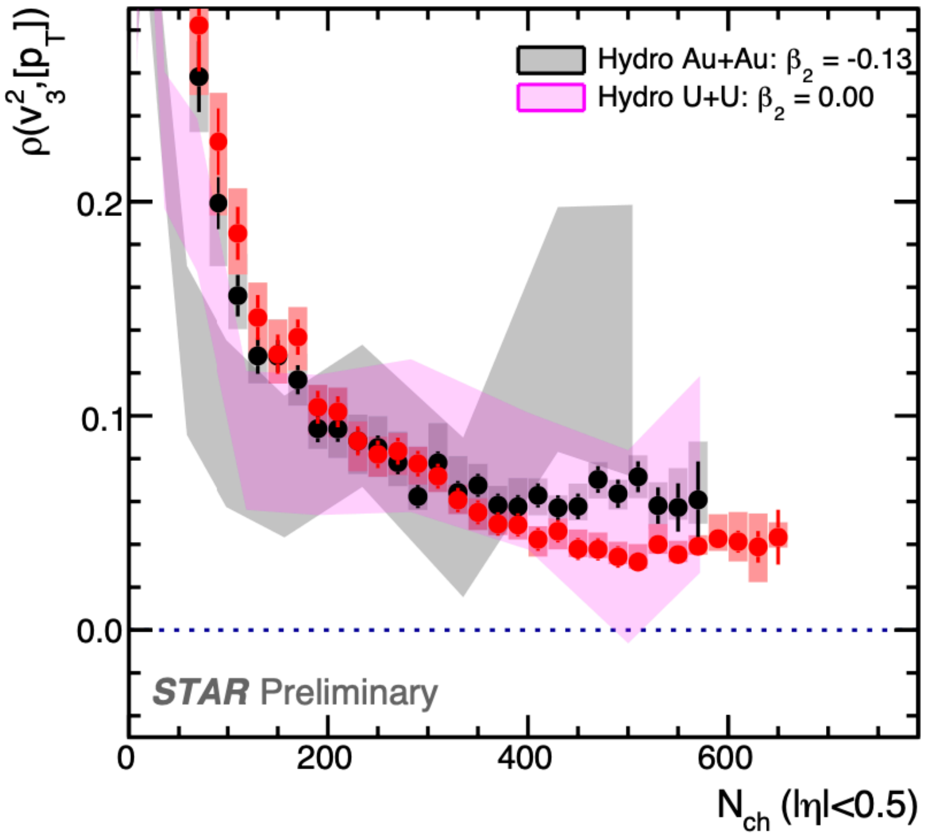

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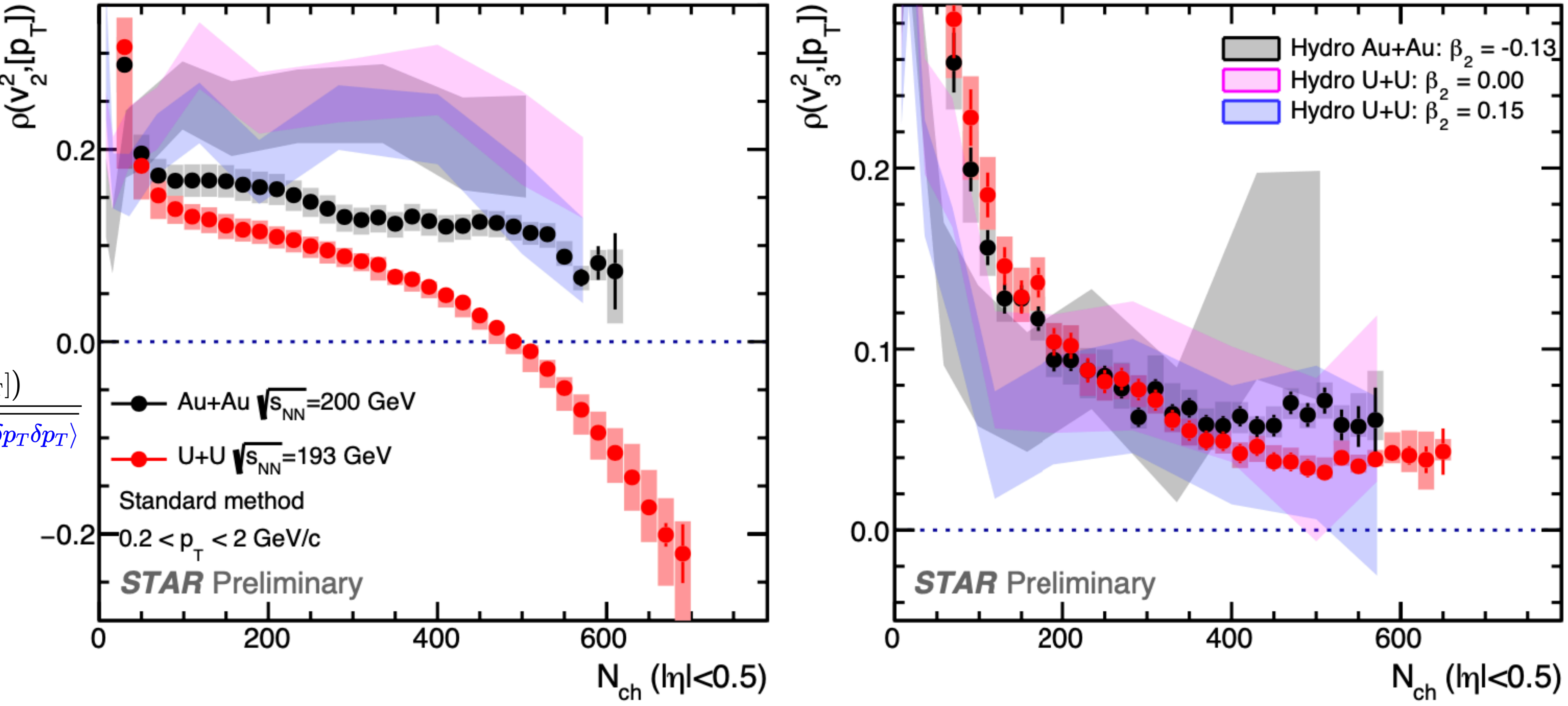

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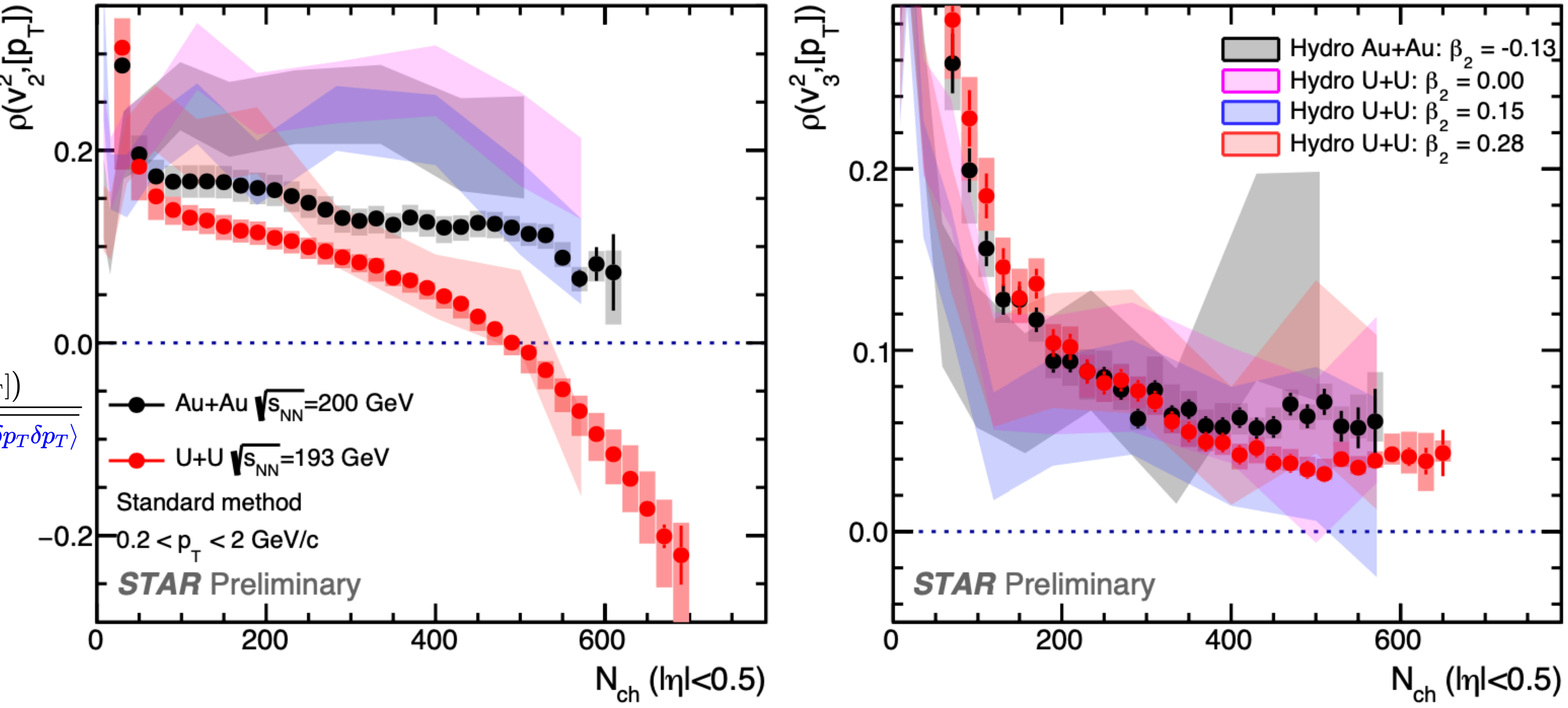

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A hierarchical behavior shows the β_2 dependence in Uranium $\rho(v_2^2, [p_T])$ but not in $\rho(v_3^2, [p_T])$.

Pearson coefficient $\rho(v_n^2, [p_T])$ comparing with IP-Glasma+Hydro

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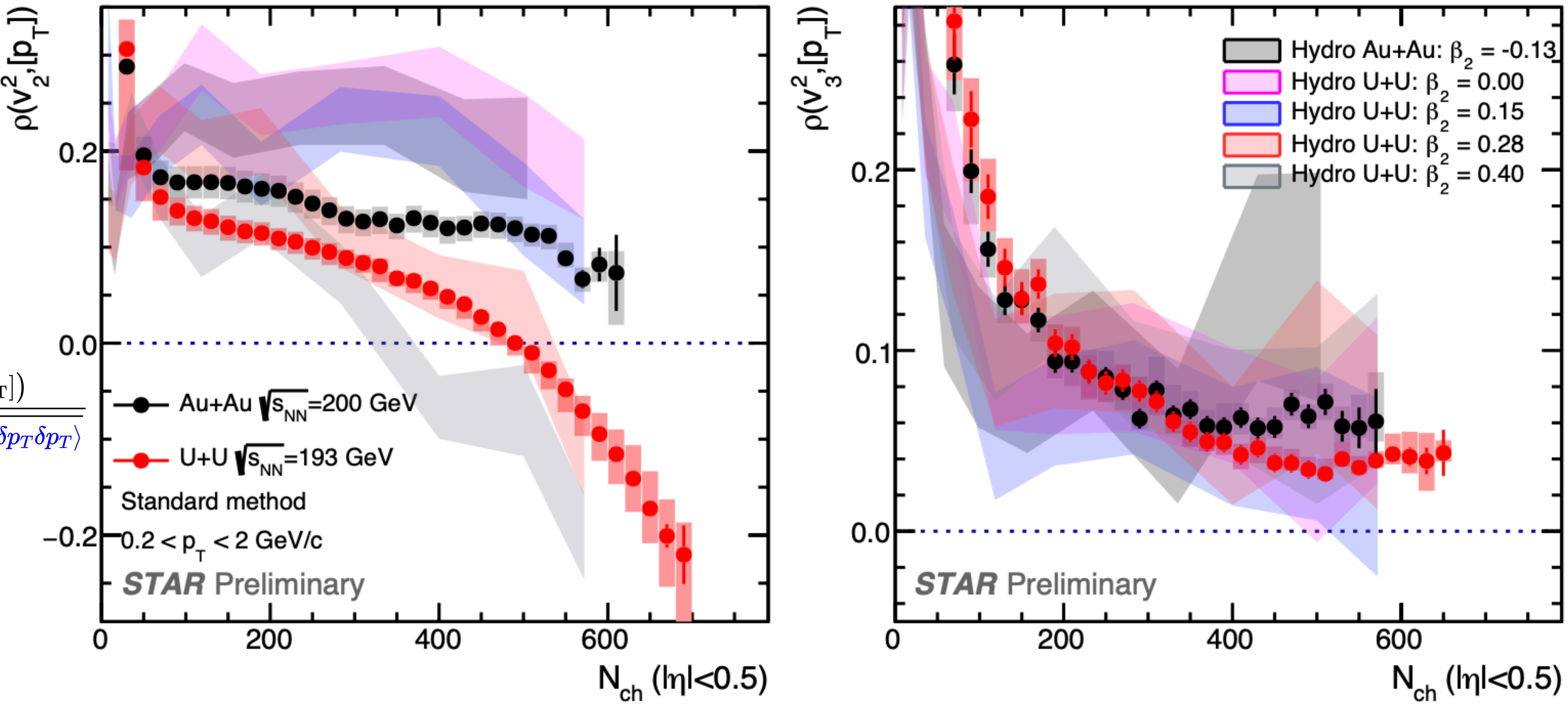

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A hierarchical behavior shows the β_2 dependence in Uranium $\rho(v_2^2, [p_T])$ but not in $\rho(v_3^2, [p_T])$.

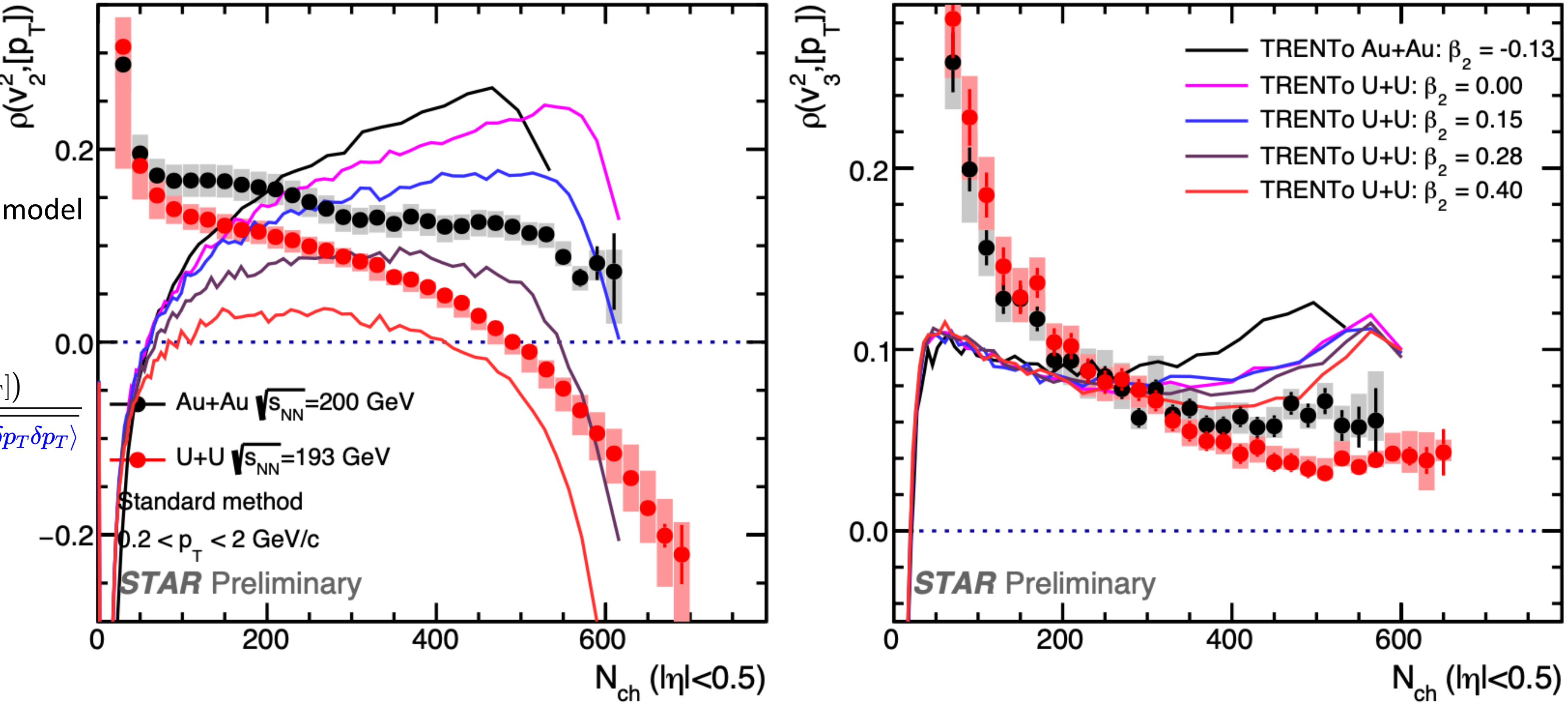
The sign-change is due to deformation effect and it quantifies the Uranium deformation value around 0.28 with large uncertainty.

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

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

TRENTo: initial condition model

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



TRENTo overestimates the STAR data but still shows an hierarchical β_2 dependence in Uranium $\rho(v_2^2, [p_T])$.

TRENTo also confirm the sign-change behavior is due to deformation effect.

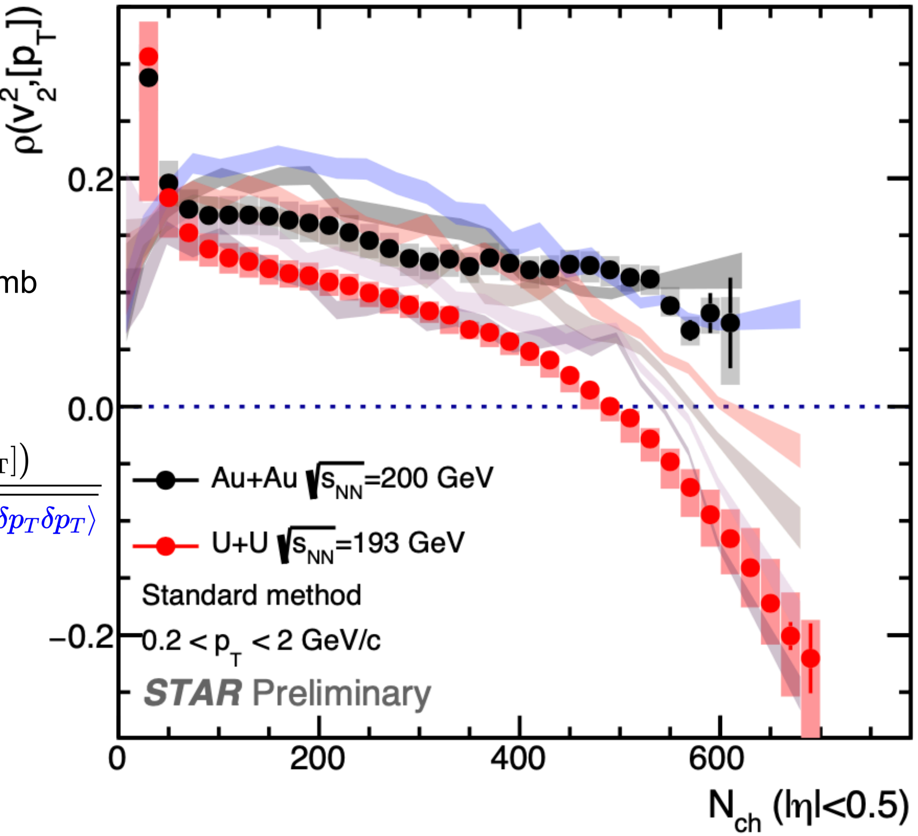
TRENTo predicts the Uranium deformation value from 0.28 to 0.4.

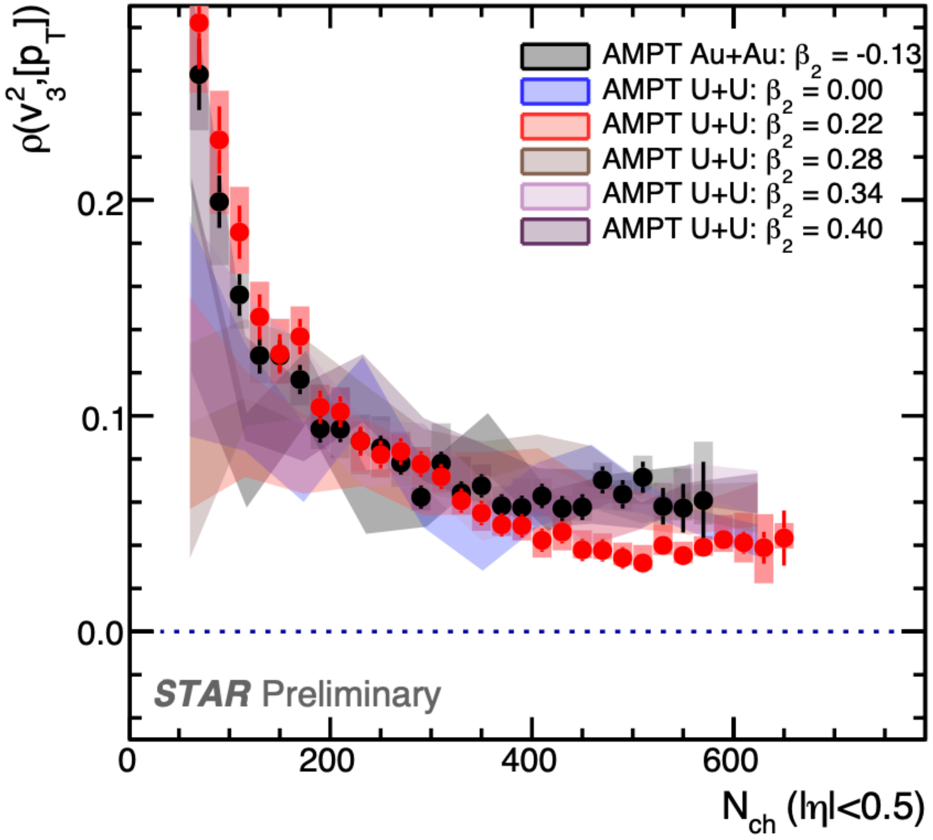
Pearson coefficient $\rho\left(v_n^2, [p_T]\right)$ comparing with transport AMPT model

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

String melting v2.26t5
Parton cross section: 6mb

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





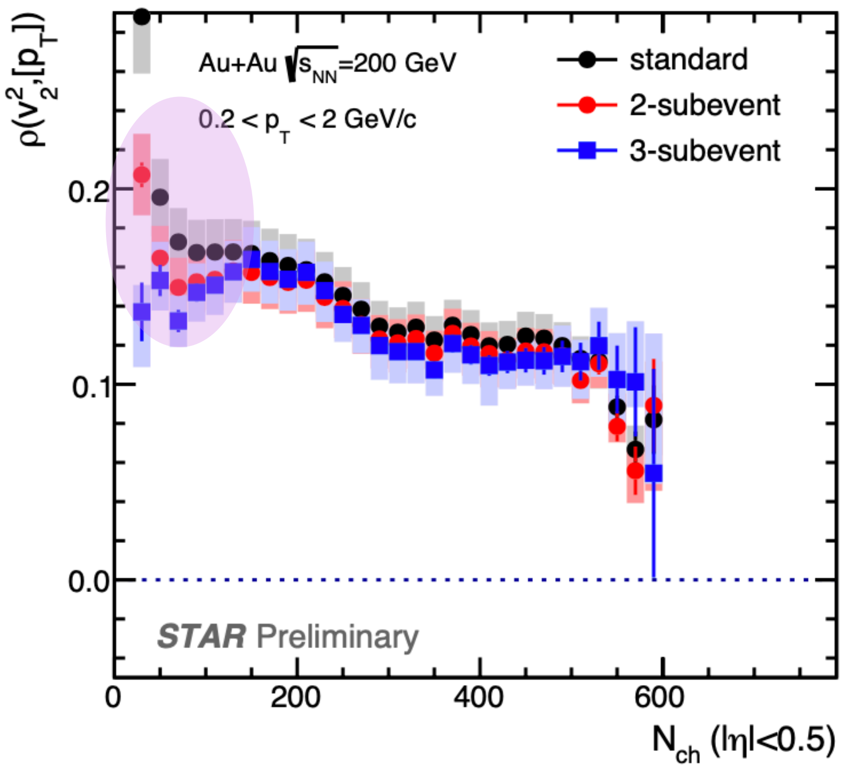
AMPT shows a clear β_2 dependence in Uranium $\rho(v_2^2, [p_T])$ while not in $\rho(v_3^2, [p_T])$.

AMPT also confirms the sign-change behavior is due to deformation effect.

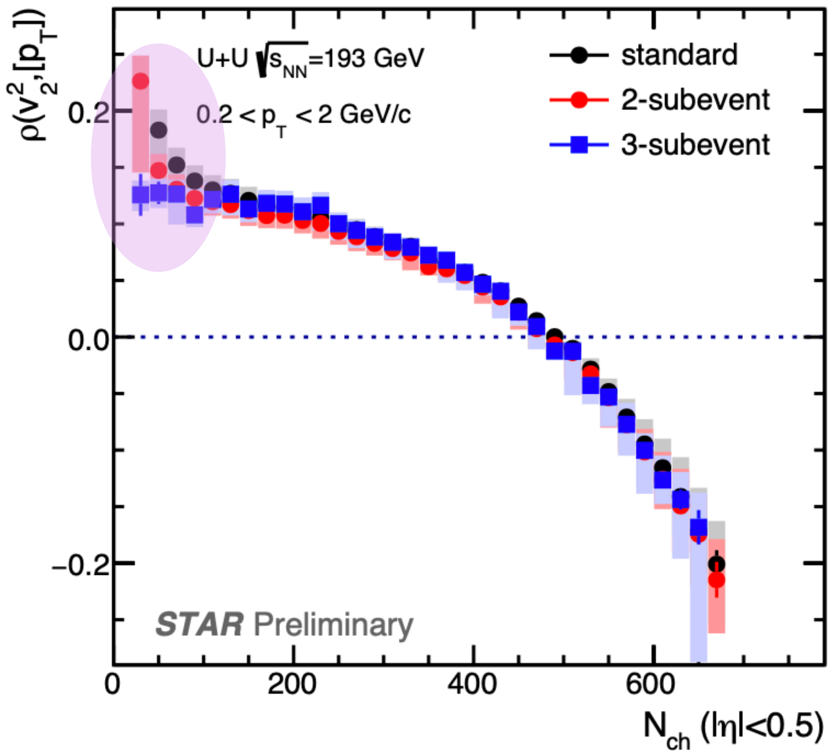
It is helpful to fully understand the initial conditions and the evolution of transportation.

Pearson coefficient $\rho\left(v_n^2, [p_T]\right)$ and effects of non-flow

Au+Au collisions



U+U collisions



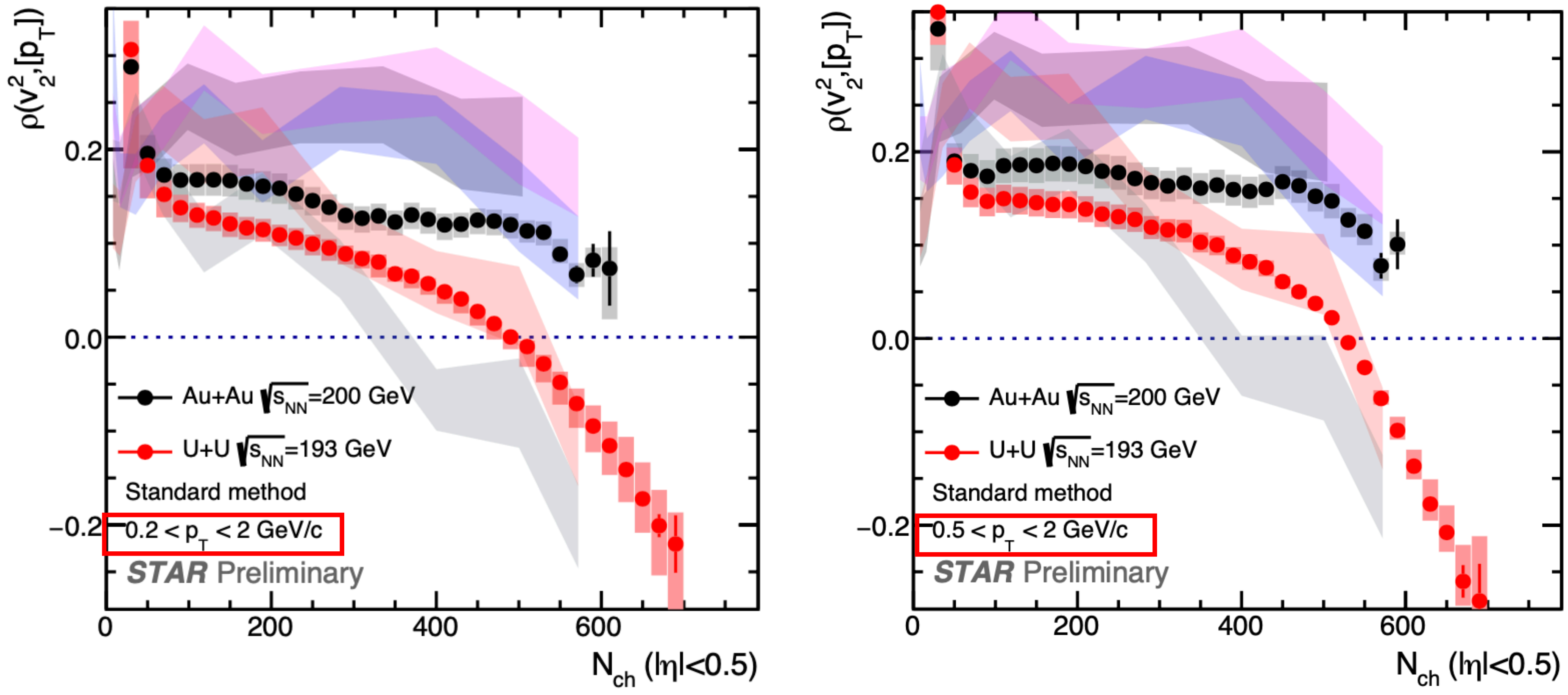
Standard method is consistent with subevent methods at high N_{ch}.

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

Non-flow effect is not responsible for the Uranium sign-change.

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

Conclusions and outlooks

1. We presented flow and mean transverse momentum correlation from STAR that demonstrate a clear shape–flow transmutation.
    - Study of mean p_T fluctuation is also an intriguing possibility to probe nuclear deformation..

2. The sign-change behavior in Pearson coefficient $\rho(v_2^2, [p_T])$ in central U+U collisions could be used to constrain deformation parameters.
    - Subevent calculations could decrease non-flow contributions in peripheral collisions.
    - Main features are robust against p_T selection.

3. IP-Glasma+Hydro model partially reproduces the data with Uranium deformation parameter β_2 around 0.28 with large uncertainty.

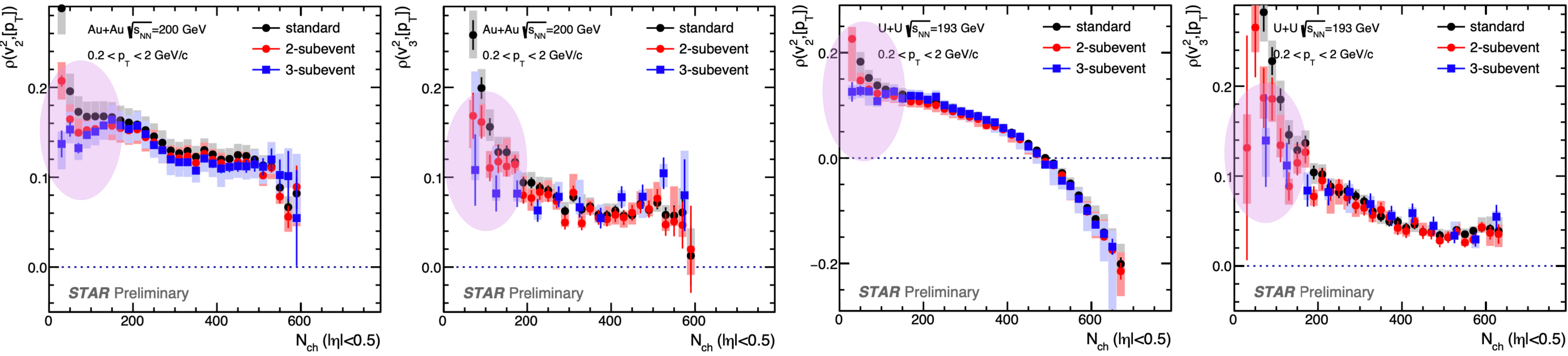
4. Precise data-model comparison (IP-Glasma+Hydro, TRENTo, AMPT) could be helpful to constrain the initial conditions such as nuclear deformation parameters, shear/bulk viscosity and speed of sound in EoS.

5. Heavy ion collisions open up an avenue for studying nuclear structure.

Thank you for listening.

$\rho(v_n^2, [p_T])$ is not affected by non-flow

Au+Au collisions U+U collisions

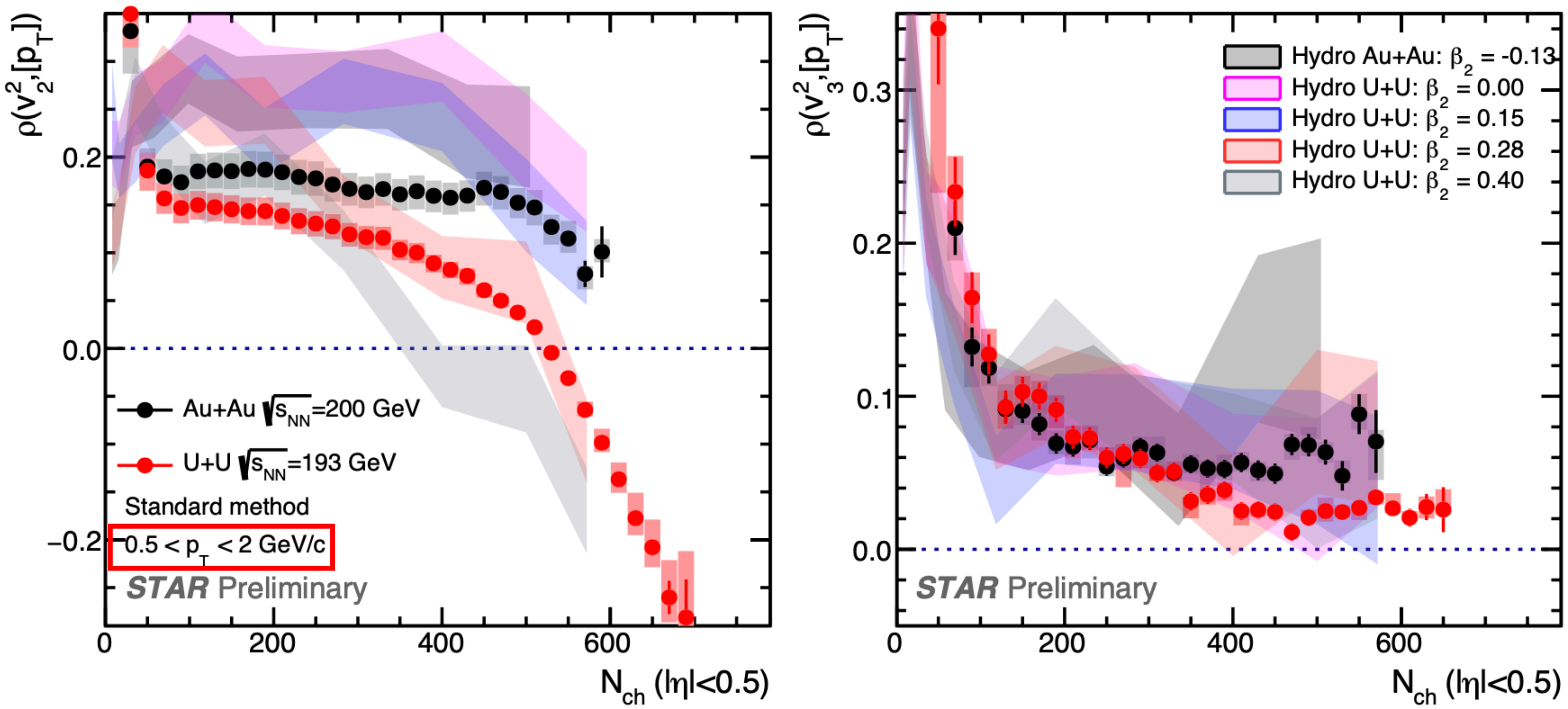


Standard method is consistent with subevent methods at high N_{ch}.

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

Pearson coefficient $\rho\left(v_n^2, [p_T]\right)$ in 0.5< p_T < 2 GeV/c

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<2GeV/c as 0.2<p_T<2GeV/c.