Stony Brook University | The State University of New York

STAR

Supported in part by U.S. DEPARTMENT OF ENERGY

Nuclear deformation effects via U+U collisions from STAR

Jiangyong Jia for the STAR Collaboration

See poster by Chunjian Zhang on Jan 11, id105

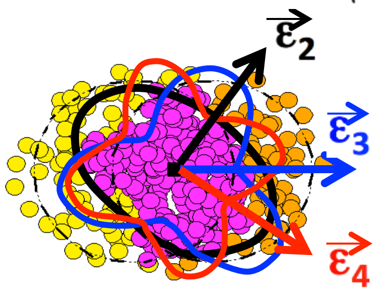
IS2021

The VIth International Conference on the **INITIAL STAGES** OF HIGH-ENERGY NUCLEAR COLLISIONS

Connecting the final state to the initial state

Initial Shape

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



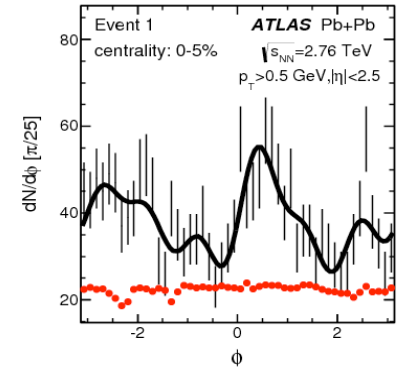
Hydro-response

Space-time dynamics

$$\epsilon_n \to v_n$$

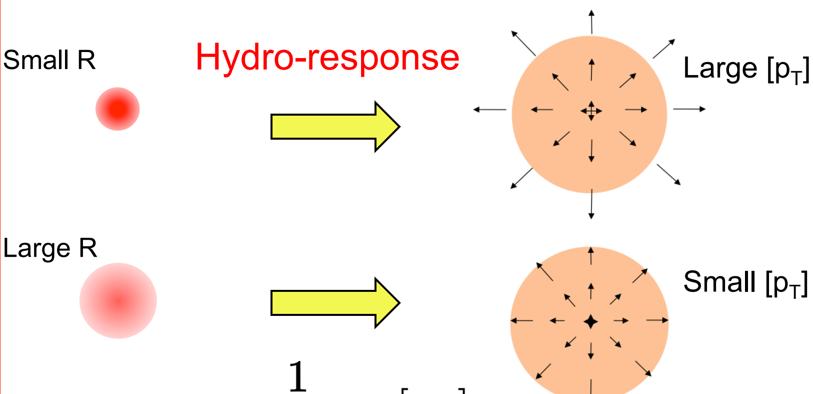
Harmonic flow

$$\frac{dN}{d\phi} \propto 1 + 2\sum_n v_n \cos n(\phi - \Phi_n)$$



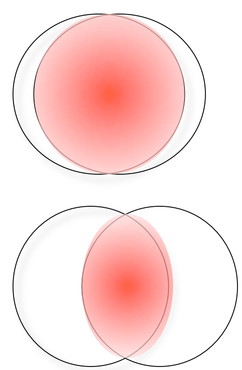
Initial Size

Radial flow [p_T]



$$\frac{1}{R} \to [p_T]$$

Correlated fluctuations in shape & size
→Correlated fluctuations in v_n and [p_T]



small ε_2, larger R and density

large ε_2, small R and density

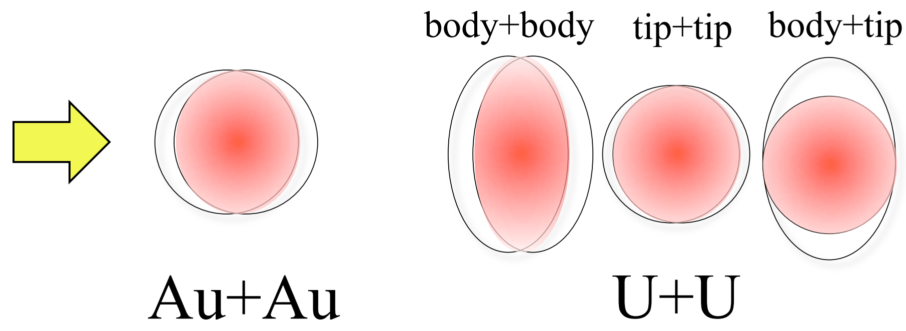
$$\langle \epsilon_n^2 \frac{1}{R} \rangle \to \langle v_n^2 \, p_T \rangle$$

Reflected by p(v_n), p([p_T]), and p(v_n,[p_T])

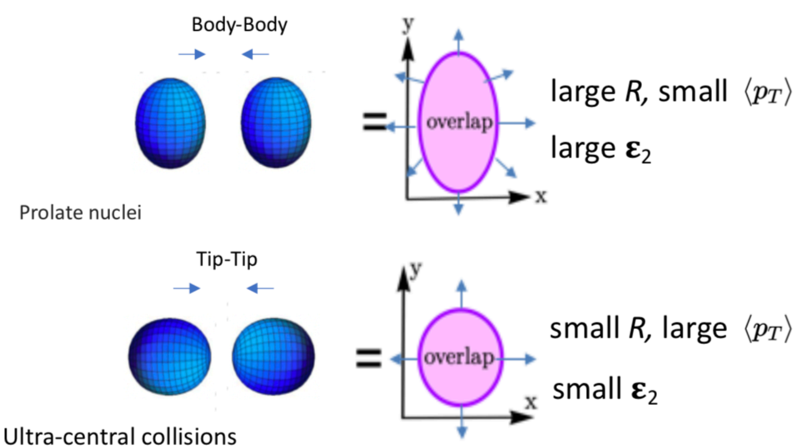
Connecting the initial state to nuclear geometry

- Fluctuations of v_n and $[p_T]$ are sensitive to nuclear geometry

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



- Fluctuations are broader in U+U than Au+Au due to large β_2



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

BNL nuclear database

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

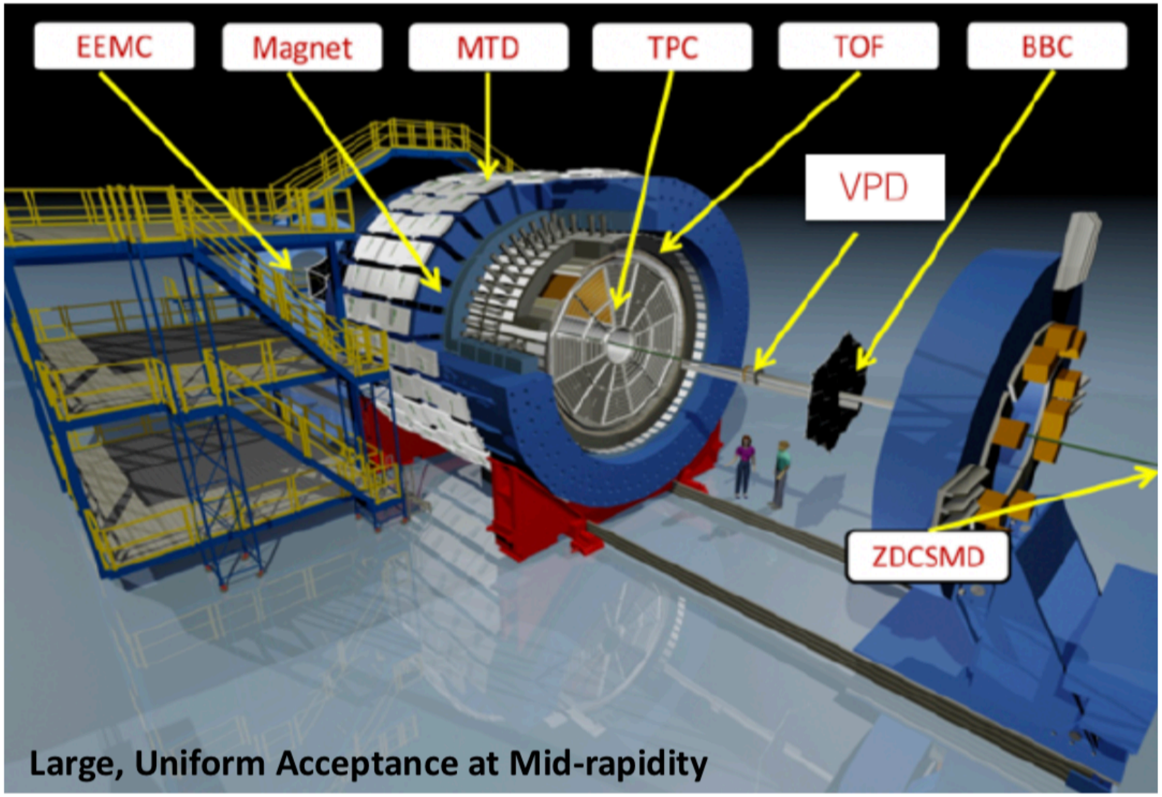
reference	Möller et al.	Möller et al.	CEA DAM
method	FRDM	FRLDM	HFB
β_2	−0.131	−0.125	−0.10

U+U: expect anti-corr. for v_2-$[p_T]$ in UCC

G. Giacalone PRL124, 202301 (2020)

Probe nuclear structure at a shorter time scale:
$\sim 10^{-23}$s vs 10^{-8}-10^{-12}s for isomer

STAR detector and datasets



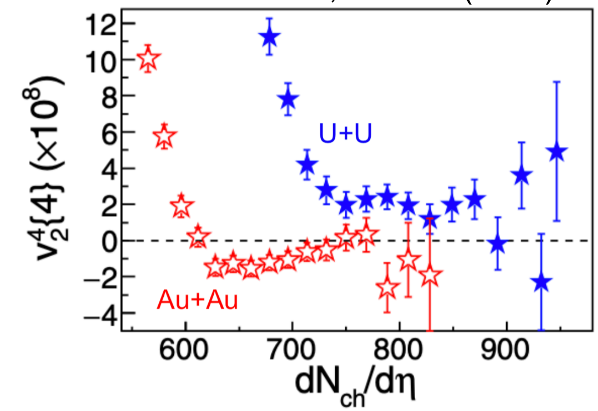
- Datasets
  - Au+Au@200 GeV 2010 and 2011
  - U+U@193 GeV 2012.
- Measurement based on TPC
  - $|\eta|<1.0$, $0.2<p_T<2$ GeV/c
- Centrality based on N_{ch}^{rec} with $|\eta|<0.5$

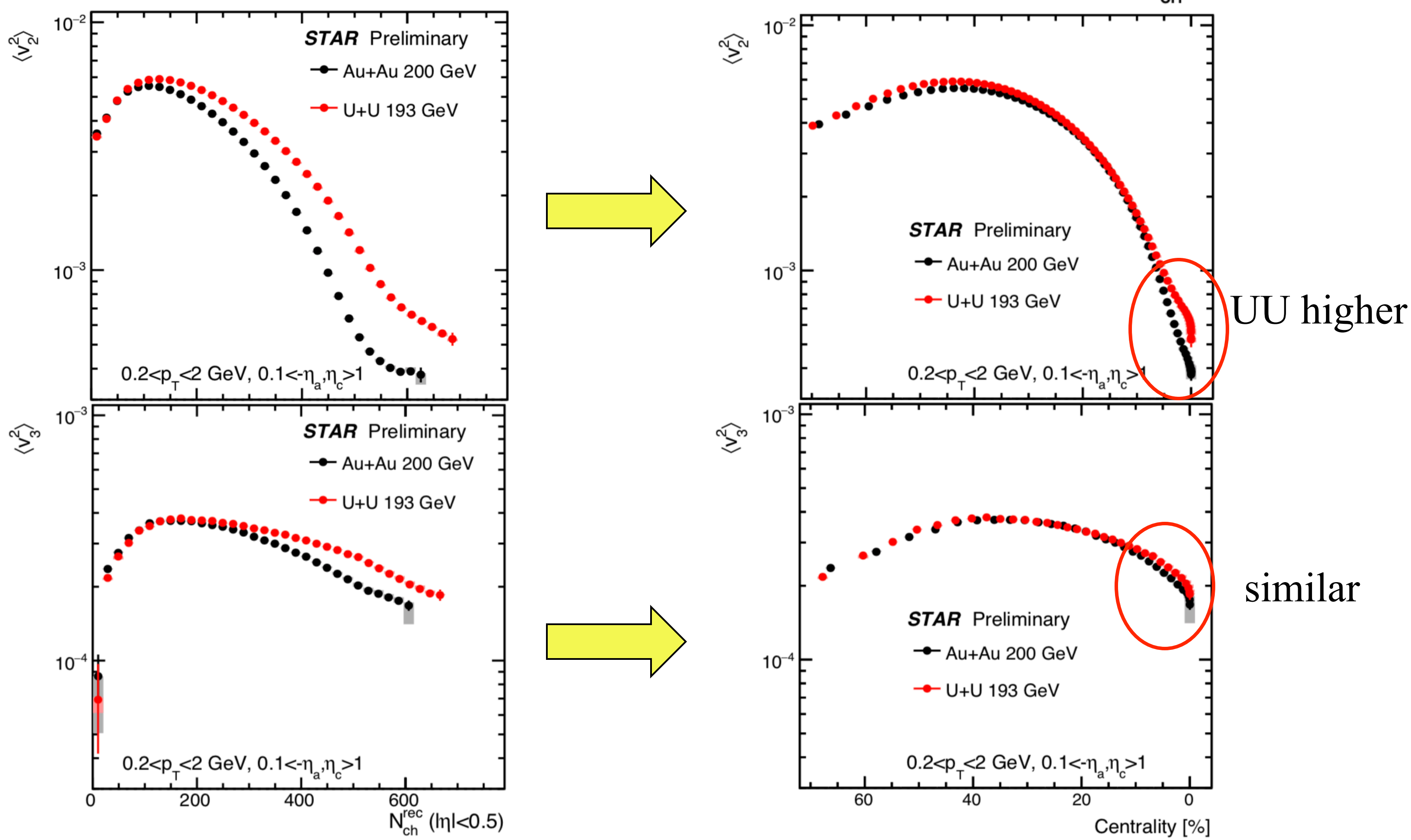
Three topics: $p(v_n)$, $p([p_T])$, and $p(v_n,[p_T])$

Flow fluctuations

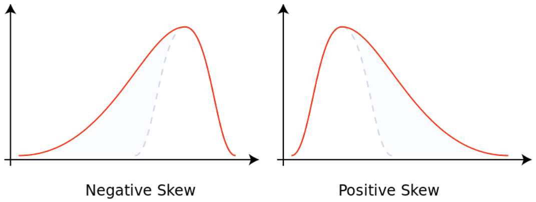
- STAR has shown flow fluctuations $v_2\{4\}$ in central collisions are influenced by nuclear deformation
  - Negative in near-spherical Au+Au, positive in deformed UU
- Nuclear deformation also seen in 2PC v_n in UCC.

PRL 115, 222301 (2015)





[p_T] fluctuations



- Quantified with variance and skewness

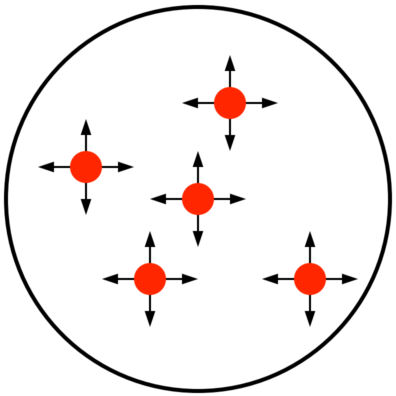
$$\langle \delta p_T \delta p_T \rangle = \left\langle \frac{\sum_{i\neq j} w_i w_j (p_{T,i} - \langle\langle p_T \rangle\rangle)(p_{T,j} - \langle\langle p_T \rangle\rangle)}{\sum_{i\neq j} w_i w_j} \right\rangle_{\rm evt}$$

$$\delta p_T = p_T - [p_T]$$

self-correlations removed
w is weight for each particle

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

<u>Independent source picture:</u> convolution of signal from each source



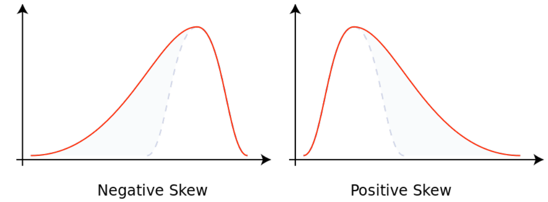
$$\langle \delta p_T \delta p_T \rangle_{AA} \sim \frac{\langle \delta p_T \delta p_T \rangle_{pp}}{N_{\rm part}}$$

$$\langle \delta p_T \delta p_T \delta p_T \rangle_{AA} \sim \frac{\langle \delta p_T \delta p_T \delta p_T \rangle_{pp}}{N_{\rm part}^2}$$

- Expected to follow a power-law function of N_{part} or N_{ch}
- Particle $p_T > 0$ → skewness in each source is positive

$[p_T]$ fluctuations

- Quantified with variance and skewness



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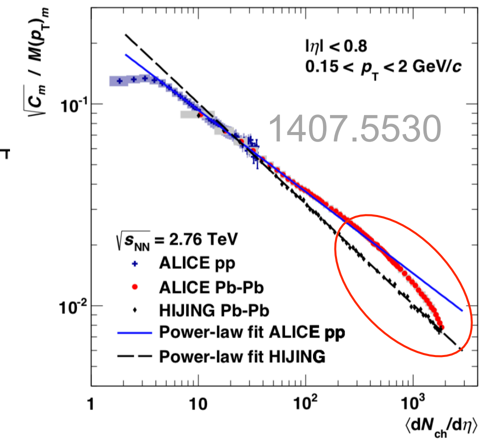
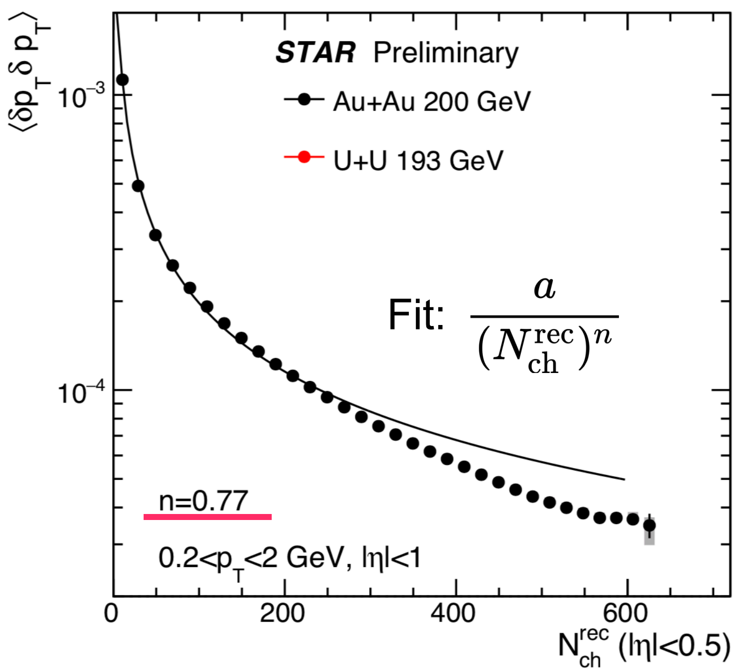
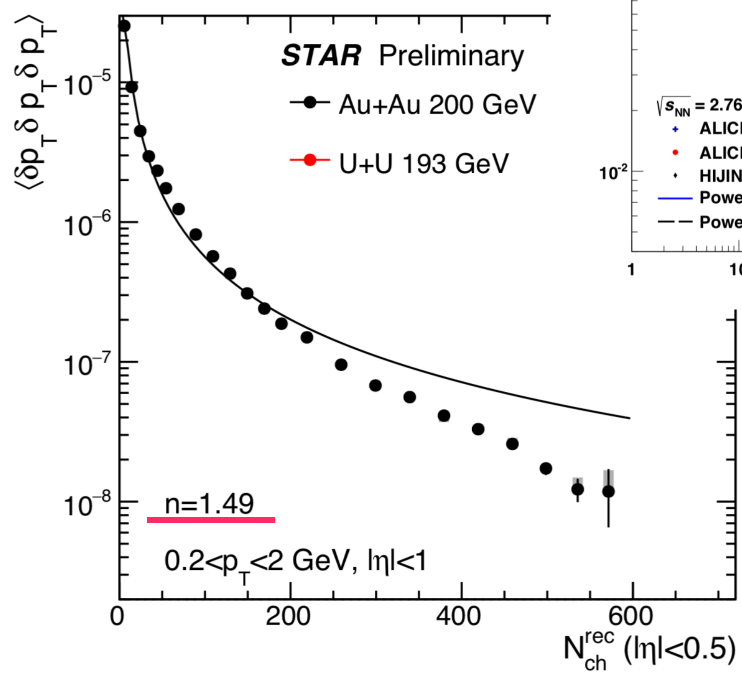


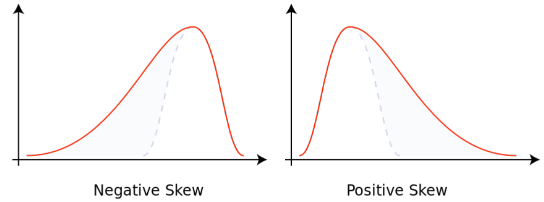




- Au+Au: follow power-law decrease, but with strong deviation in central

$[p_T]$ fluctuations

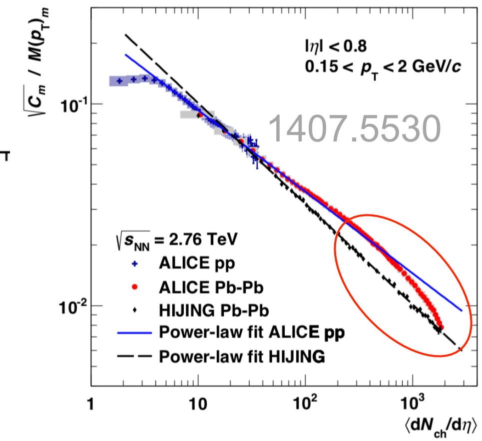
- Quantified with variance and skewness

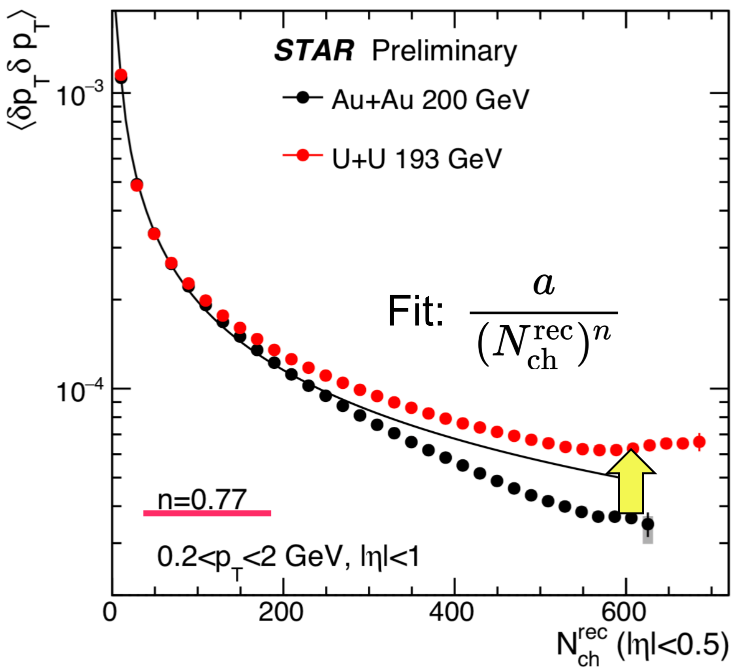


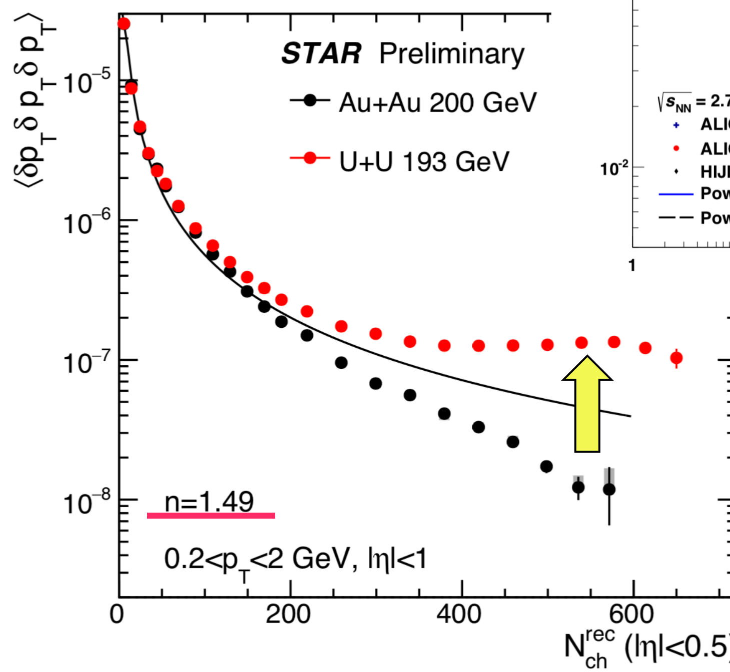
$$\langle \delta p_T \delta p_T \rangle = \left\langle \frac{\sum_{i\neq j} w_i w_j (p_{T,i} - \langle\langle p_T \rangle\rangle)(p_{T,j} - \langle\langle p_T \rangle\rangle)}{\sum_{i\neq j} w_i w_j} \right\rangle_{\rm evt} \qquad \delta p_T = p_T - [p_T]$$

self-correlations removed
w is weight for each particle

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







- Au+Au: follow power-law decrease, but with strong deviation in central
- U+U: large enhancement in mid-central and central→size fluctuations

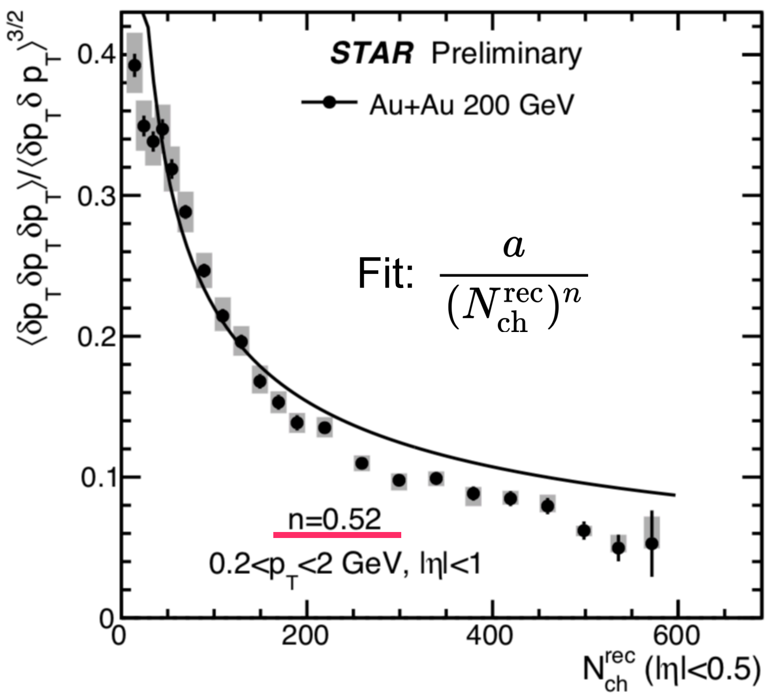
$[p_T]$ skewness: Au+Au data

- Quantify with normalized quantities

G Giacalone, F.Gardim, J.Noronha-Hostler, J.Ollitrault 2004.09799

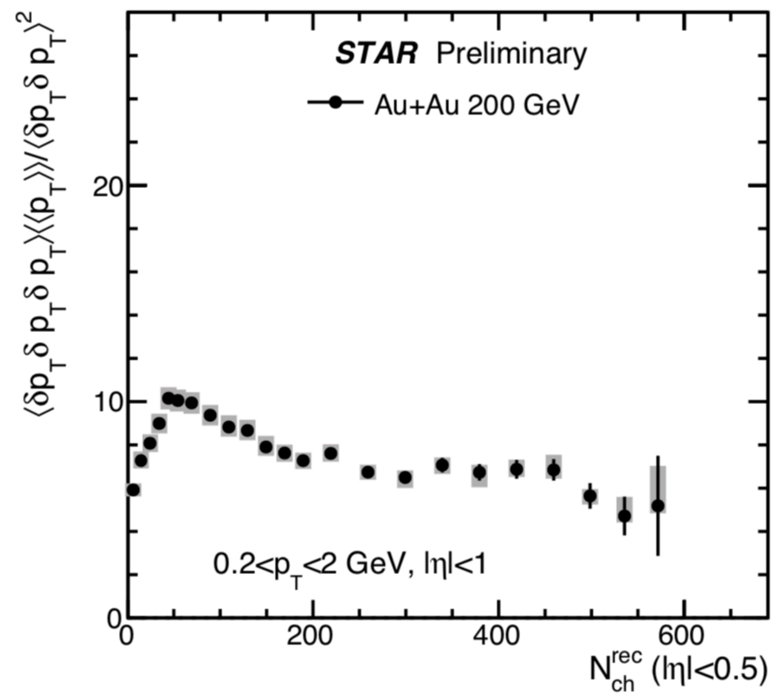
Standard skewness

$$\gamma_{p_t} \equiv \frac{\langle \Delta p_i \Delta p_j \Delta p_k \rangle}{\langle \Delta p_i \Delta p_j \rangle^{3/2}} = \frac{C_3}{C_2^{3/2}} \propto \frac{1}{\sqrt{N_{\mathrm{part}}}}$$



Intensive skewness

$$\Gamma_{p_t} \equiv \frac{\langle \Delta p_i \Delta p_j \Delta p_k \rangle \langle\langle p_t \rangle\rangle}{\langle \Delta p_i \Delta p_j \rangle^{2}} = \frac{C_3 C_1}{C_2^2} \sim \mathrm{const}$$



Standard skewness approximately follows $1/\sqrt{N_{ch}}$ scaling

Intensive skewness is ~ const

$[p_T]$ skewness: compare to U+U data

- Quantify with normalized quantities

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Standard skewness

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Intensive skewness

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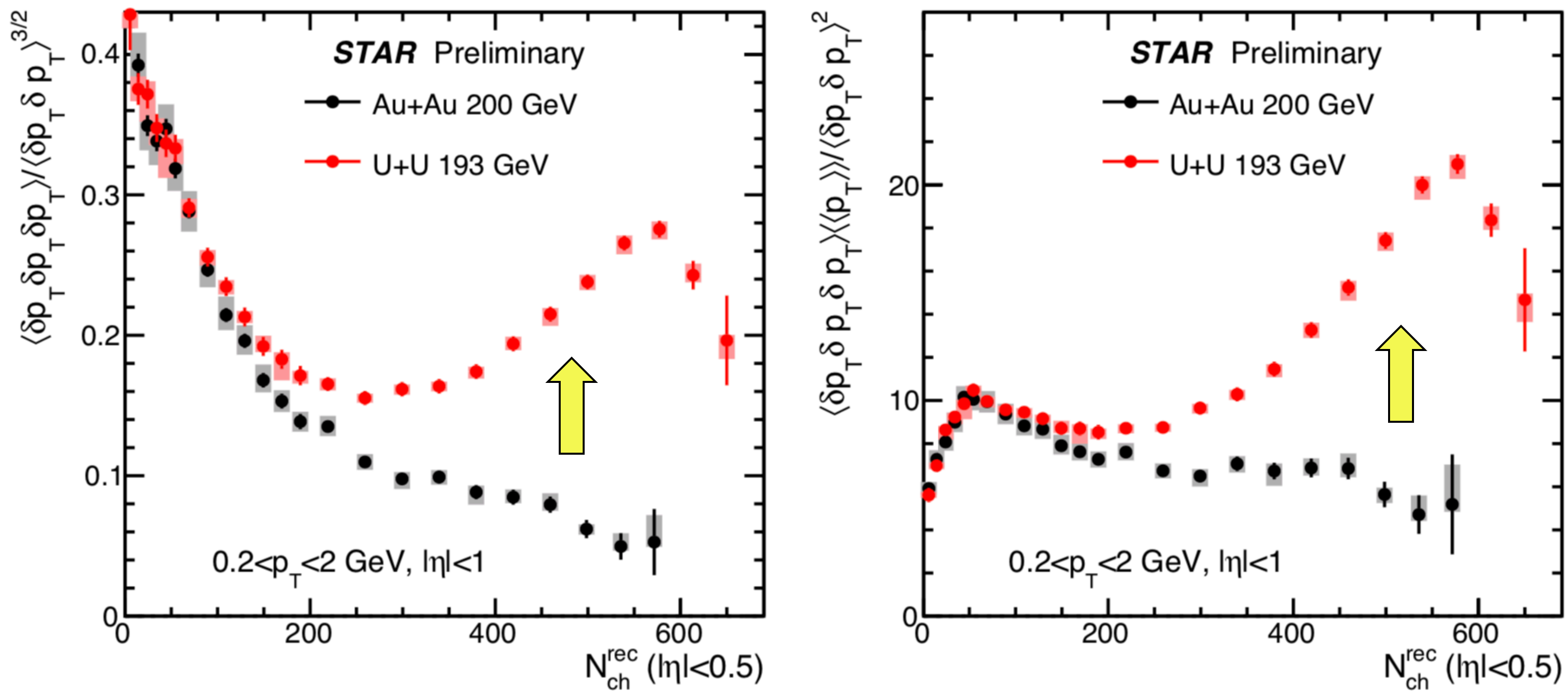

U+U shows significant enhancement in central region

$[p_T]$ skewness: compare to Trento

- Quantify with normalized quantities

G Giacalone, F.Gardim, J.Noronha-Hostler, J.Ollitrault 2004.09799

Standard skewness

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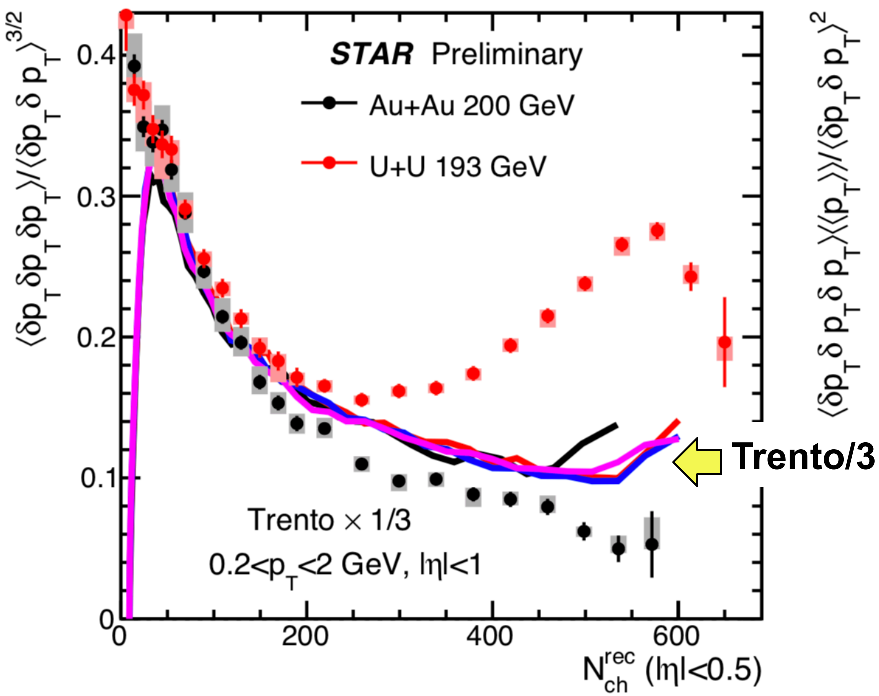

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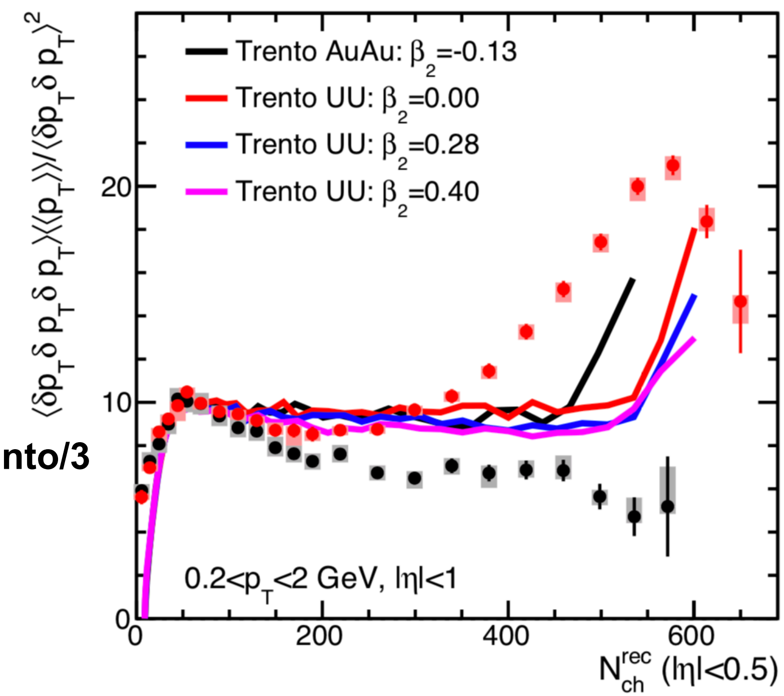
$$\Gamma_{p_t} \equiv \frac{\langle \Delta p_i \Delta p_j \Delta p_k \rangle \langle\langle p_t \rangle\rangle}{\langle \Delta p_i \Delta p_j \rangle^{2}} = \frac{C_3 C_1}{C_2^2} \sim \text{const}$$



<u>Initial state predictor:</u> $[p_T] \propto \frac{E}{S}$ $\frac{\text{Energy}_{\rm ini}}{\text{Entropy}_{\rm ini}}$

$\langle \delta p_T \delta p_T \rangle \sim \left\langle \delta\frac{E}{S}\delta\frac{E}{S}\right\rangle$ $\langle \delta p_T \delta p_T \delta p_T \rangle \sim \left\langle \delta\frac{E}{S}\delta\frac{E}{S}\delta\frac{E}{S}\right\rangle$

Trento model sknewness lacks sensitivity to nuclear deformation

Flow-[p_T] correlations

Three-particle v_n-v_n-[p_T] correlator in a normalized form:

$$\delta p_{\mathrm{T}} = p_{\mathrm{T}} - [p_{\mathrm{T}}] \quad \mathbf{cov}\left(v_n^2, [p_{\mathrm{T}}]\right)$$

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

Pearson correlation coefficient

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

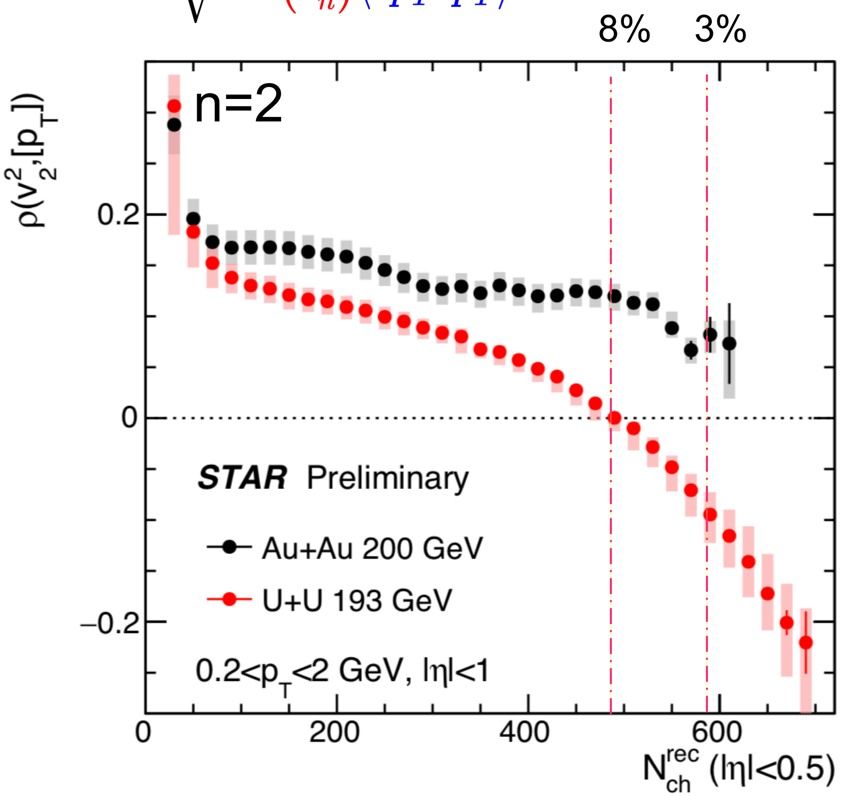
P. Bozek 1601.04513

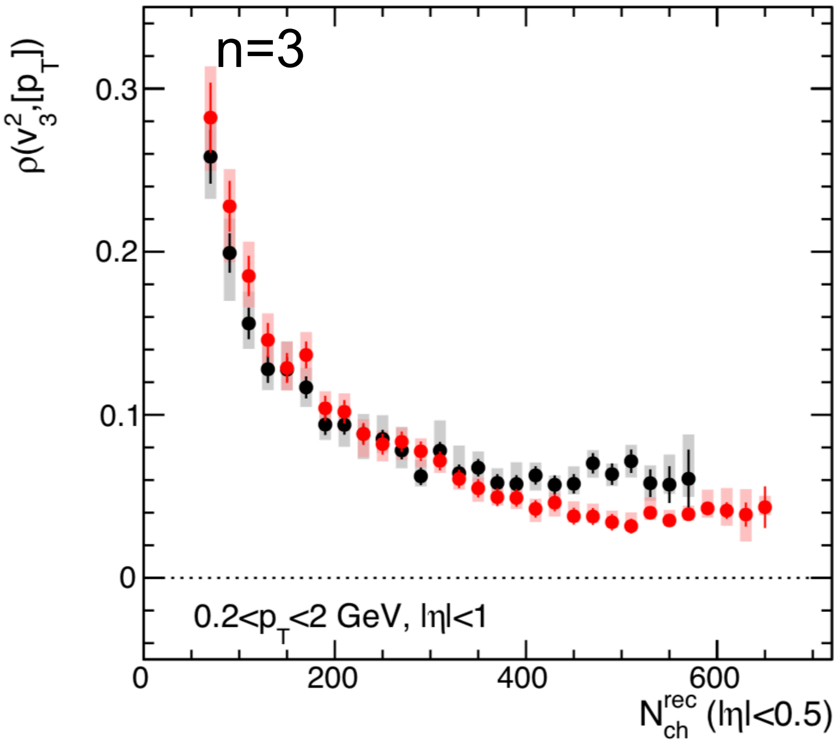
$$\mathbf{var}\left(v_n^2\right) = v_n\{2\}^4 - v_n\{4\}^4$$

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

v_n^2-$[p_T]$ correlation

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





Clear sign change in UU around 8% centrality
Au+Au remains positive

Similar between Au+Au and UU

Compare to Trento initial-state model

Trento: private calculation provided by Giuliano Giacalone, PRC102, 024901(2020), PRL124, 202301(2020)

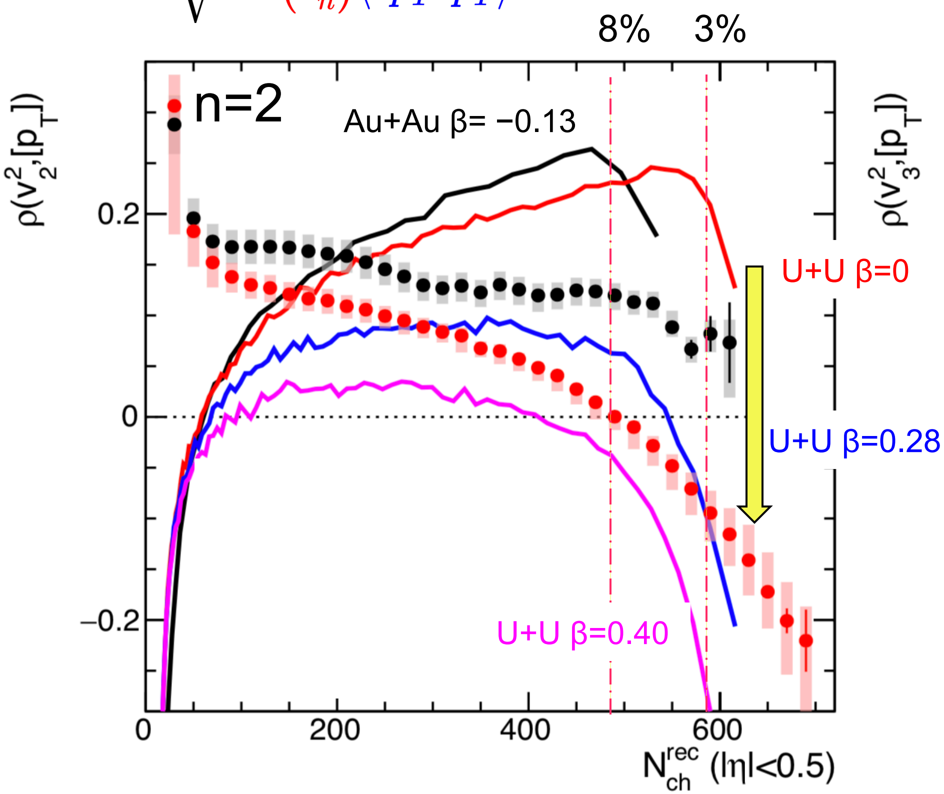
$$\rho(v_n^2,[p_T]) = \frac{\langle v_n^2 \delta p_T \rangle}{\sqrt{\mathrm{var}(v_n^2)\langle \delta p_T \delta p_T \rangle}}$$

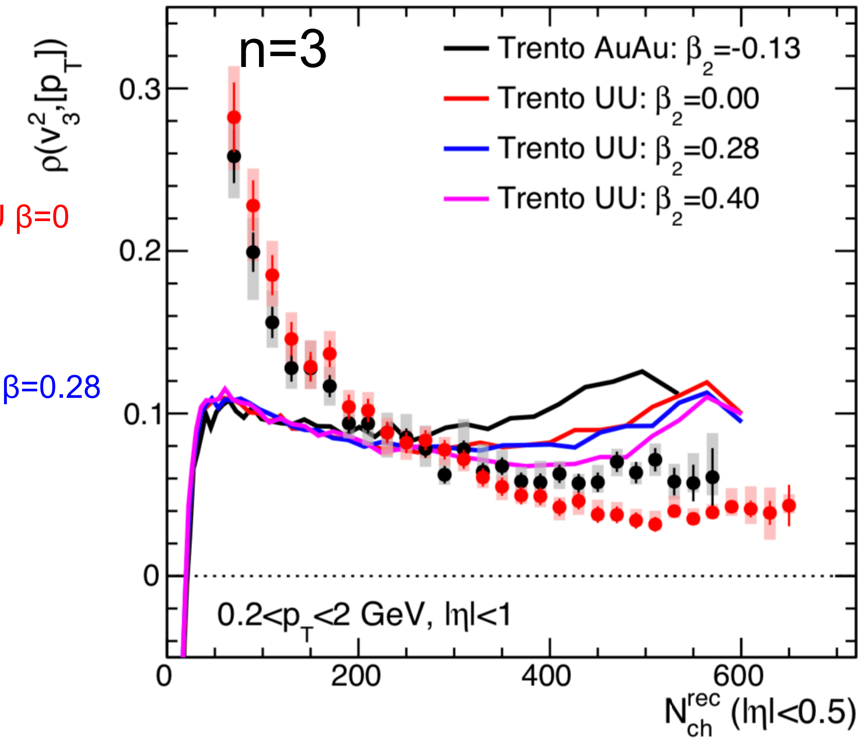
Calculated via predictor with assumption

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

$v_n \propto \epsilon_n$

$[p_T] \propto \frac{E}{S}$ $\frac{\mathrm{Energy_{ini}}}{\mathrm{Entropy_{ini}}}$



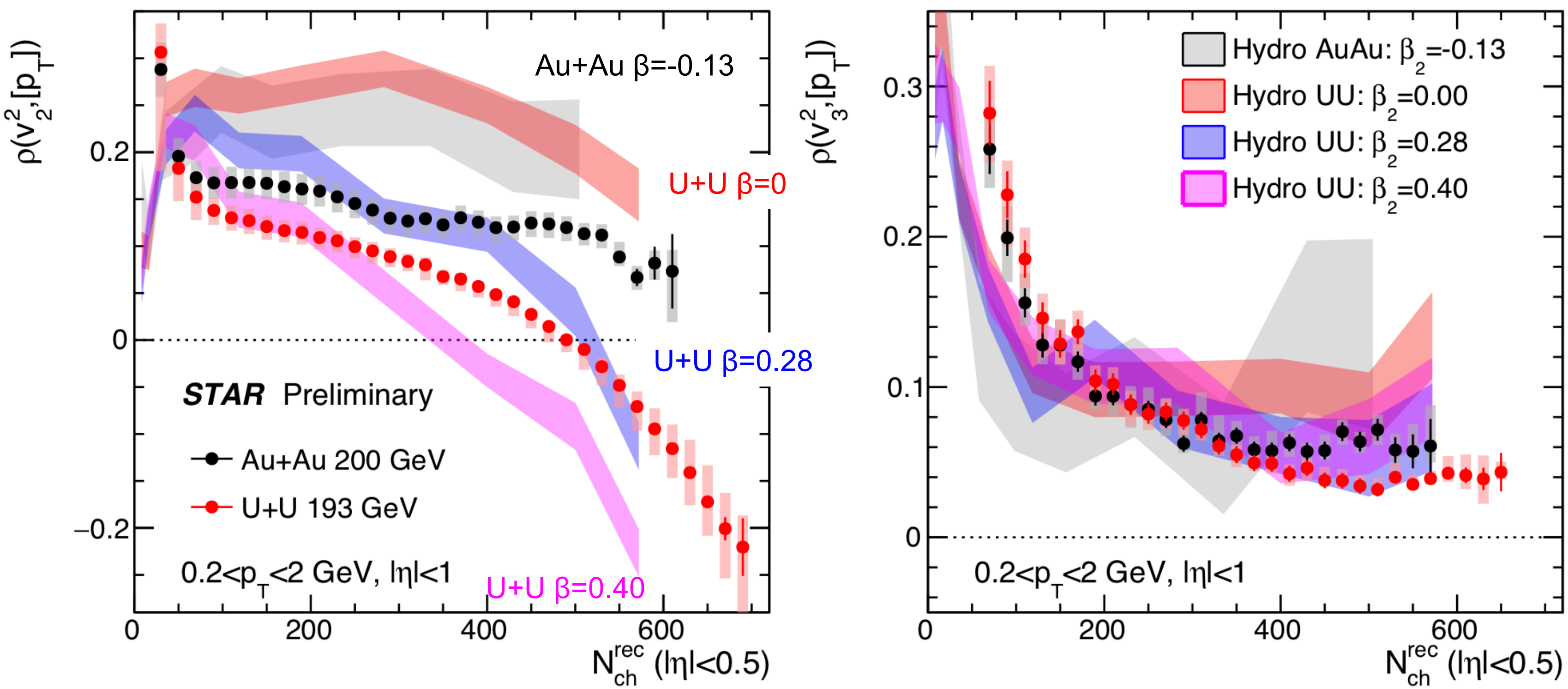


Trento does not describe data but shows an hierarchical β dependence for v_2-p_T in U+U.
Trento shows sign-change from Uranium deformation, prefers 0.28<β<0.4
Trento shows that v_3-p_T correlations are insensitive to deformation.

Compare to (boost-invariant) CGC+Hydro model

IP-Glasma+Hydro: private calculation provided by Bjoern Schenke Phys. Rev. C 102, 034905 (2020)

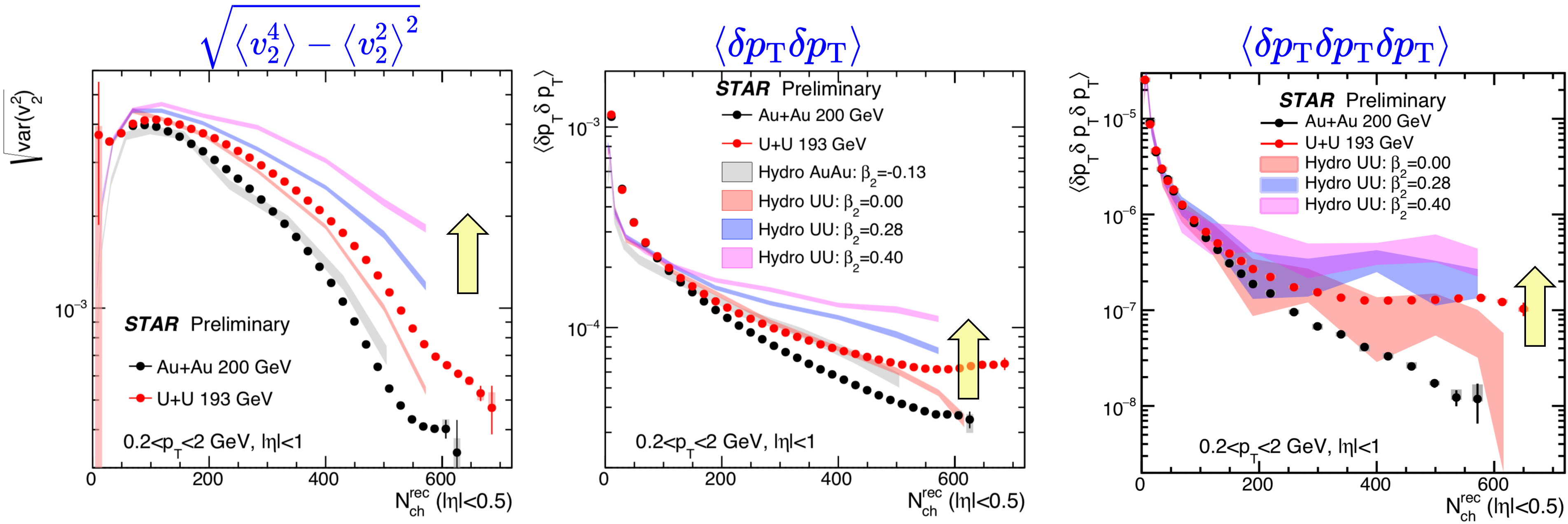
- Without deformation, CGC+hydro model over-predicts the $\rho(v_2^2, p_T)$
- With increasing β_2, model could describe the trend of $\rho(v_2^2, p_T)$.
- Model shows that the $\rho(v_3^2, p_T)$ are insensitive to β_2.



Sign-change of $\rho(v_2^2, p_T)$ is due to deformation effect, model prefers a β_2 value around $0.28<\beta_2<0.4$ with large uncertainty.

Can CGC+hydro model describe other observables?

IP-Glasma+Hydro: private calculation provided by Bjoern Schenke Phys. Rev. C 102, 034905 (2020)



UU with β=0.28 overshoots the v_2 and $[p_T]$ fluctuations

Model cannot describe all observables simultaneously.
Our data provide lot of inputs for improvement.

Summary

- Hydro response: azimuthal and radial flow→shape and size fluctuations
  - Inferred from fluctuations in v_n, $[p_T]$ and v_n-$[p_T]$ correlations

Linear response approximation: $\epsilon_n \to v_n$ $\quad \frac{1}{R} \to [p_T]$ $\quad \langle \epsilon_n^2 \frac{1}{R} \rangle \to \langle v_n^2\, p_T \rangle$

- These observables are sensitive to the quadrupole deformation parameter β_2
  - Strategy: compare highly-deformed $^{238}U+^{238}U$ and near-spherical $^{197}Au+^{197}Au$

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

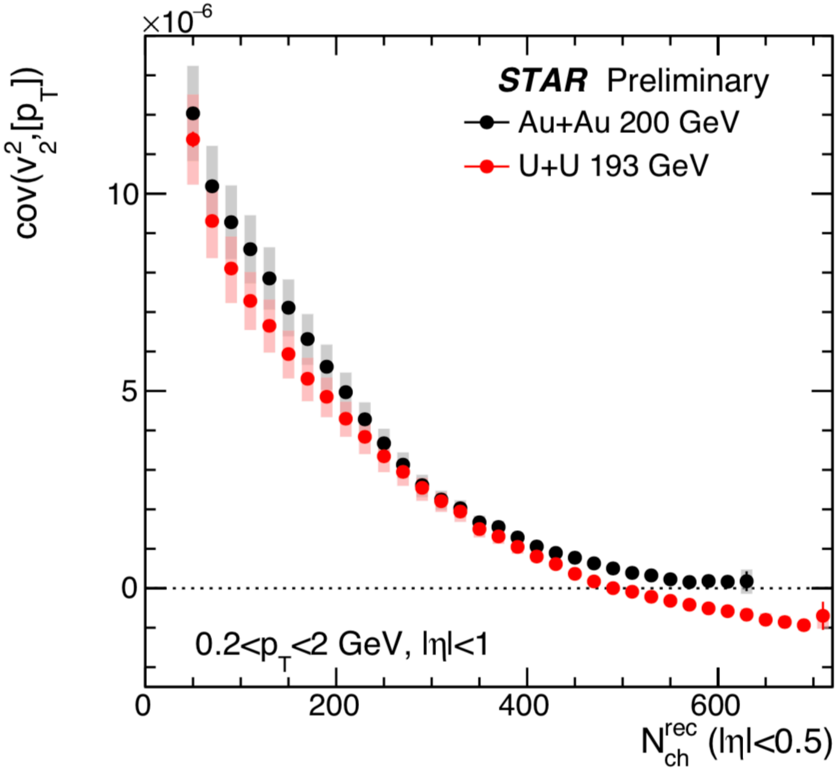
- Compared to Au+Au, results from U+U collisions show
  - Enhance v_2, $[p_T]$ and v_2-$[p_T]$ fluct., but little influence on v_3 and v_3-$[p_T]$ fluct.
  - Effects largest in central collisions, but also observed in mid-central collisions.

→ nuclear deformation influences collisions over a wide centrality range.

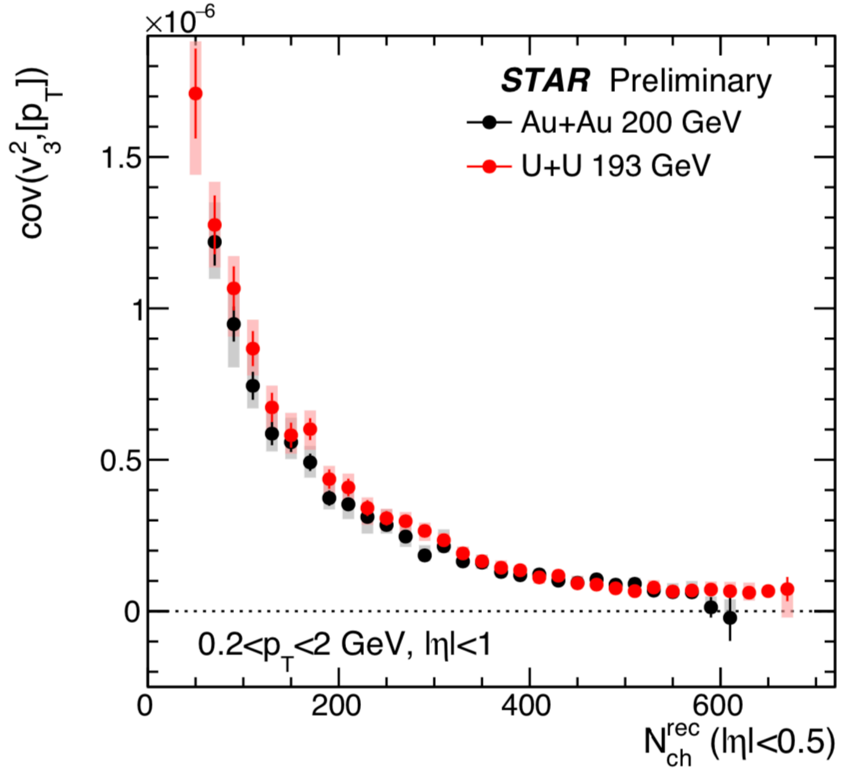
- Qualitatively described by IS model & IS+hydro model, but not quantitatively.
  - Data prefers a quadrupole deformation of $0.28 \lesssim \beta_2 \lesssim 0.40$ with large uncertainty
  - Data can improve model tuning and provide new ways to probe nuclear structure.

Additional materials

Covariance: $\langle v_n^2 \delta p_T \rangle$

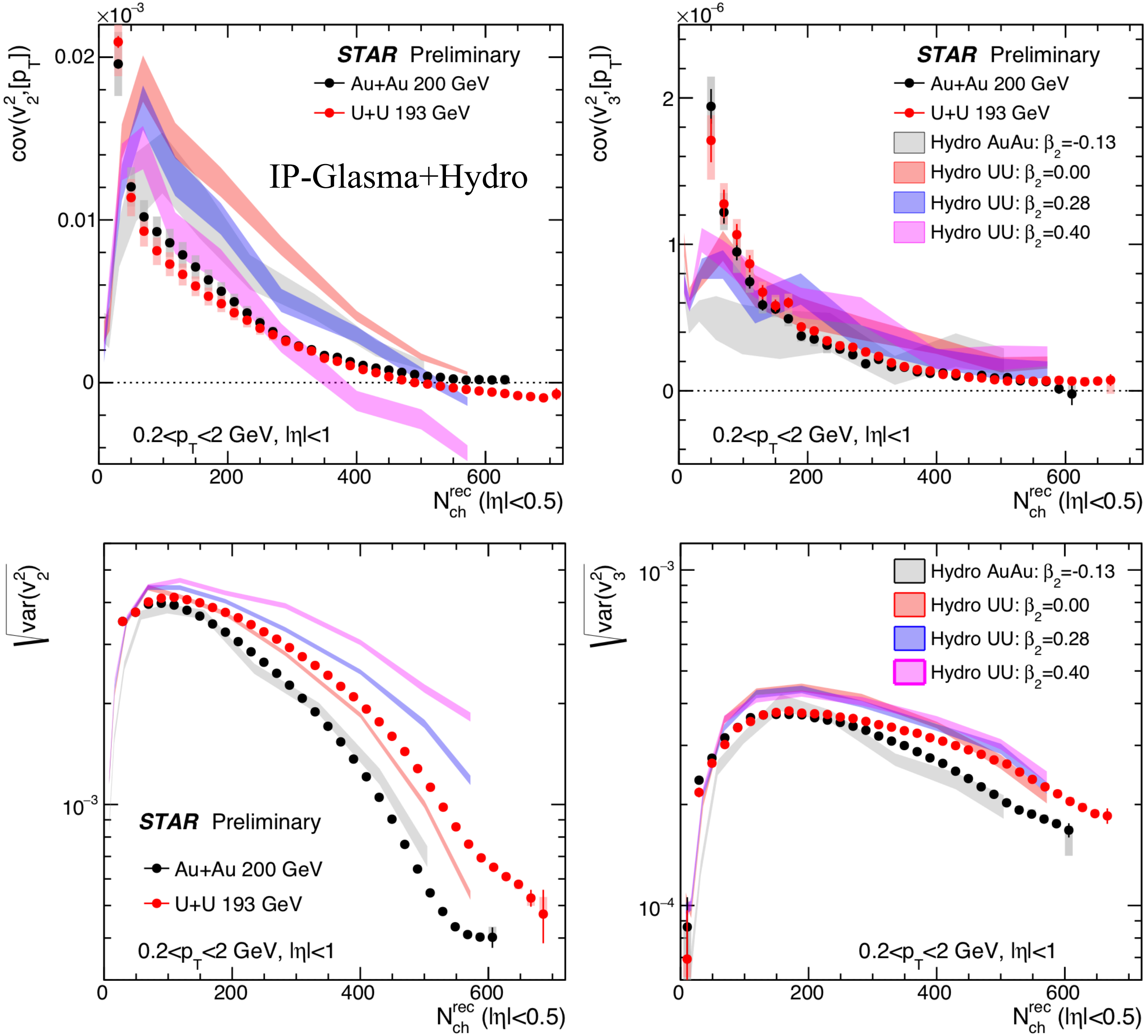


$\langle v_2^2 \delta p_T \rangle$: Difference in low and high N_{ch}

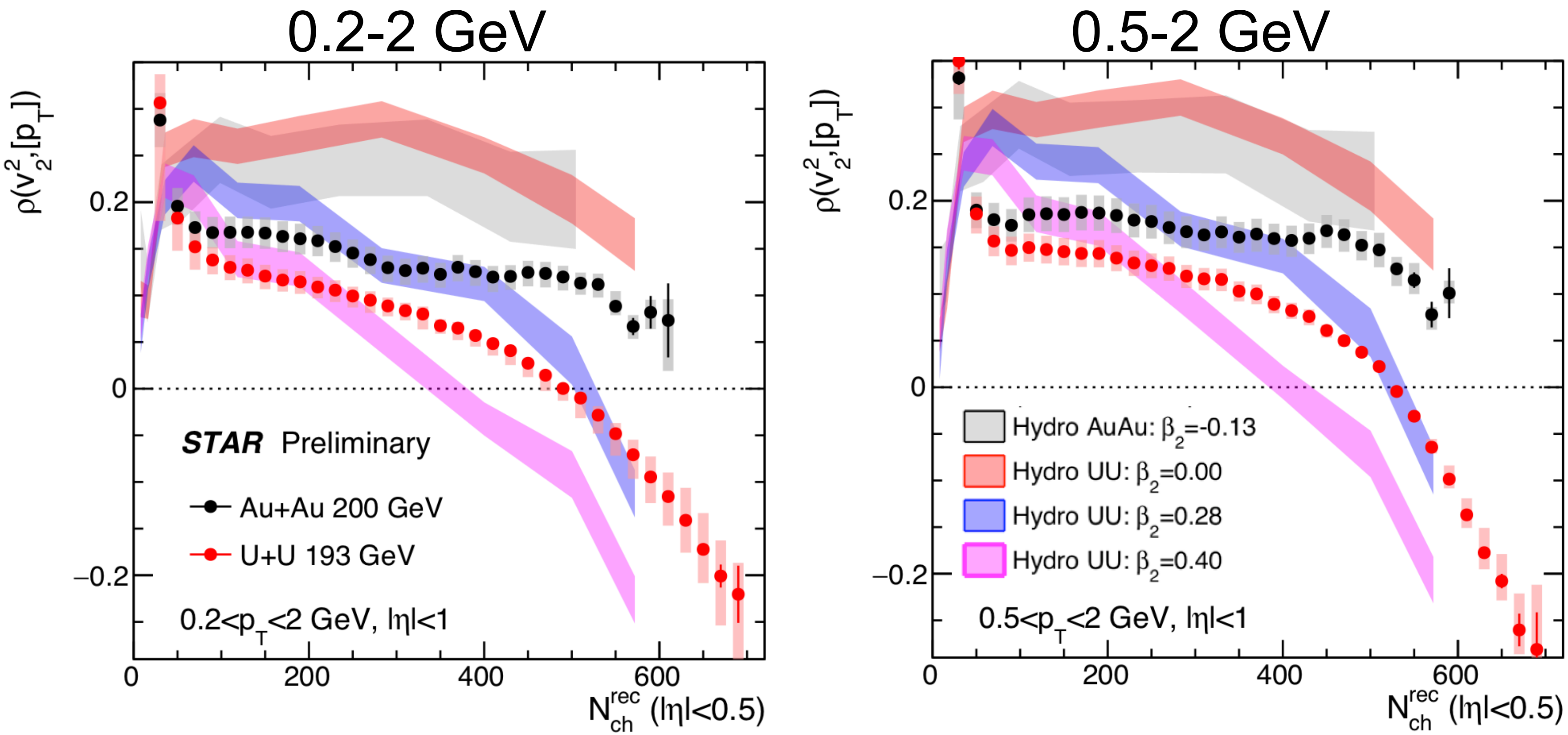


$\langle v_3^2 \delta p_T \rangle$: common scaling with N_{ch}

Hydro description for $\langle v_n^2 \delta p_T \rangle$ and v_n



p_T dependence



- Increase at low N_{ch} and decrease at high N_{ch}: more significant sign change
- Similar p_T dependence also seen in hydro model.

$[p_T]$ skewness: hydro prediction

- Quantify with normalized quantities

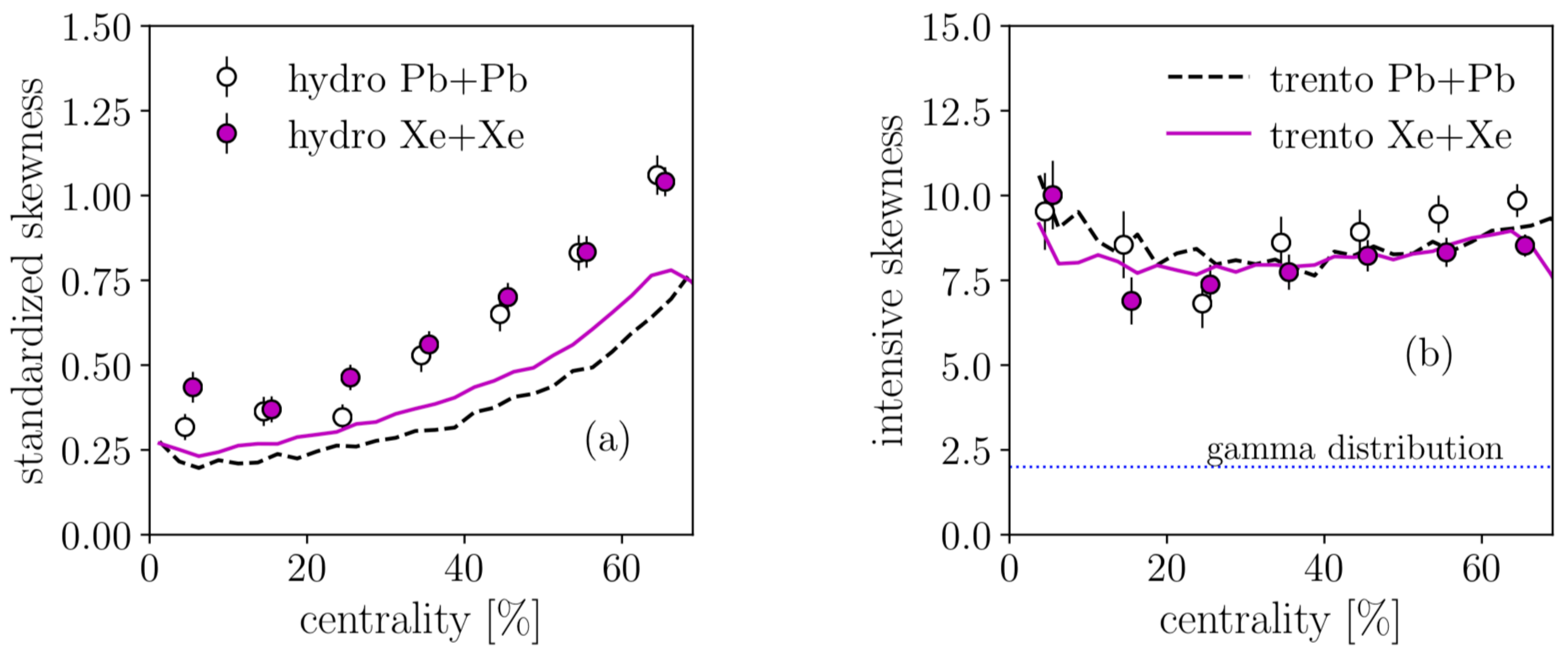
G Giacalone, F.Gardim, J.Noronha-Hostler, J.Ollitrault 2004.09799

Standard skewness

$$\gamma_{p_t} \equiv \frac{\langle \Delta p_i \Delta p_j \Delta p_k \rangle}{\langle \Delta p_i \Delta p_j \rangle^{3/2}} \sim \frac{C_3}{C_2^{3/2}} \propto \frac{1}{\sqrt{N_{\rm part}}}$$

Intensive skewness

$$\Gamma_{p_t} \equiv \frac{\langle \Delta p_i \Delta p_j \Delta p_k \rangle \langle\langle p_t \rangle\rangle}{\langle \Delta p_i \Delta p_j \rangle^2} \sim \frac{C_3/C_1}{(C_2/C_1)^2} \sim \text{const}$$



Hydro calculation (points) can be approximated by initial-state predictor (lines): $[p_T] \propto \frac{\text{Energy}_{\rm ini}}{\text{Entropy}_{\rm ini}} \sim \frac{1}{R}$