9th Workshop of the APS Topical Group on Hadronic Physics

Measurement of flow harmonics correlations with mean transverse momentum at RHIC and LHC

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April 14, 2021

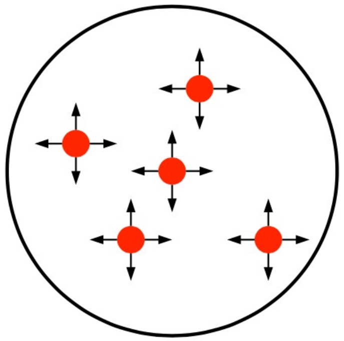
Session: QGP at RHIC and LHC I (14:50 - 15:10)

Stony Brook University

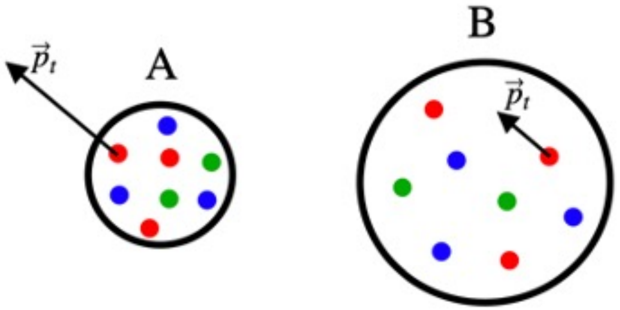
Connecting the initial state to the nuclear geometry

- System size affects the transverse momentum of particles

initial density profile



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



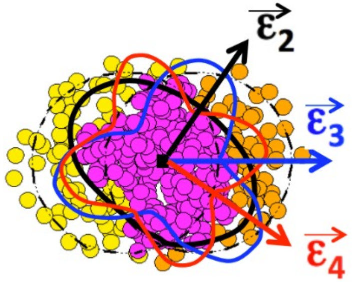
$$c_s^2 = \frac{dP}{d\epsilon} = \frac{d\ln T}{d\ln s} = \frac{d\ln\langle p_T\rangle}{d\ln N_{ch}}$$

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

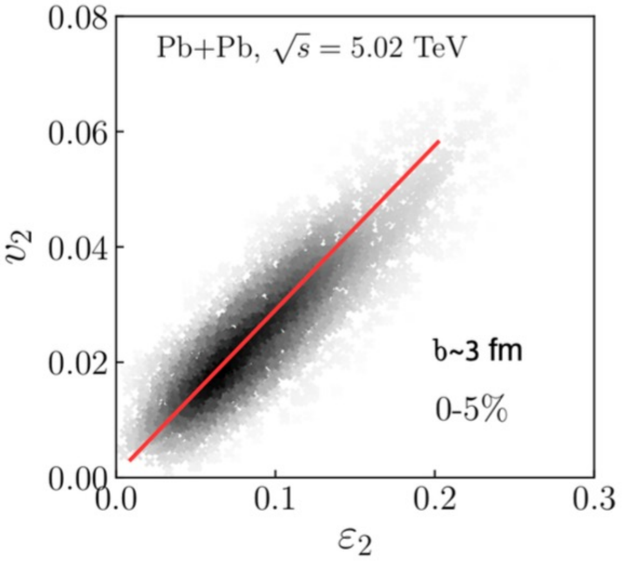
(Hydrodynamic approximation)

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

- Shape affects anisotropic flow of particles



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

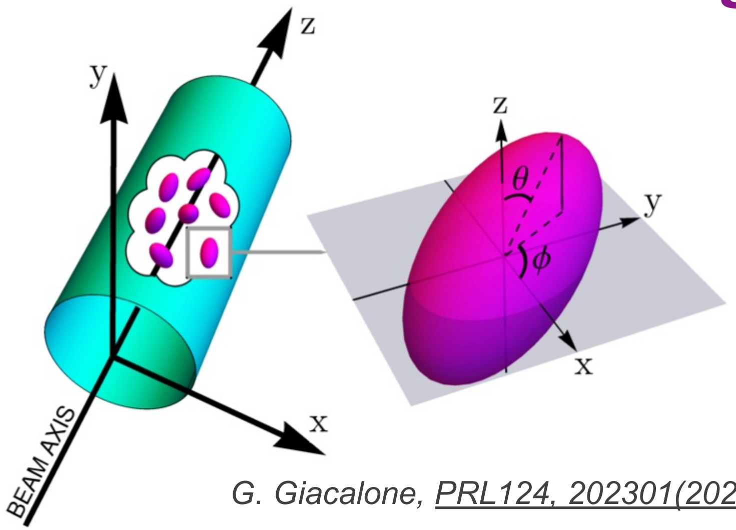


$$v_n \propto \epsilon_n, n = 2, 3$$

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



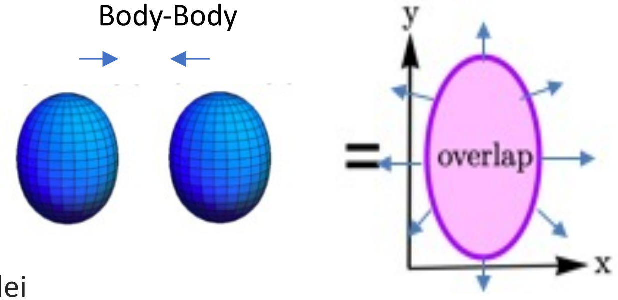
G. Giacalone, PRL124, 202301(2020)

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

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

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

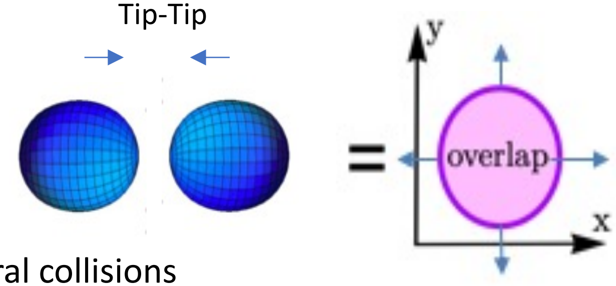
Deformation is dominated by quadrupole component β_2



large R, small $\langle p_T \rangle$

large $\boldsymbol{\varepsilon}_2$

Prolate nuclei



small R, large $\langle p_T \rangle$

small $\boldsymbol{\varepsilon}_2$

Ultra-central collisions

- $\boldsymbol{\varepsilon}_2$ and R are influenced by the quadrupole deformation β_2
- $\langle p_T \rangle \sim 1/R$ and $v_2 \propto \boldsymbol{\varepsilon}_2$: $\left\langle \epsilon_n^2 \frac{1}{R} \right\rangle \rightarrow \langle v_n^2\, p_T \rangle$

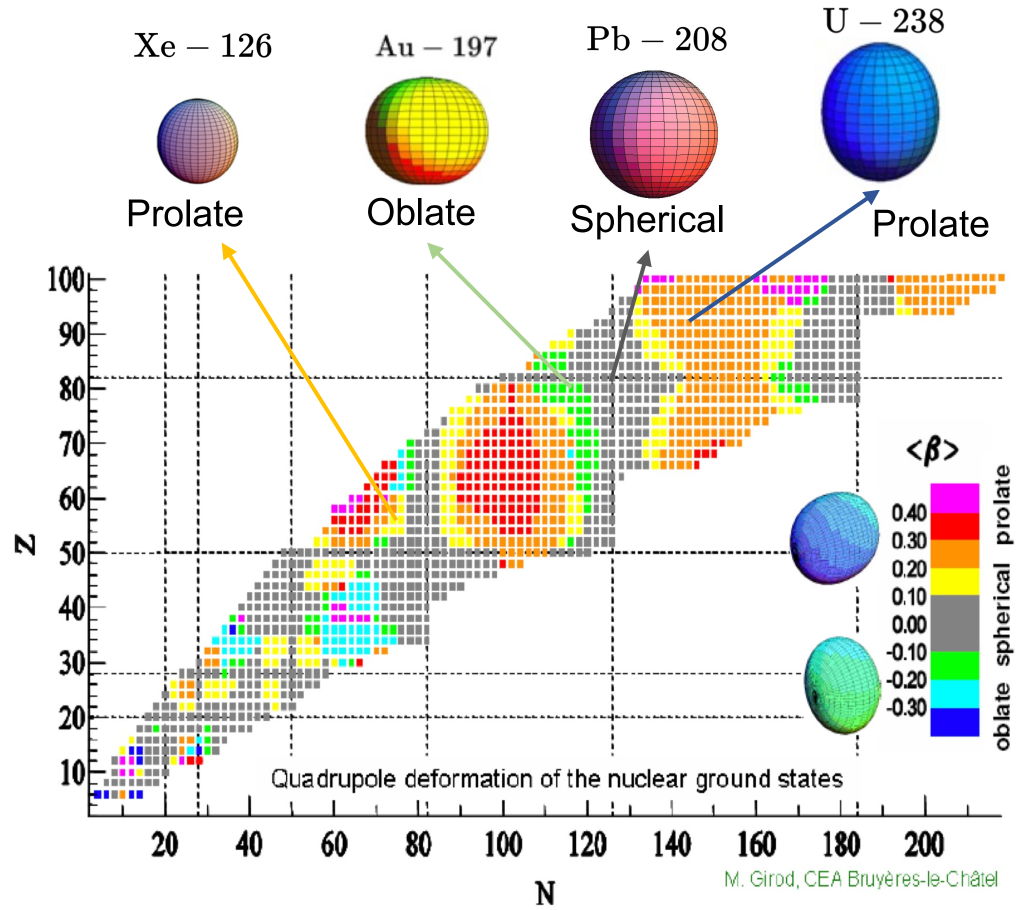
deformation contributes to anticorrelation between v_2 and $\langle p_T \rangle$

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

RHIC:

The β_2 of ^{238}U has a large value:

BNL nuclear data center

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

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

LHC:

The β_2 of ^{129}Xe has a moderate value:

reference	Raman et al.	Möller et al.	Möller et al.
method	exp	FRDM	FRLDM
β_2	0.1881	0.143	0.162

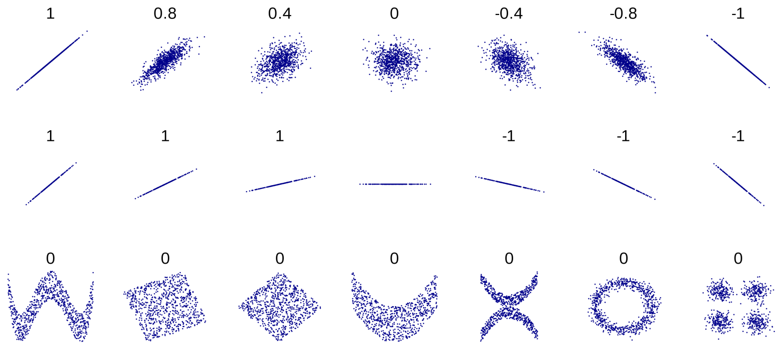
$$\beta_2^{\mathrm{Pb+Pb}} = 0$$

New way to constrain β_2 of uranium at a much shorter time scale (~10^{-23}s) in heavy-ion collisions.

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

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

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

w_i is track weight

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

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

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

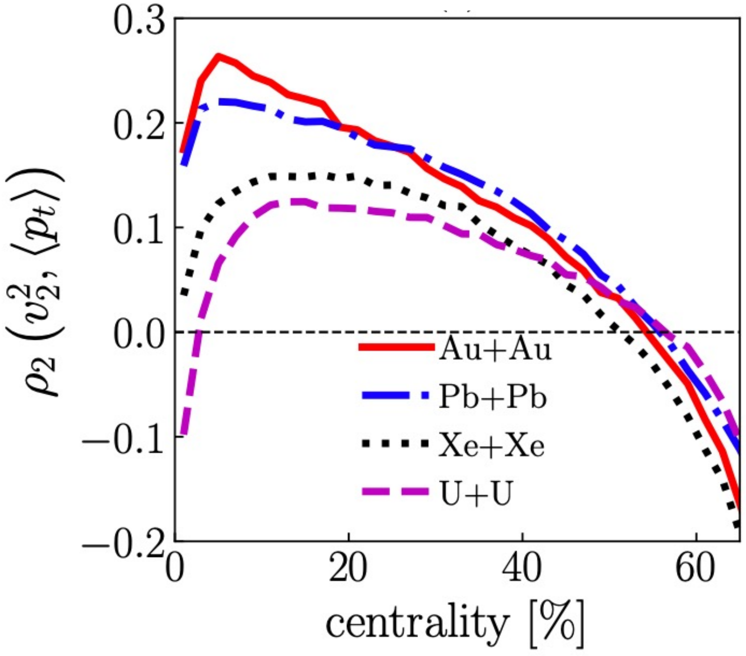
(1) Insensitive to medium properties of QGP. (2) Insensitive to trivial statistical fluctuation. (3) Isolate the correlations coming from genuine collective effect.

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;

Theory predictions at RHIC and LHC energy

Deformation sensitivity

Giuliano Giacalone, 102, 2024901 (2020)

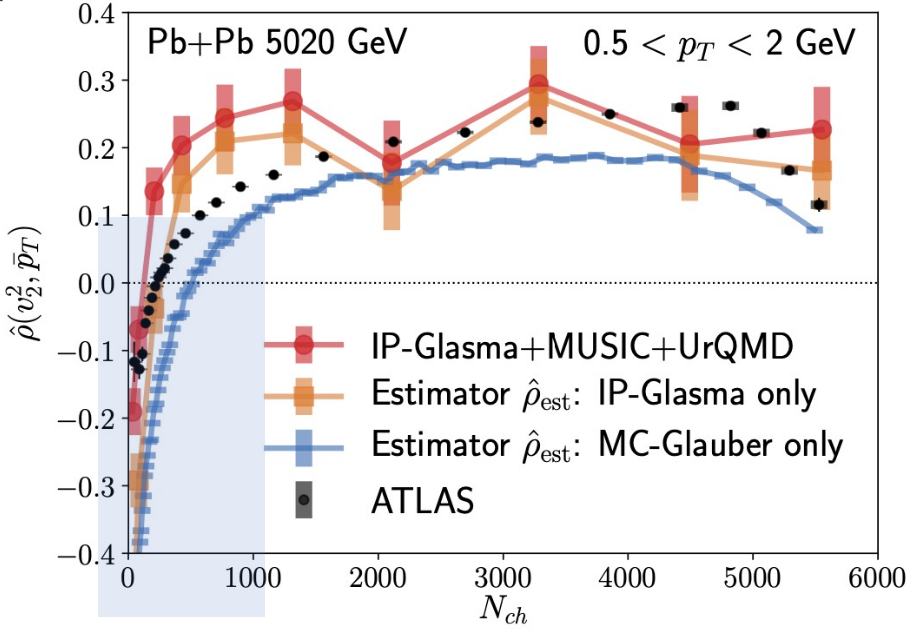


Deformation dominates the negative correlation in central U+U.

Clear initial geometry effect due to shape of nuclei.

Geometric effect

Bjoern Schenke et al., PRC102, 034905 (2020)

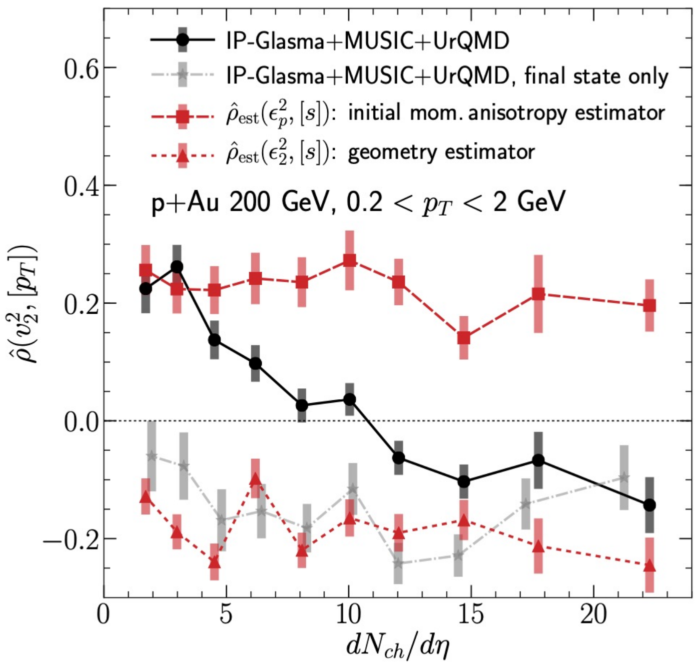


The sign change is a geometrical effect:

- In mid-central: a smaller area at fixed Nch, fluctuating to larger b increasing ϵ_2.
- in quite peripheral collisions: a smaller area at fixed N_{ch}, clustering participants

Initial state momentum correlations

Giuliano Giacalone et al., PRL125, 192301(2020)



Bjoern Schenke, arXiv:2102.11189

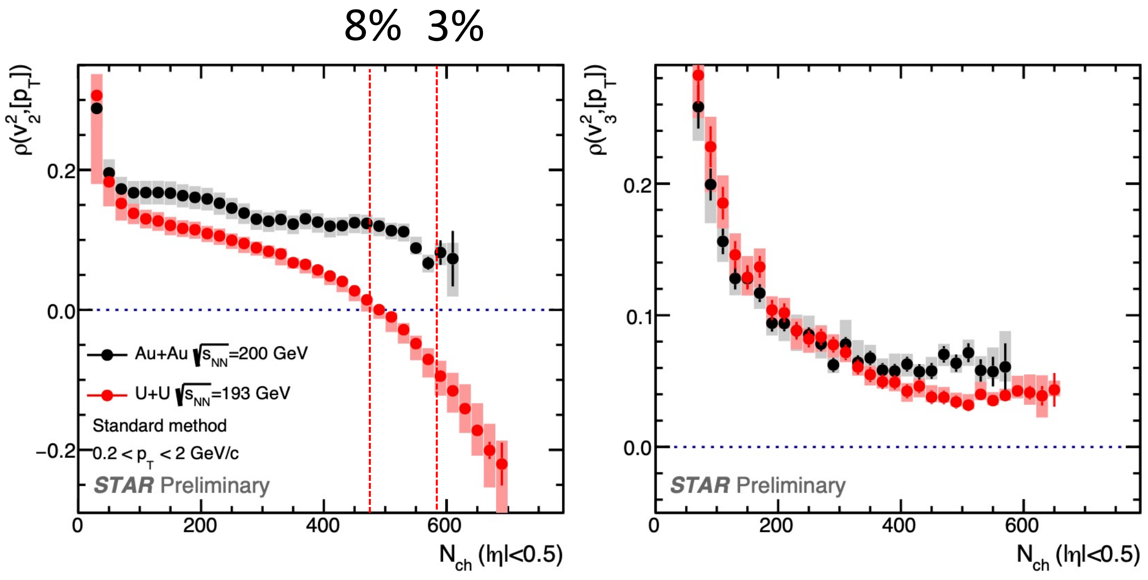
ε_p is the dominant source in small system

Initial momentum anisotropy lead positive correlation

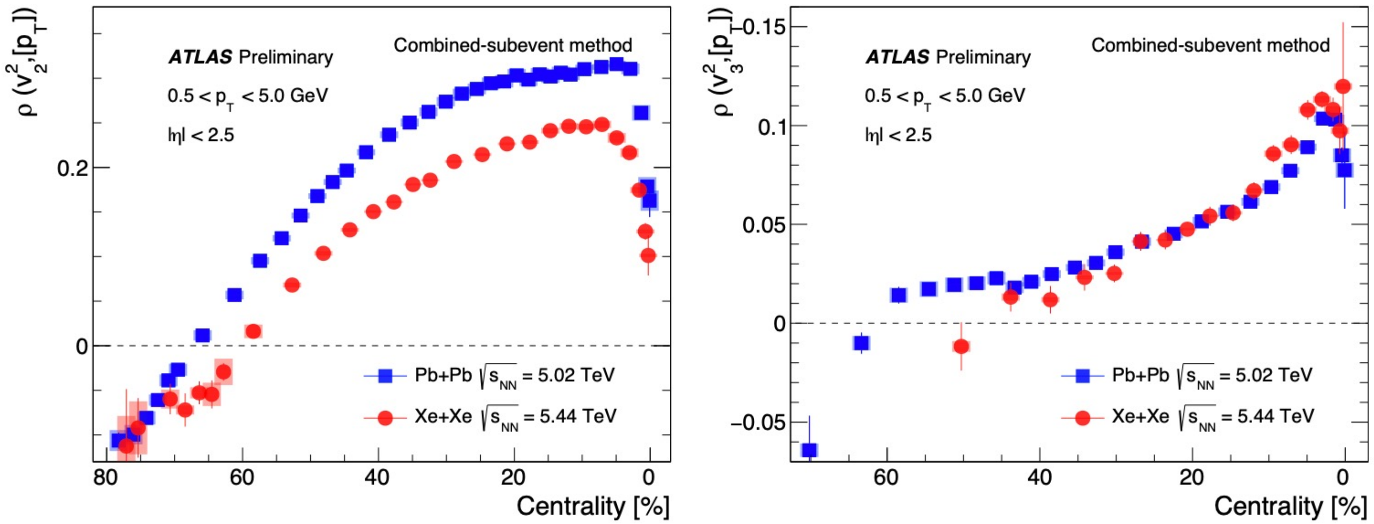
Pearson coefficient $\rho(\mathrm{v}_n^2, [\mathrm{p_T}])$

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

STAR results



ATLAS results



$\rho(\mathrm{v}_2^2, [\mathrm{p_T}])$ has a clear difference:
negative (anticorrelation) in U+U central
positive in Au+Au central.

$\rho(\mathrm{v}_3^2, [\mathrm{p_T}])$ is positive and similar in Au+Au and U+U.

$\rho(\mathrm{v}_2^2, [\mathrm{p_T}])$ is smaller in Xe+Xe.

$\rho(\mathrm{v}_2^2, [\mathrm{p_T}])$ is negative in peripheral LHC energy.

$\rho(\mathrm{v}_3^2, [\mathrm{p_T}])$ is comparable in Pb+Pb and Xe+Xe.

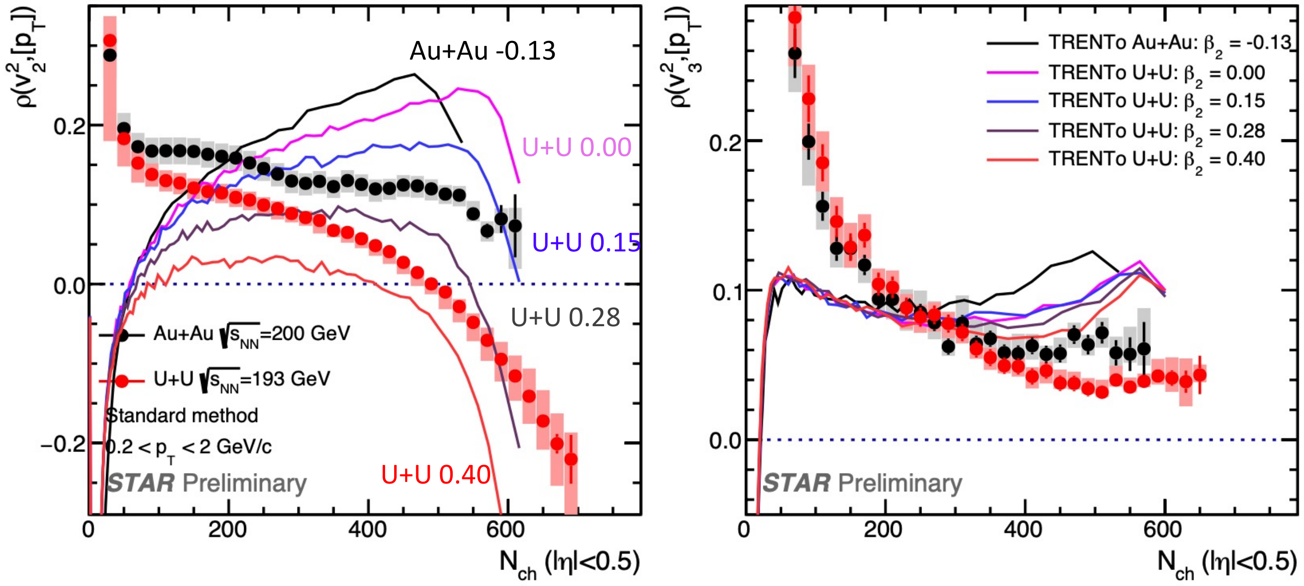
$\rho(v_n^2, [p_T])$ compared to TRENTo initial condition model

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

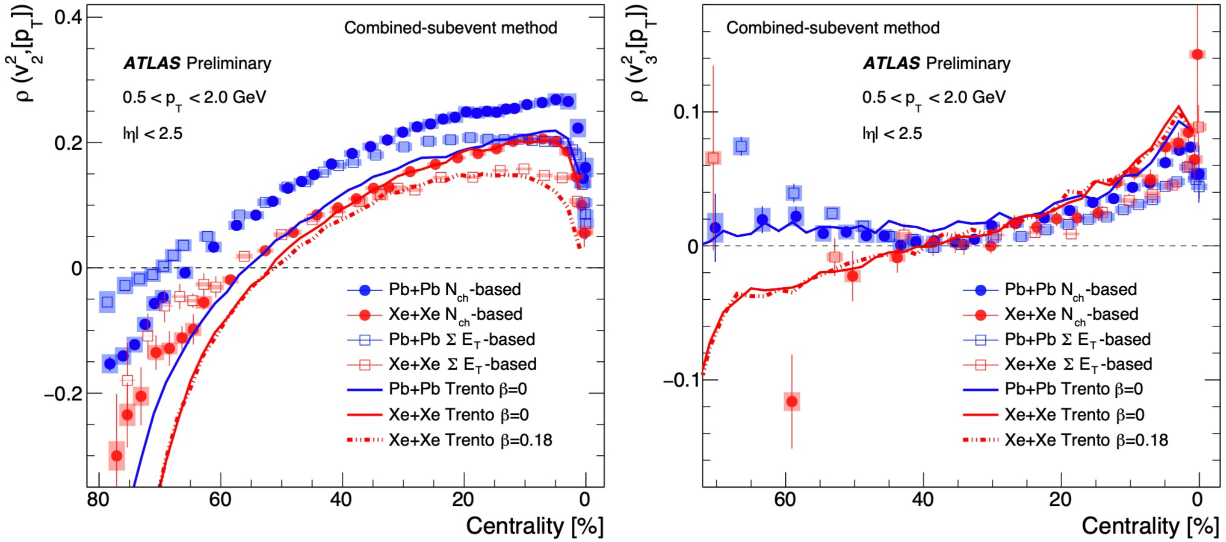
In TRENTo, calculated via predictor with assumption :

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

STAR results



ATLAS results



TRENTo fails to describe the STAR data

TRENTo shows a hierarchical β_2 dependence in U+U collisions.

Deformation dominates sign-change in central U+U collisions.

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

Model qualitatively captures centrality trends of data .

Results based on E_T, comparison to TRENTo better in central but worse in peripheral.

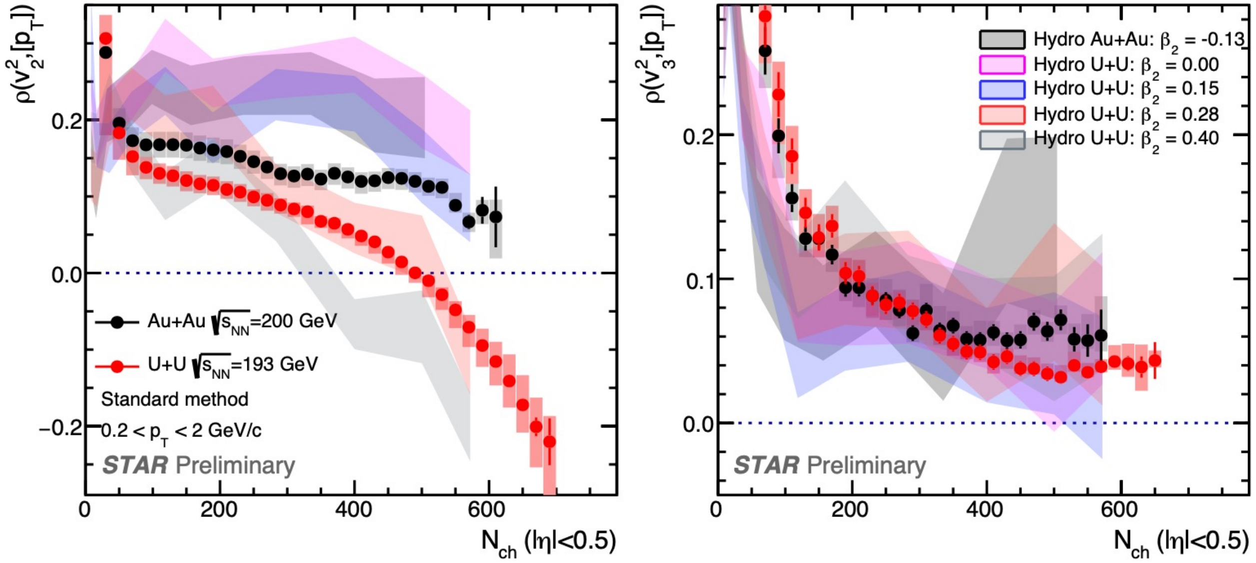
$\rho(v_3^2, [p_T])$ is insensitive to the β_2.

$\rho(\mathrm{v}_n^2, [\mathrm{p_T}])$ compared to (boost-invariant) CGC+Hydro

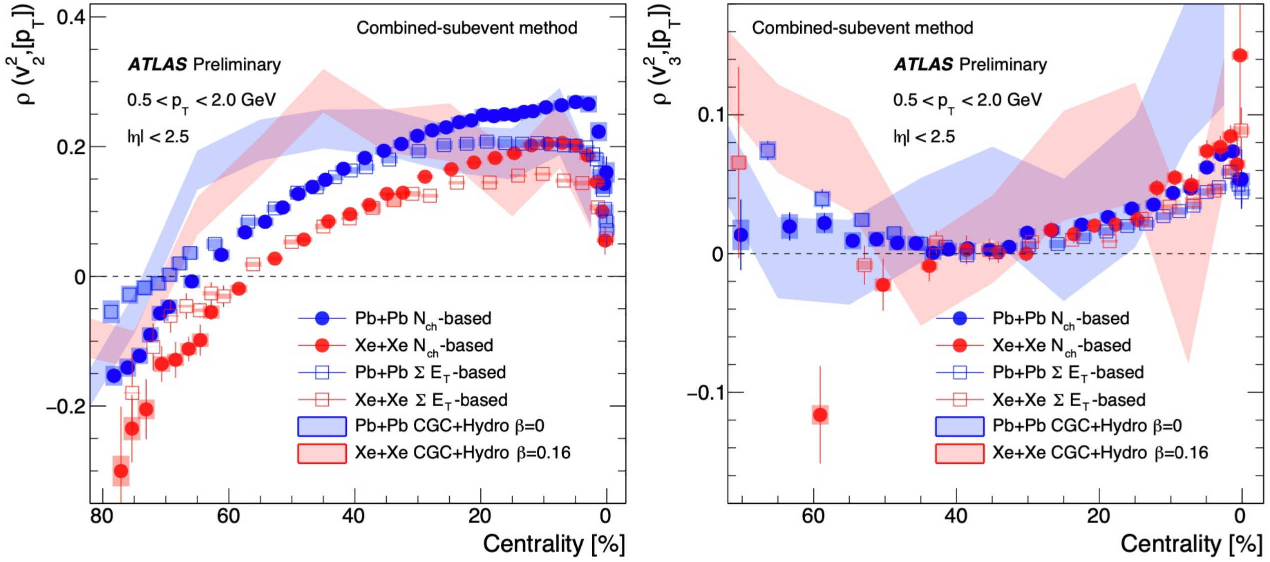
CGC+Hydro: private calculation provided by Bjoern Schenke (based on B. Schenke, C. Shen, P. Tribedy, PRC102, 044905(2020))

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

STAR results



ATLAS results



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

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

Model shows that $\rho(\mathrm{v}_3^2, [\mathrm{p_T}])$ are insensitive to β_2.

The sign-change is due to deformation effect.

Model quantifies the β_2 value around 0.3

Better agreement but still can not describe data quantitatively.

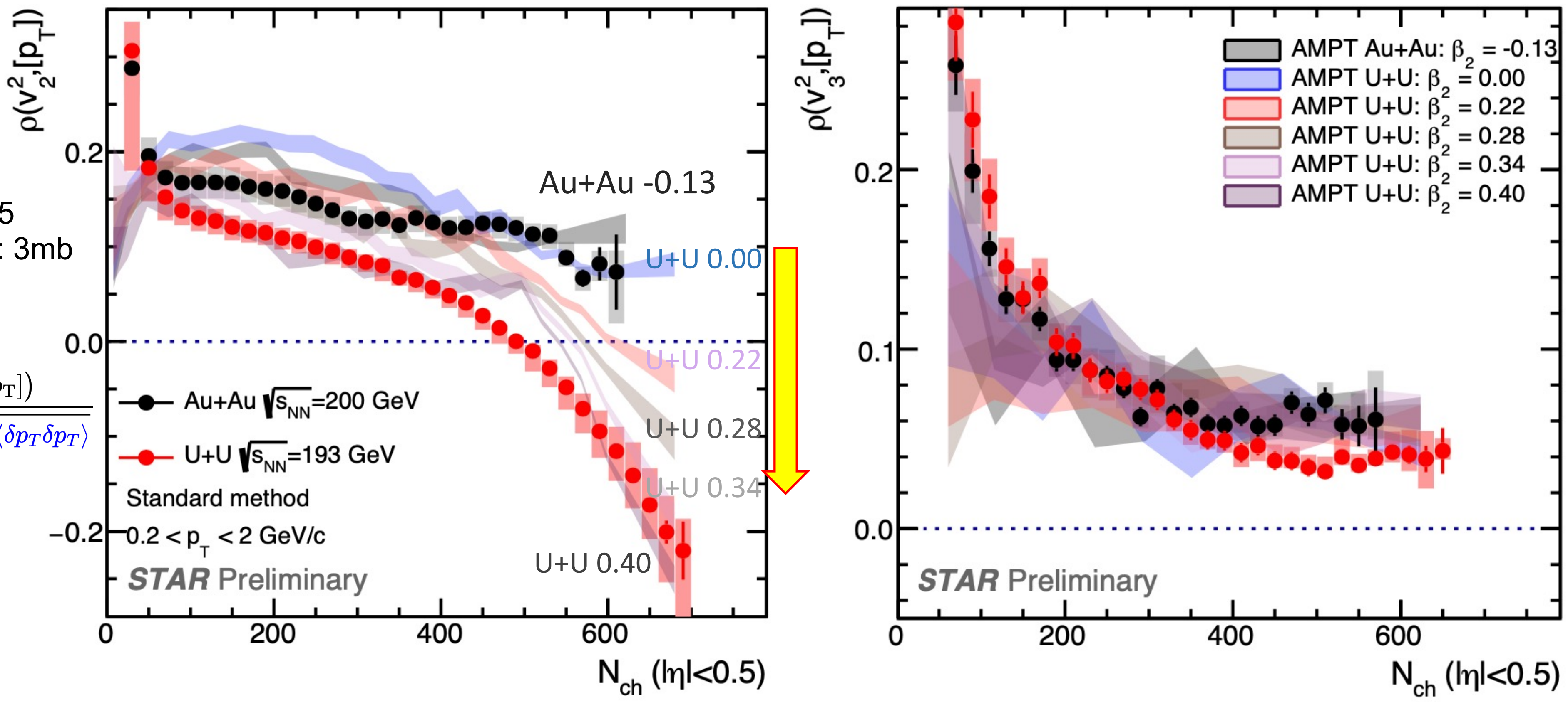
No significant difference between Pb+Pb and Xe+Xe due to limited statistics.

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

AMPT: Chunjian Zhang, Jiangyong Jia and Shengli Huang, (to be submitted)

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

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

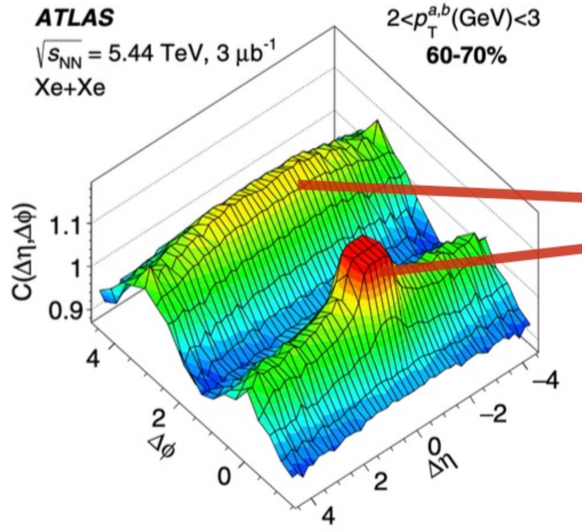


AMPT also shows a clear β_2 dependence in Uranium $\rho(v_2^2, [p_T])$ while not in $\rho(v_3^2, [p_T])$.

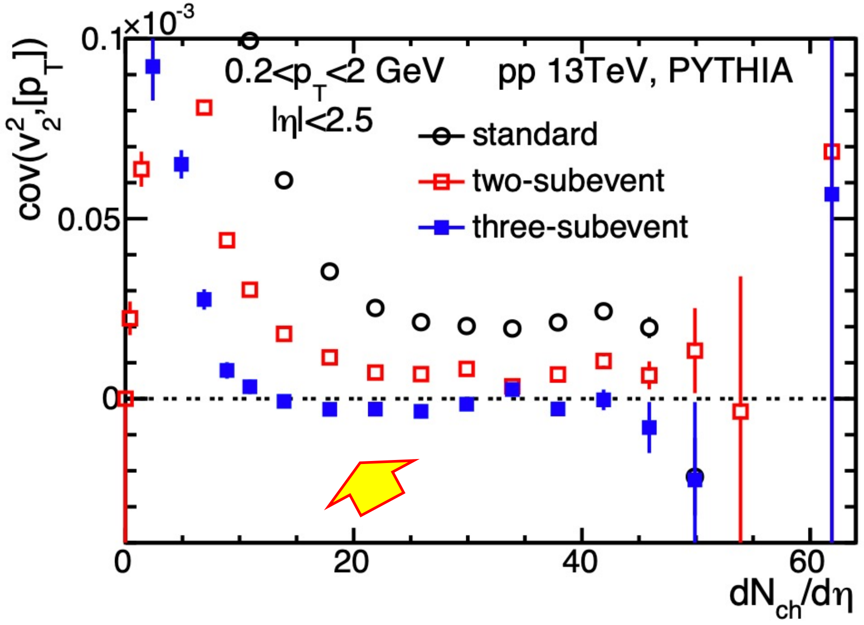
AMPT also supports the sign-change of $\rho(v_2^2, [p_T])$ in U+U is due to deformation effect .

AMPT favors the β_2 value around 0.3 for uranium with large uncertainties.

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

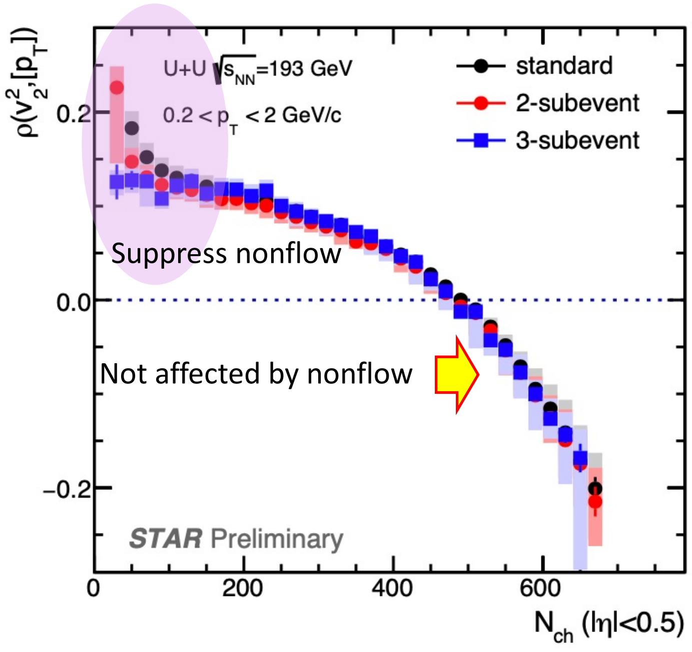
	Full event	Two-subevent		Three-subevent		
STAR	$v_2, p_T\ \|\eta\| < 1.0$	$v_2^A\ \eta < -0.1$	$v_2^B\ \eta > 0.1$	$v_2^A\ \eta < -0.35$	$v_2^B \|\eta\| < 0.3$	$v_2^C \eta > 0.35$
ATLAS	$v_2, p_T\ \|\eta\| < 2.5$	$v_2^A\ \eta < -0.75$	$v_2^B\ \eta > 0.75$	$v_2^A\ \eta < -0.75$	$v_2^B\ \|\eta\| < 0.5$	$v_2^C \eta > 0.75$

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

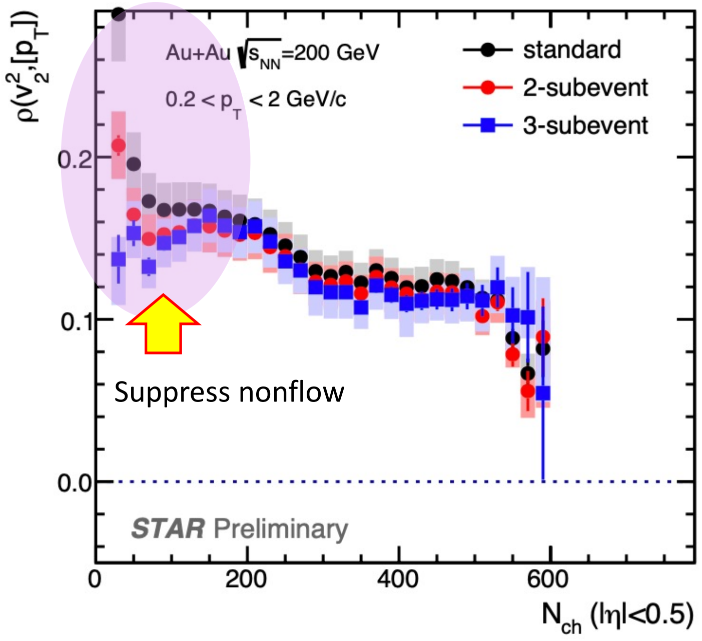
P. Bozek, PRC93, 044908(2016), PRC96.014904(2017); B. Schenke et al., PRC102, 034905(2020); G. Giacalone et al., PRC103, 024910(2021), 2101.00168; F.G. Gardim et al., PLB809, 135749(2020) ; ATLAS EPJC79, 985(2019); J. E. Bernhard et al., Nature Physics 15, 1113(2019); ALICE EPJC 74, 3077(2014); thesis1_STAR;

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

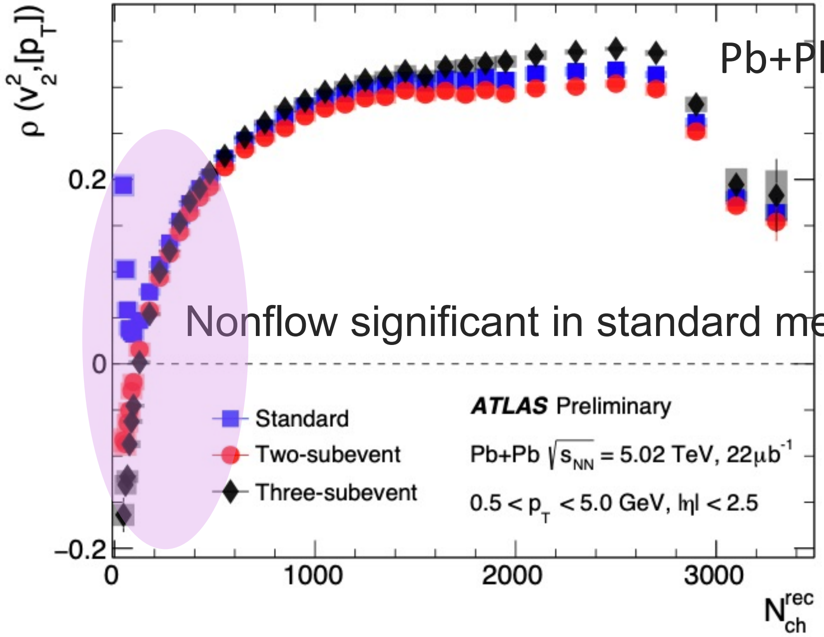
U+U collisions



Au+Au collisions

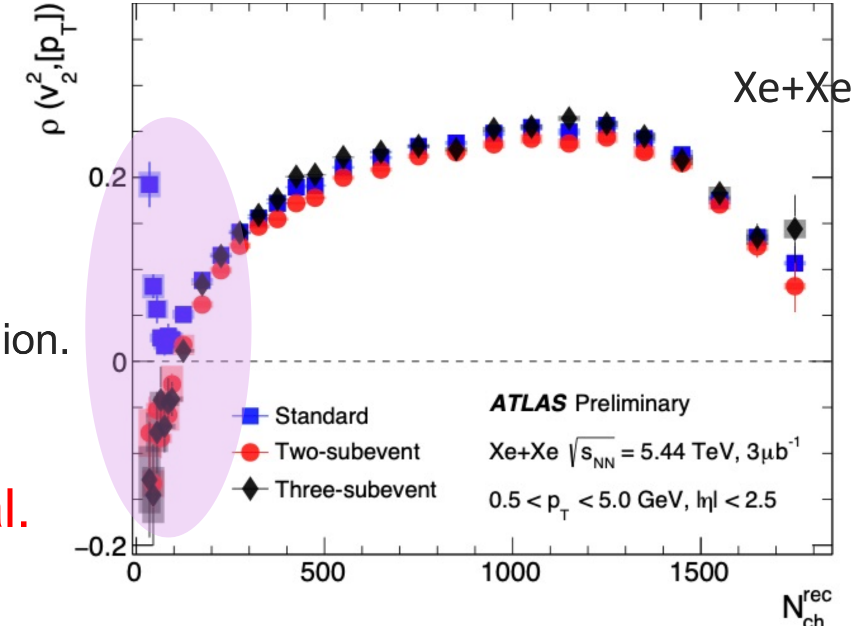


Pb+Pb collisions



Nonflow significant in standard method at low N_{ch}.

Xe+Xe collisions



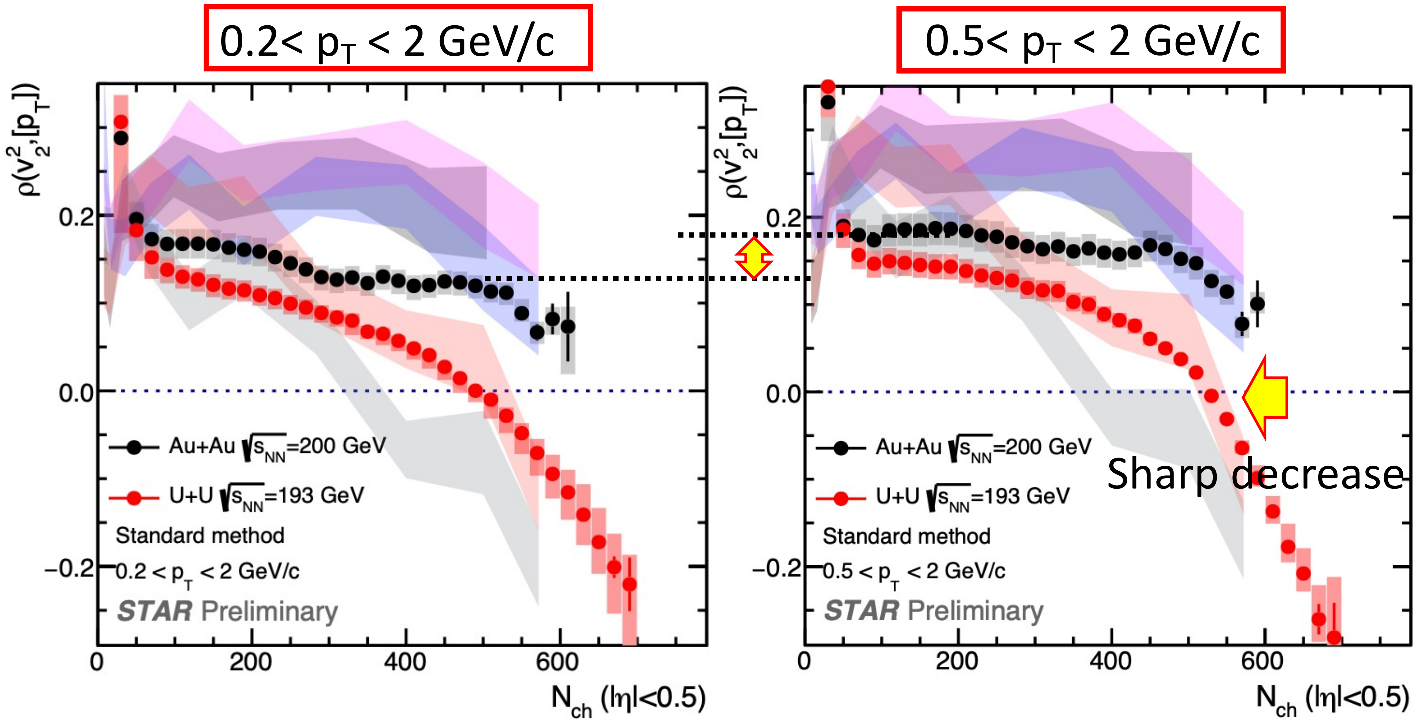
Standard method is consistent with subevent methods at high N_{ch}.

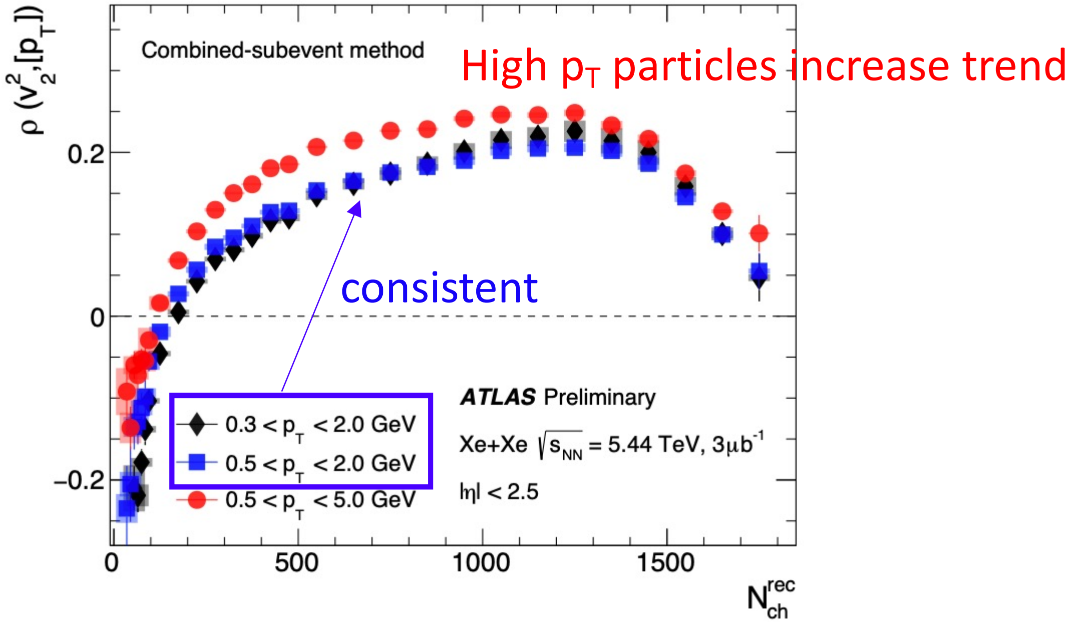
Subevent methods could decrease non-flow contributions in peripheral region.

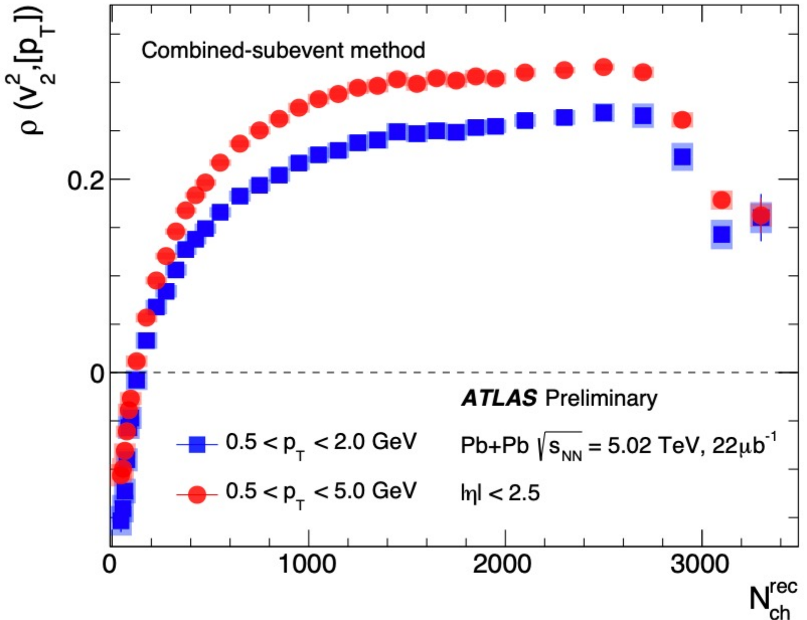
Non-flow effect is not responsible for mid-central and central.

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

B. Schenke, C. Shen, P. Tribedy, PRC102, 044905(2020)





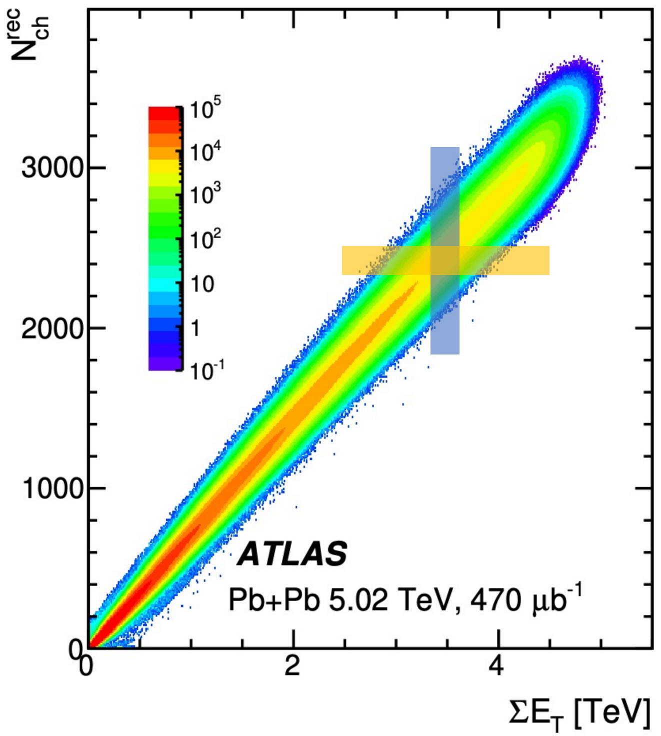


Features are same for different p_T selection.

Centrality fluctuation in $\rho\left(v_n^2, [p_T]\right)$

ATLAS, JHEP51 (2020)

J. Jia et. al., PRR2, 023319(2020)

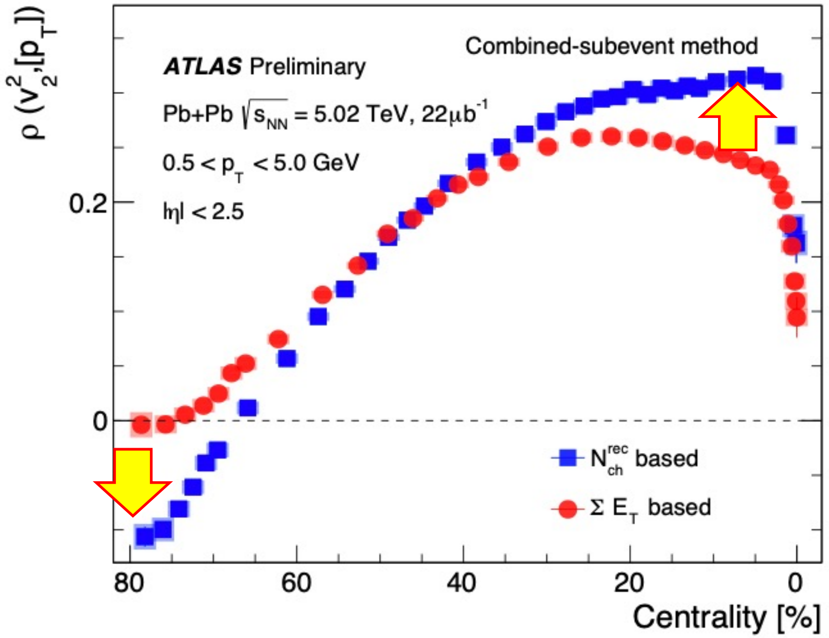


$$p(Obs|N_{ch}) = \sum_{cent} p(Obs.|cent) \otimes p(cent|N_{ch})$$

Ture centrality unknow

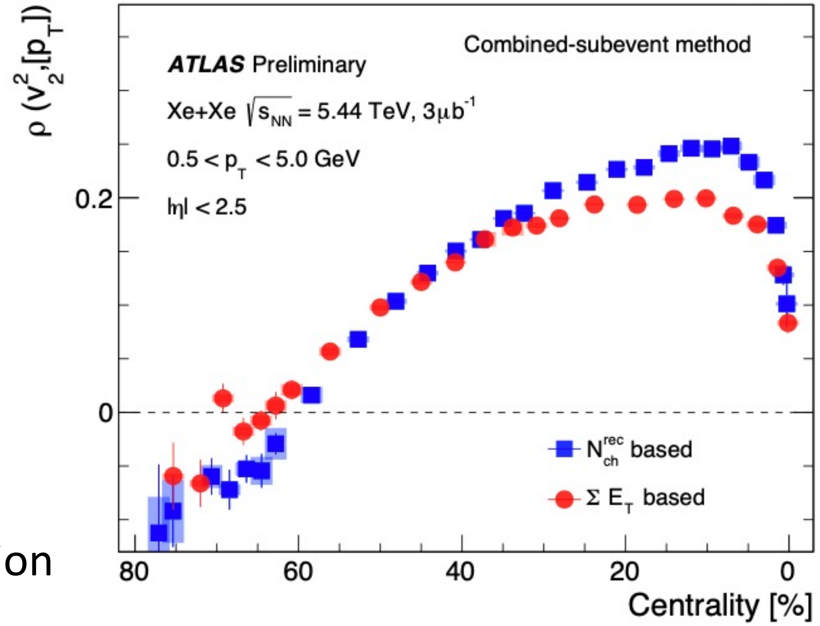
Smearing between N_{ch} and E_T : Same N_{ch} but different E_T, same E_T but different N_{ch}

Event averaging in N_{ch} and E_T bins: centrality fluctuation



E_T and N_{ch} are mapped to centrality (based on E_T cuts)

Significant large centrality fluctuation in peripheral and central.

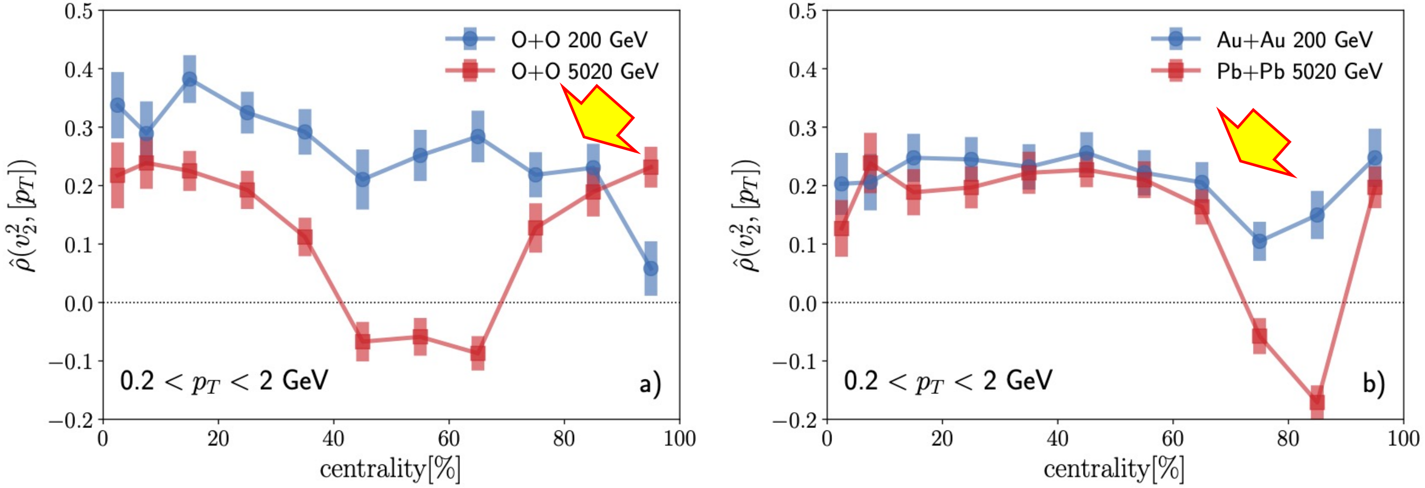


Less prominent in Xe+Xe but still has similar trends (lower centrality Resolution in Xe+Xe).

The opportunities in isobar and O+O collisions

Two questions could be addressed:

1. Role of initial state momentum anisotropy



Giuliano Giacalone et al., PRL125, 192301(2020)

Bjoern Schenke, arXiv:2102.11189

At low N_{ch}, stronger initial momentum anisotropy will make v_2-p_T correlation keep positive at RHIC energy.

Use EPD to suppress more nonflow contribution and get better centrality definition.

2. Which specimen is more deformed?

(Decipher the puzzle of nuclear deformation)

Ru(0.158) >Zr(0) — *H.Hammelmann et al., PRC101, 061901(2020)*

Set I: Ru(0.158)>Zr(0.08) — *W.T. Deng et al., PRC97, 044901(2018)*

Set II: Ru(0.053)<Zr(0.217)

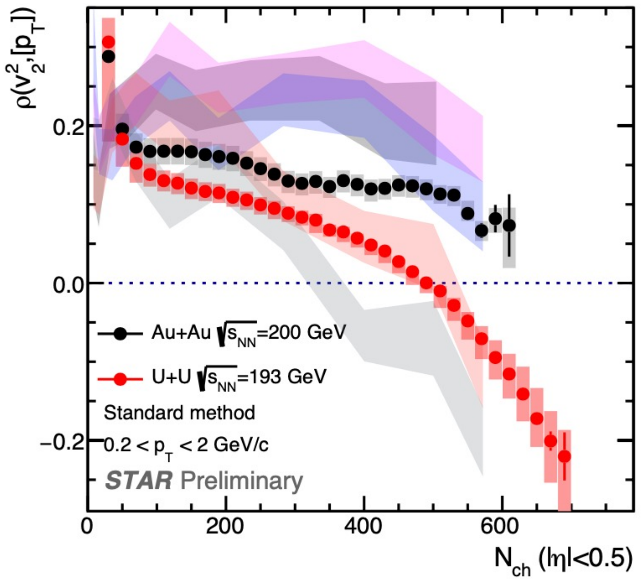
Giuliano et al., arXiv:2102.08158v1

	model	β_{Zr}	β_{Ru}	
(transition B(E2) values)	from B(E2↑)	0.062	0.154	*Pritychenkoa et al., arXiv:1312.5975*
Empirical liquid-drop deductions	FRLDM	0.240	0	*Moller et al., arXiv:1508.06294*
Five dimensional collective Hamiltonian	5DCH	0.197	0.151	*J.P. Delaroche et al., arXiv:0910.2490*
Beyond-mean-field EDF(HFB+SLy4/Gogny D1S)	BBH	0.020	-0.020	*Bender el al., nucl-th/0508052*

Conclusions and outlooks

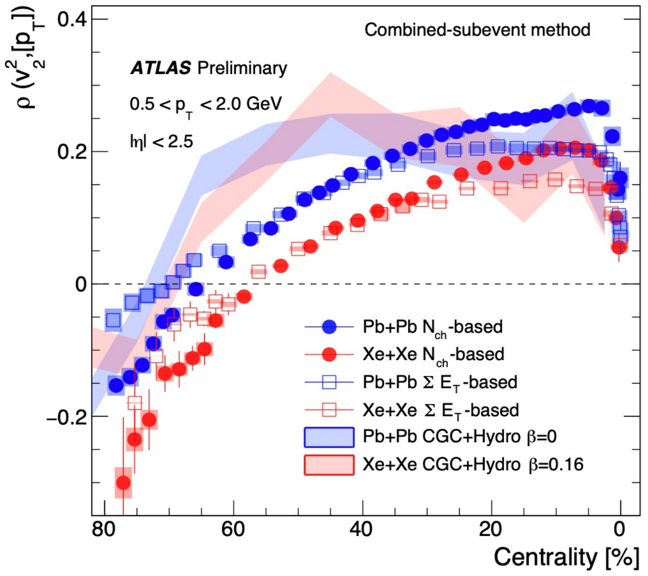
1. $\mathbf{v_n}$-$\langle \mathbf{p_T} \rangle$ correlations:

- In STAR, strong suppression and sign-change for n=2, but no difference for n=3.
- In ATLAS, negative in peripheral for n=2, comparable for n=3
- 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.
- Centrality fluctuation could affect the trend.



2. Qualitatively described by TRENTo, CGC+hydro and AMPT models:

- Prefer a quadrupole β_2 value around 0.3
- Help model to constrain the initial conditions.
- A new experimental test to study nuclear shape in heavy-ion collisions.



3. Outlooks: isobar and O+O collisions could help to address two questions

- Study the initial state momentum anisotropy from the CGC prediction.
- Decipher the puzzle of nuclear deformation in Ru and Zr.

Many thanks to GHP conference and also thank you for listening.

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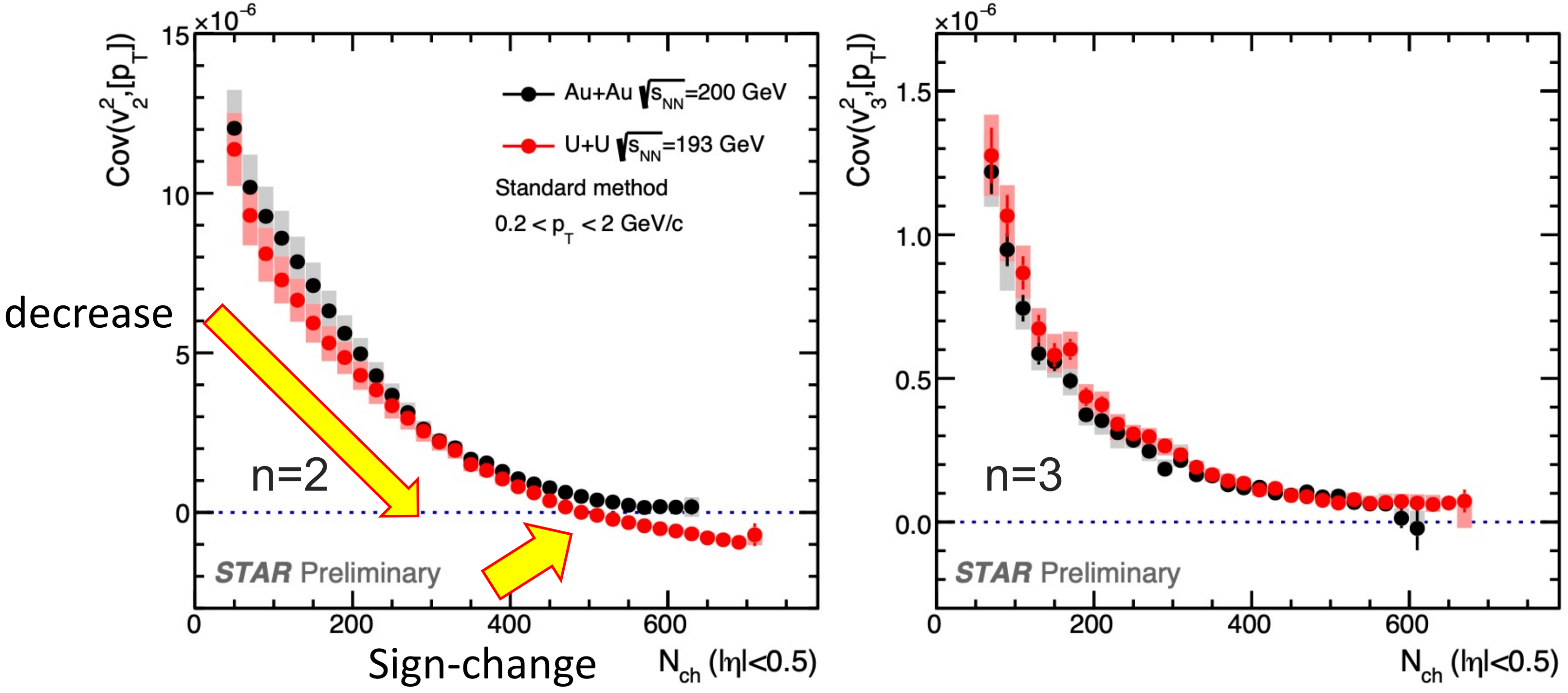
Covariance $\mathrm{Cov}\left(v_n^2, [p_T]\right)$

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

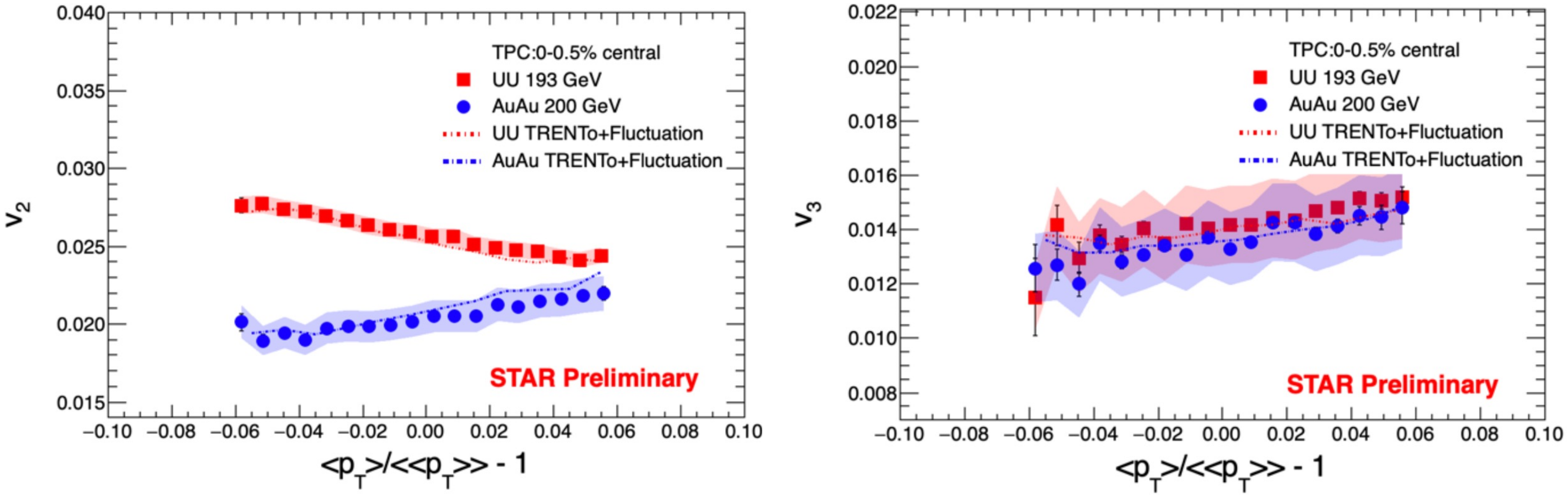


U+U collisions show a sign-change behavior in $\mathrm{Cov}(v_2^2, [p_T])$ while not in Au+Au. But they are consistent for $\mathrm{Cov}(v_3^2, [p_T])$.

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.