ZIMÁNYI SCHOOL 2020

J. E.: From darkness, the light

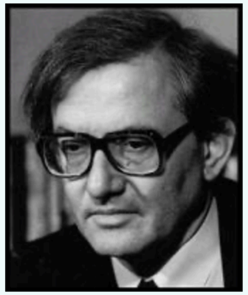
20th ZIMÁNYI SCHOOL

WINTER WORKSHOP

ON HEAVY ION PHYSICS

December 7-11, 2020

Budapest, Hungary



József Zimányi (1931 - 2006)

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

Chunjian Zhang

(For the STAR Collaboration)

December 9, 2020

Supported in part by

U.S. DEPARTMENT OF ENERGY

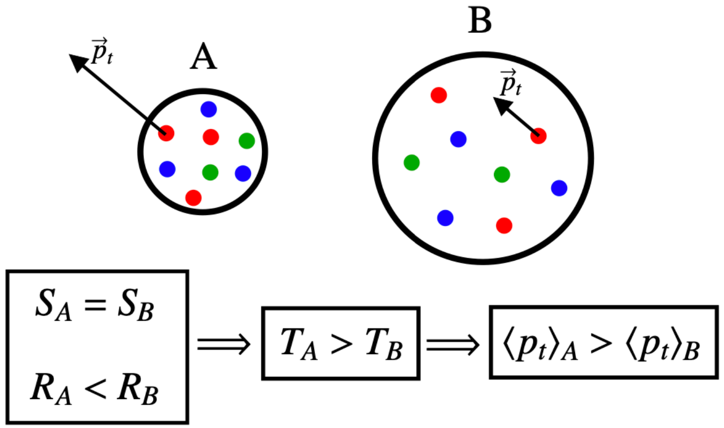
Stony Brook University

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



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

G. Giacalone, PRC102, 024901(2020)

Shape-flow transmutation

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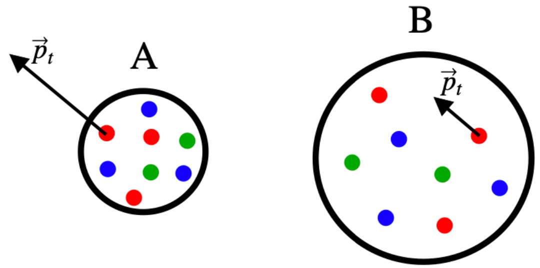
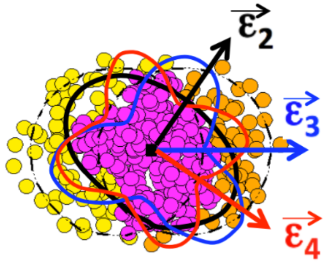


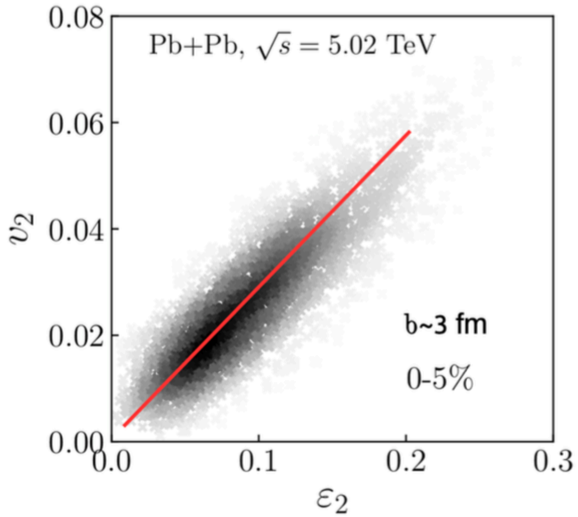
$$\begin{array}{c} S_A = S_B \\ R_A < R_B \end{array} \Longrightarrow T_A > T_B \Longrightarrow \langle p_t \rangle_A > \langle p_t \rangle_B$$

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

- Shape affect anisotropic flow of particles



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



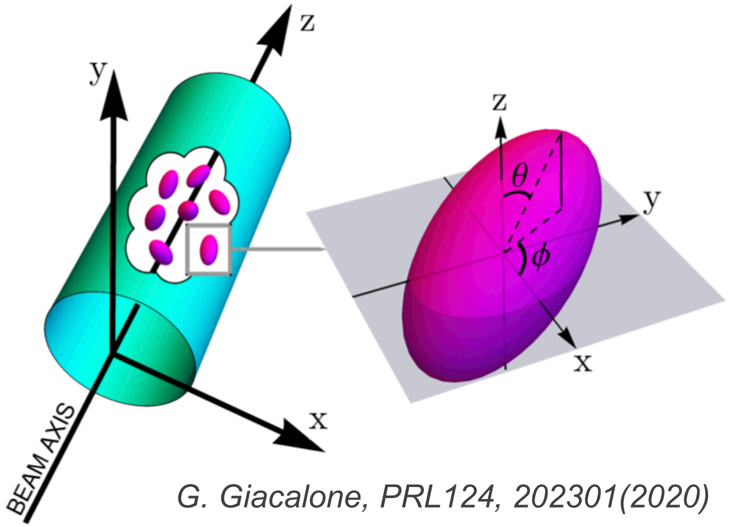
$$v_n \propto \epsilon_n$$

G. Giacalone, PRC102, 024901(2020)

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

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

How the deformation affect the v_2- $\langle p_T \rangle$ correlation



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 dominated by quadrupole component β_2

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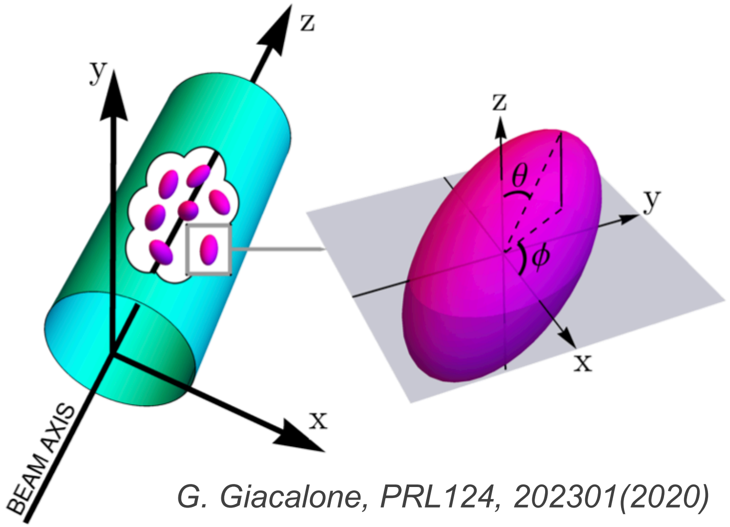

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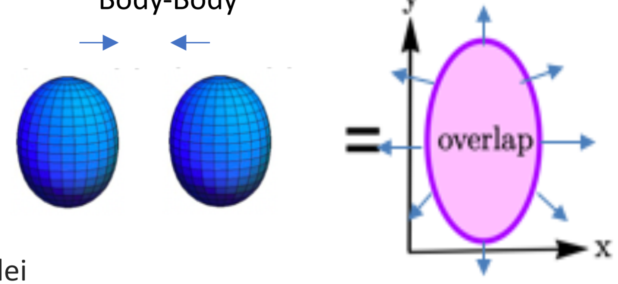
Body-Body

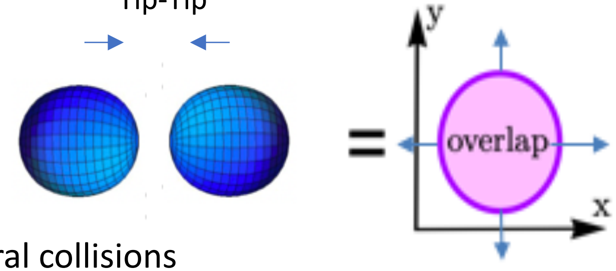


large R, small $\langle p_T \rangle$

large $\boldsymbol{\varepsilon}_2$

Prolate nuclei

Tip-Tip



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

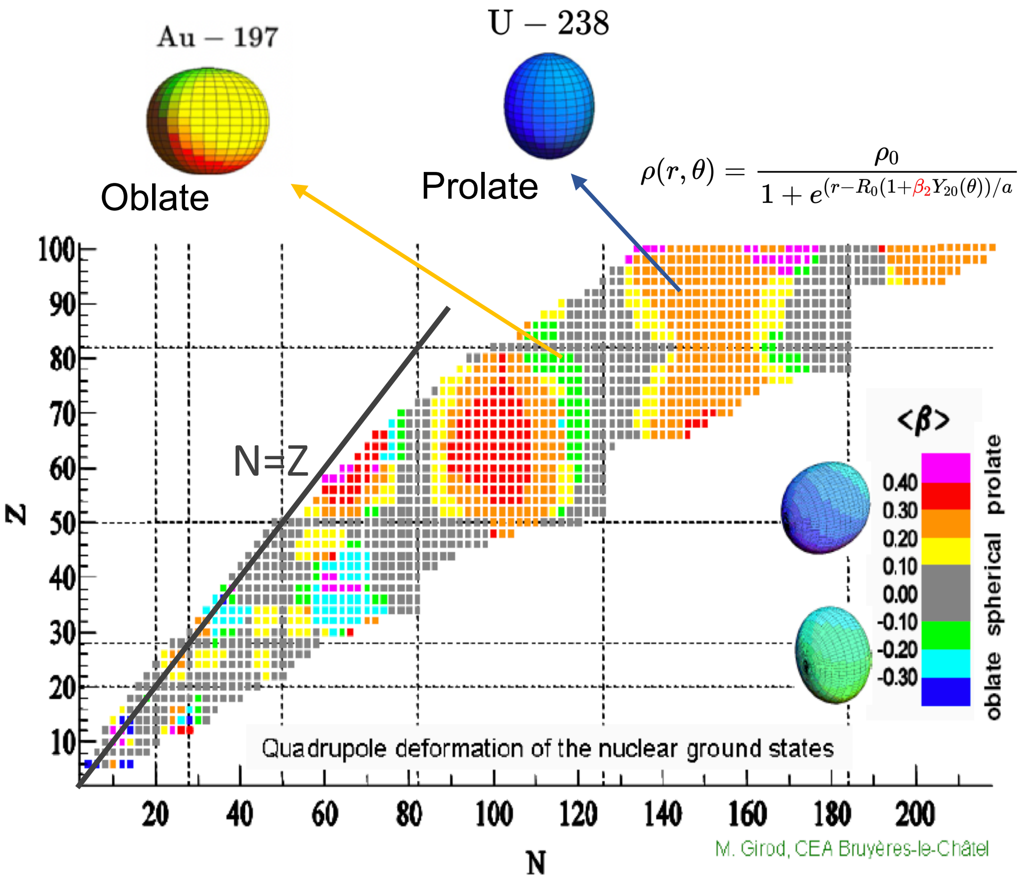
- $\langle p_T \rangle \sim 1/R$ and $v_2 \propto \boldsymbol{\varepsilon}_2$:

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)

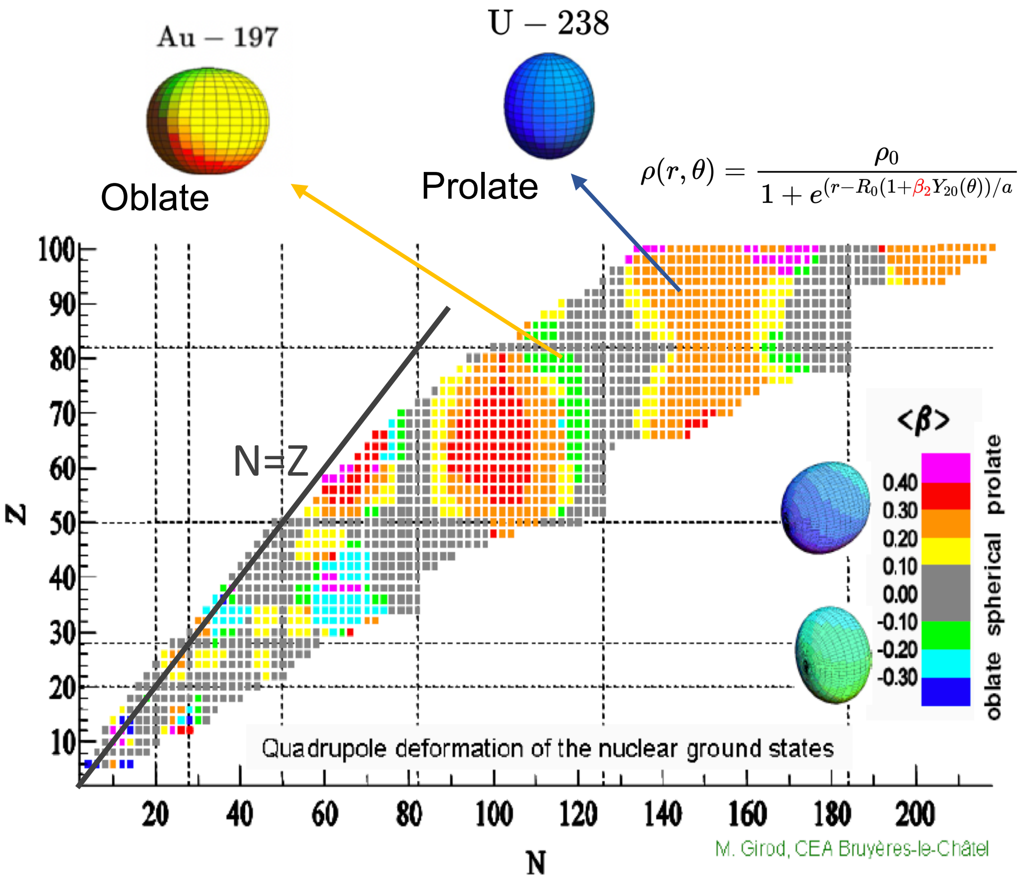


Hartree-Fock-Bogolyubov (Gogny D1S effective interaction)

Quadrupole deformations β_2 of different nuclei

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

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



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)]

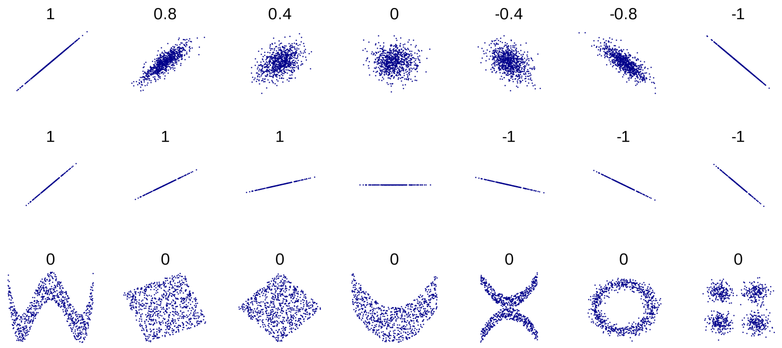
Or access BNL nuclear data center

Can we constrain β_2 of uranium using v_2 - $\langle p_T \rangle$ 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

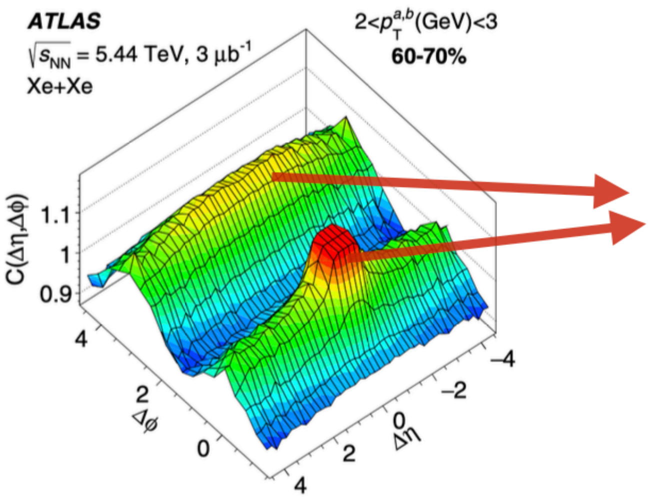
$$\rho\left(v_n^2, [p_T]\right) = \frac{\mathrm{cov}\left(v_n^2, [p_\mathrm{T}]\right)}{\sqrt{\mathrm{Var}\left(v_n^2\right)_\mathrm{dyn} \langle \delta p_T \delta p_T \rangle}}$$

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

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

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



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

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

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

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

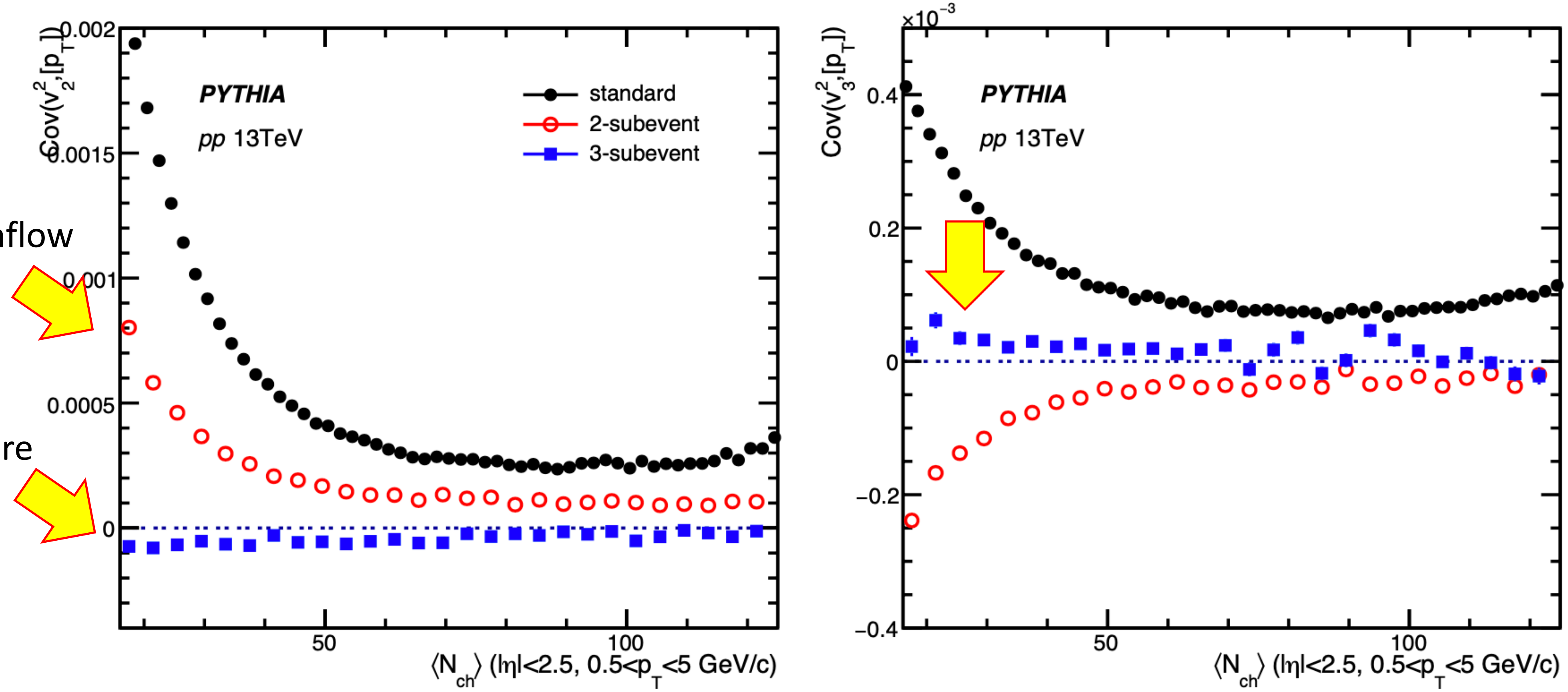
P. Bozek, PRC93, 044908(2016); B. Schenke et al., PRC102, 034905(2020); G. Giacalone, PRC102, 024901(2020), PRL124, 202301(2020), arXiv:2006.15721; F.G. Gardim et al., PLB809, 135749(2020) ; ATLAS EPJC79, 985(2019)

Non-flow suppression in PYTHIA testing model

PYTHIA only have non-flow.

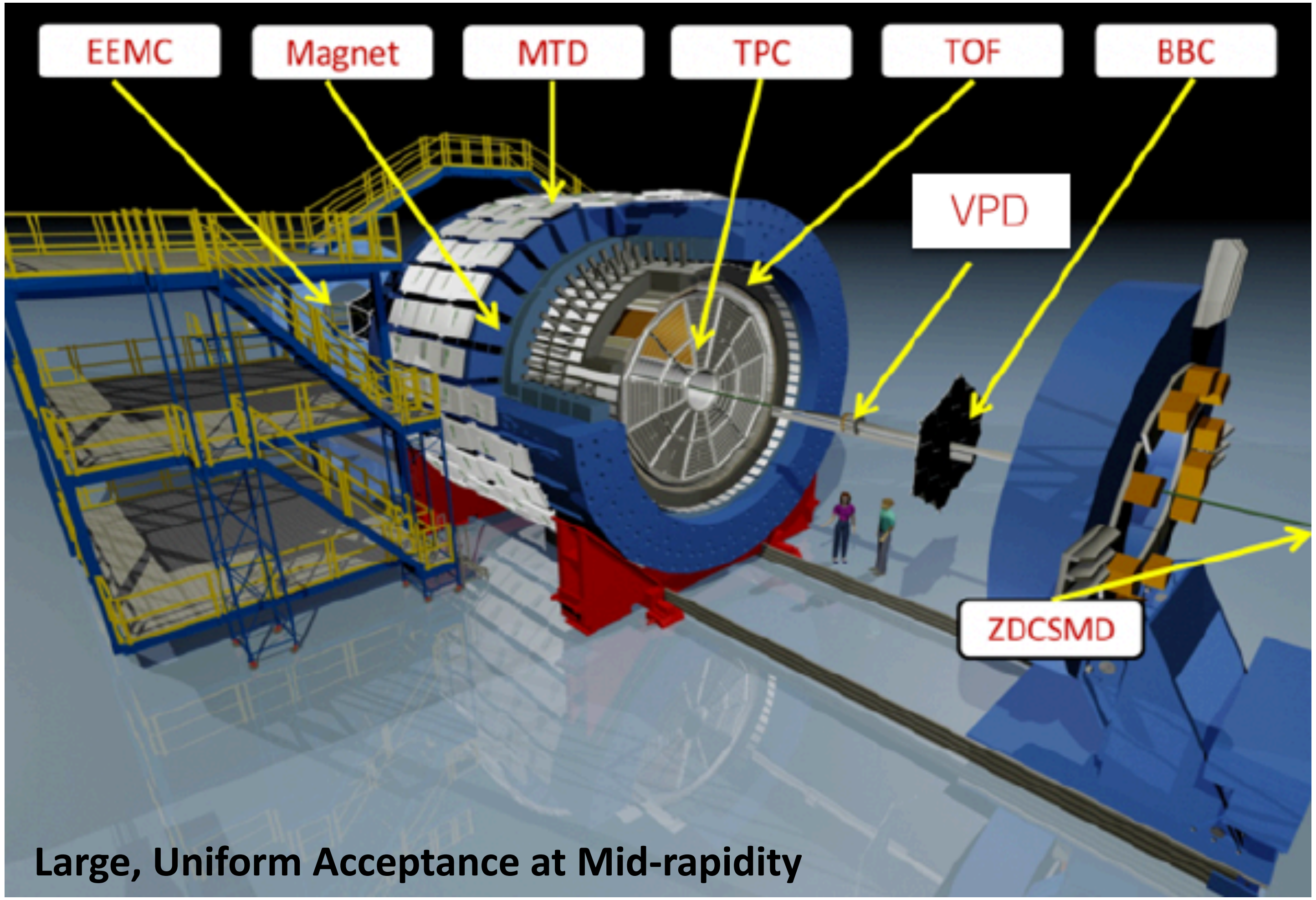
Suppress nonflow

Suppress more



Subevent method do 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:

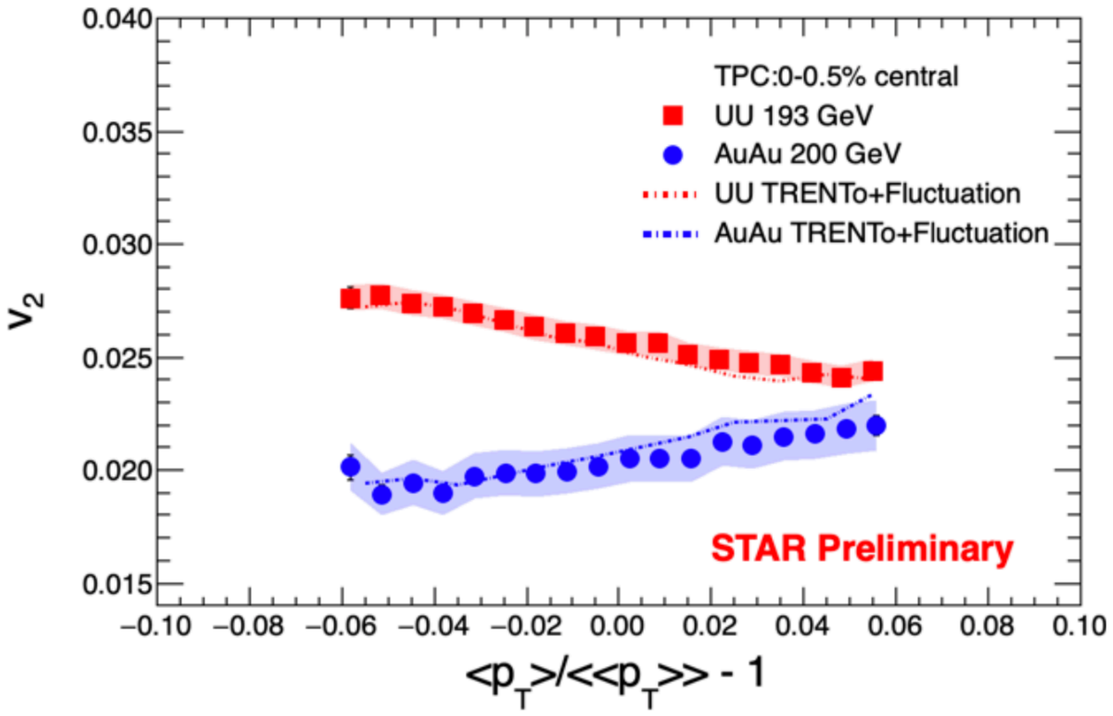
  $0.2 < p_T < 2.0\ \mathrm{GeV/c}$ and $0.5 < p_T < 2.0\ \mathrm{GeV/c}$

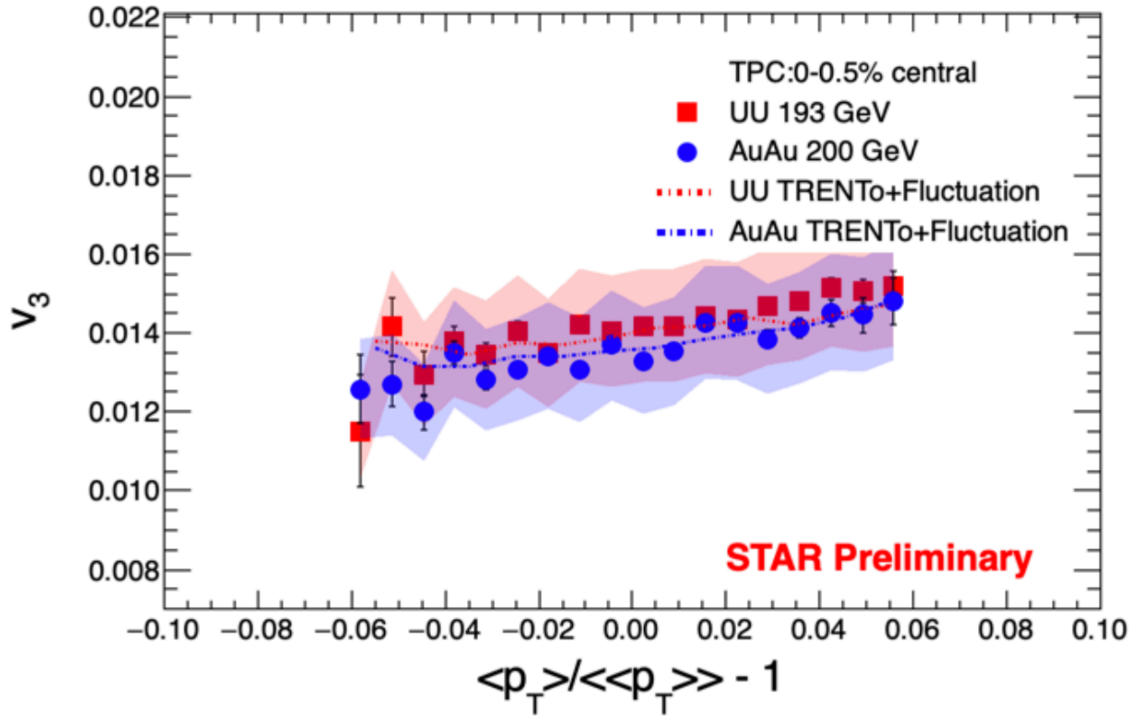
  $|\eta| < 1.0$

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

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.

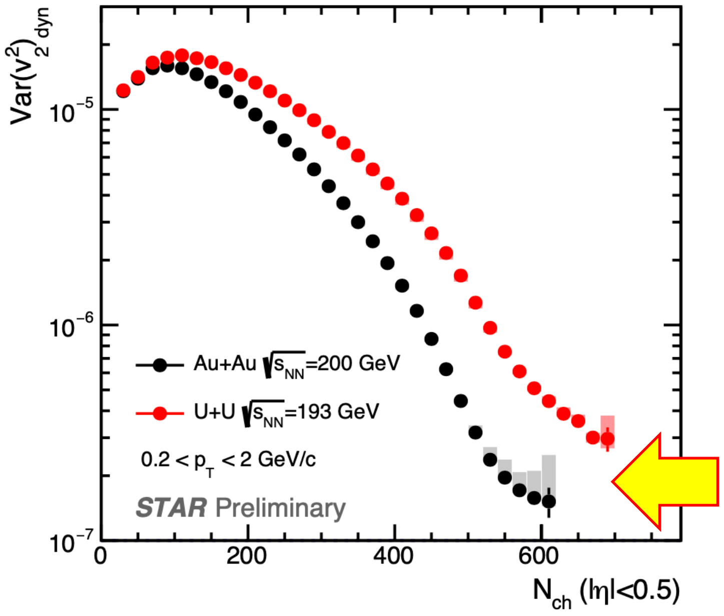
The anticorrelation in v_2 vs. $\langle p_T \rangle$ for U+U is due to deformation.

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

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

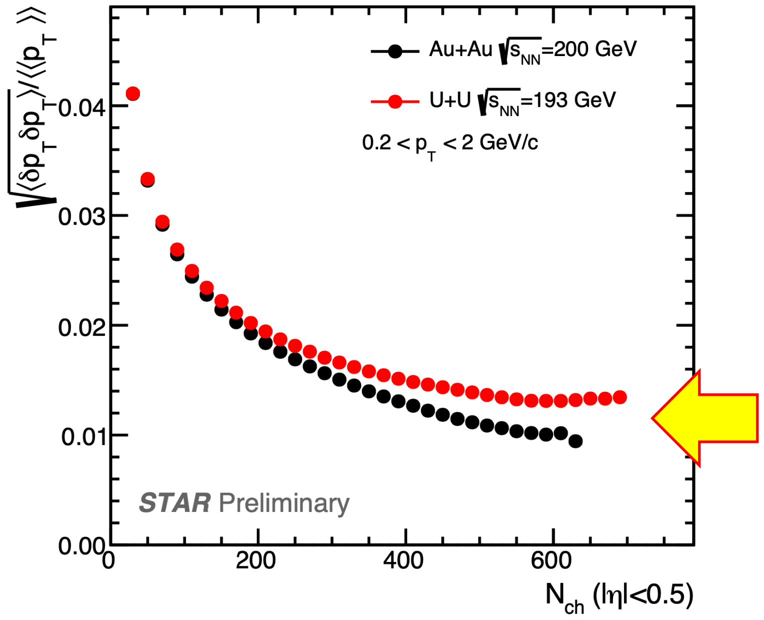
$$\mathrm{Var}\,(v_n^2)_{\mathrm{dyn}} = v_n\{2\}^4 - v_n\{4\}^4$$

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



difference

difference of flow fluctuation due to deformation.



difference

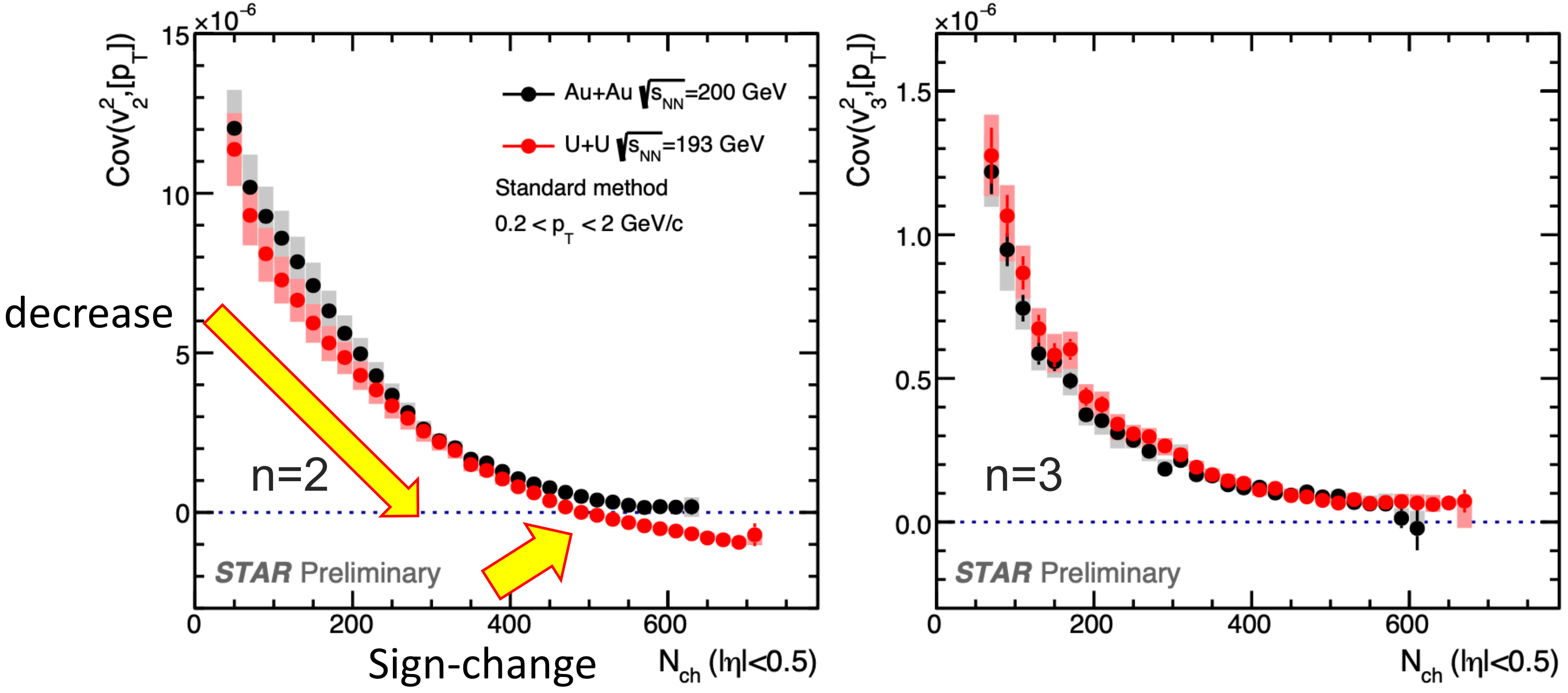
difference of $\langle p_T \rangle$ fluctuation due to deformation .

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

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

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

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

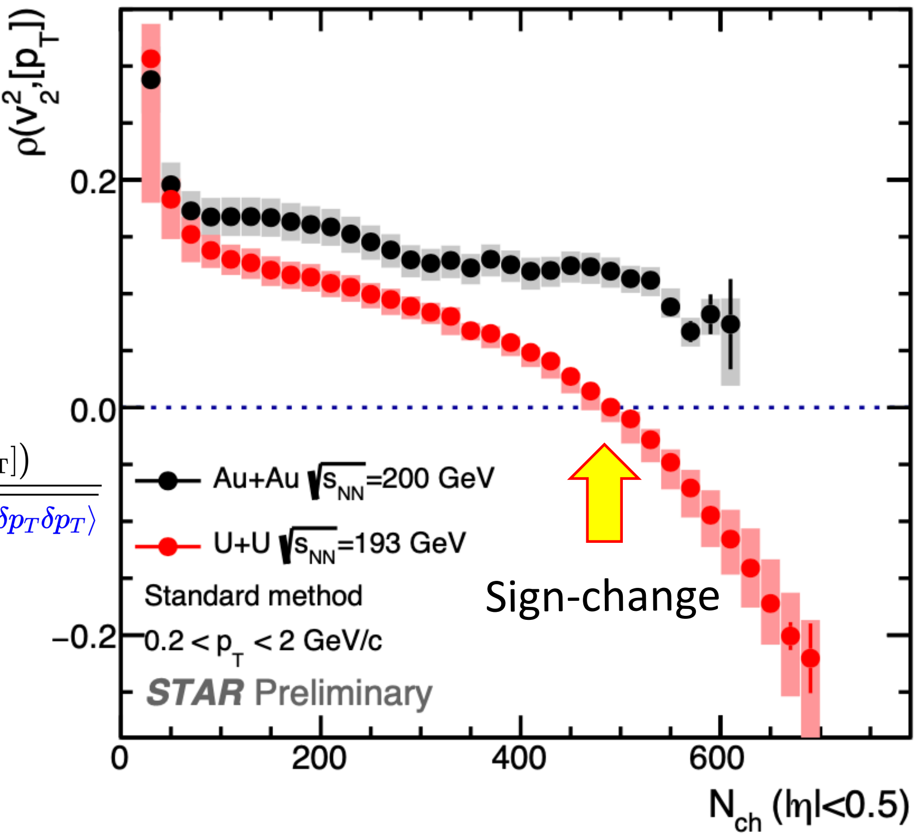


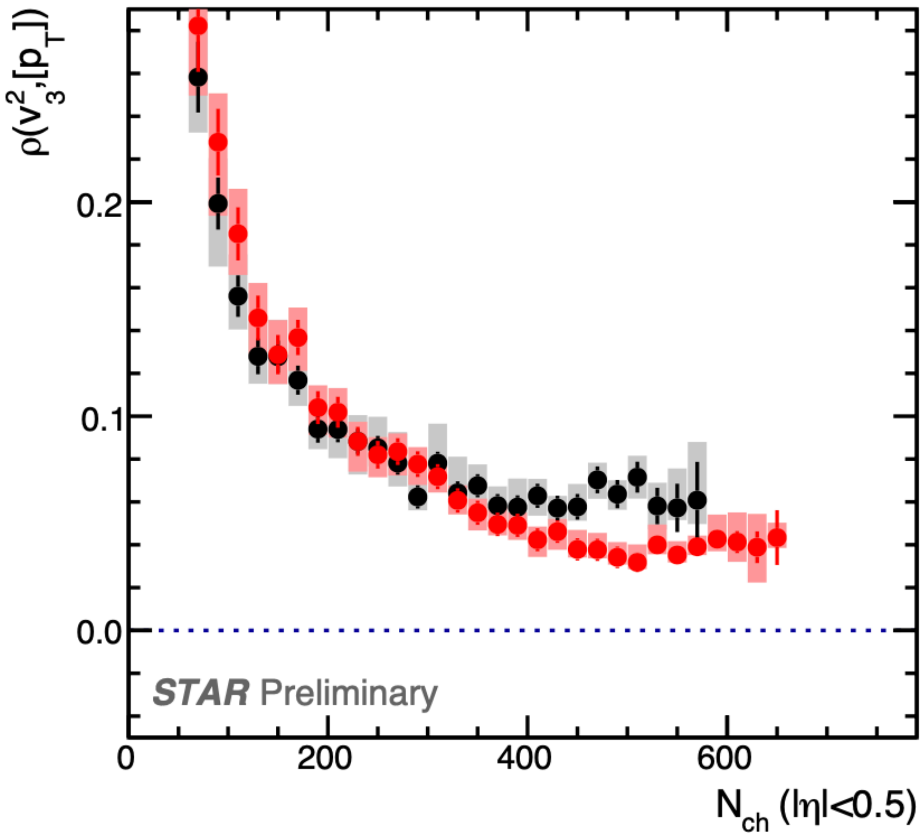
U+U collisions show a sign-change behavior in $\mathrm{Cov}(v_2^2, [p_T])$ while not in Au+Au. But they are consistent for $\mathrm{Cov}(v_3^2, [p_T])$.

This sign-change behavior indicates the effect of deformation.

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

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





$\rho(v_2^2, [p_T])$ 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.

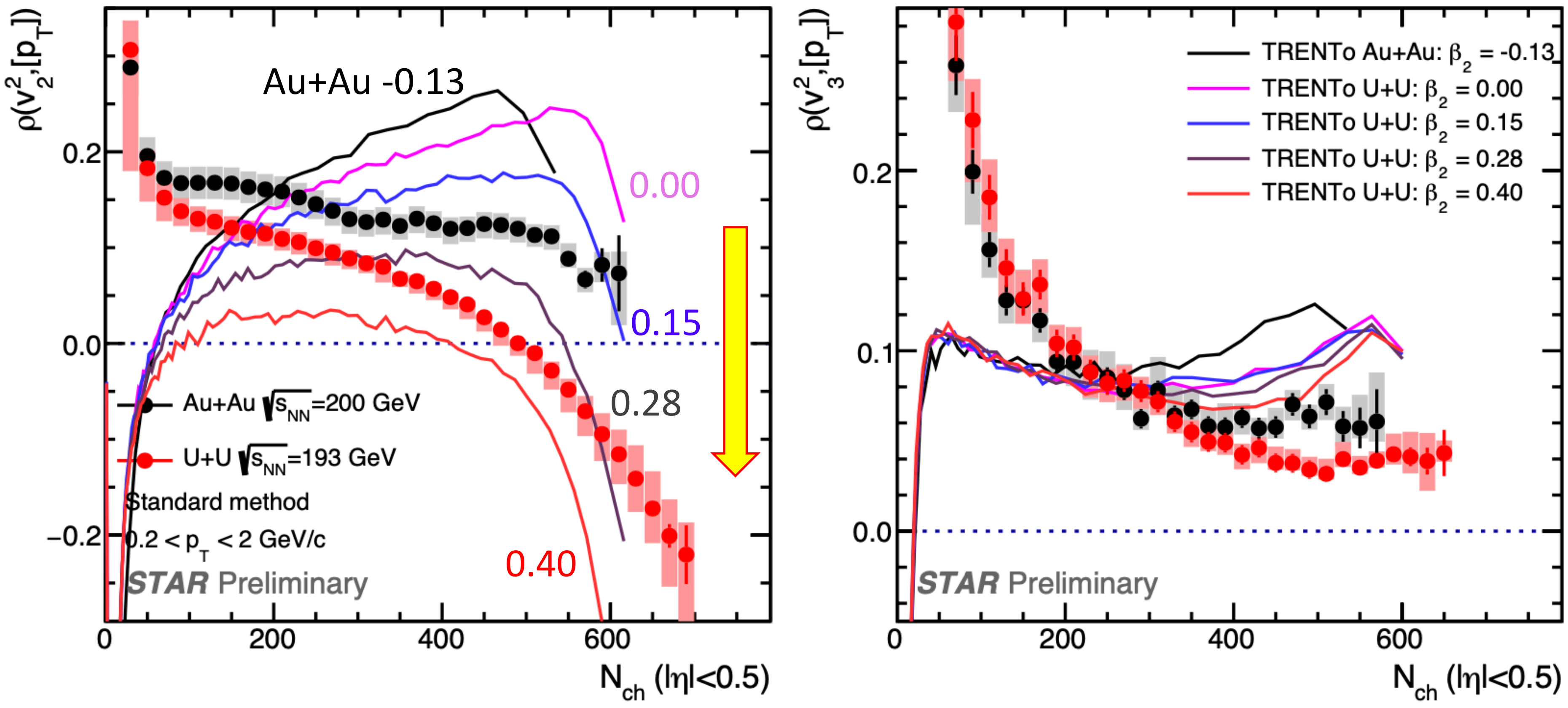
$\rho(v_n^2, [p_T])$ compared with TRENTo initial condition model

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 show an hierarchical β_2 dependence in U+U collisions.

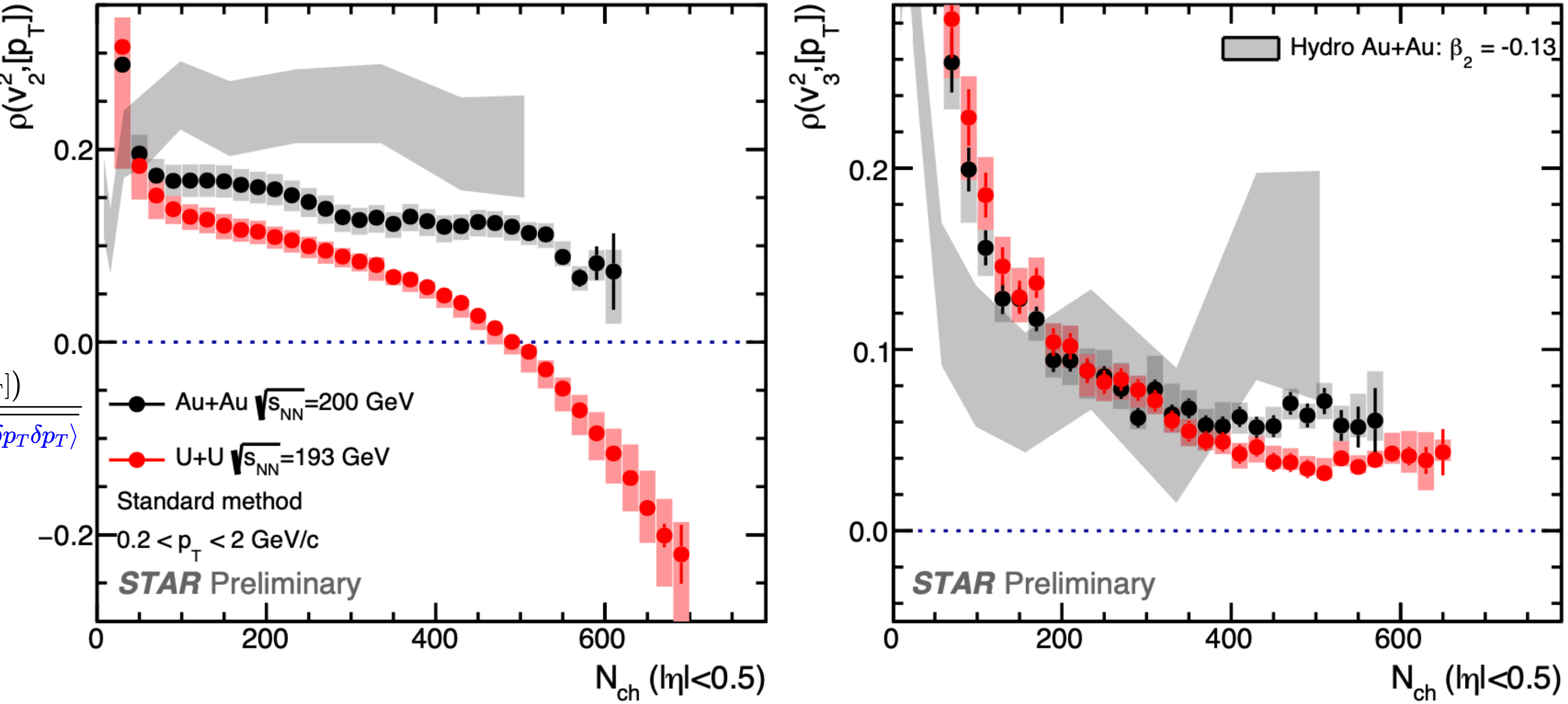
TRENTo suggests this sign-change in the central collisions could be due to deformation effect.

TRENTo prefers the β_2 value between 0.28 to 0.4.

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

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

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



$\rho(v_2^2, [p_T])$ 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.

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

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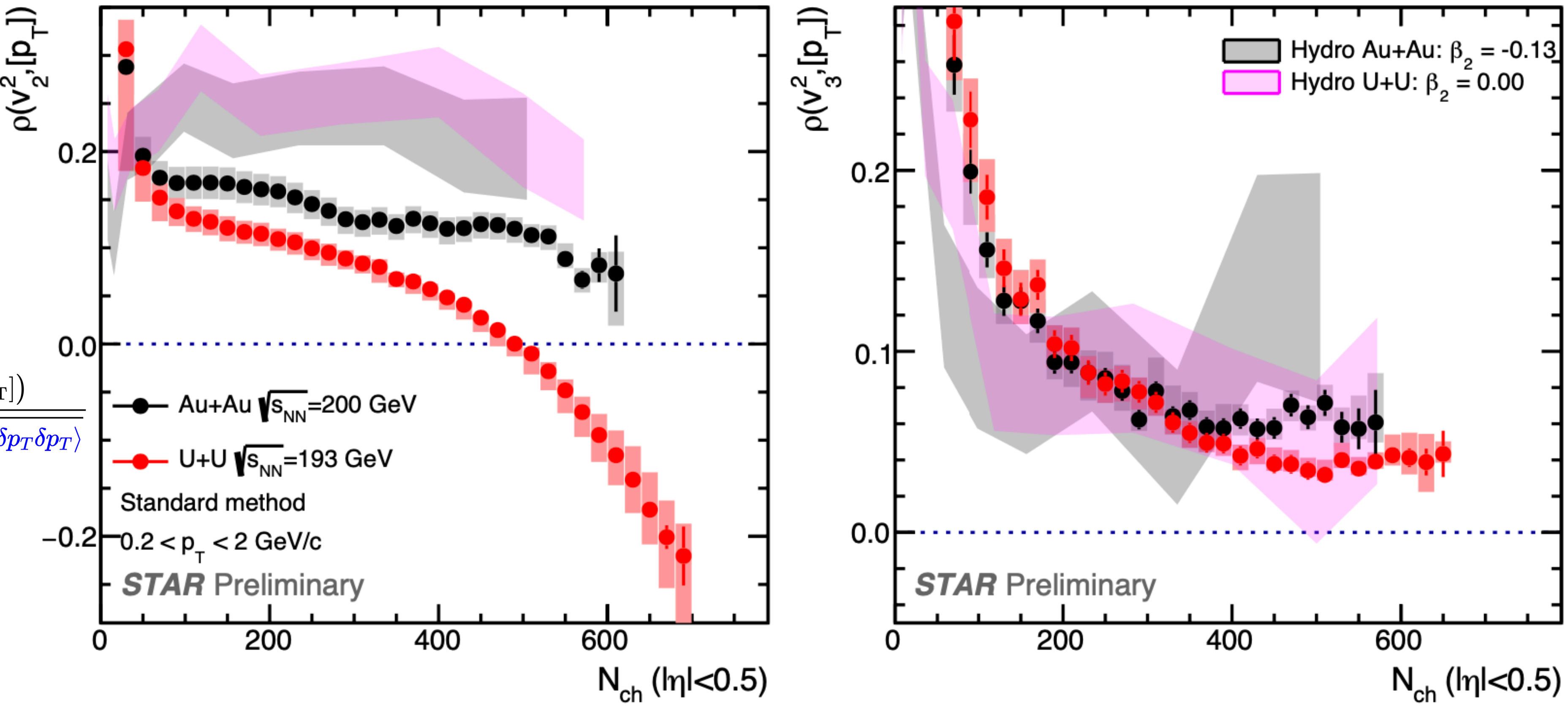

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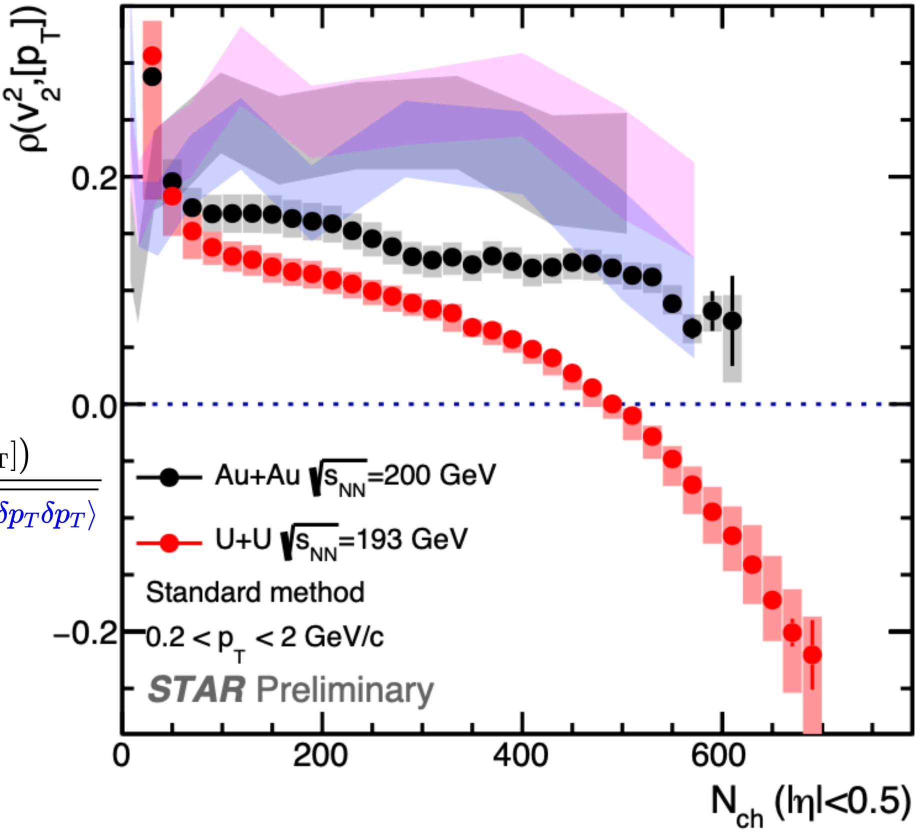

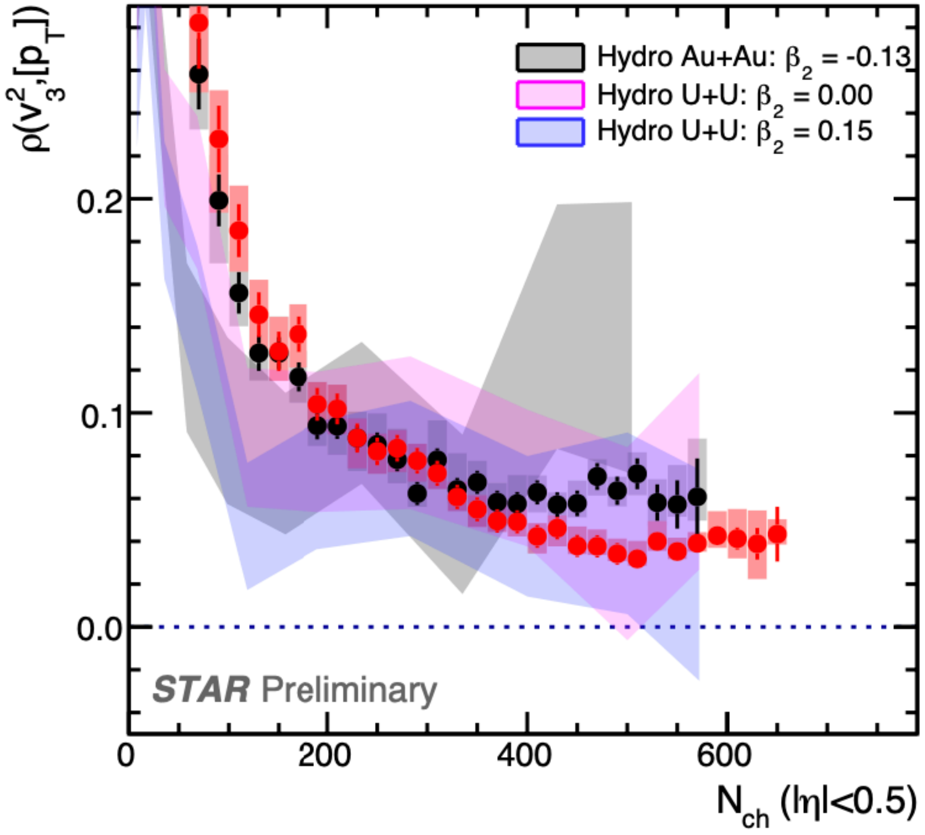

$$\rho(v_n^2,[p_T]) = \frac{\mathrm{cov}(v_n^2,[p_T])}{\sqrt{\mathrm{Var}\,(v_n^2)_{\mathrm{dyn}}\langle\delta p_T \delta p_T\rangle}}$$

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

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

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

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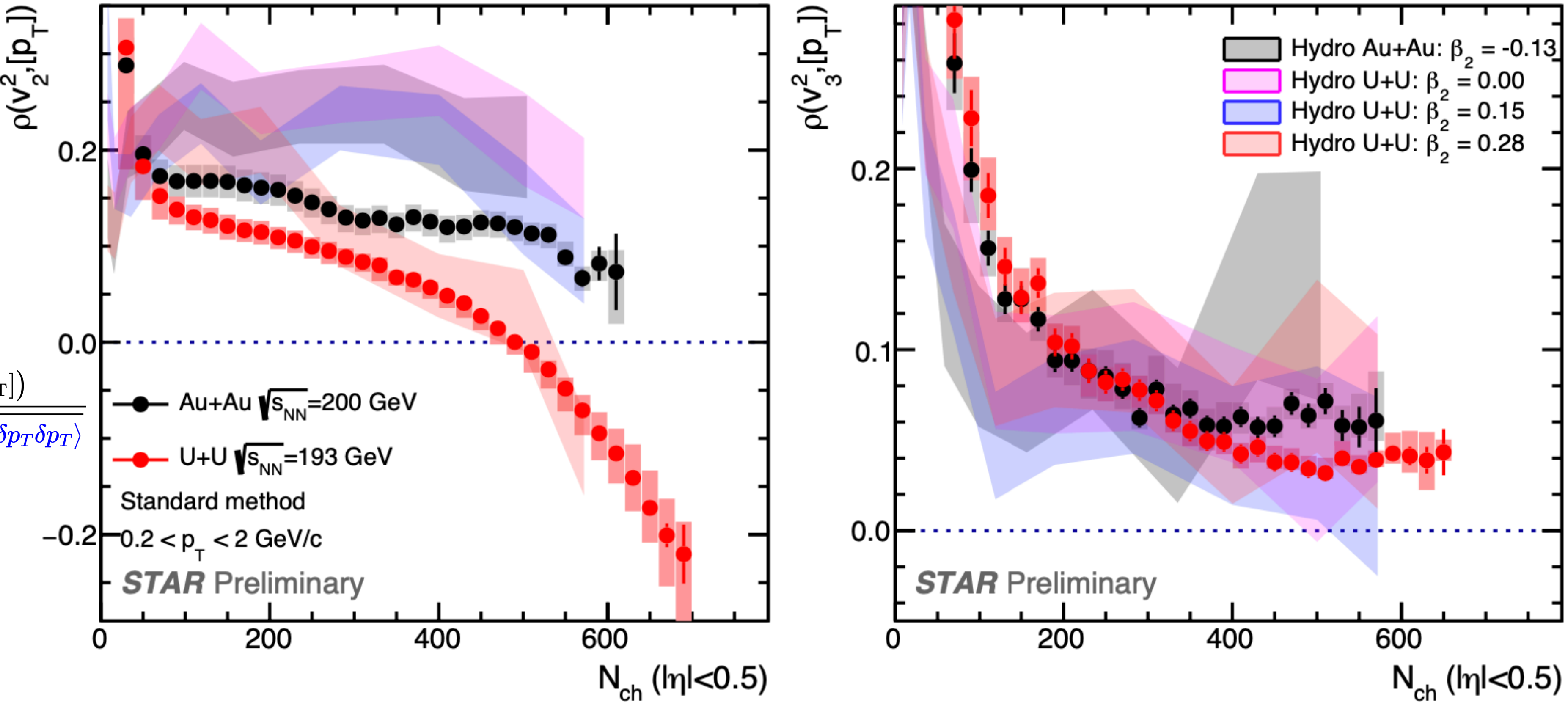

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$\rho(v_3^2, [p_T])$ is always positive in Au+Au and U+U collisions.

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

$\rho(\mathrm{v}_n^2, [\mathrm{p_T}])$ compared with IP-Glasma+Hydro

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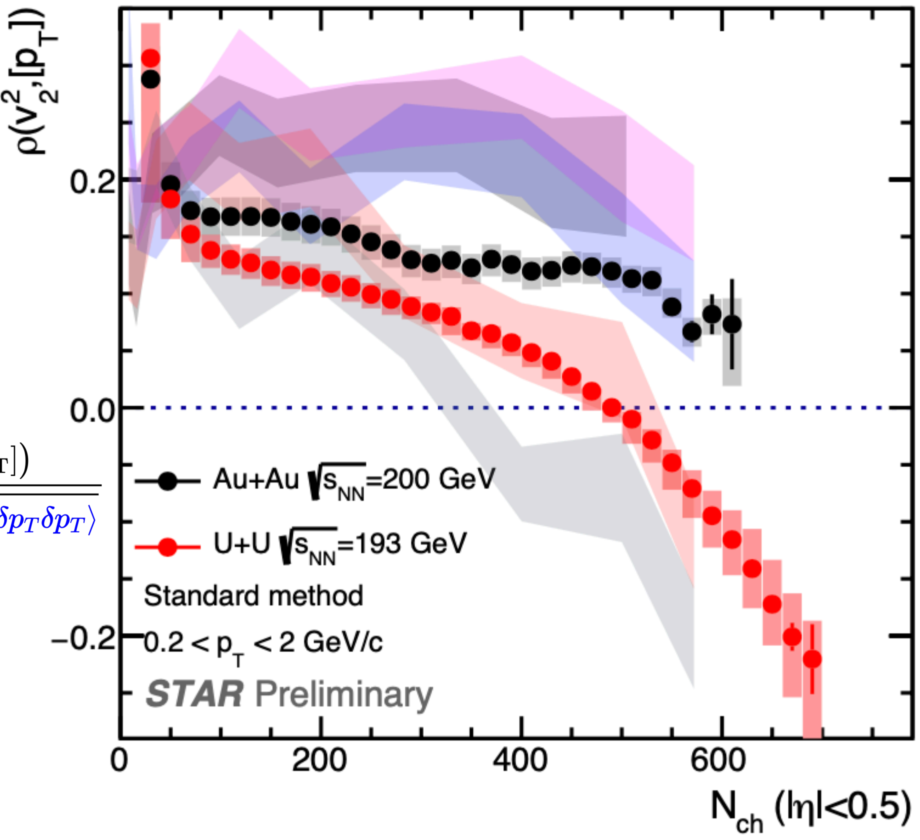

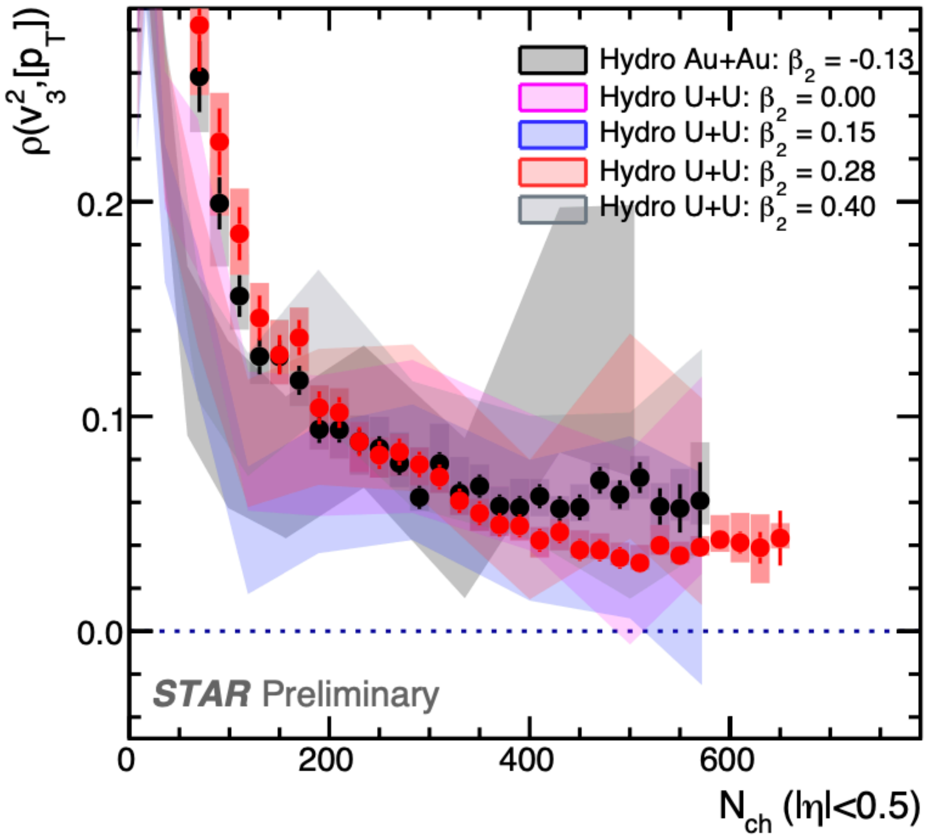

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A hierarchical behavior shows the β_2 dependence in Uranium $\rho(\mathrm{v}_2^2, [\mathrm{p_T}])$ but not in $\rho(\mathrm{v}_3^2, [\mathrm{p_T}])$.

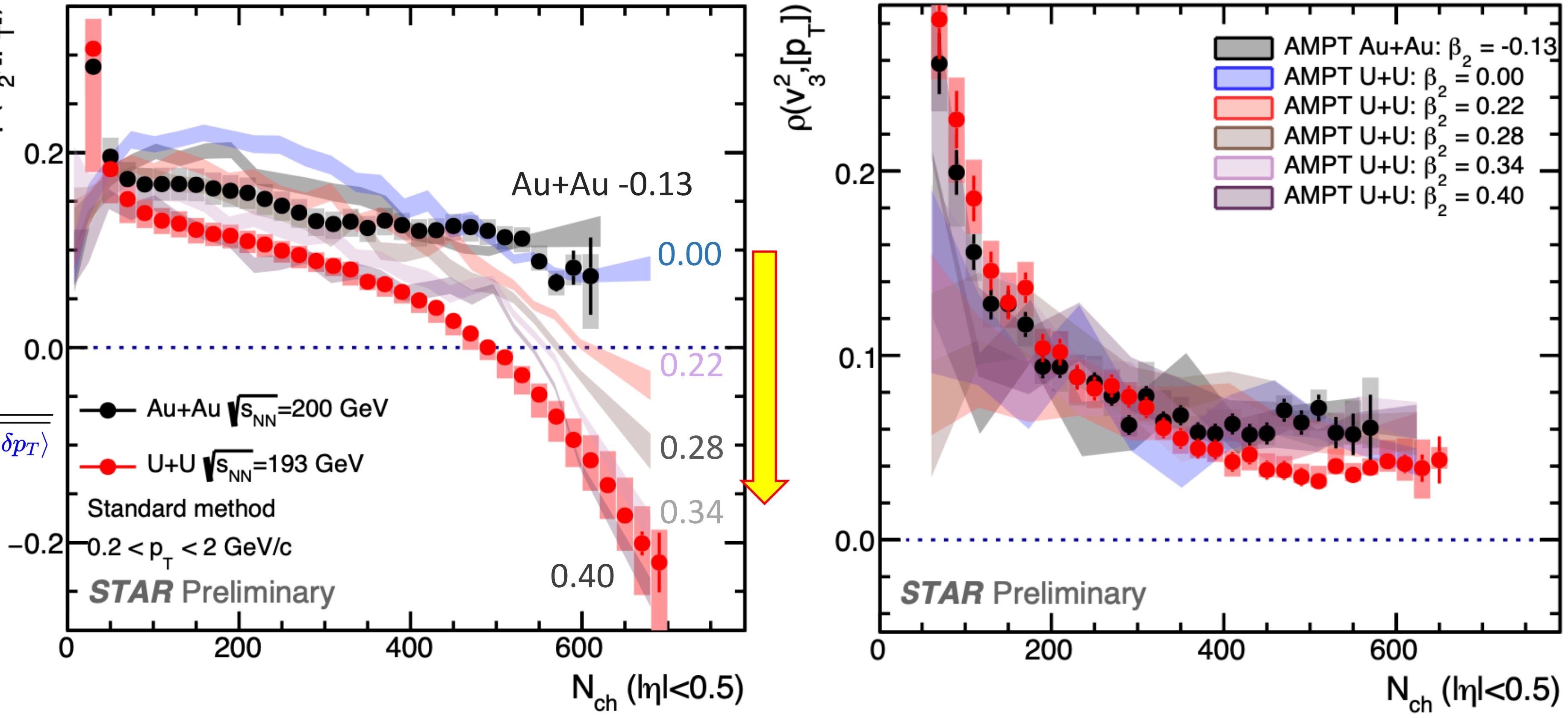
The sign-change is due to deformation effect and it quantifies the β_2 value around 0.28 with large uncertainty.

$\rho(\mathrm{v}_n^2, [\mathrm{p_T}])$ compared with transport AMPT model

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

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

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

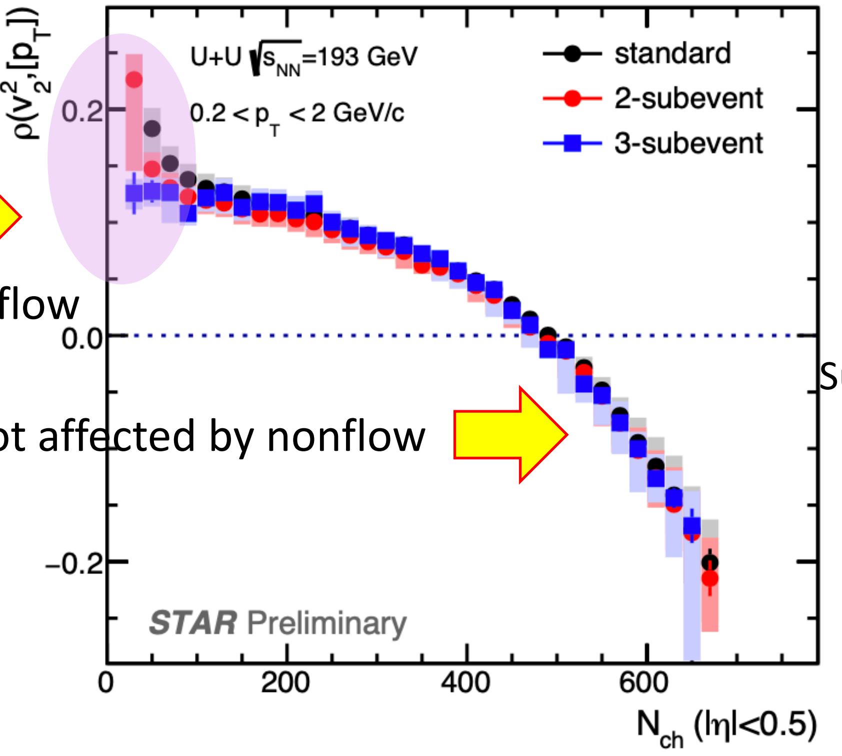


AMPT shows a clear β_2 dependence in Uranium $\rho(\mathrm{v}_2^2, [\mathrm{p_T}])$ while not in $\rho(\mathrm{v}_3^2, [\mathrm{p_T}])$.

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

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

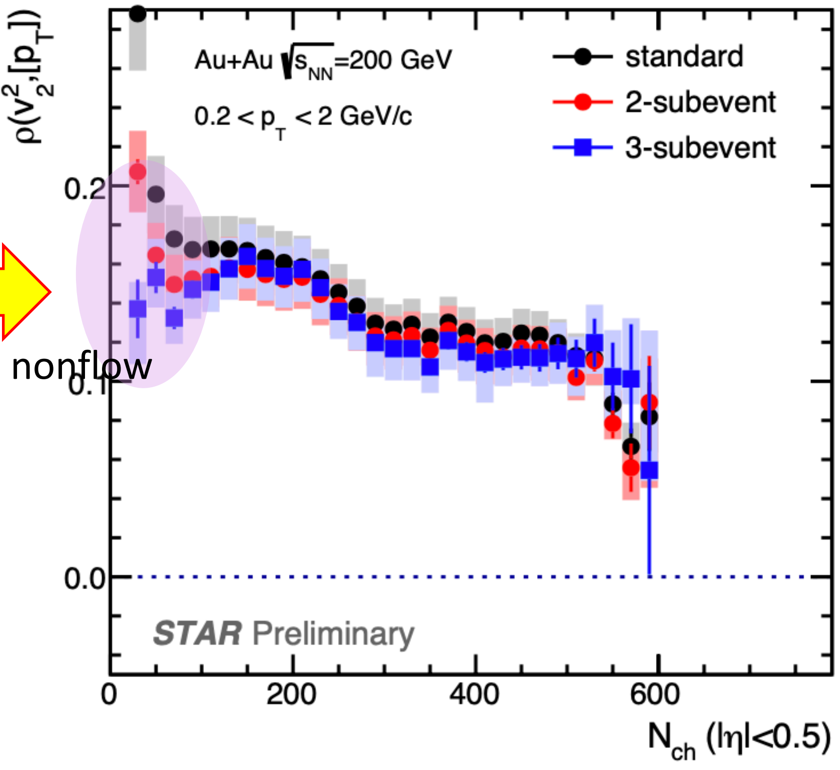
U+U collisions



Suppress nonflow

Not affected by nonflow

Au+Au collisions



Suppress nonflow

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

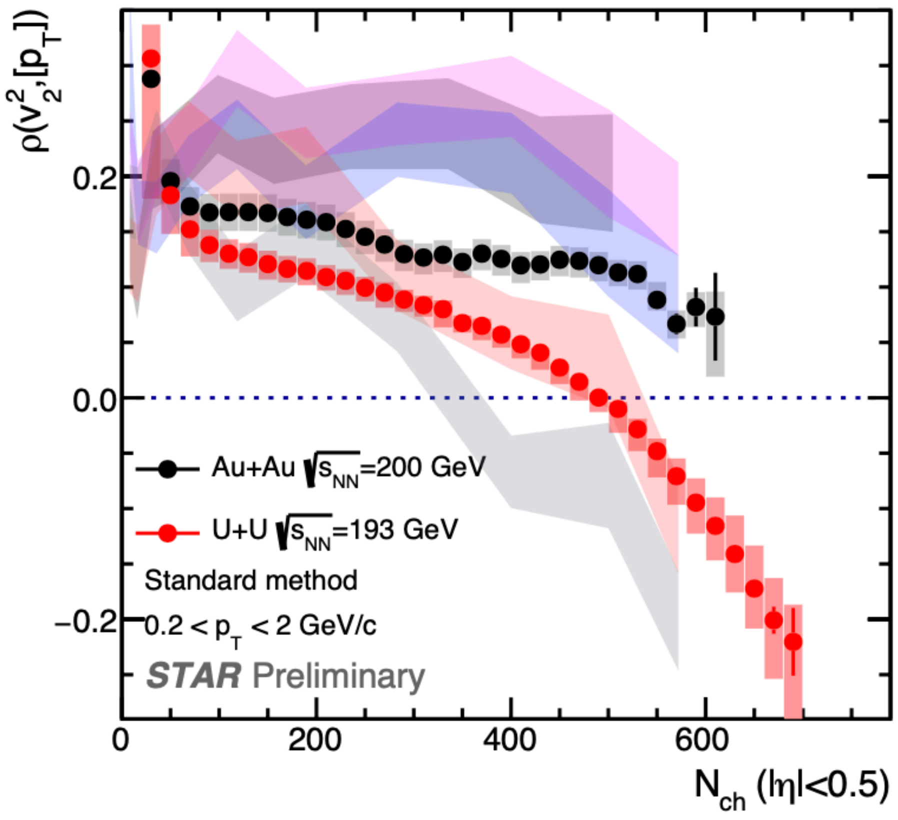
Subevent methods could decrease non-flow contributions in peripheral collisions.

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

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

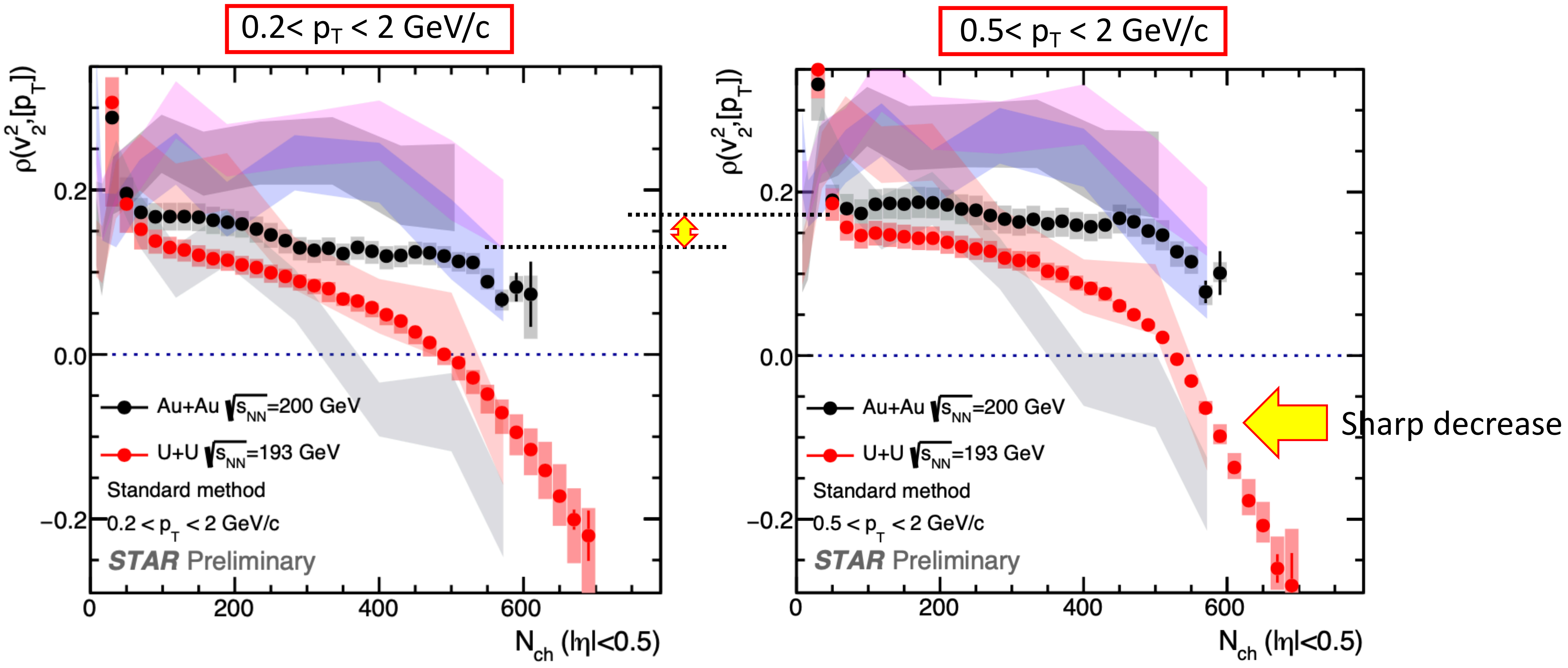
IP-Glasma+Hydro: private calculation provided by Bjoern Schenke (based on B. Schenke, C. Shen, P. Tribedy, PRC102, 044905(2020))

0.2< p_T < 2 GeV/c



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



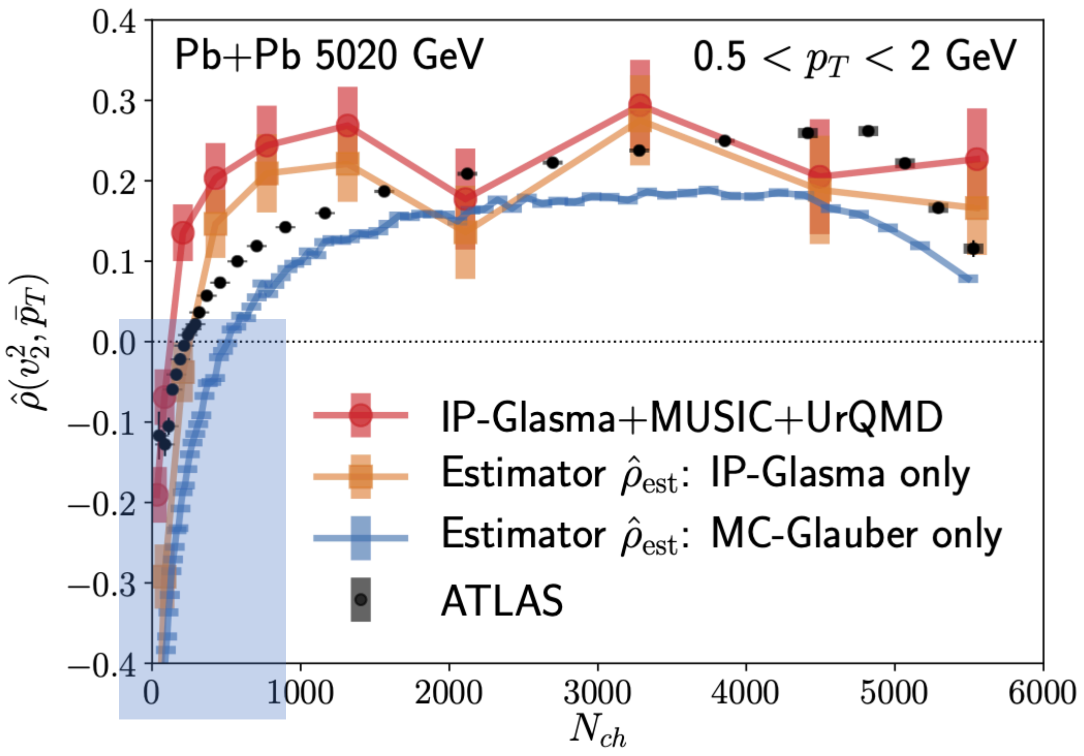
Features are same for $0.5<p_T<2$ GeV/c as $0.2<p_T<2$ GeV/c.

Conclusions and outlooks

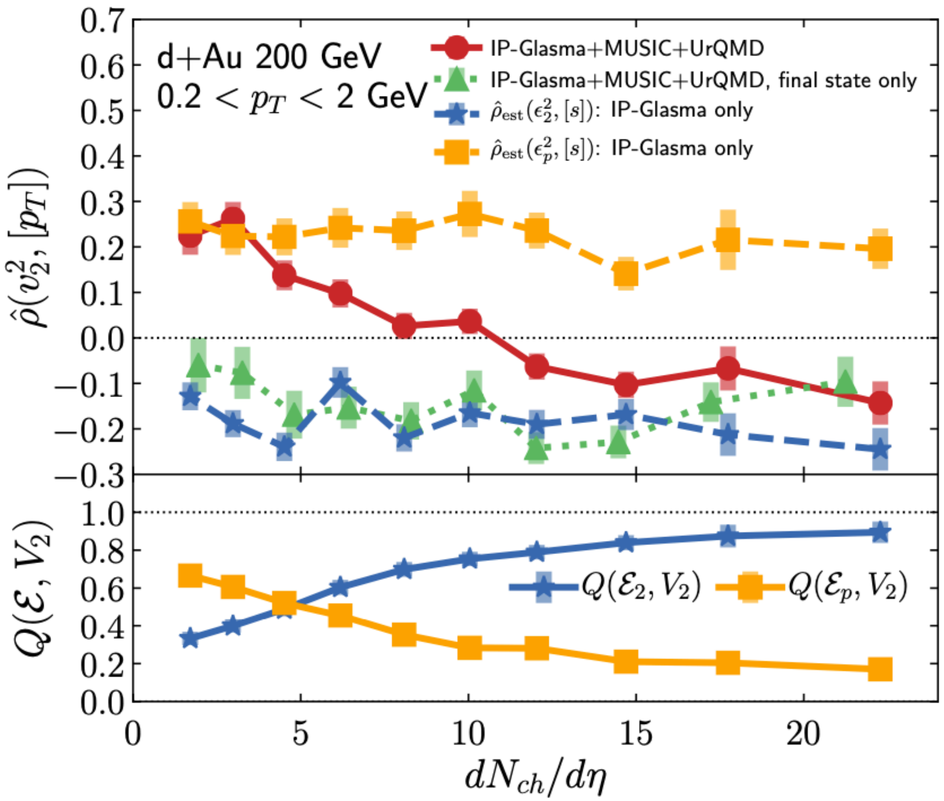
1. We presented flow and mean transverse momentum correlation from STAR that demonstrate a clear shape–flow transmutation.
   - Study of mean p_T fluctuation is also an intriguing possibility to probe nuclear deformation.
2. The sign-change behavior in Pearson coefficient $\rho(v_2^2, [p_T])$ in central U+U collisions could be used to constrain deformation parameters.
   - Subevent methods 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.

Many thanks to ZiManYi School and also thank you for listening.

predictions in IP-Glasma+MUSIC+UrQMD



Bjoern Schenke, Chun Shen and Derek Teaney, PRC102, 034905 (2020)

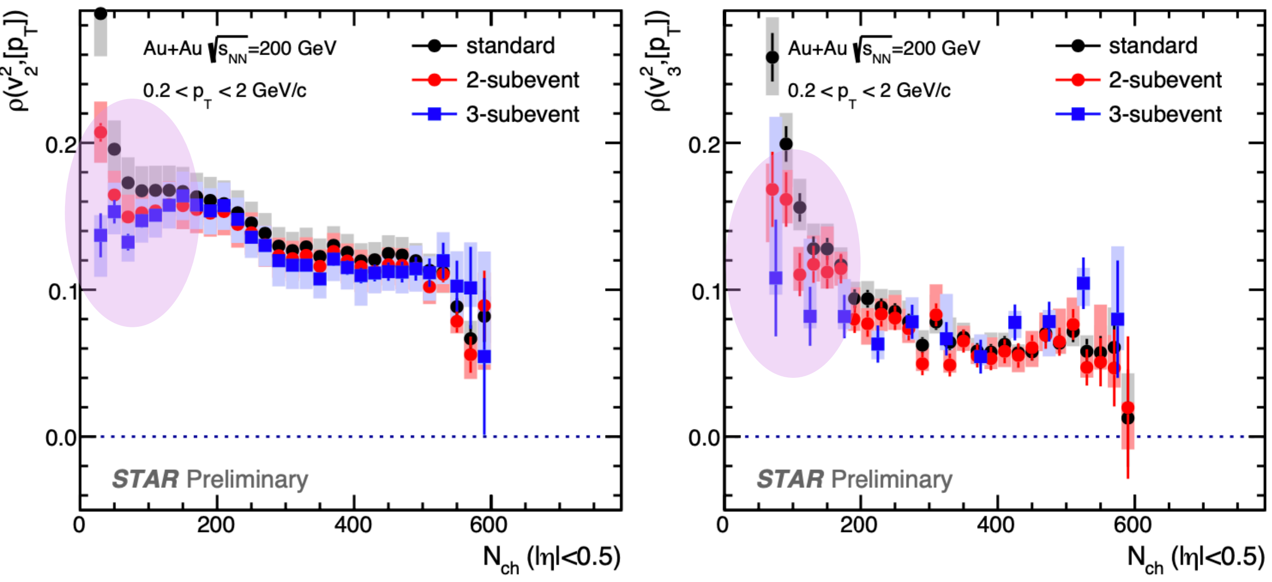


Giuliano Giacalone, Bjoern Schenke and Chun Shen, PRL125, 192301(2020)

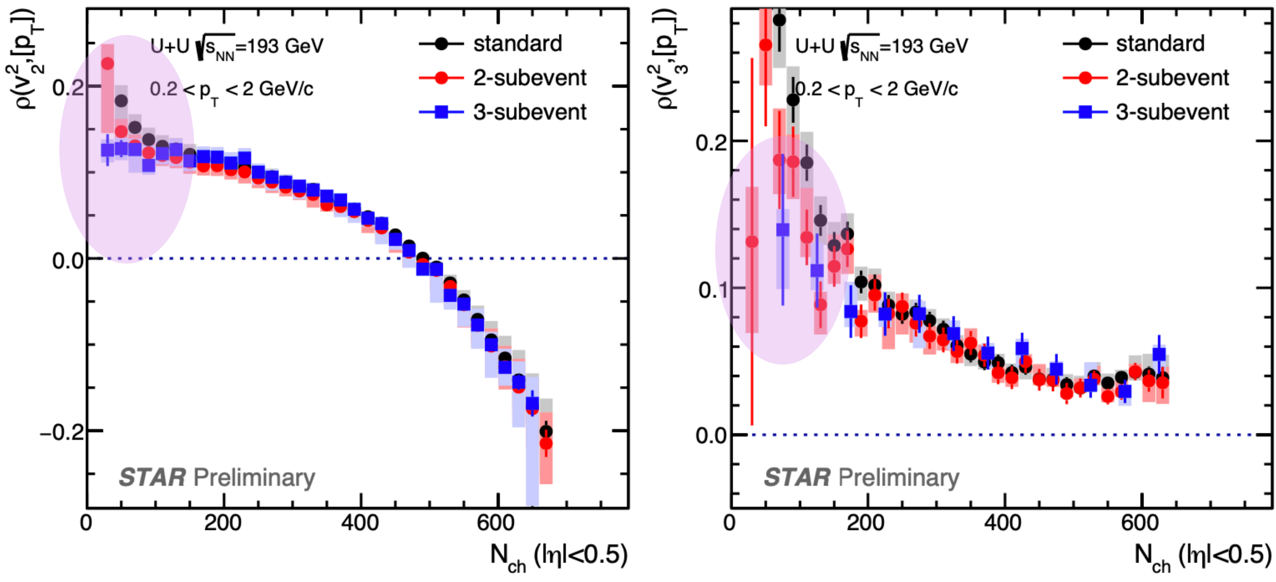
Initial geometry leads negative correlation in peripheral region and initial momentum anisotropy lead positive correlation

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

Au+Au collisions



U+U collisions

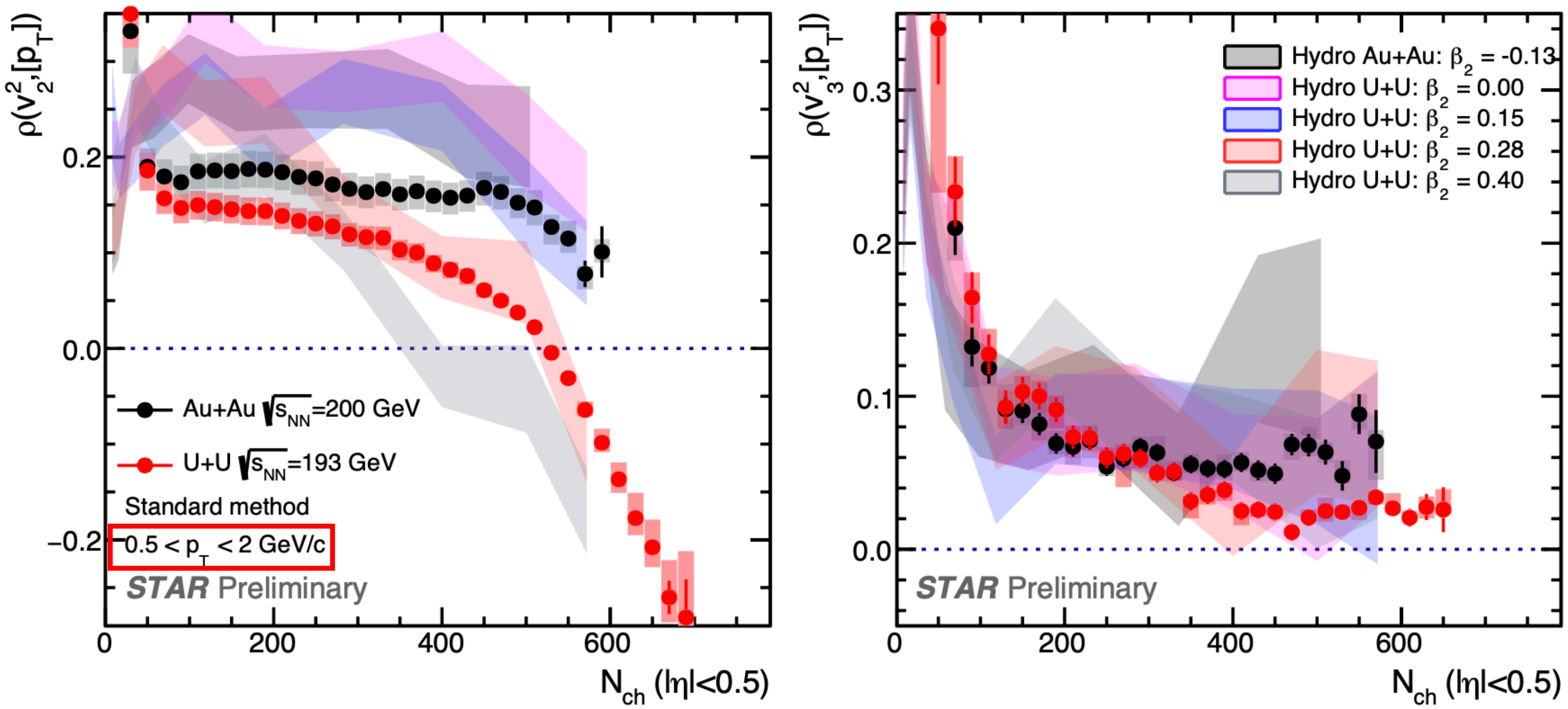


Standard method is consistent with subevent methods at high N_{ch}.

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

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