



Explore the Nuclei Deformation with an Expanding QGP Fireball

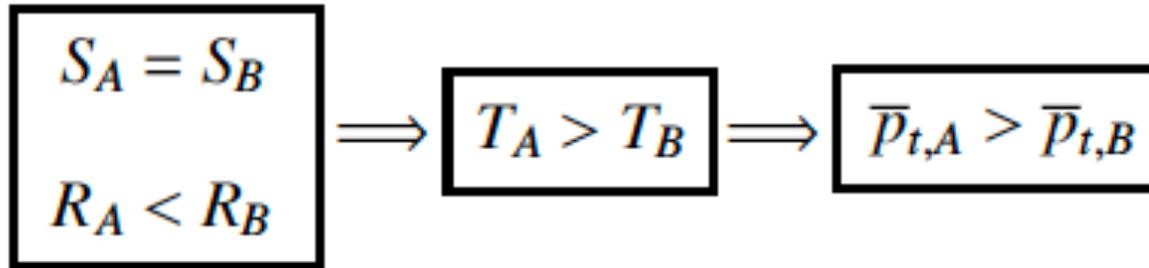
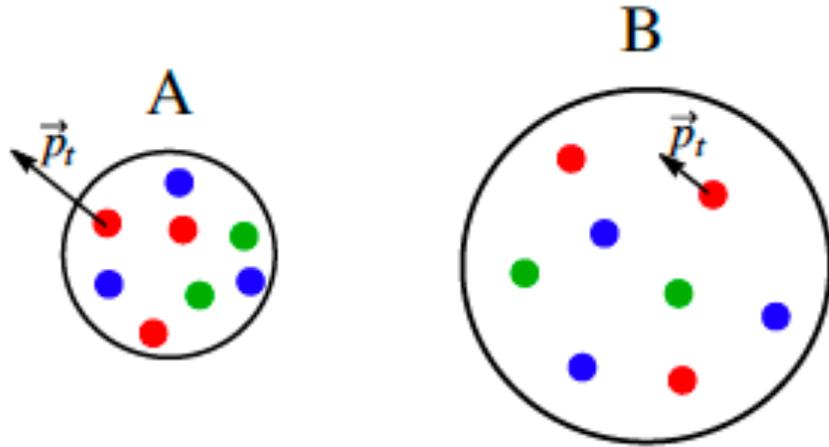
Shengli Huang for STAR Collaboration

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Outline

- 1. Motivations
- 2. Data set and analysis detail
- 3. $\langle p_T \rangle$ vs multiplicity (N_{ch}) in ultra-central A+A collisions
- 4. v_n vs. $\langle p_T \rangle$ in ultra-central A+A collisions
- 5. Comparison with model calculations
- 6. Summary

 $\langle p_T \rangle$ vs. Size of Fireball (R)

For two systems (A,B) with the fixed final-state multiplicity (same entropy), the temperature is higher in smaller system (A), therefore the smaller system will have a larger $\langle p_T \rangle$

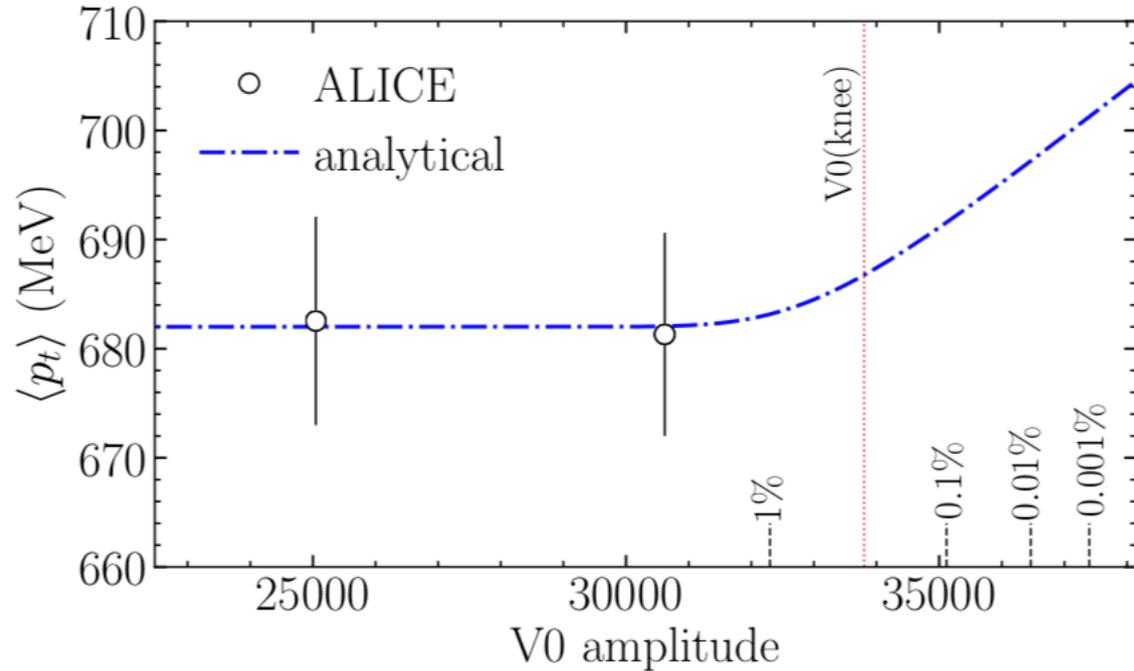
Hydrodynamic models predicted:

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

Wojciech Broniowski: [PhysRevC.80.051902](https://arxiv.org/abs/hep-ph/0503124)

Aleksas Mazeliauskas: [PhysRevC.93.024913](https://arxiv.org/abs/hep-ph/0309101)

Piotr Bozek: [PhysRevC.96.014904](https://arxiv.org/abs/hep-ph/0606092)



1. In ultra-central A+A collisions, the multiplicity (entropy) increases while the system size R is saturated
2. A sharp increasing of $\langle p_T \rangle$ is predicted, which will be proportional to the square of speed of sound c_s

F. Gardim, G. Giacalone and J. Ollitrault
arXiv:1909.11609



Eccentricity and system size in deformed nuclei



Giuliano Giacalone, BNL seminar

Nuclear matter density:

$$\rho(r) = \frac{\rho_0}{1 + \exp\left[\frac{1}{a}\left(r - R(1 + \beta_2 Y_{20})\right)\right]}$$

Quadrupole deformation, β_2

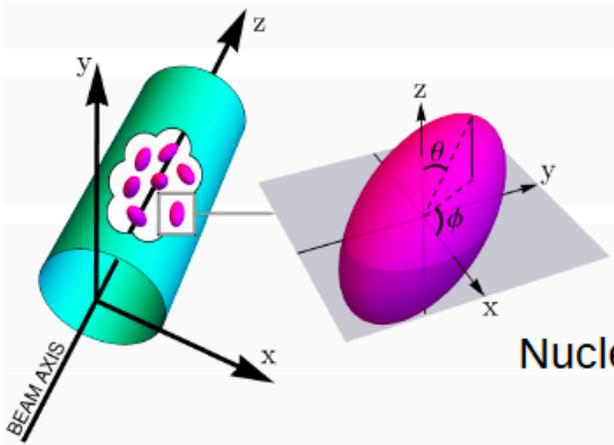
Usually from:

BNL nuclear data center

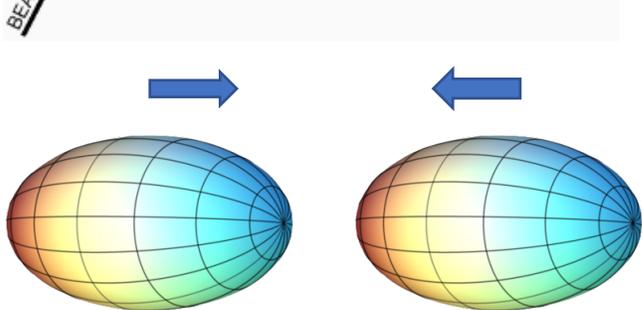
<https://www.nndc.bnl.gov/>

Or calculations e.g. [Möller, Sierk, Ichikawa, Sagawa, **1508.06294**]

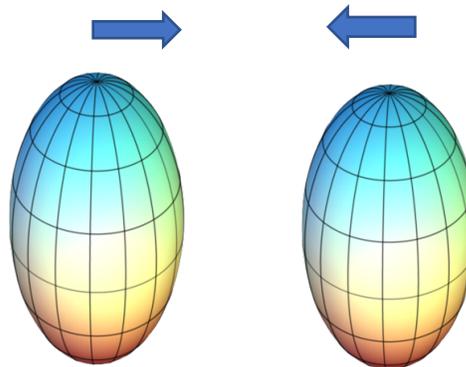
$$Y_{20} = \sqrt{\frac{5}{16\pi}} (3 \cos^2 \theta - 1)$$



Nuclei are randomly oriented in space.



Tip-Tip: Smaller R and ϵ_2



Body-Body: Larger R and ϵ_2

1. ϵ_2 and system size depend on the deformation factor

2. ϵ_2 is bigger in larger system: Tip-Tip vs. Body-Body

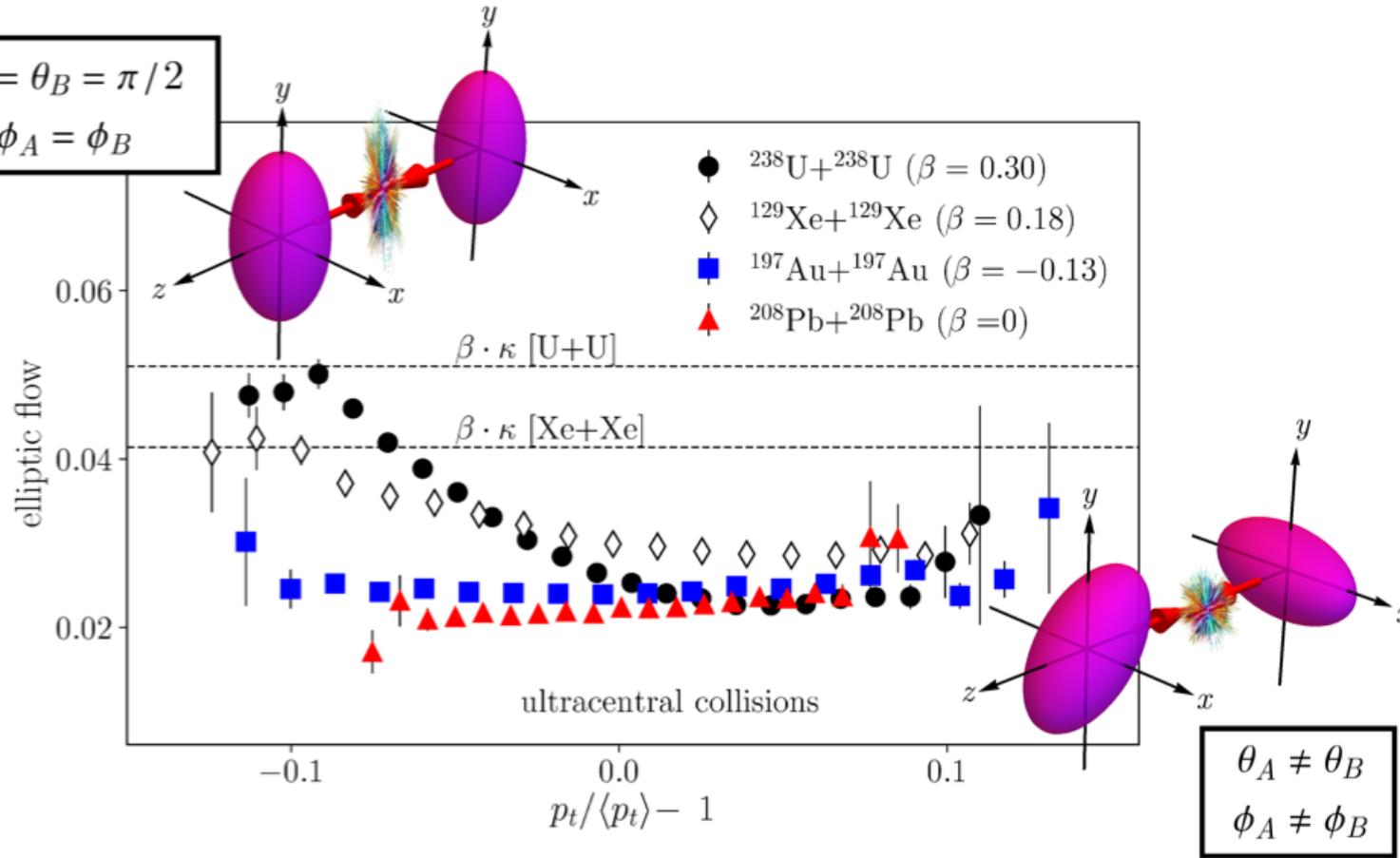
3. $\langle p_T \rangle \propto 1/R$ and $v_2 \propto \epsilon_2$:
Anticorrelation between v_2 and $\langle p_T \rangle$ due to deformation

Measuring the v_2 vs. $\langle p_T \rangle$ can be used to reveal the deformation factor!



v_2 vs. $\langle p_T \rangle$

Giuliano Giacalone, 1910.04673

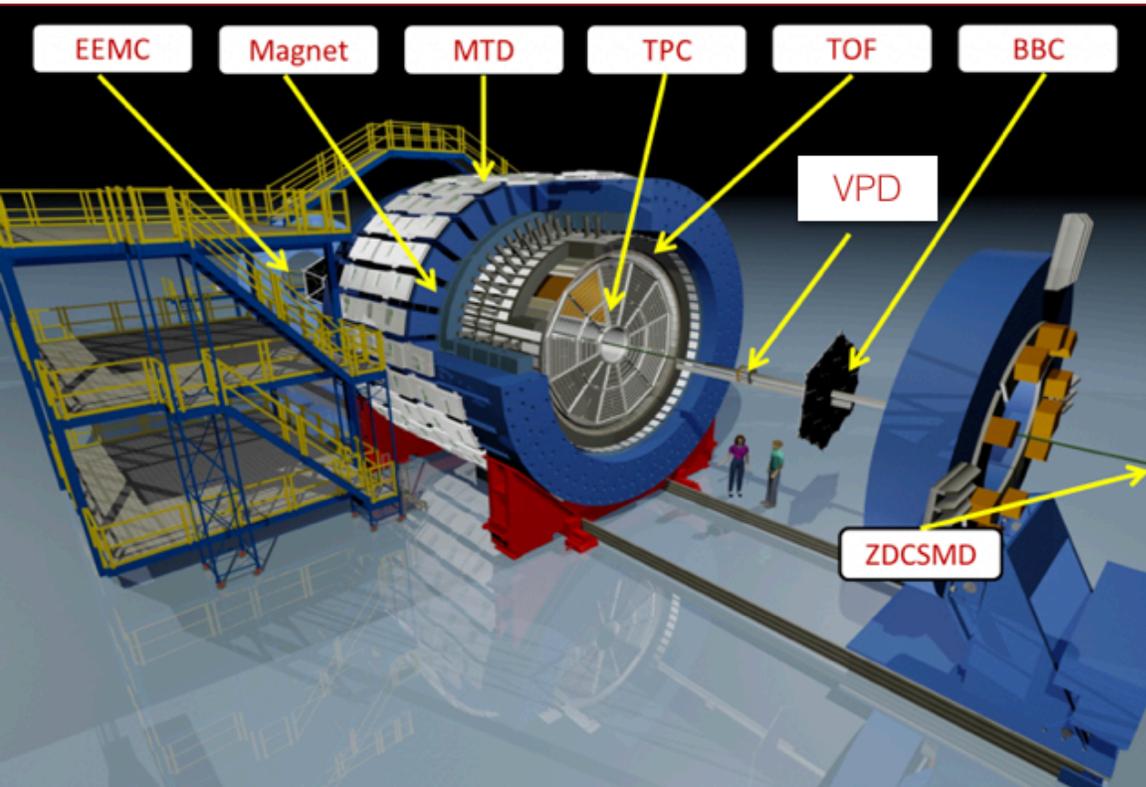


1. $\langle p_T \rangle$ is converted from R by TRENTo initial model, no final-state effects and statistical fluctuations

2. Uranium nuclei are largely deformed comparing with Au nuclei. An anticorrelation between elliptic flow and $\langle p_T \rangle$ is expected in ultracentral U+U collisions

$$\frac{\bar{p}_t}{\langle \bar{p}_t \rangle} - 1 = -3c_s^2 \left(\frac{R}{\langle R \rangle} - 1 \right) \quad c_s^2 = 0.19: \text{Speed of Sound}$$

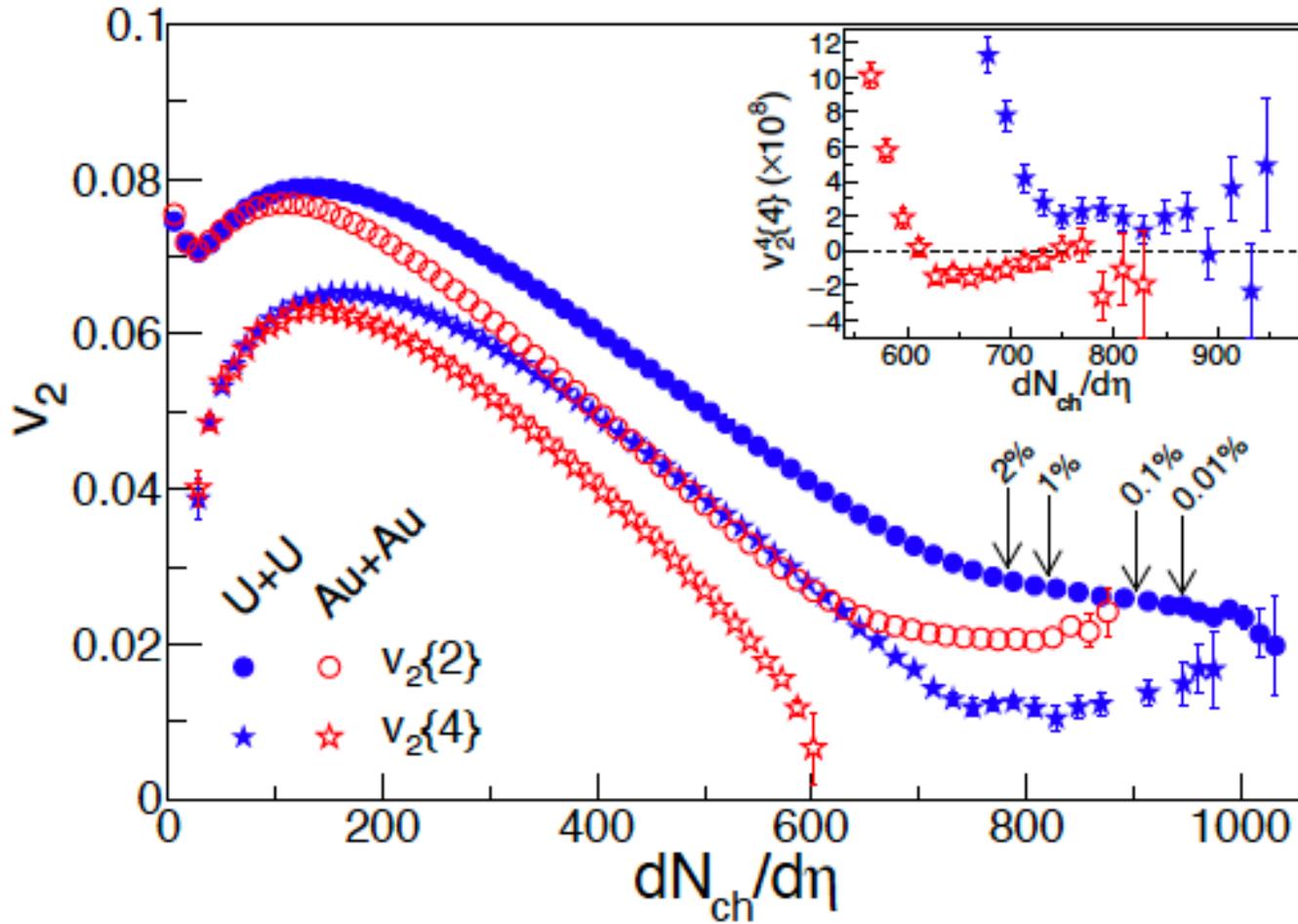
The STAR Detector



- $\langle p_T \rangle$, v_n and N_{ch} are measured within $0.2 < p_T < 2.0$ GeV/c and $|\eta| < 1.0$
- Centrality is defined by N_{ch} or ZDC energy
- The track efficiency is corrected from embedding data



V_2 vs. N_{ch}



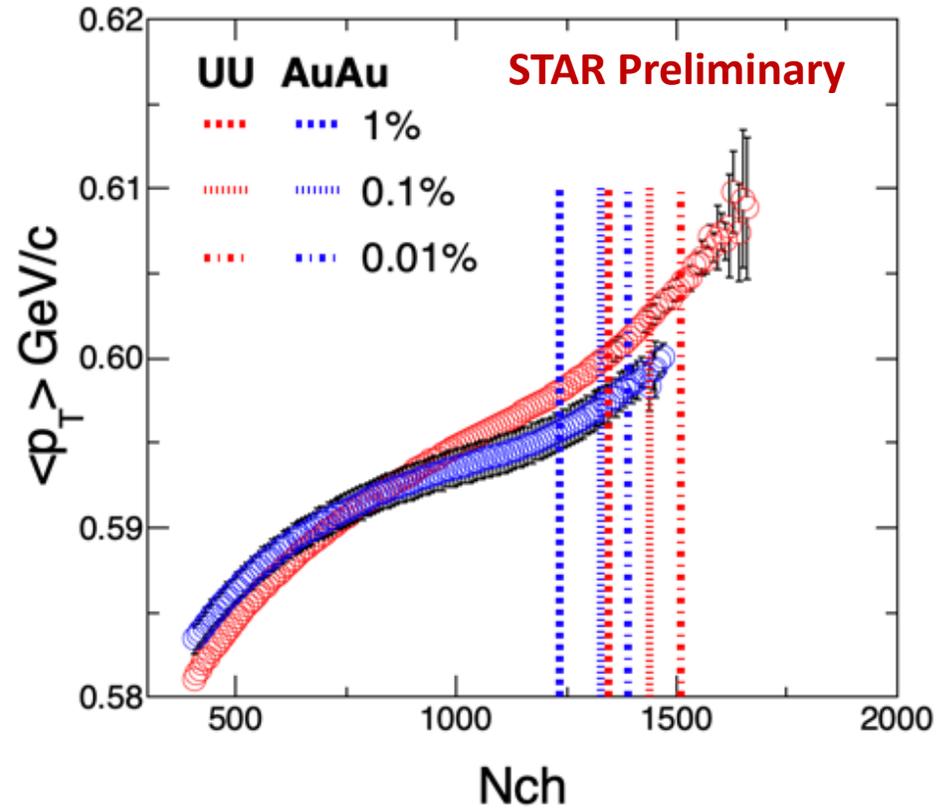
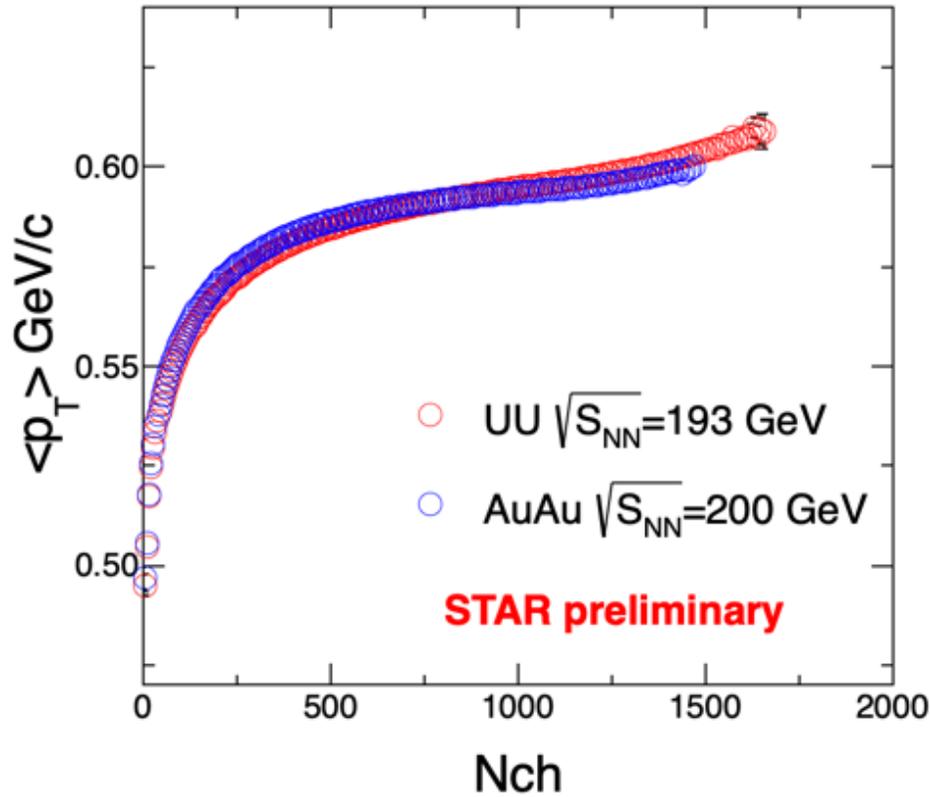
In ultra-central A+A collisions, the $v_2\{2\}$ shows different slopes between Au+Au and U+U

$v_2\{4\}$ from Au+Au changes the sign while not for $v_2\{4\}$ from U+U

The difference between Au+Au and UU indicates that deformation affects the flow behavior in ultra-central A+A collisions

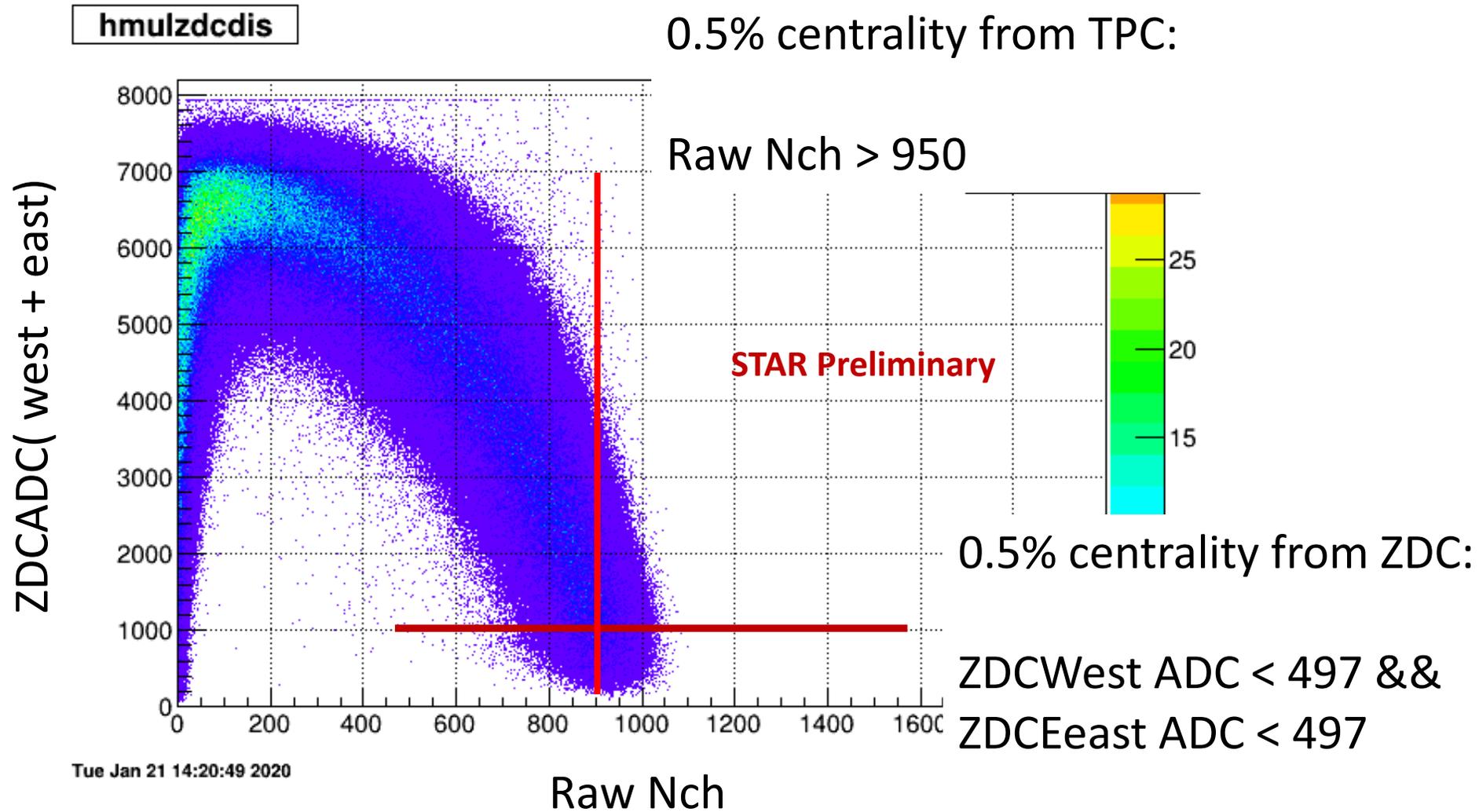


$\langle p_T \rangle$ vs. Nch



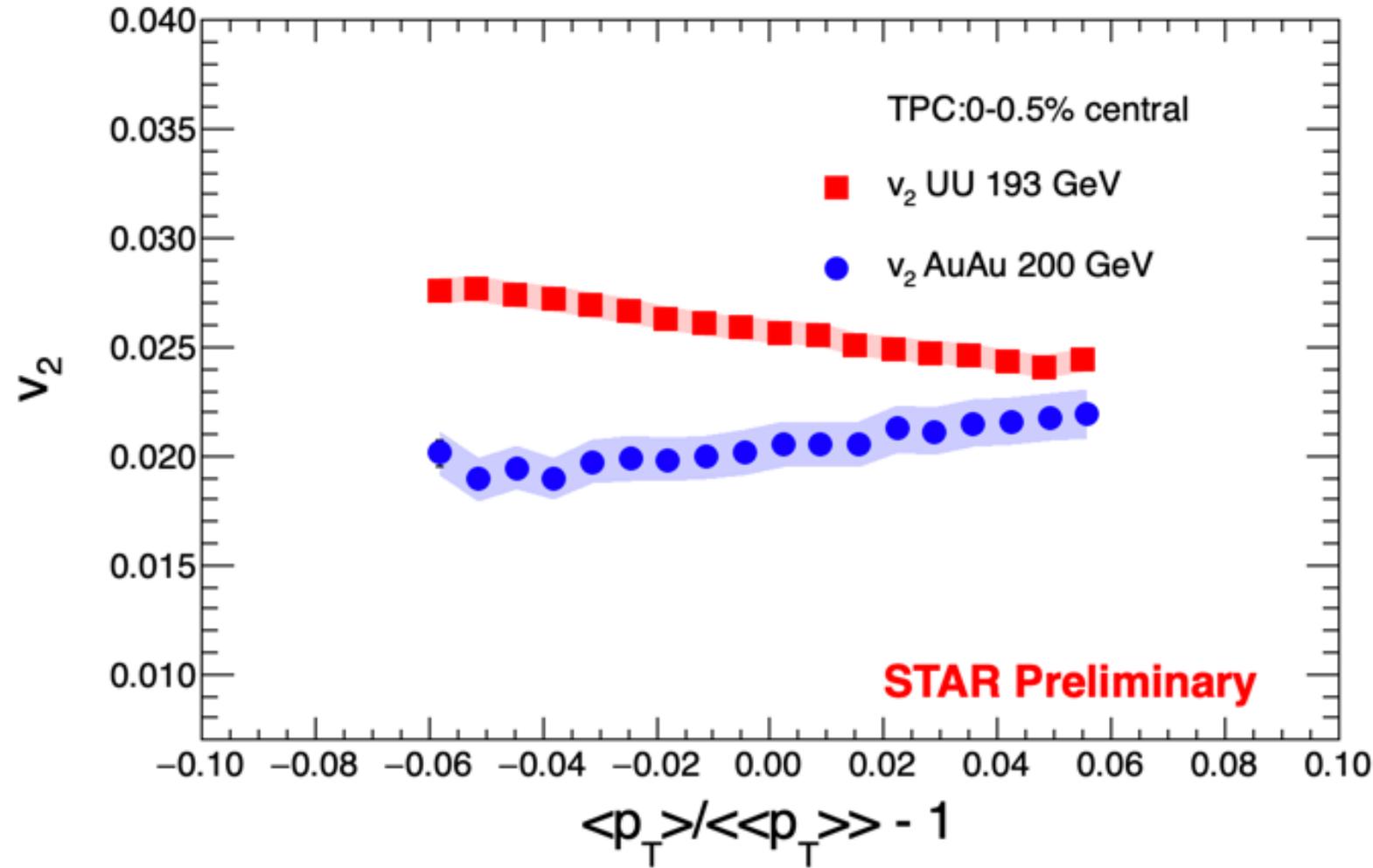
$\langle p_T \rangle$ increasing trend becomes sharper in ultra-central A+A collisions
 It indicates a tight correspondence between $\langle p_T \rangle$ and system size, and will be useful to extract the speed of sound (C_s) of fireball

Centrality From TPC vs. ZDC





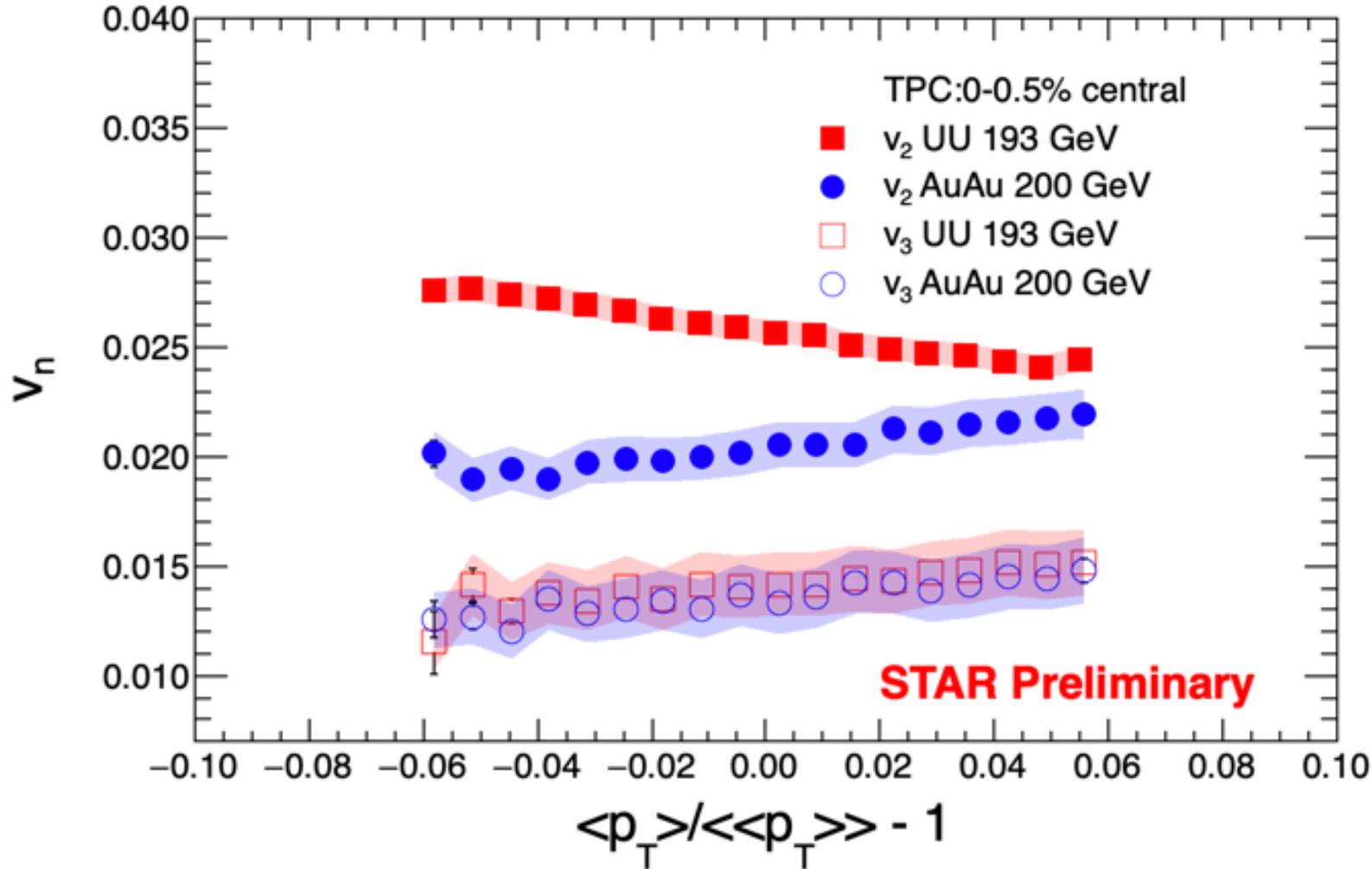
v_2 vs. $\langle p_T \rangle$



An anticorrelation is observed between v_2 and $\langle p_T \rangle$ in top 0.5% UU collisions while not in AuAu



v_3 vs. $\langle p_T \rangle$

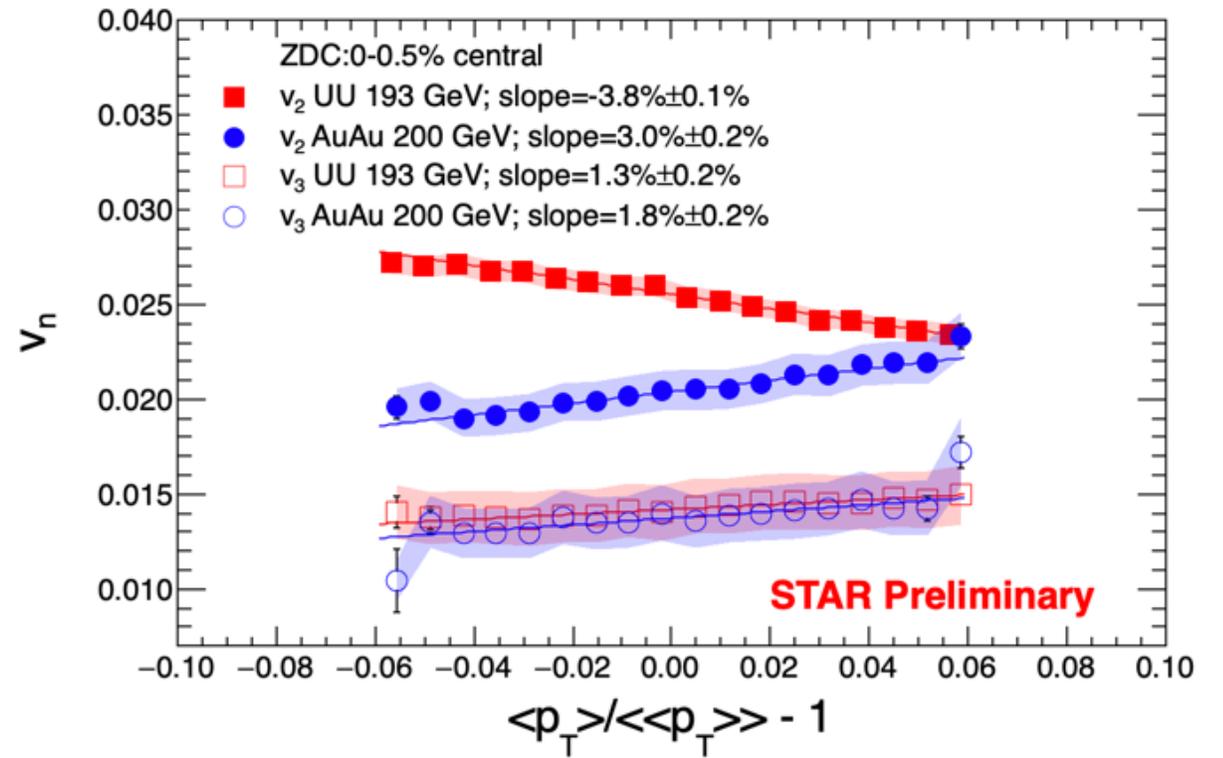
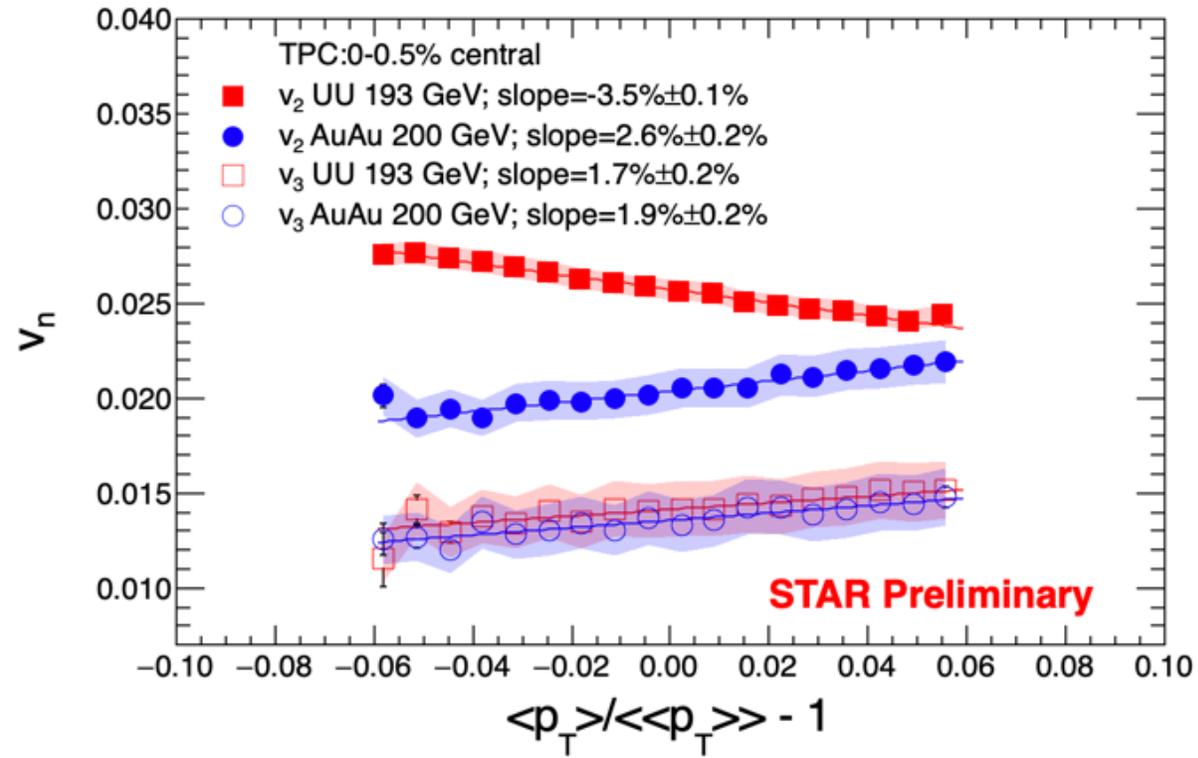


An anticorrelation is observed between v_2 and $\langle p_T \rangle$ in top 0.5% U+U collisions while not in Au+Au

v_3 and $\langle p_T \rangle$ correlations are positive and similar for AuAu and UU collisions



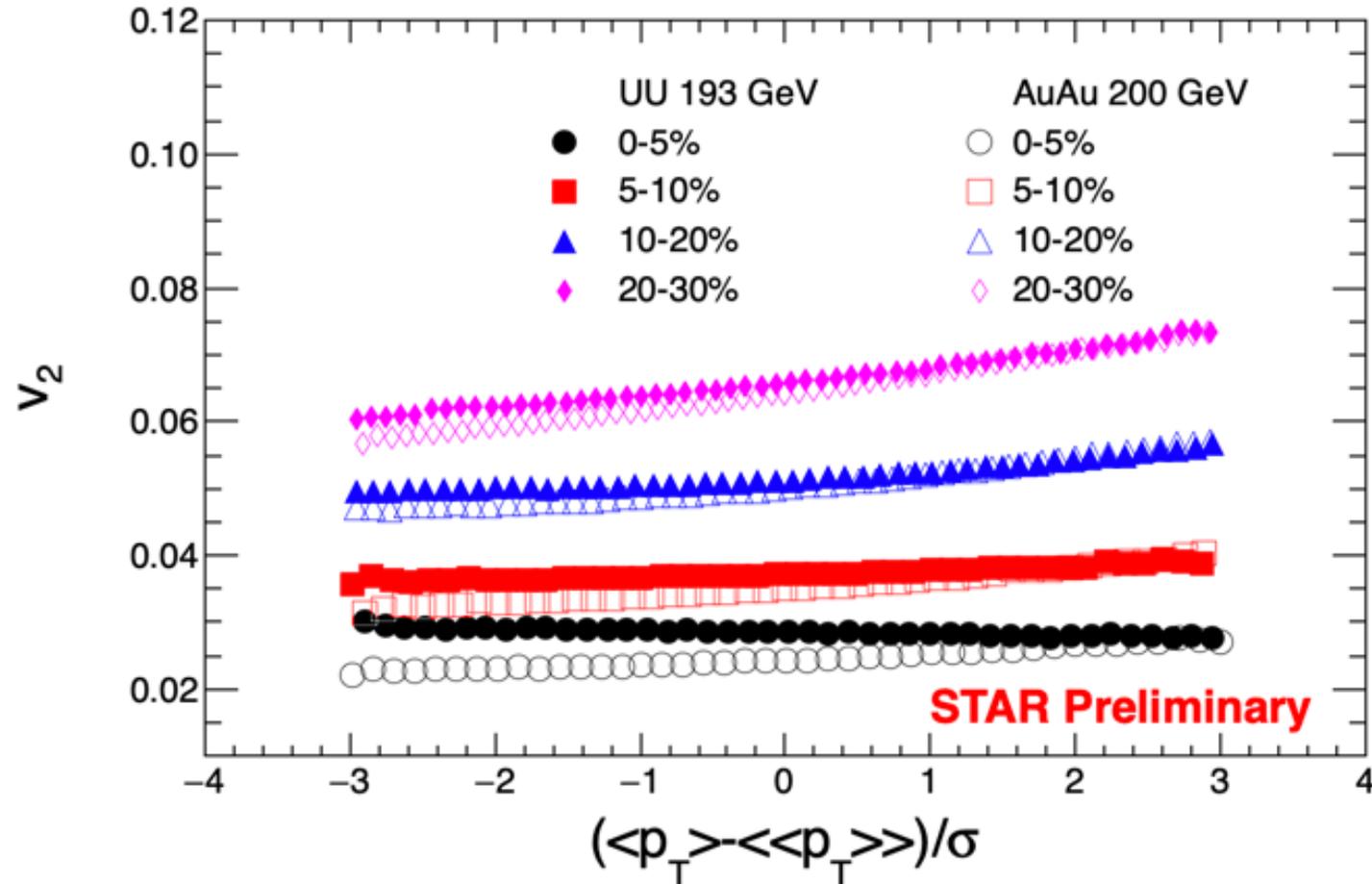
TPC Centrality vs ZDC Centrality



	System	TPC Centrality	ZDC Centrality
v_2 slope	U+U	$-3.5\% \pm 0.1\%$	$-3.8\% \pm 0.1\%$
v_2 slope	Au+Au	$2.6\% \pm 0.2\%$	$3.0\% \pm 0.2\%$
v_3 slope	U+U	$1.7\% \pm 0.2\%$	$1.3\% \pm 0.2\%$
v_3 slope	Au+Au	$1.9\% \pm 0.2\%$	$1.8\% \pm 0.2\%$



Centrality Dependence

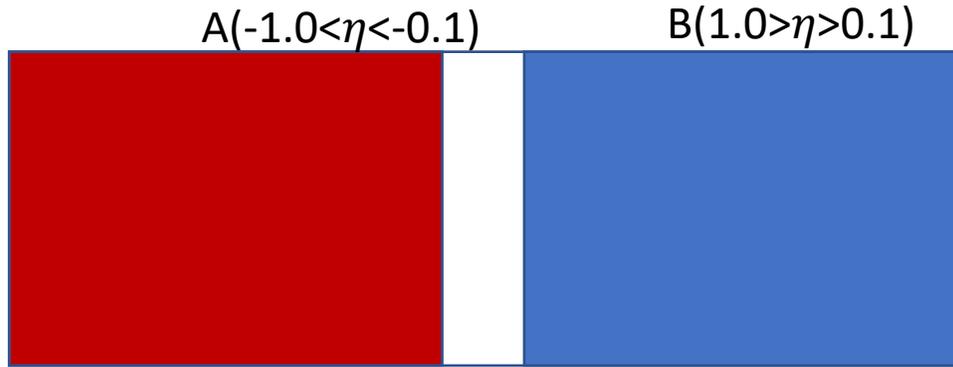


Besides ultra-centrality, the v_2 slopes between Au+Au and U+U are also different in other centralities.

It is due to the deformation effect and consistent with the Glauber model prediction!

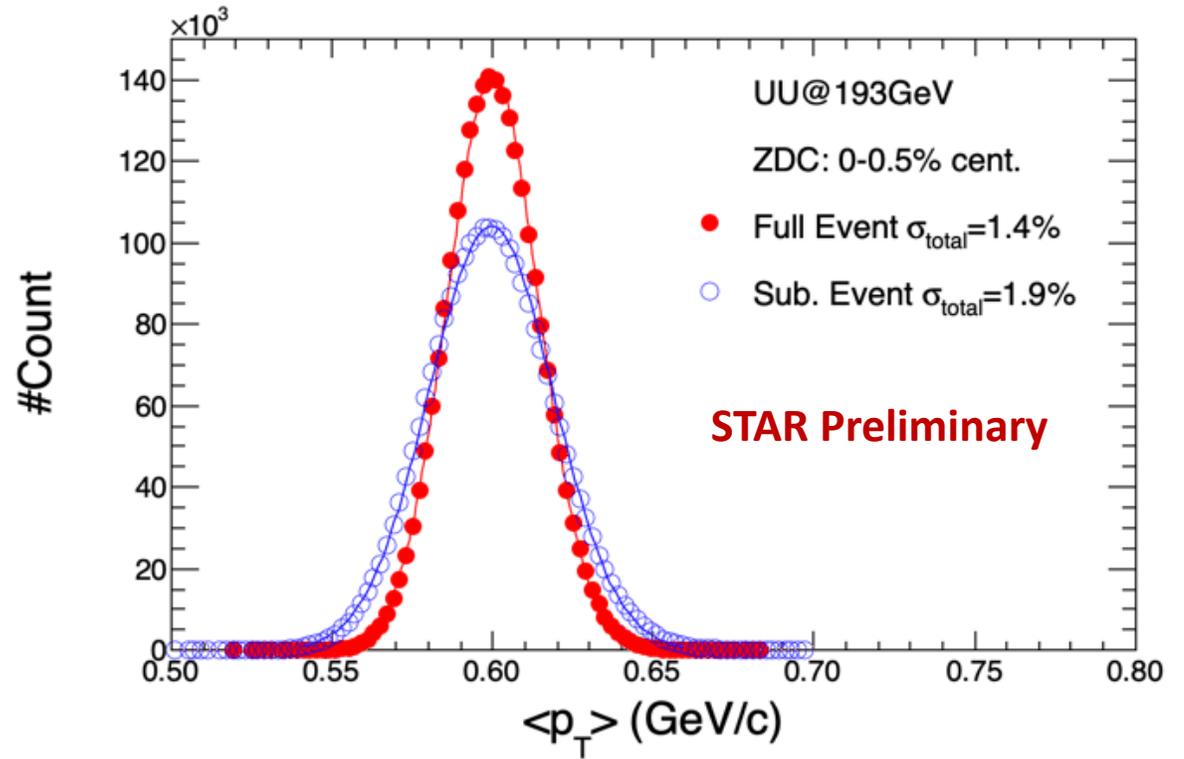
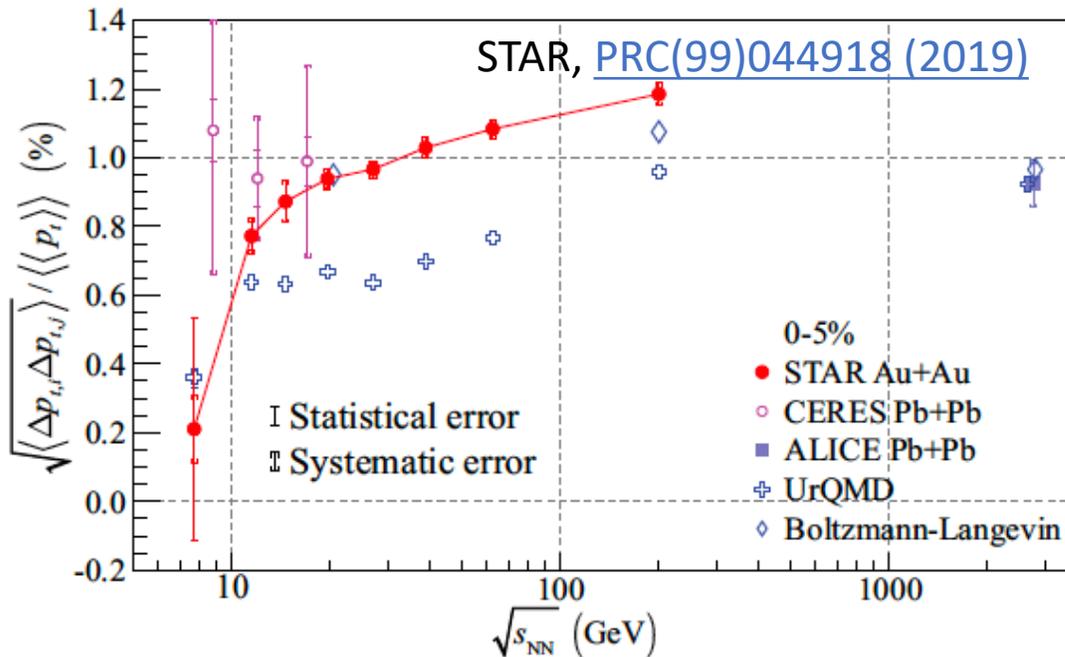


Two-subevent Method



$$\langle V_{nn} \rangle = \langle Q_{n,A} \times Q_{n,B}^* \rangle$$

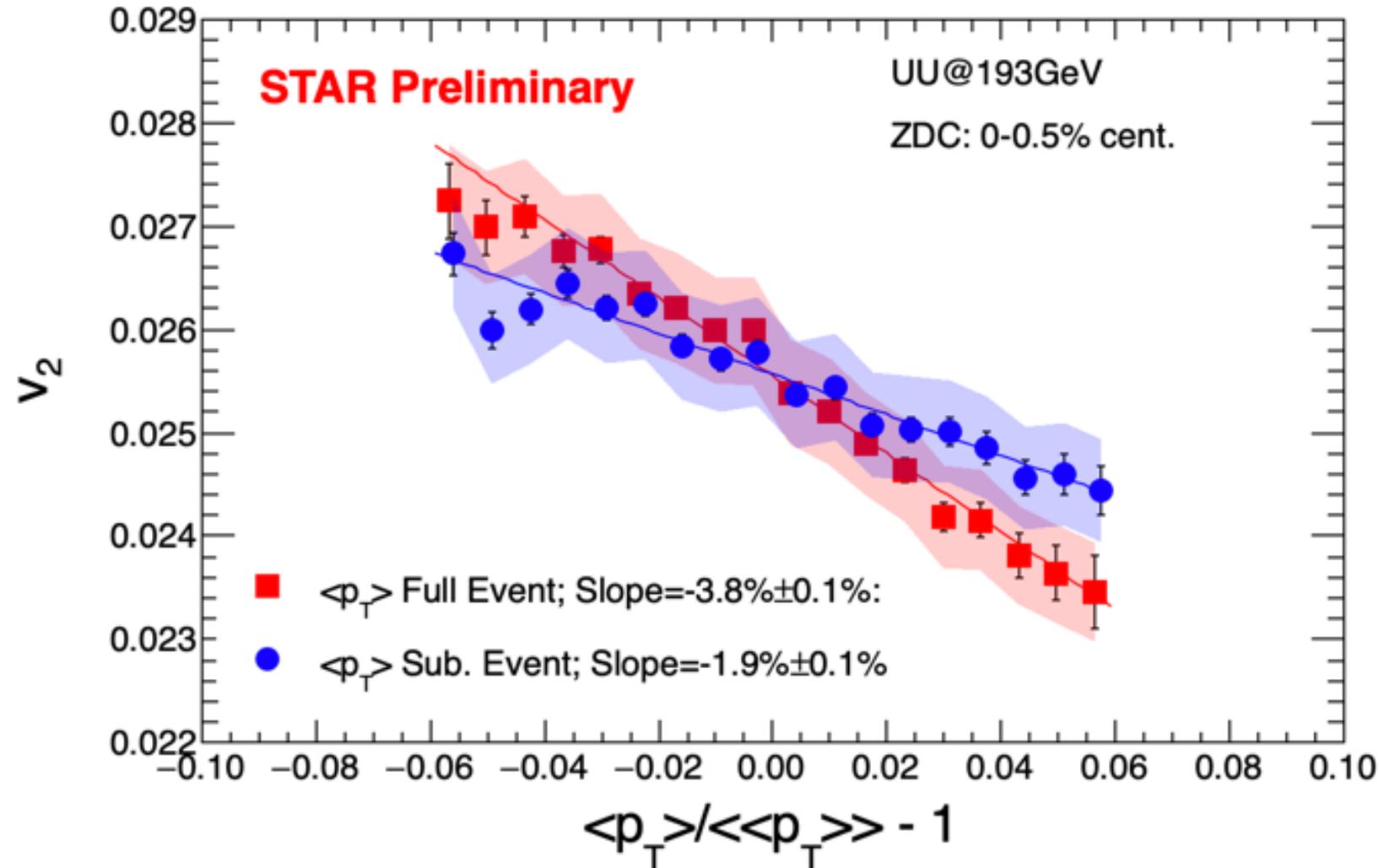
$\langle \langle p_T \rangle \rangle$: Full Event, Subevent (A, B)



$$\sigma_{total}^2 = \sigma_{statistical}^2 + \sigma_{dynamical}^2$$

$$\sigma_{dynamical} / \langle \langle p_T \rangle \rangle = 1.2\%$$

$$\langle \langle p_T \rangle \rangle = 0.6 \text{ GeV}/c$$

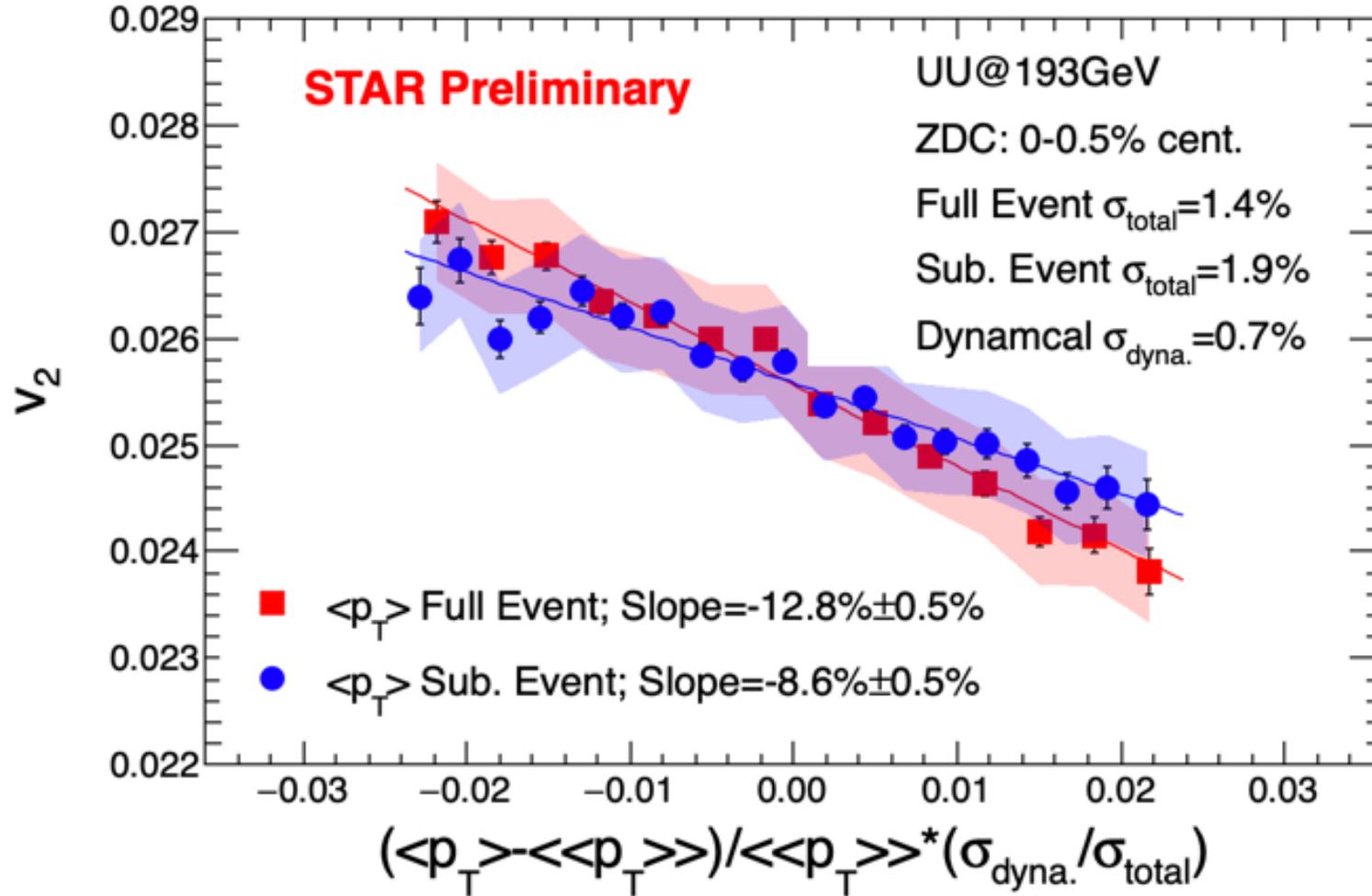


The slope is a factor of two smaller for $\langle p_T \rangle$ from sub-events

The effect of statistical fluctuations is huge!



Normalized Slope

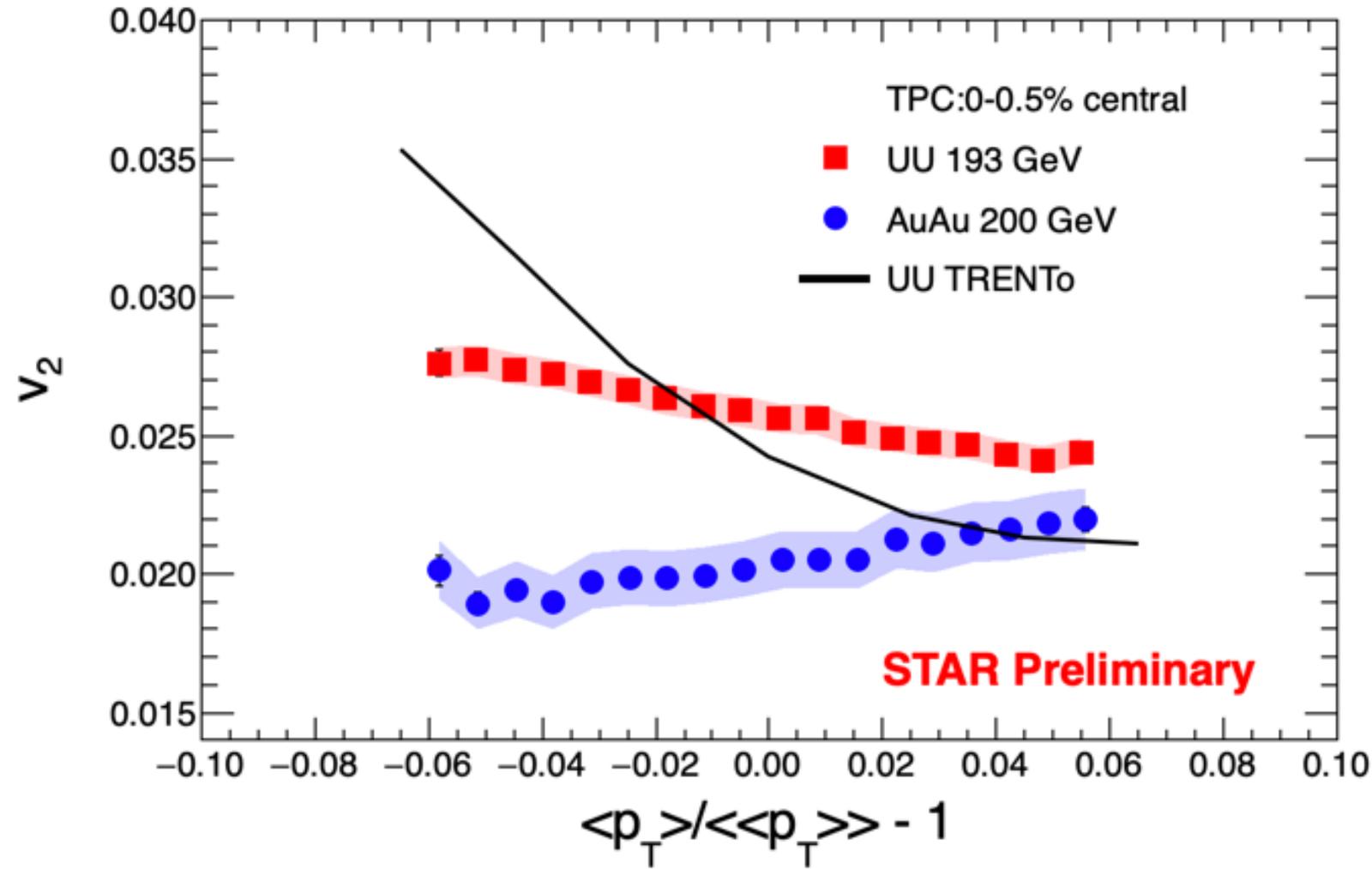


After normalized by the sigma of $\langle p_T \rangle$ distribution, the slope difference between full event and half event drop to 50%

Still working to understand the residual difference



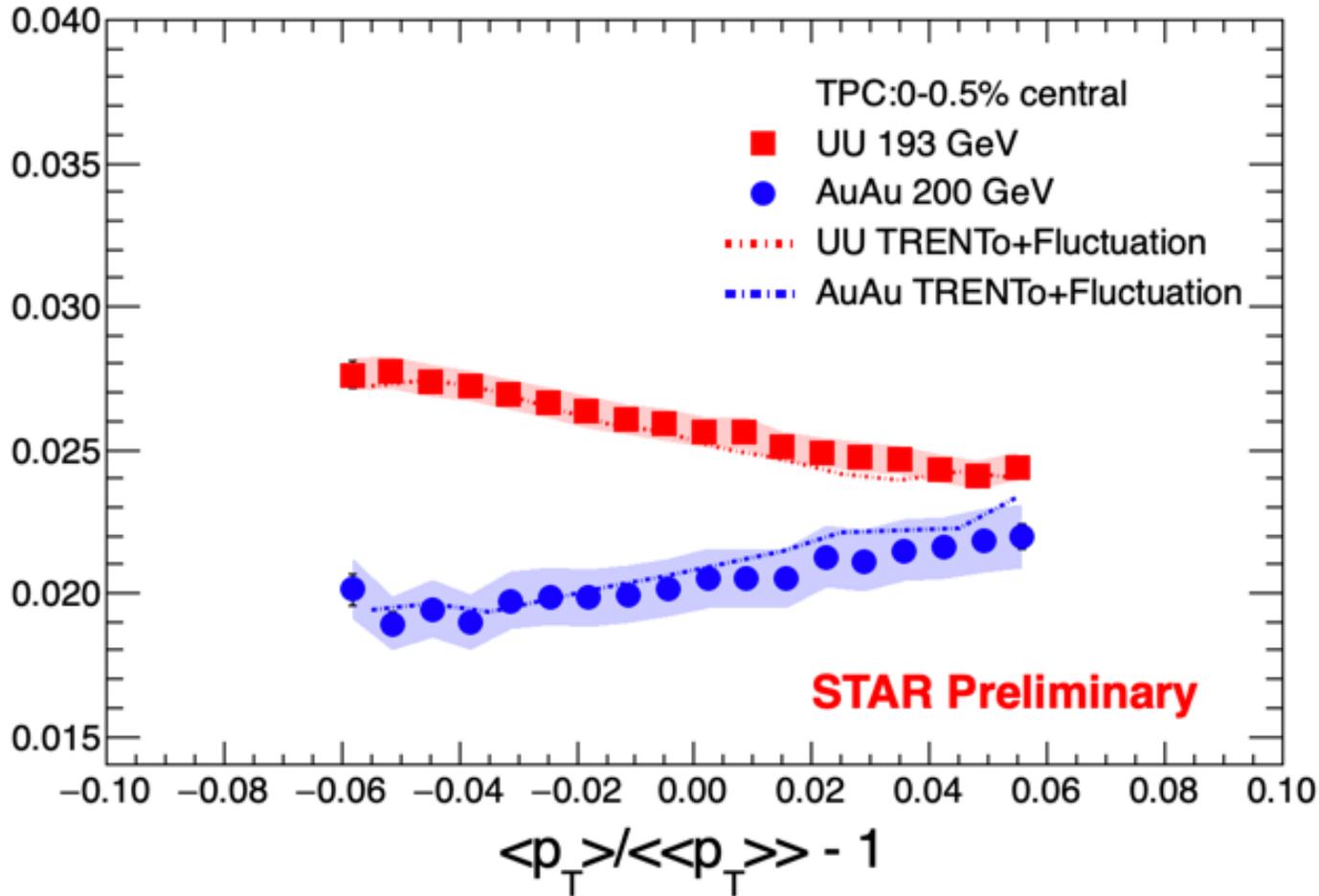
Comparing with TRENTo



Without the statistical fluctuations, TRENTo initial-state model overpredicts the slope with $\beta_2(\text{UU})=0.30$ and $\beta_2(\text{AuAu})=-0.13$



Comparing with TRENTo+Fluctuation: v_2



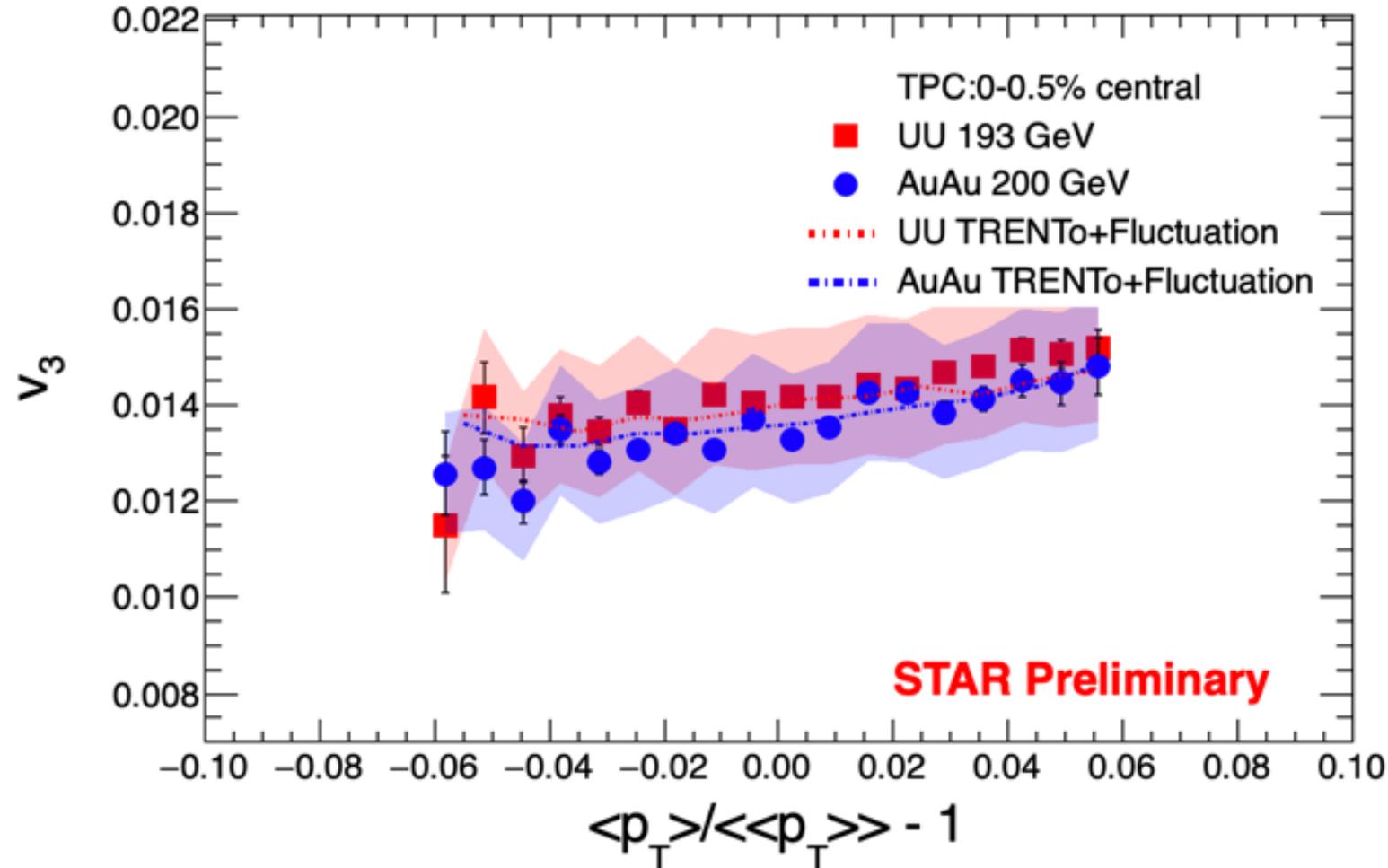
Statistical fluctuations added by hand in model: $\frac{\delta \langle p_T \rangle}{\langle \langle p_T \rangle \rangle} = 0.018$

After adding the statistical fluctuations, the model can reproduce data

The statistical fluctuations are crucial!



Comparing with TRENTo+Fluctuation $\sim v_3$



Model can reproduce v_3 slope
with same parameters!



Summary

- We observed that increasing trend of $\langle p_T \rangle$ vs. N_{ch} become shaper in ultra-central A+A collisions, which maybe useful to extract the c_s as predicted by hydrodynamics
- The slope of v_2 vs $\langle p_T \rangle$ are different between Au+Au and U+U due to the deformation
- After adding the statistical fluctuations by hand, the TRENTo initial-state model can reproduce the data with deformation factor $\beta_2=0.30$ for U+U and $\beta_2=-0.13$ for Au+Au