System Size and Shape Dependence of Anisotropic Flow

Niseem Magdy
STAR Collaboration
Stony Brook University
niseem.abdelrahman@stonybrook.edu

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II. Results

i. System size effect

ii. System shape effect

III. Conclusion

Motivation

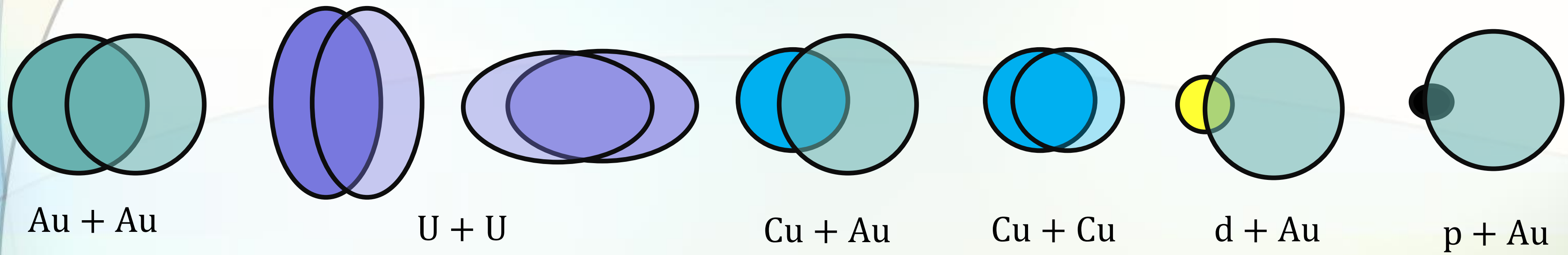
- Is the observed anisotropy in ion-ion collision a final- or initial state effect?

- What are the essential differences between the medium created in small (p+A) and large (A+A) collision systems?

- Is there a limiting size to lose final-state effects ?

Motivation

- STAR collectd data for different systems;



- v_n measurements for different systems are sensitive to system shape (ε_n), dimensionless size (RT) and transport coefficients $\left(\frac{\eta}{s}, \frac{\zeta}{s}, \ldots\right)$.

- Scaling out the system shape and size $\xrightarrow{\text{yields}} \left(\frac{\eta}{s}, \frac{\zeta}{s}, \ldots\right)$ effect on v_n for each system.

Transport coefficients

- The v_n measurements are sensitive to ε_n, RT and $\left(\frac{\eta}{s}, \frac{\zeta}{s}, \ldots\right)$.

- Acoustic ansatz
  - ✓ Sound attenuation in the viscous matter reduces the magnitude of v_n.

- Anisotropic flow attenuation;

PRC84 034908 (2011)
P.Staig and E.Shuryak

$$\frac{v_n}{\varepsilon_n} \propto e^{-\beta n^2}, \beta \propto \frac{\eta}{s}\frac{1}{RT} + \cdots$$

arXiv:1305.3341
Roy A. Lacey, A. Taranenko, J. Jia, et al.

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- From macroscopic entropy considerations $(RT)^3 \propto \frac{dN}{d\eta}$

$$ln\left(\frac{v_n}{\varepsilon_n}\right) = a\frac{\eta}{s}\left(\frac{dN}{d\eta}\right)^{\frac{-1}{3}} + ln(b)$$

arXiv:1601.06001
Roy A. Lacey, Peifeng Liu, Niseem Magdy, et al.

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$$ln(v_n) = a\left(\frac{\eta}{s}\right)\left(\frac{dN}{d\eta}\right)^{\frac{-1}{3}} + ln(\varepsilon_n) + ln(b)$$

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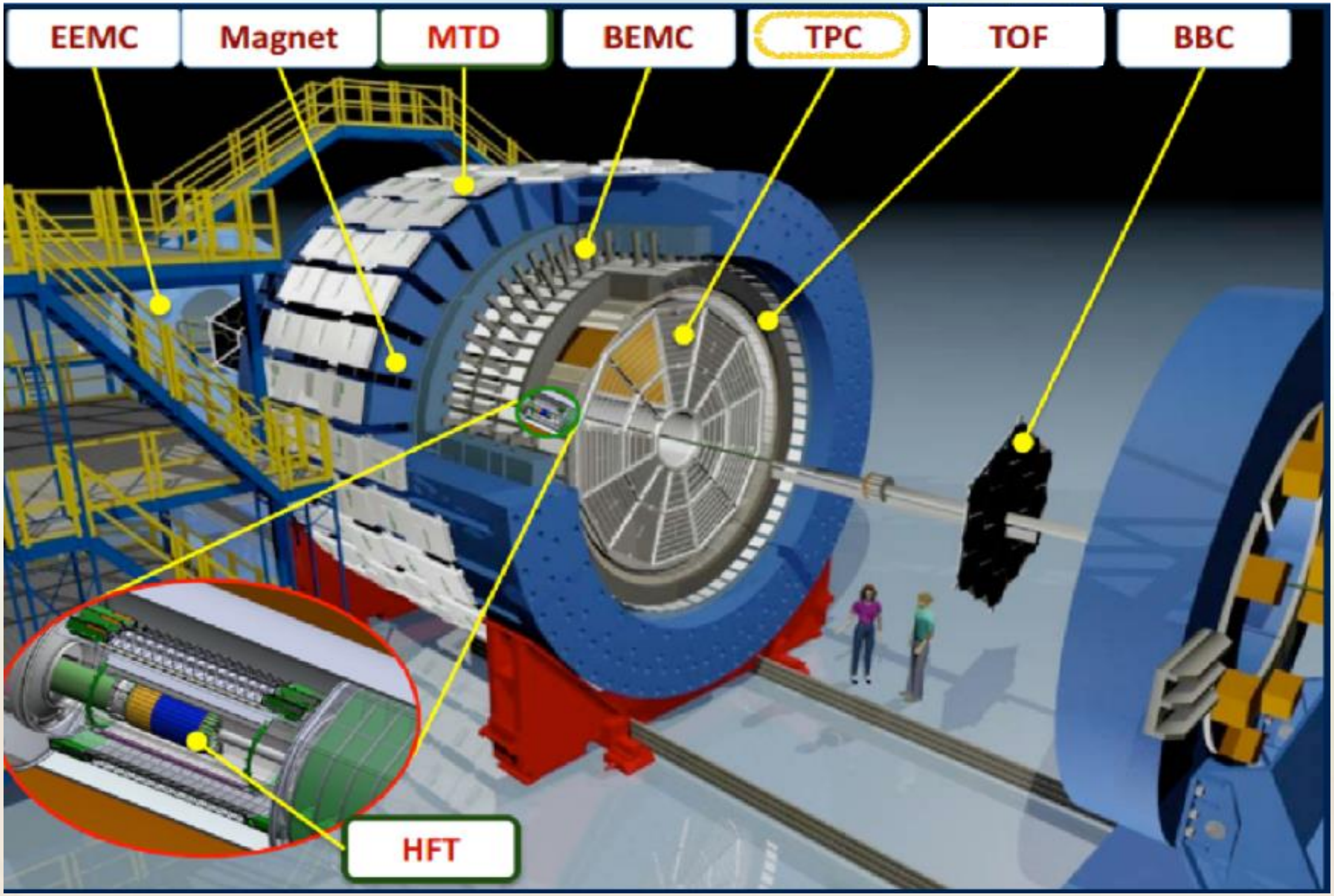
✓ Scaling out the system size $\left(\frac{dN}{d\eta}\right)$ and shape (ε_n) should give similar transport coefficient $\left(\frac{\eta}{s}\right)$ (i.e. similar v_n) for different systems (final state-effect).

STAR Detector at RHIC



- Uniform acceptance in $|\eta| < 1$

Correlation function technique

- All current techniques used to study v_n are related to the correlation function.

- Two particle correlation function $Cr(\Delta\varphi)$ *used in this analysis*,

$$Cr(\Delta\varphi) = \frac{dN/d\Delta\varphi(same)}{dN/d\Delta\varphi(mix)} \quad \text{and} \quad v_{nn} = \frac{\sum_{\Delta\varphi} Cr(\Delta\varphi)\cos(n\,\Delta\varphi)}{\sum_{\Delta\varphi} Cr(\Delta\varphi)} \qquad (5)$$

- Non-flow signals, as well as some residual detector effects (track merging/splitting) suppressed with $|\Delta\eta = \eta_1 - \eta_2| > 0.7$ cut.

$$v_{nn}(p_T^a, p_T^t) = v_n(p_T^a)\, v_n(p_T^t) \qquad n > 1 \qquad (6)$$

✓ Factorization ansatz for v_n $(n > 1)$ verified.

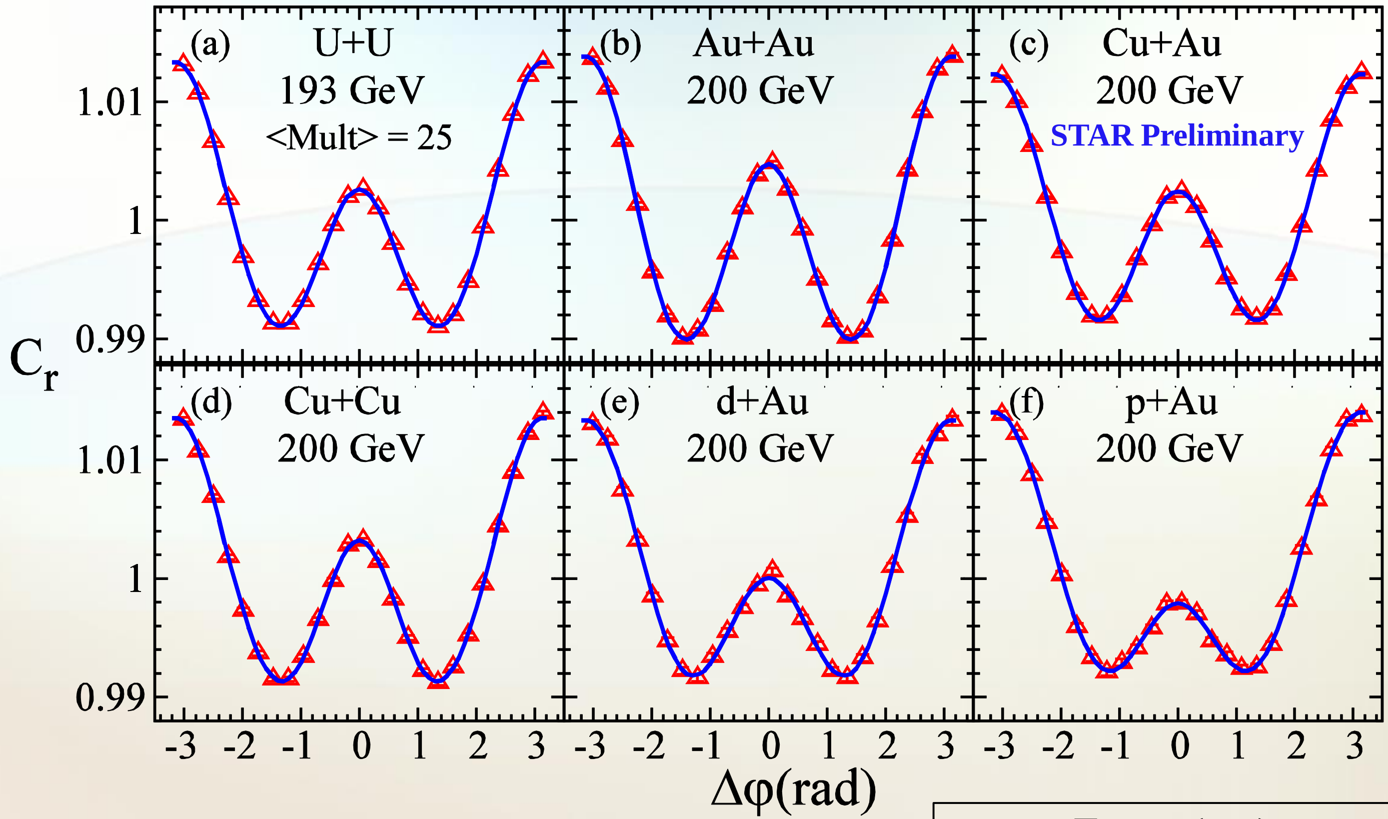
$$v_{11}(p_T^a, p_T^t) = v_1^{even}(p_T^a) v_1^{even}(p_T^t) - C\, p_T^a\, p_T^t \qquad (7)$$

PRC 86, 014907 (2012)
ATLAS Collaboration

- C is the momentum conservation parameter $C \propto \frac{1}{<Mult><p_T^2>}$

Correlation function

Different system correlation function



Using the correlating function we can extract v_{nn}

$$v_{nn} = \frac{\sum_{\Delta\varphi} Cr(\Delta\varphi)\cos(n\,\Delta\varphi)}{\sum_{\Delta\varphi} Cr(\Delta\varphi)}$$

$v_n(p_T)$ for $n \neq 1$ as

$$v_n(p_T) = v_{\mathrm{nn}}(p_{T_{ref}}, p_T) / \sqrt{v_{\mathrm{nn}}(p_{T_{ref}})}$$

For $\boldsymbol{n = 1}$?

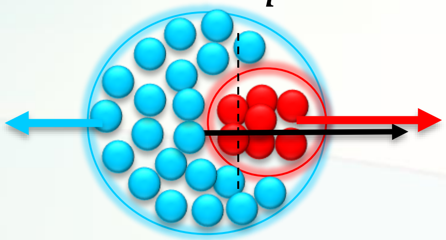
For $n = 1$

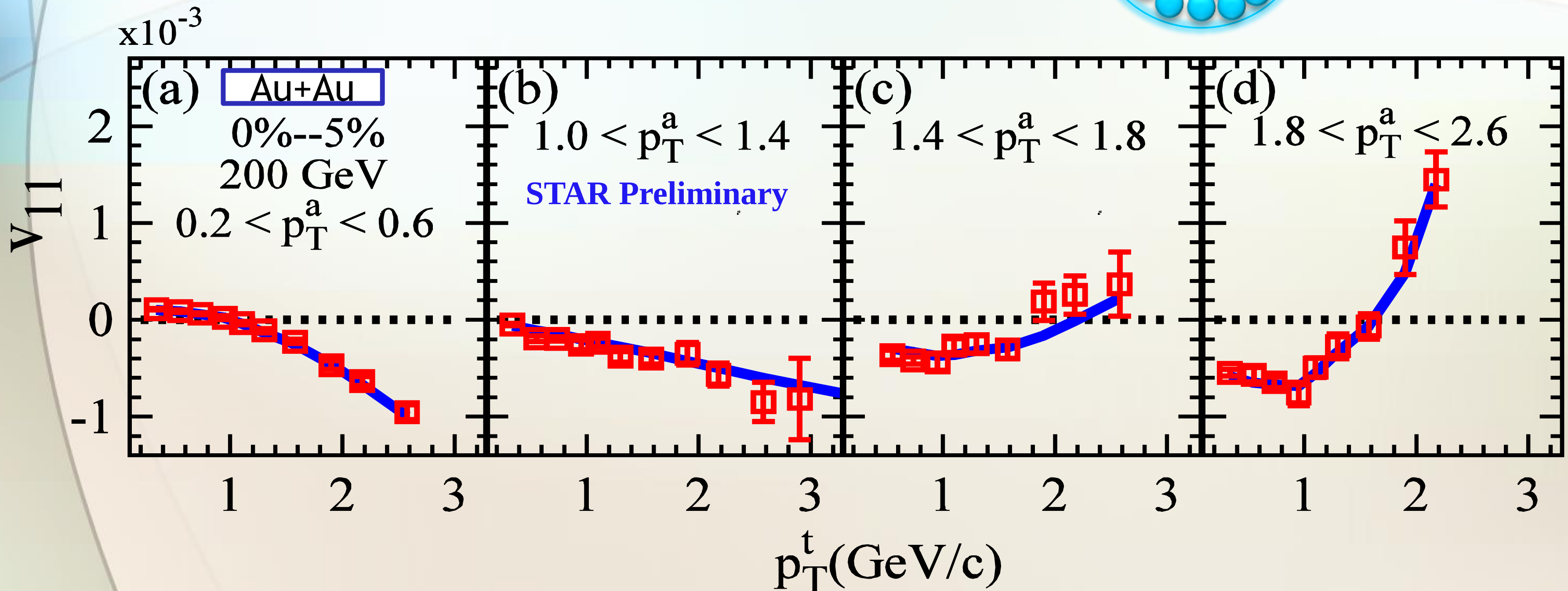
Dipolar Flow

Simultaneous fit

$$v_{11}(p_T^a, p_T^t) = v_1^{even}(p_T^a)\, v_1^{even}(p_T^t) - C\, p_T^a\, p_T^t \quad (7)$$

- v_{11} $Eq[7]$ *represents* $N \times N$ *matrix which we fit with* $N+1$ *parameters*
- Dipolar nature require that $\int_0^{\infty} \frac{dN}{dp_T}\, p_T\, v_1^{even} = 0$





- Good simultaneous fit obtained with fit function Eq[7].
- v_{11} characteristic behavior gives a good constraint for $v_1^{even}(p_T)$ extraction.

Dipolar Flow

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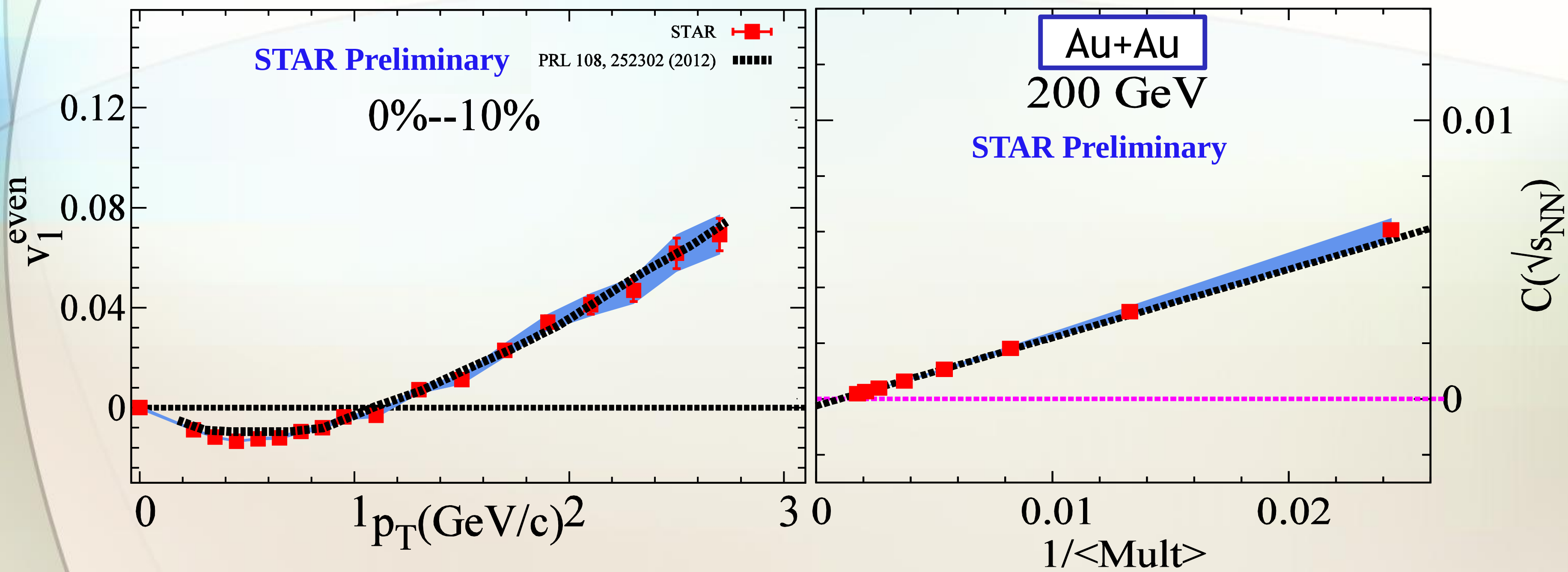
$$v_{11}(p_T^a, p_T^t) = v_1^{even}(p_T^a) v_1^{even}(p_T^t) - C\, p_T^a\, p_T^t$$

- *The extracted* $v_1^{even}(p_T)$ and the momentum conservation parameter C at 200 GeV



- The characteristic behavior of $v_1^{even}(p_T)$ in good agreement with the hydrodynamics calculations
  - The momentum conservation parameter C scales as 1/<Mult>

Results

$|\eta| < 1$ and $|\Delta\eta| > 0.7$

System size effect

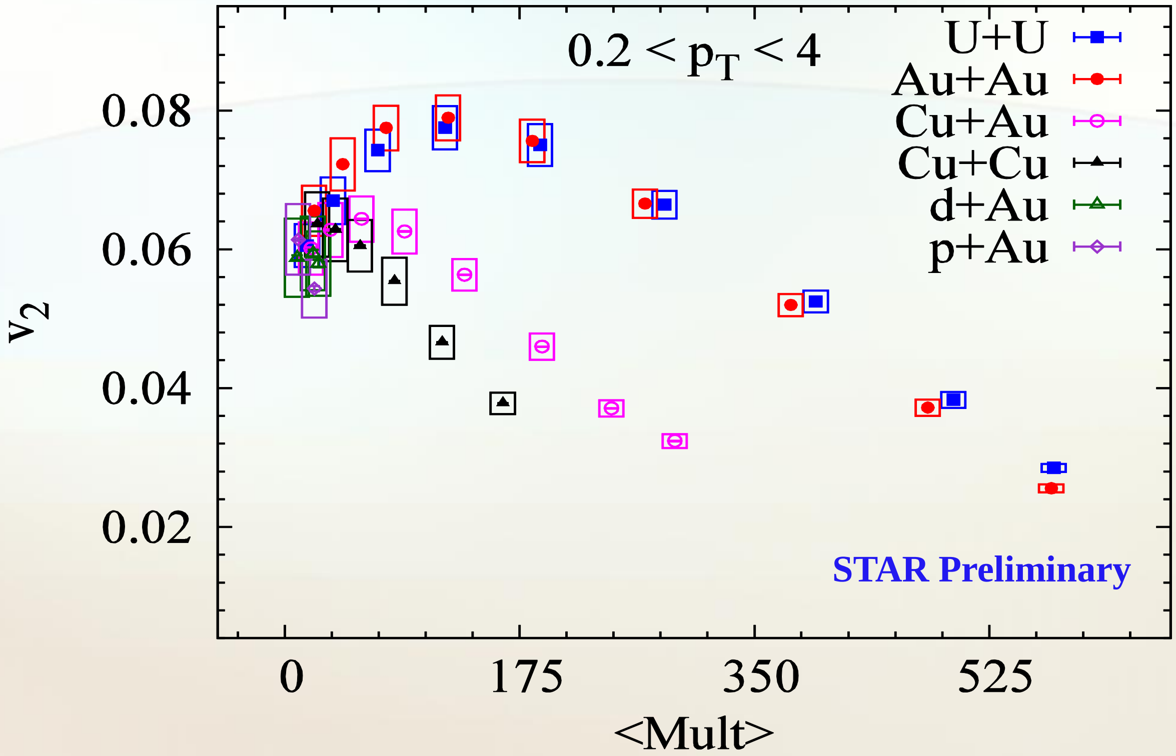
$$\boldsymbol{ln(v_n) = a\left(\frac{\eta}{s}\right)\left(\frac{dN}{d\eta}\right)^{\frac{1}{3}} + ln(\varepsilon_n) + ln(b)}$$

System size and shape effect

$$\boldsymbol{ln(v_n) = a\left(\frac{\eta}{s}\right)\left(\frac{dN}{d\eta}\right)^{\frac{1}{3}} + ln(\varepsilon_n) + ln(b)}$$

$v_n(Mult)$
System size and shape
$|\eta| < 1$ and $|\Delta\eta| > 0.7$

v_2 vs mean multiplicity for all systems



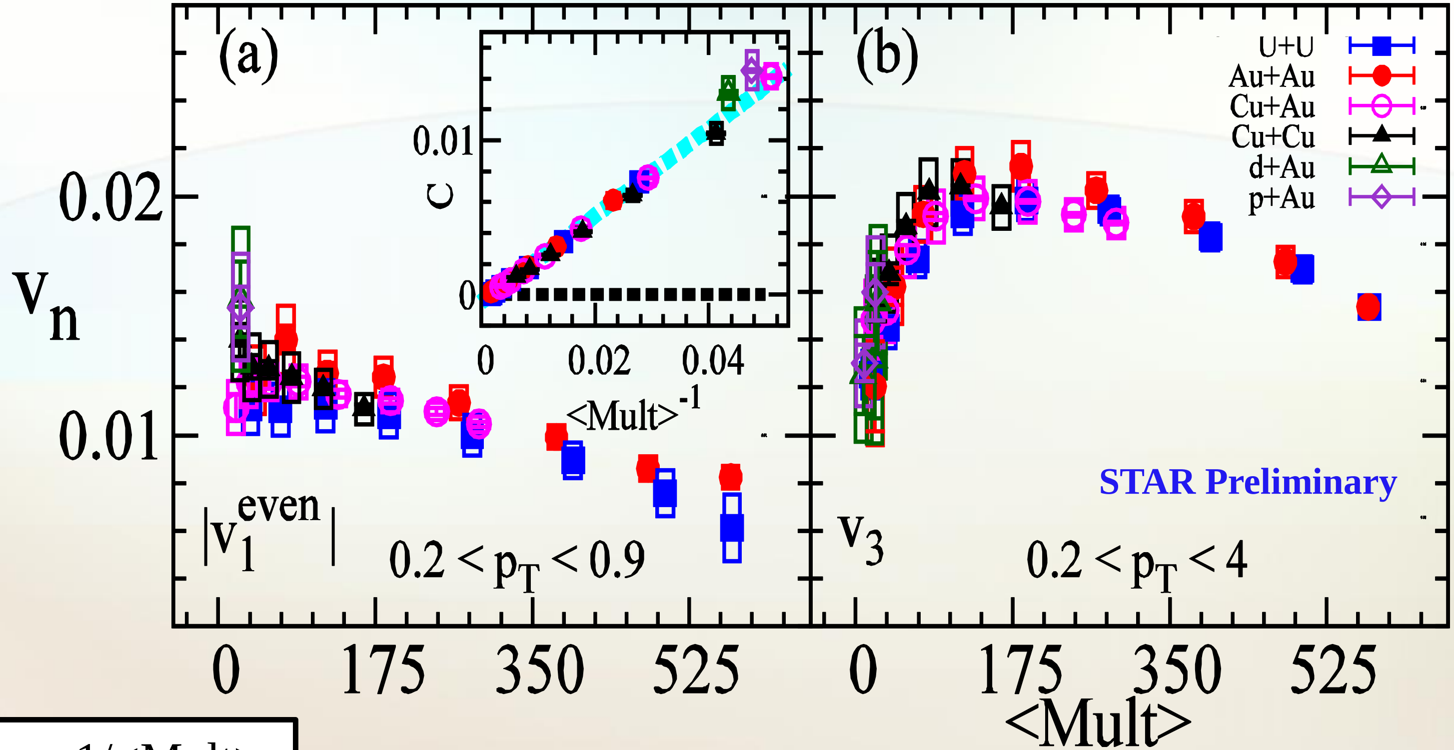
- ➢ $v_2(Mult)$ show similar trends for all systems.
- ➢ v_2 is system dependent (shape).

$v_n(Mult)$

System size

$|\eta| < 1$ and $|\Delta\eta| > 0.7$

v_1^{even} and v_3 vs mean multiplicity for all systems



C scales as 1/<Mult>

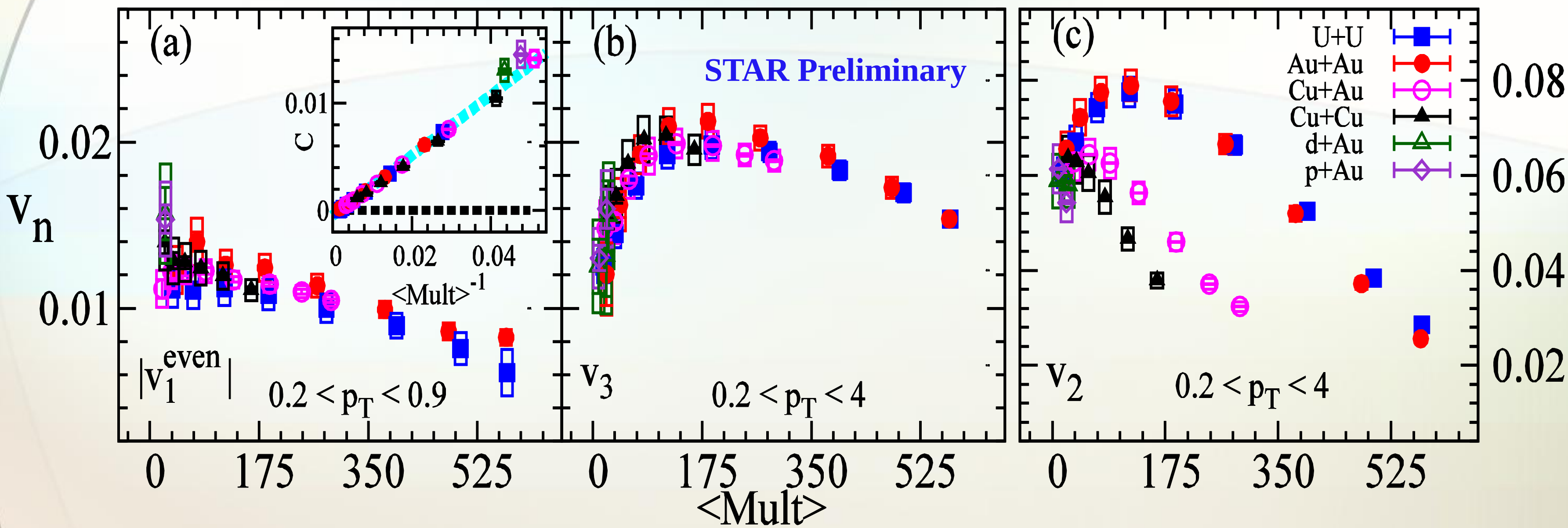
- v_1^{even} and v_3 show similar trends and magnitudes for all systems.
- v_1^{even} and v_3 are system independent (similar $\frac{\eta}{s}$).

$v_n(Mult)$

Summary

$|\eta| < 1$ and $|\Delta\eta| > 0.7$

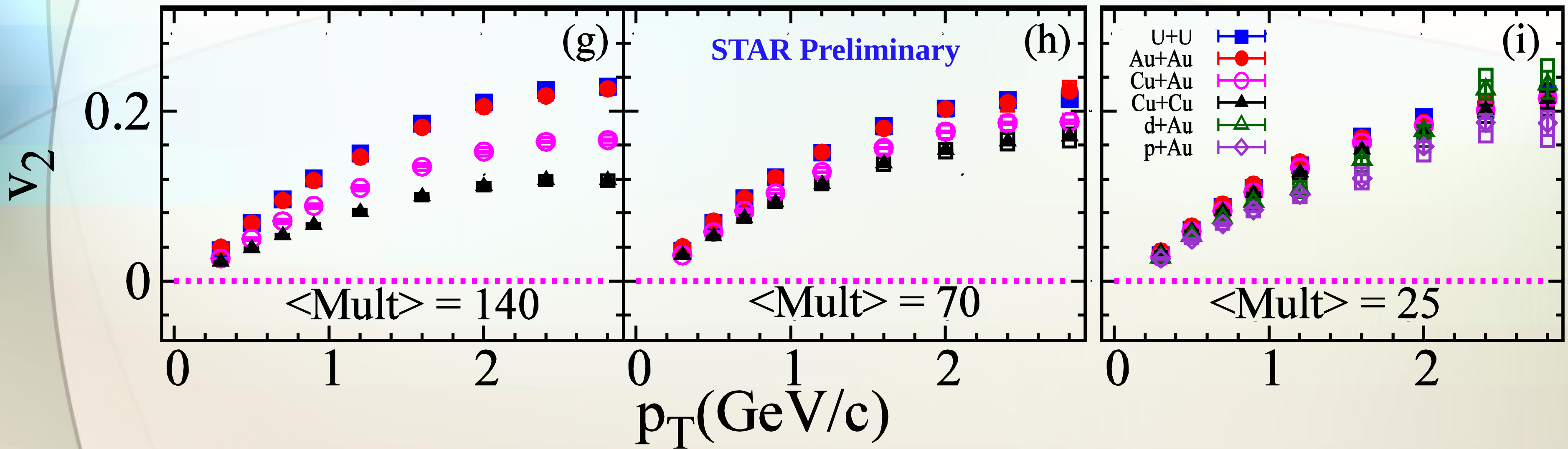
v_n mean multiplicity dependence for all systems



- For a given n, $v_n(p_T)$ show similar trends for all systems.
  - v_1^{even} and v_3 are system independent (similar $\frac{\eta}{s}$).
    - v_2 is system dependent.

$v_n(p_T)$
System size
$|\eta| < 1$ and $|\Delta\eta| > 0.7$

v_2 vs p_T at fixed mean multiplicity for all systems



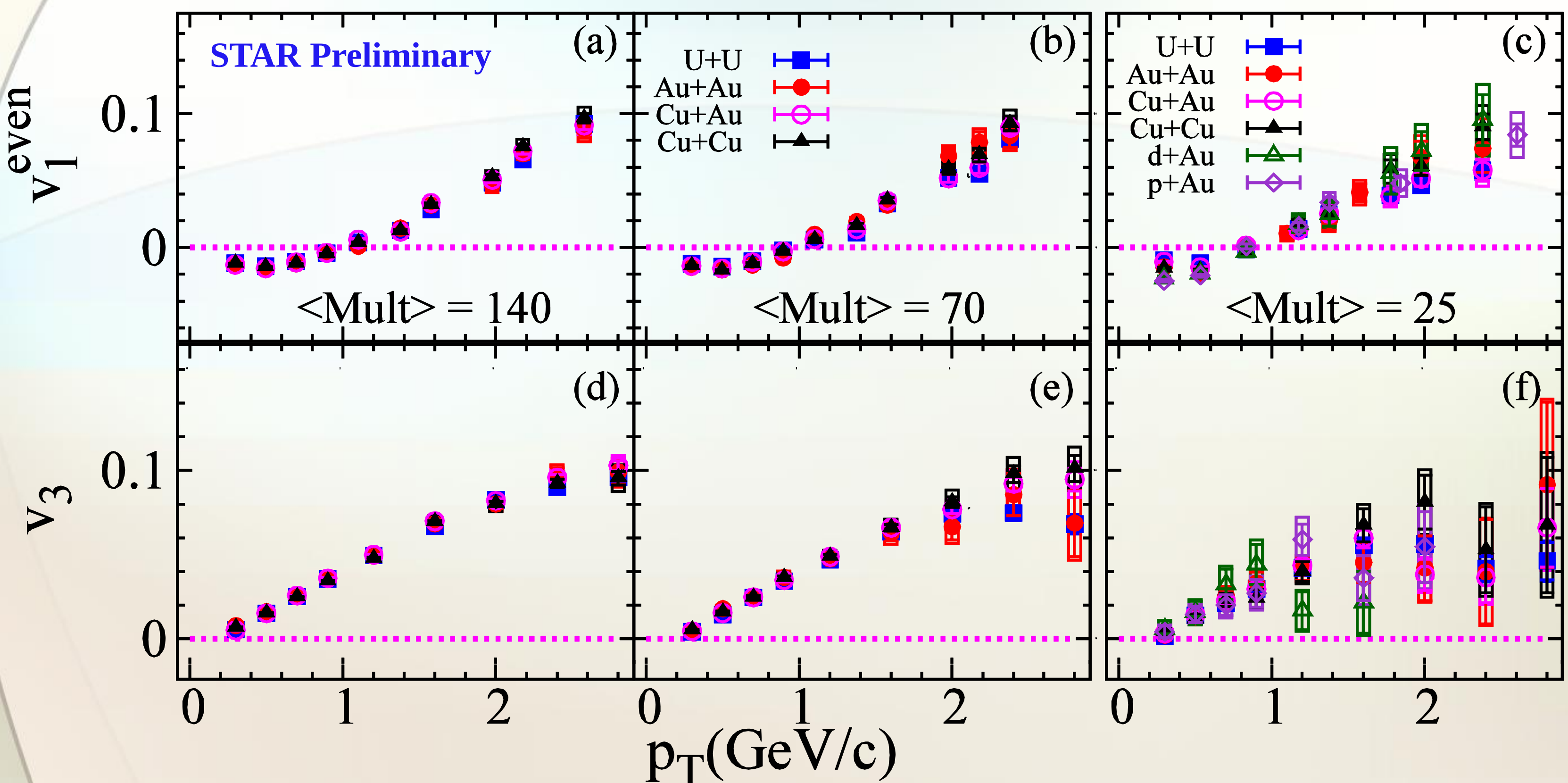
- ➢ v_2 show similar trends for all systems.
- ➢ v_2 is system dependent (shape).

$v_n(p_T)$

System size

$|\eta| < 1$ and $|\Delta\eta| > 0.7$

v_1^{even} vs p_T at fixed mean multiplicity for all systems



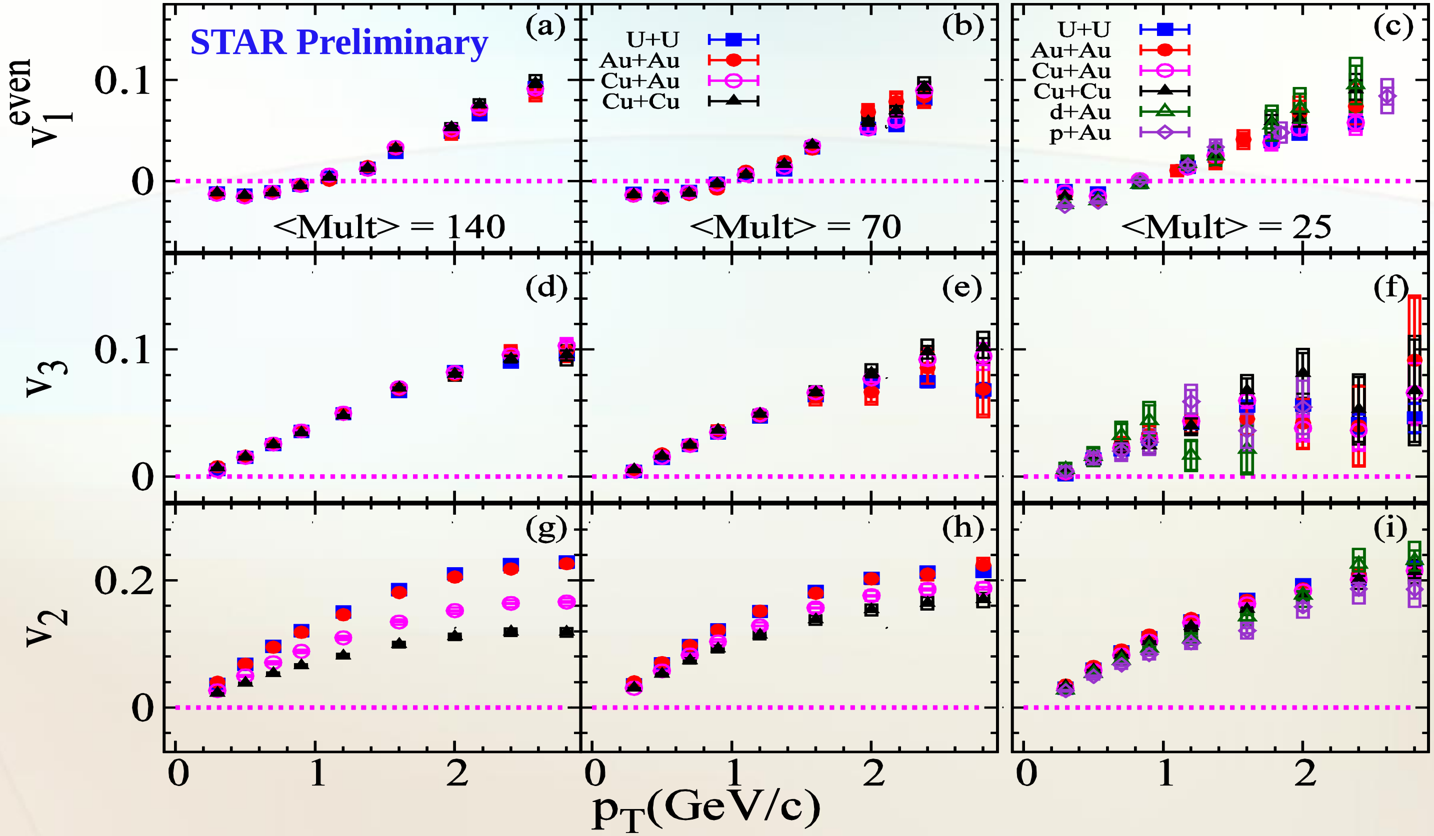
- ➢ v_1^{even} and v_3 show similar trends and magnitudes for all systems.
- ➢ v_1^{even} and v_3 *is* system independent (similar $\frac{\eta}{s}$).

$v_n(p_T)$

Summary

$|\eta| < 1$ and $|\Delta\eta| > 0.7$

v_n vs p_T at fixed mean multiplicity for all systems



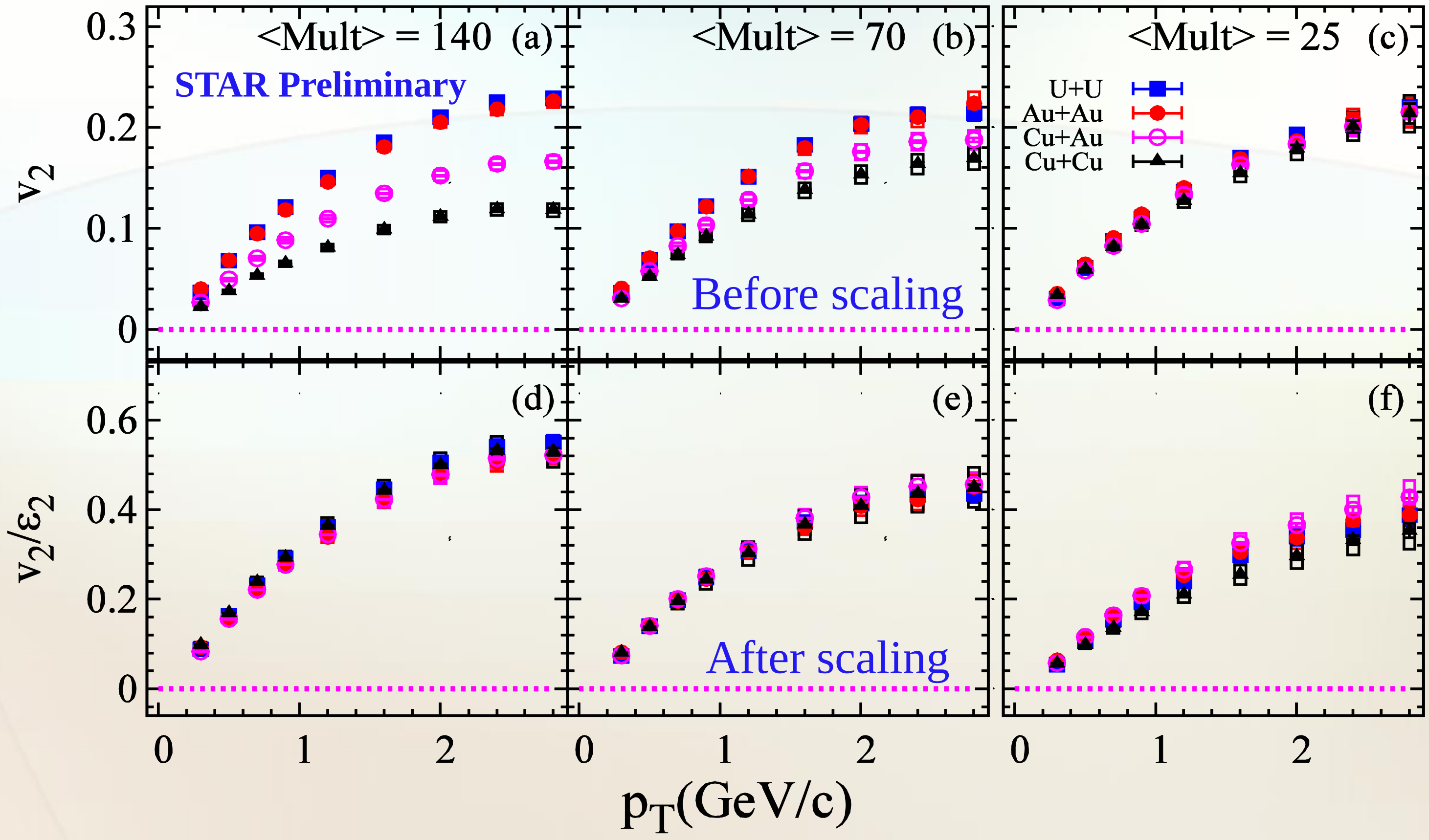
- For a given n, $v_n(p_T)$ show similar trends for all systems.
  - v_1^{even} and v_3 are system independent (similar $\frac{\eta}{s}$).
  - v_2 is system dependent (shape).

$v_n(p_T)$

System size and shape

$|\eta| < 1$ and $|\Delta\eta| > 0.7$

$\frac{v_2}{\epsilon_2}\, p_T$ dependence at fixed mean multiplicity for all systems



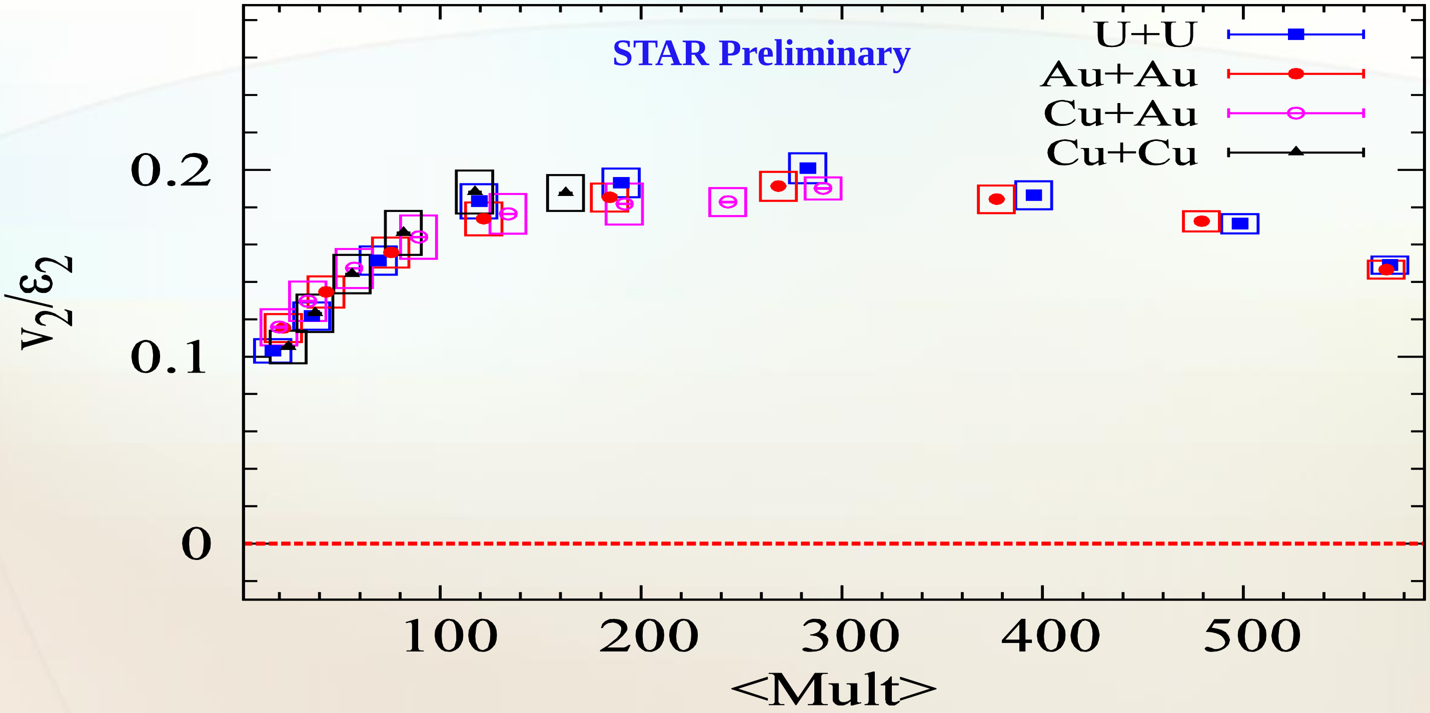
- ➢ $\frac{v_2}{\epsilon_2}(p_T)$ for all systems scales to a single curve.
- ➢ Similar $\frac{\eta}{s}$ for all systems.

$v_n(Mult)$

System size and shape

$|\eta| < 1$ and $|\Delta\eta| > 0.7$

$\frac{v_2}{\epsilon_2}$ mean multiplicity dependence for all systems



- $\frac{v_2}{\epsilon_2}(Mult)$ for all systems scales to a single curve.
- Similar $\frac{\eta}{s}$ for all systems.

III. Conclusion

Comprehensive set of STAR measurements presented for $v_n(p_T, Mult)$ for several collision systems.

- For all systems;
  - ✓ For n =1, v_1^{even} (p_T) shows the same characteristic behavior.
  - ✓ For n >1, v_n decreases with the harmonic order.

- Scaling the system size;
  - ✓ The odd harmonics $v_1^{even}$and v_3 are shape independent
  - ✓ $\frac{v_2}{\epsilon_2}$ for all systems scaled onto one curve
  - ✓ Final state ansatz hold for presented systems

Scaling features suggest that all presented systems have similar transport coefficient ($\frac{\eta}{s}$) at $\sqrt{s_{NN}} \sim 200\ GeV$

(final-state effect)

III. Conclusion

Answers to initial questions?

- Is the observed anisotropy in ion-ion collision final- or initial state effect?
  - ✓ Final state ansatz hold for presented systems (p+Au, d+Au, Cu+Cu, Cu+Au, Au+Au and U+U).

- What are the essential differences between the medium created in small (p+A) and large (A+A) collision systems?
  - ✓ Size and shape are system dependent.
  - ✓ Scaled results suggest similar ($\frac{\eta}{s}$) for p+Au, d+Au, Cu+Cu, Cu+Au, Au+Au and U+U.

- Is there a limiting size to lose final state effects ?
  - ✓ All presented systems show evidence for strong final state effects.

THANK YOU