Recent results of the azimuthal anisotropic flow measurements from STAR experiment

Initial Stages 2017

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

Data Studied

- Collected data for Au+Au at $\sqrt{s_{NN}} = 200 - 7.7\ GeV$

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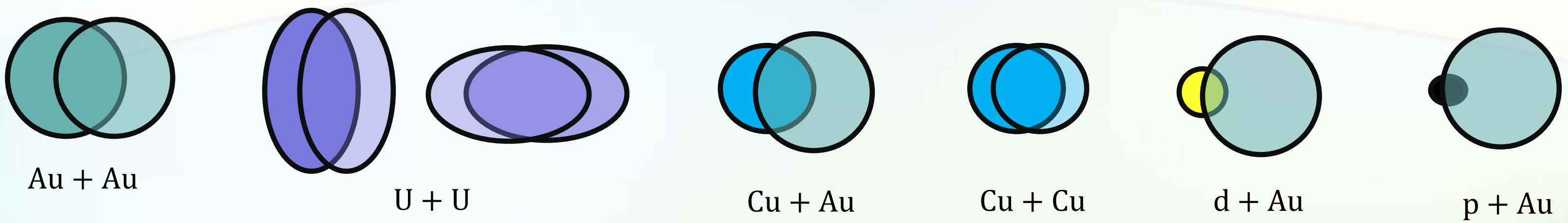

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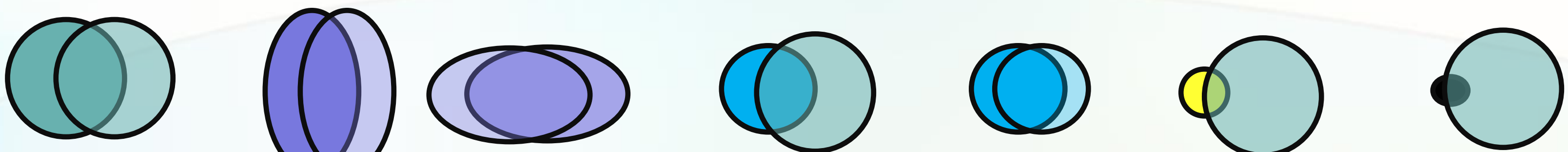
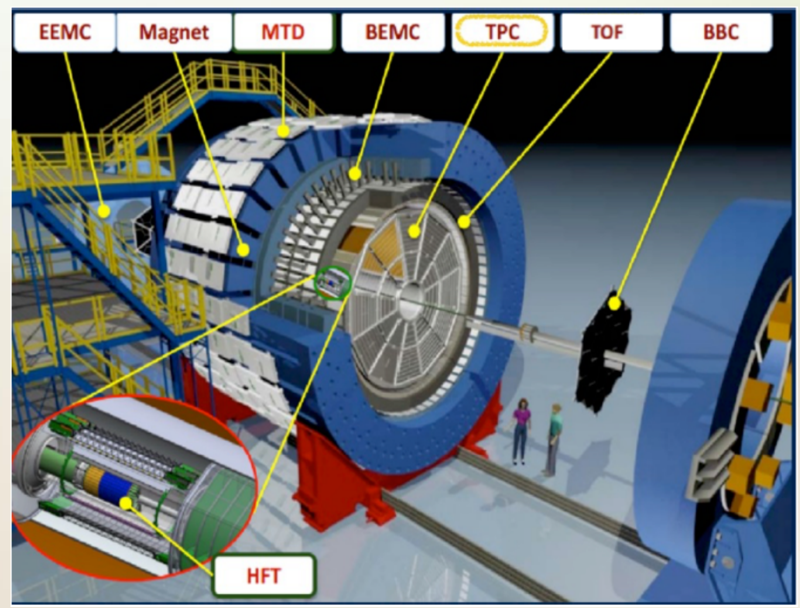


STAR Detector at RHIC

- TPC detector mainly get used in the current analysis



Azimuthal anisotropy measurements

Correlation function

Two-particle correlation function $Cr(\Delta\varphi = \varphi_{\mathrm{a}} - \varphi_b)$,

$$Cr(\Delta\varphi) = dN/d\Delta\varphi \quad \text{and} \quad v_n^{ab} = \frac{\sum_{\Delta\varphi} Cr(\Delta\varphi)\cos(n\,\Delta\varphi)}{\sum_{\Delta\varphi} Cr(\Delta\varphi)}$$

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Flow

Non-flow

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$n > 1$

$$v_n^{ab} = v_n^a v_n^b + \delta_{short}$$

Flow

$n = 1$

$$v_1^{ab} = v_1^a v_1^b + \delta_{long}$$

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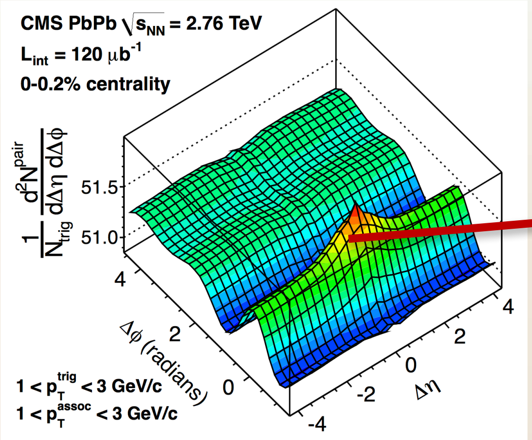

Short − range

Azimuthal anisotropy measurements

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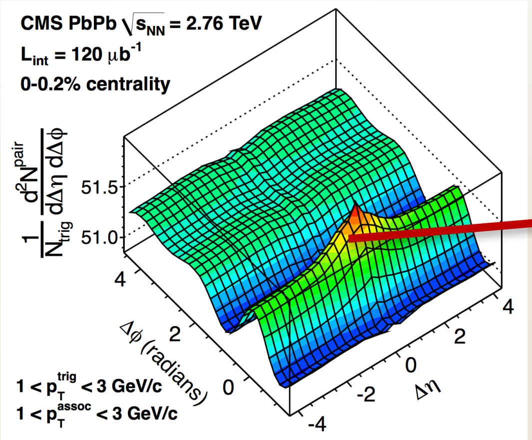

Short − range

HBT

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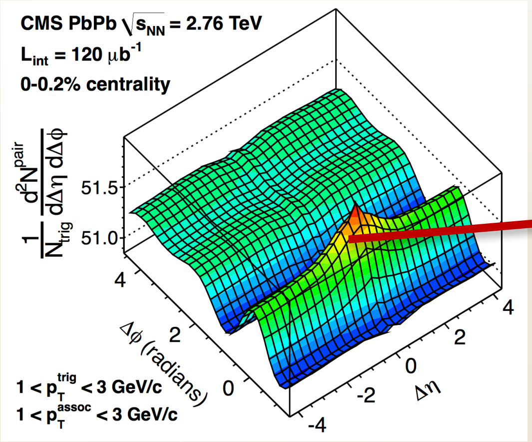

Short – range

HBT

Decay

Charge

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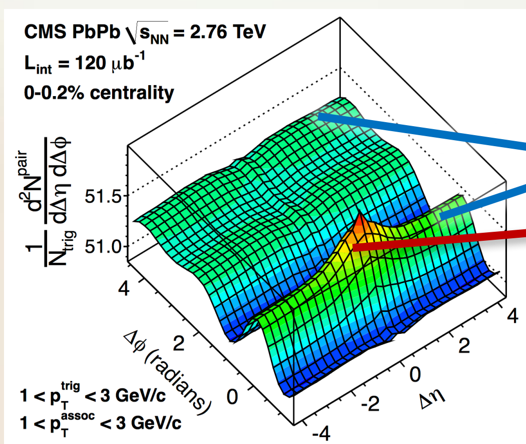

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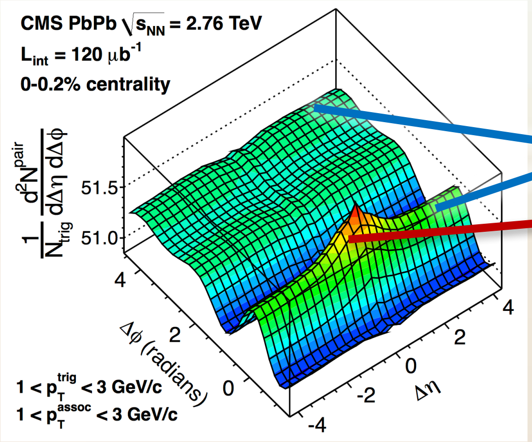

Long − range

Short − range

Momentum Conservation

HBT

Decay

Charge

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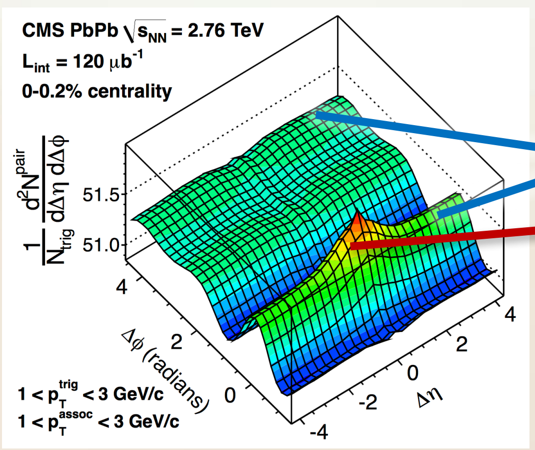


Long − range

Short − range

Momentum Conservation

HBT

Di−jets

Decay

Charge

Non-flow suppression is needed

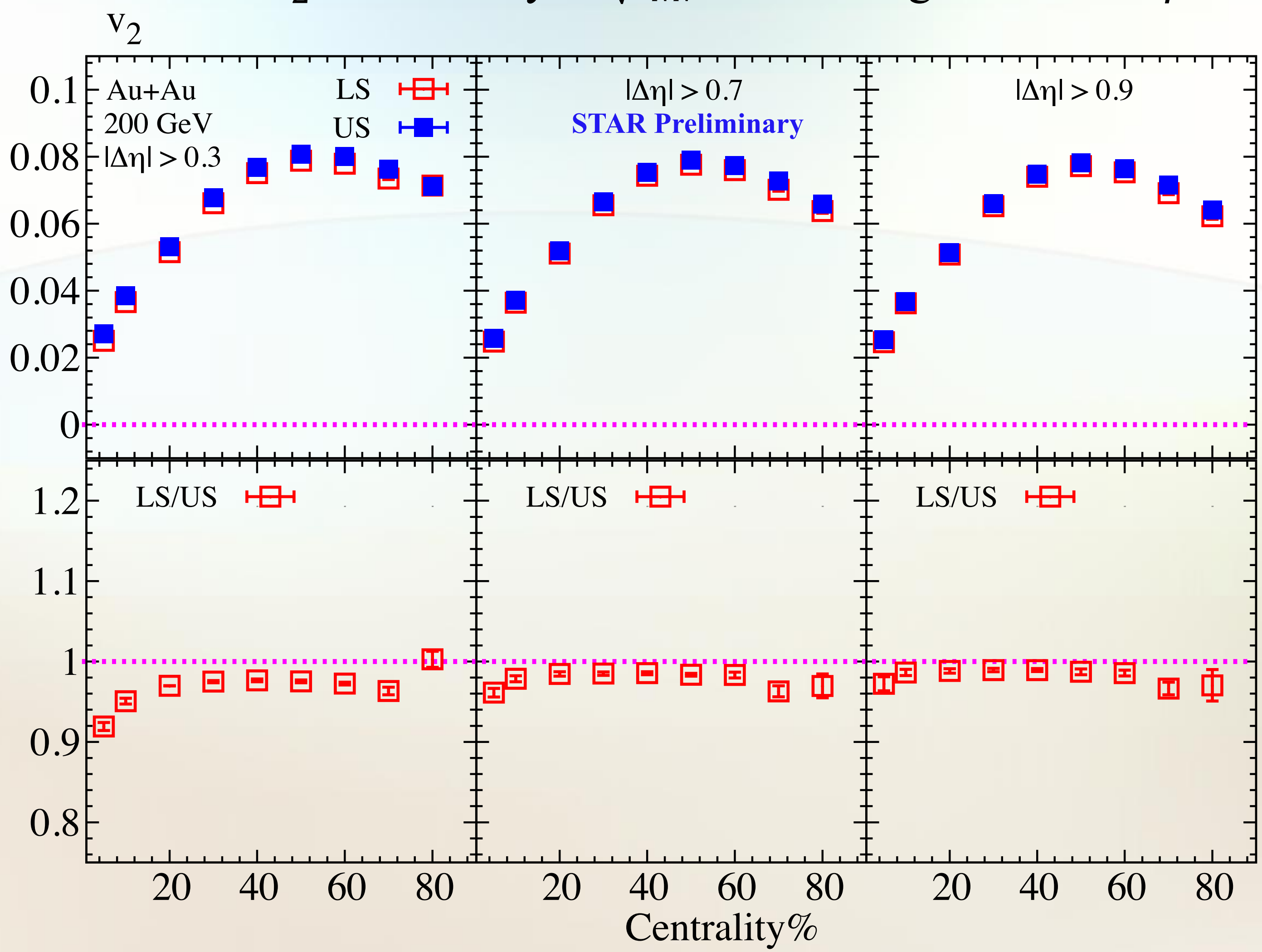
Short-range non-flow suppression

Short – range Non–flow

HBT

Decay

The v_2 vs centrality at $\sqrt{s_{NN}} = 200$ using different $\Delta\eta$ cuts



- Short-range non-flow effect get reduced using $|\Delta\eta| > 0.7$ cut

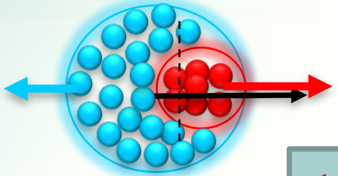
Long-range non-flow suppression

Long − range

Momentum Conservation

arXiv:1203.0931
arXiv:1203.3410
arXiv:1208.1874
arXiv:1208.1887
arXiv:1211.7162

$$v_1^{ab} = v_1^a v_1^b + \delta_{long} \quad n = 1$$



1

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

$C \propto (< Mult >)^{-1}$

Long – range

Long-range non-flow suppression

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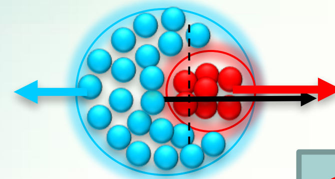

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v_{11} in Eq(1) represents NxM matrix which we fit with N+1 parameters

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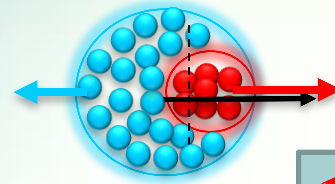

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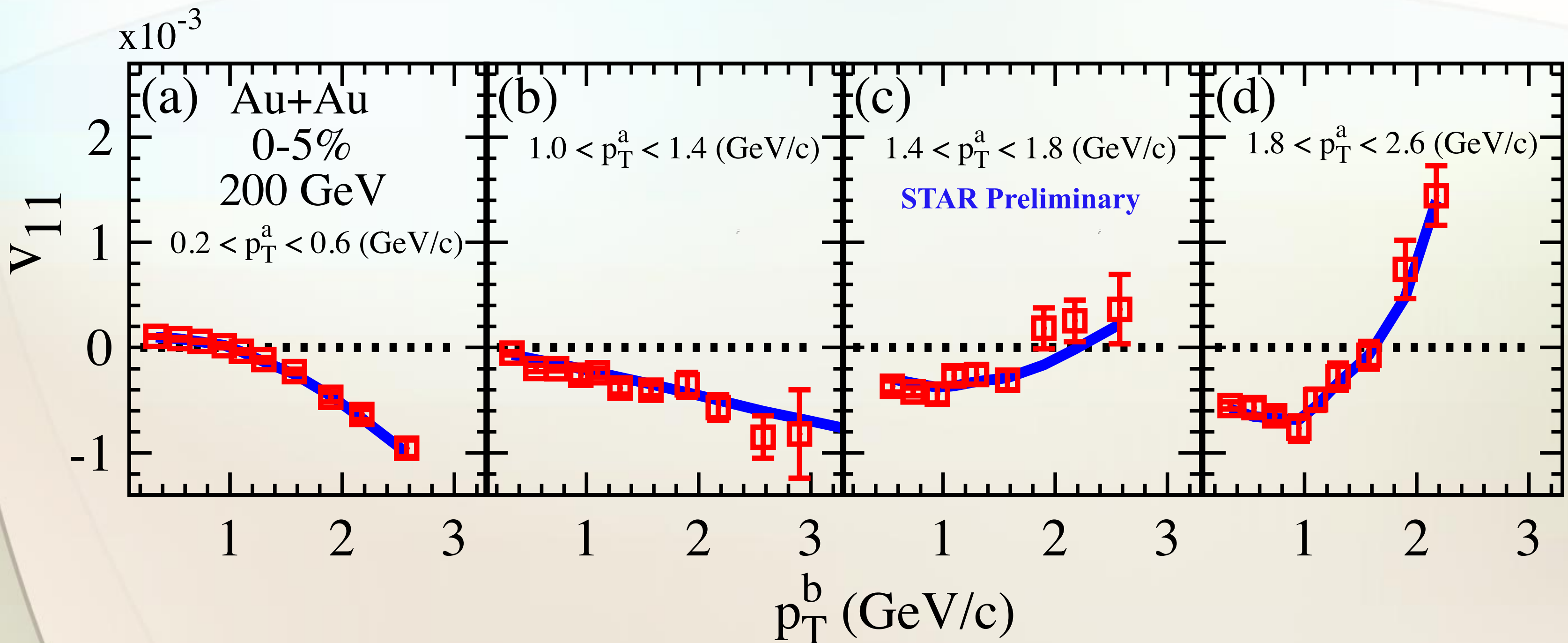

- Good simultaneous fit ($\frac{\chi^2}{ndf} \sim 1.1$) obtained with Eq. 1

Long – range

Momentum Conservation

Long-range non-flow suppression

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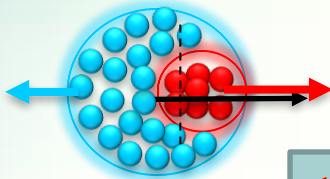

$$v_{11}(p_T^a, p_T^b) = v_1^{even}(p_T^a) v_1^{even}(p_T^b) - C\, p_T^a\, p_T^b \quad (1)$$

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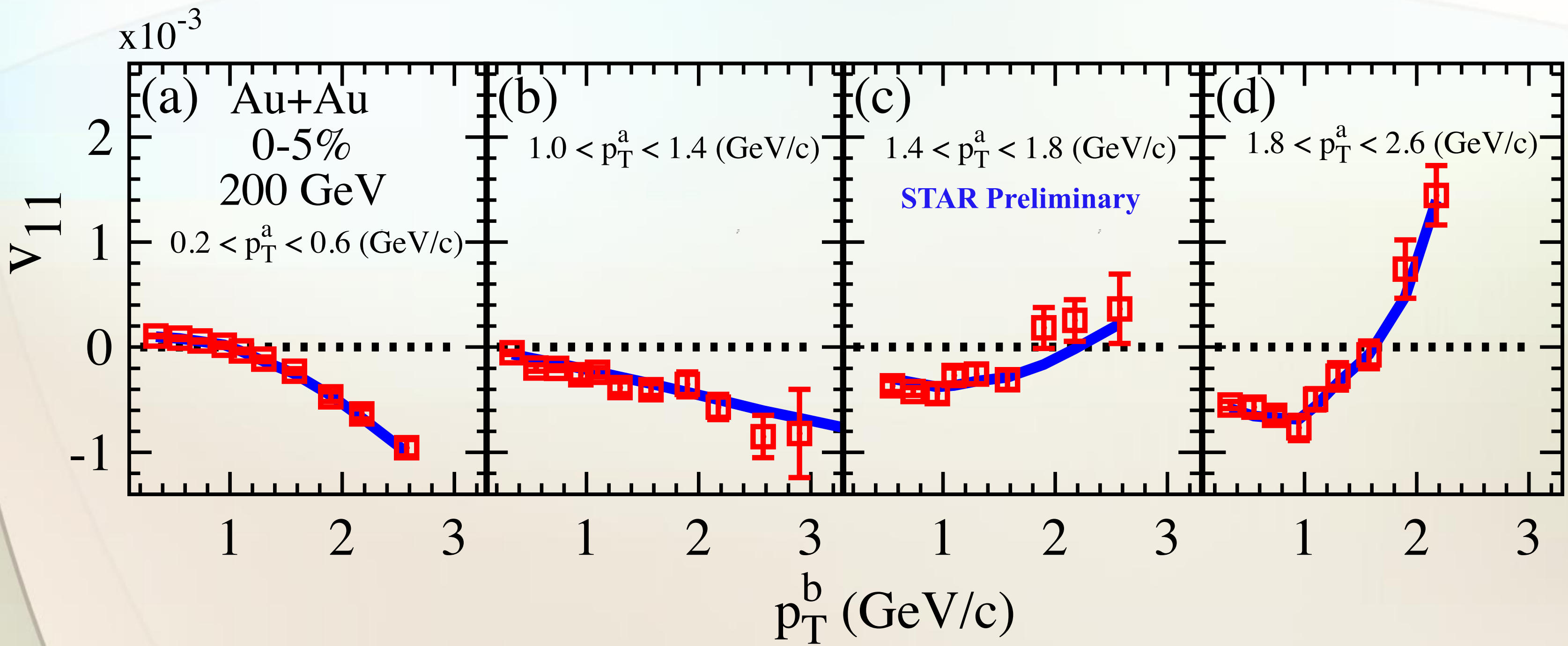


- Good simultaneous fit ($\frac{\chi^2}{ndf} \sim 1.1$) obtained with Eq. 1
- v_{11} characteristic behavior gives a good constraint for $\boldsymbol{v_1^{even}}(\mathbf{p_T})$ extraction

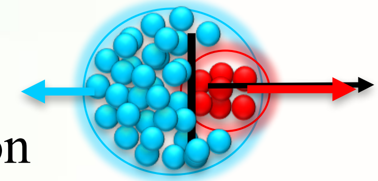
Long − range

Momentum Conservation

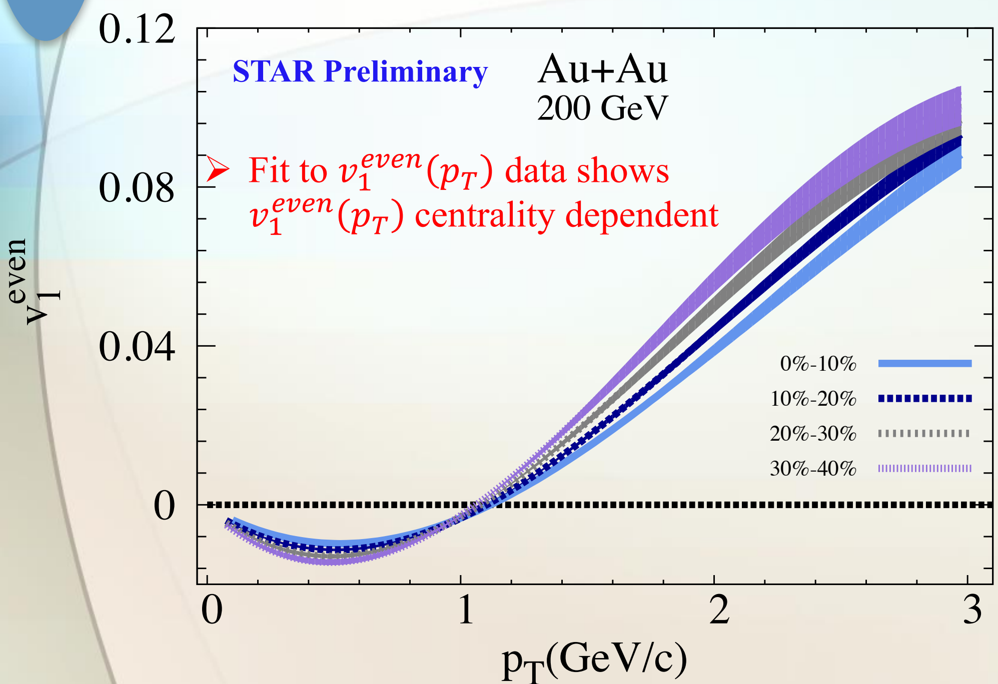
Long-range non-flow suppression

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

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



The extracted $v_1^{even}(p_T)$ and the momentum conservation parameter C at $\sqrt{s_{NN}} = 200$



➢ The characteristic behavior of $v_1^{even}(p_T)$ shows a weak centrality dependence

Long – range

Momentum Conservation

Long-range non-flow suppression

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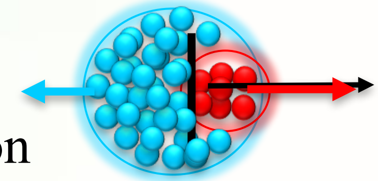
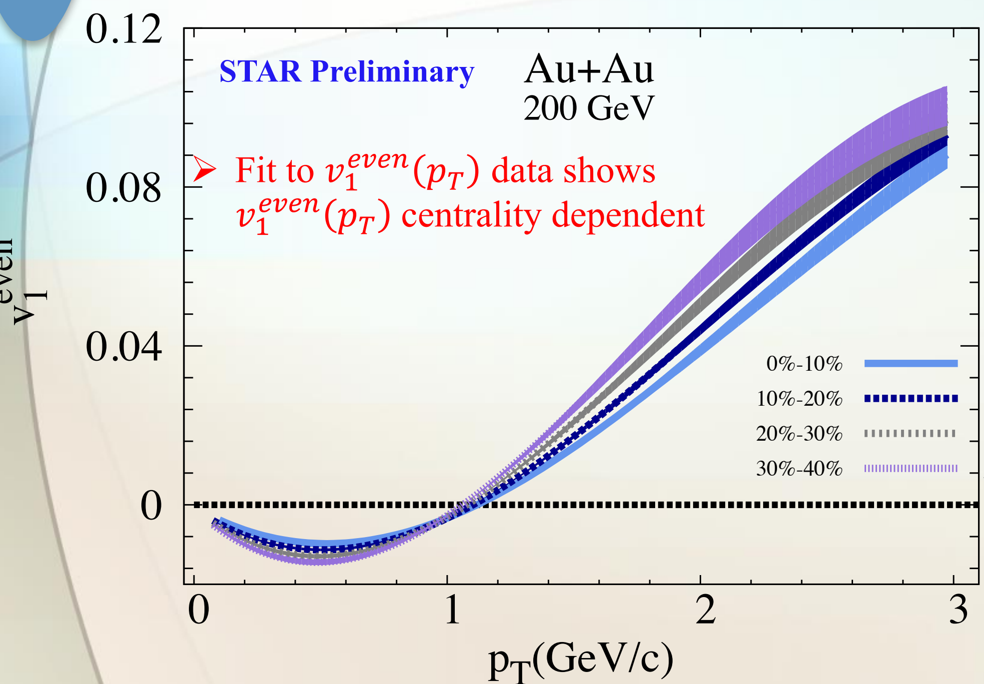
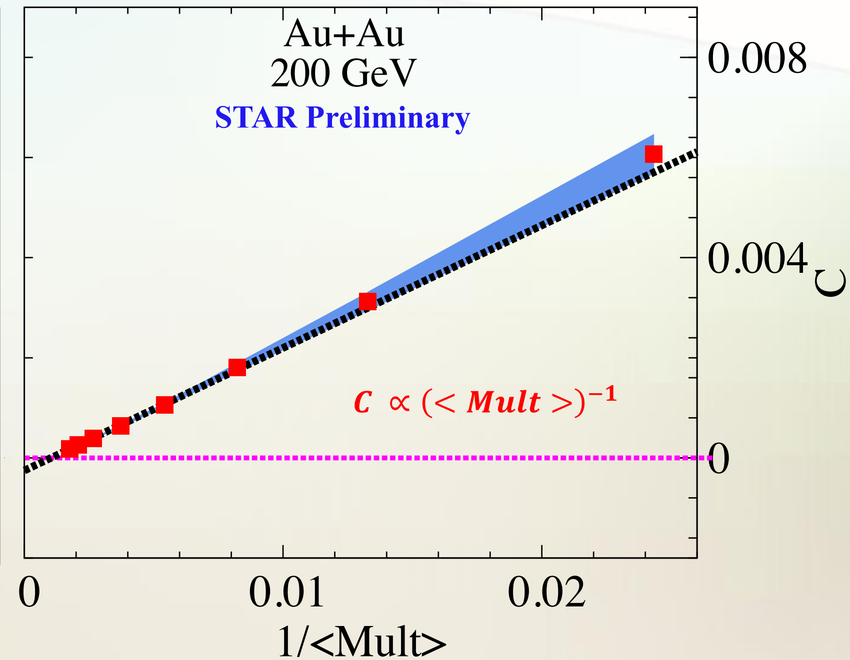
$$\mathbf{v_{11}}\left(p_T^a, p_T^b\right) = v_1^{even}(p_T^a)\, v_1^{even}(p_T^b) - C\, p_T^a\, p_T^b$$



The extracted $\boldsymbol{v_1^{even}(p_T)}$ and the momentum conservation parameter C at $\sqrt{s_{NN}} = 200$





- The characteristic behavior of $v_1^{even}(p_T)$ shows a weak centrality dependence
- The momentum conservation parameter C scales as $< \boldsymbol{Mult} >^{-1}$

Non-flow suppression

Long − range

Short − range

Momentum Conservation

HBT

Di−jets

Decay

- η gap between particles in each pair used to suppress the short-range non-flow

Non-flow suppression

Long − range	Short − range
Momentum Conservation	HBT
Di−jets	Decay

- η gap between particles in each pair used to suppress the short-range non-flow
- Simultaneous fit used to suppress long-range non-flow associated with momentum conservation

Non-flow suppression

Long – range

Momentum Conservation

Di-jets

Short – range

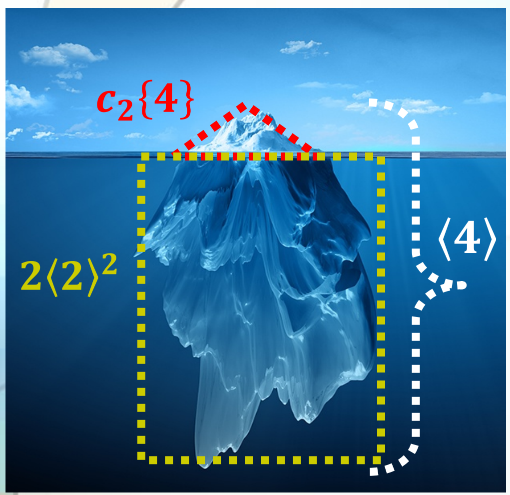
HBT

Decay

- η gap between particles in each pair used to suppress the short-range non-flow
- Simultaneous fit used to suppress long-range non-flow associated with momentum conservation
- Multi-particle correlations also used to further suppress non-flow

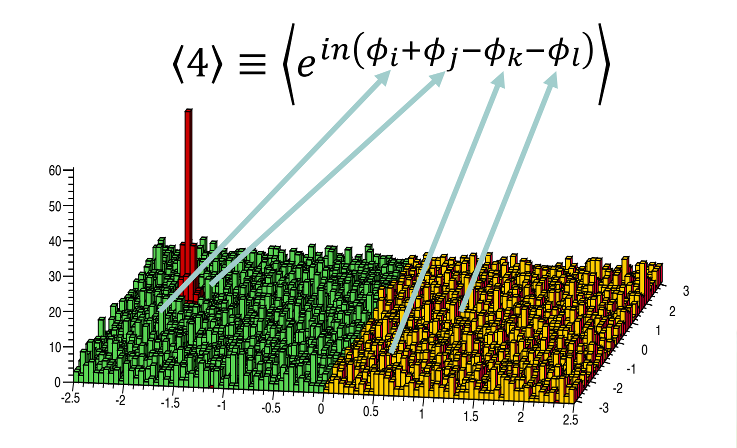
Multi-particle correlations and the non-flow suppression

$c_2\{4\} \equiv \langle 4\rangle - 2\langle 2\rangle^2$



In the subevent method, particles are correlated across all subevents (long-range)

Short-range non-flow dominate



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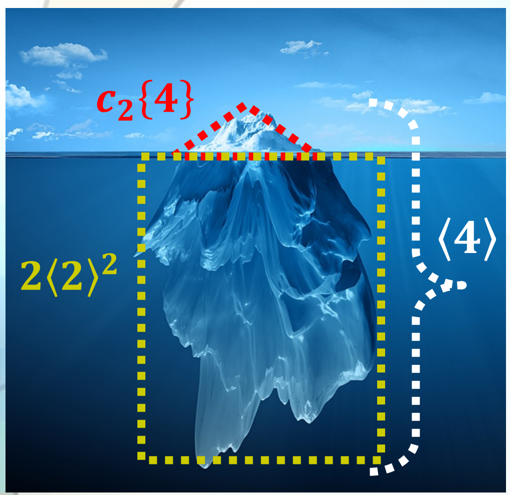
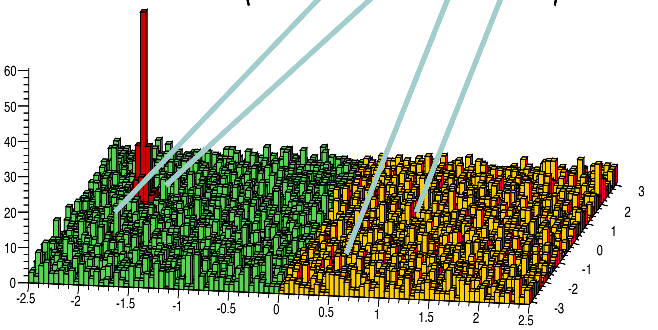


In the subevent method, particles are correlated across all subevents (long-range)

Three subevent cumulant can further suppress away-side jet contribution

Short-range non-flow dominate

$\langle 4 \rangle \equiv \left\langle e^{in(\phi_i+\phi_j-\phi_k-\phi_l)} \right\rangle$



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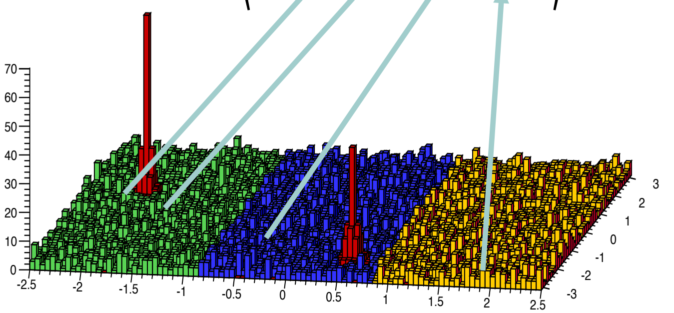

arXiv: 1701.03830

Multi-particle correlations and the non-flow suppression

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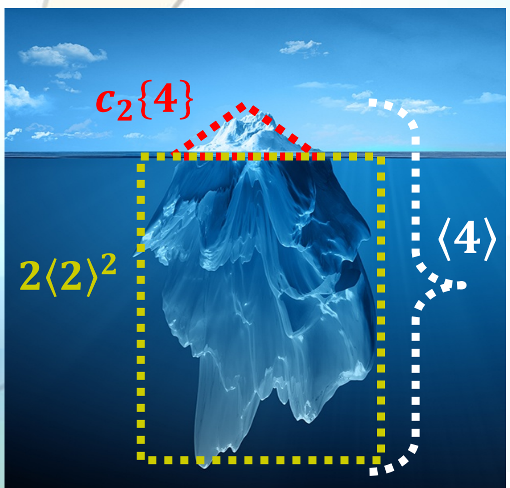
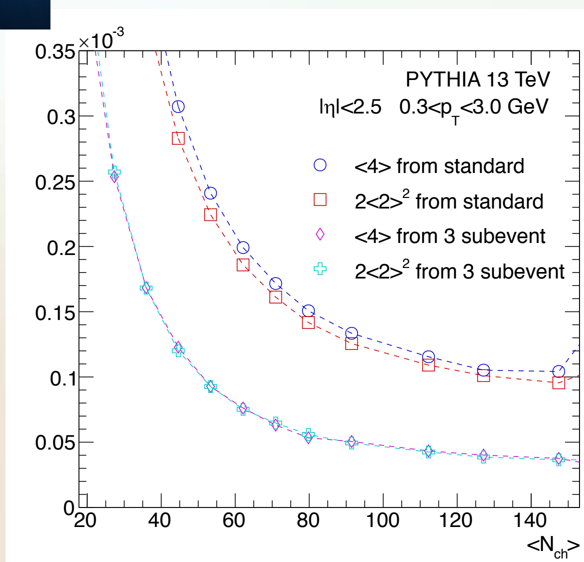


In the subevent method, particles are correlated across all subevents (long-range)

Three subevent cumulant can further suppress away-side jet contribution

Both $\langle 4 \rangle$ and $2\langle 2 \rangle^2$ are much smaller with subevent



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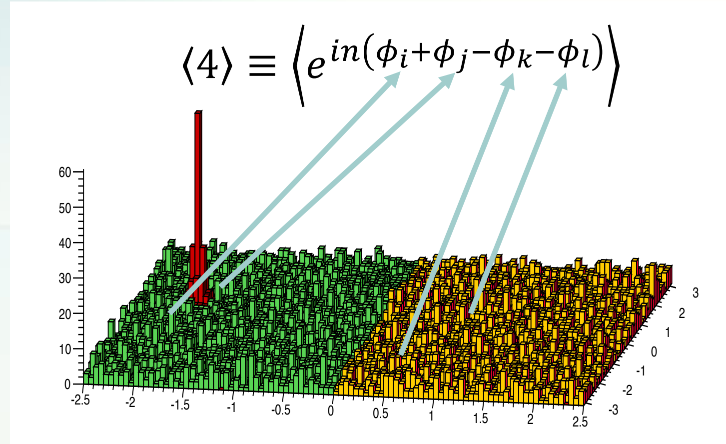

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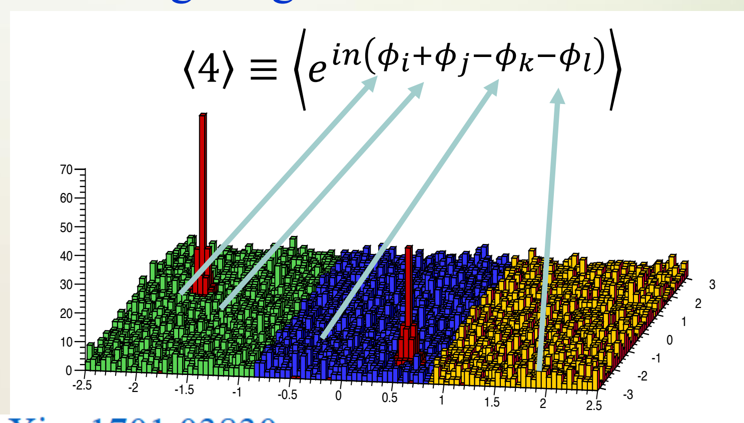


arXiv: 1701.03830

Subevent cumulant measures long-range collectivity.

Results

Au+Au Beam Energy Scan

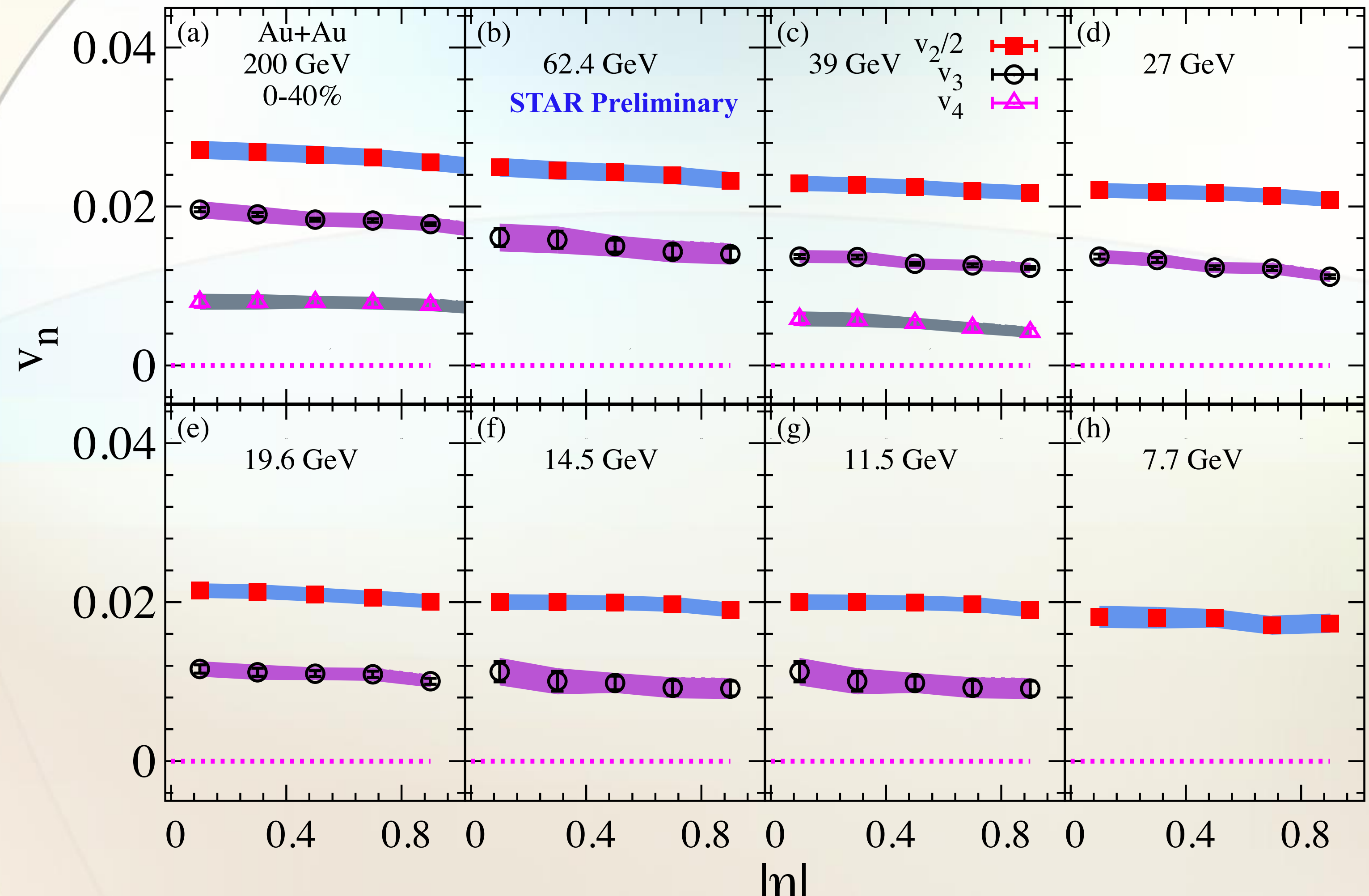
$v_n(\eta)$

$v_n(\sqrt{s_{NN}})$

Pseudorapidity dependence of $v_{n>1}$

$|\eta| < 1$ and $|\Delta\eta| > 0.7$
$0.2 < p_T < 4\ GeV/c$

The extracted $v_{n>1}(\eta)$ at all BES energies



- $v_n(\eta)$has similar trends for different beam energies.
- $v_n(\eta)$decreases with harmonic order n.

Pseudorapidity dependence of $v_{n>1}$

The extracted $v_{n>1}(\eta)$

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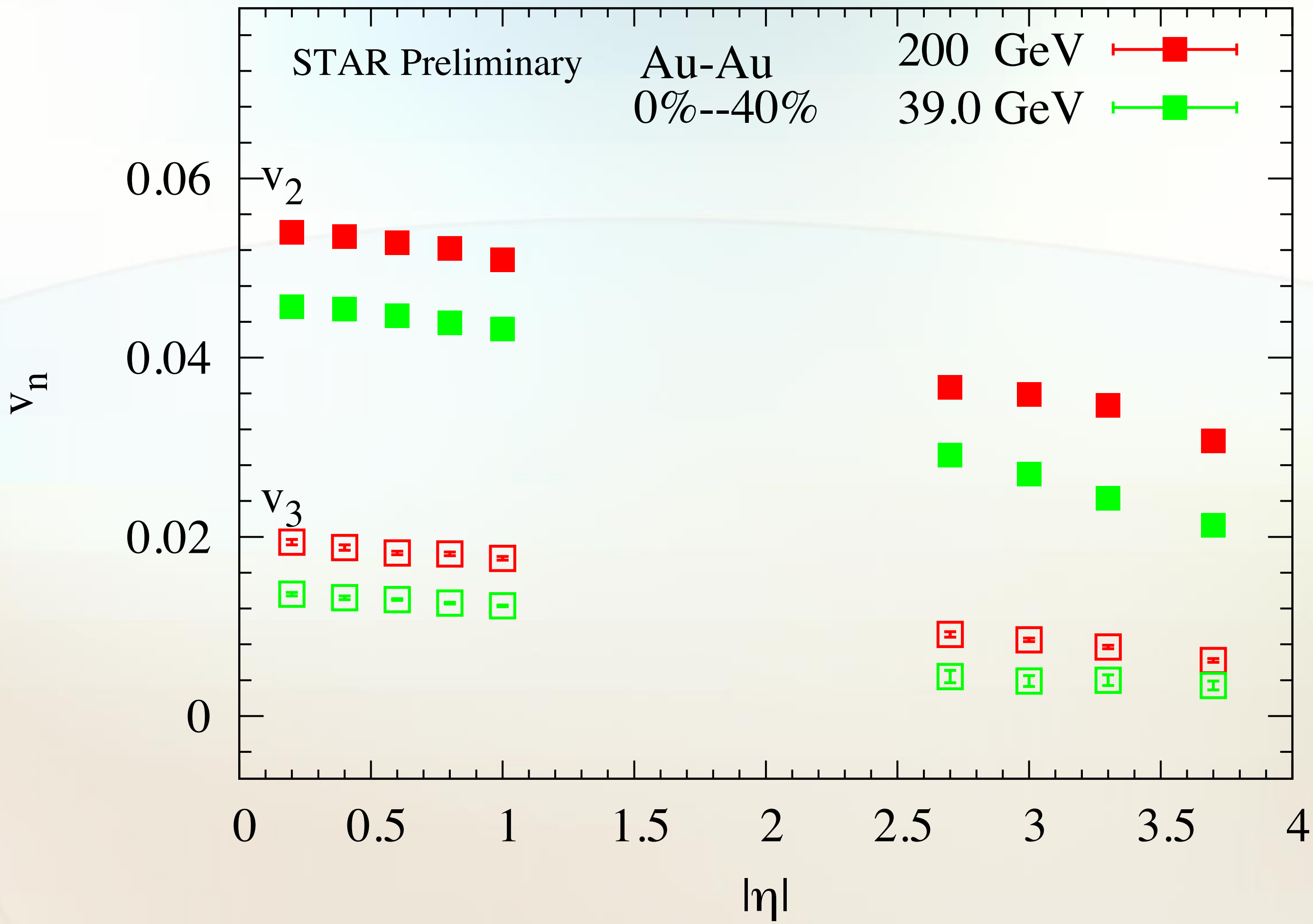
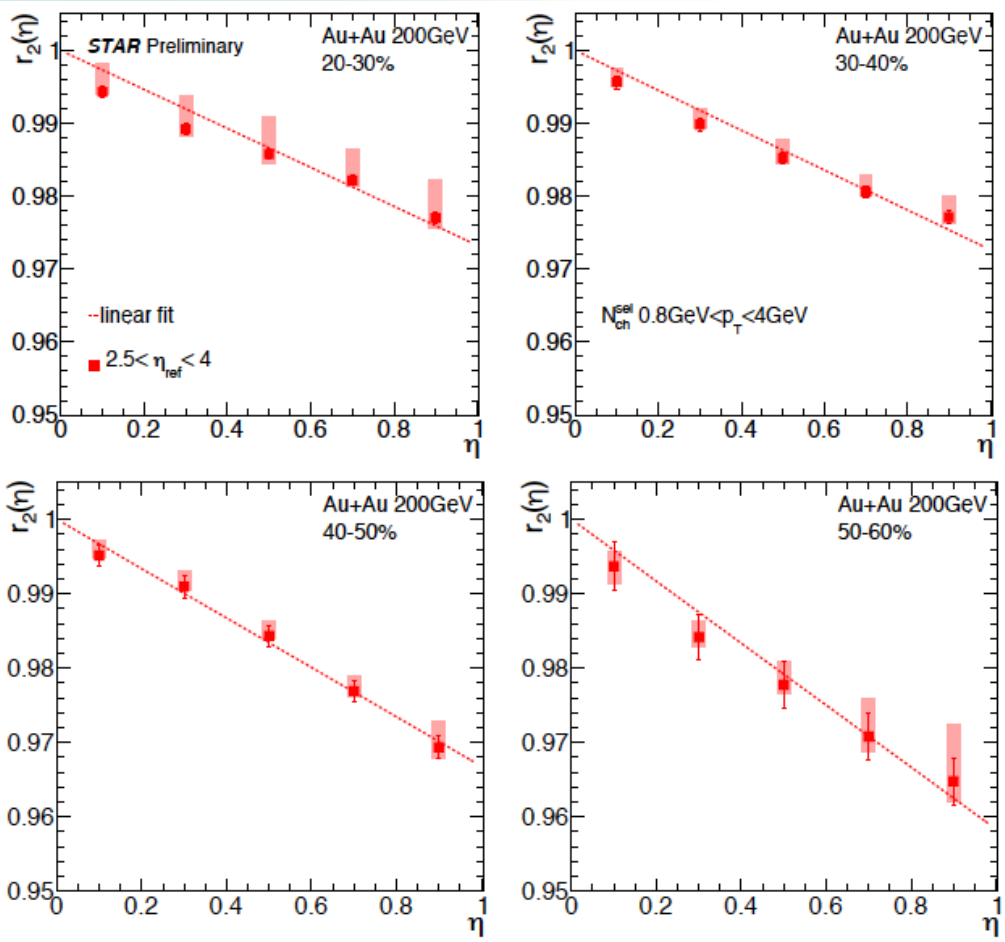


- $v_n(\eta)$ has similar trends for different beam energies.
- $v_n(\eta)$ decreases with harmonic order n.

Longitudinal decorrelation of v_2 in Au+Au 200 GeV

$$r_n(\eta) = \frac{\langle \boldsymbol{v}_n(-\eta)\boldsymbol{v}_n^*(\eta_{\rm ref})\rangle}{\langle \boldsymbol{v}_n(\eta)\boldsymbol{v}_n^*(\eta_{\rm ref})\rangle}$$

- $r_n(\boldsymbol{\eta})$ decrease linearly for different centrality studied



Longitudinal decorrelation of v_2 in Au+Au 200 GeV

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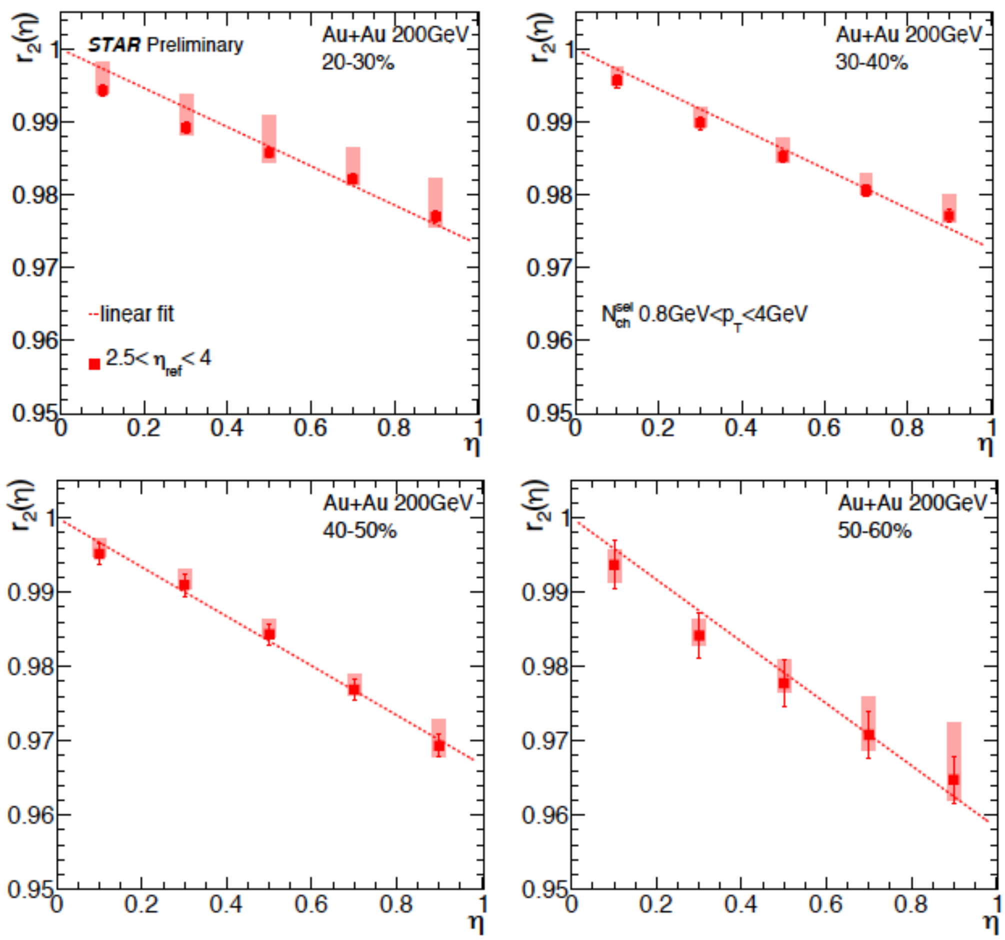


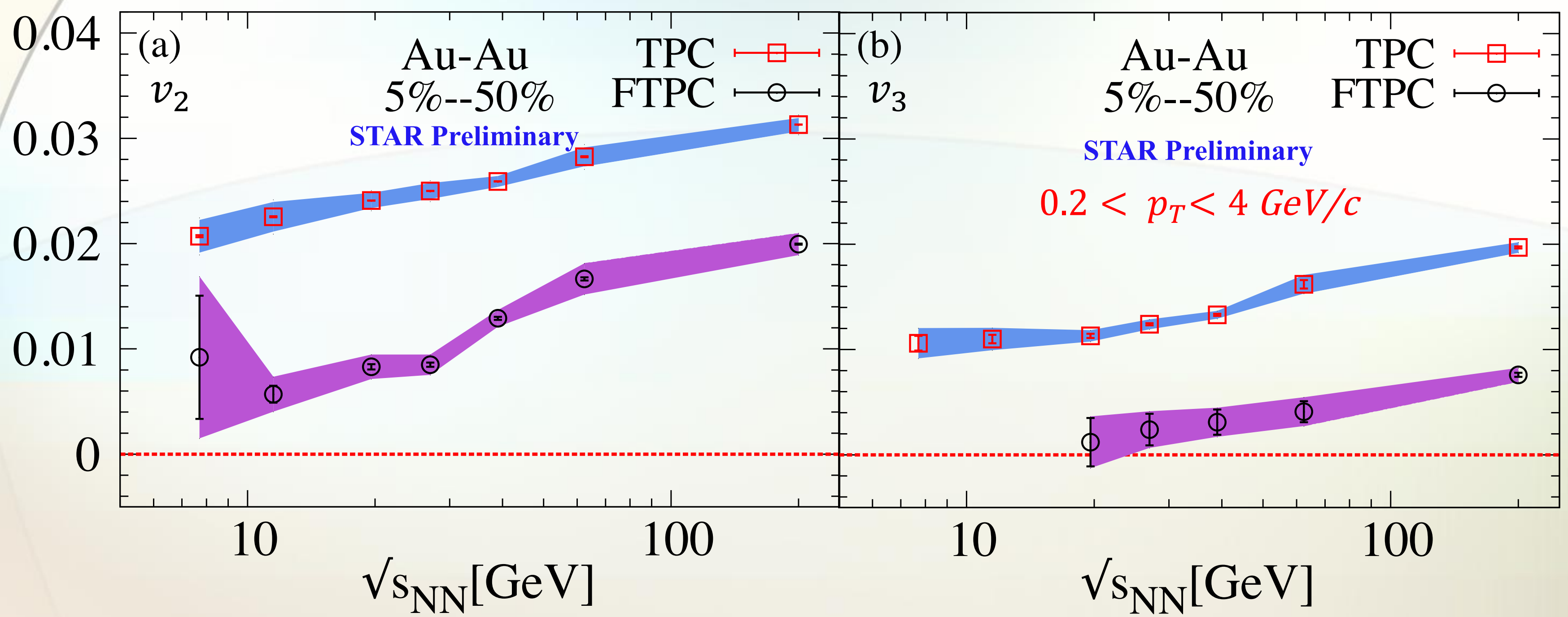
- $r_n(\boldsymbol{\eta})$ decrease linearly for different centrality studied

- The decorrelation effect gets stronger as the collision become more peripheral

- More information will be given today by Maowu Nie

Beam-energy dependence of $v_{n>1}$

The extracted $v_{n>1}$ vs $\sqrt{s_{NN}}$ for TPC($|\eta| < 1$) and FTPC($2.5 < |\eta| < 4$)



- At mid and forward rapidity;
  - ✓ $v_n(\sqrt{s_{NN}})$ shows a monotonic increase with beam-energy.
  - ✓ $v_n(\sqrt{s_{NN}})$ decreases with harmonic order n (viscous effects).

Summary-1

- η gap between particles in each pair used to suppress the short-range non-flow

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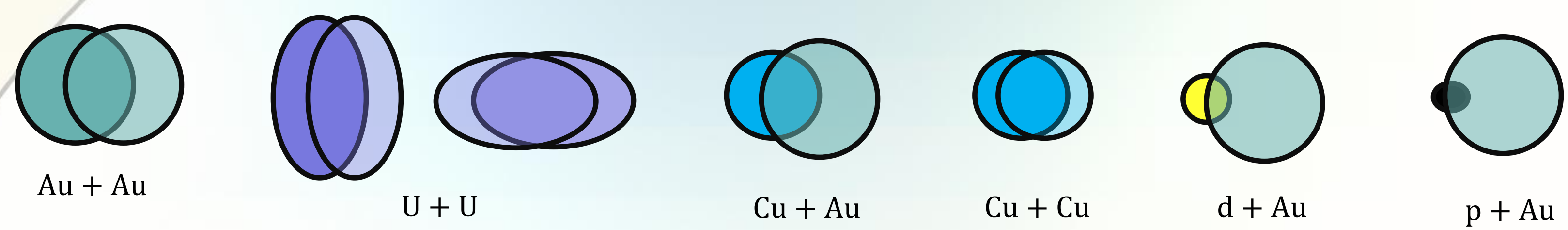
- η gap between particles in each pair used to suppress the short-range non-flow
- Simultaneous fit used to suppress long-range non-flow associated with momentum conservation
- The longitudinal decorrelation of v_2 was observed for Au+Au at 200 GeV

Summary-1

- η gap between particles in each pair used to suppress the short-range non-flow
- Simultaneous fit used to suppress long-range non-flow associated with momentum conservation
- The longitudinal decorrelation of v_2 was observed for Au+Au at 200 GeV
- At mid and forward rapidity;
  - ✓ $v_n(\sqrt{s_{NN}})$ shows a monotonic increase with beam-energy.
  - ✓ $v_n(\sqrt{s_{NN}})$ decreases with harmonic order n (viscous effects).

Collectivity in small systems

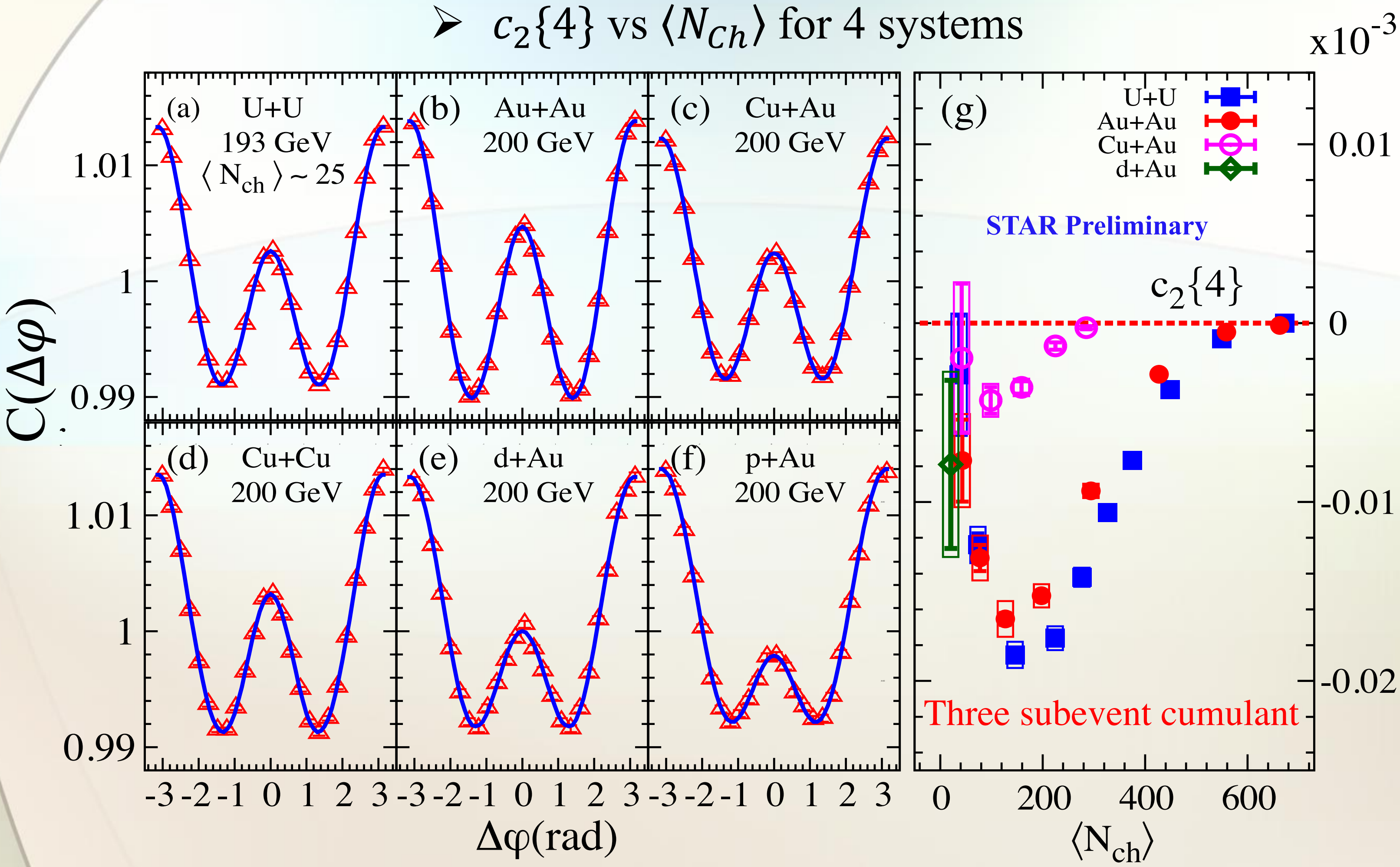


$v_n(p_T)$

$v_n\{2,4\}(N_{ch})$

Collectivity in small systems

- The correlation function C($\Delta\varphi$) for all systems at one $\langle N_{ch} \rangle$ value
- $c_2\{4\}$ vs $\langle N_{ch} \rangle$ for 4 systems



- C($\Delta\varphi$) shows similar trend for all systems
- $c_2\{4\}$ shows negative value for different systems

Acoustic ansatz

PRC 84, 034908 (2011)
P. Staig and E. Shuryak.

PRC 88, 044915 (2013)
E. Shuryak and I. Zahed

arXiv:1305.3341
Roy A. Lacey, et al.

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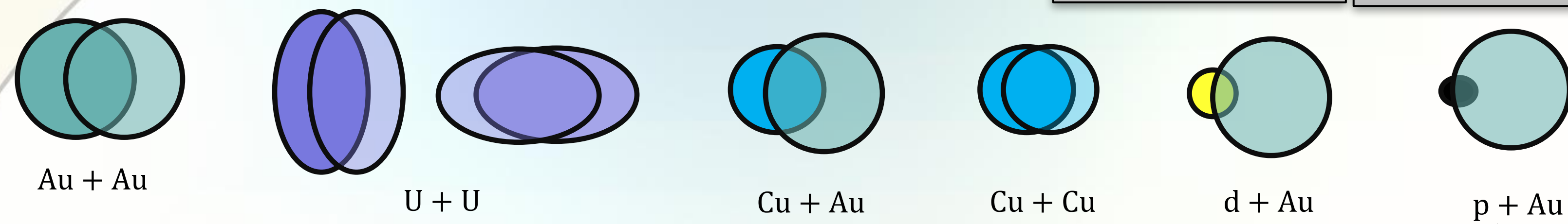

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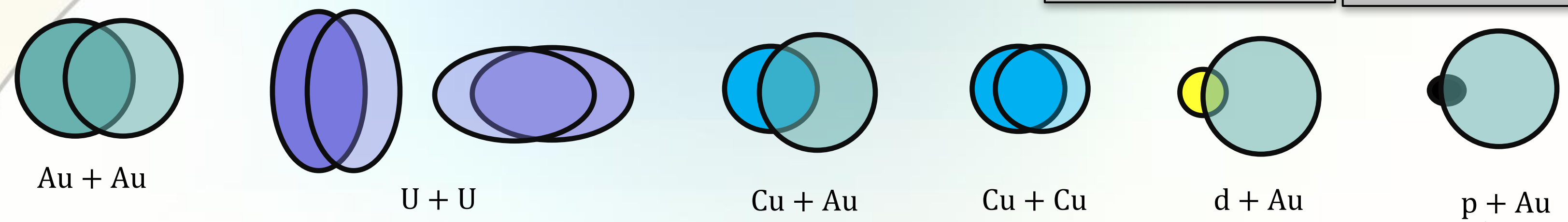

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$$v_n/\epsilon_n \propto e^{-A\left(\frac{\eta}{s}\frac{n^2}{RT}\right)}$$

A is a constant

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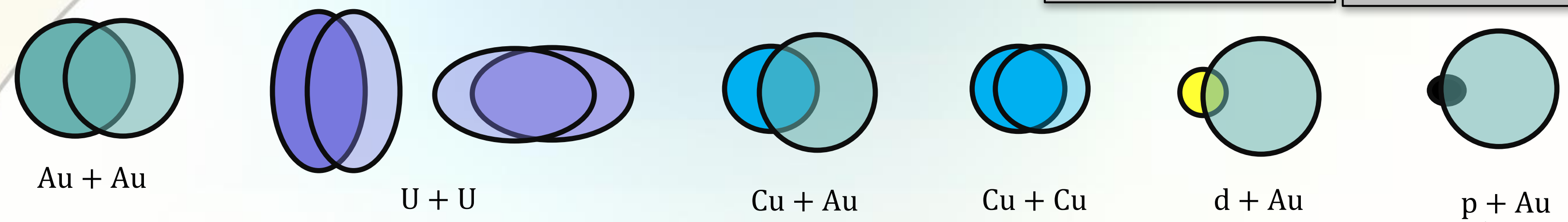

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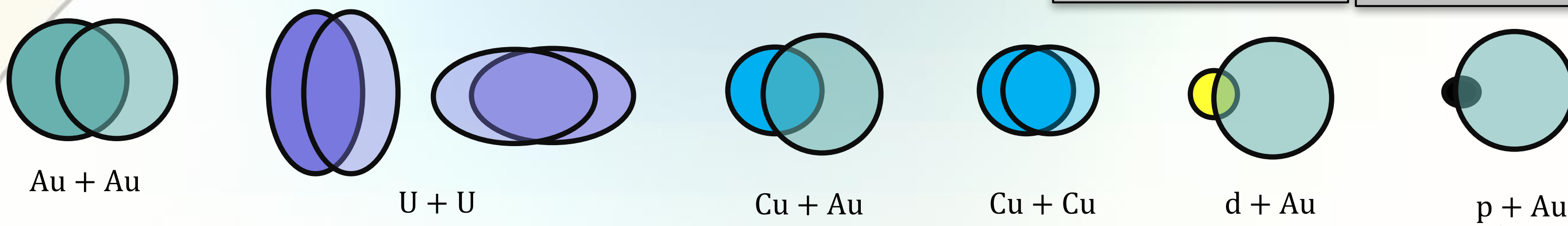

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At the same $\frac{\eta}{s}$ *and* $\langle N_{Ch} \rangle^{-1/3}$

$$v_n \xrightarrow{\text{driven by}} \varepsilon_n + \dots$$

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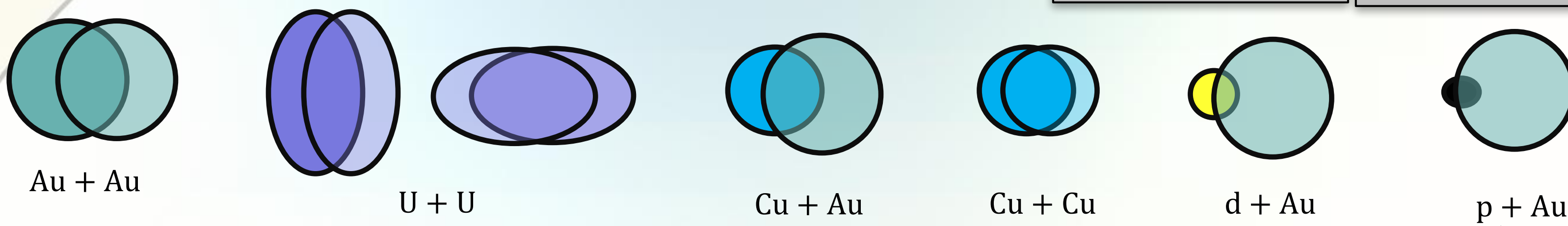

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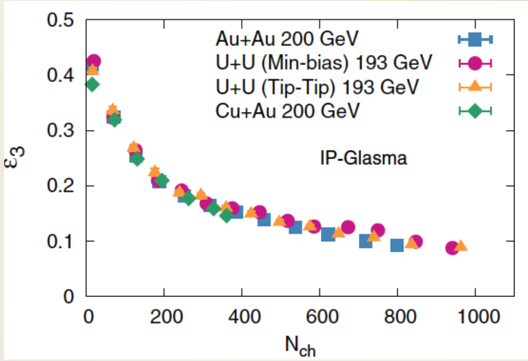
Odd Harmonic v_3

$$\varepsilon_3 \propto \frac{1}{\sqrt{N}}$$



B.Schenke, et al.
PRC 89, 064908 (2014)

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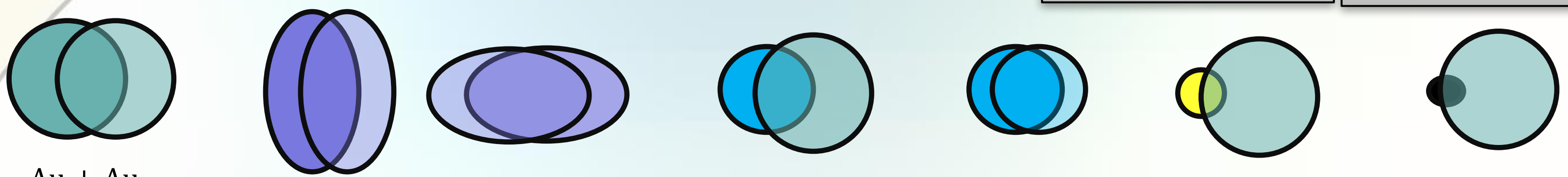

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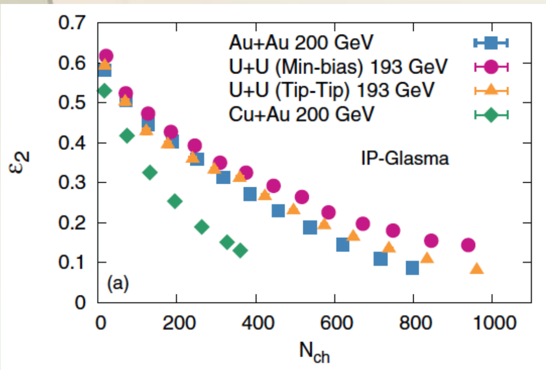
Even Harmonic v_2

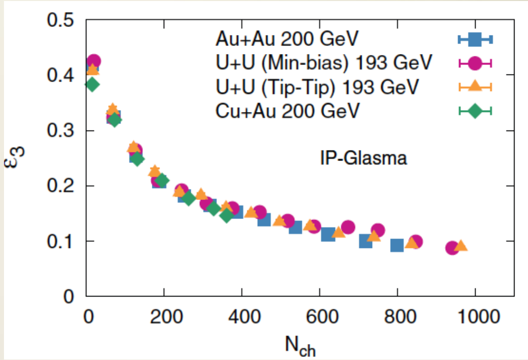
ε_2 scaling is needed



B.Schenke, et al.
PRC 89, 064908 (2014)

Odd Harmonic v_3

$$\varepsilon_3 \propto \frac{1}{\sqrt{N}}$$



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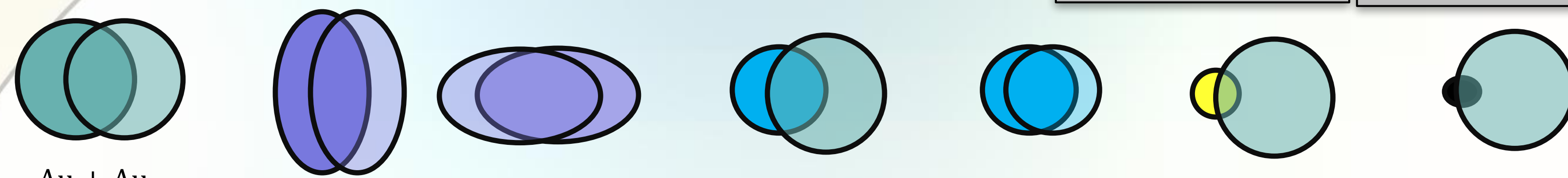

Au + Au U + U Cu + Au Cu + Cu d + Au p + Au

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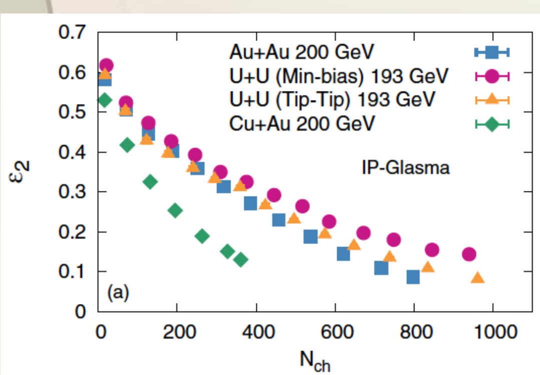

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PRC 89, 064908 (2014)

At the same $\frac{\eta}{s}$ and $\langle N_{Ch}\rangle^{-1/3}$

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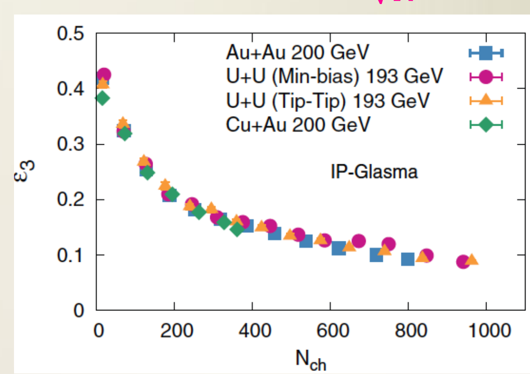
Expectations

- v_1^{even} and v_3 are system independent
- v_2 is system dependent

Odd Harmonic v_3

$$\varepsilon_3 \propto \frac{1}{\sqrt{N}}$$



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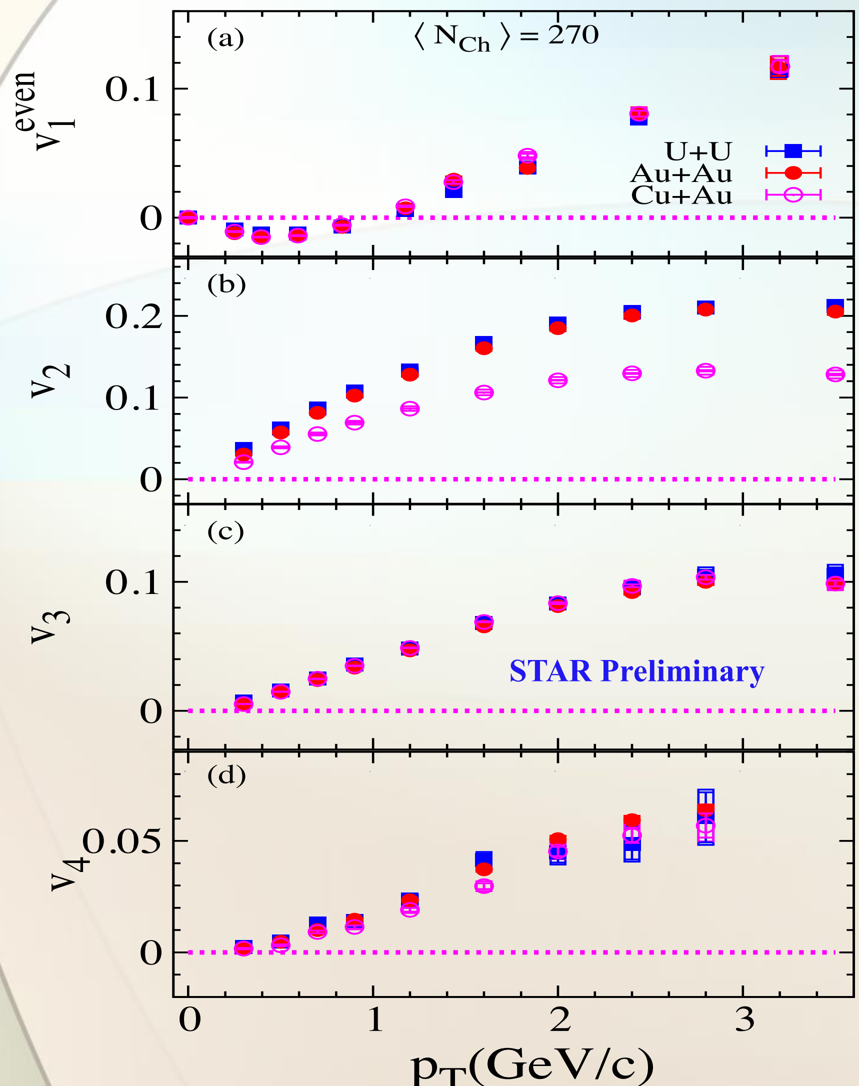
v_n for large systems (A + B)

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

v_n vs p_T at fixed $\langle N_{Ch} \rangle = 270$



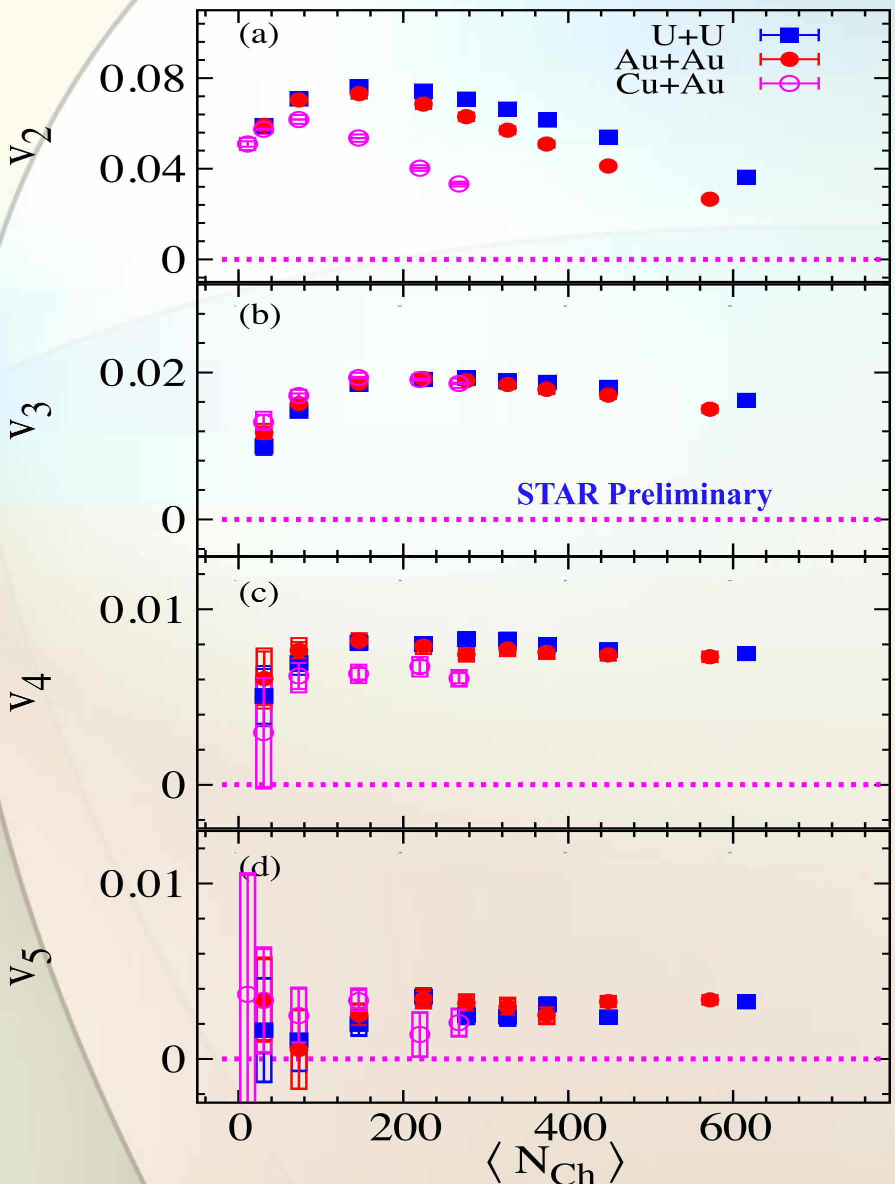
$$ln\left(\frac{v_n}{\varepsilon_n}\right) \propto -A\,(\eta/s)\langle N_{Ch}\rangle^{-1/3}$$

- Odd harmonics are system independent.
- Even harmonics are system dependent, with weak system dependence for the higher harmonics

v_n for large systems $(A + B)$

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

v_n vs $\langle N_{Ch} \rangle$ at fixed p_T[0.2:4 GeV/c]



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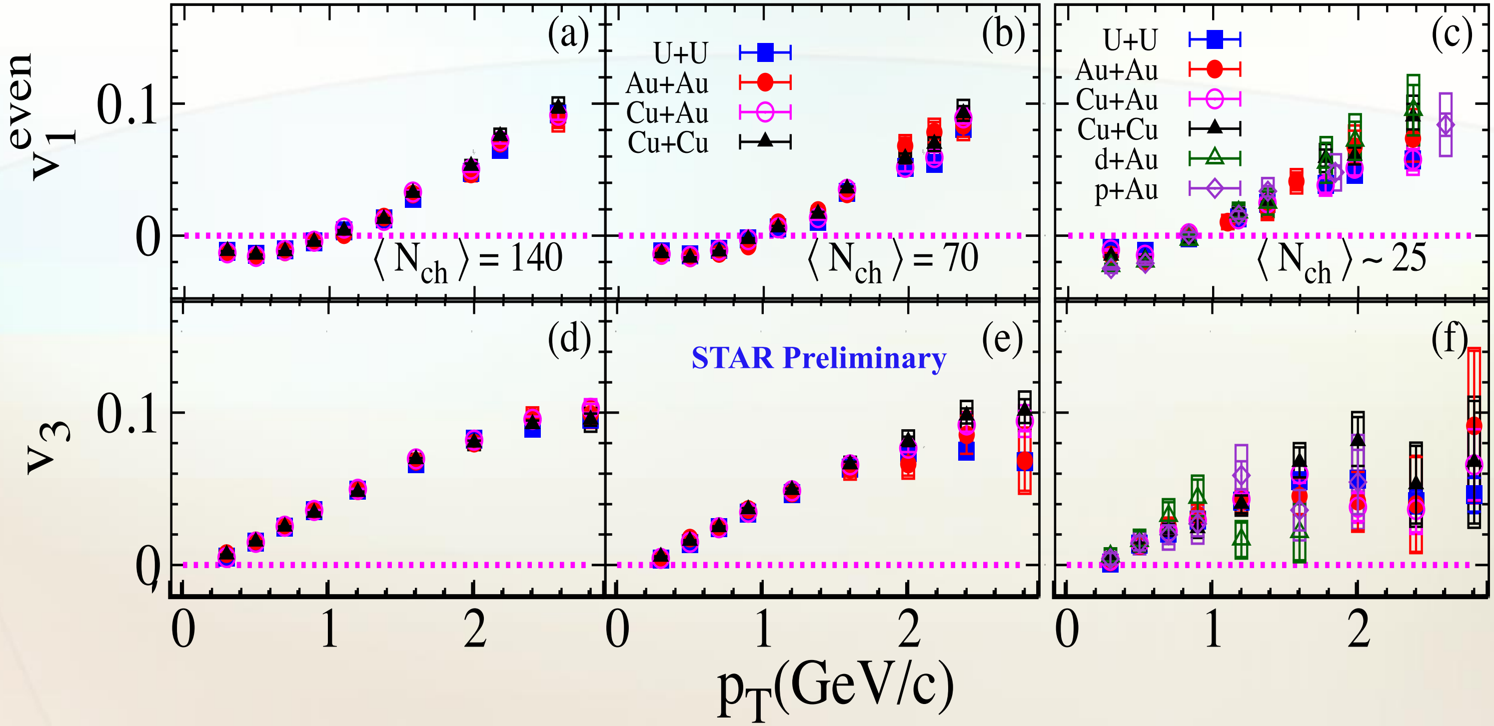
v_n for different systems

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

$$\ln\left(\frac{v_n}{\varepsilon_n}\right) \propto -A\,(\eta/s)\langle N_{Ch}\rangle^{-1/3}$$

v_1^{even} and v_3 vs p_T at different $\langle N_{Ch}\rangle$ for all systems



- v_1^{even} and v_3 show similar trends and magnitudes for all systems.

- v_1^{even} and v_3 are system independent.

v_n for different systems

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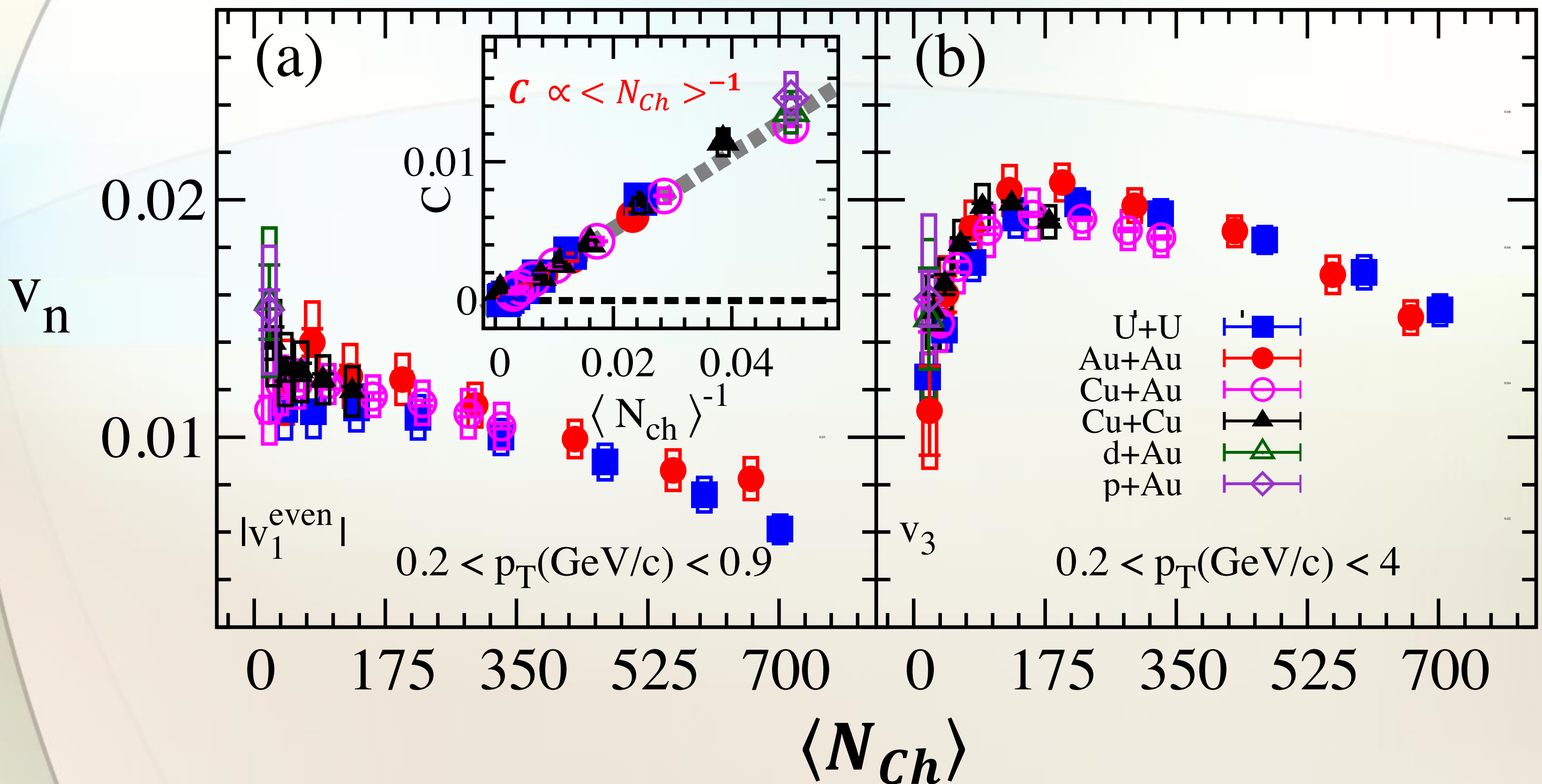

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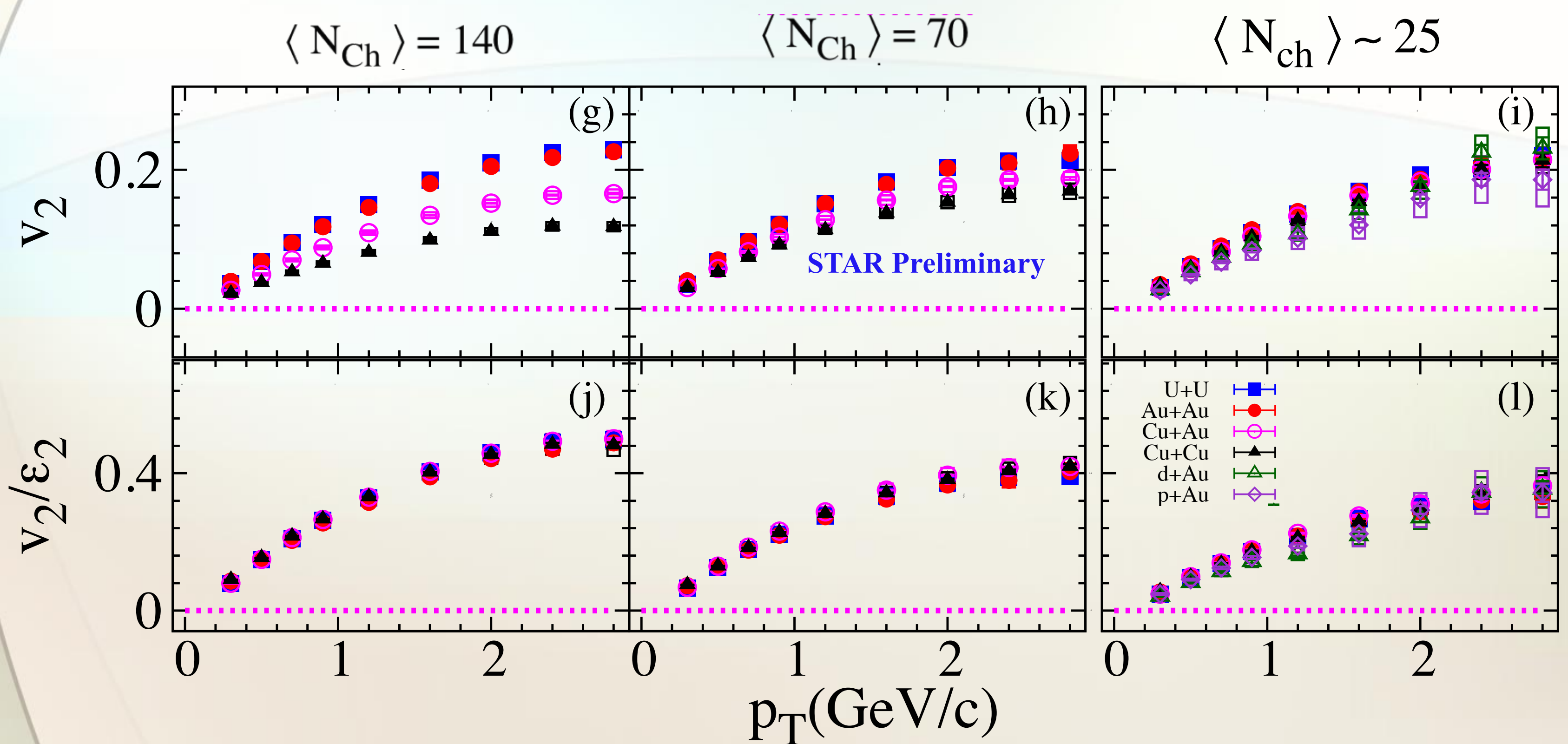
v_2 vs p_T at different $\langle N_{Ch}\rangle$ for all systems



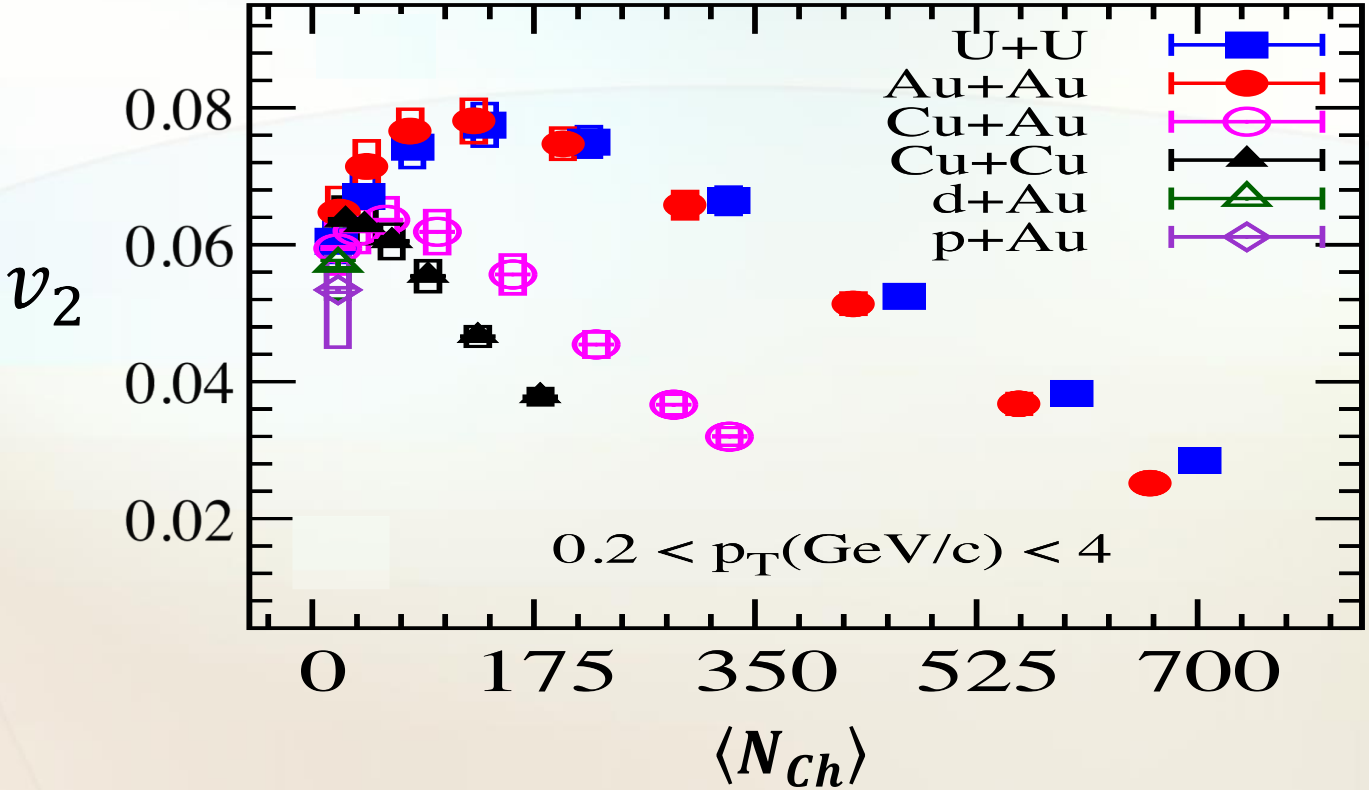
- ➢ v_2 is system dependent (shape).
- ➢ $\frac{v_2}{\epsilon_2}(p_T)$ for all systems scales to a single curve.

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

v_n for different systems

$$ln\left(\frac{v_n}{\varepsilon_n}\right) \propto -A\,(\eta/s)\langle N_{Ch}\rangle^{-1/3}$$

v_2 vs $\langle N_{Ch}\rangle$ for all systems



- v_2 show similar trends but different magnitudes for different systems.
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v_n for different systems

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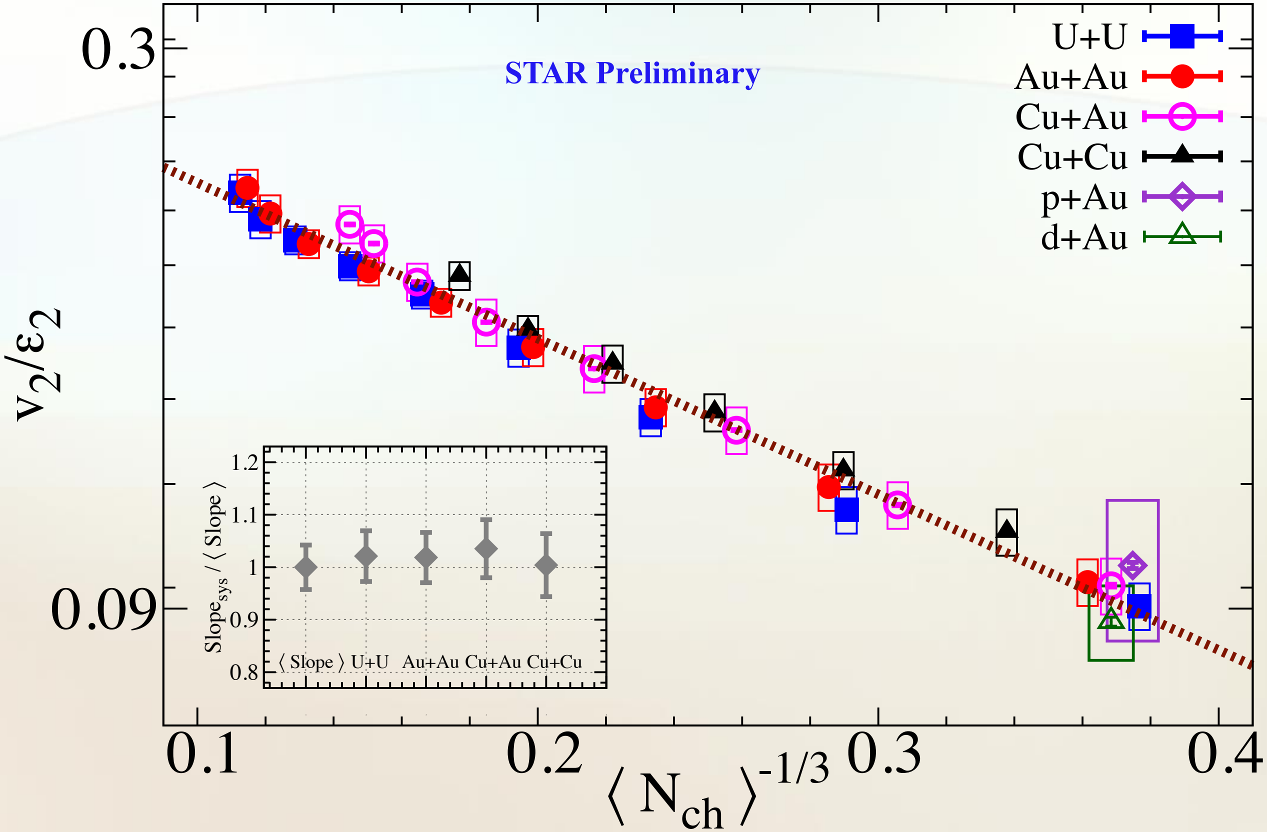
$\ln\left(\frac{v_2}{\epsilon_2}\right)$ vs $\langle N_{Ch}\rangle^{-1/3}$ for all systems



- $\frac{v_2}{\epsilon_2}$ for all systems scales to a single curve.
- Similar slopes implies similar viscous coefficient ($A\,\eta/s$) for all systems.

Conclusion

Comprehensive set of STAR measurements presented for $v_n(\eta, p_T, \langle N_{Ch}\rangle)$ for several collision systems/energies.

- Non-flow suppression
  - ✓ $\Delta\eta$ cut used to suppress the short range non-flow
  - ✓ $c_2\{4\}$ shows negative value for all presented systems.

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  - ✓ The odd harmonics are system independent

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At the same energy, the scaling features suggest similar viscous coefficient ($A\frac{\eta}{s}$) for different systems.

THANK YOU