Collectivity in small and large systems

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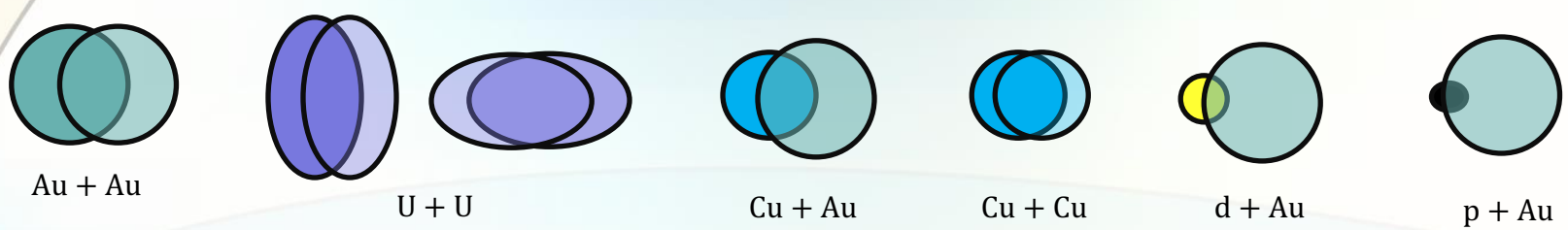
RHIC & AGS
Annual Users' Meeting
From Protons to Heavy Ions, and Back Again
Hosted By Brookhaven National Laboratory

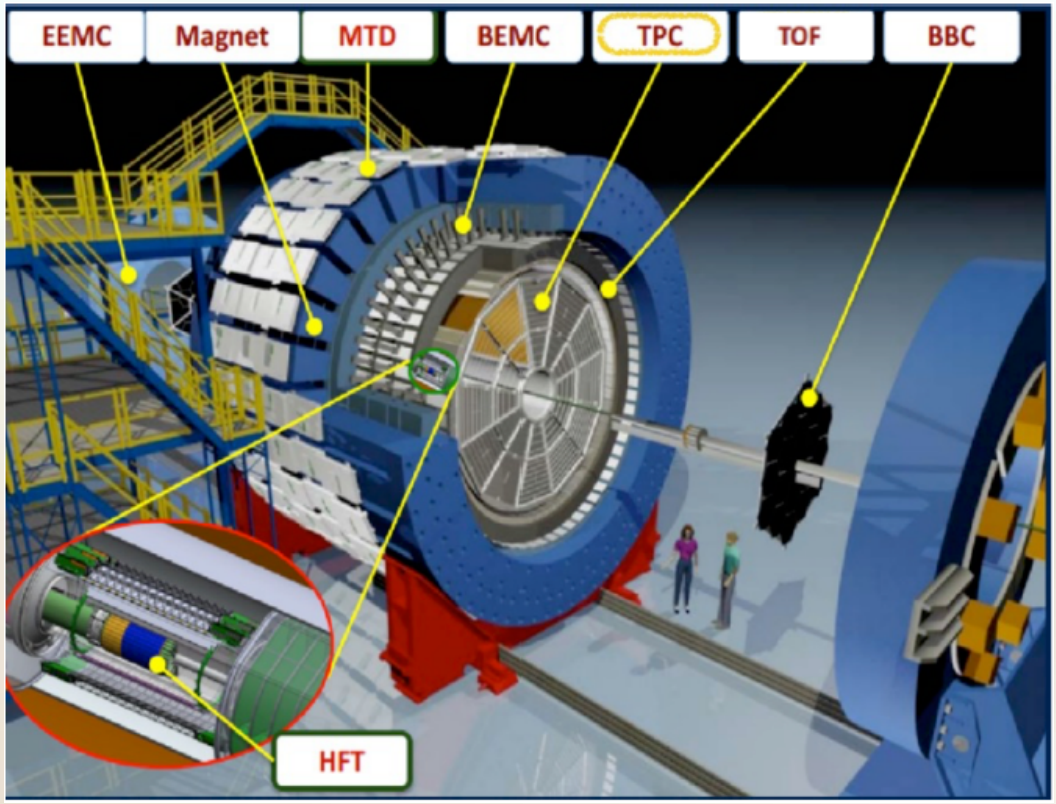
Collectivity in small and large systems

- Collected data for different systems;



STAR Detector at RHIC

- TPC detector covers $|\eta| < 1$



Azimuthal anisotropy measurements

Correlation function

Two particle correlation function $Cr(\Delta\varphi)$,

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

$n > 1$

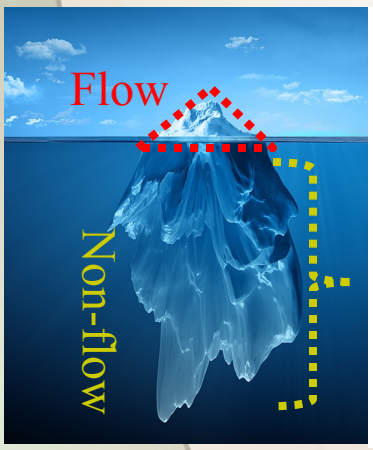
$$v_{nn} = v_n^a v_n^b + \delta_{short}$$

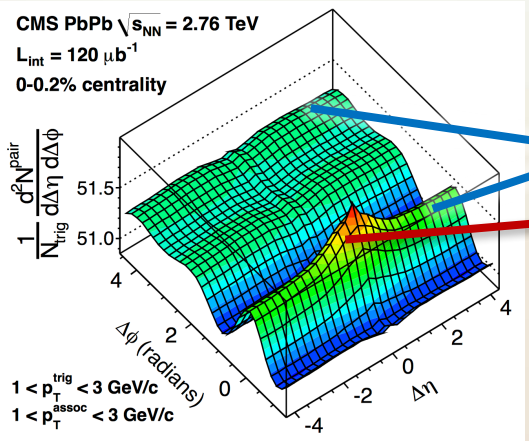
$n = 1$

$$v_{11} = v_1^a v_1^b + \delta_{long}$$

Flow

Non-flow





- ***Long – range***
  - ***Momentum Conservation***
  - ***Di–jets***
- ***Short – range***
  - ***HBT***
  - ***Decay***
    - Charge

Non-flow suppression is needed

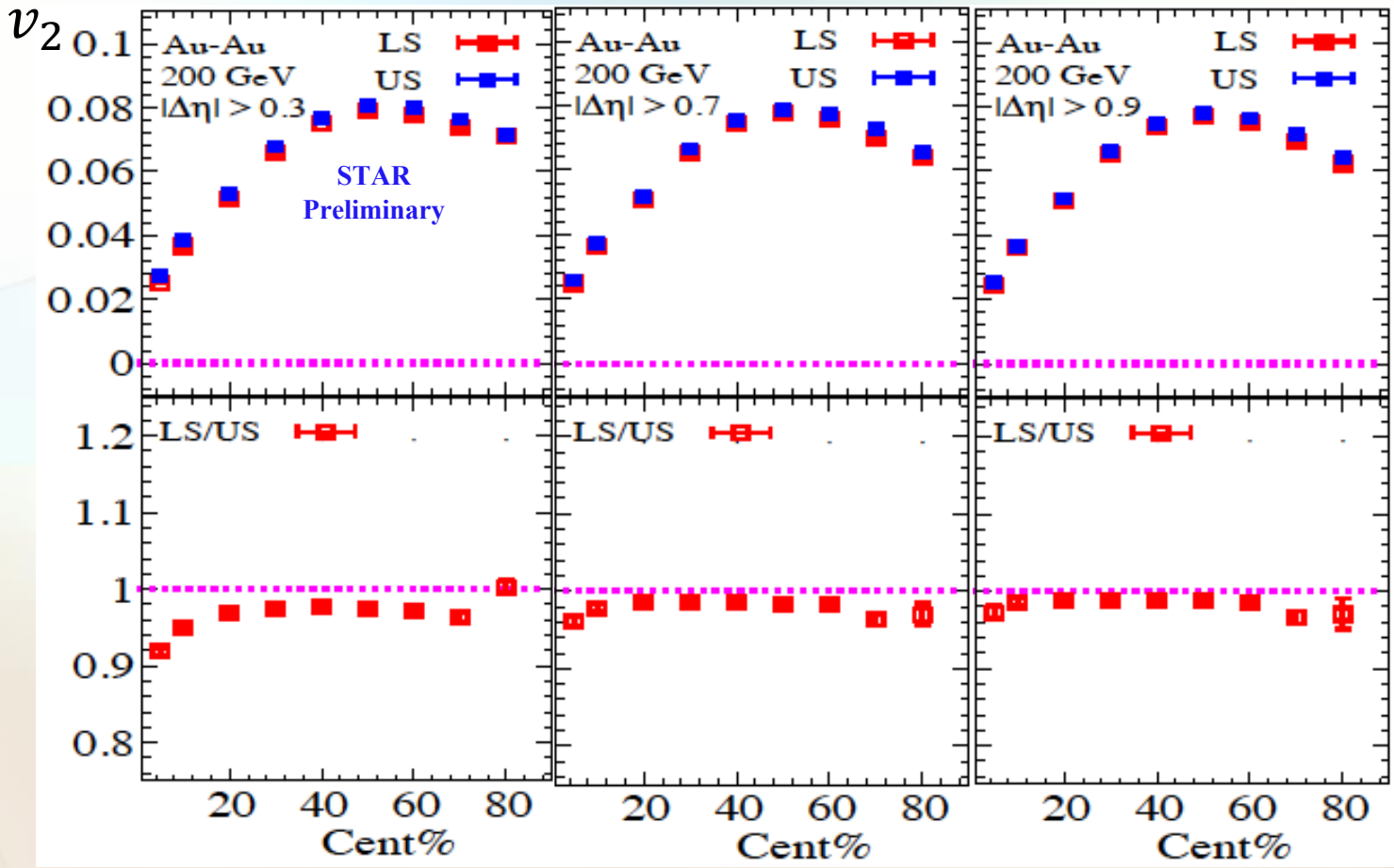
Short − range Non−flow

HBT

Decay

Short range non-flow suppression

The $\Delta\eta$ dependence of v_2 vs centrality



- The short range non-flow shows $\Delta\eta$ dependence
- The short range non-flow reduced using $\Delta\eta > 0.7$ cut
- Wider $\Delta\eta$ cuts degrade the statistical certainties

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

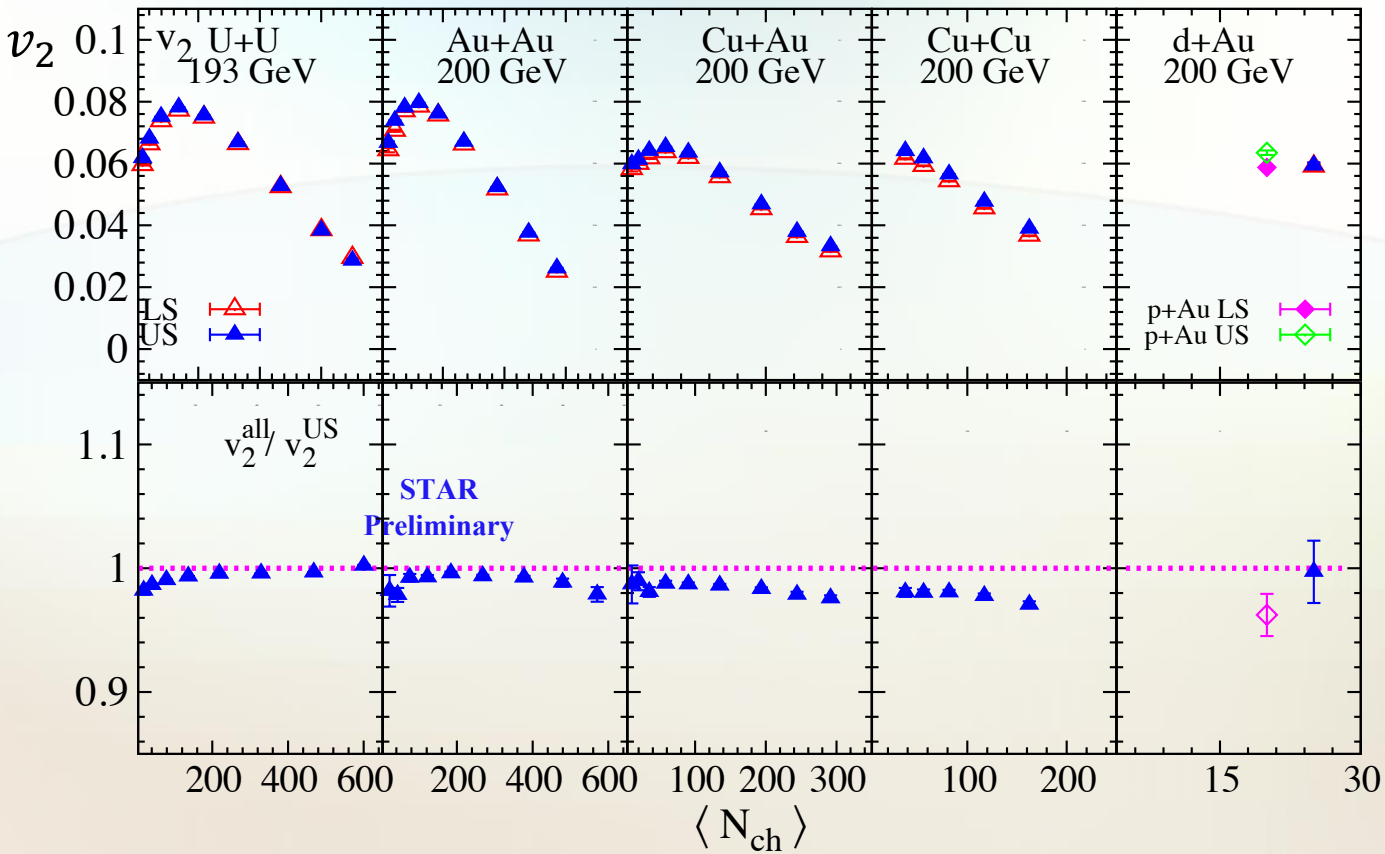
Short – range Non–flow

HBT

Decay

Short range non-flow suppression

The v_2 vs $\langle N_{Ch} \rangle$ for all systems using $\Delta\eta > 0.7$ cut



➢ The non-flow effect using $\Delta\eta > 0.7$ cut get reduced into 1:2% for all systems.

Long – range

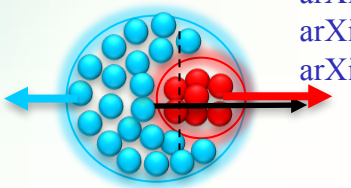
Momentum Conservation

Di–jets

Long range non-flow suppression

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

$$v_{11} = v_1^a v_1^b + \delta_{long} \quad n = 1$$

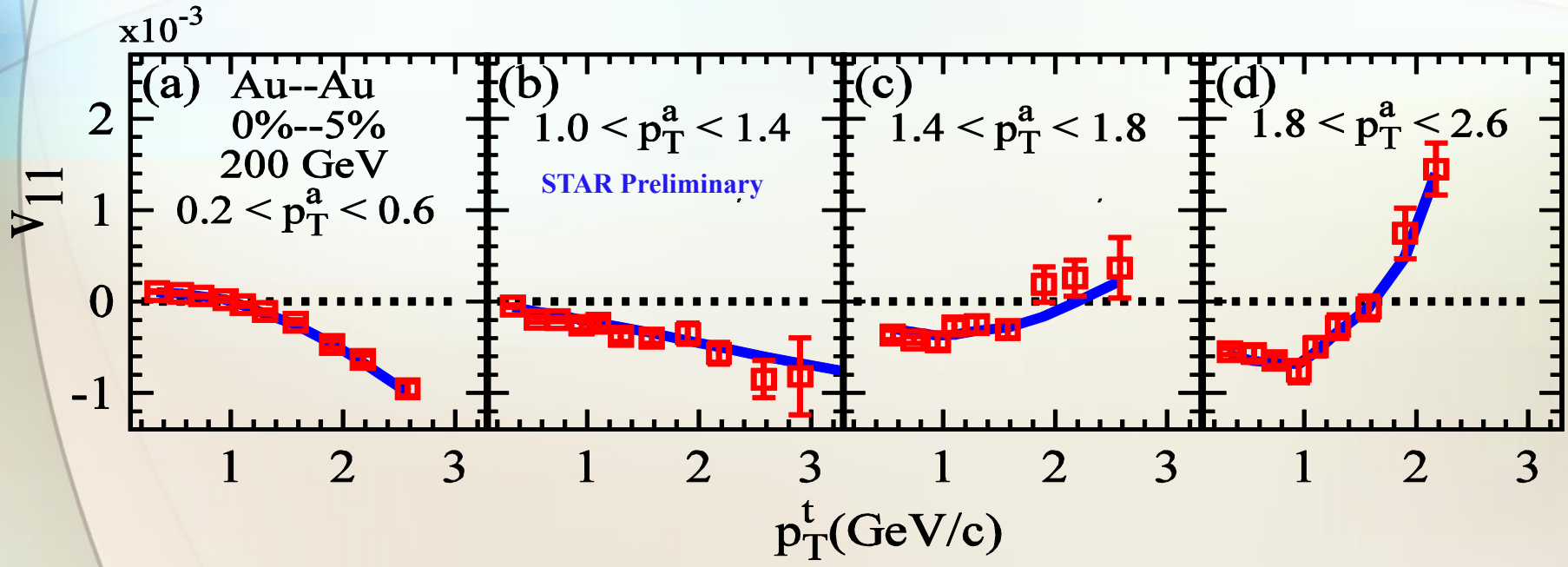


$$v_{11}(p_T^a, p_T^t) = v_1^{even}(p_T^a) v_1^{even}(p_T^t) - C\, p_T^a\, p_T^t$$

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

1

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



- Good simultaneous fit obtained with fit function.
- $\mathbf{v_{11}}$ characteristic behavior gives a good constraint for $\boldsymbol{v_1^{even}}(\mathbf{p_T})$ extraction.

Long – range

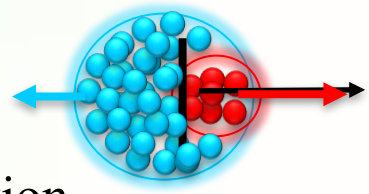
Momentum Conservation

Di–jets

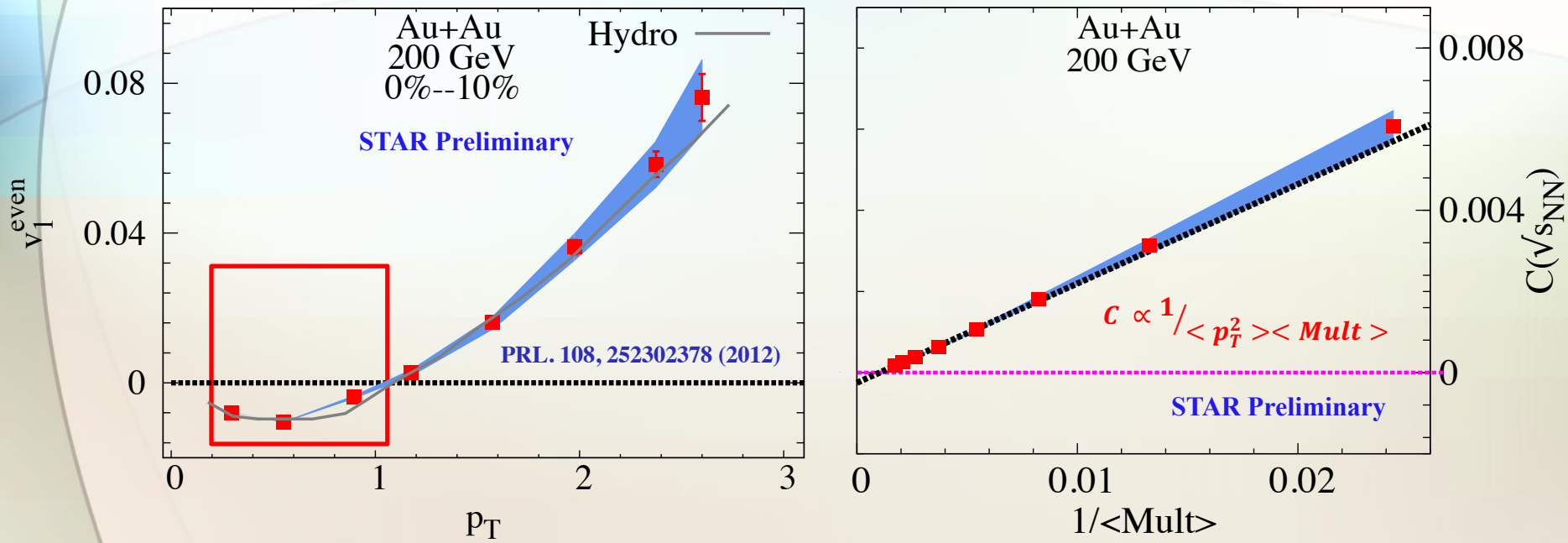
Long range non-flow suppression

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

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



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>

Non-flow suppression

Long – range

Momentum Conservation

Di–jets

Short – range

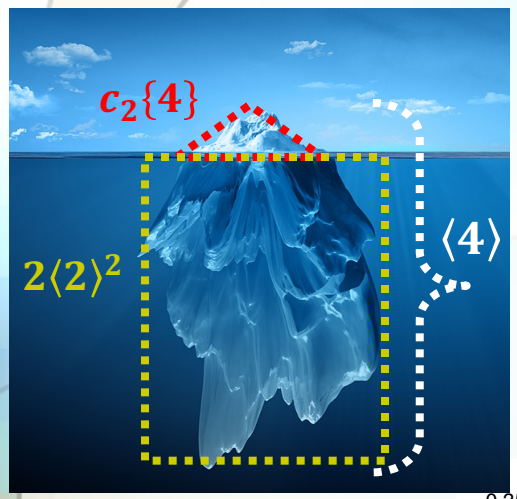
HBT

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

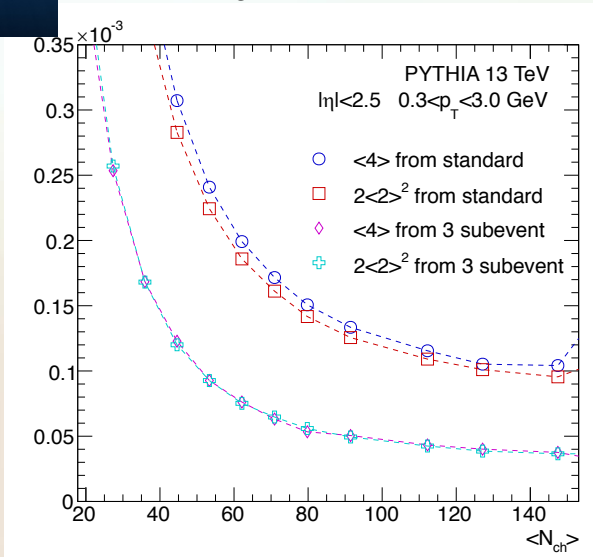
$c_2\{4\} \equiv \langle 4 \rangle - 2\langle 2 \rangle^2$



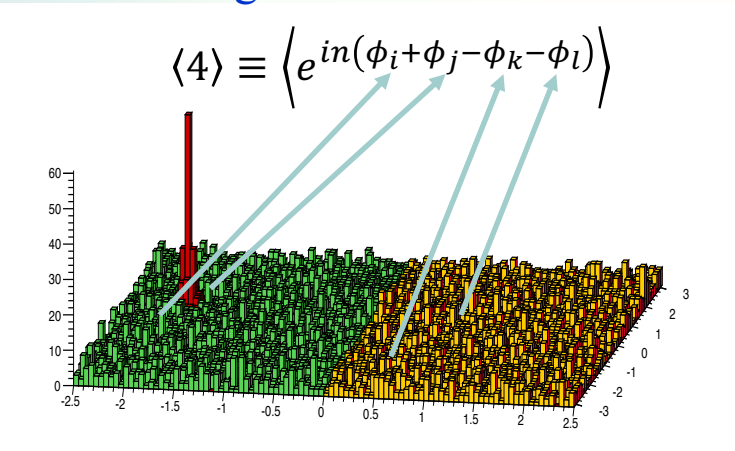
In the subevent method, particles are correlated across all subevents (long-range)

Three subevent cumulant can further suppress away-side jet contribution

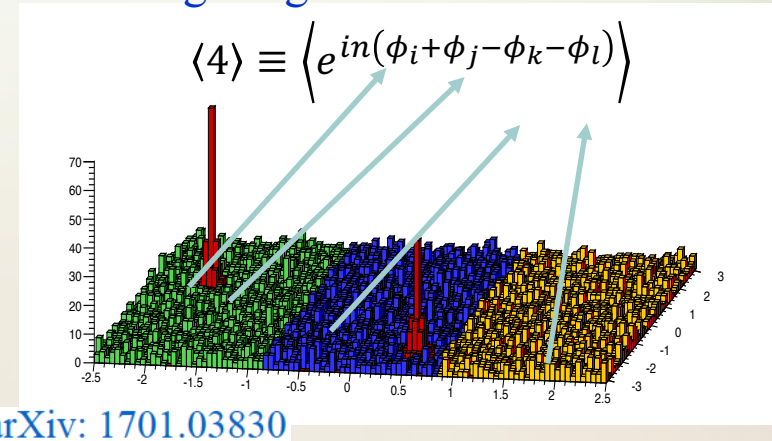
Both $\langle 4 \rangle$ and $2\langle 2 \rangle^2$ are much smaller with subevent



Short-range non-flow dominate



Long-range non-flow dominate



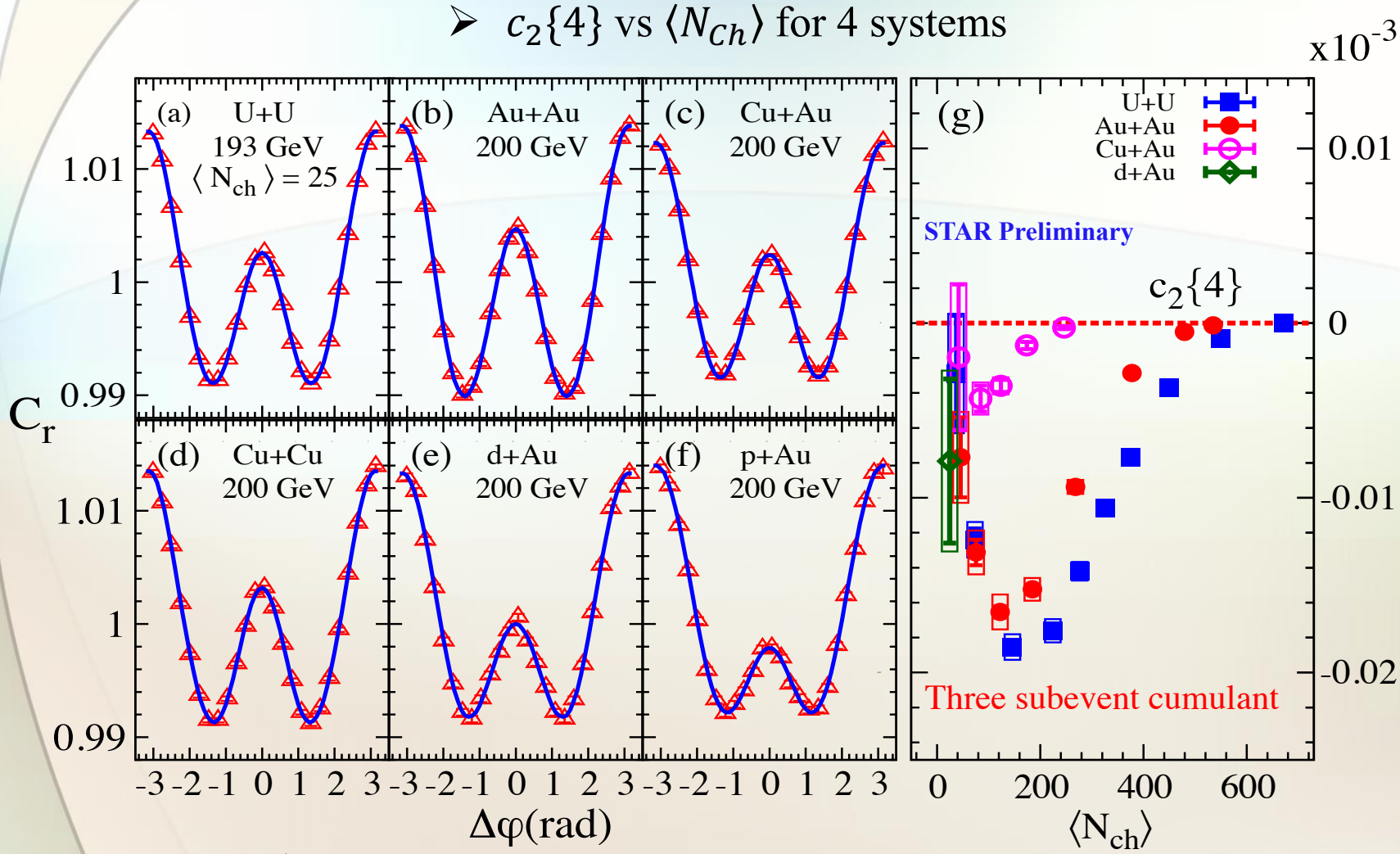
arXiv: 1701.03830

Subevent cumulant measures long-range collectivity.

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

Collectivity in small systems

- The correlation function Cr for all systems at one $\langle N_{Ch} \rangle$ value
  - $c_2\{4\}$ vs $\langle N_{Ch} \rangle$ for 4 systems

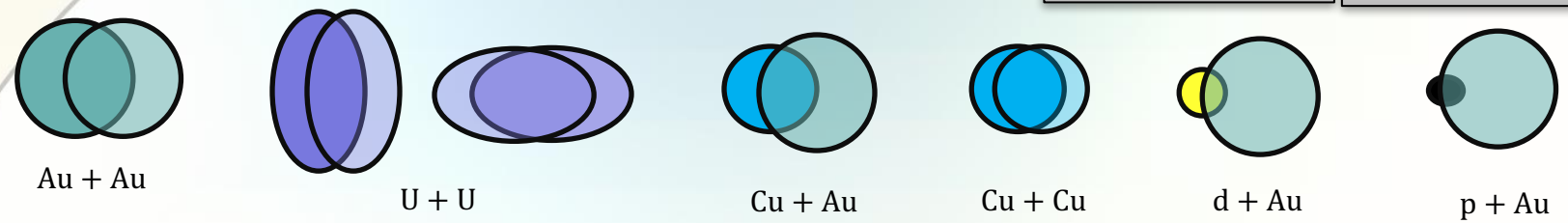


- Cr shows similar trend for all systems

- $c_2\{4\}$ shows negative value for different systems

Acoustic ansatz

PRC 84, 034908 (2011) P. Staig and E. Shuryak.	arXiv:1305.3341 Roy A. Lacey, et al.
PRC 88, 044915 (2013) E. Shuryak and I. Zahed	arXiv:1601.06001 Roy A. Lacey, et al.



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

$v_n/\epsilon_n \propto e^{-A\left(\frac{\eta}{s}\frac{n^2}{RT}\right)}$ $\quad S \sim (RT)^3 \sim \langle N_{Ch}\rangle$ then $RT \sim \langle N_{Ch}\rangle^{1/3}$ $\quad \ln\left(\frac{v_n}{\varepsilon_n}\right) \propto -A\left(\frac{\eta}{s}\right)\langle N_{Ch}\rangle^{-1/3}$

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

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

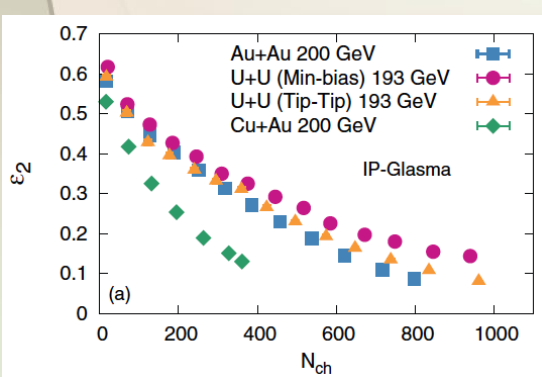
$$v_n \xrightarrow{\textit{driven by}} \varepsilon_n + \ldots$$

Expectations

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

Even Harmonic v_2

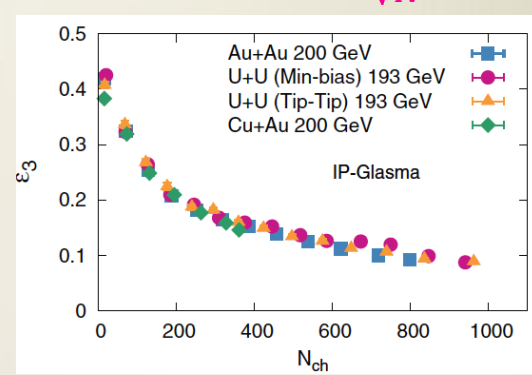
ε_2 *scaling is needed*



PRC 89, 064908 (2014)

Odd Harmonic v_3

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



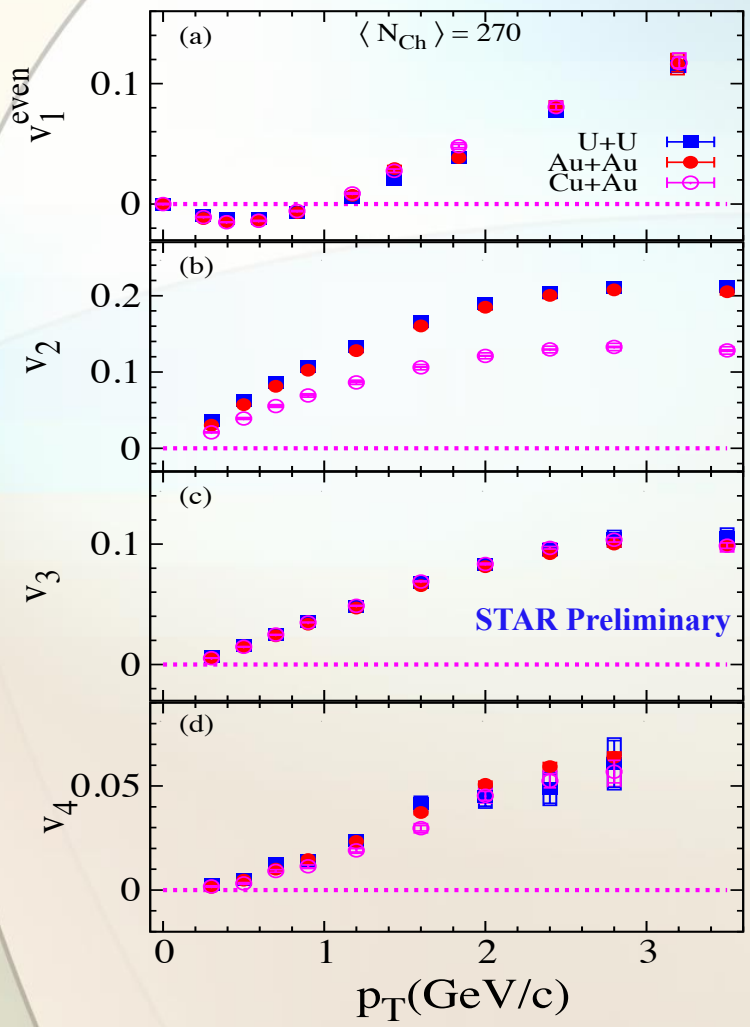
PRC 89, 064908 (2014)

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

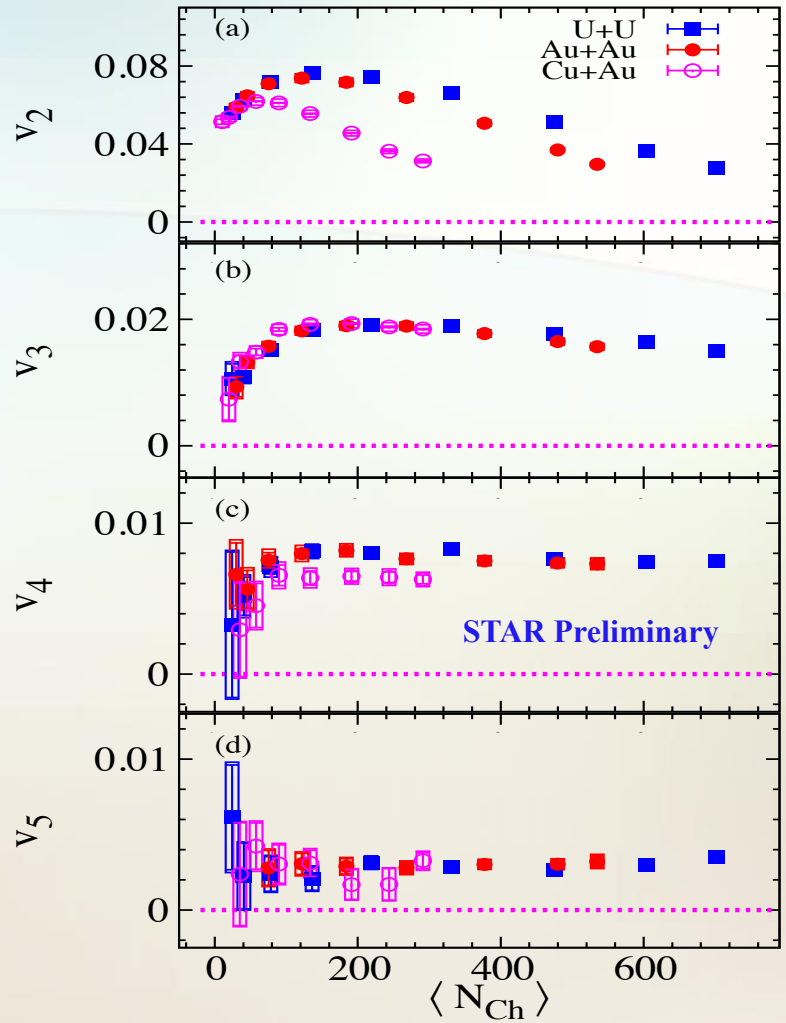
v_n for large systems $(A+B)$

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

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



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



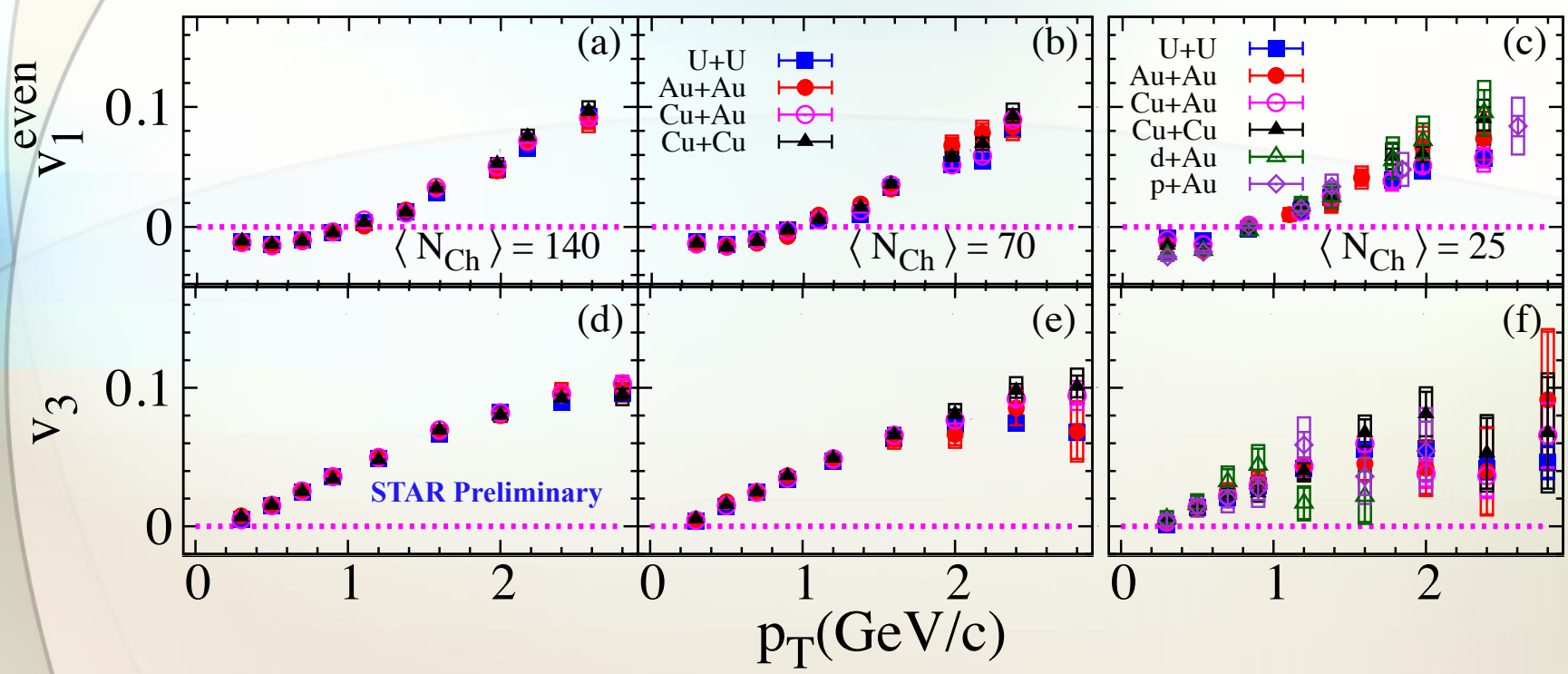
- Odd harmonics are system independent.
- Even harmonics are system dependent.

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

v_n for different systems

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

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



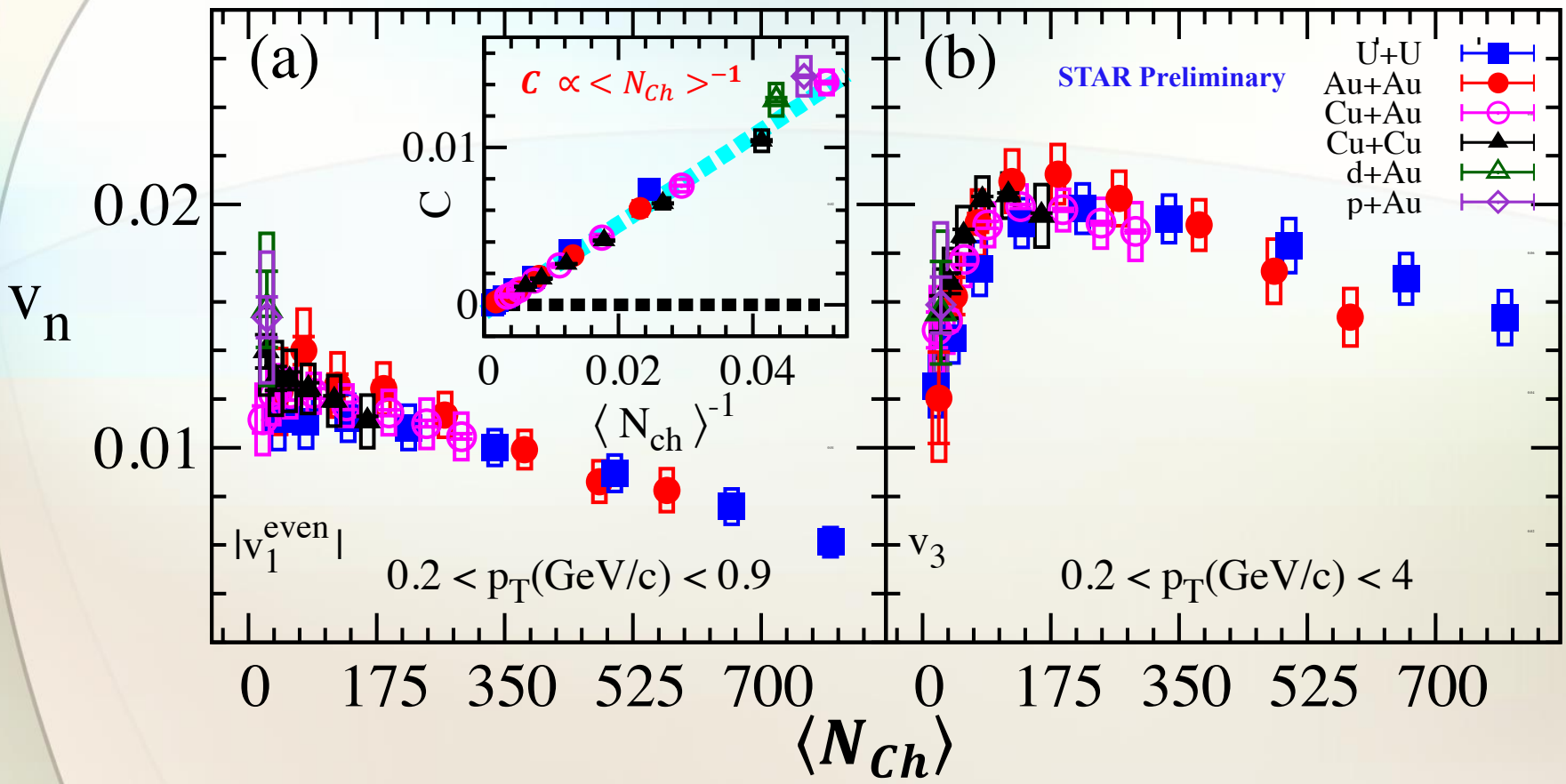
- v_1^{even} and v_3 show similar trends and magnitudes for all systems.
- v_1^{even} and v_3 are system independent.

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

v_n for different systems

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

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



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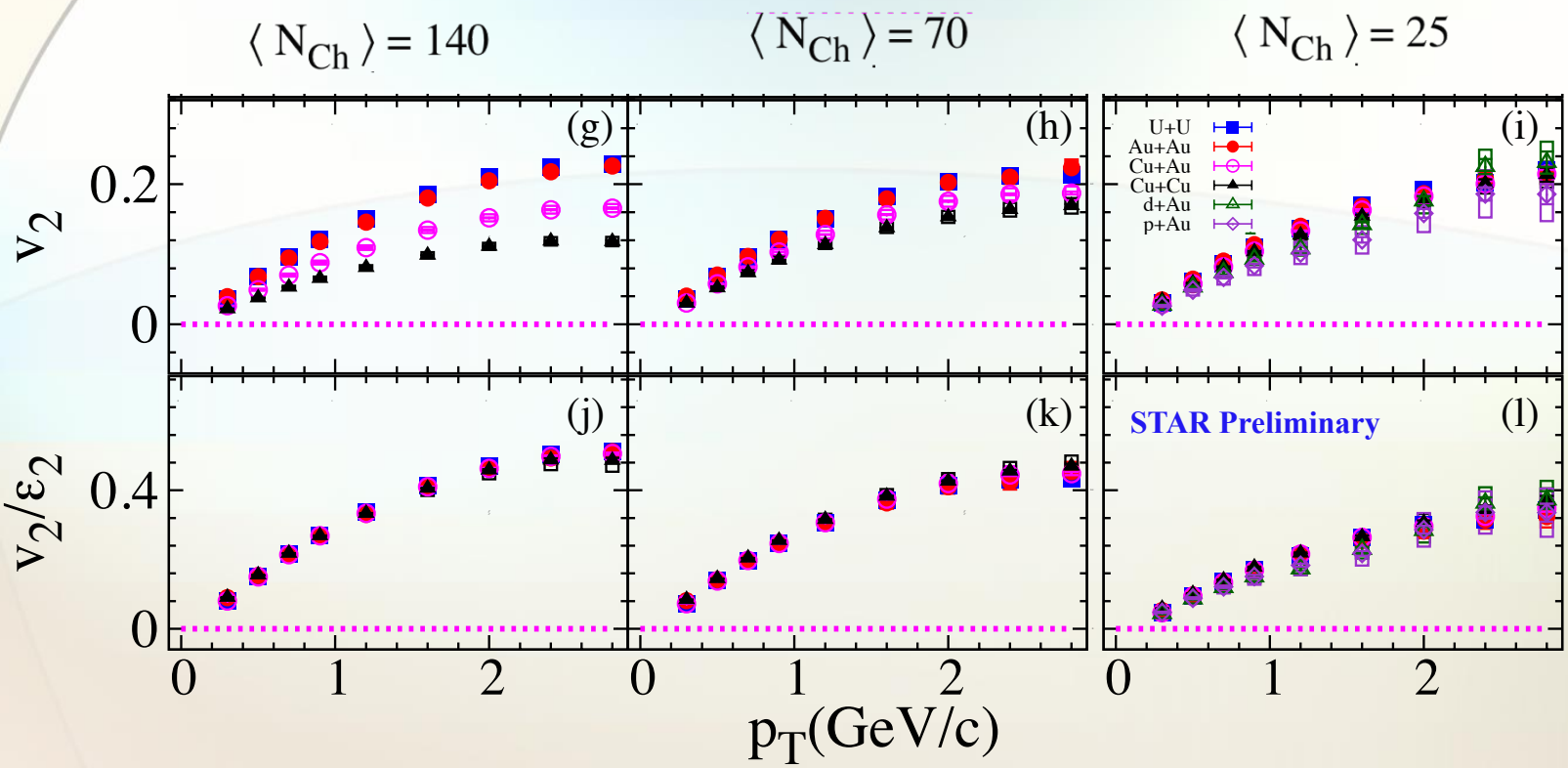
v_n for different systems

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

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



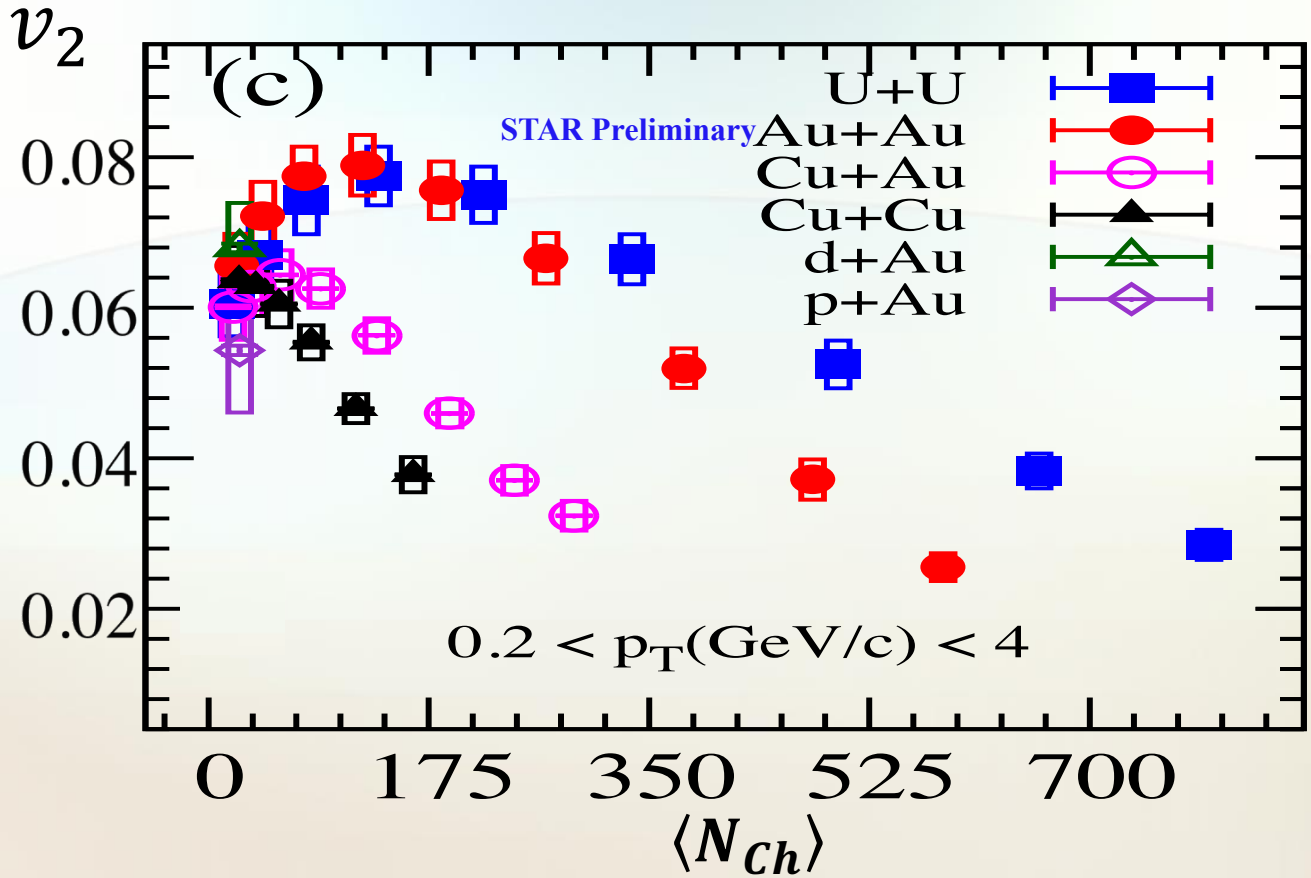
- v_2 show similar trends for all systems.
- v_2 is system dependent (shape).
- $\frac{v_2}{\epsilon_2}(p_T)$ for all systems scales to a single curve.

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

v_n for different systems

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

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



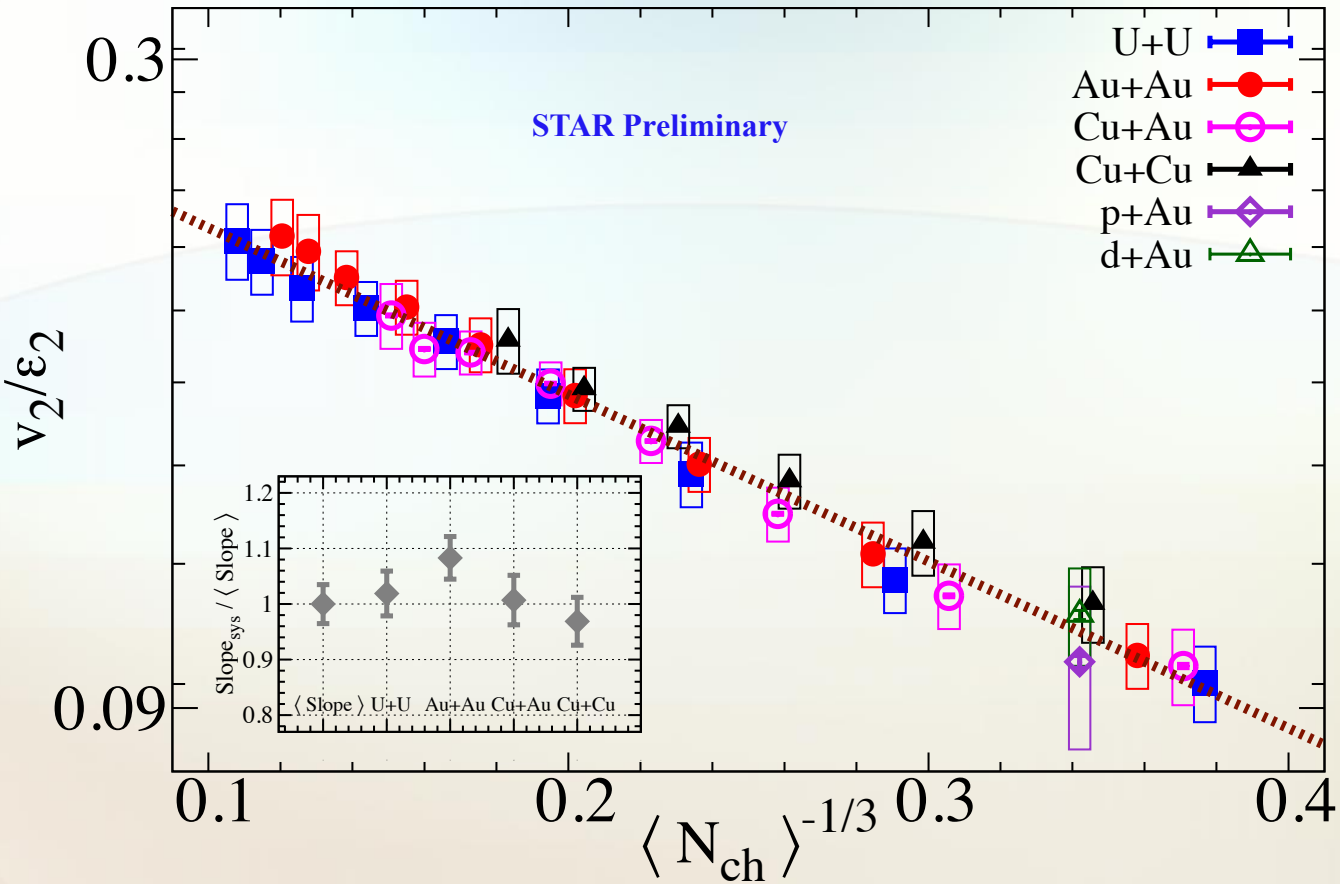
- v_2 show similar trends but different magnitudes for different systems.
- v_2 is system dependent (shape).

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

v_n for different systems

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

$\ln\left(\frac{v_2}{\epsilon_2}\right)$ 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 $v_n(p_T, \langle N_{Ch} \rangle)$ for several collision systems.

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

- Scaling the system size;
  - ✓ The odd harmonics are system independent
  - ✓ The even harmonics are system dependent
  - ✓ $\frac{v_2}{\epsilon_2}$ for all systems scaled onto one curve to ~15% in slope

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

THANK YOU