Beam energy and system dependence of rapidity-even dipolar flow

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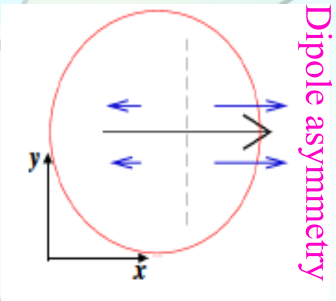
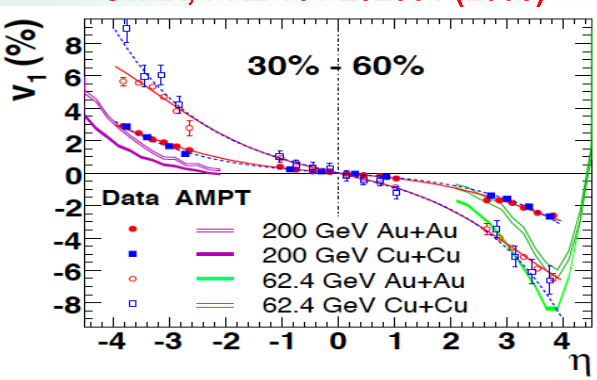
Directed flow



$$v_1(\eta) = v_1^{\text{even}}(\eta) + v_1^{\text{odd}}(\eta)$$

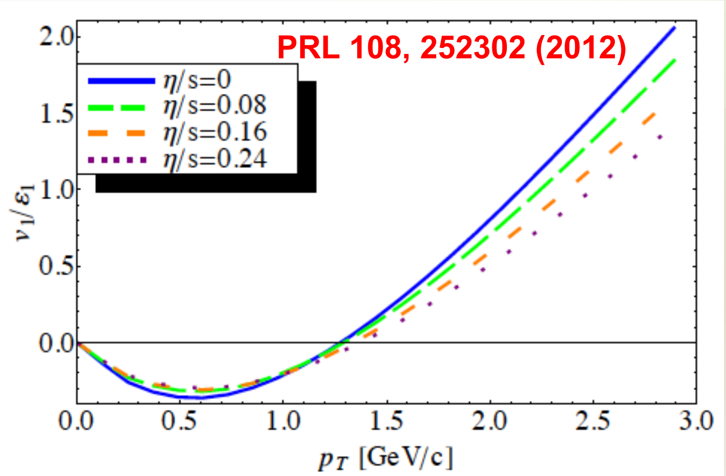
STAR, PRL 101 252301 (2008)



- The rapidity-even directed flow v_1^{even} stems from initial-state fluctuations acting in concert with hydrodynamic-like expansion

- The rapidity-odd directed flow v_1^{odd} develops along the direction of the impact parameter and is an odd function of pseudorapidity.

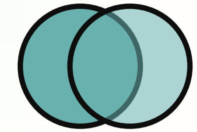
- The magnitude of v_1^{even} is sensitive to:
  - ✓ Initial-state eccentricity & its fluctuations
  - ✓ Transport coefficients (η/s , etc) but with less sensitivity than for higher order harmonics.



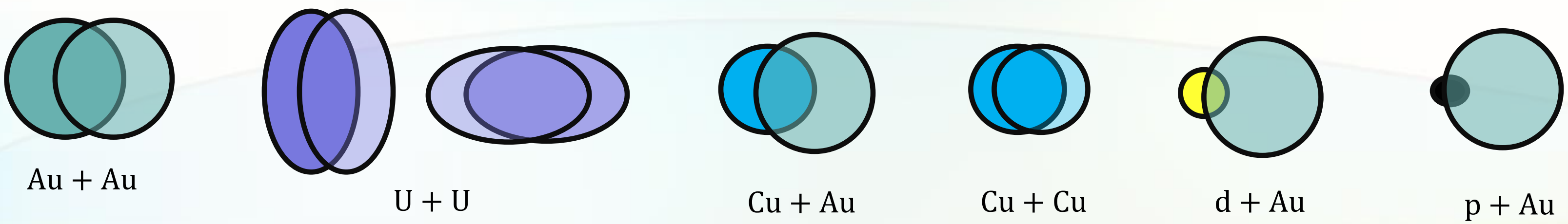
- The v_1^{even} constitutes a new set of experimental constraints that can help to:
  - ✓ Differentiate between initial-state models
  - ✓ Pin down the temperature dependence of the transport coefficients.

Datasets

- Collected data for Au+Au at different $\sqrt{s_{NN}}$

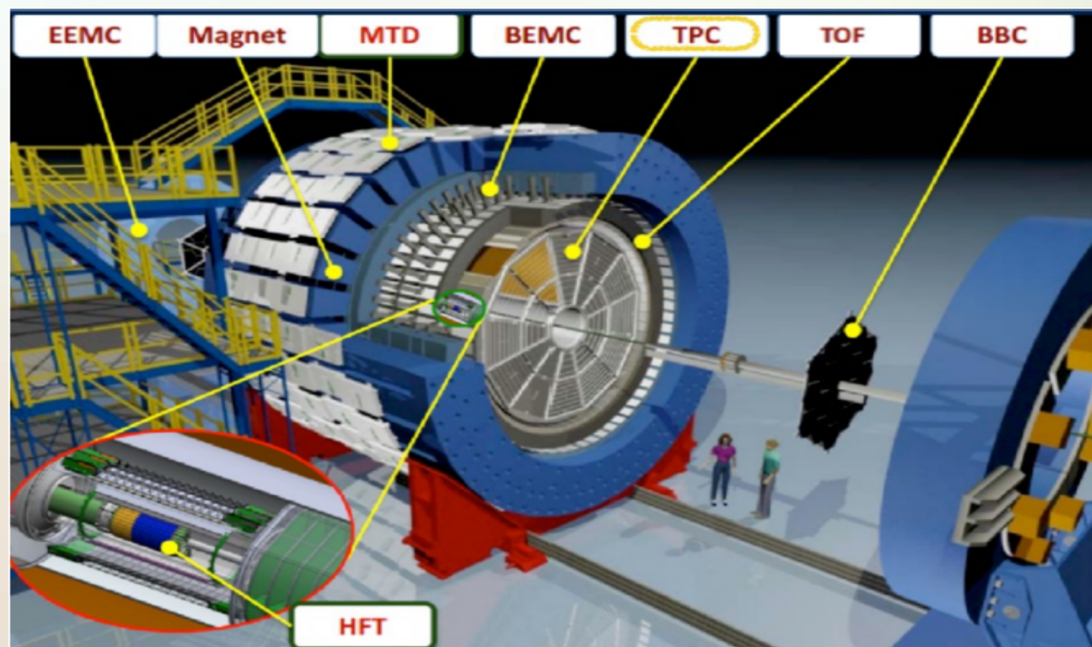


- Collected data for different systems at $\sqrt{s_{NN}} \approx 200$ GeV;



STAR Detector at RHIC

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



Azimuthal anisotropy measurements

Correlation function

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

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

$n > 1$

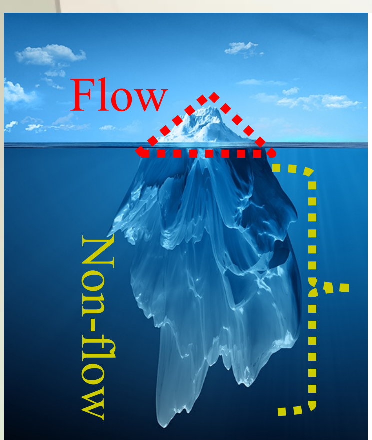
$$v_{nn} = v_n^a v_n^b + \delta_{short}$$

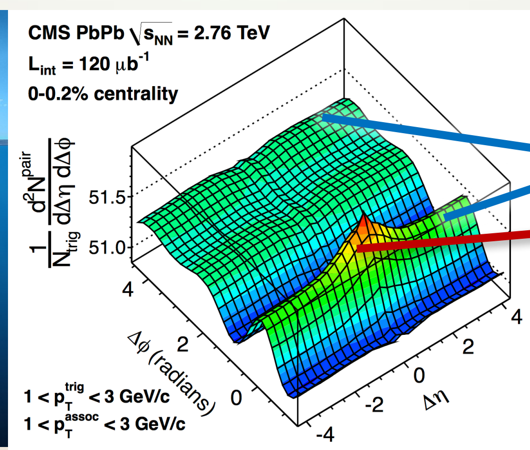
$n = 1$

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

Flow

Non-flow





- *Long – range*
- *Momentum Conservation*
- *Di–jets*

- *Short – range*
- *HBT*
- *Decay*

Charge

Non-flow suppression is needed

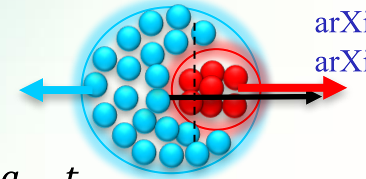
Long − range

Momentum Conservation

Long range non-flow suppression

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

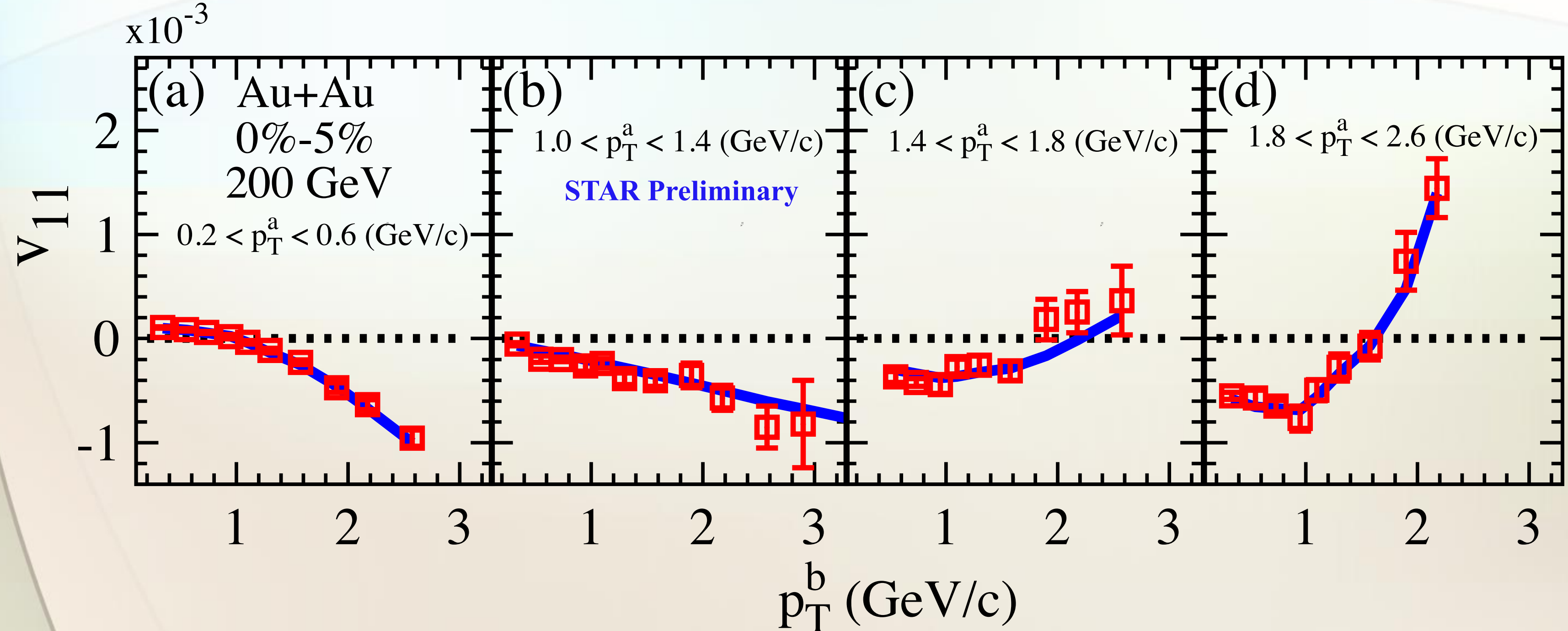
$$v_{11} = v_1^a v_1^b + \delta_{long} \quad n = 1$$



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

$C \propto 1/\langle p_T^2 \rangle \langle Mult \rangle$

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



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

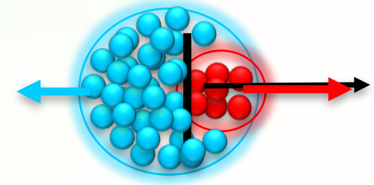
Long − range

Momentum Conservation

Long range non-flow suppression

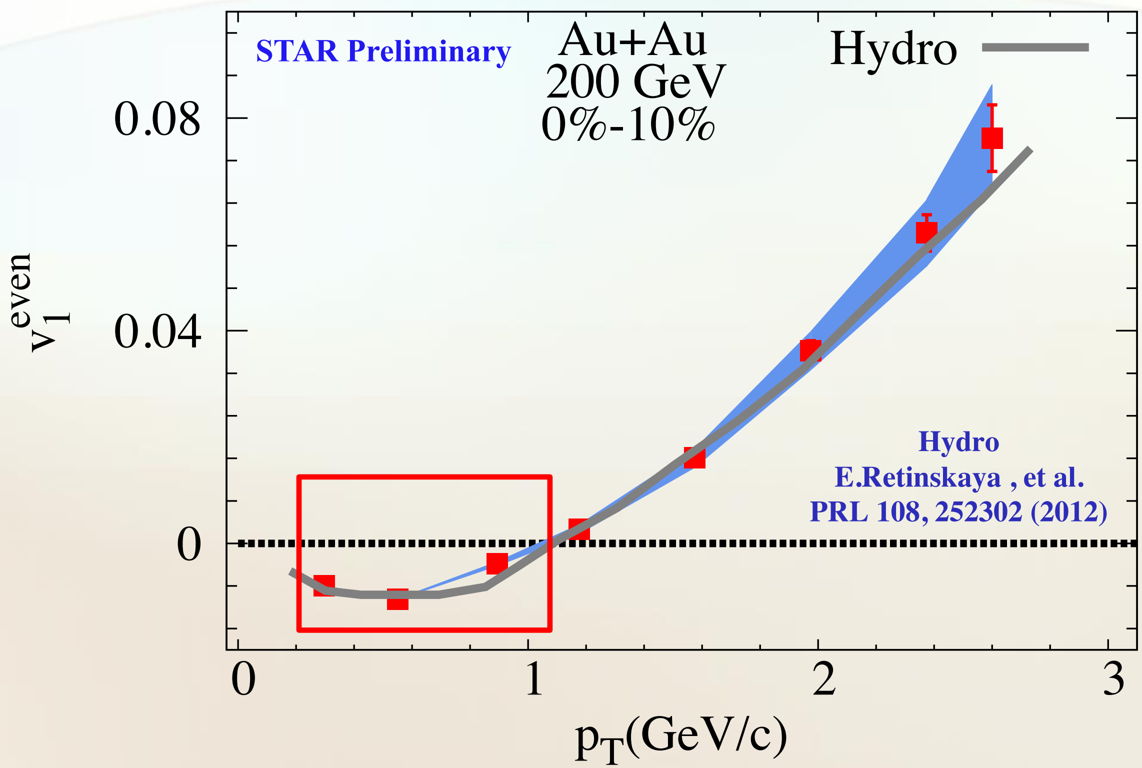
$|\eta| < 1$ and $|\Delta\eta| > 0.7$

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



Dipolar nature requires that $\int_0^\infty \frac{dN}{dp_T}\, p_T\ v_1^{even} = 0$

The extracted $\boldsymbol{v_1^{even}}(\boldsymbol{p_T})$ at 200 GeV and 0%-10% centrality



➢ The characteristic behavior of $v_1^{even}(p_T)$ agrees with hydrodynamic expectations.

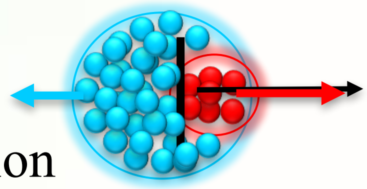
Long – range

Momentum Conservation

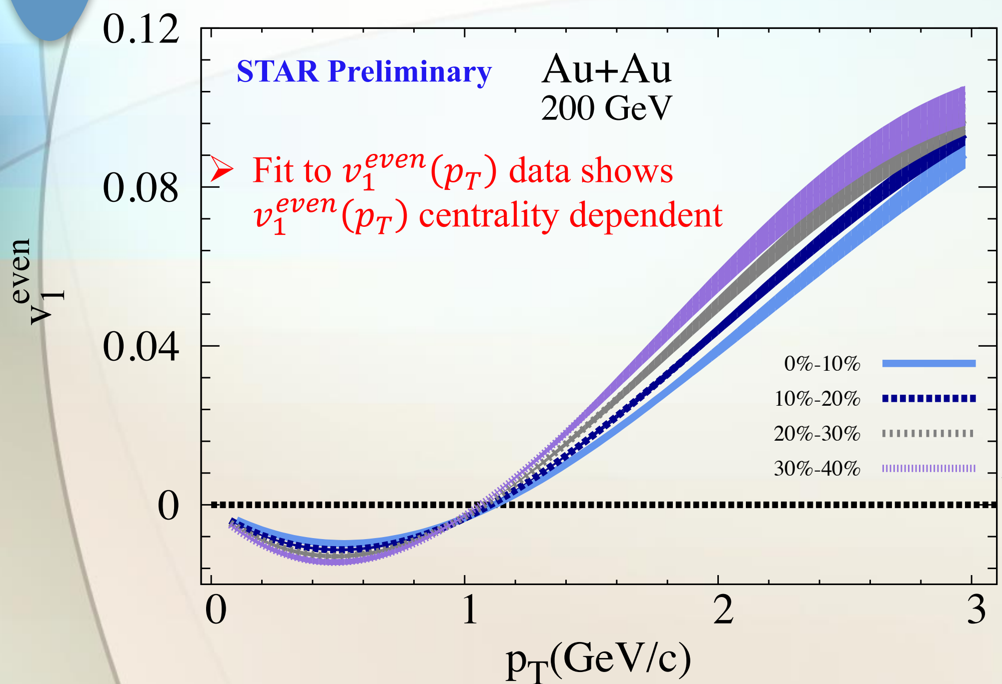
Long range non-flow suppression

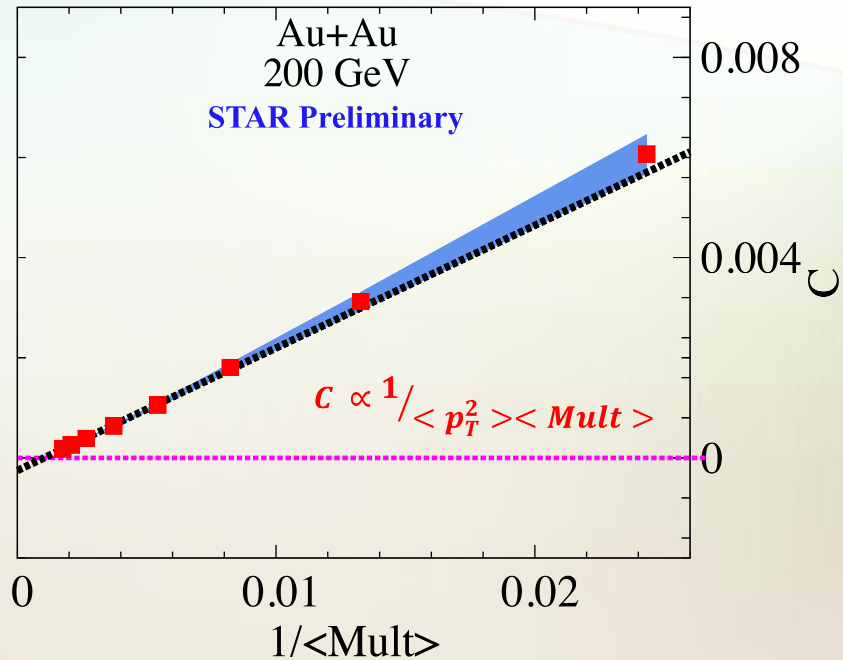
$|\eta| < 1$ and $|\Delta\eta| > 0.7$

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



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





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

Rapidity-even dipolar flow

- $v_1^{even}(p_T)$
- $v_1^{even}(\sqrt{s_{NN}})$
- $v_1^{even}(Cent)$

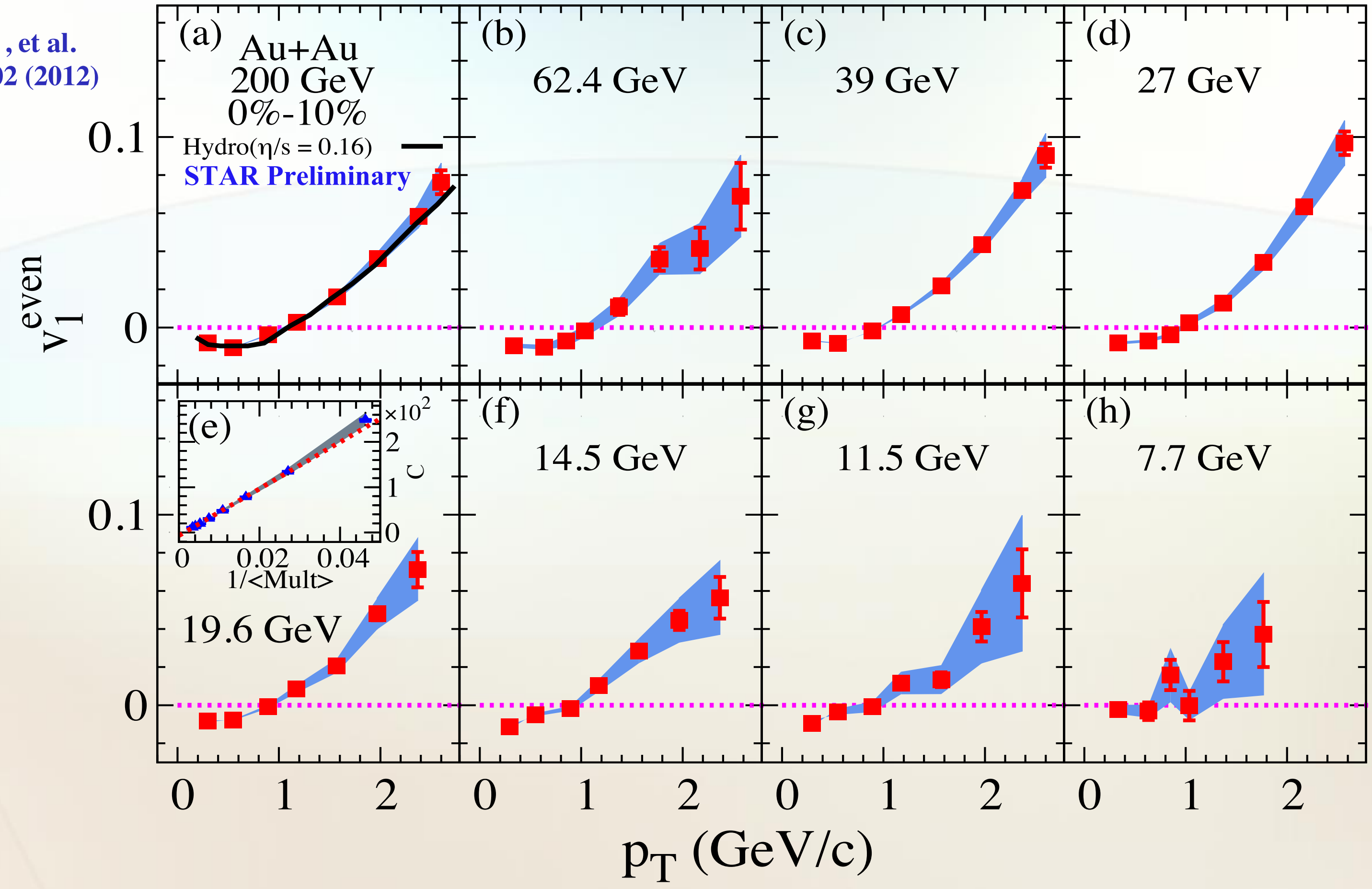
Beam energy dependence of v_1^{even}

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

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

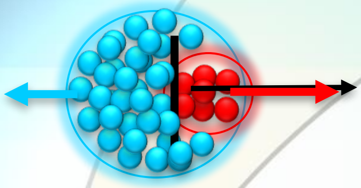
The extracted $v_1^{even}(p_T)$ at all BES energies

Hydro
E.Retinskaya , et al.
PRL 108, 252302 (2012)



➢ Similar characteristic behavior of $v_1^{even}(p_T)$ at all energies

➢ $v_1^{even}(p_T)$ agrees with hydrodynamic calculations at 200 GeV

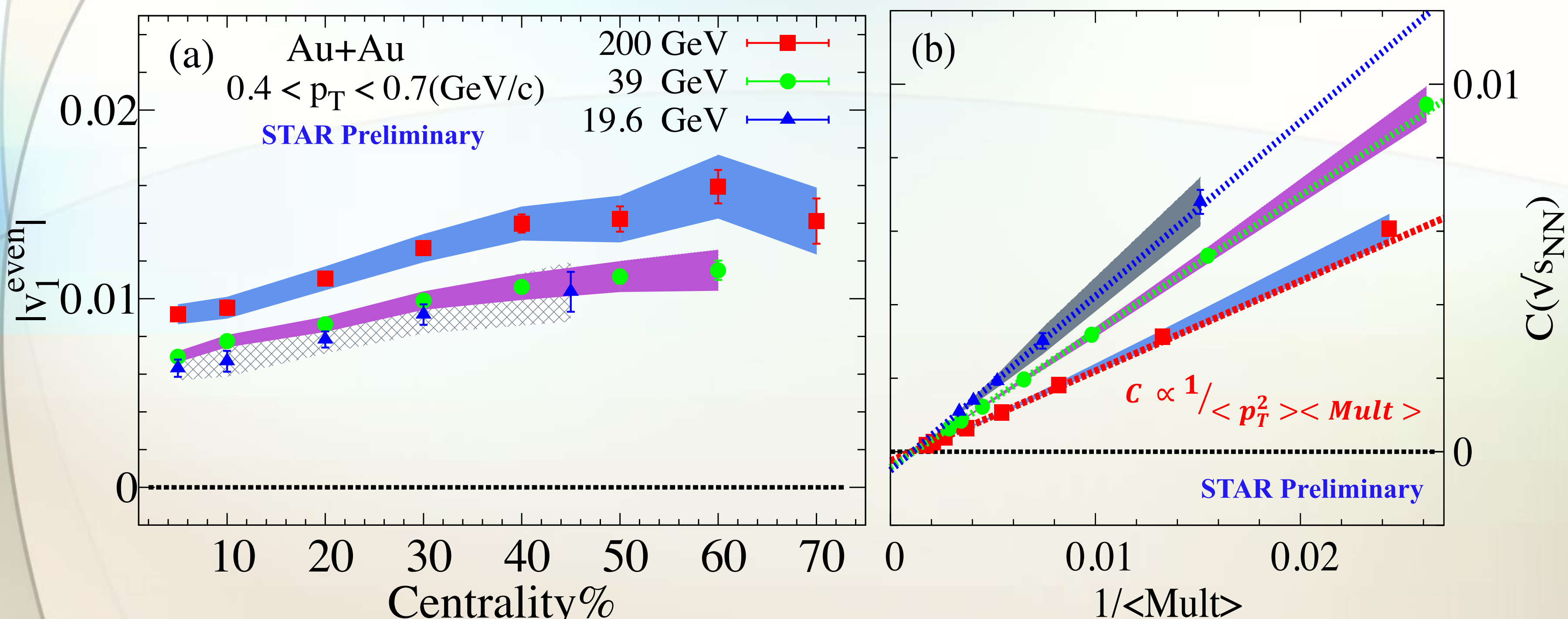


Beam energy dependence of v_1^{even}

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

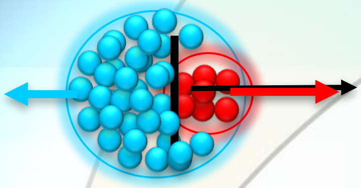
$$\mathbf{v_{11}}(p_T^a, p_T^t) = v_1^{even}(p_T^a)v_1^{even}(p_T^t) - C\, p_T^a\, p_T^t$$

The extracted $v_1^{even}(Cent)$ and the momentum conservation parameter at different beam energies



➢ For different energies

- ✓ v_1^{even} increases as collisions become more peripheral
- ✓ v_1^{even} shows a weak centrality dependence
- ✓ Momentum conservation parameter C scales as $\langle Mult \rangle^{-1}$

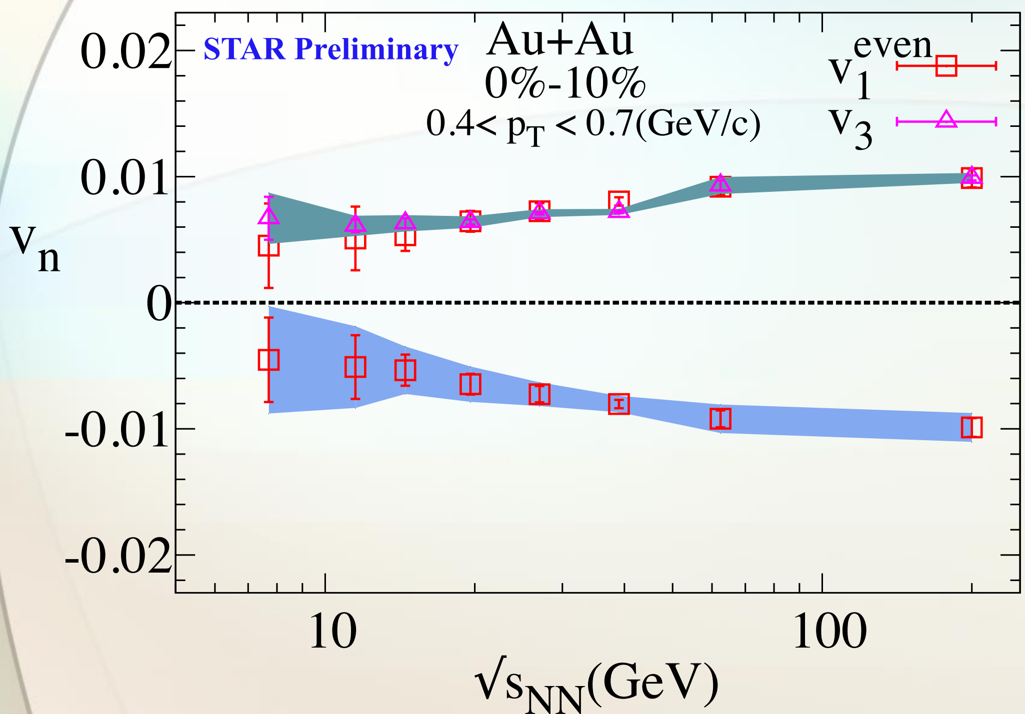


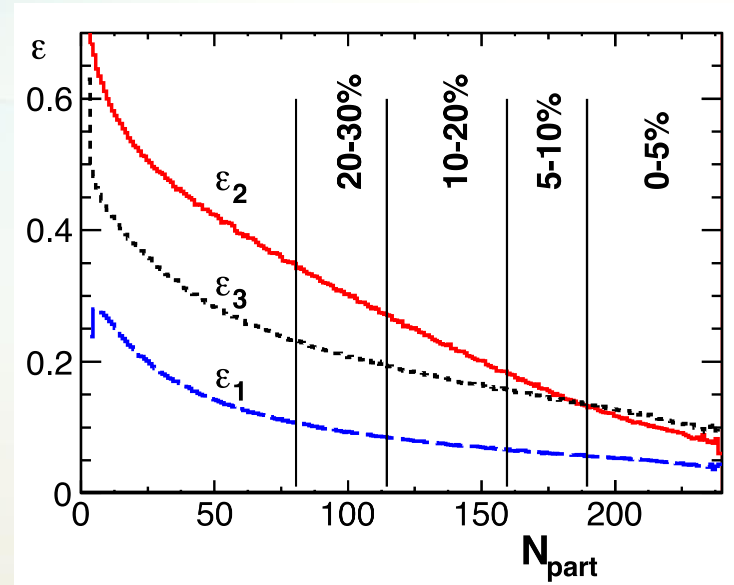
$|\eta| < 1$ and $|\Delta\eta| > 0.7$

Beam energy dependence of v_1^{even}

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

The extracted $\boldsymbol{v_1^{even}}$ vs $\sqrt{s_{NN}}$ at 0%-10% centrality





P.Bożek
PLB 717 287-290 (2012)

- ➢ $|v_1^{even}|$ shows similar values to v_3 at $0.4 < p_T < 0.7(GeV/c)$
- ➢ $\varepsilon_3 > \varepsilon_1$
  - ✓ v_3 has larger viscous effect than v_1^{even}

Rapidity-even dipolar flow

$v_1^{even}(p_T)$

$v_1^{even}(\langle N_{Ch} \rangle)$

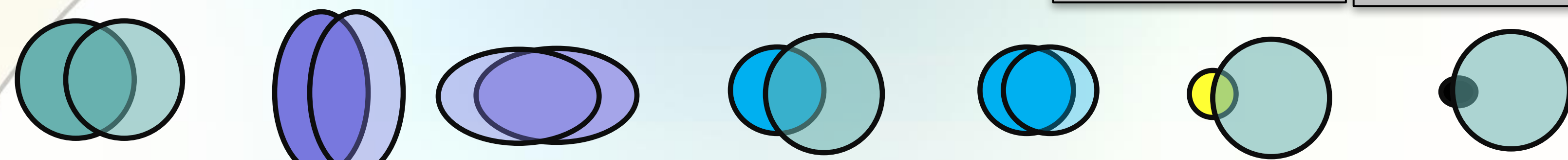
Acoustic ansatz

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.

arXiv:1601.06001
Roy A. Lacey, et al.



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

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

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

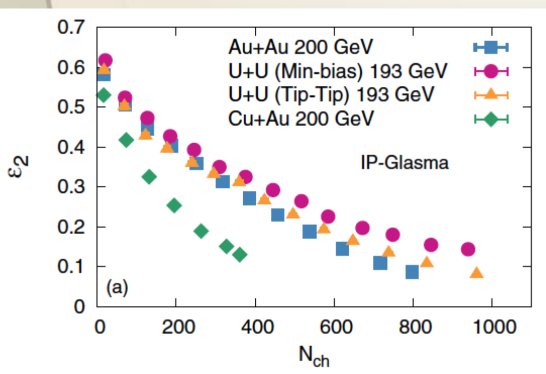
PRC 88, 044915 (2013)
E. Shuryak and I. Zahed

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

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

Even Harmonic v_2

ε_2 *scaling is needed*



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

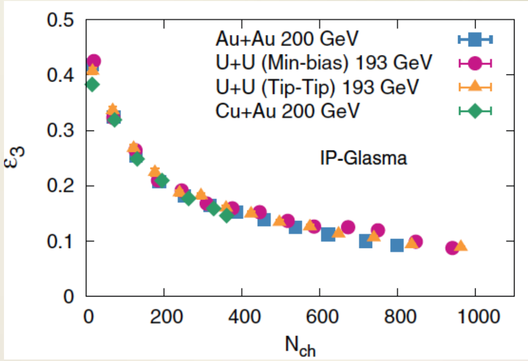
Expectations

➢ Odd harmonics are system independent

➢ Even harmonics are system dependent

Odd Harmonic v_3

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



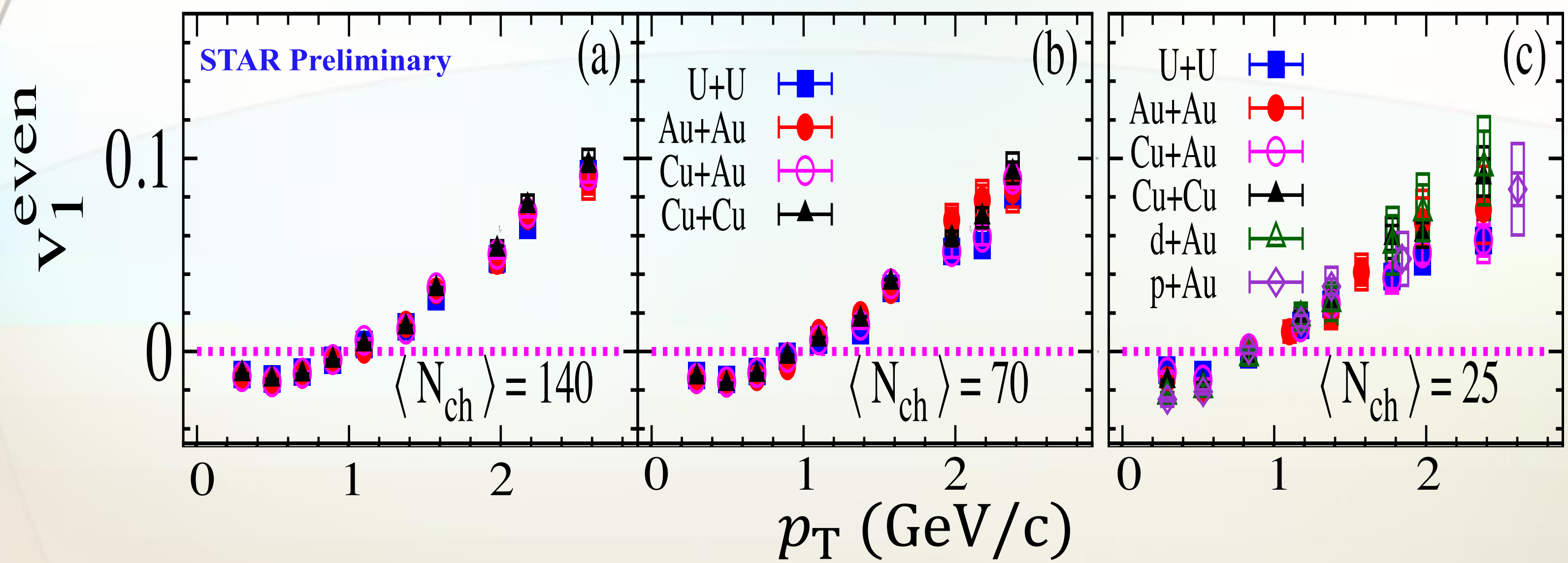
B.Schenke , et al.
PRC 89, 064908 (2014)

v_1^{even} for different systems

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

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

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



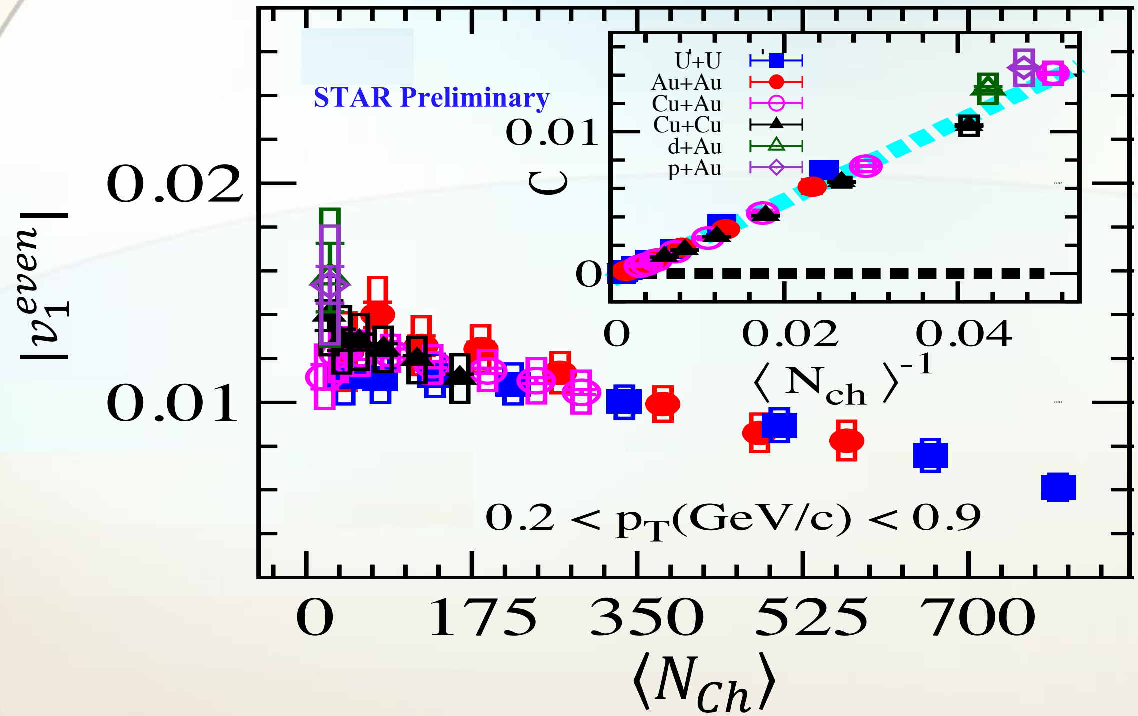
- The efficiency corrections for N_{Ch} have applied for Au+Au and U+U collisions.
  - Within the experimental uncertainties v_1^{even} shows similar trends and magnitudes for all systems.
  - v_1^{even} is system independent.

v_n for different systems

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

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

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



- Momentum conservation parameter C scales as $\langle N_{Ch}\rangle^{-1}$ for all systems

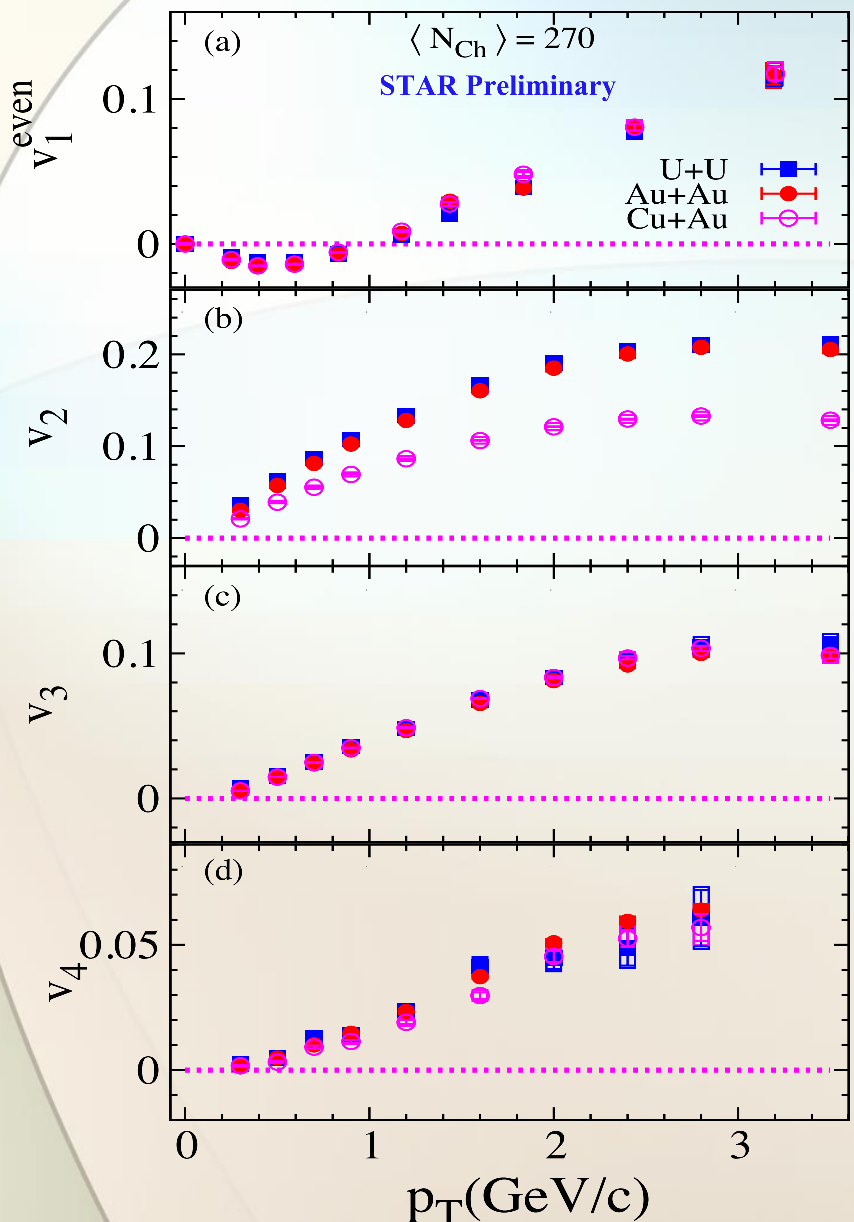
- The efficiency corrections for N_{Ch} have applied for Au+Au and U+U collisions.
- Within the experimental uncertainties v_1^{even} shows similar trends and magnitudes for all systems.
- v_1^{even} is system independent.

v_n for large systems $(A + B)$

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

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

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



- Odd harmonics are system independent.
- Even harmonics are system dependent with less dependence for higher harmonics.

Conclusion

Comprehensive set of STAR measurements presented for $v_1^{even}(p_T, \text{Cent\%} \text{ and} \sqrt{s_{NN}})$ for several collision systems.

- For $Au + Au$ beam energy scan
  - ✓ v_1^{even} shows a weak dependence on centrality and beam energy
  - ✓ Within the experimental uncertainties $|v_1^{even}|(\sqrt{s_{NN}})$ shows a similar magnitude to v_3 suggesting that v_3 has larger viscous effect than v_1^{even}
- For different systems at similar multiplicity (200 GeV)
  - ✓ Within the experimental uncertainties v_1^{even} shows similar trends and magnitudes for all systems
  - ✓ v_1^{even} is system independent.

Within the experimental uncertainties, the similar trends and magnitudes of the measured v_1^{even} for different colliding systems at $\sqrt{s_{NN}} \sim 200\ GeV$ suggest a comparable viscous coefficient $\left(\mathrm{A}\frac{\eta}{s}\right)$

THANK YOU