Beam-energy dependence of the viscous damping of anisotropic flow

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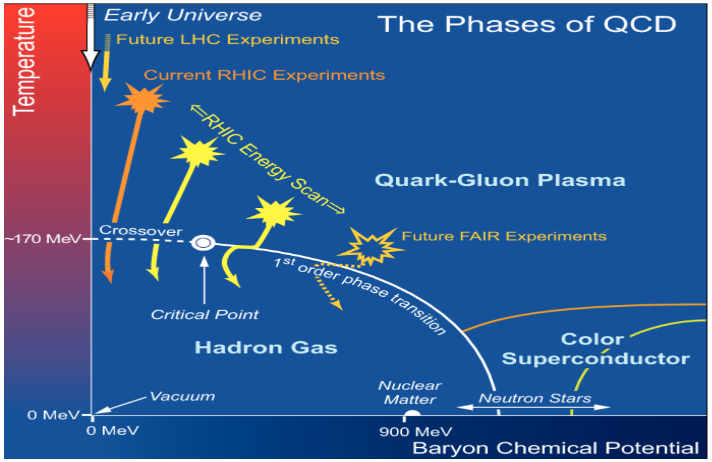
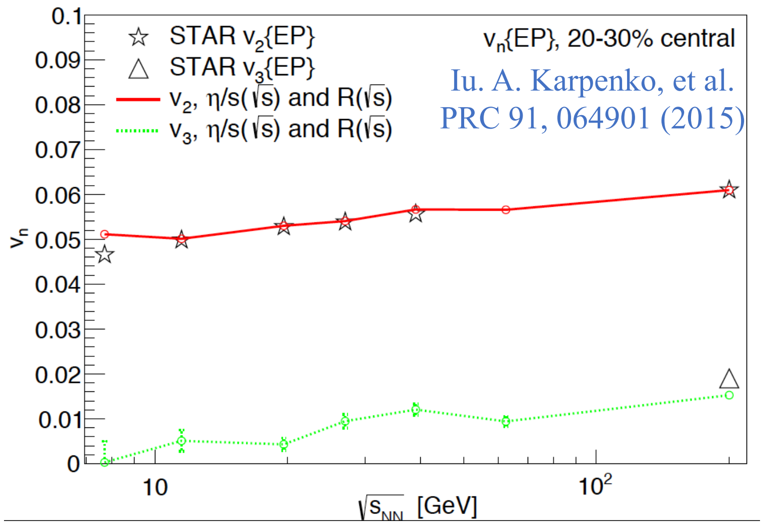
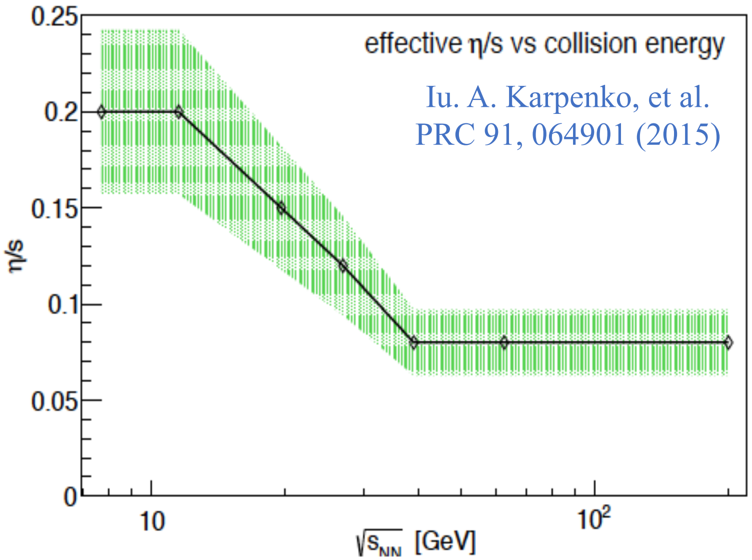
Introduction

QCD Phase Diagram



➢ Strong interest in the theoretical calculations which span a broad (T, μ_B) domain.

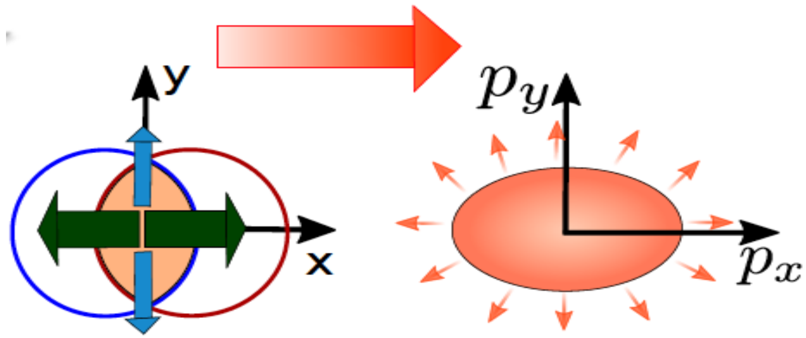


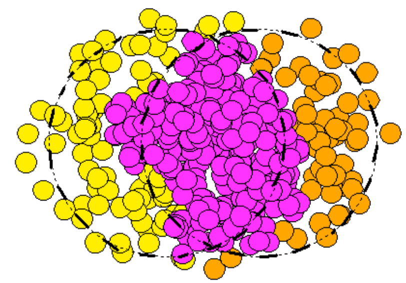


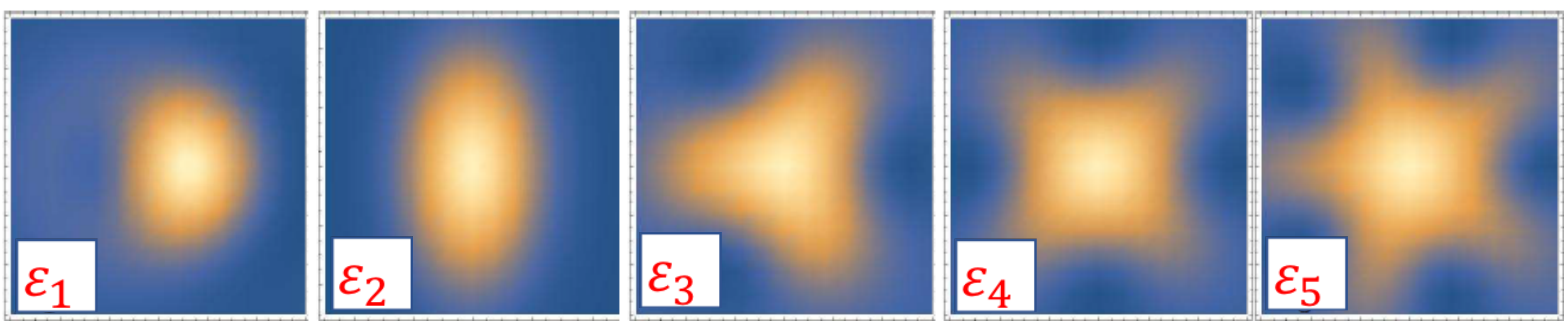
➢ The beam energy dependence of the anisotropic flow measurements can aid the extraction of $\frac{\eta}{s}(T, \mu_B)$

Anisotropic flow

Asymmetry in initial geometry → Final state momentum anisotropy (flow)







$$dN/d\varphi = 1 + 2\sum_{n}^{\infty} v_n \cos(\varphi - \Psi_n)$$

- The flow harmonic coefficients v_n are influenced by eccentricities (ε_n), fluctuations, system size, speed of sound $c_s(\mu_B, T)$, and transport coefficient $\frac{\eta}{s}(\mu_B, T)$

Azimuthal anisotropic flow

- Comprehensive set of flow measurements are important to study;
  - ✓ Differentiate between initial-state models
    - ❑ Initial-state eccentricity & its fluctuations
  - ✓ Transport coefficients ($^{\eta}/_{s}$, etc)
    - ❑ Pin down the temperature dependence of the transport coefficients
  - ✓ Detailed flow measurements could aid ongoing efforts to search for the critical end point(CEP)

What are the respective roles of ε_n and its fluctuations, system size and transport coefficient $\frac{\eta}{s}(T,\mu_B)$?

4

Azimuthal anisotropy measurements

Correlation function

Two-particle correlation function $Cr(\Delta\varphi = \varphi_a - \varphi_b)$,

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

$n > 1$

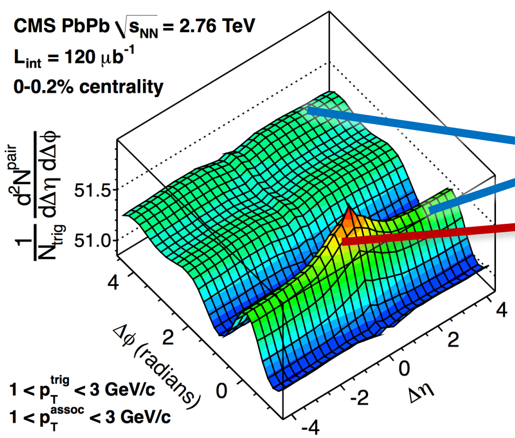
$$v_n^{ab} = v_n^a v_n^b + \delta_{short}$$

$n = 1$

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

Flow

Non-flow



Long − range

Short − range

Momentum Conservation

HBT

Di−jets

Decay

Charge

Non-flow suppression is needed

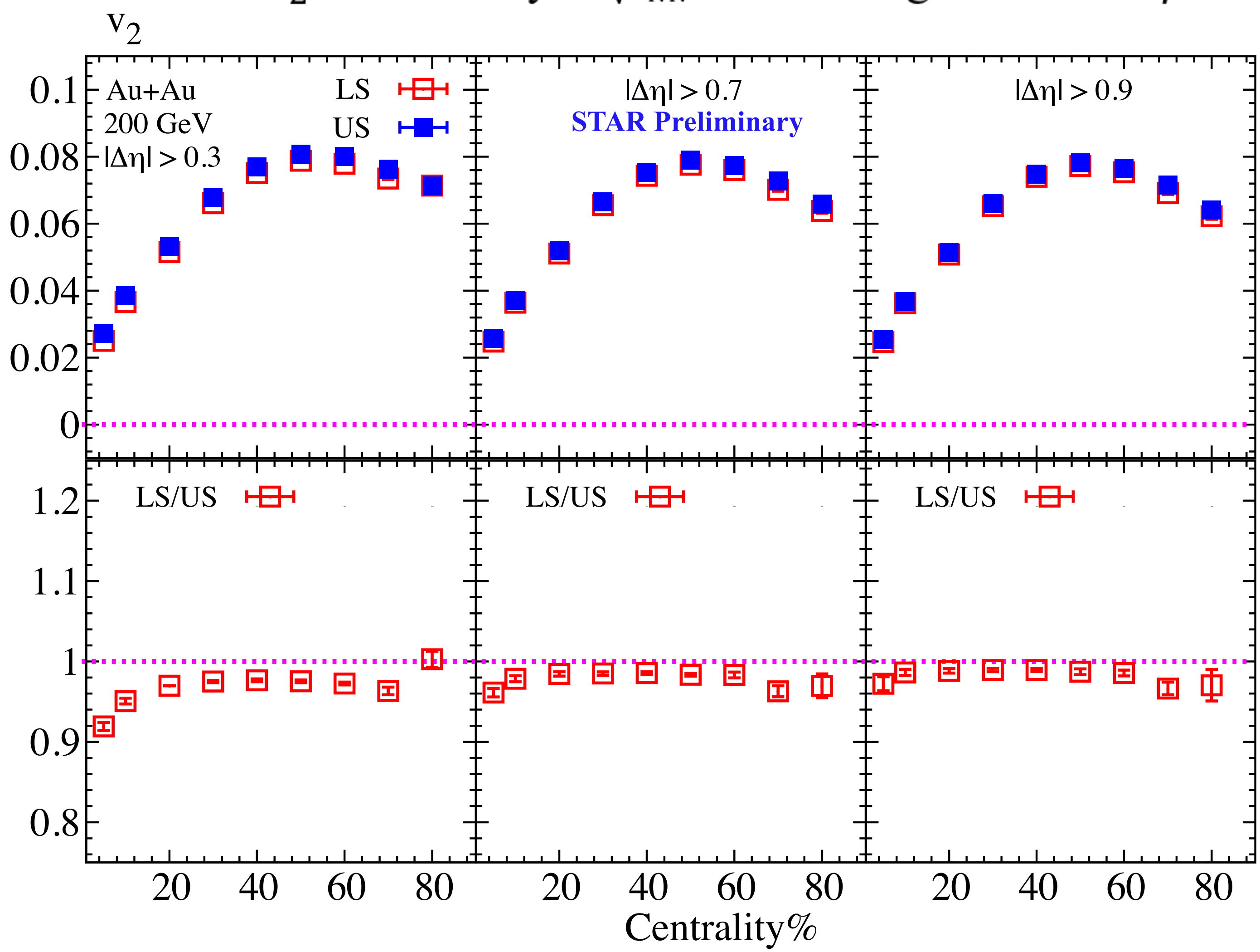
Short – range Non–flow

Short-range non-flow suppression

HBT

Decay

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



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

Long − range

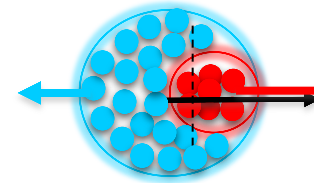
Momentum Conservation

Long-range non-flow suppression

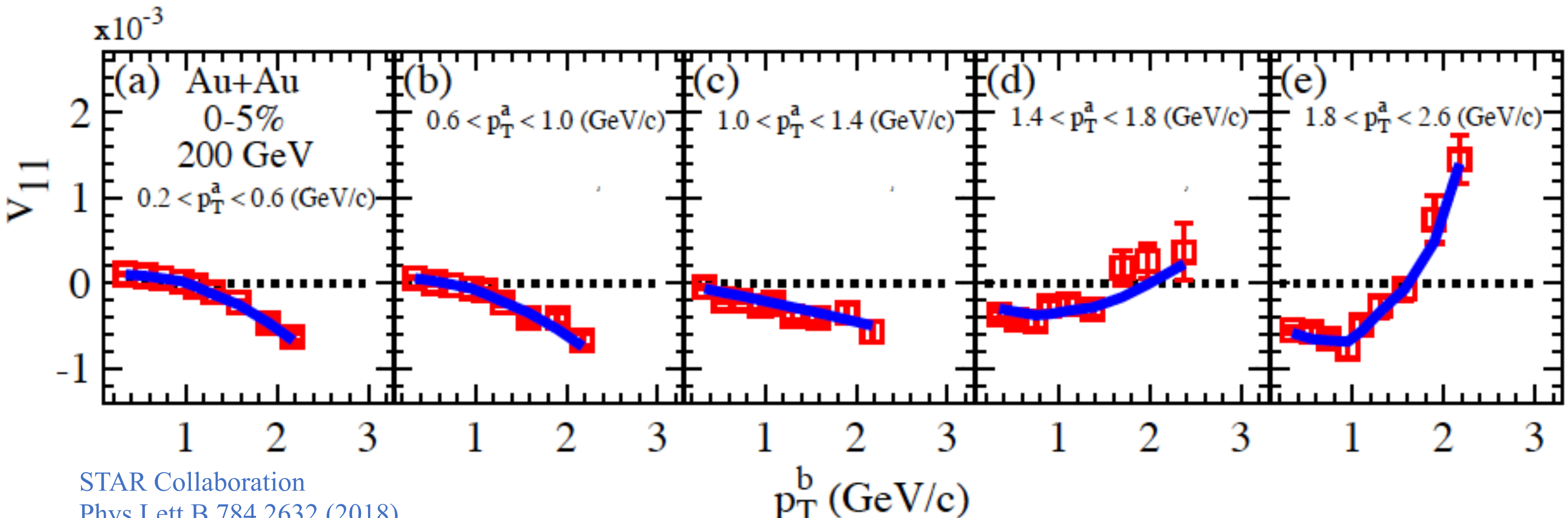
arXiv:1203.0931
arXiv:1203.3410
arXiv:1208.1874
arXiv:1208.1887
arXiv:1211.7162

$$v_{11}^{ab} = v_1^{even}(p_T^a)\, v_1^{even}(p_T^b) + \delta_{long}$$

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



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



STAR Collaboration
Phys.Lett.B 784 2632 (2018)

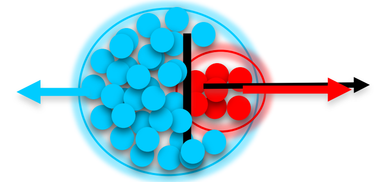
➢ v_{11} characteristic behavior gives a good constraint for $\boldsymbol{v_1^{even}}(\mathbf{p_T})$ extraction

Long − range

Momentum Conservation

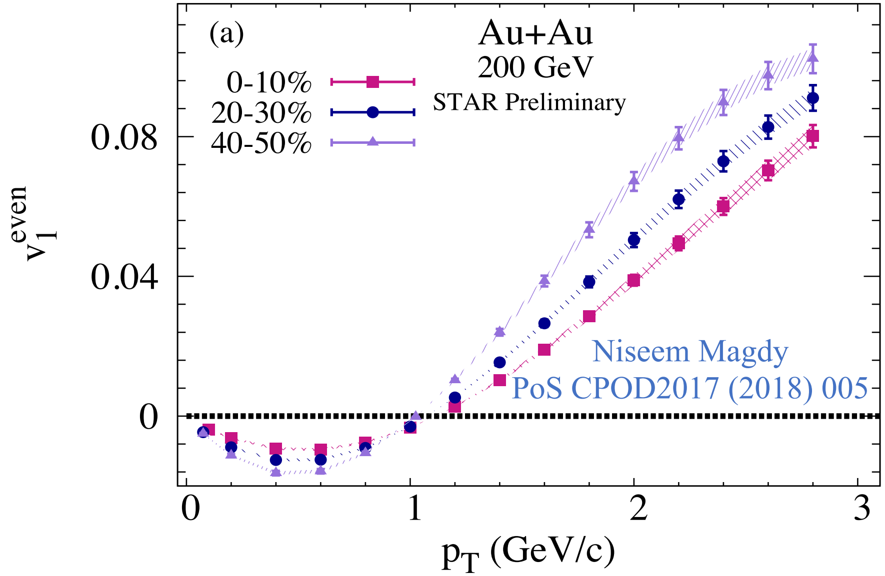
Long-range non-flow suppression

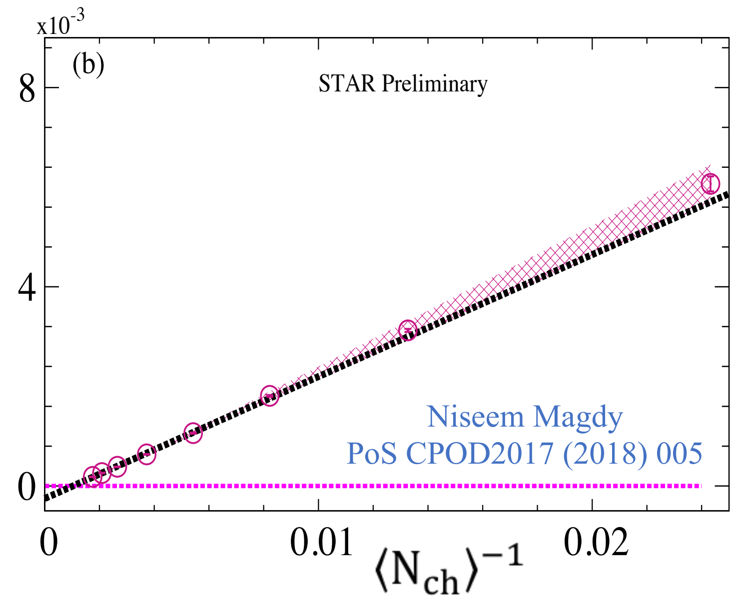
$|\eta| < 1$ and $|\Delta\eta| > 0.7$



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

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





- The characteristic behavior of $v_1^{even}(p_T)$ shows a weak centrality dependence
- The momentum conservation parameter K scales as $\langle N_{ch}\rangle^{-1}$

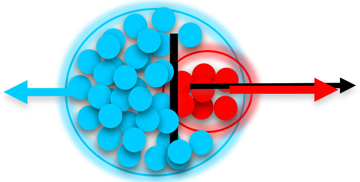
Flow harmonics

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

$v_n(p_T)$

$v_n(Centrality)$

Beam Energy Dependence of v_1^{even}



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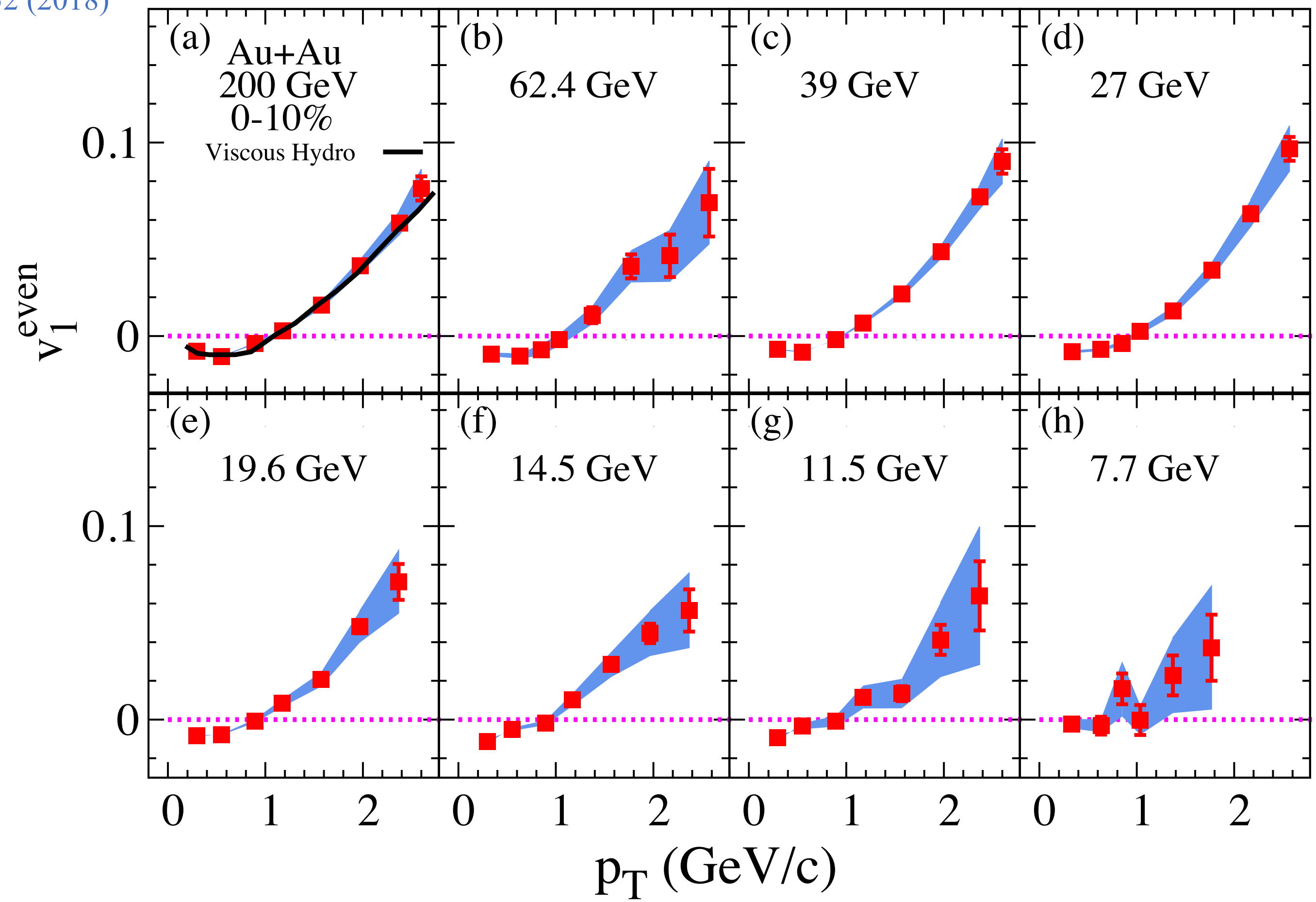
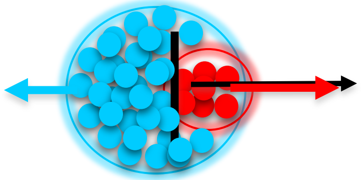
PLB 784 2632 (2018)

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

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



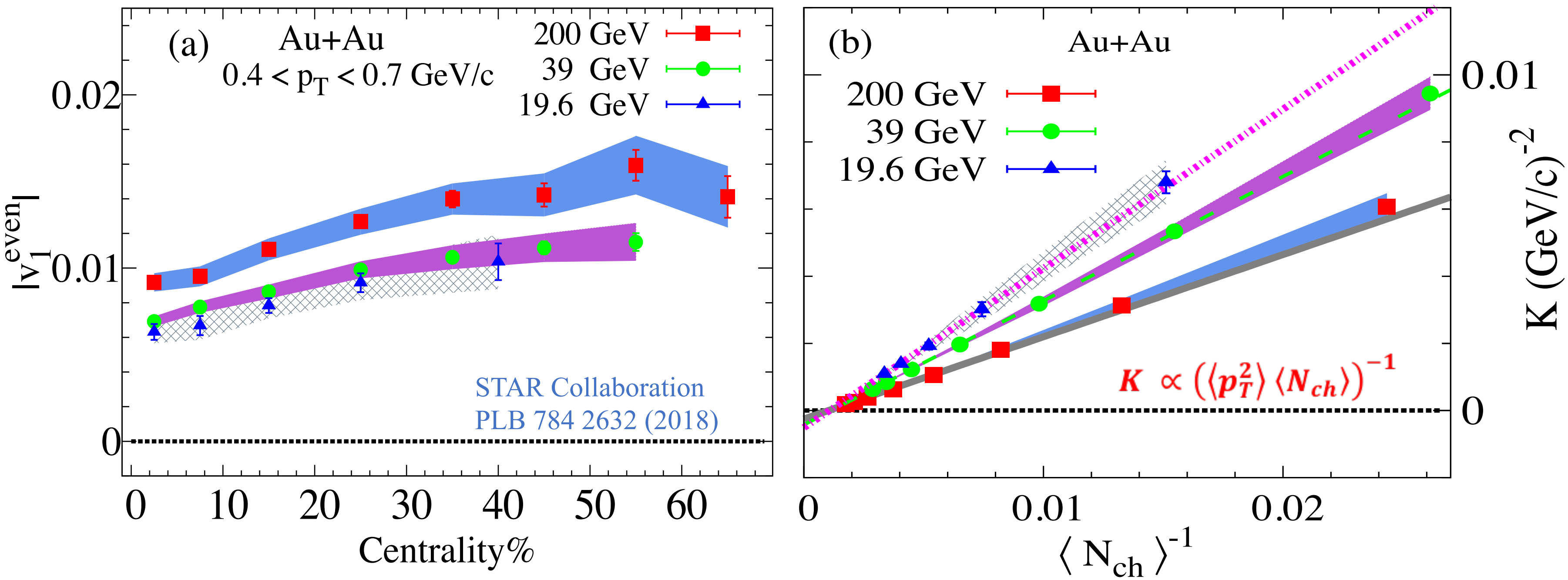
- Similar characteristic behavior of $v_1^{even}(p_T)$ at all energies
- $v_1^{even}(p_T)$ agrees with hydrodynamic calculations at 200 GeV



Beam Energy Dependence of v_1^{even}

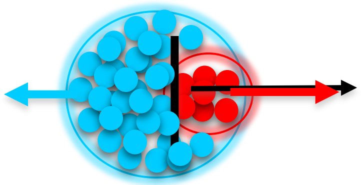
$$v_{11}(p_T^a, p_T^t) = v_1^{even}(p_T^a)v_1^{even}(p_T^t) - K\, p_T^a\, p_T^t$$

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



For different beam energies;

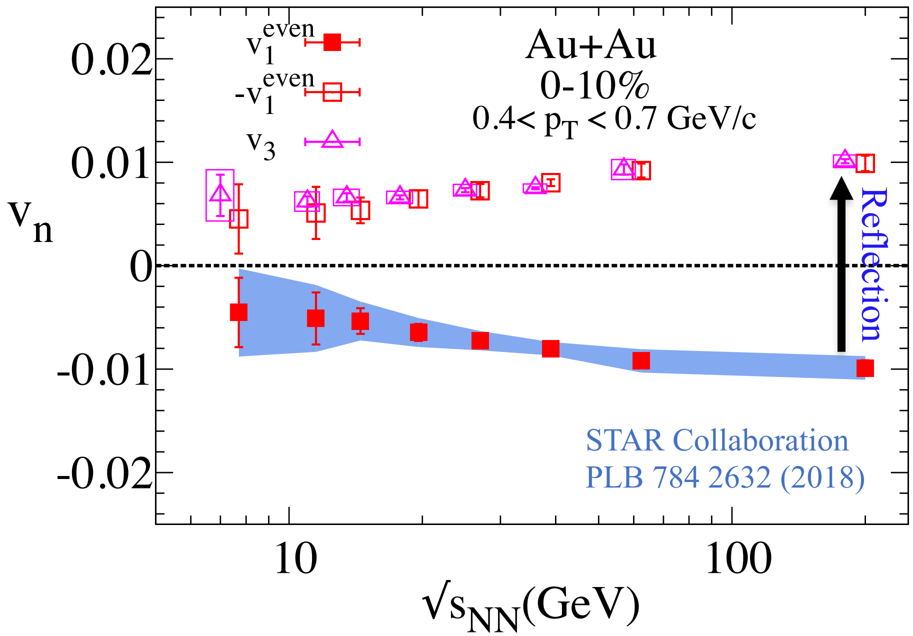
- v_1^{even} increases weakly as collisions become more peripheral
- Momentum conservation parameter K scales as $\langle N_{ch} \rangle^{-1}$

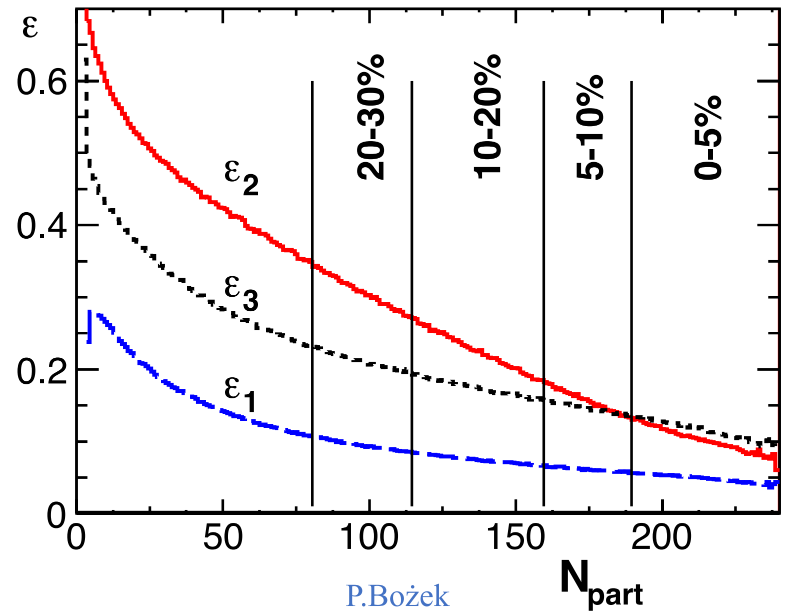


Beam Energy Dependence of v_1^{even}

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

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





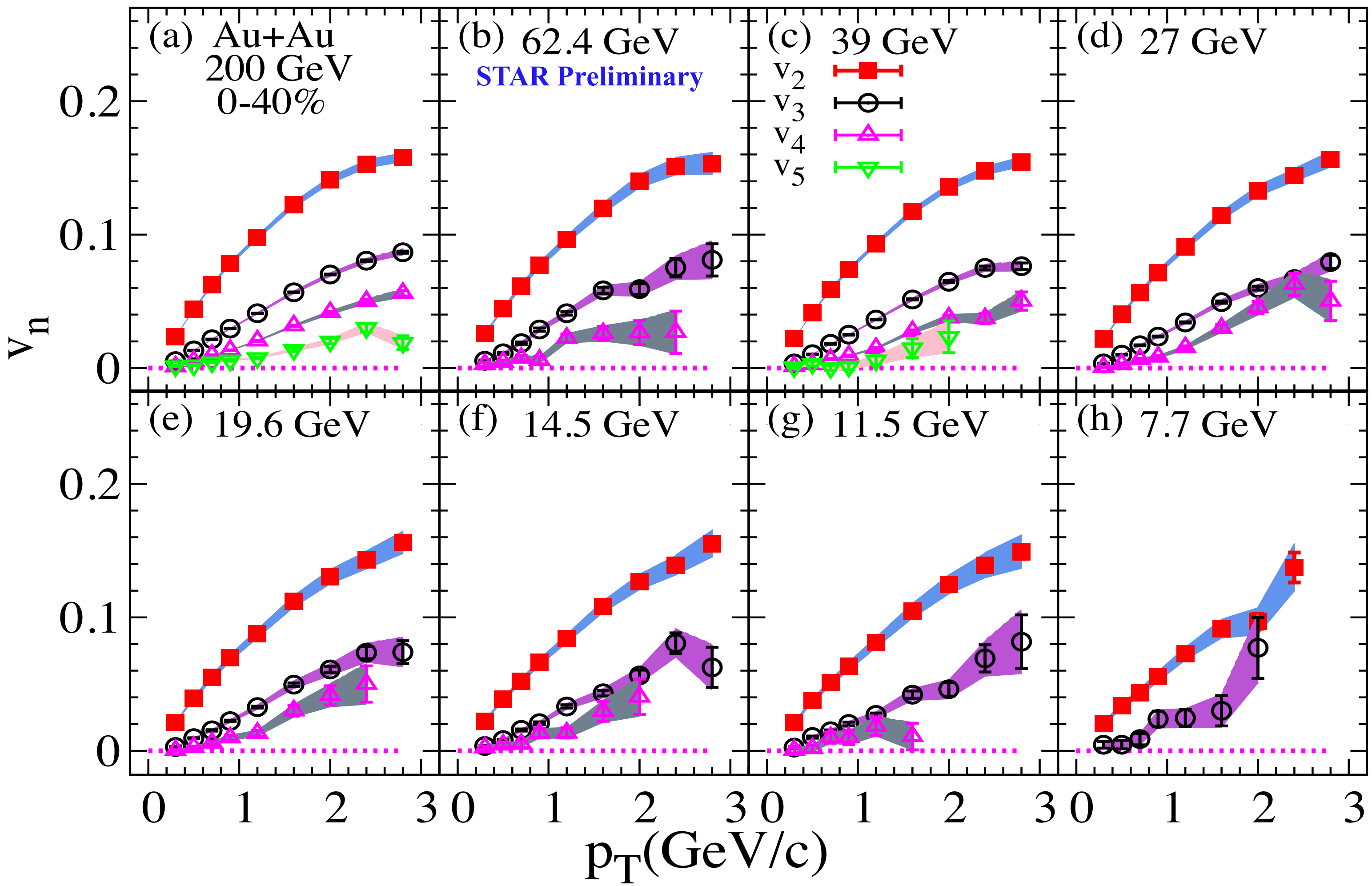
P.Bożek
PLB 717, 287-290 (2012)

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

Beam Energy Dependence of v_n

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

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

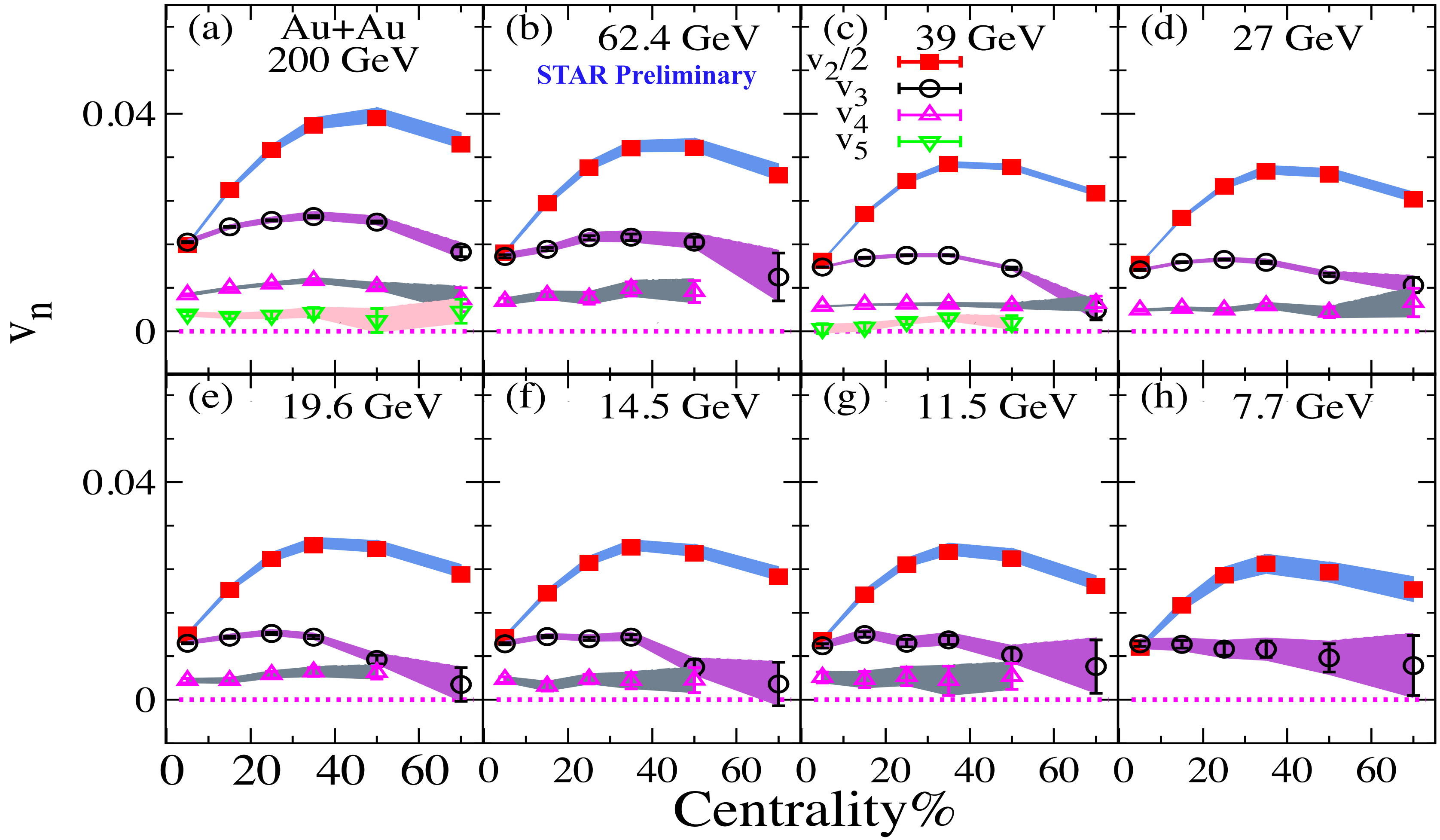


- ➢ $v_n(p_T)$ has similar trends for different beam energies.
- ➢ $v_n(p_T)$ decreases with harmonic order n.

Beam Energy Dependence of v_n

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

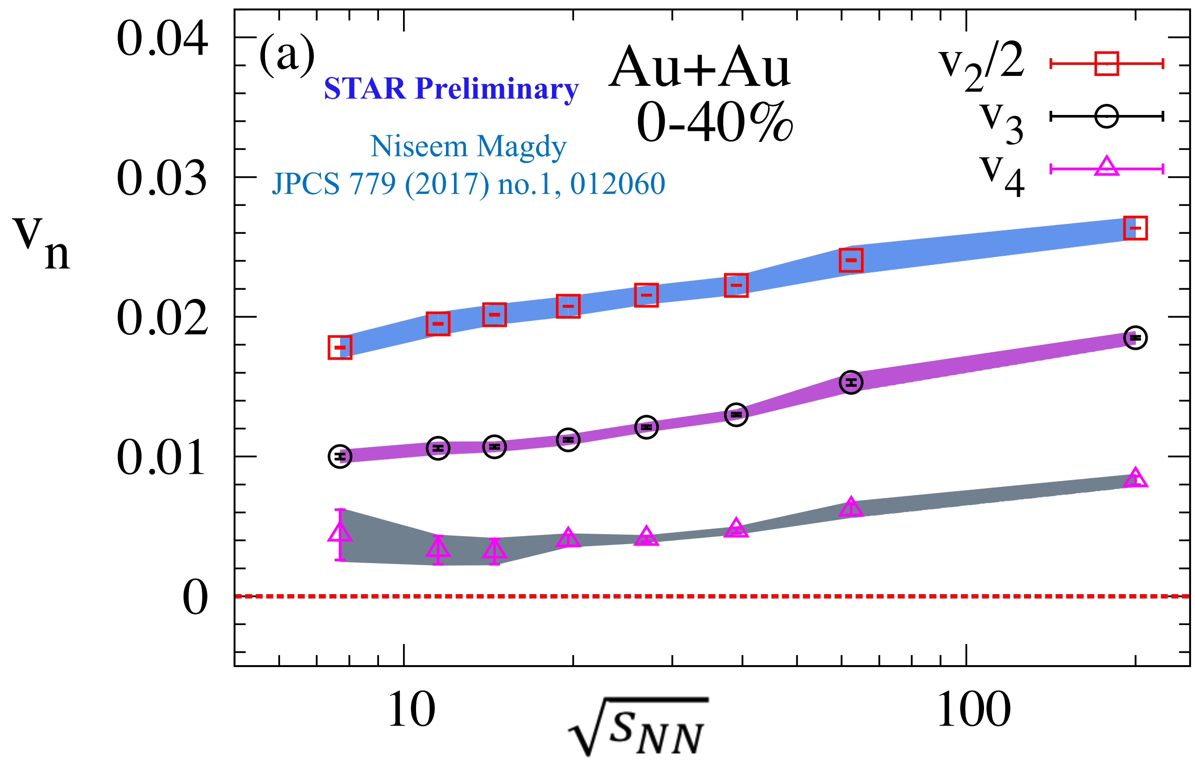
The extracted $v_{n>1}$(Centrality) at all BES energies



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

Beam Energy Dependence of v_n

The extracted $v_{n>1}$ vs. $\sqrt{s_{NN}}$ at 0-40% centrality



- $v_n(\sqrt{s_{NN}})$ shows a monotonic increase with beam-energy.
- $v_n(\sqrt{s_{NN}})$ decreases with harmonic order n (viscous effects).

Beam Energy Dependence of Flow Fluctuations

$$\langle\langle 2m \rangle\rangle_n = \left\langle\left\langle e^{in\sum_{j=1}^{m}(\phi_{2j-1}-\phi_{2j})}\right\rangle\right\rangle$$

$$c_n\{2\} = \langle\langle 2 \rangle\rangle_n$$

$$c_n\{4\} = \langle\langle 4 \rangle\rangle_n - 2\,\langle\langle 2 \rangle\rangle_n\,\langle\langle 2 \rangle\rangle_n$$

$$c_n\{6\} = \langle\langle 6 \rangle\rangle_n - 9\,\langle\langle 2 \rangle\rangle_n\,\langle\langle 4 \rangle\rangle_n + \langle\langle 2 \rangle\rangle_n^3$$

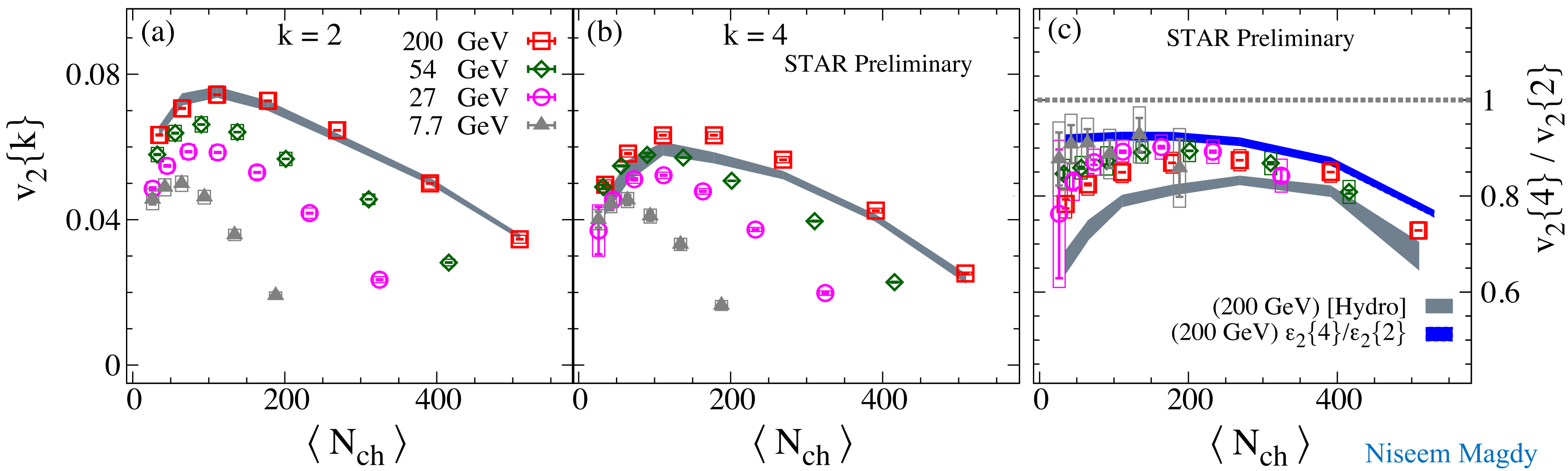
$$v_n^2\{2\} = c_n\{2\}$$

$$v_n^4\{4\} = -c_n\{4\}$$

$$v_n^6\{6\} = \frac{1}{6}c_n\{6\}$$

Beam Energy Dependence of Flow Fluctuations

Hydro
P. Alba, at el.
Phys. Rev. C 98, 034909 (2018)



Niseem Magdy
NPA 982 (2019) 255-258

- The elliptic flow fluctuations, $\frac{v_2\{4\}}{v_2\{2\}}$ show:
  - ✓ Modest dependence on centrality
  - ✓ Weak dependence on beam energy

- The model calculations for $(v_2\{4\}/v_2\{2\})$ and $(\epsilon_2\{4\}/\epsilon_2\{2\})$ bracket the data at 200 GeV

Viscous Attenuation

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.

- Acoustic ansatz
  - ✓ Sound attenuation in the viscous matter reduces the magnitude of $v_{n=2,3}$.

- Anisotropic flow attenuation:

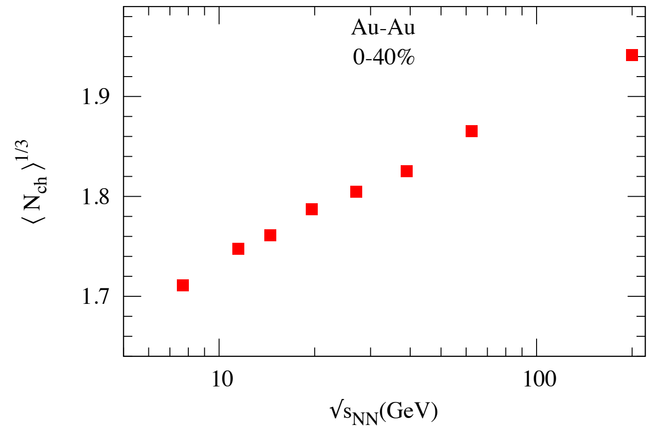
$$v_n \propto k\,\varepsilon_n, \qquad k = e^{-\beta\, n^2}$$

$$\frac{v_n}{\varepsilon_n} \propto e^{-\beta\, n^2}, \qquad \beta \propto \frac{\eta}{s}\frac{1}{R\,T}$$

- From macroscopic entropy considerations:

$$S \sim (RT)^3 \sim \langle N_{Ch}\rangle \text{ then } RT \sim \langle N_{Ch}\rangle^{1/3}$$

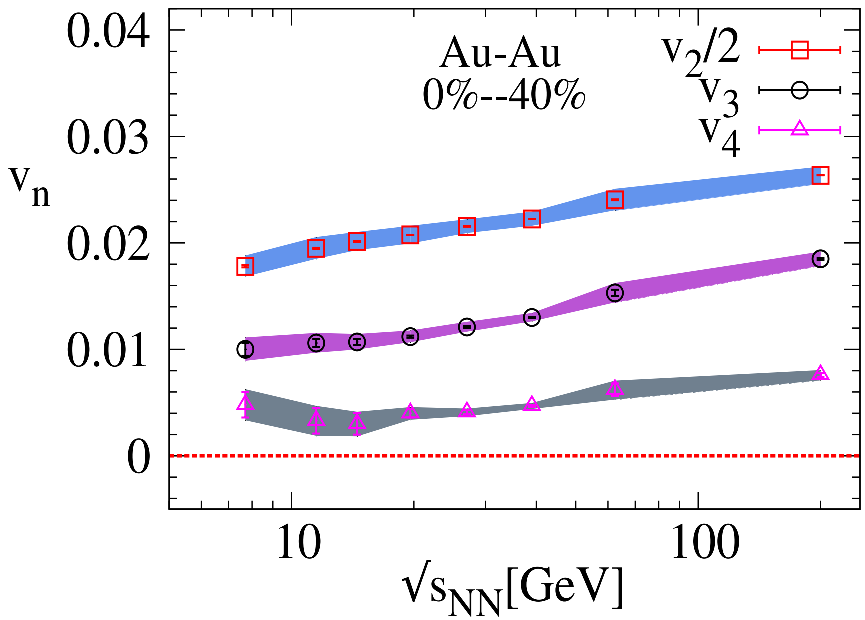
$$\ln\left(\frac{v_n}{\varepsilon_n}\right) \propto -\left(\frac{\eta}{s}\right)\langle N_{Ch}\rangle^{-1/3}$$

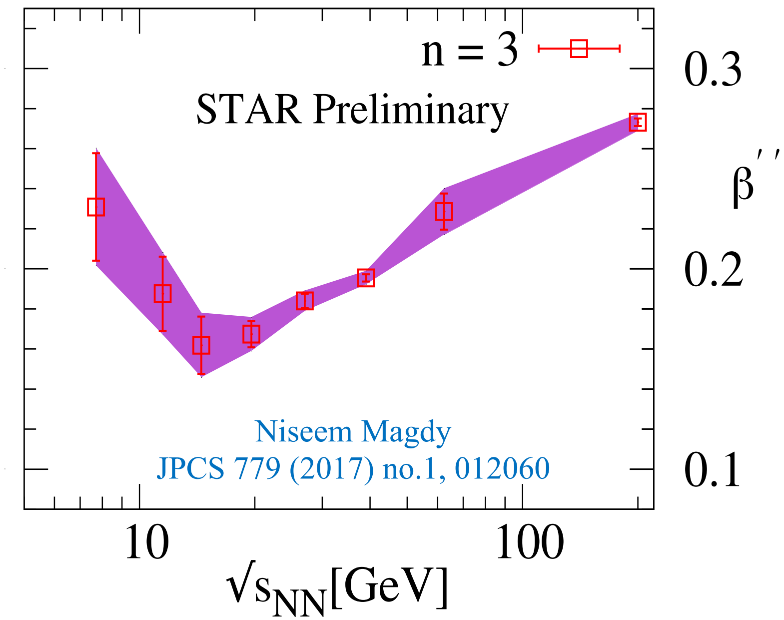


What are the respective roles of ε_n and its fluctuations, system size ($\langle N_{Ch}\rangle^{-1/3}$) and transport coefficient $\frac{\eta}{s}(T,\mu_B)$?

Viscous coefficient

$$\beta'' = ln\left(\frac{v_n^{1/n}}{v_2^{1/2}}\right) \langle N_{Ch}\rangle^{\frac{1}{3}} \, (n-2)^{-1} = A\frac{\eta}{s}$$





- The viscous coefficient shows a non-monotonic behavior with beam-energy

Summary

Comprehensive set of flow measurements were studied for Au+Au collision system at all BES energies with one set of cuts.

- For v_n:
  - ✓ v_n vs centrality indicates a similar trend for different beam energies.
  - ✓ Momentum conservation parameter K scales as $\langle \mathrm{N_{ch}} \rangle^{-1}$
  - ✓ $v_n\left(\sqrt{s_{NN}}\right)$ shows a monotonic increase with beam-energy.

- The elliptic flow fluctuations, $\frac{v_2\{4\}}{v_2\{2\}}$ show:
  - ✓ Modest dependence on centrality
  - ✓ Weak dependence on beam energy

- The viscous coefficient shows a non-monotonic behavior with beam-energy

For different beam energies, these comprehensive measurements provide additional constraints for theoretical models, as well as $\frac{\eta}{s}$ extraction.

THANK YOU