Beam-energy dependence of the azimuthal anisotropic flow from RHIC

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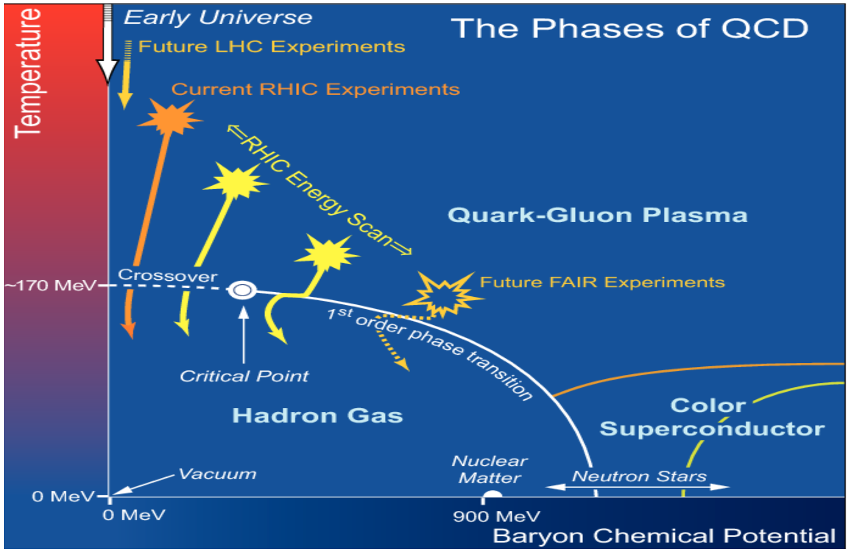
QCD Phase Diagram

- Lattice QCD finds a smooth crossover at large T and $\mu_B \sim 0$ MeV

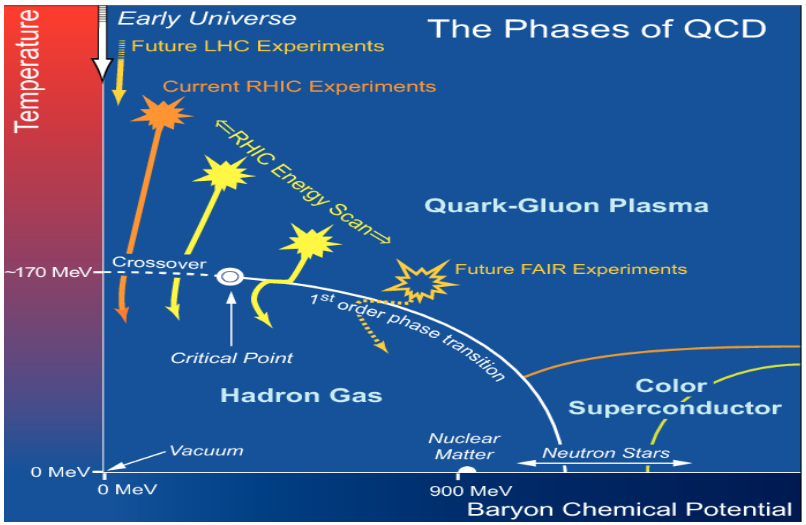


- Various models find a strong 1st-order phase transition at large μ_B

- Strong interest in the theoretical calculations which span a broad (T, μ_B) domain.
  - ✓ Search for QCD critical point
  - ✓ Search for signals of the 1-st order phase transition
  - ✓ Search for turn-off of the QGP signatures

QCD Phase Diagram

Step-by-step on the QCD Phase Diagram



Beam-Energy Scan (BES-I) at RHIC

$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	Year
200	350	2010
62.4	67	2010
54.4	1300	2017
39	39	2010
27	70	2011
19.6	36	2011
14.5	20	2014
11.5	12	2010
7.7	4	2010

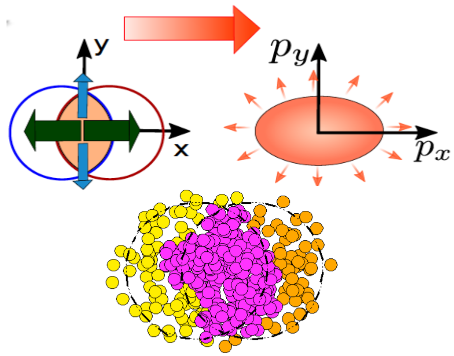
Beam-Energy Scan (BES-II) at RHIC

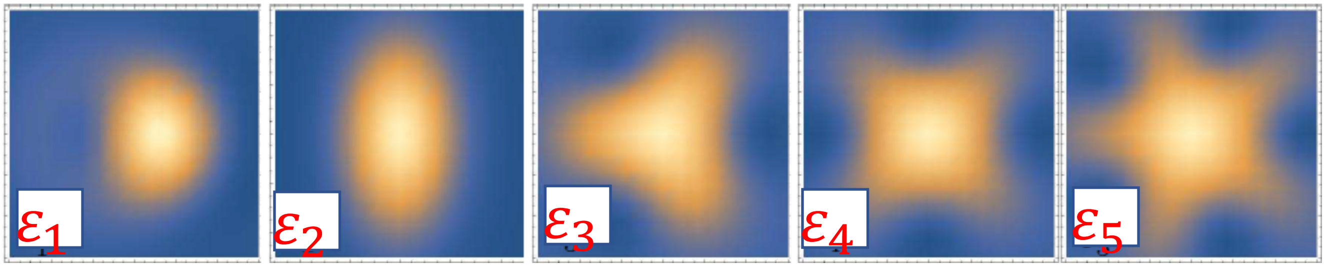
	Collision Energy (GeV)				
	7.7	9.1	11.5	14.5	19.6
μ_B (MeV) in 0-5% central collisions	420	370	315	260	205
Fixed Target Energy (GeV)	3.0	3.2	3.5	3.9	4.5
Fixed Target μ_B (MeV)	721	699	666	633	589
Proposed Event Goals in BES-II	100	160	230	300	400
BES-I Events	4	N/A	12	20	36

Introduction

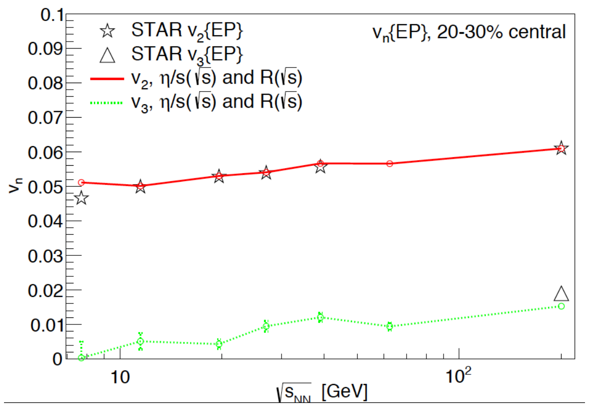
Anisotropic flow

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

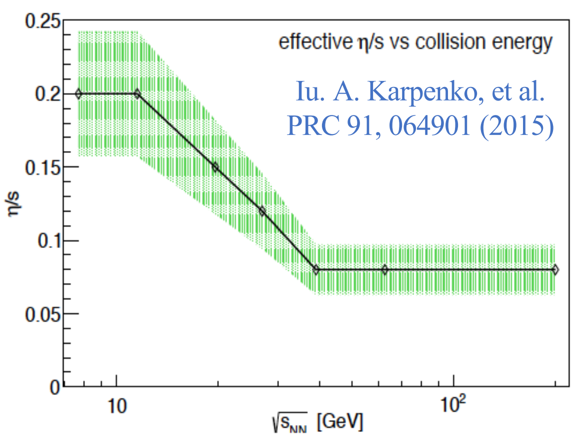




$$dN/d\varphi = 1 + 2\sum_{n}^{\infty} v_n \cos(\varphi - \Psi_n)$$



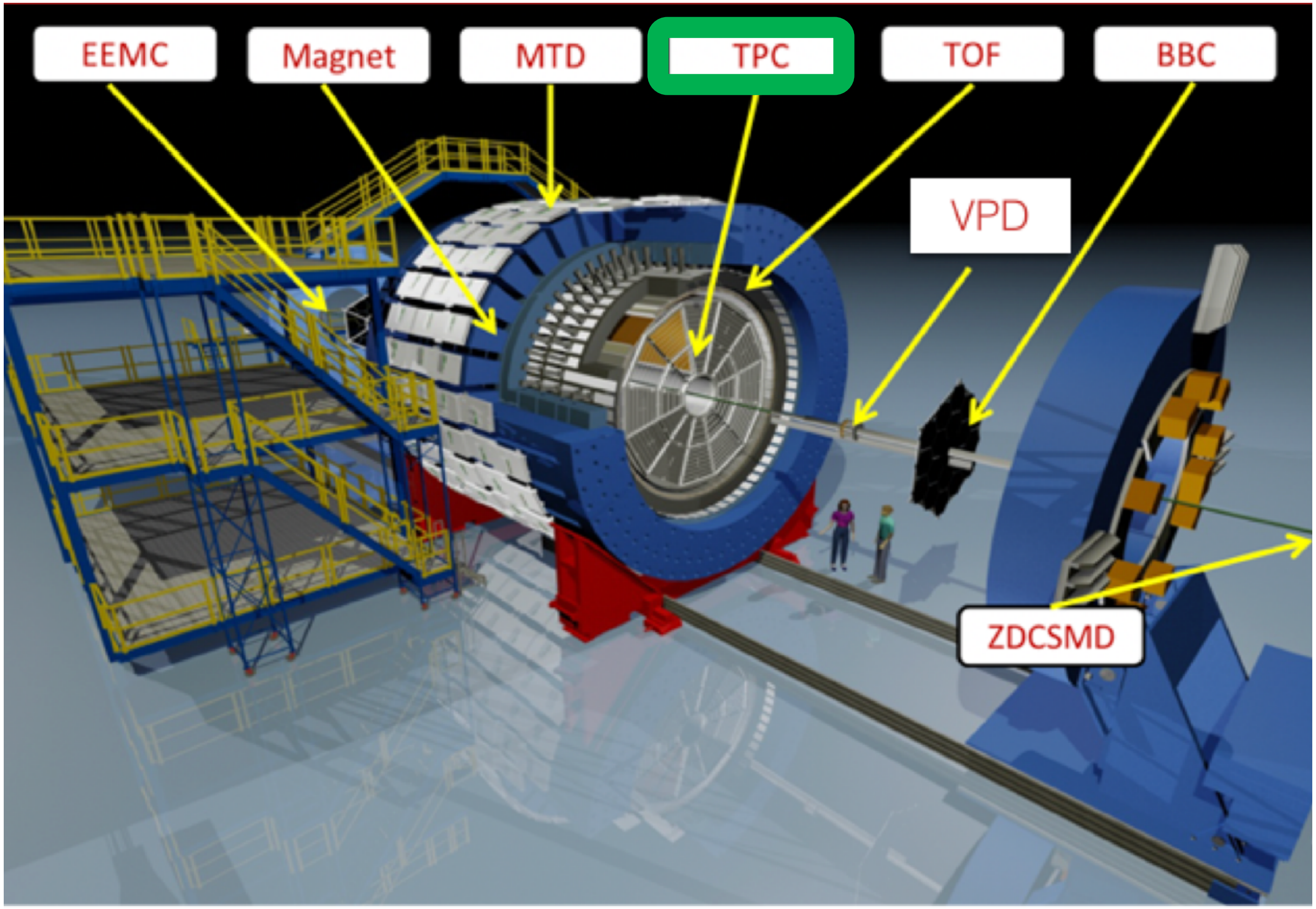
- The flow harmonic coefficients (v_n) are influenced by eccentricities (ε_n), fluctuations, speed of sound ($c_s(\mu_B, T)$), and specific shear viscosity $\frac{\eta}{s}(\mu_B, T)$



- Comprehensive set of flow measurements are important for:
  - ✓ Differentiate between initial-state models
  - ✓ Aid the extraction of $\frac{\eta}{s}(T, \mu_B)$

Introduction

The Solenoidal Tracker At RHIC



➢ Time Projection Chamber

- ✓ Tracking and identification of charged particles
- ✓ Full azimuthal coverage
- ✓ $|\eta|<1$ coverage

Azimuthal anisotropy measurements

Correlation function

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

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

$n > 1$

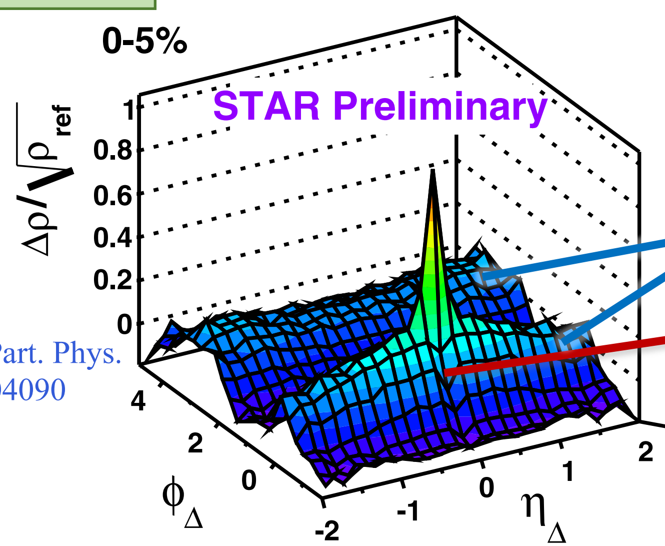
$$v_n^{ab} = v_n^a v_n^b + \delta_{short}$$

$n = 1$

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

Flow

Non-flow



Phys. G: Nucl. Part. Phys. 35(2008) 104090

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

Non-flow suppression is needed

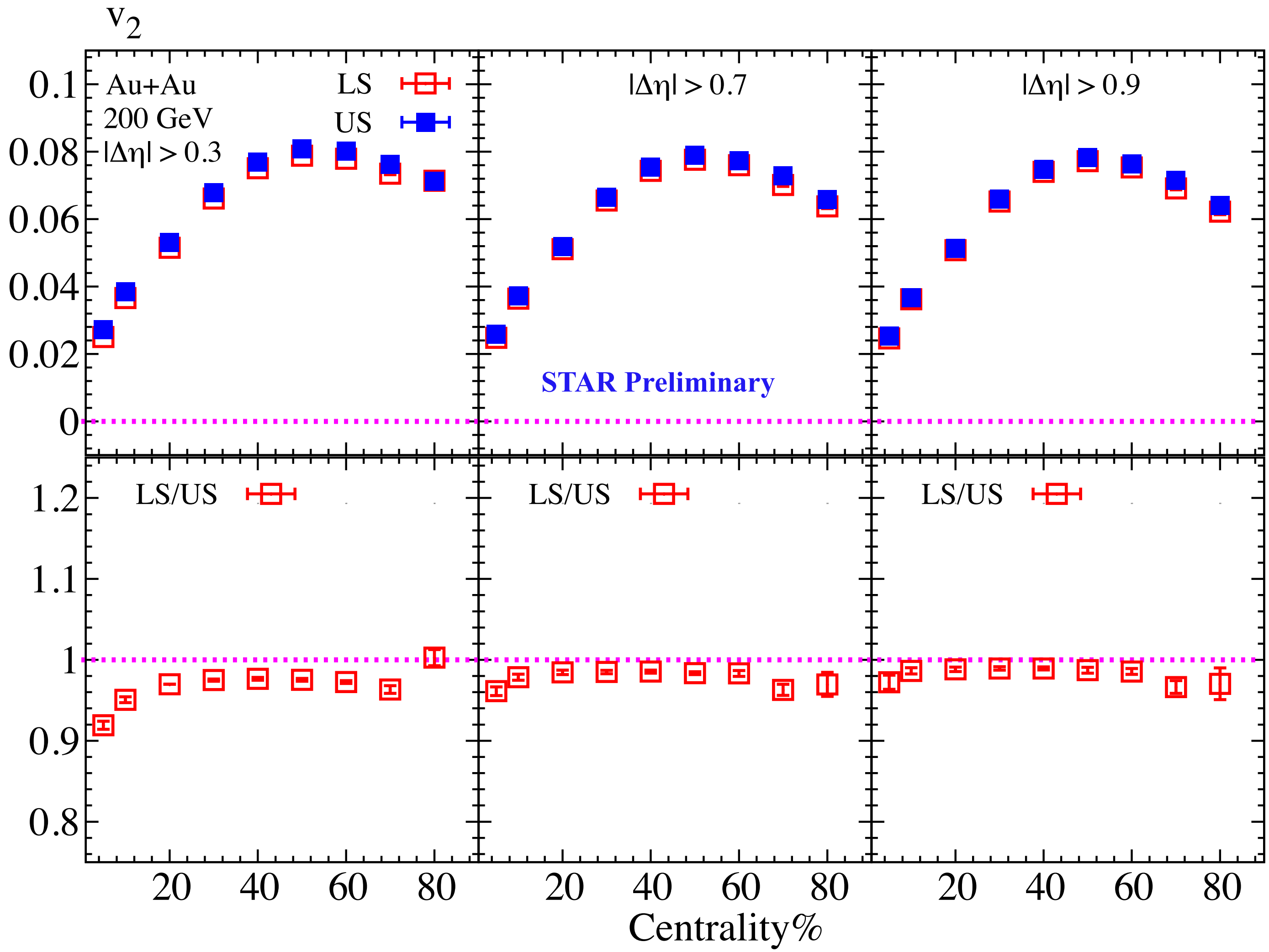
Short – range
Non–flow

Short-range non-flow suppression

HBT

Decay

The v_2 vs. centrality at $\sqrt{s_{NN}}$ = 200 GeV different using Δη cuts



✓ Short-range non-flow effect reduced using Δη > 0.7 cut

Long-range non-flow suppression

Long − range

Momentum Conservation

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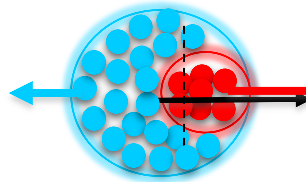
Phys.Lett.B 784 2632 (2018)

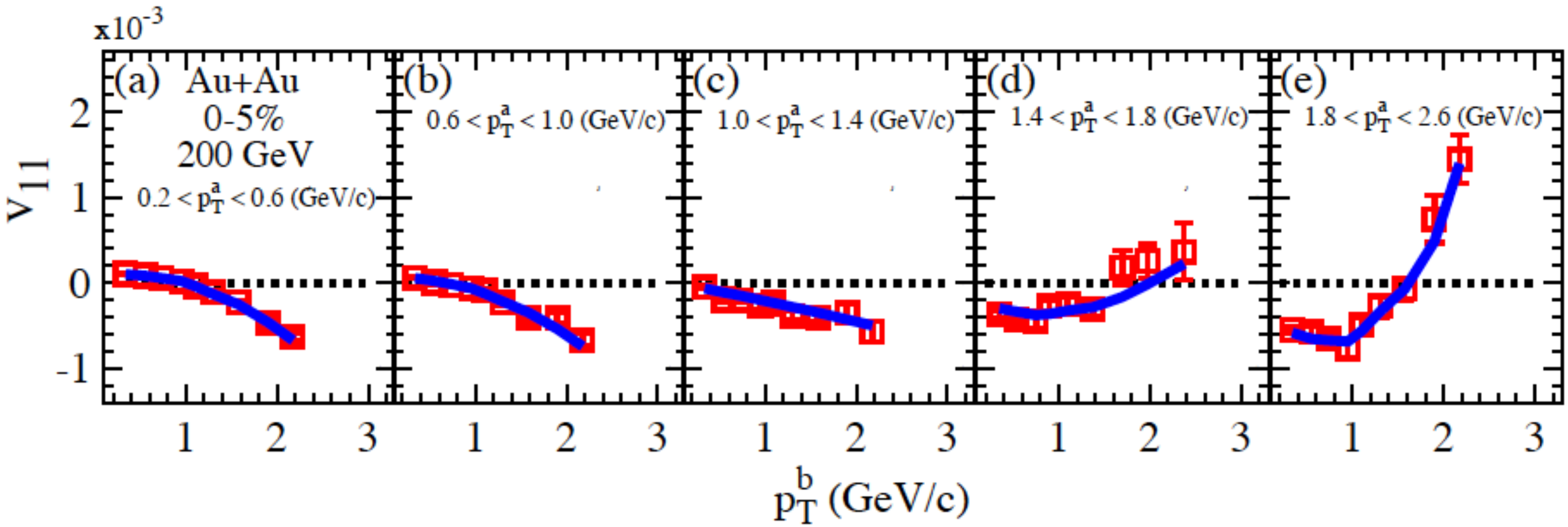
arXiv:1203.0931
arXiv:1203.3410
arXiv:1208.1874
arXiv:1208.1887
arXiv:1211.7162

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

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



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



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

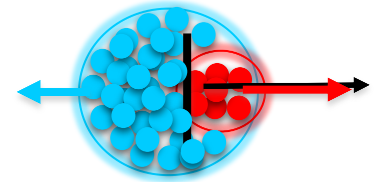
Long − range

Momentum Conservation

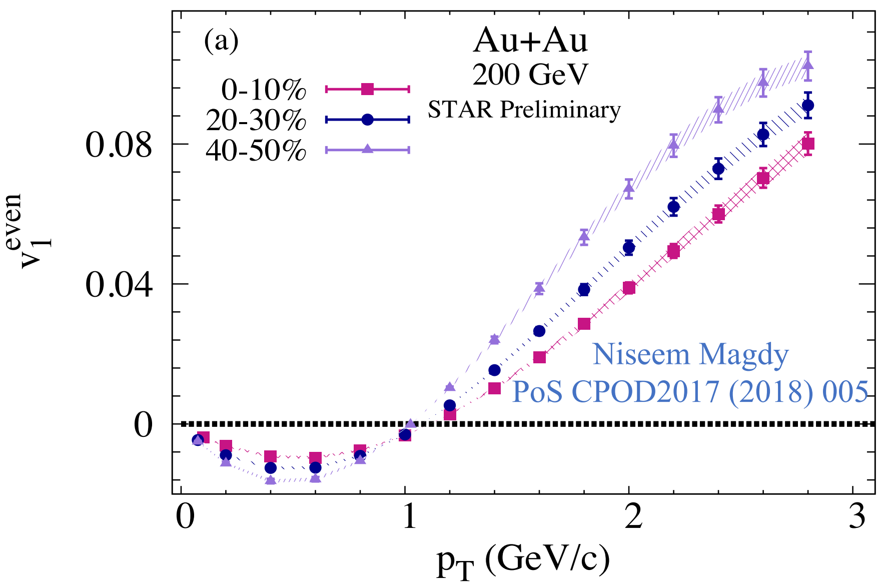
$|\eta| < 1$ and $|\Delta\eta| > 0.7$

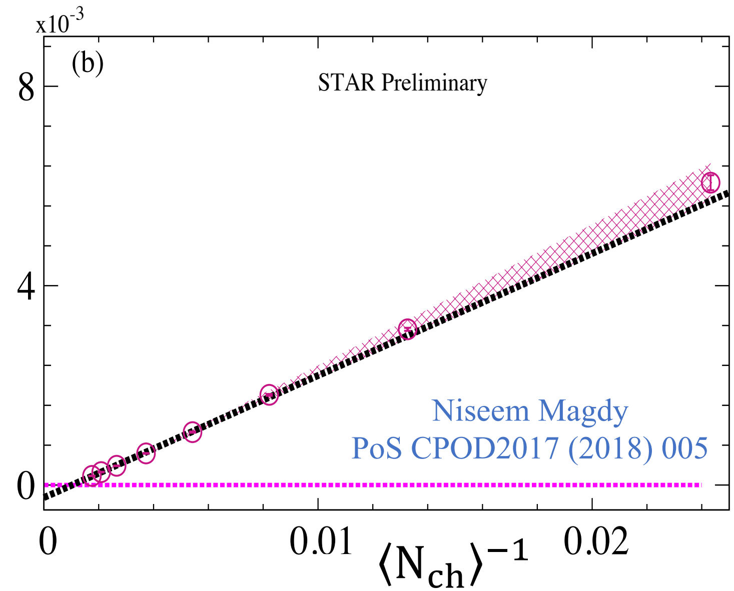
Long-range non-flow suppression

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



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

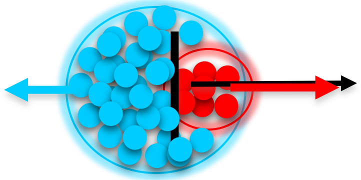




- The characteristic behavior of $v_1^{even}(p_T)$ shows a weak centrality dependence
- The momentum conservation parameter, K, scales as $\langle \boldsymbol{N_{ch}} \rangle^{-1}$

Flow harmonics

Beam-Energy Dependence of v_1^{even}



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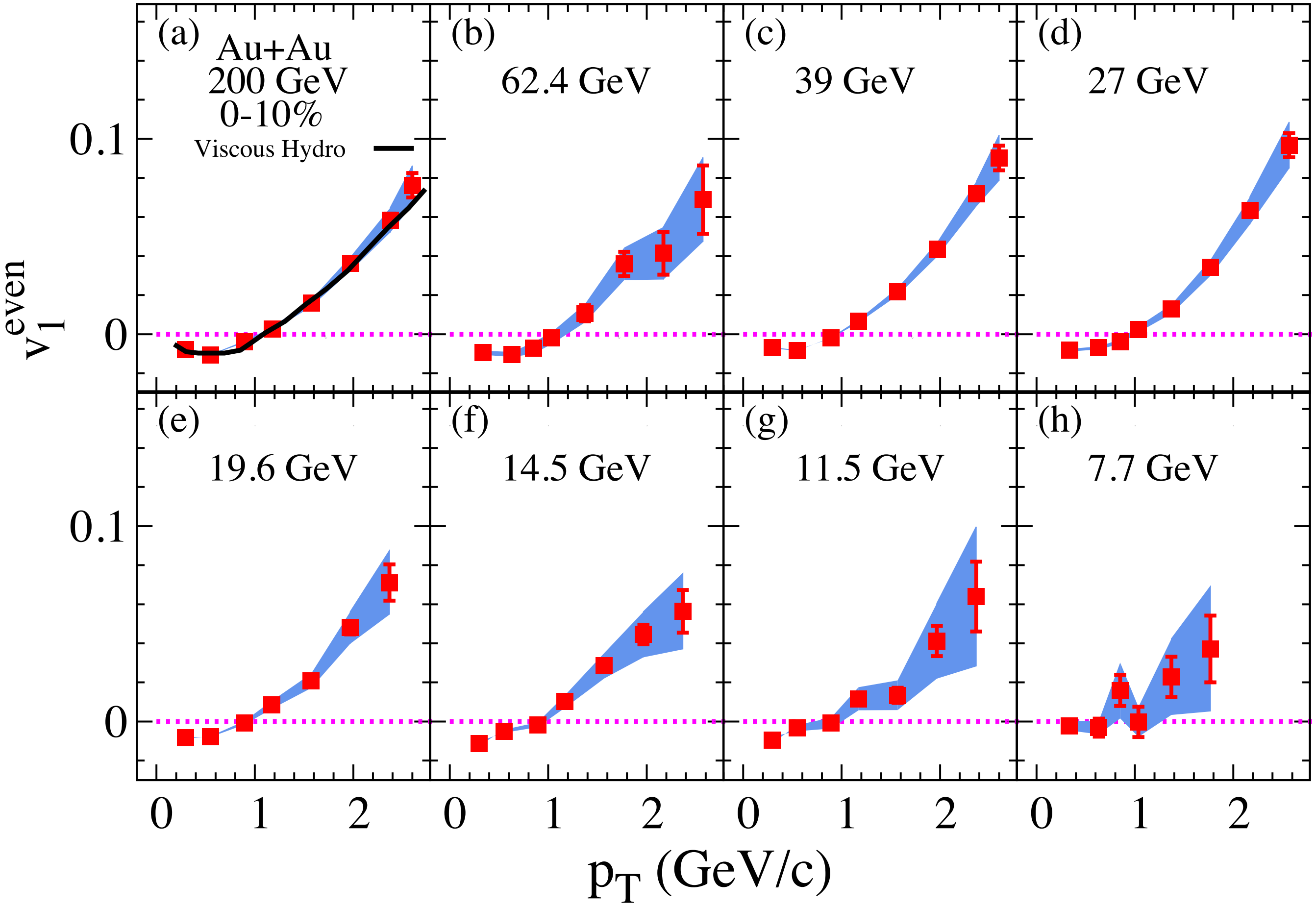
PLB 784 2632 (2018)

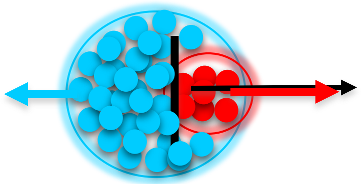
$$v_{11}(p_T^a, p_T^t) = v_1^{even}(p_T^a)\, v_1^{even}(p_T^t) - K\, p_T^a\, p_T^t$$

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

Hydro
E. Retinskaya, at el.
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



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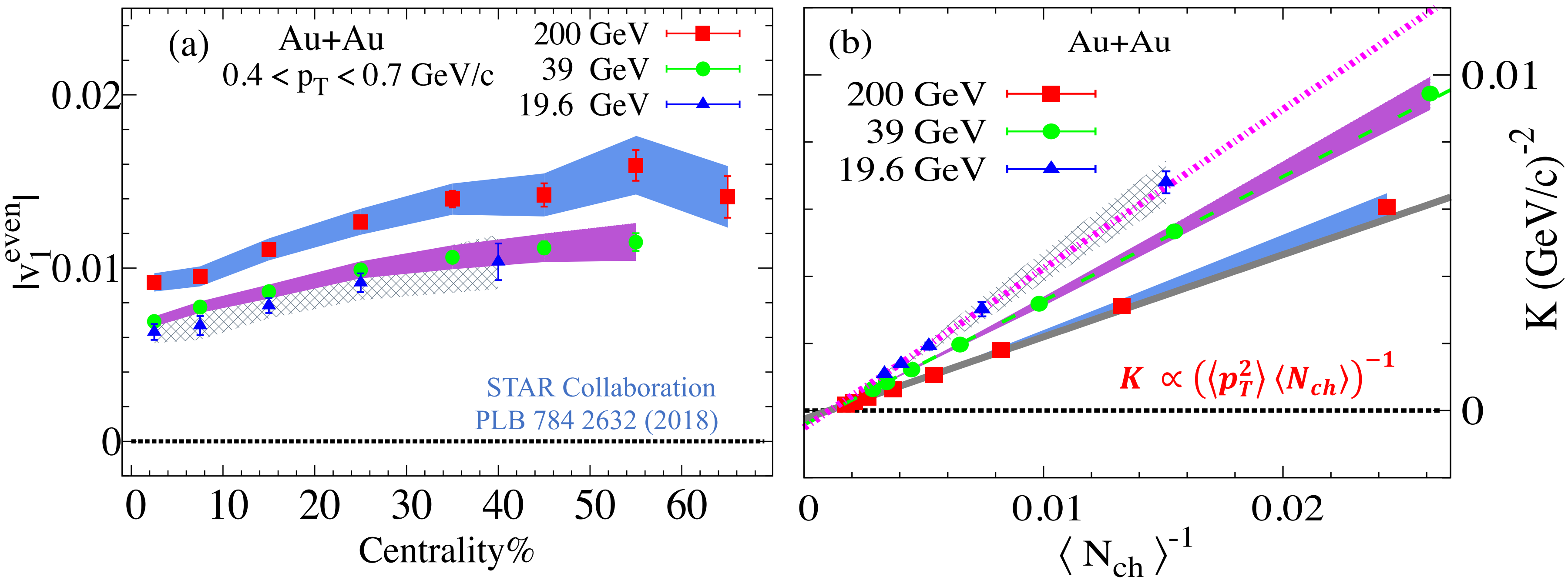
Beam-Energy Dependence of v_1^{even}

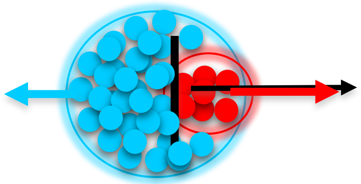
$$v_{11}(p_T^a, p_T^t) = v_1^{even}(p_T^a) v_1^{even}(p_T^t) - K\, p_T^a\, p_T^t$$

The extracted $\boldsymbol{v_1^{even}}$(Centrality) 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 $\langle N_{ch} \rangle^{-1}$



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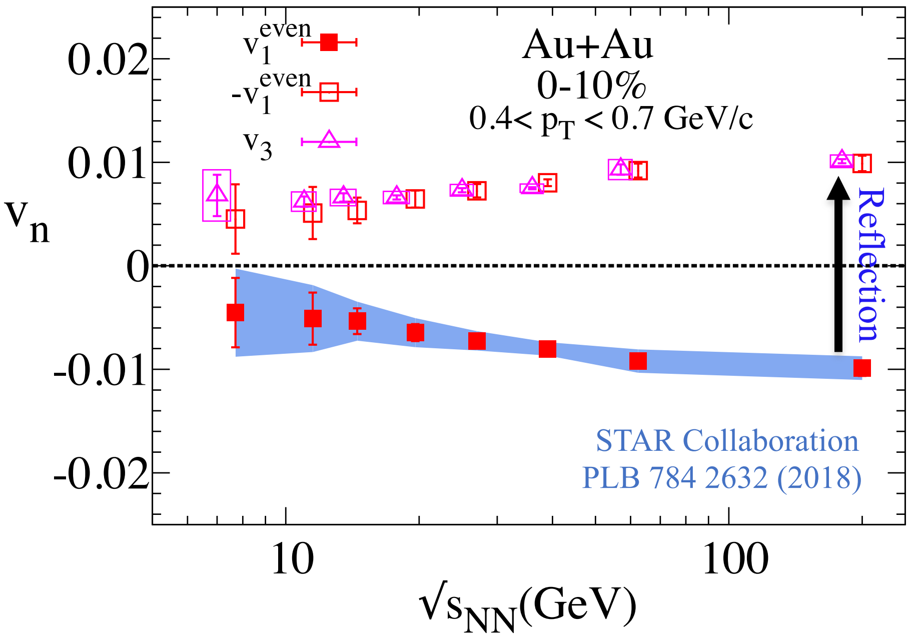
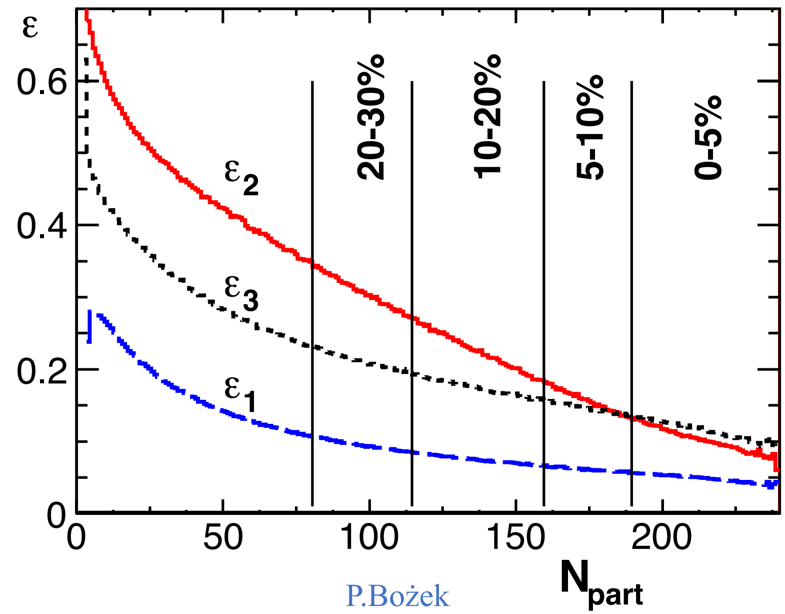
Beam-Energy Dependence of v_1^{even}

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

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





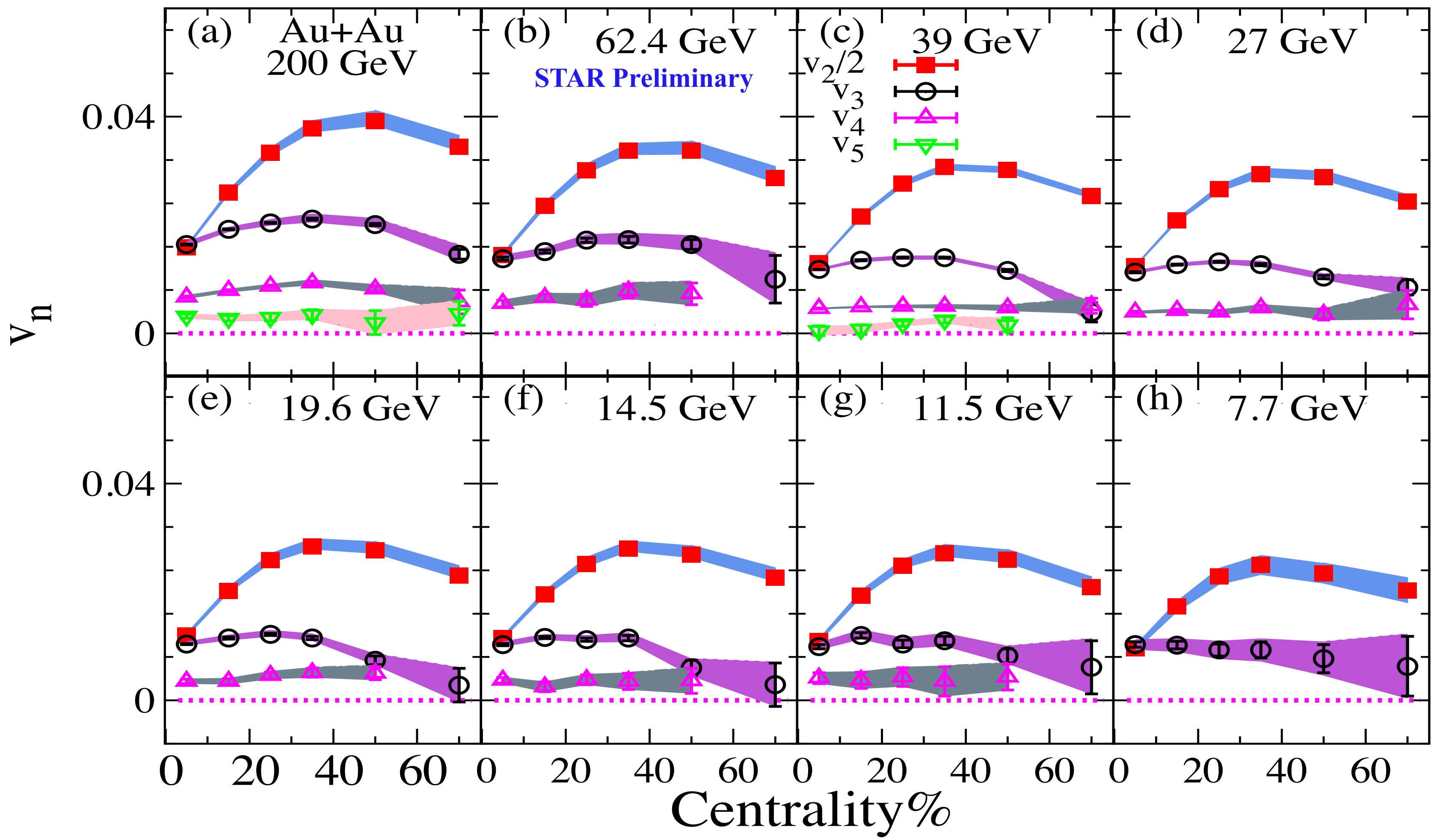
P.Bożek
PLB 717, 287-290 (2012)

- ➢ $|v_1^{even}|$ 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 $|\Delta\eta| > 0.7$

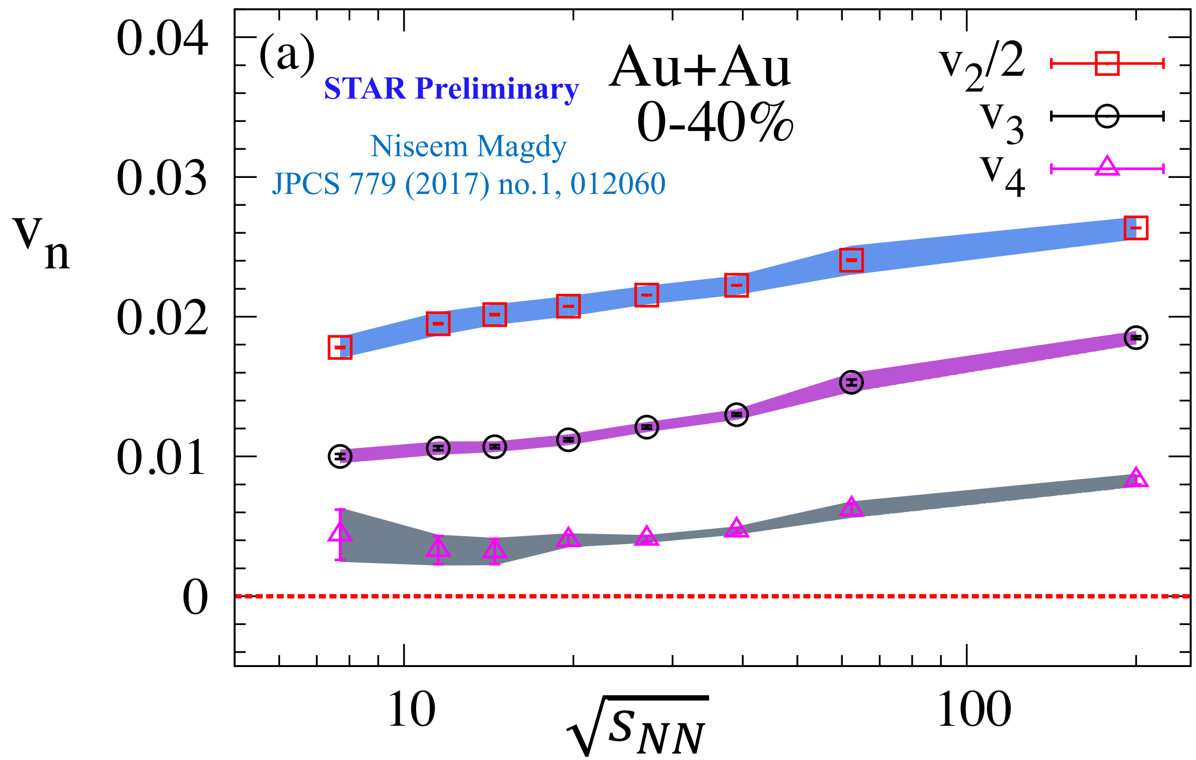
The extracted $v_{n>1}$(Centrality) at all BES energies



- 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).

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 $v_{n=2,3}$.

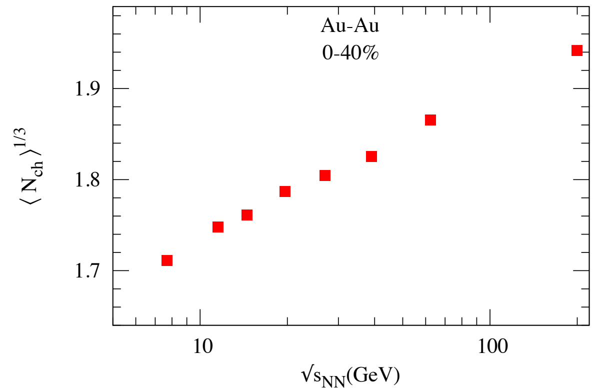
$$v_{\mathrm{n}} \propto k\,\varepsilon_n, \qquad k = e^{-\beta\, n^2}$$

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

- From macroscopic entropy considerations:

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

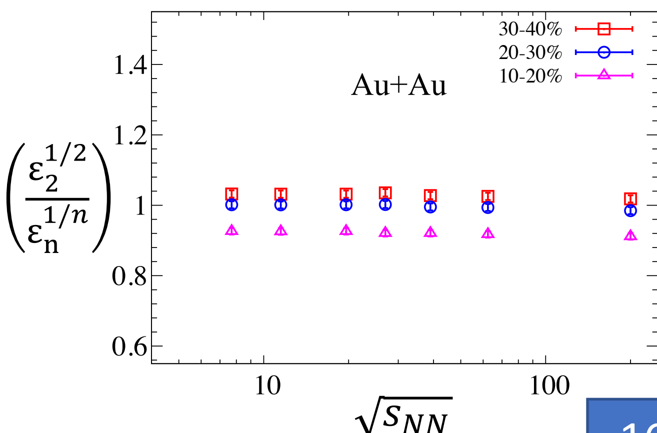
$$\ln\left(\frac{\mathrm{v_n}}{\varepsilon_\mathrm{n}}\right) \propto -\left(\frac{\eta}{s}\right)\langle \mathrm{N_{Ch}}\rangle^{-1/3}$$



Using two different harmonics:

$$\left[\ln\left(\frac{v_\mathrm{n}^{1/n}}{v_2^{1/2}}\right) + \ln\left(\frac{\varepsilon_2^{1/2}}{\varepsilon_\mathrm{n}^{1/n}}\right)\right]\langle \mathrm{N_{Ch}}\rangle^{1/3} \propto -\mathrm{A}\left(\frac{\eta}{s}\right)$$

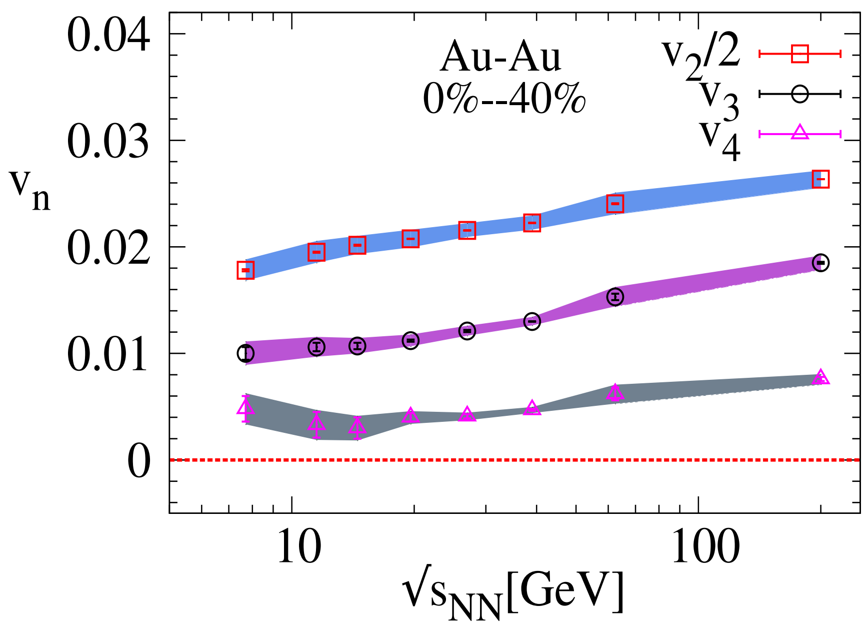
$$\beta'' = \ln\left(\frac{v_\mathrm{n}^{1/n}}{v_2^{1/2}}\right)\langle \mathrm{N_{Ch}}\rangle^{1/3} \propto -\mathrm{A}\left(\frac{\eta}{s}\right)$$

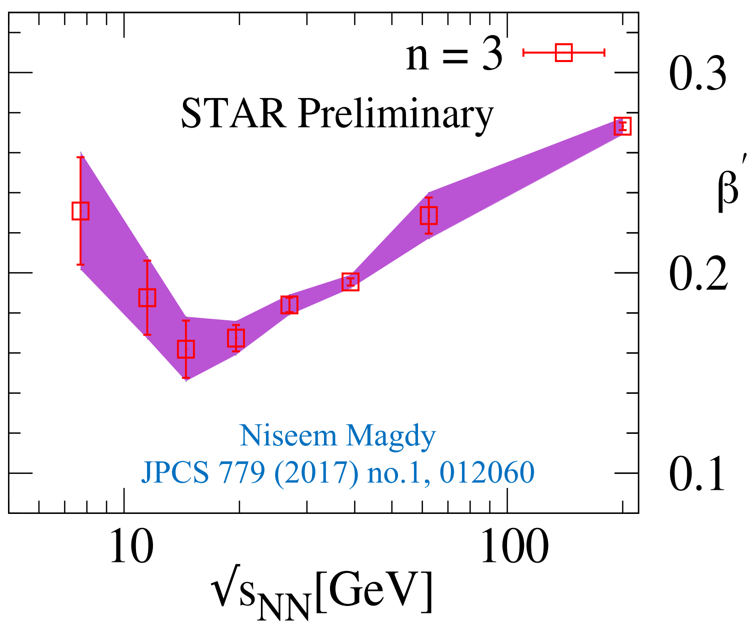


Viscous coefficient

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

A: is constant





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

Summary

Comprehensive set of flow measurements were presented 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 $\langle N_{ch} \rangle^{-1}$
  - ✓ $v_n(\sqrt{s_{NN}})$ shows a monotonic increase with 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