Elliptic (v_2) and triangular (v_3) anisotropic flow of identified hadrons from the STAR Beam Energy Scan program

Petr Parfenov
for the STAR Collaboration

National Research Nuclear University MEPhI

ICPPA 2020 – The 5th international conference on particle physics and astrophysics

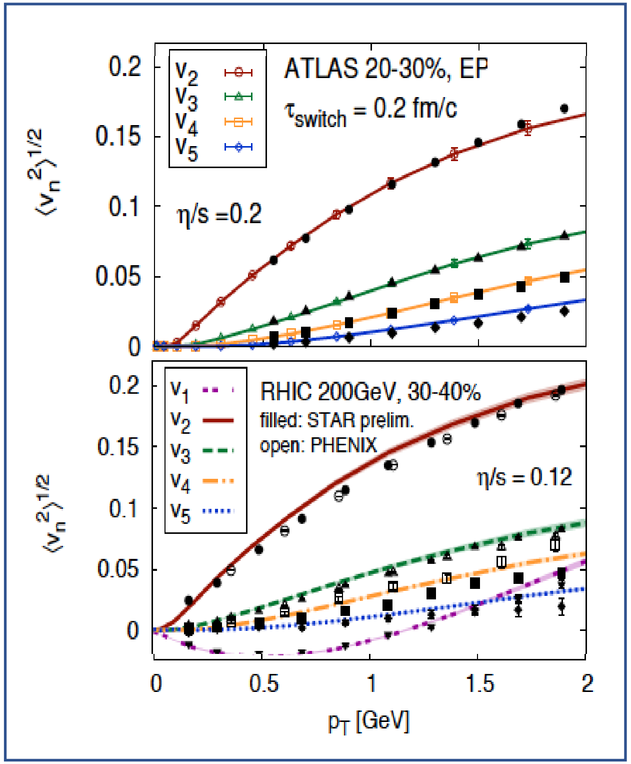
Moscow (Russia), Oct. 5-9, 2020

Outline

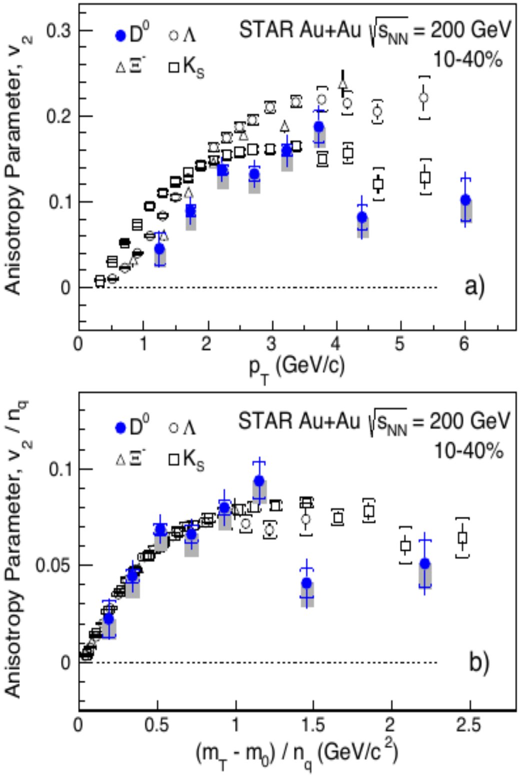
- Introduction
- Anisotropic flow at RHIC
- The STAR detector at RHIC
- Analysis methods
- Results
- Summary and Outlook

Anisotropic collective flow at RHIC/LHC

Gale et al., Phys. Rev. Lett. 110, 012302



STAR PRL118 (2017) 212301



v_n (p_T, centrality) - sensitive to the early stages of collision.
Important constraint for transport properties: EOS, η/s, ζ/s, etc.

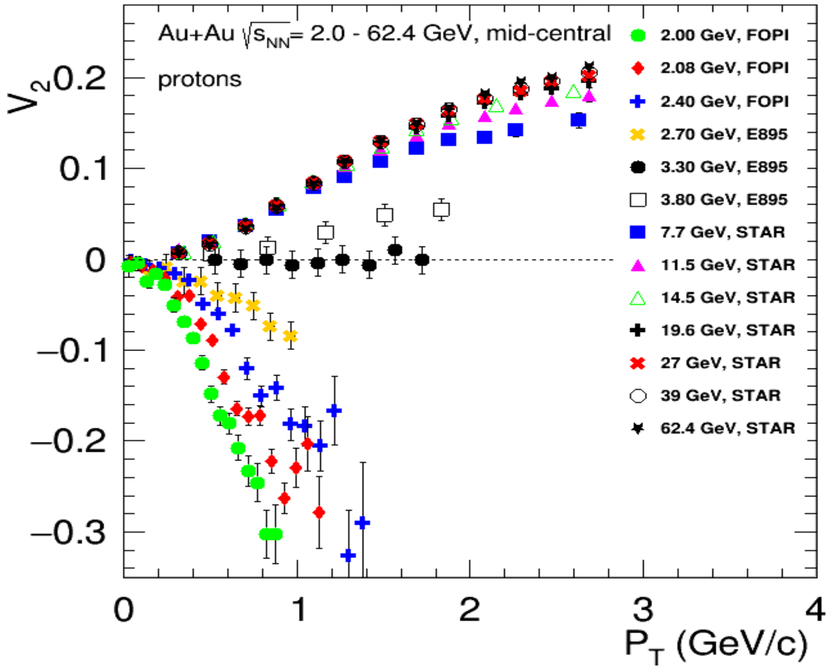
v_n of identified hadrons:

Mass ordering at p_T < 2 GeV/c
(hydrodynamic flow, hadron rescattering)

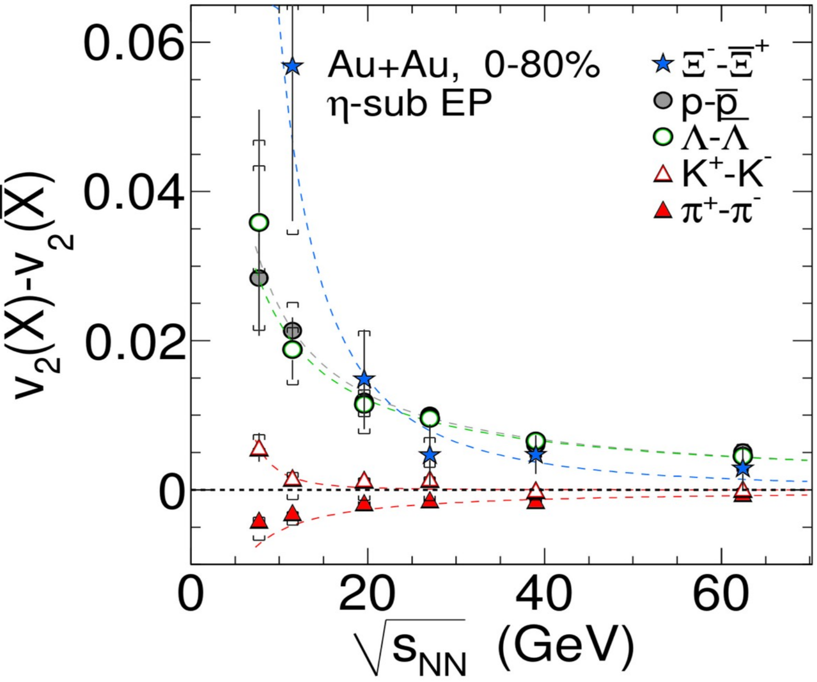
Baryon/meson grouping at p_T > 2 GeV/c
(recombination/coalescence),
Number of constituent quark (NCQ) scaling

Anisotropic collective flow at STAR BES

FOPI(15-29%) E895(12-25%) STAR(10-40%)

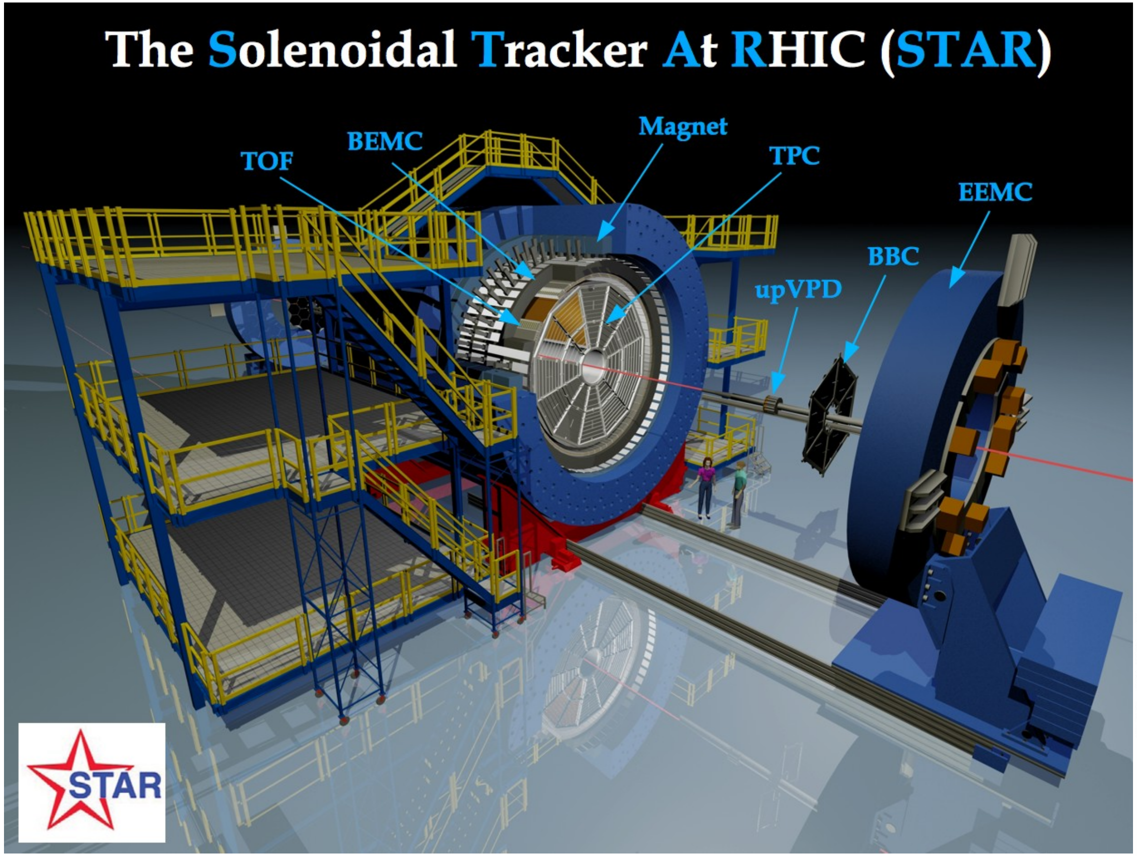


Taranenko, EPJ Web Conf. 204 (2019) 03009
STAR Collaboration, Phys. Rev. C 88 (2013) 14902



- Small change in $v_2(p_T)$ for Au+Au s_{NN}=7.7 – 62.4 GeV (STAR BES-I)
- Strong energy dependence of the difference in v_2 of particles and antiparticles
- **$v_3(\sqrt{s_{NN}}$,centrality,PID,p_T) - ???**

The STAR detector at RHIC



Time Projection Chamber (TPC):

- Tracking of charged particles with ($|\eta| < 1$, 2π in φ)
- PID using dE/dx measurements

Time-Of-Flight (TOF):

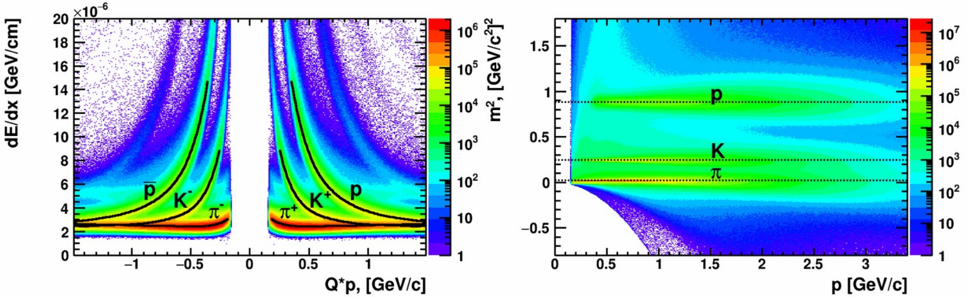
- $|\eta| < 0.9$, 2π in φ
- PID using time-of-flight information

Event planes:

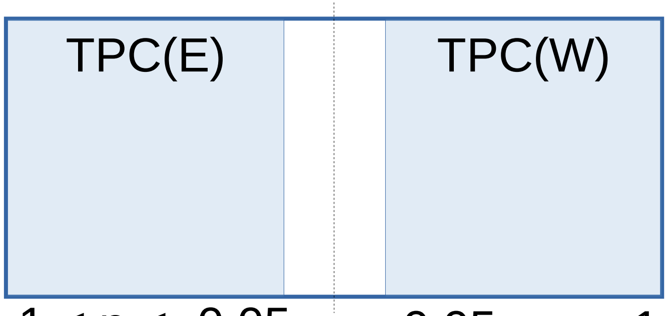
- TPC ($|\eta| < 1$), BBC ($3.8 < |\eta| < 5.2$)

Data set:

- Au+Au at $\sqrt{s_{NN}}$ = 11.5-62.4 GeV



Analysis technique: Event Plane Method (EP)



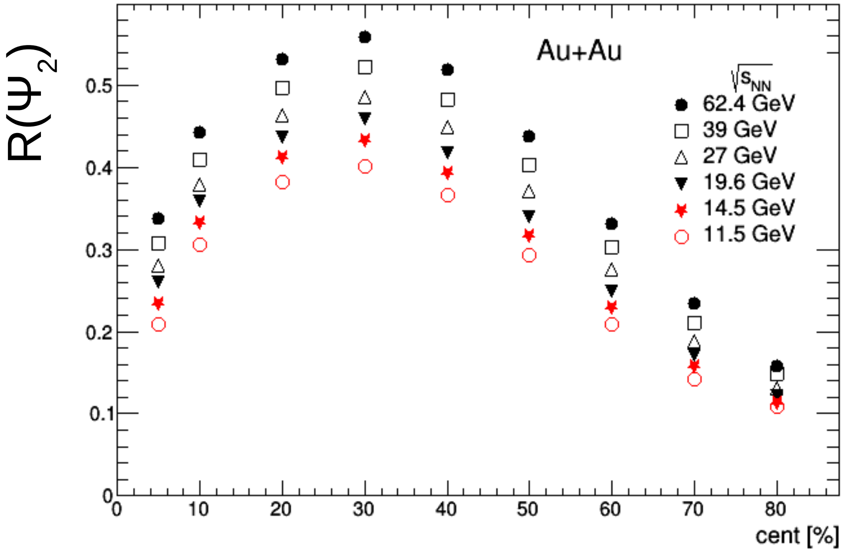
-1 < η < -0.05 0.05 < η < 1

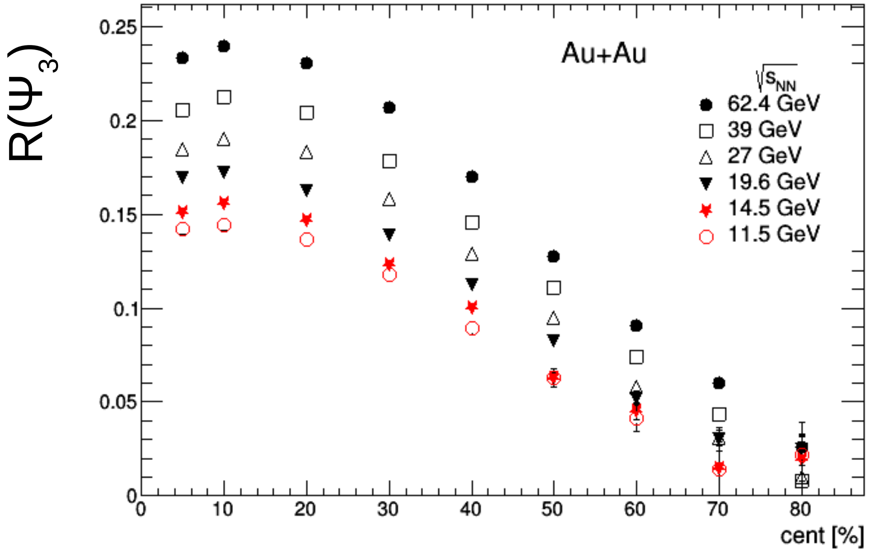
TPC (E) half $(\eta<0) \rightarrow \eta_-$

TPC (W) half $(\eta>0) \rightarrow \eta_+$

$$v_n = \frac{\langle \cos[n(\varphi_{\eta\pm} - \Psi_{n,\eta\mp})] \rangle}{R(\Psi_n)}$$

$$R(\Psi_n) = \sqrt{\langle \cos[n(\Psi_{n,\eta+} - \Psi_{n,\eta-})] \rangle}$$

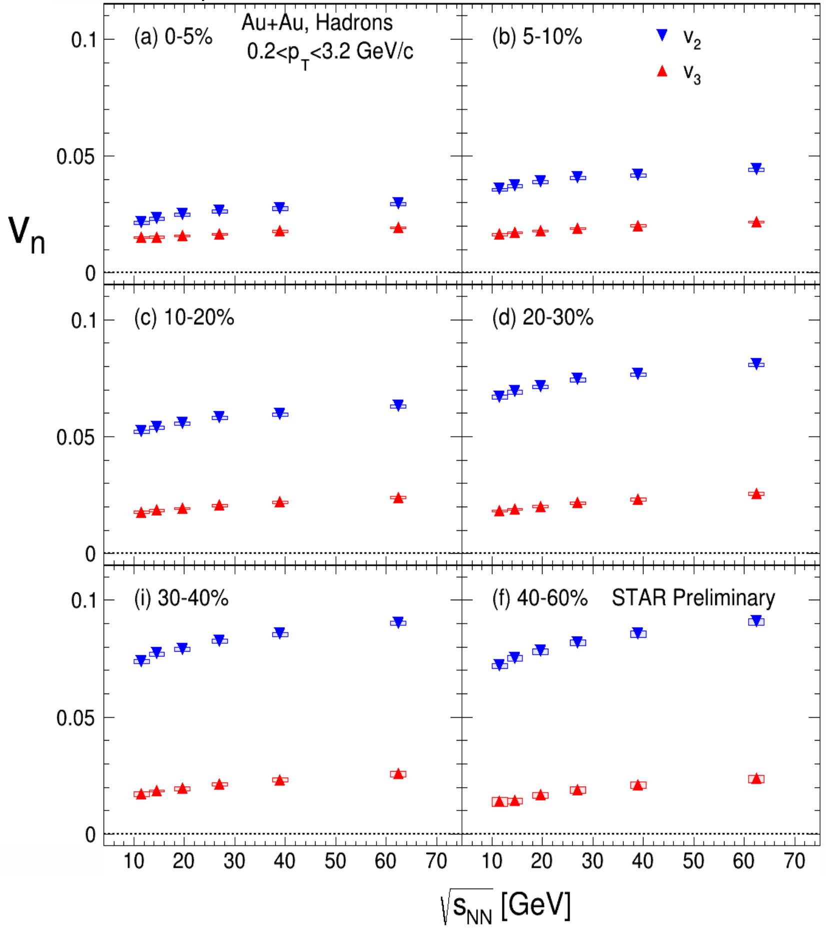


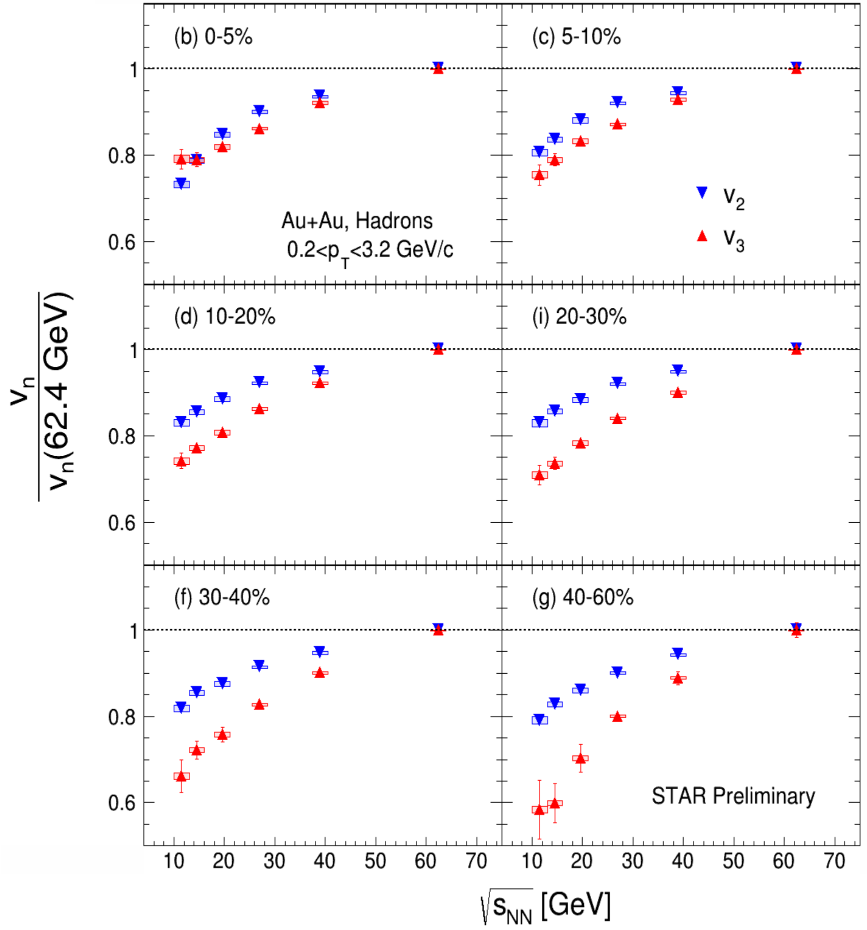


Used the same method as in Phys. Rev. C 88 (2013) 14902

Beam-energy dependence of v_2 and v_3

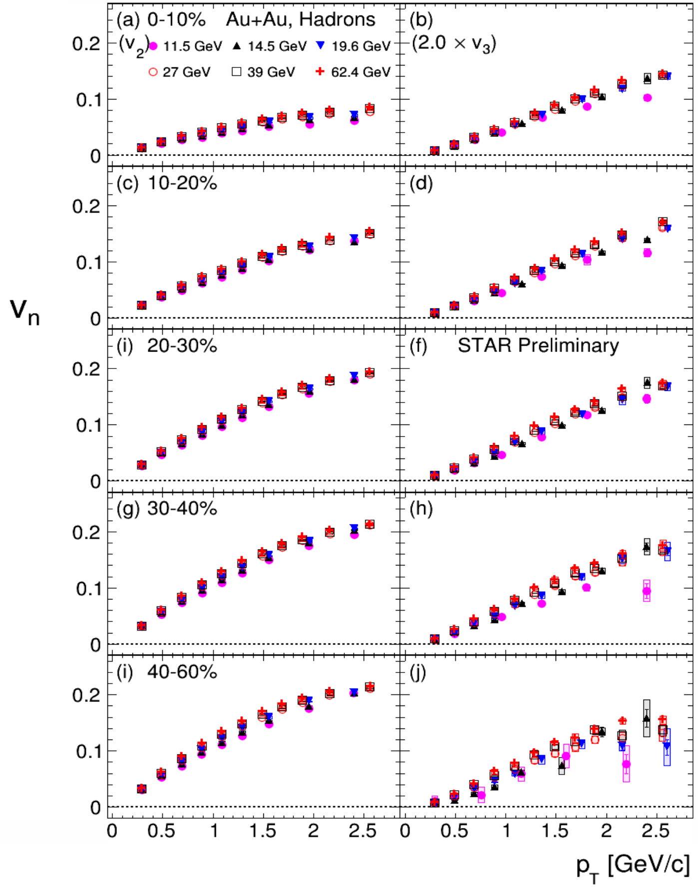
*No p_T-dependent efficiency was applied

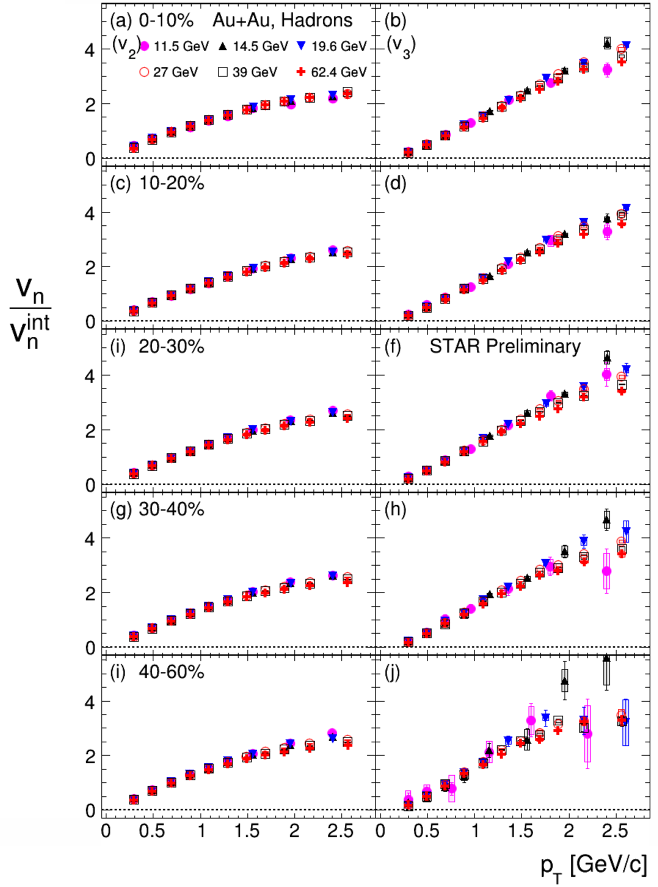




Integrated v_2 and v_3 decrease with decreasing collision energy

$v_2(p_T)$ and $v_3(p_T)$ of charged hadrons

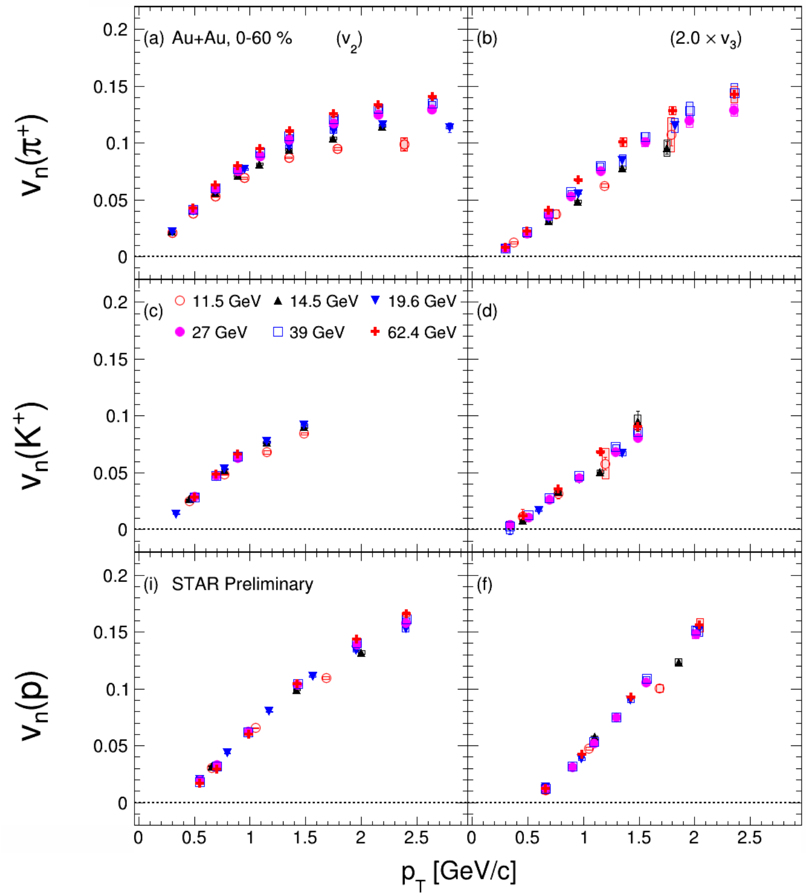


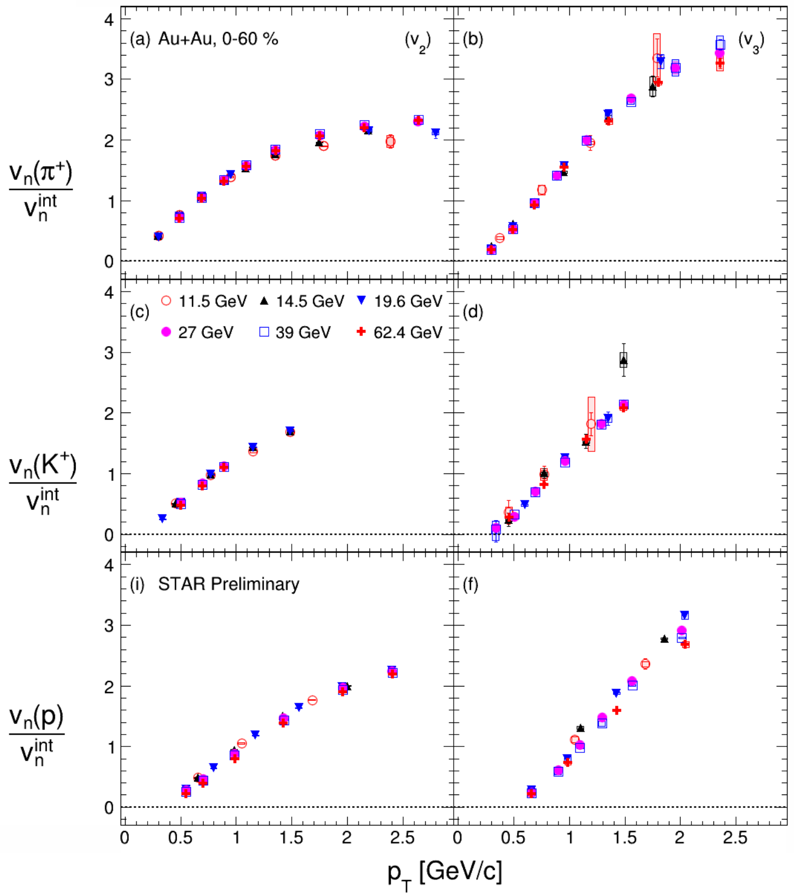


$$v_n^{int} = \int v_n(p_T)\, dp_T$$
$$0.2 < p_T < 3.2\, GeV/c$$

- Similar shape of p_T dependence of normalized v_2 and v_3 for all centralities and beam energies
- Small change of the shape of the $v_n(p_T)$ dependence with beam energy

$v_2(p_T)$ and $v_3(p_T)$ of identified hadrons

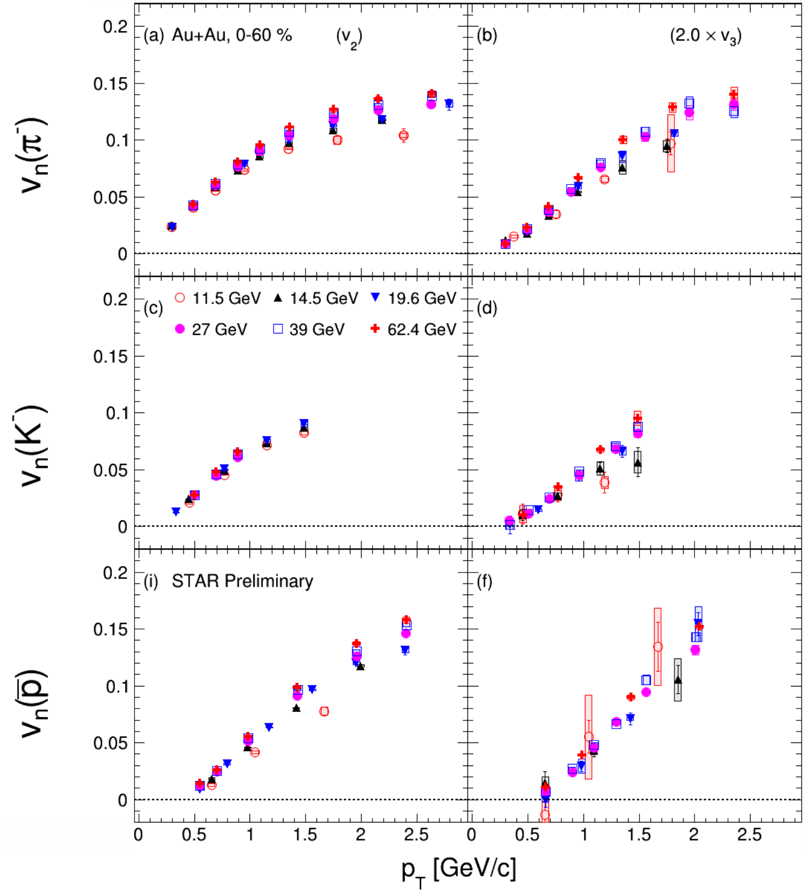


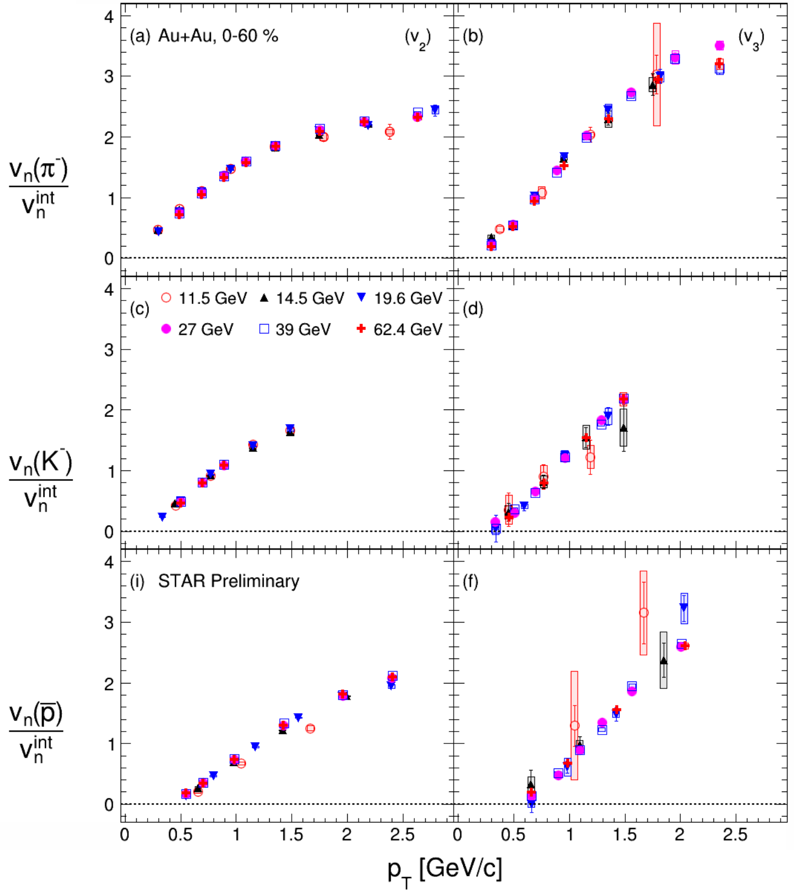


$$v_n^{int} = \int v_n(p_T)\, dp_T$$
$$0.2 < p_T < 3.2\, GeV/c$$

- Similar shape of p_T dependence of normalized v_2 and v_3 for all particle species
- Small change of the shape of the $v_n(p_T)$ dependence with beam energy

$v_2(p_T)$ and $v_3(p_T)$ of identified hadrons

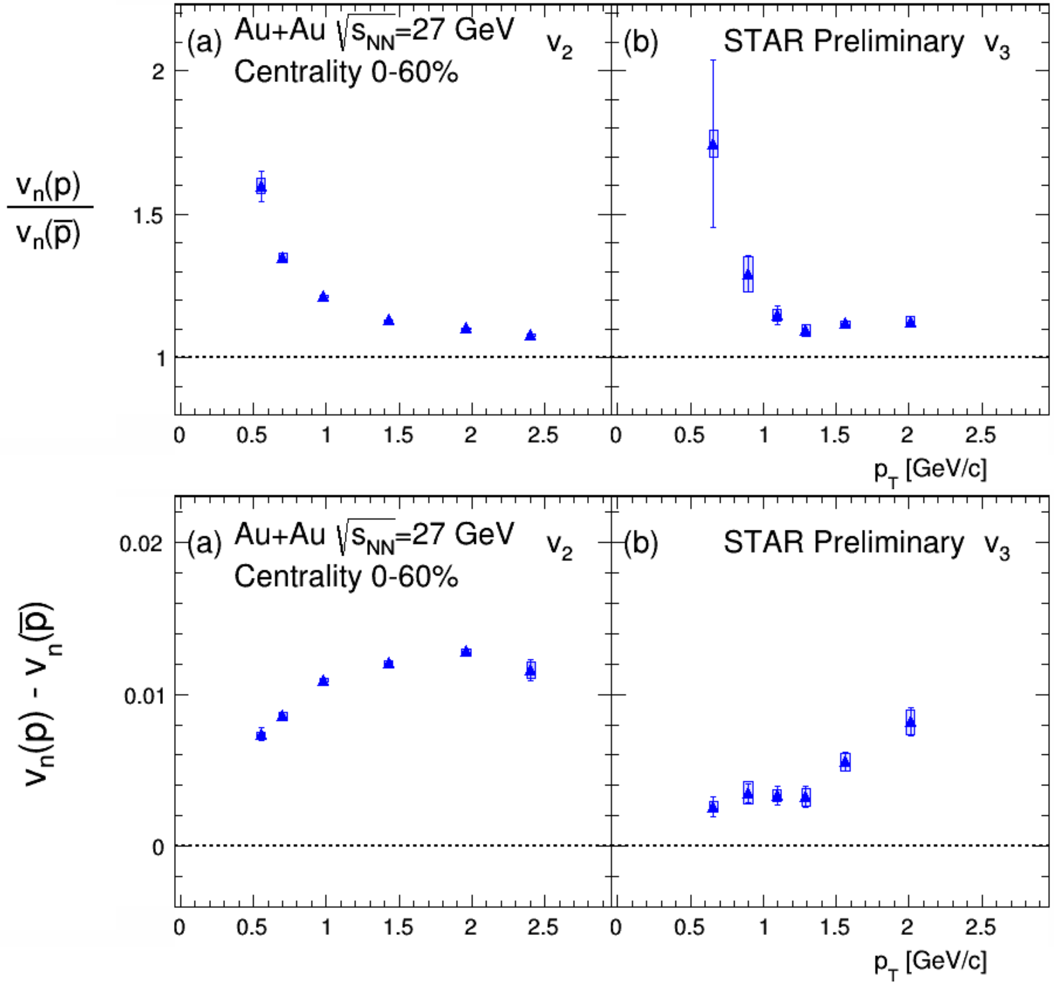




$$v_n^{int} = \int v_n(p_T)\, dp_T$$
$$0.2 < p_T < 3.2\, GeV/c$$

- Similar shape of p_T dependence of normalized v_2 and v_3 for all particle species
- Small change of the shape of the $v_n(p_T)$ dependence with beam energy

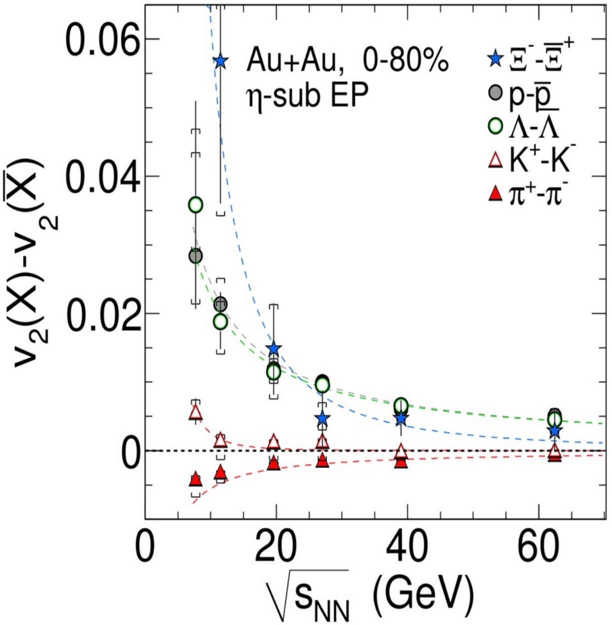
v_2 and v_3 of protons and antiprotons for s_{NN}=27 GeV



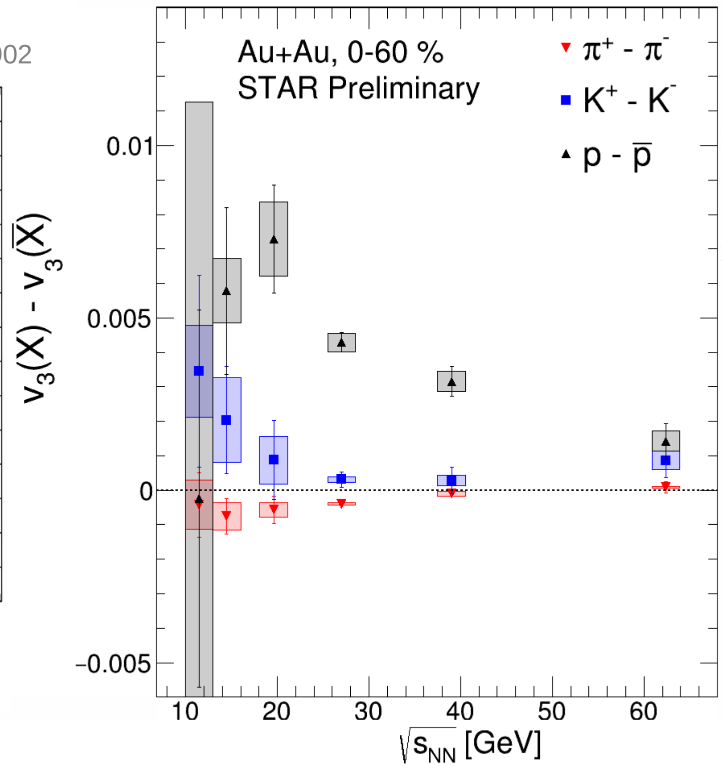
Similar difference for v_2 and v_3 between p and $\bar{p}$

Beam-energy dependence of v_2 and v_3 particle-antiparticle difference

STAR Collaboration, Phys. Rev. C 88 (2013) 14902

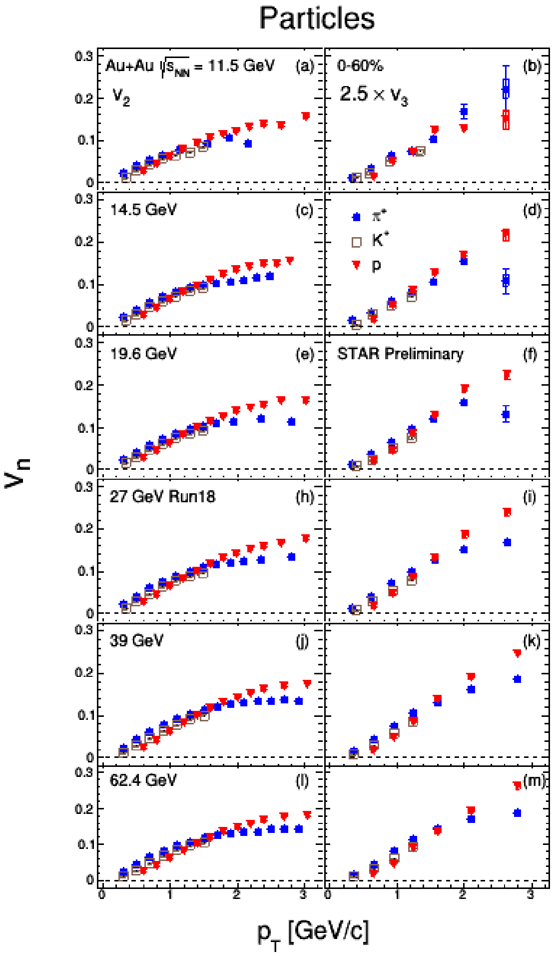


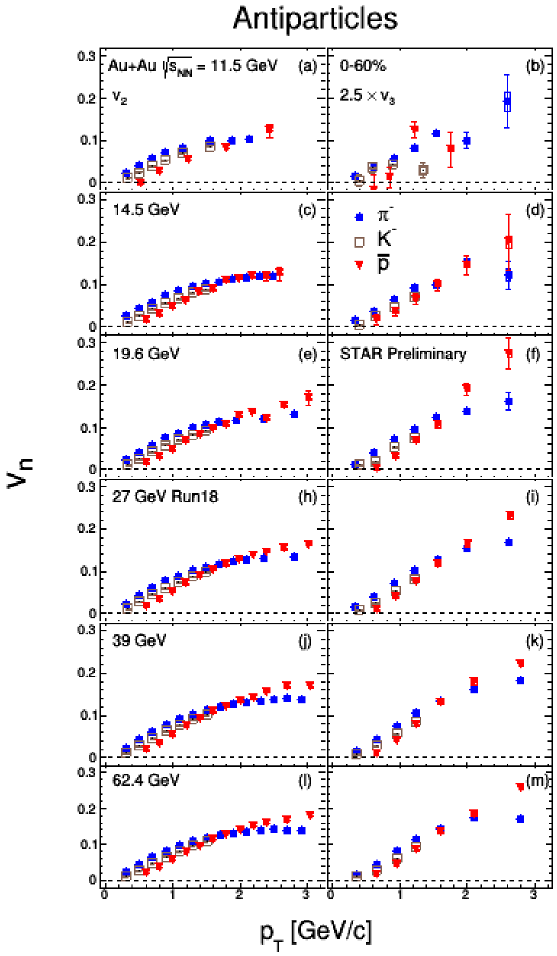
New results

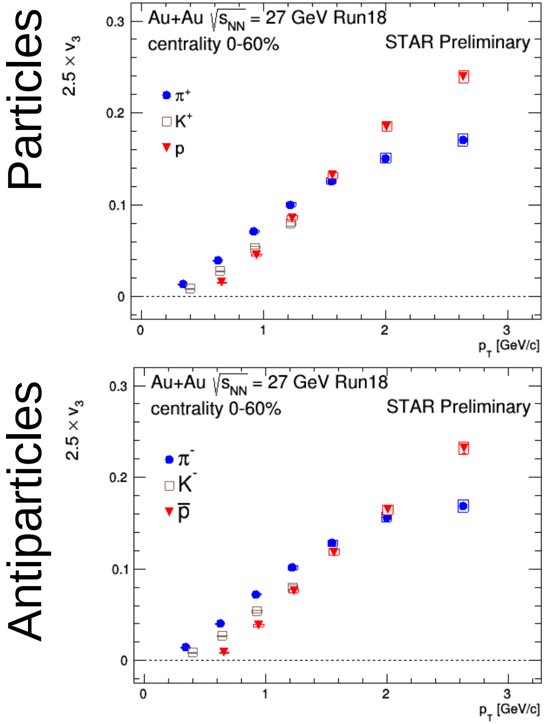


- **Differences for v_2 and v_3 between particles and antiparticles increase with decreasing beam energy**
- **$v_n(p) – v_n(\bar{p})$ shows steep rise with decreasing collision energy**
- **Absolute value of $v_n(X)-v_n(\bar{X})$ is larger for $(p,\bar{p})$ than for $\pi^{\pm}$ and $K^{\pm}$**

$v_2(p_T)$ and $v_3(p_T)$ of identified hadrons



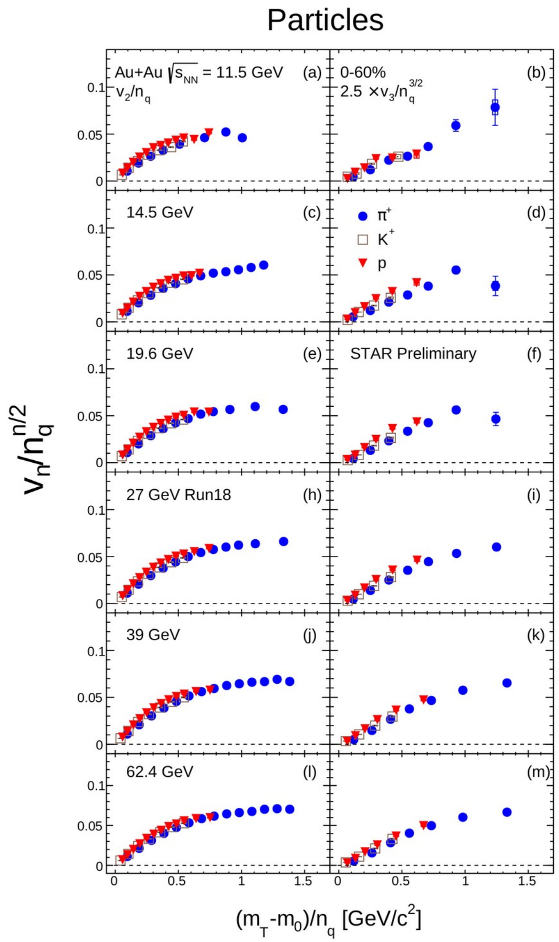


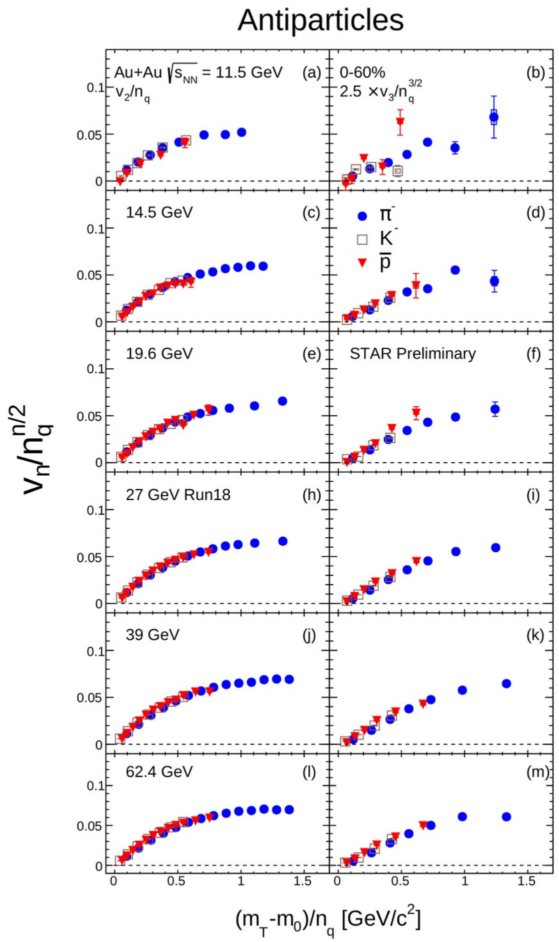


Mass ordering for p_T<1.5 GeV/c

Baryon/meson grouping for p_T>2 GeV/c

NCQ scaling of v_2 and v_3





- NCQ scaling tests were performed for v_2 and v_3 for particles and antiparticles
- Scaling holds better for higher energies

Summary and outlook

Results of $\mathbf{v_2}$, $\mathbf{v_3}$ in Au+Au collisions at BES energies $\sqrt{s_{NN}}$ = 11.5 - 62.4 GeV are presented.

($\sqrt{s_{NN}}$,centrality,PID,p_T)-dependence of v_2 and v_3:

- Normalized v_2 and v_3 have similar p_T shape for all centralities and beam energies for each particle species
- Mass ordering for p_T<1.5 GeV/c and baryon/meson grouping for p_T>2 GeV/c
- NCQ scaling holds better for higher energies

$v_n(X) - v_n(\bar{X})$:

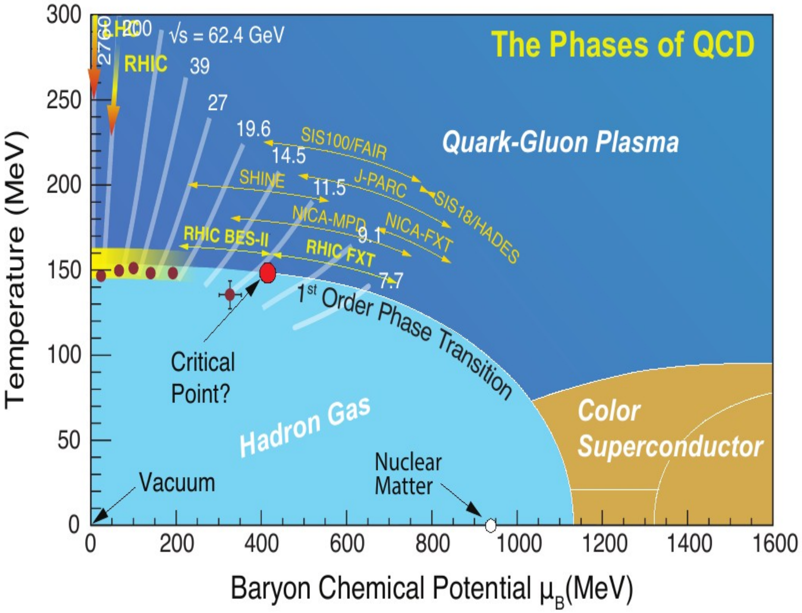
- The difference increases with decreasing collision energy
- $v_n(p)-v_n(\bar{p})$ shows steep rise at lower collision energies
- Absolute value of $v_n(X)-v_n(\bar{X})$ is larger for $(p,\bar{p})$ than for $\pi^\pm$ and $K^\pm$

Thank you for your attention!

Backup

STAR Beam Energy Scan (BES) program

- A search for turn-off of new phenomena already established at higher RHIC energies (NCQ scaling breaking, R_{CP}, pair correlations, local parity violation)
- A search for signatures of a phase transition and a critical point ($v_{1,2}(\sqrt{s_{NN}})$, femtoscopy, fluctuations)

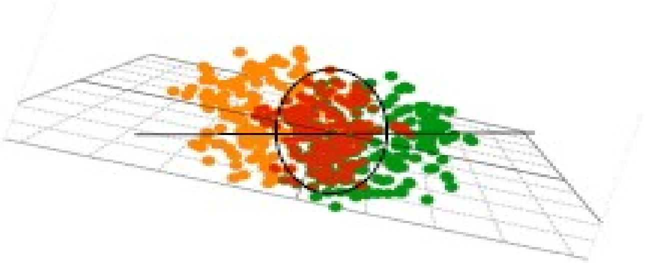


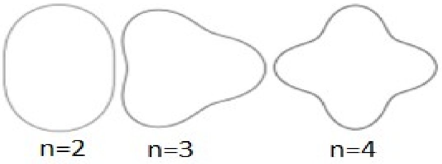
http://drupal.star.bnl.gov/STAR/starnotes/public/sn0493
Nuclear Physics A, **967** (2017), 800-803
Phys. Rev. C 96, 044904 (2017)

$\sqrt{s_{NN}}$	Events (10^6)	BES-I	μ_B (MeV)	T (MeV)
62.4	**67**	**2010**	**69**	**164**
39	**130**	**2010**	**105**	**160**
27	**70 (1000)**	**2011 (2018)**	**152**	**160**
19.6	**36**	**2011**	**196**	**157**
14.5	**20**	**2014**	**260**	**156**
11.5	**12**	**2010**	**292**	**150**

BES-II and Fixed Target programs extend STAR's physics reach to region of compressed baryonic matter

Anisotropic collective flow

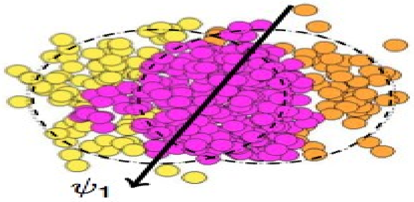


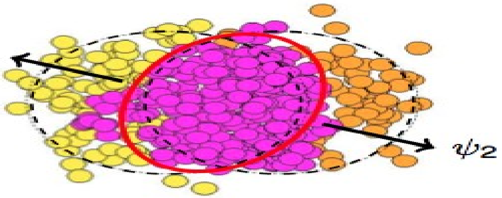


$$\epsilon_n = \sqrt{\frac{\langle r^n \cos n\phi\rangle + \langle r^n \sin n\phi\rangle}{\langle r^n\rangle}}$$

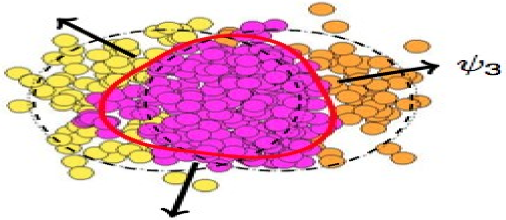
$$\frac{dN}{d\phi} \propto \left(1 + 2\sum_{n=1} v_n \cos\left[n\left(\phi - \Psi_n\right)\right]\right)$$

Initial eccentricity (and its attendant fluctuations), ε_n, drives momentum anisotropy, v_n, with specific viscous modulation





v_2 - elliptic flow



v_3 - triangular flow

Particle identification

TPC
Particle identification via specific ionization energy loss (dE/dx).
Particle identification at low momentum.

TOF
Particle identification at high momentum using time-of-flight information.