9th International Workshop on Multiple Partonic Interactions at the LHC

11–15 December 2017
Shimla, India

Measurement of Azimuthal Anisotropy of Hadrons in Au+Au Collisions at RHIC

Md. Nasim, for the STAR Collaboration
(University of California, Los Angeles)

Outline

- **Motivation**
- **STAR experiment**
- **Results**
- **Summary**

Au+Au, $\sqrt{s_{NN}}$ = 200 GeV :

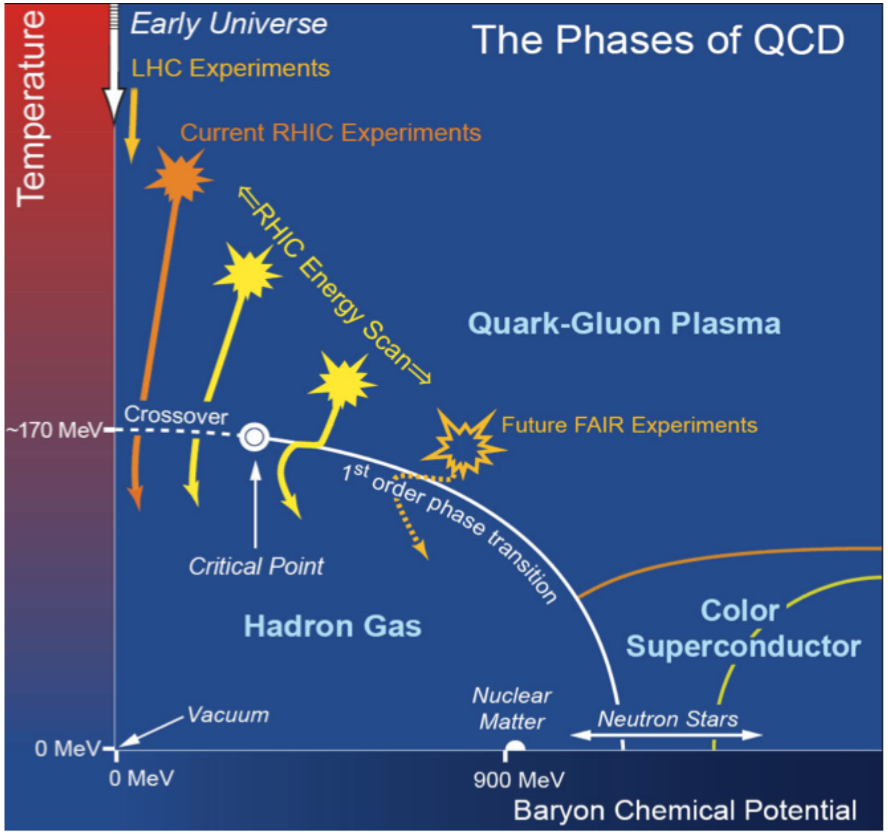
- Azimuthal anisotropy of multi-strange hadrons
- Azimuthal anisotropy of open-charm mesons
- Correlation between different order of anisotropy

RHIC BES Program :

- Beam energy denpendence of azimuthal anisotropy

Motivation

QCD phase diagram: A phase diagram of strongly interacting matter.



M. M. Aggarwal (STAR collaboration)
arXiv:1007.2613

Theory predicts:

- ✓ A cross-over at μ_B ~0
- ✓ At high μ_B, the transition is the first order
- ✓ Critical point: where the first order transition ends

Goals of the STAR Experiment

Top RHIC Energy

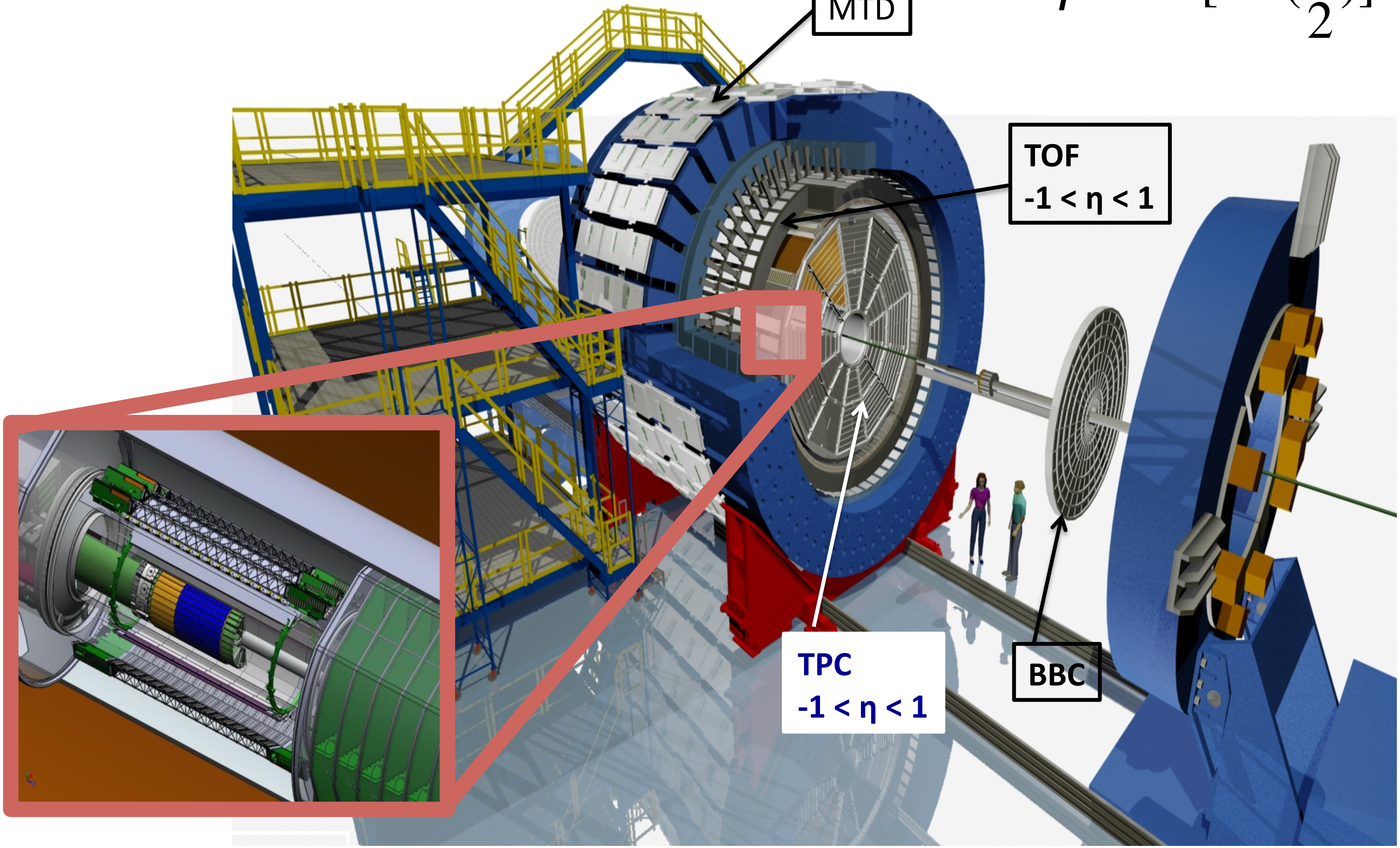
- Study the properties of QGP

Beam Energy Scan (BES)

- Search for phase boundary
- Search for the QCD Critical point

The STAR Detector

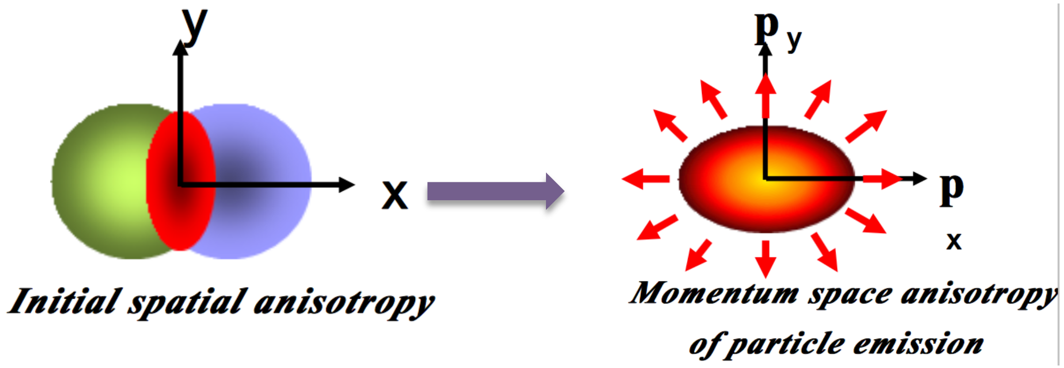
$$\eta = -\ln[\tan(\frac{\theta}{2})]$$



Heavy Flavor Tracker
-1 < η < 1

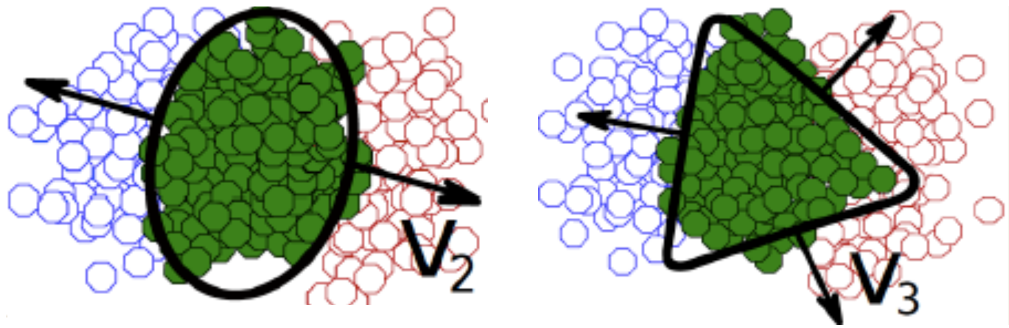
Azimuthal Anisotropy (v_n)

Pressure gradient transfers initial spatial anisotropy to final state momentum space anisotropy



$$\frac{dN}{d\phi} = 1 + 2\sum_{n=1}^{\infty} v_n \cos\{n(\phi - \psi_n)\}$$

$$v_n = \langle \cos\{n(\phi - \psi_n)\} \rangle$$

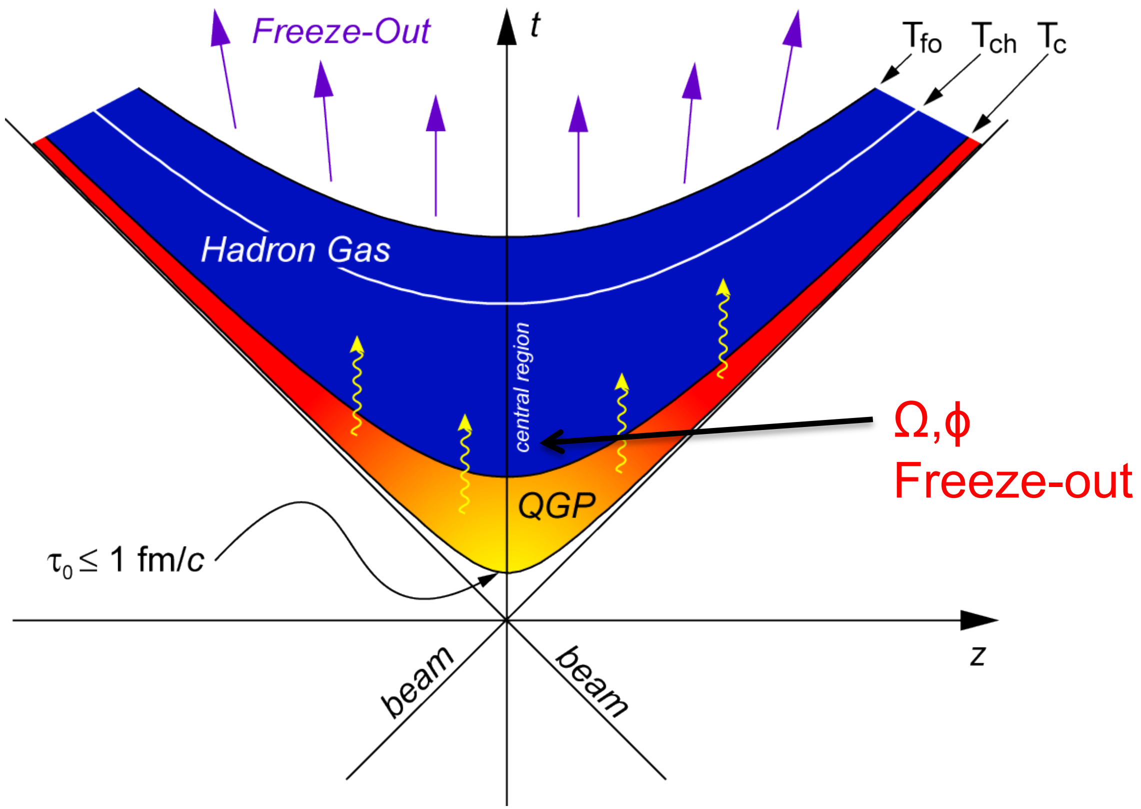


- sensitive to early times in the evolution of the system
- sensitive to the equation of state

A.M. Poskanzer, S.A. Voloshin, Phys. Rev. C 58, 1671 (1998)
P. Kolb, U. W. Heinz, Nucl. Phys. A 715, 653c (2003)

Role of Multi-Strange Hadrons Ω(sss), ϕ(s$\bar{s}$)

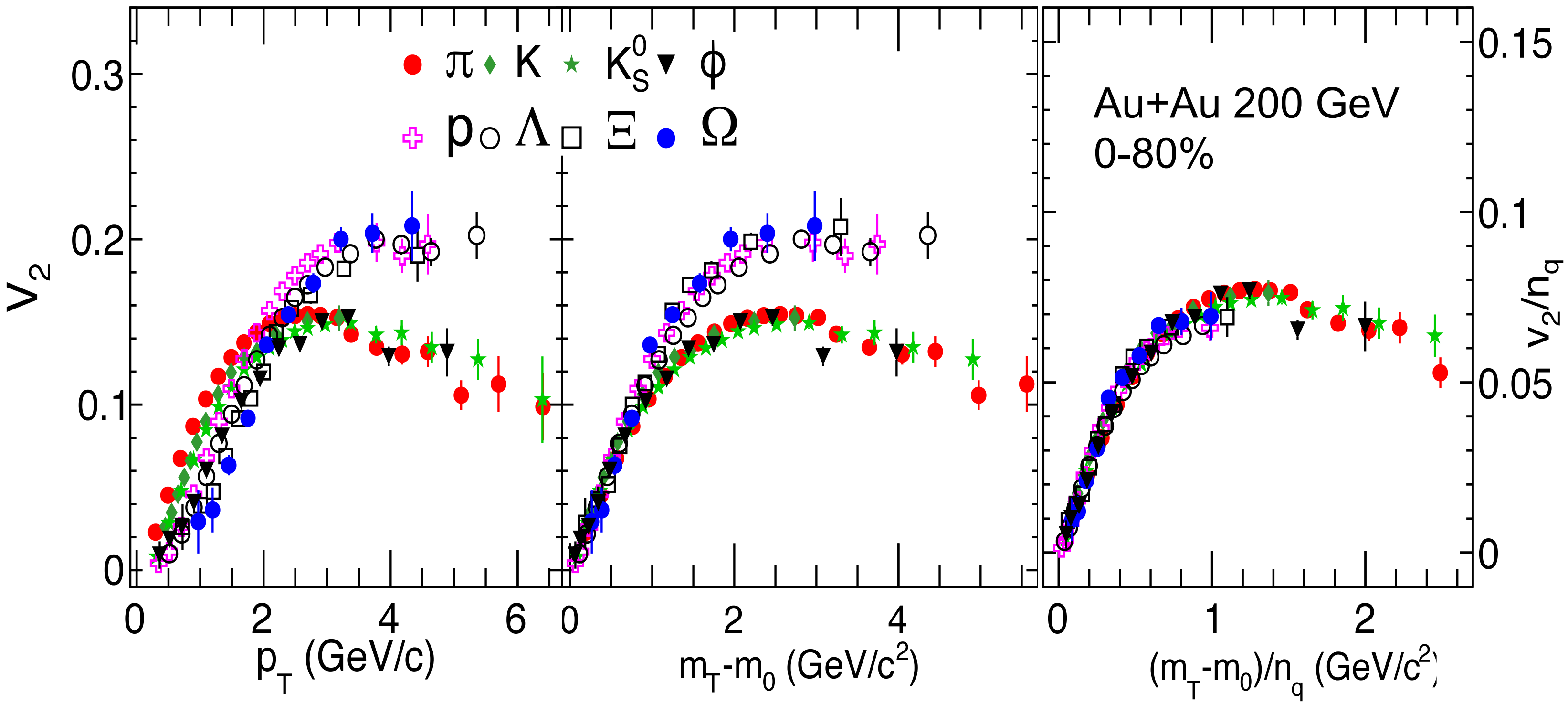
- Early Freeze-out (close to Tc)
- Hadronic interaction cross-section with non-strange hadrons is expected to be small



Reflect flow/collectivity mostly from partonic/ QGP phase

A. Shor, Phys. Rev. Lett. *54*, 1122 (1985)
Md. Nasim et.al Phys. Rev. C *87*,014903 (2013)
STAR: Nucl. Phys. *A 757*, 101 (2005)
STAR: Phys. Rev. Lett. *99*, 112301 (2007)

The NCQ Scaling Test for Multi-strange Hadrons



The NCQ scaling is considered as a signature of deconfinement.

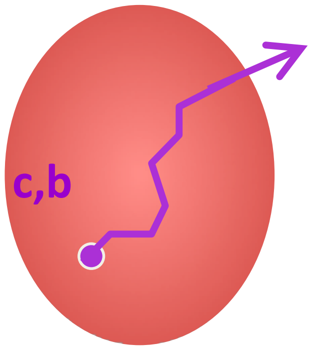
- **$v_2(\phi) \sim v_2(\pi)$ and $v_2(\Omega) \sim v_2(p)$ at intermediate p_T**

- evidence for partonic collectivity

STAR: Phys. Rev. Lett. 116, 062301 (2016)

Role of Heavy-Quarks (c , b)

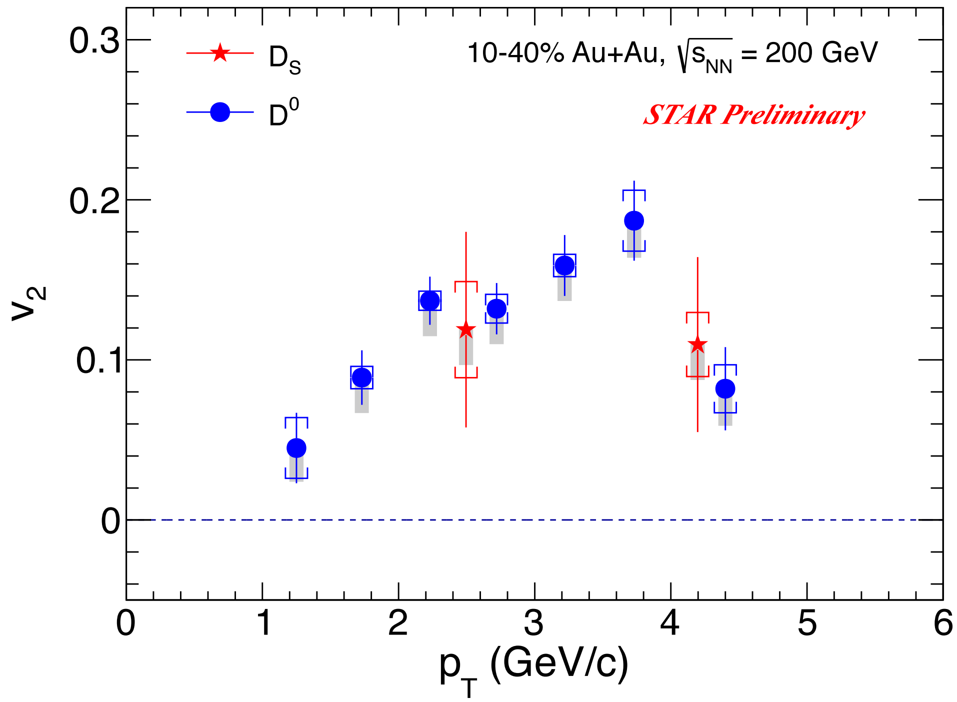
$M_b \approx 4.8$ GeV
$M_c \approx 1.3$ GeV $\gg T_{QGP}, M_{uds}$

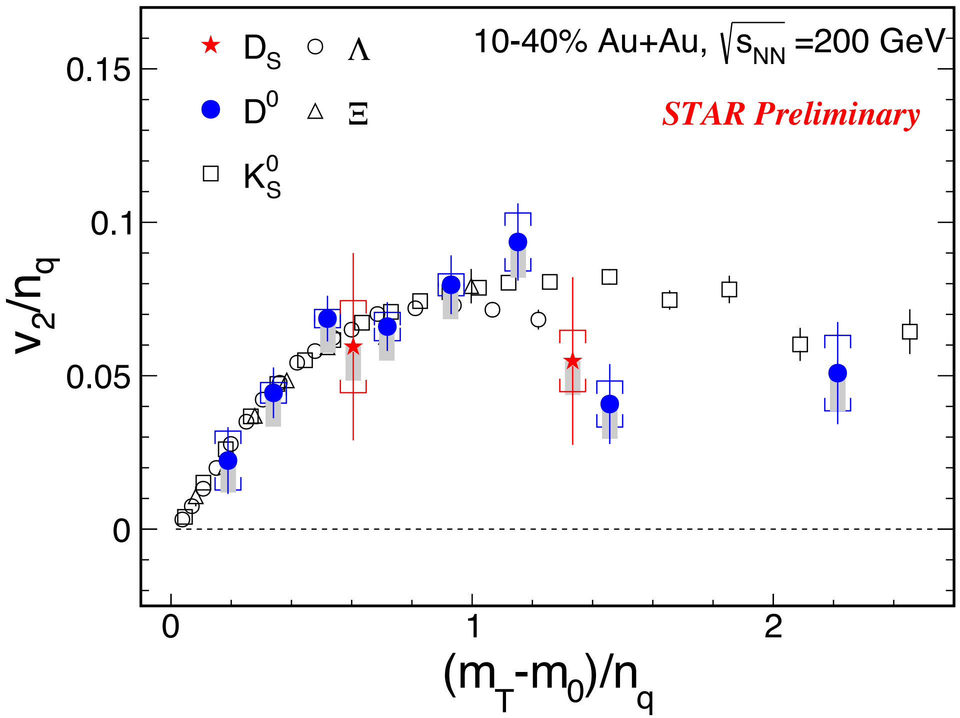


- Heavy quarks are produced during initial hard-scattering
- Thermal production of heavy quarks in QGP is very small
- Brownian motion approach : sensitive to the diffusion coefficient of QGP
- Heavy quark thermalization : delayed by m_Q/T (~ 5 fm/c for charm quark)

Do heavy quarks participate in the collective expansion and thermalize in the medium ?

Elliptic flow of D^0 and D_S





- Finite positive D^0 and D_S v_2 observed
- D^0 and D_S v_2 for 10-40% centrality follow the NCQ scaling
  - Due to interactions, open charm mesons acquired as strong collectivity as light-quark hadrons

(D^0 v_2) [STAR] : Phys. Rev. Lett. 118, 212301 (2017)

Correlation Between Flow Harmonics

Symmetric Cumulant {SC(m,n)}:

$$< \cos(m\phi_1 + n\phi_2 - m\phi_3 - n\phi_4) >_c = < v_m^2 v_n^2 > - < v_m^2 >< v_n^2 >$$

- SC(m,n) gives correlation between v_n^2 and v_m^2
- Correlation between flow harmonics (especially for v_2 and v_4) is found to be sensitive to transport properties of the QCD medium.
- Symmetric cumulant is almost free from effect of non-flow

– New way of constraining η/s(T) of the QGP

ALICE: Phys. Rev. Lett. **117**, 182301, (2016)

ATLAS: Phys. Rev. C **92**, 034903 (2015) and A. Bilandzic et. al. Phys. Rev. C 89, 064904 (2014)

Symmetric Cumulant

NSC in Final Momentum Space :

$$NSC(m,n)^{v} = \frac{<v_m^2 v_n^2> - <v_m^2><v_n^2>}{<v_m^2><v_n^2>}$$

NSC in Initial Geometry Space :

$$NSC(m,n)^{\varepsilon} = \frac{<\varepsilon_m^2 \varepsilon_n^2> - <\varepsilon_m^2><\varepsilon_n^2>}{<\varepsilon_m^2><\varepsilon_n^2>}$$

NSC(2,4):

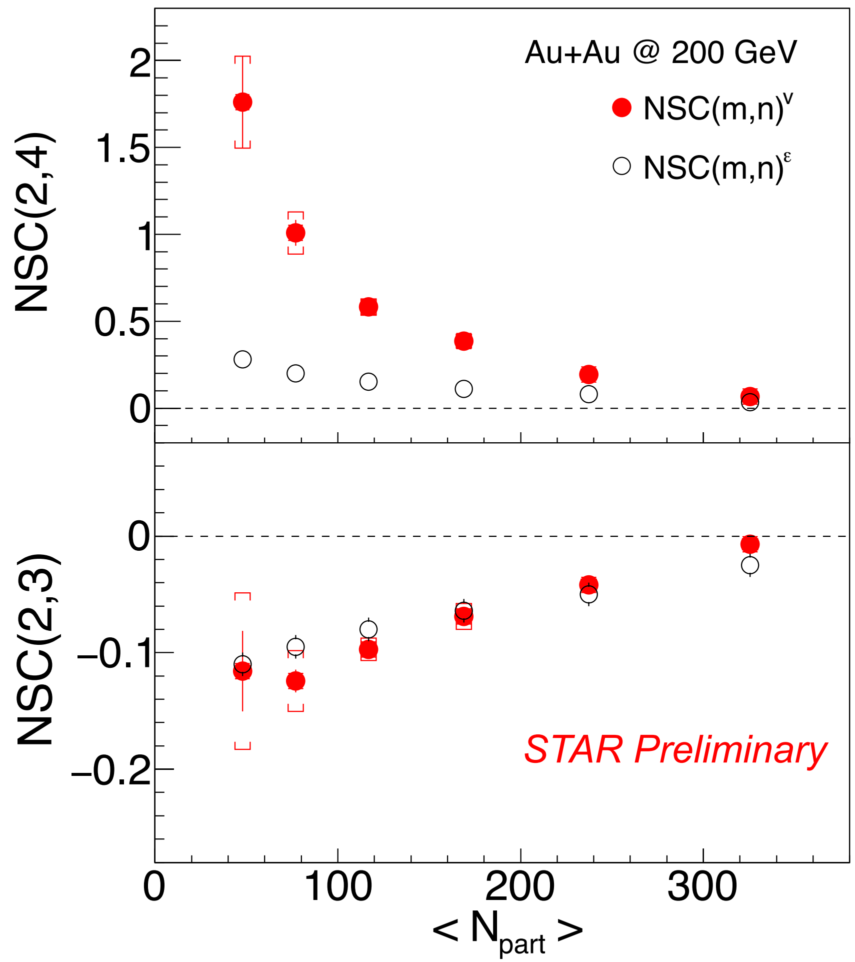
Positive correlation between v_2 and v_4

- Correlation between ε_2 and ε_4 + medium response

NSC(2,3):

Negative correlation between v_2 and v_3

- Mainly due to anti-correlation between ε_2 and ε_3

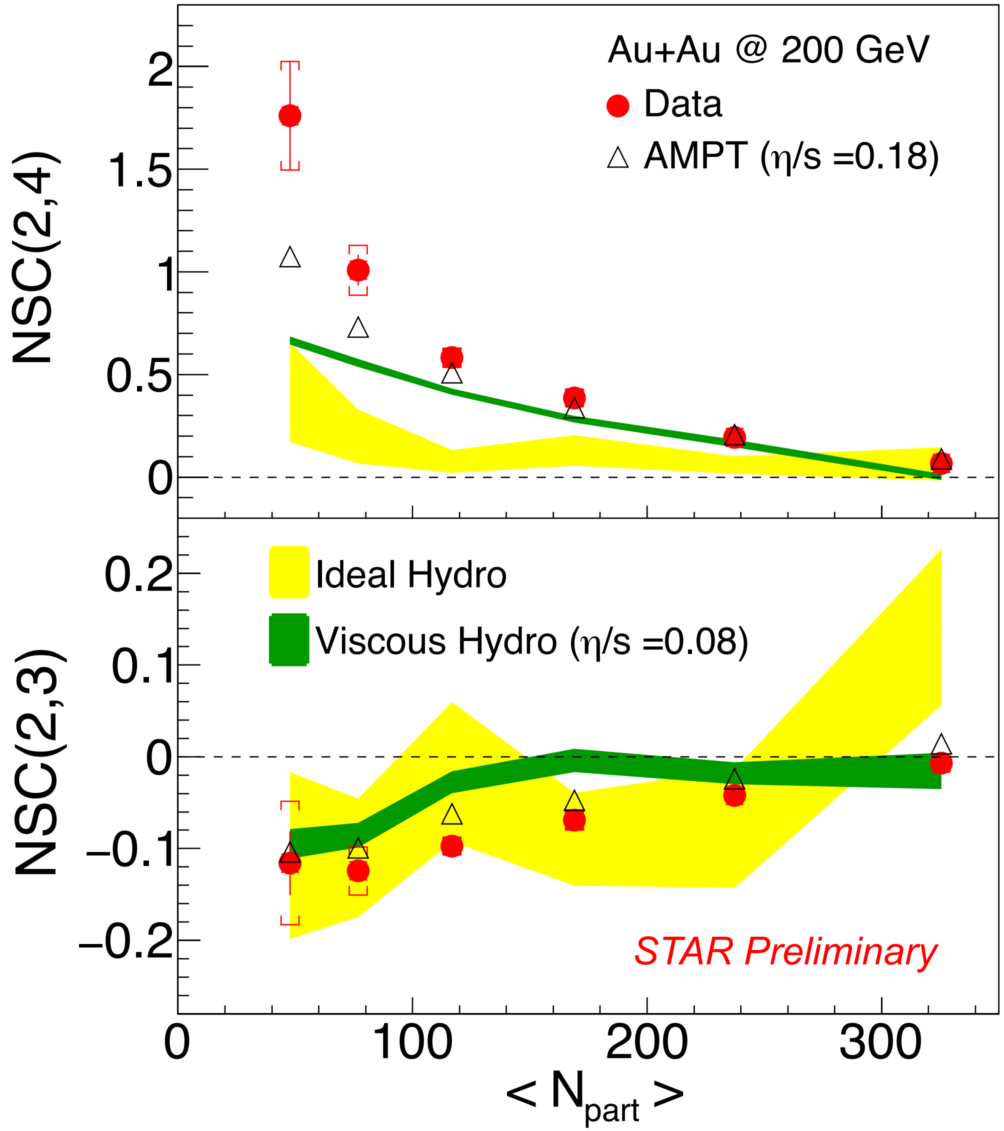


Symmetric Cumulant: Model Comparison

Ideal Hydro :
Initial condition: MC Glauber
η/s =0

Viscous Hydro :
Initial condition: MC Glauber
η/s = 0.08

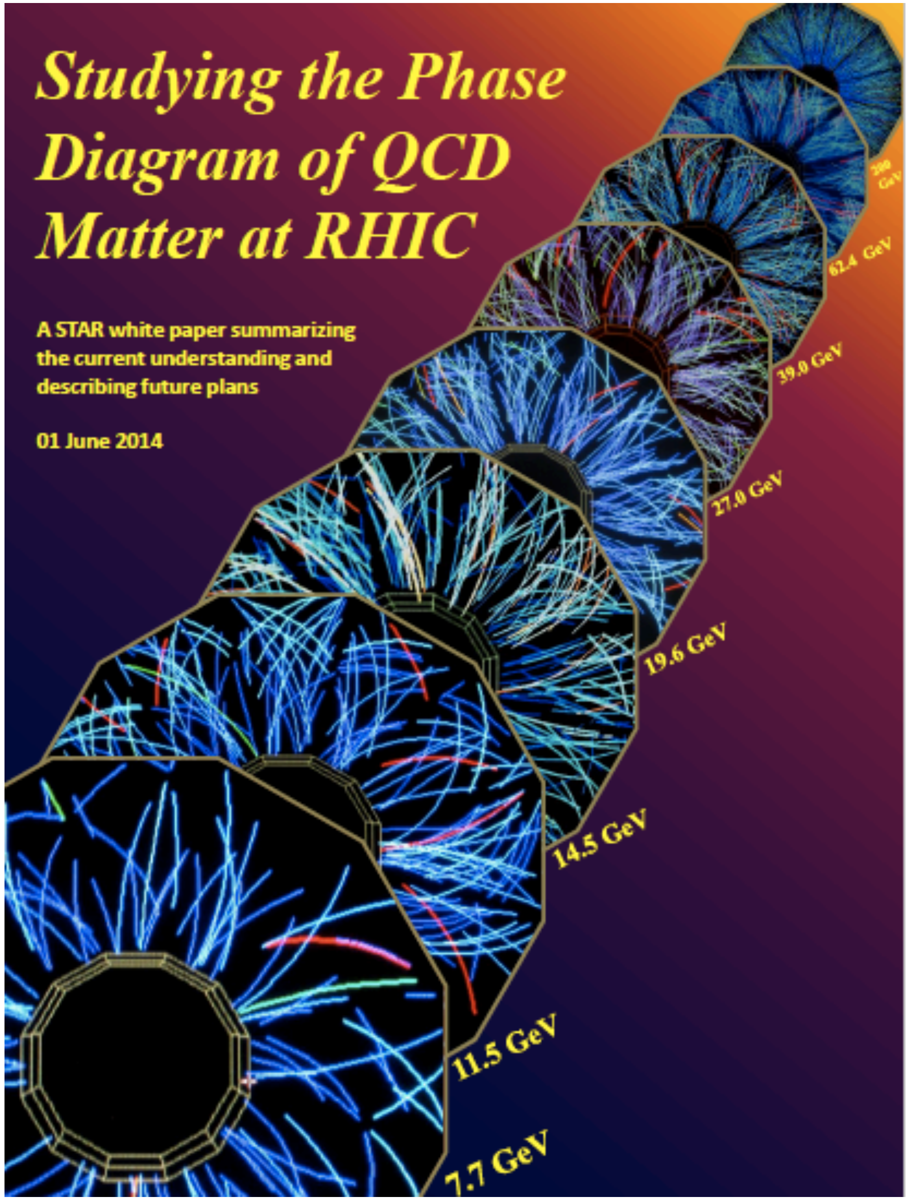
AMPT :
Initial condition: MC Glauber
η/s = 0.18



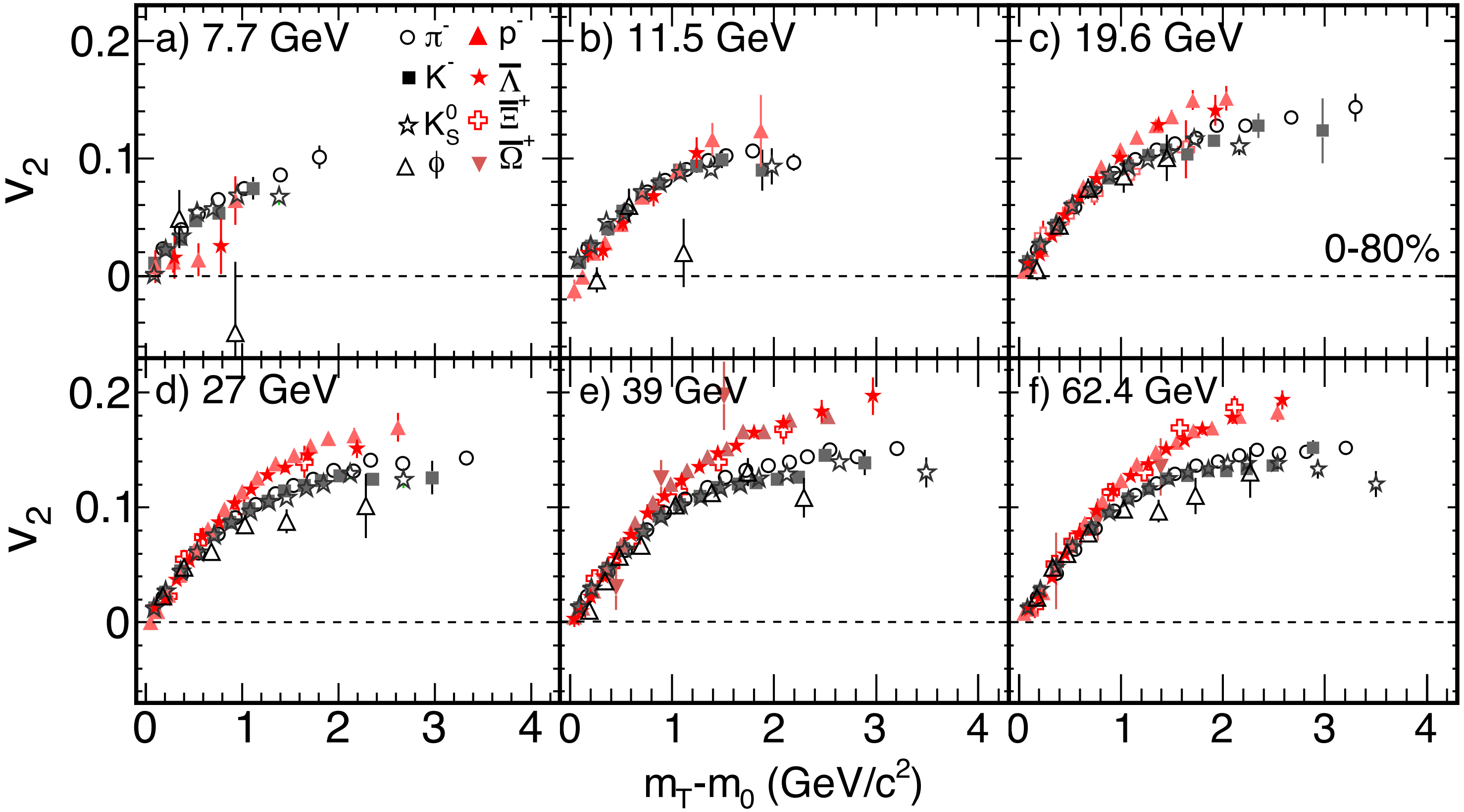
A viscous medium with η/s (T) > 0.08 is needed to explain the v_2-v_4 correlation data

M. Nasim , Phys. Rev. C 95 , 034905 (2017)
F. G. Gardin et al. , Phys. Rev. C 95 , 034901 (2017)

Results from RHIC BES Phase - I



NCQ Scaling: Baryon-Meson Separation at Low Beam Energy



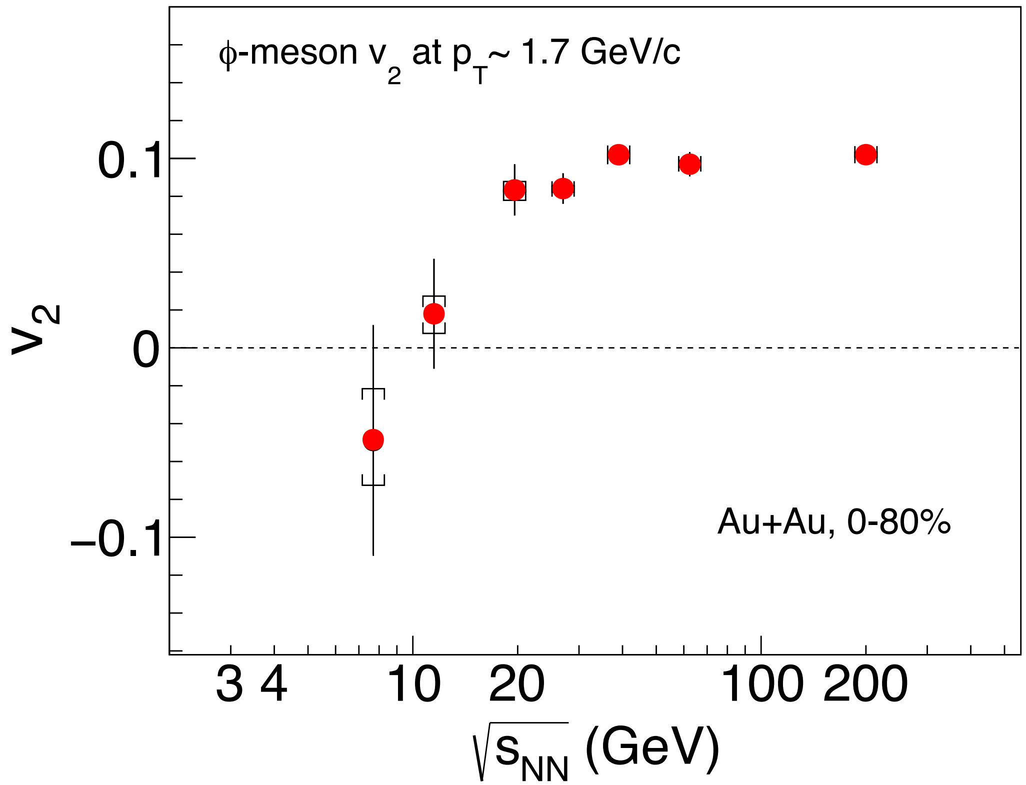
- Separation between baryon-meson splitting decreases with decreasing beam energy
- Baryon-meson splitting disappear at $\sqrt{s_{NN}} \leq 11.5$ GeV, breaking of NCQ scaling

  - decrease of partonic interaction with decreasing beam energy

STAR: Phys. Rev. Lett. 110, 142301 (2013)

ϕ meson v_2

ϕ meson v_2 reflect collectivity mostly from partonic phase



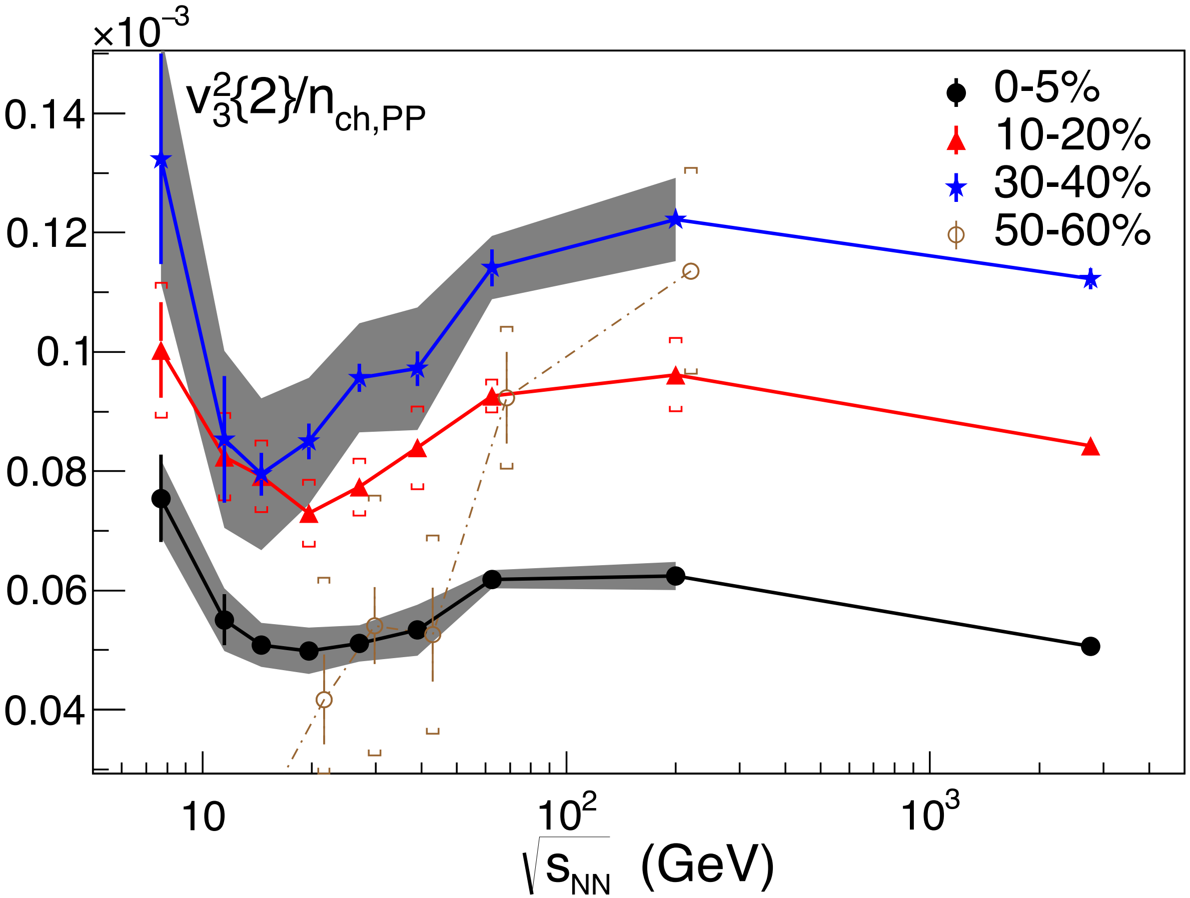
Need more statistics for ϕ meson at low beam energies !

- ϕ meson v_2 at intermediate p_T is close to zero at 11.5 and 7.7 GeV

– Contribution to the collectivity from partonic phase decreases with decreasing beam energy.

STAR: Phys. Rev. Lett. 110, 142301 (2013)

Beam Energy Dependence of v_3



Higher energy collisions producing more particles should be more effective at converting initial state geometry fluctuations into $v^2_3\{2\}$.

$$n_{\rm ch,PP} = \frac{2}{N_{\rm part}} dN_{\rm ch}/d\eta$$

- Local minimum in $v^2_3\{2\}/n_{ch,PP}$ near 15-20 GeV

  – softening of the equation-of-state ?

[STAR]: Phys. Rev. Lett. 116, 112302 (2016)

Summary

Au+Au at $\sqrt{s_{NN}}$ = 200 GeV :

- We established clear evidence of partonic collectivity with the high precision measurement of Ω and ϕ meson v_2

- D^0 v_2 follow the NCQ scaling; due to interactions open charm mesons acquired as strong collectivity as light-quark hadrons

- Flow correlation measurement suggest η/s (T) > 0.08

BES –I :

- The baryon-meson separation disappears at $\sqrt{s_{NN}} \leq 11.5$ GeV

- Measured ϕ meson v_2 indicates less partonic collectivity at $\sqrt{s_{NN}} \leq 11.5$ GeV. More statistics is needed to confirm

- Local minimum in $v^2_3\{2\}/n_{ch,PP}$ near 15-20 GeV could be an indication of a softening of the equation-of-state

Back-up

Symmetric Cumulant

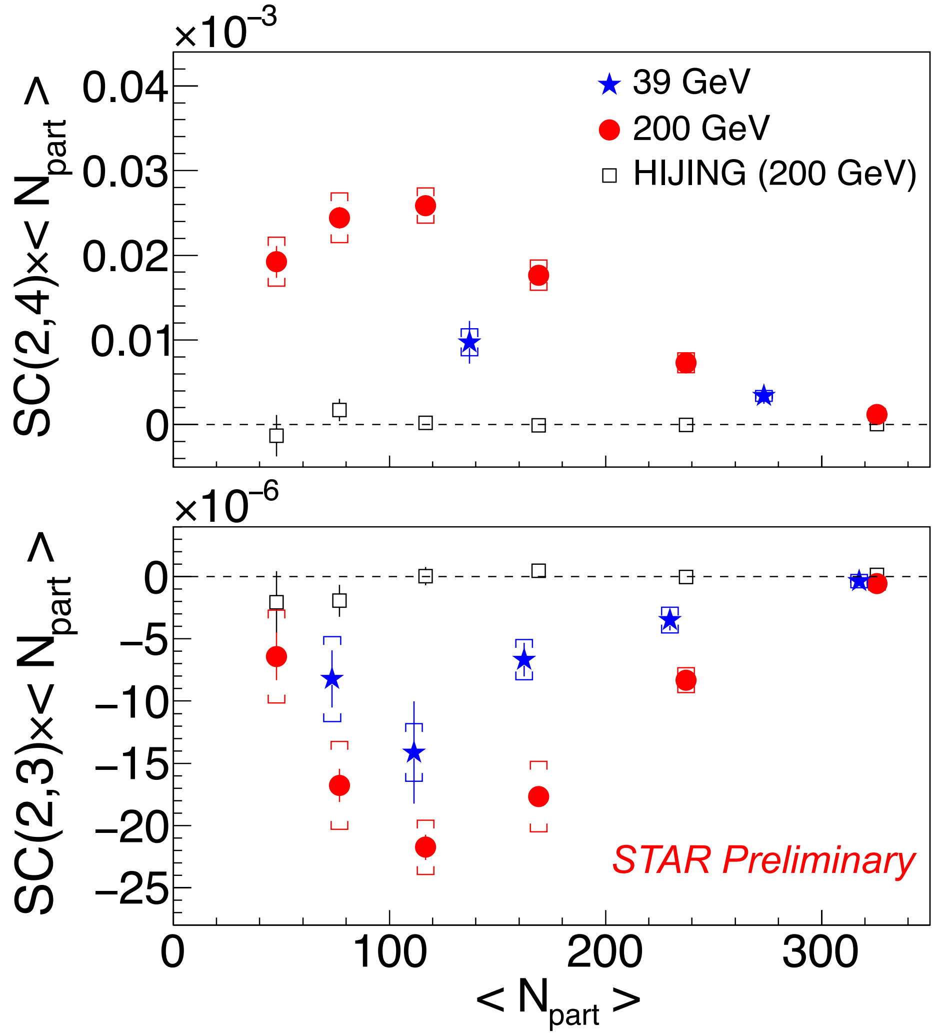
$$SC(n,m) = \langle v_m^2 v_n^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle$$

SC(2,4) : Correlation between v_2 and v_4

- Positive correlation
- The magnitude of correlation increases from central to peripheral collisions

SC(2,3) : Correlation between v_2 and v_3

- Negative correlation
- The magnitude of anti-correlation increases from central to peripheral collisions



Symmetric Cumulant: Energy Dependence

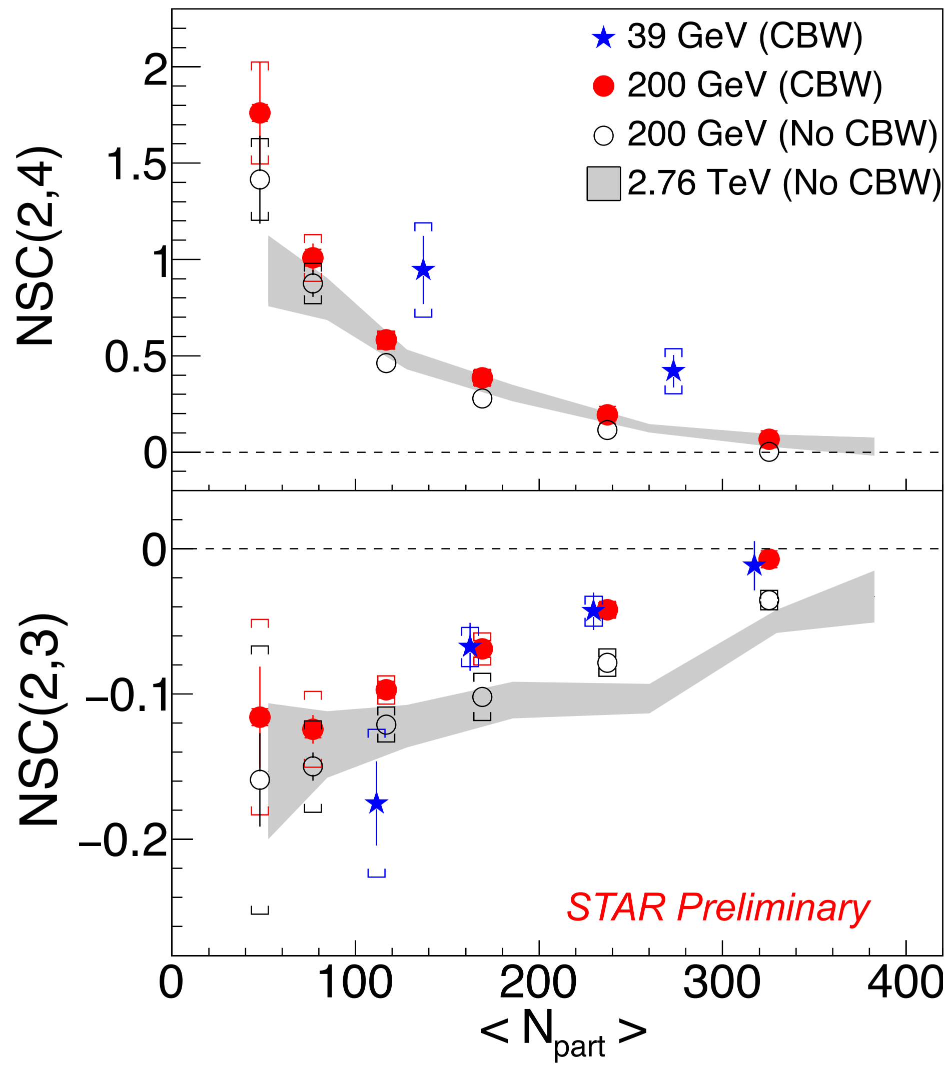
Centrality Bin Width Correction:

The symmetric cumulants were measured in small multiplicity windows and then combined into 10% centrality bins.

NSC(2,4) is systematically higher at the lower energy (39 GeV) compared with 200 GeV and 2.76 TeV

NSC(2,3) at 39 and 200 GeV are consistent with each other.

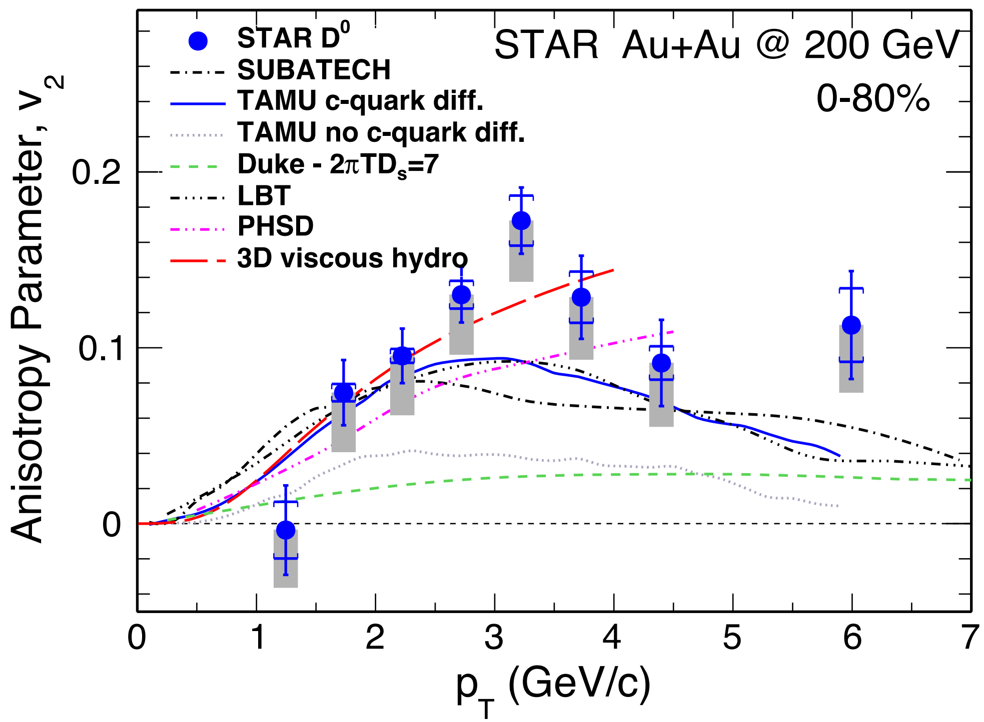
RHIC and LHC data are very close to each other when measured in similar way



ALICE: Phys. Rev. Lett. **117**, 182301, (2016)

F. G. Gardin et al. , Phys. Rev. C 95 , 034901 (2017)

D^0 v_2 and Model Comparison



[Theory:
TAMU: Eur. Phys. J. C (2016) 76: 107 & private comm.;
SUBATECH: PRC 91(2015) 054902 & private comm.;
Duke: PRC 92(2015) 024907 & private comm.;
PHSD: PRC 90, 051901 (2014), PRC 92, 014910 (2015);
LBT: Phys. Rev. C 94, 014909 (2016);
3D viscous hydro: PRC 86, 024911 (2012), PRD 91, 074027 (2015) & private comm.]
[STAR: PRL 118, 212301 (2017)]

TAMU model with no charm quark diffusion and Duke model and are inconsistent with data

- Charm quark diffusion is clearly needed
- Diffusion coefficient: $D_s \times 2\pi T \sim 2\text{-}12$ within T_c-$2T_c$
- 3D hydro model (tuned to light hadron): agrees with data quite well
  - Suggest charm quarks have achieved thermal equilibrium