Collectivity in Heavy-Ion Collisions

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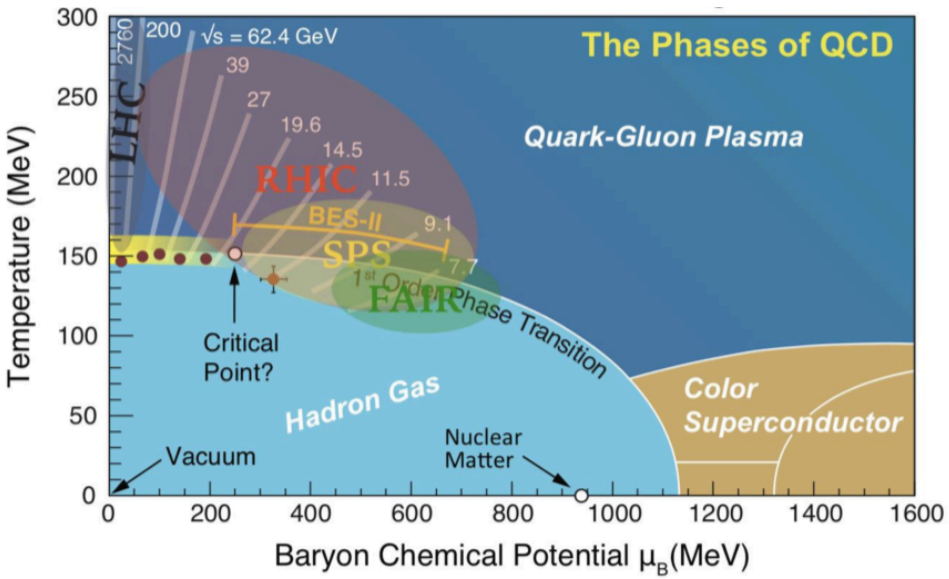
Introduction

Goal:

To create and study the properties of QGP – a state of deconfined, quarks and gluons over a large volume predicted by the theory of QCD at high energy density and temperature.

Credit: S. Mukherjee/BNL



In this talk, I will discuss :

What are properties of QGP ?

What is the threshold energy for QGP formation ?

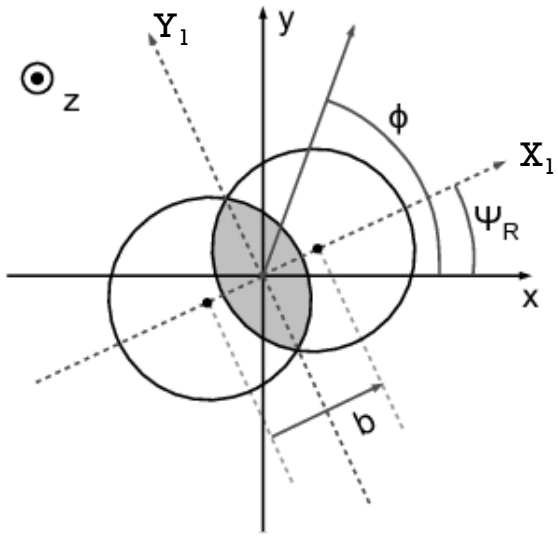
These questions will be addressed by the measure of collectivity

Selected Results

- Flow of Light and Strange Hadrons
  - η/s of QGP
  - Initial state in heavy-ion collisions
  - Partonic collectivity
- Flow of Charm and Beauty
  - Diffusion coefficients

Collectivity/Flow

Initial spatial anisotropy



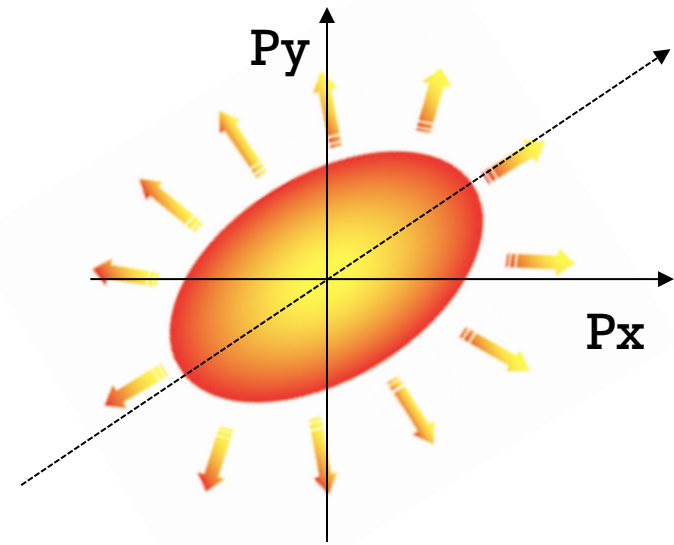
Interaction

↓

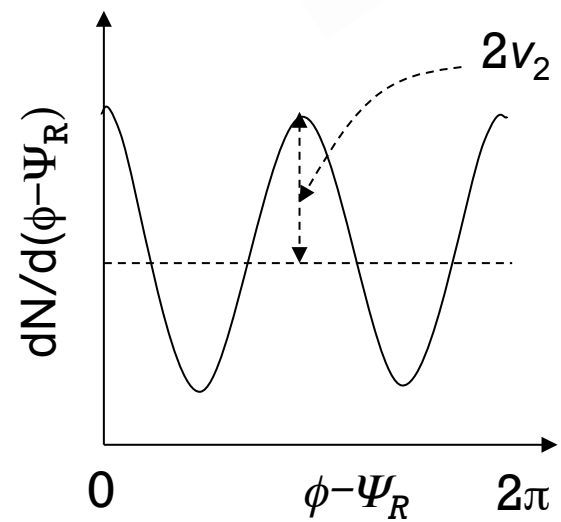
Pressure (P)

$$\frac{\partial P}{\partial X_1} > \frac{\partial P}{\partial Y_1}$$

Final momentum anisotropy



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

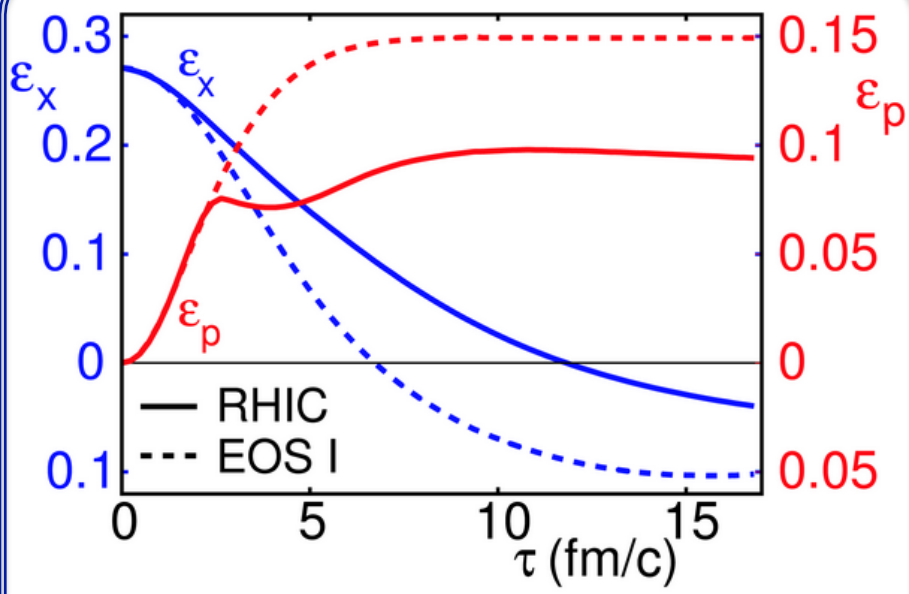


v_1, - directed flow
v_2, - elliptic flow
v_3, - triangular flow
etc.

A. Poskanzer, et.al, PRC 58, 1671 (1998)
J-Y Ollitrault, PRD 46, 229 (1992)

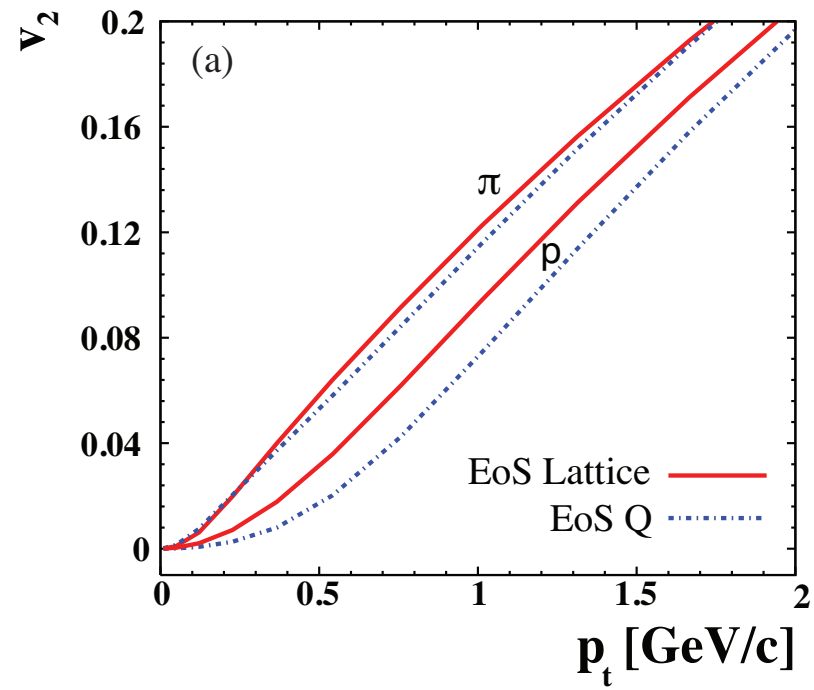
Elliptic Flow as a Probe

Sensitive to Early Dynamics & Equation of States



– sensitive to early times in the evolution of the system

– sensitive to the equation of state



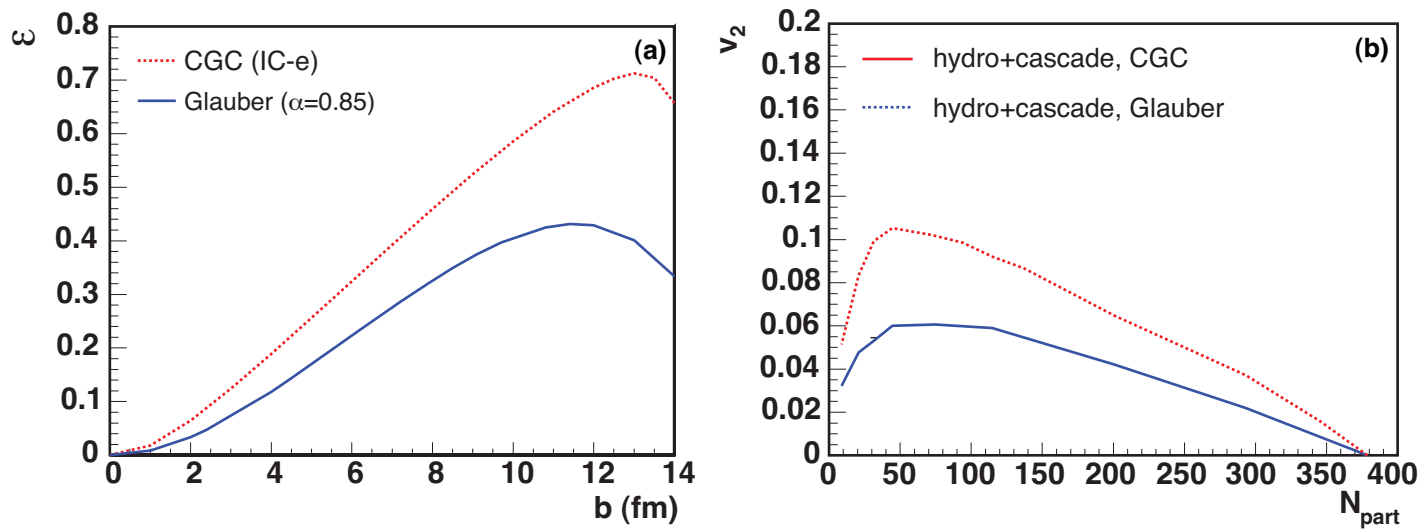
– Heavier hadrons are more sensitive to the equation of state

P. Kolb, U. W. Heinz, NPA715, (2003) 653c

P. Huovinen, P. Petreczky, NPA 837, 26-53 (2010)

Elliptic Flow as a Probe

Sensitive to Intial of States , *Glauber* vs *CGC*



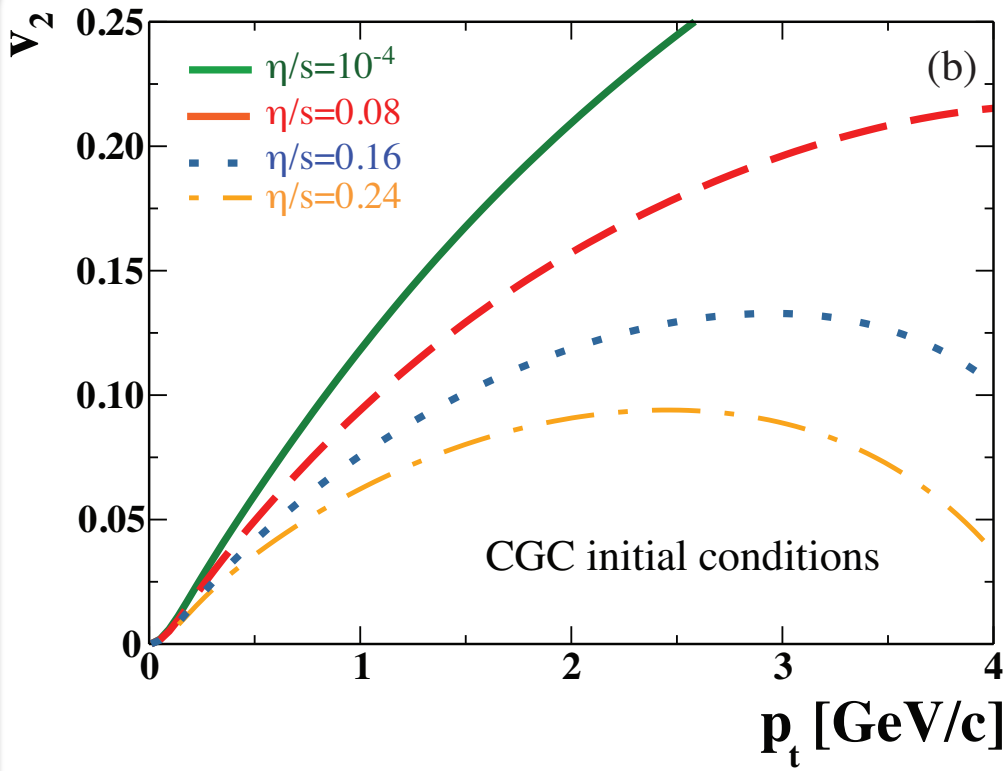
Magnitude of final state momentum anisotropy depends on initial condition

M. Luzum, P. Romatschke, PRC 78, 034915 (2008).

See talk by
Y. Zhou at 17.42 (Sat)

Elliptic Flow as a Probe

Sensitive to Transport Properties of Medium



Dissipative effects like viscosity reduce elliptic flow.

Anisotropic flow parameter (v_2) has been extensively used to extract viscous properties of QGP.

η/s : viscosity over the entropy density

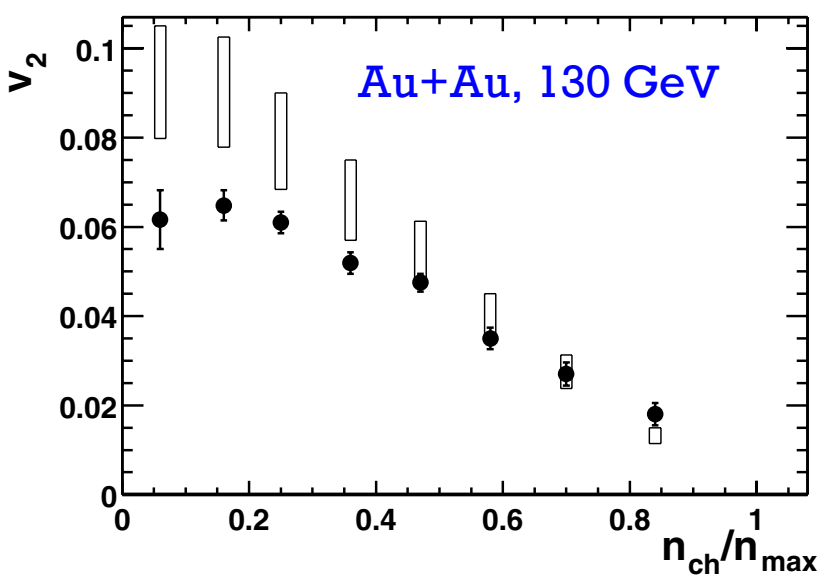
M. Luzum, P. Romatschke, PRC 78, 034915 (2008).

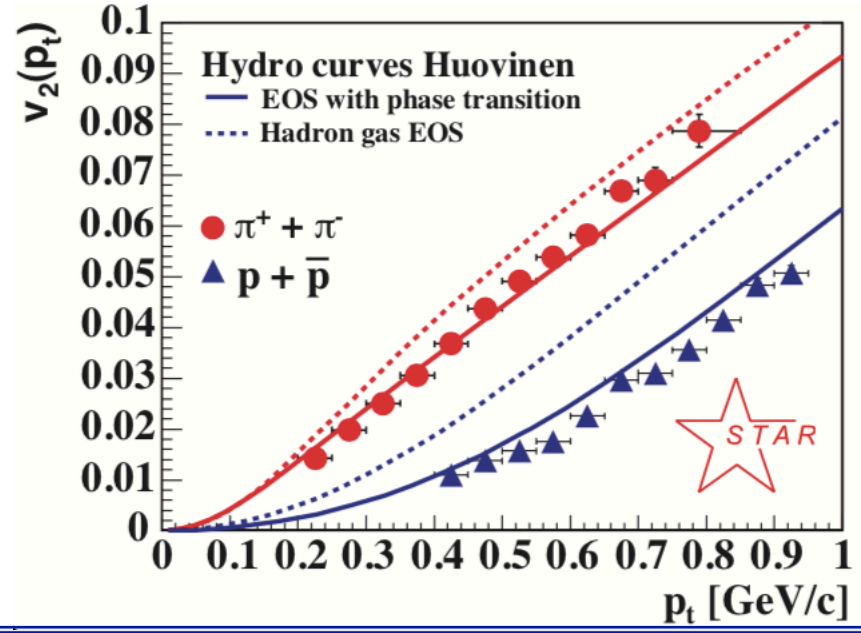
Flow of Charged Hadrons

Viscous Properties of QGP

Hydro Works at RHIC

First RHIC result



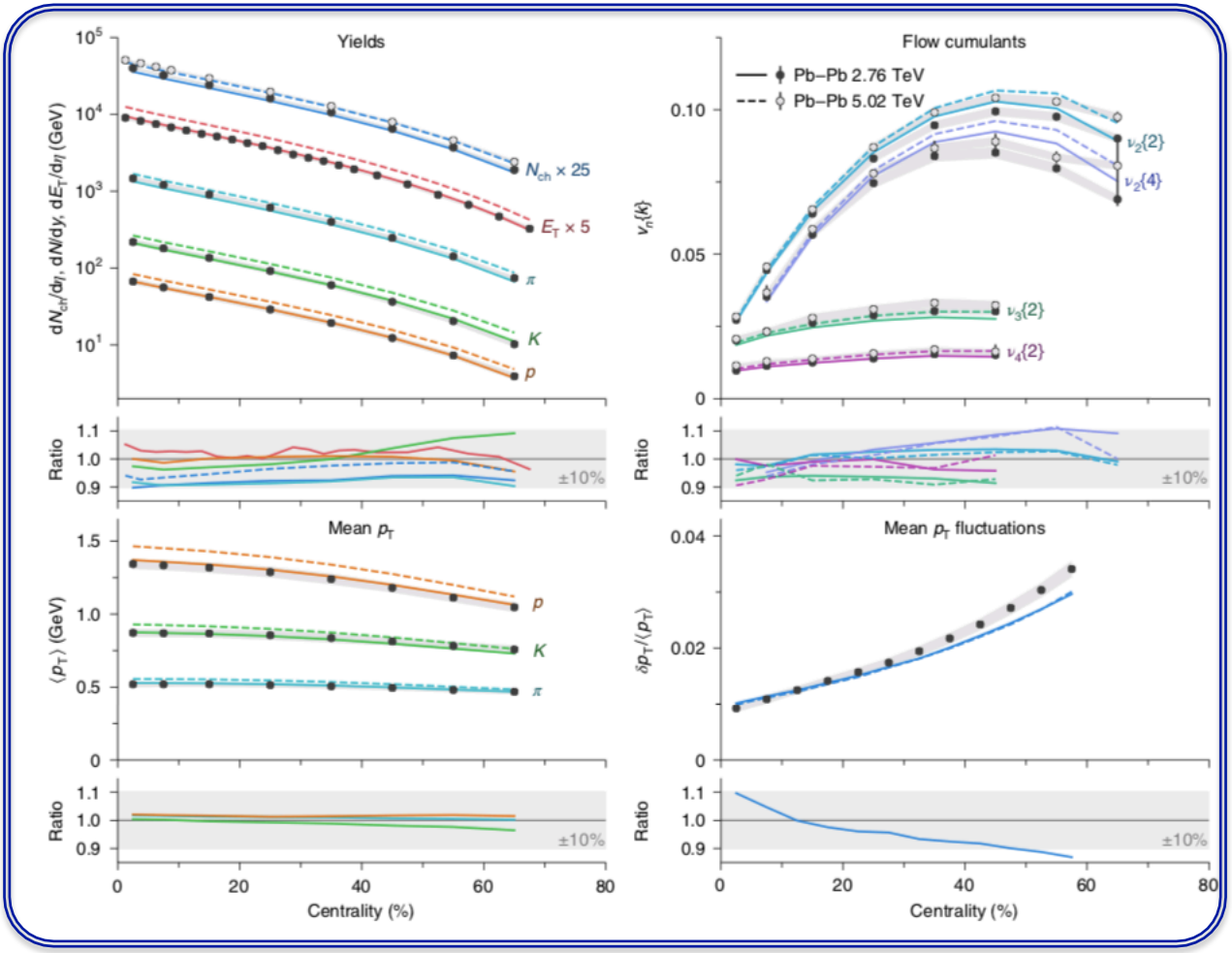


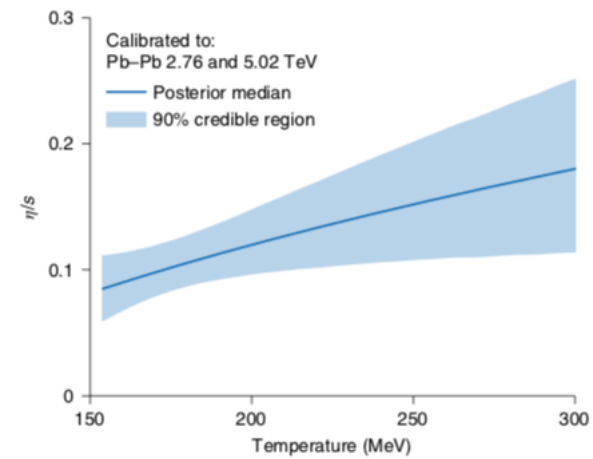
Quantitative agreement with hydrodynamic model predictions

STAR: PRL 86, 402 (2001)
P.Huovinen, et al ,PLB503,58 (2001)

η/s of QGP

Using Bayesian Technique





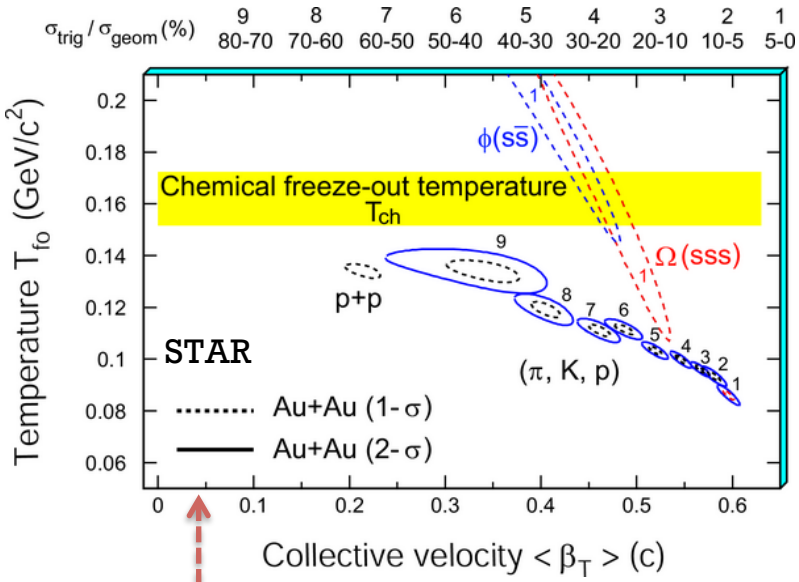
Most precise estimation of η/s so far

J. E. Bernhard, Nature Physics, 15 ,1113–1117 (2019)

Flow of Identified Hadrons

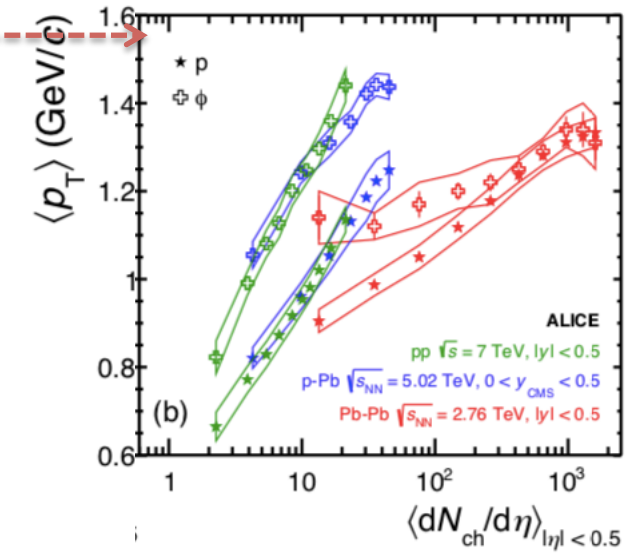
Partonic Collectivity

Multi-strange v_2: Probe to Partonic Collectivity

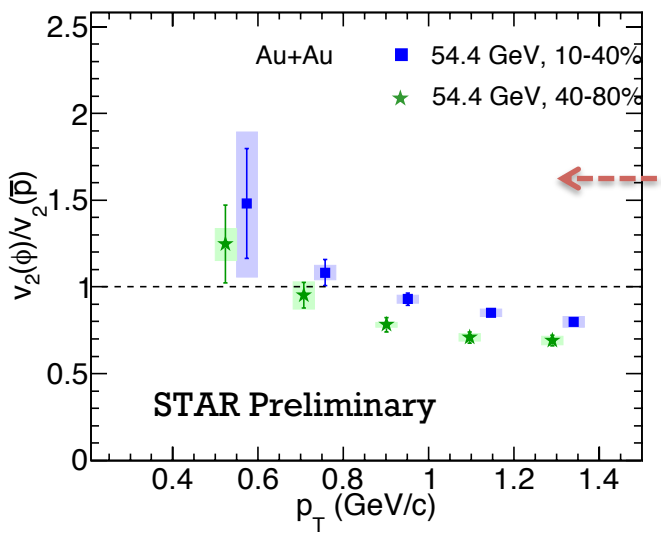


ϕ freezes out at higher temperature than π,k,p

<p_T> of ϕ is almost independent of centrality unlike protons



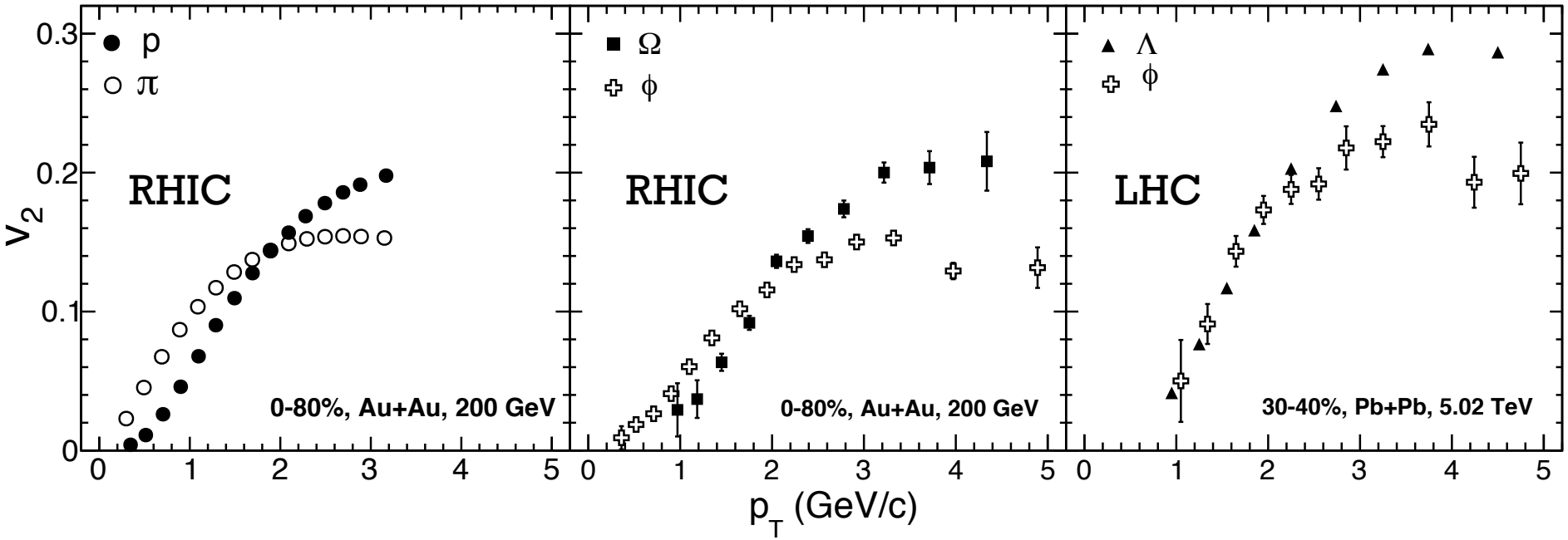
ALICE: PRC 99, 024906



ϕ v_2 less affected by hadronic interaction compared to anti-proton

- Indicates possibly ϕ and Ω decouples early in the interaction
- Clean probe to partonic collectivity

Elliptic Flow of Strange Hadrons



- $v_2(p_T)$ follows a mass ordering at low p_T – **Hydrodynamics**
- Intermediate p_T:

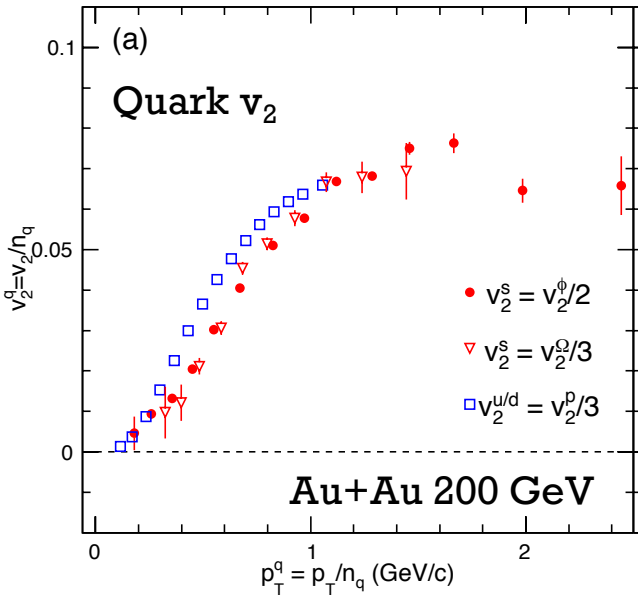
  (i) baryons vs Mesons – **Recombination**

  (ii) $v_2(\phi) \sim v_2(\pi)$, $v_2(\Omega) \sim v_2(p)$ } Partonic Collectivity

ALICE: JHEP 09 (2018) 006
STAR: PRL 116 (2016) 6, 062301

Quark v_2

Quark coalescence model: $$v_2^h(p_T) = n v_2^q\left(\frac{p_T}{n}\right)$$



STAR: PRL 116 (2016) 6, 062301

- **s-quark v_2 obtained from ϕ and Ω are consistent, coalescence works.**
- v_2 of s-quarks is smaller than v_2 of light quarks at p_T/n_q <1 GeV/c

Effect of radial flow on quarks in the QGP phase ?

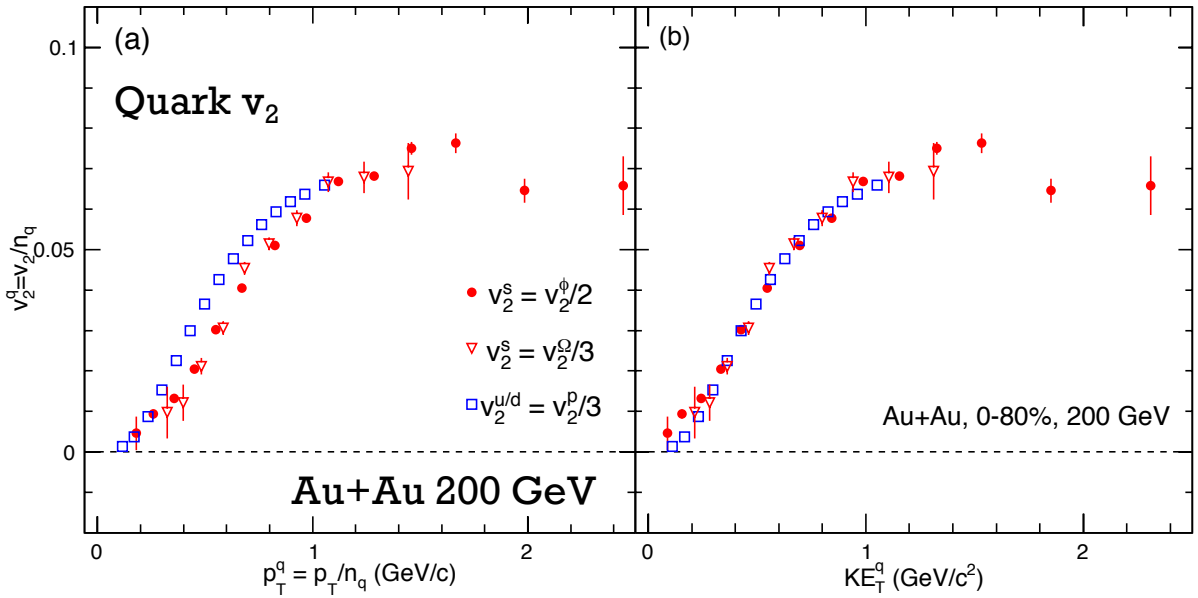
Plot quarks v_2 as a function of its Transverse K.E.

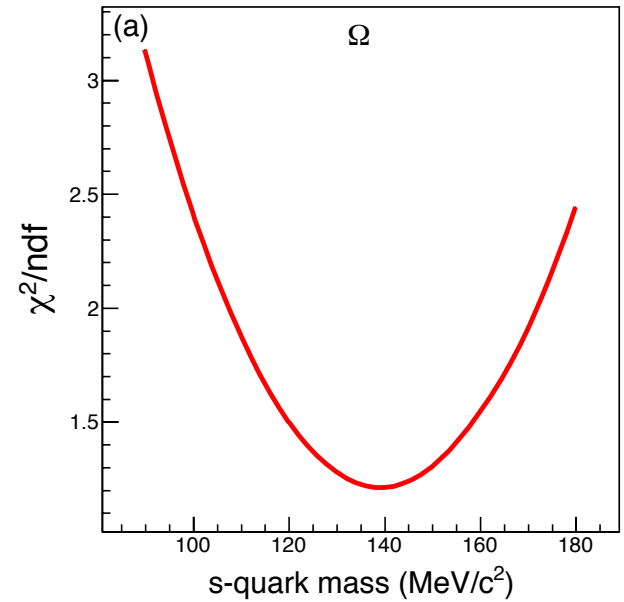
Transverse Kinetic Energy of Quarks: $$KE_T^q = \sqrt{(p_T^q)^2 + (m_0^q)^2} - m_0^q$$

$$KE_T^q \neq \left(\sqrt{p_T^2 + m_0^2} - m_0\right) / n_q$$

Quark v_2

Quark coalescence model: $$v_2^h(p_T) = n v_2^q\left(\frac{p_T}{n}\right)$$





$$KE_T^q = \sqrt{(p_T^q)^2 + (m_0^q)^2} - m_0^q$$

Light quark mass= 4 MeV
s-quarks Mass =140 MeV

Scaling work with bare-parton mass.
In the absence of QGP phase this scaling should not hold

P. Dixit, M. Nasim, arXiv:2110.08573

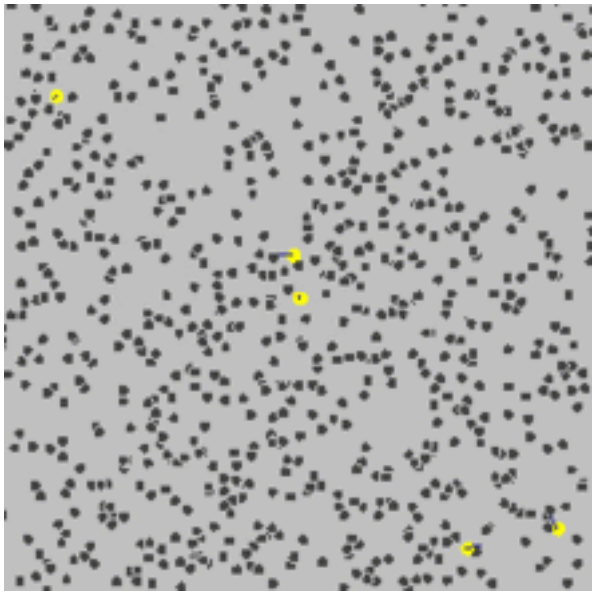
Heavy-flavor

Diffusion coefficient

See talk by
Yi-Fei Zhang at 11.40 (Sun)

Propagation of Heavy Quarks in QGP

Brownian motion of big particles that collides with a large number of smaller particles



Credit: Wikipedia

Diffusion coefficient measures the mobility of the big particle in the medium

$$< x^2 >= 2D_s t$$ (Einstein's theory)

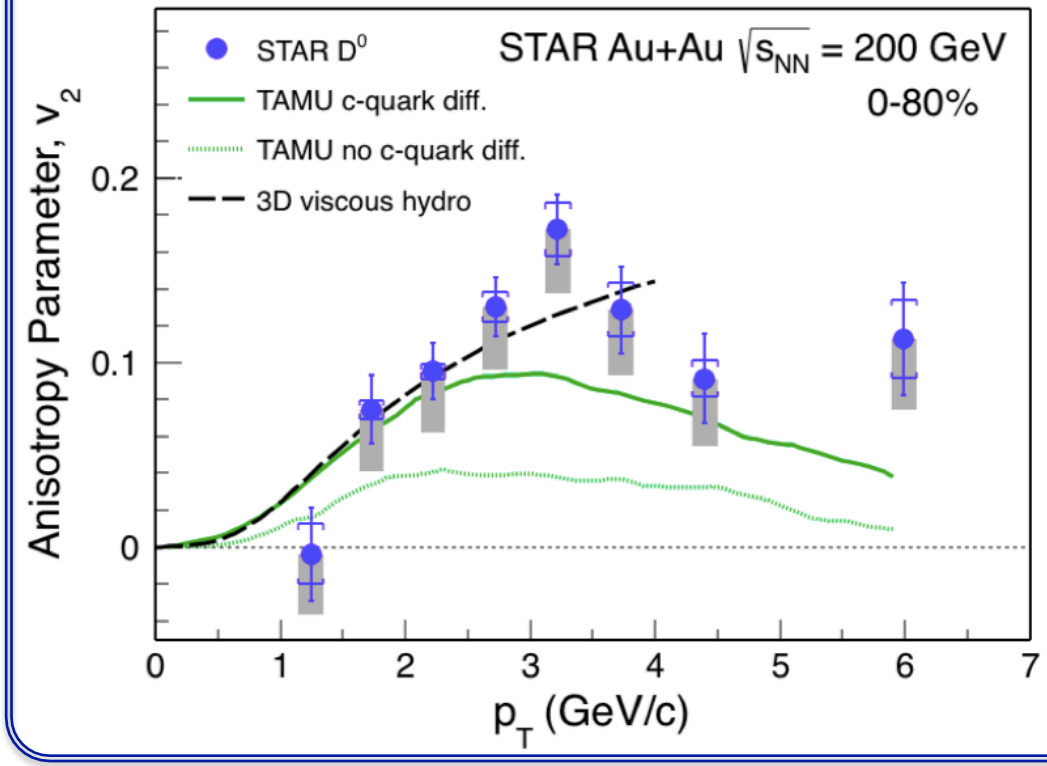
Propagation of heavy quarks in QGP medium is analogous to Brownian motion in molecular physics

Motion of heavy quarks in a bath of light partons can be used to extract Ds

Quark	Mass
u/d	2-4 MeV
c	1.3 GeV
b	4.1 GeV

Flow of Charm-Hadron

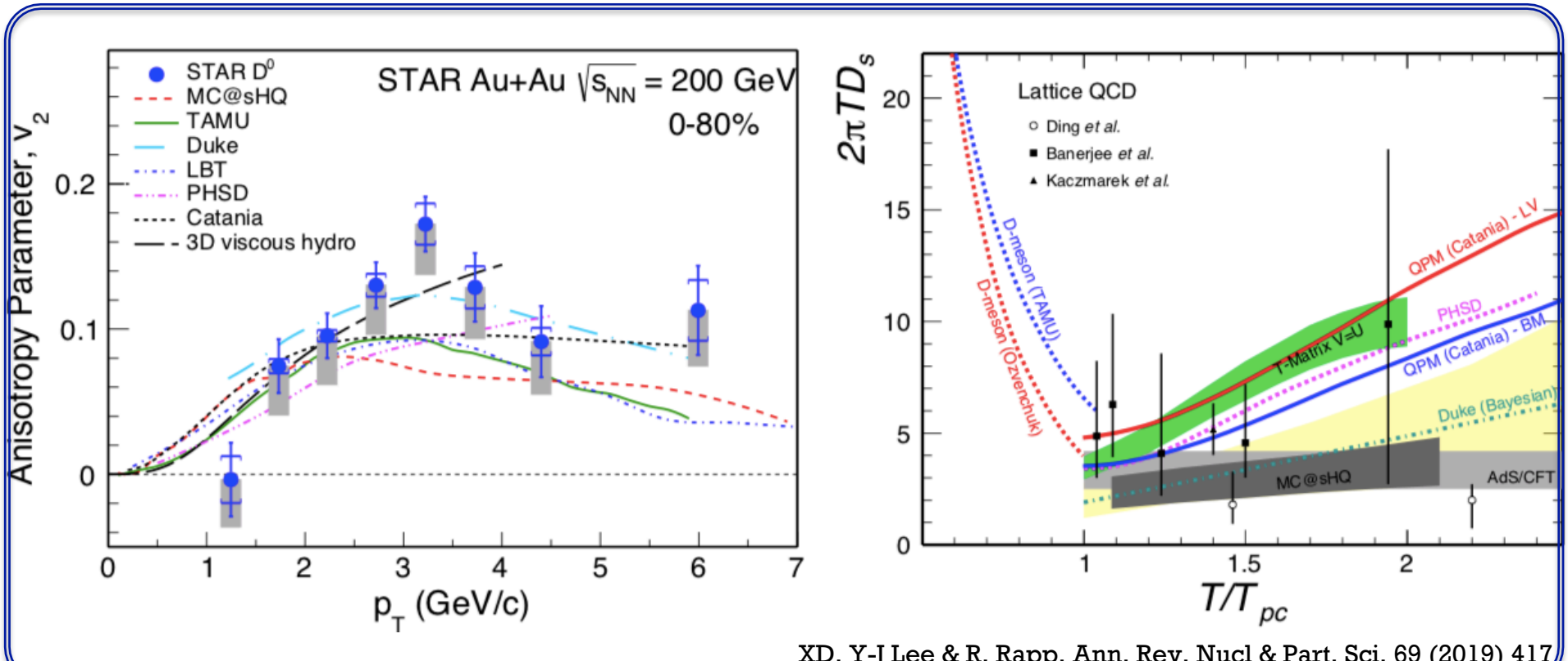
Probing interaction of charm quarks with the QGP medium



- Model calculation with no c-quark diffusion fails to describe data
- Large D^0 v_2 originated from charm quark diffusion in QGP
- 3D viscous hydro explain the D^0 v_2 data up to $p_T \sim 4$ GeV/c

STAR, PRL 118 (2017) 212301

Diffusion Coefficient (D_S)



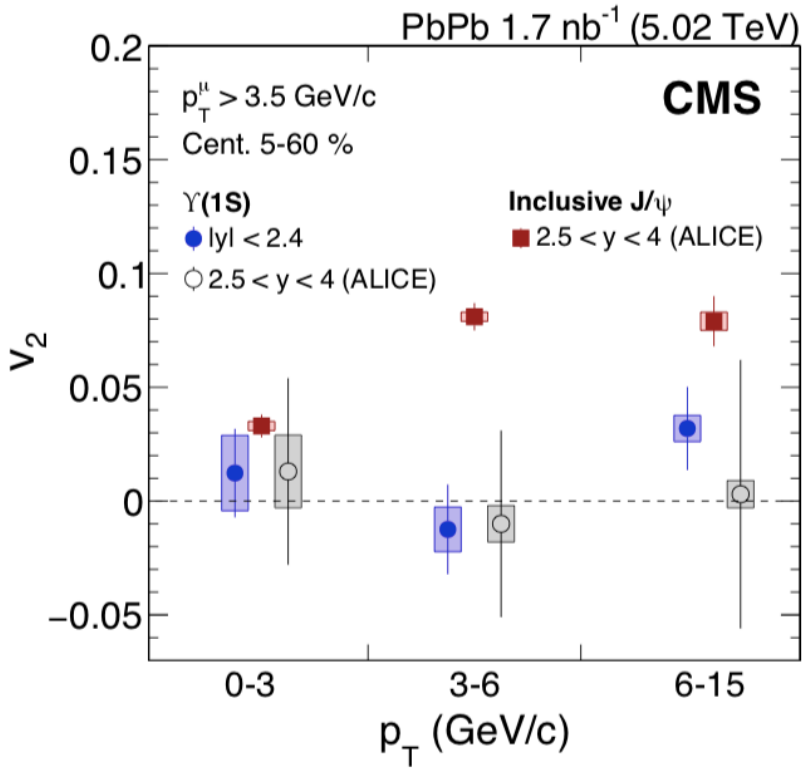
XD, Y-J Lee & R. Rapp, Ann. Rev. Nucl & Part. Sci. 69 (2019) 417

Model calculation with $2\pi TD_S$ = 2 – 5, can explain measured D^0 v_2

- Consistent with LQCD predictions

Flow of Beauty-Hadron

Probing interaction of beauty quarks with the QGP medium



Upsilon (1s) state

- Sizeable flow of J/ψ
- Flow of ϒ is consistent with zero in the measured p_T range.

Blast-Wave model calculation show that, even with full thermalization a sizable elliptic flow of ϒ would only be expected at $p_T > 10$ GeV/c. (Due to its heavy mass)

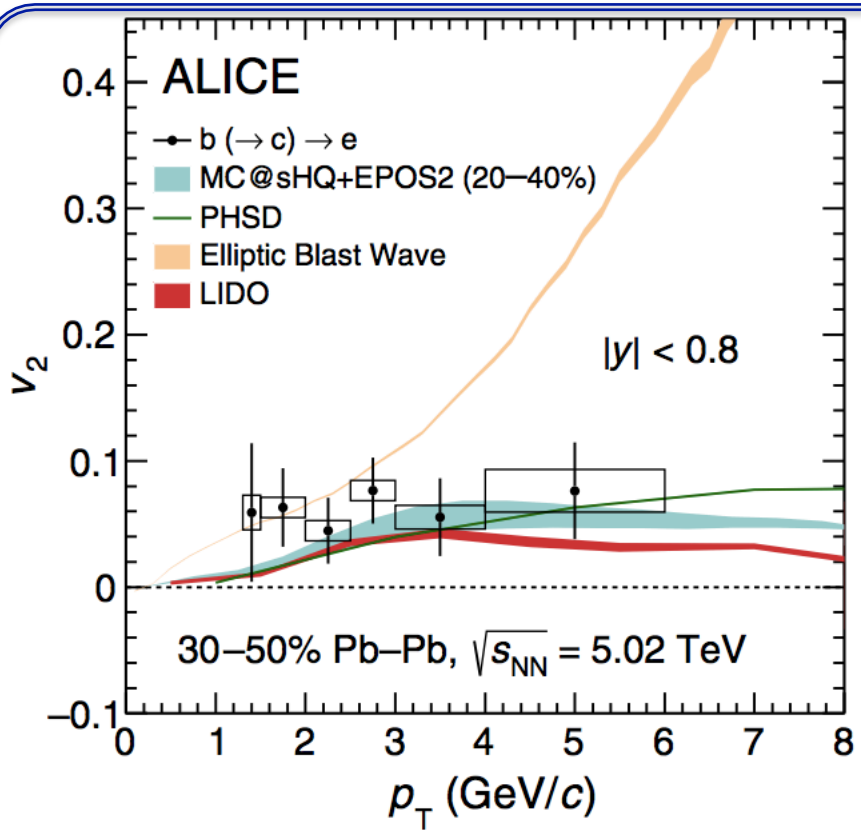
K. Reygers, et al. PRC 101, 064905 (2020)

ALICE: PRL123, 192301 (2019)

CMS: PLB 819, 136385 (2021)

Flow of Beauty-Hadron

Probing interaction of beauty quarks with the QGP medium



Beauty-hadron decay electron

Non-zero v_2 of electrons from beauty hadron decays.

Transport models, which include significant interaction of beauty quarks with QGP, explain data.

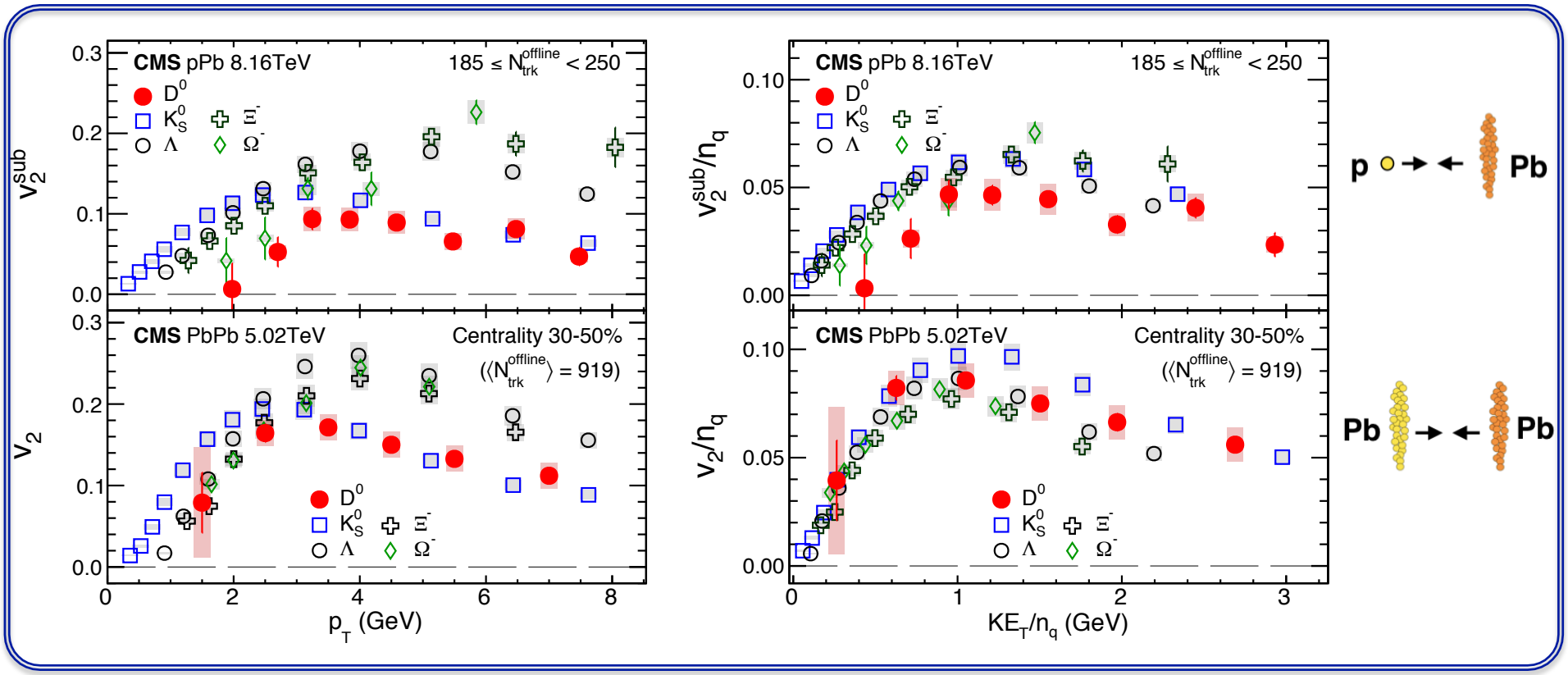
Full thermalization of beauty quarks is strongly disfavored at high p_T, but is in agreement with the results at low p_T.

ALICE: PRL126, 162001 (2021)

Collectivity in Small System

See talk by
S. Lim at 11.40 (Sat)

Charm and Strange hadrons in p+Pb



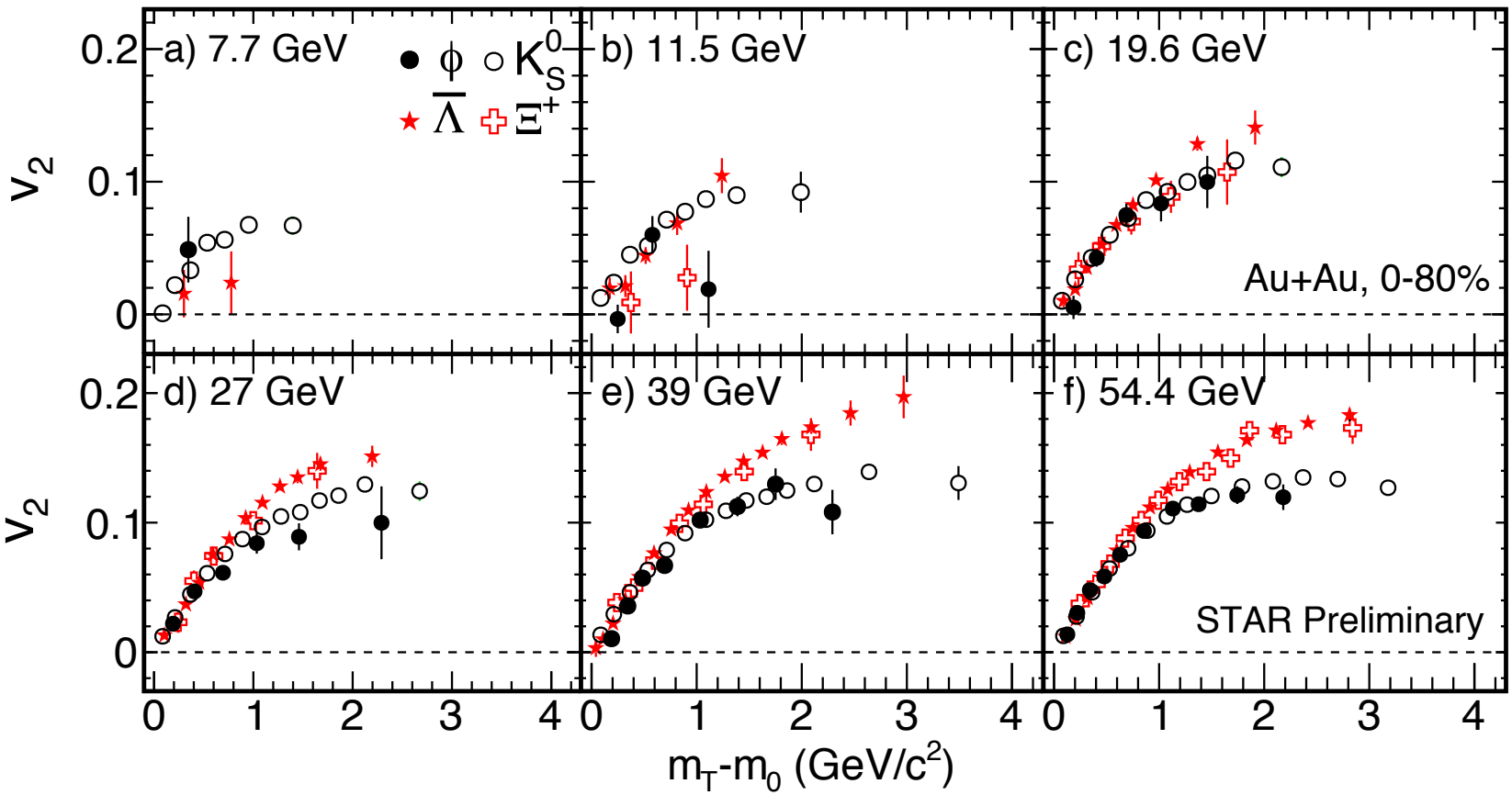
- D^0 v_2 values are found to be smaller in p+Pb than Pb+Pb compared to strange hadrons.
- The collective behavior of charm quarks is weaker than that of the light-flavor quarks in small p+Pb system unlike Pb+Pb collisions

CMS: PRL. 121, 082301 (2018)

Energy Dependence of Flow

Threshold Energy of QGP Formation

Disappearance of QGP Signal ?



STAR: PRL 110, 142301 (2013)

$\sqrt{s_{NN}}$ >19.6 GeV

- Baryon-meson separation at intermediate m_T-m_0

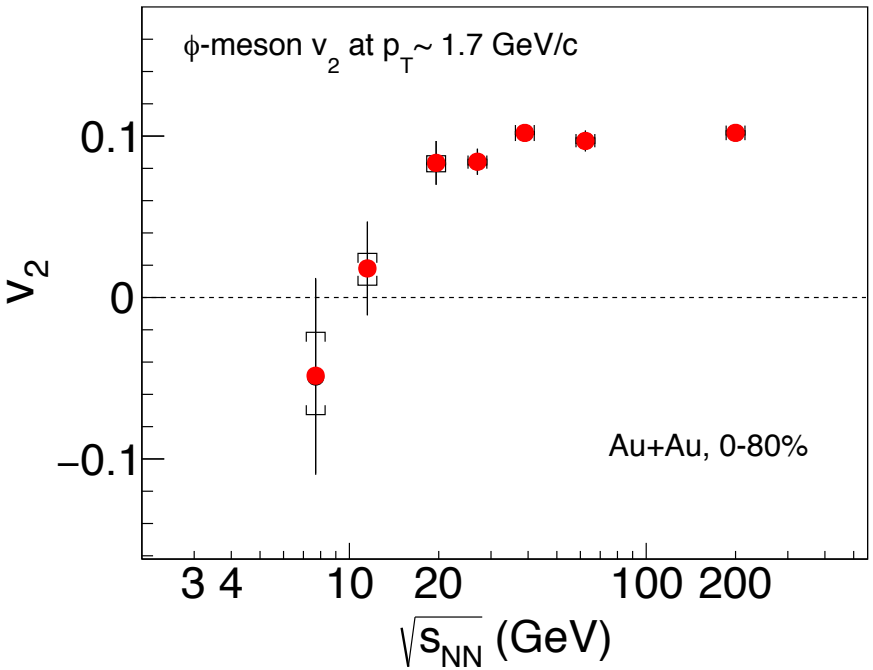
→ Parton recombination, QGP formation

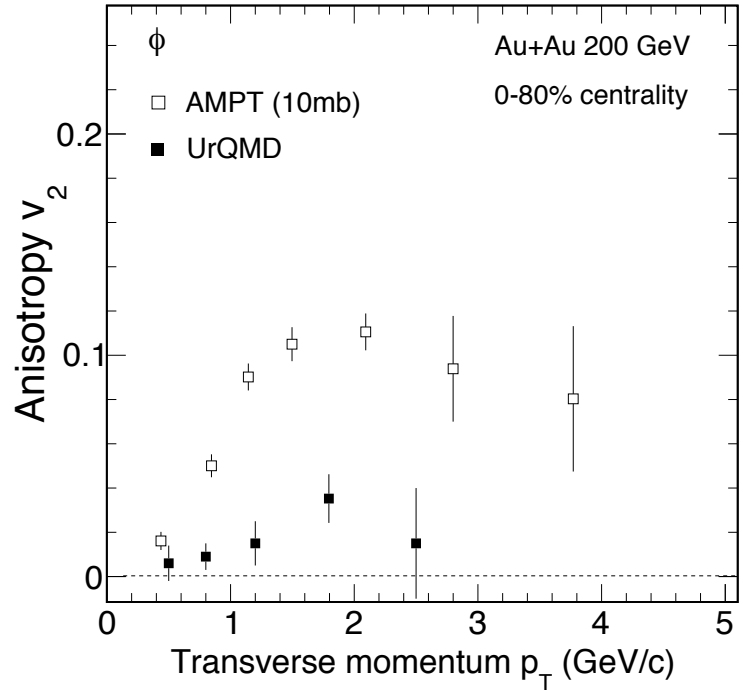
$\sqrt{s_{NN}}$ < 19.6 GeV

- No baryon –meson separation for the highest measured m_T-m_0

→ Possibly hadronic interaction dominated, absence of QGP

Disappearance of QGP Signal ?



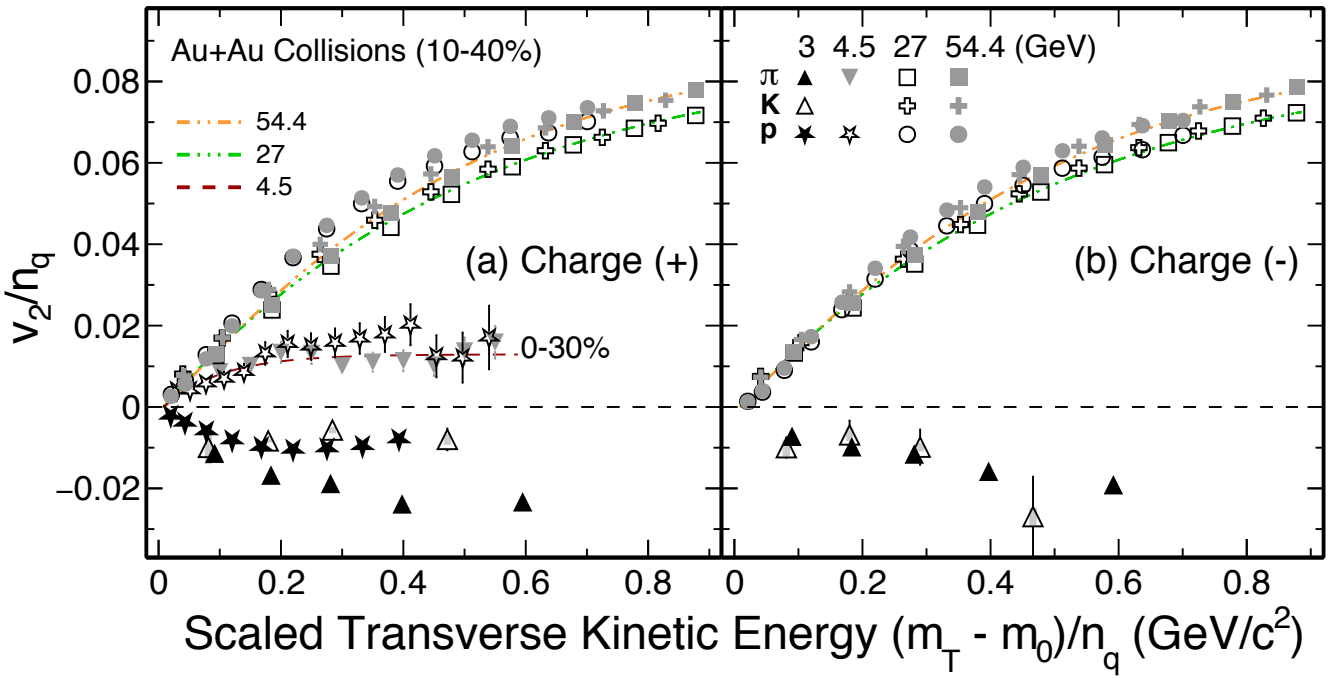


- ϕ meson v_2 at intermediate p_T is close to zero at 11.5 and 7.7 GeV

Hadronic interaction dominated matter at $\sqrt{s_{NN}} < 19.6$ GeV

STAR: PRC 88, 014902 (2013)
M. Nasim et al. PRC 87, 014903 (2013)

Disappearance of QGP Signal ?



- The measured v_2 for all particles are negative at 3 GeV
- The NCQ scaling breaks, especially for positively charged particles

→Hadronic interaction dominated matter

STAR: arXiv:2108.00908

Summary

- Evidence for the formation of QGP at top RHIC and LHC where quarks and gluons move collectively
- Viscosity over entropy density of QGP is ~ 0.1-0.2, lowest viscosity ever measured in any experiment
- The heavy quarks (c & b) exhibit Brownian motion in a thermal bath of light partons. ($2\pi TD_S = 2 - 5$)
- Signature of QGP-like collectivity in high-multiplicity p+Pb collisions
- Signature of QGP seems to dis-appear below $\sqrt{s_{NN}} < 19.6$ GeV (more data needed to confirm)

Thank You