Collectivity in Heavy-Ion Collisions

Md. Nasim
Department of Physics
Indian Institute of Science Education and Research, Berhampur

ATHIC, 2021
Inha Univ. Incheon, South Korea
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.

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
  • $\eta/s$ of QGP
  • Initial state in heavy-ion collisions
  • Partonic collectivity

• Flow of Charm and Beauty
  • Diffusion coefficients
Collectivity/Flow

Initial spatial anisotropy

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.

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

Elliptic Flow as a Probe
Sensitive to Initial Conditions, \textit{Glauber vs CGC}

Magnitude of final state momentum anisotropy depends on initial condition

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

Flow of Charged Hadrons

Viscous Properties of QGP
Hydro Works at RHIC

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
Flow of Identified Hadrons

Partonic Collectivity
Multi-strange $v_2$: Probe to Partonic Collectivity

$\phi$ freezes out at higher temperature than $\pi, k, p$

$<p_T>$ of $\phi$ is almost independent of centrality unlike protons

$\phi$ $v_2$ less affected by hadronic interaction compared to anti-proton

- Indicates possibly $\phi$ and $\Omega$ 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:**

\[ v_2^h(p_T) = n v_2^q \left( \frac{p_T}{n} \right) \]

- $s$-quark $v_2$ obtained from $\phi$ and $\Omega$ are consistent, coalescence works.

- $v_2$ of $s$-quarks is smaller than $v_2$ of light quarks at $p_T/n_q < 1 \text{ GeV/c}$

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:**

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

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

STAR: PRL 116 (2016) 6, 062301
Quark $v_2$

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

Scaling work with bare-parton mass.

In the absence of QGP phase this scaling should not hold.

Light quark mass = 4 MeV

s-quarks Mass = 140 MeV
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

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

\[ \langle x^2 \rangle = 2D_s t \quad \text{(Einstein’s theory)} \]

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

<table>
<thead>
<tr>
<th>Quark</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>u/d</td>
<td>2-4 MeV</td>
</tr>
<tr>
<td>c</td>
<td>1.3 GeV</td>
</tr>
<tr>
<td>b</td>
<td>4.1 GeV</td>
</tr>
</tbody>
</table>
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
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

- Sizeable flow of \( J/\psi \)

- Flow of \( \Upsilon \) 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 \( \Upsilon \) would only be expected at \( p_T > 10 \) GeV/c. (Due to its heavy mass)


ALICE: PRL123, 192301 (2019)
CMS: PLB 819, 136385 (2021)
Flow of Beauty-Hadron

Probing interaction of beauty quarks with the QGP medium

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)
• $D^0$ $v_2$ 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
Energy Dependence of Flow

Threshold Energy of QGP Formation
**Disappearance of QGP Signal?**

\[ \sqrt{s_{NN}} > 19.6 \text{ GeV} \]
- Baryon-meson separation at intermediate \( m_T - m_0 \)
  \( \rightarrow \) Parton recombination, QGP formation

\[ \sqrt{s_{NN}} < 19.6 \text{ GeV} \]
- No baryon-meson separation for the highest measured \( m_T - m_0 \)
  \( \rightarrow \) Possibly hadronic interaction dominated, absence of QGP
Disappearance of QGP Signal?

- $\phi$ 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

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
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. \(2\pi T D_s = 2 - 5\).

• 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