Anisotropic Flow in the Detection of QGP

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Overview

1. Introduction to quark-gluon plasma and high energy heavy ion collisions
   - What is quark-gluon plasma(QGP)?
   - Where can we find QGP?
   - Relativistic heavy-ion collisions
   - Some running experiments for detection of QGP
2. Flow Analysis Methodology
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4. Summary

What is quark-gluon plasma(QGP)?

Quantum Chromodynamics,QCD

- the theory of the strong interaction between quarks and gluons.
- non-abelian gauge theory, with symmetry group SU(3).
- force carrier are Gluons, like photons in QED.

Important corollaries of QCD

Color confinement

Increase the separation between two quarks within a hadron, ever-increasing amounts of energy are required.
The energy becomes great as to spontaneously produce a quark–antiquark pair instead of producing an isolated color charge.

Asymptotic freedom

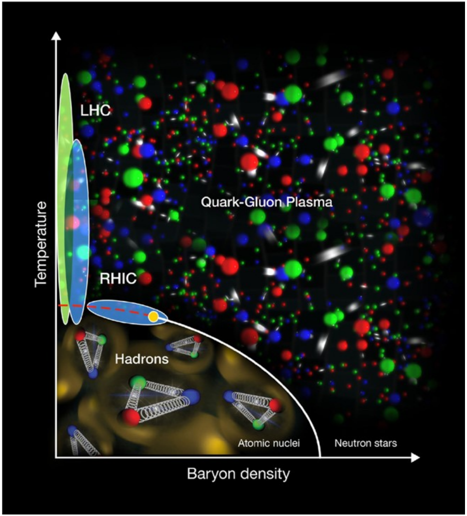
A steady reduction in the strength of interactions between quarks and gluons as the energy scale of those interactions increases (and the corresponding length scale decreases).

What is quark-gluon plasma(QGP)?

Quark–gluon plasma(QGP) is an interacting localized assembly of quarks and gluons at thermal (local kinetic) and (close to) chemical (abundance) equilibrium.

QCD phase diagram

The QGP phase diagram of substance calculated by Lattice QCD Theory.In the case of high chemical potential, the transition from hadron phase to QGP may occur. When the temperature increases to 170-190MeV, the smooth transition of hadron gas to QGP also occurs.



*Garth Huber.QCD phase diagram
http://dnp.phys.uregina.ca/content/photo/qcd-phase-diagram

Where can we find QGP?

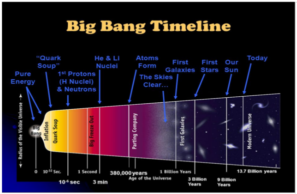
Asymptotic freedom and Color confinement suggest two methods for the creation of the quark-gluon plasma (QGP).

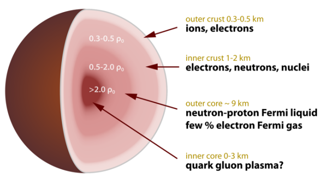
1. Recipe for QGP at high T.
2. Recipe for QGP at high ρ.

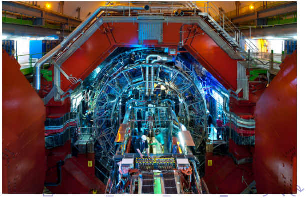
So there are three places to consider.

Extremely high temperature and high densit environment

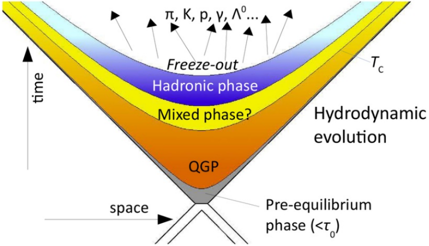
1. In the early Universe.
2. At the center of compact stars.
3. In the initial stage of colliding heavy ion at high energies.







Relativistic heavy-ion collisions



- The inelastic nucleon-nucleon collision happens through parton–parton (quark or gluon) scattering. QGP is formed within 1 fm/c after the collision.
- As the scatterings continue, the system expands in both longitudinal and transverse directions. The temperature decreases as the system expands. The photons and leptons radiated from the color medium leave the system without further (strong) interactions with QGP.

Relativistic heavy-ion collisions

- When the temperature drops below the phase-transition critical value, the system starts to convert back into the hadronic state, to form baryons and mesons.
- After hadronization, the system enters hadron gas phase. In the hadron gas phase, hadronic inelastic scatterings modify the particle species at the level of hadrons instead of partons.
- When further hadronic inelastic scattering ceases, hadron species are frozen. Particle elastic scatterings continue until their distances become too large as the system expands.
- Finally, elastic scattering ceases and particles stream freely and are recorded in detectors.

Some running experiments for detection of QGP

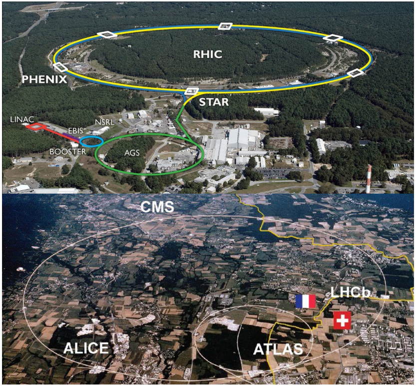


Figure: Aerial views of RHIC and LHC

*photographed by Thomas Ludlam August 15, 2016
*https://spectrum.ieee.org/computing/software/analyzing-the-lhc-magnet-quenches

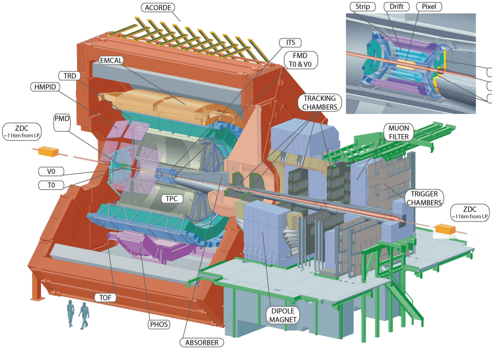


Figure: Cut-away view of ALICE showing the 18 detectors of the experiment

*The ALICE Collaboration et al., J. Inst., vol. 3, no. 08, pp. S08002–S08002, Aug. 2008.

Anisotropic Flow

***Motivation**

The azimuthal anisotropy of the transverse momentum distribution in non-central heavy-ion collisions, suggested as a signature of collective flow by Ollitrault, is argued to be **sensitive** to the properties of the QGP.

Use a Fourier expansion of the invariant triple differential distribution to characterize the patterns of anisotropic flow,

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos\left[n\left(\varphi - \Psi_n\right)\right]\right)$$

nth-order flow coefficients

$$v_n = \left\langle \cos\left[n\left(\varphi - \Psi_n\right)\right]\right\rangle$$

Event Plane Method

The symmetry plane is reconstructed from the azimuthal distribution of particles in a detector[16].

Event plane, is given for each harmonic n by

$$EP_n = \frac{\arctan 2\left(Q_{n,y}, Q_{n,x}\right)}{n}$$

where $Q_{n,y}$ and $Q_{n,x}$,are the x and y components of the **Q-vector** given by

$$Q_{n,x} = \sum_i w_i \cos\left(n\varphi_i\right)$$
$$Q_{n,y} = \sum_i w_i \sin\left(n\varphi_i\right)$$

where w_i is a weight which might depend on the centrality, transverse, pseudorapidity, particle species *et.al*.

The experimentally measured flow coefficient, v_n, is then given by,

$$\boxed{v_n^{obs}\left(p_T, \eta\right) = \left\langle \cos\left[n\left(\varphi - EP_n\right)\right]\right\rangle}$$

Scalar Product Method

This method is based on the scalar product of a unit vector for particle i denoted as $u_{n,i}(p_T;\eta)$ with the complex conjugate of the flow vector Q^* [17].

It follows that the differential flow of the particle of interest can be calculated by,

$$v_n\{\mathrm{SP}\} = \frac{\left\langle u^{\mathrm{A}}_{n,i}\left(p_T,\eta\right)\cdot\frac{Q^*_{n,B}}{M_B}\right\rangle}{\sqrt{\left(\frac{Q_{n,A}}{M_A}\cdot\frac{Q^*_{n,B}}{M_B}\right)}}$$

Q-Cumulant Method

The advantage using the Q-Cumulant method is that it provides a fast **(one loop over the data)** and exact **(no approximations and no interference between differential harmonics)** estimations of the correlators[18].

Standard Q-Cumulant method's steps

1. Calculate the reference flow,
2. Involves the correlation of the particle of interest with the reference ow established in the first step.

Reference Flow

Obtain the **single-event average** two-particle azimuthal correlations in the following way,

$$\langle 2 \rangle = \frac{|Q_n|^2 - M}{M(M-1)}$$

The **event average** two-particle azimuthal correlations is given by,

$$\langle\langle 2 \rangle\rangle = \frac{\sum_{\text{events}} \left(W_{\langle 2 \rangle}\right)_i \langle 2 \rangle_i}{\sum_{\text{events}} \left(W_{(2)}\right)_i}$$

$$W_{(2)} \equiv M(M-1)$$

The two-particle cumulant is given by,

$$c_n\{2\} = \langle\langle 2 \rangle\rangle$$

The two-particle **reference flow** is obtained by,

$$\boxed{v_n\{2\} = \sqrt{c_n\{2\}}}$$

Differential Flow

Proceed to the calculation of the differential flow of the Particles Of Interests (POIs).
Define the p_n and q_n vectors calculated via,

$$p_n = \sum_{i=1}^{m_p} e^{in\phi_i}$$
$$q_n = \sum_{i=1}^{m_q} e^{in\phi_i}$$

$$\langle 2' \rangle = \frac{p_n Q_n^* - m_q}{m_p M - m_q}$$

$$\langle\langle 2' \rangle\rangle = \frac{\sum_{\text{events}} \left(W_{\langle 2' \rangle}\right)_i \langle 2' \rangle_i}{\sum_{\text{events}} \left(W_{\langle 2' \rangle}\right)_i} \quad W_{\langle 2' \rangle} \equiv m_p M - m_q$$

$$d_n\{2\} = \langle\langle 2' \rangle\rangle$$

$$\boxed{v_n\{2\}(p_T, \eta) = \frac{d_n\{2\}}{\sqrt{c_n\{2\}}}}$$

Q-Cumulant Method with Gaps

Remove those two-particle correlation pair contributed by non-flow from the total Q-vector.
Divide whole data sample into two non-overlapping sub-groups (say I and II) based on η of each particle, with η gap ($\Delta\eta$) between them (0.3 may vary according to different analysis)[19].

Flow Type	**Sub-Group I**	**Sub-Group II**
Reference	$1 < \eta < -0.3$	$0.3 < \eta < 1$
1st Time Differential	$1 < \eta < -0.3$(POI)	$0.3 < \eta < 1$(RFP)
2nd Time Differential	$1 < \eta < -0.3$(RFP)	$0.3 < \eta < 1$(POI)

Table: The rule of dividing sub-group

$$\langle 2 \rangle or \langle 2' \rangle = \frac{Q_1 Q_2^*}{M_1 M_2}$$

Anisotropic flow in experiments I

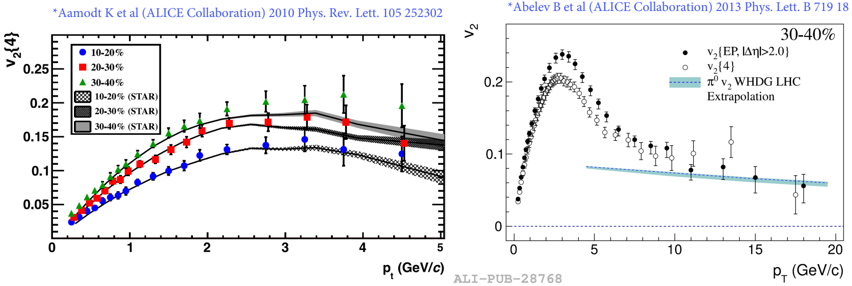
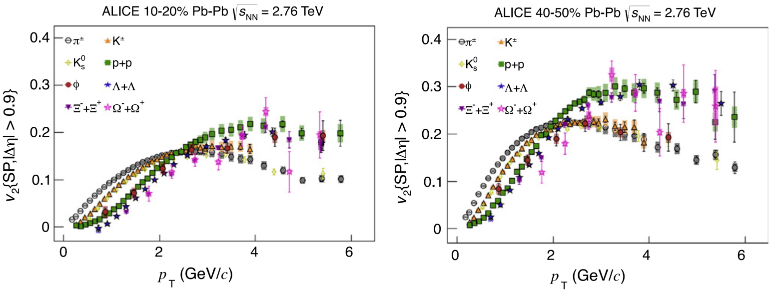


Figure: **Left:** A comparison between p_T-differential elliptic flow of charged particles as a function of centrality at RHIC and LHC energies. **Right:** p_T-differential elliptic flow of charged particles compared to jet energy loss model calculations.

Anisotropic flow in experiments II



*Abelev B B et al (ALICE Collaboration) 2012 arXiv:1405.4632 [nucl-ex]

Figure: p_T-differential elliptic flow of identified particles for the 10–20% (left) and 40–50% (right) centrality class.

Summary

- QCD is the theory of the strong interaction between quarks and gluons, and there are two important corollaries of QCD —— Color confinement and Asymptotic freedom.
- QGP is an interacting localized assembly ofquarks and gluons at thermal(local kinetic) and (close to) chemical (abundance) equilibrium, QCD phase diagram calculated by Lattice QCD Theory tell us to find QGP high T or high ρ.
- The physical process of Relativistic heavy ion collisions and Some running experiments for detection of QGP.

Summary

- Anisotropic Flow is sensitive to the properties of the QGP, and there are three flow calculation methods all with advantages and disadvantages——Event Plane Method, Scalar Product Method and Q-Cumulant Method.
- Some Anisotropic flow measurement results of ALICE and STAR experiments.

The End. Thank you!

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