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Property of Quark-Gluon Plasma

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Abstract. During the nascent stages of the universe's evolution, matter existed in the form of quark-gluon plasma (QGP), characterized by its presence under conditions of exceedingly high temperature and pressure. Presently, the ability to replicate the QGP state has been attained through relativistic heavy-ion collision experiments. Key indicators of QGP generation encompass the initial collision configuration, which exerts a discernible influence on the subsequent momentum and scattering angles of emitted hadrons. This study endeavors to recapitulate the findings of the CMS XeXe collision experiment by meticulously scrutinizing data stemming from PbPb collisions at a center-of-mass energy of $\sqrt{s} = 5.02$ TeV. Specifically, our focus centers on an exhaustive analysis of the transverse momentum (p_t), azimuthal angle (ϕ), and pseudorapidity (η) of scattered particles. Through this comprehensive approach, we aim to corroborate the implications drawn from the CMS XeXe experiment, thereby contributing to a deeper understanding of the mechanisms underlying quark-gluon plasma creation and behavior.

Keywords: Quark-gluon plasma, Relativistic heavy-ion collisions, Anisotropic flow, Elliptic flow, Triangular flow

1. Introduction

During the early stages of the universe, there was a brief existence of quark-gluon plasma. In the beginning, there was only energy - pure, dense, extremely hot energy. As the universe rapidly expanded and cooled in the first fractions of a second after the Big Bang, this energy began to coalesce into fundamental particles like quarks and gluons (Figure 1).

The conditions were intense, with temperatures reaching a blazing temperature of 150 MeV (1 MeV is equivalent to about 1.16×10^10 K). At these extreme temperatures, quarks and gluons could not bind together to form larger particles like protons and neutrons. Instead, they existed as a hot, dense soup called quark-gluon plasma. This exotic state of matter filled the entire universe in these early moments.Within the first microsecond after the Big Bang, the universe had expanded and cooled enough for the quarks to start coming together into composite particles like protons and neutrons. The primordial quark-gluon plasma condensed and faded away as matter took on the more familiar forms we see today.

The existence of Quark-Gluon Plasma in the early universe is critical for our understanding of physics because it represents a unique state of matter that is impossible to reproduce on Earth. By studying this exotic plasma that filled the universe moments after the Big Bang, physicists gain insight into the fundamental nature of matter and the interactions between subatomic particles under extremes of heat and density. Theorists predict that quark-gluon plasma behaves almost as a perfect liquid with very low

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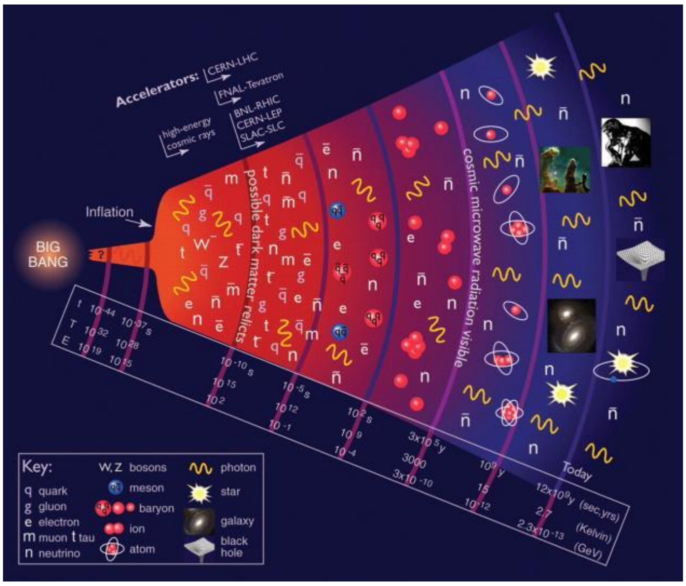

Figure 1. A schematic of the evolution of the universe

viscosity. Analyzing its nearly frictionless fluid properties can reveal new physics principles that are obscured in the matter we observe today (Figure 2).

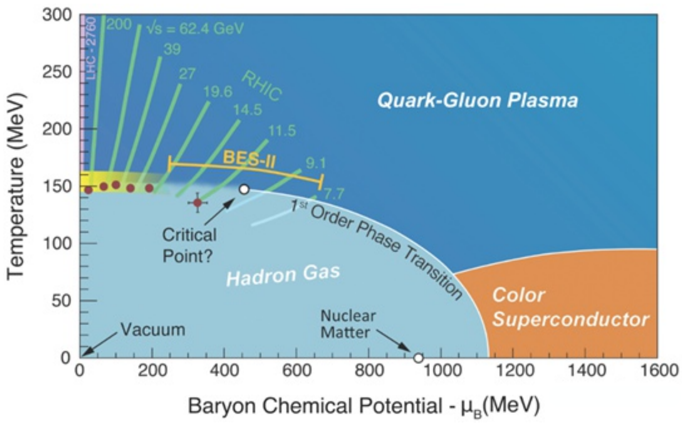

Figure 2. Early phase of universe

Modern particle accelerators like RHIC and LHC enable the creation of quark-gluon plasma, an exotic state of matter that provides insights into the conditions of the early universe. By colliding heavy ions like plumbum and gold at close to the speed of light, tremendous energy densities are achieved in the impact. This melts protons and neutrons into their constituent quarks and gluons (Figure 3).

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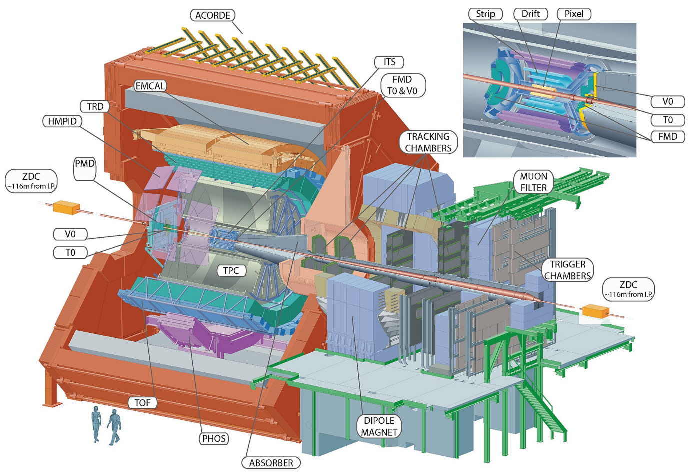

Figure 3. LHC ALICE detector

When two nuclei collide at relativistic speeds (Pb collision are imposed approximate 200 GeV), they are Lorentz contracted into flat shapes along the beam direction. At sufficiently high energies, the nuclei can fully penetrate through each other, concentrating immense energy density in the overlap region. The extreme collision energy melts the nucleons into their constituent quarks and gluons due to the high temperatures momentarily reached. Usually confined within hadrons, the quarks and gluons become deconfined and able to move freely in this energetic environment, forming a unique state of matter called quark-gluon plasma. This plasma behaves almost like a perfect fluid with low viscosity due to the independent quark interactions.

Within yoctoseconds after the collision, the incredibly hot and dense quark-gluon plasma rapidly expands and cools. The quarks and gluons recombine as the plasma cools, transitioning back into familiar hadrons like protons, neutrons and mesons. These hadrons stream outward in a radial flow from the collision point, eventually reaching the detectors surrounding the collision to provide insights into the plasma's properties and the state of matter in the early universe (Figure 4).

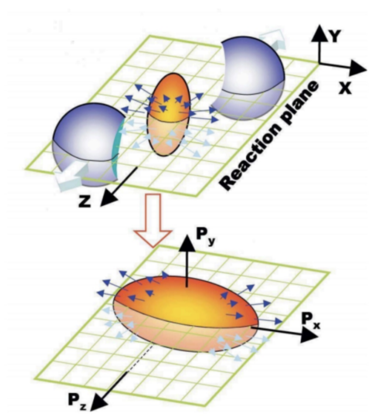

Figure 4. Schematic illustration of a lead nucleus collision

2. Using Galuber model to determine the property

In the quark-gluon plasma (QGP), due to the extremely high energy density, the calculation of QGP fluid requires the use of the equations of relativistic fluid dynamics [1-3]:

$$\partial_\mu T^{\mu v}(x) = 0$$
$$\partial_\mu j^\mu(x) = 0$$

Where $T^{\mu v}(x)$ and $j^\mu(x)$ are the energy-momentum tensor and the flow density, respectively:

$$T^{\mu v}(x) = (e(x) + p(x))u^\mu(x)u^v(x) - g^{\mu v}p(x)$$

$$j^\mu(x) = n(x)u^\mu(x)$$

Where $e(x)$ is the energy density, $p(x)$ is the pressure, and $n(x)$ is the conservation density at

$$x^\mu = (t, x, y, z).$$

Relativistic fluid dynamics equations are required for theoretical computations of QGP properties. However, in practice, the calculation of QGP states generated through data analysis of relativistic heavy-ion collisions needs to be approached from other perspectives. In the context of the NEXSPHERIO hydrodynamic model, it has been demonstrated that the introduction of non-smooth initial conditions gives rise to the formation of ridge and broad away-side structures in two-particle correlations. Sorensen has proposed that these structures may be the result of fluctuations in the initial collision geometry, leading to higher-order Fourier components in the azimuthal correlation function due to collective effects. Mishra and colleagues have put forth an analysis of these higher-order Fourier components in the azimuthal particle distributions, including the odd terms, as a means to investigate superhorizon fluctuations during the thermalization stage. The ridge and broad structures on the away-side can be effectively characterized by considering the first three coefficients of a Fourier expansion applied to the azimuthal correlation function [4-6].

$$\frac{\mathrm{d}N}{\mathrm{d}\Delta\phi} = \frac{N}{2\pi}(1 + \sum_n 2V_n cos(n\Delta\phi))$$

In this equation, the first component, denoted as $V_{1\Delta}$, is attributed to momentum conservation and directed flow. The second component, represented as $V_{2\Delta}$, is primarily influenced by contributions from elliptic flow. Studies conducted within a multi-phase transport model (AMPT) indicate that not only the elliptic flow term, $V_{2\Delta}$, but also a significant portion of the correlations measured by the $V_{3\Delta}$ term, are a consequence of the hydrodynamic expansion of the medium. What's more, the participant eccentricity [7] is given as

$$\varepsilon_2 = \frac{\sqrt{(\sigma_y^2 \sigma_x^2)^2 + 4\sigma_{xy}^2}}{\sigma_y^2 + \sigma_x^2}$$

In this context, σ_x, σ_y, and σ_{xy} represent the event-specific variances and covariances of the participant nucleon distributions in the transverse directions of x and y.in the coordinate system of center of mass of the nucleons, we can gain:

$$\varepsilon_2 = \frac{\sqrt{\langle r^2 cos(2\phi)\rangle^2 + \langle r^2 sin(2\phi)\rangle^2}}{\langle r^2 \rangle}$$

$$\psi_2 = \frac{arctan2(\langle r^2 \sin(2\phi_{part})\rangle, \langle r^2 \cos(2\phi^{part})\rangle) + \pi}{2}$$

v_2 can be refer to the second Fourier coefficient of particle distribution with respect to ψ_2

$$v_2 = \langle cos(2(\varphi - \psi_2))\rangle$$

under the same definition we can obtain:

$$\varepsilon_3 \equiv \frac{\sqrt{\langle r^2 cos(3\phi)\rangle^2 + \langle r^2 sin(3\phi)\rangle^2}}{\langle r^2\rangle}$$

$$\psi_3 = \frac{arctan2(\langle r^2 \sin(3\phi_{part})\rangle, \langle r^2 \cos(3\phi^{part})\rangle) + \pi}{3}$$

$$v_3 = \langle cos(3(\varphi - \psi_3))\rangle$$

With these parameters, we can characterize the influence o f t he fl uid pr operties of el liptic and triangular flows in the QGP phase of relativistic heavy-ion collisions on the subsequent scattering angles of baryons formed through re-hadronization of quarks. In this paper, we, in turn, analyze the fluid properties of the QGP phase from the azimuthal features of particles produced in $20,000$ detected collisions.

3. Investigation of anisotropic flow

By using two-particle correlation function, the anisotropic flow can be characterized by fourier expansion [8]:

$$\frac{dN^{pairs}}{d\Delta\phi} \propto (1 + \sum_{i=1}^{\infty} 2v_n^2 \cos(n\Delta\phi)) \tag{1}$$

where $\frac{dN^{pairs}}{d\phi}$ is the azimuthal particle density and ϕ is the particle azimuthal angle with respect to reference angle and v_n is used to characterized the magnitude of azimuthal anisotropy.

v_2 refers to elliptical flow and v_3 refers to triangular flow.

Now how do we figure out the value of v_2 and v_3 ?

We have the data of final state of particles (p_t, η, ϕ) from Alice, and we first plot a histogram of $\Delta\phi$ and $\Delta\eta$ which can be seen in Figure (Figure 5):

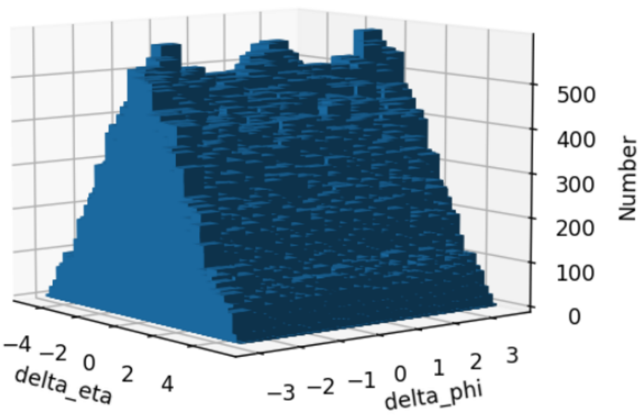

Figure 5. histogram of $\Delta\phi$ and $\Delta\eta$

As the particles in the center of the histogram is too large, thereby we only care about the particles that $|\Delta\eta| > 1$ and $|\Delta\phi| > 1$. We separate p_t into various intervals and find the v_2 and v_3 of each intervals. (Figure 6)

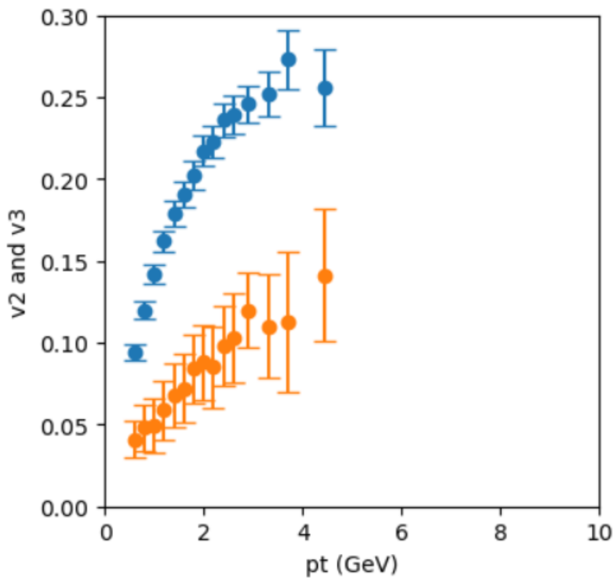

Figure 6. v_2 and v_3 against p_t

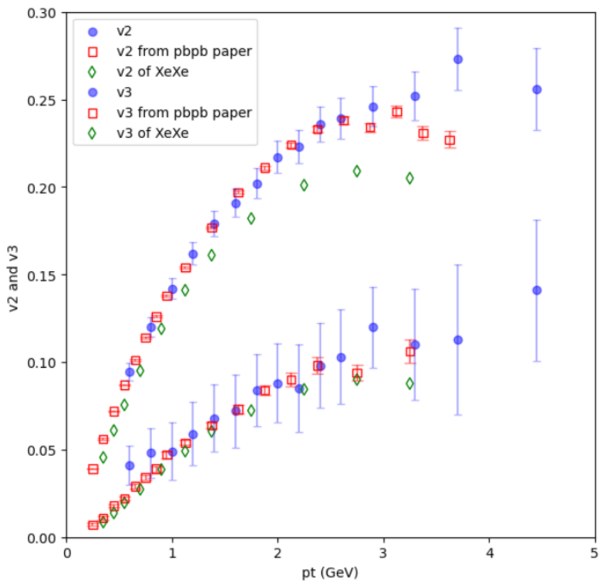

Figure 7. results comparing with other's results

By comparing with other papers' result (Figure 7, [9, 10]), From the graphical representation presented, it testify that within the domain of low transverse momentum ($p_t \leq 3$ GeV), the elliptic flow parameter denoted as v_2, as well as the delta flow parameter indicated as v_3, exhibit a progressively ascending pattern concerning the Pt variable for both Xe-Xe and Pb-Pb collisions. However, once Pt surpasses the 3 GeV threshold, v_2 and v_3 for both Xe-Xe and Pb-Pb begin to diminish in correspondence to the increasing Pt values. It is remarkable that v_2 consistently exceeds v_3 in magnitude for both Pb-Pb and Xe-Xe collisions. Furthermore, under various collisional centripetal and transverse momentum conditions, it becomes apparent that the values of the elliptic flow parameter v_2 decline as the approximate viscosity coefficient ($\frac{\eta}{s}$) escalates. Comparing our experimental data with those from other papers, our results exhibit a similarity with another set of Xe-Xe collision curves found in relevant literature. However, they are notably higher than the experimental results for the Pb-Pb group. This disparity may be attributed to the differing atomic masses (momenta) of the nuclei involved.

4. Conclusion

In this paper, we engage in a comprehensive discussion pertaining to the anisotropic flow and the low viscosity characteristics displayed by the quark-gluon plasma (QGP) when it behaves as an ideal fluid.The emergence of anisotropic flow within the QGP stems from the transformation of the initial spatial anisotropy in the interaction region into anisotropies present in the momentum distribution of the final-state particles following the collision of atomic nuclei.These anisotropic flows are categorized into three distinct types: direct, elliptic, and triangular flows.The magnitudes of these three anisotropic flows are quantified through the coefficients obtained by performing Fourier decomposition on the azimuthal distribution function of the final-state particles.Specifically, the elliptic and triangular flow parameters are closely linked to the descriptors of initial spatial anisotropy, namely, centrality ϵ_2 and triangularity ϵ_3, which are utilized to characterize the anisotropy present in the initial spatial configuration. The state of the end-state particles is elucidated with respect to their transverse momentum p_t, azimuthal angle ϕ, and pseudorapidity η, which are established within the framework of a laboratory coordinate system.The particle's polar coordinates, denoted as ϕ_{part} and r, are employed to compute the event plane angle θ.This angle, in conjunction with the azimuthal angle ϕ, is subsequently employed to calculate both the elliptic flow parameter denoted as v_2 and the triangular flow parameter denoted as v_3.

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