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Exploring formation of Quark-Gluon Plasma through two-particle correlations functions in A+A and p+p data

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Abstract:

This paper is the result of team's hard work, which delves into the correlation functions in proton-proton and PbPb(Lead-Lead) collisions, scrutinizing their relevance in the formation of quark-gluon plasma. This project first simulated these high-energy collisions and generated a comprehensive dataset of proton-proton and PbPb(Proton-Proton) interactions. The entire analysis is designed around the task of calculating azimuthal and pseudorapidity correlation functions, and wish to compare the differences and similarities between the two collision types. Also delved into these correlation functions in proton-proton collisions as potential evidence for QGP(Quark-gluon plasma), a type of matter typically found in heavy metal collisions such as Pb-Pb. The results reveal unique patterns lurking in the correlation functions that suggest that QGPs may form even in smaller collision systems. Also Quark-Gluon Plasma (QGP) is a state where quarks and gluons move freely at extremely high energy densities. The two-particle correlation function helps identify QGP by measuring how particles are correlated after a collision. Specific patterns in these correlations, like a "ridge" structure, indicate the collective behavior of particles, signaling the formation of QGP. These findings are expected to shed more light on the intricate dynamics in particle collisions and the specific conditions that lead to the formation of QGPs.

Keywords: PP collision; PbPb collision; quark-gluon plasma; correlation function; QGP Formation.

1. Introduction

Previous researches examined relationships in two-particle azimuthal angle and pseudo rapidity of hadron-hadron collisions, including Pb-Pb collisions and Au-Au collisions (Citation 1). Researchers studying events of high energy Pb-Pb and Au-Au collisions scrutinized the data of azimuthal angle, denoted as phi, and pseudo rapidity, denoted as eta, respectively of 2 million events. Because of the major elliptical and minor triangle shape of the QGP, the resulting graph of delta phi is a cosine curve, while graph of delta eta is a triangle. After mathematically divide the data for each event from 10 random background events, scientists obtained two slightly curved lines around y=1, the vertex of which indicating the existence of a peak at delta eta=0 and delta phi=0. By analyzing the experimental statistics and applying technologies of 3D modeling, they uncovered the fact that the graph of delta eta versus delta phi has a ridge and a peak. In addition, in former studies, researches observed the formation of Quark-Gluon Plasma in heavy ion collisions and high energy proton-proton collisions.[10]

Despite the fact that previous studies have covered various aspects, few mentioned the existence of QGP in terms of low energy p-p collisions. Hence, it is intriguing to investigate the two-particle correlation between protons at low initial energy.

This paper includes examination of two particle correlation of azimuthal angle and pseudorapidity in Pb-Pb and p-p collision respectively; additionally, it discusses the possibility of generation of Quark-Gluon Plasma within lead-lead and proton-proton collisions of different initial energy. Results obtained via analysis of graphs of 100,000 groups of data of proton-proton collision with initial energy of 13 TeV, 2 million events of lead-lead collision at center of mass energy of 2.76 TeV, as well as 50,000 series of proton-proton collision with initial energy of 200 GeV simulated by Pythia stipulates a ridge-like structure together with a peak at Δη=0 and Δφ=0. When analyzing the statistics of Pb-Pb collisions, the team utilized signal-background correspondence, through which researchers determined the existence and the approximate location of the “ridge” structure. With the existing events, the research team managed to sketch the graph of Δη versus Δφ as its correlation function with Python programming and offer a possible explanation to the phenomenon. The results indicated a strong correlation of QGP formation with high-energy Pb-Pb collisions and p-p collisions while low possibility of QGP formation in low energy proton-proton collision. Additionally, the 3-dimensional graph vindicated the existence of the ridge structure and the peak together with the basis of their formation.

Details of event readout and analysis of the correlation function of Pb-Pb collision are described in Section 2; results of Pythia-simulated p-p collision events and its two-particle correlation function is given in Section 3; a brief description of hot Quark-Gluon Plasma and the preconditions of its generation are listed in Section 4; a summary is presented in Section 5.

2. Methodology

2.1 PbPb collision correlation function

2.1.1 Two-Particle Correlation Function

Particle correlations are very useful and commonly used for the study of particle production and dynamics of relativistic nuclear collisions. Two-particle correlations are often presented in the *Δη* and *ΔΦ* referring to the pseudorapidity difference and azimuth difference between the two hadrons in each pair, respectively. The two-particle correlation function *R(Δη,Δφ)* is defined as the ratio of *S(Δη,Δφ)* over the B*(Δη,Δφ)*.As showed in formula 2 and 3.

The pT-inclusive charged two-particle correlation as a function of Δη and Δφ is defined as follows:

$$R(\Delta\eta,\Delta\phi) = (N-1)\left(\frac{S_N(\Delta\eta,\Delta\phi)}{B_N(\Delta\eta,\Delta\phi)} - 1\right) \quad (1)$$

, where *SN* and *BN* are the signal and random background distributions, for the signal function S(Δη,Δφ) we determined by calculate all particle pairs with each event, *N(N − 1)* is the weighting factor, then averaging over all the events. It is defined is:

$$S_N(\Delta\eta,\Delta\varphi) = \frac{1}{N(N-1)}\frac{d^2N^{\text{signal}}}{d\Delta\eta d\Delta\varphi} \quad (2)$$

The random background distributions *B(Δη,Δφ)* represents the distribution of unrelated particle pairs. The background in the context of particle collision analysis is typically calculated using randomly sampled pairs of particles from different events or through some permutation method within the same event. The idea is to create a background distribution that represents the particle correlations expected from random combinations, which can then be compared to the actual signal from the events being studied. It is defined as below.

$$B_N(\Delta\eta,\Delta\varphi) = \frac{1}{N^2}\frac{d^2N^{\text{mixed}}}{d\Delta\eta d\Delta\varphi} \quad (3)$$

As showed in correlation function, the ratio of *S(Δη, Δφ)* to *B(Δη, Δφ)* was first calculated in each bin. The reason of dividing the background is to correct for detector effects. And the final two-particle correlation function *R(Δη, Δφ)* is after weighted by the track multiplicity and averaged over all the bins.[1][2]

2.1.2 Correlation function in $\sqrt{s_{NN}}$ = 2.76TeV

In the data obtained from the CMS Large Hadron Collider, ϕ and η can be derived by calculating P_x, P_y,andP_z. ϕ represents the angle between the particle’s momentum in the transverse plane (the plane perpendicular to the beam axis) and the positive xxx-axis. It is measured in radians and typically ranges from −π to π. Defined as follow,

$$\varphi = atan2(p_y, p_x) \quad (4)$$

η is a measure of the angle of the particle’s trajectory relative to the beam axis (the z-axis). It is particularly useful in high-energy physics because it remains invariant under Lorentz boosts along the beam axis, making it a natural coordinate in particle physics experiments. Defined as follow,

$$\eta = -ln\left(tan\left(\frac{\theta}{2}\right)\right) \quad (5)$$

Where θ is the polar angle, defined as follow,

$$\theta = atan2\left(\sqrt{p_x^2 + p_y^2}, p_z\right) \quad (6)$$

Through computer programs, the visualization of Δϕ and Δη can be achieved.

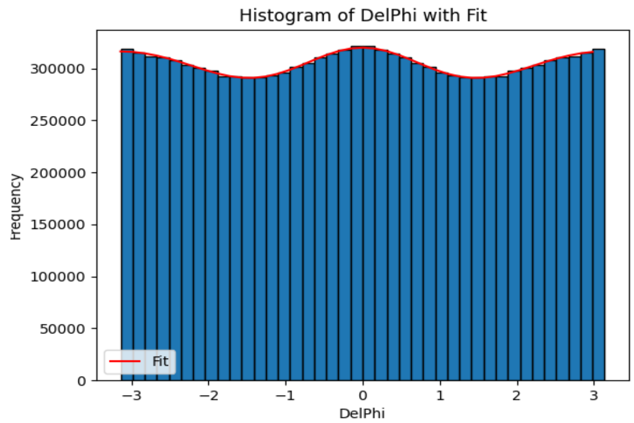

Figure1: the histogram of 1k events Δϕ data under $\sqrt{s_{NN}}$ = 2.76TeV, by 40 bins, the fit function of this Δϕ is defined as below

$$f(\Delta\varphi) = n_0\left(1 + 2v_2^2 cos(2\Delta\varphi) + 2v_3^2 cos(3\Delta\varphi)\right) \quad (7)$$

A shape histogram helps to generate a fit that can describe the physical parameters underlying it. Fitting a theoretical function to the histogram data allows us to simultaneously compare models and extract flow coefficients that best describe experimental spectra. The *n0* is the normalisation factor, it is a scaling constant to convert the fitting function so that its integral matches total counts in your histogram. And basically, it shifts the fit curve up and down to correct against the data so that its area is equivalent with respect to below both histogram. Flow Coefficients v2 and v3 are two objects correlated with the anisotropic flow, which can be measured in heavy-ion collision experiments. They explain how the anisotropy of particle distribution is measured in various angular directions. v2 is a second-order flow coefficient and relates to the elliptic flow which means the anisotropy in particle distributions for particles produced at different azimuthal angles w.r.t. to collision plane. v3 is the third-order flow coefficient. It characterizes action on triangular (Δη, Δφ) distribution of particles where all arms are shifted by two units to reflect a symmetric offset bundle shape in the collision plane.

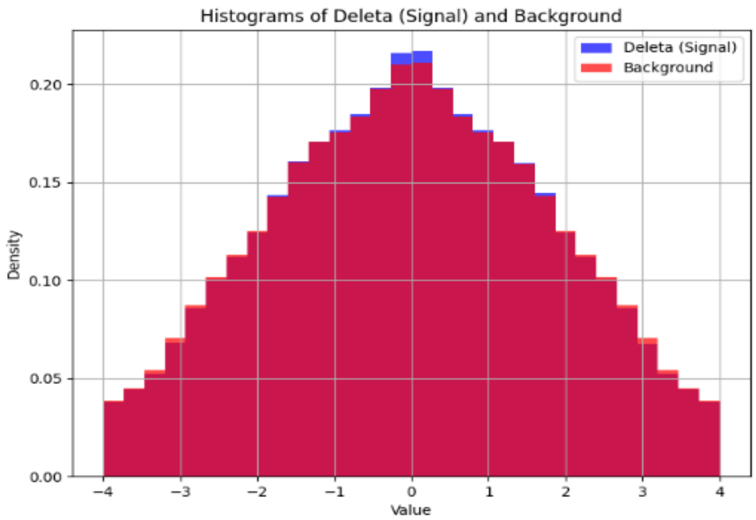

Figure 2: two histograms of Δϕ with color blue and red represents the signal and background value of Δϕ respectively.

Signal histogram of the distribution in Δη = η2 − η1 for particle pairs accepted to belong to a common event. Such a histogram is likely to show features that are characteristic of the real, underlying physics processes in proton-proton collisions citation Particularly, we seek out peaks and patterns that would imply correlations between particles produced in such high-energy interactions.

The background histogram shows the distribution of Δη values from particle pairs obtained by sampling particles uniformly over different events. This method is useful for accounting correlations that are unrelated to the collision dynamics but might be produced randomly. As we know easliest, the signal measurement should be compared to background 'measurement' to see if there are real correlation.

When both histograms are plotted together, we can access and study the ratio of signal to background. This comparison allows us to point out which are the most extreme (that is, those that deviate dramatically from the background) correlations and are hence distinctive particle-particle interactions. The signal distribution of Δη is usually characterised by a pronounced peak at 0 (where particle pairs are produced in some correlated fashion, and possibly other structures reflecting back-to-back production).[3]

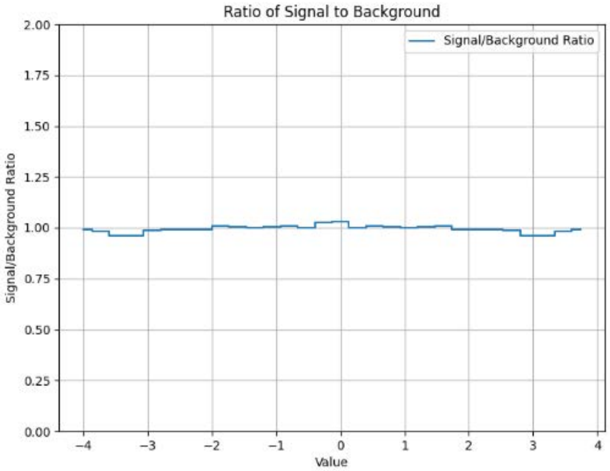

Figure 3: the ratio after signal divide background.

The ratio plot is obtained by dividing the bin values of the signal histogram by the corresponding bin values of the background histogram. This results in the signal-to-background (S/B) ratio for each Δη bin.

This ratio highlights where the signal significantly deviates from the background. A ratio greater than 1 indicates that the signal exceeds the background, suggesting genuine particle correlations, while a ratio around 1 suggests that the observed correlations are similar to those expected from random particle pairings.

The ratio plot typically shows a pronounced peak at Δη ≈ 0. This peak indicates that there are significantly more particle pairs with small Δη in the signal than would be expected by random chance, pointing to genuine correlations resulting from the collision.

A ridge structure around Δη ≈ π signifies correlations at larger pseudorapidity differences, often associated with back-to-back particle production.[4]

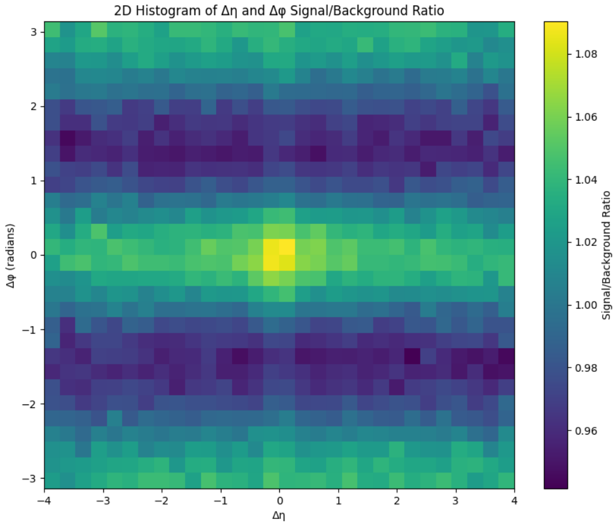

Figure 4: the 2D histogram plot of Δη and Δφ for PbPb Collisions

From that graph we can speak of a central peak at (Δη, Δφ) = (0, 0). That peak shows a high density of particle pairs and with the smallest possible distance in both Δη (pseudorapidity) and Δφ, azimuthal angle. Rather, it reveals the existence of strong correlations between particles originating in close proximity within a phase space region from e.g. initial collision dynamics.

This peak, observed in heavy-ion collisions, is an indication of the co-operative behavior (radial flow) due to radial pressure gradients in quark-gluon plasma(QGP), responding which particles are emitted with correlation signal. Resonance decays and partonic jet fragmentation account for a high density of particles also near (0, 0) Both Δη and Δφ fall off in correlation strength as we move away from the central peak. The exponential decay reflects the decreasing (four) probability of finding two particles correlated when they are further apart, corresponding to a finite range associated with such pure short-ranged correlations.

This peak is due to the presence of particles arising through manly decay of resonances (ρ, ω and φ mesons) that all go into this bin essentially as they are central firing productions with no relative angles nor rapidity difference.

The pronounced ridge structure at Δφ ≈ π and beyond in a range of Δη corresponds to particle production back-to-back. This effect is frequently attributed to jet production, which involves the fragmentation of a high-energy parton into many hadrons moving in opposite directions. Collective flow effects could also influence the ridge structure, particularly elliptic flow (v2). For non-central collisions the anisotropic pressure gradients result in a deformation of the particle emission pattern, with elliptic symmetry that gives rise to ridges in Δφ.

During high-energy collisions, such as those occurring in particle accelerators, quarks and gluons are emitted. Because these particles carry a color charge, this force is confined as described by quantum chromodynamics. This is known as color confinement since quarks and gluons can't exist independently. This process is known as hadronization, it changes them into color-neutral hadrons (quark particles composed of quarks held together by the strong force). So you get a jet of hadrons; this is the output from that process.

In the case of heavy-ion collisions, this ridge too can arise from jet quenching, when partons lose energy in traversing the QGP forest. Energy loss affects jet structures and may cushion direct-row correlations where particles wind out in the azimuth due to quenching. Among these peaks, it is able to find the so-called central peak accompanied by a tall ridge as new implications of the jet modified structures in QGP. These changes are essential for interpreting the energy loss mechanisms and features of QGP such as opaqueness and viscosity.[5][6][7]

2.2 PP collision correlation function

2.2.1 Two Angle Correlation Function of Proton-Proton Collisions

In PbPb collisions, it is abundantly clear that a quark gluon plasma will be generated at energies of 2.76 TeV. However, there are distinguishable differences between the outputs of PbPb collisions and pp collisions, especially for low energy pp collisions. For one, jet quenching is a much mor prevalent phenomenon in PbPb collisions, as they produce pronounced quark gluon plasmas able to significantly dampen jets (Source 1). It is well established that at high energies, pp collisions generate quark gluon plasmas. What is less known is what happens at lower energies, such as 500GeV and below.

For reference, our group used PYTHIA 8.3 to generate an image for pp collisions at 13 TeV and compared it to the results of pp collisions at lower energies, namely 200GeV. For the parameters to our correlation function, our group chose high multiplicity events (n>50) with a minimum $\Delta\eta$ of 1.1 radians, and a minimum transverse momentum p_T of 1GeV/c:

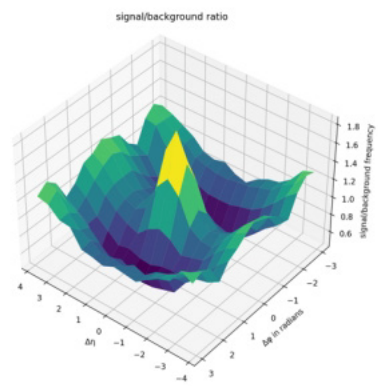

Figure 5: the Angle Correlation Function for energies of 200Gev

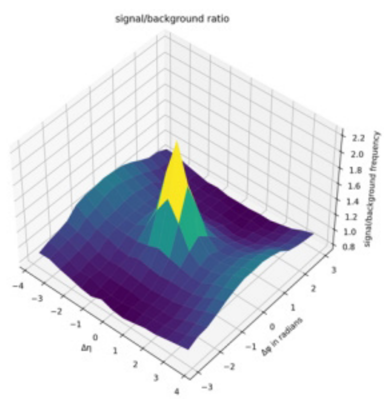

Figure 6: the Angle Correlation Function for energies of 13TeV

For the high energy PYTHIA simulation, a very visible peak at $(\Delta\eta, \Delta\varphi) = (0, 0)$ is present. However, there is the lack of a second peak at $\Delta\varphi = \pi$, indicating that a quark gluon plasma was possibly able to form and interfere with the subleading jet. Given that high energy pp collisions are known for creating quark gluon plasmas, this is a possible explanation.

On the contrary, although the angle correlation function for low energy collisions also has a peak at $(\Delta\eta, \Delta\varphi) = (0, 0)$, there was also a regional peak present at $\Delta\varphi = \pi$. This indicates that less interference blocked out the subleading jet, suggesting that either the generated quark gluon plasma was smaller in volume or was not created. However, it is noteworthy that the regional peak of the subleading jet was not insignificantly smaller than the peak at $(\Delta\eta, \Delta\varphi) = (0, 0)$, so the explanation that a less voluminous quark gluon plasma was created seems more plausible.

2.3 Quark Gluon Plasma Overview

Quark-gluon plasma is formed in heavy-ion collisions. Usually, in a quark-antiquark pair, Notably, the Quantum

Chromodynamic binding force of the quarkpair is proportional to its distance. Gluons are particles which moderate the force between the quark and antiquark. The linear potential, or constant force at zero temperature, maintains the position of the quarks inside dimensions of the hadron. At the high nuclear densities the hadrons are at in a particle collision, separation of the quarks is possible. During this situation, the contents of the hadrons are pressed together and the quarks cannot find their respective pairs. Recall that the QCD binding force is proportional to the distance between quarks, and in this situation, the distance is small. Therefore, the force becomes small which allows for free movement. [8]

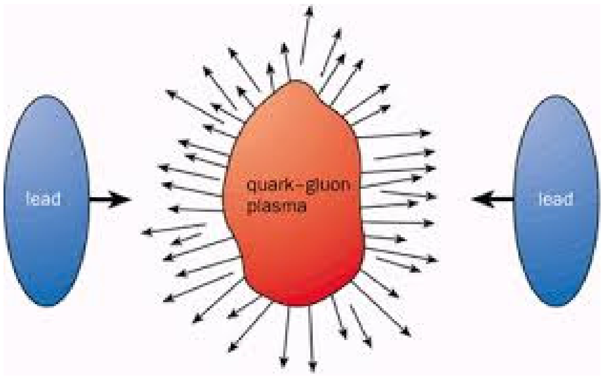

Figure 7: Simple diagram of QGP formation

3. Results

3.1 Relation to Pb+Pb collisions

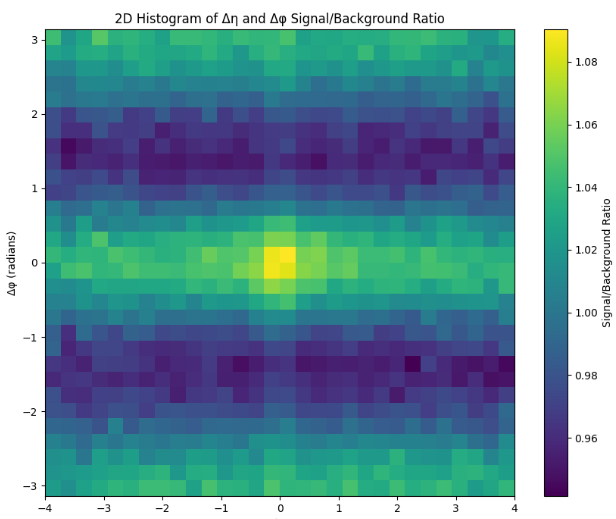

Figure 8: The 2D graph of azimuthal angle and pseudorapidity taken from a 2.76 TeV PbPb collision

Data taken from Pb+Pb collisions can be utilized to prove properties of Quark-Gluon Plasma. As mentioned in Section 2.2, the graph demonstrates a peak at approximately $(\Delta\eta, \Delta\phi) = (0, 0)$ which is a near-side ridge. And, as mentioned in the said section, this demonstrates a strong correlation. It was said that the strong correlation is an outcome of initial collision dynamics. However, the strong correlation and the existence of the near-side peak could also reveal the liquid nature of QGP. The reasons are:

1. The existence of the ridge demonstrates a strong collective behavior in the particles of the QGP. This is consistent with a liquid-like medium where there is strong interaction between particles. The medium will modify jet structures due to high amounts of density and interaction, which verifies that it is indeed similar to liquid.
2. It contrasts with the properties of gas. In a gas-like medium, particles are not as likely to show strong correlations as the particles have weaker interactions and not as much collective behavior.

3.2 Relation to p+p collisions

Researchers have conventionally believed that p+p collisions have been used as a base to distinguish Pb+Pb collisions. However, some high energy TeV p+p collisions at the LHC have shown characteristics similar to heavy nuclei collisions that produce QGP.

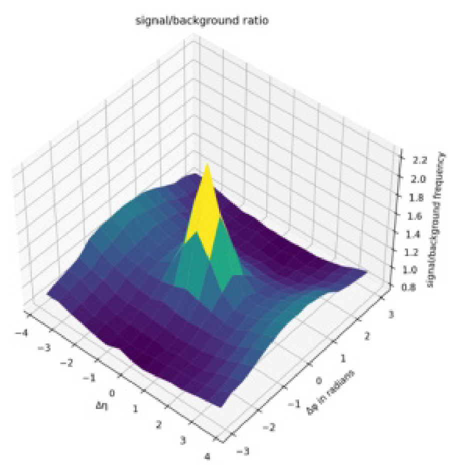

Figure 9: a graph of angular correlation for p+p collisions at 13 TeV.

There is a clear near-side ridge in the graph shown above. According to the reasoning in section 4.2, this theoretically should be a situation that produces a partonic matter (QGP). This is a system that is very low in size and very high in energy, adding on to the reason why QGP should be produced. However, although experiments have paralleled this reasoning, results of this from the AMPT model have been “consistent with the experiment data qualitatively but not quantitatively”. The reason is that a partonic matter is indeed created, but its equilibrium might be differ from that of a quark-gluon plasma. (Citation) Further research is needed to be done in order to have a clear understanding of possible QGP production in p+p collisions. [9]

4. Conclusion

Based on the data, 100 thousand with s^0.5=13TeV, and 500 thousand with s^0.5=0.2GeV, obtained from the CMS Large Hadron Collider, the graphs of two-particle angular correlation functions of Pb-Pb collisions and pp collisions can be drawn by using programming techniques. The two-particle angular correlations function is measured by $\Delta\eta$(pseudorapidity) and $\Delta\varphi$(azimuth difference). Through the graphs, we learned that a ridge-like structure was formed in both collision and at the position where both $\Delta\eta$ and $\Delta\varphi$ are zero, a visible peak forms. The graphs also show the differences between pp collision and Pb-Pb collision. The direction of the ridge-like structures in pp collision and Pb-Pb collision are vertical to each other, the former has such a structure that appears more intensively and concentrated in a certain range of $\Delta\eta$(usually where $|\eta| < 1$), while the latter has such a structure that appears more pronounced, spanning the central pseudorapidity region and a wider azimuthal angle range.

The program also includes some research about QGP (Quark Gluon Plasma). Quark–gluon plasma (QGP or quark soup) is an interacting localized assembly of quarks and gluons at thermal (local kinetic) and (close to) chemical (abundance) equilibrium. QGP has close relationship with the distribution of the particles after the collision, which influences the shape of our graphs a lot. Basically, the formation of QGP occurs under high density situation, generally in heavy ions' collision. In the Pb-Pb collision, QGP was going to form two possible shapes, oval and triangle. The distribution of the particles of these two shapes of QGP can be written into two different cosine-like functions. By using Fourier transform, two functions can be combined with each other. The shape of this function is highly similar to our graphs, and this explains why the ridge-like structure occurs in such rhythms. Moreover, although proton-proton collisions in modern particle accelerators like the LHC and RHIC can reach very high energies, the energy density of these collisions remains lower than that achieved in heavy-ion collisions, such as lead-lead collisions. For this reason, QGP can't form.

In the following days, our team will keep doing research on such a project, and we will try to do our best to use the latest data to draw the most accurate picture. Additionally, we'll keep doing research on the formation of QGP such as, high-energy collisions, deconfinement of Quarks and Gluons, phase transition and thermal equilibrium. By studying such processes which work together to lead to the formation of QGP and analyse what conditions they reflect to those in the early universe. Also, gain a deeper understanding of the fundamental properties of strong interactions.

Acknowledgments

Sihan Chen,Yuhe Dai,Pinzhen Gong,Haoran Hu and Zhixuan Luo contributed equally to this work and should be considered co-first authors.

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