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The Theoretical Research of Two Particle Angular Correlation in Pb-Pb Collisions

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Abstract:

This literature review explores the significance of two-particle angular correlation in comprehending the complex dynamics of proton-heavy ion collisions in the quark gluon plasma (QGP) and the CMS detector at the LHC. We present a detailed account of the experimental setup and the findings derived from our measurements. The one-particle distribution equation and the two-particle angular correlation functions are fundamental components for comprehensively investigating the theoretical aspects of the two-particle angular correlation. Following that, we present a concise summary of significant metrics, such as centrality, uncertainty, and Fourier coefficient, that may be determined from the available data. Additionally, we provide a concise summary of prior investigations into the two-particle angular correlation in collisions involving pp, p-Pb, or Pb-Pb at various energy levels. Specifically, we have utilized the MC model for the analysis and modeling of collision data. Various MC models are listed and evaluated using specific situations. Higher order correlations are now possible to help clarify information from proton or heavy ion collisions.

Keywords: two-particle angular correlation, quark-gluon plasma, LHC, CMS, Monte Carlo Models.

1. Introduction

Measuring the angular correlation function between two particles is a potent method for comprehending the properties of the strong nuclear force in collisions. High-energy nuclear collisions provide a distinctive means to understand the characteristics of quark gluon plasma (QGP), a kind of substance thought to have formed soon after the big bang. The Compact Muon Solenoid (CMS) detector is employed at CERN's Large Hadron Collider (LHC) to identify a wide range of particles generated by high-energy collisions. During these collisions, the high temperature and density of energy allow quarks and gluons to exist in a state of unconstrained freedom.

Understanding the behaviors and properties of QGP is very important. The cms experiment has been instrumental in studying the QGP by measuring various observables, especially two particle angular correlations.

By analysing the angular correlations between two particles , researchers could extract information about the anisotropic flow coefficient.

Particle angular correlations, obtained by measuring angle distributions in $\Delta\eta\Delta\varphi$ space, serve as a dependable method for studying the fundamental physics events associated with particle creation in collisions involving protons and heavy ions [1, 2]. This is particularly useful in proton-proton (pp) or proton-heavy ion collision systems [1]. The azimuthal angle difference is denoted as $\Delta\eta$ and the pseudorapidity difference is denoted as $\Delta\varphi$ between two particles [2]. These linkages allow for the simultaneous study of many pathways. Correlations emerge due to the fundamental rules of energy and momentum conservation, along with the characteristics of strangeness, baryon number, and electric charge; this is the baseline, the physics mechanism. As a result, the entire phase-space takes on the structure of "$-\cos(\Delta\varphi)$". Several processes, including as elliptic flow, Bose-Einstein correlations, resonance decays, and mini-jets, provide additional correlations. Each of these processes leads to a unique distribution in $\Delta\eta\Delta\varphi$ space [2]. They establish the correlation function's final form together with the baseline. The hadronisation procedures are affected by several physical phenomena, such as Coulomb interactions, conservation of momentum and energy, resonance decay [2]. These effects arise due to the quark composition of the particles involved.

2. Theoretical background

2.1 Single particle distribution

An elevation in the azimuthal correlation of particle generation, including a wide range of pseudorapidity, is indicative of the hydrodynamic expansion of QGP.

Here, this particle give the result of single particle distribution:

$$\frac{dN}{d\varphi} = N_0(1+2\sum_{n=1}^{\infty} V_n cos(n(\varphi - \Phi_n))) \quad (1)$$

where phase of the anisotropy of order n and the amplitude are denoted by the harmonics v_n and phase Φ_n, respectively.The azimuthal angle of the particle emission is indicated by φ [3]. These anisotropies arise from the unique asymmetry in the interactions between off-centre ions and the fluctuations in collision geometry.

2.2 Two-particle correlation function

Two-particle correlations can be characterized by measuring a function of the difference in azimuthal angle ($\Delta\varphi \equiv \varphi^a - \varphi^b$) and the difference in pseudorapidity ($\Delta\eta \equiv \eta^a - \eta^b$). The correlation function can be defined as:

$$C(\Delta\varphi, \Delta\eta) = \frac{S(\Delta\varphi, \Delta\eta)}{B(\Delta\varphi, \Delta\eta)}, \quad (2)$$

where $S(\Delta\varphi,\Delta\eta)$ represents a distribution created using the same event, and $B(\Delta\varphi,\Delta\eta)$ is formed using mixed events [3].

To obtain the one-dimensional correlation function C(Δφ), do integration on the numerator and denominator of Eq. (2) across |Δη|:

$$C(\Delta\varphi) = \frac{\int_2^5 d|\Delta\eta| S(\Delta\varphi, \Delta\eta)}{\int_2^5 d|\Delta\eta| B(\Delta\varphi, \Delta\eta)} = \frac{S(\Delta\varphi)}{B(\Delta\varphi)}[3]. \quad (3)$$

To decrease effects from short range correlations (such as resonance decays and jets), the range 2 < |Δη| < 5 was used. "Per-trigger-particle yield" has a more concrete meaning and is represented by the C(Δφ) function with extra normalization:

$$Y(\Delta\varphi) = \frac{\int_{-\pi/2}^{3\pi/2} B(\Delta\phi) d\Delta\phi}{N^a \int_{-\pi/2}^{3\pi/2} d\Delta\phi} C(\Delta\varphi), \quad (4)$$

Where the symbol N^a represents the total number of trigger particles [3].

2.3 Key Parameters

2.3.1 Centrality

To accurately portray an event, it is crucial to ascertain the impact parameter, denoted as b, or the centrality of a heavy-ion collision. Understanding the importance of reaction centrality enables us to make meaningful comparisons with baseline data collected from simpler collisions involving protons or protons and nuclei. Additionally, it provides a geometric evaluation of the area where the colliding nuclei intersect, which could be utilized in investigations of the fundamental dynamics of the collision [4]. The primary criterion for assessing significance in high-energy nucleus-nucleus collisions is the quantification of transverse energies or the number of charged particles in different pseudorapidity regions [4].These signals provide a centrality statistic by partitioning the whole cross section into bins according to percentage. The effectiveness of this strategy depends on the assumption that there is a reliable correlation between the extent of overlap between nuclei and the quantity of charged particles or transverse energy [4].

The amount of transverse energy that is absorbed by the calorimeters, known as E_T^{tot}, offers a direct approach to estimating the impact parameter in CMS for each individual event [4]. The energy exhibits a significant decline as the collisions move from the center to the periphery. The CMS Hadron Forward (HF) or CASTOR calorimeters cover a region of very high forward rapidity, |η| > 3 [4]. The final-state rescattering in this region is expected to be lower compared to the core rapidity zone because of its comparatively low initial particle density. Thus, the primary factor that determines the amount of energy deposited in the CMS forward calorimeters, particularly in the transverse direction, is the initial nuclear geometry of the collision, rather than the behavior of the end state.

2.3.2 Uncertainty

The relative uncertainty of the momentum measurement can be defined as $\sigma(p\mathrm{T})/p\mathrm{T}$. In previous literature, the relative uncertainty is required to be less than 5% [5].The relative uncertainty is employed to exclude tracks that may have inaccurately reconstructed momentum values. Rebuilt trucks are deemed primary-track candidates if both the distance between primary vertex and the track along the beam axis, dz/σ(dz), and their impact parameter relative to the primary vertex transverse to the beam, dxy/σ(dxy), are less than 3. Researchers evaluate the uncertainty by following these descriptions. They provided summaries of several systematic resources. There are a number of explanations for the uncertainty. For instance, the tracking weighting closure test accounted for 3.3% of the yield associated with each trigger particle, while the tracking efficiency accounted for the highest percentage of the total uncertainty, 5.0% [5]. Track selection reliance was roughly equal to vertex dependence, contributing 2.2% of the uncertainty [5].There was 2.9–3.6% ambiguity due to the mixed-event background's construction [5]. They arrived at a total systematic uncertainty estimate of 7.3 to 7.6 by summing up all of these sources of uncertainty [5].

2.3.3 Fourier Decomposition (2011 3.3)

The anisotropic hydrodynamic expansion of the medium created in collisions between heavy ions moving at relativistic speeds could potentially lead to long-range correlations in the azimuthal direction. The expansion is controlled by the initial anisotropy of the collision zone on a per-event basis. The correlations observed in non-central collisions are primarily driven by the second-order Fourier component of the $|\Delta\varphi|$ distribution, sometimes referred to as elliptic flow or v2 [5-7]. The distribution of the one-dimensional Δφ can be separated into its constituent parts using a Fourier transformation within a particular area of delta phi. Through this type of transformation, researchers were able to observe long-range relationships.

$$\frac{1}{N_{trig}}\frac{dN^{pair}}{d\Delta\varphi}=\frac{N_{assoc}}{2\pi}\left\{1+\sum_{n=1}^{\infty}2V_{n\Delta}cos(n\Delta\varphi)\right\}, \qquad (5)$$

where N_{assoc} indicates the total count of hadron pairs for each trigger particle inside a specific range of $|\Delta\eta|$ and (p_T^{trig} , p_T^{assoc}) bin [5].

Fourier coefficient can be obtained from fitting the PbPb data. This alternative method of assessing correlation data offers a chance to examine different theoretical models, such as the current hydrodynamic computations of higher-order Fourier components.

The researchers noticed that a ridge-like structure, extending across long distances, is particularly noticeable when the azimuthal angles are about equal ($\Delta\varphi \approx 0$), especially in the intermediate range of transverse momentum. The CMS detector have very broad solid angle coverage, which is good for statistical accuration of the sample and it is good for the observation of short and long range particle correlations.

3. Experimental Methods and Techniques

3.1 LHC & CMS

The research primarily employed the Compact Muon Solenoid (CMS) detector and the Large Hadron Collider (LHC) for conducting experiments and collecting data. The CMS detector was designed with the objective of studying collisions involving protons and protons, as well as lead and lead, at a center-of-mass energy of 14 TeV (equal to 5.5 TeV per nucleon-nucleon) [8-10]. In addition, it was designed to accommodate luminosities ranging from 1034cm-2s-1 to 1027cm-2s-1 [8]. The central component of the detector comprises a superconducting solenoid with a substantial magnetic field and a large aperture. The solenoid contains a silicon pixel and strip tracker, an electromagnetic calorimeter composed of lead-tungstate scintillating crystals, and a hadron calorimeter constructed of brass and scintillator materials. The flux-return iron yoke is equipped with four muon detector stations that effectively cover the whole 4π solid angle. By incorporating more forward sampling calorimeters, the coverage of pseudorapidity is extended to high values ($|\eta| \leq 5$), ensuring a high degree of hermeticity [8]. The CMS detector has dimensions of 21.6 meters in length and 14.6 meters in diameter, with a total weight of 12,500 tons [8]. The wide angular range covered by the CMS detector and the precise statistical analysis of the sample examined in this study have greatly improved the detection of particle correlations, both at short and long distances, in comparison to previous data.

3.2 Data analysis & error analysis

Data on the angular correlation of two particles was acquired using the CMS detector at the LHC. The main factors being considered in the data are the integrated luminosity and the beam energy for lead nuclei, which will determine the center of mass energy per nucleon pair. The proton beam's direction was really suitable. The researchers originally planned to set the practical orientation of the proton beam as clockwise, but ultimately opted to reverse it. Due to the disparity in energy levels of the colliding beams, the center of mass of the nucleon-nucleon system is not stationary with respect to the laboratory framework during the collisions [10]. Particles of negligible mass that are emitted at ηcm = 0 in the center-of-mass reference frame of the nucleon-nucleon system will be detected at either a negative η value (when the proton beam rotates clockwise) or a positive η value (when the proton beam rotates counterclockwise) [10]. During the 2011 heavy-ion run at the LHC, data was gathered from peripheral PbPb collisions. The researchers are conducting a comparison between a subset of peripheral PbPb data and PbPb data that possesses a comparable charged particle range [8].

4. Related Studies and Discussions

In 2011, researchers conducted the first study on long-range azimuthal correlations in PbPb interactions, focusing on a significant variation in pseudorapidity, by analyzing data from CMS detector from LHC [5]. The researchers conducted measurements of angular correlation among charged particles over the range of Δη, which is $-4 < \Delta\eta < 4$, and across the whole range of Δφ [5]. These measurements were performed in the 0-5% most central PbPb collisions at a collision energy of $\sqrt{s_{NN}}$ = 2.76 TeV [5].

In heavy-ion collisions, the yield distributions show unique features not seen in minimum bias pp interactions. The transverse momentum of the trigger particles was tak-

en into consideration when the researchers examined the azimuthal correlations at both short and long distances.
They compared the experimental data of the distribution of charged hadrons associated with each trigger particle, as a function of the difference in pseudorapidity ($|\Delta\eta|$) and azimuthal angle ($|\Delta\varphi|$), in the most central 0-5% PbPb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV [5]. The data was compared to theoretical simulation data generated by a pythia8 Monte Carlo simulation (version 8.135) of pp collisions at the identical collision energy, as shown in Figure 1. The purpose of the comparison is to understand the effects of the dense and intense medium produced by this collision. The transverse momentum range was selected for this picture because to its ability to clearly demonstrate the disparity between correlations observed in PbPb data and simulation data.

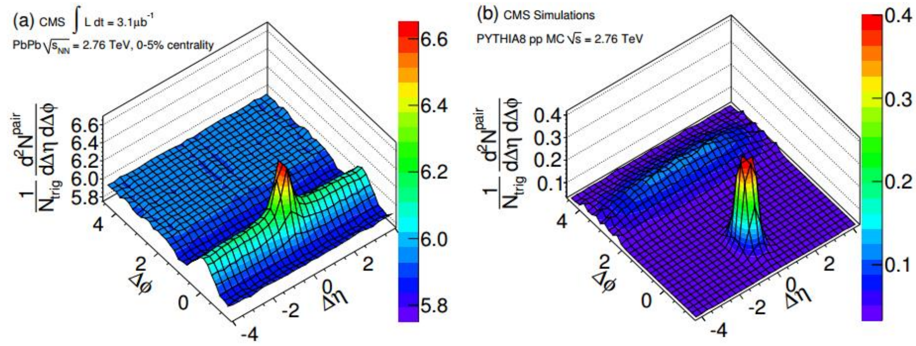

Figure 1:Two-dimensional (2-D) yield per trigger molecule of charged hadrons as an element of |Δη| and |Δφ| for 4 < p_T^{trig} < 6 GeV/*c* and 2 < p_T^{assoc} < 4 GeV/*c* from (a) 0-5% most focal PbPb impacts at $\sqrt{s_{NN}}$ = 2.76 TeV, and (b) PYTHIA8 pp MC re-enactment at $\sqrt{s}$ = 2.76 TeV [5].

In 2018, researchers conducted a study to analyze the relationship between two particles: a weird hadron (K_s^0 or $\Lambda/\bar{\Lambda}$) and a charged particle. The data was gathered from the CMS detector at $\sqrt{s_{NN}}$ =5.02 TeV [10]. The determination of the second-order (v2) and third-order (v3) anisotropy harmonics of K_s^0 and /particles is achieved through the analysis of azimuthal correlations observed at significant relative pseudorapidity [10]. The levels of V2 and V3 are evidently affected by the particle's nature.
As depicted in Figure 2.

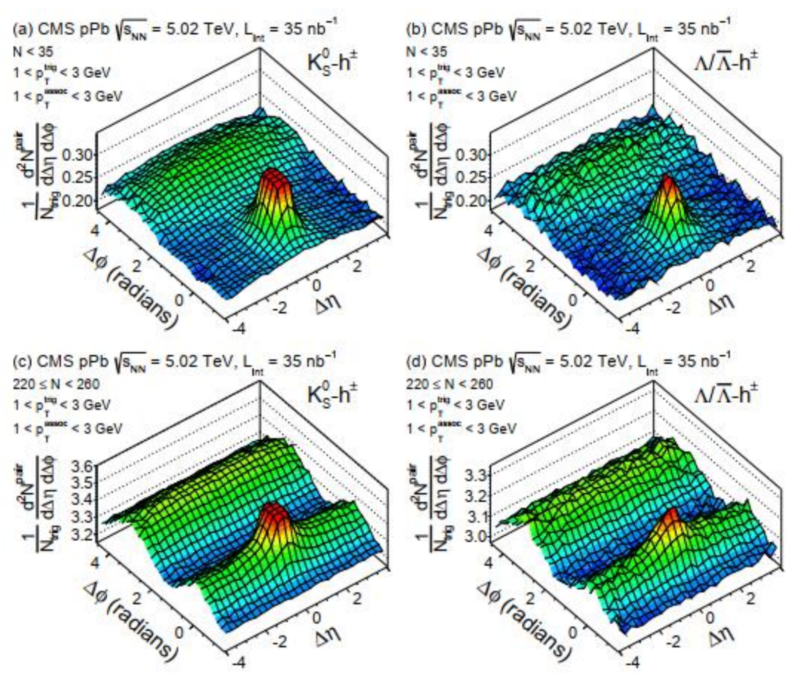

Figure 2: For pairs of charged associated particles ($h^{\pm}$) and trigger particles K_s^0 or $\Lambda/\bar{\Lambda}$ (b,d)

in pPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, the two-particle correlation functions in two dimensions are found in the multiplicity ranges 220 ≤ $N_{trk}^{offline}$ < 260 (c,d) and $N_{trk}^{offline}$ < 35 (a,b), respectively, where 1 < p_T^{trig} < 3 GeV and 1 < p_T^{assoc} < 3 GeV. By removing the prominent peak on the near side of the jet correlations, the underlying structure beyond this area becomes visible [10].

Table 1: Summary of the systematic uncertainties in v_n^{sig} for the pPb and PbPb data [10].

Source	pPb (%)	PbPb(%)
V^0 mass distribution range used in fit	1	1
Size of V^0 mass region for signal	2	2
Size and location of V^0 mass sideband region	2.2	2.2
Misidentified V^0 mass region	2	2
V^0 selection criteria	3	3
Tracker misalignment	2	2
MC closure test	4	4
Trigger efficiency	2	—
Pile-up	1	—
Total	6.9	6.6

4.1 Monte Carlo Models

The Monte Carlo Model is a computing methodology that employs random sampling and statistical methods to model intricate systems and processes [2].

In high energy physics, Monte Carlo models are widely used to simulate particle collision events. For example, in particle accelerator experiments such as the Large Hadron Collider (LHC), researchers use Monte Carlo models (e.g. PYTHIA, PHOJET, etc.) to generate simulated particle collision data [2]. These simulated data help to understand and analyse the behaviour of particles observed in real experiments and verify the accuracy of theoretical models.

Monte Carlo simulations enable researchers to predict probability distributions and the expected values of various physical quantities in complex systems, yielding valuable quantitative information even when precise analyses of these systems are not available through analytical methods.

Researchers use Monte Carlo simulations as a tool to compare theoretical predictions with actual experimental results, specifically for data of proton-proton collisions of $\sqrt{s} = 7$ TeV [2, 11]. This simulation uses two generators including PYTHIA and PHOJET [2]. The Monte Carlo models successfully produce the correlation patterns for mesons. However, it performs poorly when it comes to the anti-correlation feature observed in the baryon-baryon correlation, suggesting that the model is deficient in the baryon generation mechanism [2].In other cases, the losses in the data are not even qualitatively reproduced by the model. This simply indicates that the fragmentation function in the Monte Carlo model and/or the particle generation method in this model needs to be changed [2].

This challenge was solved by another team of Chinese scientists using a novel model known as the multiphase transport model (AMTP) [12]. At √s = 7 TeV, they studied the angular correlation of two particles in particle collisions. The angular correlation function for pairings of mesons was not only explained, but the angular correlations for pairings of baryons and pairings of antibaryons were also significantly increased [12]. Furthermore, they asserted that the observed negative correlation characteristics of baryon-baryon correlations in experiments were more precisely elucidated by the AMPT model incorporating neo-quark aggregation. In addition, their analysis was expanded to include p-Pb collisions at a center-of-mass energy of √s = 5.02 TeV, which yielded similar outcomes [12]. These findings have enhanced their comprehension of the mechanisms responsible for particle generation during collisions between protons and lead ions at the energy level of the Large Hadron Collider (LHC). The AMPT model was employed to replicate heavy ion collisions throughout a wide range of collision energy, spanning from the AGS to the LHC [12]. The system consists of four main components: hadronic interactions, parton rescattering, conversion of partonic matter into hadronic matter, and initial conditions [12]. The AMPT model has well explained multiple phenomena observed in heavy ion collisions, including two-particle correlations, anisotropic flows, and particle production mechanisms.

A team of scientists conducted an ALICE investigation on the angular correlations between two particles observed at the Large Hadron Collider during proton-proton collisions with a center-of-mass energy of $\sqrt{s}$ = 7 TeV [13]. The study predicted that the pseudorapidity (Δη) and relative azimuthal angle (Δϕ) would exhibit different patterns due to specific physical factors.This would enable researchers to investigate a broad spectrum of correlations. Two distinct models, Pythia Perugia-0 and Phojet, produced Monte Carlo (MC) events that were analyzed using identical methods [13-16]. Furthermore, the ALICE architecture utilized the reconstruction chain to handle the MC-generated events and accurately replicate the detector's reaction. The particles chosen for examination must adhere to the identical course and trajectory as the ALICE collision data, traversing through the precise combination of cut sets. Upon comparing the results obtained merely from studying the generator data, no major alterations were seen. By doing an analysis, they acquired results on the relationship between the correlation function and factors such as event multiplicity, charge combination, and particle species (meson, meson, or proton).

5. Conclusion

This literature review talks about the important role of two-particle angular correlation in revealing complex behaviour of quark gluon plasma (QGP) , proton and heavy ions collision from CMS detector at LHC. We introduce measurements and experimental devices. Theoretical knowledge about two-particle angular correlation is also introduced in detail, from one-particle distribution equation to two-particle angular correlation functions. Then the important parameters are presented that could be extracted from existing data, such as centrality, uncertainty and Fourier coefficient. We summarised some previous literature about research on two-particle angular correlation from pp, p-Pb or Pb-Pb collision at different energy. Notably, we introduced MC model in application for simulation and analysis of collision data. Different MC model are listed and compared with example. This pave the way for higher-order correlation to further elucidate information in proton or heavy ion collisions.

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