



**INVESTIGATION OF ELLIPTIC FLOW AND CHIRAL MAGNETIC
EFFECT IN Pb-Pb COLLISIONS IN ALICE AT LHC**

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DECLARATION

I declare that the thesis entitled “Investigation of Elliptic Flow and Chiral Magnetic Effect in Pb-Pb collisions in ALICE at LHC” has been prepared by me under the guidance of Dr. M. M. Aggarwal and Prof. A.K. Bhati, Department of Physics, Panjab University, Chandigarh. No part of this thesis has formed the basis for the award of any degree or fellowship previously.

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Dedicated To The Strongest Women I Have Seen

Mrs. Sudesh Kumari

&

Mrs. Sanyogita Sharma

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ABSTRACT

The study of the quark-gluon plasma (QGP), a state of matter which is supposed to have existed after big-bang, is the objective of ultra-relativistic nuclear collisions. At the Large Hadron Collider (LHC), ALICE (A Large Ion Collider Experiment) is designed to produce and investigate the characteristics of QGP, whose presence at high temperature is predicted by Quantum Chromodynamics (QCD). The QCD has also predicted about the local parity (P) violation effects in strong interactions. These parity violation effects when coupled with the strong magnetic field, created by spectator protons in non-central heavy-ion collisions, result into the back-to-back charge separation along the direction of magnetic field. This phenomenon is known as the Chiral Magnetic Effect (CME).

The expected charge separation due to CME is very small and can be diluted when searching in a whole sample. So, it is essential to search CME signal in each and every event to isolate potential events exhibiting the back-to-back charge separation with significantly enhanced signal in these events rather than looking the signal taking all events together in a given collision centrality. The novel method, Sliding Dumbbell Method (SDM), is developed to search for the back-to-back charge

separation on an event-by-event basis.

Events in a given collision centrality are characterised depending on the fractional charge separation across the 90° dumbbell using the SDM. Here, azimuthal plane of an event is scanned by sliding the 90° dumbbell by 1° to get the maximum value of charge separation ($f_{D\bar{b}CS}$) across the dumbbell. The obtained ($f_{D\bar{b}CS}$) distribution is sliced into ten percentile bins; top 0-10% being highest charge separation and 90-100% being lowest charge separation. Therefore, events are categorised according to their charge separation to get CME-like enrich sample. The charged-particle angular correlations which are the most favourable method to study the charge separation due to CME, are studied for the different $f_{D\bar{b}CS}$ bins.

The SDM is tested on the AMPT generated events samples. The default AMPT with no CME like signal does not differentiate between γ correlator for data and backgrounds. Here, the background contribution is determined by shuffling the charges of the particles in an event and shuffled events are analyzed in similar way as of given data. The varying percentages, i.e., from $\sim 0.5\%$ to $\sim 8\%$, of the CME like signals are externally injected in the events by flipping the charges of pairs of the particles perpendicular to the reaction plane. As the externally injected CME like signal in AMPT is increased, the values of γ correlators found to increase. The CME fraction calculated through AMPT samples increases with increase in externally injected signal. The SDM is able to detect the signal as small as $\sim 0.5\%$.

After testing its credibility, the SDM is then applied on ALICE's data of Pb-Pb collisions of $\sqrt{s_{NN}} = 2.76$ TeV and $\sqrt{s_{NN}} = 5.02$ TeV. The charge separation binning effect is seen in 3-particle correlator based on 2nd order event plane (γ_{112}). The γ_{112} increases significantly for the top 10% $f_{D\bar{b}CS}$ events, while 3-particle correlator based on 3rd order event plane i.e, γ_{123} , remains independent of charge separation binning as expected. Moreover, the magnitudes of γ_{112} for same sign charge pair and γ_{112} for opposite sign charge pair for the top 10% $f_{D\bar{b}CS}$ percentile bin are equal. The $\sqrt{|\gamma|}$ for same sign charge pair is seen to vary linearly with positive charge asymmetry across the dumbbell (term proportional to the parity violating parameter) for the

top 10% $f_{D_{bCS}}$ events. Also, it is observed that elliptic flow increases by 5% in the top 10% of $f_{D_{bCS}}$ events, whereas mean multiplicity decreases. Furthermore, out-of-plane correlations are seen to be more prominent in same-sign charge pairs than those of in-plane correlations for the top $f_{D_{bCS}}$ bins. The H-correlator representing the CME signal also enhances many times for the top 10% $f_{D_{bCS}}$ events. The f_{CME} is around $18 \pm 8\%$ for 0-50% collision centrality for the top 10% $f_{D_{bCS}}$ events in a given collision centrality which corresponds to $1.8 \pm 0.8\%$ for a given collision centrality and seems to be independent of collision energy.

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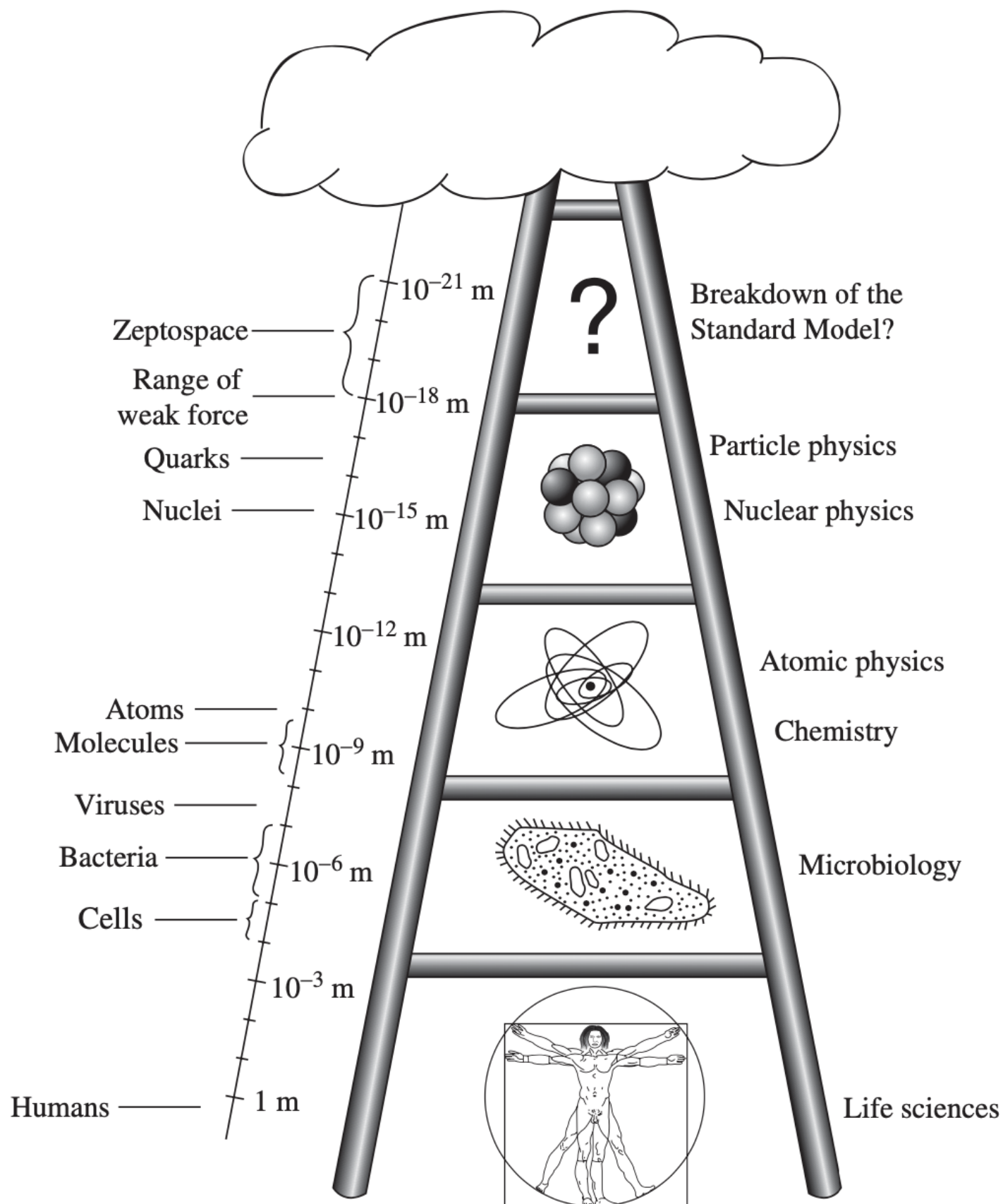
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If you study history far back enough it becomes
biology, then geography, and lastly

PHYSICS



CHAPTER

1

INTRODUCTION

“The true fundamental building blocks of the universe are not particles, but moments in time.”

Khalid Masood

This chapter provides the brief introduction of the Standard Model (SM), the theory of strong interaction, Quantum Chromo Dynamics (QCD), and the QCD-phase diagram. Then followed by review of the Quark Gluon Plasma (QGP) and its creation in heavy-ion collisions, along with the dominant signatures of QGP.

Roots of all branches of physics are ultimately connected to the “Particle Physics”. Basically, all the matter present in the entire universe, consists of particles and branch of physics that deals with the behaviour and properties of these particles is known as particle physics. Early in 1897, as a result of J. J. Thomson’s famous cathode ray experiment, the first fundamental particle “the electron” was discovered. Later, proton and neutron were discovered and believed to be fundamental particles. In the 1950s and 1960s, the improvements in particle accelerators and particle detectors resulted in a dizzying range of particles detected in high-energy experiments. Even the unstable particles were phrased as elementary particles [1]. In comparison to the diversity of species in a zoo, the phrase “particle zoo” was used informally to represent the relatively large number of known “elementary particles”. Wolfgang Pauli once remarked *“Had I known this, I would have gone into botany”*.

It became clear that certain smaller elements, which were previously unseen, combine to generate mesons and baryons, which accounted for the majority of known particles at that time and the systemization of *particle zoo* was the necessity of that time. With the advancement in quantum field theory and subatomic particle physics, classification has been done by the “Standard Model (SM)” of particle physics [2,3]. The Standard Model of particle physics is a theoretical model which theorizes the three fundamental forces except gravitational force i.e. electromagnetic, weak and strong forces.

Fig. 1.1 enlists all the elementary particles along with their basic properties. According to SM, observable universe consists of two types of particles: FERMIONS - obeying Fermi-Dirac statistics, and have half integral spin ($1/2\hbar$, $3/2\hbar$..) and BOSONS - obeying Bose-Einstein statistics and have integral spin (0 , $\hbar$, $2\hbar$..). These basic building blocks interact through four fundamental forces : Electromagnetic, Weak, Gravitational, and Strong Interactions. Fermions are matter/antimatter particles and bosons are force particles (Fig. 1.2) which mediate the interactions between fermions. There are 12 flavours of elementary fermions, divided into three generations and the members of each generation are placed in such a way that the instability and mass of the particles grow as the generation rises.

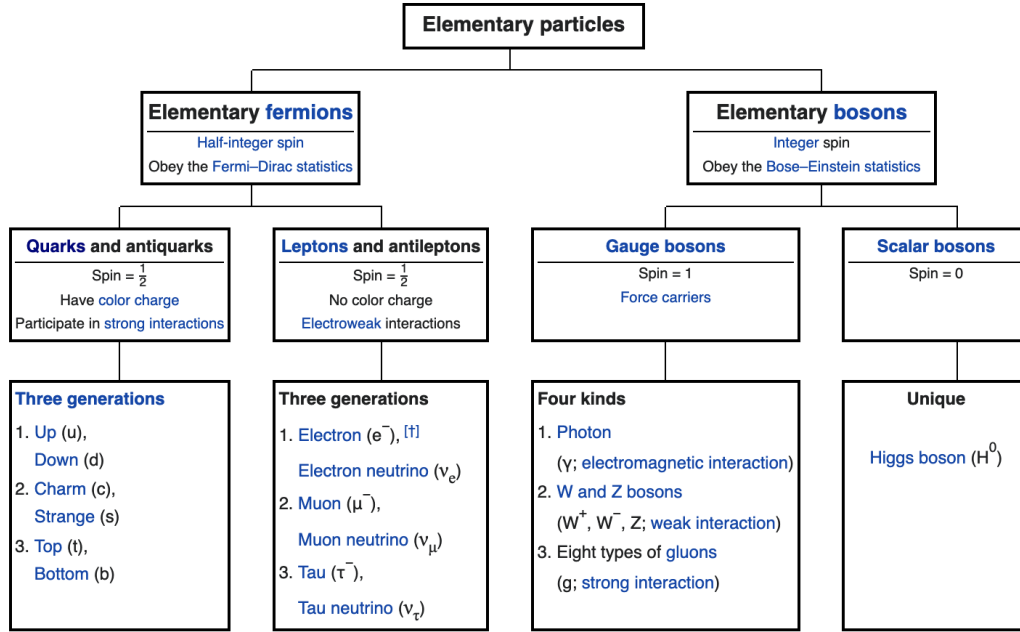


Figure 1.1: The concept map of Elementary particles [4].

Among these, six are quarks (carry color which allows them to interact via the strong interaction) and six are leptons (no color charge, interact through the electromagnetic force, which is carried by photons). To each lepton, there is a corresponding neutrino, with no charge, but interact with gauge bosons as their force carriers through the weak nuclear force. All these particles have their respective antiparticles.

Similarly, 12 bosonic particles and 1 Higgs-Boson. All other particles are only the different combinations of these fundamental particles i.e. Baryons are combination of 3 quarks/anti-quarks and mesons are combination of 1 quark and 1 anti-quark [6] [7].

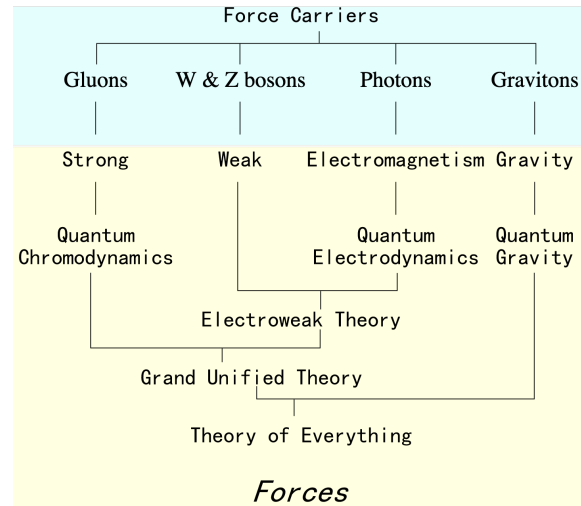


Figure 1.2: The outline of force carriers (Bosons) along with their explaining theories [5].

1.0.1 Quantum Chromodynamics (QCD)

Quantum Chromodynamics (QCD) is a non-abelian gauge theory that describes the dynamics of quarks and gluons. It was modelled in a parallel manner to Quantum Electro-Dynamics (QED) which is a well established quantum field theory for electromagnetic forces. In place of photons, we have gluons here and for electric charge, colour charge has been introduced. The QCD potential is defined as :

$$V_{QCD}(r) = -\frac{4}{3} \frac{\alpha_s}{r} + kr \quad (1.1)$$

where, “ α_s ” is the coupling constant, “ r ” is the distance between two interacting particles and “ k ” is the color string tension constant. The α_s depends on momentum transfer as:

$$\alpha_s(Q^2) = \frac{12\pi}{(11N_c - 2N_f)\ln(Q^2/\lambda_{QCD}^2)} \quad (1.2)$$

where N_c is the number of color charges, N_f is the number of quark flavors and λ_{QCD} is the QCD scale parameter. Equation 1.2 leads to the two most paramount properties of QCD : the quark confinement [8] and the asymptotic freedom [9]. According to Eq. 1.2, at large distance or small momentum transfer, α_s becomes large, hence separating quarks become more difficult. This is known as quark confinement. If, on the other hand, momentum transfer is large, α_s becomes small which culminated to free state of quarks and gluons. This is known as the asymptotic freedom. So single free quark or gluon cannot be observed at normal energy/temperature conditions but at high energies, coupling constant becomes smaller, approaching zero value. So beyond certain limit, the concept of hadron, which is a composite particle made of quarks and gluons, loses its meaning, and leads to a system whose basic constituents are unbound quarks.

The condensed matter, when heated, undergoes a phase transition to the gas phase, and again heated further, it transforms into an electric plasma containing free electrons and ions. When nuclear matter is heated or squeezed, it undergoes a

phase transition to a medium of deconfined quarks and gluons [10].

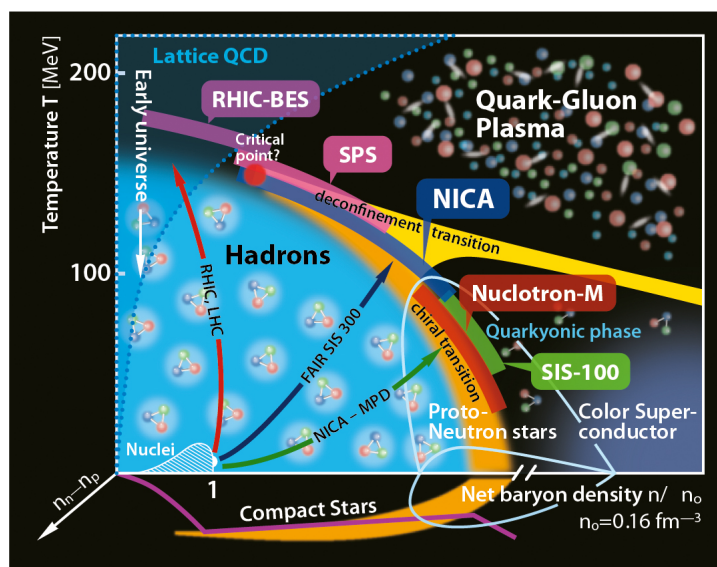


Figure 1.3: The phase diagram of nuclear matter [11].

The phase diagram of nuclear matter is shown in Fig. 1.3 [11]. The temperature (T) is on the y-axis, while net baryon density (net baryon number in the system) is on the x-axis. When the baryon density is less, the number of baryons and anti-baryons in the system is balanced. At low baryon density and high temperature, we would have similar conditions to the early universe. The normal nuclear matter is found at low temperatures (near the x-axis) and a baryon density close to 1. As the temperature rises, the system produces hadron gas. With further rise in temperature, deconfined state of quarks and gluons is attained. This deconfined state is known as “Quark Gluon Plasma (QGP)”.

1.1 Quark Gluon Plasma and Why we need to study this?

QGP is defined as “a (locally) thermally equilibrated state of matter in which quarks and gluons are deconfined from hadrons, so that color degrees of freedom become manifest over nuclear, rather than merely nucleonic volume” [12].

According to the Big Bang theory, the Universe grew from a very tiny area with limitless energy density and temperature [13]. The temperature was so high in the early microseconds of the universe's life that quarks couldn't bind together to create hadrons. Quarks and gluons might, instead, freely move in a strongly-interacting plasma phase known as Quark-Gluon Plasma (QGP) [14]. As the expansion started, the temperature and energy density of the universe dropped. When the temperature dropped below some critical value $T_c \approx 150 \text{ MeV}$, phase change occurred [15] resulted in the process of hadronisation where quarks and gluons were confined into hadrons. After further decrease in temperature, neutron, proton and other elements were

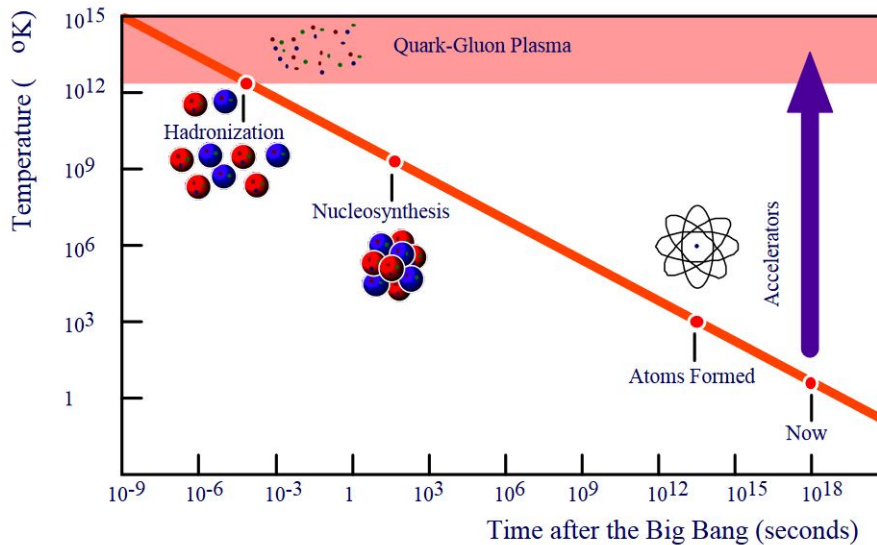


Figure 1.4: The evolution of temperature of universe as a function of time [16].

produced. When the temperature fell below 10^9 K , neutrons and protons were able to bond and create light nuclei, mostly hydrogen and helium nuclei: this is known as primordial nucleosynthesis [17]. The Universe was still ionised and so opaque to electromagnetic radiation at this time. When the Universe reached a temperature of 3000 K , however, atoms began to form and electromagnetic radiation became dissociated, resulting in a black-body spectrum. The electromagnetic radiation is red-shifted (increase in wavelength) as the Universe expands, and the wavelength is now in the microwave range, with a temperature of 2.7 K , forming the so-called Cosmic Microwave Background (CMB) [18]. When the electromagnetic-radiation

decoupling occurred, the anisotropies in matter continued to develop under the influence of gravity, and **the current Universe's structures, such as stars and galaxies, began to emerge.**

As previously stated, the Universe was opaque before the decoupling of radiation hence nothing that occurred prior to that period can be viewed in the current Universe. The fingerprints of the transition between the QGP and hadronic phase, in particular, cannot be investigated. As a result, those circumstances must be replicated in the laboratory via collider experiments. Also, along with early universe the QGP state might potentially occur in the cores of neutron stars, where the net baryonic density is extremely high but the temperature is very low.

1.2 Recreate QGP through relativistic heavy-ion collisions

Ultra-relativistic heavy-ion collisions can recreate the conditions that occurred during the early stages of the universe. The collision of heavy nuclei as heavy as Lead (Pb)/Gold (Au) at high energies, produces short lived deconfined quark gluon medium. The medium created in relativistic heavy-ion collisions lasts only a few micro seconds before the temperature drops and quarks and gluons recombine to form hadrons. Only the final state of these hadrons can be used to study the properties of such a medium. Figure 1.5 shows the sequence of events that occurs with

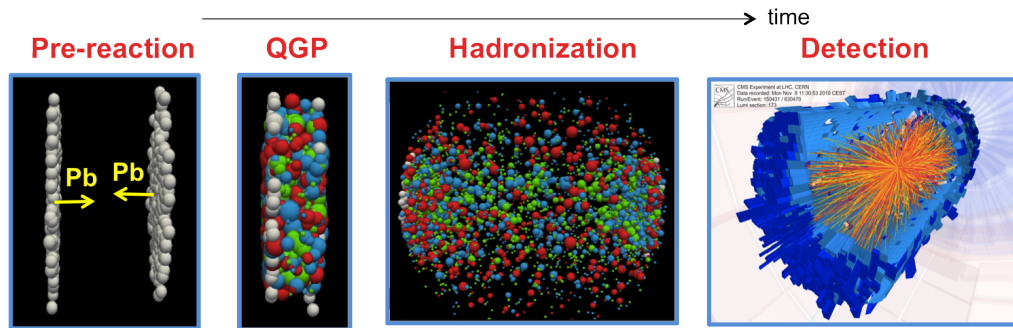


Figure 1.5: The evolution of heavy-ion collision with time.

time in heavy-ion collisions. When heavy nuclei collide with sufficiently high/low temperatures/densities, hadrons overlap and are compressed to the point that their constituents can freely travel inside the overlap region of the system without being confined inside the hadrons. The strength of interactions between quarks and gluons lessens as the temperature rises, generating Quark Gluon Plasma.

1.2.1 Space-time evolution of the collision

A strongly interacting system is generated when two ultra-relativistic nuclei collide. The development of such a system and its attributes is one of the topics investigated in heavy-ion collisions [19]. Figure 1.6 depicts the present state of knowledge about how the heavy ion collisions evolve with time.

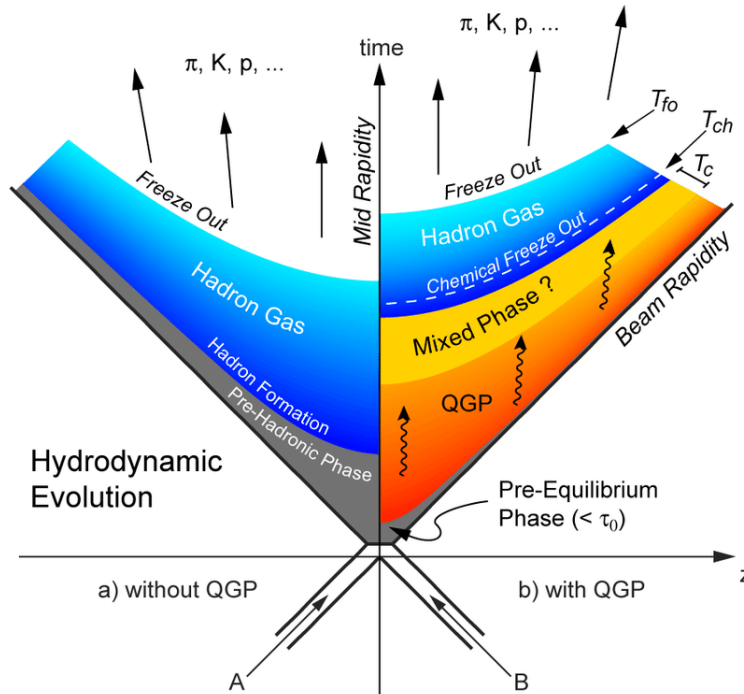


Figure 1.6: The space-time evolution of central heavy ion collision in comparison with hadronic collision [20].

The following are the various stages of the collision:

1. **Pre-collision:** Before the collision, nuclei travel with the acceleration nearly

approaching the speed of light in opposite direction. In the laboratory reference frame, nuclei are significantly Lorentz contracted at the energy attained in the accelerator (by a factor 100 and 2700 at RHIC and at LHC, respectively). The nuclei appear to be two discs.

2. **Collision:** The Glauber model [21] describes nucleus-nucleus collisions in terms of component nucleon collisions, starting with the geometrical configuration of colliding nuclei. The impact parameter “ b ”, which is defined as the distance between the centres of colliding nuclei in the transverse plane to their momenta, is a fundamental component of this model (see Fig. 1.7). The impact parameter is used to define the centrality of the collision i.e., $b \approx 0$ as the

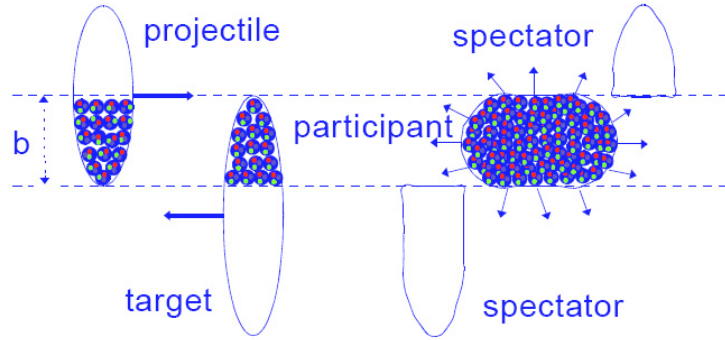


Figure 1.7: On the left, the state before the relativistic heavy-ion collision, and on the right, the subsequent production of dense matter following the impact [22].

central collisions while collisions with a large impact parameter are known as peripheral collisions. The participants nucleons are those nucleons that have at least one interaction with one of the nucleons of the other nucleus, whereas spectators are those nucleons which do not interact in a collision. Spectators continue on their original course with little disruption, while participants are left behind in an excited almond-shaped zone. The space-time evolution has two possible scenarios: (1) The system will only behave as a hadronic gas if the energy density and temperature formed in collision do not reach the threshold value required for the production of QGP (left side of Fig. 1.6) (2) Quarks and gluons may deconfine when the initial energy density and/or temperature are

sufficiently high.

3. **Pre-equilibrium:** The hard processes occur in the early stages after a collision. They are processes in which a large amount of energy is transferred between colliding partons. At this point, all high-energy particles (those with a lot of momentum and/or mass) are created.
4. **Thermal equilibrium:** The partonic matter rapidly reaches thermal equilibrium as a result of interactions among partons, with a thermalisation time of the order of 1 fm/c. This equilibrated state is the Quark Gluon Plasma state.
5. **Phase transition:** Now the thermal pressure gradients of the system increase which in result cause the QGP to expand. Relativistic hydrodynamics [23] is used to model this phase of the growth of the QGP. The system cools down due to the expansion, crossing the phase boundary between deconfined and confined strongly interacting matter. Hadronisation occurs when the threshold temperature T_c between the two phases is attained, and the system eventually develops into an interacting hadron resonance gas.
6. **Chemical freeze-out:** Both inelastic and elastic interactions between hadrons continue to occur as the system expands and cools. Chemical freeze-out occurs when the transmitted momentum between hadrons is insufficient for inelastic interaction. The numbers of particle species are fixed during the chemical freeze-out.
7. **Kinetic freeze-out:** At kinetic freeze out, the hadrons cease to interact. The kinematics of the particles are fixed during the kinetic freeze-out.
8. **Last stage:** The hadrons are able to leave the interaction zone without interacting with anything else.

The evolution for a high multiplicity p-p collisions is similar to that of a Pb-Pb collision, but no generation of quarks and gluons in the early stages of p-p collision leads to a fundamentally different final state.

Two dedicated Collider : The Relativistic Heavy Ion Collider (RHIC) in Brookhaven National Laboratory in USA and the Large Hadron Collider (LHC) in CERN are used to study baryon free quark gluon plasma at different energies and experiment like Compact Baryon Matter (CBM) at FAIR, Germany is in-progress to study properties of baryon rich QGP.

We have seen until now how heavy ion collisions can produce QGP and how that collisions evolve with time but that deconfined phase has extreme short lifetime $\sim 10^{-23}$ s. The most crucial part of the quest is to determine if any medium has been formed. To describe it, couple of signatures for probing the QGP medium creation will be discussed in the upcoming section.

1.3 Experimental probes of QGP

With a lifetime of the order of 10 fm/c [24], the direct observation of QGP is almost impossible. So, indirect evidences which are derived from the measurement of particles that have endured extensive interactions and collected by the detectors, are presently the sole option to investigate the QGP's formation. A diverse collection of observables, sensitive to the QGP formation, allows us to determine if the medium is generated in the collision. But before jumping into this river, let's know how to swim. There are some terms which are used in experimental techniques like transverse momentum, rapidity; what are they and why they come into the picture.

Some Useful Terms: The right-handed cartesian system is used for the measurements with the z axis parallel to the beam direction, the x axis aligned with the accelerator plane, pointing towards the centre of the detector, and the y axis pointing upwards. The transverse plane is the xy plane. A particle's momentum "p" may be divided into its longitudinal (p_z) and transverse momentum (p_T) and $p_T = \sqrt{p_x^2 + p_y^2}$. The polar angle θ is expressed with respect to the z axis. The rapidity of the particle is defined to describe the kinematics of a particle relative to

the beam axis as :

$$y = \frac{1}{2} \ln \left[\frac{(E + p_Z)}{(E - p_Z)} \right] \quad (1.3)$$

where E is the energy of the particle and p_Z is its longitudinal momentum. Velocity is not an additive quantity in the relativistic limit and rapidity has the advantage of being additive under Lorentz transformation. So rapidity (y) is used instead of velocity for relativistic particle. But for “ y ”, one has to know the particle and its energy, so another variable, namely pseudo-rapidity, is defined for the situations where identification of particles is difficult. The pseudo-rapidity (η) is defined as:

$$\eta = \frac{1}{2} \ln \left[\frac{p + p_Z}{p - p_Z} \right] = -\ln \left[\tan \left(\frac{\theta}{2} \right) \right] \quad (1.4)$$

The probes which are sensitive to the production of quark gluon plasma can be broadly classified into two main groups depending upon the particles’ production stages -

- Hard probes
- Soft probes

The term “hard” probes refers to the particles which are created in initial hard parton scattering whilst “soft” probes are often formed after the medium has expanded and cooled [25].

1.3.1 Hard probes

The processes which have high momentum transfer, i.e., $p_T > 6$ GeV, produce hard probes. Some of the QGP signatures which come under hard probes are described as following :-

Jet quenching

In the early stages of collisions, heavy quarks production and gluon scattering takes place. These quarks and gluons are known as “partons” and as the collision advances partons are scattered, hadronized and fragmented into the collimated spray of hadrons, known as “Jets” [26, 27]. When the jets pass through the hot, dense medium created by relativistic nuclear collisions, they interact with the medium and experience gluon radiation or elastic collisions. For high energy, in general, gluonic radiations become the reason of energy loss of jets and hence cause the alteration in structure of the jet. This phenomenon is known as “jet quenching”. As a result of jet quenching, back-to-back jets, which would have had identical energy in a pp collision, have a significant momentum imbalance in QGP medium (Fig. 1.8).

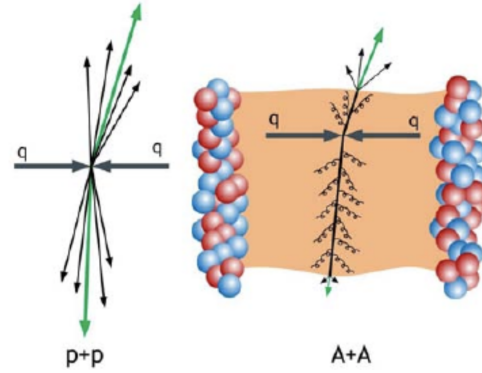


Figure 1.8: Pictorial depiction of Jet quenching in heavy ion collision in comparison to pp collision [28].

To quantify jet quenching experimentally, two methods are mainly used :

- Two particle azimuthal distribution
- Nuclear Modification factor (R_{AA})

A jet may be formed at the medium’s edge (known as the near-side jet), while another jet is produced inside the medium (known as the away-side jet). As a result of more traversing through the medium, the jet on the far side would be quenched more than the near side ones. This may be seen experimentally by observing the azimuthal correlation between a high- p_T trigger particle and its associated particles. The STAR studied the angular dependence of the jet quenching in d-Au and Au-Au central collisions (Fig. 1.9) [29]. The away-side peak, which is 180 degrees displaced

from the near-side peak, is significantly suppressed in Au–Au collisions. In d–Au ones, however, it is not greatly altered.

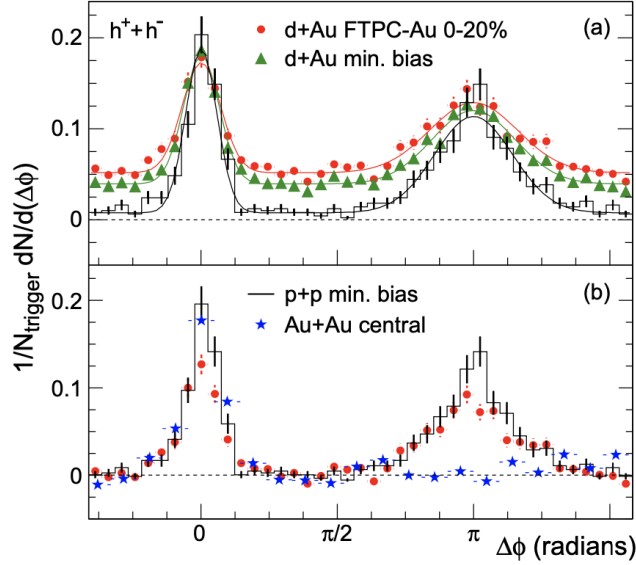


Figure 1.9: Efficiency corrected 2 - particle distributions for central d+Au collisions and minimum bias collisions. (b) Comparison of 2 - particle distributions for central p+p collisions and central Au+Au collisions [30].

The nuclear modification factor (R_{AA}) is defined as :

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{\sigma_{inel}^{AA} \frac{d^2 N_{AA}}{dp_T dy}}{\sigma_{inel}^{pp} \frac{d^2 N_{pp}}{dp_T dy}} \quad (1.5)$$

where N_{coll} is number of nucleon-nucleon collisions and $\langle \rangle$ denotes the average; σ_{inel} is inelastic cross section and AA (pp) denotes the heavy-ion (p-p) collisions. It is clear from the formula that if there is simply p-p collisions then R_{AA} should equal to 1, and any variation from 1 indicates the presence of medium effects. The jet nuclear modification factor (R_{AA}) is measured by ALICE [31–34], STAR [35], ATLAS [36,37] and CMS [38] collaborations at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV as shown in figure 1.10 for central collisions (0–10%). In Pb–Pb collisions, the observed jet spectrum shows a substantial suppression compared to p-p collisions, with a small p_T dependence. The results of multiple experiments agree within the errors.

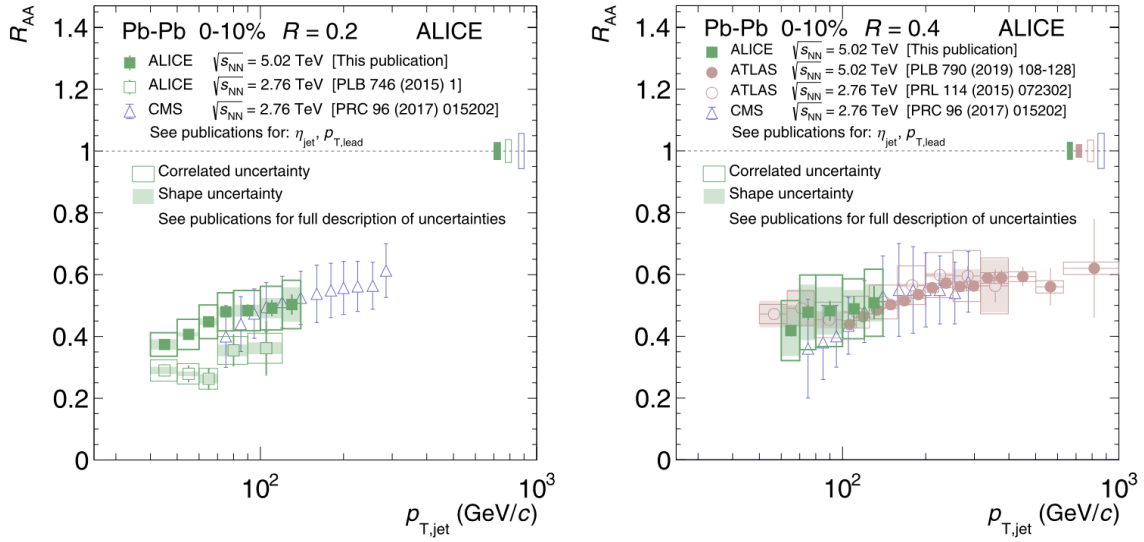


Figure 1.10: Jet R_{AA} in 0–10% central Pb-Pb collisions for $R = 0.2$ (left) and $R = 0.4$ (right) in comparison with published results [34].

Quarkonia suppression

Quarkonia, or the bound states of a heavy quark and its anti-quark, is an excellent means for studying QGP features. Due to the large masses, quarkonia are produced by hard scattering of partons at the initial stages of collision [39]. The quarkonia experiences all stages of the medium development of the collisions due to their prolonged lifespan [40]. The existence of QGP medium, on the other hand, can influence the hadronization of the quark - anti quark pairs. In the presence of dense and deconfined medium, Debye color screening which is the phenomenon of colour charge screening caused by quarks, anti-quarks, and gluons, weakens the quark and anti-quark bonding. As a result, quarkonium inside QGP dissociates, reducing the yield in nucleus-nucleus collisions. Thus, the quarkonium suppression is a helpful probe to distinguish between the p-p and A-A collisions [41]. The most common form of quarkonium found is J/Ψ ($c\bar{c}$) and was discovered by Ritcher and Ting separately in 1974.

The J/Ψ suppression is studied in Pb-Pb collisions at ALICE at $\sqrt{s_{NN}} = 2.76$ TeV [42] and 5.02 TeV [43]; and at CMS [44] through nuclear modification factor. Figure 1.11 shows the clear suppression of J/Ψ along with the comparison with

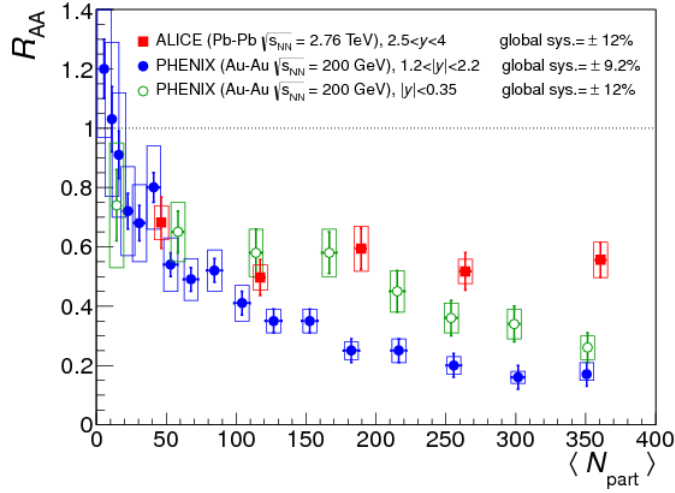


Figure 1.11: The nuclear modification factor of inclusive J/Ψ as a function of N_{part} [42].

PHENIX experiment results in Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV [45–47]. Also, ALICE studied the suppression for 2.76 TeV and 5.02 TeV collision energies and found to be almost same for both the energies [43].

1.3.2 Event-by-Event Fluctuations

The analysis of event-by-event variations is a useful technique for determining the system’s thermodynamic properties. The fluctuations of conserved variables in a finite phase space window, such as the system’s net charge, are projected to be one of the most sensitive indications of QGP production and phase transition, and may give more insight into strong interactions. Among them, net charge fluctuations are widely studied and will be discussed further.

The charge carriers in the QGP phase are “*fractional-charged*” quarks, whereas the hadron gas’s (HG) particles have unit charge and the fluctuations in net charge is proportional to the squares of the charge states existing in the system. As a result, the net-charge fluctuations in the QGP phase are substantially lower than in the HG phase [48]. At the same time, if the early QGP phase is heavily dominated by gluons, the fluctuation per entropy may be decreased even more since gluon hadronization increases entropy [49]. As a result, the net-charge variations are highly influenced

by the phase from which they arise. The ratio of charge is used to remove the influence of uncertainty caused by volume changes, $R = N_+/N_-$ where N_+ and N_- are number of positive and negative charge particles. The net charge fluctuations are measured by the quantity “ $\nu_{+-,dyn}$ ”, defined as:

$$\nu_{+-,dyn} = \frac{\langle N_+(N_+ - 1) \rangle}{\langle N_+ \rangle^2} + \frac{\langle N_-(N_- - 1) \rangle}{\langle N_- \rangle^2} - 2 \frac{\langle N_- N_+ \rangle}{\langle N_+ \rangle \langle N_- \rangle} \quad (1.6)$$

This $\nu_{+-,dyn}$ is related to the quantity “D” which is the variance of ratio of N_+ and N_- scaled by the total charged particle multiplicity as:

$$\langle N_{ch} \rangle \nu_+ \approx D - 4 \quad (1.7)$$

PHENIX studied net charge fluctuations for Au-Au collisions at center of mass energy 130 GeV, STAR measured it for Au-Au at 200, 130, 62.4 and 19.6 GeV [50, 51] and ALICE reported for Pb-Pb collisions at 2.76 TeV [52]. Fig. 1.12 shows $\langle N_{ch} \rangle \nu_{+-,dyn}^{corr}$ (left axis) and D (right axis) dependence on collision energy along with theoretical prediction for QGP and hadron gas. At ALICE, D value comes out to be $2.3 \pm 0.02(\text{stat}) \pm 0.01(\text{sys})$, approaches to the QGP state.

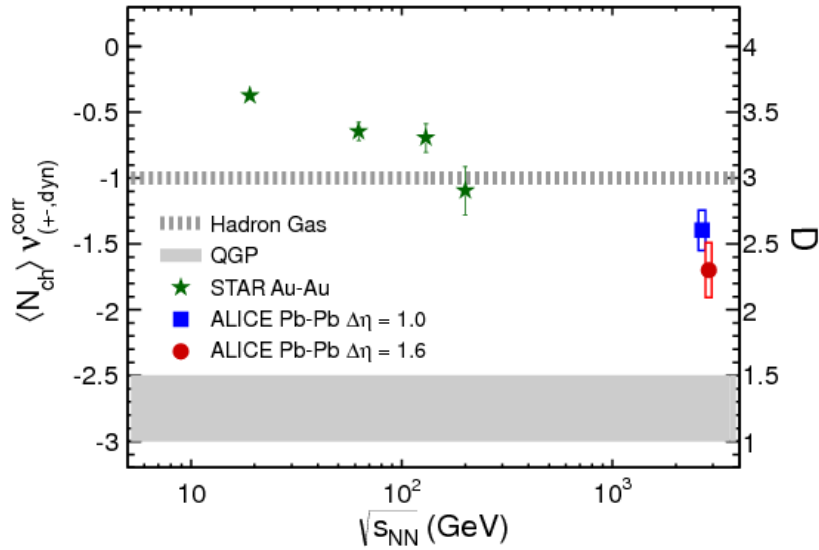


Figure 1.12: The beam energy dependence of $\langle N_{ch} \rangle \nu_{+-,dyn}^{corr}$ on left axis and D on right axis for most central collisions and theoretical predictions [52].

1.3.3 Soft probes

During heavy-ion collisions, thermal QCD matter is created in which soft partons in the momentum (temperature) range of 100-300 MeV are the most common [53]. The particles produced during the collisions emerge mostly with a momentum < 2 GeV/c. So soft probes are likely to be formed at various stages since they include a low momentum transfer procedure and can provide insight on the QGP's size, temperature, composition, and dynamics. The electromagnetic probes, nuclear modification of particle yields and their ratios, strangeness enhancement, anisotropic flow are some of the probes which come under this section.

Electromagnetic probes

Electromagnetic probes, for example, Photons, are perfect for investigating the development of a high-energy heavy-ion collision since they are formed at all phases and are unaffected by the final state interactions [54]. Also they may carry information about the highly interacting media outwards because they only interact electromagnetically and their mean free path length is substantially longer than the medium itself [55]. Experimentally, the inclusive photon, which is the sum of numerous components originating from diverse production

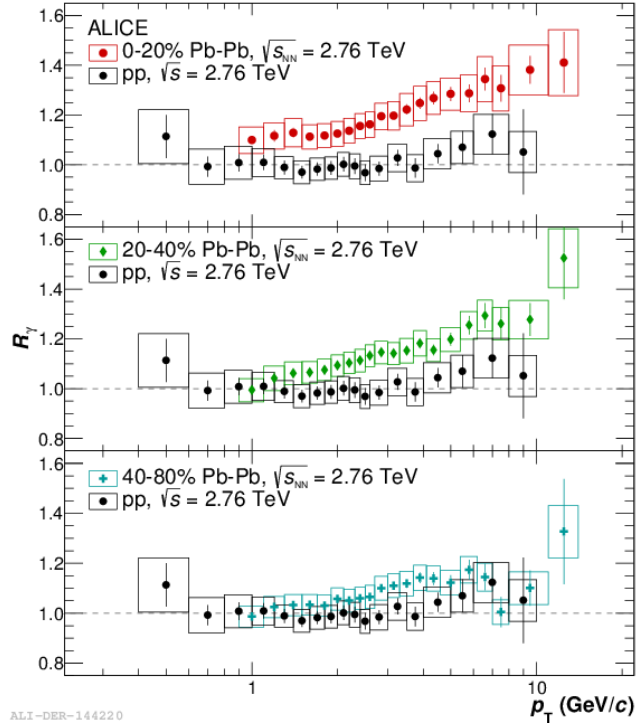


Figure 1.13: Direct photon excess ratio for Pb-Pb and p-p collisions at $\sqrt{s_{NN}}=2.76$ TeV [61].

processes, can only be measured and generally divided into two categories: decay photons (γ_{dec}), which are all photons originate from hadron decays, and the direct

photons (γ_{dir}) [56] which do not originate from hadronic decays.

In A+A collisions, the most common sources of direct photons are (1) direct photons produced from initial hard scattering, (2) thermal photons radiated by the medium, (3) thermal photons originating from the hadron gas formed after hadronization, and (4) photons produced in interactions [56]. By comparing the observed photon spectrum to the spectrum of photons from hadron decays, the direct photon yield is calculated statistically from the inclusive photon spectrum. The p_T dependent double ratio can be used to quantify an excess of direct photons over the decay photon spectrum:

$$R_\gamma \equiv \frac{\gamma_{incl}}{\pi_{param}^\circ} / \frac{\gamma_{decay}}{\pi_{param}^\circ} \quad (1.8)$$

where γ_{incl} is inclusive photon spectrum, γ_{decay} is decay photon spectrum and π_{param}° is parameterization of π° spectrum, used to reduce the systematic uncertainties.

The WA98 collaboration was first to measure the production of direct photons in S-Au (200 GeV) and Pb-Pb (158A GeV) at SPS [57, 58]. The PHENIX experiment also measured the direct photon spectrum at $\sqrt{s_{NN}}=200$ GeV in Au-Au collisions along with p-p results [59, 60] and later results were confirmed by ALICE [61, 62], CMS [63] and ATLAS [64]. The fig. 1.13 shows the R_γ vs p_T for different centralities for Pb-Pb and p-p collisions at 2.76 TeV energy. For p-p collisions, no direct photon excess was observed for any centrality while for Pb-Pb, there is a direct photon excess in all centrality classes for $p_T > 4$ GeV/c, as well as for $1 < p_T < 4$ GeV/c in the most central class.

Strangness enhancement

One of the early postulated signs for the Quark-Gluon Plasma was the strangeness enhancement in heavy-ion collisions [65–67]. The strange (s) quarks aren't present at early stages since the colliding nuclei only contain u and d quarks. This demonstrates that strange quarks are created thermally in the hot dense QGP medium during the strong interaction process. The strange quarks are produced mainly by 2 process, $g\bar{g} \rightarrow s\bar{s}$ and $q\bar{q} \rightarrow s\bar{s}$ whose dominance depends on whether the QGP medium is

gluon rich or quark rich.

NA57 [68,69], STAR [70–72] and ALICE [73] studied strangeness enhancement for different systems and different energies.

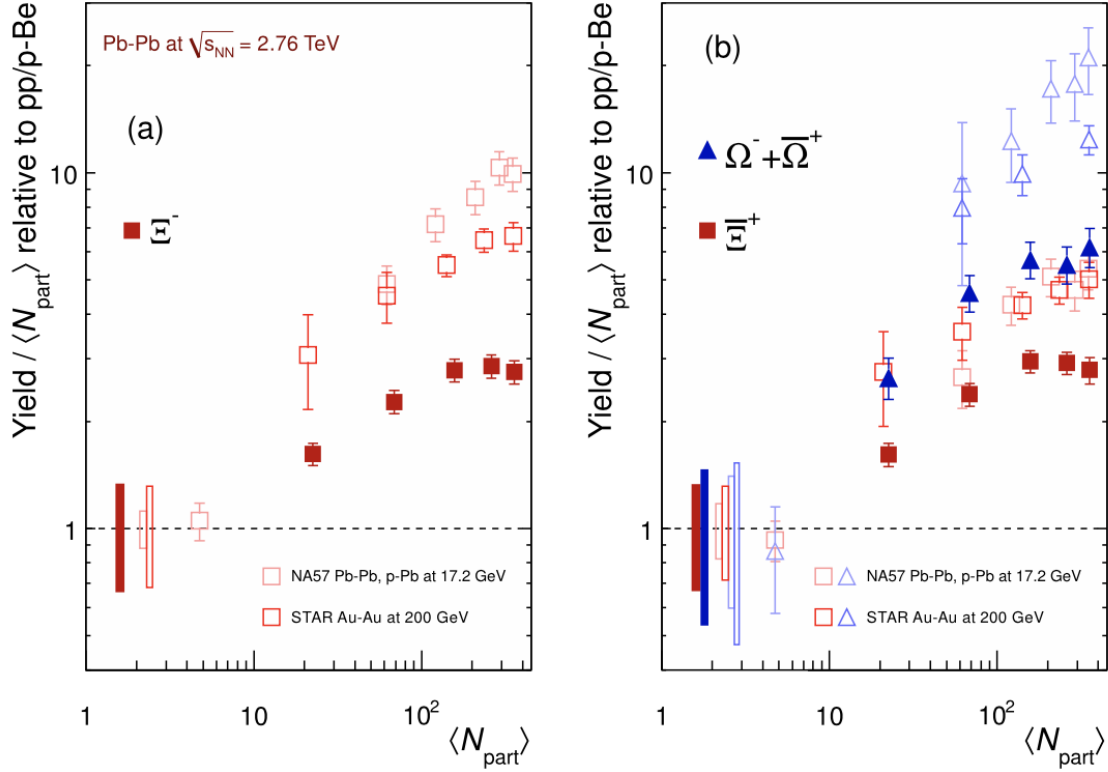


Figure 1.14: Strangeness enhancements as a function of N_{part} for a) Ξ^- and b) Ξ^+ , $\Omega^- + \bar{\Omega}^+$, showing (ALICE, solid markers), RHIC and SPS (open markers) data [73].

Fig. 1.14 shows the yields of strange particles i.e., $\Xi^- \rightarrow dss$ and $\Omega^- \rightarrow sss$, as a function of $\langle N_{part} \rangle$ for Pb-Pb collisions along with the STAR and NA57 results. The yields are greater than 1 which clearly show the enhancement in the production of strange particles.

Azimuthal Anisotropy

Another key characteristic of the particles created in heavy-ion collisions is azimuthal anisotropies in particles' production, which is a consequent of the system's thermalization. Generally, when two nuclei collide, non head-on collisions are dominated

and for these non-central collisions, the partial overlap of colliding nuclei forms an asymmetric interaction volume [74] (ellipsoidal shape), which is generally shown as an almond shape (Fig. 1.15). This spatial anisotropy creates asymmetric pressure gradient which is greater in the direction of the reaction plane (the plane formed by the impact parameter vector (“b”) and collision axis is known as Reaction plane (RP)) rather than orthogonal to it [74, 75]. As a result of the asymmetry, more particles tend to originate from the short axis of the almond than the long axis due to the higher pressure and the medium expands in a non-uniform manner due to the existing pressure gradients. In the final state, initial state spatial deformations of the overlap zone are transformed to an anisotropic momentum distribution. This transfer, also known as the anisotropic flow, indicates that partons are strongly interacting in the existence of a QGP.

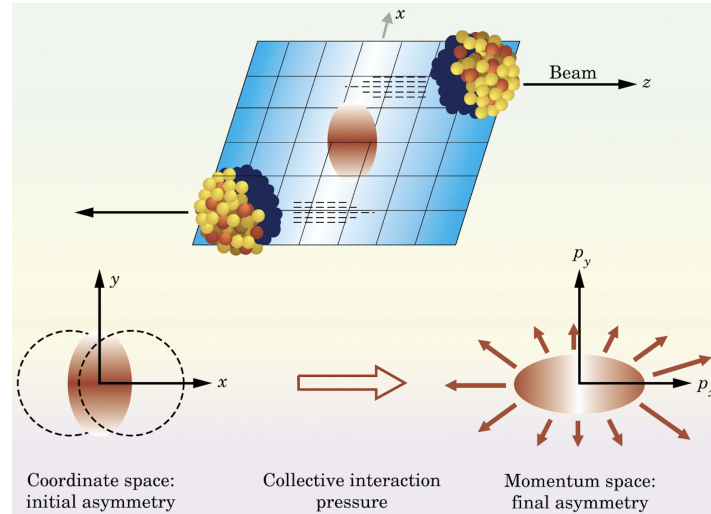


Figure 1.15: Pictorial depiction of non-central collision of heavy nuclei at very high energies [76].

The azimuthal distribution of produced particles is commonly represented using a Fourier series [77]:

$$E \frac{d^3 N}{dp^3} = \frac{1}{2\pi} \frac{d^2 N}{p_T dp_t dy} \left(1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\phi - \psi_r)) + \sum_{n=1}^{\infty} 2a_n \sin(n(\phi - \Psi_R)) \right) \quad (1.9)$$

where “E” is the energy of the particle; “p” is momentum; p_T is the transverse momentum; ϕ is the azimuthal angle; Ψ_R is reaction plane (RP) angle; and y is

the rapidity [78]. Here in eq. 1.9, v_n and a_n are the Fourier coefficients, a_n will be discussed in the next section while v_n denote the “FLOW” coefficients and $n = 1, 2, 3, \dots$ so on.

With the varying “ n ”, we have different cases for v_n :

- v_1 is known as “Directed Flow”. The non-zero value of the first coefficient of the Fourier expansion indicates that particles are emitted in a one single preferred direction.
- v_2 is known as “Elliptic Flow”. In contrast to directed flow, a non-zero v_2 indicates that the number of particles created parallel and orthogonally with regard to the impact parameter are different. If v_2 is less than zero, the emission is mostly out-of-plane; if v_2 is more than zero, the emission is mostly in-plane.

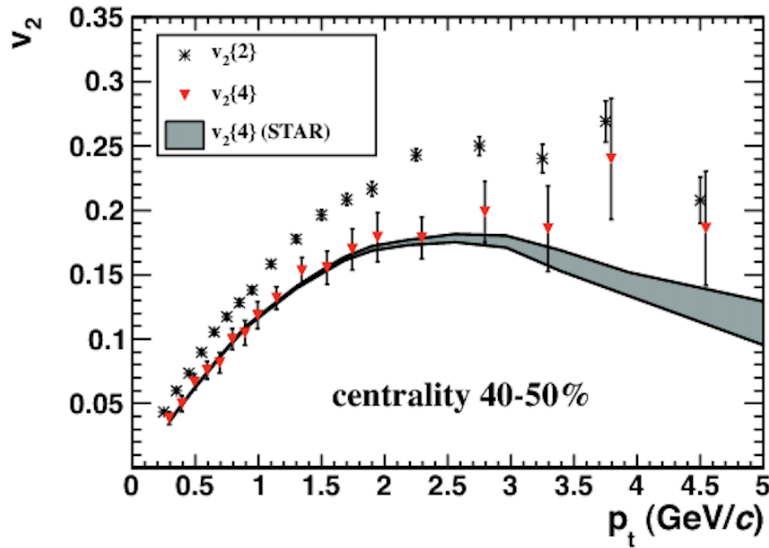


Figure 1.16: The dependence of v_2 (2-particle and 4-particle) on transverse momentum for 40-50% centrality for Pb-Pb collisions at 2.76 TeV along with the STAR results [87].

The v_2 is obtained as:

$$v_2 = \langle \cos(2(\phi - \Psi_{RP})) \rangle \quad (1.10)$$

here, $\langle \rangle$ represent the average over the particles, summed over all the events in a sample.

- v_3 and v_4 are “Triangular Flow” and “Quadilateral Flow”, respectively, and are related to the initial inhomogeneities.

Among these flows, elliptic flow is widely researched and many methods are developed to study it, namely, event-plane method [79,80], Q-cumulant method [81] and probability $p(v_2)$ [82]. The STAR [83,84], PHENIX [85], PHOBOS [86] and ALICE [87,88] have measured the v_2 using different methods and for different systems.

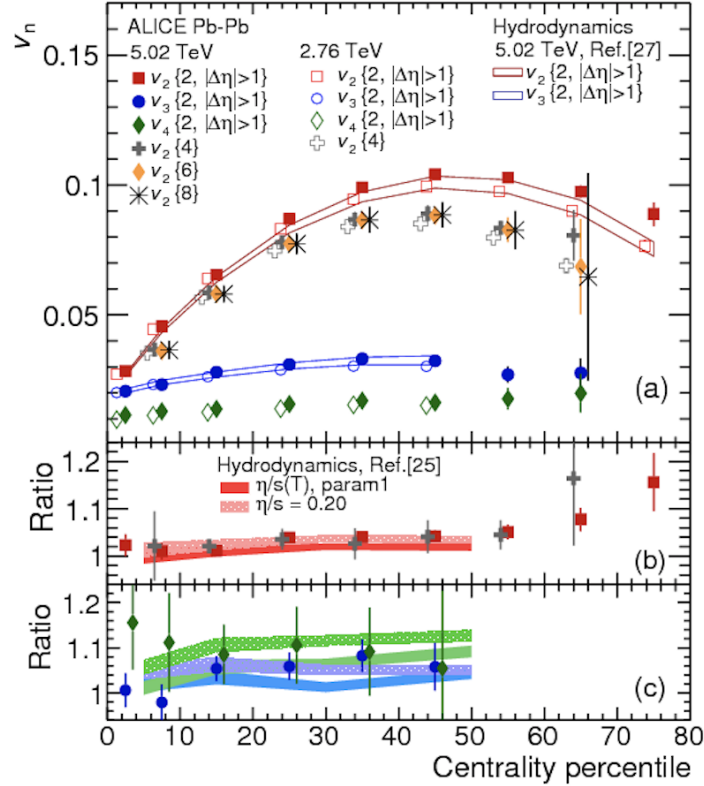


Figure 1.17: (a) Anisotropic flow as a function of centrality for 2.76 and 5.02 TeV along with the hydrodynamical model predictions. (b) and (c) are ratios of v_2 , v_3 and v_4 between 5.02 TeV and 2.76 TeV [88].

Fig. 1.16 shows the first results of elliptic flow in Pb-Pb collisions by ALICE at center of mass energy 2.76 TeV. The p_T differential elliptic flow is estimated for 40-50% centrality along with the $v_2\{4\}$ for Au-Au collisions at 200 GeV for same

centrality. The transverse momentum dependence for both the systems at different energies is almost similar within uncertainties.

For 2.76 and 5.02 TeV Pb–Pb collisions, fig. 1.17 shows the centrality dependency of elliptic flow, triangular flow and quadrilateral flow from two- and multi-particle cumulants, integrated across the $0.2 < p_T < 5.0$ GeV/c along with the hydro-dynamic model [88]. An average increase of $(3.0 \pm 0.6)\%$, $(4.3 \pm 1.4)\%$ and $(10.2 \pm 3.8)\%$, is observed for the v_2 , v_3 and v_4 flow, respectively, over the centrality range 0–50% going from 2.76 TeV to 5.02 TeV.

Energy Dependence: The p_T integrated v_2 obtained in the 20–30% centrality class in Pb–Pb collisions at the LHC energies is compared to measurements at lower energies in Fig. 1.18 [88]. From SPS/RHIC to LHC energies, there has been a steady rise in anisotropic flow for this centrality. About 30% increase in elliptic flow is observed with increasing energy from 200 GeV to 2.76 TeV and around 5% increase is seen for Pb-Pb collisions from 2.76 TeV to 5.02 TeV.

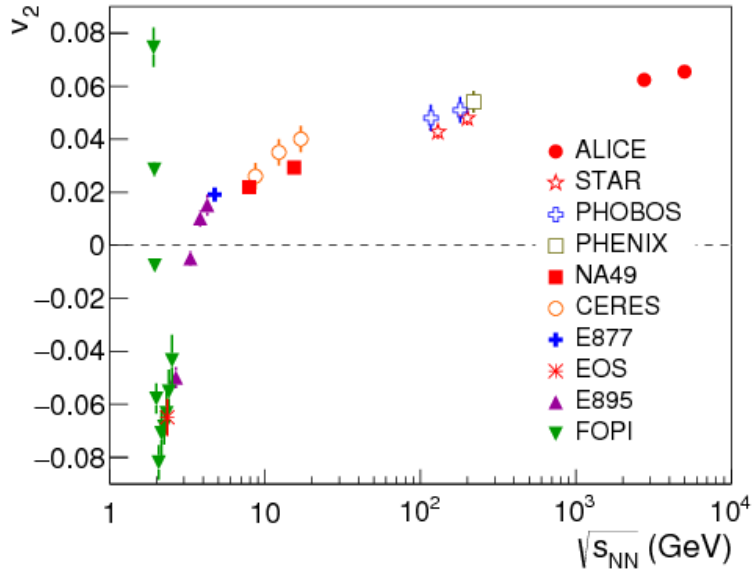


Figure 1.18: The integrated elliptic flow ($v_2\{4\}$) for the 20–30% central Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV compared with similar measurements at lower energies [88].

1.4 Chiral Magnetic Effect

Chirality (or handedness) is an important feature of fermions that is connected to the sign of the fermion's spin projection onto its momentum. If this projection is positive, the fermion is right-handed, but if it is negative, the fermion is left-handed and vice versa for anti-fermions. Because parity transformation “P” connects right- and left-handed fermions, topological vacuum transitions cause violations of P, as well as combined charge C and parity, CP symmetries. It is a well established fact that parity is violated in weak interactions while conserves in strong interactions [89, 90] but later it was discussed by Lee and Wick [91, 92]; Morley and Schmidt [93] and by Kharzeev *et al.* [94, 95] that in the vicinity of deconfined phase transition, QCD can have metastable domains where C and CP violation is possible. These “P - violating” bubbles lead to the difference in positive and negative chiralities of quarks. This difference combined with the large magnetic field (order of 10^{15} T), produced by the spectator particles in heavy-ion collisions, give rise to “Chiral Magnetic Effect (CME)” [96–99].

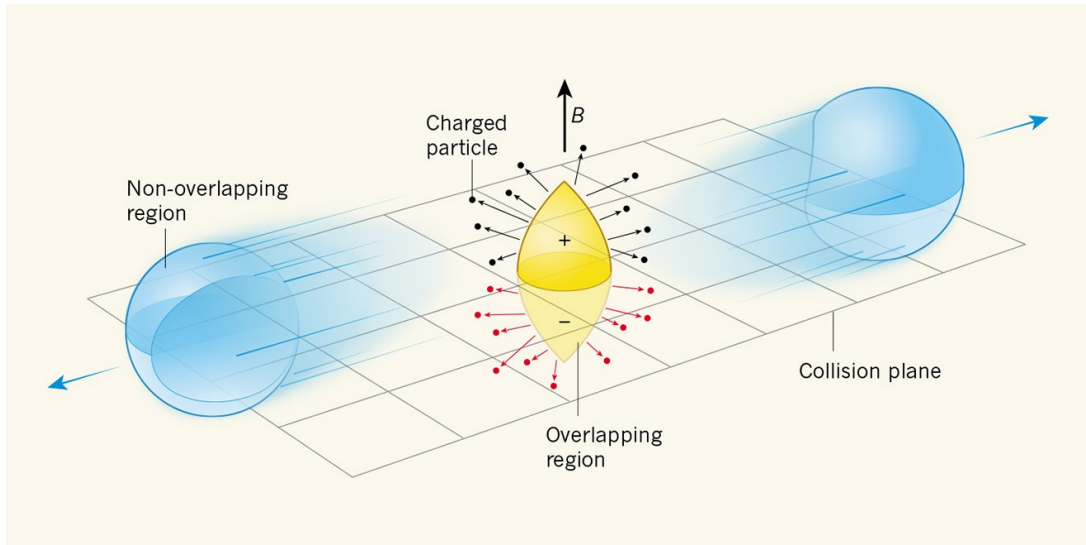


Figure 1.19: The non-overlapping areas of a heavy-ion collision with partially overlapping nuclei in the plane of the collision (blue arrows), whereas an extraordinarily strong magnetic field, B , is formed perpendicular to the plane. The chiral magnetic effect causes positively charged particles (black) and negatively charged particles (red) to be emitted from opposite regions of the overlapped area [104].

Over the last several years, most of the experiments are actively doing research on CME to develop new methods and observables to isolate CME and non-CME backgrounds. Voloshin [100] proposed the most widely studied observable, “ γ -correlator”, for measuring the charge separation with respect to the reaction plane. The STAR [101], ALICE [102] and CMS [103] have studied the CME by studying γ correlator. The detailed study of observables used to study the CME and previous measurements will be discussed in Chapter 3.

A new method “Sliding Dumbbell Method” is developed, tested on monte carlo model (Chapter 4) and applied on experimental data of Pb-Pb collisions at ALICE energies (Chapter 5). Through this new method, we study the back-to-back charge separation on an event-by-event basis. The events with back-to-back charge separation of CME kind are isolated and analyzed.

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CHAPTER

2

A LARGE ION COLLIDER EXPERIMENT

“You’re telling me that CERN dug out millions of tons of earth just to smash tiny particles?” Kohler shrugged.

“Sometimes to find truth, one must move mountains.”

Dan Brown, Angels & Demons

This chapter describes the experimental setup at CERN and its different components, which range from the particle accelerator chain to the ALICE detector subsystems. The key characteristics of the ALICE detector for data collection and reconstruction will also be discussed.

2.1 Introduction

It was in the early 20th century that the foundations of high energy nuclear and particle physics were laid. The discovery of composite nature of protons, further led to the understanding that the matter is composed of quarks and leptons and the strong interaction forces are responsible to hold all the nuclear matter together. The concept of asymptotic freedom at high QCD energies was first proposed in the 1970s, and in 1975, it was anticipated that hadronic matter would convert into another phase of matter at high temperature and low net baryon density, named the Quark Gluon Plasma (QGP). As discussed in the previous chapter, there are two methods to produce a quark-gluon plasma: either raise baryon density by compressing nuclear matter, as occurs naturally in neutron stars or increase temperature, as would occur if one could travel back in time to the initial few minutes after the Big Bang. In the latter case, at present, the Large Hadron Collider (LHC) at the European Organization for Nuclear Research (CERN) is the largest and most powerful particle accelerator allowing to collide protons at center-of-mass energies up to $\sqrt{s_{\text{NN}}} = 14$ TeV and heavy-ions with a maximum of $\sqrt{s_{\text{NN}}} = 5.5$ TeV per nucleon pair. CERN was established in 1954 in Geneva, Switzerland, and presently has 22 member states. It employs 3430 on-site scientists, engineers, and other employees and 17663 external users who have access to computational and experimental capabilities. CERN is also open to the public through guided tours of experiments and displays, bringing around 110,000 people each year into contact with its scientific program.

2.2 Large Hadron Collider

The LHC at CERN, located at the French-Swiss border near Geneva, is the world largest and the highest energetic particle accelerator. The LHC got its name as : Large because of its size (about 27 km in circumference), Hadron because it accelerates hadrons (protons or ions), and Collider because these particles collide at four spots where the machine's two rings cross. Due to the size and other essential

Quantity	number
Circumference	26 659 m
Dipole operating temperature	1.9 K (-271.3°C)
Number of magnets	9593
Number of main dipoles	1232
Number of main quadrupoles	392
Number of RF cavities	8 per direction
Energy, protons*	6.5 TeV
Energy, ions	2.56 TeV/u (**)
Peak magnetic dipole field	7.74 T
Distance between bunches	~7.5 m
Luminosity (protons)	Peak Luminosity: ~ $1.2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
No. of bunches per proton beam (design value)	2808
No. of protons per bunch (at start)	1.2×10^{11}
Number of turns per second	11 245
Number of collisions per second	1 billion

(*) Design value: 7 TeV

(**) Energy per nucleon

Table 2.1: Some parameters of the LHC [1].

elements, the maximum possible attainable energy in LHC is 7 TeV per proton beam. Also for collider experiments, the energy of the collision is the sum of the energies of two colliding beams. So, the accelerator was designed to reach center-of-mass energies up to $\sqrt{s_{\text{NN}}} = 14 \text{ TeV}$ for protons and up to $\sqrt{s_{\text{NN}}} = 5.5 \text{ TeV}$ for heavy-ions including lead, argon, xenon. These collision energies have never been achieved in a laboratory previously. Table 2.1 lists some of the important parameters of the LHC [1]. For further study refer to Ref. [1]

2.2.1 Accelerator Complex

The CERN accelerator complex comprises a series of units with escalating energies (Fig. 2.1). Each machine injects the beam into the next, which takes over to increase the beam's energy, and so on. Each particle beam is accelerated up to the record energy of 6.5 TeV at the LHC, the last link in this chain.

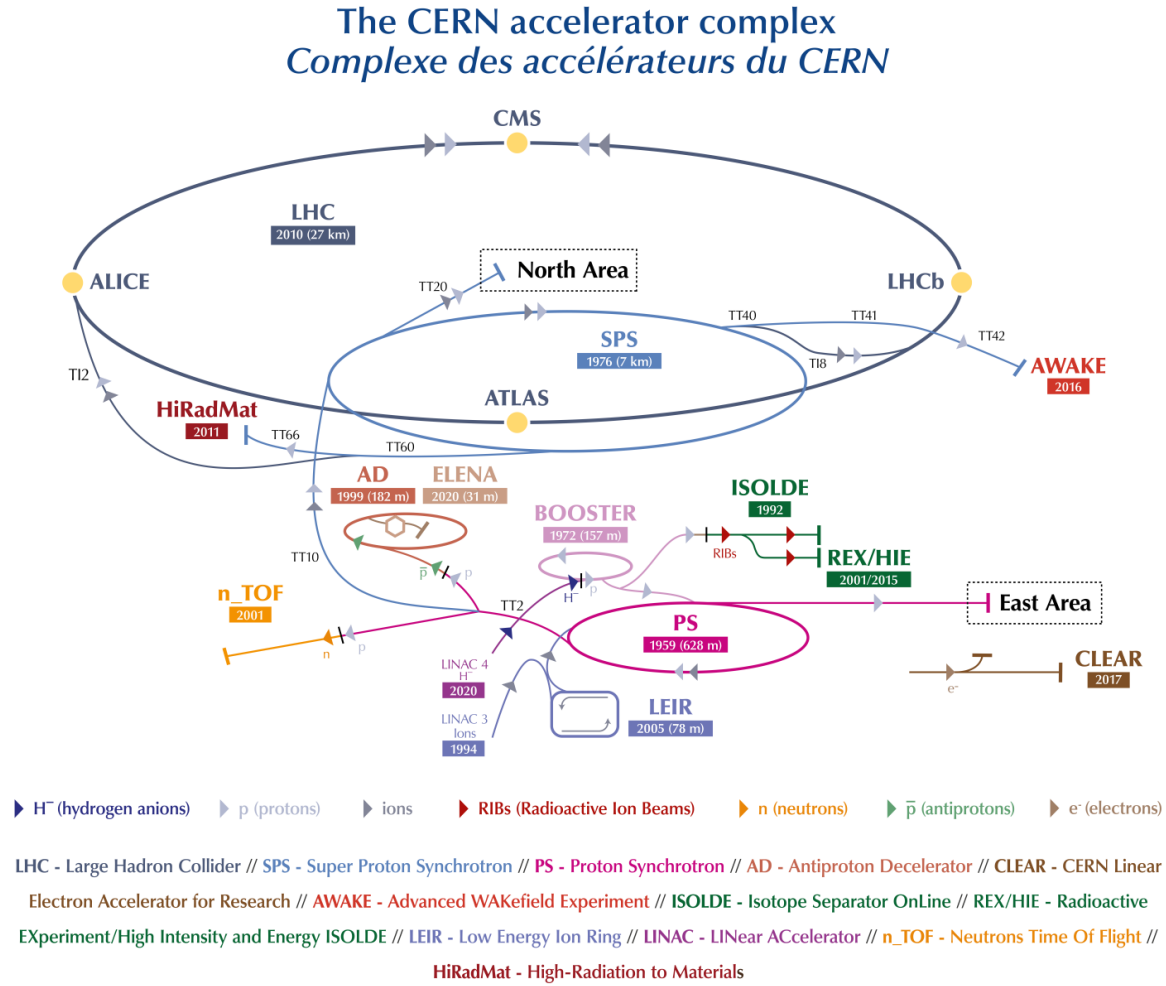


Figure 2.1: The accelerator complex at CERN [2].

The protons are extracted from an ionised hydrogen tank (hydrogen atom with stripped electron) and pumped into the LINAC2 linear accelerator, where they attain 50 MeV energy. They are then accelerated to 1.4 GeV through the Proton Synchrotron Booster (PSB). From PSB, proton are then injected to the Proton Synchrotron (PS) where they are accelerated to 25 GeV. The protons are injected into the Super Proton Synchrotron (SPS) from the PS, where they are accelerated to 450 GeV before being injected into the LHC.

The accelerator complex also accelerates heavy-ions in addition to protons and their initial stages of acceleration are somewhat different from the proton accelera-

tion. The ^{208}Pb ions are extracted from a highly purified lead sample by heating it around 800°C . Then electron currents are used to ionise the lead vapours and among many produced ions, only Pb^{29+} are chosen. These ions are then accelerated to 4.2 MeV/u (energy per nucleon) before passing through a carbon foil, which converts them to Pb^{54+} for the most part. The Pb^{54+} beam is gathered and then accelerated to 72 MeV/u in the Low Energy Ion Ring (LEIR), where they are transferred to the PS. After passing through a second foil where it is totally stripped to Pb^{82+} , the PS accelerates the beam to 5.9 GeV/u and transfers it to the SPS and follows the same steps described for the protons above.

The protons or heavy-ions are then injected into the LHC ring from two different points in different direction. These two beams collide in the four interaction locations that correspond to the four key LHC experiments: ATLAS, ALICE, CMS, and LHCb.

The pp collisions up to $\sqrt{s_{\text{NN}}} = 7$ TeV, p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV, and Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV are all part of the LHC Run1 physics programme, which began in 2009. The LHC's designed luminosity, which determines how closely packed the particles are in the beams, is $10^{34}\text{cm}^{-2}\text{sec}^{-1}$. In 2013, the Run1 finished and the Long Shutdown 1 (LS1) began. The LHC was improved during the LS1 in order to boost collision energy. The Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV, p-Pb collisions at $\sqrt{s_{\text{NN}}} = 8$ TeV, and pp collisions at $\sqrt{s_{\text{NN}}} = 13$ TeV were produced during the LHC Run2 physics programme, which began in 2015. The LHC Long Shutdown 2 began in December 2018, allowing the detectors to be upgraded in preparation for the LHC Run3 physics programme, which was supposed to be started in 2021 but due to Covid-19 started in 2022.

2.2.2 LHC experiments

For the four primary LHC experiments : ALICE (A Large Ion Collider Experiment), ATLAS (A Toroidal LHC Apparatus), CMS (Compact Muon Solenoid), and LHCb (Large Hadron Collider beauty), the particle beams of the LHC are brought to

the collision at specified contact locations. TOTEM (TOTal cross section, Elastic scattering and diffraction dissociation Measurement at the LHC), LHCf (Large Hadron Collider forward), and MoEDAL (Monopole and Exotics Detector at the LHC), which are placed along the beamline on each side of the CMS, ATLAS, and LHCb experiments, respectively, are smaller experiments that focus on particles created in forward directions. The following is a brief summary of each experiment, except ALICE, and their principal physics aims :

2.2.2.1 CMS

The Compact Muon Solenoid [3] is a versatile multilayer detector that derives its name from its relatively small dimensions of around $20 \times 15 \text{ m}^2$. Two silicon detectors, an electromagnetic calorimeter, a hadronic calorimeter, a magnet, and a muon detector system make up the center detector region, which comprises six layers in the radial direction. The innermost detector layers are silicon pixel detectors dispersed across three layers with radial lengths ranging from 5 to 10 cm, followed by 10 layers of silicon strip detectors with radial lengths ranging from 20 to 100 cm. Following the silicon layers is an electromagnetic calorimeter (ECAL). The CMS hadronic sampling calorimeter (HCAL) is primarily built of brass and plastic scintillator layers. In order to confine more significant hadronic showers, it is expanded by additional layers positioned outside of the magnet. The calorimeters are surrounded by a superconducting magnet covering a radial direction of 2.9–3.2 m. On the exterior of the magnet, a series of muon detectors cover radial lengths of 3.5 to 7 m. Fig. 2.2 depicts a sliced view of the detector, emphasizing the detector response to various particles and their track as the magnetic field changes. The CMS experiment looks for various physics and unpredicted phenomena, including supersymmetry (SUSY), physics beyond standard model and dark matter. CMS discovered the Higgs boson in 2012 alongside ATLAS, validating theoretical predictions for gauge theories to account for basic particle masses in the Standard Model.

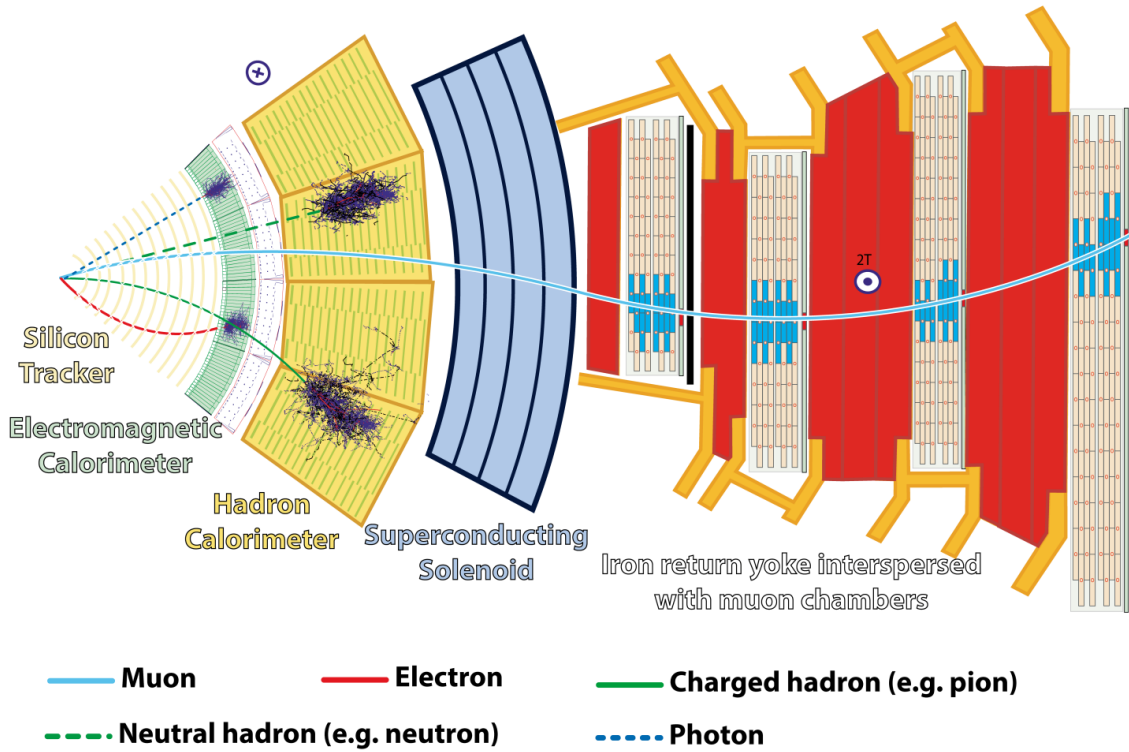


Figure 2.2: CMS detector along with its sub-detector and particle hit response [4].

2.2.2.2 ATLAS

The ATLAS detector [5] aims to achieve similar physics goals as the CMS experiment but with a different detector architecture that focuses on muon detection. Three layers of silicon pixel detectors in radial distances ranging from 5 to 25 cm are followed by further layers of silicon strip detectors at 30–60 cm from the interaction point in the detector. In the following radial layer from 0.6 to 1 m, ATLAS utilizes a transition radiation tracking (TRT) and electron identification detector. A solenoid magnet surrounds the TRT, producing a 2 T magnetic field followed radially by electromagnetic and hadronic sampling calorimeters. The ATLAS detector, like CMS, features huge muon detection systems encircling the center barrel, with extra layers at the end caps. The huge barrel toroid magnet which gives the experiment its name (A Toroidal LHC Apparatus), is the ATLAS detector's most distinguishing feature. Fig. 2.3 shows the layout of ATLAS detector. In 2012, ATLAS detected Higgs Bosons in the two-photon decay channel that agreed with CMS measurement.

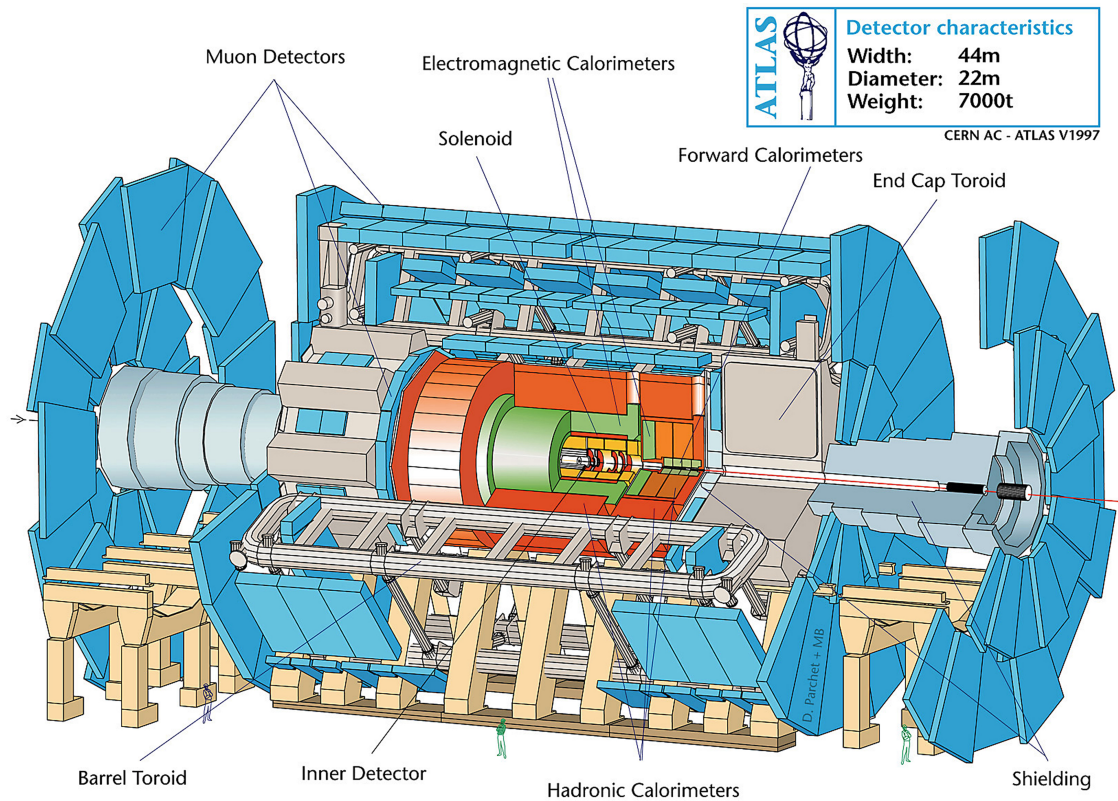


Figure 2.3: ATLAS detector's layout [6].

SUSY, the quest for new heavy bosons, CP-violation experiments, and the search for novel physics are among its other goals.

2.2.2.3 LHCb

Compared to the multifunctional experiments ATLAS and CMS, the LHCb [7] experiment took a new approach to design, focusing on forward spectrometry. It is made to precisely quantify the uncommon beauty and charm hadron decays and CP-violating observables. Because beauty hadrons are primarily generated in the front direction, the detector is designed as a forward cone to enhance its measurement acceptability. LHCb is equipped with a silicon strip detector called the VELO (Vertex Locator) that provides the collision vertex location starting at the interaction point. An array of Ring Imaging Cherenkov (RICH-1) detectors surrounds the VELO in forward direction, allowing particle identification using Cherenkov radiation (when a particle travels faster than the phase velocity of light across a medium, Cherenkov

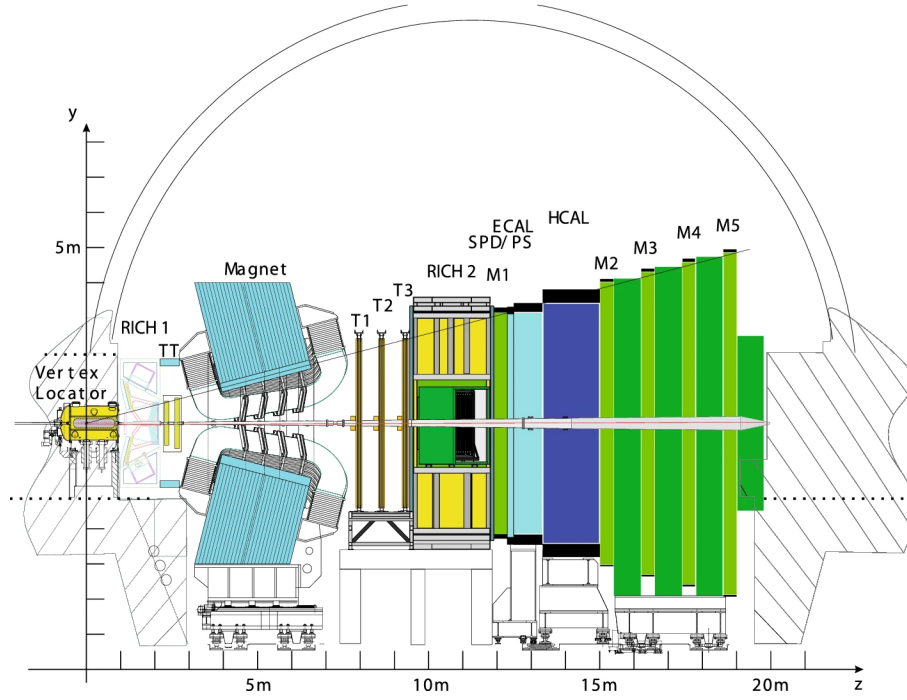


Figure 2.4: The side view of LHCb detector [8].

radiation is produced). A layer of silicon strip detectors is placed directly after the RICH, producing the trigger tracker (TT). The TT is followed by the spectrometer magnet, which generates a high magnetic field of 4 T, to better differentiate the numerous particles transiting the LHCb detector and for momentum measurements of those particles. The central tracking system, which is positioned immediately after the magnet, with the sections closest to the beam line is composed of silicon strip detectors and the outside tracker built of straw tubes. The RICH-2 Cherenkov detector, an electromagnetic and a hadronic calorimeter are used to complete the remaining particle identification and energy measurements. Finally, the experiment has five layers of Multi-Wire Proportional Chamber (MWPC) muon detectors and a section of Gas Electron Multiplier (GEM) detectors. Fig. 2.4 shows a slice image of the LHCb detector, showing its conical form and multiple sub-detector systems.

2.2.2.4 Forward Experiments

At CMS interaction point, there is TOTEM experiment [9]. Its purpose is to precisely calculate the proton-proton interaction cross-section and study the proton

structure itself. The LHCf experiment [10] consists of two sampling and imaging calorimeters on either side of the beamline, 140 metres from the ATLAS interaction point. Its goal is to monitor neutral particles created in proton-proton collisions so that Monte Carlo simulation modelling of cosmic ray interactions may be improved. The MoEDAL [11] is a forward experiment in the LHCb interaction point that aims to detect the magnetic monopoles to uncover physics beyond the standard model.

2.3 ALICE

ALICE - *A Large Ion Collider Experiment* [12], is the LHC's general-purpose heavy-ion experiment. Its primary objective is to research the QGP, and in order to do so, the detector must be able to reconstruct and identify the trajectories (tracks) of all particles created in a collision. For which ALICE is equipped with dedicated sub-detector systems. Heavy-ion data is collected for a few weeks at the end of each operating year. Data from pp collisions is collected throughout the rest of the year. While proton collisions were initially thought of as a non-QGP reference to the heavy-ion data in the context of the heavy-ion program, they are now a significant element of the ALICE physics program. The fig. 2.5 shows an overview of ALICE detector. With the dimensions of $16 \times 16 \times 26 m^3$, ALICE weighs 10,000 tonnes and 56 m underground at the village of St.Genis Pouilly in Swiss-French border.

The ALICE mainly consists of three parts [14] :

- The Central Barrel : covers the mid-rapidity region ($|\eta| < 0.9$).
- The Muon arm : covers the forward pseudorapidity range ($-4 \leq \eta \leq -2.5$).
- The Forward detectors i.e., Forward Multiplicity Detector, VZERO, TZERO etc.

The ALICE solenoid magnet generates a magnetic field of 0.5T around all of the detectors in the central barrel. Starting from the beamline and in the middle of

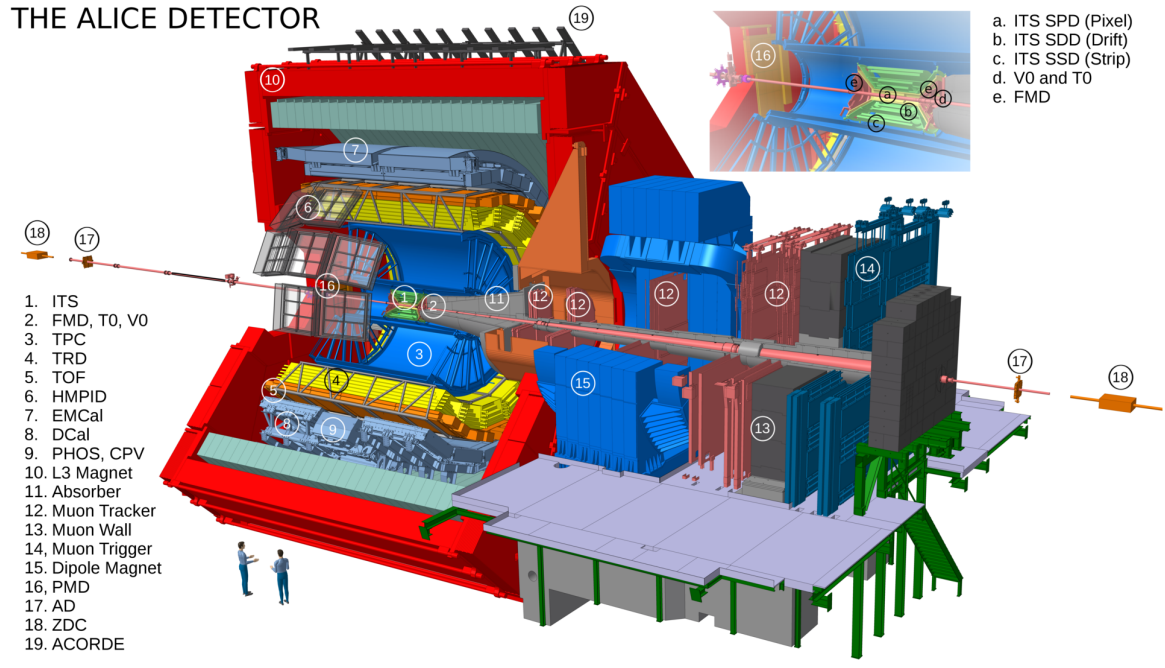


Figure 2.5: The overview of ALICE detector during LHC Run-II [13].

central barrel is the Inner Tracking System (ITS) [16] (closest to interaction point) which then surrounds with the main tracking device of ALICE, the Time Projection Chamber (TPC) [17]. The next layer in central barrel is the Transition Radiation Detector (TRD) [18] and is used for electron identification. Then comes the Time Of Flight (TOF) [19] which estimates particles' velocities. After TOF, there are the High Momentum Particle IDentification detector (HMPID) [20], the Photon Spectrometer (PHOS) [21], the ElectroMagnetic Calorimeter (EMCal) [22], the Di-jet calorimeter (DCal) [23] and the Charged Particle Veto detector (CPV) [24]. A Cosmic Ray Detector (ACORDE) [25], which is used for the study of cosmic rays, also works in same rapidity region as of central barrel but outside the barrel.

The Muon Tracker, Muon Wall, and Muon Trigger are all found in the muon arm [26]. These detectors are used to examine the creation of quarkonia and their disintegration into muons at forward rapidity.

The Zero Degree Calorimeter (ZDC) [27], the Photon Multiplicity Detector (PMD) [28], the Forward Multiplicity Detector (FMD) [29], the VZERO detector (V0) [30], and the TZERO (T0) [31] are the forward detector. The ZDC is a set

of two calorimeters, situated 116 metres distant along the beam pipe on either side of the interaction point, gathering the spectator fragments of the collision. The ZDC is used to determine the centrality of a Pb–Pb collision, whilst the PMD and FMD are employed to investigate the multiplicity of photons and charged particles, respectively. Finally, the V0 is a trigger detector that measures charged particle multiplicity, while the T0 calculates the time of the event.

Detector	Acceptance		Position	Technology	Main purpose
	Polar	Azimuthal			
SPD*	$ \eta < 2.0$	full	$r = 3.9$ cm	Si pixel	tracking, vertex
	$ \eta < 1.4$	full	$r = 7.6$ cm	Si pixel	tracking, vertex
SDD	$ \eta < 0.9$	full	$r = 15.0$ cm	Si drift	tracking, PID
	$ \eta < 0.9$	full	$r = 23.9$ cm	Si drift	tracking, PID
SSD	$ \eta < 1.0$	full	$r = 38$ cm	Si strip	tracking, PID
	$ \eta < 1.0$	full	$r = 43$ cm	Si strip	tracking, PID
TPC	$ \eta < 0.9$	full	$85 < r/\text{cm} < 247$	Ne drift+MWPC	tracking, PID
TRD*	$ \eta < 0.8$	full	$290 < r/\text{cm} < 368$	TR+Xe drift+MWPC	tracking, $e^\pm$ id
TOF*	$ \eta < 0.9$	full	$370 < r/\text{cm} < 399$	MRPC	PID
PHOS*	$ \eta < 0.12$	$220^\circ < \phi < 320^\circ$	$460 < r/\text{cm} < 478$	PbWO ₄	photons
EMCal*	$ \eta < 0.7$	$80^\circ < \phi < 187^\circ$	$430 < r/\text{cm} < 455$	Pb+scint.	photons and jets
HMPID	$ \eta < 0.6$	$1^\circ < \phi < 59^\circ$	$r = 490$ cm	C ₆ F ₁₄ RICH+MWPC	PID
ACORDE*	$ \eta < 1.3$	$30^\circ < \phi < 150^\circ$	$r = 850$ cm	scint.	cosmics
PMD	$2.3 < \eta < 3.9$	full	$z = 367$ cm	Pb+PC	photons
FMD	$3.6 < \eta < 5.0$	full	$z = 320$ cm	Si strip	charged particles
	$1.7 < \eta < 3.7$	full	$z = 80$ cm	Si strip	charged particles
	$-3.4 < \eta < -1.7$	full	$z = -70$ cm	Si strip	charged particles
V0*	$2.8 < \eta < 5.1$	full	$z = 329$ cm	scint.	charged particles
	$-3.7 < \eta < -1.7$	full	$z = -88$ cm	scint.	charged particles
T0*	$4.6 < \eta < 4.9$	full	$z = 370$ cm	quartz	time, vertex
	$-3.3 < \eta < -3.0$	full	$z = -70$ cm	quartz	time, vertex
ZDC*	$ \eta > 8.8$	full	$z = \pm 113$ m	W+quartz	forward neutrons
	$6.5 < \eta < 7.5$	$ \phi < 10^\circ$	$z = \pm 113$ m	brass+quartz	forward protons
	$4.8 < \eta < 5.7$	$ 2\phi < 32^\circ$	$z = 7.3$ m	Pb+quartz	photons
MCH	$-4.0 < \eta < -2.5$	full	$-14.2 < z/\text{m} < -5.4$	MWPC	muon tracking
MTR*	$-4.0 < \eta < -2.5$	full	$-17.1 < z/\text{m} < -16.1$	RPC	muon trigger

Table 2.2: The geometrical facts concerning the ALICE detectors' design [15].

The coverage and main purpose of the ALICE's sub-detector is listed in Table 2.2 and key detectors involved in the analysis of this thesis are described in the following sections.

2.3.1 Inner Tracking System

ALICE's Inner Tracking System (ITS) is made up of six cylindrical layers of silicon detectors that are centred on and near to the interaction point. It is arranged in between the beam pipe and the Time Projection Chamber's inner wall. The layering consists of two layers of each: the innermost - silicon pixel detectors (SPD), the central - silicon drift detectors (SDD) and the outermost - double-sided silicon strip detectors (SSD). The SPD at radial position of 3.9 and 7.6 cm, covers the pseudorapidity region of $|\eta| < 1.75$ for particles generated at $z = 0$ while whole ITS allows for $|\eta| < 0.9$ range. The radial positions of other two are: 15 and 23.9 cm for two layers of SDD and; 38 and 43 cm for SSD, respectively.

The primary goals of this detector are to trace the collision vertex and secondary vertices from weakly decaying particles in order to supplement TPC tracking information and, in the case of the SPD, to give triggering input for the whole detector. The granularity of this detector system is exceedingly fine, allowing for excellent tracking and vertexing resolution even at extremely high multiplicity. Furthermore, particle identification is attainable even below the TPC's lower momentum limit because of ITS's closeness to the beam pipe, high momentum resolution, and broad specific energy loss range.

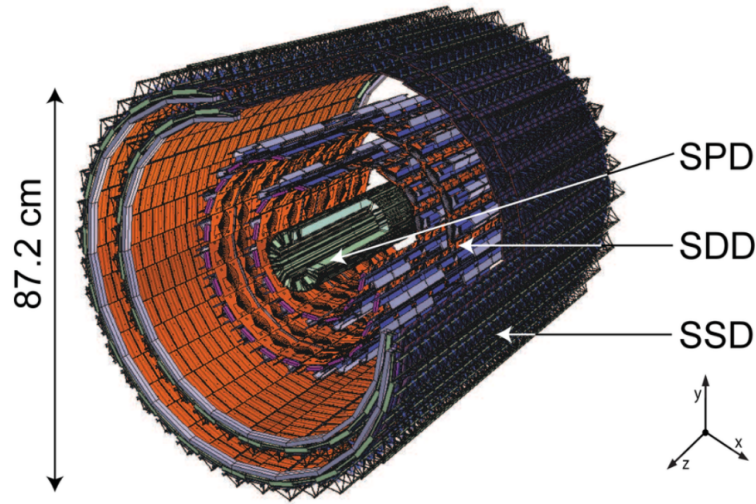


Figure 2.6: The ALICE ITS schematic diagram [32].

The figure 2.6 depicts the layout of ITS. As clear from the names of the sub-detectors, the silicon-based detector modules are employed throughout the ITS. Silicon is a semiconductor, which means it contains two bands: valence and conduction, separated by a band gap. When a charged particle (or photon) hits the detector, electron-hole pairs form along the route, resulting in a current pulse. This current will travel through the electric field and eventually be collected at the electrodes. Through this current, detector will get the information of particle's hit. The advantages of employing a semiconductor are that it produces a quick signal, making it feasible to calculate the interaction time with high precision, and that the electron diffusion length is only a few μm , allowing for extremely high tracking resolution. Each sub detector uses a different technology. While the SPD has a digital readout, the SDD and SSD have analogue readouts. As a result, the SDD and SSD can be utilized for PID (Particle Identification) by measuring the specific energy loss dE/dx .

2.3.2 V0

V0A and V0C, two circular arrays of scintillator counters, one in each of the forward sections, make the V0. Both these sub-detectors cover the full azimuthal range. The V0A is located 300 cm from the collision vertex, covering the pseudorapidity range $2.8 < \eta < 5.1$, whereas the V0C array is just 90 cm away, covering $3.7 < \eta < 1.7$. Each array consists of four layers, each with eight scintillators, each covering a 45-degree azimuthal segment. This has a low granularity, yet it is good for measuring multiplicity. A scintillator detector uses a scintillating substance stimulated by charged particles passing through it, resulting in a light pulse. A plastic scintillator is utilized in the V0 detector. The photons are transformed to electrons and multiplied in a strong electric field, which is steered to photomultiplier tubes at the detector edges. The plastic scintillator detectors are quick and have excellent timing resolution (in the V0, better than 1 ns). When employed in counting mode, as in the V0, the number of pulses exceeding a specific threshold is counted, representing event

multiplicity in the forward regions. The V0 multiplicity is employed for classifying the events into centrality classes since it is significantly connected with the overall event multiplicity and hence the collision centrality.

2.3.3 Time Projection Chamber

The center piece of the ALICE central barrel is the main tracking detector, large Time Projection Chamber (TPC). It is a gaseous ionisation detector which uses ionisation of noble gas (Ne or Ar) for detecting the charged particles and; has an inner radius and outer radius of 85 cm and 250 cm, respectively, with an overall length of 500 cm. With an active volume of 90 m^3 , this gas chamber occupies a large portion of the L3 magnet, which is thus completely covered by the magnet's 0.5 T magnetic field. It is tailored to give momentum measurements with good two-track separation, particle identification by dE/dx measurement, and vertex determination together with the other detectors in the centre barrel. The TPC covers the pseudorapidity range of $|\eta| < 0.9$ with the inner and outer read-out pads while the coverage of $|\eta| < 1.4$ is feasible when just the inner tracking section of the TPC is used. In standalone mode, it performs measurements from low p_T ($0.1 \text{ GeV}/c$) to high p_T ($100 \text{ GeV}/c$) with a transverse momentum resolution of roughly 5% for $p_T < 20 \text{ GeV}/c$ and 35% for $p_T = 100 \text{ GeV}/c$. When the ITS and TRD information are merged, the resolution improves by a factor of 5-7 (depending on the p_T).

The detector is made up of a cylindrical field cage with a central high-voltage cathode that splits the TPC in half and two end-plate anodes with readout detectors that are multi-wire proportional chambers (MWPC) (Fig. 2.7). The center cathode and end-plate anodes on either side of the TPC produce very uniform electric fields of 400 V/cm . At the center, there is a mixture of gas : a mixture of Neon and CO_2 in Run1 and in part of Run2 and a mixture of Argon and CO_2 in the other part of Run 2. This modification was required to the gas decrease space charge accumulation in the TPC and the resultant tracking distortions. The CO_2 is used as quenching agent.

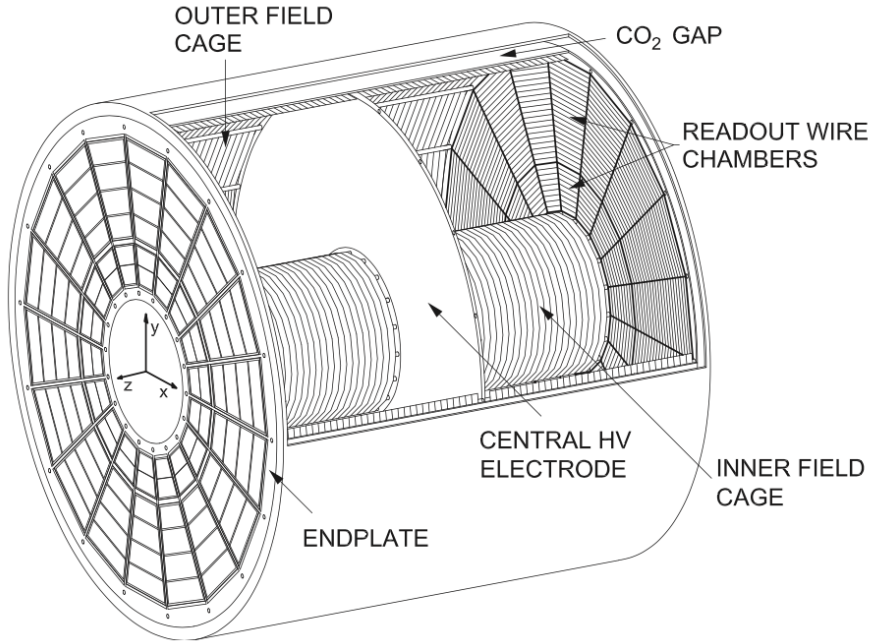


Figure 2.7: The TPC field cage [33].

When a charged particle traverse through the active volume of the TPC, it will cause ionisations and creating electron-ion pairs. The electrons produced in the ionisation, drift towards the end plates. The electric field is inversely proportional to the distance to the anode (due to it's thin wire configuration) in the region of the anode, resulting in a very strong electric field near the anode. As a result, electrons accelerated in the field will accumulate sufficient energy to generate secondary ionizations, resulting in a chain reaction known as avalanche multiplication. As a result, a few initial electrons can cause a significant voltage pulse to be created at the readout plane, which the system detects. The voltage pulse will continue until all of the ions have been captured at the cathode. The TPC is also a particle identification detector, with particle identification accomplished by measuring the specific energy loss dE/dx , which is proportional to the number of captured electrons in the reading chambers. The TPC is a superb detector for tracking and PID, but it comes at a price: a long drift time (88 μ seconds), which limits the data collecting rate (1 kHz).

The endcaps are separated into 18 sectors, each with two inner readout chambers (IROCs) and two outer readout chambers (OROCs). The IROCs have a higher

wire density and a lower voltage as they are closer to the beam pipe. There are three layers of wires in the readout chambers. The tiny anode wires are spaced 2.5 mm apart from the innermost wires. The ions emitted during avalanches are collected, and the signal is read out from cathode pad planes in the intermediate layer, which is made up of thicker cathode wires.

2.4 Tracking

A tracking algorithm is employed to rebuild the particle tracks from the detector hits. Figure 2.8 depicts a pictorial overview. The Kalman filter algorithm [34] uses track parametrization and optimizes trajectories by adding more and more space points over time. The process begins with a seed consisting of a few TPC clusters. Based on the condition that the track originates from the collision vertex, which is extrapolated from the SPD tracks, an initial guess of the trajectories is created. After eliminating this constraint, the procedure is repeated, implying that the track starts from a secondary vertex following a decay. After then, the tracking data is refined by propagating the track inwards and adding space points within 4σ (standard deviations of the trajectory) of the best guess, accounting for scattering and energy loss effects. Each iteration improves the accuracy by updating the parameters as well as the covariance matrix of the parametrisation. Several distinct propagations are evaluated if more than one detector hit meets the condition. The tracks with the lowest χ^2 (the greatest significance) are chosen until the end. When approaching the TPC's edge, space points from the ITS are added to improve tracking. When track propagation is performed in both the TPC and the ITS, the Kalman filtering is inverted by starting from the innermost layer of the ITS and propagating outwards, utilising the track parameters determined in the first iteration as an initial guess and continuing the operation. Outliers are removed from the track propagation in this way. When you get to the edge of the TPC, you can add space points from the TRD and then the TOF (and, in certain cases, HMPID and/or CPV, which don't cover the whole azimuthal angle). Finally, in order to further optimise the track

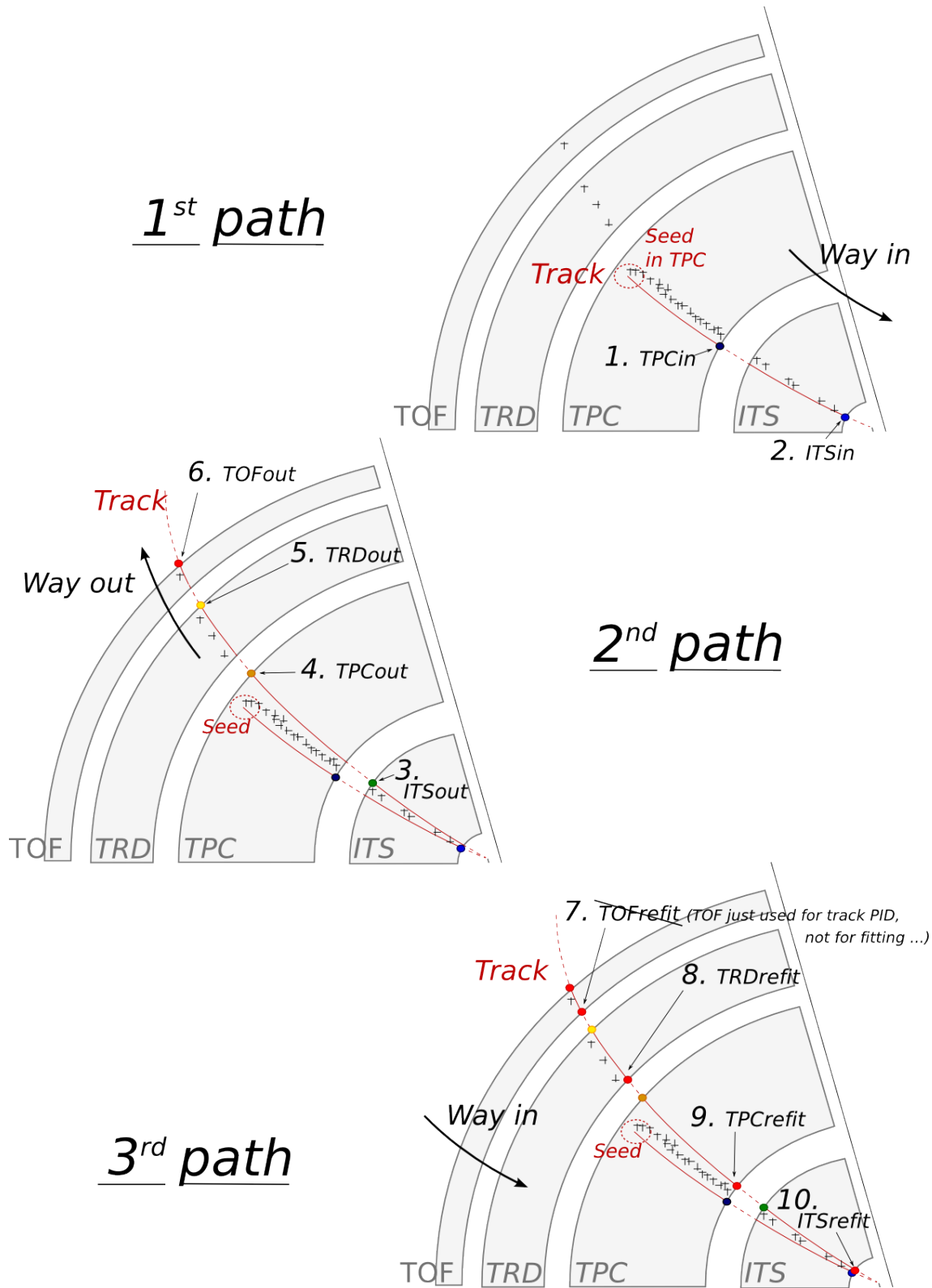


Figure 2.8: The overview of track reconstruction process in ALICE [35].

parameters, a final refit is being performed, beginning with the outer detectors and proceeding inwards.

2.5 Triggering and Data Acquisition

The ALICE subsystems can be operated with event rates of up to a few kHz. However, because the LHC bunch crossing rate is 40 MHz, significant triggering is necessary to limit the event rate and verify that all particles recorded during a single event are genuinely from the same collision, even though not all bunch crossings result in a collision. The V0 and SPD detectors are the most important for triggering, while the ZDC is also utilized in Pb–Pb collisions. The Central Trigger Processor (CTP) handles the trigger input and sends a signal to all active detectors after a successful trigger. L0, L1, and L2 are the three levels of triggers. Only events that the highest level, L2, has approved are read. The quickest inputs are included in the L0 trigger, synced with ALICE’s LHC bunch crossing clock. Within $1.2\ \mu\text{s}$ of the collision, all inputs at this level are processed. The L1 trigger, which takes $6.5\ \mu\text{s}$ to complete, handles the remaining quick inputs. All slower inputs are handled by the L2 trigger, which must be finished before the TPC read out, or within $88\ \mu\text{s}$ after the collision.

The trigger uses different detector signals depending on the trigger setup. Minimum bias (MB), which allows events that follow the complete multiplicity distribution, and high multiplicity (HM), which is only active in pp collisions and only activates on the top 0.1 percent of events with the highest multiplicity, are two key configurations. The MB trigger has been used for this thesis work. The MB trigger requires a hit in both V0 detectors, adequate for pp and p-Pb collisions with modest multiplicities. In order to limit beam-gas occurrences, additional restrictions are applied to the V0 timing information and the correlation between the number of tracklets and clusters in the SPD. Electromagnetic phenomena associated with Pb–Pb and Xe–Xe collisions, pollute the V0 trigger. So extra limits were introduced to eliminate them, including a V0 amplitude cut-off in the 2015 Pb–Pb run. The

number of V0 channels where hits were identified as beam-gas interactions (based on time) was reduced, and it was necessary that neither the preceding nor the following bunch crossing have any activity to avoid pile-up.

The call from the CTP will initiate a sequence of read-out operations in each active detector after a successful trigger and the trigger input is finally recorded locally at a Local Data Concentrator (LDC). During recording, chosen sections of the data received to the LDCs are copied and transferred to the High-Level Trigger (HLT), where it is evaluated to determine if the event should be stored or rejected. This is the final triggering stage when some compression is performed by removing unnecessary data. If approved, a portion of the data from the whole event will be transferred through DAQ (Data Acquisition system) to Global Data Concentrators (GDCs), where the entire event will be created and then recorded at a Transient Data Storage. To ensure high quality, a portion of the data from the event will be analyzed online using data quality monitoring and detection algorithms. If the ALICE shift crew is told that the quality evaluation has failed, the shift leader may opt to stop the run until the problem is resolved. Finally, the data will be duplicated and delivered to GRID for final storage and post-processing.

The offline processing is done using GRID, a distributed computing network. For example, all tracks are reconstructed here. The Event Summary Data (ESD) files are created from the processed event data and may be analyzed directly by the analysis program. However, due to the large quantity of data provided, these are quite time-consuming to analyze. Hence a second processing stage is used to choose the most relevant data for most analysis. The Analysis Oriented Data (AOD) files are then used to store this information. The operation is then repeated in numerous steps, known as analysis passes, with each pass's detector calibration fine-tuned. In addition, related Monte Carlo (MC) simulation runs are carried out depending on each run period's detector and beam conditions, in the same manner that data is.

The main analysis discussed in chapter 5 of this thesis is based on the AOD files.

2.6 Multiplicity Determination

The charged particle multiplicity, $\frac{dN_{ch}}{d\eta}$, is a crucial parameter for event categorization. The V0M signal, the combined signal of V0A and V0C, proportional to the number of charged particles that pass through the detector, is used to calculate the multiplicity of charged particles. The Glauber Monte Carlo is paired with a model for particle production based on a negative binomial distribution (NBD) to mimic the observed multiplicity distribution. The number of participants (N_{part}) and number of collisions (N_{coll}) are defined by the Glauber Monte Carlo and NBD defines the particle multiplicity per nucleon-nucleon collision. The figure 2.9 [36] shows the Glauber-NBD fit to the distributions of V0 amplitude for all accepted Pb–Pb collisions with a vertex within 10 cm at $\sqrt{s_{NN}} = 2.76$ TeV (Left) and 5.02 TeV (Right). The data sample is classified into ten multiplicity classes, as shown in figure, based on the percentiles of the V0M signal amplitude distribution. Thus

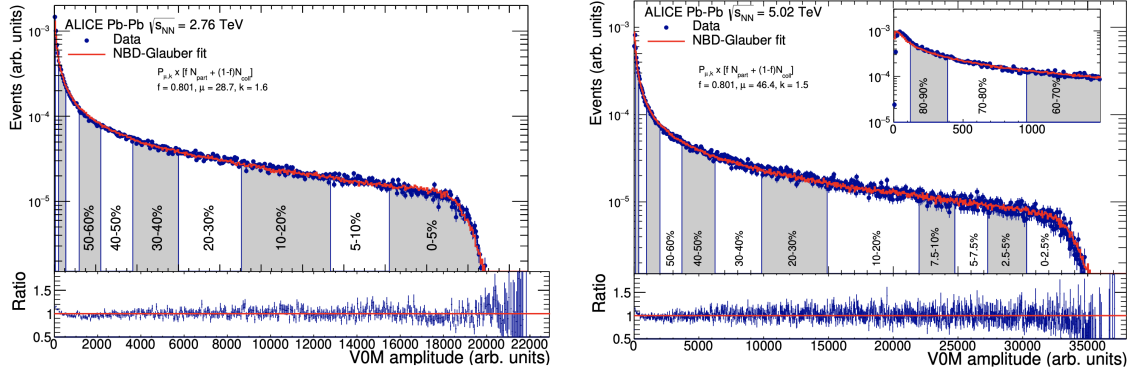


Figure 2.9: The distribution of the sum of amplitudes in the V0 scintillators for Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV (Left) and 5.02 TeV (Right). The NBD-Glauber fit is depicted as a line on the distribution [36].

multiplicity classes are defined.

2.7 Data Sets

ALICE has received a variety of particle beam configurations from the LHC, including symmetrical proton-proton (pp), lead-lead (Pb–Pb), and xenon-xenon (Xe–Xe)

collisions, as well as asymmetric proton-lead (p-Pb) collisions. All collision systems' center-of-mass energies have increased over time, and ALICE has now collected data in pp collisions at six different center-of-mass energies ranging from $\sqrt{s_{\text{NN}}} = 0.9$ TeV to 13 TeV, as well as p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ and 8.16 TeV. The Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ and 5.02 TeV, as well as Xe-Xe collisions at $\sqrt{s_{\text{NN}}} = 5.44$ TeV, were part of the heavy ion programme. Table 2.3 lists a timeline with the various beam configurations and the approximate duration of the various data collection programs.

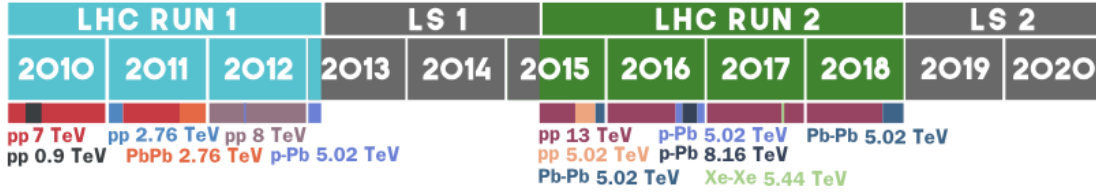


Table 2.3: Timeline diagram of the key LHC physics beam combinations till 2020.

The data used in this thesis comes from both LHC Run 1 and LHC Run 2 and follows a standard naming convention in ALICE in which the data set's name starts with the year it was collected (e.g., 2010), followed by a letter identifying the so-called data collection period.

2.7.1 Upgradation

CERN started working on 22nd April 2022, again after long shut down and upgrade. ALICE will face new opportunities and problems when luminosity increases, first in 2022 and then in the High-Luminosity LHC (HL-LHC) programme. It will be able to examine unusual events and make high-precision measurements thanks to an increase in luminosity, which will reveal insight into the thermodynamics, evolution, and flow of the QGP and quark and gluon interactions. Some major changes happen in the detector system of ALICE (Fig. 2.10). ALICE's present beam pipe will be replaced with one with a lower diameter during this upgrade. Particles traveling at almost the speed of light collide inside the detector's core, creating many new

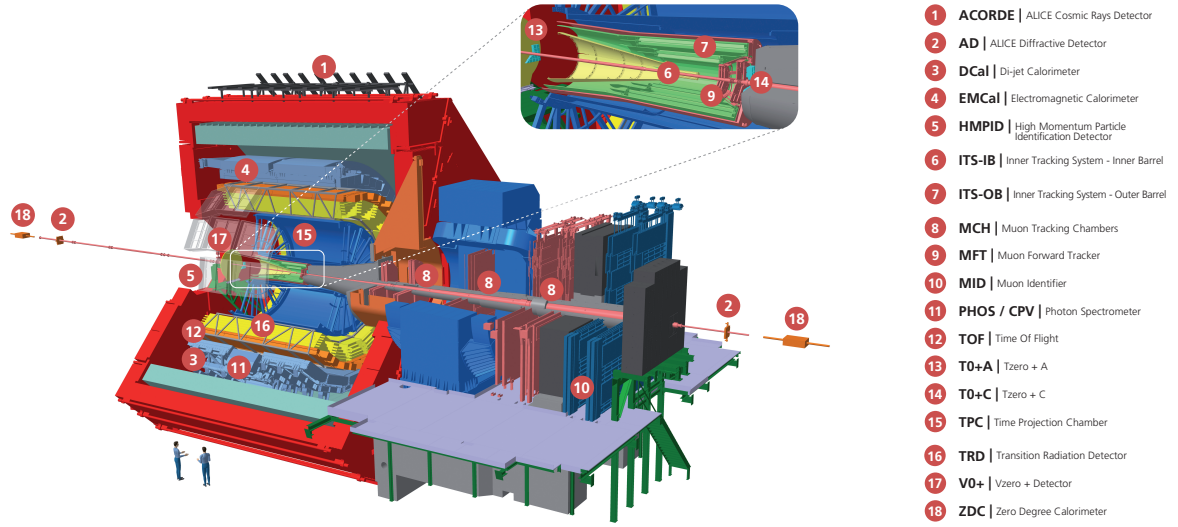


Figure 2.10: The overview of ALICE detector after upgrade [37].

particles and lowering the diameter of the beam pipe, enhancing the chances of measuring the interaction point by a factor of three over the current detector. ALICE will also improve its detection of shorter-lived particles, such as ones decaying closer to the interaction point. The replacement of the inner tracking system (ITS), which surrounds it, necessitates a new beam pipe. Innovative, small pixel sensor chips will be used in the new ITS. The new technology will boost the detector's ability to locate and reconstruct particle paths significantly. The TPC is also undergoing a major upgrade. The existing readout, based on multi-wire proportional-chamber technology, will be replaced with multi-stage gas electron multiplier (GEM) chambers to deal with increasing interaction rates. Due to this modification, nearly two orders of magnitude will increase the detector's readout rate. The PMD (India's very own contribution) has been taken out from the ALICE.

The existing trigger mechanism will be abolished when the system is upgraded to continuous read-out. The DAQ system, both on the hardware and software side, has to be upgraded as a result of the new trigger operation and increased data rates. The processing will be carried out using O^2 , a new Offline–Online technology.

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CHAPTER

3

CHIRAL MAGNETIC EFFECT

“If I have seen further it is by standing on the shoulders of giants”

Sir Isaac Newton

In this chapter, overview report of Chiral Magnetic Effect is given. What is this effect; why this effect happens and background effects; experimental observables; previously studied methods and experimental results; need of new method, all will be discussed in this chapter.

3.1 Introduction

In quantum chromodynamics, at very high temperature and/or density in the event of quark-gluon plasma formation, metastable domains containing fluctuating topological charges can change quark chirality, leading to CP violation, locally [1–3]. This local parity violation along with the strong magnetic field ($B \sim 10^{15}$ T), produced by the spectator protons can culminate in detectable electric charge separation in the direction of the magnetic field in relativistic non-central heavy-ion collisions. This phenomenon evidenced by the charge separation along the direction of magnetic field is known as Chiral Magnetic Effect (CME) [4–6] (Fig. 3.1).

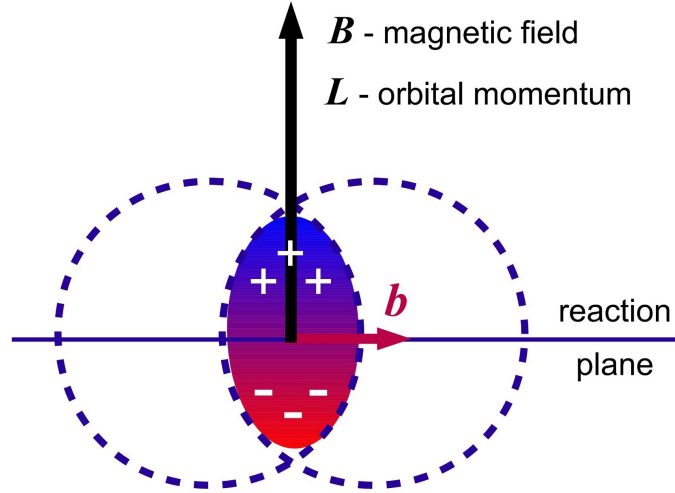


Figure 3.1: A schematic illustration of charge separation in non-central heavy-ion collision. Dashed circles represent the colliding nuclei moving outwards, the magnetic field (B) and system orbital angular momentum (L) are perpendicular to the reaction plane (plane formed between the impact parameter (b) and direction of collision).

The main ingredients for this effect to occur are quark-gluon plasma medium and the presence of strong external magnetic field. At very early stage of the heavy ion collisions, both these requirements are fulfilled.

In heavy-ion collisions, Fourier decomposition of particle azimuthal angle dis-

tribution in momentum space is described as :

$$\begin{aligned} \frac{dN}{d\phi} \propto & 1 + 2v_1 \cos(\phi - \psi_{RP}) + 2v_2 \cos 2(\phi - \psi_{RP}) + \dots \\ & + 2a_1 \sin(\phi - \psi_{RP}) + 2a_2 \sin 2(\phi - \psi_{RP}) + \dots \end{aligned} \quad (3.1)$$

where ϕ and Ψ_{RP} are the azimuthal angle of the particle and the reaction-plane angle (angle between impact parameter vector and beam axis), respectively. The parameters, v_1 accounts for the directed flow and v_2 represents the elliptic flow. The parameter a_1 can be used to describe the charge separation effect; and for positive and negative charge particles a_1 have equal and opposite values i.e., $a_1^+ = -a_1^-$ which is proportional to topological charge. The random fluctuations of topological charge from event to event leads to $\langle a_1 \rangle = 0$, making direct detection of the parity violation effect impossible and therefore, correlation study can be the best way to study the charge separation effect. The up-quark asymmetry (" A_u ") is defined [7] as:

$$A_u = \frac{N_R - N_L}{N_R + N_L} \quad (3.2)$$

where N_R and N_L are number of right and left handed up-quarks, respectively. During hadronisation, this asymmetry in quarks transfers to observable asymmetry in charged pions (N_{π^+}) as given below:

$$A_{\pi^+} = -A_{\pi^-} \simeq \frac{Q}{N_{\pi^+}} \quad (3.3)$$

where $Q = N_R - N_L$ and N_{π^+} is the number of positively charged pions in an event [7].

3.2 Experimental methods and Observations:

3.2.1 γ correlator:

One of the key scientific goals of the heavy-ion physics programme is to find a compelling experimental signature of the Chiral Magnetic Effect (CME). Over the last decade, scientists have put a lot of effort into creating novel methodologies and observables to separate the potential CME-driven signal from non-CME background contributions in charge separation measurements. The most commonly investigated experimental observable is γ correlator [8] :

$$\begin{aligned}\gamma &= \langle \cos(\phi_a + \phi_b - 2\Psi_{RP}) \rangle \\ &= \langle \cos\Delta\phi_a \cos\Delta\phi_b \rangle - \langle \sin\Delta\phi_a \sin\Delta\phi_b \rangle \\ &= v_{1,a}v_{1,b} - a_{1,a}a_{1,b}\end{aligned}\tag{3.4}$$

Here, ϕ_a, ϕ_b are azimuthal angles of particles “a” and “b”, Ψ_{RP} is the reaction plane angle, and $\Delta\phi_{a(b)} = \phi_{a(b)} - \Psi_{RP}$. The angled brackets denote an average over the particles within the event and over all the analyzed events in a given sample. In eq. 3.4, term $\langle \cos\Delta\phi_a \cos\Delta\phi_b \rangle$ denotes in-plane correlations and $\langle \sin\Delta\phi_a \sin\Delta\phi_b \rangle$ denotes out-of-plane correlations. These out-of-plane charge correlations are CME sensitive. Also, experimentally it is not possible to find the value of Ψ_{RP} , so eq. 3.4 is modified [8] as:

$$\gamma = \langle \cos(\phi_a + \phi_b - 2\phi_c) \rangle / v_{2,c}\tag{3.5}$$

where, $v_{2,c}$ is elliptic flow of the third particle “c”. The γ correlator is studied for different charge pair combinations i.e., same sign ($++/--$) and opposite sign ($+-$). If CME be the only contribution to the γ correlator then $\gamma_{++/--}$ is expected to be negative and γ_{+-} to be positive. The difference between the opposite sign (OS) and same sign (SS) charge pairs correlations i.e., $\Delta\gamma = \gamma(OS) - \gamma(SS)$, is used to study the charge separation due to CME like effect as the background effect common to both OS and SS will cancel.

Along the γ correlator, two particle δ correlator is also defined as:

$$\delta \equiv \langle \cos(\phi_a - \phi_b) \rangle = \langle \cos\Delta\phi_a \cos\Delta\phi_b \rangle + \langle \sin\Delta\phi_a \sin\Delta\phi_b \rangle \quad (3.6)$$

From γ correlator and δ correlator, in-plane and out-of-plane correlations can also be studied.

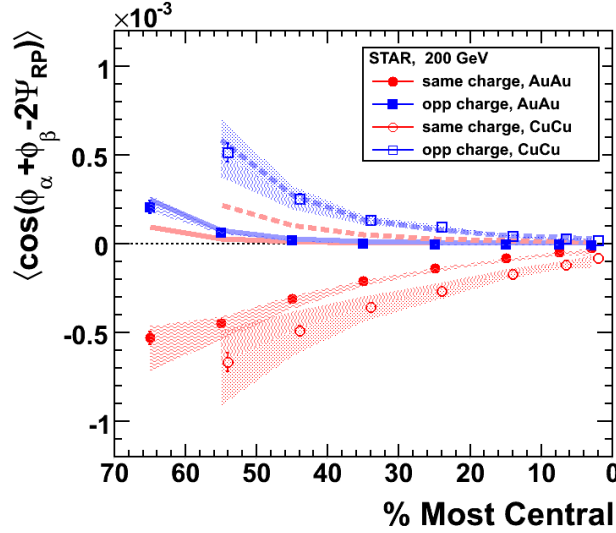


Figure 3.2: γ correlator for same sign and opposite sign charge pairs for Au-Au and Cu-Cu collisions at 200 GeV at STAR experiment [9].

Experimental Measurements:

In 2009, STAR collaboration at RHIC made first measurement of γ correlator in Au-Au and Cu-Cu collisions at 200 GeV [9–11](Fig. 3.2) and $\gamma(+ -)$ was showing positive correlations while $\gamma(+ + / - -)$ correlator was negatively correlated which was theoretically predicted. The PHENIX experiment measured charge separation [12] showing similar results. ALICE at LHC also then studied the γ correlator along with δ correlator and in-plane and out-of-plane correlations [13]. Figure 3.3 shows the γ correlator (a), δ correlator (b) and in-plane ($\langle \cos\Delta\phi_a \cos\Delta\phi_b \rangle$), out-of-plane ($\langle \sin\Delta\phi_a \sin\Delta\phi_b \rangle$) correlations (c) for Pb-Pb collisions at 2.76 TeV. The δ correlator show similar trend as STAR measurements (Fig. 3.3(b)). In-plane and out-of-plane correlations agree within errors for opposite sign charge pairs whereas out-of-plane correlations are stronger than those of in-plane for same sign charge

pairs (Fig. 3.3(c)).

To check the collision energy dependence of γ correlator, STAR carried the Beam Energy Scan (BES) for Au-Au collisions at $\sqrt{s_{NN}} = 7.7 - 200$ GeV [14]. Theoretically, CME is expected to be more at low energies as the duration of magnetic field is larger there. But the charge separation is likewise dependent on deconfinement, implying that there will be a minimum energy limit below which the CME effect will be zero or minimal. The figure 3.4 shows γ correlator for OS and SS sign charge pairs as a function of centrality for Au-Au collisions for different STAR energies along with the Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV from ALICE. It is seen from the figure that the difference between opposite and same sign γ correlator is zero for 7.7 GeV and remains almost negligible upto 27 GeV indicating the absence of CME like effect. After that a significant difference appears as collision energy increases. The γ correlator is comparable for STAR's 200 GeV and ALICE's 2.76 TeV. This is because of the reason that although the strength of magnetic effect increases with collision energy but its duration decreases.

CME in small system: Due to smaller magnitude of the magnetic field in small system collisions (i.e., p+p or p+A) as compared to heavy-ion collisions (i.e., A+A), it is predicted that the $\Delta\gamma$ correlation values for small system and heavy-ion collisions would differ significantly but various background contributions remains unaffected [15, 16]. So, small systems may have the potential to give baseline

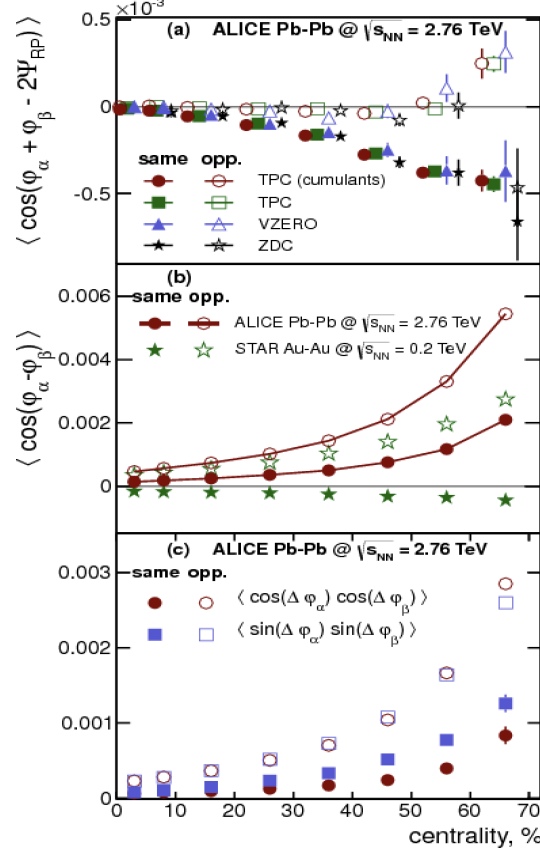


Figure 3.3: The centrality dependence of γ (a), δ (b) and In-Plane and out-of-plane (c) correlations in Pb-Pb collisions at 2.76 TeV at ALICE [13].

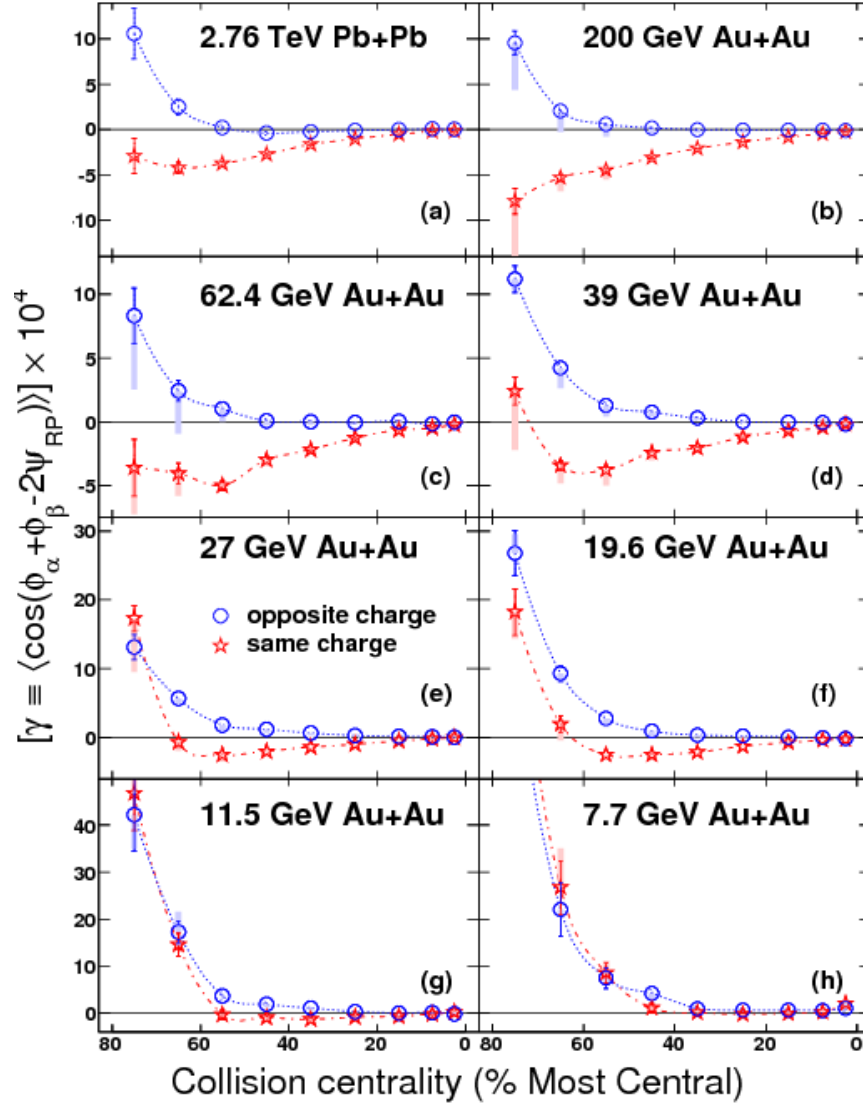


Figure 3.4: The $\gamma(\text{SS})$ and $\gamma(\text{OS})$ correlator as a function of collision centrality for Au-Au at 7.7 - 200 GeV energies [14] and Pb-Pb collisions at 2.76 TeV collision energy [13].

observations for heavy-ion collisions. Both the CMS experiment at LHC [17] and the STAR experiment at RHIC [18] studied the small system charge separation. The CMS shows the same trend and behaviour in γ correlator for p-Pb and Pb-Pb in overlapping multiplicity. The STAR experiment also shows same trend for p-Au and d-Au systems; and no expected difference is seen between small system collisions and heavy-ion collisions (Fig. 3.5).

It is clear from the small system results that the dominant contribution of the

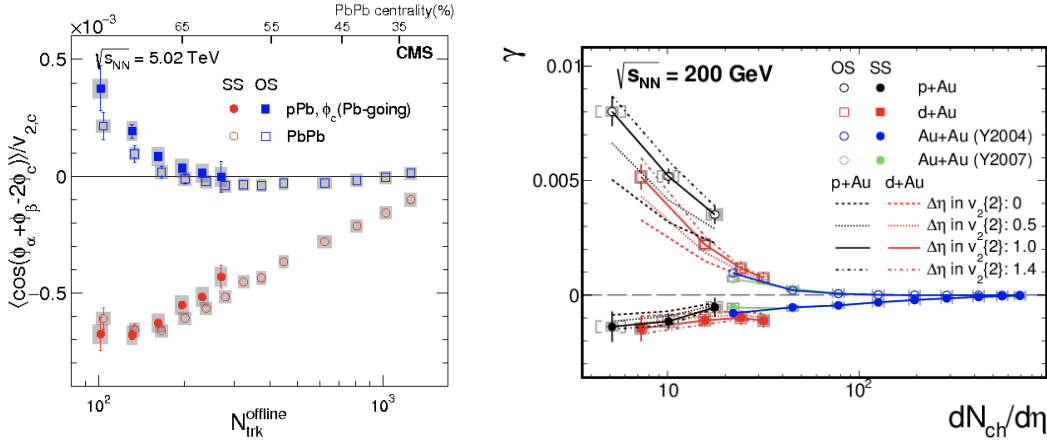


Figure 3.5: Left: The γ correlator as a function of N_{trk} and centrality for p-Pb and Pb-Pb, respectively, at 5.02 TeV at CMS experiment [17]. Right: STAR experiments results for γ correlator as a function of $dN_{ch}/d\eta$ for p-Au, d-Au and Au-Au at 200 GeV [18].

signal is not related to the CME.

The experimental measurements of various experiments are in qualitative agreement with the theoretical expectations, but a reliable separation of the CME signal from background effects is still missing and proper explanation of why small systems are showing similar values for charge separation, is under intense research.

3.3 Methods to segregate signal from backgrounds

The main and foremost thing in CME search is to distinguish between the charge separation due to CME and charge separation due to backgrounds like resonance decay, local charge conservation etc. The $\Delta\gamma$ correlator does provide some insight about CME but fails to perceive a difference in signal and backgrounds. Thus various techniques/methods (listed below) are developed to search the CME. The methods are divided into two categories : One which exploits $\Delta\gamma$ correlator and it's properties to study the CME and other which define some new correlator to study charge separation effect.

3.3.1 $\Delta\gamma$ methods

3.3.1.1 Event by Event v_2 measurements

The principle background source of $\Delta\gamma$ is elliptic flow (v_2) induced background. To suppress this background correlations, one method is to select the events with $v_2 = 0$. STAR has made the initial attempt to remove the backgrounds by utilising the event-by-event v_2 method [19]. The $v_{2,ebye}^{obs}$ is calculated by using the Q vector as:

$$v_{2,ebye}^{obs} = Q^* q_{EP} \quad (3.7)$$

$$Q = \frac{1}{N} \sum_{j=1}^N e^{2i\phi_j}, \quad \text{and} \quad q_{EP} = e^{2i\psi_{EP}}, \quad (3.8)$$

where ϕ_j is the azimuthal angle of the particle and Q sums over all particles in each event and ψ_{EP} is azimuthal angle of the event plane (EP), estimated from the final state particles. The variation of charge asymmetry correlation observable Δ ($=\Delta\langle A^2 \rangle - \Delta\langle A_+ A_- \rangle$) is seen with respect to $v_{2,ebye}^{obs}$ (Fig. 3.6), where “A” is particle multiplicity asymmetries and defined as:

$$A_{\pm,U(D)} = (N_{\pm,U} - N_{\pm,D}) / (N_{\pm,U} + N_{\pm,D}) \quad (3.9)$$

$N_{\pm,U}$ and $N_{\pm,D}$ represent the positive and negative charged particle multiplicity in “up” and “down” quadrants [19]. The results reveal that Δ has a linear dependence on $v_{2,ebye}^{obs}$. The solid line represents the linear fit of data points consistent with zero intercept.

Main problem of this method is that it mainly stresses on the v_2 influenced backgrounds which depends on the final stage particles and do not account for the backgrounds which come from the initial stage of the collisions i.e., resonance or cluster decays.

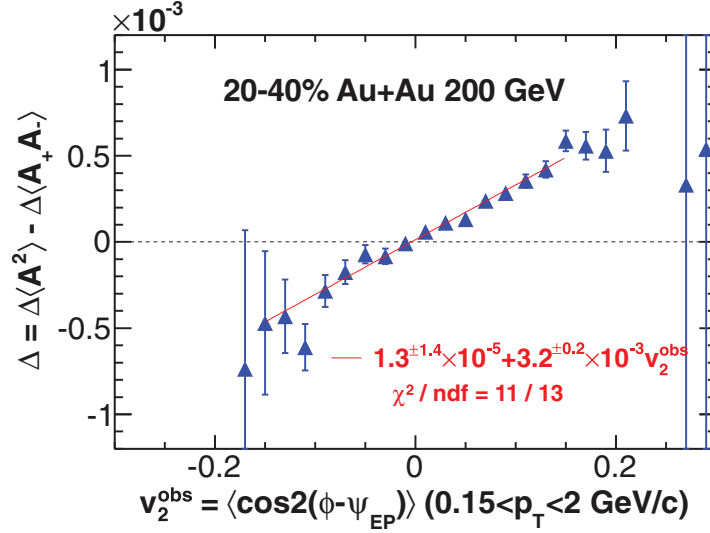


Figure 3.6: Δ as a function of $v_{2,ebye}^{obs}$ for Au-Au collisions at 200 GeV at STAR experiment [19].

3.3.1.2 Event shape engineering (ESE)

Event shape engineering also exploits the same fact as used in pervious section that background correlations are mainly proportional to the elliptic flow. But in ESE rather than selecting events with zero v_2 , events are divided into groups based on the reduced flow vector “ q_2 ” [20,21], defined as $q_2 = \frac{|Q_2|}{\sqrt{M}}$, where $|Q_2|$ is flow vector and M is the multiplicity. The γ correlator is then calculated for different sub-events divided on the basis of q_2 . Fig. 3.7(Left) presents the $\Delta\gamma$ correlator as a function of v_2 for Pb-Pb collision data at 2.76 TeV taken by ALICE collaboration [21]. To remove the multiplicity fluctuations, $\Delta\gamma$ correlator is scaled with the charged-particle density ($\frac{dN_{ch}}{d\eta}$). The linear dependence of scaled $\Delta\gamma$ on v_2 has been seen from the plot which indicates a large background contribution of v_2 on $\Delta\gamma$.

Since event shape engineering helps to separate the flow induced backgrounds from CME induced charge separation, ALICE made an attempt to calculate the fractional CME signal using the linear fit function in v_2 . The contribution of CME signal is extracted from the non-zero intercept at $v_2=0$ [21]. Fig. 3.7(right) shows the f_{CME} signal extracted from ESE method by using three different Monte Carlo

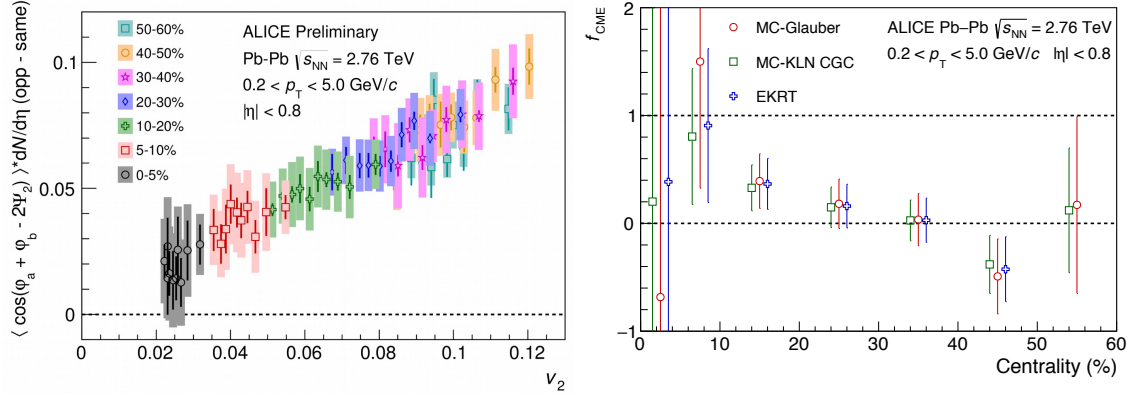


Figure 3.7: Left : The scaled $\Delta\gamma$ correlator as a function of v_2 for Pb-Pb data at 2.76 TeV, Right : fraction of CME signal (f_{CME}) using different MC glauber models for different centralities. [21]

models i.e., MC-Glauber [22], MC-KLN CGC [23, 24] and EKRT [25] in the $0.2 < p_t < 5.0$ GeV/c range. For 10-50% collision centralities, the extracted fractions are : $f_{CME} = 0.10 \pm 0.13$ for MC Glauber, $f_{CME} = 0.08 \pm 0.10$ for MC-KLN CGC and $f_{CME} = 0.08 \pm 0.11$ for EKRT model. These results are consistent with zero CME fraction; and correspond to the upper limit of 33%, 26% and 29%, respectively, at 95% confidence limit. Due to large statistical uncertainties, 0-10% and 50-60% centrality intervals are excluded from the signal extraction.

The above analysis is model dependent, relying on precise modelling of the magnetic field for a given centrality. Also to calculate the fraction, effect of centrality dependence on $\Delta\gamma$ has been neglected.

3.3.1.3 H correlator

As it is mentioned earlier that the multiparticle correlator is the most applicable observable to search for CME, this “H-correlator” method exploit the different properties of 2-particle “ δ ” correlator and 3-particle “ γ ” correlator. Both the δ and γ correlator can be divided into two parts : one is CME contribution which is flow independent and; other is flow-dependent correlations [26, 27]. Let us first consider

the flow independent CME-type correlations:

$$\gamma_{i,j} \sim -H_{i,j} \quad , \quad \delta_{i,j} \sim H_{i,j} \quad (3.10)$$

where (i,j) can either be same sign or opposite sign charge pairs and H denotes the strength of the effect, here in this case, the CME like charge separation. The flow dependent correlations will contribute as:

$$\gamma_{i,j} \sim v_2 F_{i,j} \quad , \quad \delta_{i,j} \sim F_{i,j} \quad (3.11)$$

with $F_{i,j}$ representing the strength of flow dependent correlations and v_2 is elliptic flow. By combining above two equations, we get:

$$\gamma_{i,j} \sim v_2 F_{i,j} - H_{i,j} \quad , \quad \delta_{i,j} \sim F_{i,j} + H_{i,j} \quad (3.12)$$

From these two equations, we get:

$$\Delta\gamma = \kappa v_2 \Delta F - \Delta H \quad (3.13)$$

$$\Delta\delta = \Delta F + \Delta H \quad (3.14)$$

where $\Delta H = H_{SS} - H_{OS}$, $\Delta F = F_{SS} - F_{OS}$ and κ is the proportionality constant, depends on the detector acceptance.

$$\kappa \propto 2 - \frac{\langle v_2 \rangle_F}{\langle v_2 \rangle_\Omega} \quad (3.15)$$

here, $\langle \rangle_F$ denotes the average of all particles in full phase space while $\langle \rangle_\Omega$ denotes fraction of phase space where actual measurements are done. STAR experiment calculated the ΔH correlator for Au-Au collisions for different beam energies [14](Fig. 3.8). The ΔH correlator for Pb-Pb collisions at 2.76 TeV was also shown in figure along with the model calculation (UrQMD for $\kappa=1$). The non zero ΔH observed, was the clear sign of CME-like correlations since H correlator

denotes the CME contribution. Also it is seen that as κ increases ΔH decreases.

3.3.1.4 Invariant mass technique

The major challenge in interpreting CME from $\Delta\gamma$ is the significant charge-dependent background contributions to $\Delta\gamma$. The $\Delta\gamma$ variable does not provide a clear difference between the backgrounds like correlations from a resonance decay along Ψ_2 and CME-like charge separation. So to curb this background contributions from resonance decays, the particle pair invariant mass, m_{inv} , technique is devised [28]. In this technique, cut on lower m_{inv} is applied to curb the resonance backgrounds and

$\Delta\gamma$ is then studied with respect to m_{inv} . CME being the low p_T phenomenon, it is possible that a large m_{inv} region is not the ideal spot to look for it but on the other hand if a finite signal is observed in high m_{inv} then that would provide the assurance of CME as backgrounds are negligible in high m_{inv} . Invariant mass analysis is performed by STAR collaboration for Au-Au collisions at 200 GeV [29]. The peak structure (Fig. 3.9) are observed at low m_{inv} and lower values of $\Delta\gamma$ at high m_{inv} indicated the presence of CME but with very low fraction. The upper limit on fraction of CME signal integrated over m_{inv} is set to 0.23×10^{-4} at 95% confidence level.

This m_{inv} method has lots of assumptions [28] and the dependence of the CME on m_{inv} is also undefined yet, so more theoretical research is needed for this. Qualitatively this method provides the CME assurance like other methods but there

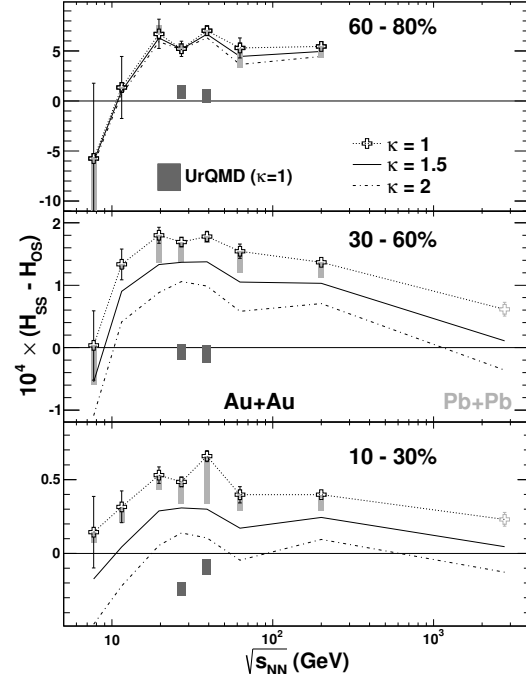


Figure 3.8: The ΔH correlator as a function of different collision energy for Au-Au and Pb-Pb collisions along with the UrQMD model [14].

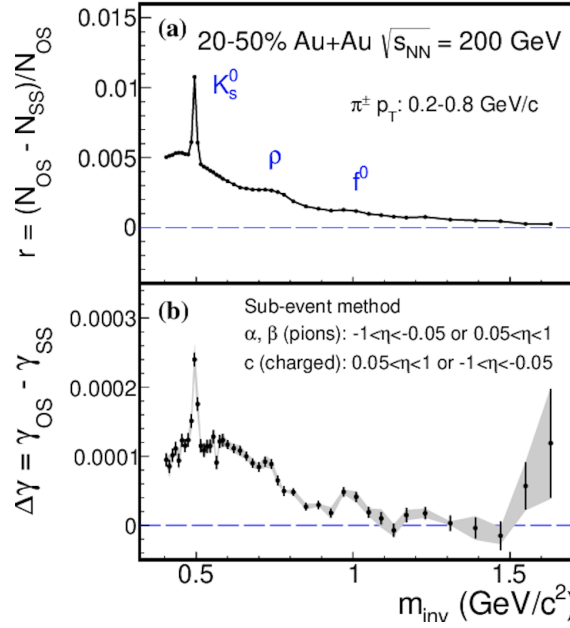


Figure 3.9: The relative excess of opposite sign over same sign pion pairs (r) as a function of pion pair invariant mass, m_{inv} , (a), and $\Delta\gamma$ as a function of m_{inv} (b) in 20-50% centrality for Au-Au collisions at 200 GeV [29].

is need for improvement to check CME, quantitatively.

3.3.1.5 Mixed harmonics measurements with second and third order event planes

In principle, charge separation effect due to CME is expected to be in the direction perpendicular to the reaction plane and along the magnetic field. Due to experimental constraints, the reaction plane is approximated by second order event plane and there is a well established fact that second order event plane (Ψ_2) is extremely weakly correlated to the third order symmetry plane (Ψ_3) [30]. So by utilising this fact, it was expected that the charge separation impact relative to Ψ_3 would be insignificant but backgrounds which are not related to reaction plane would remain the same. The charge dependent correlator with respect to Ψ_3 is defined as:

$$\gamma_{123} \equiv \langle \cos(\phi_a + 2\phi_b - 3\Psi_3) \rangle \quad (3.16)$$

where symbols have their usual meanings and

$$\Delta\gamma_{112} \approx \kappa_2 v_2 \Delta\delta_1, \quad \Delta\gamma_{123} \approx \kappa_3 v_3 \Delta\delta_1 \quad (3.17)$$

here, κ_n is proportionality constant. From $\Delta\gamma_{123}$, we can estimate the background contribution in $\Delta\gamma_{112}$ as:

$$\Delta\gamma_{112}^{bkg} \approx \Delta\gamma_{123} \times \frac{v_2 \kappa_2}{v_3 \kappa_3} \quad (3.18)$$

The κ_2 and κ_3 parameters are predicted to be identical, generally irrespective of harmonic event plane ordering, because they are based on detector acceptance and particle kinematics.

The CMS experiment at the LHC has studied the charge-dependent azimuthal correlations with respect to the second and third order event planes for p-Pb and Pb-Pb collisions at 8.16 TeV and 5.02 TeV, respectively [31]. It is found that γ

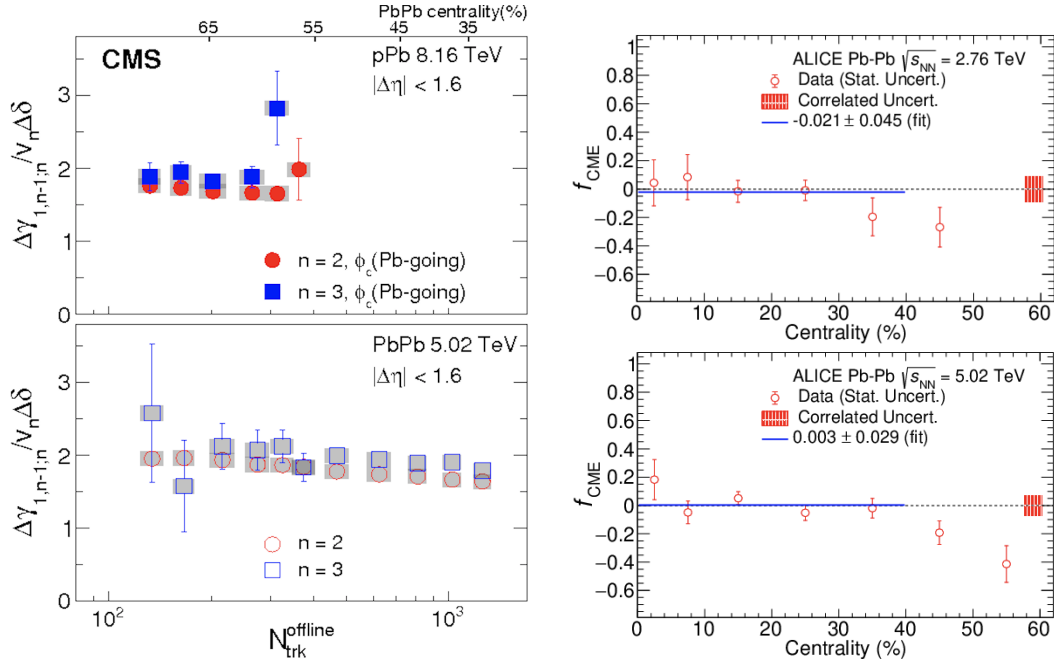


Figure 3.10: Left : The comparison of $\Delta\gamma_{112}/\Delta\delta v_2$ and $\Delta\gamma_{123}/\Delta\delta v_3$ for p-Pb (upper left) and Pb-Pb (lower left) data at CMS [31]. Right : The f_{CME} estimated for ALICE Pb-Pb data for 2.76 TeV (upper right) and 5.02 TeV (lower right) as a function of collision centrality [32].

correlator for same sign and opposite sign charge pairs have same magnitude within errors for p-Pb and Pb-Pb but γ_{123} has different values indicating the backgrounds' properties in p-Pb and Pb-Pb systems are different. Fig 3.10(Left plots) [31] shows the $\frac{\Delta\gamma_{112}}{\Delta\delta v_2}$ and $\frac{\Delta\gamma_{123}}{\Delta\delta v_3}$ for p-Pb and Pb-Pb collisions and it is clear from the plot that they are comparable within errors indicating the dominance of background in $\Delta\gamma$. CMS experiment concluded the CME signal contribution to be 13% for p-Pb data and 7% for Pb-Pb data at a 95% confidence level. ALICE also performed this study on Pb-Pb collisions at 2.76 TeV and 5.02 TeV collision energy [32]. Figure 3.10 (Right plot) shows the CME fraction calculated by ALICE and set an upper limit of 15–18% (20–24%) at 95% (99.7%) confidence level for the 0–40% centrality interval.

3.3.1.6 $\Delta\gamma$ correlators with respect to spectator and participant planes

The $\Delta\gamma$ correlator does show the charge separation but it treats back-to-back charge separation with respect to reaction plane and charge separation from resonance decay in same way. So, in a way $\Delta\gamma = \Delta\gamma_{CMESig} + \Delta\gamma_{bkg}$. To differentiate between this background and signal, a new method of calculating $\Delta\gamma$ with respect to two different planes and comparing them was suggested [33,34]. This method depends on the fact that CME depends on the magnetic field created by the spectator protons so likely to be larger in spectator plane while the flow induced background correlations are larger in the participant plane. The STAR collaboration recently reported a hint of finite positive CME signal in mid central Au+Au collisions with a 1–3 σ significance using the spectator plane and participant plane analysis [35](Fig. 3.11). STAR also studied the U+U 193 GeV collisions [36].

3.3.2 New correlators:

3.3.2.1 The $R_{\Psi_2}(\Delta S)$ variable

Recently a new observable, $R_{\Psi_m}(\Delta S)$ ($m=2,3$), has been proposed to distinguish between charge separation induced by CME and background correlations in heavy-

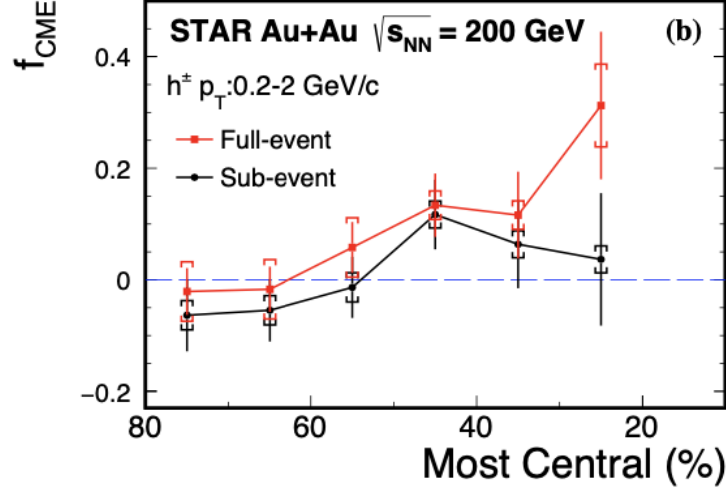


Figure 3.11: The fraction of CME signal as a function of centrality for Au-Au collisions calculated by the spectator plane and participant plane analysis [35].

ion collisions [37, 38]. For each event, $R_{\Psi_m}(\Delta S)$ correlator is measured as the ratio :

$$R_{\Psi_m}(\Delta S) = C_{\Psi_m}(\Delta S) / C_{\Psi_m}^{\perp}(\Delta S) \quad (3.19)$$

where, $C_{\Psi_m}(\Delta S)$ and $C_{\Psi_m}^{\perp}(\Delta S)$ are charge sensitive correlation functions, parallel and perpendicular, respectively, to the magnetic field (or Ψ_{RP}). The $C_{\Psi_m}(\Delta S)$ being parallel to B-field, quantifies charge separation resulting from both CME as well as from the background whereas $C_{\Psi_m}^{\perp}(\Delta S)$ incorporates only background driven charge separation since charge separation due to CME occurs only along the direction of magnetic field. This charge dependent, $C_{\Psi_m}(\Delta S)$, correlator is expressed as the ratio of two distributions :

$$C_{\Psi_m}(\Delta S) = \frac{N_{real}(\Delta S)}{N_{Shuffled}(\Delta S)}, m = 2, 3 \quad (3.20)$$

where $N_{real}(\Delta S)$ is the distribution of the events with charge separation relative to the reaction plane and $N_{Shuffled}(\Delta S)$ is the distribution similarly obtained from the same events but after randomly shuffling of the charge of each particle in

an event. Here,

$$\Delta S = \langle S_p^{h+} \rangle - \langle S_n^{h-} \rangle \quad (3.21)$$

where

$$\langle S_p^{h+} \rangle = \frac{\sum_1^{N_p} \sin(\frac{m}{2} \Delta \phi_m)}{N_p}, \langle S_n^{h-} \rangle = \frac{\sum_1^{N_n} \sin(\frac{m}{2} \Delta \phi_m)}{N_n} \quad (3.22)$$

where N_p and N_n are the number of positively and negatively charged hadrons in an event and the $\Delta \phi_m = \phi - \Psi_m$, $m=2,3$. The $C_{\Psi_m}^\perp(\Delta S)$ is also obtained by applying same procedure but by replacing Ψ_m with $\Psi_m + \pi/m$. Thus, $R_{\Psi_m}(\Delta S)$, the

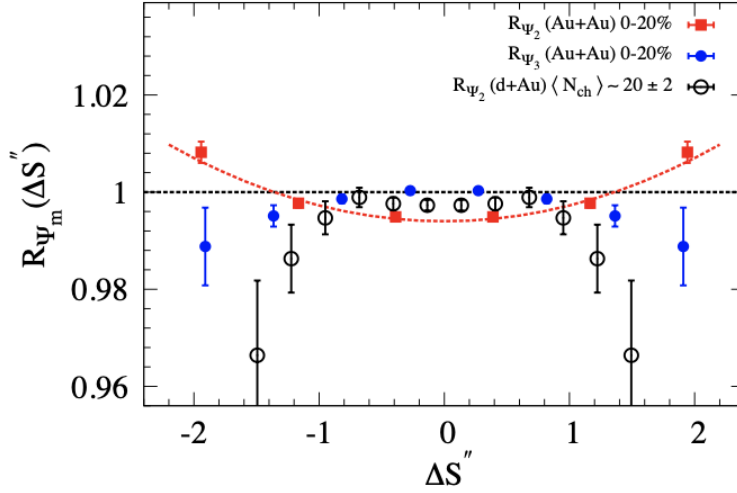


Figure 3.12: The variation of $R_{\Psi_m}(\Delta S'')$ with $\Delta S''$ for different systems as indicated in legends [40].

ratio between $C_{\Psi_m}(\Delta S)$ and $C_{\Psi_m}^\perp(\Delta S)$ is obtained to detect the charge separation due to CME. The correlator, $R_{\Psi_2}(\Delta S)$ measures the magnitude of charge separation due to CME whereas the correlator, $R_{\Psi_3}(\Delta S)$ are insensitive to CME driven charge separation as there is negligible correlation between Ψ_{RP} and Ψ_3 . Model study [37] has suggested that concave shape of $R_{\Psi_2}(\Delta S)$ is expected and concavity increases with the increase in CME like signal. Fig. 3.12 shows the $R_{\Psi_m}(\Delta S)$ vs ΔS ($\Delta S''$ consolidate for event plane resolution and particle number fluctuations) for Au+Au and d+Au collisions at 200 GeV at STAR for 0-20% centralities [39].

It is clear from the fig. 3.12 that the shape of $R_{\Psi_2}(\Delta S'')$ is concave while $R_{\Psi_3}(\Delta S'')$ being a background has convex shape. For reference d+Au system is also

plotted in figure and it also shows the convex shape. Thus this method does provide a differentiation between CME driven charge separation and charge separation due to backgrounds.

Despite the fact that $R_{\Psi_2}(\Delta S)$ variable method clearly gives the qualitative view of CME but fails to provide quantitative analysis. Moreover, extensive investigation, such as the resonance v_n and p_T dependences of the $R_{\Psi_2}(\Delta S)$, are needed to acquire a clearer understanding of the experimental data and more clear implications in terms of CME interpretation.

3.3.2.2 Signed Balance Function

Almost all the previous searches of chiral magnetic effect are on the basis of azimuthal angular correlations whereas the newly developed Signed Balance Function (SBF) technique [41] focuses on the separation in momentum phase space. The SBF technique is a four step technique :

1. **Counting pair's momentum ordering :** Two signed balance functions [42, 43] are defined to count pair's momentum ordering as:

$$B_P(S) = \frac{N_{+-}(S) - N_{++}(S)}{N_+} \quad (3.23)$$

and

$$B_N(S) = \frac{N_{-+}(S) - N_{--}(S)}{N_-} \quad (3.24)$$

where $N_{+(-)}$ is the number of positively (negatively) charged particles and subscript P and N in $B_{P(N)}(S)$ denote the positive and negative terms, respectively. The S can have values +1 and -1 depending upon which particle is leading and which is trailing.

2. **Counting the net momentum ordering event by event :** The difference

between B_P and B_N can be calculated for each event as :

$$\delta B(\pm 1) = B_P(\pm 1) - B_N(\pm 1), \quad (3.25)$$

and

$$\Delta B = \delta B(+1) - \delta B(-1) \quad (3.26)$$

When there is no CME effect, B_P and B_N are same and ΔB is only statistical fluctuation. But if there is CME then ΔB distribution has some width.

3. **Looking enhanced fluctuation of net momentum ordering :** The ratio of the width of the distributions of ΔB in the direction of reaction plane to the direction perpendicular to the reaction plane is calculated to cancel out the statistical fluctuations.

$$r = \frac{\sigma_{\Delta B_{RP}}}{\sigma_{\Delta B_{\perp to RP}}} \quad (3.27)$$

In case of CME, r will be greater than 1.

4. **Comparing results for different frames :** To incorporate the ambiguity in calculating "r" in laboratory frame and pair's rest frame of reference, $R_B = r_{rest}/r_{Lab}$ is calculated, where r_{rest} is "r" value in pair's rest frame and r_{Lab} is "r" value in laboratory frame.

In case of CME, both r_{rest} and R_B should be above unity.

Fig. 3.13 shows the STAR data results for r_{rest} (left plot) and R_B (right plot) versus centrality for 200 GeV Au-Au collisions [44]. Along with the data results, Anomalous Viscous Fluid Dynamics (AVFD) model's [45] results to check the technique and shuffled events' (events in which each particle's charge is randomized keeping total number of charged particles unchanged) results to check the consistency, are also plotted in the figure. The preliminary measurements seem to be consistent with CME expectation while for shuffled events SBF observables are at unity.

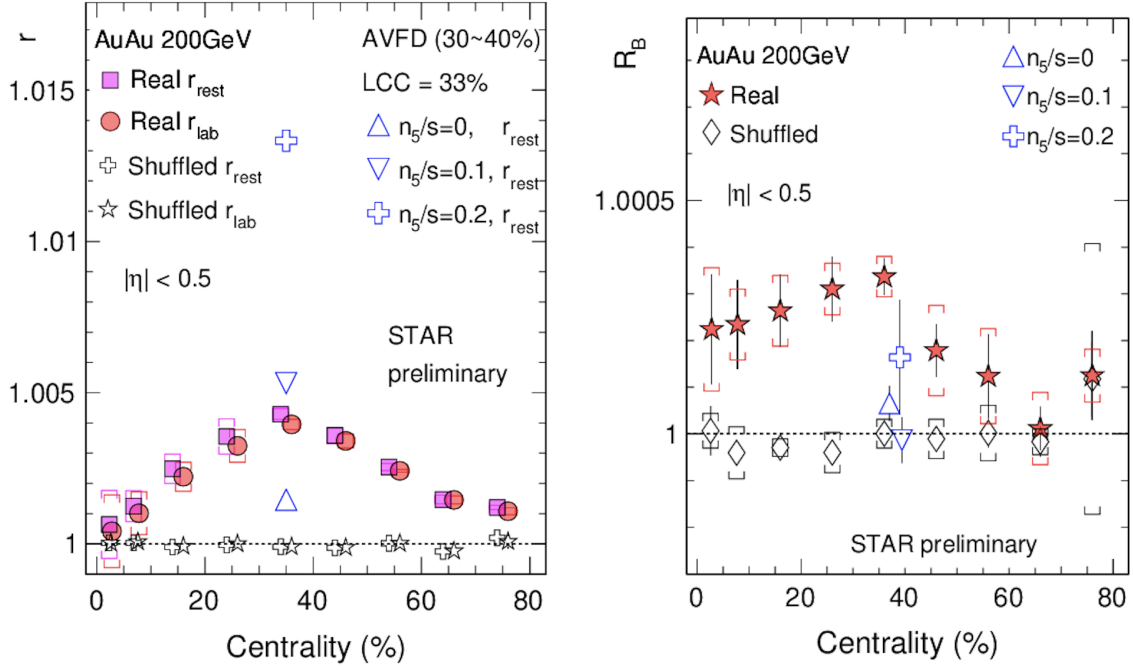


Figure 3.13: Left: Variation of r_{rest} and r_{lab} with centrality for Au-Au collisions at STAR along with the shuffled data and AVFD model. Right: R_B as a function of centrality [44]. Symbols are defined in legends.

Although, the two SBF observables give relevant information about CME with a new correlator, there are still certain underlying issues emerging from charge and momentum conservation that need to be thoroughly investigated using realistic models.

3.4 STAR isobar analysis

One of the essential components for the existence of CME is the magnetic field (B) and elliptic flow (v_2) is the main background. Isobaric ($^{96}_{44}\text{Ru} + ^{96}_{44}\text{Ru}$ and $^{96}_{40}\text{Zr} + ^{96}_{40}\text{Zr}$) collisions were proposed [46] with the fact that v_2 would be similar for two systems while magnetic field in Ru+Ru collisions would be about 10-18% larger than in Zr+Zr collisions due to higher charge in Ru+Ru. Thus it was expected that in comparison to all prior investigations, isobar collisions could give the best control of signal and background. After intensive research [47–50], blind analysis of isobaric collisions [51, 52] were proposed in the STAR experiment and the results from that

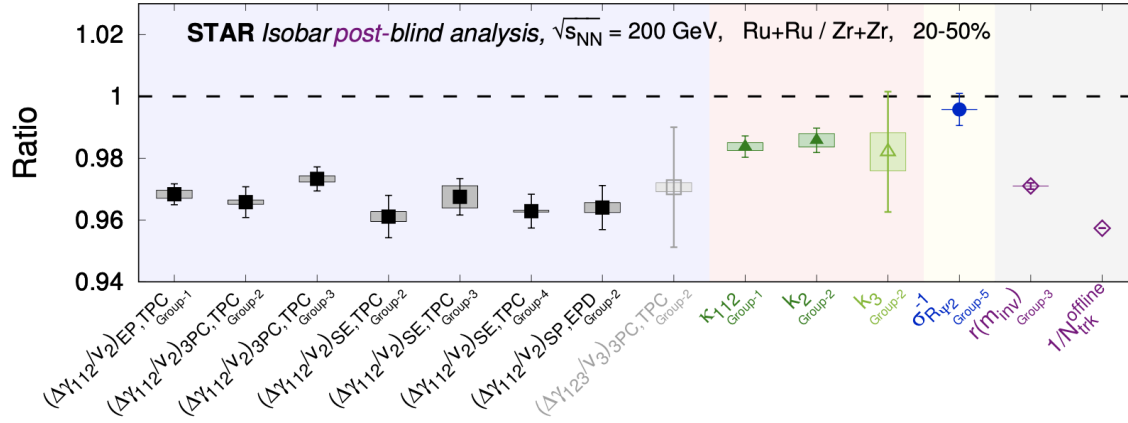


Figure 3.14: The compilation of ratios of results measures in Ru+Ru collisions over Zr+Zr collisions by different methods are shown for 20-50% centrality [53]. The CME sensitive measurements are represented by solid symbols, whereas CME-insensitive measurements are represented by open symbols. The backdrop colours are used to distinguish between different sorts of measurements.

isobaric collisions have been reported recently [53]. Fig. 3.14 shows the assembled results of different methods used to study the CME in isobaric collisions in STAR (for detailed studies Ref. [53]) and ratios of CME correlators of $^{96}_{44}Ru + ^{96}_{44}Ru$ and $^{96}_{40}Zr + ^{96}_{40}Zr$ are seen to be lying below 1. It is concluded in the paper [53] that none of the predefined parameters for observing CME excess in the Ru over Zr have been observed.

3.5 Thesis Motivation

A rigorous study for almost a decade has been done on CME and its various possible backgrounds and methods; still, there uncertainty about the presence or absence of the CME. Several different methods and techniques are under testing and on that line a new approach, Sliding Dumbbell Method (detailed description and testing on simulated model are explained in the succeeding chapter), is developed and presented in this thesis to search for the back-to-back charge separation on an event-by-event basis. An event-by-event search is performed to isolate the events which exhibit higher back-to-back charge separation and are potential CME-like events. So the

main aim is to get CME-like enriched sample for a given collision centrality by using the Sliding Dumbbell Method. The CME sensitive correlators are compared for CME enriched sample and non-CME sample to authenticate the presence of CME.

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CHAPTER

4

SLIDING DUMBBELL METHOD

“In order to make an apple pie from scratch, you must first create the universe.”

Carl Sagan

The introduction, strategy and testing on Monte Carlo model of novel method, called Sliding Dumbbell method is discussed in this chapter. This chapter provides the base for ALICE data analysis as all the formulism, techniques and backgrounds which is used to check the CME in ALICE data are defined and discussed here.

4.1 Introduction

As discussed in last chapter, P-odd metastable states formed in non-central heavy-ion collisions along with the strong magnetic field ($B \sim 10^{15}$ T) produced by the highly energetic spectator protons, give rise to the separation of oppositely charged particles along the system's angular momentum direction and perpendicular to the reaction plane. The Chiral Magnetic Effect (CME) is the name given to this phenomenon [1–4]. Strong magnetic fields formed by moving spectator protons and non-zero axial charge density established in high-energy heavy-ion collisions are two conditions required for the occurrence of CME [5, 6].

All the major heavy-ion collisions studies are focused on the search of conclusive experimental signature for CME. The importance of this search can be judged from the fact that STAR experiment at RHIC had dedicated run of isobars collisions in the year 2018 (RUN18) to confirm the production of the CME in the heavy-ion collisions. The first experimental observable used in this context is γ correlator [7], defined as:

$$\gamma = \langle \cos(\phi_a + \phi_b - 2\Psi_{RP}) \rangle \quad (4.1)$$

where ϕ_a, ϕ_b are azimuthal angles of particles “a” and “b”, respectively, Ψ_{RP} is the reaction plane angle. A positive difference between the γ correlators for opposite (γ_{OS}) and same (γ_{SS}) sign charge pairs ($\Delta\gamma = \gamma_{OS} - \gamma_{SS}$) is referred to as the charge separation signal due to the CME. In the experimental observation of non-zero $\Delta\gamma$, the initial measurement from STAR [8] also indicated numerous plausible contributions from non-CME phenomena. Further PHENIX and LHC measurements have similar results that of the STAR's [8–14]. But background contributions are still not efficiently dealt in γ correlator. Many new observable like: sign balance function [15], sine correlator [16] etc. are also defined to distinguish between CME and non-CME like charge separation. Recently, STAR's blind isobar results ($^{96}_{44}\text{Ru} + ^{96}_{44}\text{Ru}$ and $^{96}_{40}\text{Zr} + ^{96}_{40}\text{Zr}$) withhold the CME [17], however, using the participant and spectator planes, they do revealed some evidence of a finite CME signal in Au-Au collisions at 200 GeV [18].

Inline to this experimental searches, a new method “Sliding Dumbbell Method” is developed to characterize the events according to back-to-back charge separation on an event-by-event basis. Through this method, we can isolate the CME like events and then multi-particle correlators are compared along with the background correlators to differentiate between the CME and non-CME type charge separation.

4.2 Sliding Dumbbell Method

The multi-particle correlators averaged over whole events have been the most preferred method to study the chiral magnetic effect. However, there is a high chance that not each event has CME like signal which in result may dilute the overall signal one get, after averaging over whole events. Thus an attempt to separate the potential events exhibiting the higher back-to-back charge separation is made by developing a new technique, “Sliding Dumbbell Method (SDM)” to search for the back-to-back charge separation on event-by-event basis.

The SDM is alike the Sliding Window Method [19] used by WA98 collaboration [20]. A hypothetical dumbbell of 90° is considered in an azimuthal plane (perpendicular to the beam direction) (Fig. 4.1). Then by sliding that dumbbell by $\delta\phi = 1^\circ$ in anti-clockwise, whole azimuthal plane is scanned minutely. Through each slide, we calculate the sum of the positive charge fraction on one side of the dumbbell and negative charge fraction on the other side of the dumbbell and named that quantity as Db_{+-} which is defined as:

$$\begin{aligned} Db_{+-} &= Db_{+}^a + Db_{-}^b \\ &= \frac{n_{+}^a}{n_{+}^a + n_{-}^a} + \frac{n_{-}^b}{n_{+}^b + n_{-}^b} \end{aligned} \quad (4.2)$$

where n_{+}^a and n_{-}^a are the number of positive and negative charge particles on “a” side of the dumbbell (in 90° azimuth); and n_{+}^b and n_{-}^b are number of positive and negative charge particles on “b” side of the dumbbell. If $Db_{+-}=1$ then that means there are equal number of positive and negative charge particle on both sides of

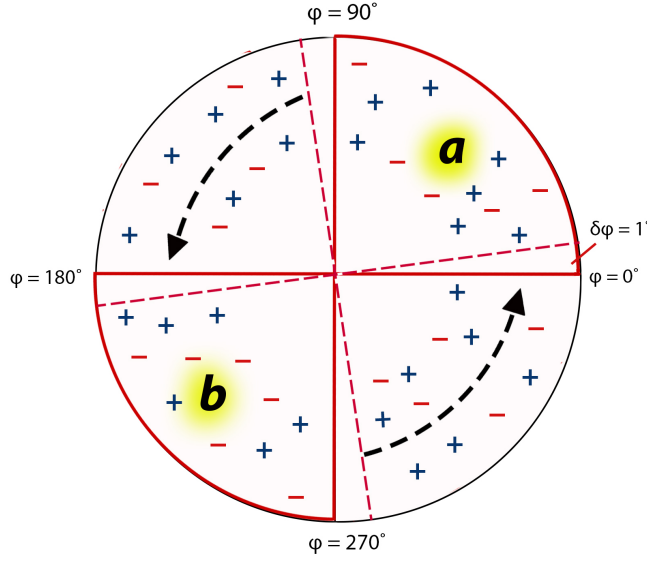


Figure 4.1: The pictorial discription of the sliding dumbbell method. The 90° dumbbell with “a” and “b” sides, dashed arrow showing the anti-clockwise slid of dumbbell by $\delta\phi = 1^\circ$ is also displayed.

the dumbbell, thus no back-to-back charge separation and on the other hand if $Db_{+-}=2$ then there is 100% back-to-back charge separation. Along with Db_{+-} , we also calculate charge excess asymmetry across the dumbbell denoted as Db_{asy} :

$$Db_{asy} = \frac{N_+^{ex} - N_-^{ex}}{N_+^{ex} + N_-^{ex}} \quad (4.3)$$

where $N_+^{ex} = n_+^a - n_-^a$ is positively charged particle excess on “a” side of the dumbbell and $N_-^{ex} = n_-^b - n_+^b$ is negatively charged particle excess on “b” side of the dumbbell. This Db_{asy} is used to select the events which are similar to the CME like events. By applying the $|Db_{asy}| < 0.25$, the maximum value of Db_{+-} is searched for each event which is denoted as Db_{+-}^{max} . From Db_{+-}^{max} , we defined the back-to-back fractional charge separation across the dumbbell (f_{DbCS}) as:

$$f_{DbCS} = Db_{+-}^{max} - 1 \quad (4.4)$$

and we get f_{DbCS} distributions for each collision centrality.

Thus through sliding dumbbell method an event-by-event search is performed

to isolate the events which show higher back-to-back charge separation and we get CME like enriched sample for a given collision centrality.

If we recall the Fourier decomposition of particle azimuthal angle distribution in momentum space:

$$\begin{aligned} \frac{dN}{d\phi} \propto & 1 + 2v_1 \cos(\phi - \psi_{RP}) + 2v_2 \cos 2(\phi - \psi_{RP}) + \dots \\ & + 2a_1 \sin(\phi - \psi_{RP}) + 2a_2 \sin 2(\phi - \psi_{RP}) + \dots \end{aligned} \quad (4.5)$$

where “ a_n ” parameter used to describe the charge separation effect and is proportional to topological charge. However, due to random fluctuations of the topological charges $\langle a \rangle = 0$, which makes the direct calculation of “ a ” difficult. Further

$$\gamma \approx v_{1,a} v_{1,b} - a_{1,a} a_{1,b} \quad (4.6)$$

where if rapidity is symmetric, $v_{1,a} = v_{1,b} \sim 0$ [2] so $\gamma \propto |a_{1,a} a_{1,b}|$. We also define the positive charge asymmetry (A^+) across the dumbbell which is related to a_1 [2] in an event as:

$$A^+ = \frac{|n_+^a - n_+^b|}{N_+} \quad (4.7)$$

where N_+ denotes the total number of positive charge particles in an event.

4.3 AMPT

Many theoretical models have been developed to simulate and analyse the phase space development of the QGP, including transport models [21–25], hydrodynamic models [26–29], and hybrid models [30–32]. One such model is A Multi-Phase Transport (AMPT) model [24]. The AMPT model, which consists of four basic components: the fluctuating initial condition, partonic interactions, hadronization, and hadronic interactions, is a dynamical transport model containing the information

about the transition of matter from partonic phase to hadronic phase. It tries to apply the kinetic theory technique to describe the development of heavy-ion collisions and can generate events with energies ranging from 5 GeV to 5.5 TeV for various collision systems such as pp, pA and AA.

Mainly, AMPT has two versions: Default and String Melting ON version.

Default Version: For the default version of AMPT uses the Heavy Ion Jet Interaction Generator (HIJING) two-component model to create the initial state. HIJING is a realistic Monte Carlo (MC) event generator that creates a complete set of produced particles, including their dynamic attributes like energy and momentum, at the main vertex. It includes mechanisms such as soft beamjets, multiple minijet creation, a model for jet quenching, and a parton structure for nuclear shadowing studies. The impact parameter's dependency on the number of inelastic processes is also described using the geometry of the nuclei. After the creation of initial state, minijet partons enter the parton cascade and finally reunite with their parent strings to hadronize through the Lund string fragmentation. In heavy ion collisions at SPS and RHIC, the default AMPT model could well describe the transverse momentum (p_T) spectra of detected particles. *However, the elliptic flow (v_2) at RHIC is severely underestimated by the default AMPT.*

String Melting Version: In SM version, all the excited strings are converted into partons, and a spatial quark coalescence model is invented to describe the hadronization process. String melting increases parton density, resulting in the over-populated partonic matter, whereas quark coalescence improves hadron elliptic flow. Consequently, the string melting AMPT model with a tiny parton cross-section can represent the massive elliptic flow in Au+Au collisions at RHIC energies.

Around April 2004, the AMPT model's source code was made freely available online, and a subsequent paper [24] offered full explanations of the model, including the included physical processes and modelling assumptions. Since then, the AMPT model has been frequently utilised to explain the development of dense matter produced in high-energy nuclear collisions. At both RHIC and LHC energies, the string

melting version of the AMPT model can well characterise **anisotropic flows** and particle correlations in collisions of small and large systems.

4.3.1 Injecting the CME like signal in AMPT generated events

As mentioned in previous chapter, that azimuthal anisotropy is the main background in CME and AMPT is the closest model which predict the elliptic flow accurately but it does not have CME. So, to study the charge separation due to CME, CME like signal is injected externally in the AMPT generated events by flipping the charges of particles in an event. The **11 million** AMPT events of Pb-Pb collisions at center of mass energy 2.76 TeV are generated having reaction plane angle equal to zero using string melting ON configuration. Three different AMPTs' sets are obtained depeneding upon the external signal injection, namely :

- **AMPT:** This is default AMPT string melting ON sample with no CME like signal and denoted as “AMPT” in the forthcoming discussions.
- **Fix-1 CME:** This sample is generated by flipping the charge of one -ve particle to +ve particle in the ϕ range 45° - 135° and one +ve particle to -ve particle in the ϕ range 225° - 315° i.e., perpendicular to the reaction plane as reaction plane angle was set to zero in AMPT generated events. In this way a CME like back-to-back charge separation is injected in the AMPT and this sample is denoted as “Fix-1 CME”. Table 4.1 lists the percentage of CME like signal (i.e., Number of particles' charge flipped/Total number of particles) injected in given collision centrality.
- **Fix-2 CME:** Fix-2 CME is similar to the Fix-1 CME except here two negative particles are changed to two positive particles in the ϕ range 45° - 135° and two positive particles are changed to negative particles in the ϕ range 225° - 315° . This set of AMPT is denoted as “Fix-2 CME”. The percentage of CME like signal injected in given collision centrality is listed in Table 4.1.

Centrality	Average Multiplicity	Percentage of Signal	
		Fix-1 CME	Fix-2 CME
60-70 %	116	1.72	3.44
50-60 %	233	0.85	1.71
40-50 %	421	0.47	0.95
30-40 %	698	0.28	0.57
20-30 %	1087	0.18	0.36
10-20 %	1627	0.12	0.24
5-10 %	2176	0.09	0.18
0-5 %	2679	0.07	0.14

Table 4.1: The percentage of CME like signal injected in Fix-1 CME and Fix-2 CME for different collision centralities.

These three sets of AMPT i.e.; One with no CME and two with externally injected CME signal, are treated in the same way and their results are analysed and discussed in detail in Section 4.5.

4.4 Analysis Details

Before going further into the analysis strategy, we present below the multi-particle correlators and backgrounds estimation used to study the CME.

4.4.1 Multi particle Azimuthal Correlations

Since 3-particle γ correlator defined in Eq. 4.1 is a multi-particle correlator and direct calculations of them require a lot of computer resources to run through all of the conceivable particle multiplets. Furthermore, the heavy-ion collision data contains high multiplicity, which means that the computations will take a long time. So the Q-cumulant method is proposed to ease out the computing process and numerical errors [33].

The 2-, 3- and 4-particle azimuthal correlations are calculated through Q-vector.

The “Q” vector is defined as:

$$Q_n \equiv \sum_{i=1}^M e^{in\phi_i} \quad (4.8)$$

where “n” is the harmonics; ϕ_i is the azimuthal angle ϕ of the i^{th} particle and summation is applied to all particles in an M-multiplicity event.

The multi-particle correlations are defined through two steps:

Step I: The average multi-particle correlations for each event is defined as:

$$\langle 2 \rangle_{n|n} \equiv \frac{1}{P(M, 2)} \sum_{\substack{i,j=1 \\ (i \neq j)}}^M e^{in(\phi_i - \phi_j)}, \quad (4.9)$$

$$\langle 3 \rangle_{n,n|2n} \equiv \frac{1}{P(M, 3)} \sum_{\substack{i,j,k=1 \\ (i \neq j \neq k)}}^M e^{in(\phi_i + \phi_j - 2\phi_k)}, \quad (4.10)$$

$$\langle 4 \rangle_{n,n|n,n} \equiv \frac{1}{P(M, 4)} \sum_{\substack{i,j,k,l=1 \\ (i \neq j \neq k \neq l)}}^M e^{in(\phi_i + \phi_j - \phi_k - \phi_l)}. \quad (4.11)$$

where $P(n, m)$ is $\frac{n!}{(n-m)!}$

Step II: After defining correlation for each event, an average over all the events is performed to get the final multi-particle azimuthal correlation:

$$\langle \langle 2 \rangle \rangle_{n|n} \equiv \frac{\sum_{i=1}^N (w_2)_i (\langle 2 \rangle_{n|n})_i}{\sum_{i=1}^N (w_2)_i} \quad (4.12)$$

$$\langle \langle 3 \rangle \rangle_{n,n|2n} \equiv \frac{\sum_{i=1}^N (w_3)_i (\langle 3 \rangle_{n,n|2n})_i}{\sum_{i=1}^N (w_3)_i} \quad (4.13)$$

$$\langle \langle 4 \rangle \rangle_{n,n|n,n} \equiv \frac{\sum_{i=1}^N (w_4)_i (\langle 4 \rangle_{n,n|n,n})_i}{\sum_{i=1}^N (w_4)_i} \quad (4.14)$$

The multiplicity weights, w_2 , w_3 , w_4 , are introduced to get rid of the multi-

plicity (M) fluctuations and are defined as:

$$w_2 \equiv M(M-1) \quad (4.15)$$

$$w_3 \equiv M(M-1)(M-2) \quad (4.16)$$

$$w_4 \equiv M(M-1)(M-2)(M-3) \quad (4.17)$$

Q-cumulants are defined as:

$$c_2\{2\} = \langle 2 \rangle \quad (4.18)$$

$$c_2\{4\} = \langle 4 \rangle - 2 * \langle 2 \rangle^2 \quad (4.19)$$

and these cumulants are related to the flow as:

$$v_n^2\{2\} = c_n\{2\} \quad (4.20)$$

$$v_n^4\{4\} = -c_n\{4\} \quad (4.21)$$

The general strategy to calculate the multi-particle correlations from Q-cumulants consists of the following steps:

- **Step I:** The Q-vector compositions like $|Q_n|^2$, $Q_n Q_n Q_{2n}^*$ and $|Q_n|^4$ are decomposed in terms of $\langle 2 \rangle_{n|n}$, $\langle 3 \rangle_{n,n|2n}$ and $\langle 4 \rangle_{n,n|n,n}$.
- **Step II:** The system of coupled equations produced in the first phase is solved for 2-, 3-, and 4- particle azimuthal correlations in this step, and the results are represented entirely in terms of various combinations of Q-vectors.
- **Step III:** After solving for $\langle 2 \rangle$, $\langle 3 \rangle$ and $\langle 4 \rangle$, average over whole events is calculated to get $\langle \langle 2 \rangle \rangle$, $\langle \langle 3 \rangle \rangle$ and $\langle \langle 4 \rangle \rangle$.

- **Step VI:** Results of $\langle\langle 2 \rangle\rangle$, $\langle\langle 3 \rangle\rangle$ and $\langle\langle 4 \rangle\rangle$ are used to calculate Q-cumulants $c_2\{2\}$ and $c_2\{4\}$.
- **Step V:** From eq. 4.20 and 4.21, final estimation of integrated flow is calculated.

2-particle correlation:

Same Sign: Q-vector for $|Q_n|^2$ is defined as:

$$|Q_n|^2 = \sum_{i,j=1}^M e^{in(\phi_i - \phi_j)} \quad (4.22)$$

where “i” and “j” are the particles which can either be same or different.

- If $i=j$ then that correlation is known as auto-correlation and gives multiplicity “M” as contribution.
- If $i \neq j$ then correlation is between different particles and 2-particle contribution is calculated as:

$$\langle 2 \rangle_{n|n} * P_{M,2} \quad (4.23)$$

The total contribution of 1- and 2- particle correlations in Q-vector is:

$$|Q_n|^2 = \langle 2 \rangle_{n|n} * P_{M,2} + 1 * M \quad (4.24)$$

After rearranging the above equation, the two particle correlator for same sign charge pairs becomes,

$$\langle 2 \rangle_{n|n} = \frac{|Q_n|^2 - M}{M(M-1)} \quad (4.25)$$

where by using Euler’s formula, $|Q_n|^2 = \cos^2\phi + \sin^2\phi$.

Opposite Sign: For opposite sign charge pairs, particles are considered from two different groups. So there is no chance of having an auto-correlation as “i” and “j”

can not be equal. The $|Q_n|^2$ for opposite sign is defined as:

$$|Q_n|^2 = q_n Q_n^* \quad (4.26)$$

where q_n also denotes the Q-vector but from different group (either positive or negative) of multiplicity “m”.

And after following the same procedure of same sign charge pair, 2-particle correlation for opposite sign charge pairs is calculated as:

$$\langle 2 \rangle_{n|n} = \frac{q_n Q_n^*}{m * M} \quad (4.27)$$

where $q_n Q_n^* = \cos\phi_i \times \cos\phi_j + \sin\phi_i \times \sin\phi_j$.

This 2-particle correlators (same sign and opposite sign) are represented as “ $\delta_{n,n}$ ” correlator and using Eq. 4.18 and 4.20, $v_2\{2\}$ is calculated.

3-particle correlation:

Firstly, 3-particle correlation with (112) combination is discussed:

Same Sign: The Q-vector for 3-particle correlator can be defined as:

$$Q_n Q_n Q_{2n}^* = \sum_{i,j,k=1}^M e^{in(\phi_i + \phi_j - 2\phi_k)} \quad (4.28)$$

here, i, j and k are particles and for same sign i and j are from same group while k is from whole set of particles (irrespective of charges), three distinct cases arise:

- When all three indices are different, $i \neq j \neq k$ and it gives:

$$\langle 3 \rangle_{n,n|2n} * M(M-1)(M-2) \quad (4.29)$$

- When any of the two indices are different, either $i \neq j = k$ or $i = j \neq k$

1. For $i \neq j = k$

$$(\phi_i + \phi_j - 2\phi_j) = (\phi_i - \phi_j), \text{ 2-particle correlation}$$

and its contribution is:

$$\langle 2 \rangle_{n|n} * M(M-1)2! \quad (4.30)$$

2. For $i = j \neq k$

$(\phi_i + \phi_i - 2\phi_k) = (2\phi_i - 2\phi_k)$, again 2-particle correlation but with $2n-2n$ and contribution is:

$$\langle 2 \rangle_{2n|2n} * M(M-1) \quad (4.31)$$

- When $i=j=k$ (auto-correlation), the contribution is:

$$1 * M \quad (4.32)$$

After putting these terms in Eq. 4.28:

$$\begin{aligned} Q_n Q_n Q_{2n}^* &= \langle 3 \rangle_{n,n|2n} * M(M-1)(M-2) + \langle 2 \rangle_{n|n} * M(M-1)2! \\ &\quad + \langle 2 \rangle_{2n|2n} * M(M-1) + M \end{aligned} \quad (4.33)$$

Re-arranging the above equation and inserting the value of $\langle 2 \rangle_{n|n}$ in that from Eq. 4.27, we get:

$$\langle 3 \rangle_{n,n|2n} = \frac{Q_n Q_n Q_{2n}^* - 2 * |Q_n|^2 - |Q_{2n}|^2 + 2 * M}{M(M-1)(M-2)} \quad (4.34)$$

The final 3-particle correlator after using Euler's formula becomes :

$$\begin{aligned} \langle 3 \rangle_{n,n|2n} &= (\cos 2\phi_k (\cos \phi_{i(j)}^2 - \sin \phi_{i(j)}^2) + \sin 2\phi_k (2 \times \sin \phi_{i(j)} \cos \phi_{i(j)})) \\ &\quad - (\cos 2\phi_k \times \cos 2\phi_{i(j)} + \sin 2\phi_k \times \sin 2\phi_{i(j)}) \\ &\quad - 2 \times (\cos 2\phi_{i(j)}^2 + \sin 2\phi_{i(j)}^2) \\ &\quad + 2 \times M / M(M-1)(M-2) \end{aligned} \quad (4.35)$$

Opposite Sign: Opposite sign 3-particle correlator is obtained by one type of

particle (either positive or negative) taken from one set of group and other one from different set. In this case, auto-correlation term is vanished out as $i \neq j$ and other two possibilities are:

- For $i \neq k$
 $(\phi_i + \phi_j - 2\phi_k)$, 3-particle correlation
 and its contribution is:

$$\langle 3 \rangle_{\underline{n}, n|2n} * M(M-1)m \quad (4.36)$$

- For $i = k$
 $(\phi_i + \phi_j - 2\phi_i) = (\phi_j - 2\phi_i)$, 2-particle correlation
 and contribution is:

$$\langle 2 \rangle_{\underline{n}|n} * m \times M \quad (4.37)$$

The 3-particle correlator for opposite sign is:

$$\langle 3 \rangle_{\underline{n}, n|2n} = \frac{q_{\underline{n}} Q_n Q_{2n}^* - q_{\underline{n}} Q_n^*}{mM(M-1)} \quad (4.38)$$

The final 3-particle correlator for opposite sign after using Euler's formula becomes :

$$\begin{aligned} \langle 3 \rangle_{\underline{n}, n|2n} = & \cos 2\phi_k (\cos \phi_i * \cos \phi_j - \sin \phi_i * \sin \phi_j) \\ & + \sin 2\phi_k (\cos \phi_i * \sin \phi_j - \sin \phi_i * \cos \phi_j) - 2 * (\cos \phi_i * \cos \phi_j + \sin \phi_i * \sin \phi_j) \\ & / m * M * (M-1) \end{aligned} \quad (4.39)$$

For (123) combination, 3-particle correlator is derived as:

Same Sign: The Q-vector for 3-particle correlator can be defined as:

$$Q_n Q_{2n} Q_{3n}^* = \sum_{i,j,k=1}^M e^{in(\phi_i + 2\phi_j - 3\phi_k)} \quad (4.40)$$

the distinct cases arise:

- For all three indices are different, $i \neq j \neq k$ and it gives:

$$\langle 3 \rangle_{n,2n|3n} * M(M-1)(M-2) \quad (4.41)$$

- When any of the two indices are different, either $i \neq j = k$ or $i = j \neq k$

1. For $i \neq j = k$

$(\phi_i + 2\phi_j - 3\phi_j) = (\phi_i - \phi_j)$, 2-particle correlation

and contribution is:

$$\langle 2 \rangle_{n|n} * M(M-1) \quad (4.42)$$

2. For $i = j \neq k$

$(\phi_i + 2\phi_i - 3\phi_k) = (3\phi_i - 3\phi_k)$, again 2-particle correlation but with $3n-3n$

and contribution is:

$$\langle 2 \rangle_{3n|3n} * M(M-1) \quad (4.43)$$

3. For $i = k \neq j$

$(\phi_i + 2\phi_j - 3\phi_i) = (2\phi_j - 2\phi_i)$, again 2-particle correlation with $2n-2n$

and contribution is:

$$\langle 2 \rangle_{2n|2n} * M(M-1) \quad (4.44)$$

- When $i=j=k$ (auto-correlation), the contribution is:

$$1 * M \quad (4.45)$$

After putting these terms in Eq. 4.40:

$$\begin{aligned} Q_n Q_{2n} Q_{3n}^* &= \langle 3 \rangle_{n,2n|3n} * M(M-1)(M-2) + \langle 2 \rangle_{n|n} * M(M-1) \\ &\quad + \langle 2 \rangle_{2n|2n} * M(M-1) + \langle 2 \rangle_{3n|3n} * M(M-1) + M \end{aligned} \quad (4.46)$$

Re-arranging the above equation and inserting the value of $\langle 2 \rangle_{n|n}$ in that from

Eq. 4.27, we get:

$$\langle 3 \rangle_{n,2n|3n} = \frac{Q_n Q_{2n} Q_{3n}^* - |Q_n|^2 - |Q_{2n}|^2 - |Q_{3n}|^2 + 2 * M}{M(M-1)(M-2)} \quad (4.47)$$

The $\langle 3 \rangle_{n,2n|3n}$, after applying Euler's formula:

$$\begin{aligned} \langle 3 \rangle_{n,2n|3n} = & \cos 3\phi_k (\cos \phi_{i(j)} * \cos 2\phi_{i(j)} - \sin \phi_{i(j)} * \sin 2\phi_{i(j)}) \\ & + \sin 3\phi_k (\sin \phi_{i(j)} * \cos 2\phi_{i(j)} + \cos \phi_{i(j)} * \sin 2\phi_{i(j)}) \\ & - (\cos 3\phi_{i(j)} * \cos 3\phi_k) - (\sin 3\phi_{i(j)} * \sin 3\phi_k) \\ & - \cos 2\phi_{i(j)}^2 - \sin 2\phi_{i(j)}^2 - \cos \phi_{i(j)}^2 - \sin \phi_{i(j)}^2 \\ & + 2 * M / M(M-1)(M-2) \end{aligned} \quad (4.48)$$

Opposite Sign: The procedure to derive the opposite sign (123) 3-particle correlator is similar to (112) opposite sign charge pairs correlator. The “i” and “j” can not be equal as they are from different pools and possibilities arise are: $i \neq j = k$, $i \neq j \neq k$ and $i = k \neq j$ and from these the $\langle 3 \rangle_{\underline{n},2n|3n}$ is calculated as:

$$\langle 3 \rangle_{\underline{n},2n|3n} = \frac{q_n Q_{2n} Q_{3n}^* - q_n Q_n^*}{mM(M-1)} \quad (4.49)$$

and after applying Euler's formula:

$$\begin{aligned} \langle 3 \rangle_{\underline{n},2n|3n} = & \cos 3\phi_k (\cos \phi_i * \cos 2\phi_j - \sin \phi_i * \sin 2\phi_j) \\ & + \cos \phi_i * \cos 2\phi_j - \sin \phi_j * \sin 2\phi_i / 2. \\ & + \sin 3\phi_k (\sin \phi_i * \cos 2\phi_j + \cos \phi_i * \sin 2\phi_j) \\ & + \sin \phi_i * \cos 2\phi_j + \cos \phi_j * \sin 2\phi_i / 2. \\ & - (\cos \phi_i * \cos \phi_j + \sin \phi_i * \sin \phi_j) \\ & - (\cos 2\phi_i * \cos 2\phi_j + \sin 2\phi_i * \sin 2\phi_j) \end{aligned} \quad (4.50)$$

4-particle correlation

The 4th order Q-vector ($|Q_n|^4$) is defined as:

$$|Q_n|^4 = \sum_{i,j,k,l=1}^M e^{in(\phi_i + \phi_j - \phi_k - \phi_l)} \quad (4.51)$$

Since 4-particle correlations are only used for calculating elliptic flow in this analysis, so here only the same sign cases are discussed. On taking the account for only same sign either ++ or --, four possible cases of indices combinations exit.

- The $i \neq j \neq k \neq l$ gives:

$$\langle 4 \rangle_{n,n|n,n} * M(M-1)(M-2)(M-3) \quad (4.52)$$

- When any three indices are different; either $i = j \neq k \neq l$ or $i \neq j = k \neq l$ or $i \neq j \neq k = l$.

1. For $i = j \neq k \neq l$

$$(\phi_i + \phi_i - \phi_k - \phi_l) = (2\phi_i - \phi_k - \phi_l), \text{ three-particle correlation}$$

and its contribution is:

$$\langle 3 \rangle_{2n|n,n} * M(M-1)(M-2) \quad (4.53)$$

2. For $i \neq j \neq k = l$

$$(\phi_i + \phi_j - \phi_k - \phi_k) = (\phi_i + \phi_j - 2\phi_k), \text{ again three-particle correlation but}$$

with $(n, n|2n)$ and its contribution is:

$$\langle 3 \rangle_{n,n|2n} * M(M-1)(M-2) \quad (4.54)$$

3. For $i \neq j = k \neq l$

$$(\phi_i + \phi_j - \phi_j - \phi_l) = (\phi_i - \phi_l), \text{ which is 2-particle correlation}$$

and the contribution is:

$$\langle 2 \rangle_{n|n} * M(M-1)2!(M-2)2! \quad (4.55)$$

- When any two indices are different; either $i \neq j = k = l$ or $i = j \neq k = l$ or $i = j = k \neq l$.

1. For $i \neq j = k = l$

$(\phi_i + \phi_j - \phi_j - \phi_j) = (\phi_i - \phi_j)$, makes it 2-particle correlation with contribution:

$$\langle 2 \rangle_{n|n} * M(M-1) * 2! * 2! \quad (4.56)$$

2. For $i = j \neq k = l$

$(\phi_i + \phi_i - \phi_k - \phi_k) = (2\phi_i - \phi_k)$, which is again 2-particle correlation and its contribution is:

$$\langle 2 \rangle_{2n|2n} * M(M-1) \quad (4.57)$$

3. For $i = j = k \neq l$

$(\phi_i + \phi_i - \phi_i - \phi_l) = (\phi_i - \phi_l)$, which is similar to first combination.

- The final case of auto-correlation ($i=j=k=l$) gives the contribution of

$$1 * M \quad (4.58)$$

Put all the computed values in Eq. 4.51 to get the four particle correlation

term:

$$\begin{aligned}
|Q_n|^4 &= \langle 4 \rangle_{n,n|n,n} * M(M-1)(M-2)(M-3) \\
&+ [\langle 3 \rangle_{2n|n,n} + \langle 3 \rangle_{n,n|2n}] * M(M-1)(M-2) \\
&+ \langle 2 \rangle_{n|n} * [M(M-1)2!(M-2)2! + M(M-1)2! * 2!] \\
&+ \langle 2 \rangle_{2n|2n} * M(M-1) + M(M-1)2 + M
\end{aligned} \tag{4.59}$$

And 4-particle correlation, $\langle 4 \rangle_{n,n|n,n}$, is expressed in terms of Q-vectors as:

$$\begin{aligned}
\langle 4 \rangle_{n,n|n,n} &= \frac{(|Q_n|^4 + |Q_{2n}|^2 - 2 * R[Q_{2n}Q_n^*Q_n^*] - 4(M-2)|Q_n|^2)}{M(M-1)(M-2)(M-3)} \\
&+ \frac{2}{(M-1)(M-2)}
\end{aligned} \tag{4.60}$$

here in above equation, $\langle 2 \rangle$ and $\langle 3 \rangle$ is substituted from Eq. 4.27 and 4.34.

From $\langle 4 \rangle_{n,n|n,n}$, cumulant is calculated using Eq. 4.19 and the $v_2\{4\}$ is calculated using Eq. 4.21. In this analysis, average of both $v_2\{2\}$ and $v_2\{4\}$ is used as elliptic flow v_2 .

4.4.2 Background Estimation

The main focus of this analysis is not only isolating the CME like events but also estimating the background in the observed signal as given below: In order to determine the background contribution in each sliced f_{D_bCS} bin, the charges of particles in each event for a given centrality shuffled randomly to destroy the charge dependent correlations amongst the particles but keeping θ and ϕ of each particle unchanged in an event so that the flow does not get affected. The f_{D_bCS} distribution is obtained for the charge shuffled events for a given collision centrality and is sliced into ten percentile bin. The γ of charged shuffled events' sample is obtained for a given sliced f_{D_bCS} bin representing the contribution due to statistical fluctuation and is termed as γ_{ChS} .

Now to recover the correlations amongst particles, which were destroyed in charge shuffling, for sliced f_{DbCS} bin of charge shuffled events, we calculated γ correlator from the corresponding events in the original events' sample and termed as γ_{Cor} . Fig. 4.2 displays the scatter plots for $f_{DbCS}(\text{ChS})$ vs $f_{DbCS}(\text{Fix-2 CME})$ for 50-60% and 30-40% collision centralities with a vertical line corresponding to the top 10% $f_{DbCS}(\text{ChS})$ on the right side of the line. It is noticed that charge shuffled events corresponding to the top 10% $f_{DbCS}(\text{ChS})$ are spread over 0-100% $f_{DbCS}(\text{CME})$. So, after restoring the charges, the correlated background comes from actual events that span practically all f_{DbCS} bins of actual data but corresponds to the f_{DbCS} bin of charge shuffled sample for a given collision centrality.

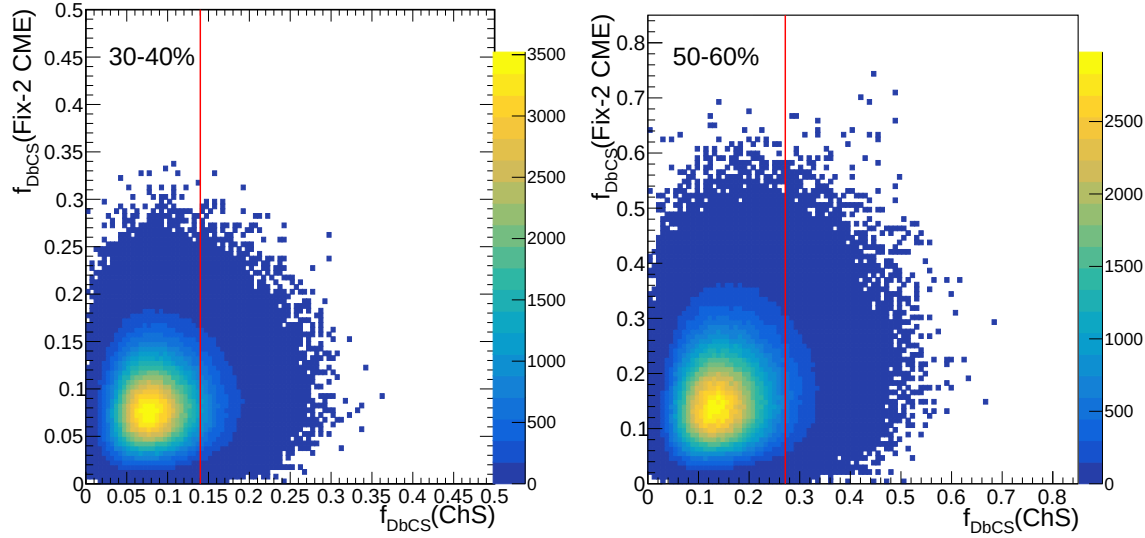


Figure 4.2: The scatter plots of $f_{DbCS}(\text{ChS})$ versus $f_{DbCS}(\text{Fix-2 CME})$ for 30-40% collision centrality (Left) and 50-60% collision centrality (Right) with vertical lines corresponding to top 10% $f_{DbCS}(\text{ChS})$.

Thus total background contribution to the 3-particle γ correlator is:

$$\gamma_{\text{bkg}} = \gamma_{\text{ChS}} + \gamma_{\text{Cor}} \quad (4.61)$$

4.4.3 Statistical Error Estimation

The statistical errors are estimated through “**Sub-Sampling**” method. As name suggests, in sub sampling method, whole data set is divided into “n” sub samples having equal number of events. The desired observable “x” is then calculated for each sub sample. Then standard deviation is obtained for each sub sample as :

$$\sigma = \sqrt{\frac{\sum (x_n - \langle x \rangle)^2}{N - 1}} \quad (4.62)$$

where x_n is the value of “x” calculated for “ n^{th} ” sub sample, N is the total number of events in the data set and

$$\langle x \rangle = \frac{1}{N} \sum_{n=1}^N x_n \quad (4.63)$$

From this σ (Eq. 4.62), the final statistical error in the mean value of “x” is defined as:

$$\sigma_{\langle x \rangle} = \frac{\sigma}{\sqrt{N}} \quad (4.64)$$

To study the SDM through AMPT, data sets are divided into 10 sub samples to estimate the statistical errors and 1σ error is used.

4.4.4 Strategy

Analysis technique is divided into following steps as :

- **Step-I:** In first step, whole azimuthal plane is scanned as explained in Section 4.2 and $f_{D b C S}$ distributions are obtained for each collision centrality and for each set.
- **Step-II:** The obtained $f_{D b C S}$ distributions are divided into ten percentile bins (0-10%, 10-20%...90-100%) for each collision centrality. The top 10% (0-10%) corresponds to the highest fractional charge separation across the dumbbell and 90-100% bin denotes the lowest.

- **Step-III:** After dividing the $f_{D bCS}$ distributions into ten percentile bins, multi-particle correlators (detailed formulism given in Sub-section 5.3) are calculated for each bin and for each centrality.
- **Step-IV:** From $\Delta\gamma$ correlators, CME fraction is calculated through the formula :

$$f_{CME} = \frac{1}{N} \sum_{i=1}^{10} N_i \times \frac{(\Delta\gamma_i - \Delta\gamma_{bkg,i})}{\Delta\gamma_i} \quad (4.65)$$

where N_i is the number of events in the i^{th} bin of $f_{D bCS}$ and N is the total number of events in a given collision centrality. For $\Delta\gamma_{bkg.} < 0$, $\Delta\gamma_{bkg.}$ is taken as 0. Also if $\Delta\gamma < 0$ then $\Delta\gamma=0$, as $\Delta\gamma < 0$ implicates $\gamma_{OS} < 0$ and $\gamma_{SS} > 0$ which is not the case for CME like signal.

4.5 Results and Discussion

A charged dependent single particle azimuthal distribution [35] is defined as:

$$f_\chi(\phi, q) \propto 1 + 2v_2 \cos[2(\phi - \Psi_{RP})] + 2q\chi d_1 \cos(\phi - \Psi_{CS}) \quad (4.66)$$

where $\chi = \pm 1$ represents the sphaleron (parallel to magnetic field) or anti-sphaleron (anti-parallel to magnetic field) transitions; ϕ and q represent the azimuthal angle and charge of a particle, respectively. The reaction plane angle is represented by Ψ_{RP} and Ψ_{CS} specifies the charge separation angle. The d_1 and v_2 quantifies the charge separation effect and elliptic flow. The contribution to the 2- particle δ correlator due to this charge dependent single-particle distribution is:

$$\delta_{++/--} \equiv \langle \cos(\phi_i - \phi_j) \rangle_{++/--} = +d_1^2 \quad (4.67)$$

$$\delta_{+-} \equiv \langle \cos(\phi_i - \phi_j) \rangle_{+-} = -d_1^2 \quad (4.68)$$

and the contribution to the 3- particle γ correlator due to charge dependent single-particle distribution is:

$$\gamma_{++/--} \equiv \langle \cos(\phi_i + \phi_j - 2\Psi_{RP}) \rangle_{++/--} = d_1^2 \cos(2\Delta\Psi_{CS}) \quad (4.69)$$

$$\gamma_{+-} \equiv \langle \cos(\phi_i + \phi_j - 2\Psi_{RP}) \rangle_{+-} = -d_1^2 \cos(2\Delta\Psi_{CS}) \quad (4.70)$$

The CME predicts $\Psi_{CS} = \pi/2$ and if $\Psi_{RP} = 0$ then,

$$\gamma_{++/--} = \langle \cos(\phi_i + \phi_j - 2\Psi_{RP}) \rangle_{++/--} = d_1^2 \cos(2 \times \pi/2) < 0 \quad (4.71)$$

and

$$\delta_{++/--} = \langle \cos(\phi_i - \phi_j) \rangle_{++/--} = +d_1^2 > 0 \quad (4.72)$$

while

$$\gamma_{+-} = \langle \cos(\phi_i + \phi_j - 2\Psi_{RP}) \rangle_{+-} = -d_1^2 \cos(2 \times \pi/2) > 0 \quad (4.73)$$

$$\delta_{+-} = \langle \cos(\phi_i - \phi_j) \rangle_{+-} = -d_1^2 < 0 \quad (4.74)$$

which means γ_{112} should be +ve for OS and -ve for SS while δ should be complete opposite of that. Also their magnitude should be equal if the only contribution in the correlators is CME. Along with δ and γ correlators¹, γ_{123} and H-correlators are also studied.

These correlators are studied first with respect to the centralities as well as for different charge separation bins (i.e., f_{DbCS} bins). The dependence of the main background “elliptic flow” (v_2) is also studied with respect to fractional charge separation across the dumbbell to see its effect on γ_{112} correlators.

¹In this thesis γ means γ_{112} if otherwise mentioned.

4.5.1 Multi-particle correlations as a function of Centralities

2-particle “ δ ” correlator:

Fig. 4.3 shows the 2-particle “ δ ” correlator as a function of centrality for various AMPT sets. Both opposite sign (OS) and same sign (SS) charge pairs correlators have positive values except for 60-70% OS correlations of Fix-2 CME. As it is also clear from the figure that OS correlator has more +ve values for 0-50% collision centralities than those of same sign correlator. The δ correlator seems to be independent of the CME injected signal for 0-50% centralities.

3-particle correlator:

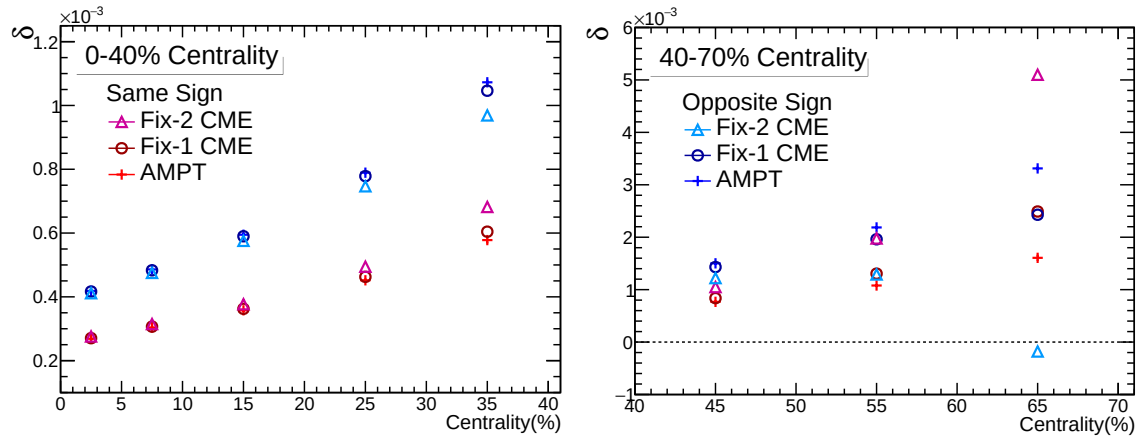


Figure 4.3: The centrality dependence of δ correlator for AMPT, Fix-1 CME and Fix-2 CME : Right Plot for 0-40% collision centrality and left for 40-70% collision centrality. The legends indicate the connection between different set and charge combinations and y-axis for 0-40% collision centralities are magnified for the sake of clarity.

The variation of overall 3-particle correlators (γ_{112} and γ_{123}) with centrality for different AMPT sets are displayed in Fig. 4.4 and Fig. 4.5, respectively. These and forthcoming plots are divided into two sets of 0-40% and 40-70% centralities for the sake of clarity and their Y-axes are zoomed for the 0-40% collision centralities.

The 3-particle γ_{112} correlator for SS charge pairs are negative and show stronger correlations whereas weaker correlations are observed for OS. In addition, with increase in injected signal, strength of correlations also increase. Both OS and SS

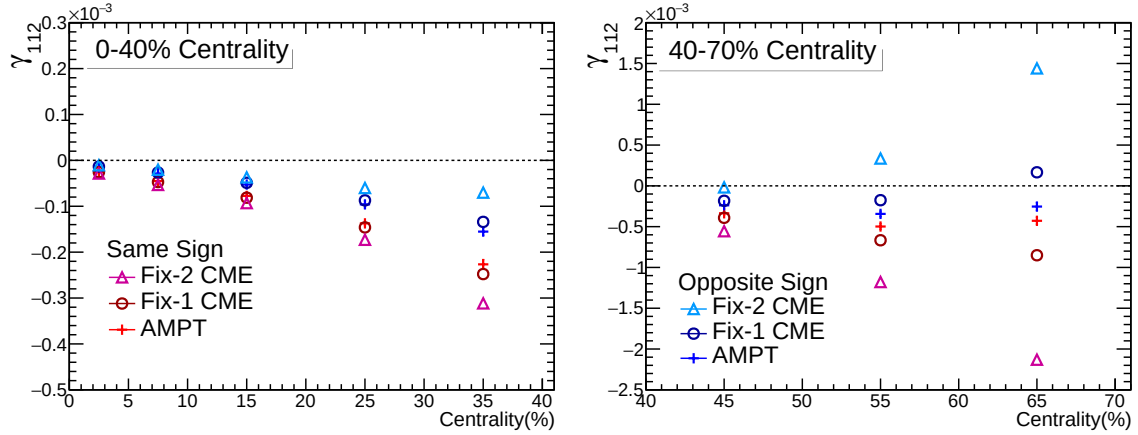


Figure 4.4: Left: The centrality dependence of γ_{112} for same sign and opposite sign charge pairs for different samples as indicated in legends for 0-40% collision centralities. Right : Same for 40-70% collision centralities. The y-axis for 0-40% collision centralities are magnified for the sake of clarity.

have small negative values for the AMPT. The difference between OS and SS also increases as injected signal increases. Also because the externally injected signal is independent of collision centrality, the strength of correlations reduces as collision centrality increases. The 3-particle γ_{123} (Fig. 4.5) correlators show +ve correlations

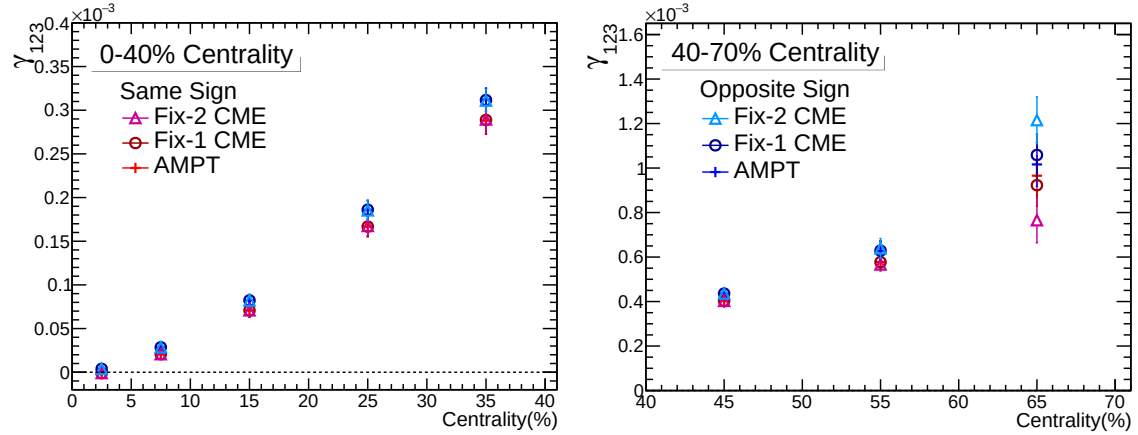


Figure 4.5: Left: The centrality dependence of γ_{123} for same sign and opposite sign charge pairs for different AMPT samples for 0-40% collision centralities. Right: Same for 40-70% collision centralities. The y-axis for 0-40% collision centralities are magnified for the sake of clarity.

for both OS and SS charge pairs and do not depend (within errors) on the externally injected CME like signal.

$\Delta\gamma$ correlators:

The dependence of $\Delta\gamma_{112}$ and $\Delta\gamma_{123}$ on collision centrality for AMPT, Fix-1 CME

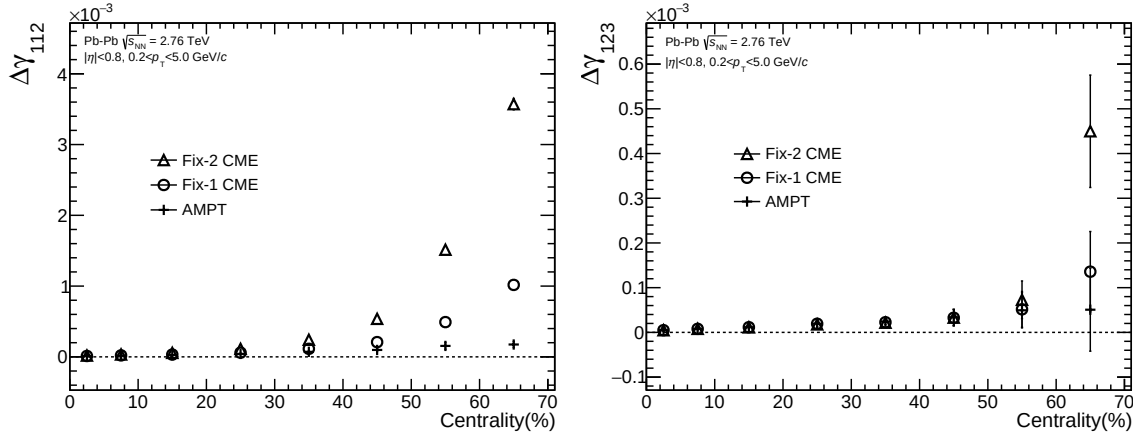


Figure 4.6: The centrality dependence of $\Delta\gamma_{112}$ (Left) and $\Delta\gamma_{123}$ (Right) for different AMPT sets.

and Fix-2 CME samples is displayed in Fig. 4.6. It is seen from the figure that $\Delta\gamma_{112}$ increases with increase in externally injected signal indicating the strong dependence of three particle correlator on the injected signal strength; and for the AMPT events, the $\Delta\gamma_{112}$ is approximately zero for all collision centralities as there is no CME in AMPT. In the $\Delta\gamma_{123}$, AMPT, Fix-1 CME and Fix-2 CME remains undistinguishable for upto 0-60% centralities, indicating that γ_{123} correlator does not depend on CME like signal.

ΔH correlator:

The γ and δ correlators depend on the flow independent CME-type correlations and flow dependent correlations [34].

$$\gamma_{i,j} \sim -H_{i,j} \quad , \quad \delta_{i,j} \sim H_{i,j} \quad (4.75)$$

$$\gamma_{i,j} \sim v_2 F_{i,j} \quad , \quad \delta_{i,j} \sim F_{i,j} \quad (4.76)$$

here (i,j) can either be same sign or opposite sign charge pairs, v_2 is elliptic flow and; H and F represent the strength of the non-flow dependent CME correlations

and flow dependent contributions. By combining above two equations, we get:

$$\gamma_{i,j} \sim v_2 F_{i,j} - H_{i,j} \quad , \quad \delta_{i,j} \sim F_{i,j} + H_{i,j} \quad (4.77)$$

From which, we get:

$$\gamma = \kappa v_2 F - H \quad (4.78)$$

$$\delta = F + H \quad (4.79)$$

and after re-arranging we get:

$$H = \frac{\kappa v_2 \delta - \gamma}{1 + \kappa v_2} \quad (4.80)$$

where κ is the proportionality constant, depends on the detector acceptance and defined as:

$$\kappa \propto 2 - \frac{\langle v_2 \rangle_F}{\langle v_2 \rangle_\Omega} \quad (4.81)$$

where $\langle \rangle_F$ is the average of all particles in full phase space while $\langle \rangle_\Omega$ denotes fraction of phase space where actual measurments are done.

The variation of ΔH ($= H_{SS} - H_{OS}$) correlator with centrality is shown for various

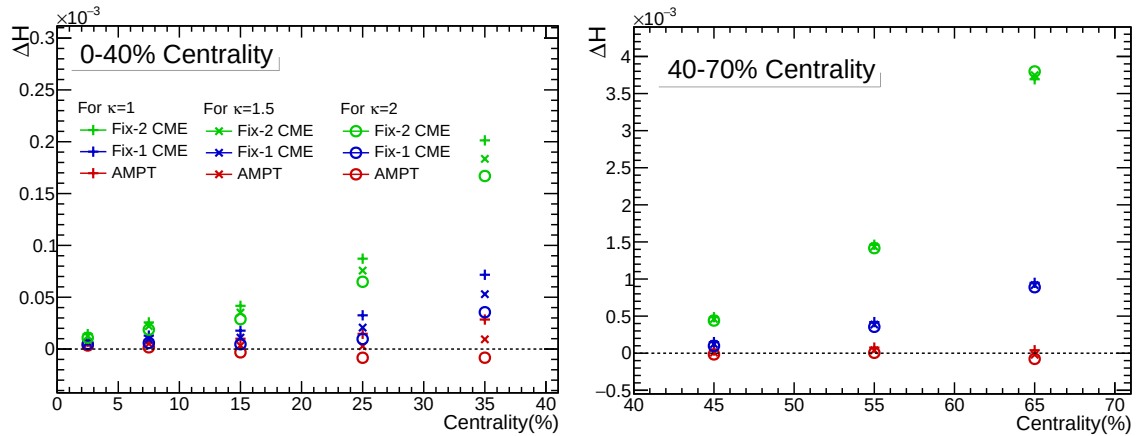


Figure 4.7: The variation of ΔH with collision centrality (Right Plot for 0-40% collision centralities and left for 40-70% collision centralities) for different κ values (indicated in legends) for AMPT, Fix-1 CME and Fix-2 CME. The y-axis for 0-40% collision centralities are magnified for the sake of clarity.

κ values in Fig. 4.7. ΔH is seen to be independent of κ for AMPT, Fix-1 CME and Fix-2 CME. The correlation values are positive and increases with increase in externally injected signal. The $\Delta H \approx 0$ for the AMPT without any CME like signal.

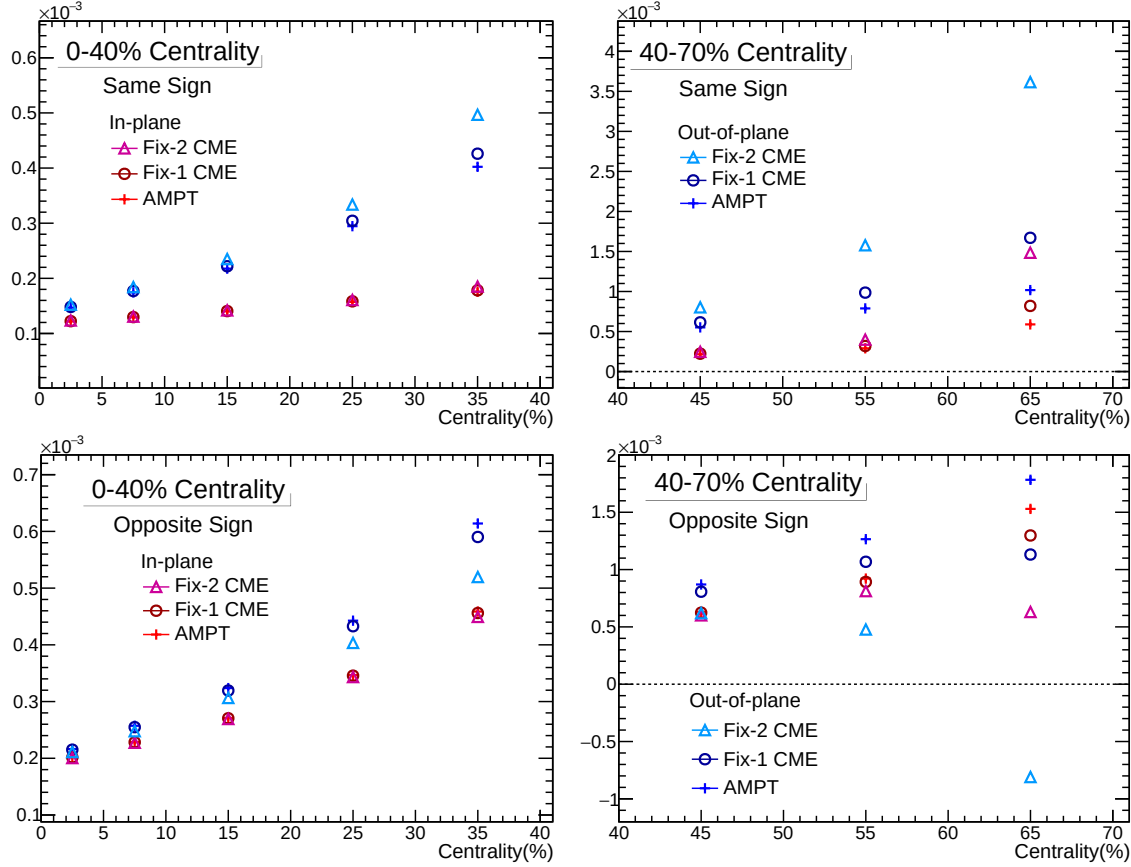


Figure 4.8: The variation of In-plane and out-of-plane correlations for same sign and opposite sign charge pair combination with collision centrality (Left: 0-40% centralities, Right: 40-70% centralities) for different AMPT's sets. The y-axis for 0-40% collision centralities are magnified for the sake of clarity.

In-plane and out-of-plane correlations:

The δ and γ_{112} correlation function can be decomposed into in-plane ($\sim \langle \cos(\phi_i) \cos(\phi_j) \rangle$) and out-of-plane ($\sim \langle \sin(\phi_i) \sin(\phi_j) \rangle$) components as:

$$\gamma = \langle \cos(\phi_i + \phi_j - 2\Psi_{RP}) \rangle = \langle \cos(\Delta\phi_i) \cos(\Delta\phi_j) \rangle - \langle \sin(\Delta\phi_i) \sin(\Delta\phi_j) \rangle \quad (4.82)$$

$$\delta = \langle \cos(\phi_i - \phi_j) \rangle = \langle \cos(\Delta\phi_i)\cos(\Delta\phi_j) \rangle + \langle \sin(\Delta\phi_i)\sin(\Delta\phi_j) \rangle \quad (4.83)$$

where $\Delta\phi_{i(j)} = \phi_{i(j)} - \Psi_{RP}$. For CME, same sign charge pair should be out-of-plane. We also studied in-plane and out-of-plane correlation (Fig. 4.8) for different centralities. The same sign charge pairs correlations are out-of-plane and increase with the increase in the externally injected signal; in contrast, weak and independent of injected signal in-plane correlations are seen. However, for AMPT without CME like signal, the out-of-plane correlations are slightly larger for opposite sign charge pairs than those for same sign charge pairs. Also, for the opposite sign charge pairs, out-of-plane correlations decrease with increase in the CME like signal.

4.5.2 Analysing using SDM

4.5.2.1 The f_{DbCS} (fractional charge separation across the dumbbell) Distributions

The fractional charge separation across the dumbbell is calculated using Eq. 4.4 by scanning the whole azimuthal plane. These f_{DbCS} distributions for various centralities are displayed in fig. 4.9 for AMPT, Fix-1 CME and Fix-2 CME along with the charge shuffle background. For higher centralities, all distributions are indistinguishable but as we move to the lower centralities, the Fix-2 CME distributions move towards the higher f_{DbCS} values (approaching to 1). The AMPT and charge shuffle show similar distributions for all centralities. As the externally injected signal increased, the distributions are well distinguishable and move towards 1 (complete charge separation).

These distributions are now sliced into 10 percentile bins of f_{DbCS} , starting from the right. The top bin (0-10% f_{DbCS}) denotes the highest charge separation and are the potential candidates for CME like events, whereas the 90-100% f_{DbCS} bin with lowest charge separation are like the normal events. Therefore, we can separate the events on the basis of charge separation to look for the CME signal.

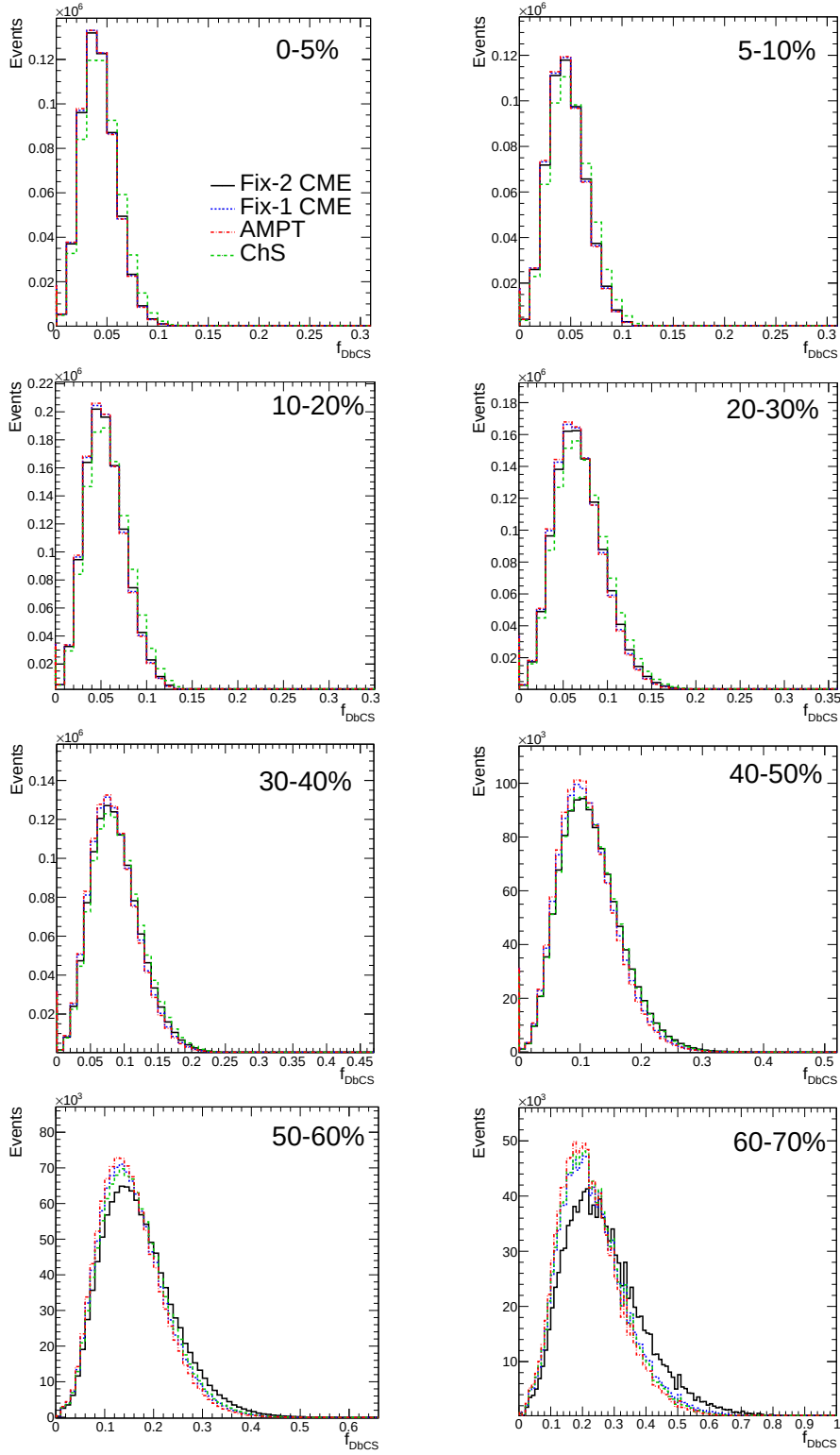


Figure 4.9: The centrality dependence of f_{DbCS} distributions obtained by sliding dumbbell method for AMPT, Fix-1 CME, Fix-2 CME compared with Charge shuffle background.

All the multi-particle correlations i.e., the CME sensitive γ correlator, the δ correlator, H-correlator and elliptic flow are studied again for the different charge separation bins to investigate the CME signal.

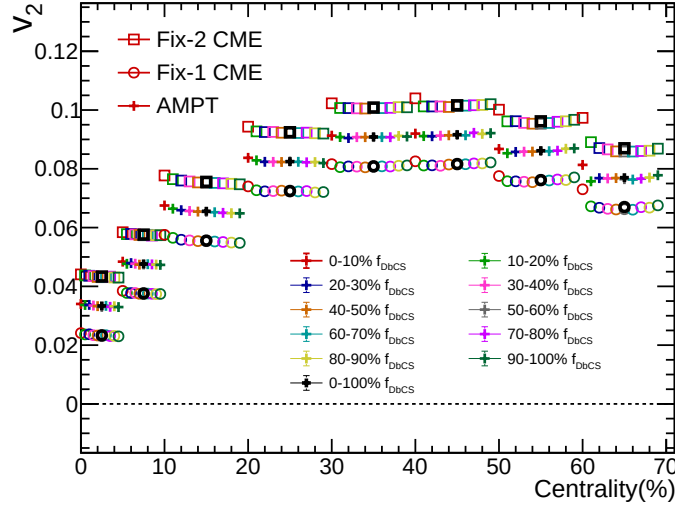


Figure 4.10: The charge separation dependence of v_2 for different collision centralities and for different AMPT sets. The points for Fix-1 CME are decreased by 1% and increased by 1% for Fix-2 CME for the sake of clarity.

4.5.2.2 Elliptic flow

The charge dependent azimuthal particle correlations include a considerable contribution from flow-induced correlations so it is foremost to study the v_2 variation with respect to the charge separation. Fig. 4.10 shows the v_2 variation for ten f_{DbCS} percentile bins and for different centrality classes. The points for Fix-2 and Fix-1 CME are shifted by +1% and -1% for the sake of clarity. Here also, the averaged (0-100% f_{DbCS} bins) v_2 is plotted (black markers) along with the ten bins for each centrality. The elliptic flow is same for AMPT, Fix-1 CME and Fix-2 CME. As one moves from more central collisions to semi-central collisions, the v_2 increases and saturates at 40-50% centrality and then starts decreasing. It is seen that for the top (0-10%) f_{DbCS} bins, v_2 is larger (14% for 60-70% for Fix-2 CME) and then becomes independent of charge separation. This trend is seen for all collision centralities. The normalized flow i.e., $v_2(\text{Top } 10\% f_{DbCS})/v_2(\text{avg})$, is shown in figure 4.11. All

the points are greater than 1 which means the v_2 is higher for top $f_{D_{bCS}}$ bin and this normalized v_2 increases as the externally injected CME type signal increases. The variation of multiplicity with $f_{D_{bCS}}$ bins is shown in Fig. 4.12(Left) and here,

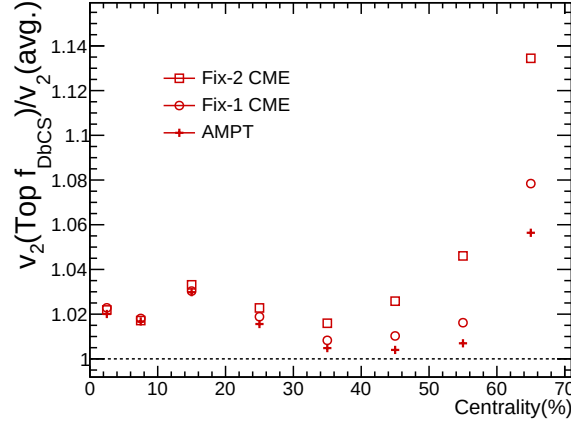


Figure 4.11: The normalize flow for different centralities and different AMPT sets.

the trend of decrease in multiplicity for top $f_{D_{bCS}}$ bins is seen for all collision centralities and after that multiplicity remains unaffected by charge separation. The similar trend of decrease is seen in normalized multiplicity (mult(Top 10% $f_{D_{bCS}}$ bin)/mult (avg)) (Fig. 4.12(Right)).

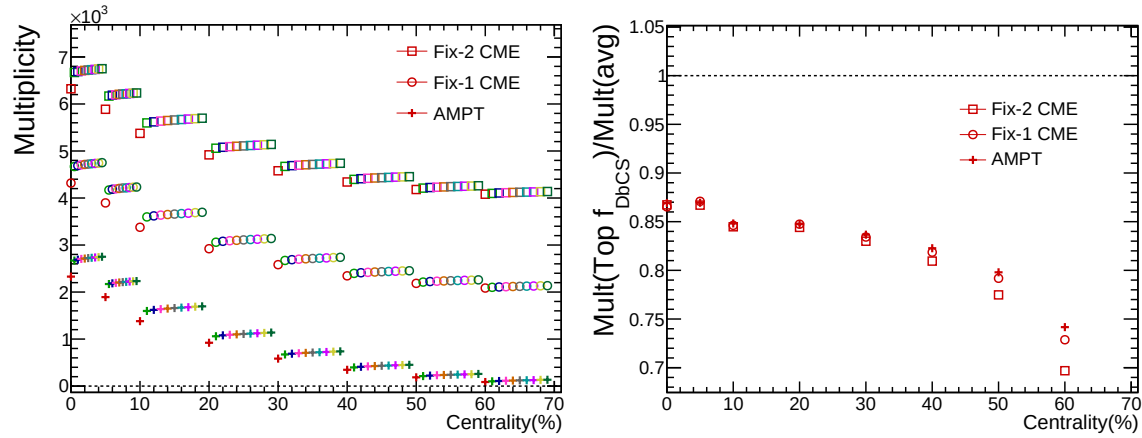


Figure 4.12: Left: The charge separation dependence of multiplicity for different collision centralities and for different AMPT sets. The points for Fix-1 CME are increased by 2000 and increased by 4000 for Fix-2 CME for the sake of clarity. Right: The normalize multiplicity i.e., Mult(Top 10% $f_{D_{bCS}}$)/Mult(avg) for different centralities and different AMPT sets.

4.5.2.3 Dependence of multi-particle correlators on charge separation (f_{DbCS})

2-particle δ correlator:

The δ correlator is calculated for each ten percentile bins and for each centrality for different AMPTs sets and is shown in figure 4.13. For maximum charge separation

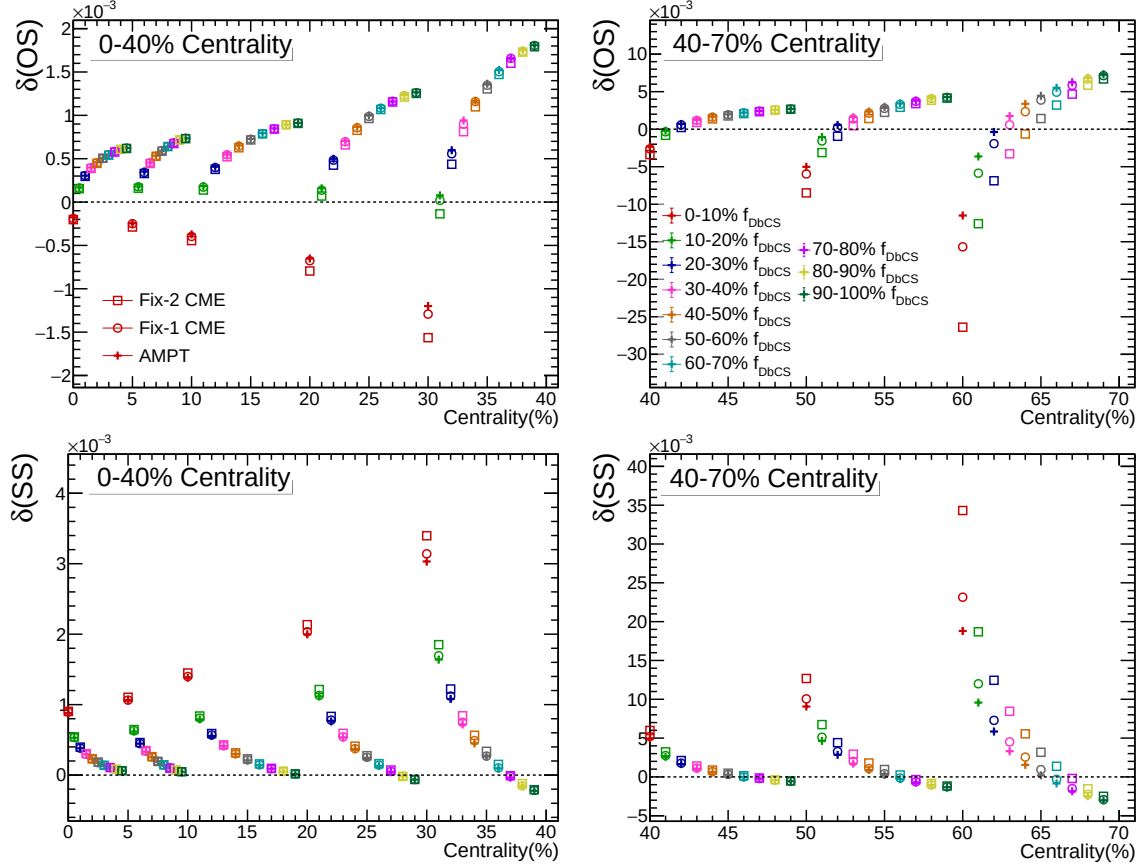


Figure 4.13: The charge separation (f_{DbCS}) dependence of 2- particle δ correlator for OS (Top Row) and SS (Bottom Row) for AMPT, Fix-1 CME and Fix-2 CME. The left column plots are for 0-40% collision centralities and right column plots are for 40-70% collision centralities and; y-axes for 0-40% collision centralities are magnified for the sake of clarity.

(top 10% f_{DbCS} bin) values of correlations are much higher than the other bins. The opposite sign charge pairs exhibit negative correlations (i.e., negative $\delta(OS)$) for the top f_{DbCS} bins whereas $\delta(SS)$ is positive for top f_{DbCS} bins. The strength of $\delta(OS)$ increases with increase in the externally injected CME like signal. Also, with the decrease in centrality, the correlation values increases.

3-particle correlators:

The γ_{112} correlator for opposite sign (Top Row) and same sign (Bottom Row) versus centrality for ten f_{D_bCS} percentile bins are shown in figure 4.14 for AMPT, Fix-1 CME, Fix-2 CME along with the charge shuffle and correlated background. The

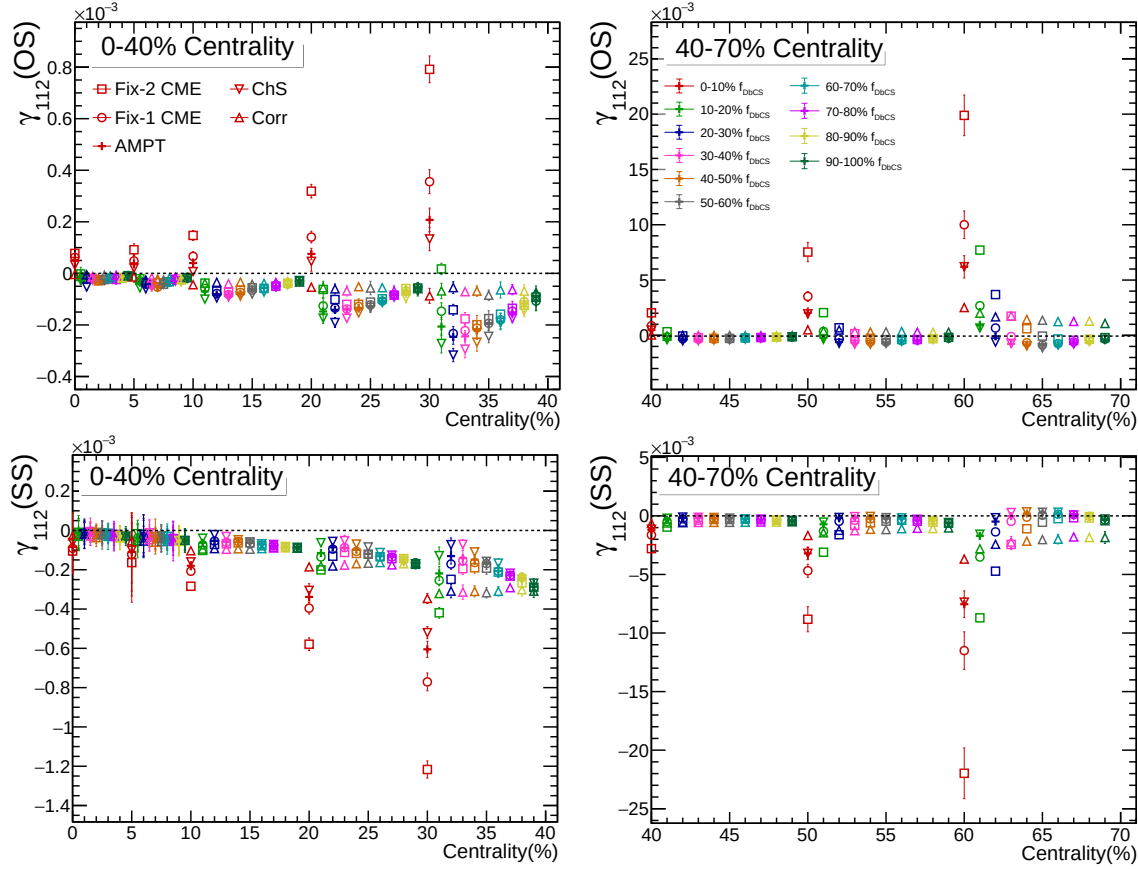


Figure 4.14: The charge separation (f_{D_bCS}) dependence of 3- particle γ_{112} correlator for OS and SS for AMPT, Fix-1 CME and Fix-2 CME with charge shuffle and correlated backgrounds. The left column plots are for 0-40% collision centralities and right column plots are for 40-70% collision centralities and; The y-axes for 0-40% collision centralities are magnified for the sake of clarity.

OS shows positive values for γ_{112} correlators and for higher f_{D_bCS} bins, correlation become more positive. The AMPT and charge shuffle background matches with each other within uncertainties. As the externally injected CME signal increases, the correlation become more positive. The correlations are negative for same sign charge pair combination indicating the presence of strong correlation and as we move towards lower centrality and higher injected signal, the correlation become

more and more negative. Here also, AMPT and charge shuffle agree within errors. The γ_{123} is also studied for various $f_{D_{bCS}}$ bins for AMPT, Fix-1 CME and Fix-2

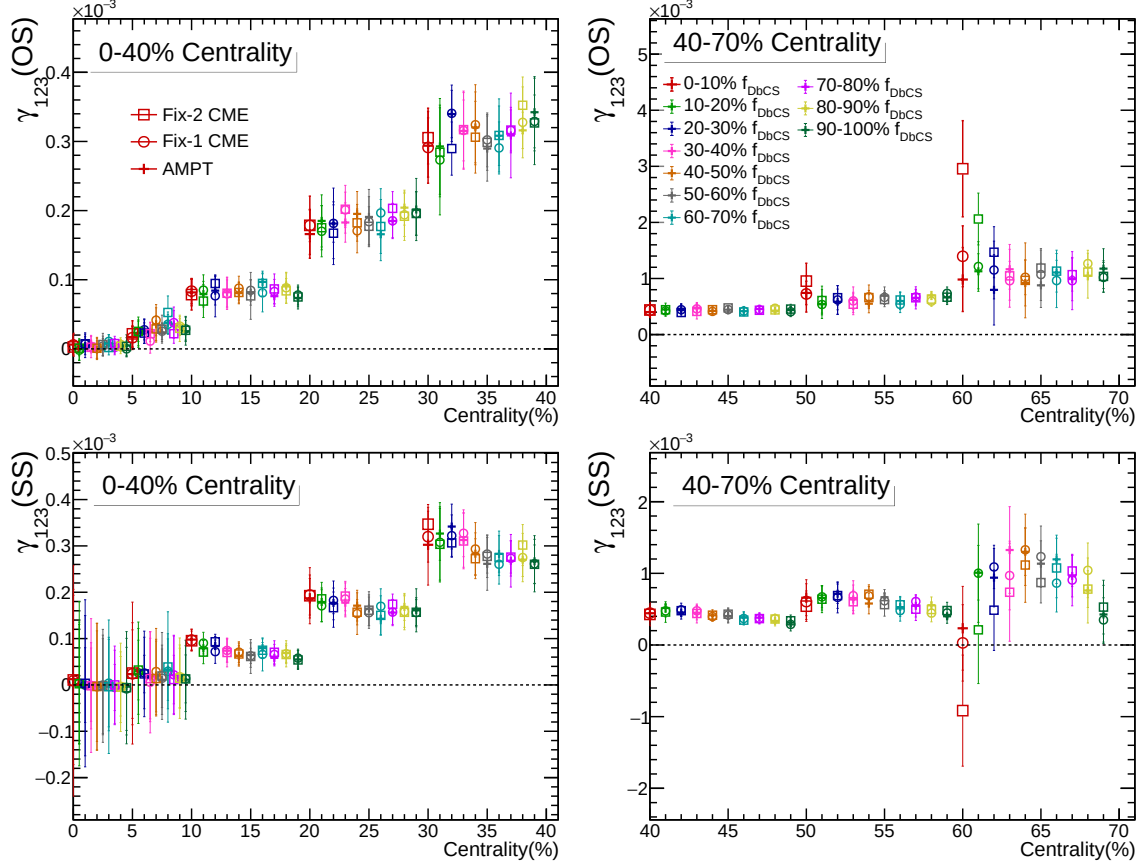


Figure 4.15: The charge separation ($f_{D_{bCS}}$) dependence of γ_{123} correlator for OS and SS charge pairs for AMPT, Fix-1 CME and Fix-2 CME. The left column plots are for 0-40% collision centralities and right column plots are for 40-70% collision centralities and; The y-axes for 0-40% collision centralities are magnified for the sake of clarity..

CME (Fig. 4.15). It is seen that $\gamma_{123}(\text{OS})$ and $\gamma_{123}(\text{SS})$ are independent of charge separation ($f_{D_{bCS}}$) bins for 0-60% collision centralities indicating that it does not depend on the CME signal as expected.

$\Delta\gamma$ correlators:

Figure 4.16 (Left) presents the $\Delta\gamma_{112}$ ($=\gamma(\text{OS})-\gamma(\text{SS})$) as a function of $f_{D_{bCS}}$ for different collision centrality for different AMPTs sets, charge shuffle and correlated backgrounds. The $\Delta\gamma_{112}$ exhibits more positive values for top $f_{D_{bCS}}$ bins and increases with the increase in the strength of externally injected signal. The charge

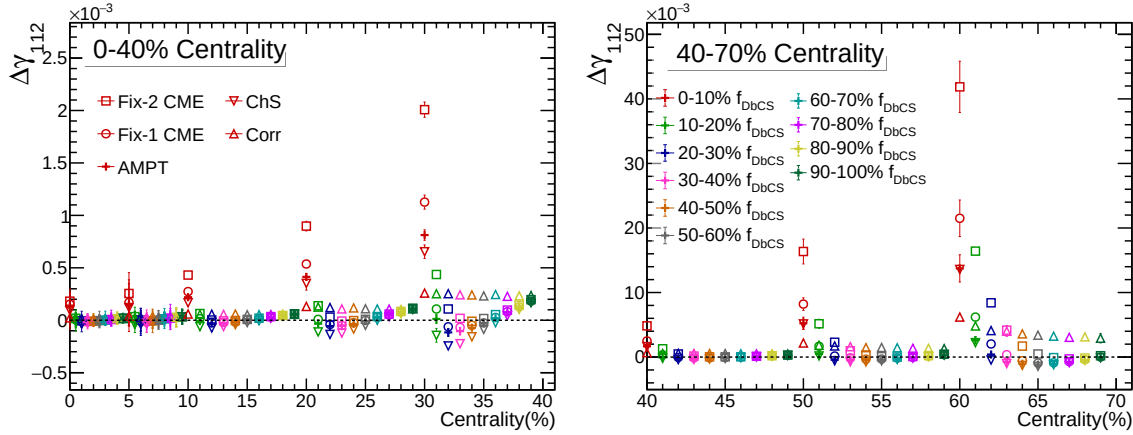


Figure 4.16: Left: The charge separation dependence of $\Delta\gamma_{112}$ for AMPT, Fix-1 CME, Fix-2 CME along with the charge shuffle and correlated backgrounds for 0-40% collision centralities. Right: Same for 40-70% collision centralities.

shuffle background and AMPT agrees within the errors. The correlated background remains almost independent of f_{DbCS} bins.

ΔH correlator:

Since ΔH is independent of κ values in figure 4.7, so here in figure 4.17, variation

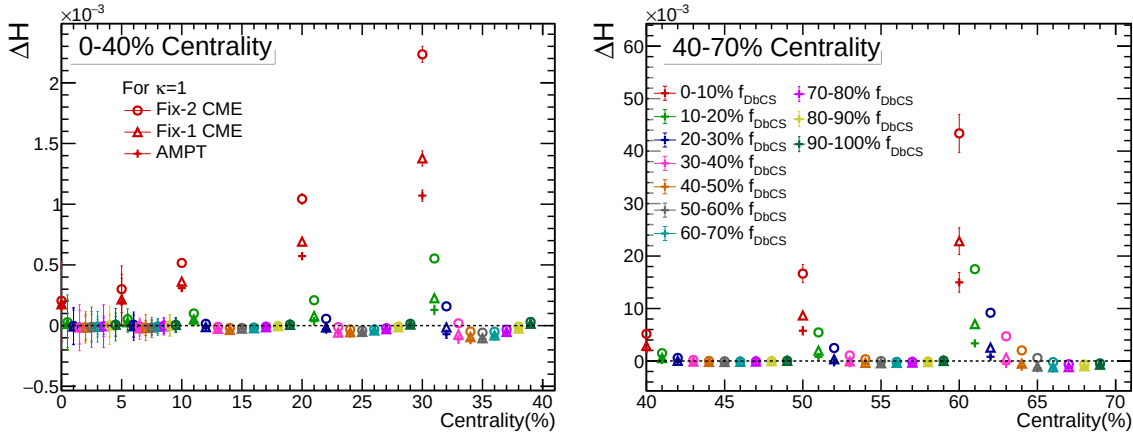


Figure 4.17: Left: The charge separation dependence of ΔH correlator AMPT, Fix-1 CME and Fix-2 CME for 0-40% collision centralities. Right: Same for 40-70% collision centralities. The y-axis for 0-40% collision centralities are magnified for the sake of clarity.

of ΔH for different f_{DbCS} bins is shown for $\kappa=1$ only. It is clear from the plot that as externally injected signal increases, the values of correlation also increase. The ΔH correlator signifies charge separation due to CME, it increases as one move from

lower $f_{D_{bCS}}$ bin to higher $f_{D_{bCS}}$ bin. As the CME like effect increases in the sample, value of ΔH also increases.

In-plane and out-of-plane correlations:

The overall in-plane and out-of-plane correlations for both same and opposite sign

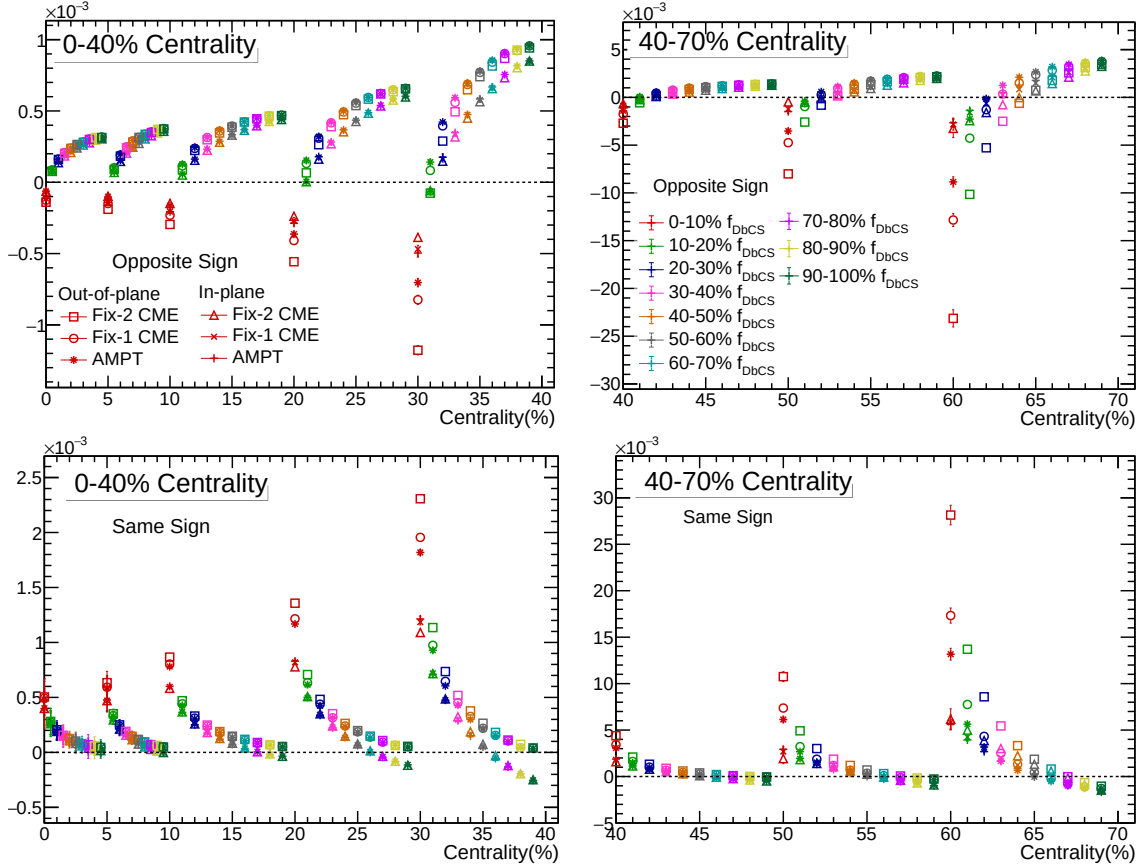


Figure 4.18: The charge separation ($f_{D_{bCS}}$) dependence of in-plane and out-of-plane correlations for OS (Top Row) and SS (Bottom Row) for AMPT, Fix-1 CME and Fix-2 CME and for different centralities. The left column plots are for 0-40% collision centralities and right column plots are for 40-70% collision centralities and; y-axes for 0-40% collision centralities are magnified for the sake of clarity.

charge pairs are positive. The correlations for OS and SS charge pairs are further investigated for different charge separation ($f_{D_{bCS}}$) bins, shown in Fig. 4.18. The opposite sign charge pairs shows -ve correlations while same sign charge pairs shows +ve correlations. For top $f_{D_{bCS}}$ bins out-of-plane correlations are dominated and this domination increases with increase in externally injected signal as expected for the CME-like events.

4.5.3 Positive charge asymmetry across the dumbbell

The variation of positive charge asymmetry across the dumbbell, A^+ , (defined in Eq. 4.7) with $\sqrt{|\gamma_{SS}|}$ for top $f_{D\bar{b}CS}$ bin i.e. 0-10% $f_{D\bar{b}CS}$ is shown in figure 4.19. Here different points corresponds to different centrality, leftmost is for 0-5% and then increases as one goes to right. The points are fitted with straight lines, $\sqrt{|\gamma_{SS}|} = p_0 + p_1 \langle A^+ \rangle$. The $\sqrt{|\gamma_{SS}|}$ varies linearly with positive charge asymmetry across the dumbbell with $\sqrt{|\gamma_{SS}|}$ for Fix-1 CME and Fix-2 CME with $p_0 = -0.021 \pm 0.00184$ and $p_1 = 0.60 \pm 0.024$ for Fix-1 CME and; $p_0 = -0.031 \pm 0.0016$ and $p_1 = 0.76 \pm 0.020$ for Fix-2 CME. The $\langle A^+ \rangle$ is proportional to parity violating parameter “a” (Section 4.2).

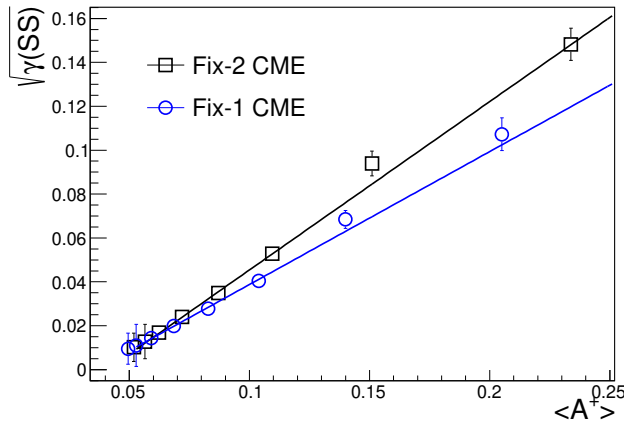


Figure 4.19: The correlation between the positive charge asymmetry ($\langle A^+ \rangle$) across the dumbbell and $\sqrt{|\gamma_{SS}|}$ for Fix-1 CME and Fix-2 CME for different centralities.

4.5.4 CME Fraction (f_{CME})

The fraction of CME is calculated from $\Delta\gamma_{112}$ for AMPT, Fix-1 CME and Fix-2 CME as discussed in Section 4.4.4 (Step IV) and variation of calculated f_{CME} with various centralities is shown in figure 4.20. The f_{CME} increases as the externally injected CME-like signal increases and decreases with increasing collision centrality as the constant CME signal was introduced externally irrespective of centralities. The fraction is 0 for default AMPT for all collision centralities as expected. It is

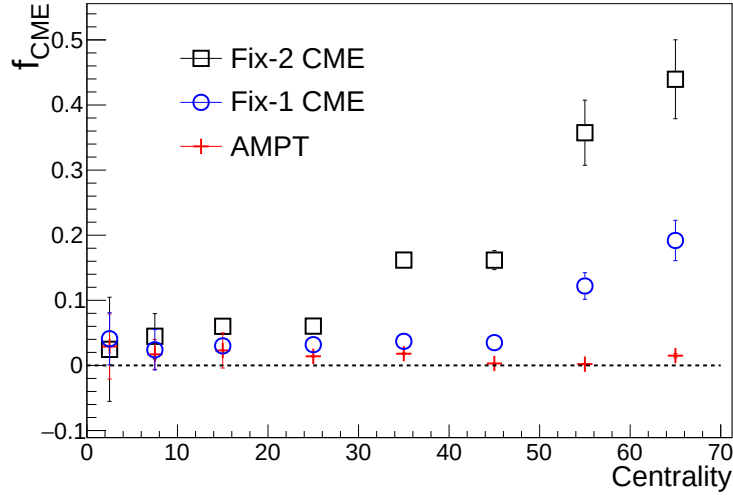


Figure 4.20: The variation of CME fraction (f_{CME}) with collision centrality for AMPT, Fix-1 CME and Fix-2 CME.

noticed that if the externally injected signal is $< 5\%$ (Table 4.1), f_{CME} is < 0.05 for both Fix-1 and Fix-2 CME.

4.6 Summary

In heavy-ion collisions, the coupling of the magnetic and electric fields causes charge separation along the reaction plane. This charge separation, known as Chiral Magnetic Effect (CME) has become the hot topic in heavy-ion physics. Many methods have been developed by the scientists to get the insight of CME and on those tracks a new method, called Sliding Dumbbell Method (SDM) is developed to search the event-by-event charge separation. Through SDM, whole azimuthal plane is scanned to search the back-to-back charge separation and f_{DbCS} (fractional charge separation across the dumbbell) distribution is determined for each centrality. To test the credibility of SDM, A Multi-Phase Transport (AMPT) model is used to generate the 11 M Pb-Pb events of $\sqrt{s_{NN}} = 2.76$ TeV with string melting on configuration. Since AMPT does not have CME like effect in built, so we put the CME like charge separation in the final stage particles by flipping the charge of particles in opposite quadrants. The Q-cumulants approach is used to quantify 2- and 3-

particle correlations for various charge combinations (same sign and opposite sign) in order to examine the CME inspired charge separation. The background is estimated through charge shuffle (where charges of particles are randomly shuffled) and correlated background (shuffling is restored).

Firstly, the variation of δ , γ_{112} , γ_{123} and ΔH correlator with centrality is studied. It is seen that δ and γ_{123} correlators stay approximately immune to the percentage of signal injection (upto 50-60% centrality) while for γ_{112} , with increase in injected signal correlations also increase. The $\Delta\gamma_{112}$ plot also encourage this observation.

Through SDM, f_{DbCS} is calculated through which events are characterized in accordance with their charge separation and distributions are plotted for each collision centrality. These distributions are further divided into ten bins and again variation of δ , γ_{112} , γ_{123} and ΔH correlator for each bin with centrality is studied, now along with the charge shuffle and correlated backgrounds. The γ_{112} correlator is negative for the same sign charge pairs and positive for opposite sign charge pairs for the top f_{DbCS} bins. In contrast, the δ correlator is positive for the same sign charge pairs and negative for opposite sign charge pairs as needed by the CME. Furthermore, for the top f_{DbCS} bins, both same and opposite sign charge pairings display out-of-plane correlations. The $\Delta\gamma$ is enhanced for the top f_{DbCS} bins and declines with decreasing f_{DbCS} , demonstrating that the top f_{DbCS} bins for each collision centrality can identify the most likely CME type events. The variation of v_2 is also studied with respect to f_{DbCS} bins and it is seen that except for top bins the fractional charge separation across the dumbbell does not have much effect on v_2 .

The variation of $\sqrt{|\gamma_{SS}|}$ for top f_{DbCS} bin seems linear with positive charge asymmetry across the dumbbell for Fix-1 CME and Fix-2 CME but not for AMPT, indicating the CME-like events in top f_{DbCS} bin for CME-like signal injected AMPTs sample. The CME fraction calculated through AMPT samples and charge shuffle, correlated backgrounds, increases with increase in externally injected signal and

reduces when collision centrality increases. The Fix-2 CME shows the highest f_{CME} for 60-70% centrality.

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CHAPTER

5

CME AND EVENT CHARACTERISATION IN Pb-Pb COLLISIONS AT 2.76 TeV AND 5.02 TeV

*“Nothing is too wonderful to be true, if it be consistent with the laws of nature;
and in such things as these, experiment is the best test of such consistency.”*

- Faraday, Laboratory Journal Entry #10,040 (March 18, 1849)

The Sliding Dumbbell method, a unique method developed to search for the back-to-back charge separation on event-by-event basis, is applied on ALICE Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV and 5.02 TeV energies.

5.1 Introduction

The QCD vacuum can produce metastable domains in the deconfined phase area, which can cause P/CP violations, locally [1–3]. These P/CP odd domains along with the presence of non-zero magnetic field in heavy-ion collisions lead to charge separation in the produced particles [4–8]. This charge separation is the clear sign of phenomenon known as the Chiral Magnetic Effect (CME) and the most widely used azimuthal correlation technique has been suggested by Voloshin [9] to study the CME.

The 2- and 3-particle correlators, used to investigate the CME, termed as δ and γ correlators, respectively, are defined as:

$$\delta \equiv \langle \cos(\phi_a - \phi_b) \rangle \quad (5.1)$$

$$\gamma \equiv \langle \cos(\phi_a + \phi_b - 2\Psi_{RP}) \rangle \quad (5.2)$$

where, ϕ_a , ϕ_b are azimuthal angles of particles “a” and “b”, respectively, and Ψ_{RP} is reaction plane angle. Since, reaction plane angle can not be determined experimentally, so Eq. 5.2 is modified [9] to:

$$\gamma = \langle \cos(\phi_a + \phi_b - 2\phi_c) \rangle / v_{2,c} \quad (5.3)$$

where, $v_{2,c}$ is **elliptic flow** of the third particle “c”. The major part of the background correlations are flow (v_2) dependent. So, determination of elliptic flow and its dependence on γ is also important to see.

The STAR collaboration at RHIC was the first to measure the γ correlator for Au-Au and Cu-Cu collisions at 200 GeV/N in 2009 [10–12]. The results obtained were theoretically expected as γ correlator for same sign (SS) charge pairs was negatively correlated while for opposite sign (OS) charge pairs, it was positive. However, it was shown in Ref. [13] that same sign charge pairs were back-to-back and

in-plane which was contrary to the CME predictions. On the other hand, ALICE also studied charge separation using γ correlator [14] along with δ correlator and in-plane, out-of-plane correlations; found that both in-plane and out-of-plane projections are positive for the same sign charge pairs, with the out-of-plane correlation being somewhat more prominent than the in-plane projection indicating the CME like behaviour. The STAR also measured the reaction-plane dependent correlator for various collision energies ranging from 7.7 to 200 GeV in the RHIC beam energy scan program [15]. It was discovered that the difference between the γ correlator for same-sign and opposite-sign charge pairs decreases when beam energy decreases due to the non formation of QGP medium. The STAR [16] and the CMS [17] studied the charge separations for small systems. In overlapping multiplicity, the CMS observed the same behaviour of the γ correlator for p-Pb and Pb-Pb. The STAR experiment [16] demonstrates the same tendency for p-Au and d-Au systems, with no discernible difference between small system and heavy-ion collisions.

With the indistinguishable behaviour observed between the small systems and heavy-ions, it was crucial to understand the backgrounds. ALICE used event shape engineering technique to separate the backgrounds from potential CME signal [18]. The δ correlator has positive values for both OS and SS charge pairs while the three-particle correlator shows negative values for SS and positive values for OS charge pairs. Also, the presence of a significant share of background correlations in the three-particle correlator is shown by its linear dependence on v_2 in each centrality interval. The upper limit of 26-33% at a 95% confidence level has been set for 2.76 TeV center of mass energy for Pb-Pb collisions. Recently, ALICE [19] has used the data driven method to constrain the background by using the fact that CME-like effect is weakly correlated to third order event plane than the second order event plane but backgrounds correlations remain same in third order event plane. They studied the charge-dependent azimuthal correlations with respect to the second and third order event planes for Pb-Pb collisions at 2.76 TeV and 5.02 TeV and set an upper limit of 15–18% (20–24%) at 95% (99.7%) confidence level for the 0–40% centrality interval for Pb-Pb 5.02 TeV.

The STAR experiment at RHIC performed a dedicated high statistics runs for confirming the CME in isobaric collisions ($^{96}_{44}\text{Ru} + ^{96}_{44}\text{Ru}$ and $^{96}_{40}\text{Zr} + ^{96}_{40}\text{Zr}$) [20]. As the backgrounds expected in the isobaric collisions are similar, so it was predicted that the ratio of the Ru to Zr CME sensitive γ correlator should be greater than 1 since Ru has four excess protons than that of Zr. But the experimental findings were far away from what would have been expected. The STAR Collaboration stated “no CME signature that satisfies the predefined criteria has been observed”.

Since the expected CME signal is very small and might get diluted with the statistical fluctuations. As a result, rather than looking for the signal averaging over events, it is critical to search for the CME signal in every event to identify probable events demonstrating the back-to-back CME-like charge separation. In view of this, a new method, Sliding Dumbbell Method, has been developed to isolate the CME enriched events in each collision centrality.

5.2 Analysis Method and Data sets

The separation of charged hadrons in the magnetic field direction is the ultimate indication of the Chiral Magnetic effect, with more positive hadrons moving in one direction and more negative hadrons moving in the opposite direction. In the situation of chiral magnetic effect, this means that charged hadrons projected onto the azimuthal plane, i.e., perpendicular to the beam axis, will display back-to-back separation of charged hadrons. This back-to-back charge separation can easily be obtained on event-by-event basis by using the Sliding Dumbbell Method (SDM). As discussed in previous chapter, in the SDM, the whole azimuthal plane in an event is scanned by sliding a dumbbell of $\Delta\phi = 90^\circ$ in steps of $\delta\phi = 1^\circ$ while calculating the fraction Db_{+-} (the sum of the positive charge fraction on one side of the dumbbell and negative charge fraction on the other side of the dumbbell) to

extract the maximum value of Db_{+-} in each event. The Db_{+-} is defined as:

$$\begin{aligned} Db_{+-} &= Db_{+}^a + Db_{-}^b \\ &= \frac{n_{+}^a}{n_{+}^a + n_{-}^a} + \frac{n_{-}^b}{n_{+}^b + n_{-}^b} \end{aligned} \quad (5.4)$$

here n_{+}^a and n_{-}^a are the number of positive and negative charge particles on one side of the dumbbell (in 90° azimuth), respectively; and n_{+}^b and n_{-}^b are number of positive and negative charge particles on other side of the dumbbell, respectively. If the charged particles are equally distributed, the value of each fraction in Eq. 5.1 will be 0.5, and the sum will be 1; however, the value of each fraction might vary owing to statistical fluctuations. As a result, in the case of total charge separation, Db_{+} or Db_{-} will not equal 1, and the highest possible value of Db_{+-} will be 2. Further, condition is imposed on Db_{+-}^{max} to get back-to-back charge separation with asymmetry $Db_{asy} < 0.25$ where Db_{asy} is:

$$Db_{asy} = \frac{N_{+}^{ex} - N_{-}^{ex}}{N_{+}^{ex} + N_{-}^{ex}} \quad (5.5)$$

where $N_{+}^{ex} = n_{+}^a - n_{-}^a$ is positively charged particle excess on one side of the dumbbell and $N_{-}^{ex} = n_{-}^b - n_{+}^b$ is negatively charged particle excess on other side of the dumbbell. This Db_{asy} is used to select the events which are similar to the CME like events. By putting the condition $Db_{asy} < 0.25$, we are focusing more on selecting the CME-like events which have back-to-back charge separation.

Once all the conditions applied, from Db_{+-}^{max} , the back-to-back fractional charge separation across the dumbbell (f_{DbCS}) is defined as follows:

$$f_{DbCS} = Db_{+-}^{max} - 1 \quad (5.6)$$

The distributions of f_{DbCS} are obtained for each centrality, and then sliced into ten percentile bins, with the first bin corresponding to the greatest value of f_{DbCS} , followed by the remainder of the bins, and the last one corresponding to the lowest f_{DbCS} . After slicing the f_{DbCS} distributions, 2- and 3- particle correlators are calcu-

lated for different charge combinations, such as same sign ($++/--$) and opposite sign ($+-$), for each f_{D_bCS} bin and for each centrality. All these δ , γ_{112} , γ_{123} , v_2 and v_3 are calculated by Q-cumulant method [21] as explained in previous chapter.

In this chapter, SDM is applied on Pb-Pb data at $\sqrt{s_{NN}}=2.76$ TeV and 5.02 TeV whose details are discussed below.

5.2.1 Data Sets

1. Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

The analysis is performed on Pb-Pb collisions data obtained by the ALICE detector during Run-I (during the year 2010) at a center-of-mass energy per nucleon of 2.76 TeV. The analysis is based on the LHC10h pass2 AOD (version 160) data file. The AOD which is short form of Analysis Object Data which is reduced version of Event Summary Data (ESD). The ESDs are the data files which have detailed information of the events while AODs are obtained after applying physics cuts on ESDs, thus suitable for physics analysis. Around 14 million events which meet the physics selection criteria by using the *AliPhysics Selection class* in the ALICE framework are tagged as good events and utilised in the present study. A Minimum Bias (MB) triggered events are investigated in this thesis. It eliminates events resulting from beam-gas interactions or other potential backgrounds.

Period: LHC10h pass2 AOD 160 (PbPb data)

Number of events analyzed: ~ 14 M events

Run numbers (total): 86 run numbers (good runs)

The good runs numbers selected from the Run Condition Table (RCT) [22] for the analysis are as:

LHC10h AOD160: 137161, 137232, 137235, 137431, 138192, 137162, 137231, 138275, 137236, 137243, 137430, 137440, 137441, 137443, 137530, 137531,

137539, 137541, 137544, 137549, 137595, 137608, 137638, 137639, 137685, 137686, 137691, 137692, 137693, 137704, 137718, 137722, 137724, 137751, 137752, 137844, 137848, 138190, 138197, 138201, 138225, 138364, 138396, 138438, 138439, 138442, 138469, 138534, 138578, 138579, 138582, 138583, 138621, 138624, 138638, 138652, 138653, 138662, 138666, 138730, 138732, 138837, 138870, 138871, 138872, 139028, 139029, 139036, 139037, 139038, 139105, 139107, 139173, 139309, 139310, 139314, 139328, 139329, 139360, 139437, 139438, 139465, 139503, 139505, 139507, 139510.

2. Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$

The SDM study is also performed on the ALICE Run-II (during the year 2015) Pb-Pb collisions at center-of-mass energy per nucleon 5.02 TeV. Around 30 million good events of data set LHC15o pass1 AOD194 are analysed.

Period: LHC15o pass1 AOD 194 (PbPb data)

Number of events analyzed: ~ 30 M events

Run numbers: 19 run numbers (good runs)

The good run numbers selected from the RCT are as:

LHC15o AOD194: 246989, 246984, 246945, 246809, 246805, 246488, 246222, 246217, 246181, 246272, 246153, 246151, 246148, 246001, 245963, 245954, 245952, 245831, 245683.

5.2.2 Event Selection

1. Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}$

The minimum bias events with a vertex found within 7 cm from the center of the detector along the beam line are used in the analysis.

The centrality is determined by using the ALICE centrality class “*AliCentrality*”. The centrality used for this thesis is obtained from VZERO multiplicity.

	Type	Range
Physics	$p_t(\text{GeV}/c)$	[0.2,5.0]
	η	[-0.8,0.8]
	Type	Requirement
Detector	Track type	TPC only
	TPC cluster	80
	χ^2 per TPC cluster	4
	DCAxy	3cm
	DCAz	3cm

Table 5.1: Track Selection criteria for Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV.

Additional pile-up event cut, $|V0M - TPC| < 7.5$ [23], is applied to remove the outliers where V0M and TPC are the centralities determined by V0 and TPC detectors respectively.

2. Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV

The vertex cut of $|V_z| < 10\text{cm}$ is used in this analysis along with the kINT7 trigger (minimum bias trigger for 150 data sets). The centrality is determined from VZERO multiplicity. Also, *fEventCuts* class is used with additional pile-up event cut, $|V0M - CL0| < 5$, to remove the outliers where CL0 is centrality determined from first layer of SPD.

5.2.3 Track Selection

1. Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV

Track cuts for Run-I data set are listed in table 5.1. In this analysis, the tracks reconstructed in the ALICE TPC detector are used. In this analysis, only primary tracks and charged particles with $0.2 < p_T < 5$ GeV/c and $|\eta| < 0.8$ are selected. The accepted tracks are required to have at least 80 out of 159 possible space points measured in the TPC and a χ^2 per degree of freedom of the momentum fit per TPC cluster to be below 4. These selections reduce the contribution from short tracks, which are unlikely to originate from

	Type	Range
Physics	$p_t(\text{GeV}/c)$	[0.2,5.0]
	η	[-0.8,0.8]
	Type	Requirement
Detector	Track type	Global
	TPC cluster	70
	χ^2 per TPC cluster	4
	DCA _{xy}	2.4cm
	DCA _z	3.2cm

Table 5.2: Track selection criteria for Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV.

the primary vertex. The distance of closest approach (DCA) with regard to the primary vertex either in transverse plane (DCA_{xy}) or longitudinal direction (DCA_z) is limited to less than 3 cm to further reduce the contribution from secondary vertices or from the interaction with the material.

2. Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV

Track cuts for Run-II 2015 data set are listed in table 5.2. The primary tracks reconstructed in the ALICE TPC+ITS (Global) detectors with $0.2 < p_T < 5$ GeV/c and $|\eta| < 0.8$ are selected. Here, 70 points are required for the track to be accepted with same χ^2 as of Run-I data. For Run-II, only tracks within a maximum distance of closest approach to primary vertex in both the transverse plane ($DCA_{xy} < 2.4$ cm) and the longitudinal direction ($DCA_z < 3.2$ cm) were considered.

5.2.4 Quality Assurance

The quality assurance (QA) checks have been performed before doing the analysis to make sure that only good quality data is being used.

1. Pb-Pb at collisions $\sqrt{s_{\text{NN}}} = 2.76$ TeV

For Run-I data, the following QA checks are done:

- Figure 5.1 shows the vertex and centrality distributions for the selected minimum bias events. The vertex cut of 7 cm is applied to get ensure that the collisions from central part of the ALICE have been taken, and with uniform acceptance. The collision centrality, estimated from V0 detector, shows uniform distributions.

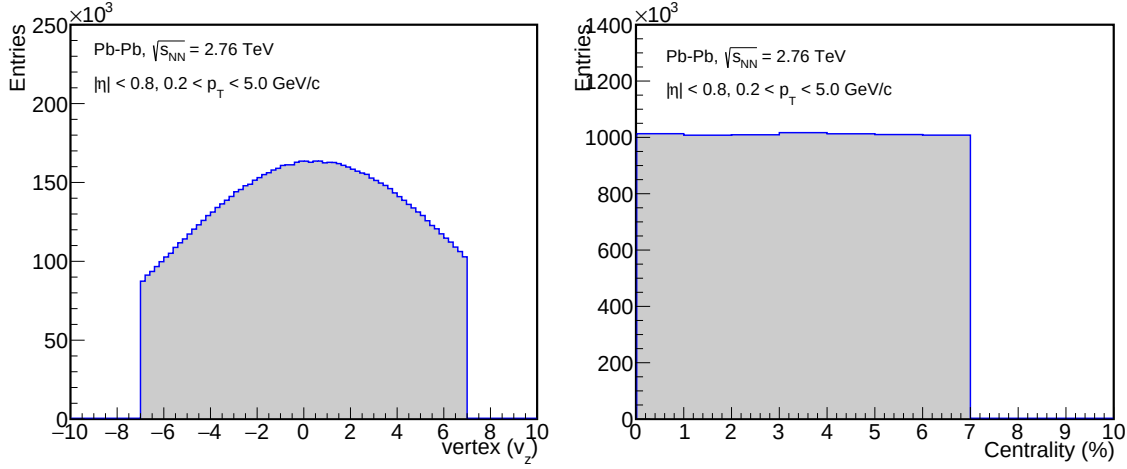


Figure 5.1: The Z-vertex distribution (left) and V0M centrality distribution (right) for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

- The distribution of transverse momentum (p_T) from $0.8 < p_T < 5$ GeV/c is shown in figure 5.2.

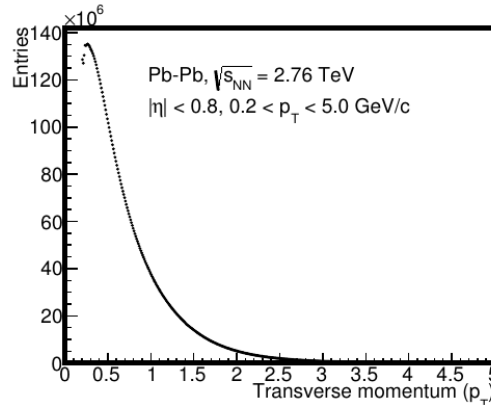


Figure 5.2: p_T distribution for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

- As discussed, the collision centrality is determined using multiplicity distribution from the V0 detector. The correlation between centrality

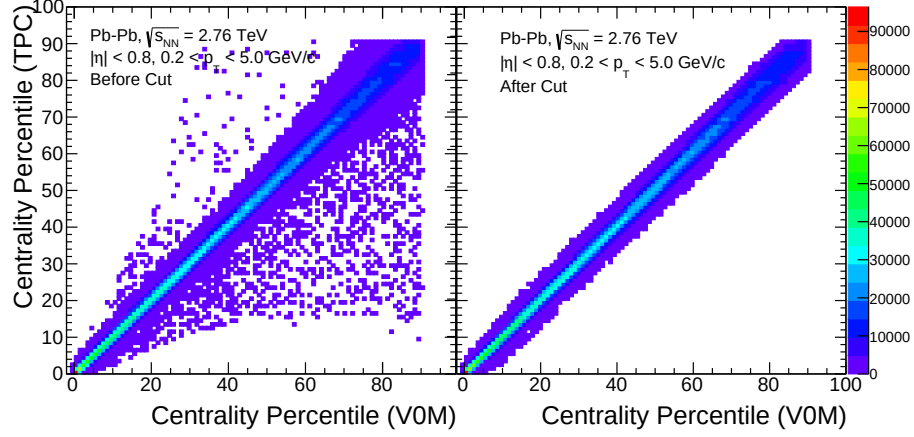


Figure 5.3: TPC centrality estimation versus V0 centrality estimation before (left) and after the cut $|V0M - TPC| < 7.5$ (right).

percentile measured using the V0 multiplicity and the TPC multiplicity is shown in figure 5.3 (left). The outliers are removed using a cut ($|V0M - TPC| < 7.5$) based on the centralities determined by TPC and V0 detectors [23]. The centrality correlations after applying cut is linear as shown in figure 5.3 (right).

- After applying the cut on centrality, multiplicity distributions for negative and positive charged particles are studied and are presented in figure 5.4 which indicates the similar behaviour for both positive and negative charged particle multiplicity distributions.

2. Pb-Pb at collisions $\sqrt{s_{NN}} = 5.02$ TeV

The quality assurance checks performed for Run-II data are:

- Transverse momentum (p_T) and z-vertex (V_Z) plots are shown in fig.5.5. The p_T range here is same as of Pb-Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV i.e., $0.8 < p_T < 5$ GeV/c and the distribution comes out as expected. The vertex cut of 10 cm is applied here to ensure the uniform detector acceptance.
- Centrality estimated from V0M is shown in fig.5.6 and centrality distribution is uniform.

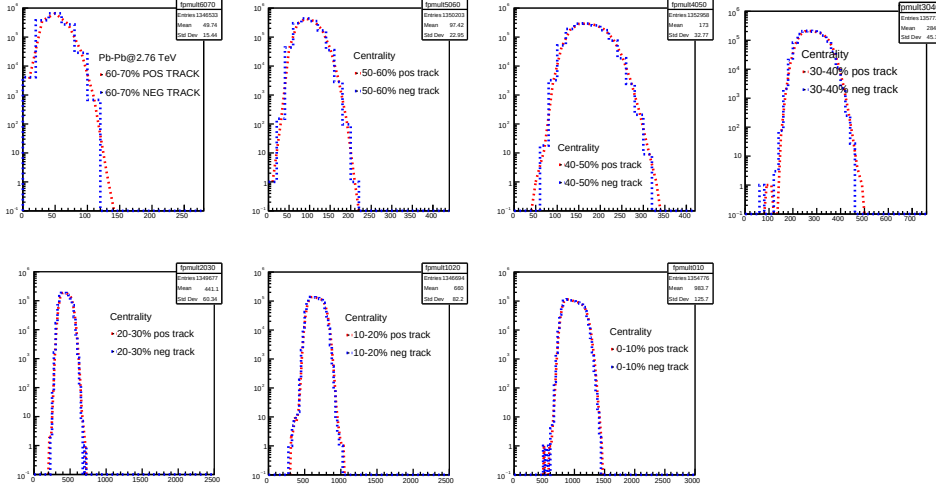


Figure 5.4: Multiplicity distributions of positive and negative charged particles for different centrality intervals as indicated in the diagram.

- To remove the outliers, the cut of $|V0M - CL0| < 5$ is applied. Fig.5.7(Left panel) shows the correlation between the centralities of V0M and CL0 before the above mentioned cut and Fig.5.7(Right panel) shows the correlation after cut.
- The multiplicity distributions for negative and positive charged particles are studied after applying the cut on centrality distributions and are displayed in fig.5.8 indicating the similar behaviour for both positive and negative charged particle multiplicities.

5.2.5 Non-uniform acceptance

- **Generalized Second Order Q-cumulant :** To take into account for the non uniform detector acceptance in azimuthal planes, 2^{nd} order cumulant is modified as:

$$c_n\{2\} = \langle\langle \cos n(\phi_1 - \phi_2) \rangle\rangle - \langle\langle \cos n\phi_1 \rangle\rangle^2 - \langle\langle \sin n\phi_1 \rangle\rangle^2 \quad (5.7)$$

The terms shown in red are the extra additional terms to counter-balance the

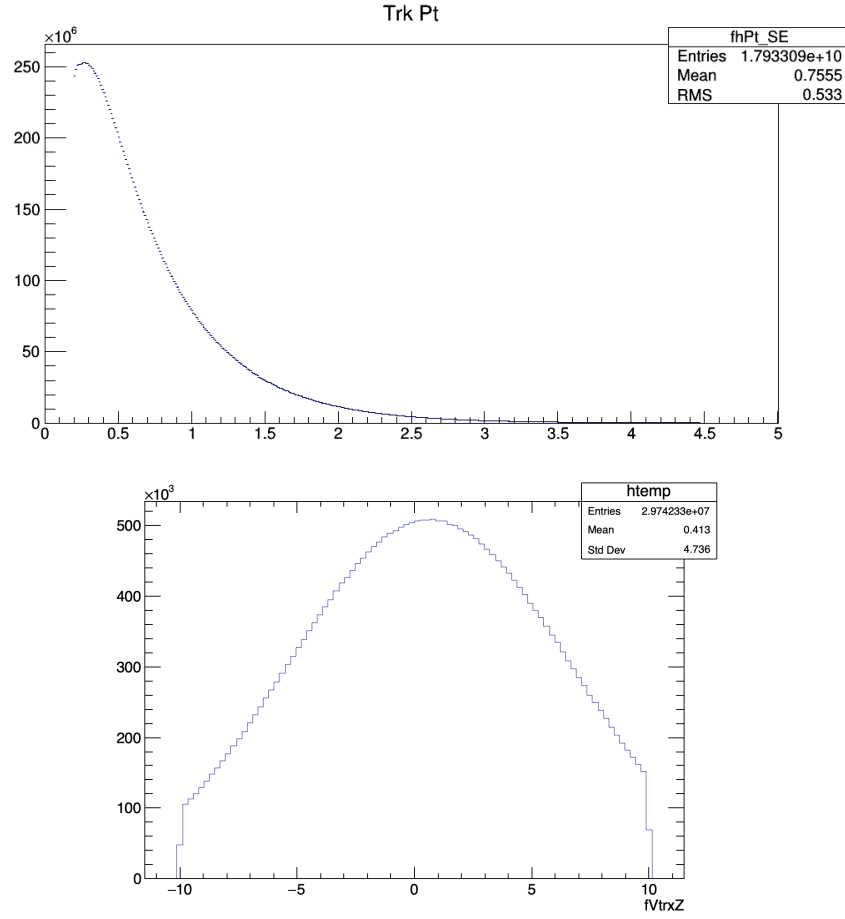


Figure 5.5: Top: The transverse momentum (p_T) distribution of tracks for Pb-Pb collisions at $\sqrt{s_{NN}}=5.02$ TeV. Bottom: The V_z distribution for same.

effect of non-uniform acceptance on second order cumulant. These terms are decomposed into real and imaginary part as:

$$\langle\langle \cos n\phi_1 \rangle\rangle = \frac{\sum_{i=1}^N (\Re[Q_n])_i}{\sum_{i=1}^N M_i} = \frac{\sum_{i=1}^N (\langle \cos n\phi \rangle)_i}{\sum_{i=1}^N M_i} \quad (5.8)$$

$$\langle\langle \sin n\phi_1 \rangle\rangle = \frac{\sum_{i=1}^N (\Im[Q_n])_i}{\sum_{i=1}^N M_i} = \frac{\sum_{i=1}^N (\langle \sin n\phi \rangle)_i}{\sum_{i=1}^N M_i} \quad (5.9)$$

where M is multiplicity and N is the total number of events. By putting these values in eq. 5.7, we get:

$$c_n\{2\} = \langle\langle 2 \rangle\rangle_{n|n} - \frac{\sum_{i=1}^N (\langle \cos n\phi \rangle)_i}{\sum_{i=1}^N M_i} - \frac{\sum_{i=1}^N (\langle \sin n\phi \rangle)_i}{\sum_{i=1}^N M_i} \quad (5.10)$$

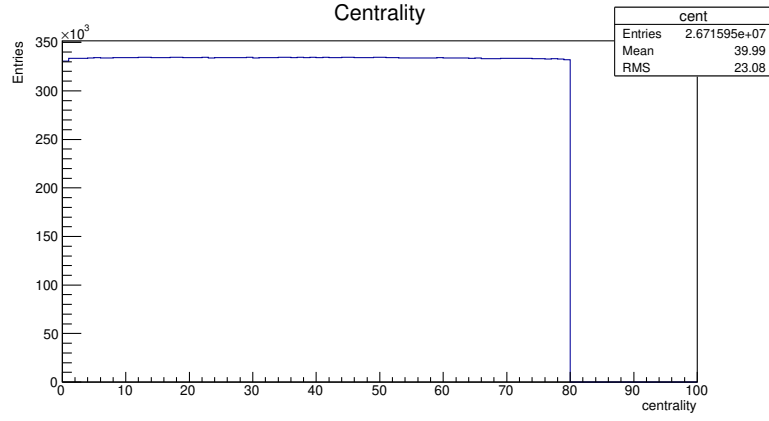


Figure 5.6: Centrality estimated from V0M for Pb-Pb collisions at $\sqrt{s_{NN}}=5.02$ TeV.

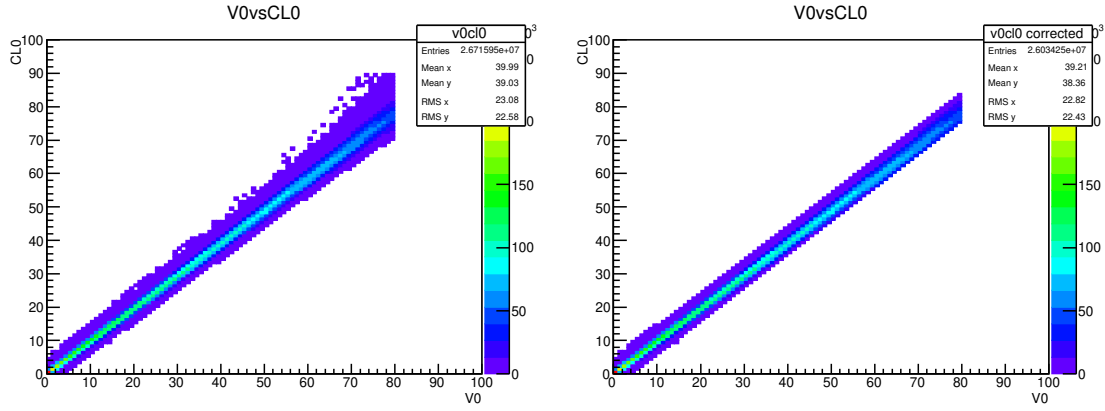


Figure 5.7: Left figure : Correlation of V0M and CL0 centralities before outlier correction. Right figure : Correlation after correction.

- **Generalized 4th Order Q-cumulant** : Similarly, generalized 4th order Q-

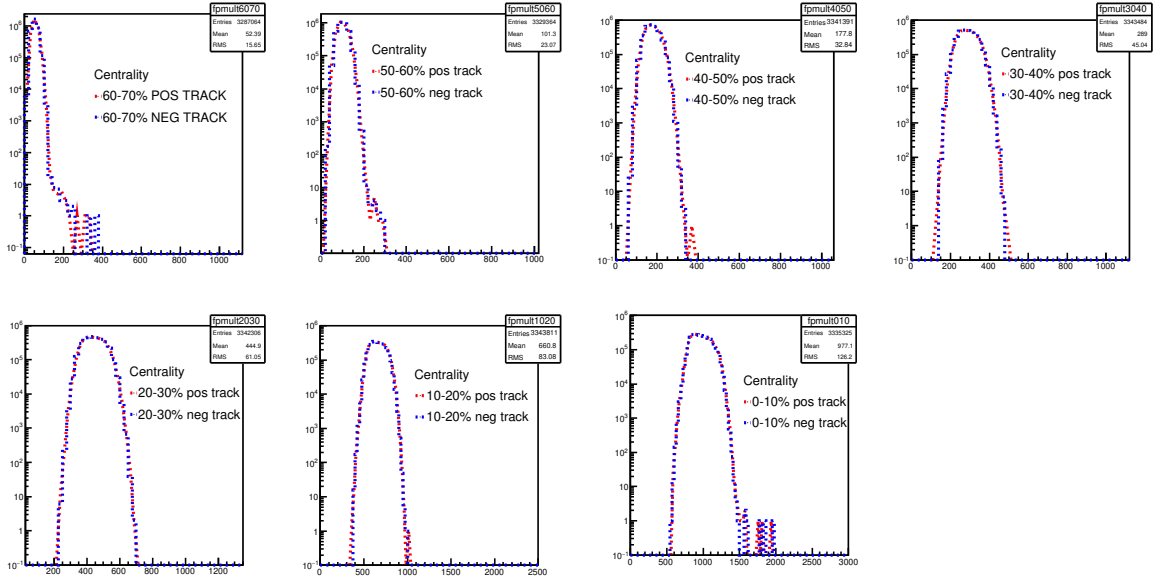


Figure 5.8: Multiplicity distributions of positive and negative charged particles for different centrality intervals as indicated in the diagram.

cumulant is modified as:

$$\begin{aligned}
 c_n\{4\} = & \langle\langle \cos n(\phi_1 + \phi_2 - \phi_3 - \phi_4) \rangle\rangle - 2 \cdot \langle\langle \cos n(\phi_1 - \phi_2) \rangle\rangle^2 \\
 & - 4 \cdot \langle\langle \cos n(\phi_1) \rangle\rangle \langle\langle \cos n(\phi_1 - \phi_2 - \phi_3) \rangle\rangle \\
 & + 4 \cdot \langle\langle \sin n(\phi_1) \rangle\rangle \langle\langle \sin n(\phi_1 - \phi_2 - \phi_3) \rangle\rangle \\
 & - \langle\langle \cos n(\phi_1 + \phi_2) \rangle\rangle^2 - \langle\langle \sin n(\phi_1 + \phi_2) \rangle\rangle^2 \\
 & + 4 \cdot \langle\langle \cos n(\phi_1 + \phi_2) \rangle\rangle [\langle\langle \cos n\phi_1 \rangle\rangle^2 - \langle\langle \sin n\phi_1 \rangle\rangle^2] \\
 & + 8 \cdot \langle\langle \sin n(\phi_1 + \phi_2) \rangle\rangle \langle\langle \sin n\phi_1 \rangle\rangle \langle\langle \cos n\phi_1 \rangle\rangle \\
 & + 8 \cdot \langle\langle \cos n(\phi_1 - \phi_2) \rangle\rangle [\langle\langle \cos n\phi_1 \rangle\rangle^2 + \langle\langle \sin n\phi_1 \rangle\rangle^2] \\
 & - 6 \cdot [\langle\langle \cos n\phi_1 \rangle\rangle^2 + \langle\langle \sin n\phi_1 \rangle\rangle^2]^2
 \end{aligned} \tag{5.11}$$

Again red terms are the additional terms and can be written as real and imaginary part of Q-vector as:

$$\langle\langle \cos n(\phi_1 + \phi_2) \rangle\rangle = \frac{\sum_{i=1}^N (\Re[Q_n Q_n - Q_{2n}])_i}{\sum_{i=1}^N M_i (M_i - 1)} \tag{5.12}$$

$$\langle\langle \sin n(\phi_1 + \phi_2) \rangle\rangle = \frac{\sum_{i=1}^N (\Im [Q_n Q_n - Q_{2n}])_i}{\sum_{i=1}^N M_i (M_i - 1)} \quad (5.13)$$

$$\langle\langle \cos n(\phi_1 - \phi_2 - \phi_3) \rangle\rangle = \frac{\sum_{i=1}^N (\Re [Q_n Q_n^* Q_n^* - Q_n Q_{2n}^* - 2(M_i - 1)Q_n^*])_i}{\sum_{i=1}^N M_i (M_i - 1)(M_i - 2)} \quad (5.14)$$

$$\langle\langle \sin n(\phi_1 - \phi_2 - \phi_3) \rangle\rangle = \frac{\sum_{i=1}^N (\Im [Q_n Q_n^* Q_n^* - Q_n Q_{2n}^* - 2(M_i - 1)Q_n^*])_i}{\sum_{i=1}^N M_i (M_i - 1)(M_i - 2)} \quad (5.15)$$

By putting these terms in $c_n\{4\}$, we get the non-uniform acceptance factor for 4^{th} order cumulant.

- **Generalized 3^{rd} Order Q-cumulant** : The 3^{rd} order generalized Q-cumulant can be modified as:

$$\begin{aligned} QC\{3\} = & \langle\langle \cos n(\phi_1 + \phi_2 - 2\phi_3) \rangle\rangle \\ & - 2 \langle\langle \cos n(\phi_1 - 2\phi_2) \rangle\rangle \langle\langle \cos n\phi_1 \rangle\rangle \\ & + \langle\langle \sin n(\phi_1 - 2\phi_2) \rangle\rangle \langle\langle \sin n\phi_1 \rangle\rangle \\ & - \langle\langle \cos n(\phi_1 + \phi_2) \rangle\rangle \langle\langle \cos 2\phi_1 \rangle\rangle \\ & - \langle\langle \sin n(\phi_1 + \phi_2) \rangle\rangle \langle\langle \sin 2\phi_1 \rangle\rangle \\ & + 2 \langle\langle \cos 2n\phi_1 \rangle\rangle [\langle\langle \cos n\phi_1 \rangle\rangle^2 - \langle\langle \sin n\phi_1 \rangle\rangle^2] \\ & + 4 \langle\langle \sin 2n\phi_1 \rangle\rangle [\langle\langle \cos n\phi_1 \rangle\rangle \langle\langle \sin n\phi_1 \rangle\rangle] \end{aligned} \quad (5.16)$$

These terms are decomposed into real and imaginary part as:

$$\langle\langle \cos n(\phi_1 - 2\phi_2) \rangle\rangle = \frac{\sum_{i=1}^N (\Re [Q_n Q_{2n}^* - Q_n^*])_i}{\sum_{i=1}^N M_i (M_i - 1)} \quad (5.17)$$

$$\langle\langle \sin n(\phi_1 - 2\phi_2) \rangle\rangle = \frac{\sum_{i=1}^N (\Im [Q_n Q_{2n}^* - Q_n^*])_i}{\sum_{i=1}^N M_i (M_i - 1)} \quad (5.18)$$

5.2.6 Background Estimation

As discussed in Chapter 4, the charge shuffled (γ_{ChS}) and correlated (γ_{Corr}) backgrounds are calculated in the same way as for the data for different collision centralities using Sliding Dumbbell Method (SDM). The total background contribution then becomes:

$$\gamma_{bkg.} = \gamma_{ChS} + \gamma_{Corr} \quad (5.19)$$

5.3 Error Analysis

In data analysis, along with the statistical errors, systematic uncertainties which arises from the system.

5.3.1 Statistical Errors

As discussed in previous chapter, here also subsampling method is used for statistical error estimation. For data, similar to AMPT, 10 sub-samples are used to study the statistical errors.

5.3.2 Systematic Uncertainty

The systematic uncertainties are estimated by varying the standard events and track cuts used in the analysis. The maximum deviation of a given observable by varying cut from the standard cut is attributed to the systematic uncertainty. The systematic errors estimated from each varied cut and are added in quadrature to obtain the final systematic uncertainty.

- **Event Cuts** : The events selected using the V0M centrality estimator are analyzed for the current study whereas the centrality estimated via multiplicity of TPC tracks (TRK) and SPD layers (CL1) is used for systematic error estimation of 2010 data and the centrality estimated via multiplicity of first

layer of SPD (CL0) and second layer SPD (CL1) is used for systematic error estimation of 2015 data. The events within the vertex range of $|v_z| < 7$ cm are analyzed for the Run 1 analysis and of $|v_z| < 10$ cm for Run 2 analysis and for the systematic study, the vertex cut is varied for ± 8 cm and ± 10 cm in Run 1 and ± 7 cm and ± 8 cm in Run 2. The Pb-Pb events were recorded with positive (B_+) and negative magnetic field polarity (B_-). The like sign charged particle correlator consists of $++$ and $--$ charge combinations. The difference between like sign charged pairs is assigned as the systematic uncertainty. The half of the difference between $v_2\{2\}$ and $v_2\{4\}$ is taken as the systematic uncertainty from the elliptic flow (v_2), where $v_2\{2\}$ is 2 particle elliptic flow and $v_2\{4\}$ is 4 particle flow.

- **Track Cuts:** The distance of closest approach (DCA) and number of TPC cluster has been varied to check the systematic errors from these two.

The values for standard cuts and varied systematic cuts from the event and track cuts are listed in table 5.3 for Run 1 data and table 5.4 for Run-II data. The systematic sources listed in tables are studied for three particle azimuthal correlators.

The Barlow check [24] is then performed to check whether the particular variation is to be considered as systematic uncertainty or not.

$$\sigma_B = \frac{X_{def} - X_{syst}}{\sqrt{|\sigma_{def}^2 - \sigma_{syst}^2|}} \quad (5.20)$$

where X_{def} and X_{syst} are the values of observable and σ_{def} and σ_{syst} are the statistical errors for default and systematic variation, respectively. If $\sigma_B > 1$ then only the variation can be considered as systematic errors. All the valid contributions of systematic sources after passes through Barlow test are then added in quadrature to get the total systematic uncertainty for a given observable.

Sources of uncertainty	Default Value	Variations
Vertex $ V_z $	$< 7cm$	$< 8cm, < 10cm$
Centrality estimator	V0M	TPC(trk), SPD(CL1)
Mag Field(B)	B_+ and B_-	Difference of B_+ and B_-
$ DCA_{xy} $	3cm	$< 2cm, < 4cm$
No. of TPC cluster	< 80	$< 70, < 90$
Charge Combination	++ and - -	Difference of ++ and - -
v_2 (Elliptic Flow)	average of $v_2\{2\}$ and $v_2\{4\}$	Difference of $v_2\{2\}$ and $v_2\{4\}$

Table 5.3: Various standard cuts and varied systematic cuts to obtain the systematic uncertainties for Pb-Pb collisions at 2.76 TeV.

Sources of uncertainty	Default Value	Variations
Vertex $ V_z $	$< 10cm$	$< 8cm, < 7cm$
Centrality estimator	V0M	CL0, CL1
Mag Field(B)	B_+ and B_-	Difference of B_+ and B_-
No. of TPC cluster	< 70	$< 60, < 80$
Charge Combination	++ and - -	Difference of ++ and - -
v_2 (Elliptic Flow)	average of $v_2\{2\}$ and $v_2\{4\}$	Difference of $v_2\{2\}$ and $v_2\{4\}$

Table 5.4: Various standard cuts and varied systematic cuts to obtain the systematic uncertainties for Pb-Pb collisions at 5.02 TeV.

5.4 Results and discussion

As mentioned earlier that for CME $\delta(SS)$ should be positive and equal in magnitude to $\gamma_{112}(SS)$; and $\gamma_{112}(OS)$ should be positive. Firstly, to check the Q-cumulant method, the δ and γ s are calculated centrality wise and compared with the published results. The fractional charge separation across dumbbell (f_{DbCS}) distributions for different centralities are plotted and then results obtained after calculating δ and γ s for different f_{DbCS} bins are discussed. Along with these, in-plane and out-of-plane

correlations; and ΔH correlator is also discussed.

5.4.1 Multi-particle correlations as a function of Centralities

The effect of collision centrality on the variation of 2- and 3-particle correlators is investigated, and the results are presented. In addition, the ΔH correlator, as well as in-plane and out-of-plane correlations, are discussed.

2-particle “ δ ” correlator:

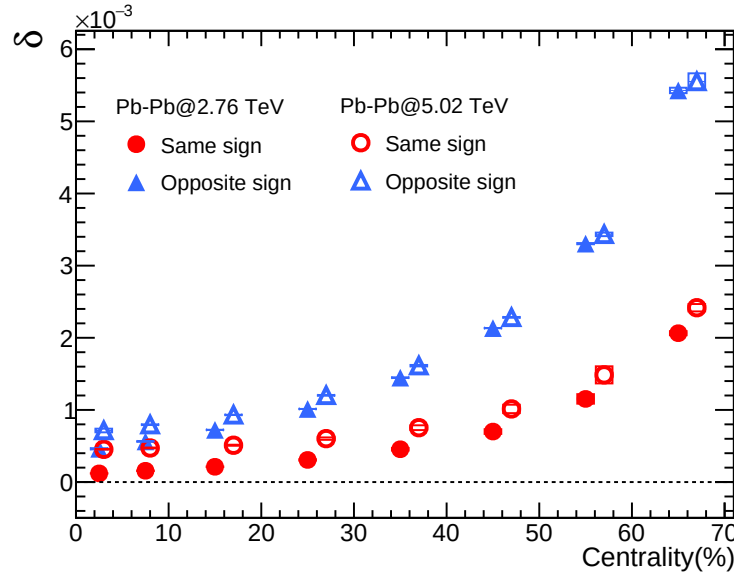


Figure 5.9: The variation of δ correlator for opposite sign (OS) and same sign (SS) charge pairs with collision centralities for Pb-Pb collisions at 2.76 TeV and 5.02 TeV as indicated in the diagram. The points at 5.02 TeV are shifted slightly for the sake of clarity.

The figure 5.9 presents the δ correlator’s variation with centrality for opposite sign and same sign charge pairs. The reds (solid for 2.76 TeV and open for 5.02 TeV collision energies) are for same sign correlator and blue ones are for opposite sign. The boxes around the data points are the systematic errors.

Both same and opposite sign charge pairs exhibit positive correlations, with opposite sign has more positive correlations and the correlations increase as we move towards the peripheral collisions. The opposite sign charge pairs are seen to

be energy independent whereas same sign charge pairs correlations are seen to have more positive values at $\sqrt{s_{\text{NN}}} = 5.02$ TeV than that of $\sqrt{s_{\text{NN}}} = 2.76$ TeV. Table 5.5 and table 5.6 summarises the sources of systematic errors for same sign and opposite sign δ correlator and their related fractional values for various collision centralities for Pb-Pb collisions at 2.76 TeV. Similarly, the systematic errors' sources and their

Sources	Collision Centrality							
	0-5%	5-10%	10-20%	20-30%	30-40%	40-50%	50-60%	60-70%
Cent. est.	0.0074	0.0033	0.0045	0.0026	0.0068	0.0018	0.0099	0.011
$ V_z $	0.0024	0.0067	0.0029	0.0033	0.0076	0.0041	0.0065	0.0029
B Field	0.0034	0.0098	0.03	0.010	0.008	0.006	0.009	0.012
$ DCA_{xy} $	0.012	0.010	0.012	0.016	0.013	0.009	0.0079	0.008
TPC clus	0.0023	0.008	0.003	0.006	0.0016	0.0055	0.0023	0.0087
Chg comb.	0.01	0.03	0.027	0.016	0.0086	0.009	0.019	0.0036
Total	0.0179	0.0348	0.0425	0.0258	0.0203	0.0157	0.0254	0.02064

Table 5.5: The values of fractional systematic uncertainty for δ correlator for same sign charge pairs for Pb-Pb collisions at 2.76 TeV.

Sources	Collision Centrality							
	0-5%	5-10%	10-20%	20-30%	30-40%	40-50%	50-60%	60-70%
Cent. est.	0.0019	0.0038	0.0011	0.006	0.001	0.0018	0.0009	0.0001
$ V_z $	0.004	0.0001	0.009	0.007	0.002	0.0009	0.001	0.001
B Field	0.005	0.02	0.006	0.001	0.005	0.002	0.004	0.004
$ DCA_{xy} $	0.014	0.013	0.0132	0.0106	0.010	0.0089	0.0083	0.0035
TPC clus	0.003	0.009	0.003	0.0001	0.004	0.003	0.002	0.002
Total	0.015	0.025	0.017	0.012	0.013	0.009	0.0095	0.005

Table 5.6: The values of fractional systematic errors for δ correlator for opposite sign charge pairs for Pb-Pb collisions at 2.76 TeV.

fractional contribution to same and opposite sign δ correlator for Pb-Pb collisions at 5.02 TeV are enlisted in table 5.7 and table 5.8, respectively.

3-particle correlators:

The 3-particle γ_{112} for opposite sign and same sign charge pairs are shown in fig. 5.10 for Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV and $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The red color markers represent same sign correlations and blue ones are for opposite sign and

Sources	Collision Centrality							
	0-5%	5-10%	10-20%	20-30%	30-40%	40-50%	50-60%	60-70%
Cent. est.	0.0013	0.006	0.008	0.004	0.012	0.003	0.017	0.019
$ V_z $	0.004	0.012	0.005	0.006	0.013	0.007	0.011	0.005
B Field	0.006	0.0017	0.04	0.018	0.014	0.01	0.016	0.021
$ DCA_{xy} $	0.021	0.030	0.02	0.028	0.023	0.016	0.014	0.015
TPC clus	0.004	0.007	0.005	0.0108	0.003	0.009	0.03	0.015
Chg comb.	0.018	0.04	0.03	0.028	0.015	0.016	0.034	0.006
Total	0.031	0.054	0.055	0.045	0.035	0.027	0.054	0.085

Table 5.7: The values of fractional systematic errors for δ correlator for same sign charge pairs for Pb-Pb collisions at 5.02 TeV.

Sources	Collision Centrality							
	0-5%	5-10%	10-20%	20-30%	30-40%	40-50%	50-60%	60-70%
Cent. est.	0.006	0.011	0.002	0.003	0.01	0.003	0.0018	0.0004
$ V_z $	0.01	0.0003	0.018	0.01	0.006	0.001	0.003	0.002
B Field	0.02	0.07	0.012	0.003	0.02	0.006	0.009	0.01
$ DCA_{xy} $	0.04	0.04	0.03	0.02	0.03	0.01	0.02	0.009
TPC clus	0.009	0.02	0.009	0.0005	0.009	0.008	0.008	0.006
Total	0.045	0.083	0.038	0.022	0.038	0.014	0.024	0.015

Table 5.8: The values of fractional systematic errors for δ correlator for opposite sign charge pairs for Pb-Pb collisions at 5.02 TeV.

boxes are systematics errors. As seen in the fig. 5.10 (Left), γ_{112} correlator has positive values for OS indicating opposite sign charge pairs are weakly correlated. The same sign charge pairs are strongly correlated and exhibit negative values and the strength of correlations decreases with increase in collision centrality. Both OS and SS correlations have energy dependence within errors. Table 5.9 and table 5.10 list the fractional systematic errors for γ_{112} (SS) and γ_{112} (OS) for Pb-Pb collisions at 2.76 TeV, respectively, obtained from different sources for given collision centrality. It is seen that the major contribution in systematic uncertainty comes from v_2 . Similarly, for Pb-Pb collisions for $\sqrt{s_{NN}} = 5.02$ TeV, the fractional systematics error contributions are listed in table 5.11 and table 5.12 for same sign and opposite sign charge pairs γ correlator.

$\Delta\gamma$ correlators:

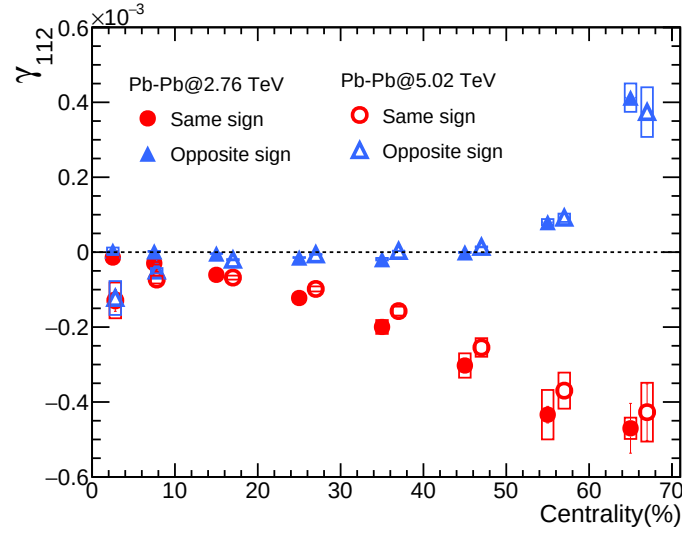


Figure 5.10: The variation of γ_{112} correlator for opposite sign (OS) and same sign (SS) charge pairs with collision centralities for 2.76 TeV and 5.02 TeV collision energies. The points at 5.02 TeV collision energy are shifted for the sake of clarity.

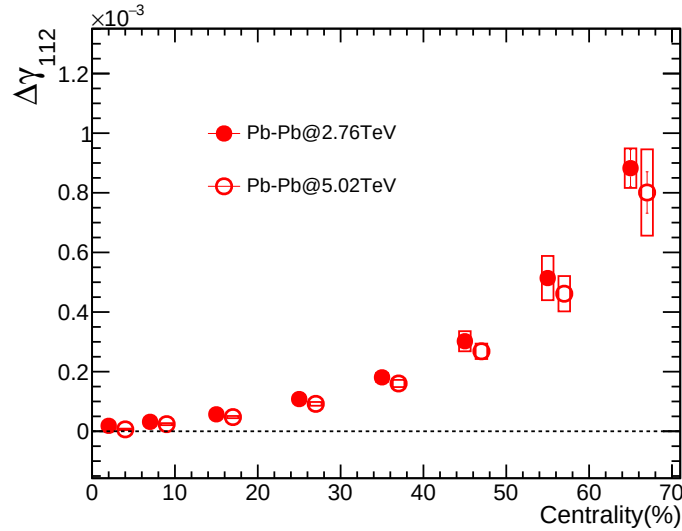


Figure 5.11: The variation of $\Delta\gamma_{112}$ correlator with collision centralities for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and 5.02 TeV. The points at 5.02 TeV collision energy are shifted for the sake of clarity.

The $\Delta\gamma$ correlator, which is defined as $\gamma(\text{OS}) - \gamma(\text{SS})$, is studied for both 2.76 TeV and 5.02 TeV collision energies and results obtained are shown in figure 5.11.

The $\Delta\gamma_{112}$ has positive correlation values and seems to be independent of collision energies. The positive values of $\Delta\gamma$ have been regarded as the signal due to the Chiral Magnetic Effect. It is observed that the $\Delta\gamma_{112}$ decreases with increase in

Sources	Collision Centrality							
	0-5%	5-10%	10-20%	20-30%	30-40%	40-50%	50-60%	60-70%
Cent. est.	0.042	0.06	0.002	0.04	0.029	0.03	0.015	0.012
$ V_z $	0.002	0.0029	0.009	0.01	0.012	0.008	0.007	0.0068
B Field	0.055	0.003	0.008	0.002	0.001	0.0204	0.019	0.006
$ DCA_{xy} $	0.020	0.006	0.01	0.013	0.011	0.003	0.002	0.009
TPC clus	0.05	0.017	0.005	0.002	0.01	0.03	0.05	0.023
Chg comb.	0.02	0.015	0.004	0.0084	0.0027	0.015	0.022	0.08
v_2	0.40	0.13	0.075	0.069	0.078	0.10	0.14	0.21
Total	0.41	0.145	0.099	0.082	0.086	0.119	0.152	0.212

Table 5.9: The values of fractional systematic uncertainties for $\gamma(\text{SS})$ for Pb-Pb collisions at 2.76 TeV.

Sources	Collision Centrality							
	0-5%	5-10%	10-20%	20-30%	30-40%	40-50%	50-60%	60-70%
Cent. est.	0.04	0.06	0.03	0.009	0.017	0.05	0.03	0.02
$ V_z $	0.009	0.005	0.02	0.024	0.04	0.009	0.05	0.02
B Field	0.03	0.009	0.0014	0.010	0.03	0.009	0.04	0.015
$ DCA_{xy} $	0.022	0.007	0.009	0.016	0.013	0.003	0.004	0.007
TPC clus	0.009	0.08	0.01	0.05	0.06	0.008	0.03	0.04
v_2	0.40	0.13	0.075	0.069	0.078	0.10	0.14	0.21
Total	0.404	0.164	0.084	0.091	0.112	0.113	0.159	0.216

Table 5.10: The values of fractional systematic uncertainties for $\gamma(\text{OS})$ for Pb-Pb collisions at 2.76 TeV.

Sources	Collision Centrality							
	0-5%	5-10%	10-20%	20-30%	30-40%	40-50%	50-60%	60-70%
Cent. est.	0.09	0.05	0.03	0.04	0.017	0.05	0.04	0.03
$ V_z $	0.06	0.03	0.012	0.02	0.05	0.02	0.05	0.039
B Field	0.07	0.027	0.033	0.017	0.061	0.009	0.02	0.01
$ DCA_{xy} $	0.02	0.007	0.009	0.016	0.013	0.003	0.004	0.007
TPC clus	0.005	0.009	0.015	0.051	0.081	0.055	0.009	0.011
Chg comb.	0.014	0.02	0.004	0.011	0.005	0.003	0.02	0.0162
v_2	0.37	0.14	0.079	0.069	0.076	0.096	0.129	0.179
Total	0.392	0.155	0.093	0.10	0.13	0.123	0.147	0.187

Table 5.11: The values of fractional systematic uncertainties for $\gamma(\text{SS})$ for Pb-Pb collisions at 5.02 TeV.

Sources	Collision Centrality							
	0-5%	5-10%	10-20%	20-30%	30-40%	40-50%	50-60%	60-70%
Cent. est.	0.007	0.001	0.0065	0.002	0.0002	0.001	0.01	0.005
$ V_z $	0.013	0.021	0.013	0.006	0.002	0.005	0.006	0.009
B Field	0.006	0.0012	0.018	0.023	0.016	0.006	0.014	0.009
$ DCA_{xy} $	0.01	0.005	0.009	0.02	0.017	0.005	0.002	0.005
TPC clus	0.06	0.04	0.003	0.05	0.07	0.02	0.002	0.011
v_2	0.37	0.14	0.079	0.069	0.076	0.096	0.129	0.179
Total	0.375	0.147	0.082	0.090	0.105	0.0985	0.13	0.179

Table 5.12: The values of fractional systematic uncertainties for $\gamma(\text{OS})$ for Pb-Pb collisions at 5.02 TeV.

the collision centrality and become zero for most central events.

In-plane and out-of-plane correlations:

The in-plane and out-of-plane correlations for opposite sign and same sign charge pairs are shown in figure 5.12 for both collision energies. For opposite sign charge

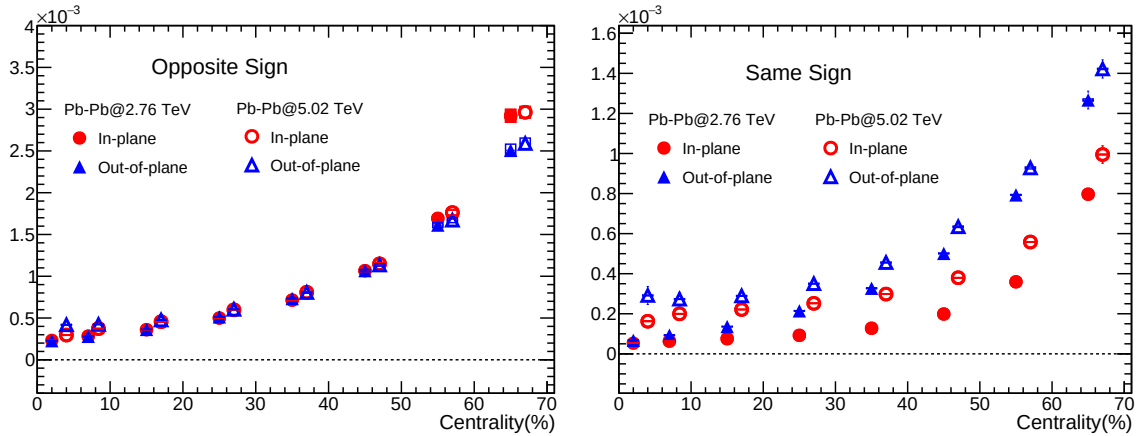


Figure 5.12: The variation of in-plane and out-of-plane correlations for, Left: opposite sign charge pairs and Right: Same for same sign charge pairs. The points at 5.02 TeV are shifted slightly for the sake of clarity.

pairs (Fig. 5.12 (Left)), in-plane and out-of-plane correlations, within errors, agree with each other except 60-70% centrality indicating that the opposite sign charge pairs correlations are similar in both planes while same sign charge pairs show more out-of-plane correlations than those of in-plane correlations. The opposite sign charge pairs do not depend on collision energies whereas same sign charge pairs

show slight energy dependence.

ΔH correlator:

As discussed in the previous chapter (Section 4.5.1), both δ and γ_{112} correlators can be divided into “flow dependent” and “flow independent” contributions. The flow independent contribution is the CME signal and denoted as “H-correlator”. The difference (ΔH) between the H-correlator for same sign and opposite sign charge pairs is defined as:

$$\Delta H = \frac{\kappa v_2 \Delta \delta_{11} - \Delta \gamma_{112}}{1 - \kappa v_2} \quad (5.21)$$

where κ is proportionality constant and depends on the detector acceptance. The

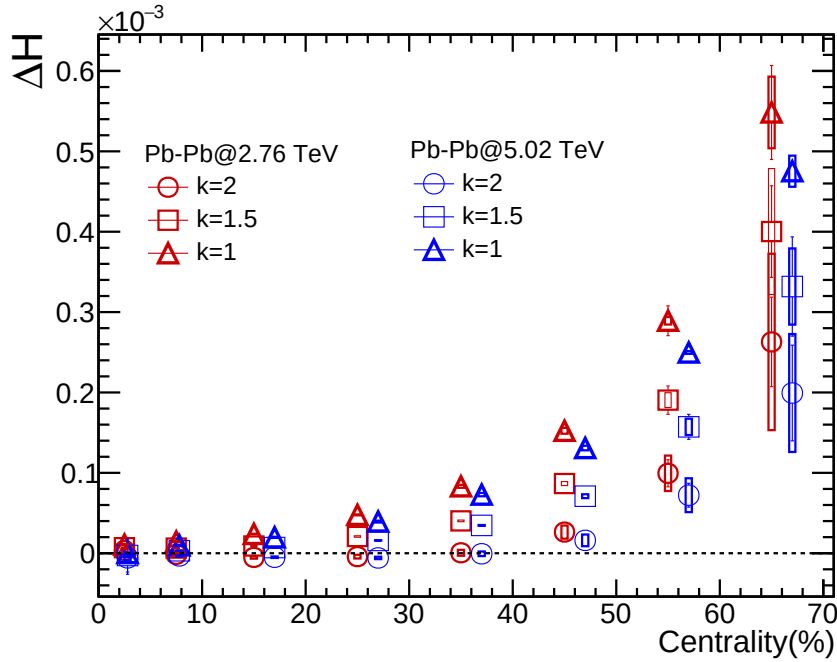


Figure 5.13: The centrality dependence of ΔH correlator for Pb-Pb collisions at both 2.76 TeV and 5.02 TeV collision energies. The points at 5.02 TeV are shifted slightly for the sake of clarity.

ΔH correlator ($=H_{SS} - H_{OS}$) are plotted for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and 5.02 TeV. It is seen that ΔH decreases with decreasing κ and also with increasing energy. Also ΔH decreases with increasing collision centrality and approaches zero for higher collision centralities. (0-20%).

5.4.2 Analysing data using SDM

It is observed from above that CME sensitive γ correlator for same sign charge pairs are strongly correlated whereas opposite sign charge pairs correlations are weak. Also, the strength of correlations decreases with the increase in collision centrality. Now, we analyze the data using SDM to get the CME enriched sample. The charge separation across the dumbbell for each collision centrality as discussed in previous chapter, is calculated and all the above discussed correlators are again investigated, depending on the charge separation across the dumbbell.

5.4.2.1 The fractional charge separation across dumbbell (f_{DbCS}) Distributions

The f_{DbCS} distributions for different collision centralities for data and charge reshuffle are calculated using sliding dumbbell method and are shown in Fig. 5.14 and Fig. 5.15 for Pb-Pb collisions at 2.76 TeV and 5.02 TeV, respectively. The distributions shift towards higher f_{DbCS} values approaching the maximum value for the f_{DbCS} , i.e., 1, as one moves from more central to semi-central collisions indicating the increase in charge separation in mid-central collisions. The charge shuffle shows similar f_{DbCS} distributions as of data. The similar trends are observed for both collision energies.

5.4.2.2 Dependence of multi-particle correlators on charge separation (f_{DbCS})

2-particle δ correlator:

The two particle δ correlator is measured for ten percentile f_{DbCS} bins for different charge combinations and for Pb-Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV and 5.02 TeV (Fig. 5.16). For opposite sign charge pairs, the top f_{DbCS} bins exhibit negative correlation values whereas these are positive for rest of the f_{DbCS} bins. The trend for same sign charge pairs is exactly opposite as that of opposite sign charge pairs. The top f_{DbCS} bins show positive values for SS charge pairs which is as expected

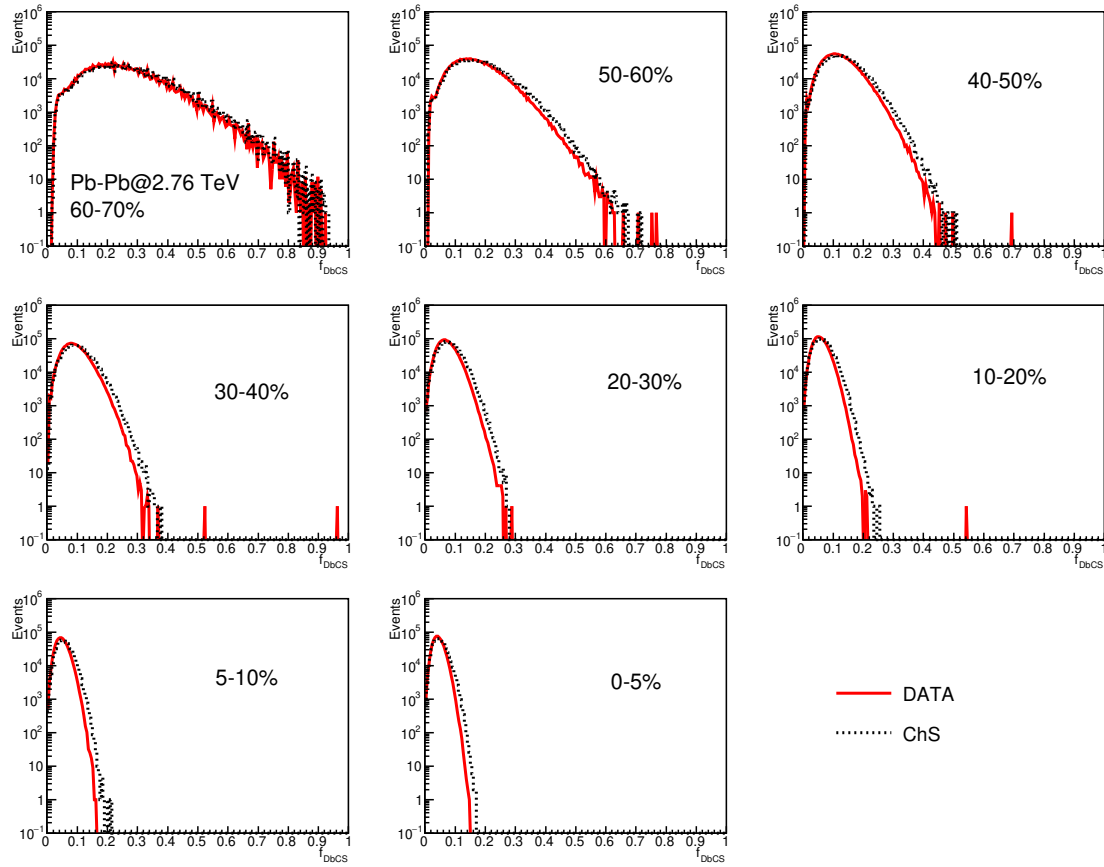


Figure 5.14: The f_{DbCS} distributions obtained by sliding dumbbell method for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV compared with charge shuffle background.

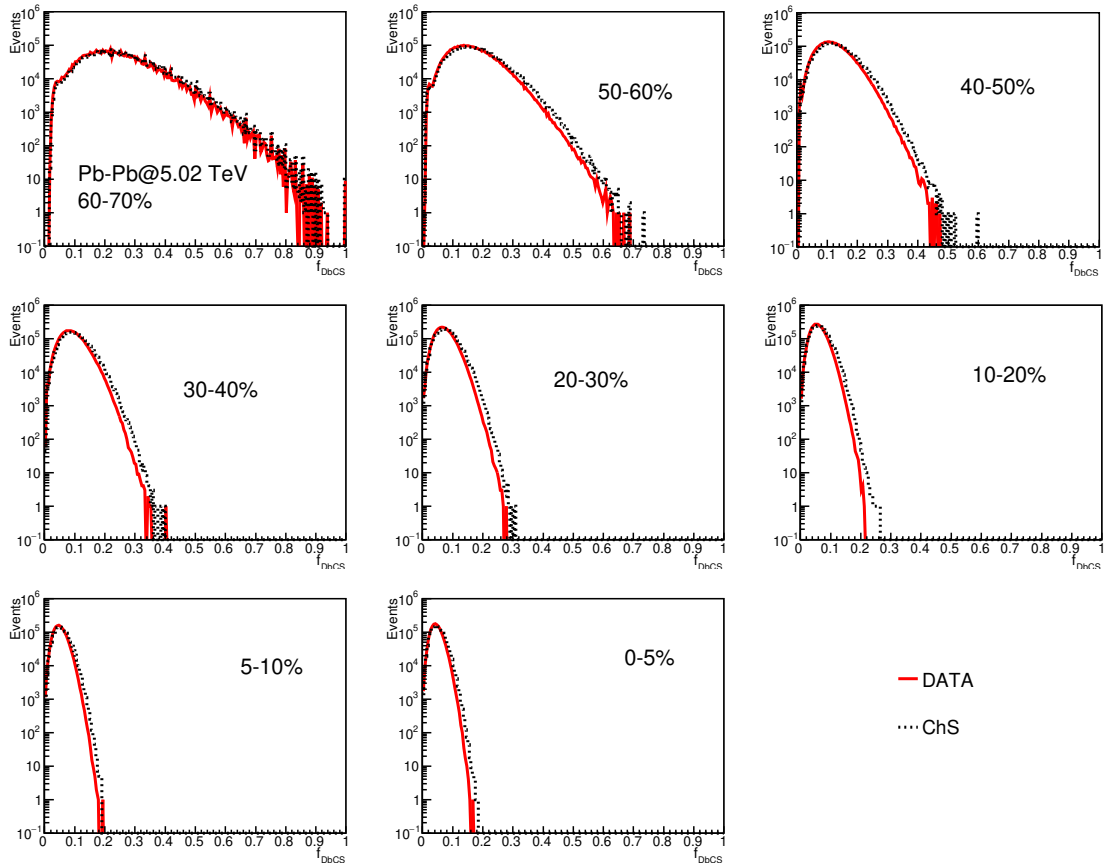


Figure 5.15: The f_{DbCS} distributions obtained by sliding dumbbell method for Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV compared with Charge shuffle background.

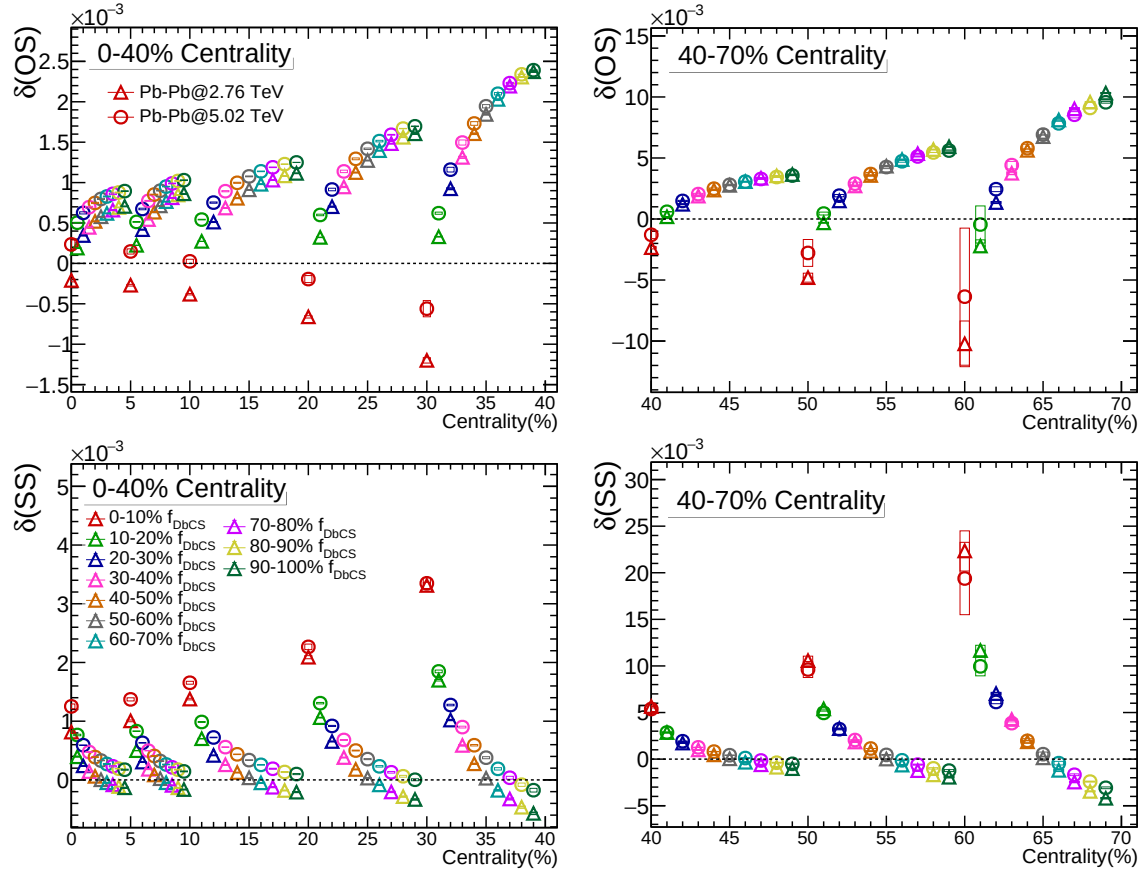


Figure 5.16: The charge separation ($f_{D_{bCS}}$) dependence of δ correlator for OS (Top Row) and SS (Bottom Row) charge pairs for Pb-Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV and 5.02 TeV. The left column plots are for 0-40% collision centralities and right column plots for 40-70% centralities and Y-axes for 0-40% collision centralities are magnified for the sake of clarity.

for the CME and becomes negative while going toward lower $f_{D_{bCS}}$ bins. These 2-particle correlations seems to be independent of collision energies.

3-particle correlators:

For further understanding, the three particle azimuthal correlator (γ_{112}) is obtained in each $f_{D_{bCS}}$ bin for different collision centralities for different charge combinations. The figure 5.17 shows the variation of γ_{112} correlator for opposite sign and same sign charge pairs combinations with charge separation ($f_{D_{bCS}}$) bins for different collision centralities and Y-axes scale for 0-40% centrality is magnified many times as their values are small. The strength of correlations decrease with decreasing charge separation and increasing collision centrality. The number of $f_{D_{bCS}}$ bins exhibiting

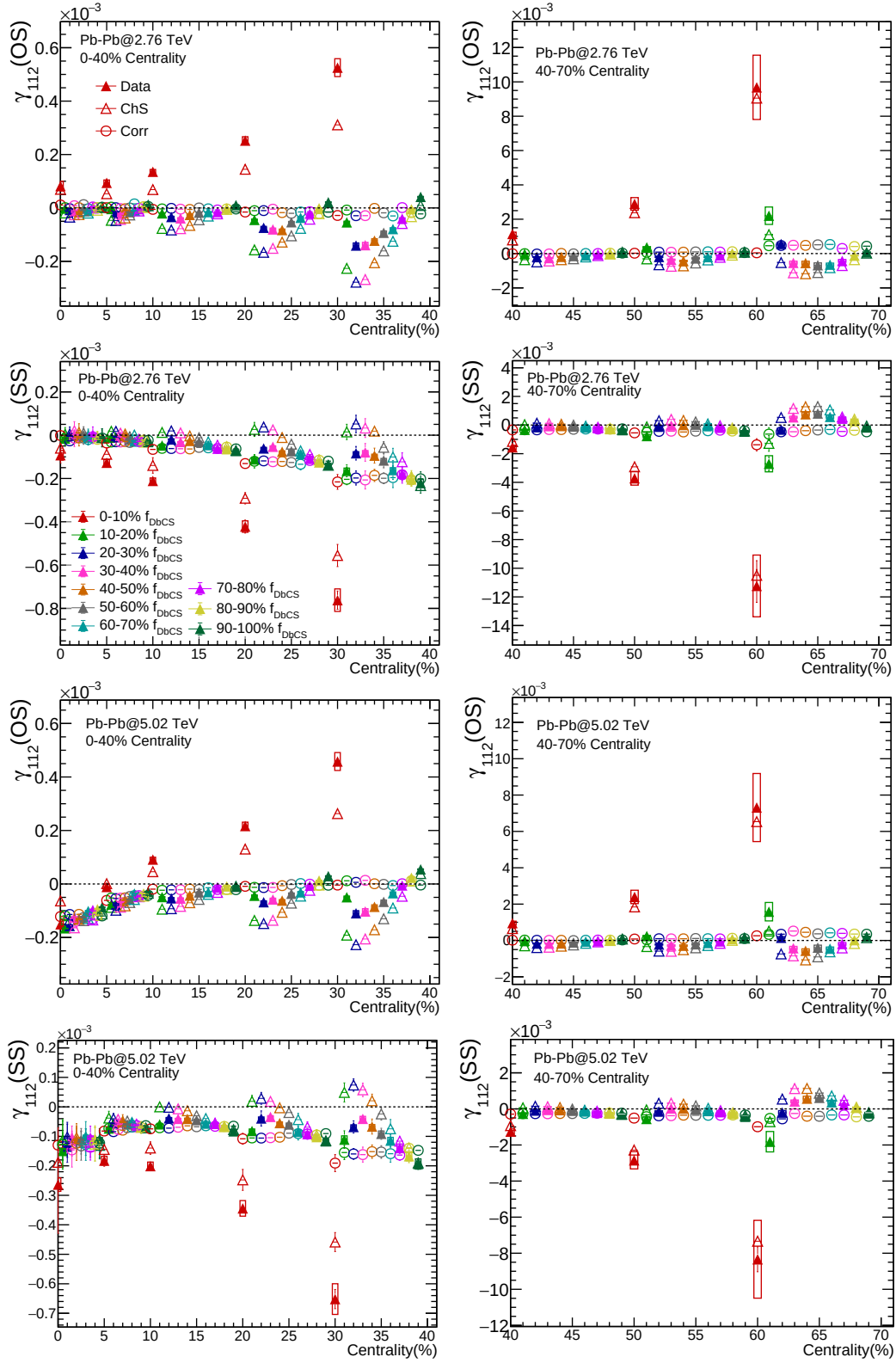


Figure 5.17: The charge separation (f_{DbCS}) dependence of γ_{112} correlator for OS and SS charge pairs for Pb-Pb collisions at 2.76 TeV and 5.02 TeV along with the charge shuffle and correlated backgrounds. The Y-axes for 0-40% collision centralities are magnified for the sake of clarity.

strong correlations decrease with increasing collision centrality. The opposite sign charge pairs are weakly correlated having positive values. The same sign charge pairs, γ correlator exhibits strong correlations for top $f_{D_{bCS}}$ bins. The charge shuffled background shows similar trend as of data but with less values and the correlated background seems to be independent of charge separation bins. It is worth noting that the magnitude of correlations of same sign charge pairs is approximately equal to that of opposite sign charge pairs for top $f_{D_{bCS}}$ bins as expected for the CME like events. Similar trends are observed for both energies. The systematic errors plots of γ are shown in the Appendix.

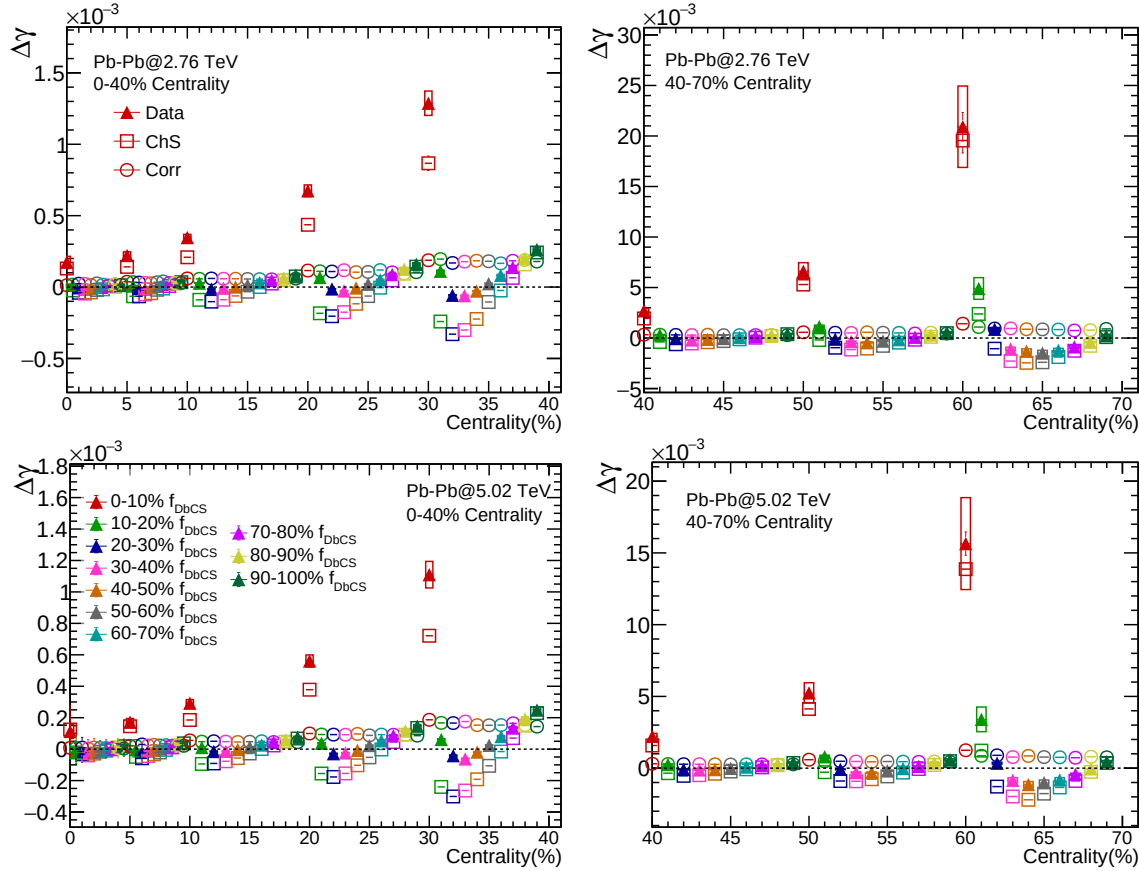


Figure 5.18: The charge separation ($f_{D_{bCS}}$) dependence of $\Delta\gamma$ correlator for Pb-Pb collisions at 2.76 and 5.02 TeV. The left column plots are for 0-40% collision centralities and right column plots for 40-70% centralities and Y-axes of 0-40% centrality are magnified for the sake of clarity.

$\Delta\gamma$ correlators:

In figure 5.18, the higher $f_{D_{bCS}}$ bins exhibit more positive values for $\Delta\gamma(= \gamma(OS) - \gamma(SS))$ than the rest of the bins in each centrality. The charge shuffle and correlated background points are also displayed as a function of $f_{D_{bCS}}$ bins. The charge shuffle have similar dependence but the correlation values are smaller in magnitude than those of data. For correlated background, correlations do not vary with $f_{D_{bCS}}$ percentile bins. The strong correlation is seen for higher $f_{D_{bCS}}$ bins indicating the presence of CME-like enriched events corresponding to these $f_{D_{bCS}}$ bins for 10-60% collision centralities.

The normalized $\Delta\gamma_{112}$ i.e., $\Delta\gamma_{112norm} = \Delta\gamma_{112}(\text{Top } 10\% f_{D_{bCS}})/\Delta\gamma_{112}(\text{avg.})$, is

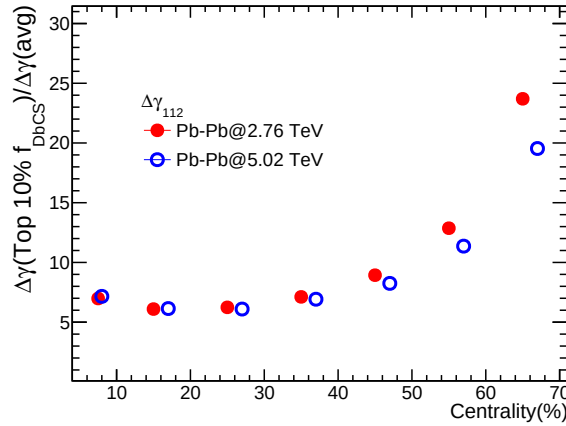


Figure 5.19: The normalized $\Delta\gamma_{112}$ for different centralities for Pb-Pb collisions at 2.76 and 5.02 TeV.

presented in figure 5.19 and it is seen that $\Delta\gamma_{112norm}$ is ≈ 7 for the top 10% $f_{D_{bCS}}$ events correspond to potential CME events for each collision centrality for 10-50% collision centralities for both enrgies.

In-plane and Out-of-plane correlations:

The in-plane and out-of-plane correlations are studied for ten percentile $f_{D_{bCS}}$ bins for Pb-Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV and 5.02 TeV and are shown in Fig. 5.20. The opposite sign shows negative correlations for top $f_{D_{bCS}}$ bin for both in-plane and out-of-plane correlations with more out-of-plane correlations than in-plane whereas

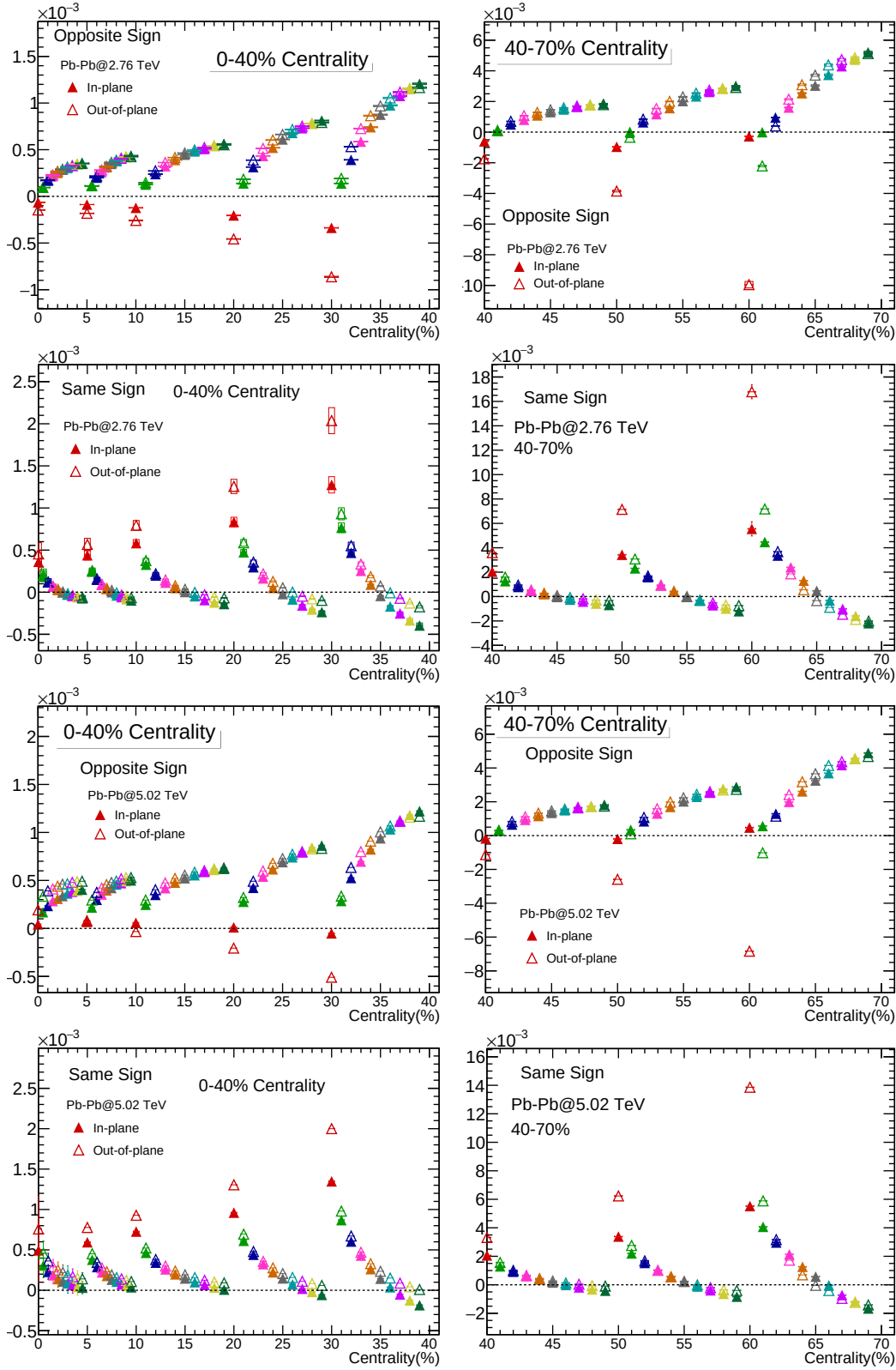


Figure 5.20: The charge separation ($f_{D_{bCS}}$) dependence of in-plane and out-of-plane correlations for opposite and same sign charge pairs for Pb-Pb collisions at 2.76 and 5.02 TeV. The left column plots are for 0-40% collision centralities and right column plots for 40-70% centralities and Y-axes for 0-40% collision centralities are magnified for the sake of clarity.

for other f_{D_bCS} bins in-plane and out-of-plane correlations agree within errors. The same sign charge pairs correlations are positive for top f_{D_bCS} bins more of out-of-plane correlations than those of in-plane correlations. Again for other f_{D_bCS} bins both in-plane and out-of-plane correlations agree within errors.

It is observed that the correlations decrease with increasing collision energy.

5.4.2.3 Event characterisation

The variations of elliptic flow v_2 with different charge separation bins are shown in Fig. 5.21. The $v_2\{2\}$ and $v_2\{4\}$ are calculated and are shown in the figure. The less non-flow contributions are expected in $v_2\{4\}$, that is why it has less values than those of $v_2\{2\}$. For the analysis in this thesis, mean of both $v_2\{2\}$ and $v_2\{4\}$ is used (solid triangle in the figure) to reduce the non-flow contribution to the v_2 . The elliptic flow is more for top 10% f_{D_bCS} percentile bin and thereafter it remain

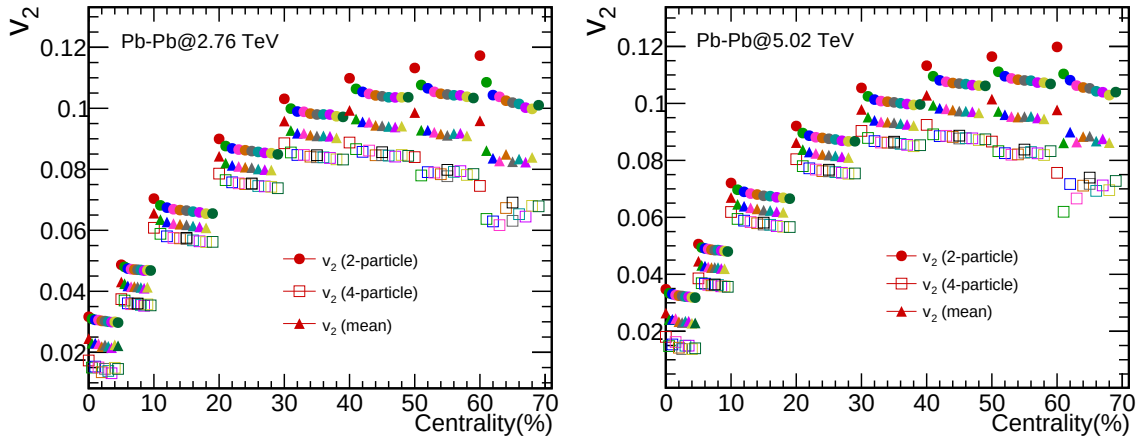


Figure 5.21: The charge separation dependence of $v_2\{2\}$, $v_2\{4\}$ and average of these two for different collision centralities for Pb-Pb collisions at 2.76 (Left) and 5.02 TeV (Right).

constant for rest of the bins. The figure 5.22 displays the normalized v_2 ($=v_2(\text{Top } 10\% \text{ bin})/v_2(\text{avg})$) for the top 10% f_{D_bCS} which shows the increase of v_2 for top 10% f_{D_bCS} events, and indeed for all centralities the value of normalized v_2 is greater than 1. Therefore, v_2 is increased 5% for the top 10% f_{D_bCS} events representing potential CME like events. The charge separation dependence of multiplicity has been studied (Fig. 5.23), it is seen that for a given centrality, the multiplicity of top

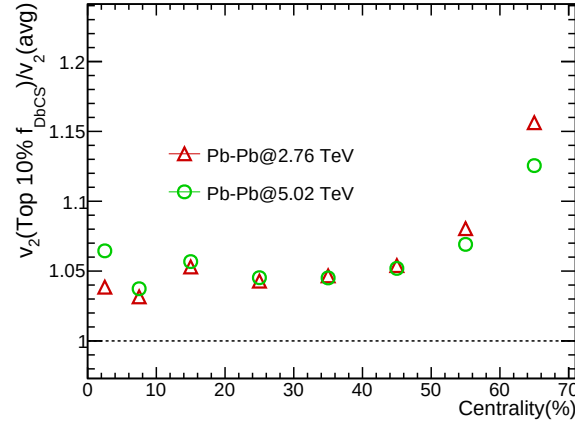


Figure 5.22: The normalize flow for different centralities and; for Pb-Pb collisions at 2.76 and 5.02 TeV.

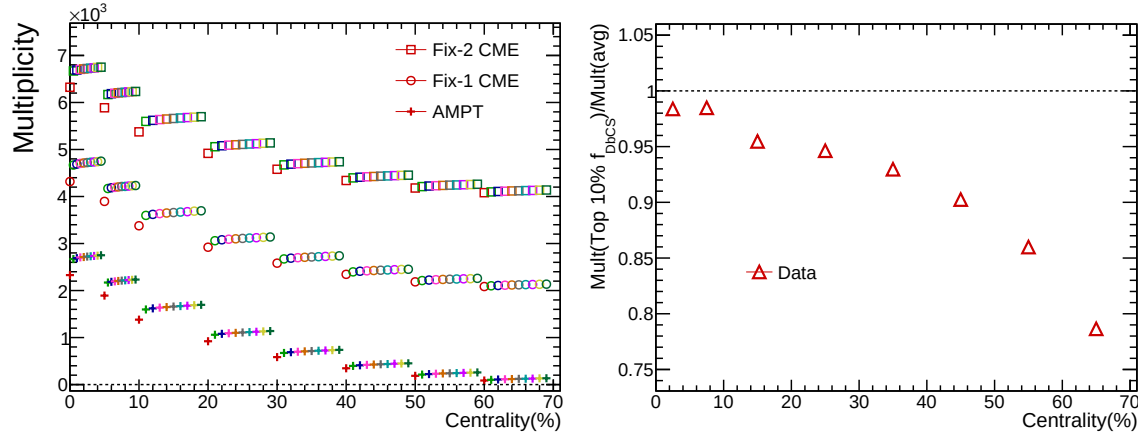


Figure 5.23: Left: The charge separation dependence of multiplicity for different collision centralities for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Right: The normalize multiplicity i.e., $\text{Mult}(\text{Top } 10\% f_{DbCS} \text{ bin})/\text{Mult}(\text{avg})$ for different centralities.

10% f_{DbCS} bin is less than those of other bins. This decrease is even seen of 20% for 60-70% centrality. As the charge separation decreases, multiplicity increases.

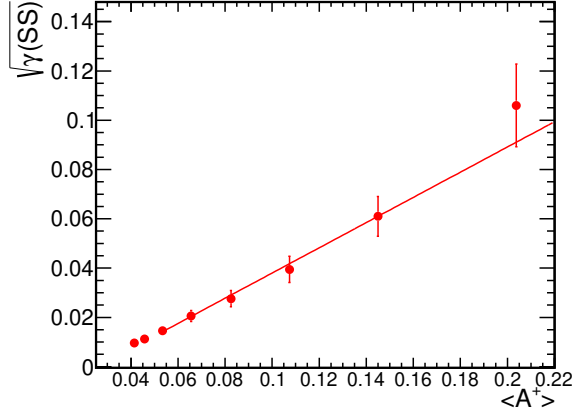


Figure 5.24: The variation of $\sqrt{|\gamma_{SS}|}$ for top 10% $f_{D^{bCS}}$ bin with the positive charge asymmetry ($\langle A^+ \rangle$) across the dumbbell for Pb-Pb collisions at 2.76 TeV for different collision centralities.

5.4.2.4 Positive charge asymmetry across the dumbbell ($\langle A^+ \rangle$)

The Fourier decomposition of particle azimuthal angle distribution in momentum space is represented as:

$$\begin{aligned} \frac{dN}{d\phi} \propto & 1 + 2v_1 \cos(\phi - \psi_{RP}) + 2v_2 \cos 2(\phi - \psi_{RP}) + \dots \\ & + 2a_1 \sin(\phi - \psi_{RP}) + 2a_2 \sin 2(\phi - \psi_{RP}) + \dots \end{aligned} \quad (5.22)$$

here, the parameter “ a_n ” used to describe the charge separation effect. Further

$$\gamma \approx v_{1,a}v_{1,b} - a_{1,a}a_{1,b} \quad (5.23)$$

and with symmetric rapidity as used in the previous analysis, $v_{1,a}=v_{1,b} \sim 0$, gives rise to $\gamma \propto |a_{1,a}a_{1,b}|$. A positive charge asymmetry (A^+) across the dumbbell, the term proportional to a_1 , is defined as:

$$A^+ = \frac{|n_+^a - n_+^b|}{N_+} \quad (5.24)$$

where, n_+^a denotes the number of positively charged particle on “a” side of the dumbbell and n_+^b denotes the number of positively charged particle on “b” side of the dumbbell; N_+ denotes the total number of positive charge particles in an event.

The variation $\sqrt{|\gamma_{SS}|}$ for top 10% $f_{D_{bCS}}$ bin with positive charge asymmetry ($\langle A^+ \rangle$) across the dumbbell with for Pb-Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV is shown in figure 5.24. The points are fitted with straight line, $\sqrt{|\gamma_{SS}|} = p_0 + p_1 \langle A^+ \rangle$ for 10-60% centralities. It is observed that $\sqrt{|\gamma_{SS}|}$ varies linearly with positive charge asymmetry across dumbbell $\langle A^+ \rangle$ as expected for CME like events. The fitted values of p_0 and p_1 are -0.013 ± 0.0038 and 0.51 ± 0.056 , respectively.

5.4.3 CME insensitive 3-particle γ_{123} correlator

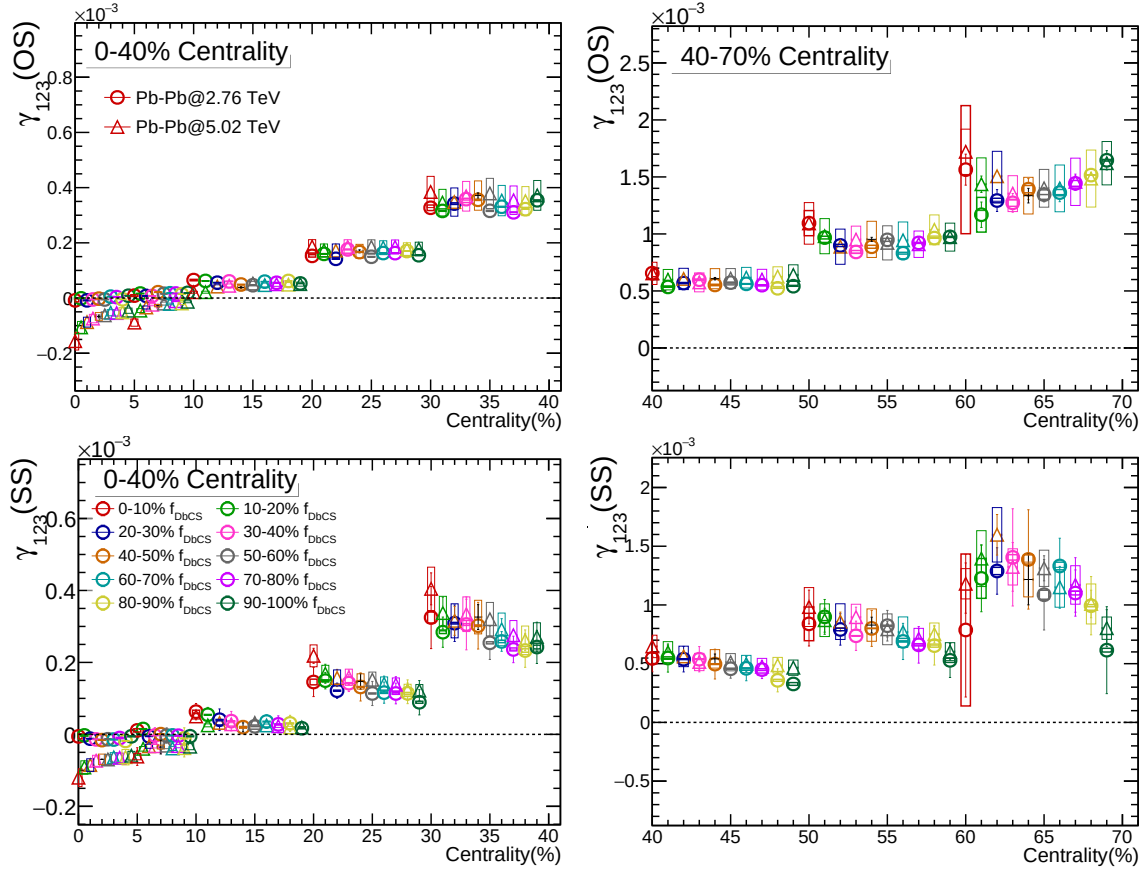


Figure 5.25: The charge separation ($f_{D_{bCS}}$) dependence of γ_{123} correlator for OS (Top Row) and SS (Bottom Row) charge pairs for Pb-Pb collisions at 2.76 and 5.02 TeV. The left column plots are for 0-40% collision centralities and right column plots for 40-70% centralities and Y-axes of 0-40% centrality are magnified for the sake of clarity.

Fig. 5.25 exhibits the dependence of γ_{123} on the charge separation for different collision centralities for same and opposite sign charge pairs. Both same sign and

opposite sign γ_{123} correlator have positive correlation values with OS has more values than those of SS. The γ_{123} seems to be independent of charge separation ($f_{D_{bCS}}$) for 0-50% collision centralities. Also, γ_{123} seems to be energy independent.

The figure 5.26 compares $\Delta\gamma_{112}$ and $\Delta\gamma_{123}$. It is seen that $\Delta\gamma_{112}$ depends on the

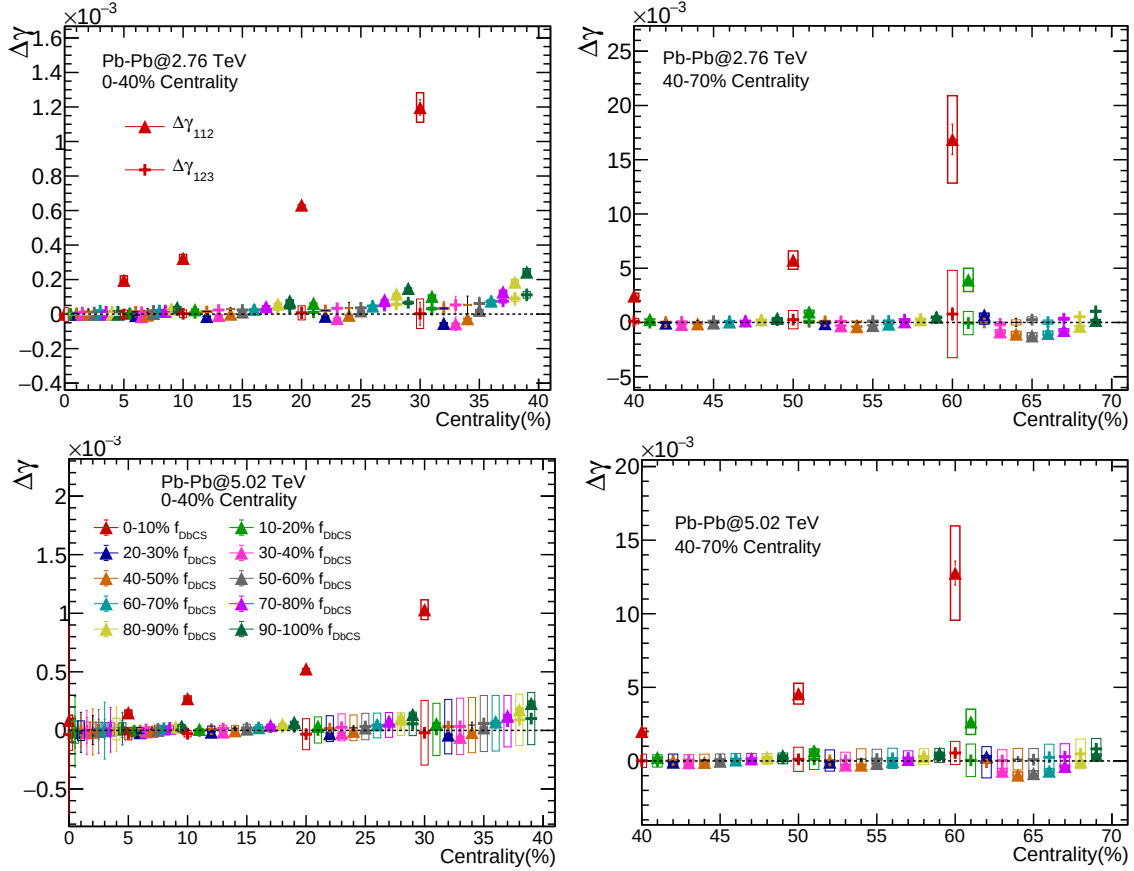


Figure 5.26: The charge separation ($f_{D_{bCS}}$) dependence of $\Delta\gamma$ s ($\Delta\gamma_{112}$ and $\Delta\gamma_{123}$) correlator for Pb-Pb collisions at 2.76 and 5.02 TeV. The left column plots are for 0-40% collision centralities and right column plots for 40-70% centralities and Y-axes of 0-40% centrality are magnified for the sake of clarity.

charge separation ($f_{D_{bCS}}$) bins whereas $\Delta\gamma_{123}$ is independent of charge separation for 0-50% collision centralities. It is worth noting that, the selection of events on the basis of charge separation across the dumbbell helps in getting the CME enriched event sample and it does not influence the correlations which depend on the 3rd order event plane.

5.4.4 ΔH

The variation of ΔH correlator which represents the CME signal in γ_{112} correlator, for different f_{D_bCS} bins is shown in Fig. 5.27 for Pb-Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV and 5.02 TeV for different κ values. As ΔH manifests the CME signal, ΔH increases

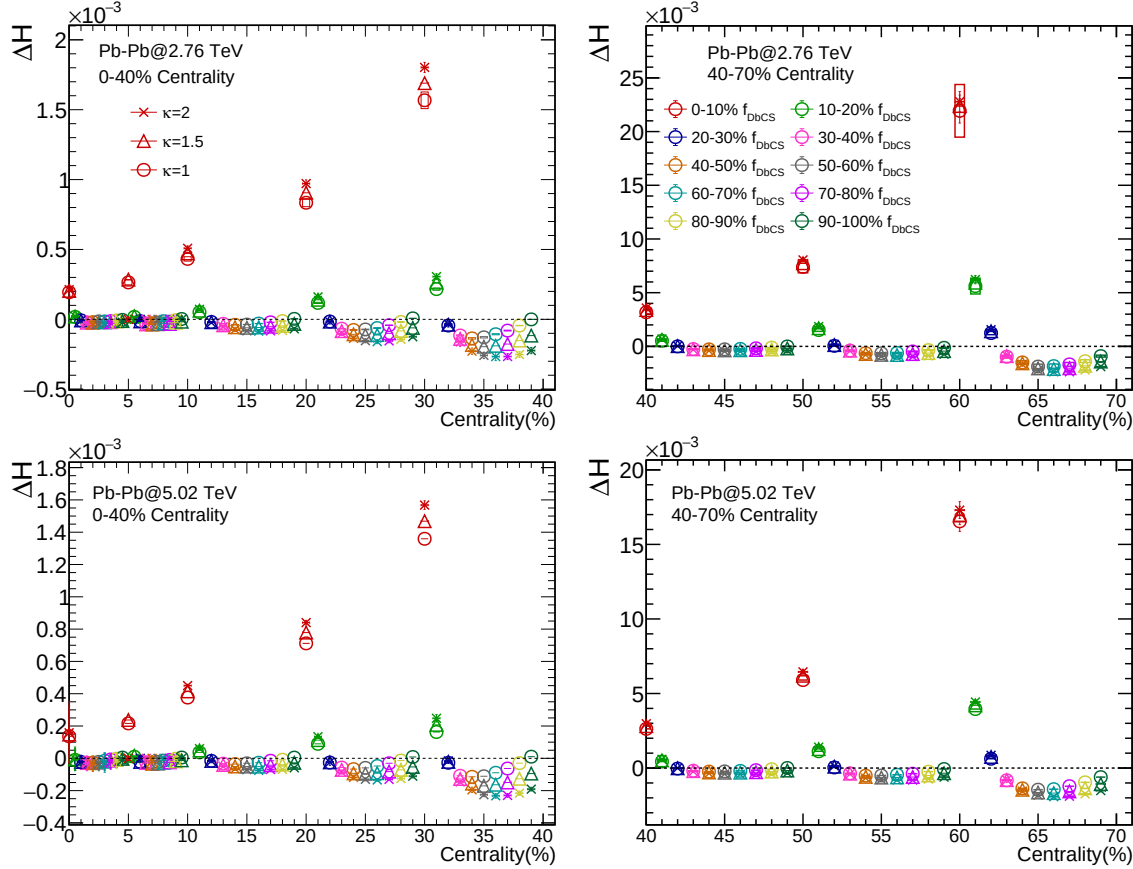


Figure 5.27: The charge separation (f_{D_bCS}) dependence of ΔH correlator for Pb-Pb collisions at 2.76 and 5.02 TeV. The left column plots are for 0-40% collision centralities and right column plots for 40-70% centralities and Y-axes of 0-40% centrality are magnified for the sake of clarity.

as the charge separation increases. For top f_{D_bCS} bins, the ΔH is positive. Also, ΔH seems to be independent of κ values. The ΔH seems to decrease with collision energy for top f_{D_bCS} bins representing the CME like event sample. It is seen that ΔH is positive for the top 20% f_{D_bCS} bins for 0-60% collision centralities.

5.4.5 CME Fraction (f_{CME})

An attempt to calculate CME fraction in top 10% f_{D_bCS} bin has also been made.

The f_{CME} (CME fraction) is calculated as:

$$f_{CME} = \frac{\Delta\gamma - \Delta\gamma_{bkg.}}{\Delta\gamma} \quad (5.25)$$

where $\Delta\gamma_{bkg.} = \Delta\gamma_{ChS} + \Delta\gamma_{Corr.}$

Figure 5.28 shows the f_{CME} for top 10% f_{D_bCS} bin, i.e., 0-10% f_{D_bCS} for different collision centralities. Here, in the plot, systematic errors and statistical errors are added in quadrature. The fraction remains somewhat constant $18 \pm 8\%$ for 0-

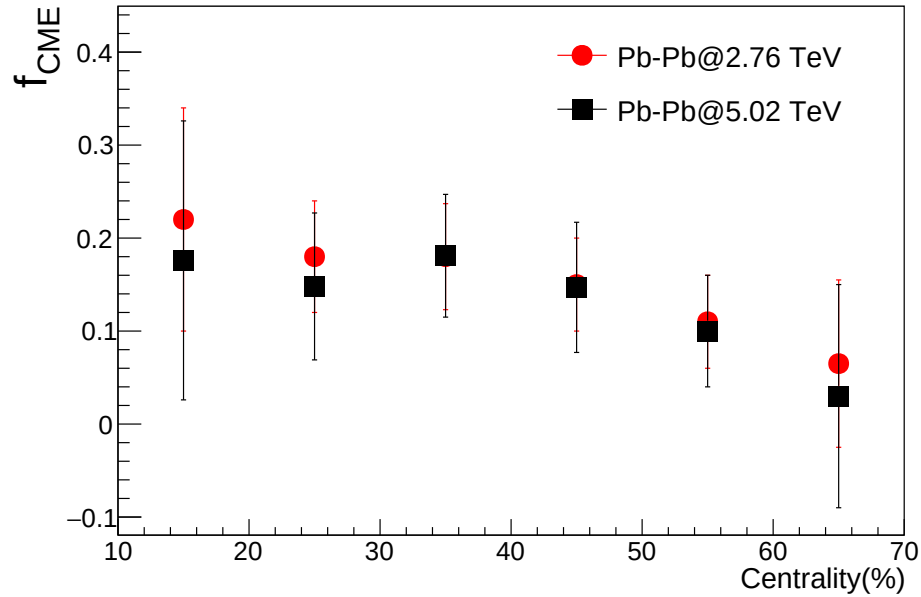


Figure 5.28: The fraction of CME (f_{CME}) for top f_{D_bCS} bin for Pb-Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV and at $\sqrt{s_{NN}}=5.02$ TeV.

50% collision centralities for both energies.

Figure 5.29 shows the CME fraction calculated through the charge shuffle and correlated backgrounds and using ΔH method. The f_{CME} calculated from ΔH correlator is much higher than the fraction calculated from charge shuffle and correlated backgrounds which is 0.02.

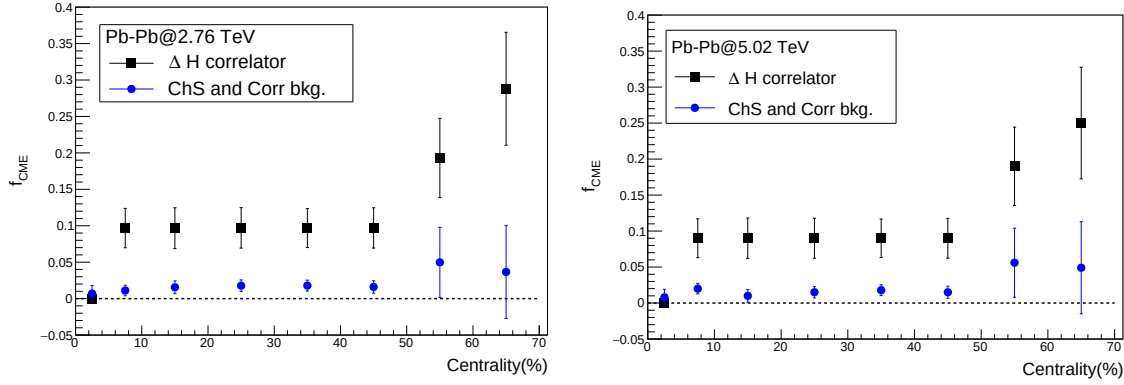


Figure 5.29: The fraction of CME (f_{CME}) calculated through $\Delta\gamma$ with charge shuffle and correlated backgrounds; data driven background and with ΔH correlator for Pb-Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV (Left) and at $\sqrt{s_{NN}}=5.02$ TeV (Right).

5.5 Summary

To search for the back-to-back charge separation of positive and negative charge particles on an event-by-event basis, a new method, Sliding Dumbbell Method (SDM), is developed. This back-to-back charge separation is the sign of chiral magnetic effect (CME) in non-central heavy-ion collisions. It is essential to search CME signal in each and every event to isolate potential events exhibiting the back-to-back charge separation with significantly enhanced signal in these events rather than searching for the signal taking all events together in a given collision centrality. The SDM is used to isolate the CME enriched events for a given collision centrality.

The Pb-Pb collisions data at $\sqrt{s_{NN}}=2.76$ TeV and at $\sqrt{s_{NN}}=5.02$ TeV have been analysed to investigate the Chiral Magnetic Effect in heavy ion collisions. The SDM has been tested on the AMPT generated events and is observed that the CME signal $\sim 0.5\%$ can be detected using the SDM (for details see Chapter 4).

The 3-particle γ correlator and 2-particle δ correlator, computed by Q-cumulant method, are used to investigate the CME in heavy-ion collisions for the given collision centrality. The centrality dependence of γ correlators for the same and opposite sign charge pairs has been studied in present analysis which agree with those of published results for Pb-Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV and at $\sqrt{s_{NN}}=5.02$ TeV. In present investigation, we tried to get the CME enriched sample for a given

collision centrality using the SDM. It is found that the sample having events with the highest back-to-back charge separation across the dumbbell i.e., events corresponding to the top 10% of charge separation (f_{DbCS}), has many times larger value of γ correlator. Also, it is observed that γ correlator for the same sign charge pair is negative and for opposite sign charge pair is positive. However, their magnitude are approximately equal. Further, 2-particle δ correlator is found to be positive for same sign and negative for opposite sign charge pairs for top f_{DbCS} bins. Moreover, same sign charge pairs exhibited more out-of-plane correlations than those of in-plane correlations. In view of the above, the top 10% f_{DbCS} events in a given sample looks CME like events. Interestingly, it is found that $\sqrt{|\gamma_{SS}|}$ varies linearly, for top 10% f_{DbCS} events, with positive charge excess across the dumbbell which is proportional to the parity violating parameter (a). Event characteristics are also investigated for the CME enriched sample. It is found that elliptic flow in these top 10% f_{DbCS} events increases by $\sim 5\%$ whereas mean multiplicities of particles decrease with decrease in collision centrality. An attempt is made to get the fraction of CME in the CME enriched sample for 0-50% collision centrality using the charge shuffled and correlated backgrounds. The f_{CME} is around $18 \pm 8\%$ for 0-50% collision centrality for top 10% f_{DbCS} events in a given sample and seems to be independent of collision energy.

The dependence of 3-particle γ_{123} on collision centrality as well as on charge separation is investigated and it is found that γ_{123} does not depend on the charge separation (f_{DbCS}) bins for a given collision centrality as expected since γ_{123} involves 3rd order event plane which does not depend on correlation related to 2nd order event plane.

An attempt also has been made to investigate H parameter which separates the CME signal from backgrounds. Here, again it is noticed that difference between same sign and opposite sign charge pairs' H enhances significantly for the top 10% charge separation representing the CME like events in comparison to the other bins. The f_{CME} calculated using ΔH comes around $\sim 10\%$ for 0-50% collisions centralities.

In view of the above, in the present study we do observe the CME signal in the top 10% events with the highest back-to-back charge separation across the dumbbell and its contribution, i.e., $f_{CME} \sim 18 \pm 8\%$ in top 10% f_{DbCS} events of a given collision centrality which corresponds to $1.8 \pm 0.8\%$ for a given collision centrality.

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APPENDIX

a

APPENDIX

I Systematic uncertainty for γ for Pb-Pb collisions at 5.02 TeV

Since $\gamma = \langle \cos(\phi_a + \phi_b - 2\phi_c) \rangle / v_2$, so systematic uncertainty in γ is calculated by quadrature sum of systematic uncertainty in $\langle \cos(\phi_a + \phi_b - 2\phi_c) \rangle$ and in v_2 . Here systematic uncertainties for γ (OS and SS) and $\Delta\gamma$ for Pb-Pb collisions at 5.02 TeV are discussed. The systematics for $\langle \cos(\phi_a + \phi_b - 2\phi_c) \rangle$ for same sign and opposite sign charge pairs are obtained from different systematic sources viz., centrality estimators, vertex cut (v_z), magnetic field polarity (B_+ and B_-) and number of TPC clusters. Eleven plots are shown in each figure for a particular systematic cut and each plot corresponds to different $f_{D^{bCS}}$ bin. The variation of different systematic sources is presented in figures a.1, a.2, a.3 and a.4 for same sign

charge pairs, a.5, a.6, a.7 and a.8 for opposite sign charge pairs and a.9, a.10, a.11 and a.12 for the difference between OS and SS.

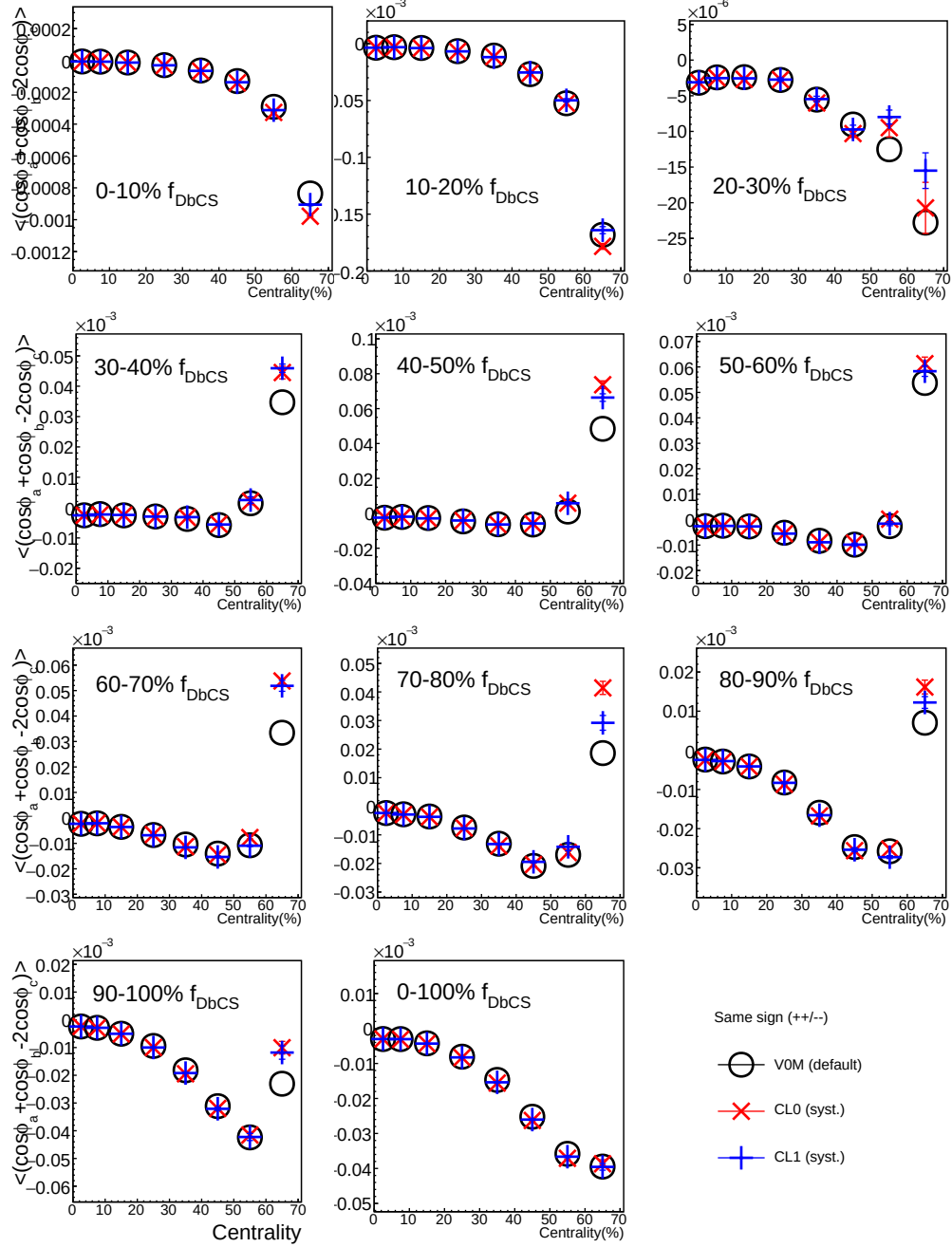


Figure a.1: Centrality dependence of $\langle \cos(\phi_a + \phi_b - 2\phi_c) \rangle$ for same sign charge pairs for different centrality definitions for different f_{DbCS} bins as indicated.

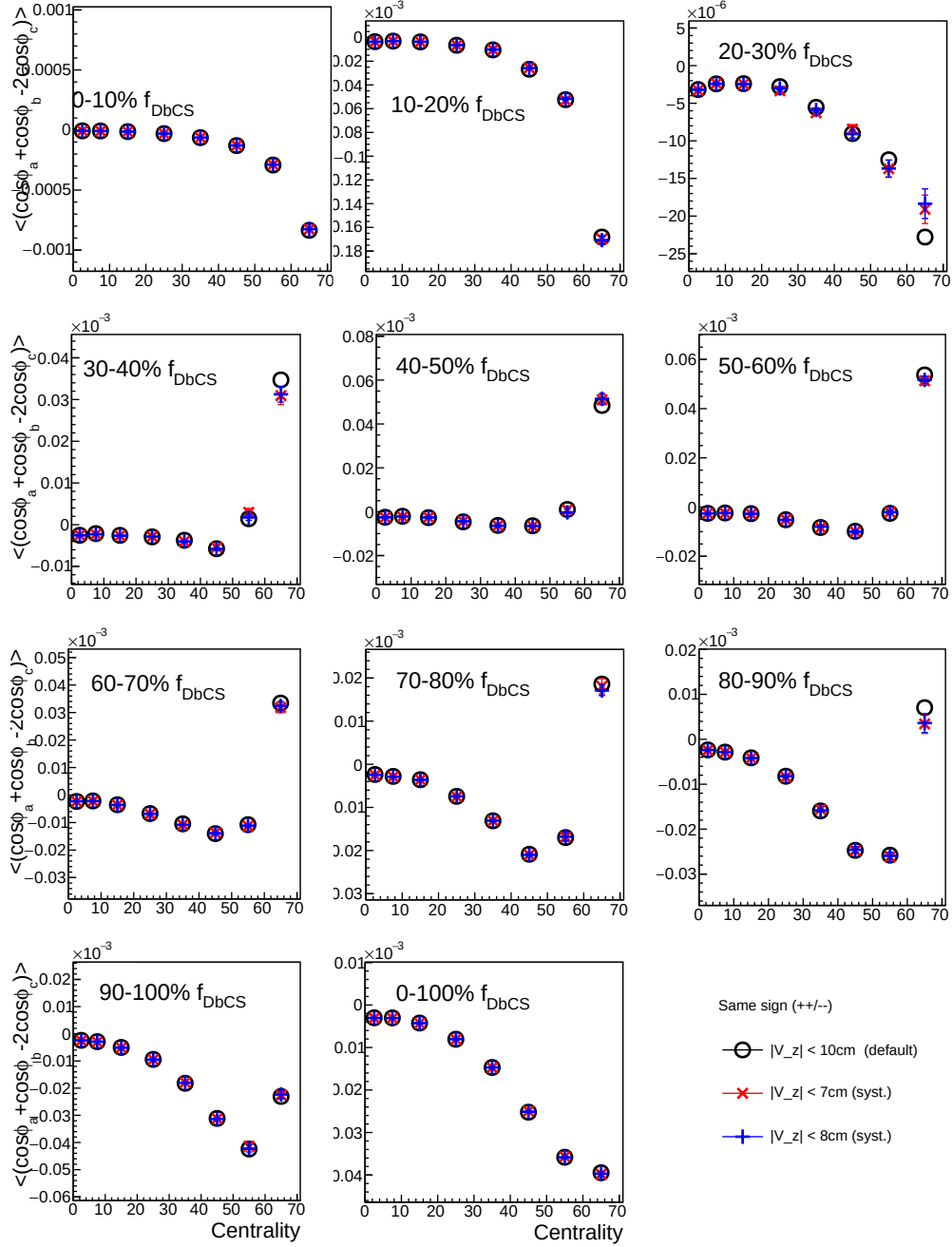


Figure a.2: Centrality dependence of $\langle \cos(\phi_a + \phi_b - 2\phi_c) \rangle$ for same sign charge pairs for different vertex cut for different f_{DbCS} bins as indicated.

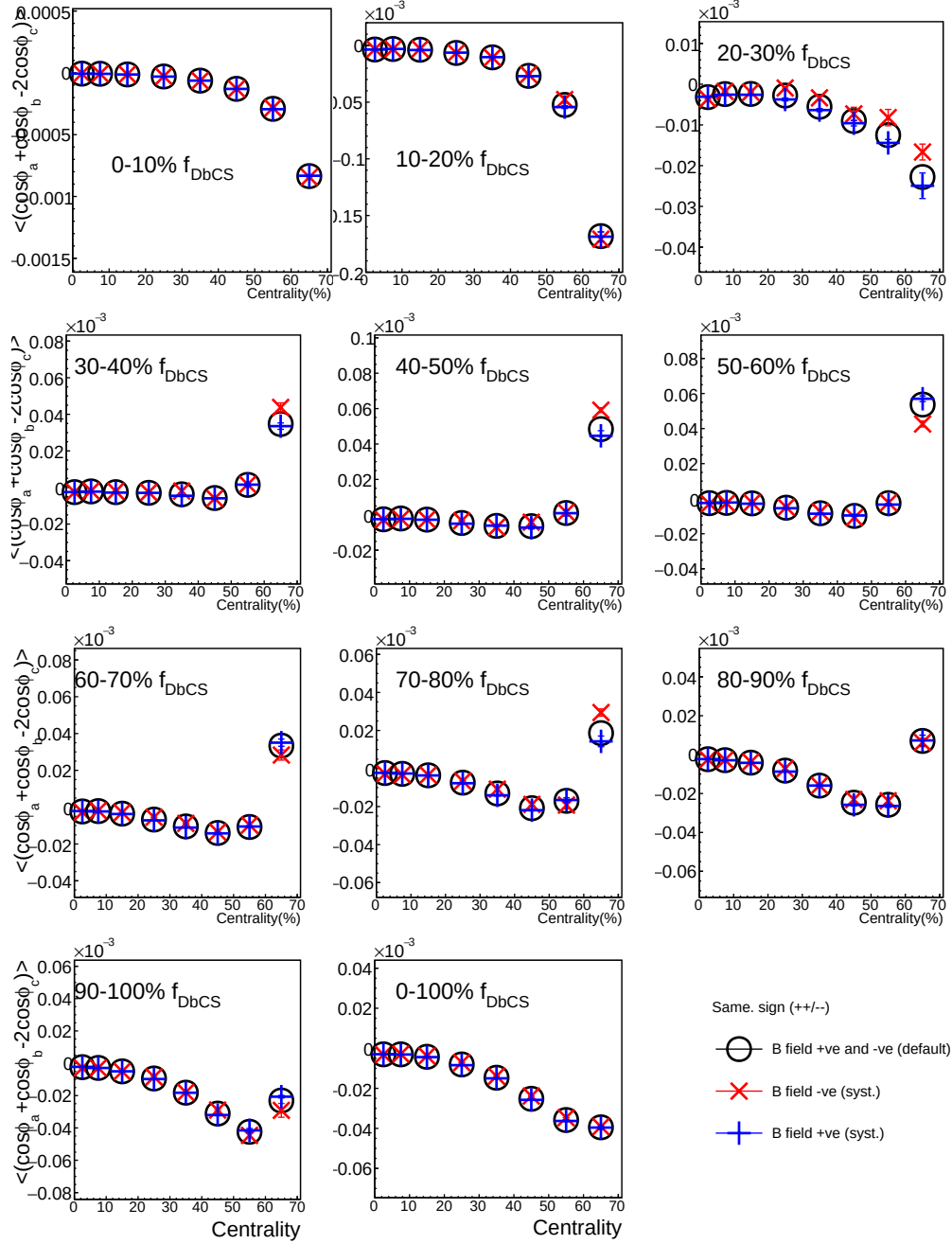


Figure a.3: Centrality dependence of $\langle \cos(\phi_a + \phi_b - 2\phi_c) \rangle$ for same sign charge pairs for different magnetic field polarity for different f_{DbCS} bins as indicated.

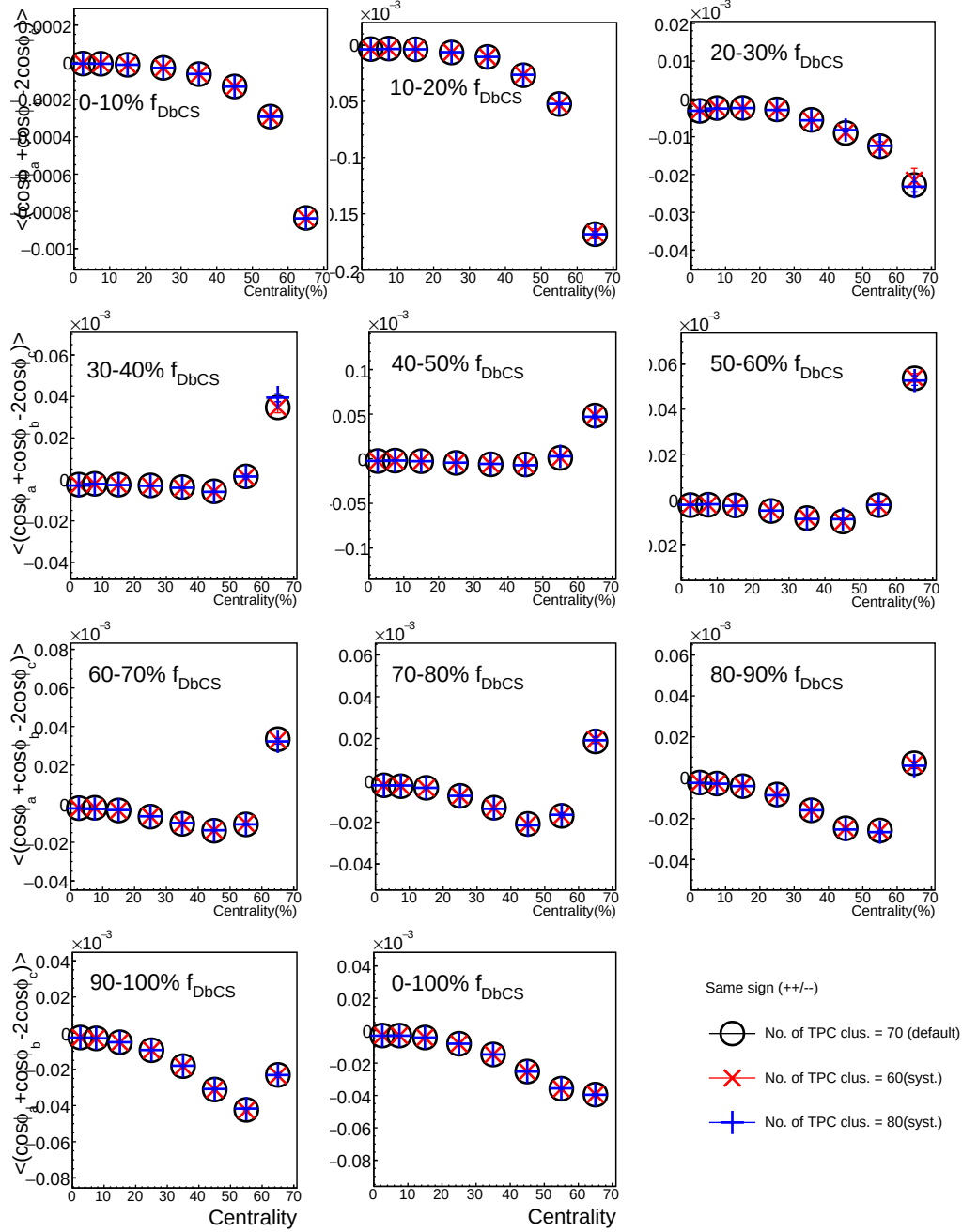


Figure a.4: Centrality dependence of $\langle \cos(\phi_a + \phi_b - 2\phi_c) \rangle$ for same sign charge pairs for number of TPC clusters for different f_{DbCS} bins as indicated.

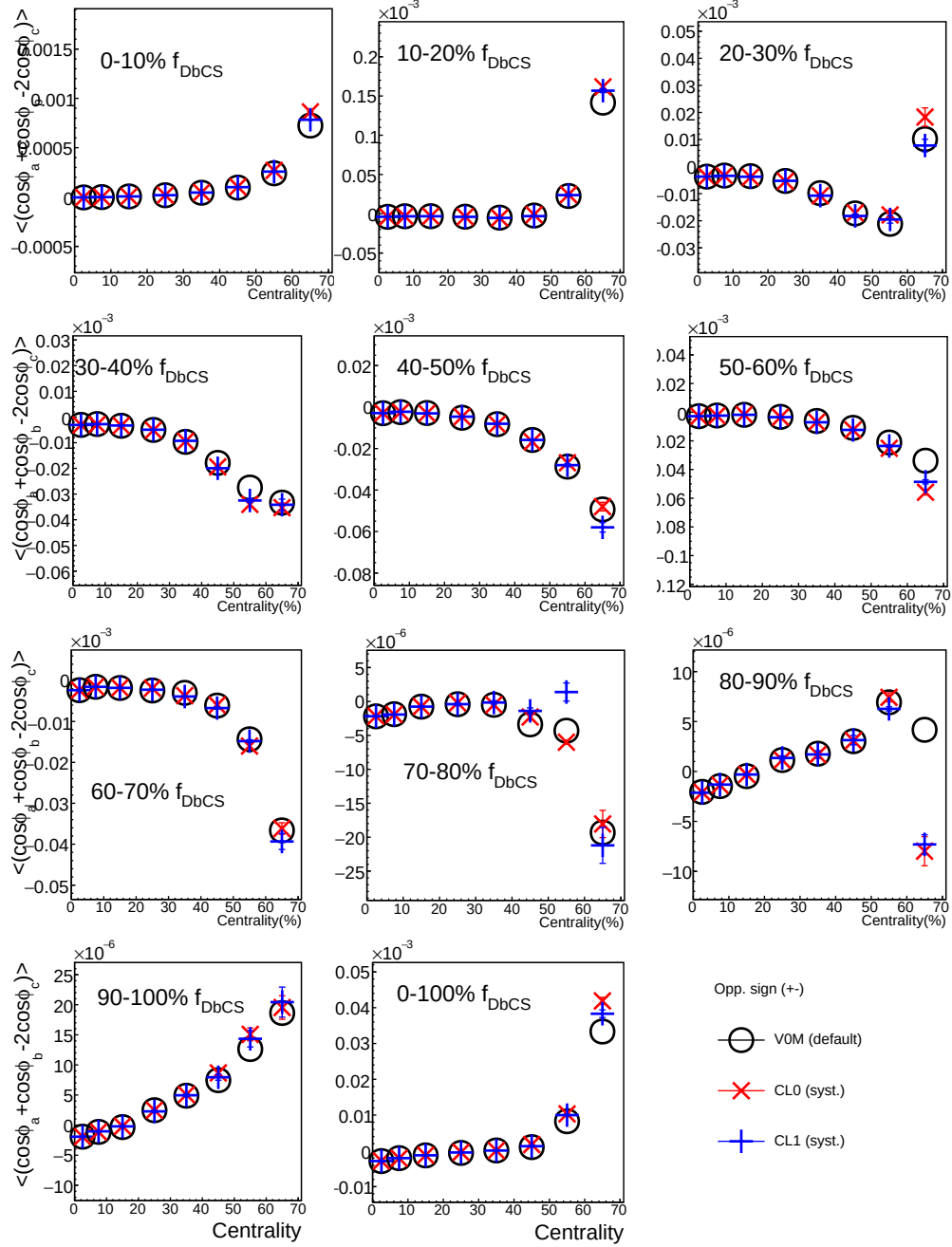


Figure a.5: Centrality dependence of $\langle \cos(\phi_a + \phi_b - 2\phi_c) \rangle$ for opposite sign charge pairs for different centrality definitions for different f_{DbCS} bins as indicated.

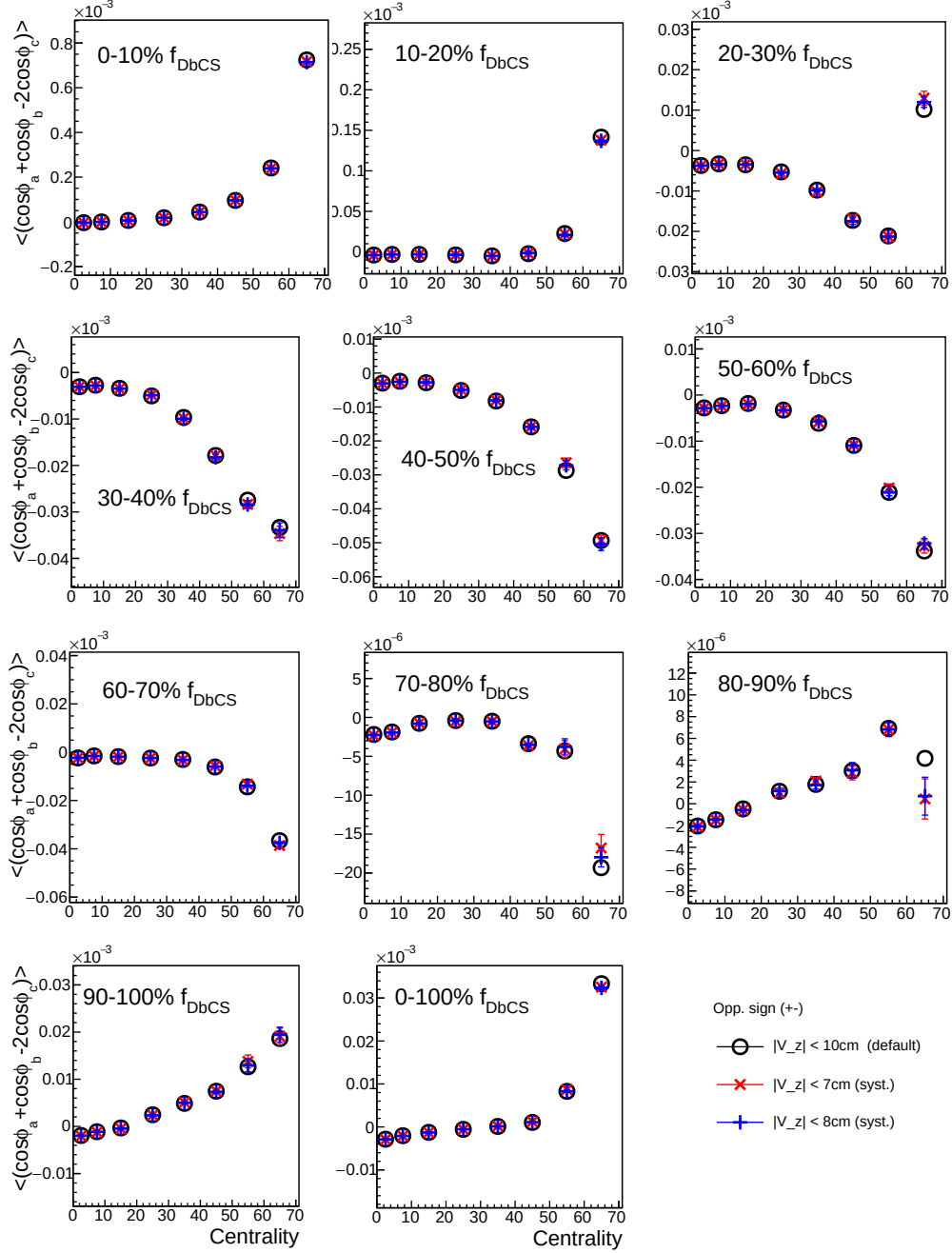


Figure a.6: Centrality dependence of $\langle \cos(\phi_a + \phi_b - 2\phi_c) \rangle$ for opposite sign charge pairs for different vertex cut for different f_{DbCS} bins as indicated.

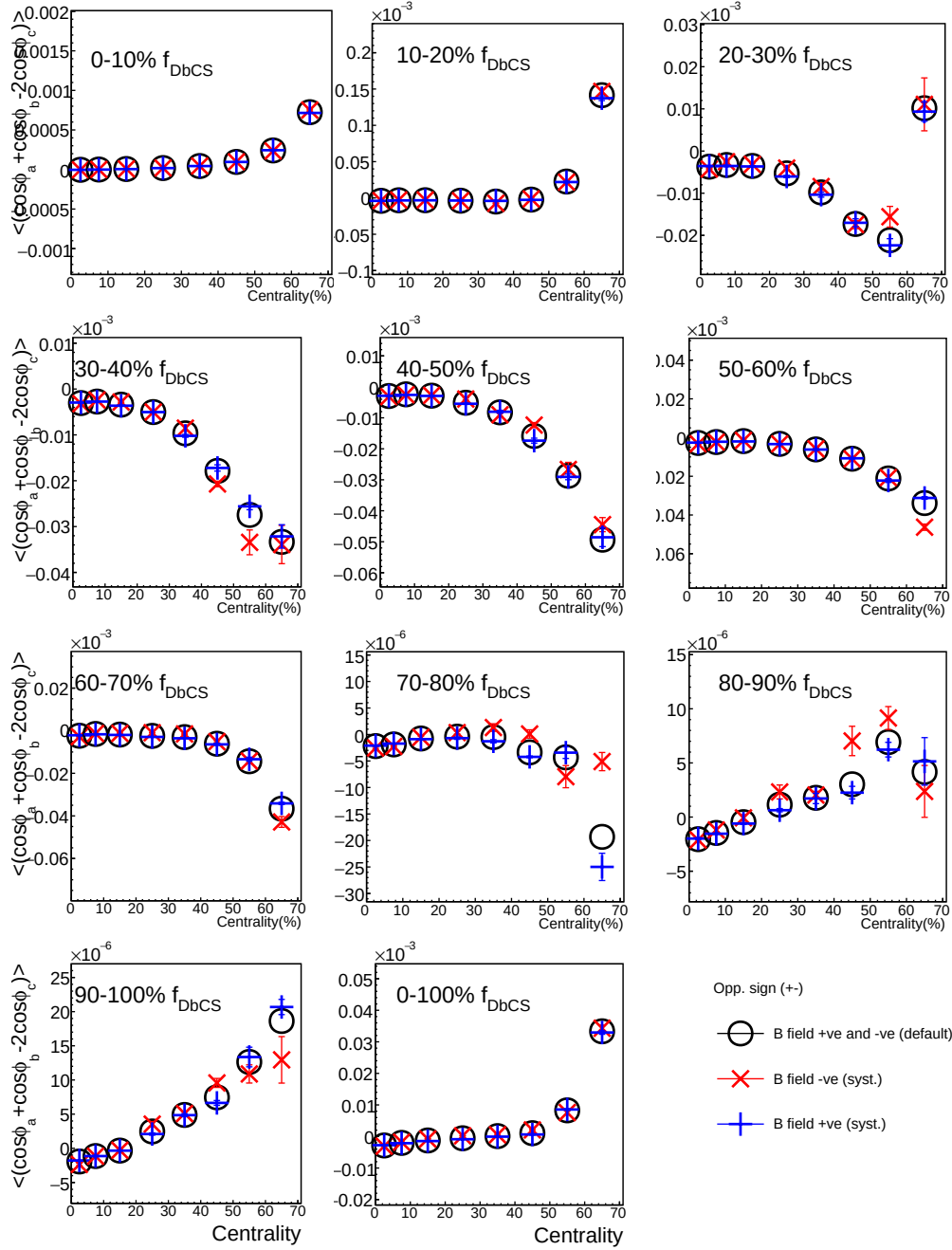


Figure a.7: Centrality dependence of $\langle \cos(\phi_a + \phi_b - 2\phi_c) \rangle$ for opposite sign charge pairs for different magnetic field polarity for different f_{DbCS} bins as indicated.

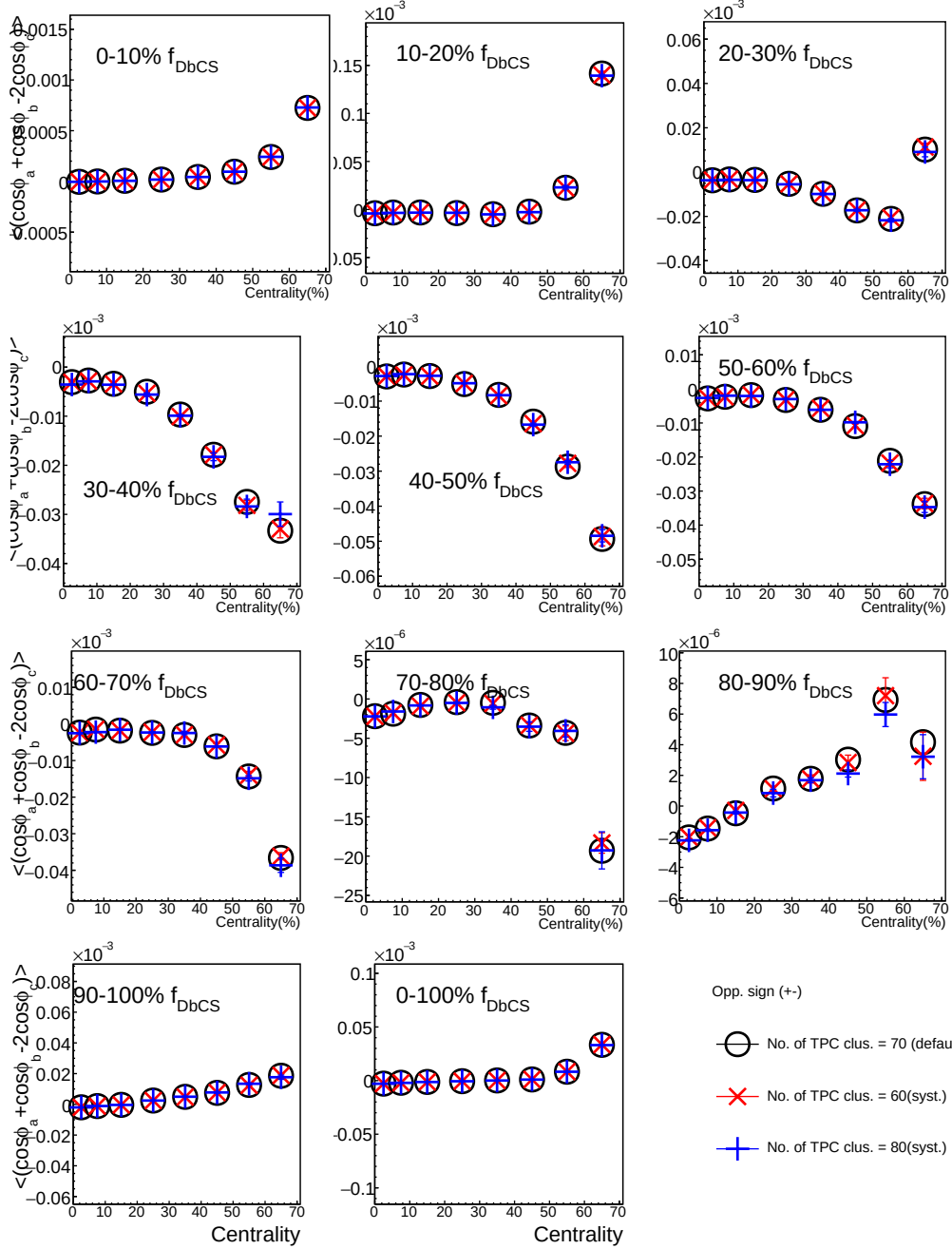


Figure a.8: Centrality dependence of $\langle \cos(\phi_a + \phi_b - 2\phi_c) \rangle$ for opposite sign charge pairs for number of TPC clusters for different f_{DbCS} bins as indicated.

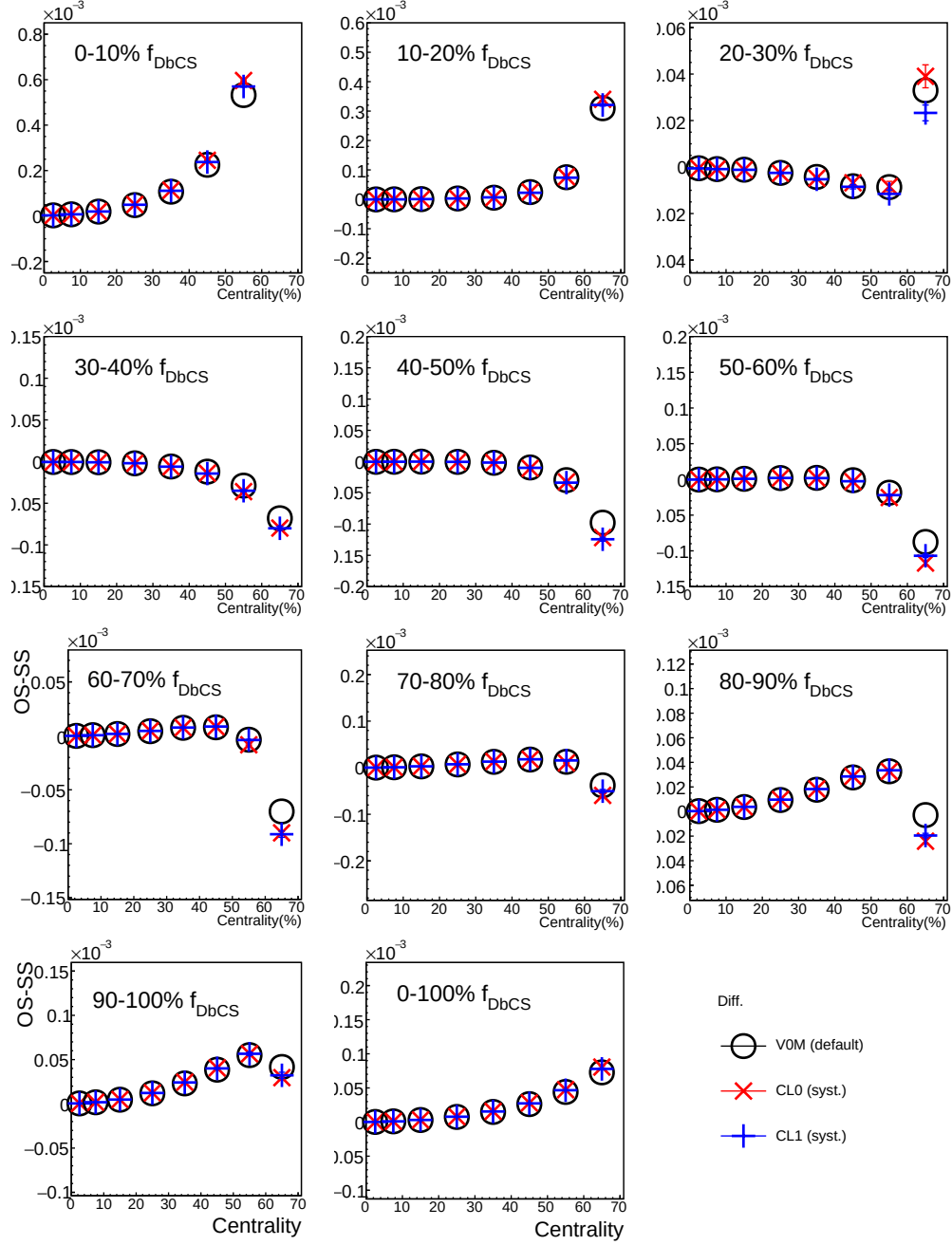


Figure a.9: Centrality dependence of $\langle \cos(\phi_a + \phi_b - 2\phi_c) \rangle$ for difference (OS-SS) for different centrality definitions for different f_{DbCS} bins as indicated.

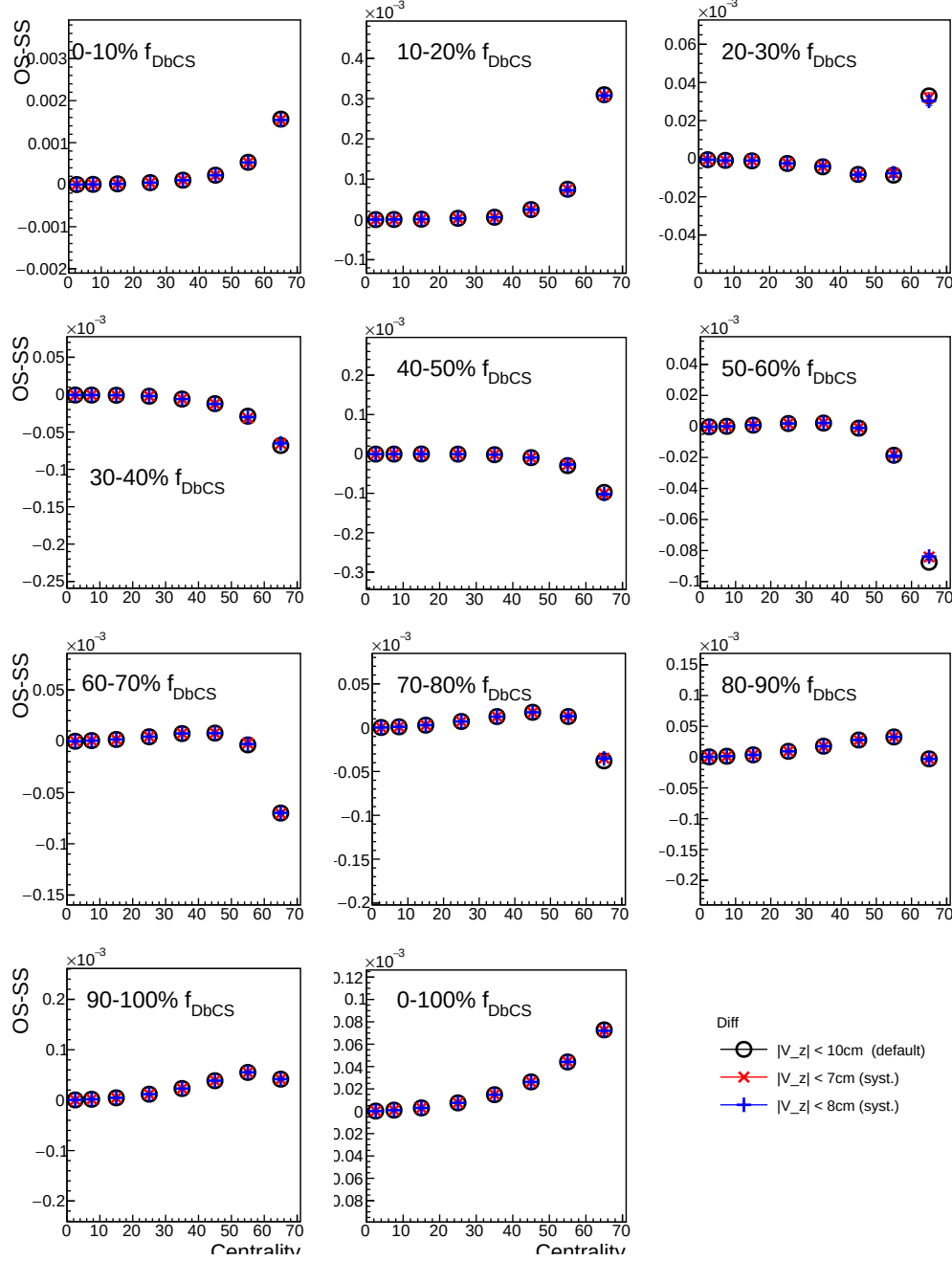


Figure a.10: Centrality dependence of $\langle \cos(\phi_a + \phi_b - 2\phi_c) \rangle$ for difference (OS-SS) for different vertex cut for different $f_{D_{bCS}}$ bins as indicated.

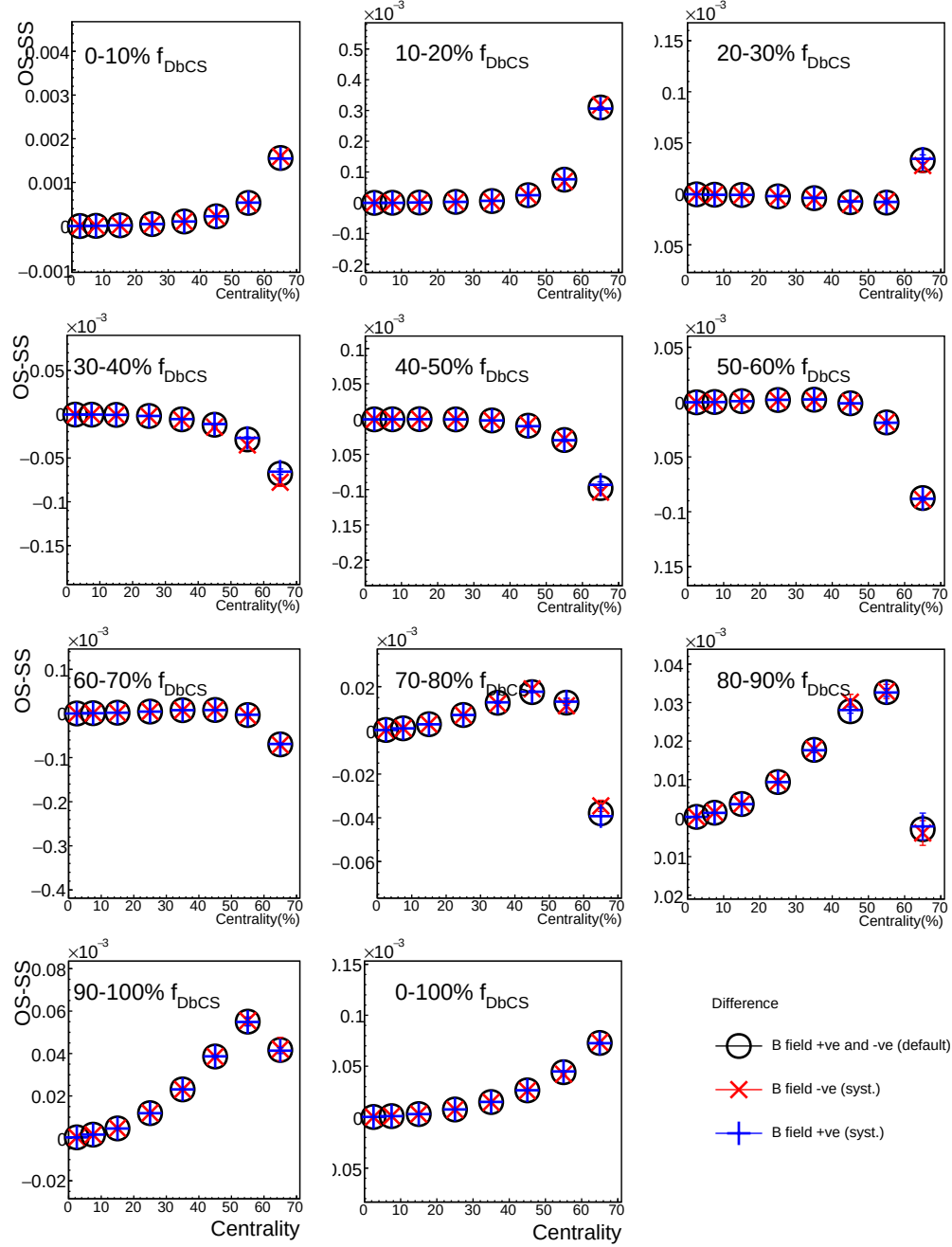


Figure a.11: Centrality dependence of $\langle \cos(\phi_a + \phi_b - 2\phi_c) \rangle$ for difference (OS-SS) for different magnetic field polarity for different f_{DbCS} bins as indicated.

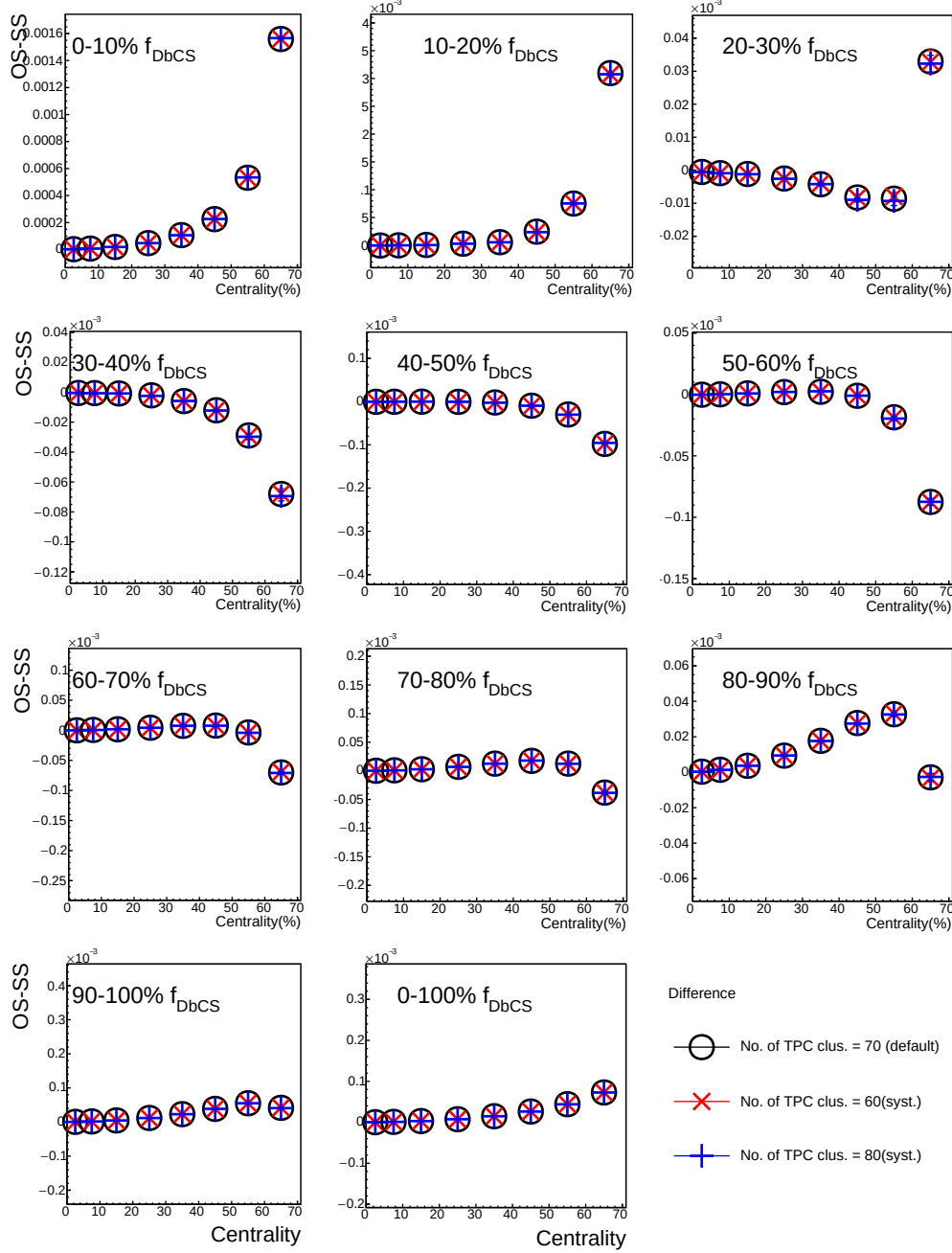


Figure a.12: Centrality dependence of $\langle \cos(\phi_a + \phi_b - 2\phi_c) \rangle$ for difference (OS-SS) for number of TPC clusters for different f_{DbCS} bins as indicated.

PUBLICATIONS/CONFERENCES

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1. Anjali Sharma *et al.* [ALICE], “Event-by-Event study of charge separation effect with ALICE”, **DAE Symposium on Nuclear Physics**, December 23-27, 2019.
2. Anjali Sharma *et al.* [ALICE], “Searching CME using Sliding Dumbbell Method in Pb-Pb collisions at $\sqrt{s_N N} = 2.76\text{TeV}$ using AMPT”, **DAE Symposium on Nuclear Physics**, December 23-27, 2019.
3. Anjali Sharma *et al.*, “Study of Charge Separation Effect in Pb-Pb Collisions Using AMPT”, Springer Proc.Phys. 261 2021.
4. Anjali Sharma *et al.*, “Constraining the Chiral Magnetic Effect in heavy ion collisions using AMPT model”, **DAE International Symposium on Nuclear Physics**, December 10-14, 2018.
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2 Conferences, Schools, Symposiums, Workshops attended

1. 10-15 January, 2021 **The VI-th International Conference on the Initial Stages of High-Energy Nuclear Collisions**, Weizmann Institute of Science, Israel.
2. 14-18 December, 2020 **DAE-BRNS HIGH ENERGY PHYSICS SYMPOSIUM**, NISER Odisha, India.
3. 2-8 November, 2019 **QUARK MATTER 2019**, Wuhan, China.
4. 10-14 December, 2018 **DAE International Symposium on Nuclear Physics**, BARC Mumbai, India.
5. 10-14 December, 2018 **XXIII DAE-BRNS High Energy Physics Symposium**, IIT Madras, India.
6. 07-27 November, 2017 **XI SERC School on Experimental High Energy Physics**, NISER Odisha, India.
7. 7-12 August, 2017 **ALICE-India Training Program**, VECC Kolkata, India.
8. 15-18 March, 2016 **National School cum Workshop in Accelerator Physics**, Department of Physics, Panjab University Chandigarh, India.
9. 15-19 Feb, 2016 **ATHIC 2016: 6th Asian Triangle Heavy-Ion Conference**, Delhi, India.

***Selected
Reprints***

Constraining the Chiral Magnetic Effect with charge-dependent azimuthal correlations in Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ and 5.02 TeV



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ABSTRACT: Systematic studies of charge-dependent two- and three-particle correlations in Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ and 5.02 TeV used to probe the Chiral Magnetic Effect (CME) are presented. These measurements are performed for charged particles in the pseudorapidity (η) and transverse momentum (p_{T}) ranges $|\eta| < 0.8$ and $0.2 < p_{\text{T}} < 5 \text{ GeV}/c$. A significant charge-dependent signal that becomes more pronounced for peripheral collisions is reported for the CME-sensitive correlators $\gamma_{1,1} = \langle \cos(\varphi_{\alpha} + \varphi_{\beta} - 2\Psi_2) \rangle$ and $\gamma_{1,-3} = \langle \cos(\varphi_{\alpha} - 3\varphi_{\beta} + 2\Psi_2) \rangle$. The results are used to estimate the contribution of background effects, associated with local charge conservation coupled to anisotropic flow modulations, to measurements of the CME. A blast-wave parametrisation that incorporates local charge conservation tuned to reproduce the centrality dependent background effects is not able to fully describe the measured $\gamma_{1,1}$. Finally, the charge and centrality dependence of mixed-harmonics three-particle correlations, of the form $\gamma_{1,2} = \langle \cos(\varphi_{\alpha} + 2\varphi_{\beta} - 3\Psi_3) \rangle$, which are insensitive to the CME signal, verify again that background contributions dominate the measurement of $\gamma_{1,1}$.

KEYWORDS: Hadron-Hadron scattering (experiments)

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1 Introduction

Heavy-ion collisions at ultra-relativistic energies are used to study the phase transition from a deconfined Quark-Gluon Plasma (QGP) state [1–3] to ordinary nuclear matter. The transition is expected to occur at high values of temperature and energy density, which is also supported by quantum chromodynamics (QCD) calculations on the lattice [4, 5]. The main aim of the heavy-ion program at the Large Hadron Collider (LHC) is to study the QGP properties, such as the equation of state, the speed of sound in the medium and the value of the ratio of shear viscosity to entropy density (η/s).

It was soon realised that heavy-ion collisions also allow for studies of novel QCD phenomena associated with parity (P) violation effects in strong interactions [6, 7]. These effects are catalysed by the presence of a strong magnetic field that develops in the early stages of heavy-ion collisions. This field is created by the motion of the charged nucleons of the incoming ions in a non-central collision, i.e. a collision with a large impact parameter, defined as the distance between the centers of the two colliding nuclei in the transverse plane. The magnitude of this field can reach values of 10^{18} Gauss [8], making it the strongest magnetic field created by any experiment on earth. The direction of the magnetic field is along the system’s angular momentum and perpendicular to the reaction plane. The latter is the plane defined by the impact parameter vector and the beam direction.

The potential to observe parity violation in the strong interaction using ultra-relativistic heavy-ion collisions has first been discussed in refs. [9–11] and was further reviewed in refs. [12, 13]. In QCD, this symmetry violation originates from the possibility that the QGP can carry net chirality [14–16], characterised by a non-zero value of the axial chemical potential μ_5 , i.e. reflecting the imbalance between left- and right-handed fermions in the system. Depending on the sign of μ_5 the QGP will have an excess of either left- ($\mu_5 < 0$) or right-handed ($\mu_5 > 0$) (anti-)quarks. In the presence of the strong magnetic field, the spins of (anti-)quarks tend to align along the direction of the field, creating a spin polarisation effect. This in turn leads to the development of a vector current along the direction of the magnetic field and the creation of an electric dipole moment of QCD matter. The experimental search for these effects has intensified lately, following the realisation that the subsequent creation of charged hadrons results in an experimentally accessible charge separation along the direction of this magnetic field, and perpendicular to the reaction plane. This phenomenon is called the Chiral Magnetic Effect (CME) and its existence was recently reported in semimetals like zirconium pentatelluride (ZrTe_5) [17].

The resulting charge separation can be identified by studying the P-odd sine terms in the Fourier decomposition of the particle azimuthal distribution [18] according to

$$\frac{dN}{d\varphi_\alpha} \sim 1 + 2 \sum_n [v_{n,\alpha} \cos(n\Delta\varphi_\alpha) + a_{n,\alpha} \sin(n\Delta\varphi_\alpha)], \quad (1.1)$$

where $\Delta\varphi_\alpha = \varphi_\alpha - \Psi_{\text{RP}}$ is the azimuthal angle φ_α of the particle of type α (either positively or negatively charged particles) relative to the reaction plane angle Ψ_{RP} . The coefficient $v_{n,\alpha}$ is the n -th order Fourier harmonic, averaged over all events, and characterises the anisotropies in momentum space. The reaction plane is not an experimental observable but can be approximated by the second-order symmetry plane, Ψ_2 , determined by the direction of the beam and the axis of the maximal particle density in the elliptic azimuthal anisotropy. This symmetry plane and more generally the plane angles of different order Ψ_n , estimated in each event, are introduced to account for the event-by-event fluctuations in the initial energy density of a heavy-ion collision [19–23]. In case of a smooth distribution of matter produced in the overlap zone, the angle Ψ_2 coincides with that of the reaction plane, i.e. $\Psi_2 = \Psi_{\text{RP}}$. The leading order P-odd coefficient $a_{1,\alpha}$ reflects the magnitude of the effects from local parity violation, while higher orders ($a_{n,\alpha}$ for $n > 1$) describe the specific shape in azimuth. However, the chiral imbalance that leads to the creation of the CME changes from event to event and the event average $\langle a_{1,\alpha} \rangle$ will be consistent with zero. Consequently, the effect can be detected only by correlation studies.

In ref. [24], it was suggested that a suitable way to probe the CME is via a two-particle correlation technique relative to the second-order symmetry plane of the form $\langle \cos(\varphi_\alpha + \varphi_\beta - 2\Psi_2) \rangle$, where the brackets indicate an average over all events. Here, α and β denote particles with the same or opposite electric charge. The advantage of using this expression is that it probes correlations between two leading order P-odd coefficients $a_{1,\alpha}$ and $a_{1,\beta}$ which do not trivially average to 0 over all events (see section 3 for the discussion). In addition, the observable is constructed as the difference between correlations in- and out-of plane which is expected to significantly suppress parity-conserving background effects. In

order to independently evaluate the contributions from correlations in- and out-of plane one measures at the same time a two-particle correlator of the form $\langle \cos(\varphi_\alpha - \varphi_\beta) \rangle$. Section 3 contains a detailed discussion about all these correlators.

Experimental results for charged particles in both Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV at the LHC [25] and in Au-Au collisions up to $\sqrt{s_{\text{NN}}} = 0.2$ TeV at the Relativistic Heavy-Ion Collider (RHIC) [26–30] are consistent with the expectation for a charge separation relative to the reaction plane due to the existence of parity violating effects. However, these measurements could be dominated by background effects whose sources have not been fully quantified yet. One of the first attempts to provide a quantitative estimate of the background in the measurement of the CME sensitive correlator (i.e. $\langle \cos(\varphi_\alpha + \varphi_\beta - 2\Psi_2) \rangle$) identified the sources as originating from local charge conservation coupled to the elliptic flow modulation quantified by v_2 [31, 32]. Therefore, the challenge is to define a way to constrain and quantify the background, while in parallel isolating the signal that comes from the CME.

A first step in this direction was taken by the ALICE Collaboration [33] using a method proposed and developed in ref. [34]. This method, called Event Shape Engineering (ESE), utilises the fluctuations of the initial geometry and selects events with different initial system shapes, e.g. central Pb-Pb collisions with large initial anisotropy. This study set an upper limit of 26–33% at 95% confidence level for the CME signal contribution to the $\langle \cos(\varphi_\alpha + \varphi_\beta - 2\Psi_2) \rangle$ correlator in the 10–50% centrality interval. The CMS [35] and the STAR [36] collaborations studied charge-dependent correlations in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV and in p-Au and d-Au collisions at $\sqrt{s_{\text{NN}}} = 0.2$ TeV, respectively. In these colliding systems, one expects the CME contribution to any charge-dependent signal to be small and the results can thus be used to gauge the magnitude of the background in heavy-ion collisions. Both results illustrate that these correlations are similar to those measured in heavy-ion collisions. First results using ESE have been reported by the CMS Collaboration in ref. [37], which set upper limits on the CME fraction of the three-particle correlator to be 13% and 7% (at 95% confidence level) for p-Pb and Pb-Pb collisions.

In this article we report results on two-particle correlations of different orders as well as various two-particle correlations relative to the second, third and fourth-order symmetry planes for charged particles in Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ and 5.02 TeV. The motivation for utilising different planes is that the charge separation originating from the CME is expected to be present along the direction of the magnetic field and thus perpendicular to the reaction plane, approximated by Ψ_2 . Since the third order symmetry plane Ψ_3 is very weakly correlated with Ψ_2 [38] the charge separation effect relative to the third harmonic symmetry plane is expected to be negligible. First results on correlations relative to Ψ_3 reported by the CMS collaboration in ref. [37] indicates that the charge separation could be originating from the coupling of two-particle correlations with the anisotropic flow. In addition, contributions from correlations induced by the CME should be strongly suppressed in the measurements of two-particle correlations relative to Ψ_4 , while the background effects stemming from local charge conservation should scale with v_4 [39]. Therefore, measurements of correlations relative to higher order symmetry planes are expected to reflect mainly, if not solely, background effects.

The article is organised as follows: section 2 describes briefly the experimental setup, while section 3 discusses the data sample, the selection criteria as well as the correlators reported; these sections are followed by section 4 and section 5 where the estimation of the systematic uncertainties of all measurements and the main physics results, respectively, are presented. We conclude in section 6 with a summary.

2 Experimental setup

By convention in ALICE, the beam direction defines the z -axis, the x -axis is horizontal and points towards the centre of the LHC, and the y -axis is vertical and points upwards. The apparatus consists of a set of detectors located in the central barrel, positioned inside a solenoidal magnet which can generate a field parallel to the beam direction with maximum magnitude of 0.5 T. A set of forward detectors completes the experimental setup.

The main tracking devices of ALICE are the Inner Tracking System (ITS) [40] and the Time Projection Chamber (TPC) [41]. The ITS consists of six cylindrical layers of silicon detectors employing three different technologies. The two innermost layers, positioned at $r = 3.9$ cm and 7.6 cm, are Silicon Pixel Detectors (SPD), followed by two layers of Silicon Drift Detectors (SDD) ($r = 15$ cm and 23.9 cm). Finally, the two outermost layers are double-sided Silicon Strip Detectors (SSD) at $r = 38$ cm and 43 cm. The TPC surrounds the ITS and provides full azimuthal coverage. The combined pseudorapidity (η) coverage of the ITS and the TPC is $-0.9 < \eta < 0.9$.

A set of forward detectors, the V0 scintillator arrays [42], were used in the trigger logic and for the determination of the collision centrality, discussed in the next section. The V0 consists of two sub-systems, the V0A and the V0C, that are positioned on either side of the interaction point and cover the pseudorapidity ranges of $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$, respectively. Finally the Zero Degree Calorimeters (ZDC) [40] positioned at both positive and negative rapidity at around 114 m away from the interaction point were also used offline to reduce the contamination from beam-induced background.

A detailed description of ALICE and its sub-detectors can be found in ref. [40] and their performance in ref. [43].

3 Analysis details

3.1 Event and track selection

The analysis is performed using the Pb-Pb data samples collected in 2010 and 2015 at a centre-of-mass energy per nucleon pair of $\sqrt{s_{\text{NN}}} = 2.76$ and 5.02 TeV, respectively. The minimum bias trigger condition is defined in the 2010 data sample by combinations of hits in the SPD and either V0A or V0C detectors, while in 2015 the trigger required a signal in both V0A and V0C detectors.

An offline event selection relying on the timing information from the V0 and the neutron ZDC is used to reject beam-gas background and parasitic beam-beam interactions. Events are analysed if the z -coordinate of the reconstructed primary vertex (V_z) resides within ± 10 cm from the nominal interaction point. The collision centrality is estimated from the amplitude of the signal measured by the V0 detectors as explained in

ref. [44]. Higher amplitude, and hence higher particle multiplicity, corresponds to more central (smaller impact parameter) events. The data sample is divided into centrality classes which span 0–70% of the inelastic hadronic cross section, which is considered in this study. The 0–5% and 60–70% intervals correspond to the most central and the most peripheral collisions, respectively.

Charged particles reconstructed using the TPC and the ITS information are accepted for analysis within η and p_T ranges of $|\eta| < 0.8$ and $0.2 < p_T < 5 \text{ GeV}/c$, respectively. The tracking algorithm, based on the Kalman filter [45, 46], starts from a collection of space points (referred to as clusters) inside the TPC, and provides the quality of the fit by calculating its χ^2 value. The track parameters at the primary vertex are then updated using the combined information from both the TPC and the ITS detectors. Tracks are accepted even if the algorithm is unable to match the track reconstructed in the TPC with associated SPD clusters (e.g. due to inefficiencies caused by dead channels in the SPD layers). In this case, a cluster from another layer of the ITS (e.g. SDD) is used to reconstruct the tracks. This tracking mode will be referred to as hybrid tracking in the rest of the text and is used as the default in this analysis since it provides a uniform distribution in azimuthal angle (φ). More details about the tracking parameters and performance are described elsewhere [40, 43]. Accepted tracks are required to have at least 70 out of 159 possible space points measured in the TPC and a χ^2 per degree of freedom of the momentum fit per TPC cluster to be below 2. These selections reduce the contribution from short tracks, which are unlikely to originate from the primary vertex. To further reduce the contamination by secondary tracks from weak decays or from the interaction with the material, only tracks within a maximum distance of closest approach (DCA) to primary vertex in both the transverse plane ($\text{DCA}_{xy} < 2.4 \text{ cm}$) and the longitudinal direction ($\text{DCA}_z < 3.2 \text{ cm}$) were considered. Moreover, if matched to ITS clusters, the tracks are required to have at least one cluster in either of the two SPD layers. These selections lead to an efficiency of about 65% for primary tracks at $p_T = 0.5 \text{ GeV}/c$, which reaches 80% above $1 \text{ GeV}/c$. The variation of these values between central and peripheral collisions is less than 3%, and does not change between $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV . The contamination from secondaries is about 10% at $p_T = 0.2 \text{ GeV}/c$, reaches 5% at $p_T = 1 \text{ GeV}/c$ and decreases further with increasing transverse momentum.

3.2 Analysis methodology

A way to probe the P-odd leading order coefficient $a_{1,\alpha}$ that reflects the magnitude of the CME is through the study of charge-dependent two-particle correlations relative to the reaction plane Ψ_{RP} . The expression proposed in ref. [24] is of the form $\langle \cos(\varphi_\alpha + \varphi_\beta - 2\Psi_{RP}) \rangle$ (α and β being particles with the same or opposite charges) that can probe correlations between the leading P-odd terms for different charge combinations $\langle a_{1,\alpha} a_{1,\beta} \rangle$. This can be seen if one decomposes the correlator using eq. (1.1)

$$\begin{aligned}
 \langle \cos(\varphi_\alpha + \varphi_\beta - 2\Psi_{RP}) \rangle &= \langle \cos[(\varphi_\alpha - \Psi_{RP}) + (\varphi_\beta - \Psi_{RP})] \rangle \\
 &= \langle \cos(\Delta\varphi_\alpha + \Delta\varphi_\beta) \rangle \\
 &= \langle \cos \Delta\varphi_\alpha \cos \Delta\varphi_\beta \rangle - \langle \sin \Delta\varphi_\alpha \sin \Delta\varphi_\beta \rangle \\
 &= \langle v_{1,\alpha} v_{1,\beta} \rangle + B_{\text{in}} - \langle a_{1,\alpha} a_{1,\beta} \rangle - B_{\text{out}}, \tag{3.1}
 \end{aligned}$$

where B_{in} and B_{out} represent the parity-conserving correlations projected onto the in- and out-of-plane directions. The terms $\langle \cos \Delta\varphi_\alpha \cos \Delta\varphi_\beta \rangle$ and $\langle \sin \Delta\varphi_\alpha \sin \Delta\varphi_\beta \rangle$ in eq. (3.1) quantify the correlations with respect to the in- and out-of-plane directions, respectively. The term $\langle v_{1,\alpha} v_{1,\beta} \rangle$, i.e. the product of the first order Fourier harmonics or directed flow, is expected to have negligible charge dependence in the midrapidity region [47]. In addition, for a symmetric collision system the average directed flow at midrapidity is zero. A generalised form of eq. (3.1) also describing higher harmonics is given by the mixed-harmonics correlations, which reads

$$\gamma_{m,n} = \langle \cos(m\varphi_\alpha + n\varphi_\beta - (m+n)\Psi_{|m+n|}) \rangle, \quad (3.2)$$

where m and n are integers. Setting $m = 1$ and $n = 1$ (i.e. $\gamma_{1,1}$) leads to eq. (3.1). The $|m+n|$ -th order symmetry plane angle $\Psi_{|m+n|}$ is introduced to take into account that the overlap region of the colliding nuclei exhibits an irregular shape [19–23]. This originates from the initial density profile of nucleons participating in the collision, which is not isotropic and differs from one event to the other. In case of a smooth distribution of matter produced in the overlap zone, the angle $\Psi_{|m+n|}$ coincides with that of the reaction plane, i.e. $\Psi_{|m+n|} = \Psi_{\text{RP}}$.

In order to independently evaluate the contributions from correlations in- and out-of-plane, one can also measure a two-particle correlator of the form

$$\begin{aligned} \langle \cos(\varphi_\alpha - \varphi_\beta) \rangle &= \langle \cos[(\varphi_\alpha - \Psi_{\text{RP}}) - (\varphi_\beta - \Psi_{\text{RP}})] \rangle \\ &= \langle \cos(\Delta\varphi_\alpha - \Delta\varphi_\beta) \rangle \\ &= \langle \cos \Delta\varphi_\alpha \cos \Delta\varphi_\beta \rangle + \langle \sin \Delta\varphi_\alpha \sin \Delta\varphi_\beta \rangle \\ &= \langle v_{1,\alpha} v_{1,\beta} \rangle + B_{\text{in}} + \langle a_{1,\alpha} a_{1,\beta} \rangle + B_{\text{out}}, \end{aligned} \quad (3.3)$$

which corresponds to the special case of $m = -n$ in eq. (3.2). This provides access to the two-particle correlations without any dependence on the symmetry plane angle

$$\delta_m = \langle \cos[m(\varphi_\alpha - \varphi_\beta)] \rangle. \quad (3.4)$$

This correlator, owing to its construction, is affected if not dominated by non-flow contributions. Charge-dependent results for δ_1 , together with the relevant measurements of $\gamma_{1,1}$ were first reported in ref. [25] and made it possible to separately quantify the magnitude of correlations in- and out-of-plane.

In this article, we report on the charge-dependent results of four correlators of the form of eq. (3.2). The first two, $\gamma_{1,1}$ and $\gamma_{1,-3}$, probe correlations of particles relative to the second order symmetry plane (Ψ_2). The correlator $\gamma_{1,1}$ (i.e. the main correlator used in previous studies) probes correlations of the first order P-odd term, i.e. $\langle a_{1,\alpha} a_{1,\beta} \rangle$ as illustrated in eq. (3.1), while the second is sensitive not only to the first but also the third order coefficient, i.e. $\langle a_{1,\alpha} a_{3,\beta} \rangle$ and thus is sensitive to the magnitude and the shape of the CME contribution. However, in both cases the background contributions from local charge conservation are expected to be significant (see refs. [31, 32] and the references therein).

In order to evaluate the background, correlations relative to the third and fourth order symmetry planes i.e., $\gamma_{1,2}$ and $\gamma_{2,2}$, are investigated. Since the charge-separation effects

originating from the CME form relative to the second order symmetry plane, both correlators are expected to have negligible contribution from it. Their charge-dependent part could thus be used as a proxy for the background that consists of local charge conservation scaled by the corresponding flow harmonics according to ref. [48]

$$\gamma_{1,1} \approx \langle \cos[(\varphi_\alpha - \varphi_\beta) + 2(\varphi_\beta - \Psi_2)] \rangle \propto \delta_1 v_2, \quad (3.5a)$$

$$\gamma_{1,2} \approx \langle \cos[(\varphi_\alpha - \varphi_\beta) + 3(\varphi_\beta - \Psi_3)] \rangle \propto \delta_1 v_3, \quad (3.5b)$$

$$\gamma_{2,2} \approx \langle \cos[2(\varphi_\alpha - \varphi_\beta) + 4(\varphi_\beta - \Psi_4)] \rangle \propto \delta_2 v_4. \quad (3.5c)$$

By taking the difference of results between opposite- and same-sign charge combinations, denoted as $\Delta\gamma_{mn}$ in the most general form of the correlator, one can eliminate the charge-independent part and probe the contribution from local charge conservation modulated by the relevant flow harmonic

$$\Delta\gamma_{1,1} \approx \kappa_2 v_2 \Delta\delta_1, \quad (3.6a)$$

$$\Delta\gamma_{1,2} \approx \kappa_3 v_3 \Delta\delta_1, \quad (3.6b)$$

$$\Delta\gamma_{2,2} \approx \kappa_4 v_4 \Delta\delta_2, \quad (3.6c)$$

where κ_n is a proportionality constant. Using eqs. (3.6), one can thus estimate the contribution of the background in the charge-dependent CME sensitive correlator $\Delta\gamma_{1,1}$ using the results of e.g. $\Delta\gamma_{1,2}$ according to

$$\Delta\gamma_{1,1}^{\text{Bkg}} \approx \Delta\gamma_{1,2} \times \frac{v_2 \kappa_2}{v_3 \kappa_3}. \quad (3.7)$$

Equation (3.7) serves as a tool to disentangle the CME contribution from the background, provided the parameter κ_2/κ_3 is estimated. In ref. [35] it was argued that the magnitude of these κ_n terms depends on the kinematic ranges (e.g. detector acceptance, event and particle selection criteria). Although κ_n may have dependency on p_T and η , we have ignored such dependency and assumed a constant magnitude of the ratio κ_2/κ_3 for the full kinematic range. In ref. [35], it was suggested that one can assume that $\kappa_2 \approx \kappa_3$ if the same kinematic conditions are used to calculate $\Delta\gamma_{m,n}$ within the same experimental setup. In this article, we also investigate the relationship between κ_2 and κ_3 using two approaches: a blast wave [49] inspired model that incorporates effects of local charge conservation and the results of A Multi Phase Transport model (AMPT) [50–52], both discussed in detail in the Results section.

3.2.1 The event-plane method

To evaluate the correlations experimentally, the event-plane method [53, 54] is used. In this method, the event plane angle is reconstructed from the azimuthal distribution of the particles produced in a collision. The event plane angle of k -th order (where $k = |m - n|$) $\Psi_{k,EP}$ is estimated according to

$$\Psi_{k,EP} = \tan^{-1} \frac{Q_{k,y}}{Q_{k,x}}, \quad (3.8)$$

where $Q_{k,x}$ and $Q_{k,y}$ are the x- and y-components of the Q-vector, calculated as

$$Q_{k,x} = \sum_{i=1}^M w_i(p_T, \eta, \varphi, V_z) \cos(k\varphi_i), \text{ and } Q_{k,y} = \sum_{i=1}^M w_i(p_T, \eta, \varphi, V_z) \sin(k\varphi_i). \quad (3.9)$$

In eq. (3.9), φ_i corresponds to the azimuthal angle of the i -th track in an event with multiplicity M . The factors $w_i(p_T, \eta, \varphi, V_z)$ are weights applied on every track in the construction of the Q-vectors, in order to correct for non-uniform reconstruction efficiency and acceptance. They are calculated as a function of the transverse momentum, pseudorapidity and azimuthal angle of particles for different V_z values of the primary vertex.

To reduce the contributions from short range effects not related to the common symmetry planes (i.e. non-flow), a subevent plane technique [53, 54] is implemented. Each event is divided into two subevents “A” and “B”, covering the ranges $-0.8 < \eta < 0$ and $0 < \eta < 0.8$, respectively, and the two subevent plane angles, namely $\Psi_{k,A}$ and $\Psi_{k,B}$ are calculated using charged particles. The correlators of eq. (3.2) are then calculated as

$$\gamma_{mn} = \frac{\langle \cos[m\varphi_\alpha + n\varphi_\beta - (m+n)\Psi_{|m+n|,EP}] \rangle}{R(\Psi_{|m+n|,EP})}, \quad (3.10)$$

where α and β correspond to any two charged particles within $-0.8 < \eta < 0.8$, and $\Psi_{|m+n|,EP}$ corresponds to subevent plane $\Psi_{k,A}$ (or $\Psi_{k,B}$ for systematic studies). Particles α or β (or both) were excluded from the determination of event plane if they were from the same η window as the one used to calculate $\Psi_{k,A}$ or $\Psi_{k,B}$.

The event plane resolution $R(\Psi_{|m+n|,EP})$ is given by

$$R(\Psi_{|m+n|,EP}) = \sqrt{\cos[|m+n|(\Psi_{|m+n|,A} - \Psi_{|m+n|,B})]}. \quad (3.11)$$

The amount of non-flow correlations in the results of both same- (SS) and opposite-sign (OS) charge combinations could also depend on the longitudinal position of the detector used for the estimation of Ψ_k . However, it was checked that the charge-dependent differences, i.e. OS-SS are not affected by this choice as these non-flow contributions (approximately) cancel out in the subtraction.

4 Systematic uncertainties

The systematic uncertainties in all measurements presented in this article were estimated by varying the event and track selection criteria as well as by studying the detector effects with Monte Carlo (MC) simulations. The contributions from different sources, described below, were extracted from the difference for the results of each correlator obtained with the primary selection criteria and the ones after the relevant variation was applied. All sources with a difference between the results larger than 1σ were then added in quadrature to form the final value of the systematic uncertainty (for each data point), where σ is the uncertainty of the difference between the default results and the ones obtained from the variation of the selection criteria, taking into account the degree of their correlation [55].

(No.) Source	Default Value	Variations
(1) Primary V_z	± 10 cm	± 8 cm
(2) Centrality Estimator	V0 amplitude	SPD cluster
(3) Magnetic field polarity	Combined	Positive, Negative
(4) Event plane	$\Psi_{k,-0.8 < \eta < 0}$	$\Psi_{k,0 < \eta < 0.8}$
(5) Residual Pile-Up	High Intensity data	Low Intensity data
(6) TPC space points	70	100
(7) DCA_{xy} (DCA_z)	2.4 (3.2) cm	2.0 (2.0) cm
(8) Tracking Algorithm	Hybrid	Global
(9) Charge Combination	“++” and “--” combined	“++” or “--”

Table 1. List of the selection criteria and the corresponding variations used for the estimation of the systematic uncertainties.

Table 1 summarises the sources and the variations that were tested. In particular, the systematic uncertainty originating from the selection of the z position of the primary vertex was investigated by changing this selection from ± 10 cm down to ± 8 cm. In order to estimate the contribution to the results from the choice of the detector used as centrality estimator, the analysis was performed using the number of hits in the second layer of the SPD instead of the amplitude of the V0 detector. Furthermore, data samples recorded with different magnetic field configurations for the solenoid magnet were analysed separately. The contribution of residual pile-up events to the results was estimated by analysing independently the high and low interaction rate samples. Finally, the results were obtained separately by calculating the event plane from different pseudorapidity ranges within the TPC acceptance. The systematic uncertainty in the extraction of the CME fraction when using different event plane angles within the TPC acceptance for the highest LHC energy was estimated considering runs with low beam intensity where the distortions in the TPC are negligible.

In parallel, to investigate any potential bias originating from the quality of the tracks used in the analysis, the number of space points measured in the TPC was varied from 70 (default) up to 100 out of 159 maximum points that a track can have. The contribution stemming from secondary tracks, either from weak decays or from the interaction of particles with the detector material, was investigated by tightening the selection on the DCA in the longitudinal direction as well as in the transverse plane. Finally, another tracking mode that relies on the combination of the TPC and the ITS detectors, henceforth called global tracking, with tighter selection criteria in addition to requirements for clusters in the SPD or the SDD detectors was used. In this case, a stricter transverse momentum dependent requirement in the value of the DCA in the transverse plane resulted in reducing even further the amount of secondary particles in the track sample. The resulting contamination from secondaries is less than 2–3% for the entire p_T range.

For each variation, new correction maps for detector inefficiencies and non-uniform acceptance were extracted using MC data samples and collision data.

Sources	$\gamma_{1,1} (\times 10^{-5})$			$\gamma_{1,2} (\times 10^{-5})$			$\gamma_{1,-3} (\times 10^{-5})$			$\gamma_{2,2} (\times 10^{-5})$		
	SS	OS	OS-SS	SS	OS	OS-SS	SS	OS	OS-SS	SS	OS	OS-SS
(1)	0.26	1.4	0.027	1.1	0.12	1.9	0.13	0.15	0.095	0.035	0.1	0.02
(2)	2.5	6.1	6	4.5	9.9	1.8	4.2	3.2	1.2	8.6	8.6	0.27
(3)	0.86	0.65	0.1	0.83	0.84	0.024	0.34	0.54	0.04	1.4	0.98	0.36
(4)	1.62	1.81	1.6	1.7	1.83	4.51	0.86	0.64	0.15	1.78	2.1	6.8
(5)	4.0	3.9	0.58	7.2	3.9	3.6	0.73	0.83	0.2	4.4	4.0	11
(6)	0.1	0.89	0.065	1.1	1.4	1.3	0.21	0.22	0.032	4.1	3.9	0.12
(7)	0.011	0.032	0.001	0.05	0.06	2.1	0.008	0.024	0.025	0.017	0.28	0.03
(8)	0.045	0.049	0.16	0.67	1.3	0.08	0.07	0.06	0.17	5.7	0.17	0.1
(9)	0.55	—	0.55	0.26	—	0.26	0.23	—	0.23	21	—	21

Table 2. Maximum systematic uncertainty (absolute value) over all centrality intervals on γ_{mn} from individual sources (see table 1 for an explanation of each source). The ranges are similar for both energies.

Tables 2 and 3 summarise the maximum magnitude, over all centrality intervals, of the systematic uncertainties from each individual source for all correlators presented in this article. The uncertainties are reported separately for the results for same-sign (SS), opposite-sign (OS) and the difference between opposite- and same-sign (OS-SS) pairs. The uncertainties for the results of the various $\gamma_{m,n}$ are reported without the common factor of $\times 10^{-5}$.

Throughout the centrality intervals reported in this article, the magnitude of $\gamma_{1,1}$ correlator varies between -2.4 to -40 for SS pair, -1.2 to 29 for OS pair and 1.2 to 68 for OS-SS. The values of $\gamma_{1,-3}$ vary between -2.1 to 38 for SS pair, -0.67 to 68 for OS pair and 1.4 to 30 for OS-SS. The magnitude of $\gamma_{1,2}$ covers the range between -2.5 to 140 for SS pair, -1.7 to 180 for OS pair and 0.71 to 3.7 for OS-SS. Finally, the results for $\gamma_{2,2}$ vary between 0.01 to 14.7 for SS and OS pair while being between 0.25 and 19 for OS-SS.

The two-particle correlators of the form δ_m are an order of magnitude larger than the three-particle correlators. Therefore, the values mentioned in the following have an exponent of $\times 10^{-4}$. The magnitude of δ_1 varies between 2.9 to 23.5 for SS pair, 5.6 to 49 for OS pair and 2.7 to 26.2 for OS-SS. The values of δ_2 spans the range between 8.2 to 97 for SS pair, 9.5 to 102 for OS pair and 1.31 to 5.2 for OS-SS. The magnitude of δ_3 varies between 4.5 to 16 for SS pair, 4.8 to 15 for OS pair and -1.3 to 0.79 for OS-SS. Finally, the results for δ_4 varies between 1.58 to 9.4 for SS pair, 1.6 to 6.8 for OS pair and -2.5 to 0.78 for OS-SS.

5 Results

The measurements of two-particle correlators (eq. (3.4)) are presented in figure 1. Each data point on this figure and in the rest of the article is drawn with the relevant statistical (vertical lines) and systematic uncertainties (shaded boxes). The plots in the left panel of figure 1 present the centrality dependence of δ_m for $m = 1, 2, 3$ and 4 for opposite (OS) and same (SS) sign pairs. The charge-dependent differences of every correlator, denoted

Sources	$\delta_1 (\times 10^{-4})$			$\delta_2 (\times 10^{-4})$			$\delta_3 (\times 10^{-4})$			$\delta_4 (\times 10^{-4})$		
	SS	OS	OS-SS	SS	OS	OS-SS	SS	OS	OS-SS	SS	OS	OS-SS
(1)	1.7	1.8	0.01	0.12	0.13	0.03	0.08	0.11	0.03	0.06	0.05	0.01
(2)	2.0	3.6	1.6	0.65	0.66	0.019	0.5	0.11	0.34	0.43	0.17	0.27
(3)	0.86	1.0	0.35	1.6	1.4	0.25	0.64	0.22	0.33	0.52	0.02	0.51
(5)	1.2	0.91	1.5	1.4	0.99	0.029	0.89	0.38	0.33	0.61	0.13	0.022
(6)	0.014	2.2	1.4	5.5	5.5	1.1	0.26	1.1	1.1	0.94	2.2	0.12
(7)	0.056	0.15	0.01	0.08	0.14	0.01	0.05	0.02	0.02	0.14	0.02	0.07
(8)	2.5	1.8	0.74	0.92	0.29	1.2	1.2	0.53	1.8	0.68	0.67	1.4
(9)	2.6	—	2.6	1.6	—	1.6	1.7	—	1.7	0.37	—	0.37

Table 3. Maximum systematic uncertainty (absolute value) over all centrality intervals on δ_m from individual sources (see table 1 for an explanation of each source). The ranges are similar for both energies.

by $\Delta\delta_1$, $\Delta\delta_2$, $\Delta\delta_3$, and $\Delta\delta_4$ as a function of collision centrality are presented in the right panel of figure 1. These charge-dependent two-particle correlators (eq. (3.4)) are primarily dominated by background effects (see discussion in section 3) and can thus be used to constrain the background in the CME sensitive correlator $\gamma_{1,1}$. The first harmonic correlator, δ_1 , exhibits a significant charge-dependent difference. This correlator is related to the balance function also studied at the LHC [56, 57]. The present results are qualitatively consistent with the ones in refs. [56] and [57], i.e. oppositely charged particles are more tightly correlated in central events resulting in a narrowing of the balance function width in $\Delta\varphi$ and thus in a smaller value of δ_1 for central events compared to peripheral Pb-Pb collisions. For higher harmonics, the charge-dependent differences become progressively smaller and are compatible with zero (up to centrality $\leq 60\%$) with a hint of negative $\Delta\delta_4$ for the most peripheral events.

The two-particle correlators were also studied in a more differential way, namely as a function of the transverse momentum difference $\Delta p_T = |p_{T,\alpha} - p_{T,\beta}|$, the average transverse momentum $\bar{p}_T = (p_{T,\alpha} + p_{T,\beta})/2$ and the pseudorapidity difference $\Delta\eta = |\eta_\alpha - \eta_\beta|$ of the pair.

The dependence of δ_1 , δ_2 , δ_3 and δ_4 on these variables for one indicative centrality interval (30–40%) is shown in figure 2 for Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. For the first harmonic correlator, δ_1 , the correlations between particles of opposite charges have larger magnitude compared with the ones for same charge particles. The absolute differences do not show any significant Δp_T dependence, however they do increase with increasing $\bar{p}_T$ of the pair. Finally, there is a significant charge-dependent difference of δ_1 , which decreases with increasing $\Delta\eta$, consistent with what is also reported in refs. [56, 57]. For higher harmonics, no significant difference is observed. For other centralities the results look qualitatively similar.

The measurements of integrated two-particle correlators relative to various order symmetry planes (eq. (3.2)) in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV are presented in figure 3.

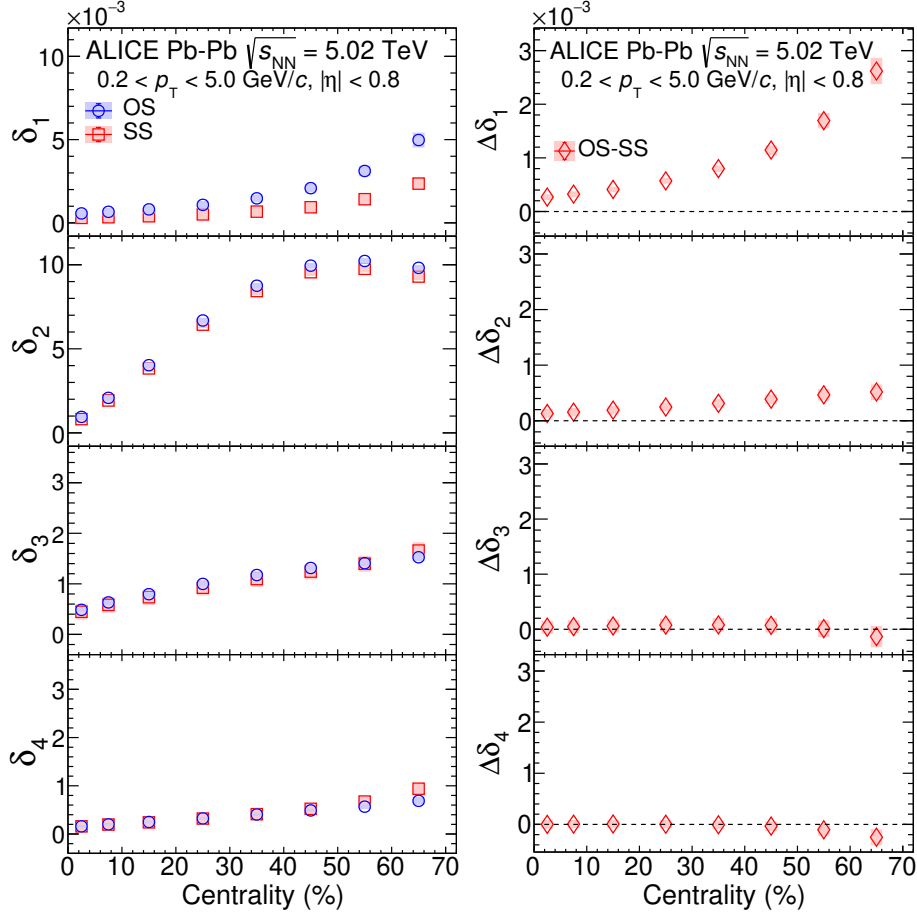


Figure 1. (Left panel) The centrality dependence of δ_1 , δ_2 , δ_3 , and δ_4 for pairs of particles of opposite (OS) and same (SS) sign measured in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. (Right panel) The charge-dependent differences, $\Delta\delta_n$ for $n = 1, 2, 3$ and 4, as a function of collision centrality. The statistical uncertainties for some data points are smaller than the marker size. The systematic uncertainties of each data point are represented by the shaded boxes.

The left panel presents the centrality dependence of $\gamma_{1,1}$, $\gamma_{1,-3}$, $\gamma_{1,2}$ and $\gamma_{2,2}$. Results for different charge combinations, i.e. OS and SS pairs are also presented here. The right panel of the same figure presents the centrality dependence of the charge-dependent differences, i.e. OS-SS. A significant charge-dependent magnitude for $\gamma_{1,1}$ is observed that increases when moving to more peripheral collisions. In particular, the magnitude of the same-sign correlations becomes progressively more negative, while correlations of oppositely charged particles are very close to zero and their magnitude turns positive for peripheral Pb-Pb events. A significant charge-dependent difference that increases for peripheral centrality intervals is also observed for $\gamma_{1,-3}$. Both correlators, as discussed in section 3, probe correlations between either the first order P-odd term of the form $\langle a_{1,\alpha} a_{1,\beta} \rangle$ or between the first and the third order coefficient $\langle a_{1,\alpha} a_{3,\beta} \rangle$. They are thus sensitive to contributions from the CME.

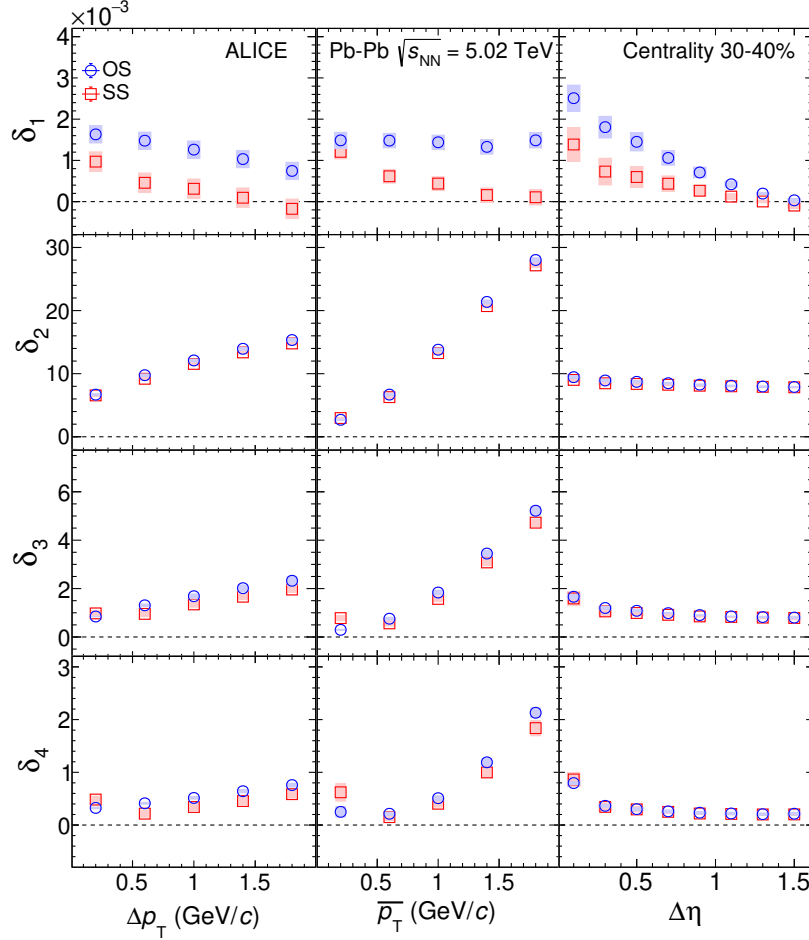


Figure 2. The dependence of δ_1 , δ_2 , δ_3 and δ_4 on the transverse momentum difference $\Delta p_T = |p_{T,\alpha} - p_{T,\beta}|$ (left panel), the average transverse momentum $\bar{p}_T = (p_{T,\alpha} + p_{T,\beta})/2$ (middle panel) and the pseudorapidity difference $\Delta\eta = |\eta_\alpha - \eta_\beta|$ (right panel) of the pair. The results for both opposite (circles) and same sign (squares) particle pairs are reported for one indicative centrality interval (30–40%) of Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

The centrality dependence of $\gamma_{1,2}$ for SS and OS pairs and their difference also demonstrate a significant charge dependence which increases for more peripheral events. Correlations of particles relative to the third order symmetry plane are expected to probe solely the background scaled by the third order flow harmonic (v_3) as expressed in eqs. (3.5). Hence these results indicate that the effects of local charge conservation coupled with v_3 can induce differences in correlations between different charges. Finally, correlations of particles with different charge relative to the fourth order symmetry plane, as quantified by $\gamma_{2,2}$, do not exhibit any significant charge dependence within the current level of statistical and systematic uncertainties.

As in the case of the two-particle correlators, δ_m , also the $\gamma_{m,n}$ were studied in a differential way, namely as a function of Δp_T , $\bar{p}_T$ and $\Delta\eta$. The results are presented in

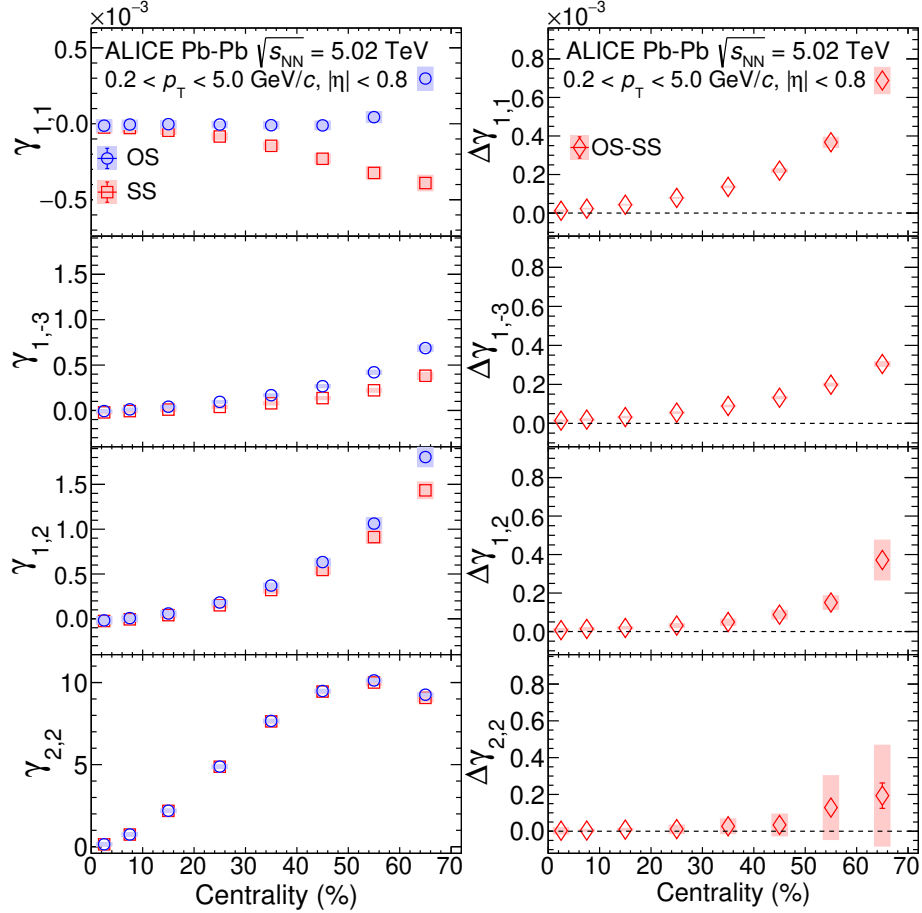


Figure 3. Left panel: the centrality dependence of $\gamma_{1,1}$, $\gamma_{1,-3}$, $\gamma_{1,2}$ and $\gamma_{2,2}$ for pairs of particles of opposite (OS) and same (SS) sign measured in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. (Right panel): the charge-dependent differences $\Delta\gamma_{1,1}$, $\Delta\gamma_{1,-3}$, $\Delta\gamma_{1,2}$ and $\Delta\gamma_{2,2}$ as a function of collision centrality.

figure 4 for the same representative centrality interval as before (30–40%) for both OS and SS. It is seen that, with the exception of $\gamma_{2,2}$, the magnitude of correlations for OS pairs is greater than the one of SS for nearly the full range of Δp_T , $\bar{p}_T$ and $\Delta\eta$ presented in this article. The results for OS and SS are compatible within the current level of statistical and systematic uncertainties for $\gamma_{2,2}$.

The correlations of particles with different charge for both $\gamma_{1,1}$ and $\gamma_{1,-3}$, i.e. the two correlators that are sensitive to different orders of the CME, have a range that extends up to one unit of $\Delta\eta$. Both OS and SS correlations have a similar trend as a function of Δp_T and $\Delta\eta$, however they exhibit different behaviour as a function of $\bar{p}_T$. On the other hand, the correlators that are solely sensitive to the background, i.e. $\gamma_{1,2}$ and $\gamma_{2,2}$, exhibit an increasing trend as a function of both Δp_T and $\bar{p}_T$. This trend has a mild charge dependence for $\gamma_{1,2}$ that increases with increasing Δp_T and $\bar{p}_T$, but not for $\gamma_{2,2}$. Both $\gamma_{1,2}$ and $\gamma_{2,2}$ have a range that extends up to $\Delta\eta = 1.6$ without any significant dependence on $\Delta\eta$.

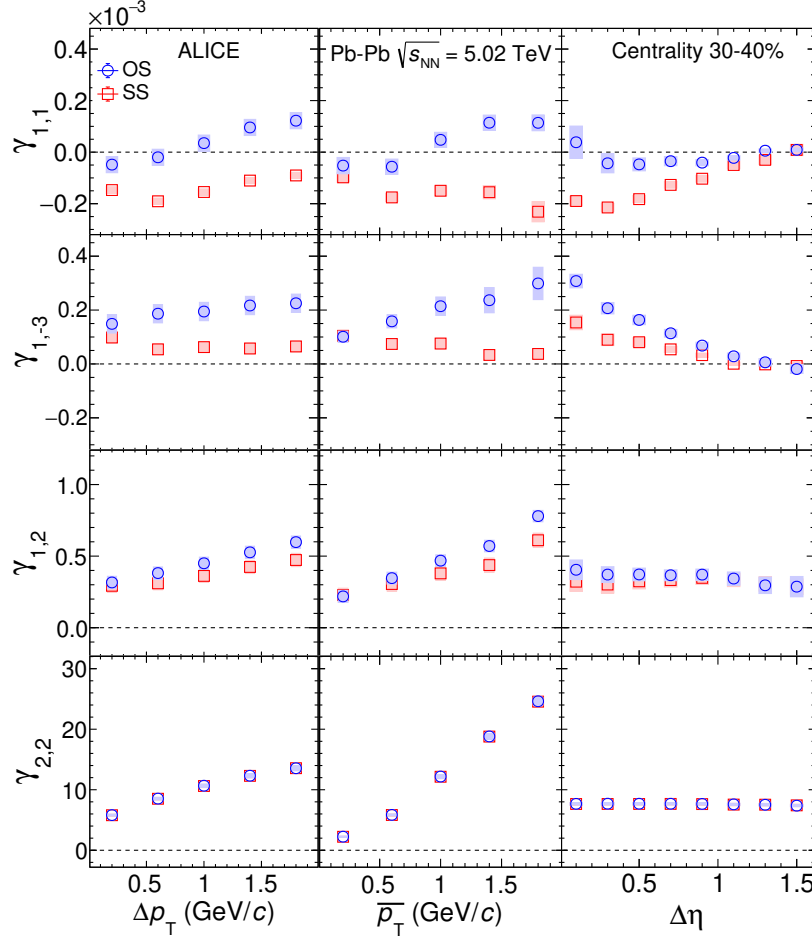


Figure 4. The dependence of $\gamma_{1,1}$, $\gamma_{1,3}$, $\gamma_{1,2}$ and $\gamma_{2,2}$ on the transverse momentum difference $\Delta p_T = |p_{T,\alpha} - p_{T,\beta}|$ (left panel), the average transverse momentum $\bar{p}_T = (p_{T,\alpha} + p_{T,\beta})/2$ (middle panel) and the pseudorapidity difference $\Delta\eta = |\eta_\alpha - \eta_\beta|$ (right panel) of the pair. The results for both opposite and same sign particle pairs are reported for one indicative centrality interval (30–40%) of Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

Finally, the charge-dependent differences of the correlators $\gamma_{1,1}$, $\gamma_{1,2}$ and $\gamma_{2,2}$ were also studied in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The centrality dependence of $\Delta\gamma_{1,1}$, $\Delta\gamma_{1,2}$ and $\Delta\gamma_{2,2}$ is presented in figure 5 in comparison with the results obtained in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. None of the correlators exhibit any significant differences between the two energies, within the current level of uncertainties. This could be explained considering that there is no significant energy dependence in the effects that constitute the background to these measurements (i.e. local charge conservation coupled to different flow harmonic modulations). Preliminary studies indicate that the correlations between balancing charges, as reflected in the width of the balance function, do not exhibit any significant dependence on collision energy. The values of v_2 , v_3 and v_4 in $\sqrt{s_{NN}} = 5.02$ TeV are between 2 to 20% higher than the values at $\sqrt{s_{NN}} = 2.76$ TeV [58]. However, the

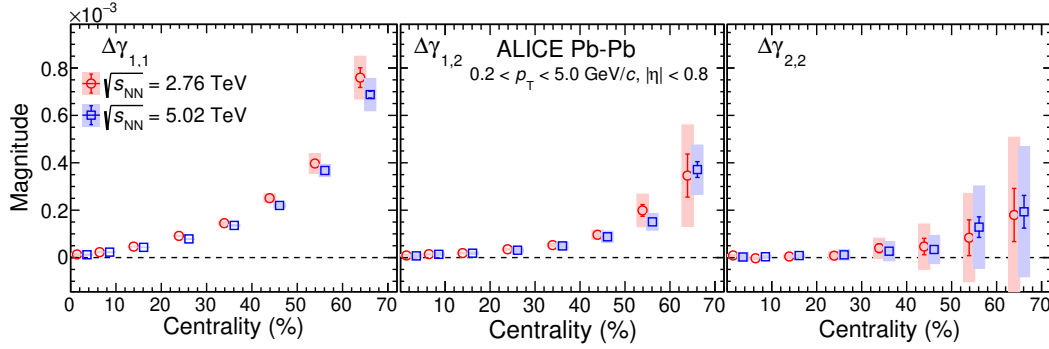


Figure 5. The dependence of $\Delta\gamma_{1,1}$, $\Delta\gamma_{1,2}$ and $\Delta\gamma_{2,2}$ on centrality, measured in Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ and 5.02 TeV. The data points for $\sqrt{s_{\text{NN}}} = 5.02$ TeV are shifted along the horizontal axis for better visibility.

Centrality	T_{kin} (MeV)	ρ_0	ρ_2	R_x/R_y
0–5%	91.3 ± 3.5	1.26 ± 0.01	0.020 ± 0.001	0.956 ± 0.001
5–10%	87.0 ± 3.5	1.27 ± 0.01	0.032 ± 0.001	0.933 ± 0.002
10–20%	84.8 ± 4.9	1.25 ± 0.01	0.045 ± 0.003	0.905 ± 0.004
20–30%	87.4 ± 4.8	1.23 ± 0.01	0.059 ± 0.007	0.872 ± 0.005
30–40%	91.6 ± 3.8	1.20 ± 0.01	0.068 ± 0.003	0.844 ± 0.004
40–50%	95.1 ± 3.3	1.15 ± 0.01	0.070 ± 0.003	0.823 ± 0.004
50–60%	98.1 ± 3.2	1.09 ± 0.01	0.065 ± 0.002	0.807 ± 0.004
60–70%	108.0 ± 3.2	0.99 ± 0.01	0.056 ± 0.002	0.786 ± 0.006

Table 4. List of the Blast-wave fit parameters.

corresponding change in the background contribution to the $\gamma_{m,n}$ correlator is of the order of a few percent, which is not distinguishable within the current level of uncertainties.

5.1 Constraining the CME contribution

5.1.1 Describing the background with Blast-wave inspired LCC model

As a first approach to constraining the CME contribution, a blast-wave (BW) parametrisation [49] that describes the phase space density at kinetic freeze-out, is used. This model assumes that the radial expansion velocity is proportional to the distance from the centre of the system and takes into account resonance production and decays. Local charge conservation (LCC) is additionally incorporated in this model by generating ensembles of particles with zero net charge. The position of the sources of balancing charges are then uniformly distributed within an ellipse. From now on this model will be denoted as BW-LCC in the text.

Each particle of an ensemble is emitted by a fluid element with a common collective velocity following the single-particle BW parametrisation. The procedure starts from obtaining BW parameters by fitting the p_T spectra [59] and the p_T -differential v_2 values [60] for charged pions, kaons, and protons (antiprotons) measured in Pb-Pb collisions

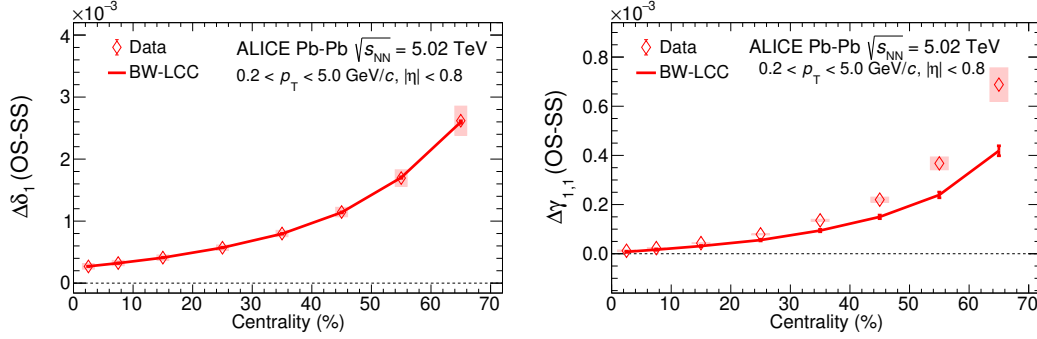


Figure 6. (Left) The centrality dependence of $\Delta\delta_1$ measured in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The curve (denoted as BW-LCC) presents the blast-wave parametrization coupled to local charge conservation effects. The model is tuned to reproduce the measured values of $\Delta\delta_1$ (see text for details). (Right) The comparison of the centrality dependence of the CME-sensitive correlator $\Delta\gamma_{1,1}$ with expectations from the BW-LCC model.

at $\sqrt{s_{NN}} = 5.02$ TeV. The fit ranges for p_T spectra are $0.5 \leq p_T \leq 1.0$ GeV/c, $0.2 \leq p_T \leq 1.5$ GeV/c and $0.2 \leq p_T \leq 3.0$ GeV/c for pions, kaons and protons, respectively. The fit range for p_T -differential v_2 and v_4 is $0.5 \leq p_T \leq 1.2$ GeV/c. Table 4 presents the resulting BW parameters, namely the kinetic freezeout temperature (T_{kin}), radial flow (ρ_0) and its second order modulation (ρ_2) as well as the spacial asymmetry (R_x/R_y). The next step required tuning the number of sources of balancing pairs for each centrality interval to reproduce the centrality dependence of $\Delta\delta_1$, the correlator which is mainly sensitive to background effects. This procedure is repeated for every centrality interval. The number of sources varies from ~ 2476 to 193 for the centrality intervals 0–5% to 60–70%. The left panel of figure 6 presents the agreement achieved between the measured results and the ones obtained from the model. Overall the model describes the measurement fairly well with deviations limited to $< 1\%$ for the whole centrality range. The tuned model is then used to extract the expectation for the centrality dependence of the charge-dependent differences of the CME sensitive correlator $\Delta\gamma_{1,1}$. The right panel of figure 6 shows the comparison between the measured values of $\Delta\gamma_{1,1}$ and estimates from the model. The estimate of $\Delta\gamma_{1,1}$ from the model originates solely from the contribution of local charge conservation effects coupled to elliptic flow modulations. The curve underestimates the measured data points by as much as $\approx 39\%$, with the disagreement increasing progressively for more peripheral events.

5.1.2 Describing the background with v_n and $\gamma_{m,n}$

In the following, we attempt to constrain the background contribution to the CME sensitive correlator $\gamma_{1,1}$ and thus give an estimation of the fraction of the signal in Pb-Pb collisions. The approach described in section 3.2 relies on the assumption that the coefficients κ_n have similar magnitude, allowing one to calculate the background contribution to $\Delta\gamma_{1,1}$, denoted as $\Delta\gamma_{1,1}^{Bkg}$ from $\Delta\gamma_{1,2}$ according to eq. (3.7). This assumption was tested using events produced with the string melting tune of A Multi Phase Transport model (AMPT) [50–52].

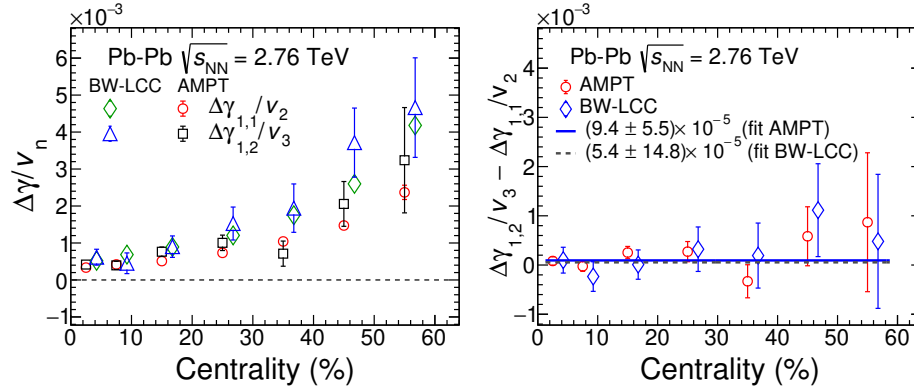


Figure 7. (Left panel) The centrality dependence of $\Delta\gamma_{1,1}/v_2$ and $\Delta\gamma_{1,2}/v_3$ for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV according to the AMPT and BW-LCC model. (Right panel) The differences between $\Delta\gamma_{1,1}/v_2$ and $\Delta\gamma_{1,2}/v_3$ in AMPT and BW-LCC, denoted as $\Delta(\Delta\gamma/v_n)$. The solid and dotted line is the result of a fit with a constant function to AMPT and BW-LCC result respectively.

In the string melting tune, the initial strings are melted into partons whose interactions are described by a parton cascade model [61]. These partons are then combined into final-state hadrons via a quark coalescence model. In this model, the final-state hadronic rescattering is implemented including resonance decays as well. The input parameters $\alpha_s = 0.33$ and a partonic cross section of 1.5 mb were used to reproduce the centrality dependence of v_2 and v_3 for charged particles, as reported in ref. [62], for Pb-Pb events at $\sqrt{s_{NN}} = 2.76$ TeV. About 40 million simulated Pb-Pb events were analysed, split into centrality based on the values of the impact parameter. Only primary particles having the same kinematic selections as in the experimental data (i.e. $|\eta| < 0.8$ and $0.2 < p_T < 5$ GeV/c) were considered. The left panel of figure 7 presents the ratio of the charge-dependent differences $\Delta\gamma_{1,1}$ and $\Delta\gamma_{1,2}$ to the relevant harmonics v_2 and v_3 , respectively. Similar ratios are also shown from the BW-LCC model, which is discussed in the previous subsection. The two sets of data points are compatible within uncertainties over the entire centrality range for both AMPT and BW-LCC model. This is also illustrated in the right panel of figure 7, which presents the centrality dependence of $(\Delta\gamma_{1,1}/v_2) - (\Delta\gamma_{1,2}/v_3)$, denoted as $\Delta(\Delta\gamma/v_n)$. The corresponding data points from AMPT and BW-LCC are fitted with a constant function, which yields a result compatible with zero within the uncertainties of the fit i.e., $\Delta(\Delta\gamma/v_n) = (9.4 \pm 5.5) \times 10^{-5}$ and $(5.4 \pm 14.8) \times 10^{-5}$ respectively. This observation illustrates that within these models one can assume $\kappa_2 \approx \kappa_3$. Results presented in this article have been also reproduced using the AMPT version reported in [63].

The same procedure was used with Pb-Pb data recorded at both LHC energies. Since the results of $\gamma_{2,2}$ do not give any significant charge-dependent difference as a function of centrality within statistical and systematic uncertainties (see figure 3), only the values of $\gamma_{1,2}$ are used in the rest of the article to estimate the background.

Although, CME sensitive $\gamma_{1,-3}$ correlator could have similar dependence on the background as $\gamma_{1,1}$ (i.e., $\gamma_{1,-3} \propto \delta_1 v_2$), we observe in figure 3 that their magnitude are not the same. This difference, which is being investigated as part a of future publication, makes

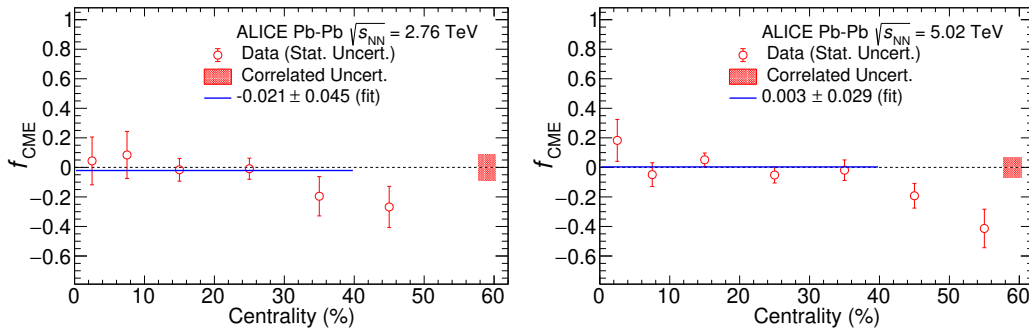


Figure 8. (Left panel) The CME fraction extracted in Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV. (Right panel) The CME fraction extracted in Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The systematic uncertainty is shown as hatched band at zero line around the centrality value of 60%. The solid blue lines correspond to fit with a constant function to the data points. See text for details.

the $\gamma_{1,-3}$ correlator ambiguous to extract the CME contribution at this stage. Therefore, in the following we only use $\gamma_{1,1}$ correlator to make quantitative measurement of CME. The values of v_2 and v_3 used to scale the charge-dependent differences of $\gamma_{1,1}$ and $\gamma_{1,2}$, are the ones measured by ALICE in Pb-Pb collisions reported in ref. [62] and ref. [58] for $\sqrt{s_{\text{NN}}} = 2.76$ TeV and $\sqrt{s_{\text{NN}}} = 5.02$ TeV, respectively. The value of v_2 is estimated as the average of $v_2\{2\}$ and $v_2\{4\}$ to reduce the biases due to fluctuations assuming a Gaussian probability distribution [64]. Assuming $\kappa_2 \approx \kappa_3$ as supported by the model study, the value of $\Delta\gamma_{1,2} \times v_2/v_3$ was used according to eq. (3.7) as a proxy for the magnitude of the background contribution to the measurement of $\Delta\gamma_{1,1}$, denoted as $\Delta\gamma_{1,1}^{\text{Bkg}}$, for both LHC energies. The CME fraction is then defined as

$$f_{\text{CME}} = 1 - \frac{\Delta\gamma_{1,1}^{\text{Bkg}}}{\Delta\gamma_{1,1}}, \quad (5.1)$$

where $\Delta\gamma_{1,1}$ is the measured value of the correlator presented on the left panel of figure 5. Figure 8 presents the centrality dependence of the CME fraction at $\sqrt{s_{\text{NN}}} = 2.76$ TeV (left plot) and $\sqrt{s_{\text{NN}}} = 5.02$ TeV (right plot). The systematic uncertainties on f_{CME} have been estimated from the same sources as mentioned in section 4. In addition, the contribution to the systematic uncertainty stemming from v_2 was also estimated using $v_2\{2\}$ in eq. (3.7) instead of the average of $v_2\{2\}$ and $v_2\{4\}$. All individual sources are then added in quadrature to get the total systematic uncertainty. We have excluded any systematic variation in the assumption of $\kappa_2 \approx \kappa_3$ for the reported values of f_{CME} .

The total, centrality-independent systematic uncertainty is indicated by the shaded box on the line at zero. It is seen that for both energies f_{CME} is compatible with zero up to centrality $\approx 40\%$. For more peripheral collisions, the value of f_{CME} is negative. There could be several possible reasons behind this observation. The event plane resolution starts to decline for peripheral events giving rise to fluctuations in the measured observables. The non-flow, the effect of which is negligible for $\Delta\gamma_{m,n}$ but significant for v_n , can affect the measurement for peripheral events. There is another possibility that the ratio of the pro-

portionality constants, i.e. κ_2/κ_3 have a centrality dependence instead of being a constant. Therefore the observation of negative f_{CME} for peripheral events could be a convoluted effect of all these underlying phenomena. However, within the scope of this analysis, we have limited ourselves with constant behavior of κ_2/κ_3 as a function of centrality.

Finally, to estimate an upper limit on the contribution of the CME signal to the measurement of $\gamma_{1,1}$, the data points of f_{CME} are fitted with a constant function up to the 40% centrality interval. The fit yields values -0.021 ± 0.045 and 0.003 ± 0.029 in Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ and 5.02 TeV, respectively. These results are consistent with zero CME fraction and correspond to upper limits on f_{CME} of 15–18% (20–24%) at 95% (99.7%) confidence level for the 0–40% centrality interval. The latter values are estimated assuming Gaussian distributed uncertainties and taking into account that the CME fraction has a lower bound of 0 (see figure 8).

6 Summary

In this article, we reported charge-dependent results for various two-particle correlators as well as two-particle correlations relative to different order symmetry planes. These measurements are extracted from the analysis of Pb-Pb collisions recorded by ALICE at $\sqrt{s_{\text{NN}}} = 2.76$ and 5.02 TeV. These correlators exhibit different sensitivity to the signal induced by the CME and to background effects, dominated by local charge conservations coupled to anisotropic flow.

All two-particle correlations of the form δ_m for $m = 1, 2, 3$ and 4 are dominated by background effects and exhibit a significant centrality dependence. Among them, only δ_1 exhibits a notable charge-dependent difference, which does not change significantly as a function of Δp_T , but increases with increasing $\bar{p}_T$ and decreases with increasing $\Delta\eta$ of the pair. For higher harmonics, on the other hand, the charge-dependent differences become progressively smaller and are compatible with zero for δ_3 and δ_4 .

The CME sensitive two-particle correlations relative to the second order symmetry plane, $\gamma_{1,1}$ and $\gamma_{1,-3}$, exhibit a significant charge-dependent difference, which increases towards peripheral centrality intervals. Results on particle correlations relative to the third order symmetry plane, expressed by $\gamma_{1,2}$, that probe background effects associated with local charge conservation modulated by triangular flow (v_3), also show a significant charge-dependent difference, which increases for more peripheral events. Finally, correlations between two particles relative to the fourth order symmetry plane, that also have the potential to probe mainly background effects, show no significant difference for pairs with same and opposite electric charges, however they are suffering from large statistical and systematic uncertainties.

A blast wave parametrisation that incorporates local charge conservation tuned to reproduce the components of the background, is not able to fully describe the magnitude of the charge-dependent differences of the CME-sensitive correlator $\gamma_{1,1}$. Finally, the results of correlations relative to Ψ_3 and Ψ_4 that probe mainly, if not solely, the contribution of the background clearly show that these background effects are the dominating factor to the measurements of $\gamma_{1,1}$.

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Event-by-Event study of charge separation effect with ALICE

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1. Introduction

In the QCD deconfined phase region, QCD vacuum can possess metastable domains which leads to P/CP violations [1]. These P/CP odd domains along with the presence of non-zero magnetic field in heavy-ion collisions leads to charge separation in the produced particles [2]. Voloshin and others [3] proposed an experimental observable (γ) related to 3- particle correlator as defined in Eq. 1 to measure the charge separation.

$$\gamma = \frac{\langle \cos(\phi_a + \phi_b - 2\psi_{RP}) \rangle}{\langle \cos(\phi_a + \phi_b - 2\phi_c) \rangle / v_{2,c}} \quad (1)$$

Here $\phi_{a/b/c}$ are azimuthal angles of particles "a", "b" and "c", ψ_{RP} is the reaction plane angle (angle between impact parameter vector and beam axis) and $v_{2,c}$ is elliptic flow of the third particle "c". The angled brackets denote an average over the particles within the event and over all the analyzed events in a given sample.

STAR, ALICE and CMS investigated the Chiral Magnetic Effect using γ correlator [4–7]. In this contribution, we will search the localized event-by-event back-to-back charge separation, with the background effects estimated by a new technique called Sliding Dumbbell Method (SDM).

2. Analysis Details

A. Sliding Dumbbell Method

The ultimate manifestation of the Chiral Magnetic effect is the separation of charged hadrons along the direction of the initial magnetic field. This back-to-back charge separation can easily be checked on event-by-event

basis by using Sliding Dumbbell Method in which sum of positive charge fraction (Db_+) of particles on one side and negative charge fraction (Db_-) on opposite side is calculated as depicted in the fig.1.

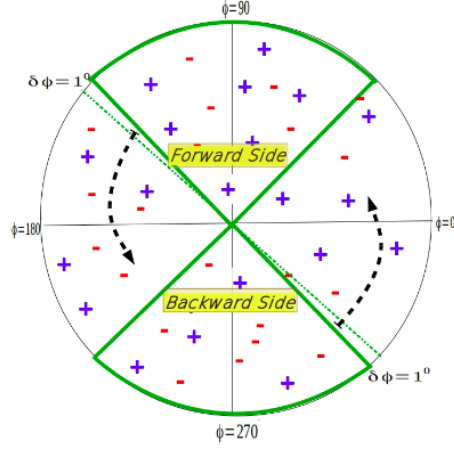


FIG. 1: Pictorial discription of SDM

Fraction $Db_{\pm}$ is defined as:

$$Db_{\pm} = Db_+ + Db_-$$

$$= \frac{N_+^{forw}}{N_+^{forw} + N_-^{forw}} + \frac{N_-^{back}}{N_+^{back} + N_-^{back}} \quad (2)$$

where N_+^{forw} and N_-^{forw} are the number of positively and negatively charged particles on the forward side of dumbbell, respectively whereas N_+^{back} and N_-^{back} are the number of positively and negatively charged particles backward side of dumbbell, respectively. The whole azimuthal plane in an event is then scanned by sliding a dumbbell of $\Delta\phi = 90^\circ$ in

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steps of $\delta\phi = 1^\circ$ while calculating the fraction $Db_\pm$ to extract the maximum value of $Db_\pm$ in each event. If the charged particles are uniformly distributed then the value of each fraction in Eq. 2, will be equal to 0.5 and the sum will be 1, but due to statistical fluctuations the value of each fraction can be different. Hence, $Db_\pm$ will not be equal to 1 and the maximum possible value of the fraction is 2 in case of complete charge separations.

The maximum value of $Db_\pm$ in each event is extracted with asymmetry $|Db_{asy}| < 0.25$. Here Db_{asy} is defined as:

$$Db_{asy} = \frac{(Pos_{ex}^{forw} - Neg_{ex}^{back})}{(Pos_{ex}^{forw} + Neg_{ex}^{back})} \quad (3)$$

where, $Pos_{ex}^{forw} = N_+^{forw} - N_-^{forw}$ is positive charge excess in the forward side of dumbbell and $Neg_{ex}^{back} = N_-^{back} - N_+^{back}$ is negative charge excess in the backward side of dumbbell. Thus obtained $Db_\pm^{max}$ distributions are then sliced into ten $Db_\pm^{max}$ bins. After slicing, 3- particle correlators for different charge combinations (same sign and opposite sign), are calculated for each $Db_\pm^{max}$ bin for each centrality. 3- particle correlators, $v_2\{2\}$, $v_2\{4\}$ are calculated using Q- cumulant method [5]. For background, we have used charge reshuffle method, in which we are reshuffling the charges of the particles randomly keeping ϕ and θ same. Reshuffling the charges randomly is expected to kill the charge dependent correlations.

B. Data set, Event and track cuts

ALICE Pb-Pb data at center of mass energy $\sqrt{s_{NN}} = 5.02$ TeV is used for this analysis. Minimum bias events with vertex in the z-direction within $|V_z| < 10$ cm from interaction point are analyzed. Charged particle tracks measured with $0.2 < p_T < 5$ GeV/c and $-0.8 < \eta < 0.8$ with the distance of closest approach (DCA) to the primary-vertex less than 3.2 cm is used. The tracks with at least 70 hits in the Time Projection Chamber used in track reconstruction.

3. Results and Discussion

$Db_\pm^{max}$ distributions for different centralities have been studied and these distributions have sliced into ten bins. γ correlator for same sign charge pairs and opposite sign charge pairs is calculated for each ten bins in each centrality. Along with this, $\Delta\gamma = \gamma_{OS} - \gamma_{SS}$ is also obtained and its variation with centrality will be presented. Along with $\Delta\gamma$ for data, we have also calculated $\Delta\gamma$ for charge reshuffle as background. This study will provide a new approach to estimate background effect of CME and thus might show a new possibility to extract the CME fraction in the future studies.

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Searching CME using Sliding Dumbbell Method in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV using AMPT

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1. Introduction

Chiral imbalance along the magnetic field produced during the heavy-ion collisions causes the charge separation along the magnetic field direction. This phenomena is known as chiral magnetic effect (CME) [1]. Experimental observable (γ) was proposed [2] to measure the charge separation.

$$\gamma = \langle \cos(\phi_a + \phi_b - 2\psi_{RP}) \rangle = \langle \cos(\phi_a + \phi_b - 2\phi_c) \rangle / v_{2,c} \quad (1)$$

Here $\phi_{a/b/c}$ are azimuthal angles of particles "a", "b" and "c", ψ_{RP} is the reaction plane angle and $v_{2,c}$ is elliptic flow of the third particle "c". The average is taken over the particles within the event and over all the analyzed events in a given sample. We developed a new method to study event-by-event back-to-back charge separation, Sliding Dumbbell Method (SDM), and checked its reliability on AMPT model which will be presented here alongwith the method discription.

2. Analysis Details

A. Sliding Dumbbell Method

Sliding dumbbell method will be used to characterize the events which exhibit enhanced chiral magnetic effect. In SDM, sum ($Db_{\pm}$) of positive charge fraction (Db_{+}) on one side of the dumbbell and negative charge fraction (Db_{-}) on opposite side of the dumbbell is calculated. For an event, the whole azimuthal plane is investigated by sliding the dumbbell of $\Delta\phi = 90^\circ$ in steps of $\delta\phi = 1^\circ$ to get the maximum value of $Db_{\pm}$. Asymmetry cut $|Db_{asy}| < 0.25$ is applied to extract the

maximum value of $Db_{\pm}$ in each event. Here Db_{asy} is defined as:

$$Db_{asy} = \frac{(Pos_{ex}^{forw} - Neg_{ex}^{back})}{(Pos_{ex}^{forw} + Neg_{ex}^{back})} \quad (2)$$

where, $Pos_{ex}^{forw} = N_{+}^{forw} - N_{-}^{forw}$ is positive charge excess in the forward side of dumbbell and $Neg_{ex}^{back} = N_{-}^{back} - N_{+}^{back}$ is negative charge excess in the backward side of dumbbell. Obtained distributions of $Db_{\pm}^{max}$ for each centrality are divided into ten bins and γ correlator is calculated for each bins. Background study is done by reshuffling the charges of particles randomly, hence omitting any charge dependent correlation.

B. Data sets and Selection Criteria

A Multi Phase Transport (AMPT) model [3] is a monte carlo model used for to describe nuclear collisions ranging from center-of-mass energies from about $\sqrt{s_{NN}} = 5$ GeV up to 5500 GeV. We have tested the reliability of the SDM using Pb-Pb events at $\sqrt{s_{NN}} = 2.76$ TeV generated through AMPT String Melting ON with reaction plane angle, $\Psi_{RP} = 0$. CME type signal is externally injected in the AMPT generated events as default AMPT does not have CME. We are analyzing 4 different sets of AMPT events having 1.6M events as listed below:

1. Default AMPT : Default AMPT SM on data having zero CME signal.
2. 1.Fix CME signal : Sample generated by flipping the charges of one +ve and one -ve particles perpendicular to the reaction plane in AMPT generated events.
3. 50% Default + 50% 1.Fix : Sample created by taking 50% events from default

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AMPT and 50% events from 1.Fix signal.

4. 2.Fix CME signal : Same as 1.Fix except charges of two +ve and two -ve particles are flipped here.

Injected CME signal has been kept constant i.e., independent of collision centrality and event multiplicity. Transverse momentum and pseudorapidity track cuts are used as $0.2 < p_T < 5$ GeV/c and $-0.8 < \eta < 0.8$.

3. Results and Discussion

Figure 1 shows the $Db_{\pm}^{max}$ distributions for 4 different AMPT data sets for 40-50% and 50-60% centralities. It can be seen from the figure that data sets with higher injected CME signal have higher $Db_{\pm}^{max}$ values.

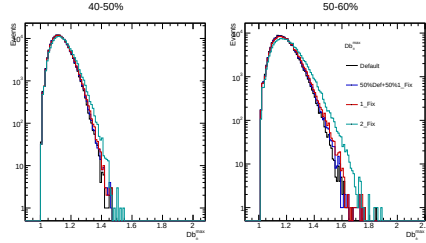


FIG. 1: $Db_{\pm}^{max}$ distributions obtained using the sliding dumbbell method for data and charge reshuffled for 40-50% and 50-60% centrality intervals.

Figure 2 shows the centrality dependence of $\Delta\gamma = \gamma_{OS} - \gamma_{SS}$ for each ten bins. The correlation values become more positive as the signal contribution increases indicating the strong dependence of three particle correlator on the injected signal strength. It is also observed that the number of $Db_{\pm}^{max}$ bins exhibiting positive value of $\Delta\gamma$ are different for different data sets and centralities indicating different no. of events exhibiting CME type effect.

From $\Delta\gamma$, we calculate the fraction of CME by using the following equation for those $Db_{\pm}^{max}$ bins for which $\Delta\gamma_{AMPT} > 0$ where $\Delta\gamma_{AMPT}$ is $\Delta\gamma$ for different sets of AMPT

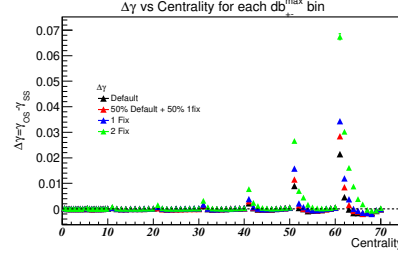


FIG. 2: Centrality dependence of $\Delta\gamma$ for different $Db_{\pm}^{max}$ bins for data and charge reshuffle.

samples.

$$f_{CME} = \left(\frac{\Delta\gamma_{AMPT} - \Delta\gamma_{ch.re}}{\Delta\gamma_{AMPT}} \right) * f_{nevt} \quad (3)$$

where f_{nevt} is the fraction of events exhibiting positive value of $\Delta\gamma$ and $\Delta\gamma_{ch.re}$ is $\Delta\gamma$ for charge reshuffle background. Fig.?? shows the f_{CME} versus collision centrality for different sets of AMPT generated events. We can see from the figure that fraction is almost zero for default AMPT as expected and for different sets of CME injected AMPTs, fraction decreases with increasing collision centrality.

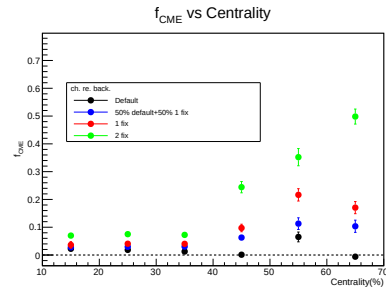


FIG. 3: Centrality dependence of f_{CME}

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Certificate

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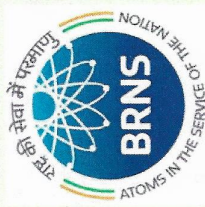
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