Chapter 4

Charged-neutral correlation Analysis
at forward rapidity

4.1 Introduction

This chapter focusses on the measurement of event-by-event (e-by-e) fluctuations and correlations between charged (ch) and neutral particle (γ) multiplicities at the forward rapidity for Au+Au collisions at RHIC. In the framework of the STAR experiment, the two forward detectors, the Photon Multiplicity Detector (PMD) and the Forward Time Projection Chamber (FTPC) simultaneously measure photons and charged particles respectively. The common pseudorapidity coverage of the two detectors in which the measurement is performed is -3.7 < η < -2.8. This unique analysis has been done for the first time at STAR for a wide range of Au+Au Beam Energy Scan (BES) energies, \( \sqrt{s_{NN}} = 200, 62.4, 39, 27, 19.6 \) GeV, to gather information regarding the nature of the chiral phase transition. The primary objective is to investigate the possible evidences of dynamical charged-neutral correlations beyond model predictions for generic pion production. A comparative study of charged-neutral correlations and net-charge correlations has also been undertaken, where results obtained for the BES energies have been compared to published results obtained at \( \sqrt{s_{NN}} = 200 \) GeV [8]. Details of the energy, collision
centrality and charge dependence of charged-neutral correlation for the energies 200, 62.4, 39, 27, 19.6 GeV has been presented in this thesis. Two special observables, \( \nu_{dyn}^{\gamma-ch} \) and \( r_{m,1}^{\gamma-ch} \) (\( m = 1-3 \)) constructed out of the factorial moments of the charged and neutral particle multiplicities have been used for this analysis. These observables are designed to study the \( \text{ch-} \gamma \) correlation and are robust against detector inefficiencies by construction. The details about the analysis procedure, datasets used, data cleanup and limitations of the measurement of \( \text{ch-} \gamma \) correlation in the context of the STAR experiment and the experimental results obtained have been discussed in this chapter in detail.

### 4.2 Method of analysis

The predominant contribution to the charged and neutral particle multiplicity produced in heavy-ion collisions is in the form of charged (\( \pi^\pm \)) and neutral pions (\( \pi^0 \)) [1] respectively. As the neutral pion decays into photons, the experimental detection of neutral pions is via photons. The presence of any kind of correlation in pion production is reciprocated by a correlation between charged and neutral particles, or more specifically between charged particles and photons. As has been already discussed, a phase transition from the sQGP phase to the Hadronic gas phase can lead to the creation of metastable domains of Disoriented Chiral Condensate (DCC) [2–5].

The distribution of the neutral pion fraction as a result of the decay of the metastable DCC domains is theoretically predicted to be distinctly different from the generic expectation of pion production in equal abundances due to isospin symmetry [3][5]. This phenomenon manifests in the form of an anti-correlation between charged and neutral pion multiplicities [4]. As predicted in [2–5], the ratio of charged-to-neutral pions carries sensitive information about the chiral phase transition. The quantity of interest for this analysis is the neutral pion fraction (\( f \)) which can be expressed as

\[
f = \frac{N_{\pi^0}}{N_{\pi^0} + N_{\pi^\pm}}
\]  

(4.1)
to a close approximation [6][7], the value of $f$ can be written as

$$f^{\gamma - \text{ch}} = N_{\gamma}/(N_{\gamma} + 2N_{\text{ch}}) \quad (4.2)$$

which explains the study of the ch-$\gamma$ correlation.

The motivation behind this analysis is to look for dynamical evidences of ch-$\gamma$ (anti)correlation beyond generic expectation in Au+Au collisions at RHIC and to search for qualitative differences with net-charge correlation in the same acceptance [8]. It will also be interesting to look at the energy dependence of the ch-$\gamma$ correlation for the BES energies. Measurement of ch-$\gamma$ correlation requires a simultaneous measurement of charged particles and photons within a common acceptance. In the framework of the STAR experiment [9], this is possible both at mid-rapidity and forward rapidity. At midrapidity ($|\eta| < 1$), the TPC [10] measures charged particles, while the BEMC [11] measures photons. The inability of the BEMC to detect photons less than 500 MeV in momentum is a major impediment to this analysis, considering theoretical predictions that claim the average momentum of pions produced from the decay of DCC domains is inversely proportional to DCC domain size [12]. At forward rapidity ($-3.7 < \eta < -2.8$), the FTPC [13] and PMD [14] detectors measure charged particles and photons respectively. The FTPC measures charged particles of transverse momentum ($p_T$) as low as 150 MeV/c, while the PMD measures photons down to 20 MeV/c in transverse momentum with reasonable efficiency. This analysis deals with the e-by-e measurement of charged and neutral particle multiplicity fluctuation in the common PMD-FTPC acceptance within the pseudorapidity range $-3.7 < \eta < -2.8$. The observables chosen for this analysis $\nu^{\gamma - \text{ch}}_{\text{dyn}}$ and $r^{\gamma - \text{ch}}_{m_i}$ ($m = 1-3$), to be described in detail in the next section, have been developed using a proper combination of factorial moments of the charged and neutral particle multiplicities, expressed in terms of the neutral pion fraction ($f$). The use of these observables and the methodology followed for the charged-neutral analysis described in this thesis is well documented [7][15][16]. The observables have been specifically constructed for
sensitivity towards dynamical signals of ch-γ correlation.

### 4.2.1 Choice of suitable observables for ch-γ correlation

In heavy-ion collisions, there are inherent limitations in the measurement of experimental observables. The detector response being binomial [6], fluctuations in the measurements of particle numbers is automatically introduced. Additional detector artefacts like limited acceptance, particle decay and mis-identification of particles introduce further spurious correlations in data. Selection of robust observables for the event-by-event study of multiplicity fluctuations, that minimize the effects of spurious correlations is naturally very important. Specifically designed observables that are sensitive towards ch-γ correlation have been used for this analysis [6]. The use of the observable $\nu_{\text{dyn}}$ for studying particle ratio fluctuations in heavy ion collisions is well known and was introduced in [16]. The observable $\nu_{\text{dy}n}^{\gamma-\text{ch}}$, for the special case of charged-neutral correlation is defined as

$$
\nu_{\text{dy}n}^{\gamma-\text{ch}} = \frac{\langle N_{\text{ch}} (N_{\text{ch}} - 1) \rangle}{\langle N_{\text{ch}} \rangle^2} + \frac{\langle N_{\gamma} (N_{\gamma} - 1) \rangle}{\langle N_{\gamma} \rangle^2} - 2 \frac{\langle N_{\text{ch}} N_{\gamma} \rangle}{\langle N_{\text{ch}} \rangle \langle N_{\gamma} \rangle}
$$

(4.3)

$$
= \omega_{\text{ch}} + \omega_{\gamma} - 2 \times \text{corr}_{\gamma-\text{ch}}
$$

(4.4)

$$
= \left( \frac{\langle (1 - f)^2 \rangle}{\langle 1 - f \rangle^2} + \frac{\langle f^2 \rangle}{\langle f \rangle^2} - 2 \frac{\langle f(1 - f) \rangle}{\langle f \rangle \langle 1 - f \rangle} \right) \frac{\langle N(N - 1) \rangle}{\langle N \rangle^2} + \frac{1}{2 \langle f \rangle \langle N \rangle}.
$$

(4.5)

As shown in Eqns 4.3 and 4.4, $\nu_{\text{dy}n}^{\gamma-\text{ch}}$ consists of three terms, $\omega_{\text{ch}}$, the fluctuation of the number of charged particles, $\omega_{\gamma}$, the fluctuation of the number of photons and $\text{corr}_{\gamma-\text{ch}}$, which is the scaled ch-γ correlation term. The individual terms are constructed out of factorial moments of charged particle and photon multiplicities. In Eqn. 4.5, $\nu_{\text{dy}n}^{\gamma-\text{ch}}$ has been expressed in terms of the neutral pion fraction $f$. The Poissonian limit for the individual terms is unity, hence, for purely statistical fluctuations, the observable $\nu_{\text{dy}n}$, is zero by design. In presence of dynamical fluctuations from any source of origin, the value of $\nu_{\text{dy}n}$ should be non-zero [16–18]. The other advantage of using $\nu_{\text{dy}n}$ is its robustness against detector effects like efficiency, acceptance
Using the generating function approach [15], the robustness of the observables against detector inefficiencies and sensitivity towards signals of ch-γ correlation has been shown [6][7]. \( \nu_{\text{dyn}} \) has a strong centrality dependence which arises due to its dependence on the initial gluon multiplicity [7]. According to the “Central Limit Theorem (CLT)” [21][22], the observable \( \nu_{\text{dyn}}^{\gamma-\text{ch}} \) has a \( A + B/\sqrt{(N_{\text{ch}})(N_{\gamma})} \) dependence on the charged particle and photon multiplicities, for the generic case of pion production. The centrality dependence of \( \nu_{\text{dyn}} \) in terms of the average experimental multiplicity observable \( \sqrt{(N_{\text{ch}})(N_{\gamma})} \) in the context of ch-γ correlation has been explored in this thesis for a range of energies.

The second observable \( r_{m,1} \), also called the Minimax or the robust observable was used for the first time by the Minimax collaboration [15] for the search of DCC-like phenomenon in p+p collisions. \( r_{m,1} \) is defined in terms of charged particle and photon multiplicities and the neutral pion fraction \( f \) as

\[
r_{m,1}^{\gamma-\text{ch}} = \frac{\langle N_{\text{ch}}(N_{\text{ch}} - 1) \cdots (N_{\text{ch}} - m + 1) N_{\gamma} \rangle \langle N_{\text{ch}} \rangle}{\langle N_{\text{ch}}(N_{\text{ch}} - 1) \cdots (N_{\text{ch}} - m) \rangle \langle N_{\gamma} \rangle} = \frac{\langle f(1-f)^m \rangle \langle 1-f \rangle}{\langle (1-f)^{m+1} \rangle \langle f \rangle} .
\]

(4.6)

The observable is designed to give a value of unity for Poissonian distributions, i.e. statistical fluctuations for all the moments. The observable \( r_{m,1} \) for the lowest order of \( m \) \( (r_{1,1} , m = 1) \) can be written in terms of \( \omega_{\text{ch}} \) and \( \text{corr}_{\gamma-\text{ch}} \) as

\[
r_{1,1} = \text{corr}_{\gamma-\text{ch}} / \omega_{\text{ch}}
\]

(4.7)

So, the information carried by \( r_{1,1} \) is the same as \( \nu_{\text{dyn}} \), but the higher order terms \( r_{2,1} \), \( r_{3,1} \) are more sensitive to ch-γ correlation signals. \( r_{m,1} \) is independent of detector efficiency [7][15] and the extra sensitivity of its higher order terms towards ch-γ correlation is the added advantage of using this observable. \( r_{m,1} \) as a function of \( m \) can be expressed as [7][15][23]

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\[
    r_{m,1}^{\gamma-\text{ch}} = 1 - \frac{m \zeta}{m + 1}
\]

(4.8)

where the parameter \( \zeta \) depends on the strength of \( \text{ch-}\gamma \) (anti-)correlation and its value lies between \( 0 \leq | \zeta | \leq 1 \). \( \zeta > 0 \) implies anti-correlation and \( \zeta < 0 \) implies the presence of correlation between charged and neutral particles. \( \zeta = 0 \) is the Poissonian limit for merely statistical fluctuations and this is the generic scenario, when the production of pions following isospin symmetry is in equal abundance. This leads to \( r_{m,1}^{\text{gen}} = 1 \) \([7][15]\) for the generic case. In the scenario of DCC events \( \zeta = 1 \) and \( r_{m,1}^{\text{DCC}} = \frac{1}{m+1} \) \([7][15]\). The centrality and charge dependence of the observables \( \nu_{\text{dyn}} \) and \( r_{m,1} \) for a range of energies has been explored in this work.

### 4.2.2 Detectors used for the analysis

The simultaneous measurement of photons and charged particles in a common \( \eta-\phi \) phase space at forward rapidity is performed using the Photon Multiplicity Detector (PMD) and the Forward Time Projection Chamber (FTPC). The minimum bias trigger selection for the analysis has been done using a combination of the Zero Degree Calorimeter and the Vertex Position Detector. To prevent self-correlation, charged tracks for the \( \gamma-\text{ch} \) correlation measurement and for centrality selection have been chosen from different detector systems ensuring there is no overlap between their rapidity ranges \([24]\). The minimum-bias uncorrected charged particle multiplicity, also known as reference multiplicity (refmult), measured by the Time Projection Chamber in the pseudorapidity range \( | \eta | < 0.5 \) has been used to determine the collision centrality for this analysis.

The pre-shower PMD detector which has already been discussed in Sec. 2.3.3 is designed to measure the multiplicity of photons in the pseudorapidity range of \(-3.7 \leq \eta \leq -2.3\). The detector consists of two proportional counter planes separated by a lead converter of a thickness equivalent of 3 radiation lengths. The front plane or the CPV (Charged Particle Veto) plane that faces the interaction point is used as a veto plane for hadron rejection. The data from the pre-shower plane, located behind the lead converter which detects the electromagnetic shower
from the photons incident on the converter in the form of large clusters, is used for the analysis.

The two FTPC's located on either side of the collision vertex, at the forward pseudorapidity region $2.5 < |\eta| < 4.0$, measure the charge state and transverse momentum of charged particles. The limited space in the FTPC does not allow identification of charged tracks but the use of a radial drift field perpendicular to the magnetic field direction of the STAR magnet helps the FTPC to put up with the high track density. Simulation results show that this design helps the FTPC achieve a two-track resolution up to 2 mm [25]. The detector is described in detail in Sec. 2.3.4. Fig. 4.1 shows the common PMD-FTPC $\eta$-$\phi$ coverage used in this analysis for the simultaneous measurement of photons and charged particles in the overlapping pseudorapidity region $-3.7 < \eta < -2.8$.

Figure 4.1: A schematic diagram of the common PMD-FTPC acceptance for the measurement of $\gamma$-ch correlation.
4.2.3 Datasets and Kinematic Cuts for the BES energies

The charged-neutral correlation has been done for Au+Au collisions at the RHIC Beam Energy Scan (BES) energies $\sqrt{s_{NN}} = 62.4$, 39, 27, 19.6 GeV and compared with the results obtained at $\sqrt{s_{NN}} = 200$ GeV. The details of the analysis at 200 GeV can be found in [6]. The Au+Au collisions at the four different BES energies took place over the course of two years, 2010 and 2011. The details of the datasets used for this analysis can be found in Table 4.1. As described in the previous section, the analysis was done in the common PMD-FTPC geometric acceptance. The statistics shown against the dataset of each energy is the number of events after the removal of bad runs and applying a narrow z-vertex cut ($-5 < V_z < 5$). The z-vertex is the position of the collision vertex along the z-direction or the direction of the beam axis. The narrow z-vertex cut helps to minimize the variation of the combined geometric acceptance of the PMD and the FTPC detectors, event-by-event.

**Table 4.1: Summary of data sets and different kinematic cuts used in this analysis.**

| Data Set: | Run 10, Au+Au $\sqrt{s_{NN}} = 62.4$ GeV, $\sim 0.5$M after correction |
| Data Set: | Run 10, Au+Au $\sqrt{s_{NN}} = 39$ GeV, $\sim 2.2$M after correction |
| Data Set: | Run 11, Au+Au $\sqrt{s_{NN}} = 27$ GeV, $\sim 1.1$M after correction |
| Data Set: | Run 11, Au+Au $\sqrt{s_{NN}} = 19.6$ GeV, $\sim 0.7$M after correction |

FTPC: Primary track: number of fit points $> 5$

$-3.7 < \eta < -2.8$ (Common $\eta - \phi$ with PMD)

$0.15 < p_T < 1.5$ GeV/c

$d\alpha < 3$ cm

PMD: Cluster ADC cut $> 8 \times$ MIP

$-3.7 < \eta < -2.8$ (Common $\eta - \phi$ with FTPC)

number of cells in a cluster $> 1$

The basis of this analysis is the simultaneous measurement of charged particles and photons in the common PMD-FTPC acceptance. The details of the kinematic cuts applied for the selection of charged tracks from the FTPC and the identification of photon clusters after hadron discrimination in the PMD have also been highlighted in Table 4.1. The FTPC does not have particle identification capability, so the analysis is performed on inclusive charged particles. The criteria for the validity of a charged track are at least 5 hits in the FTPC and a distance of
closest approach (dca) from the collision vertex less than 3 cm. The transverse momentum cut for the FTPC, $0.15 < p_T < 1.5$ GeV/c facilitates the selection of pions of low momentum relevant to this analysis. As discussed in Ref. [25], the choice of the particular set of cuts used here minimizes the contribution from split tracks and keeps the contamination of charged tracks due to $\gamma$ conversion ($\gamma \rightarrow e^+ e^-$) background below $\sim 5\%$. A set of kinematic cuts are also imposed on the PMD for photon cluster selection. The details of the photon cluster extraction procedure can be found in [14]. Charged hadrons giving signals in the PMD affect a single cell on average, hence, the validity of a photon cluster requires the number of cells in a cluster to be more than 1, while the signal strength of the cluster has to be 8 times greater than the average signal strength of all the cells due to a minimum ionizing particle (MIP). A purity of $\sim 70\%$ can be obtained for photon clusters using this particular set of validity criteria [8] lowering the contribution due to charged particle contamination. The purity of the sample cannot be improved upon by the use of stricter kinematic cuts and an impurity of $\sim 30\%$ in the photon sample is inherent.

4.2.4 Quality Assurance (QA) plots and Run-by-Run QA for the BES energies

Figs. 4.2 - 4.5 illustrate the plots relevant to this analysis for the energies 62.4, 39, 27 and 19.6 respectively. In these QA plots, the top-left plots shows the distribution of reference multiplicity (refmult), having characteristic shape of the minimum-bias distributions. The reference multiplicity distribution is the uncorrected charged particle multiplicity from the TPC measured in the pseudorapidity region $|\eta| < 1$. The top-right plot shows the $z$-vertex ($V_z$) distribution and the accepted range. The two plots at the bottom of Figs 4.2 - 4.5 show the distributions of the minimum-bias photon cluster (left) and charged track (right) multiplicities from the PMD and FTPC detectors, respectively. These are uncorrected distributions and their ranges reduce as we go down to lower $\sqrt{s}$ values. The shapes of the photon cluster and the charged track distributions mimic the characteristics of a minimum-bias distribution, highlighting the robustness of
the observables. The selection of event centrality [26] and the correction of the bin-width effect for this analysis have been performed using the refmult distribution. The $z$-vertex distribution is shown for the range $-30 < V_z < 30$. 

Figure 4.2: QA plots for $\sqrt{s_{NN}} = 62.4$ GeV
Figure 4.3: QA plots for $\sqrt{s_{NN}} = 39$ GeV
Figure 4.4: QA plots for $\sqrt{s_{NN}} = 27$ GeV
Figure 4.5: QA plots for $\sqrt{s_{NN}} = 19.6$ GeV
Figure 4.6: Run-by-Run QA plots for $\sqrt{s_{NN}} = 19$ GeV

Figs. 4.6 - 4.9 illustrate the run-by-run QA plots of the photon and charged particle multiplicities along with the quantities related to them plotted versus the run numbers for all BES energies, from 19.6 - 62.4 GeV. The run-by-run QA over the range of run numbers has been done with a stable PMD-FTPC geometric acceptance. The x-axis of the plot shows the range of run numbers for a particular collisional energy, converted into a Run Index for convenience. The y-axis represents the variation of the quantities $\langle N_\gamma \rangle$, $\langle N_{ch} \rangle$, $\langle \eta_{ch} \rangle$, $\langle \phi_{ch} \rangle$, $\langle \eta_{\gamma} \rangle$, $\langle \phi_{\gamma} \rangle$ averaged over the most central (0-10%) events in a particular run number. The mean of the quantities over the range of run numbers is represented by the solid line, while the two dashed lines represent a 2-$\sigma$ variation w.r.t. the mean value. A variation greater than 2-$\sigma$ from the mean-value
for quantities other than the charged particle and photon multiplicities is used to determine the bad runs and those runs have been rejected.

4.2.5 Correction of the Bin-width effect

The selection of centrality (binning of events in terms of multiplicity) in this analysis has been performed using the uncorrected minimum-bias multiplicity distribution at midrapidity (refmult), measured by the TPC within (|η| < 1). This minimum-bias distribution is divided into different centrality bins, but, since the distribution is not flat, this leads to an artefact known as the centrality bin-width effect. The centrality binning is done in terms of a range of the reference
multiplicities and is done by dividing the multiplicity distribution accordingly. The distribution has a distinct falling nature at higher multiplicity. So, in the case of most central events and wide centrality bins that include greater variation of the nature of the distribution, the bin-width correction becomes critical. This artefact can thus introduce additional fluctuations by means of an artificial centrality dependence in the final observable [6][24][27][28]. Simulations using the UrQMD model clearly demonstrate the effect of bin-width [24]. The weighted averages of the event-by-event multiplicities of photons and charged particles across the min-bias reference multiplicity distribution corrects for the bin-width effect.
4.2.6 Error Analysis

Statistical Error:

The estimation of statistical error for different observables used in this analysis has been performed using the Bootstrap method [29]. In this statistical technique, the error is estimated by multiple uses of the data sample according to the following procedure:

- ‘n’ number of identical minimum bias data samples are created by reorganizing the event numbers. The number of events in the ‘n’ samples remain the same, but, since the events are not identical, the samples give rise to statistical fluctuations in the values of the
observables.

- The relevant observables $\nu_{\text{dyn}}$ and $r_{m,1}$ after bin-width correction are calculated centrality-wise, individually for the 'n' event samples.

- The values of the bin-width corrected observables for the different event samples result in an approximate Gaussian distribution. The variance of this distribution provides the statistical error.

**Systematic Error:**

The systematic errors for the two observables $\nu_{\text{dyn}}$ and $r_{m,1}$ have been calculated by varying the kinematic cuts applied on charged particles and photons, shown in Table 4.1. The sources of systematic error in this case are variation of the distance of closest approach (dca), variation of the cluster adc cut also known as the MIP cut and the z-vertex cut. The final systematic error value for the observable $\nu_{\text{dyn}}$ is obtained by adding the three different sources of errors in quadrature as shown below:

$$sysErr(\nu_{\text{dyn}})^{total} = \sqrt{(\nu_{\text{std}}^{\text{dca}} - \nu_{\text{dyn}}) \Delta \text{dca}^2 + (\nu_{\text{std}}^{\text{MIP}} - \nu_{\text{dyn}}) \Delta \text{MIP}^2 + (\nu_{\text{std}}^{\text{Vz}} - \nu_{\text{dyn}}) \Delta \text{Vz}^2} \ (4.9)$$

while the final systematic error value for $r_{m,1}$ can be expressed as:

$$sysErr(r_{m,1})^{total} = \sqrt{(r_{m,1}^{\text{dca}} - r_{m,1}) \Delta \text{dca}^2 + (r_{m,1}^{\text{MIP}} - r_{m,1}) \Delta \text{MIP}^2 + (r_{m,1}^{\text{Vz}} - r_{m,1}) \Delta \text{Vz}^2} \ (4.10)$$

The standard values of the observables, $\nu_{\text{std}}^{\text{dyn}}$ and $r_{m,1}^{\text{std}}$ have been obtained by calculating the observables after implementing the standard cuts as shown in Table 4.1.
4.2.7 Limitations of the ch-γ correlation analysis

The ch-γ correlation in the framework of the STAR experiment certainly has its share of limitations. They have been highlighted below:

- The PMD detector does not have the capability to measure photon momentum. As such, the analysis cannot be performed specifically with low momentum photons as is the requirement according to theoretical predictions [8].

- Ideally, this analysis should be restricted to photons coming from the decay of neutral pions (π⁰), but, due to unavailability of the momentum information, all photons are selected [8].

- Similarly, for the charged tracks, a lack of particle identification in the FTPC means all charged tracks are selected for the analysis, not just charged pions (π±) [8].

- Although there is an overlap in the photon and charged particle momentum ranges, their momentum ranges are not identical. The photons selected in this analysis have reasonable efficiency for p_T > 20 MeV/c are selected in the analysis, while all charged particles within 0.15 < p_T < 1.5 GeV/c are selected [8].

So, to work around all these limitations, it is extremely crucial to have an identical η-φ phase space for the photons and charged particles. That is why, the analysis is done with charged particles and photons selected within the common PMD-FTPC acceptance. Moreover, for the published charged-neutral correlation results at the top RHIC energy, conclusions are derived only after detailed comparisons with particle production models like HIJING, GEANT+HIJING and Mixed event study, as will be shown in the next section [8].
4.3 Results for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV and at BES energies

The centrality (multiplicity) dependence of the three individual terms $\omega_{\mathrm{ch}}$, $\text{corr}_{\gamma-\mathrm{ch}}$ and $\omega_{\gamma}$ of the observable $\nu_{\text{dyn}}^{\gamma-\mathrm{ch}}$ have been shown in Fig. 4.10(a)-4.10(c) [8] for $\sqrt{s_{NN}} = 200$ GeV and all three terms show a similar trend. The values of real data have been compared with mixed events. At higher values of multiplicity, all three terms approach their Poissonian limit. The mixed events are created by mixing raw charged tracks and photon clusters from different events of identical centrality and narrow $z$-vertex cut. The multiplicity of raw tracks and clusters is the same as that of a particular real event and similar kinematic cuts as real data are applied to it. Mixed events by design have only statistical fluctuations and the large deviation from the Poissonian limit can be attributed to finite multiplicity. Mixed event values approach their Poissonian limit for most central events. The higher values of $\omega_{\mathrm{ch}}$ [Fig. 4.10 (a)] and $\omega_{\gamma}$ [Fig. 4.10 (c)] compared to mixed events indicate the presence of fluctuations other than statistical in origin.

The decay of neutral pions ($\pi^0$) to photons, introduces additional fluctuations in the $\omega_{\gamma}$ term which explains the higher difference in values between the real and mixed events for the observable, a feature seen also for the simulated HIJING events. The correlation term $\text{corr}_{\gamma-\mathrm{ch}}$ [Fig. 4.10(b)] is higher compared to mixed events for peripheral events, comparable at mid-central events and lower for most central events. The variation of the observable $\nu_{\text{dyn}}^{\gamma-\mathrm{ch}}$ as a function of $\sqrt{\langle N_{\mathrm{ch}} \rangle \langle N_{\gamma} \rangle}$ is shown in Fig. 4.10(d). While real data show a non-zero, positive value of $\nu_{\text{dyn}}$ at all centralities, mixed event values for all centralities are consistent with Poissonian expectations, as per the design of $\nu_{\text{dyn}}$ that statistical fluctuations are eliminated. The data is fit with a function of the form $A + B/\sqrt{\langle N_{\mathrm{ch}} \rangle \langle N_{\gamma} \rangle}$ consistent with CLT predictions [7]. The calculations for data are also compared to results obtained for simulated events using the particle production model HIJING and HIJING simulated through GEANT to incorporate detector effects that might be present in the data sample. The simulation results are close
Figure 4.10: The observable $\nu_{\text{dyn}}$ and the three individual terms plotted as a function of the multiplicity variable in the acceptance of interest $\sqrt{\langle N_{\text{ch}}, N_{\gamma} \rangle}$ at $\sqrt{s_{NN}} = 200$ GeV. The statistical and systematic uncertainties are represented by vertical lines and boxes respectively. For model calculations, the statistican uncertainties are represented by bands [8].

to the Poissonian limit for most central events while the lower HIJING+GEANT values in the peripheral bins can be attributed to effects of mis-identification of photons [8], which the observable $\nu_{\text{dyn}}$ is not designed to eliminate. The non-zero positive data values seen for all centralities shows the evidence of the presence of dynamical signals at all centralities and the dissimilarity in trend with the GEANT+HIJING simulation result indicates that it is not due to detector effects [8]. In the experimental setup, there are two FTPC’s located on either side of the collision side. The measurements of $\nu_{\text{dyn}}$ in Fig. 4.11(a) have been done with charged particles and photons measured in the identical pseudorapidity region $-3.7 < \eta < -2.8$. This
is known as the measurement on the “same side”. The measurement of photons in the range 
$-3.7 < \eta < -2.8$ and charged particles in the range $2.8 < \eta < 3.7$ is known as the “away side”
measurement and is shown in Fig. 4.11(b). The reconstruction efficiency for the FTPC in the
pseudorapidity range $2.8 < \eta < 3.7$ being lower, there is a difference in multiplicity $\sqrt{\langle N_{ch} N_\gamma \rangle}$
between the two sides, in spite of having the same coverage in $\eta$-$\phi$ space.

Figure 4.11: Measurement of $\nu_{\text{dyn-ch}}^{\gamma}$ from charged particles and photons at $\sqrt{s_{NN}} = 200$ GeV
in the same pseudorapidity range $-3.7 < \eta < -2.8$ (same side) is compared to photons measured
in the range $-3.7 < \eta < -2.8$ and charged particles measured in the range of $2.8 < \eta < 3.7$
(away-side). Values of $\nu_{\text{dyn-ch}}^{\gamma}$ measured for the same side are significantly different for data and
model calculations, whereas, $\nu_{\text{dyn-ch}}^{\gamma}$ values for the away side are in good agreement, ruling out
detector effects as the reason and hinting strongly at dynamical origin [8].

There is a significant difference between real data and simulation results for the same side
which vanishes in the case of the away side. This result bolsters the argument that the difference
between real data and model studies as seen in the case of the same side is not a detector effect.
The difference observed for the case of same side between the HIJING and HIJING+GEANT
curves quite obviously vanishes when photons and charged particles are measured in different acceptances as the contamination is absent. Any other artefacts related to measurement are taken care of by the robustness of the observable $\nu_{\text{dyn}}$. Another thing evident from the away side plot is that data and model seem to follow a universal trend with multiplicity $\sim 1/\sqrt{\langle N_{\text{ch}} N_{\gamma} \rangle}$.

Taking the away side plot as a reference seems to suggest that the deviation between real data and model seen in the same side is dynamical in origin [8].

Figure 4.12: $\omega_{\gamma}$ as a function of multiplicity at all energies ($\sqrt{s_{NN}} = 200$ GeV - 19 GeV). The statistical error is shown by vertical lines and systematic error is represented by boxes.

Fig. 4.12 - 4.14 show a comparison plot of the centrality dependence of the terms $\omega_{\gamma}$, $\omega_{\text{ch}}$ and $\text{corr}_{\gamma-\text{ch}}$ at all energies $\sqrt{s_{NN}} = 200, 62.4, 39, 27$ and 19 GeV. Charged particles and photons are measured in the same pseudorapidity coverage $-3.7 < \eta < -2.8$. The individual photon and charged particle fluctuation terms, $\omega_{\gamma}$ and $\omega_{\text{ch}}$ show a monotonic energy dependence and approach the Poissonian limit (unity) for higher values of multiplicity. The Correlation term $\text{corr}_{\gamma-\text{ch}}$ shows a weak energy dependence. Compared to the top energy, the fall in the values of the observables $\omega_{\text{ch}}$, $\text{corr}_{\gamma-\text{ch}}$ and $\omega_{\gamma}$ at lower energies is quite sharp.

Fig. 4.15 shows the comparison plot of the centrality dependence of the observable $\nu_{\gamma-\text{ch}}$.
Figure 4.13: $\omega_{\text{ch}}$ as a function of multiplicity at all energies. The statistical error is shown by vertical lines and systematic error is represented by boxes.

Figure 4.14: $\text{corr}_{\gamma-\text{ch}}$ as a function of multiplicity at all energies. The statistical error is shown by vertical lines and systematic error is represented by boxes.
Figure 4.15: A comparison plot of the multiplicity dependence of the observable $\nu_{\gamma}^{ch}$ as a function of the multiplicity term $\sqrt{\langle N_{ch} N_\gamma \rangle}$ in the acceptance of interest at all energies. The statistical error is shown by vertical lines and the systematic error is represented by boxes.

at all energies. A non-zero, positive value of $\nu_{\gamma}^{ch}$ is observed for all energies at all centralities along with a monotonic decrease with energy. The non-zero $\nu_{\gamma}^{ch}$ value could be indicative of the presence of dynamical fluctuations. Although nothing firm can be concluded from the preliminary results obtained for the BES energies, the study of the energy dependence and the consistent non-zero positive signals obtained for all the energies substantiates the belief that the physics origin of the charged-neutral correlation signal is dynamical in nature. It shows that the $\nu_{\gamma}^{ch}$ value along with all other terms decreases with energy, thereby showing the reduction in dynamical fluctuations.

To understand the dynamics of the ch-$\gamma$ correlation better, we have studied the correlation of positively and negatively charged particles using the observable $\nu_{\text{dyn}}$. The charge dependence of $\nu_{\text{dyn}}$ has been studied for all energies. The results obtained at the top RHIC energy [8] have been shown in Fig. 4.16. The results obtained for the correlation between different combinations of charged particles and photons are very similar. However, for the combination of positively
and negatively charged particles, the value of the observable $\nu_{\text{dyn}}^{ch^+ - ch^-}$ is different both in sign and in magnitude when compared to $\nu_{\text{dyn}}^{\gamma - ch^-}$.

![Graph showing charge dependence of observable $\nu_{\text{dyn}}$ at $\sqrt{s_{NN}} = 200$ GeV as a function of multiplicity.](image)

Figure 4.16: Charge dependence of the observable $\nu_{\text{dyn}}$ at $\sqrt{s_{NN}} = 200$ GeV as a function of multiplicity. The correlation between the charged particles and photons have been measured using the FTPC and PMD detectors in the pseudorapidity region $-3.7 < \eta < -2.8$. The statistical uncertainties have been represented by vertical lines while systematic uncertainties have been represented by boxes [8].

As a consequence of the correlated production of charged particles from neutral resonance decay [8], the large correlation term $\text{corr}_{ch^+ - ch^-}$ leads to negative values of the observable $\nu_{\text{dyn}}^{ch^+ - ch^-}$. The negative values obtained for $\nu_{\text{dyn}}$ are in good agreement with previous STAR results at $\sqrt{s_{NN}} = 200$ for Au+Au collisions at midrapidity [30]. The nature of $\nu_{\text{dyn}}$ to be negative has also been previously shown in simulation study with a particle production model where resonance decay heavily influences particle production [16]. The difference in the nature of $\gamma$-ch and $ch^+ - ch^-$ correlation clearly indicates that the decay of resonances does not contribute to the dynamical signal obtained for $\gamma$-ch correlation the way it does for $ch^+ - ch^-$ correlation and hints at the existence of a different correlated production mechanism for charged particles.
and photons. The decay of resonances ($\rho^\pm \to \pi^\pm + \pi^0$ or $\omega \to \pi^+ + \pi^- + \pi^0$) enhances correlations between charged and neutral particles, but, at the same time possible suppression of this correlation due to the dominance of hadronic rescattering [31][32] processes like meson-meson charge exchange [31] ($\pi^+ + \pi^- \to \pi^0 + \pi^0$) or baryon-meson reactions [31][32] ($p + \pi^- \to n + \pi^0$) might be responsible for the nature of the correlation observed for charged and neutral particles.

Figure 4.17: Charge dependence of the observable $\nu_{\text{dyn}}$ for $\sqrt{s_{NN}} = 62$ GeV as a function of multiplicity.

Consistent with observations at the top RHIC energy, the $ch^+ - ch^-$ correlation is different in sign and magnitude from $ch-\gamma$ correlation at all energies for all centralities as shown in Figures 4.17 - 4.20, within error bar. The study of the charge dependence of the observable $\nu_{\text{dyn}}$ for the BES energies highlights the fact that charged-neutral correlation and net-charge correlation are different in nature and are influenced by contrasting correlation mechanisms.

The robust observable $r_{m,1}$ that was introduced by the MiniMax Collaboration enhances our knowledge about charged-neutral correlation by extracting information about deviation of charged-neutral correlation from expectations based on generic production of pions due to isospin symmetry. This observable has a value of unity for the case of generic pion production ($r_{m,1}^{\text{gen}} = 1$) as has already been discussed earlier. A deviation from unity in the value of $r_{m,1}$ would thus be indicative of anomalous pion production, possibly due to the occurrence of DCC-like
Figure 4.18: Charge dependence of the observable $\nu_{\text{dyn}}$ for $\sqrt{s_{NN}} = 39$ GeV as a function of multiplicity.

Figure 4.19: Charge dependence of the observable $\nu_{\text{dyn}}$ for $\sqrt{s_{NN}} = 27$ GeV as a function of multiplicity.

events. The multiplicity dependence of the first three orders $r_{1,1}$, $r_{2,1}$, and $r_{3,1}$ as a function of $\sqrt{\langle N_{\text{ch}}N_{\gamma} \rangle}$ at $\sqrt{s_{NN}} = 200$ GeV have been shown in Fig. 4.21 [8]. The figure shows the variation of $r_{m,1}$ ($m = 1 - 3$) for real data, mixed events and simulation results using HIJING and GEANT+HIJING. The value of the observable obtaind for the HIJING and mixed event
Figure 4.20: Charge dependence of the observable $\nu_{\text{dyn}}$ for $\sqrt{s_{NN}} = 19$ GeV as a function of multiplicity.

cases is almost constant for the three cases ($m = 1-3$) and approaches the generic limit. This could essentially highlight similarities in the nature of pion production in the HIJING event generator and the generic case of pion production. Real data and GEANT+HIJING results show a similarity in trends, but, the value of the observable $r_{m,1}$ at higher centralities is negative for data compared to GEANT+HIJING values, which is always positive. The contamination introduced in the sample when it is passed through GEANT due to detector effects like misidentification is likely responsible for the difference in HIJING and GEANT+HIJING values, which increases for higher orders of $r_{m,1}$. The deviation from the generic limit observed in case of data at higher centralities is $\sim 1\%$ [8]. Fig. 4.22 shows the value of $r_{m,1}$ plotted as a function of its order $m$ for most central events within the multiplicity limit of $47 < \sqrt{N_{\text{ch}}N_{\gamma}} < 54$. The trend seen for data is the opposite of model behaviour, showing a deviation $\sim 1\%$ from generic expectation [8].

The values of the different orders of the robust observable for the BES energies have been calculated and shown in Figs. 4.23 - 4.25. Definitive conclusions cannot be drawn from the preliminary results, other than the fact that the values are close to the generic expectation over the energy range.
Figure 4.21: The first three orders of the observable $r_{m,1}$ ($m = 1 - 3$) as a function of multiplicity at $\sqrt{s_{NN}} = 200$ GeV. Results obtained from real data, mixed-events and simulation results using HIJING and GEANT+HIJING have been compared. Statistical errors are represented by vertical lines and systematic errors are represented by boxes. The statistical errors for simulation results have been represented by bands [8].

4.4 Conclusions

The measurement of event-by-event correlations between inclusive charged particle and photon multiplicities at forward rapidity using the detectors, the FTPC and PMD respectively in the common pseudo-rapidity coverage $-3.7 < \eta < -2.8$ has been discussed in this chapter. The results obtained for the RHIC Beam Energy Scan (BES) energies $\sqrt{s_{NN}} = 62.4, 39, 27, 19.6$ GeV have been compared with the published results for $\sqrt{s_{NN}} = 200$ GeV [8]. The measurement of charged-neutral (photon) correlation is a first such attempt at the RHIC energies. $\text{ch-}\gamma$ correlation is heavily influenced by the correlated production of charged and neutral pions and
the objective of this analysis is to look for manifestations of dynamical physics signals beyond generic expectations for pion production following isospin symmetry. The observables \( \nu_{\text{dyn}} \) and \( r_{m,1} \), created from factorial moments of charged particle and photon multiplicities, designed to study ch-\( \gamma \) correlation have been used for this analysis. The datasets for the analysis have been selected after extensive cleanup. The analysis has been performed in the overlapping PMD-FTPC \( \eta-\phi \) phase space and to take care of the non-uniformity in the detector acceptance, a run-by-run QA has been performed to ensure data quality. The bad run numbers have been extracted by putting a 2-\( \sigma \) cut on the averages of quantities related to charged particle and photon multiplicities. Statistical and Systematic uncertainties have been estimated and binwidth correction has been performed. The value of the observable \( \nu_{\text{dyn}}^{\gamma-\text{ch}} \) at \( \sqrt{s_{NN}} = 200 \text{ GeV} \) has been measured for two distinct scenarios, charged particles and photons measured in the identical \( \eta-\phi \) acceptance \((-3.7 < \eta < -2.8) \) [same side] and charged particles measured in the acceptance \((3.7 < \)
Figure 4.23: $r_{1,1}$ as a function of multiplicity for the BES energies compared to $\sqrt{s_{NN}} = 200$ GeV.

Figure 4.24: $r_{2,1}$ as a function of multiplicity for the BES energies compared to $\sqrt{s_{NN}} = 200$ GeV.

$\eta < 2.8$) and photons in the acceptance ($-3.7 < \eta < -2.8$)[away side]. The $\nu_{\gamma_{\text{ch}}}$ value obtained for the same side is non-zero and positive at all centralities beyond model predictions, while
Figure 4.25: $r_{3,1}$ as a function of multiplicity for the BES energies compared to $\sqrt{s_{NN}} = 200$ GeV.

no significant deviation in the $\nu_{\gamma-\text{ch}}^{\text{ch}}$ value from model predictions has been observed for the away side. This is possibly indicative of the fact that signals of ch-\gamma correlation are dynamical in origin [8]. The study of the centrality dependence of the $\nu_{\gamma-\text{ch}}^{\gamma-\text{ch}}$ observable reveals an $A + B/\sqrt{\langle N_{\gamma}\rangle}$ dependence as per Central Limit Theorem (CLT) predictions [8]. $\nu_{\gamma-\text{ch}}^{\gamma-\text{ch}}$ shows an energy dependence for the BES energies and is non-zero and positive for all centralities and all energies. As we go down to lower energies ($\sqrt{s_{NN}}$), the fall in the value of $\nu_{\text{dy}}$ as a function of multiplicity is very sharp. In order to understand ch-\gamma correlation dynamics better, the correlation between positively and negatively charged particles measured in the same acceptance has also been studied. The $\nu_{\text{dy}}^{\text{ch}^{+}-\text{ch}^{-}}$ term is qualitatively and quantitatively different from $\nu_{\text{dy}}^{\text{ch}^{-}}$, in sign and magnitude [8]. The negative values of $\nu_{\text{dy}}^{\text{ch}^{+}-\text{ch}^{-}}$ can be attributed to the large $\text{corr}_{\text{ch}^{+}-\text{ch}^{-}}$ term arising due to correlated production of charged particles from resonance decays. The difference in the nature of the values of the observable $\nu_{\text{dy}}$ for the two cases emphasises on different production mechanisms for positively and negatively charged particles and charged particles and photons. While there is a predominance of decay correlation in case of net-charge
correlation, ch-γ correlation seems to be influenced by hadronic rescattering processes [8]. The charge dependence of the observable $\nu_{\text{dyn}}$ has been studied at the BES energies and the results obtained are consistent with observation at the top RHIC energy. Correlations between different combinations of charged particles and photons yield results different in sign and magnitude from correlations between positively and negatively charged particles at all energies. The robust or the MiniMax observable $r_{m,1}$ that has been used in this analysis is specially designed to highlight differences arising in ch-γ correlation beyond expectations from the isospin symmetry dominated generic production of charged and neutral pions. The centrality dependence of the first three orders of the observable $r_{m,1}$ at $\sqrt{s_{NN}} = 200$ GeV indicates an opposite trend to model calculations and its value at higher centralities is lower than the generic expectation ($r_{m,1}^{\text{gen}} = 1$) [8]. In the multiplicity limit of $47 < \sqrt{\langle N_{\text{ch}}N_{\gamma} \rangle} < 54$ for most central events, the value of $r_{m,1}$ plotted versus its order $m$ indicates a slight deviation, less than 1% from expectation based on generic pion production [8]. Results obtained using the $r_{m,1}$ observable for the BES energies is close to the Poissonian-generic (unity) limit and inconclusive as far as any deviation from generic pion production expectation is concerned.
Bibliography


