Chapter 6

Azimuthal Anisotropy in Inclusive Photons

Flow has been studied in STAR extensively at mid-rapidity. At forward rapidity, due to limited detection efficiency, STAR has studied only charge particle $v_2$ using FTPC. PMD provides a good opportunity to complement this measurement. PMD measures inclusive photons which are primarily produced by the decay of neutral pions and eta. The charge particles formed in the initial stages of matter would undergo final state interactions with the medium long after formation. Neutral pions do not undergo Coulomb interactions in the final state. The distributions of photons are governed by known kinematics of neutral pion decay, and is incorporated in most event generators.

6.1 Software for Flow

The flow in azimuthal distribution of photons is determined using a software chain with the following makers:

(i) **StFlowMaker** : This maker reads the STAR muDST.root files and selects events based on trigger, centrality and the quality of the event, e.g. event vertex. For each selected event, charged particle tracks are selected for construction of the event plane. The selected tracks have to fulfill the conditions
given in Table 6.1. Event plane angle for each harmonic is calculated using the equation:

\[
\Psi_n = tan^{-1}\left( \frac{\sum_i w_i \sin(n\phi_i)}{\sum_i w_i \cos(n\phi_i)} \right) / n
\] (6.1)

where \(\phi_i\) is the azimuthal angle of the \(i^{th}\) particle in an event and the \(w_i\) are the weights. Each event is divided into two subevents, and the event plane is obtained for each of them. The information of event, subevents for each harmonic and all selection criteria (different \(\eta\) gap between subevents, elaborated later in this chapter) can be shared with other Makers in the chain.

(ii) **StPmdFlowMaker**: This Maker reads the information from muDST after StFlowMaker. It obtains the value of different harmonics of event plane and subevent planes calculated in StFlowMaker. In addition, the information of PMD Clusters from StPmdClusterCollection is stored in a tree which is stored in a nanoDST.root file. The nanoDSTs are downloaded locally for further analysis.

<table>
<thead>
<tr>
<th>Track Cut</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>(</td>
<td>\eta</td>
</tr>
<tr>
<td>nHitFits</td>
<td>(&gt; 15)</td>
</tr>
<tr>
<td>nHitFits / nHitsPoss</td>
<td>(&gt; 0.52)</td>
</tr>
<tr>
<td>DCA-Global (cm)</td>
<td>(&lt; 2)</td>
</tr>
<tr>
<td>(p (\text{GeV/c}))</td>
<td>(&gt; 0.5)</td>
</tr>
</tbody>
</table>

**Table 6.1**: Track cuts on TPC tracks used for flow analysis

Two passes of data are required for flow analysis. In the first pass, StFlowMaker fills the plots required to calculate the inverse azimuthal acceptance correction factors. The event plane calculated in the first pass, therefore, is the uncorrected event plane. During the second pass, StFlowMaker reads the acceptance plots, calculates the azimuthal acceptance correction factors and applies them when calculating the event plane. The event plane calculated in second pass is corrected for acceptance variation of TPC.
6.2 Event Plane and Resolution Using TPC

The event plane was measured using the charge particles tracks in Time Projection Chamber [69]. Since TPC takes data from $-1.3 \leq \eta \leq 1.3$ and PMD rapidity range is $-3.7 \leq \eta \leq -2.3$, there is a minimum of 1.0 unit of rapidity gap between any TPC track used for event plane calculation and any PMD cluster. This rapidity gap minimises any non-flow correlations in cluster distribution on PMD due to charged particles tracks in TPC.

The raw TPC event plane is obtained using the cuts on TPC tracks mentioned in Table 6.1. The event cuts are based on trigger, event centrality and vertex position. Any event showing large forward-backward asymmetry is also excluded, because these events were either at a $v_z$ position far removed from the nominal center of STAR or some part of TPC was not working. A cut on minimum number of tracks in TPC was also applied since these are necessary to calculate the event plane.

A total of 337K events were used for analysis. Table 6.2 shows the number of events in each centrality. The data of day 101 of Au+Au 39 A GeV collisions during BES Run was used for this analysis.

<table>
<thead>
<tr>
<th>Centrality (%)</th>
<th>No. of Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 5</td>
<td>21927</td>
</tr>
<tr>
<td>5 - 10</td>
<td>21724</td>
</tr>
<tr>
<td>10 - 20</td>
<td>44865</td>
</tr>
<tr>
<td>20 - 30</td>
<td>45344</td>
</tr>
<tr>
<td>30 - 40</td>
<td>44879</td>
</tr>
<tr>
<td>40 - 50</td>
<td>43192</td>
</tr>
<tr>
<td>50 - 60</td>
<td>43752</td>
</tr>
<tr>
<td>60 - 70</td>
<td>37380</td>
</tr>
<tr>
<td>70 - 80</td>
<td>35235</td>
</tr>
</tbody>
</table>

Table 6.2: This table shows number of events in each centrality bin.

6.2.1 Flattening TPC Event Plane

As mentioned earlier, the raw event plane from TPC was not isotropic in azimuthal plane as shown in Figure 6.1 by the solid line (in blue color). Each plot is for events
of different centralities, the plot in the right bottom box is for the most central and left top box is for the most peripheral events. A number of methods have been suggested in [48] to obtain a flat distribution of event plane angles. Inverse $\phi$ correction was employed to obtain a reasonable flattening. The results are shown in the Figure 6.1 by solid line (in red color). While this method removed most of the asymmetry of the event plane, the distribution was still not flat. This could be observed by fitting the event plane distribution to a first order polynomial, a straight line with a slope. A finite slope which was larger as compared to the error estimates on slope from fitting demonstrated that the event plane was not truly flat. An additional correction method of shifting the event planes was used to flatten the distribution.

In the first pass through the data locally, we calculated $< \sin(\text{inv}\psi_n) >$ and $<
The distribution of event plane angle $\psi_2$ obtained from the charged particle in the positive rapidity region of TPC (i) uncorrected event plane (blue line) (ii) corrected by phi weights (red line) and (iii) shifting method (black line). The green line is a straight line fit to the data after shifting.

$\cos(in\psi_n) >$ for different values of $n$ (harmonics) and for $i=\sim 1$ to $\sim 32$ for the whole data set and stored it for further use. In the second pass through the data, for each event, the amount of shifting was calculated using Equation 6.2 as given in [48]:

$$n\Delta\Psi_n = \sum_{i=1}^{i_{\text{max}}} \frac{2}{i} (\langle sin(in\Psi_n)\rangle \cos(in\Psi_n) + \langle cos(in\Psi_n)\rangle sin(in\Psi_n))$$  \hspace{1cm} (6.2)

Figure 6.1 shows the raw event plane (Blue solid line), event plane after acceptance correction (Red line) as well as shifted event plane (Black line) for each centrality. The shifted event plane distributions given by the black line can be seen to fit nicely
to a straight line (green line) where the slope parameter is consistent with zero
within the error estimates of this value.

The same procedure was also implemented for each subevent (see details of
subevents in the next section). Figure 6.2 and Figure 6.3 also gives the subevent
planes for the three cases mentioned above.

![Figure 6.3](image.png)

**Figure 6.3**: The distribution of event plane angle $\psi_2$ obtained from the charged
particle in the negative rapidity region of TPC (i) uncorrected event plane (blue
line) (ii) corrected by phi weights (red line) and (iii) shifting method (black
line). The green line is a straight line fit to the data after shifting.

### 6.2.2 Event Plane Resolution Correction

The event plane reconstructed through the TPC tracks is an estimate of the actual
reaction plane of that event. This estimate fluctuates about the reaction plane
because the number of tracks used for event plane reconstruction is finite. The
flow measured with respect to the estimated event plane would be less than the
flow with respect to the actual event plane. This uncorrected flow needs to be corrected for the event plane resolution. In order to estimate the flow correctly, it is important to estimate the resolution correction factor correctly.

For estimating the event plane resolution, two subevents were made out of each event. We used rapidity of the tracks to divide them into the subevents; all positive rapidity tracks make up one subevent and the negative tracks were the part of the other subevent. Event plane was estimated for each subevent and this event plane is also flattened using the same procedures used for full event plane and can be seen in above section. The correlation between the two subevent planes is a measure of the event plane resolution correction factor (RCF). The event plane resolution is determined from these subevent plane angle using the expression given below [48].

\[
< \cosn(\Psi_n - \Psi_r) = \frac{\sqrt{\pi}}{2\sqrt{2}} \chi_n \exp \left( \frac{-\chi_n^2}{4} \right) \left[ I_{\frac{1}{2}} \left( \frac{\chi_n^2}{4} \right) + I_{\frac{3}{2}} \left( \frac{\chi_n^2}{4} \right) \right] \]
\]

(6.3)

where \( \chi_n = v_n/\sigma \) and \( I_\nu \) is the modified Bessel function of order \( \nu \).

To remove non-flow correlations, the two subevents were created with a rapidity gap between them, the gap removes short range correlations between tracks in the two subevents. The data was analysed using two values of the gaps: 0.2 and 0.4 units of rapidity. These were called Selection 1 and Selection 2 respectively. The resolution correction factors for all centralities are shown in Figure 6.4 for Au+Au collisions at 39 GeV. The resolution is maximum for semi-central collisions, and decreases on both sides. Increasing the gap between the subevents decreases non-flow correlations, causing the RCF to decrease.

Subevent plane angles can also be used for obtaining the flow in photons. Since the number of tracks in a subevent is half of the number of tracks in the full event, the subevent plane is expected to have larger fluctuations about the reaction plane. The RCF values for subevent are given in Figure 6.5.
In the present study, besides the full event plane, the subevent plane on the west side TPC (away from PMD) has been used to further minimise non-flow correlation by increasing the gap between particles used to determine event plane and particles of interest. For this case, the RCF values will be lower, as seen in Figure 6.5. These are also obtained for two different $\Delta \eta$ and the value of RCF for larger rapidity gap is smaller, as expected.

6.3 Photon $v_2$ Using TPC Event Plane

The elliptic flow coefficient $v_2$ of photon like clusters in PMD is determined using the event plane from TPC. The event plane used is corrected for TPC acceptance and has also been shifted for additional flattening. Figure 6.6 shows the $v_2$ for
Figure 6.5: Centrality dependence of event plane resolution correction factor for subevents. The numbers on the x-axis indicate the nine centrality intervals, 1 corresponding to most peripheral.

different event centralities for different rapidity intervals for the following three cases.

(i) $v_2$ with respect to full event plane, without any weighting, corrected for full event plane resolution

(ii) $v_2$ with respect to subevent plane, without any weighting, corrected for subevent plane resolution

(iii) $v_2$ with respect to full event plane, weighted with acceptance of PMD and HLCF, corrected for full event plane resolution

Here HLCF is the hit loss correction Factor for each chain of PMD as discussed in Chapter 3.
Figure 6.6: Pseudorapidity dependence of $v_2$ for different centralities in Au+Au collisions at 39 A GeV.

The above three cases are shown for two different rapidity gaps between the two subevents. The legend in the top left panel shows two sets of symbols; the first column refer to smaller rapidity gap (0.2 units) and the second column are for larger rapidity gap (0.4 units). The errors plotted in the figure are statistical. Large error bars for the peripheral events are because of the smaller number of tracks per event, even though the number of events is not so small and due to poor event plane resolution.

The data shows that the elliptic flow clearly increases towards mid-rapidity for centrality bins 0 to 60%. For most peripheral events the errors are too large to conclude anything from the data. The elliptic flow also shows an increase from most central to mid-central events and then decreases for more peripheral collisions. This is exactly what is expected from the eccentricity values which are small for near symmetric central events and large for highly asymmetric mid-central events. Small differences are observed for all the 6 cases shown for each
centrality in the Figure 6.6 and these are included as systematic errors.

Besides acceptance and HLCF, each photon like cluster is also weighted with either Cluster ADC or Cluster Size. While the reasons for weighting with acceptance and HLCF are self evident, weighting with Cluster ADC or Cluster Size and not so evident and are elaborated here.

6.3.1 Photon $v_2$ Weighted with Cluster Properties

![Figure 6.7: Pseudorapidity dependence of $v_2$ weighted by cluster adc and cluster size, for different centralities in Au+Au collisions at 39 A GeV.](image)

It is now known that the efficiency and purity of photon sample measured in PMD depends on the occupancy of the detector. In an event, since particle density in-plane and out of plane is different, the occupancy in-plane and out of plane is different. This causes the efficiency and purity to change with azimuthal angle with respect to the event plane. The observed variation in efficiency and purity is because in a higher occupancy environment, clusters have a higher probability of
merging. This causes the mean cluster size to depend on occupancy. The bigger clusters have a higher probability of crossing the threshold conditions and resulting in higher efficiency as observed in previous chapters. If we only count the number of clusters, we are losing part of the information, since due to possible merging of clusters, the clusters are fewer, but bigger. This loss of anisotropic signal is countered by weighting the clusters with ADC or Cluster size. This weighting also takes into account the variation of efficiency and purity of $N_{\gamma-like}$ sample, with respect to the event plane.

If there is a slight effect of merging, then we expect a slightly higher value of $v_2$ when we use the Cluster ADC weighting as compared to ClusterSize weighting. This is because when two clusters merge due to their proximity, the resultant cluster size is smaller than the size of the two unmerged clusters. On the other hand the ADC being additive, the ADC of the merged cluster is sum of the

Figure 6.8: Pseudorapidity dependence of $v_2$ (mean of values obtained by weighting with cluster adc and cluster size) for different centralities in Au+Au collisions at 39 A GeV along with results of AMPT.
ADC of the individual clusters and hence provides a higher weight. All the four estimates of $v_2$ (two different weights and two different event plane resolution) are plotted in Figure 6.7 which shows $v_2$ as a function of pseudorapidity for each centrality bin. The estimates of $v_2$ obtained without any weighting are also shown for comparison. The mean values of $v_2$ for all four estimates are shown Figure 6.8. The estimated values of $v_2$ from AMPT are also shown in the same figure and seem to be in reasonable agreement with the data.

6.4 Photon $v_2$: Data and AMPT

![Figure 6.9: $v_2$ for photons at forward rapidity for different centrality bins in Au+Au collisions at 39 GeV. The results of AMPT are also shown.](image)

The measurements of $v_2$ of photons in the forward rapidity are now compared with AMPT [80] results for Au+Au collisions at 39 A GeV. The parameters of AMPT
version used for this purpose were tuned to multiplicity as detailed in Chapter 5. $v_2$ has been measured with respect to the event plane determined from TPC tracks while the participant plane has been used for AMPT. The values in data are expected to be a little smaller that those from AMPT as argued in Chapter 5, and also observed in Figure 6.9. Elliptic flow of photons integrated over the rapidity range $-3.7 \leq \eta \leq -2.3$ was obtained for Au+Au collisions at 39 A GeV. The Figure 6.9 shows the $v_2$ obtained for data along with predictions from AMPT in the same rapidity window. The errors on the data points include the systematic error due to difference in event planes and different resolution correction factors due to the two subevent selections. The systematic errors also include variations in the values obtained by different weighting methods. The AMPT(SM) gives a good qualitative description of the elliptic flow observed in data, and is quantitatively consistent with the measured values and the systematic errors.

6.5 Summary

The elliptic flow of photons has been measured at forward rapidity in Au+Au collisions at 39 A GeV. The rapidity dependence of flow has been obtained for different centralities. Systematic errors due to different event planes and their corresponding resolutions, due to weighting of photon like clusters with cluster size and cluster ADC are estimated. This weighting with cluster parameters takes special significance because of the occupancy dependence of cluster profile, and the occupancy in-plane and out-of-plane being different because of flow.

The results for photons $v_2$ have been compared to the predictions from AMPT including string melting. We are grateful to the authors of AMPT for incorporating the decay of $\pi^0$ on our request which made this study possible.

The rapidity integrated values of $v_2$ of photons, within the systematic errors, compare well with predictions of AMPT.