Chapter 4

Data Analysis

4.1 Introduction

This chapter describes basically the reduction of PMD raw data, taken either in mode 2 (pixel space) or mode 3 (pad space) as described in section 3.5.4, to the corrected physics data, which shows the phase space coordinates of the photon hits. A typical single event display is shown in fig. 4.10. In data reduction the first step was to select the proper events using appropriate trigger conditions. After the selection of good events it was necessary to carry out a clustering calculation to determine the location of individual photon/hadron hits on the detector plane. Finally, an appropriate threshold was used to reject hadron contamination. For mode 2 data, first pixel-to-fibre maps were used before clustering to convert mode 2 to mode 3 data. The main problem here was that the threshold used does not remove all the contamination rather it rejects some low energy photons which deposit energy within the threshold. This has been taken in to account by correcting the data against efficiency and purity.
factors. After all these corrections the photon multiplicity, $N_\gamma$ and its pseudorapidity distribution, $dN/d\eta$ were obtained. This chapter also describes the correlation of $N_\gamma$ with other global observables, $viz.$ charge particle multiplicity, $N_{ch}$ as measured by the SPMD, transverse energy, $E_T$ as measured by the MIRAC and forward energy, $E_p$ as measured by the Zero Degree Calorimeter used in the WA98 experiment. Use of $E_T$ from MIRAC and $N_\gamma$ from PMD within a overlapping phase space, to measure average transverse momentum, $\langle p_T \rangle$ of photons on an event by event basis is also discussed. The systematics of photon production with various targets, $viz.$ Ni and Nb and Pb is also a part of this chapter.

4.2 Event Selection

The data presented in this work were taken during the December 1996 Pb beam period at the CERN SPS with the magnet turned off. The thicknesses of the three targets were 250 $\mu$m, 254 $\mu$m, and 213 $\mu$m for Ni, Nb, and Pb, respectively. The fundamental “beam” trigger condition consisted of a signal in a gas Čerenkov start counter located 3.5 meter upstream of the target and no coincident signal in a veto counter with a 3 mm circular hole located 2.7 meters upstream from the target. A beam trigger was considered to be a minimum-bias interaction if the transverse energy sum in the full MIRAC acceptance exceeded a low threshold. The data analyzed for this thesis includes only type 2 and type 3 events as discussed earlier in chapter 2.

Beam pile up, where a second beam trigger occurred at a time when the detectors were integrating their signals from the triggered event, was rejected by (a) using the timing information from both the early and the delay TDCs in the trigger detectors,
and (b) requiring that the sum of energies in the ZDC and the MIRAC were within $3\sigma$ from the average. Double interactions were removed by using the ADC and TDC cuts listed in table 4.1. The table 4.2 and table 4.3 lists the trigger cuts used for event cleanup. Downstream interactions were also rejected by requiring a coincident signal from the forward hemisphere of the Plastic Ball detector which surrounded the target. To correct for other sources of background, data were also taken with no target in place. The target-out contributions were found to be negligible except for the most peripheral reactions.

The CCD readout of the PMD was cleared every 10 $\mu$s using a clear pulse of 1 $\mu$s width generated every 10 $\mu$s. This ensured that there was no substantial noise buildup on the CCD pixels between successive event triggers. A gate of 2 $\mu$s around the clear pulse was used to veto partially or fully cleared events. The clear clock operated asynchronously and was vetoed with a 5.6 ms wide pulse when a valid trigger occurred to allow for a complete readout of all the pixels. A further check on possible pile up in the CCD cameras was made by using a 10 $\mu$s range TDC to measure the time difference between the arrival of the last clear clock and any valid event trigger. Events with multiple interactions within the 10 $\mu$s between clear pulses were rejected in the off-line analysis. About 30% events were rejected by using different cuts.

The centrality of the interaction was determined by the total transverse energy measured in the MIRAC. For the $\langle p_T \rangle$ analysis, which used the MIRAC data directly, the centrality was determined instead by the forward energy, $E_F$, measured in the ZDC. The centralities are expressed as fractions of the minimum bias cross section as a function of the measured total transverse energy or measured $E_F$. The most
central selection corresponds to the top 5% of the minimum bias cross section, \( \sigma_{mb} = 6200 \pm 620 \text{ mb} \) and the peripheral selection corresponds to the lower 50–80% range. Extreme peripheral events in the 80–100% range were not analyzed.
TABLE 4.1
Start ADC and TDC cuts used to reject bad triggers and double interaction events.

<table>
<thead>
<tr>
<th>Start ADC</th>
<th>DST variable</th>
<th>ADC cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up</td>
<td>istaadcu</td>
<td>305 - 395</td>
</tr>
<tr>
<td>Down</td>
<td>istaadcd</td>
<td>332 - 476</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Start TDC</th>
<th>DST variable</th>
<th>TDC cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up</td>
<td>istatdcu</td>
<td>- 450</td>
</tr>
<tr>
<td>Down</td>
<td>istatdcd</td>
<td>- 850</td>
</tr>
</tbody>
</table>

TABLE 4.2
Early TDC cuts used to eliminate the pileup events. TDCs falling into this ranges are rejected.

<table>
<thead>
<tr>
<th>Trigger Detectors</th>
<th>Rejects</th>
<th>Early TDC cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>Little veto</td>
<td>Halo interactions</td>
<td>0 - 1380</td>
</tr>
<tr>
<td>Inner Halo</td>
<td>Upstream interactions</td>
<td>0 - 1319</td>
</tr>
<tr>
<td>Outer Halo</td>
<td>Upstream Interactions</td>
<td>0 - 610</td>
</tr>
<tr>
<td>$E_T$(Peripheral)</td>
<td>Pileup</td>
<td>0 - 617</td>
</tr>
<tr>
<td>$E_T$(Low)</td>
<td>Pileup</td>
<td>0 - 600</td>
</tr>
<tr>
<td>$E_T$(Low)</td>
<td>Pileup</td>
<td>0 - 600</td>
</tr>
<tr>
<td>PBall Interaction</td>
<td>Pileup</td>
<td>0 - 591</td>
</tr>
</tbody>
</table>

4.3 Transverse Energy ($E_T$) Measurement

Transverse energy was measured by the mid rapidity calorimeter, MIRAC, in the WA98 experimental setup, placed 24 m downstream of the target. MIRAC covered a pseudo-rapidity range $3.5 \leq \eta \leq 5.5$ with full azimuthal coverage. $E_T$ was measured by full energy deposition of various particles in the calorimeter modules weighted with $\sin \theta_i$, $\theta_i$ corresponding to the angle subtended by $i^{th}$ module to the beam axis.

The transverse energy, $E_T$ measurement was very important, because it was used
for trigger purpose for classifying the events into different centrality classes for any physics analysis. Therefore, it was essential to compare the $E_T$ from simulated and measured data and see how well they matched. Since $E_T$ was obtained from total energy measured in MIRAC, the statistical fluctuation was very small. This helped to estimate $E_T$ through a fast simulation without using a full GEANT simulation, which otherwise takes a long time. The fast simulation made use of a set of detector resolution function given in the table 4.4, depending on particle type, by which the energy deposition by the particles was smeared up before calculating $E_T$. Fig. 4.1 shows the $E_T$ distribution for both the data and the VENUS after fast simulation. The data and fast simulation $E_T$ are seen to match very well.

### TABLE 4.3
Delay TDC cuts used to reject pileup events. TDCs falling into this ranges are rejected.

<table>
<thead>
<tr>
<th>Trigger Detectors</th>
<th>Rejects</th>
<th>Delay TDC cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_T$(Peripheral)</td>
<td>Pileup after event</td>
<td>0 - 617</td>
</tr>
<tr>
<td>$E_F$(Low)</td>
<td>Pileup after event</td>
<td>0 - 600</td>
</tr>
</tbody>
</table>
TABLE 4.4

The energy deposition and detector resolution function for MIRAC for different types of particles. These numbers were used for estimation of transverse energy, $E_T$ from MIRAC through a fast simulation without going through a full GEANT simulation.

<table>
<thead>
<tr>
<th>Particle type</th>
<th>Energy Deposition($\Delta E$)</th>
<th>Detector Resolution Function($R$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma, e^+, e^-$</td>
<td>All</td>
<td>$1.4% + 11% / \sqrt{\Delta E}$</td>
</tr>
<tr>
<td>$\mu^+, \mu^-$</td>
<td>2 GeV</td>
<td>None</td>
</tr>
<tr>
<td>Baryons</td>
<td>$E - m$</td>
<td>$3% + 34% / \sqrt{\Delta E}$</td>
</tr>
<tr>
<td>Anti Baryons</td>
<td>$E - m$</td>
<td>$3% + 34% / \sqrt{\Delta E}$</td>
</tr>
<tr>
<td>Mesons</td>
<td>All</td>
<td>$3% + 34% / \sqrt{\Delta E}$</td>
</tr>
</tbody>
</table>

4.4 Data Reduction in the PMD

The following sections describe the procedure adopted to reduce the data to obtain the particle hit position and the energy deposition signal for subsequent physics analysis. The digitized pixel charges in terms of pixel ADCs were processed by using the pixel-to-fibre maps to form fibre signal corresponding to each scintillator pad. This has been done either online where data were recorded in mode 3 (fibre or pad coordinate) or offline where data were recorded in mode 2. Photons, in general, on passing through Pb converter plate placed behind the scintillator plates produce shower which spread to several pads. Therefore, signals from several neighboring scintillator pads are combined together to form clusters, characterized by the total ADC content and the hit position. Because of the use of pads of different sizes in WA98 PMD, the pad matrix over the entire detector cannot be represented by a single two-dimensional matrix to allow processing of all the pad hits in one pass. Hence the hits are clustered separately for each box module. Some tracks may produce more than one cluster.
Figure 4.1: Comparison of transverse energy, $E_T$ for data and simulation for minimum bias case for Pb + Pb system. Solid histogram corresponds to simulation and empty circles for data.
either because of upstream conversion or because of splitting at the boundaries of the box modules. For photon tracks, the cluster with the higher signal is assigned a photon identity and the other one is treated as a contaminant. A suitable threshold was applied to reject hadrons and clusters above this were treated as $\gamma$-like clusters. The total number of photons was obtained by correcting $N_{\gamma-like}$ against photon counting efficiency and purity factors as discussed in the following sub sections.

4.4.1 Clustering

Clustering of hits is one of the most important steps in the analysis of raw data for counting of photons. In order to extract photon hit positions and deposited energy the overlapping showers were separated by employing an unfolding algorithm. The ADC content of all the pads were placed in a two dimensional matrix with detector pads by matrix elements. The method was to compute the weight of each pad in the detector matrix relative to all its neighbors in a $7 \times 7$ matrix according to an assumed two-dimension Gaussian shape. The weights were then normalized and applied to the matrix to redistribute the contents of each cell to its neighbors. Local maxima collected the contents of neighboring cells. This made the maxima sharper and total distribution smoothing over small local fluctuations in the distribution. This procedure was used iteratively with decreased widths of the Gaussian shapes. This prevented the merging of overlapping showers. The iteration stopped when either the total redistributed contents were very small or the width of the highest cluster approached zero.

A nearest neighbor clustering algorithm was applied to this unfolded data. If there were more than one local maximum in a big cluster, it was split, the weight of the
different pads in the local maxima taken proportional to the distance of the pads from the local maxima as determined by the Gaussian distribution function. The width parameters of the Gaussian were tuned by using the test data. The centroid of the cluster was taken as the hit position and ADC content as the energy of the cluster.

4.4.2 Photon Counting

The main task of PMD was the counting of photons. It has already been discussed in previous sections how we get \( \gamma - like \) clusters labeled as \( N_{\gamma-like} \) from the raw data after clustering and applying a suitable threshold. These \( \gamma - like \) clusters originate predominantly from photons. Their distribution also contained a fraction of the clusters originating from hadronic interactions in the converter material giving signals similar to those of photons. These hadronic clusters are not rejected by applying a threshold. These are treated as background which reduces the purity of the photon sample. Suitable correction factors were applied to get photon multiplicity, \( N_\gamma \) from \( N_{\gamma-like} \) clusters.

We define the following two variables:

\[
\epsilon_\gamma = \frac{N_{\gamma}^{th}}{N_{\gamma}^{inc}}
\]

\[
f_p = \frac{N_{\gamma}^{th}/N_{\gamma-like}}{N_{\gamma-like}}
\]

where \( \epsilon_\gamma \) is the photon counting efficiency and \( f_p \) is the fractional purity of the photon sample. \( N_{\gamma}^{inc} \) is the number of incident VENUS photons on the PMD, \( N_{\gamma}^{th} \) is the number of photon clusters above the threshold and \( N_{\gamma-like} \) is the total number of clusters above the threshold.

Using the estimated values of \( \epsilon_\gamma \) and \( f_p \), defined above one can estimate the number \( (N_{\gamma}^{est}) \) of photons incident on the detector in the event using the relation:
\[ N_{\gamma}^{est} = N_{\gamma-\text{like}} \cdot f_p / e_{\gamma} \]

An estimate of the optimum value of hadron rejection threshold and the achievable purity of the photon sample along with the estimates of photon counting efficiency was made by a detailed study of the simulated data, which were generated using the VENUS event generator and GEANT simulation after all possible corrections, viz. light leakage to the surrounding pads, MEV - ADC calibration, readout resolution etc. for all the box modules through parameterization already described in previous chapter.

### 4.4.3 Photon Counting Efficiency and Purity

It has been discussed in above section that we correct \( N_{\gamma-\text{like}} \) against photon counting efficiency and purity factors to get the real \( N_{\gamma} \). The photon counting efficiency depends on several factors, e.g., the energy spectrum of photons, the conversion probability, the hadron rejection threshold applied, the granularity, the associated clustering efficiency etc. These parameters have been obtained using the VENUS event generators and GEANT detector simulation package. No lower threshold on the energy spectrum of photons was applied.

By adjusting the discrimination threshold it is possible to obtain a reasonably pure sample of photons, although some contaminants always remain. Fig. 4.2 shows the photon counting efficiency and the purity as a function of hadron rejection threshold (in MIP units) for two different centralities of Pb+Pb collisions. The centrality and \( \eta \) dependence of efficiency and purity are shown in the fig. 4.3 and fig. 4.4 respectively. A study of these dependences is needed for obtaining the corrected rapidity distribution for photons for various centralities. The centrality of the reaction was defined by
the transverse energy ($E_T$) obtained from the mid-rapidity calorimeter in the WA98 experiment [110]. Central events span the region $E_T \geq 330$ GeV corresponding to the top 5% of minimum bias cross section and peripheral events correspond to the region $40$ GeV $\leq E_T \leq 100$ GeV. In both cases the photon counting efficiency was found to decrease with increasing threshold. The purity improves significantly with increasing threshold only up to $\sim 3$ MIPs and then rather slowly at higher thresholds.

The estimated photon counting efficiency is dependent on both the detector hardware and the clustering software. A photon is labeled as "converted" on depositing a minimum energy equivalent to 0.2 MIP. The mean conversion probability for VENUS photons within the PMD acceptance in the case of Pb + Pb collisions is found to be 95%. This gives an upper limit to the photon counting efficiency when no hadron rejection threshold is applied, i.e., when all the "converted" photons can be counted. Photon counting efficiency close to this value (93%) is achieved only for peripheral events with no threshold as shown in fig. 4.2. The maximum value for central events is about 84%. The decrease in photon counting efficiency for central events arises primarily because of loss of clusters due to their overlap in the higher multiplicity environment of central collision events.

For all practical purposes a 3 MIP threshold appears as an optimum choice for hadron rejection leading to reasonable values for both the photon counting efficiency and the purity. With this, the photon counting efficiencies for central and peripheral cases were found to be about 68% and 73%, respectively. The purity of the photon sample in the two cases were 65% and 54%, respectively.

One can see that the efficiency values were better than that of the WA93 PMD. The WA98 PMD is therefore quite suitable to handle the increased particle density.
The purity of the photon sample is somewhat lower in the present case.

4.4.4 Errors

4.4.4.1 Statistical errors

Statistical error on $N_{\gamma}^{\text{est}}$ was governed mainly by the nature of counting statistics. In the present case the values obtained for the statistical error are 4.6% for central collision events, where the average number of incident VENUS photons, $< N_{\gamma}^{\text{inc}} >$, is $\sim 428$, and 11% for peripheral collision events having $< N_{\gamma}^{\text{inc}} > \sim 116$. The fig. 4.5 and fig. 4.6 show the statistical error on $N_{\gamma}^{\text{est}}$ for central($E_T \geq 330$ GeV) and peripheral($40$ GeV $\leq E_T \leq 100$ GeV) collisions respectively.

4.4.4.2 Systematic errors

Several different sources contribute to the systematic errors in the determination of the number of photons, $N_{\gamma}$. The error due to the effect of clustering of the pad signals is the dominant one. This error is determined from the simulation by comparing the number of known tracks on the PMD with the total number of clusters obtained after clustering. Apart from the effect of multiplicity as discussed in [122], the arrangement of box modules in the present setup leads to splitting of clusters at the box boundaries. The net result is that the number of clusters exceeds the number of tracks with a deviation of 3% in the case of peripheral events to 7% for high multiplicity central events.

The number of $\gamma$-like clusters depends on the ADC value of the MIP peak as determined from Pb+Pb data. It has been estimated [116] that because of an
Figure 4.2: Variation of photon counting efficiency (filled circles) and the fractional purity (open circles) with hadron rejection threshold (in MIP units). Top part shows the result for central events and lower for peripheral events.
Figure 4.3: Variation of photon counting efficiency (filled circles) and the fractional purity (open circles) with centrality after 3MIP cut.
Figure 4.4: Variation of photon counting efficiency (filled circles) and the fractional purity (open circles) with pseudorapidity after 3MIP cut. This is only for central events.
Figure 4.5: The relative difference of incident and estimated photons, i.e $(N_{\gamma}^{inc} - N_{\gamma}^{est})/N_{\gamma}^{inc}$, from simulation for Pb + Pb collisions at 158 A.GeV for central events.
Figure 4.6: The relative difference of incident and estimated photons, i.e. \( \frac{N^{inc} - N^{est}}{N^{inc}} \), from simulation for Pb + Pb collisions at 158 A.GeV for peripheral events.
admixture of ~20% photons in the MIP sample in the data, the extracted MIP ADC value is higher by 2 ADC channels. This causes the extracted photon multiplicity to be lower by 2.5%. This has been included as a source of systematic error. The error on $\epsilon_\gamma$ because of the variation in pad-to-pad gains is found to be less than 1%.

The purity factor, $f_p$, depends on the ratio of the number of photons and charged particles within the PMD coverage. The systematic error associated with this ratio has been studied using the FRITIOF [118] event generator in addition to VENUS. The average photon multiplicity from FRITIOF is found to be higher by about 4% in peripheral and by 1% in central collisions as compared to VENUS results.

The combined systematic error on the final photon multiplicity is asymmetric and varies with centrality of the reaction. The total systematic errors are $-3.4\%$ and $+7.5\%$ for peripheral collisions and $-7.1\%$ and $+3.4\%$ for central collisions, varying little throughout the PMD acceptance. The negative error implies overestimation of number of photons.

The photon counting efficiency determined in the present case relies on the energy spectra of photons as given by the VENUS event generator. As the conversion probability for low energy photons falls sharply [108] with decreasing energy below 500 MeV, the estimate of $\epsilon_\gamma$ may be affected if the energy spectra in the actual case is different. Preliminary measurements of the photon energy spectra with the WA98 lead glass spectrometer indicate that there is an enhancement of photons below $p_T = 250$ MeV/c over that given by VENUS. Taking into account this excess of low energy photons in the PMD acceptance, the photon counting efficiency would be overestimated by 2–9% for central events and 3–13% for peripheral events, the smaller value being for large pseudorapidity and the larger value being for the smaller
pseudorapidity region of the PMD acceptance. The effect would be to increase the quoted PMD photon multiplicities.

### 4.5 Correlation with Other Detectors

As already discussed before, WA98 setup consisted of several detector systems, and it is very important to see how the different observables measured with different detectors are correlated to each other. The fig. 4.7 shows the nice correlation of $N_{\gamma-like}$ with the transverse energy, $E_T$ measured by MIRAC and with forward energy, $E_F$ measured by the ZDC. The correlation of $E_T$ with $E_F$ and $N_{\gamma-like}$ with charge particle multiplicity, $N_{hit}$ measured by SPMD is shown in fig. 4.8. From these figures is is clear that with increasing centrality, or transverse energy, $E_T$, the photon and charge particle multiplicities increase and there is a decrease in zero degree energy, $E_F$. $E_T$ and $E_F$ were used to classify the events into different centrality classes. From the observed correlation of these with $N_{\gamma-like}$ and $N_{hit}$, these can also be used to divide the events into different centrality classes as well.

### 4.6 Photon Multiplicity

For physics analysis, data from 22 cameras in the central region have been used. The rapidity coverage of these 22 cameras is shown in fig. 4.9. The photon multiplicity is determined using equation (3) on an event-by-event basis from the total number of $\gamma$-like clusters within the PMD coverage. A typical event display for a central event is shown in fig. 4.10. This shows random distribution of $\gamma$ – like clusters
Figure 4.7: Correlation of $E_T$ measured by MIRAC with the $N_{\gamma-like}$ measured by PMD (top) and correlation of $E_F$ measured by ZDC with the $N_{\gamma-like}$ measured by PMD (bottom).
Figure 4.8: Correlation of $E_T$ measured by MIRAC with the $E_F$ measured by ZDC (top) and $N_{\gamma-like}$ with the charge particle multiplicity $N_{hit}$ measured by SPMD (bottom).
throughout the detector. The resulting minimum bias distributions of $N_\gamma$ are shown in fig. 4.11 for Pb+Ni, Pb+Nb, and Pb+Pb reactions at 158-A GeV. For comparison, the corresponding photon multiplicity distributions as obtained from the VENUS 4.12 event generator with default parameter settings, are superimposed in the same figure. The shape of these three distributions is governed by the collision geometry. For asymmetric collisions of Nb and Ni targets, small shoulders are present around $N_\gamma$ of 300 and 200, respectively. This shoulder is produced when a decrease in the impact parameter leads to little increase in particle production and the cross sections for these small impact parameters pile up at a relatively narrow range of $N_\gamma$. The VENUS event generator does not reproduce this shoulder well. The $N_\gamma$ values are higher for the data compared to those of VENUS.

### 4.7 Pseudorapidity Distribution of Photons

The pseudorapidity distribution of photons at different centralities are shown in fig. 4.12(a) for Pb+Pb collisions. The data have been corrected for geometry, efficiency, and purity factors. The filled symbols represent the measured data, and the open symbols are reflections of the filled symbols at $\eta_{c.m.}(= 2.95)$. The histograms show the corresponding distributions obtained from the VENUS event generator. The discrepancy between the VENUS results and the data is about 10% for central collisions at mid-rapidity. The pseudorapidity distribution of photons at different centralities for Pb+Nb and Pb+Ni are shown in fig. 4.12(b) and (c), respectively. The discrepancies between the data and VENUS are larger for these reactions compared to that of Pb+Pb.
Figure 4.9: The pseudorapidity coverage of PMD with inner 22 cameras.
Figure 4.10: Single event display of PMD with 22 inner cameras. The solid dots are the position of $\gamma$–like clusters.
Figure 4.11: Minimum bias inclusive photon cross sections for Pb+Ni, Pb+Nb, and Pb+Pb reactions at $158\times 10^4$ GeV. Solid histograms are the corresponding distributions obtained from the VENUS event generator.
Figure 4.12: Pseudorapidity distributions of photons in Pb induced reactions at 158-A GeV on (a) Pb, (b) Nb, and (c) Ni targets. The solid histograms are the corresponding distributions obtained from the VENUS event generator.
4.8 Scaling of Total Photon Yield with Participant Nucleons

The scaling behavior of the number of produced particles, transverse energy etc. may provide important informations about the reaction dynamics. The scaling behavior has already been observed experimentally, for example, the scaling of cross section with target mass in P+A collisions which was stronger than expected [123]. This was later attributed to multiple partons scattering in the initial state [124, 125].

The gross features of particle production in p+A and A+A collisions with lighter nuclei are well described in the framework of wounded nucleon model [126]. A scaling of particle production and transverse energy with the number of wounded nucleons have been observed by the WA80 collaboration in the reactions of $^{16}O$ and $^{32}S$ projectiles with various targets where $dE_T/d\eta|_{max}$ was found to depend approximately linearly on the average of total number of participants [127].

In heavy ion reactions many experimental signatures require a comparison of observables for different system sizes. A scaling principle based on the overlapping volume in various systems often becomes handy in getting an idea about the produced particle multiplicities, their transverse energies etc.. It can also be used as a valuable test for models of particle production in heavy ion reactions [128]. Any deviation from the scaling behavior based on geometry would be rather interesting and must be looked into carefully.

The observation of anomalous $J/\Psi$ suppression in central Pb+Pb collisions in contrast to peripheral collisions [129, 130] implies there may be qualitative change in behavior in heavy ion reactions once a certain system size is reached.
TABLE 4.5

\[ N_{\text{part}} \] as calculated from VENUS and hard sphere approximation of the colliding nuclei for various centrality cases shown in terms of percentage of cross section and for Pb+Pb, Pb+Nb and Pb+Ni systems. This also shows the average impact parameter for different centrality cases obtained from VENUS.

<table>
<thead>
<tr>
<th>System</th>
<th>Cross section(%)</th>
<th>Impact Parameter (fm)</th>
<th>[ N_{\text{part}} ] (Hard Sphere)</th>
<th>[ N_{\text{part}} ] (VENUS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb + Pb</td>
<td>0-5</td>
<td>2.388</td>
<td>363.31</td>
<td>353.40</td>
</tr>
<tr>
<td></td>
<td>5-10</td>
<td>4.153</td>
<td>302.22</td>
<td>300.39</td>
</tr>
<tr>
<td></td>
<td>10-20</td>
<td>5.678</td>
<td>244.48</td>
<td>237.69</td>
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<td></td>
<td>20-30</td>
<td>7.327</td>
<td>181.94</td>
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<td>30-40</td>
<td>8.709</td>
<td>132.46</td>
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<td></td>
<td>40-50</td>
<td>9.749</td>
<td>98.43</td>
<td>87.51</td>
</tr>
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<td></td>
<td>50-80</td>
<td>11.48</td>
<td>50.49</td>
<td>43.67</td>
</tr>
<tr>
<td>Pb + Nb</td>
<td>0-10</td>
<td>2.353</td>
<td>219.71</td>
<td>221.8</td>
</tr>
<tr>
<td></td>
<td>10-30</td>
<td>4.855</td>
<td>166.79</td>
<td>162.9</td>
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<td></td>
<td>30-60</td>
<td>7.619</td>
<td>90.48</td>
<td>86.48</td>
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<td></td>
<td>60-80</td>
<td>9.912</td>
<td>38.22</td>
<td>33.23</td>
</tr>
<tr>
<td>Pb + Ni</td>
<td>0-10</td>
<td>2.087</td>
<td>141.48</td>
<td>168.4</td>
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<tr>
<td></td>
<td>10-30</td>
<td>4.291</td>
<td>135.50</td>
<td>130.0</td>
</tr>
<tr>
<td></td>
<td>30-60</td>
<td>6.963</td>
<td>75.79</td>
<td>72.98</td>
</tr>
</tbody>
</table>

Based on all these observation it was decided to study the scaling of total photon yield and maximum pseudorapidity density with the participant nucleons as described below.

The pseudorapidity distributions for various systems (Pb+Pb, Pb+Nb, Pb+Ni) for various centralities were fitted with Gaussian distributions. The peak position of the distribution \( \eta_{\text{peak}} \), the pseudorapidity density at maximum \( \rho_{\text{max}} \), and the width \( \sigma \) are extracted from the fits. The \( \eta_{\text{peak}} \) values for Pb+Pb distributions remain constant at 2.95 for all centralities. For Pb+Nb, \( \eta_{\text{peak}} \) decreases from 3.03 ± 0.15 for central collisions to 2.95 ± 0.32 in the case of peripheral collisions. The corresponding
values for the Pb+Ni reaction are $3.10 \pm 0.16$ and $2.99 \pm 0.31$. Fig. 4.13(a) and (b) show $p_{\text{max}}$ and $\sigma$ for the three reactions as functions of the number of participant nucleons, $N_{\text{part}}$, at different centralities, tabulated in table 4.5. The table gives the $N_{\text{part}}$ values calculated in two different ways. In one method, the colliding nuclei are assumed to be hard spheres. Hence the $N_{\text{part}}$ was calculated by calculating the overlapping volume of two spheres in different impact parameters, given in table 4.5 and using normal nuclear matter density $n_0 = 0.17/fm^3$. In another method the $N_{\text{part}}$ was calculated from VENUS event generator directly. The $N_{\text{part}}$ values determined from VENUS event generator are used here. $p_{\text{max}}$ increases with $N_{\text{part}}$ while $\sigma$ doesn't change with increase of $N_{\text{part}}$.

More insight into the systematics of the particle production can be obtained by computing the integrated number of photons ($N^{\text{tot}}_\gamma$) over the full phase space. This has been obtained from the Gaussian fit parameters to the pseudorapidity distributions. Fig. 4.13(c) shows the extracted values of $N^{\text{tot}}_\gamma$ for Pb+Pb as a function of $N_{\text{part}}$. The solid line shows a fit to the data using the function:

$$N^{\text{tot}}_\gamma = C \cdot (N_{\text{part}})^\alpha$$  \hspace{1cm} (4.1)$$

where $C$ is a proportionality constant. The value of the exponent, $\alpha$, is extracted to be $1.13 \pm 0.03$. To further explore the systematics, we have divided the full $\eta$ region (0–6) into two parts, one corresponding to the central rapidity region, $2.4 \leq \eta \leq 3.4$, and the other beyond this. For both of these cases, the Pb+Pb data yields a value of $\alpha = 1.13$. In comparison, fitting the photon distribution from the VENUS event generator in the same two regions yields different exponents, with $1.10 \pm 0.07$ at mid-rapidity and $1.0 \pm 0.05$ for the outer region.
Figure 4.13: (a) Pseudorapidity density ($\rho_{\text{max}}$), (b) width of the pseudorapidity distributions ($\sigma$), and (c) integrated values of number of photons ($N_{\gamma}^{\text{tot}}$), as functions of the number of participant nucleons at different centrality bins for Pb induced reactions on Ni, Nb, and Pb targets at 158-A GeV. The solid line in (c) is a power-law fit to the data, which yields a value of the exponent $\alpha = 1.13 \pm 0.03$. 
### 4.9 Average Transverse Momentum, $\langle p_T \rangle$ of Photons

In a given event, the average transverse momentum of produced photons may be expressed as

$$\langle p_T \rangle = \frac{E_{\text{em}}}{N_\gamma}$$  \hspace{1cm} (4.2)

where $E_{\text{em}}$ is the transverse component of the electromagnetic energy and $N_\gamma$ is the number of photons in the $\eta$-region under consideration. In the WA98 experiment, $E_{\text{em}}$ and $N_\gamma$ were measured with the MIRAC and the PMD respectively, on an event-by-event basis. These detectors had complete overlap in azimuth in the region $3.5 \leq \eta \leq 4.0$. Hence the data in this region were used for computing the $\langle p_T \rangle$ using the above equation.

In order to obtain the final $E_{\text{em}}$ for equation 4.1, the measured electromagnetic energy in the MIRAC towers must be corrected for 1) the hadronic contribution to the electromagnetic section of the MIRAC, and 2) the energy deposited in the lead converter of the PMD because of its position in front of the MIRAC. The final expression may be written as:

$$E_{\text{em}} = \sum_{i=1}^{N} \left[ E_{i}^{\text{em}} - f_h \cdot f_{\text{bal}} \cdot \left( E_{i}^{\text{had}} / (1 - f_h) \right) \right] \sin \theta_i \cdot \frac{1}{1 - f_{\text{PMD}}}$$  \hspace{1cm} (4.3)

where, $E_i^{\text{em}}$ and $E_i^{\text{had}}$ are the energies measured in the electromagnetic and hadronic sections of the MIRAC towers, $f_h$ is the fraction of the hadronic energy deposited in the electromagnetic section, $f_{\text{bal}}$ is the balance factor taking into account the different responses for electromagnetic and hadronic particles in the EM section [117], $N$ is the number of towers in the MIRAC within the given $\eta$ range, $\theta_i$ is the polar angle.
of the $i^{th}$ tower, and $f_{PMD}$ is the fraction of the electromagnetic energy deposited in the lead converter of the PMD. The value of $f_{PMD}$ is found to be 15%. Details of the corrections are similar to those of Ref. [120].

The mean transverse momentum, $\langle p_T \rangle$, as a function of $\rho_{max}$, the pseudorapidity density of photons at mid-rapidity, are shown in fig. 4.14 for Pb+Pb collisions. The data point at $\rho_{max} \approx 525$ corresponds to the highest centrality bin, 0 – 1% of the minimum bias cross section for Pb+Pb. The systematic error on the absolute values are indicated by the upper and lower brackets on the data. The $\langle p_T \rangle$ value for different centralities is seen to be almost constant within the quoted error. For comparison, the results obtained from the VENUS event generator are superimposed in the same figure. The $\langle p_T \rangle$ value obtained from VENUS are systematically higher compared to data, and show very little change with centrality. The indication of a small rise and saturation of $\langle p_T \rangle$ seen in the data is similar to what has been reported for neutral pions [121].

4.10 Systematic errors on $\langle p_T \rangle$

The systematic error on the determination of $\langle p_T \rangle$ depends on the error in both $E_{Tm}$ and $N_\gamma$. The major sources of errors in $E_{Tm}$ are fluctuations in the hadronic energy deposited in the electromagnetic section of the MIRAC and the uncertainty in the electromagnetic energy deposited in the lead converter of the PMD. Including these the total error in $E_{Tm}$ is estimated to vary from 8.8% to 10.5% from peripheral to central events. Taking an uncertainty in the photon multiplicity, the combined systematic error on $\langle p_T \rangle$ has been estimated to vary from 11.5% to 12.7%.
Figure 4.14: The mean transverse momentum, \( \langle p_T \rangle \), of photons as a function of the pseudorapidity density of photons at mid-rapidity, \( \rho_{\text{max}} \), corresponding to different centralities. The \( \langle p_T \rangle \) values obtained from the VENUS event generator for Pb+Pb are superimposed for comparison.