Photon Detection in heavy-ion experiments

Abhi Modak$^{1}$ and Sidharth Kumar Prasad$^{1}$

$^{1}$Department of Physics (CAPSS), Bose Institute, EN-80, Sector V, Kolkata-700091, India

E-mail: abhimodak@jcbose.ac.in; abhi.modak@cern.ch

Abstract. We present the measurements of multiplicity and pseudorapidity distributions of inclusive photons in proton-proton (pp) and heavy-ion (AA) collisions using the Photon Multiplicity Detector (PMD) employed at STAR and ALICE experiments. The working principle, design and features of PMD are discussed. The results are compared to different Monte Carlo (MC) predictions. The dependence of average photon multiplicity on centre-of-mass energy in pp collisions is discussed. The limiting fragmentation scenario for inclusive photon production in both pp and AA collisions are also reported.

1. Introduction

One of the fundamental objectives of ultra-relativistic heavy-ion collision program is to study and understand the strongly interacting matter commonly known as Quark Gluon Plasma (QGP) [1] created at extremely high temperature and low baryon density. This matter comprised of deconfined quarks and gluons exists for a very short time after the collisions and then it is converted into the normal hadronic matter by undergoing cooling, expansion and hadronization. Therefore, the evidence of the formation of QGP is hidden in the properties of the produced final state particles. Multiplicity and pseudorapidity distributions of the produced particles are the most fundamental measurements for the proper understanding of the physics processes occurring in the collision. Multiplicity distribution is defined as the distribution of probability $P(n)$ which indicates the probability of occurring an event (or a collision) with ‘$n$’ number of produced particles. The pseudorapidity distribution represents the average number of particles produced in a collision per unit pseudorapidity ($\eta$). These observables are very sensitive to the variables such as centre-of-mass energy ($\sqrt{s}$), initial energy density deposited during the collision and collision centrality (in case of AA collision).

Measurement of inclusive photon multiplicity aims to provide complementary information to those of charged particles as the majority of the photons are originated by the decay of neutral mesons. By measuring photon and charged particle multiplicity on an event by event basis one can get the possible signature of the formation of Disoriented Chiral Condensate (DCC) [2].

In this article, we report the measurements of multiplicity and pseudorapidity distributions of inclusive photons in proton-proton (pp) and heavy-ion (AA) collisions using the Photon Multiplicity Detector (PMD). Results in pp and AA collisions are obtained from the ALICE [3] and STAR [4] experiments at LHC [5] and RHIC [6] respectively. These results are compared to the corresponding results obtained using various Monte Carlo (MC) models. The variation of average photon multiplicity as a function of centre-of-mass energy in pp collisions is discussed. The photon multiplicity measurements
are presented for different collision centrality classes in AA collisions. The limiting fragmentation behaviour for inclusive photon production and its dependence on $\sqrt{s}$ and centrality are also reported.

2. Photon Multiplicity Detector

Photon Multiplicity detector is a granular preshower detector for the measurements of photon multiplicity and its pseudorapidity distributions in the forward rapidity region where the traditional technique for the measurement of photons using calorimeter is difficult to implement due to large spatial density of produced particles. First-ever PMD was implemented in the WA93 experiment [7, 8] at CERN SPS then it was employed in the WA98 experiment [9, 10], the STAR experiment [11] at RHIC and the ALICE experiment [12] at LHC. In general, PMD consists of an array of sensitive detection elements (cells of filled gas or scintillator pads), known as preshower plane (PRE), placed behind a lead converter of suitable thickness. An incident photon, while passing through the lead material, produces electromagnetic shower by the combined effect of pair production and bremsstrahlung radiation. These shower particles are likely to give signals in several cells or pads of the sensitive volume of the detector. Unlike photons, charged hadrons usually hit one or two cells/pads and produce MIP (Minimum Ionizing Particle) like signal. In the fixed-target experiments WA93 and WA98, plastic scintillator pads were used as sensitive medium and wavelength shifting (WLS) plastic optical fibres were used to transport light from the scintillator to the readout system. But later on, it was realised that this type of technology is not suitable for collider experiments like STAR, ALICE due to increased multiplicity of produced particles as well as the readout systems were quite expensive. Proportional counter based hexagonal cells filled with Ar (70%) and CO$_2$ (30%) was introduced in place of scintillator pads and a new chips (GASSIPLEX/MANAS) based readout system was developed. A Charged Particle Veto (CPV) plane identical with PRE plane was also introduced in front the lead material to improve the photon-hadron discrimination. The basic features of PMD are summarized in Table 1.

Table 1. Basic features of Photon Multiplicity Detector (PMD)

| Basic features       | WA93       | WA98       | STAR       | ALICE      |
|----------------------|------------|------------|------------|------------|
| Position from target | 10.09 m    | 21.5 m     | 5.4 m      | 3.67 m     |
| $\eta$ coverage      | 2.8 – 5.2  | 2.5 – 4.2  | 2.3 – 3.7  | 2.3 – 3.9  |
| Sensitive medium     | Plastic scintillator | Plastic scintillator | Gas (Ar + CO$_2$) Ratio – 70:30 | Gas (Ar + CO$_2$) Ratio – 70:30 |
| Pad / cell size      | Size : 2 cm $\times$ 2 cm, Thickness : 0.3 cm | Size : 1.5 cm $\times$ 1.5 cm, 2 cm $\times$ 2 cm, 2.3 cm $\times$ 2.3 cm, 2.5 cm $\times$ 2.5 cm, Thickness : 0.3 cm | Size : 1 cm$^2$, Depth : 0.8 cm | Size : 0.22 cm$^2$, Depth : 0.5 cm |
| No. of pads/cells    | 7500       | 53200      | 82,944     | 221184     |
| Readout system       | WLS fibres + CCD camera | WLS fibres + CCD camera | GASSIPLEX + CRAM modules | MANAS + CROCUS system |

3. Measurements of photons in pp collisions

Photon multiplicity distributions have been measured for inelastic (INEL) pp collisions within the region $2.3 < \eta < 3.9$ at $\sqrt{s} = 0.9, 2.76$ and 7 TeV by the ALICE experiment at LHC and these are shown in top panels of Figure 1 [13]. The statistical and systematic uncertainties are represented by
the error bars and shaded area respectively. These results are compared to the corresponding results obtained from PHOJET, PYTHIA Perugia-0, PYTHIA Perugia-2011 and PYTHIA ATLAS-CSC. The bottom panels of Figure 1 represent the ratios of experimental result to various MC results. PHOJET result agrees with the data at 0.9 TeV within systematic uncertainty but it does not explain the data at all other energies. Other MC results show that they are not in good agreement with the experimental results.

Figure 2 shows the fitted multiplicity distributions using the Negative-binomial-distributions (NBD) of the form:

\[ P(m, k; n) = \frac{\Gamma(n + k)}{\Gamma(n + 1)\Gamma(k)} \left(\frac{m}{k + 1}\right)^n \]

where \( n \) is the photon multiplicity, \( m \) denotes the average photon multiplicity (\(<n>\)), the parameter \( k \) indicates the shape of the distribution. This fitting is performed to extract information regarding the nature of the particle production mechanism. The parameters of the fitting function are given in Table 2. It is observed that \(<n>\) increases with increasing collision energy (\(\sqrt{s}\)) and the value of \( k \) decreases with increasing \(\sqrt{s}\).

Table 2. Fit parameters of the NBD function

| \(\sqrt{s}\) (in TeV) | \(k\) | \(<n>\) |
|-----------------------|------|--------|
| 0.9                   | 1.89 ± 0.11 | 5.39 ± 0.14 |
| 2.76                  | 1.72 ± 0.10 | 7.73 ± 0.22 |
| 7                     | 1.35 ± 0.07 | 9.03 ± 0.24 |

Figure 3 shows the variation of average photon multiplicity (\(<N_\gamma>\)) as a function of \(\sqrt{s}\) in pp collisions for both INEL and Non-Single Diffractive (NSD) events. The data points at lower \(\sqrt{s}\) (below 0.9 TeV) are taken from the results of the UA5 experiment. For the NSD events, it is observed that the energy dependence of \(<N_\gamma>\) is followed by both logarithmic and power-law. In the present measurement both fitting functions explain the data points very well. But at higher energies, the predictions from logarithmic fit and power-law fit are becoming different. Therefore, measurements at higher \(\sqrt{s}\) are needed to draw an appropriate conclusion.

Pseudorapidity distributions of photons are shown in Figure 4 at \(\sqrt{s} = 0.9, 2.76\) and 7 TeV for INEL pp collisions along with results from various MC event generators. At \(\sqrt{s} = 0.9\) TeV, all the MC calculations except PYTHIA (tune Perugia-0) describe the experimental result well within systematic uncertainties, whereas at \(\sqrt{s} = 2.76\) TeV, only PHOJET and PYTHIA (tune ATLAS-CSC) seems to
agree with the data. All MC models underestimate the data at $\sqrt{s} = 7$ TeV except PYTHIA (tune ATLAS-CSC).

Figure 2. NBD fit of multiplicity distributions for INEL pp collisions [13].

Figure 3. Variation of average photon multiplicity with collision energy in pp collisions [13].

4. Measurements of photons in heavy-ion collisions

Photon multiplicity and its pseudorapidity distributions have been measured at forward pseudorapidity in Cu + Cu and Au + Au collisions at $\sqrt{S_{NN}} = 62.4$ and 200 GeV by the STAR experiment at RHIC [14, 15, 16]. Results are represented in Figure 5 and Figure 6. The observation shows that multiplicity distributions for both colliding systems with different energies have a characteristic shape with a rise at small multiplicity. This signifies that the probability of occurrence of peripheral collisions is higher. This rise is followed by a near plateau region with the increases of photon multiplicity. This nature is more prominent in Au + Au collisions in compared to Cu + Cu collisions. It corresponds to mid-central collisions. The open circle points in Figure 5 represents top central (0-5%) Au + Au collisions and top central (0-10%) Cu + Cu collisions. These data points reflecting higher photon multiplicity, are fitted by the gaussian distribution.

Figure 6 shows the pseudorapidity distributions of photons for inelastic events in pp collisions at $\sqrt{s} = 0.9$ (top), 2.76 (middle) and 7 TeV (bottom) [13].

Figure 4. Pseudorapidity distributions of photons for inelastic events in pp collisions at $\sqrt{s} = 0.9$ TeV (top), 2.76 TeV (middle) and 7 TeV (bottom) [13].
5. Limiting fragmentation behaviour of photons

Limiting fragmentation (LF) behaviour means that at forward rapidity particle production measuring from the rest frame of one of the colliding hadrons/ions approaches a limiting value even if the collision energy is increased [17]. This kind of behaviour of photons has been studied in pp and heavy-ion collisions.

Figure 7 shows the measurements of the LF behaviour of photon production in pp collisions. It is studied by looking at the pseudorapidity density of photons as a function of $\eta - \eta_{beam}$. In the range of present measurement, it is observed that photon production does not follow the LF scenario in pp collisions. Measurements at larger rapidity may help in better understanding.

Figure 8 shows the photon pseudorapidity density normalized by the average number of participating nucleon pairs as a function of $\eta - \eta_{beam}$. The red points indicate the results from central (0-5%) and peripheral (40-50%) Au + Au collisions at $\sqrt{s_{NN}} = 62.4$ GeV and they are compared with central (0-5%) photon data for Pb + Pb collisions at top SPS energy. This comparison suggests that photon production follows an energy independent LF behaviour. It is also observed that photon production within the measured $\eta$ range follows centrality independent LF behaviour.
6. Summary

We have presented the measurements of multiplicity and pseudorapidity distributions of inclusive photons in proton-proton (pp) and heavy-ion (AA) collisions using the Photon Multiplicity Detector (PMD) employed at STAR and ALICE experiments. The working principle, design and features of PMD have been discussed. The dependence of average photon multiplicity on centre-of-mass energy in pp collisions is discussed. We observed that it is consistent with both logarithmic and power-law dependence. The limiting fragmentation scenario for inclusive photon production in both pp and AA collisions have been reported. It is seen that photon production in pp collisions does not follow the LF behaviour, whereas in heavy-ion collisions photon production follows both energy and centrality independent LF behaviour.

References

[1] E. V. Shuryak, Phys. Rept. 61, 71 (1980).
[2] Mohanty B. and Serreau B., 2005, Phys. Rept. 414 263 and references therein.
[3] ALICE Collaboration, ALICE Technical Proposal for A Large Ion Collider Experiment at the CERN LHC, CERN/LHCC 95-71 (1995).
[4] K. H. Ackermann et al., Nucl. Instr. Meth. A499, 624 (2003).
[5] T. S. Pettersson (ed.), P. Lefevre (ed.), The Large Hadron Collider: conceptual design, CERN-AC-95-05 LHC (1995).
[6] Harrison, T. Ludlam, S. Ozaki, RHIC project overview, Nucl. Instr. Meth. A499 (2003) 235-244.
[7] WA93 Collaboration, CERN/SPSC/90-14, SPSC/P-252, 1990.
[8] Aggarwal M.M. et al., 1996, Nucl. Instr. Meth. A372 143.
[9] H. H Gutbrod et al., Proposal for a large acceptance hadron and photon spectrometer, CERN-SPSLC-91-17, CERN-P260, 1991,87p.
[10] Aggarwal M.M. et al., 1999, Nucl. Instr. Meth. A424 395.
[11] Aggarwal M.M. et al., 2003, Nucl. Instr. Meth. A499 751.
[12] Aggarwal M.M. et al., 2002, Nucl. Instr. Meth. A488 131.
[13] Abelev, B., Adam, J., Adamová, D. et al. Inclusive photon production at forward rapidities in proton–proton collisions at √s = 0.9, 2.76 and 7 TeV. Eur. Phys. J. C 75, 146 (2015).
[14] J. Adams. et al, STAR Collaboration, Phys. Rev. C73 034906.
[15] J. Adams. et al, STAR Collaboration, Nucl.Phys.A832:134-147,2010.
[16] J. Adams. et al, STAR Collaboration, Phys.Rev.Lett. 95 (2005) 062301 nucl-ex/0502008.
[17] Limiting fragmentation in high-energy nuclear collisions at the CERN Large Hadron Collider, Phys.Rev. C99 (2019) no.4, 044906.