Inclusive photon production at forward rapidities in pp collisions at LHC energies with the ALICE experiment

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Abstract. Measurements of multiplicity and pseudorapidity distributions of particles produced in pp collisions are important for the study of particle production mechanisms and to obtain baseline distributions to be compared with those from heavy-ion collisions. The inclusive photon measurements (dominated by π⁰ decays) are complementary to the charged particle measurements. The present work focuses on the forward rapidity region with comparisons to different models such as PYTHIA and PHOJET.

We report the measurements of multiplicity and pseudorapidity distributions of inclusive photons using the ALICE Photon Multiplicity Detector (PMD) at forward rapidities (2.3 < η < 3.9) in pp collisions at √s = 0.9, 2.76 and 7 TeV. It is observed that the photon multiplicity distributions are well described by negative binomial distributions (NBD). Multiplicity distributions are studied in terms of KNO variables for each energy. It is shown that the increase in the average photon multiplicity as a function of beam energy is compatible with both a logarithmic and power law dependence. The results are compared to different model predictions. These models reproduce experimental results at lower energy while they are not accurate at higher energies.

1. Introduction
The increase in particle production at midrapidity with increasing center-of-mass energy in pp collisions has been studied in detail by the ALICE experiment [1, 2] at the CERN LHC. As the particle production mechanism could be different in different regions of pseudorapidity, it is interesting to see how particle production varies with center-of-mass energy at forward rapidity. One of the major goals of ALICE is to study the state of matter called quark-gluon plasma (QGP). Measurements in pp collisions provide a very important baseline for this kind of study [3]. Since the majority of the photons are produced from the π⁰ decays, this measurement provides complementary information to those of charged particles.

In the present article, we report the measurement of inclusive photon production in the forward pseudorapidity region (2.3 < η < 3.9) with the ALICE experiment for pp collisions at center-of-mass energies of √s = 0.9 TeV, 2.76 TeV and 7 TeV. Multiplicity and pseudorapidity distributions of photons are measured using the Photon Multiplicity Detector (PMD) [4, 5], which has been designed to measure the multiplicity of inclusive photons in the forward rapidity region. Additionally we present the beam-energy dependence of the average photon multiplicity.
and the limiting fragmentation behavior of photons. The results are compared to different tunes of PYTHIA [6] and PHOJET [7, 8] generators.

2. Analysis details
This work is based on data collected by ALICE [9] in pp collisions at $\sqrt{s} = 0.9$, 2.76 and 7 TeV. Events with a vertex-Z position within ±10 cm from the nominal interaction point are selected. Results are presented both for inelastic (INEL) and non-single diffractive (NSD) events.

Photons are detected by using the preshower technique of the PMD [5]. The detector is sensitive to transverse momenta as low as $\sim 50$ MeV [5]. However, we have considered the incident photons of all energy, which makes the present photon measurement inclusive. Each photon produces a cluster, which is formed by a number of contiguous cells having non-zero energy deposition. Clusters with high probability of having come from photons are obtained by applying photon hadron discrimination thresholds on the number of hit cells and on the energy deposited in the clusters. The number of photon-like clusters in an event which pass through the threshold cuts are labelled as $N_{\gamma-like}$ [5].

An unfolding method [1, 10] has been used to correct the $N_{\gamma-like}$ distributions for efficiency, acceptance and other detector effects. A regularized unfolding method based on $\chi^2$ minimization is used. The unfolded multiplicity distribution, $U(N_{\gamma})$ is found by minimizing the $\chi^2$ function, which is defined as:

$$\hat{\chi}^2(U) = \sum_m \left( \frac{M_m - \sum_t R_{mt} U_t}{\epsilon_m} \right)^2 + \beta P(u),$$

where $M_m$ is the measured distribution and $R_{mt}$ is the response matrix, representing the conditional probability of measuring a true multiplicity $t$ as a measured multiplicity $m$. $\epsilon_m$ is the error in the measurement, $P(u)$ is the regularization term and $\beta$ is the regularization coefficient.

In this work the response matrices have been constructed using MC event generators within the PMD acceptance ($2.3 < \eta < 3.9$) at each energy [5]. They represent the correlations between generated true photon multiplicity ($N_{\gamma\text{-true}}$) and reconstructed measured photon multiplicity ($N_{\gamma\text{-like}}$). After unfolding, the results are corrected for trigger and vertex reconstruction efficiencies to obtain the final results [5].

A detailed study was performed to calculate the systematic uncertainties from various sources [5].

3. Results and discussions
Figure 1 shows the multiplicity distributions of photons at $\sqrt{s} = 0.9$, 2.76 and 7 TeV within $2.3 < \eta < 3.9$ for inelastic collisions. The error bars in the data points represent statistical uncertainties while the systematic uncertainties are shown by the shaded bands. The lines represent the predictions from the different event generators: PHOJET, PYTHIA (tune Perugia-0) [11], PYTHIA (tune Perugia-2011) [12], and PYTHIA (tune ATLAS-CSC) [13]. The bottom panels of the figures show the ratios between data and event generators. PHOJET reproduces the data at $\sqrt{s} = 0.9$ TeV while PYTHIA (tune ATLAS-CSC) is closer to data at all the energies.

Figure 2 shows the multiplicity distributions fitted with Negative Binomial Distribution (NBD) function of the form:

$$P(m, k; n) = \frac{\Gamma(n + k)}{\Gamma(n + 1)\Gamma(k)} \frac{(m/k)^n}{(m/k + 1)^{n+k}},$$

where $n$ is the photon multiplicity, $m = \langle n \rangle$ and $k$ is a parameter responsible for shape of the distribution. The multiplicity distributions are fitted with NBD for $N_{\gamma} > 0$. The fit parameters
Figure 1. Multiplicity distributions of photons for pp collisions at $\sqrt{s} = 0.9$ (left), 2.76 (middle) and 7 TeV (right) within $2.3 < \eta < 3.9$ for INEL events. Predictions from the different event generators are shown in different lines. Lower panels show the ratios between the data and MC. The error bars in the data points are statistical uncertainties and the shaded regions represent the systematic uncertainties.

Figure 2. NBD fit to the photon multiplicity spectra for pp collisions at $\sqrt{s} = 0.9$, 2.76 and 7 TeV. The error bars in the data points represent the statistical uncertainties and the shaded regions show the systematic uncertainties.

are shown in the table 1. Average photon multiplicity $\langle n \rangle$ increases with beam energy and the $k$, related to the dispersion of multiplicity, decreases with beam energy.

Table 1. Fit parameters of the NBD fitting to the photon multiplicity distributions.

| $\sqrt{s}$ in TeV | $k$      | $\langle n \rangle$ |
|------------------|----------|----------------------|
| 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 |

In 1972 Koba, Nielsen and Olesen (KNO) proposed that multiplicity distributions of produced particles should follow a scaling behavior called KNO scaling. In Figure 3 photon multiplicity
distributions are plotted in terms of KNO variables, $z = N_\gamma / \langle N_\gamma \rangle$. The bottom part of the figure shows the ratios of the $z$ values at $\sqrt{s} = 2.76$ and 7 TeV with respect to $\sqrt{s} = 0.9$ TeV. The ratios are close to unity up to $z = 3$; while for $z > 3$ the ratios started to deviate from unity. This indicates a deviation of the KNO scaling at high multiplicities. This behavior is similar to what has been observed for charged particles at mid-rapidity [1].

Figure 4 shows the energy dependence of the average photon multiplicity for INEL and NSD events within $2.3 < \eta < 3.9$, with the inclusion of UA5 results [14] for lower center of mass energies ($\sqrt{s} = 0.2, 0.546, 0.9$ TeV) within the same pseudorapidity region. The average photon multiplicity increases with increasing $\sqrt{s}$. The data points for NSD events are fitted with both a logarithmic and a power-law dependence on $\sqrt{s}$. The fit functions are shown in the figure along with corresponding fit parameters. The increase of average photon multiplicity is compatible with both $\ln \sqrt{s}$ and power-law. Data points at higher energies are needed to draw a conclusion on the behavior of the increase of photon multiplicity.

Figure 5 shows the pseudorapidity distributions of photons at $\sqrt{s} = 0.9, 2.76$ and 7 TeV for inelastic collisions together with predictions from different event generators. The statistical uncertainties are within the symbol size and the systematic uncertainties are shown by the shaded bands. At $\sqrt{s} = 0.9$ TeV, all models except PYTHIA (tune Perugia-0), describe the data within uncertainties, whereas at $\sqrt{s} = 2.76$ TeV, only PHOJET and PYTHIA (tune ATLAS-CSC) seems to explain the data. All models under-predict the data at $\sqrt{s} = 7$ TeV except PYTHIA (tune ATLAS-CSC).

The hypothesis of limiting fragmentation in high energy hadron-hadron collisions was suggested by J. Benecke et al. [15]. It states that the produced particles, in the rest frame of one of the colliding hadrons, will approach a limiting distribution. This behavior is studied by shifting the pseudorapidity bins by the beam rapidity, $y_{\text{beam}}$. For the present analysis the values of $y_{\text{beam}}$ are 6.86, 7.98 and 8.97 for $\sqrt{s} = 0.9, 2.76$ and 7 TeV, respectively. The results are presented in Figure 6 for INEL collisions with the expectation from the PYTHIA (tune ATLAS-CSC) event generator. The limiting fragmentation behavior is not observed in the
**Figure 4.** Average photon multiplicity within $2.3 < \eta < 3.9$ as a function of center of mass energy in pp collisions. The data points from UA5 experiment [14] are superimposed on the ALICE data.

**Figure 5.** Pseudorapidity distributions of photons for inelastic events in pp collisions at $\sqrt{s} = 0.9$ (top), 2.76 (middle) and 7 TeV (bottom). The different lines represent the expectations from the different event generators. The statistical errors are within the symbol sizes and the shaded bands represent the systematic uncertainties.
Figure 6. Pseudorapidity density as a function of $\eta - y_{\text{beam}}$ for pp collisions at $\sqrt{s} = 0.9$, 2.76 and 7 TeV. The statistical uncertainties are within symbol sizes and the shaded bands represent the systematic uncertainties. The lines show the prediction from PYTHIA (tune ATLAS-CSC) event generator.

pseudorapidity region probed by this measurement, suggesting that at the LHC this behavior may be confined to a pseudorapidity interval closer to beam rapidity.

4. Summary
We report the multiplicity and pseudorapidity distributions of photons in pp collisions at $\sqrt{s} = 0.9$, 2.76 and 7 TeV at the forward rapidity region ($2.3 < \eta < 3.9$) using the Photon Multiplicity Detector (PMD) in ALICE. The results are compared to expectations from different event generators. We observed that PHOJET is able to describe the photon multiplicity distributions well at $\sqrt{s} = 0.9$ TeV but under-predicts the data at others energies. The results from the PYTHIA (tune ATLAS-CSC) describe better the data than the other PYTHIA tunes at $\sqrt{s} = 2.76$ and 7 TeV. Multiplicity distributions of photons are well described by NBD distributions. A deviation of KNO scaling has been observed for $z > 3$. The beam energy dependence of average photon multiplicity within $2.3 < \eta < 3.9$ has been presented. It is found that the average photon multiplicity increases with beam energy and is compatible with both a power law and a logarithmic dependence on $\sqrt{s}$. We observed that the PYTHIA (tune ATLAS-CSC) predictions are in good agreement with the measured pseudorapidity distributions of photons. Limiting fragmentation behavior has been studied at $\sqrt{s} = 0.9$, 2.76 and 7 TeV. Longitudinal scaling of the produced photons is not observed within the measured pseudorapidity acceptance.

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