Measurement of forward photon production cross-section in \( pp \) collisions at \( \sqrt{s} = 510 \) GeV with RHICf detector

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Abstract

This study reported the inclusive differential production cross-section of

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photons in six pseudorapidity regions: $6.1 < \eta < 6.5$, $6.5 < \eta < 7.0$, $7.0 < \eta < 7.5$, $7.5 < \eta < 8.0$, $8.0 < \eta < 8.5$, and $\eta > 8.5$, measured through the RHICf experiment with $pp$ collisions at $\sqrt{s} = 510$ GeV conducted in June 2017. In addition, the cross-sections in the three regions of the $x_{F^{-}p_{T}}$ phase space coverage that are same as those of the LHCf results at $\sqrt{s} = 7$ and 13 TeV were obtained and compared. Considering the uncertainties, the results were observed to be consistent with both the Feynman scaling law and the model predictions of EPOS-LHC, QGSJET-II-04, Sibyll 2.3d, and DPMjet-III 2019.1, although certain models exhibited weak collision energy dependencies.

Keywords: RHIC, UHECR, Hadronic interaction

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1. Introduction

A precise understanding of hadronic interactions over a wide energy range is among the most important parameters for solving the problem of ultra-high-energy cosmic rays (UHECRs). The Pierre Auger Observatory and Telescope Array observe UHECRs with energies above $10^{18}$ eV using the extensive air shower technique, and they have reported their observation results with high-statistics data [1, 2, 3]. However, their observation results of chemical composition, which is an important parameter for studying the acceleration mechanism of UHECRs at the sources, strongly depend on the selection of the hadronic interaction model used in their air shower simulation. The uncertainty of the models is primarily a result of the lack of calibration data from the accelerator experiments. Particles produced in the very forward region of interactions carry most of the projectile particle energy, and are crucial to air shower development. The LHC forward (LHCf) experiment measured the production cross-sections of very forward photons, $\pi^{0}$, and neutrons at LHC [4, 5, 6, 7, 8, 9]. The maximum center-of-mass collision energy of $\sqrt{s} = 13$ TeV corresponds to $10^{17}$ eV in cosmic ray interactions. In addition to their measurement, experimental data at lower collision energies are necessary because an air shower is caused by complex interactions with various interaction energies ranging from GeV to the UHECR energy.

The RHIC forward (RHICf) experiment was designed to perform a measurement similar to the LHCf at RHIC located in Brookhaven National Lab-
oratory and investigate the collision-energy scaling law of forward particle production proposed in Ref. [10], so-called the Feynman scaling, via comparisons of the LHCf results. Whereas the LHCf reported the scaling of forward \( \pi^0 \) production between \( \sqrt{s} \) 2.76 and 7 TeV [7], the scaling can be tested by a LHCf–RHICf comparison in more than 10 times wider energy range than that. This study analyzed the data acquired with the RHICf detector in June 2017 with \( pp \) collisions at \( \sqrt{s} = 510 \) GeV and presented the measured inclusive differential production cross-section of photons in the six pseudorapidity regions covering \( \eta > 6.1 \) as a function of Feynman \( x \) (hereafter \( x_F^1 \)). Furthermore, the results in three additional regions covering the same \( x_F-p_T \) phase spaces as the LHCf result at \( \sqrt{s} = 7 \) and 13 TeV were obtained and subsequently compared to test the Feynman scaling.

2. Detector and Data

The RHICf detector comprises two compact sampling and positioning calorimeters composed of tungsten, 16 GSO scintillator plates, and 4 XY horoscopes of GSO bars. Two calorimeter tower have diamond-shaped acceptances transverse to the beam directions of 20 mm × 20 mm and 40 mm × 40 mm, which are referred to as the TS and TL, respectively. It is the former LHCf-Arm1 detector [11] and its performance has been well studied via beam tests using electron and proton beams at CERN-SPS [12]. The energy and position resolutions of photons with energies greater than 30 GeV are better than 5% and 0.2 mm, respectively, [13].

The detector was installed 18 m west of the Solenoidal Tracker at the RHIC (STAR) interaction point (IP) during the low-luminosity operation period from 24th to 27th June 2017. Because of the magnetic field of the dipole magnet located between the IP and detector, only neutral particles, photons, and neutrons hit the detector. Further, the acceptance at the location was restricted because of the shadow of the beam pipe structure located in front of the detector, which corresponded to a pseudorapidity coverage greater than 6.1. The detector was moved vertically to cover full acceptance, and the data acquisition was performed in three detector positions: BOTTOM (\( \Delta y = -47.4 \) mm), MIDDLE (\( \Delta y = 0 \) mm), and TOP (\( \Delta y = +24.04 \) mm), where \( \Delta y \) corresponds to the relative vertical position to MIDDLE.

\[ \text{It is calculated as } x_F = \frac{E_\gamma}{E_{\text{beam}}} \text{, where } E_\gamma \text{ and } E_{\text{beam}} \text{ are the energies of photons and beams (255 GeV).} \]
In this analysis, the data acquired with the two trigger modes, *Shower* and *High-EM* [13] was used. The *Shower* trigger was the baseline trigger designed to detect both electromagnetic and hadronic showers induced by photons and neutrons, and a large prescale factor of 8–30 was applied. The trigger efficiency was 100% for photons with energies greater than 20 GeV. Further, *High-EM* triggers were generated only for events with high-energy deposits in the 4th layer of the GSO scintillator to enrich high-energy photon events in the sample. The prescale factor for the *High-EM* trigger was approximately 10 times smaller than that for the *Shower* trigger. In addition, the trigger efficiencies of the *High-EM* trigger were 96% for photons with energies over 100 GeV.

The beam energy was 255 GeV, and the proton beams were radially polarized. The direction of beam polarization was rotated by 90 degrees from vertical polarization around the beam direction. The luminosity during the operation period was measured at \( L = (0.7 - 1.5) \times 10^{31} \text{cm}^{-2}\text{s}^{-1} \) using the coincidence rate of signals from the STAR-ZDC detectors [14] located on both the east and west sides of the IP. The recorded integral luminosities of the *Shower* (*High-EM*) trigger sample were 4.5 (27.6), 12.0 (96.0), and 20.2 (120.0) nb\(^{-1}\) for the BOTTOM, MIDDLE, and TOP detector positions, respectively.

### 3. Analysis

#### 3.1. Event reconstruction and selection

For the analysis, the event reconstruction algorithm reported in Ref. [6] was employed; further details can be found in Ref. [13]. The criteria in this analysis were reoptimized for the RHICf configuration using a detector simulation implemented with the GEANT4 library. Events that satisfied the criteria of particle identification (PID) for photons and a single hit were selected, corresponding to only one particle hit in a calorimeter tower.

The energy scale of the calorimeters was calibrated using the factor estimated in a study using \( \pi^0 \) events where photon pairs were observed in the calorimeters. Thereafter, the invariant mass was calculated from the energies and hit positions of a photon pair, assuming a decay vertex at the IP. The factor was calculated to shift the peak of the mass distribution to the rest mass of \( \pi^0 \).

Analysis regions were defined for the production cross-section measurement through the division of the pseudorapidity coverage at the location.
from 6.1 to infinity by six; 6.1 < η < 6.5, 6.5 < η < 7.0, 7.0 < η < 7.5
7.5 < η < 8.0, 8.0 < η < 8.5, and η > 8.5. The region is a sector-shape
area defined by the range of the distance from the beam center R and the
azimuthal angle φ, whereas the region for η > 8.5 is a disk shape with R < 7.25 mm. In addition to these regions, three analysis regions were defined to
test the Feynman scaling law. Each region covered the same xF-pT phase
space as one of LHCf measurements; pT < 0.124 xF, 0.87 xF < pT < 1.04
xF for η > 10.94 and 8.81 < η < 8.99 at √s = 7 TeV [5], respectively, and
pT < 0.23 xF for η > 10.94 at √s = 13 TeV [6]. The R and φ ranges of
each region and the data set (detector position and calorimeter tower) used
for the analysis regions are listed in Tab. 1. However, region 7.0 < η < 7.5
was not covered by a single dataset. Therefore, subregions corresponding to
7.00 < η < 7.25 and 7.25 < η < 7.50 were defined, which were combined to
obtain the final result.

The measurement performed discovered a large transverse single-spin
asymmetry of forward π0 production using the same dataset [15]. Owing
to the π0 asymmetry inducing dependency of the photon spectrum on the
spin direction of the incoming beams to the detector, the events were cat-
egorized with the spin direction inward or outward of the bunch associated
with each event. The difference of the integral luminosity between the spin
samples was only 1–4%.

3.2. Corrections

The final result of the inclusive differential production cross-section of
photons dσγ/dxF was obtained considering the number of events passing
the event selection Nsingle−γ with a bin-by-bin correction procedure.

\[
\frac{d\sigma}{dx_F} = C_{\text{geo}} C_{\text{ct}} C_{\text{MC}} \sum_{\text{spin}} C_{\text{PID}}^{\text{spin}} (1 - R_{\text{BKG}}^{\text{spin}}) \frac{\Delta N_{\text{single}−\gamma}^{\text{spin}}}{2 L_{\text{spin}} \Delta x_F},
\]

where C_{\text{geo}}, C_{\text{ct}}, C_{\text{MC}}, C_{\text{PID}}^{\text{spin}}, and R_{\text{BKG}}^{\text{spin}} are the correction factors described
below, and L_{\text{spin}} is the recorded integral luminosity of the beams in the spin
direction. Subsequently, the PID purity correction C_{\text{PID}}^{\text{spin}} and the beam-gas
background R_{\text{BKG}}^{\text{spin}} were estimated for each spin sample, whereas the other

\[\text{2}\text{The beam center was defined as the projection of the beam direction at the IP on the detector surface, which was measured using data [13].}\]
Table 1: Analysis regions and data sets used for this analysis.

| Region            | R [mm]       | φ [degrees] | Dataset       |
|-------------------|--------------|-------------|---------------|
| $\eta > 8.5$      | < 7.3        | 0 - 360     | BOTTOM-TL     |
| $8.0 < \eta < 8.5$| 7.3 - 12.0   | 50 - 130, 230 - 310 | BOTTOM-TL     |
| $7.5 < \eta < 8.0$| 12.0 - 19.7  | 75 - 105, 255 - 285 | BOTTOM-TL     |
| $7.0 < \eta < 7.5$| 7.25 - 7.50  | 19.7 - 25.3 | TOP-TS        |
| $7.00 < \eta < 7.25$| 25.3 - 32.5 | 80 - 100    | MIDDLE-TL     |
| $6.5 < \eta < 7.0$| 32.5 - 53.6  | 80 - 100    | MIDDLE-TL     |
| $6.1 < \eta < 6.5$| 53.6 - 79.9  | 80 - 100    | TOP-TL        |
| $p_T < 0.124 x_F$ | < 8.7        | 45 - 135, 225 - 315 | MIDDLE-TL     |
| $p_T < 0.23 x_F$  | < 16.1       | 70 - 110, 250 - 290 | MIDDLE-TL     |
| $0.87 x_F < p_T < 1.04 x_F$ | 60.7 - 72.8 | 80 - 100    | TOP-TL        |

correction factors were common. The difference of photon cross-sections between the two spin samples was 20% at maximum, which originated from the $\pi^0$ asymmetry. Consequently, upon combining the two spin samples, the effect of spin asymmetry was expected to be negligible in the final result even considering the systematic uncertainty of the integral luminosity.

- **Beam-gas background $R_{\text{spin}}^{BKG}$**:
  The background photons produced at collisions between the beam protons and residual gas in the beam pipe were estimated using the events associated with the non-colliding bunches of the incoming beam to the detector. Further, the background fraction $R_{\text{spin}}^{BKG}$ was calculated for each spin-direction sample by considering the difference in the total beam intensities between the colliding and non-colliding bunches \[13\]. However, owing to the limited statistics of non-colliding samples and little energy dependency, the correction was applied as a photon energy-independent factor. The estimated factors were $1.5 - 2.5\%$. In addition, the observed energy dependency was considered a systematic uncertainty.

- **PID purity correction $C_{\text{spin}}^{\text{PID}}$**:
  In this analysis, particle identification was performed by introducing a PID estimator $L_{90\%}$, which was defined as the longitudinal depth at which the energy deposit integral measured by the sampling layers reached 90% of the total energy deposition. Subsequently, the
purity of the photons in the selected events for each energy bin was estimated from the template-fit results of the $L_{90\%}$ distribution with MC distributions for photons and hadrons \cite{13}. The correction factor $C^{\text{PID}}_{\text{spin}}$ ($= 1 / \text{purity}$) was typically 0.9 – 1.0.

- MC based correction factor $C^{\text{MC}}$; This factor was introduced as an overall correction of several contributions related to event reconstruction: inefficiencies of the trigger, PID selection and single-hit selection, misreconstruction of multi-hit events (two particles hit in a tower) as single-hit events, and recovery of photon yield in the multi-hit events rejected by the single-hit selection. The total of these contributions was estimated using the detector simulation with $pp$ event generation by the interaction model of EPOS-LHC or QGSJET-II-04 as

$$C^{\text{MC}} = \frac{N^{\gamma}_{\text{MC,true}}}{N^{\text{single-} \gamma}_{\text{MC,rec}}},$$

where $N^{\gamma}_{\text{MC,true}}$ is the number of photons hitting the analysis region and $N^{\text{single-} \gamma}_{\text{MC,rec}}$ is the number of events reconstructed as single photons with the reconstructed hit position in the region. It is noted that hadron contamination was not considered in $N^{\text{single-} \gamma}_{\text{MC,rec}}$ because it should be corrected using PID correction. Thus, the average of the results obtained using the two interaction models was used as the correction factor. The typical value of the factor was $1.1 – 1.2$. The difference from one mainly originates from the inefficiency of PID selection (0.1) and the recovery of photon yield in multi-hit events (0.02 – 0.08). Moreover, the interaction-model dependency of the factor is primarily caused by the difference in multi-hit events, and it was assigned as systematic uncertainty.

- Correction of long-life particle contribution $C^{\text{ct}}$; The dominant source of photons measured by the detector is the $\pi^0$ decay produced at collisions, while decays of long-life particles such as $K^0$ and $\Lambda$ along the beam pipe located between the IP and the detector contribute to the photon yield. The contribution of long-life particles was estimated using an MC simulation by comparing the photon flux at the IP with that after transportation from the IP to the detector location. It was removed via the application of the correction factor. The contribution was relatively large in low $x_F$ regions, typically 8% of
Figure 1: Systematic uncertainties of the photon production cross-section measurement for the pseudorapidity region $8.0 < \eta < 8.5$. The colored and dashed lines indicate the estimated systematic uncertainties after normalization based on the mean values of the experimental data. The black line indicates the total systematic uncertainties, calculated as the quadratic summations of all uncertainties.

The total yield at $x_F$ approximately 0.1, whereas it was less than 1% in the high $x_F$ region of more than 0.5. The correction factors were calculated as the average of the results obtained using the four interaction models: EPOS-LHC [16], QGSJET-II-04 [17], Sibyll 2.3d [18], and DPMjet-III 2019.1 [19]. Furthermore, the systematic uncertainty of the factor was estimated as the maximum deviation from the average of each model result.

- Geometrical correction factor $C_{geo}$;
A correction factor was introduced to correct the limitation of the $\phi$ range, and it was calculated as $C_{geo} = 360^\circ/\Delta \phi$.

3.3. Systematic uncertainties

The following contributions were considered as systematic uncertainties of the measured production cross-section, in addition to those related to the correction factors $R_{BKG}$, $C_{MC}$, and $C_{ct}$ described in Sec. 3.2. Fig. 1 shows the estimated systematic uncertainties for the pseudorapidity region $8.0 < \eta < 8.5$ as a typical example.

- Energy scale
Three components were considered as the systematic uncertainty of
the energy scale. The first was the stability of the energy scale during the operation, which was monitored using the peak position of the $\pi^0$ mass on the reconstructed mass distribution, and it was stable within $\pm 1\%$ [13]. The second was the nonlinearity. It was observed that the peak mass value of $\pi^0$ was shifted with increasing $\pi^0$ energy corresponding to the total energy of the photon pair [13]. Assuming that the shift originates only from the nonlinearity of the energy scale conservatively, the corrected photon energy $E'$ was obtained as $E' = (1.03 - 0.025 (E/100\text{GeV}))E$, where $E$ is the original value of the reconstructed energy. The last factor is the nonuniformity of the energy scale, which was evaluated from the consistency test of the spectra obtained by dividing the $\phi$ range. The impact of each energy-scale uncertainty on the final result was estimated by repeating the analysis by artificially changing the energy scale. Owing to the steep slope of the spectrum, large systematic uncertainties of over 50% were induced in the highest energy bin.

- **PID selection**
  The experimental distribution of the PID estimator $L_{90\%}$ was not perfectly reproduced by the template distributions obtained from the MC. The systematic effect of the difference on the final result through the purity and efficiency estimation of PID was estimated using a method similar to that used in Ref. [5, 8]; Another template-fitting method that allowed artificial displacement and widening of the template distributions was performed. Consequently, the difference in the results between the methods was assigned as systematic uncertainty.

- **Beam center**
  The effect of the uncertainty of the beam-center determination was evaluated via repeating the analysis procedure by shifting the beam center by $\pm 1$ mm vertically or horizontally. The maximum deviation in these results from the original results was assigned as the systematic uncertainty.

- **Luminosity**
  The uncertainty of the integral luminosity is $\pm 5\%$, which is due to the uncertainty of the conversion factor from the ZDC signal rate to the absolute luminosity determined from the Vernier scans using the method similar to that described in Ref. [20].
4. Results

4.1. differential production cross-section

Fig. 2 presents the differential production cross-section of photons as a function of $x_F$, $d\sigma/\!d x_F$, for the six pseudorapidity intervals measured by the RHICf detector. The data points in the $x_F$ range below 0.45 were obtained from the Shower trigger samples, while those in the higher $x_F$ region were obtained from the High-EM trigger samples because of large statistics. The colored lines in Fig. 2 show the prediction of the interaction models, EPOS-LHC, QGSJET-II-04, Sibyll 2.3d, DPMjet-III 2019.1, that were calculated using the event generator CRMC version 1.8.0 [21]. Fig. 3 presents the ratios of these predictions to the experimental results. EPOS-LHC and DPMjet-III 2019.1 were consistent with the experimental result in the low $x_F$ region below 0.6 and 0.3, respectively, for any pseudorapidity regions, although it predicted larger flux than the data in the higher $x_F$ region. QGSJET-II-04 and Sibyll 2.3d well reproduced the shape of $x_F$ spectra in the highest pseudorapidity regions; however, the slope of their spectra became progressively softer and harder, respectively, than that of the data in the lower pseudorapidity regions. They can be interpreted as the difference in $p_T$ distributions between the data and the model. Thus, these features of the data-model comparisons are very similar to those at the LHC energies reported by LHCf [4, 5, 6], thereby suggesting that the source of the difference is common to wide collision energies.

4.2. Collision-energy scaling

The measured cross-sections were compared with the results of LHCf at $pp$ collisions at $\sqrt{s} = 7$ and 13 TeV to test the collision energy dependency of forward photon production. Fig. 4 shows the results obtained for the same coverage of $x_F$-$p_T$ phase space as that of the LHCf results. In this comparison, an additional normalization factor $1/\sigma_{\text{inela}}$ was introduced, where $\sigma_{\text{inela}}$ was the inelastic cross section. For normalization of the LHCf results, the values of $\sigma_{\text{inela}} = (72.9 \pm 1.5)$ mb and $(79.5 \pm 1.8)$ mb reported in Ref. [22, 23] were used\(^3\). The $pp$ inelastic cross section at $\sqrt{s} = 510$ GeV was estimated to be $(48.3 \pm 1.1)$ mb using the fit results of total and elastic cross-sections by the COMPETE [24] and TOTEM [23] collaborations, respectively. The

\(^3\)A slightly lower value $\sigma_{\text{inela}} = 71.5$ mb was used in Ref. [5]. Their results were rescaled using this ratio.
Figure 2: Inclusive photon production cross-section measured by the RHICf detector. Each figure represents that for one of the pseudorapidity regions: $\eta > 8.5$, $8.0 < \eta < 8.5$, $7.5 < \eta < 8.0$, $7.0 < \eta < 7.5$, $6.5 < \eta < 7.0$, and $6.1 < \eta < 6.5$. The bars and hatched areas correspond to the statistical and systematic uncertainties, respectively. Colored lines indicate the MC predictions of DPMjet-III 2019.1, EPOS-LHC, QGSJET-II-04, and Sibyll 2.3d.

RHICf result was consistent with the LHCf results within the uncertainties, and the ratios are shown in Fig. 5. The values of the ratios were slightly lower than those in the middle panel, which can be interpreted as the difference in analysis methods: corrections of photon yield in the rejected multi-hit events and photons from long-life particle decays were not performed in the LHCf 7 TeV result, whereas they were performed in both the RHICf and LHCf 13 TeV results. The correction increased the ratio by $0 - 15\%$ in $x_F$ below 0.6.

All four models reproduced the ratio obtained, as shown in Fig. 5. Certain models predicted a weak $x_F$ dependency of the ratio; however, the dependency could not be confirmed owing to the large uncertainties in the results.
Figure 3: Ratio of inclusive photon production cross-sections predicted by hadronic interaction models to the experimental result. The bars and hatched areas around one correspond to the normalized statistical and systematic uncertainties of the data, respectively.

Figure 4: Comparison of the measured cross-section with the results of LHCf at $\sqrt{s} = 7$ and 13 TeV [5, 6]. The two left panels show the comparison with the LHCf result at $\sqrt{s} = 7$ TeV and the pseudorapidity region of $\eta > 10.94$ (left) and $8.81 < \eta < 8.99$ (middle). The right panel shows a comparison between $\sqrt{s} = 13$ TeV and $\eta > 10.94$. The bars and hatched areas correspond to statistical uncertainties and quadratic summation of statistics and systematic uncertainties, respectively.
Figure 5: Ratios of the RHICf results to the LHCf results [5, 6]. The error bars represent the uncertainties calculated as a quadratic summation of the uncertainties in these results. Colored lines indicate MC predictions.
5. Summary

This study measured the inclusive differential production cross-section of photons in the very forward region $\eta > 6.1$ with $pp$ collisions at $\sqrt{s} = 510$ GeV. Through comparisons of the obtained results with the LHCf, the Feynman scaling law of forward photon production in a wide energy range from 510 GeV to 13 TeV was confirmed within the uncertainties. However, the precision is not sufficient to discuss the weak $x_F$ dependency predicted by certain models, and future studies must focus on reducing the uncertainties together with LHCf collaboration. Moreover, tests of the Feynman scaling law with other neutral hadrons $\pi^0$ and neutrons are an interesting concept and will be addressed in future publications. They will contribute to improving the predictions of models with intermediate and even higher collision energies than LHC.

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Appendix A. Cross-section tables
Table A.2: Differential photon production cross-section $d\sigma_\gamma/dx_F$ [nb] for each $x_F$-bin in the pseudorapidity ranges: $\eta > 8.5$, $8.0 < \eta < 8.5$ and $7.5 < \eta < 8.0$. Upper and lower total uncertainties are also reported.

| Energy [GeV] | $\eta > 8.5$ | $8.0 < \eta < 8.5$ | $7.5 < \eta < 8.0$ |
|--------------|--------------|---------------------|---------------------|
| 0.10-0.15    | $(2.51^{+0.18}_{-0.18}) \times 10^5$ | $(4.30^{+0.30}_{-0.29}) \times 10^5$ | $(1.18^{+0.08}_{-0.08}) \times 10^5$ |
| 0.15-0.20    | $(1.93^{+0.13}_{-0.13}) \times 10^5$ | $(3.29^{+0.21}_{-0.21}) \times 10^5$ | $(9.00^{+0.56}_{-0.56}) \times 10^5$ |
| 0.20-0.25    | $(1.49^{+0.10}_{-0.11}) \times 10^5$ | $(2.55^{+0.19}_{-0.19}) \times 10^5$ | $(6.76^{+0.42}_{-0.42}) \times 10^5$ |
| 0.25-0.30    | $(1.09^{+0.07}_{-0.10}) \times 10^5$ | $(1.89^{+0.12}_{-0.17}) \times 10^5$ | $(4.83^{+0.30}_{-0.30}) \times 10^5$ |
| 0.30-0.35    | $(7.52^{+0.47}_{-0.85}) \times 10^4$ | $(1.28^{+0.08}_{-0.12}) \times 10^5$ | $(3.51^{+0.22}_{-0.27}) \times 10^5$ |
| 0.35-0.40    | $(5.35^{+0.34}_{-0.59}) \times 10^4$ | $(8.97^{+0.58}_{-0.74}) \times 10^4$ | $(2.38^{+0.16}_{-0.17}) \times 10^5$ |
| 0.40-0.45    | $(3.76^{+0.25}_{-0.39}) \times 10^4$ | $(6.31^{+0.42}_{-0.50}) \times 10^4$ | $(1.70^{+0.12}_{-0.13}) \times 10^5$ |
| 0.45-0.50    | $(2.78^{+0.19}_{-0.24}) \times 10^4$ | $(4.61^{+0.34}_{-0.34}) \times 10^4$ | $(1.17^{+0.09}_{-0.09}) \times 10^5$ |
| 0.50-0.55    | $(1.78^{+0.14}_{-0.18}) \times 10^4$ | $(3.02^{+0.23}_{-0.24}) \times 10^4$ | $(7.97^{+0.87}_{-0.91}) \times 10^4$ |
| 0.55-0.60    | $(1.08^{+0.08}_{-0.10}) \times 10^4$ | $(1.83^{+0.15}_{-0.17}) \times 10^4$ | $(4.85^{+0.66}_{-0.66}) \times 10^4$ |
| 0.60-0.65    | $(6.02^{+0.04}_{-0.04}) \times 10^3$ | $(1.04^{+0.10}_{-0.12}) \times 10^4$ | $(2.65^{+0.36}_{-0.39}) \times 10^4$ |
| 0.65-0.70    | $(3.07^{+0.44}_{-0.44}) \times 10^3$ | $(5.46^{+0.72}_{-0.72}) \times 10^3$ | $(1.41^{+0.23}_{-0.27}) \times 10^4$ |
| 0.70-0.75    | $(1.74^{+0.30}_{-0.34}) \times 10^3$ | $(2.85^{+0.68}_{-0.68}) \times 10^3$ | $(4.51^{+1.15}_{-1.15}) \times 10^3$ |
| 0.75-0.80    | $(8.07^{+2.45}_{-2.02}) \times 10^2$ | $(1.17^{+0.44}_{-0.49}) \times 10^3$ | $(2.10^{+0.73}_{-0.76}) \times 10^3$ |
| 0.80-0.85    | $(2.39^{+1.19}_{-0.88}) \times 10^2$ | $(2.79^{+1.42}_{-2.01}) \times 10^2$ | $(5.58^{+3.00}_{+3.80}) \times 10^2$ |
| 0.85-0.90    | $(8.05^{+5.01}_{-5.24}) \times 10^1$ | $(8.62^{+8.74}_{-8.74}) \times 10^1$ | $(2.03^{+2.11}_{-1.62}) \times 10^2$ |
| 0.90-0.95    | $(1.01^{+0.92}_{-1.08}) \times 10^1$ | $(1.76^{+1.70}_{-2.43}) \times 10^1$ | $(2.91^{+2.94}_{-3.50}) \times 10^1$ |
Table A.3: Differential photon production cross-section $d\sigma/dx_F$ [nb] for each $x_F$-bin in the pseudorapidity ranges: $7.0 < \eta < 7.5$, $6.5 < \eta < 7.0$ and $6.1 < \eta < 6.5$.

| Energy [GeV] | $7.0 < \eta < 7.5$ | $6.5 < \eta < 7.0$ | $6.1 < \eta < 6.5$ |
|--------------|---------------------|---------------------|---------------------|
| 0.10-0.15    | $(3.32^{+0.22}_{-0.21}) \times 10^6$ | $(8.24^{+0.31}_{-0.51}) \times 10^6$ | $(1.34^{+0.08}_{-0.08}) \times 10^7$ |
| 0.15-0.20    | $(2.46^{+0.15}_{-0.14}) \times 10^6$ | $(5.91^{+0.35}_{-0.33}) \times 10^6$ | $(8.81^{+0.50}_{-0.49}) \times 10^6$ |
| 0.20-0.25    | $(1.82^{+0.11}_{-0.11}) \times 10^6$ | $(4.20^{+0.26}_{-0.23}) \times 10^6$ | $(5.69^{+0.35}_{-0.31}) \times 10^6$ |
| 0.25-0.30    | $(1.31^{+0.08}_{-0.08}) \times 10^6$ | $(2.79^{+0.16}_{-0.16}) \times 10^6$ | $(3.54^{+0.21}_{-0.20}) \times 10^6$ |
| 0.30-0.35    | $(9.05^{+0.62}_{-0.57}) \times 10^5$ | $(1.85^{+0.13}_{-0.11}) \times 10^6$ | $(2.21^{+0.15}_{-0.13}) \times 10^6$ |
| 0.35-0.40    | $(6.17^{+0.45}_{-0.41}) \times 10^5$ | $(1.22^{+0.09}_{-0.08}) \times 10^6$ | $(1.34^{+0.09}_{-0.08}) \times 10^6$ |
| 0.40-0.45    | $(4.07^{+0.29}_{-0.26}) \times 10^5$ | $(8.02^{+0.61}_{-0.55}) \times 10^5$ | $(8.16^{+0.54}_{-0.54}) \times 10^5$ |
| 0.45-0.50    | $(2.75^{+0.22}_{-0.19}) \times 10^5$ | $(4.91^{+0.39}_{-0.37}) \times 10^5$ | $(4.66^{+0.35}_{-0.33}) \times 10^5$ |
| 0.50-0.55    | $(1.78^{+0.12}_{-0.14}) \times 10^5$ | $(3.02^{+0.25}_{-0.25}) \times 10^5$ | $(2.58^{+0.21}_{-0.20}) \times 10^5$ |
| 0.55-0.60    | $(1.06^{+0.15}_{-0.16}) \times 10^5$ | $(1.68^{+0.16}_{-0.17}) \times 10^5$ | $(1.37^{+0.12}_{-0.12}) \times 10^5$ |
| 0.60-0.65    | $(5.62^{+0.73}_{-0.66}) \times 10^4$ | $(8.68^{+1.03}_{-1.15}) \times 10^4$ | $(6.71^{+0.68}_{-0.78}) \times 10^4$ |
| 0.65-0.70    | $(2.87^{+0.50}_{-0.47}) \times 10^4$ | $(4.28^{+0.62}_{-0.75}) \times 10^4$ | $(3.18^{+0.49}_{-0.49}) \times 10^4$ |
| 0.70-0.75    | $(1.25^{+0.32}_{-0.31}) \times 10^4$ | $(1.99^{+0.51}_{-0.45}) \times 10^4$ | $(1.43^{+0.22}_{-0.30}) \times 10^4$ |
| 0.75-0.80    | $(5.87^{+2.05}_{-2.12}) \times 10^3$ | $(8.47^{+1.74}_{-2.55}) \times 10^3$ | $(5.83^{+1.13}_{-1.66}) \times 10^3$ |
| 0.80-0.85    | $(2.98^{+1.57}_{-1.10}) \times 10^3$ | $(2.68^{+0.67}_{-1.10}) \times 10^3$ | $(1.65^{+0.40}_{-0.65}) \times 10^3$ |
| 0.85-0.90    | $(1.05^{+0.69}_{-0.77}) \times 10^3$ | $(7.23^{+3.32}_{-3.89}) \times 10^2$ | $(4.85^{+2.08}_{-2.81}) \times 10^2$ |
| 0.90-0.95    | $(4.50^{+4.24}_{-4.69}) \times 10^1$ | $(8.99^{+7.97}_{-10.41}) \times 10^1$ | $(8.58^{+7.69}_{-8.62}) \times 10^1$ |
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