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PROMPT PHOTON PRODUCTION IN p - p COLLISIONS

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Abstract

A systematic study of the inclusive photon cross-section in $p - p$ collisions is presented. The dependence of the γ rates on the renormalization and factorization scales is discussed. A comparison is made with experimental data for centre-of-mass energies ranging from 23 GeV to 1.8 TeV. Predictions of the cross-sections are given for two different sets of structure functions for RHIC and LHC energies.

INTRODUCTION

We present estimates of the rates for prompt photon production in proton-proton collisions at SPS, RHIC and LHC energies, according to our present theoretical knowledge. They have been calculated using two sets of structure functions [1] giving good fits to recent data from HERA [2, 3]. Our results are summarized in the tables and

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figures at the end of this paper. The tables list separately the contributions from the lowest order QCD diagrams (denoted by BORN in the tables) and the sum of lowest and higher order terms as calculated by Aurenche et al. (denoted by INCLUSIVE in the tables) [4] – [8].

A comparison with experimental data from the NA24, WA70, UA6, E706, UA2, D0 and CDF collaborations [9] – [15] has been made and in general good agreement has been found. We can thus be fairly confident about the predictions for higher energies.

At higher energies the sensitivity to the choice of structure functions becomes more apparent and can be as large as a factor of three at $\sqrt{s} = 14$ TeV. Other uncertainties are related to the photon fragmentation function and the choice of scale parameters. These are discussed more fully in the text and in the cited literature.

THEORETICAL DESCRIPTION

At large values of the transverse momentum p_t of the photon, the inclusive cross section is dominated by hard collisions proceeding via subprocesses involving only a very few partons. To lowest order these are

$$\text{Compton :} \quad q(\bar{q}) + g \rightarrow \gamma + q(\bar{q}) \quad (1)$$

$$\text{Annihilation :} \quad q + \bar{q} \rightarrow \gamma + g \quad (2)$$

Contributions of higher order in the strong coupling have been calculated by Aurenche et al. [4] – [8], and our calculations are based on their programs. The general structure of the differential cross section is calculated from the following expression

$$E_\gamma \frac{d\sigma}{d^3p_\gamma}(A + B \rightarrow \gamma + \dots) = \sum_{a,b} \int dx_a dx_b F(a, A; x_a) F(b, B; x_b) E_\gamma \frac{d\hat{\sigma}}{d^3p_\gamma} \quad (3)$$

The structure functions F give the probability of finding partons with momentum fractions x_i . They can be determined in deep inelastic scattering of electrons on protons. At high energies the main contribution to the cross section comes from the small x region and thus a precise knowledge of the structure functions in this region is essential.

To lowest order the invariant cross-section for the subprocess

$$a + b \rightarrow c + \gamma \quad (4)$$

can be written as

$$E_\gamma \frac{d\hat{\sigma}}{d^3p_\gamma} = \frac{\hat{s}}{\pi} \frac{d\sigma}{dt} \delta(\hat{s} + \hat{t} + \hat{u}) \quad (5)$$

where $\hat{s}, \hat{t}$ and $\hat{u}$ are the Mandelstam variables for the subprocess.

The elementary cross-sections for the leading ($O(\alpha_s)$) subprocesses (2) and (3) are

$$\frac{d\sigma}{d\hat{t}}(qg \rightarrow q\gamma) = -\frac{\pi\alpha\alpha_s}{3\hat{s}^2}e_q^2 \frac{\hat{u}^2 + \hat{s}^2}{\hat{u}\hat{s}} \quad (6)$$

and

$$\frac{d\sigma}{d\hat{t}}(\bar{q}q \rightarrow g\gamma) = \frac{8\pi\alpha\alpha_s}{9\hat{s}^2}e_q^2 \frac{\hat{u}^2 + \hat{t}^2}{\hat{u}\hat{t}} \quad (7)$$

where e_q is the charge of the interacting quark.

The running coupling constant is given to lowest order by,

$$\alpha_s(Q^2) = \frac{12\pi}{(33 - 2N_f)\ln(Q^2/\Lambda^2)} \quad (8)$$

where N_f is the number of flavours and Λ is the QCD scale parameter. Following Aurenche et al [4, 8] we have taken the number of flavours as four and $\Lambda = 0.231$ GeV. The relation between Q^2 and p_T^2 for the evaluation of direct photons introduces a new parameter in the description.

Corrections to the Compton and annihilation graphs have been calculated by Aurenche et al. [4, 8], and we have used their programs to calculate the tables and figures presented at the end of this paper. The single-photon inclusive cross section can be written as

$$E \frac{d\sigma^{Inclusive}}{d^3p} = E \frac{d\sigma^B}{d^3p} + E \frac{d\sigma^{HO}}{d^3p} + E \frac{d\sigma^A}{d^3p} \quad (9)$$

where the separate terms are the leading order Born term, higher order and anomalous contribution.

The photon couples to the charge of the quark and the resulting fragmentation function to lowest order is ,

$$zD_{q \rightarrow \gamma}(z, Q_f^2) = e_q^2 \frac{\alpha}{2\pi} [1 + (1-z)^2] \ln(Q_f^2/\Lambda^2) \quad (10)$$

and

$$zD_{g \rightarrow \gamma}(z, Q_f^2) = 0 \quad (11)$$

where z represents the fraction of the jet momentum carried by the (collinear) photon.

In general there are three places where scales have to be discussed :

1. The renormalization scale in the running coupling constant. We will denote this by C_1 , so that in Eq. (8) one has $Q^2 = C_1 p_t^2$, typically C_1 varies between 1/16 and 16.
2. The factorization scale in the structure functions. This is chosen to be the same as the previous one.
3. The factorization scale in the fragmentation functions. This will be denoted by C_f . Thus the Q_f^2 appearing in Eq. (10) is given by $Q_f^2 = C_f p_t^2$.

In many cases it is possible to use a general prescription like the principle of minimal sensitivity (PMS)[19] to treat this arbitrariness in a more satisfactory way. In PMS one looks at the differential cross section as a function of C_1 and C_f , and tries to find a minimum. This procedure has been followed when comparing with the experimental data of the NA24 collaboration. It is however not always possible to find such a minimum and in many cases one has to accept that the cross section is not very sensitive to a change in scales.

COMPARISON WITH EXPERIMENTAL DATA

In the comparison to existing data, we consider $p - p$ and $p - \bar{p}$ collisions at various energies ranging from 23 GeV to 1.8 TeV. The cross-sections always refer to the invariant form

$$E \frac{d\sigma}{d^3p} = \frac{1}{2\pi p_t} \frac{d\sigma}{dp_t dy} \quad (12)$$

and are shown for fixed y or a y interval as a function of p_t .

The parametrization chosen for the structure functions used in all calculations is the one denoted by $D-'$ [1]. The change in the results when other structure functions such as $D0'$ [1] or ABFOW[18] are used is of the order of 10%. This relative insensitivity is due to the energy range at which present data are taken, higher energies probe the small x -region of the parton distribution functions and thus lead to a higher sensitivity on the precise form of the structure functions in the low x region.

In Fig. (1) we compare the data of the NA24 collaboration[9] with the results of our calculations. The data taken in a finite y interval were extrapolated to $y = 0$ using the procedure of Aurenche and Whalley[20]. The calculation is carried out using the PMS scheme (full line) and at a fixed scale of $Q^2 = p_t^2/4$ (dashed line). In both cases good agreement is obtained with the data.

For the other experiments we used the fixed scale of $Q^2 = p_t^2/4$.

In Fig. (2) this calculation is compared to the data of WA70 taken at $\sqrt{s} = 22.96$ GeV. The plotted data were measured in a small bin symmetric around $y = 0$.

Fig. (3) shows the comparison with UA6 pp data [11] taken at $\sqrt{s} = 24.3$ GeV. These data were averaged in the interval $-0.2 \leq y \leq 1.$, the same averaging was applied to the theoretical calculation.

The most recent data of the E706 collaboration [12] for $p - Be$ at $\sqrt{s} = 30.6$ GeV are shown in Fig. (4) together with the results of our calculations.

In Fig. (5) we compare results obtained from $p - \bar{p}$ collisions [16] at $\sqrt{s} = 630$ GeV. To test for the sensitivity on the choice of scale parameter the results are shown for $Q^2 = p_t^2/4$ and a somewhat higher value $Q^2 = 16p_t^2$. As seen in Fig. (5) the agreement with experimental data is very good and only weakly dependent on the choice of the scale parameter.

In Figs. (6a) and (6b) we compare results obtained from $p - \bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV at the Tevatron by the D0 [14] and the CDF collaborations [15]. The agreement between data and theoretical prediction is illustrated in Fig. (7) where we

show the relative difference. As can be seen the deviations in the whole p_t range are very small.

As two further typical cases we also show a comparison with low energy $\pi^- p$ and $\pi^+ - p$ data in Figs. (8a) and (8b) where the full lines correspond to the parametrization of structure functions given by SMRS-P1, the short-dashed line to SMR-P2 and the long-dashed line to SMRS-P3 [17].

In all cases good agreement with the data is obtained, sometimes even very good, which provides us with confidence for the extrapolation towards higher energies.

PREDICTIONS

The calculations presented above were done for energies corresponding to RHIC energies, $s^{1/2} = 0.2$ and 0.5 TeV and for the LHC energy range, 5.5 and 14 TeV. These are presented in the form of tables and in the form of figures. In Fig. (9a) the dependence of γ -rates on C_1 defined above in section 2, for fixed $C_f = 16$ and $p_t = 2.0$ GeV is studied at the energy $\sqrt{s} = 14$ TeV. As seen in this figure the cross section is very flat for $C_1 > 2$. In Fig. (9b) we show the dependence on the factorization scale in the fragmentation function C_f for fixed $C_1=16$ at the same values of p_t and $\sqrt{s}$. It is seen that the cross section is only weakly dependent on C_f for $C_f > 5$. In conclusion from Figs. (9a-b), we use in the following the scale $C_1 = C_f = 16$ to get a result which is only weakly scale dependent for the rates. In the following figures (10) - (13) and tables (1) to (4) we present the predictions for the inclusive cross sections $d\sigma/dp_t dy$ (pb/GeV) for the energies relevant for RHIC and LHC using the structure functions $D-'$ (figures (10a)-(13a)) and $D0'$ (figures (10b)-(13b)). Note that these cross sections differ by a factor $2\pi p_t$ as compared to those shown in section 3.

Finally in Fig. (14) we show the rapidity dependence of the cross section for a number of values of the transverse momentum. We see that the cross-section remains essentially constant up to large values of the rapidity y and then falls off rapidly near the kinematic limit.

SUMMARY

It is felt that the predictions for photon production at RHIC and LHC energies are quite reliable as they reproduce most of the existing data. We also feel that they will be useful for planning experiments at these facilities.

Acknowledgment

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Figure Captions

- 1.) Comparison between data from the NA24 collaboration and theoretical calculations. Only statistical errors are shown.
- 2.) Comparison between data from the WA70 collaboration and theoretical calculations. Only statistical errors are shown.
- 3.) Comparison between data from the UA6 collaboration and theoretical calculations. Only statistical errors are shown.
- 4.) Comparison between data from the E706 collaboration and theoretical calculations. Only statistical errors are shown.
- 5.) Comparison between data from the UA2 collaboration and theoretical calculations. Only statistical errors are shown.
- 6a.) Comparison between data from the D0 collaboration and theoretical calculations. Only statistical errors are shown.
- 6b.) Comparison between data from the CDF collaboration and theoretical calculations. Only statistical errors are shown.
- 7.) Deviation of the theoretical prediction from the experimental values measured by the CDF collaboration.
- 8a.) Comparison between data from the WA70 collaboration on $\pi^- - p$ collisions and theoretical calculations. Only statistical errors are shown.
- 8b.) Comparison between data from the WA70 collaboration on $\pi^+ - p$ collisions and theoretical calculations. Only statistical errors are shown.
- 9a.) Dependence of the cross section on the scale C_1 at $p_t = 2$ GeV for $\sqrt{s} = 14$ TeV for the structure function $D-'$.
- 9b.) Dependence of the cross section on the scale C_f at $p_t = 2$ GeV for $\sqrt{s} = 14$ TeV for the structure function $D-'$.
- 10a.) Predictions for the photon cross section at $\sqrt{s} = 200$ GeV for the structure function $D-'$.
- 10b.) Predictions for the photon cross section at $\sqrt{s} = 200$ GeV for the structure function $D0'$.
- 11a.) Predictions for the photon cross section at $\sqrt{s} = 500$ GeV for the structure function $D-'$.
- 11b.) Predictions for the photon cross section at $\sqrt{s} = 500$ GeV for the structure function $D0'$.

- 12a.) Predictions for the photon cross section at $\sqrt{s} = 5.5$ TeV for the structure function $D-'$.
- 12b.) Predictions for the photon cross section at $\sqrt{s} = 5.5$ TeV for the structure function $D0'$.
- 13a.) Predictions for the photon cross section at $\sqrt{s} = 14$ TeV for the structure function $D-'$.
- 13b.) Predictions for the photon cross section at $\sqrt{s} = 14$ TeV for the structure function $D0'$.
- 14.) Photon cross section as a function of the rapidity y at $p_t = 2$ GeV for $\sqrt{s} = 14$ TeV for the structure function $D-'$.

Table 1 : Inclusive γ production in p-p collision $d\sigma/dydp_t _{y=0}$ [pb/GeV] $s^{1/2} = 200$ GeV				
p_t [GeV]	Inclusive D^-	Born D^-	Inclusive $D0'$	Born $D0'$
2.0	0.729 10^6	0.292 10^6	0.811 10^6	0.316 10^6
3.0	0.124 10^6	0.584 10^5	0.141 10^6	0.659 10^6
4.0	0.348 10^5	0.178 10^5	0.399 10^5	0.203 10^5
5.0	0.128 10^5	0.685 10^4	0.147 10^5	0.783 10^5
6.0	0.558 10^4	0.305 10^4	0.639 10^4	0.347 10^4
7.0	0.280 10^4	0.155 10^4	0.318 10^4	0.175 10^4
8.0	0.145 10^4	0.802 10^3	0.164 10^4	0.903 10^4
9.0	0.818 10^3	0.453 10^3	0.922 10^3	0.507 10^3
10.0	0.485 10^3	0.268 10^3	0.544 10^3	0.298 10^3
15.0	0.554 10^2	0.298 10^2	0.602 10^2	0.321 10^2
20.0	0.943 10^1	0.494 10^1	0.996 10^1	0.517 10^1
25.0	0.195 10^1	0.993 10^0	0.200 10^1	0.101 10^1
30.0	0.444 10^0	0.221 10^0	0.443 10^0	0.218 10^0
40.0	0.251 10^{-1}	0.119 10^{-1}	0.237 10^{-1}	0.112 10^{-1}
50.0	0.124 10^{-2}	0.560 10^{-3}	0.112 10^{-2}	0.507 10^{-2}
60.0	0.447 10^{-4}	0.195 10^{-4}	0.392 10^{-4}	0.174 10^{-4}
70.0	0.843 10^{-6}	0.360 10^{-6}	0.733 10^{-6}	0.323 10^{-6}
80.0	0.444 10^{-8}	0.194 10^{-8}	0.400 10^{-8}	0.187 10^{-8}

Table 2 : Inclusive γ production in p-p collision $d\sigma/dydp_t _{y=0}$ [pb/GeV] $s^{1/2} = 500$ GeV				
p_t [GeV]	Inclusive $D-'$	Born $D-'$	Inclusive $D0'$	Born $D0'$
2.0	0.199 10 ⁷	0.637 10 ⁶	0.196 10 ⁷	0.587 10 ⁶
3.0	0.344 10 ⁶	0.136 10 ⁶	0.365 10 ⁶	0.140 10 ⁶
4.0	0.986 10 ⁵	0.442 10 ⁵	0.108 10 ⁶	0.477 10 ⁵
5.0	0.373 10 ⁵	0.181 10 ⁵	0.418 10 ⁵	0.201 10 ⁵
6.0	0.168 10 ⁵	0.858 10 ⁴	0.190 10 ⁵	0.966 10 ⁴
7.0	0.874 10 ⁴	0.465 10 ⁴	0.994 10 ⁴	0.527 10 ⁴
8.0	0.473 10 ⁴	0.258 10 ⁴	0.539 10 ⁴	0.294 10 ⁴
9.0	0.282 10 ⁴	0.156 10 ⁴	0.323 10 ⁴	0.178 10 ⁴
10.0	0.177 10 ⁴	0.989 10 ³	0.203 10 ⁴	0.113 10 ⁴
15.0	0.283 10 ³	0.161 10 ³	0.321 10 ³	0.182 10 ³
20.0	0.721 10 ²	0.411 10 ²	0.808 10 ²	0.459 10 ²
25.0	0.236 10 ²	0.134 10 ²	0.262 10 ²	0.148 10 ²
30.0	0.903 10 ¹	0.510 10 ¹	0.988 10 ¹	0.554 10 ¹
40.0	0.175 10 ¹	0.973 10 ⁰	0.187 10 ¹	0.103 10 ¹
50.0	0.411 10 ⁰	0.224 10 ⁰	0.429 10 ⁰	0.232 10 ⁰
60.0	0.112 10 ⁰	0.601 10 ⁻¹	0.115 10 ⁰	0.610 10 ⁻¹
70.0	0.329 10 ⁻¹	0.173 10 ⁻¹	0.329 10 ⁻¹	0.172 10 ⁻¹
80.0	0.100 10 ⁻¹	0.520 10 ⁻²	0.983 10 ⁻²	0.506 10 ⁻²
90.0	0.312 10 ⁻²	0.159 10 ⁻²	0.299 10 ⁻²	0.152 10 ⁻²
100.0	0.968 10 ⁻³	0.483 10 ⁻³	0.911 10 ⁻³	0.454 10 ⁻³

Table 3 : Inclusive γ production in p-p collision $d\sigma/dydp_t _{y=0}$ [pb/GeV] $s^{1/2} = 5.5$ TeV				
p_t [GeV]	Inclusive $D-'$	Born $D-'$	Inclusive $D0'$	Born $D0'$
2.0	$0.133 \cdot 10^8$	$0.213 \cdot 10^7$	$0.258 \cdot 10^8$	$0.565 \cdot 10^7$
3.0	$0.301 \cdot 10^7$	$0.652 \cdot 10^6$	$0.475 \cdot 10^7$	$0.129 \cdot 10^7$
4.0	$0.101 \cdot 10^7$	$0.265 \cdot 10^6$	$0.142 \cdot 10^7$	$0.444 \cdot 10^6$
5.0	$0.427 \cdot 10^6$	$0.128 \cdot 10^6$	$0.557 \cdot 10^6$	$0.192 \cdot 10^6$
6.0	$0.207 \cdot 10^6$	$0.689 \cdot 10^5$	$0.256 \cdot 10^6$	$0.953 \cdot 10^5$
7.0	$0.116 \cdot 10^6$	$0.415 \cdot 10^5$	$0.137 \cdot 10^6$	$0.540 \cdot 10^5$
8.0	$0.654 \cdot 10^5$	$0.252 \cdot 10^5$	$0.753 \cdot 10^5$	$0.313 \cdot 10^5$
9.0	$0.413 \cdot 10^5$	$0.166 \cdot 10^5$	$0.461 \cdot 10^5$	$0.198 \cdot 10^5$
10.0	$0.272 \cdot 10^5$	$0.113 \cdot 10^5$	$0.298 \cdot 10^5$	$0.131 \cdot 10^5$
15.0	$0.539 \cdot 10^4$	$0.250 \cdot 10^4$	$0.544 \cdot 10^4$	$0.260 \cdot 10^4$
20.0	$0.167 \cdot 10^4$	$0.827 \cdot 10^3$	$0.161 \cdot 10^4$	$0.809 \cdot 10^3$
25.0	$0.663 \cdot 10^3$	$0.343 \cdot 10^3$	$0.621 \cdot 10^3$	$0.324 \cdot 10^3$
30.0	$0.310 \cdot 10^3$	$0.165 \cdot 10^3$	$0.284 \cdot 10^3$	$0.152 \cdot 10^3$
40.0	$0.914 \cdot 10^2$	$0.506 \cdot 10^2$	$0.821 \cdot 10^2$	$0.455 \cdot 10^2$
50.0	$0.340 \cdot 10^2$	$0.192 \cdot 10^2$	$0.302 \cdot 10^2$	$0.171 \cdot 10^2$
60.0	$0.153 \cdot 10^2$	$0.882 \cdot 10^1$	$0.135 \cdot 10^2$	$0.777 \cdot 10^1$
70.0	$0.772 \cdot 10^1$	$0.450 \cdot 10^1$	$0.680 \cdot 10^1$	$0.395 \cdot 10^1$
80.0	$0.424 \cdot 10^1$	$0.249 \cdot 10^1$	$0.373 \cdot 10^1$	$0.219 \cdot 10^1$
90.0	$0.249 \cdot 10^1$	$0.147 \cdot 10^1$	$0.219 \cdot 10^1$	$0.129 \cdot 10^1$
100.0	$0.154 \cdot 10^1$	$0.912 \cdot 10^0$	$0.135 \cdot 10^1$	$0.803 \cdot 10^0$

Table 4 : Inclusive γ production in p-p collision $d\sigma/dydp_t _{y=0}$ [pb/GeV] $s^{1/2} = 14\text{TeV}$				
p_t [GeV]	Inclusive $D-'$	Born $D-'$	Inclusive $D0'$	Born $D0'$
2.0	0.678 10^8	0.138 10^8	0.249 10^8	0.328 10^7
3.0	0.128 10^8	0.320 10^7	0.608 10^7	0.109 10^7
4.0	0.390 10^7	0.111 10^7	0.214 10^7	0.464 10^6
5.0	0.155 10^7	0.486 10^6	0.933 10^6	0.233 10^6
6.0	0.718 10^6	0.244 10^6	0.464 10^6	0.130 10^6
7.0	0.389 10^6	0.140 10^6	0.266 10^6	0.803 10^5
8.0	0.214 10^6	0.816 10^5	0.152 10^6	0.500 10^5
9.0	0.132 10^6	0.518 10^5	0.975 10^5	0.335 10^5
10.0	0.860 10^5	0.345 10^5	0.653 10^5	0.233 10^5
15.0	0.161 10^5	0.706 10^4	0.136 10^5	0.554 10^4
20.0	0.487 10^4	0.225 10^4	0.439 10^4	0.193 10^4
25.0	0.191 10^4	0.920 10^3	0.180 10^4	0.836 10^3
30.0	0.890 10^3	0.440 10^3	0.866 10^3	0.417 10^3
40.0	0.263 10^3	0.136 10^3	0.269 10^3	0.136 10^3
50.0	0.986 10^2	0.523 10^2	0.104 10^3	0.545 10^2
60.0	0.451 10^2	0.244 10^2	0.484 10^2	0.261 10^2
70.0	0.231 10^2	0.127 10^2	0.252 10^2	0.138 10^2
80.0	0.129 10^2	0.722 10^1	0.142 10^2	0.795 10^1
90.0	0.773 10^1	0.436 10^1	0.858 10^1	0.485 10^1
100.0	0.486 10^1	0.277 10^1	0.544 10^1	0.310 10^1

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6a

Figure 6b

Figure 7

Figure 8a

Figure 8b

Figure 9a

Figure 9b

Figure 10a

Figure 10b

Figure 11a

Figure 11b

Figure 12a

Figure 12b

Figure 13a

Figure 13b

Figure 14