A GLOBAL TEST OF
QCD THEORIES FOR DIRECT PHOTON PRODUCTION

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Abstract

Direct photon production data at fixed target and collider experiments from \(pp\) and \(\bar{p}p\) collisions are analysed in NLO QCD. The results are grouped into three sets having \(\sqrt{s} = 20 - 30\) GeV, 630 GeV and 1.8 TeV. It is seen that at the lowest energies considered, the theory systematically underpredicts the results for all the values of the transverse momentum. At the intermediate energy of the UA2 experiment, the data are more accurately described at high \(p_T\), and at the highest collider energies no significant underprediction is seen even at low \(p_T\), when using recent structure functions as measured at HERA.

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Experimental and theoretical studies of direct or prompt photon production in hadron-hadron collisions at large transverse momenta have been pursued extensively in the literature. This interest stems from the expectation that direct photons may provide a clean test of perturbative QCD, and also give valuable information about the parton distribution functions of the hadrons. The production of direct photons in lowest order proceeds through the annihilation ($q\bar{q} \rightarrow g\gamma$) and the Compton ($qg \rightarrow q\gamma$) processes. The Compton processes have the unique distinction of being sensitive to the gluon structure function. At the same time a fairly precise next to leading order QCD treatment is available for the analysis [1].

This offers us an opportunity to perform a global test of the QCD theories for the direct photon production. Huston et al. [2] have recently performed this task using CTEQ2M [3] structure functions, and reported that in general the theory underpredicts the data. They find a general trend of a larger deviation at lower $p_T$, and a smaller deviation at larger $p_T$ at all the energies, which they claim should require an additional nonperturbative $p_T$ broadening of the initial state parton distribution.

In this note, we will demonstrate how this apparent gap between theory and data is strongly reduced when using more recent structure functions, and how NLO QCD nicely describes the data in the region where this is to be expected.

This analysis relies on the NLO QCD calculation of direct photon production by P.Aurenche et al. [1]. This treatment was recently applied to the data for direct photon production from the Fermilab collider, see for instance [4], to the global analysis mentioned above [2], as well as to an overview of existing data in order to form a basis for the prediction of direct photon production at future (LHC,RHIC) experiments [5].

In a spirit similar to that of ref. [1,2,4,5], we use the NLO QCD theory but with a different parametrization of the structure functions, we now compute the cross section of direct photon production in $pp$ and $\bar{p}p$ reactions and compare our results with the existing data. The available experimental results for direct photon production in $pp$ and $\bar{p}p$ collisions can be broadly categorized into three groups, depending on the centre of mass energy; $\sqrt{s} = 20-30$ GeV, 630 GeV, and 1.8 TeV. This increase of energy corresponds to a decrease of the momentum fraction $x$ which is probed by the photon production process inside the hadron. The elementary parton–parton collision occurs at $\hat{s} = x_1x_2s$, where $\sqrt{s}$ is the c.m. energy of the hadron–hadron reaction, and $x_1$ and $x_2$ are the momentum fractions of the parton from the beam and target hadron, respectively. For a photon emitted at $\theta = 90^o$ in the c.m.s., corresponding to a rapidity of $y = 0$, the expressions are symmetric in $x_1$ and $x_2$, which we then simply denote by $x$ (kinematically, the process actually converts a quark into a photon momentum). All of the data we consider here are taken around midrapidity. Calculating the production process involves an integration over $x_1$, $x_2$ within the limits $x_{min} \leq x \leq 1$. For $y = 0$, and using the normalized transverse momentum variable $x_T = 2p_T/\sqrt{s}$, we have

$$x_{min} = \frac{x_T}{2 - x_T} = \frac{p_T}{\sqrt{s} - p_T} \quad (1)$$

Therefore, the data for the first group should be sensitive to parton structure functions down to $x_{min}=0.16$, whereas for the second group this sensitivity should be down to $x_{min}=0.02$. For the highest energy considered, the structure function is explored down to $x=0.0067$. 

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In our calculation, we use the structure functions $MRSD-\prime$ from Martins, Stirling and Roberts \[6\], which provides a good fit to recent HERA data. We first illustrate the difference to the $CTEQ2M$ structure function, which was used previously in this context, by comparing both parametrizations in the $x$ and $Q^2$ range which is relevant to the data we are considering. Fig. 1 shows the parton distribution functions provided by $CTEQ2M$ and $MRSD-\prime$ for values of $Q^2 = (10 \text{ GeV})^2$ and $Q^2 = (100 \text{ GeV})^2$, which is about the range covered by the UA2 and Tevatron photon data. For the gluon distribution, plotted in fig. 1a, one observes a strong effect of the $Q^2$ evolution on both structure functions. However, the parametrizations are also different. With decreasing $x$, which corresponds to going to smaller values of $p_T$, more gluons are provided by $MRSD-\prime$ than by $CTEQ2M$. Going to higher $\sqrt{s}$, corresponding to probing of smaller $x$, similarly opens a gap between the gluon luminosities provided by the two structure functions. Since the low $p_T$ region is dominated by the Compton processes involving gluonic fusion, the calculation which uses the $CTEQ2M$ structure function therefore results in a lower cross section than the one using $MRSD-\prime$. For a comparison, we also show the gluon density provided by the latest (1995) parametrization $MRSG$. It has the same trend of providing more gluon luminosity, even somewhat more pronounced than $MRSD-\prime$. For a better comparison to existing calculations, we are going to use $MRSD-\prime$ in the following calculation. In fig. 1b we plot the valence ($u$ only) and the sea quark distributions. Here, less difference is seen when comparing the two structure functions $CTEQ2M$ and $MRSD-\prime$, which is of the order of the effect of the $Q^2$ evolution. Correspondingly, the result for the photoproduction cross section for both distributions shows only little difference. This applies to the high $p_T$ region where $q\bar{q}$ annihilation is the dominating process.

We now turn to the results for direct photoproduction in $pp$ and $\bar{p}p$ reactions. For the three groups of energies, we show the comparison of the NLO QCD calculation and the data in the form of the fractional difference $\frac{\text{data} - \text{theory}}{\text{theory}}$ using the invariant cross section

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

The results are shown for the different energy regions with increasing energy in fig.'s 1a–1c.

The low energy group, shown in fig. 1a, contains the data of NA24 \[7\], WA70 \[8\], UA6 \[9\] and E706 \[10\] as compared to our result. Here and in the following, we extrapolated data taken in a finite $y$ interval to $y = 0$ by using the procedure of Aurenche and Whalley \[11\]. This calculation as well as the following ones are carried out at a fixed scale of $Q^2 = p_t^2/4$ as is that of Huston et al. \[2\]. As discussed for instance in \[3\], the dependence on the scale is weak in this domain and mainly affects the overall normalization, rather than the slope. We also note at this point that a possible overall uncertainty in the normalization of the data will also not affect the slope, as is discussed in \[2\].

What we find in the comparison with the low energy data is a general trend of an underestimate of the data by the NLO calculation, however no significant $p_T$ dependence of the discrepancy.

At intermediate energy, only the data of UA2 \[12\] exist and are shown in the comparison to theory in fig. 2b. As is seen in the plot, the data are already better described by theory, and the trend of a better agreement at high $p_T$ might be read off. However, the absolute deviation is reduced as compared to the calculation based on the $CTEQ2M$
distributions (apparently, the first point in fig. 2b is not contained in fig. 4 of [2] or is outside of the scale).

In the last figure, 2c, we show our results compared to the collider data from D0 [13] and CDF [14]. Here, the agreement is satisfactory, and no significant trend of a discrepancy increasing with decreasing $p_T$ can be read off. The apparent discrepancy between our result and the corresponding one of Huston et al. has its origin in the lower gluon luminosity provided by the $CTEQ2M$ parametrization in the $x$ region relevant for the low $p_T$ data, as we discussed before. It is also felt that the introduction of an additional broadening of the initial state parton distribution by some value $<\Delta k_T> \sim 1$ GeV of presumably nonperturbative origin would not have provided a resolution of this discrepancy. For the UA2 as well as for the high energy data, $<\Delta k_T> \ll p_T$ at which the data are taken and thus the effect of the additional $<\Delta k_T>$ broadening would be hardly visible. For the data in the low energy region, on the other hand, the underestimate of the data is present for all values of $p_T$.

We conclude that by using the recent structure function $MRSD-\prime$ (and even more so by the latest parametrization $MRSG$), we find that deviations are in general much less as compared to the results of Ref. [2], and follow the logical sequence of being large at lower energies and smaller $p_T$ and becoming insignificant at the highest energy over the entire range of $p_T$, for which the data are available. This conclusion is corroborated by the differences in the structure functions used at lower $x$ values. The behavior we find is precisely what is expected from any NLO calculation in general, here $O(\alpha_s^2)$. At small $\sqrt{s}$, the NLO QCD calculation necessarily underpredicts the data, then starts to give a quantitative prediction at sufficiently high $\sqrt{s}$ first at high values of $p_T$, and finally provides a satisfactory quantitative description of direct photon production over the entire range of $p_T$ range at high $\sqrt{s}$.

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REFERENCES

[1] P. Aurenche, R. Baier, M. Fontannaz and D. Schiff, Nucl. Phys. B286, 509 (1987); B297, 661 (1988); P. Aurenche, R. Baier and M. Fontannaz, Phys. Rev. D42, 1440 (1990)

[2] J. Huston, E. Kovacs, S. Kuhlmann, H. Lai, J. Owens and W. Tung, Phys. Rev. D 51, 6139 (1995)

[3] J. Botts et al., CTEQ Collab., Phys. Lett. B304, 159 (1993)

[4] M. Glück, L. Gordon, E. Reya and W. Vogelsang, Phys. Rev. Lett. 73, 388 (1994)

[5] J. Cleymans, E. Quack, K. Redlich and D. Srivastava, Preprint GSI–94–55, to appear in Int. J. Mod. Phys. A, 1995

[6] A. D. Martin, W. J. Stirling and R. G. Roberts, Phys. Lett. 306B, 145 (1993); H. Plothow-Besch, Comp. Phys. Comm. 75, 396 (1993)

[7] C. De Marzo et al. (NA24 collaboration), Phys. Rev. D36, 8 (1987)

[8] M. Bonesini et al. (WA70 collaboration) Z. f. Phys. C38, 371 (1988)

[9] G. Sozzi et al. (UA6 collaboration) Phys. Lett. B317, 243 (1993)

[10] G. Alverson et al. (E706 collaboration), Phys. Rev. D48, 5 (1993)

[11] P. Aurenche and M. R. Whalley, Rutherford Appleton Laboratory preprint RAL-89-106 (unpublished)

[12] R. Ansari et al. (UA2 collaboration), Z. f. Phys. C41, 395 (1988); Phys. Lett. B 263, 544 (1991)

[13] A. Smith (D0 collaboration), private communication.

[14] F. Abe et al. (CDF collaboration), Phys. Rev. Lett. 73, 2662 (1994); erratum: Phys. Rev. Lett. 74, 1891 (1995)
FIGURE CAPTIONS

1.) Comparison of the two structure functions used in the QCD analysis, MRS D-’ and CTEQ2M, in the \( x \) and \( Q^2 \) range relevant to the collider experiment, \( Q^2 \sim (p_T^2)^2 \). Also shown is the most recent parametrization MRS G. Fig. 1a: Density distribution of gluons, fig. 1b: Valence and sea quark distribution.

2a.) Fractional difference between the NLO QCD calculation and data taken at low energies, \( \sqrt{s} \leq 30.6 \) GeV.

2b.) Fractional difference between the NLO QCD calculation and data taken at the intermediate energy of \( \sqrt{s} = 630 \) GeV by UA2.

2c.) Fractional difference between the NLO QCD calculation and data taken at the Tevatron at \( \sqrt{s} = 1.8 \) TeV.
$\frac{(\text{Data} - \text{NLO QCD})}{\text{NLO QCD}}$
\frac{(\text{Data} - \text{NLO QCD})}{\text{NLO QCD}}

\begin{align*}
D -, \mu = p_T / 2
\end{align*}

\text{Photon } x_T

\text{UA2}
\[ \frac{(\text{Data} - \text{NLO QCD})}{\text{NLO QCD}} \]