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Prompt Photon Production as a Probe of the Proton's Gluon Distribution*

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Abstract

We analyze the capability of prompt photon production in pp and $p\bar{p}$ collisions to constrain the proton's gluon distribution, considering data from fixed-target experiments as well as collider data and taking also into account information coming from deep-inelastic scattering. Special attention is paid to theoretical uncertainties such as the scale dependence of the results or the NLO fragmentation contribution to the prompt photon cross section.

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1 Introduction

The production of high-p_T prompt photons in pp or $p\bar{p}$ collisions provides an important probe of the proton's gluon distribution, $g(x,Q^2)$, due to the presence and dominance of the leading order (LO) $\mathcal{O}(\alpha\alpha_s)$ 'Compton-like' subprocess $qg \to \gamma q$. In fact, constraints on $g(x,Q^2)$ for $0.3 \lesssim x \lesssim 0.6$ at $Q^2 \lesssim 10$ GeV^2, derived mainly from the WA70 fixed-target $pp \to \gamma X$ data [1], have been the backbone of the gluon determination in many parton density analyses [2, 3, 4, 5] ever since the pioneering work of [6]. Since then, major theoretical and experimental developments concerning direct-γ production have taken place. Experimentally, the accessible range of fractional gluon momenta x has been considerably enlarged by the recent, partly very precise measurements at the Fermilab Tevatron [7, 8, 9]. By now, the region $0.01 \lesssim x \lesssim 0.6$ is completely covered, with the data from WA70 [1], R806 [10], UA2 [11] and CDF [8] presently dominating in their respective kinematical regimes. On the theoretical side, it has become possible to perform a complete and fully consistent calculation of the NLO prompt photon cross section by including the NLO fragmentation contribution which is based on the partonic $2 \to 3$ QCD subprocesses [12] and on corresponding parton-to-photon fragmentation functions [13, 14]. Even more, the development of a proper NLO theoretical implementation of isolation cuts [15, 16], imposed on the cross section in the high-energy $Sp\bar{p}S$ and Tevatron experiments, was finished recently [17] and demonstrated to be phenomenologically important [18]. For these reasons, it seems time now for a reanalysis of the prompt photon data and their implications on the gluon density. In doing so, it is a crucial issue to take into account the main uncertainties inherent to the theoretical calculation, namely the dependence of the theoretical cross section on unphysical scales, such as the renormalization scale μ_R and the factorization scale μ_F, and the experimentally virtually unknown photonic fragmentation functions. These issues have not been thoroughly addressed in previous analyses. A complete version of the study presented here can be found in [19].

2 General Framework

Two types of processes contribute to the prompt photon production cross section: the so-called 'direct' piece, where the photon is emitted via a pointlike (direct) coupling to a quark, and the fragmentation piece, in which the photon originates from the fragmentation of a final state parton. Both the direct and the fragmentation pieces can be consistently calculated to order $\alpha\alpha_s^2$, since NLO corrections to the corresponding subprocesses have been calculated [16, 20, 21, 12]. The cross section for the fully inclusive production of a prompt photon with momentum p_γ schematically reads

$$d\sigma \equiv d\sigma_{dir} + d\sigma_{frag} = \sum_{a,b=q,\bar{q},g} \int dx_a dx_b f_a(x_a,\mu_F^2) f_b(x_b,\mu_F^2) \times \tag{1}$$

$$\left[d\hat{\sigma}^{\gamma}_{ab}(p_\gamma, x_a, x_b, \mu_R, \mu_F, M_F) + \sum_{c=q,\bar{q},g} \int_{z_{min}}^{1} \frac{dz}{z^2} d\hat{\sigma}^{c}_{ab}(p_\gamma, x_a, x_b, z, \mu_R, \mu_F, M_F) D^{\gamma}_{c}(z, M_F^2) \right] ,$$

where $z_{min} = x_T \cosh(\eta)$ with the prompt photon's rapidity η, and $x_T = 2p_T/\sqrt{s}$. In eq. (1), $d\hat{\sigma}^i_{ab}$ represent the subprocess cross sections for partons a, b producing a particle i ($i = \gamma$, q, g). $f_i(x, \mu_F^2)$ denotes the number density of the parton type i in the proton (or antiproton) at momentum fraction x and scale μ_F, and $D_c^\gamma(z, M_F^2)$ is the photon fragmentation function at scale M_F, z being the fraction of energy of the fragmenting parton c transferred to the photon. As already mentioned in the introduction, the cross section in any fixed order of perturbation theory depends on unphysical scales which have to be introduced in the procedure of renormalization (μ_R) and of factorization of initial (μ_F) and final (M_F) state mass singularities. At very high-energy $p\bar{p}$ colliders the photon is experimentally required to be 'isolated' in order to suppress the huge hadronic background. This means that the amount of hadronic energy E_{had} allowed in a cone $\sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} \leq R$ around the photon direction is limited to a small fraction of the photon energy, $E_{had} \leq \epsilon E_\gamma$ with $\epsilon \lesssim 0.1$. In [17] a simple, yet accurate and consistent way of incorporating this isolation criterion into the calculation has been developed for both the NLO direct and the NLO fragmentation pieces. Here the main result is that the cross section is significantly decreased by isolation, which is mainly due to a strong reduction of the fragmentation part [17, 22].

We note that the recent study in [23] reports a (rather p_T independent) $\mathcal{O}(10\%)$ discrepancy between the NLO programs of [16] and [21] in the kinematic regime of the CDF measurements, which persists also if the fully inclusive cross section is considered. In this context it is interesting to mention that there is no such discrepancy between the two calculations of [20] and [21], which are in *exact* agreement concerning the NLO direct contribution to the fully inclusive cross section for all p_T and $\sqrt{s}$. For all calculations to follow the program of [21, 17] is used, which relies on the one of [12] for the NLO fragmentation contribution.

3 Theoretical Uncertainties

In this section, we address the main uncertainties entering the NLO calculation of the prompt photon cross section, namely the dependence on the photon fragmentation functions and on the renormalization and mass factorization scales. We first calculate the cross section for a fixed 'standard' set of input distributions and parameters and confront it with the data. For this purpose, the parton distributions and photon fragmentation functions are taken from GRV [4, 14]. We choose $\mu_R = \mu_F = M_F = p_T/2$ for the renormalization and factorization scales except for the isolated prompt photon data, where $M_F = Rp_T$ seems more appropriate [15].

Fig. 1 displays the results for our 'standard' choice of input distributions and parameters. We show the 'default quantity' (data − theory)/theory versus x_T which is a good representative of the Bjørken-x values predominantly probed in the gluon distribution at given p_T and $\sqrt{s}$. As can be seen from Fig. 1, the overall agreement between data and the NLO theoretical prediction is good though not complete, if the very small errors of the CDF data are taken seriously. The agreement between theory and the fixed-target and ISR measurements is very good, whereas the comparison with the high-energy collider results seems to be slightly less successful, since both the CDF and the UA2 data show a somewhat stronger rise for small x_T than the theoretical cross section. This effect is more pronounced and statistically more meaningful for the CDF results, which possess the smallest point-to-point errors of all data sets and therefore provide a very precise measurement of the *slope* of the cross section. It has to be emphasized that a *much* stronger discrepancy between high-energy collider data and NLO calculations was reported previously [7, 8]. As was shown in [18], a dramatic improvement is obtained by using 'modern' sets of (steep) parton distribution functions like, e.g., those of GRV [3, 4] or the most recent MRS(A′,G) sets [2] as well as, equally important, by including a properly isolated *NLO* fragmentation contribution in the calculation. According to Fig. 1a), the latter amounts to a 20% slope effect for CDF conditions, thus its inclusion is clearly crucial for a quantitative comparison between the experimental and theoretical cross sections. One furthermore infers from the figure that fragmentation also plays an important role in the calculations in the ISR and fixed-target regions.

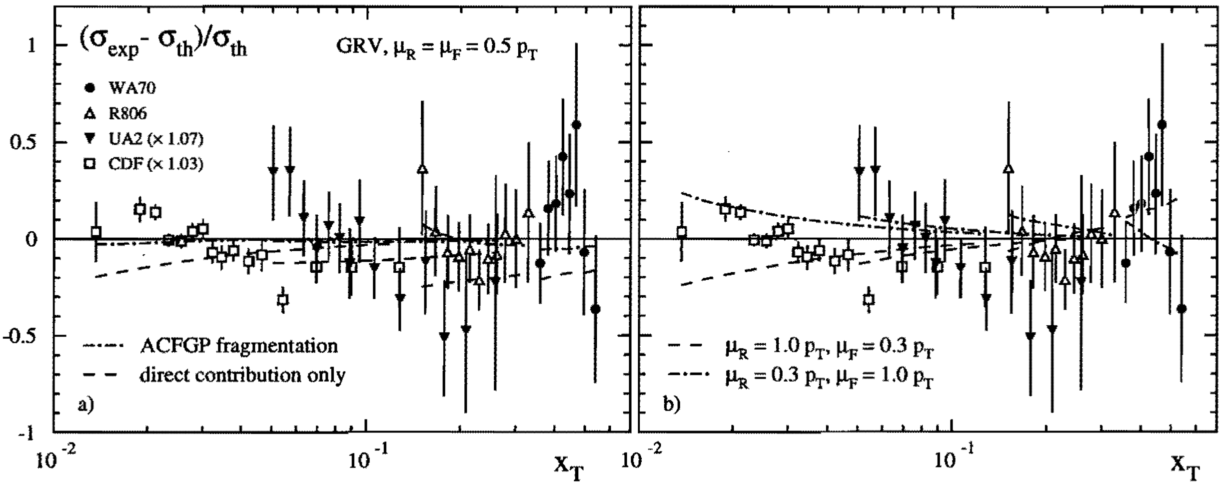

Figure 1: **a)** $(\sigma_{exp}-\sigma_{th})/\sigma_{th}$ vs. x_T for the data of [1, 10, 11, 8] as compared to the NLO theoretical cross section σ_{th}, using the GRV parton distributions and photon fragmentation functions [4, 14]. The curves present the shifts $(\sigma_{th'}-\sigma_{th})/\sigma_{th}$, where $\sigma_{th'}$ denotes the theoretical cross section if the fragmentation contribution is neglected or if the fragmentation functions of [13] are used. **b)** Same as a), but the lines displaying the shifts in the theoretical results if the renormalization and factorization scales are varied as indicated in the figure.

An important uncertainty in the calculation is the dependence of the cross section on the parton-to-photon fragmentation functions which are experimentally unknown so far. Two NLO sets of such distributions have been suggested in the literature, namely in [13] (ACFGP) and in [14] (GRV). Despite significant differences in the underlying methodology of setting up these, they yield very similar results for the total fragmentation contribution, as can be seen from Fig. 1a) (see [19] for further details).

Let us now discuss the scale dependence of the results, i.e. the changes in the theoretical predictions for varying μ_R and μ_F. We keep the fragmentation scale M_F fixed at $M_F = p_T/2$ for the fixed-target and ISR experiments and $M_F = Rp_T$ for the isolated cross sections in the following, since the dependence on M_F is very weak. It turns out that varying μ_R and μ_F

subject to the constraint $\mu_R = \mu_F$ only amounts to almost a constant shift in the normalization of the theoretical cross section as far as the CDF and UA2 data are concerned, and does not provide a change in the *slope* of the cross section. There is, however, no argument that enforces μ_R and μ_F to be exactly equal. They are just expected to be of the same order of magnitude, given by the prompt photon's p_T. For instance, a smaller renormalization scale μ_R along with a larger factorization scale μ_F can be expected to create a steeper slope of the theoretical cross section. In fact, the curves in Fig. 1b) show that these effects are quite significant. The choices of, e.g., $\mu_R = 0.3\,p_T$, $\mu_F = p_T$ or $\mu_R = p_T$, $\mu_F = 0.3\,p_T$ do lead to about $\pm 20\%$ shape changes in the CDF region, respectively. The rather strong scale dependence of the NLO cross section for prompt photon production indicates the importance of corrections of even higher order and sets severe limits on the accuracy of gluon determinations from these data.

4 Combined Analysis of DIS and Prompt Photon Data

In this section, we examine the question of whether the agreement between NLO calculation and the isolated prompt photon data can be further improved by adapting the proton's parton content, in particular its gluon density. For this purpose, we perform combined NLO fits to direct-γ and DIS data. The technical procedure for the fits is explained in much detail in [19]. At the reference scale of $Q_0^2 = 4$ GeV^2 the gluon input is parametrized as

$$xG(x, Q_0^2) = Ax^{\alpha}(1-x)^{\beta}\left(1 + \gamma\sqrt{x} + \delta x\right) \quad . \tag{2}$$

For each given set of $\alpha, \beta, \gamma, \delta$, a fit of the quark densities to F_2^p data of BCDMS [24], NMC [25], ZEUS [26], and H1 [27] is performed. Finally, we use the complete set of parton distributions obtained from this F_2^p fit to determine the χ_γ^2 for the prompt photon data of WA70 [1], NA24 [28], UA6 [29], R806/7 [10], UA2 [11] and CDF [8]. Due to the very small point-to-point errors of the CDF data [8] their overall normalization factor is important for the fit and is therefore allowed to float. The whole procedure is repeated until $\chi^2_{tot.} = \chi^2_{DIS} + \chi^2_\gamma$ is minimized. In order to examine the uncertainty coming from the choice for the QCD scale parameter Λ, we perform fits for $\Lambda^{(4)}_{\overline{MS}} = 200$ MeV and 300 MeV. Furthermore, in view of our findings for the scale dependence of the prompt photon cross section, fits are performed for various combinations of the renormalization/factorization scales μ_R, μ_F. Fig. 2 shows some of our results. It becomes obvious that there is quite a sizeable improvement, especially concerning the CDF data, for which the χ^2 decreases to ~ 25, about 10 of which are contributed by the data point at $p_T = 48.9$ GeV. In particular, Fig. 2 demonstrates that there is no slope effect for these data any more. The description of the UA2 data also improves slightly, although these only give a small contribution to χ^2_γ due to their rather large errors. As before, the fixed-target and ISR data are well described. The overall χ^2_γ for the 60 prompt photon data points is 52.8 for the $\mu_R = 0.3p_T$, $\mu_F = 0.7p_T$ fit. Fig. 2 also shows that we do not find a significant difference in the quality of the fits for the two Λ values.

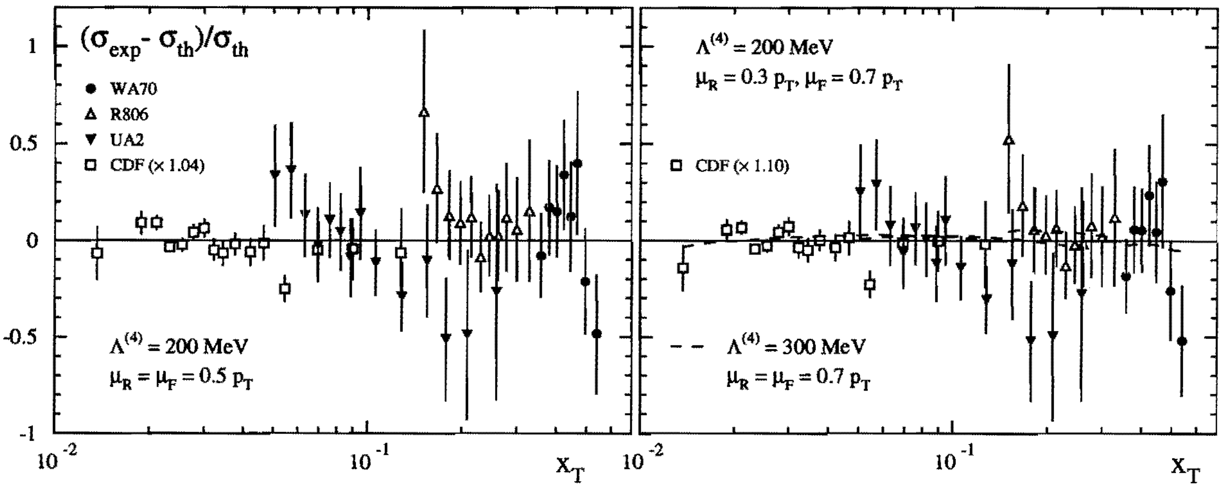

Figure 2: Results for our fits [19] for the scale combinations and $\Lambda^{(4)}$ as indicated in the figure.

Our fits demonstrate that presently published data on pp, $p\bar{p} \to \gamma X$ can be described quantitatively by NLO perturbative QCD. This finding is at variance with the results of a recent, partly comparable analysis of the CTEQ group [23]. In that paper, it is concluded that (at least) the p_T-shapes of the ISR and collider data can not be satisfactorily fitted, unless an 'intrinsic' k_T-smearing is introduced, which is as large as even $< k_T > \approx 4$ GeV for $Sp\bar{p}S$ and Tevatron conditions. It should be clear that we do not claim positive evidence for the absence of any smearing, but we emphasize that the data considered here can be accounted for without this assumption. Let us note some obvious differences between our study and [23]. With respect to data, we use the latest results of R806/7 [10], whereas [23] includes previous superseded steeper results of this collaboration [30]. Using the results of [10], there is obviously no slope offset between NLO theory and data, neither for the standard distributions, see Fig. 1, nor for our fits discussed above. With respect to the theoretical treatment, in contrast to [23] we fully incorporate *NLO* fragmentation and the NLO treatment of isolation into our analysis. The very small errors of the CDF data [8] make a complete and consistent NLO analysis mandatory in order to arrive at any solid statements on the viability of the NLO description of prompt photon production.

We are therefore convinced that it seems reasonable in the present situation to adjust as far as possible the proton's parton distributions in order to improve the agreement between data and NLO theory, as we have done above. Fig. 3 shows the gluon distribution at $Q^2 = 20$ GeV^2 obtained for our fits displayed in Fig. 2, compared with the GRV [4] gluon. It becomes obvious that all our gluon distributions turn out to be larger than the GRV gluon (or other 'standard' gluon distributions such as MRS(A',G) [2]) at $x \sim 10^{-2}$, which is an effect of including the CDF data in the analysis, but smaller at $x \sim 0.1$. The latter feature becomes particularly visible in the linear plot. As expected from our results in section 3, Fig. 3 also indicates that the gluon distribution obtained from prompt photon data is subject to uncertainties due to the scale dependence of the cross section [19].

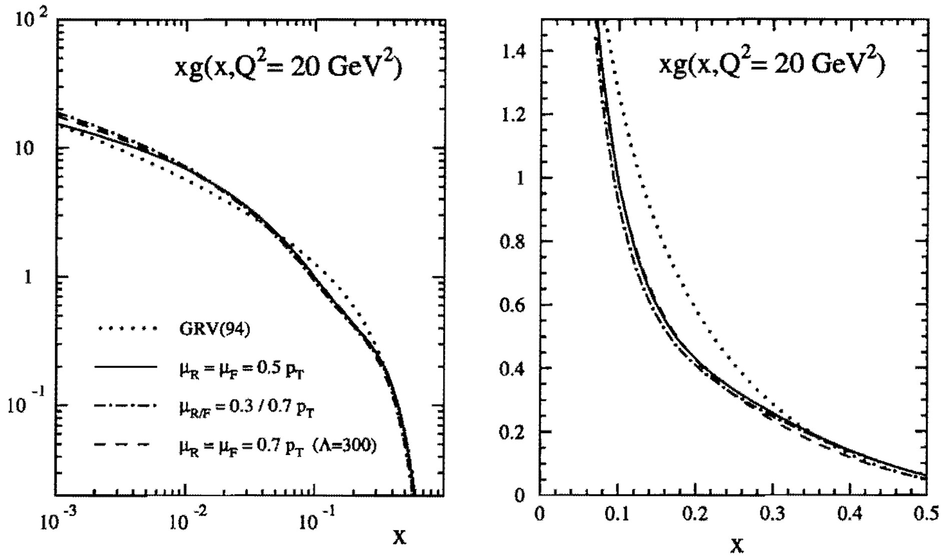

Figure 3: Gluon distributions corresponding to the fits in Fig. 2 as compared to the GRV [4] gluon.

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