

**Global Photon Summary**

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1 Introduction

Isolated high transverse energy (“prompt”) photons have a point-like coupling to the hard interaction, allowing for direct probes and precision tests of perturbative QCD (pQCD). The particular virtue of prompt photon processes is that the observed final state photon emerges directly from a QCD diagram without the subsequent hadronisation which complicates the study of high E_T quarks and gluons. This avoids all the systematics associated with jet measurement.

A strong motivation for the early prompt photon measurements from hadron collisions was the extraction of the gluon density in nucleons. However, due to large statistical and systematic uncertainties in the experiments and large uncertainties in the theoretical predictions, the first generation of prompt photon experiments failed to distinguish between hard gluon and soft gluon distributions.

Over the past few years many theoretical studies of prompt photon production have been performed with continuous improvements in the theoretical precision and new phenomenological modelling was introduced to interpret the experimental results. It included the definition of the scale of the interaction, unknown amounts of effective transverse momentum of the initial state partons, and a lack of a complete calculation of higher-order contributions for prompt photon production.

In addition, there are a large number of theories which predict new physics with photons in the final states. These theories include: $H \rightarrow \gamma\gamma$, Grand Unified Theories, composite models of quarks and leptons, large extra dimensions, SUSY models and technicolor models. Therefore it is important to understand QCD photon production in order to reliably search for new physics with photons in the final states.

The aim of this talk is to present the recent measurements of prompt photon production to lead us to a deeper understanding of some fundamental questions of QCD and the partonic nature of matter. The recent experimental results of prompt photon production in the hadronic collisions, $p\bar{p}$ and ep , will be briefly discussed and the current issues in prompt photon production will then be reviewed.

2 Prompt photon production at the Tevatron

In Run I both CDF and $D\bar{O}$ experiments at the Tevatron have performed pure QCD tests with prompt photons in a number of different ways [1,2]: (1) the cross section measurement of inclusive photon production at $\sqrt{s} = 1.8$ TeV and $\sqrt{s} = 630$ GeV to provide some constraint on the gluon distributions through the LO Compton scattering process, (2) photon plus two jet angular distributions to make a distinction between prompt photon production and bremsstrahlung, (3) photon plus charm production to test the heavy flavor content of the proton, and (4) diphoton production for a direct measurement of the parton intrinsic transverse momentum, k_T . In particular, the Run II data will provide an important testing ground for novel approaches and improvements in the understanding of the prompt photon process. This can help to solve the present issues which will be discussed in section 4.

The CDF and $D\bar{O}$ experiments have different analysis tools to identify the photon signal from the mixture of photons and a neutral meson background. For the CDF measurement the fraction of photon candidate events that have an observed conversion in the material just in front of the calorimeter is used, along with the transverse shower shape measured in a proportional chamber at shower maximum in the calorimeter itself. In the end one of the two methods is used to evaluate point-by-point the fraction of photons in the data sample. For the $D\bar{O}$ measurement the fraction of energy observed in the first two longitudinal layer of the EM calorimeter is used. The fraction is then fitted to a smooth function as a function of transverse energy of the photon and this smooth curve is used to evaluate the photon purity.

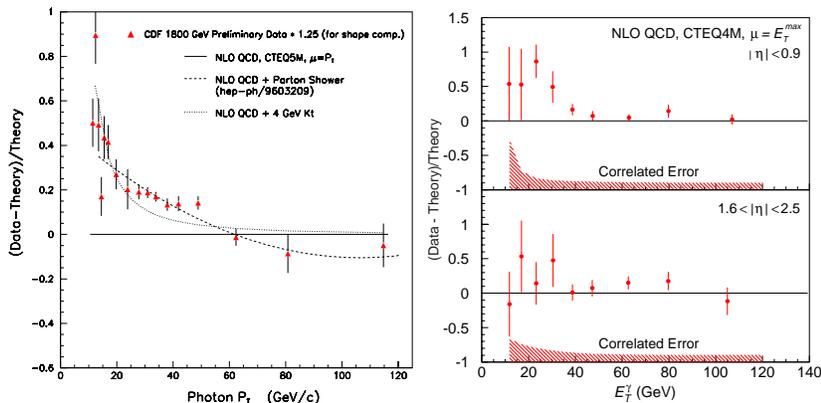


Fig. 1. (Left) Comparison of the CDF isolated prompt photon cross sections at $\sqrt{s} = 1.8$ TeV to CTEQ5M, CTEQ5M with a 4 GeV k_T correction, and CTEQ5M with parton showering. (Right) Difference between the measured differential cross section for $D\bar{O}$ isolated photon production at $\sqrt{s} = 1.8$ TeV and prediction from NLO QCD.

2.1 Run I results

Recent CDF and DØ measurements of the inclusive prompt photon cross section at $\sqrt{s} = 630$ GeV and 1.8 TeV are quite consistent with NLO QCD predictions for the high E_T^γ region (> 25 GeV), while both lie above theory at lower E_T^γ [1,2]. These discrepancies are difficult to explain with conventional theoretical uncertainties such as scale dependence and parton distribution parameterizations. One explanation proposed for the discrepancy at low E_T^γ is an inadequate description of the initial-state parton shower in the NLO QCD calculation which could give a recoil k_T to the photon-jet system. Including an additional transverse momentum, k_T , by adding a few GeV of simple Gaussian smearing to the NLO QCD calculation yields better agreement with the CDF data. This can be seen in the CDF results shown in Fig.1 (left). Using diphoton events, CDF has also measured $\langle k_T \rangle = 3.6 \pm 0.8$ GeV at $\sqrt{s} = 1.8$ TeV. At high p_T , the CDF data and theory disagree by an overall normalization factor and similar deficit is observed for the UA2 data; the CDF data in Fig.1 (left) have been normalized upwards by a factor of 1.25 for the benefit of a shape comparison. There is currently no explanation for this effect.

DØ has measured the production cross section for isolated photons at $\sqrt{s} = 630$ GeV and compared the cross section with that measured at $\sqrt{s} = 1.8$ TeV. The measurement is higher than the theoretical prediction at low E_T in the central rapidity region but agrees at all other E_T and in the forward rapidity region, as shown in Fig.1 (right). The difference between data and theory for $E_T^\gamma < 36$ GeV suggests that a more complete theoretical understanding of the origin of the low E_T^γ behavior of the photon cross section is needed before information on the gluon distribution at lower x can be extracted.

More recently, CDF has made the first measurement of the heavy flavor content of associated prompt photon plus muon events [3]. The measured cross section as a function of photon p_T agree in shape with the theoretical predictions, but fall below the theory in normalization by two standard deviations. The ratio of charm/bottom production is measured to be 2.4 ± 1.2 , in good agreement with QCD models.

2.2 Run II prospects

Studies of the prompt photon cross section will continue into Run II at Tevatron, where a full 15 fb^{-1} of data are anticipated. In addition, other photon analyses such as diphoton production and photon + heavy flavor production will play a leading role in test of QCD and searches for new phenomena. In diphoton events, for example, where the final state kinematics can be completely reconstructed, the diphoton mass can be measured with good resolution out to nearly 600 GeV.

3 Prompt photon production at HERA

Prompt photon processes at HERA could yield information about the quark and gluon content of the photon, together with the gluon structure of the proton. As with all photoproduction processes at HERA, two major classes of prompt photon production can be defined in lowest-order QCD, depending on how the photon interacts with a parton in the proton: direct and resolved processes. In this section the prompt photon production at HERA is discussed. Cross sections for inclusive prompt photons and for prompt photons accompanied by jets are compared with theory, and the latter is used to determine the effective transverse momentum of the quarks in the proton.

3.1 Inclusive photoproduction of prompt photons

The ZEUS experiment has measured the cross sections for prompt photon production as a function of the pseudorapidity and the transverse energy of the photon in the γp center-of-mass energy, $W_{\gamma p}$, range 134–285 GeV[4]. Fig. 2 shows the inclusive prompt photon cross section as a function of η^γ for photons with $5 < E_T^\gamma < 10$ GeV. Comparisons have been made with predictions from LO Monte Carlo models, and from NLO parton-level calculations. The models are able to describe the data well for forward η^γ , but are low in the rear direction. None of the available variations of the model parameters was found to be capable of removing the discrepancy with the data. This result would appear to indicate a need to review the present theoretical modelling of the parton structure of the photon. The recent FGH calculation[6] contains the NLO terms in LG and also a box diagram term that is included in K&Z. It is a slight improvement, but again fails to account fully for the backward cross section.

The H1 experiment has also measured the cross sections for inclusive prompt photon production as a function of the E_T^γ and η^γ for $E_T^\gamma > 5$ GeV and $-1 < \eta^\gamma < 0.9$ in the $W_{\gamma p}$ range 142–266 GeV[7]. The measured cross sections are quite well described by recent NLO calculations by FGH[6], but the prediction is above the data in the forward region. This small difference may be due to the lack of the effect of multiple parton interactions (MI) in the NLO calculation. The H1 results are roughly consistent with ZEUS results, but systematically tend to be lower at negative η^γ .

3.2 Photoproduction of prompt photon + jets

Most recently, photoproduced final states containing a prompt photon balanced by a recoil jet have been measured by ZEUS[5]. Events in the $W_{\gamma p}$ range between 134 and 251 GeV were selected containing a photon with $E_T^\gamma > 5$ GeV and $-0.7 < \eta^\gamma < 0.9$ and a jet with $E_T^{\text{jet}} > 5$ GeV and $-1.5 < \eta^{\text{jet}} < 1.8$. The kinematic properties of the photon-jet system were used to investigate

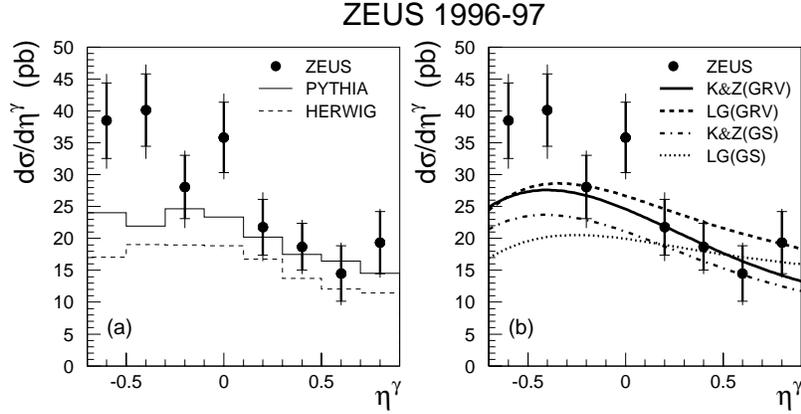


Fig. 2. Inclusive prompt photon distribution in ZEUS for events in the range $134 < W_{\gamma p} < 285$ GeV. The data are compared with (a) PYTHIA and HERWIG predictions using the GRV(LO) photon parton densities, (b) NLO calculations of Krawczyk and Zembrzuski (K&Z) and Gordon (LG) using GRV(HO) and GS(HO) photon parton densities.

the effective transverse momentum of the quarks in the proton, within the framework of the PYTHIA 6.129 Monte Carlo. In these events, the transverse momentum $\langle p_{\perp} \rangle$ of the prompt photon perpendicular to the jet direction in the r - ϕ plane is sensitive to the momentum of the quarks in the proton, as is the azimuthal angle between the prompt photon and the jet. The normalised distribution of $\langle p_{\perp} \rangle$ was used to fit the PYTHIA parameter k_0 , the so-called “intrinsic” parton momentum in the proton. By combining k_0 with the effects of the initial-state parton showers, it is possible to obtain an overall value for the effective transverse momentum of the partons in the proton. A fit to the data gave a $\langle k_T \rangle$ value of $1.69 \pm 0.18^{+0.18}_{-0.20}$ GeV. The ZEUS result is consistent with the trend shown by all the measurements, namely that the value of $\langle k_T \rangle$ rises with hadronic interaction energy. This may be attributed to the effects of initial-state gluon radiation, but a full theoretical description is still awaited.

3.3 Prompt photons in deep inelastic scattering

First measurements of cross sections for isolated prompt photon production in deep inelastic scattering were made with the ZEUS detector for photon virtualities above 35 GeV^2 [8]. A signal for isolated photons in the transverse energy and pseudorapidity range $5 < E_T^{\gamma} < 10 \text{ GeV}$, $-0.7 < \eta^{\gamma} < 0.9$ was observed, after the subtraction of the background from neutral mesons. Cross sections are measured for inclusive prompt photons and for those accompanied by one jet in the range $E_T^{jet} \geq 6 \text{ GeV}$, $-1.5 < \eta^{\gamma} < 1.8$. Theoretical

calculations made to $O(\alpha^2\alpha_s)$ describe reasonably well the measured photon plus jet cross sections.

4 Current issues in photon production

As described already the prompt photon production in hadron collisions has long been viewed as a clean test of QCD, and large amounts of data exist now from fixed target and $p\bar{p}$, as well as γp interactions. However there are several problems associated with the interpretation of these data. As seen in Fig. 3 (left), a pattern of deviations has been observed between measured prompt photon cross sections and QCD calculations. Much larger deviations from QCD are observed in the higher-statistics photon data from the E706 experiment [10]. Recent results from CDF and DØ also have a steeper slope above theory at low E_T region [1,2].

One possible explanation is that the partons in the proton may effectively have considerably higher mean intrinsic transverse momentum, $\langle k_T \rangle$, than the traditionally assumed value of a few hundred MeV. Evidence for significant $\langle k_T \rangle$ effects has been found in several measurements of dimuon, diphoton, and dijet pairs. Fig. 3 (right) shows the summary of $\langle k_T \rangle$ for a wide range of the hadronic center-of-mass energy, W , of the incoming particles. Although each experiment use different experimental methods to determine the parton $\langle k_T \rangle$, it can be seen that all measurements are consistent with the trend for $\langle k_T \rangle$ to rise with increasing W .

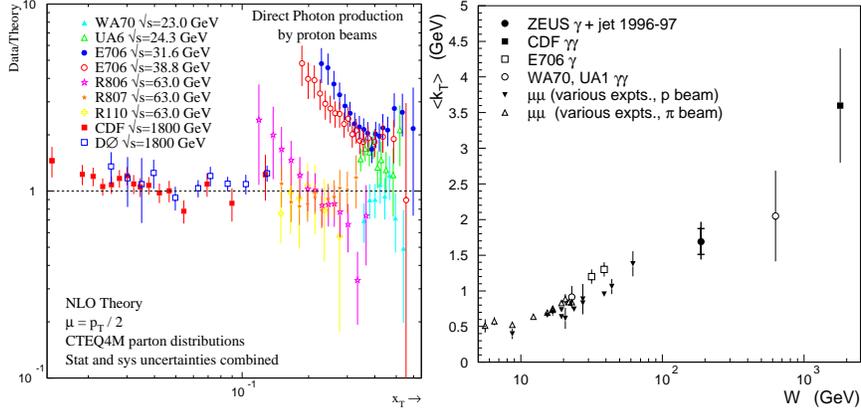


Fig. 3. (left) Comparison of photon $X_T (= 2E_T^{\gamma}/\sqrt{s})$ for different prompt photon experiments, (right) Measurement of effective $\langle k_T \rangle$ for a number of experiments are plotted against the center-of-mass energy.

From a more basic point of view, the presence of additional initial-state multiple gluon emission beyond NLO in QCD can increase the effective k_T

values of hard-scattering partons, and may help to generate the effects observed. In the recent theoretical work the resummed pQCD calculations for inclusive prompt photon production are currently under development in order to interpret the k_T issues in prompt photon physics. The full (threshold and recoil) resummation formalism can be expected to provide a solid foundation for the treatment of k_T [12].

5 Summary

We have considered the our current knowledge of prompt photon production in hadronic collisions, the status of experimental results and current issues in this area, in both experimental and theoretical aspects. Prompt photon analyses at the Tevatron in Run II and HERA are well underway and high luminosity photon data should provide experimental guidance to a better theoretical modelling of prompt photon production. A better theoretical understanding of prompt photon production will also give us a deeper understanding of some fundamental questions of QCD and the partonic nature of matter.

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