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Photon and Diphoton Production, and k_T Effects

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Abstract

Isolated photon production at the DØ experiment is reviewed and recent results on di-photon production are presented.

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I. INTRODUCTION

The motivation for studying photon production is the precision testing of perturbative QCD. The lowest order production processes are all proportional to $\alpha_s\alpha$; therefore, the smallness of the electromagnetic coupling assures a more rapid convergence of the perturbative series than is possible with all jets in the final state. The invariant cross section [1] is given by

$$E\frac{d^3\sigma}{dp^3} = \sum_{a,b} x_a G(x_a, Q^2) x_b G(x_b, Q^2) \frac{d\hat{\sigma}}{d\hat{t}}(a\ b \rightarrow jet\ \gamma) = \frac{d^3\sigma}{dE_T^2 d\eta_\gamma d\eta_{jet}},$$

where the first expression shows explicitly the factorization into a partonic cross section (which depends only on center-of-mass quantities), and parton distribution functions (PDF), which parameterize the beam composition resolvable with a momentum transfer (Q^2). The next equality shows this expression in variables that are directly measured in the detector: transverse energy (E_T) and pseudo-rapidity (η).

Historically, it was believed that photon production was the most precise way to measure the gluon PDF at low parton momentum fractions in hadronic interactions. To date, hadron-hadron collider experiments have not lived up to this expectation. There are several reasons for this. At leading order(LO), two processes are responsible for direct photon production: Compton ($qg \rightarrow q\gamma$) and annihilation ($q\bar{q} \rightarrow g\gamma$). Only the first process probes the gluon composition of the proton. While this process dominates production for $E_T < 100$ GeV, the signal is diluted by the annihilation process. Next, the minimum x_{parton} that can be measured by an experiment is dictated by kinematics: $x_{min} = 2E_T^{min} e^{-\eta_{max}}/\sqrt{s}$. This implies measurement at both low E_T and high η. High η is difficult because calorimetry and tracking are hampered by the usual small angle problems. Low E_T measurements are limited by the difficulty of pairing photons from neutral meson decays that are widely separated. For the region accessible to Tevatron, photon measurements ($10^{-2} < x < 10^{-1}$), the variations in PDFs [2] are less than 10%.

To date, the theory of direct photon production [3] has been solved at next-to-leading order (NLO) in perturbation theory. The basic 2 $\rightarrow$2 processes include corrections from 2 $\rightarrow$ 3 tree level and 2 $\rightarrow$ 2 one loop processes. An additional complication arises from the so-called Bremsstrahlung processes where a photon is emitted colinear to a final state parton. For large angles of emission this is included in the 2 $\rightarrow$ 3 graphs; however, when the angle becomes small the cross sections become singular. This is handled by a phenomenological fragmentation function. It was shown analytically [4] that the general form of this function is $D(z, Q^2) \sim \alpha\ ln(Q^2/\Lambda_{QCD}^2) f(z)$. The arguments of the logarithm are the lower and upper limits from integration over the emission angle, which are estimated to be of order Λ_{QCD}^2 and Q^2 [5]. The function describing the z-dependence is usually parameterized from data [6] [7]. The interesting point about this form is that the logarithmic term is inversely proportional to the strong coupling. Naively, the fragmentation contribution is of order $\alpha_s^2\alpha$; however, the logarithmic term results in a process of order $\alpha_s\alpha$, which is of leading order. For most values probed by the Tevatron experiments ($0.8 < z < 0.98$), the current fits differ at most by a factor of two. The current theoretical approach is to use the fragmentation function only in regions where the exact 2 $\rightarrow$ 3 process is singular. Experimental cuts on energy near the

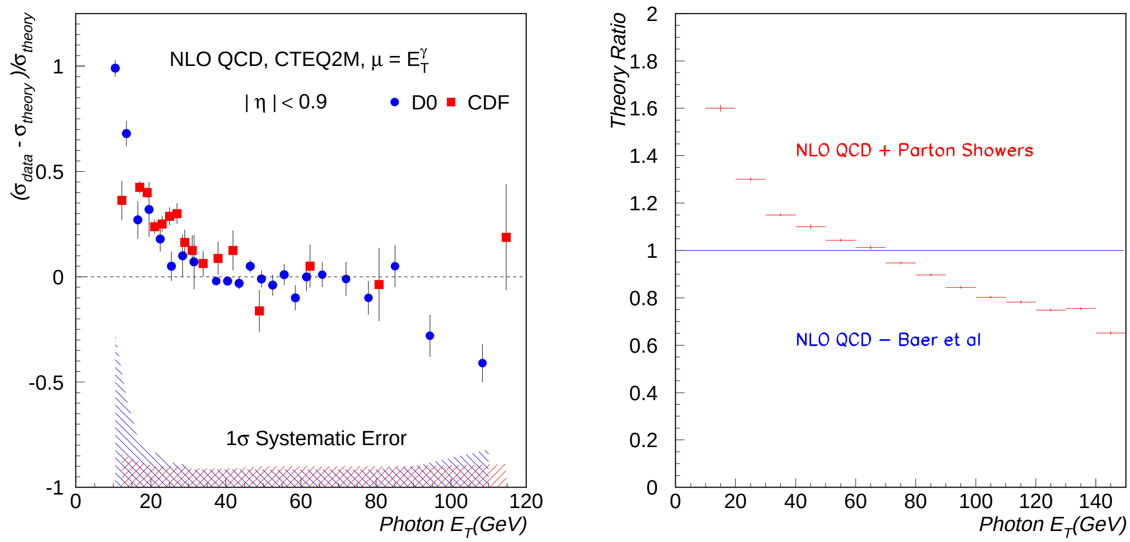

FIG. 1. Left - CDF(square) and DØ(round) isolated photon E_T spectrum shown relative to the NLO calculation of Baer, Owens, and Ohnemus, using CTEQ2M PDFs and $\mu_F = \mu_R = 1.0 E_{T\gamma}$. The correlated systematic error is represented by the fill areas at the bottom, CDF(right slanting) and DØ (left slanting). Right - NLO + parton shower calculation of Baer and Reno shown relative to the NLO calculation alone.

photon are necessary to reduce backgrounds to a manageable level. This involves clustering the photon energy over a finite region of the detector. Generally, the additional energy is measured by subtracting the cluster energy from the energy in a larger area centered on the photon, a process which is difficult to mimic theoretically [8] .

II. ISOLATED PHOTON CROSS SECTION

Details of the DØ and detector can be found in reference [9]. The isolated E_T distribution is the simplest of all possible measurements because it uses only the photon, and jets in the event are ignored. CDF and DØ have published measurements of this distribution [10] [11] with an isolation cut of 2 GeV for energy in the vicinity of the photon. For CDF (DØ), this vicinity is defined by a cone of radius 0.7 (0.4) in $\eta - \phi$ space. This cut reduces the QCD background by three orders of magnitude resulting in background of the same order as the signal.

At high E_T we exploit the fact that the two nearly colinear photons from a neutral meson decay are twice as likely to convert to an e^+e^- pair as detector material is traversed. If the detector response is well understood, Monte Carlo simulation can be used to provide test samples of pure signal and background and discrimination is possible. Both experiments measure the cross section in the central rapidity region ($|\eta| < 0.9$); however, DØ has also measured the cross section in the forward region ($1.6 < |\eta| < 2.5$).

The data and corresponding theory are shown in Fig. 1 on a linear scale ($\sigma_{\rm data} - \sigma_{\rm theory}/\sigma_{\rm theory}$). Both experiments are in agreement with each other and consistent with

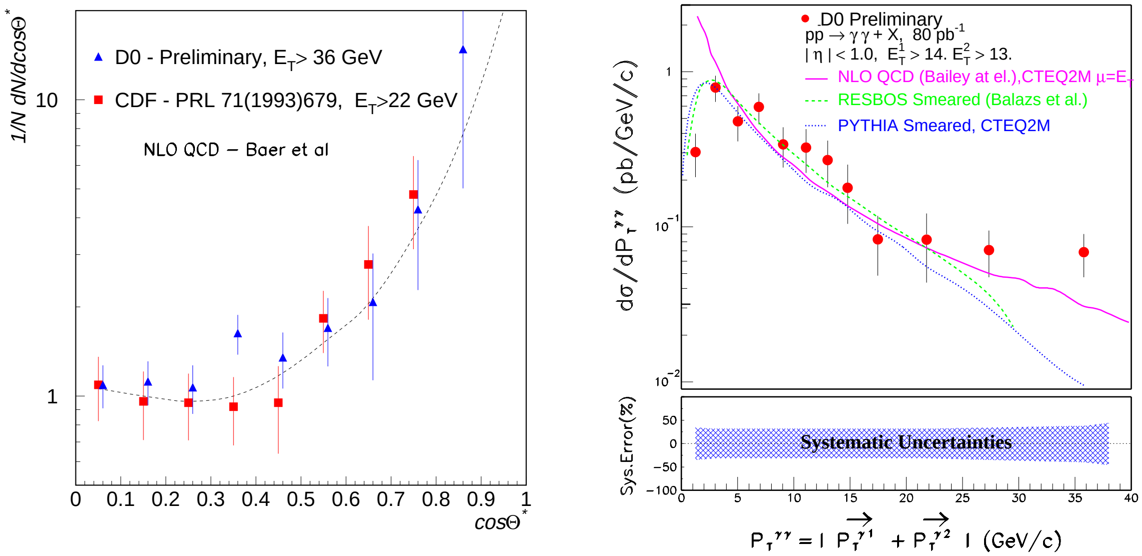

FIG. 2. Left - DØ(triangle) and CDF(square) angular distributions. Errors are statistical and systematic. The dotted line is the NLO calculation. Right - The DØ di-photon $P_T^{\gamma\gamma}$ spectrum and theory predictions for: NLO QCD, RESBOS, and PYTHIA.

QCD over a large range of E_T . The most notable feature of this plot is the apparent rise of the cross section over the prediction at low E_T . The rise has been interpreted as a signal that the NLO calculation does not include enough initial state gluon radiation [12]. This has been demonstrated by an *ad hoc* calculation [13] which adds parton showers to the NLO calculation. The general features of this procedure reproduce the rise at low E_T and also predict a deficit at high E_T . The DØ data show evidence of this deficit, which is due to the isolation cut failing when an initial state jet falls into the isolation cone. Other explanations of this phenomena come from more conventional sources. First, the set of structure functions used in the above comparison are rather dated and do not include deep inelastic scattering data from HERA. The later set CTEQ4 [2] includes this data and introduces a 15% shape change at low E_T . An analysis of the theory has also been done which allows the factorization and renormalization scales to be different [14]. The effects of different scales also changes the shape relative to the standard calculation (all scales equal to E_T). Were it not for the DØ high E_T data points, one might conclude from these analysis that additional gluon radiation is not necessary to explain the spectrum.

III. PHOTON JET ANGULAR DISTRIBUTION

The angular distribution is a measure of the partonic cross section since the effect of structure functions is removed by boosting the system to the center-of-mass frame. Figure 2 shows the angular distribution for both Tevatron experiments [16] [15]. The overall agreement with QCD is quite good, except for a slight excess at small angles observed by CDF. This could be due to an underestimation of the fragmentation contribution which rises steeply at small angles. Prompt photon production (Compton and annihilation) is mediated by quark exchange which has an angular distribution $\sim (1 - cos\theta^*)-1$, while both the background and fragmentation angular distributions have components of gluon exchange with the form $\sim (1 - cos\theta^*)^{-2}$. The only flexibility the theory can accomodate at this order is in the choice of scale factors and parameterization of the fragmentation function. Neither of these variations has a large effect on the shape of the theory distribution. Because of the very restrictive isolation cut done at the Tevatron, the fragmentation contribution is a small portion of the cross section, and it is not surprising that changes of this component have little effect. An alternative currently under study [17] is whether the NNLO fragmentation is larger than expected.

IV. DI-PHOTON CROSS-SECTION

The vector sum $P_T^{\gamma\gamma} = |\vec{P}_T^{\gamma 1} + \vec{P}_T^{\gamma 2}|$ of the di-photon system is sensitive to the initial-state gluon radiation, since no jet measurement complicates the process. The DØ method is described in reference [18] [19] for a luminosity $\sim 90 pb^{-1}$. The background for this process comes from both single isolated photons accompanied by a highly electromagnetic jet (which fakes a photon), and dijet events where both jets fragment into fakes. Figure 2 shows the di-photon $P_T^{\gamma\gamma}$ data distribution and several different theory calculations. The NLO calculation [20] describes the data well except at low $P_T^{\gamma\gamma}$, where the prediction becomes singular as the additional parton in the event becomes soft. The Pythia [22] event generator agrees with the data over the entire kinematic range, because the low $P_T^{\gamma\gamma}$ singularity is moderated by the parton shower model of inital state radiation. The region of low $P_T^{\gamma\gamma}$ has also been treated with a calculation [21] which re-sums the singular leading logarithms, and the agreement at low $P_T^{\gamma\gamma}$ is very good.

V. CONCLUSIONS

The study of photons produced by hadrons in collision is providing a wealth of information about QCD. Indeed, it is possible to compare data and theory on linear scales, and differences of less than 50% are common. These precise measurements are pushing the theory to the limits of applicability, and new methods such as resummation are now being used. With the large run 1B data sample, the experimental errors are limited by systematic effects. Some theoretical progress has been made in understanding the two outstanding problems confronting the theory. First, it has been demonstrated that additional gluon radiation can reproduce the shape of the isolated photon E_T distributions over the full range of measurement; however, it has also been shown that modern PDFs and scale variations can also change the shape of the distributions at low E_T . Second, precision measurements of the size of the Bremsstrahlung/fragmentation component are necessary and await analysis of the full run 1B data set and completion of the full NNLO calculation.

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