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ISOLATED PROMPT SINGLE PHOTON AND DIPHOTON
PRODUCTION IN $\bar{p}p$ COLLISIONS AT $\sqrt{s} = 1.8$ TeV

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A measurement of the differential cross section $d^2\sigma/dE_T d\eta$ of isolated prompt photons, $\bar{p}p \rightarrow \gamma + X$ is presented for two pseudorapidity ranges, $|\eta| < 0.9$ and $1.6 < |\eta| < 2.5$, at $\sqrt{s} = 1.8$ TeV. The data were accumulated during the 1992-1993 tevatron collider run (1A), consisting of 13 pb^{-1} of integrated luminosity. The background is estimated by measuring the longitudinal shower profile in the four layers of the electromagnetic (EM) calorimeter. The results show good agreement with the next-to-leading-order QCD (NLO) calculations in the range $30 \lesssim E_T \lesssim 80$ GeV. A preliminary measurement of isolated prompt diphoton production, $\bar{p}p \rightarrow \gamma\gamma + X$ is also presented for the pseudorapidity range $|\eta| < 1.0$. The data sample corresponds to an integrated luminosity of 80.0 pb^{-1} from the 1994-1995 run (1B). Preliminary cross section measurements of $d\sigma/dE_T$, $d\sigma/dM$ and $(1/\sigma)d\sigma/dK_T$ are reported and compared to the Pythia Monte Carlo. The K_T (defined as $K_T = |\vec{P}_T^1 + \vec{P}_T^2|$) of the two photon system is measured in the range $0 < K_T < 22$ GeV. The shape at low K_T data favors NLO QCD with an intrinsic $\langle K_T \rangle = 2$ GeV rather than the Pythia Monte Carlo or the NLO QCD calculation without an intrinsic $\langle K_T \rangle$.

1 Introduction

The production of prompt photons with large transverse momentum in hadronic collisions ($\bar{p}p$) is a clean process to test QCD and extract information about the constituents of the hadron.^{1,2} A measurement of the prompt photon cross section has the advantage that the photon transverse energy is not affected by fragmentation and hadronization, resulting in smaller experimental uncertainties than those obtained in jet cross sections. Next-to-leading order QCD calculations are available for both single^{3,4} and double photon production^{6,7}, and can be directly compared to the experimental data.

The DØ detector⁸ has several features well suited for the detection of prompt photons. The uranium-liquid argon calorimeter has good electromagnetic energy resolution $\sigma_E/E = 13.5\%/\sqrt{E} \oplus 1.4\%$, fine transverse granularity $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ (0.05×0.05 at shower maximum) and good $r\phi$ and z shower position resolutions. The EM calorimeter has four longitudinal layers segmented as $2 + 2 + 6.8 + 9.8$ radiation lengths. The fine depth segmentation provides a method to distinguish the prompt photons from the background of photon decays of π^0 and η which are copiously produced in jet fragmentation.

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The central tracking chamber has high hit-finding and tracking efficiency and good $r\phi$ resolution $\sigma(r\phi) = 200\mu\text{m}$, which is used to find the position of the event vertex and help to reduce the isolated EM jet background.

2 Isolated Prompt Single Photon Production

2.1 Trigger and Event Sample Selection

Prompt photon signals can be distinguished from the overwhelming jet background by selecting local, isolated and well-profiled EM showers in the calorimeter. DØ uses a three-level trigger systems. The first level trigger (level 0) is made of scintillator counters near the beam pipe to detect a $\bar{p}p$ collision. The second level (level 1) is a hardware trigger which makes a fast sum of the EM energy in calorimeter towers ($\Delta\eta \times \Delta\phi = 0.2 \times 0.2$). Photon candidates must have their summed energy above the E_T thresholds, which are 2.5, 7.0 and 10.0 GeV. Multiple thresholds are used so that data populate the rapidly-falling E_T spectrum over the whole range of 10-125 GeV. The third level (level 2) is a software trigger which performs a fast clustering of calorimeter cells and calculates the cluster's transverse energy, its isolation value, and its longitudinal and transverse shower shape quantities. Shower shape cuts are applied to select photon candidates whose shower shapes are consistent with test beam electrons. The candidate events are further required to satisfy isolation cut. The three level 2 E_T thresholds are 6.0, 14.0 and 30.0 GeV respectively.

Offline, more sophisticated cuts are applied to photon candidates. Fiducial cuts are applied to restrict candidates to the regions of pseudorapidity $|\eta| < 0.9$ and $1.6 < |\eta| < 2.5$. All candidates are required to be away from the boundary of a central calorimeter module by at least 5% of the module width. No tracks can be found in the road of $\Delta\phi \times \Delta\eta$ between the shower center and the event vertex, where $\Delta\phi = 0.2$ and $\Delta\eta$ is tuned to

Figure 1: Distribution of $\log(E_{EM1}/E_{total})$ for $E_T^\gamma = 40 \pm 5$ GeV central photon candidates (solid points), and the fitted distribution (solid curve) made up of Monte Carlo photons (dashes), neutral pions (dots), and η mesons (dot-dash curve). The neutral pion and η meson distributions at small $\log(E_{EM1}/E_{total})$ fluctuate due to limited Monte Carlo statistics.

the resolution of the shower position along z and the vertex. The EM fraction of the shower must be greater than 96%. The transverse isolation energy, defined as the E_T in the cone of $R = 0.4$ minus the E_T in the EM core cone of $R = 0.2$ ($R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$), is required to be less than 2.0 GeV. The longitudinal and transverse shower profiles (measured by a 41×41 matrix) must be consistent with those expected for electrons.⁹ Having found events with one well-identified, isolated photon, two additional cuts are applied to the whole event that the event z vertex is required to be within 50 cm of the nominal vertex and the missing transverse energy $\cancel{E}_T$ of the event has to be less than 20.0 GeV.

2.2 Background Subtraction

After the above tight event selection cuts, the prompt photon sample still contains a significant background, primarily due to $\gamma\gamma$ decays of π^0 and η when the fluctuations in the jet fragmentation lead to a single meson carrying most of the jet transverse energy. The transverse granularity of the DØ calorimeter is not fine enough to distinguish two γ 's ($\pi^0 \rightarrow \gamma\gamma$ or $\eta \rightarrow \gamma\gamma$) from a single prompt photon at transverse energy $E_T > 10$ GeV. But longitudinally two photons from a meson decay are likely to start showering earlier and deposit more energy in the first layer EM1 of the EM calorimeter than a single prompt photon. The distribution of $\log(E_{EM1}/E_{TOTAL})$ is used to estimate the fraction of candidate events which are true photons. (see fig. 1) We assume the data are composed of true prompt photons and meson backgrounds (π^0 and η). Fitting to the distributions of $\log(E_{EM1}/E_{TOTAL})$ at several E_T points results in an E_T dependent photon purity, $\mathcal{P}$, with an exponential form $\mathcal{P} = 1 - e^{-(a+b \cdot E_T)}$.

Figure 2: The inclusive isolated prompt photon cross section $\sigma_e = d^2\sigma/dE_T^\gamma d\eta$ as a function of photon transverse energy E_T^γ , for central (circles) and forward regions (squares). The errors are statistical only. The NLO QCD calculated cross sections σ_t , using CTEQ2M parton distributions with $\mu = E_T^\gamma$, are shown for comparison.

2.3 Inclusive Single Photon Cross Section

The differential cross section $d^2\sigma/dE_T d\eta$ for inclusive isolated prompt photon production is shown in fig. 2, using a data set of 13 pb^{-1} of integrated luminosity (1A). The data are compared to next-to-leading-order QCD calculations³ with CTEQ2M parton distribution function and renormalization scale $\mu = E_T$. Fig. 3 plots $(\sigma_e - \sigma_t)/\sigma_t$ where σ_e and σ_t are the experimental and theoretical values respectively. The experimental cross sections are in good agreement with NLO QCD for both pseudorapidity regions for the range $30 < E_T < 80 \text{ GeV}$. At the low transverse energy $E_T < 20 \text{ GeV}$, the data show an excess over the NLO QCD prediction. At the high transverse energy $E_T > 74 \text{ GeV}$, the data for the central region lie below the QCD calculations, which is within the experimental uncertainties.

3 Isolated Prompt Double Photon Production

3.1 Data Sample and Efficiencies

Just as in the single photon analysis, prompt diphoton signals can be distinguished from the background of $\gamma + \text{"jet"}$ and $\text{"jet"} + \text{"jet"}$ by selecting isolated EM showers in the calorimeter. The diphoton candidates are taken when two or more level 1 EM trigger towers pass an E_T threshold of 7 GeV . In the level 2 trigger, they must have at least two clusters with E_T greater than 12 GeV , a longitudinal and transverse shower shape consistent with test beam electrons for both clusters, and one cluster has to be isolated.

Rather low E_T cuts are used offline to preserve good statistics. It becomes important to understand the E_T dependent trigger efficiencies and offline cuts efficiencies. The trigger efficiencies in the range $E_T < 25 \text{ GeV}$ are measured by using special run data with lower trigger thresholds. The efficiencies in the range $E_T > 25 \text{ GeV}$ are determined using an inclusive $Z \rightarrow ee$ sample. The whole E_T dependent efficiency curve is shown in fig. 4 (a).

Figure 3: Difference between the measured isolated photon cross section σ_e and the NLO QCD prediction σ_t , normalized to the latter. The shaded bands show the magnitude of the combined experimental systematic errors (1σ) for each of the two regions.

The diphoton sample is then streamed through “loose” photon ID cuts, which results in a “clean” sample of 3477 candidates. The “clean” sample was re-reconstructed using the latest reconstruction package. The final candidate sample is selected by applying “tight” photon ID cuts, which results in 418 remaining events.

Figure 4: (a) The trigger efficiency per photon as a function of the photon transverse energy for the diphoton trigger. (b) The combined photon ID cuts efficiency per photon vs. the photon E_T . The shape is measured by developing a detailed simulation of the showers of electrons and photons in the calorimeter with overlaid minimum bias events to model the calorimeter noise and underlying events. The normalization is determined from data.

The “tight” photon ID cuts include the fiducial cuts, which are $|\eta| < 1.0$ and ϕ position being away from the boundary of a central calorimeter module by at least 5% of the module width, and the kinematic cuts, which are $E_T^1 > 14 \text{ GeV}$ and $E_T^2 > 13 \text{ GeV}$. Each photon must satisfy the following quality cuts. No tracks can be found in the road (as in the single photon analysis), the EM fraction be greater than 90%, the isolation transverse energy $E_T < 2 \text{ GeV}$, the tight longitudinal and transverse shower profile cut⁹, and the central tracking cuts which require the ratio of CDC hit wires to total wires to be less than 0.85 and no CDC hits have z position information. The E_T dependent efficiency of the offline cuts is shown in Fig. 4 (b).

A large Pythia⁵ Monte Carlo sample (2 million events) was generated to study the geometric acceptance of the diphoton events. The acceptance values are flat over a large range of E_T of each photon and the mass, the K_T and the $\Delta\phi$ of the diphoton system. The average geometric acceptance is 0.688 ± 0.002 .

3.2 Background Evaluation

A method similar to that used in the single prompt photon analysis was developed to estimate the diphoton background. Instead of fitting to the whole distribution of $\log(E_{EM1}/E_{Total})$, a simple exponential function $e^{A-B \cdot E_T}$ fit is performed to the central region of the distributions (see Fig. 5). The distribution of the data is fitted as a sum of the distributions of photon, π^0 and η . The diphoton candidate sample is divided into three subsamples, $E_T^1 < 20 \text{ GeV}$ and $E_T^2 < 20 \text{ GeV}$, $E_T^1 > 20 \text{ GeV}$ and $E_T^2 < 20 \text{ GeV}$, and $E_T^1 > 20 \text{ GeV}$ and $E_T^2 > 20 \text{ GeV}$.

Subsamples	$\alpha_{\gamma\gamma}$
$E_T^1 < 20, E_T^2 < 20$	0.257 ± 0.095
$E_T^1 > 20, E_T^2 < 20$	0.301 ± 0.112
$E_T^1 > 20, E_T^2 > 20$	0.375 ± 0.227

Table 1: Evaluated purity $\alpha_{\gamma\gamma}$

Figure 5: Distribution of $\ln(E_{EM1}/E_{total})$ for $E_T = 20$ GeV of γ , π^0 and η respectively. A simple exponential function fit is shown for each curve.

$E_T^2 > 20$ GeV. Table 1 lists the fitted purity $\alpha_{\gamma\gamma}$ for the three subsamples.

3.3 Cross Section Measurements and Comparison with QCD

The differential cross sections $d\sigma/dE_T$ and $d\sigma/dM$ for inclusive isolated prompt diphoton production, using a data set of 80 pb^{-1} of $p\bar{p}$ collisions during the 1994-1995 run (1B), are shown in Figure 6(a). A Pythia Monte Carlo program is developed to compare to the data. It uses the CTEQ2M parton distribution functions and smears the kinematic values of a photon with calorimeter energy and angular resolutions.

For the two photon system, K_T is defined as $|\vec{P}_T^1 + \vec{P}_T^2|$. At leading order QCD, $d\sigma/dK_T$ peaks at $K_T = 0$. Only next-to-leading order (or higher order) QCD gives the two photon system a P_T push which results in a shift of the peak of $d\sigma/dK_T$ to a nonzero value. The distribution of $d\sigma/dK_T$ is therefore a good test of higher-order QCD. Figure 6(b) shows a normalized distribution $(1/\sigma)d\sigma/dK_T$ for the data, the Pythia monte carlo, the NLO QCD calculation⁶ and the NLO QCD calculation with an additional $\langle K_T \rangle = 2 \text{ GeV}$. The NLO QCD calculation with an additional $\langle K_T \rangle = 2 \text{ GeV}$ describes the data the

(a) The inclusive isolated prompt diphoton cross sections $d\sigma/dE_T$ vs. E_T of each photon (the upper) and $d\sigma/dM$ vs. mass of $\gamma\gamma$ (the lower). The Pythia monte carlo is shown for comparison.

(b) The normalized cross section $(1/\sigma)d\sigma/dK_T$ vs. K_T in the range $0 < K_T < 22$ GeV. It is compared to the pythia MC, the NLO QCD and the NLO QCD with $\langle K_T \rangle = 2$ GeV.

better at the low K_T .

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