The Ratio of Isolated Photon Cross Sections at $\sqrt{s} = 630$ GeV and 1800 GeV

V.M. Abazov,[23] B. Abbott,[58] A. Abdesselam,[11] M. Abolins,[51] V. Abramov,[26] B.S. Acharya,[17] D.L. Adams,[60] M. Adams,[38] S.N. Ahmed,[21] G.D. Alexeev,[23] G.A. Alves,[2] N. Amos,[50] E.W. Anderson,[43] M.M. Baarmand,[55] V.V. Babintsev,[26] L. Babukhadia,[55] T.C. Bacon,[28] A. Baden,[47] B. Baldin,[37] P.W. Balm,[20] S. Banerjee,[17] E. Barberis,[30] P. Baringer,[44] J. Barreto,[2] J.F. Bartlett,[37] U. Bassler,[12] D. Bauer,[28] A. Bean,[44] M. Begel,[54] A. Belyaev,[35] S.B. Beri,[15] G. Bernardi,[12] I. Bertram,[27] A. Besson,[9] R. Beuselinck,[28] V.A. Bezzubov,[26] P.C. Bhat,[37] V. Bhatnagar,[11] M. Bhattacharjee,[55] G. Blazey,[39] S. Blessing,[35] A. Boehnlein,[37] N.I. Bojko,[26] F. Borcherding,[37] K. Bos,[20] A. Brandt,[60] R. Breedon,[31] G. Briskin,[59] R. Brock,[51] G. Brooijmans,[37] A. Bross,[37] D. Buchholz,[40] M. Buehler,[38] V. Buescher,[14] V.S. Burtovoi,[26] J.M. Butler,[48] F. Canelli,[54] W. Carvalho,[3] D. Casey,[51] Z. Casilum,[55] H. 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The inclusive cross section for production of isolated photons has been measured in $p\bar{p}$ collisions at $\sqrt{s} = 630$ GeV with the DØ detector at the Fermilab Tevatron Collider. The photons span a transverse energy range (E_T) from 7-49 GeV and have pseudorapidity $|\eta| < 2.5$. This measurement is combined with our previous result at $\sqrt{s} = 1800$ GeV to form a ratio of the cross sections. Comparison of next-to-leading order QCD with the measured cross section at 630 GeV and ratio of cross sections show satisfactory agreement in most of the E_T range.

13.85.Qk, 12.38.Qk

DRAFT

Photons produced directly from parton-parton interactions provide a powerful and effective means of studying the constituents of hadronic matter. Because the primary production mechanism for modest E_T photons at the Tevatron is gluon Compton scattering ($qg \to \gamma q$), the cross section for direct-photon production is sensitive to the gluon distribution in the proton [1]. A measurement of the final state photons provides a probe of Quantum Chromodynamics (QCD) without additional complications from jet identification and fragmentation.

Previous experiments, at center of mass energies of both 630 GeV [2] and 1800 GeV [3] [4], have reported photon production in excess of next-to-leading order (NLO) QCD predictions at low transverse energies ($E_T^\gamma \lesssim$ 30 GeV). This disagreement with data could result from gluon radiation not included in NLO calculations [5] or because the parton distributions are not well known [6].

In this Letter, we present a measurement of the isolated direct-photon cross section in $p\bar{p}$ collisions for photons in two pseudorapidity regions, $|\eta| < 0.9$ and $1.6 < |\eta| < 2.5$, where $\eta = -\ln\tan\frac{\theta}{2}$ and θ is the polar angle with respect to the proton beam. We compare the production cross section at $\sqrt{s} = 630$ GeV with previously published results at $\sqrt{s} = 1800$ GeV [3]. This comparison reduces systematic uncertainties and minimizes the sensitivity of theory to choice of parton distribution functions (PDF) because the measurements at both energies use the same detector and the same analysis method.

In the simple parton model, the dimensionless cross section, $E_T^4 \cdot E\frac{d^3\sigma}{d^3p}$, as a function of $x_T = \frac{2E_T}{\sqrt{s}}$, is independent of $\sqrt{s}$. Although deviations from such naive scaling are expected, the dimensionless cross section provides a useful context for comparison with QCD. This Letter presents a comparison of the ratio of photon production cross sections at different center-of-mass energies, using the same detector, and covering a broad range of η values.

The cross section measurment at 630 GeV uses a sample of 520 nb^{-1} of data recorded in 1995 [7] with the DØ detector at the Fermilab Tevatron [8]. The analysis uses the uranium/liquid argon calorimeter to identify photons, and the drift chambers in front of the calorimeter to differentiate photon showers from electron showers. The calorimeter provides full azimuthal coverage (ϕ), and consists of a central cryostat (CC) with $|\eta| \lesssim 1.0$, and two forward cryostats (EC) with $1.0 \lesssim |\eta| \lesssim 4.0$, each divided into four longitudinal electromagnetic layers (EM1-EM4) of 2, 2, 7, and 10 radiation lengths respectively. Layers EM1, EM2, and EM4 are transversely segmented into projective towers of angle $\Delta\phi \times \Delta\eta = 0.1 \times 0.1$ while EM3 is segmented into 0.05×0.05 sections, The electromagnetic energy resolution in the central and forward calorimeter is given by $\sigma_E/E = \{15\%/\sqrt{E(\text{GeV})}\} \oplus 0.3\%$.

Photons interacting in the calorimeter are detected using a three-level triggering system. The first level consists of scintillation counters near the beam pipe, which detect inelastic $p\bar{p}$ collisions. The second level requires a minimum energy deposition in a $\Delta\phi \times \Delta\eta = 0.2 \times 0.2$ trigger tower, with trigger thresholds of 2.0, 3.0, and 7.0 GeV. In the final step, calorimeter clusters are formed with energy thresholds of 4.5, 8.0, and 14.0 GeV, respectively. The trigger efficiency for photons with energies near threshold is determined for the two highest energy triggers by taking the ratio of events passing the 14.0 (8.0) GeV trigger to those passing the 8.0 (4.5) GeV trigger in an energy regime where the lower energy trigger is 100% efficient. Monte Carlo studies of the trigger algorithms show agreement with the data for the two higher energy triggers, and are used to determine the trigger efficiency for the lowest energy trigger. Trigger efficiencies are typically about 20% at the nominal energy threshold and rise to almost 100% a few GeV above the threshold value. Consequently, photon candidates are accepted only for transverse energies of at least 7.35, 10, and 16 GeV for the three triggers, respectively.

Photon candidates are identified as energy clusters in the calorimeter. Clusters are required to be well within the boundaries of the central calorimeter ($|\eta| < 0.9$), or in the forward calorimeter ($1.6 < |\eta| < 2.5$), and in the central region were required to be at least 1.6 cm from the azimuthal boundaries of the calorimeter sections. The event vertex position is required to be within 50 cm of the center of the detector. The resulting geometric acceptance is $A = 0.622 \pm 0.007$ (0.787 ± 0.007) in the central (forward) region.

The photon showers are required to have shapes consistent with that of single electromagnetic showers, as determined in studies using test beams of charged pions and electrons. The shower is required to have 96% of its energy deposited in the electromagnetic section of the calorimeter. The transverse energy around any cluster defining an isolated photon must satisfy the requirement $E_T^{\mathcal{R}\leq 0.4} - E_T^{\mathcal{R}\leq 0.2} < 2.0$ GeV, where $\mathcal{R} = \sqrt{\Delta\eta^2 + \Delta\phi^2}$. The efficiency of these last three selection criteria, ϵ_s, is estimated using a detailed Monte Carlo simulation of the DØ detector. ϵ_s varies as a function of E_T^γ from about 60% (75%) in the CC (EC) at 8.0 GeV, to 88% (90%) beyond 20 GeV. To minimize background from electrons, photon candidates are rejected if any tracks in the drift chamber extrapolate to within a road of width $\Delta\phi \times \Delta\theta = 0.2 \times 0.2$ defined by the angle subtended by the candidate photon cluster and the initial interaction vertex. This criterion can discard photon candidates that convert in the material in front of the calorimeter, or that have additional tracks in the road due to tracks from the underlying event. This selection efficiency and the efficiency for reconstructing charged tracks, are estimated by studying electrons from $Z^0 \to e^+e^-$ events. The total charged tracking efficiency is measured to be 0.858 ± 0.013 (0.593 ± 0.079) in the central (forward) region.

The predominant background to direct photon pro-

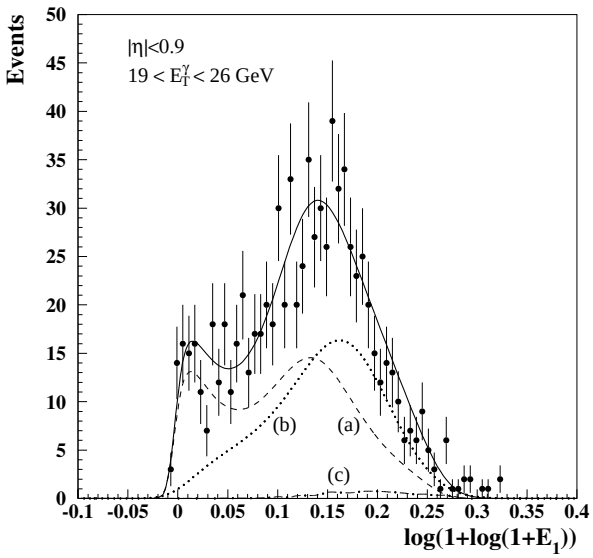

FIG. 1. Distribution in $\log_{10}[1 + \log_{10}\{1 + E_1(\mathrm{GeV})\}]$, which is the discriminant used to determine the purity of the final photon candidates. Points with error bars indicate data. Broken lines indicate simulated distributions of (a) photons, (b) jet background without charged tracks, and (c) jet background with charged tracks. The solid line depicts the sum of all three distributions.

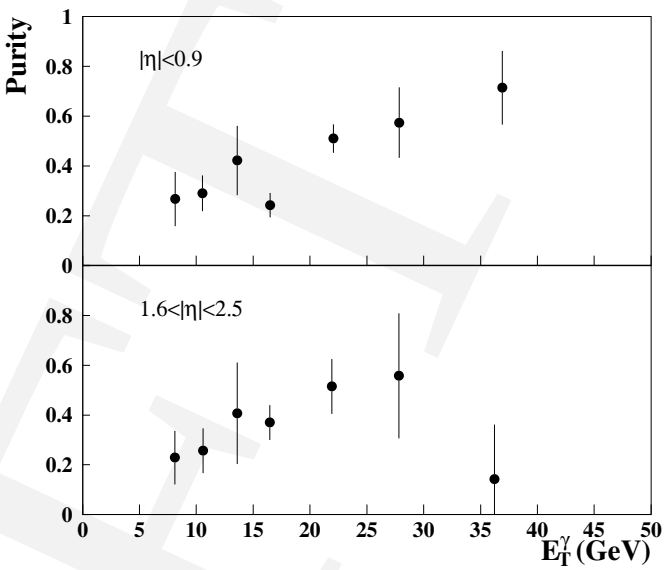

FIG. 2. The photon purity as a function of E_T^γ for central and forward photons.

duction arises from the decay of π^0 or η mesons to two photons. The fraction of direct photons is determined from the energy (E_1) deposited in the innermost longitudinal section of the calorimeter (EM1). The relatively small probability that a photon begins to shower in the calorimeter cryostat or first absorber plate for a neutral meson decaying to two photons is approximately twice that for a single photon. Consequently, neutral mesons tend to deposit a larger fraction of their energy in EM1, and a distribution that emphasizes this difference can statistically determine the purity of the direct photon signal. We use the distribution of $\log_{10}[1 + \log_{10}\{1 + E_1(\mathrm{GeV})\}]$ as our discriminant.

The expected distributions for signal and background are simulated with the PYTHIA Monte Carlo [9], overlaid with with data acquired using a random trigger to model noise, pileup, underlying event, and multiple $p\bar{p}$ interactions. Three categories of fully simulated events are generated; those containing photons, and background events with and without charged tracks pointing from the interaction vertex to the electromagnetic cluster. The two different background samples are generated so that charged and neutral background fractions can be separately fit to the data, thus minimizing constraints from the tracking efficiency and from the model used for jet fragmentation. A systematic uncertainty on modeling jet fragmentation is estimated by varying the multiplicity of neutral mesons in the core of PYTHIA jets by $\pm 10\%$. The detector response is modeled using a detailed GEANT simulation. The energy response in E_1 is corrected in the Monte Carlo to match the data from $W \to e\nu$ events.

Identical selection criteria that determine photon candidates in the data are applied to the Monte Carlo events. The distribution of $\log_{10}[1 + \log_{10}\{1 + E_1(\mathrm{GeV})\}]$ from the data are fitted to a normalized linear combination of Monte Carlo photons and background with and without charged tracks in the road pointing back to the interaction vertex. The fit is performed as a function of E_T^γ using the fitting package HMCMLL, with the fractions of signal and background constrained to be between 0.0 and 1.0 [10]. The purity ($\mathcal{P}$), is defined as the fraction of Monte Carlo photons in the normalized fitted distribution. A representative fit is shown in Fig. 1 and the photon purity as a function of E_T^γ is plotted in Fig. 2.

The final cross section $d^2\sigma/dE_T^\gamma d\eta$, after applying efficiency and purity corrections, is shown in Fig. 3, and tabulated in Table I. The error bars show all uncorrelated uncertainties, which include the statistical uncertainty, the error from the fitted purity, and the uncertainty from the selection criteria and trigger efficiency. The contribution from the fit to purity is the largest source of uncorrelated uncertainty. The correlated uncertainty consists of the uncertainty on the luminosity, the tracking efficiency, the geometric acceptance, the calorimeter energy scale, and the largest contribution, that from the fragmentation model.

The results are compared with NLO QCD calculations using CTEQ5M [11] [12]. Renormalization and factorization scales of $\mu_R = \mu_F = E_T^{\max}$ are used, where $E_T^{\max}$ is the maximum photon transverse energy in the event. Fig. 4 compares the data and theory. A covariance matrix χ^2 provides a measure of the probability that the

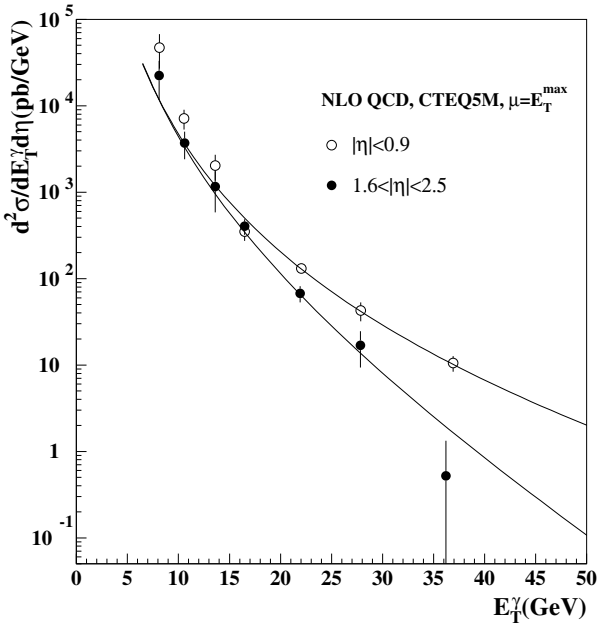

FIG. 3. The cross section for production of isolated photons in central and forward regions at $\sqrt{s} = 630$ GeV. The error bars show the complete uncorrelated error, and the curves show cross sections predicted from NLO QCD.

theory describes the data. A complete covariance matrix, comprised of correlated and uncorrelated uncertainties, is determined and the theoretical cross section is compared to the data with a χ^2 value of 11.4 (4.55) for 7 degrees of freedom in the CC (EC) region. This gives a standard χ^2 probability that the theory consistent is consistent with the data at 12.2% (71.4%) probability in the CC (EC) regions. Deviations between theory and data are largest at low E_T^γ in the central region.

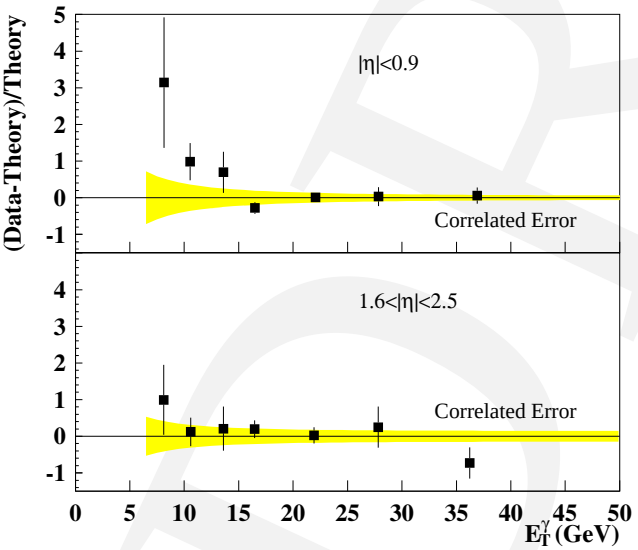

FIG. 4. Comparison of the measured cross section for production of isolated photons at $\sqrt{s} = 630$ GeV to the prediction of NLO QCD using CTEQ5M parton distribution functions.

We combine the cross section measured in this Letter

E_T^γ Range (GeV)	Plotted E_T^γ (GeV)	$d\sigma/dE_T^\gamma d\eta$ (pb/GeV) NLO QCD	Measured	$\delta\sigma_U$ (%)	$\delta\sigma_C$ (%)
		$\lvert\eta\rvert < 0.9$			
7.35- 9.1	8.2	11400	47000	43	52
9.1-12.6	10.5	3610	7160	26	36
12.6-14.7	13.6	1200	2040	33	25
14.7-18.9	16.5	487	351	22	19
18.9-26.25	22.1	129	131	11	13
26.25-29.75	27.9	41.4	42.6	25	10
29.75-49.0	36.9	9.95	10.5	21	7
		$1.6 < \lvert\eta\rvert < 2.5$			
7.35- 9.1	8.1	11200	22400	48	42
9.1-12.6	10.6	3310	3700	35	31
12.6-14.7	13.6	964	1170	50	24
14.7-18.9	16.5	338	403	20	21
18.9-26.3	21.9	65.4	67.3	22	17
26.25-29.75	27.8	13.6	16.9	45	16
29.75-49.0	36.2	1.91	.522	160	15

TABLE I. The measured and predicted isolated photon production cross section at $\sqrt{s} = 630$ GeV. The value for the column labeled "Plotted E_T^γ" is determined according to Ref. [13]. The columns labeled δ_U and δ_C are, respectively, the uncorrelated and correlated uncertainties.

with that measured at 1800 GeV [3]. The cross section at 1800 GeV is increased in every bin by 3.4% from the previously published result to account for the latest value of the proton-antiproton total cross section [14]. The experimental dimensionless cross section, averaged over azimuth, is given by $\sigma_D = \frac{E_T^3}{2\pi} \cdot d^2\sigma/dE_T d\eta$. The ratio of the dimensionless cross sections at different center-of-mass energies, $\sigma_D(\sqrt{s} = 630\,\text{GeV})/\sigma_D(\sqrt{s} = 1800\,\text{GeV})$, is shown in Fig. 5 as a function x_T. The results of the measurement of the ratio are shown in Table II.

A comparison between the measured ratio and that from the NLO QCD calculation is obtained from a χ^2 value that matches the theory with the data, using the complete covariance matrix. The comparison of the theoretical cross section to the data gives a χ^2 value of 6.48 (3.00) for 7 degrees of freedom in the CC (EC), which corresponds to a standard χ^2 probability of 48.5% (88.5%) in the CC (EC) region. Although the lowest x_T points are systematically higher than NLO QCD predictions in both the EC and the CC regions, the overall results indicate good agreement between the measured ratio and theory.

The DØ collaboration has measured the production cross section for isolated photons in $p\overline{p}$ collisions at $\sqrt{s} = 630$ GeV and compared this cross section with that measured at $\sqrt{s} = 1800$ GeV. Although some discrepancies exist between the measurement and NLO QCD at low E_T in both the cross section measurement and int the ratio, there is good agreement between the data and

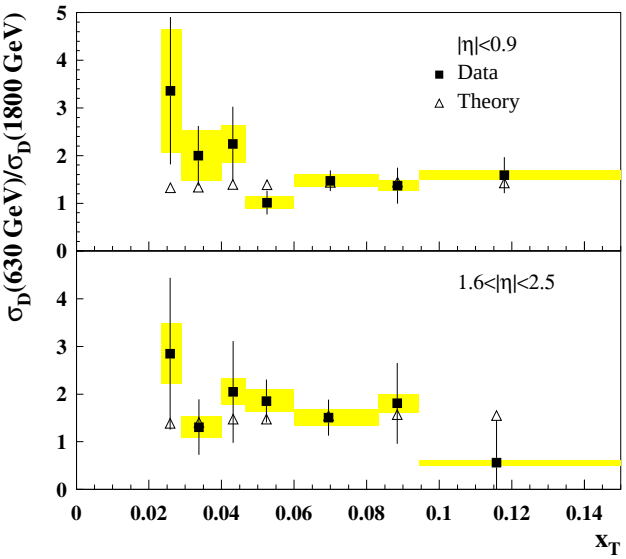

FIG. 5. The ratio of the dimensionless cross sections, $\sigma_D(\sqrt{s} = 630\ \text{GeV})/\sigma_D(\sqrt{s} = 1800\ \text{GeV})$. The error bars show the uncorrelated uncertainty and the shaded bands show the correlated contribution to the diagonal terms of the covariance matrix.

x_T Range	Fit x_T	Ratio	Theory	$\delta\sigma_U$(%)	$\delta\sigma_C$ (%)
		$\lvert\eta\rvert < 0.9$			
0.023-0.029	0.026	3.36	1.32	46	39
0.029-0.040	0.034	2.00	1.34	31	27
0.040-0.047	0.043	2.24	1.40	35	18
0.047-0.060	0.053	1.01	1.39	25	13
0.060-0.083	0.070	1.47	1.44	15	9
0.083-0.094	0.089	1.37	1.45	27	8
0.094-0.156	0.118	1.59	1.42	23	7
		$1.6 < \lvert\eta\rvert < 2.5$			
0.023-0.029	0.026	2.84	1.39	56	22
0.029-0.040	0.034	1.31	1.41	45	17
0.040-0.047	0.043	2.05	1.47	52	14
0.047-0.060	0.052	1.86	1.48	24	13
0.060-0.083	0.070	1.51	1.54	24	11
0.083-0.094	0.088	1.81	1.57	47	11
0.094-0.156	0.116	0.563	1.55	160	10

TABLE II. The measured ratio (Ratio) and NLO QCD prediction (Theory) for the dimensionless cross section at $\sqrt{s} = 630$ GeV to that at $\sqrt{s} = 1800$ GeV. The columns labeled δ_U and δ_C are the uncorrelated and correlated uncertainties, respectively.

the theoretical prediction at higher E_T values.

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