Direct photon cross section with conversions at CDF

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We present a measurement of the isolated direct photon cross section in $p\bar{p}$ collisions at \( \sqrt{s} = 1.8 \) TeV and $|\eta| < 0.9$ using data collected between 1994 and 1995 by the Collider Detector at Fermilab.
(CDF). The measurement is based on events where the photon converts into an electron-positron pair in the material of the inner detector, resulting in a two track event signature. To remove $\pi^0 \rightarrow \gamma \gamma$ and $\eta \rightarrow \gamma \gamma$ events from the data we use a new background subtraction technique which takes advantage of the tracking information available in a photon conversion event. We find that the shape of the cross section as a function of photon $p_T$ is poorly described by next-to-leading-order QCD predictions, but agrees with previous CDF measurements.

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I. INTRODUCTION

The CDF Collaboration recently published a measurement of the the direct photon cross section\[1\]. This analysis found that the shape of the cross section as a function of $p_T$ is poorly described by next-to-leading-order (NLO) QCD calculations \[2\], and that the discrepancy persists at $\sqrt{s} = 1800$ GeV and 630 GeV. This conclusion is supported by measurements by the D0 collaboration \[3\], \[4\], and by other hadron-hadron experiments \[5\].

Photon measurements in hadron collisions are complicated by the large number of $\pi^0 \rightarrow \gamma \gamma$ and $\eta \rightarrow \gamma \gamma$ events produced in these experiments. These backgrounds are traditionally suppressed by requiring that the photon be isolated from other energy in the calorimeter, but this requirement also eliminates some of the direct photon signal. Special calculations which take the isolation requirement into account have been developed in order to compare these measurements to NLO QCD \[2\].

To remove the remaining meson events from the data sample, experimentalists have relied upon understanding the shape and development of electromagnetic (EM) showers in the calorimeter \[6\]. At CDF two techniques are used: a shower transverse profile method, and a pre-shower method \[1\]. The datasets are based on photon triggers, where a high $E_T$ EM shower is found in the central calorimeter with no associated charged tracks.

In this article we report on a new measurement of the direct photon cross section at CDF based on events where the photon converts to an $e^+e^-$ pair in the material of the inner detector prior to passing through the central tracking chamber. The EM showers in these events have tracks associated with them, and so are explicitly rejected by conventional photon measurements. Furthermore, the addition of tracking information to the event makes possible a new background subtraction technique which is systematically independent from the standard calorimeter methods.

The primary motivation for studying the direct photon cross section is the potential to extract information about the parton distribution function (PDF) of the gluon inside the proton, due to the large contribution of $gq \rightarrow \gamma q$ diagrams to the process \[6\]. This program has been frustrated by differences between the measurements and calculations which are difficult to explain by altering the gluon PDF alone \[7\], \[8\]. The direct photon cross section measurement with conversions therefore serves as a cross check of conventional photon techniques, as well as a demonstration of a new method for future high $p_T$ photon studies.

II. DETECTOR AND DATASETS

The data was collected at the Fermilab Tevatron collider between 1994 and 1995 (Run 1b) with a center-of-mass energy of 1.8 TeV. A detailed description of CDF in Run 1 may be found elsewhere \[10\]. Here we briefly describe those detector components critical for the conversion measurement. The central tracking system consists of a silicon vertex detector (SVX), a vertex TPC (VTX), and a large central tracking chamber (CTC). These detectors are located inside a 1.4 Tesla solenoidal magnet. The transverse momenta of charged particles in the tracking system are measured primarily by the CTC, which has a momentum resolution of $\sigma(p_T)/p_T^2 = 0.002$ GeV$^{-1}$. Outside the tracking system are the CDF calorimeters, which are subdivided in $\eta$ and $\phi$ into projective towers which point to the nominal $p\bar{p}$ interaction point at the center of the detector. The central region ($|\eta| < 1.1$) is instrumented with the central electromagnetic (CEM), central hadronic (CHA), and wall hadronic (WHA) calorimeters. EM showers in the CEM generally deposit their energy in two or three towers in $\eta$, and these towers are referred to as a CEM cluster. The energy resolution of the CEM is

$$\frac{\sigma(E)}{E} = \sqrt{\frac{13.5%}{\sqrt{E \sin \theta}}} + (1.6%)^2$$

where $\theta$ is the polar angle of the shower measured with respect to the proton beam direction. The CEM is equipped with a layer of crossed wire and strip gas chambers (CES) located at a depth of six radiation lengths (the typical shower maximum) to measure the transverse shape of the shower. A second layer of wire chambers, known as the CPR, is located between the solenoid and the CEM. The CPR is used as a pre-shower detector in conventional photon measurements, with the 1.1 $X_0$ radiation lengths of the solenoid acting as the converting material.

We use a three level trigger system to collect the two datasets used in the photon cross section measurement with conversions. The first data sample, known as the 8 GeV electron data, requires a cluster in the CEM of at least 8 GeV at Level 1. Level 2 requires an associated track found by the fast hardware track finder.
(CFT) with $p_T > 7.5$ GeV, and an associated CES cluster found by a hardware cluster finder (XCES). This trigger applies several electron identification requirements at Level 3, including requirements on the transverse shape of the shower seen in the CES, the geometric matching between the shower and the track, the lateral sharing of the shower energy over the several CEM towers, and the electromagnetic fraction of the shower. The integrated luminosity of this dataset is $73.6 \text{ pb}^{-1}$.

The second data sample, known as the 23 GeV photon data, requires an 8 GeV CEM cluster at Level 1, but at Level 2 this requirement is increased to 23 GeV. The Level 2 trigger also applies an isolation requirement to the CES cluster by requiring that the neighboring calorimeter towers have $E_T < 4$ GeV. The 23 GeV photon trigger does not require that a track be found by the CFT, and it does not apply any electron identification requirements, although at least one CES cluster must be found with more than 0.5 GeV of energy at Level 3. Note that this trigger was designed to collect non-conversion photons (hence its name), but since it does not veto photon candidates which have associated tracks, we can use it to search for conversion events as well. The integrated luminosity is $83.7 \text{ pb}^{-1}$.

Inner detector photon conversions are characterized by two opposite sign CTC tracks which pass near each other in the material of the beampipe, SVX, VTX, or inner cylinder of the CTC. Two conversion identification requirements are applied to the raw CTC tracks. The first requires that the absolute value of the difference between the track cot $\theta$s be less than 0.05. The second requires that the absolute value of the distance between the tracks in the x-y plane at the radial location where they are parallel be less than 0.3 cm. At least one of these tracks is required to point at a CEM cluster, and the softer track is required to have $p_T > 0.4$ GeV.

Track pairs satisfying these requirements are fitted to a conversion vertex. The fit requires that the tracks meet at a point in space where they are parallel, which improves the spatial and momentum resolutions of the reconstructed photon candidate. In addition, the vertex fit partially corrects for a $p_T$ bias present in the raw conversion tracks. This bias occurs when the spatial separation of the conversion tracks in the inner CTC superlayers is less than the two track resolution of the device. The final requirement of the conversion selection is that the fitted conversion radius is required to be between 2 and 30 cm. The radius of conversion distribution of the 8 GeV electron data is shown in Figure 1.

Conversion candidate events at CDF divide naturally into two sets based on their detector topology. In 1-tower conversions both tracks point to the same CEM tower, and in 2-tower conversions the tracks point to separate towers. 1-tower conversions have the potential to confuse the electron identification requirements applied by the 8 GeV electron trigger at Level 3, due to the presence of two EM showers in the same CES chamber. Therefore in the 8 GeV electron data we require that the conversion be 2-tower. Conversely, in the 23 GeV photon data we require that the conversion be 1-tower, in order to insure that the two datasets have no events in common.

In a 1-tower event, the CEM cluster measures the summed $E_T$ of both tracks. In a 2-tower event, however, the softer track is outside the high $E_T$ cluster formed by the first track, and its own $E_T$ usually falls below the clustering threshold of the CEM reconstruction algorithm. In this case, only the higher $E_T$ cluster is found, but the $p_T$ of both tracks is measured by the CTC. When dividing the conversion events into $p_T$ bins, we use the summed $E_T$ measurement for 1-tower events, while for 2-tower events we use the $E_T$ measurement of the higher energy track plus the $p_T$ measurement of the lower energy track.

The offline data reduction proceeds as follows. For the 8 GeV electron data we require a 2-tower conversion at $|\eta| < 0.9$ and $|z_0| < 60$ cm, where $z_0$ is the position of the primary event vertex along the beamline measured from the center of the detector. The conversion must be associated with a fiducial CEM cluster, and we re-apply the electron identification requirements imposed by the Level 3 trigger. The reconstructed CEM cluster must have $E_T > 8.0$ GeV, and at least one of the conversion track must have $p_T > 6.0$ GeV. To suppress the contribution of $\pi^0$ and $\eta$ events
III. BACKGROUND SUBTRACTION

A. \(\pi^0\) and \(\eta\) backgrounds

Most \(\pi^0 \rightarrow \gamma \gamma\) and \(\eta \rightarrow \gamma \gamma\) events are rejected by the isolation requirements. Those that remain are statistically subtracted from the data by a new technique based on \(E/p\). \(E/p\) is the ratio of the \(E_T\) measured in the CEM and the \(p_T\) measured by the CTC. For a 1-tower conversion the \(E_T\) is the two-track summed energy measured by the CEM, and the \(p_T\) is the sum of the two vertexed track momenta. For a 2-tower conversion, the CEM cluster measures only the \(E_T\) of the higher energy track, and in this case the \(E/p\) ratio includes only the \(E_T\) and vertexed \(p_T\) of that track.

Under this definition, the \(E/p\) distribution for a direct photon conversion should be a narrow peak centered on 1.0 whose width is determined by the CTC and CEM resolutions. In a \(\pi^0\) or \(\eta\) event, however, the second unconverted photon usually showers in the same CEM cluster as the high \(E_T\) conversion electron. Therefore in a meson event the \(E_T\) measures the \(\pi^0\) energy, and the \(p_T\) measures the energy of one of the decay photons. Since two-body decay kinematics are understood, the shape of the meson \(E/p\) distribution is relatively easy to calculate with a Monte Carlo simulation.

To predict the signal \(E/p\) distribution we generate direct photon events using PYTHIA version 6.115. The prompt photon is tracked through a material map of the CDF inner detector where it is allowed to convert into an electron-positron pair. The two tracks pass through the remaining material, where they are allowed to undergo bremsstrahlung, and through the tracking chamber and calorimeter. To simulate the \(p_T\) and \(E_T\) measurements the true track parameters are smeared by the known resolutions of the CTC and CEM.

We find that for the purpose of predicting the meson \(E/p\) distribution, it is adequate to simulate single mesons, rather that complete events, because the mesons in the data are highly isolated. The generated mesons decay to two photons which are tracked through the detector in the same manner as the PYTHIA direct photons. The two meson samples are combined using a \(\eta/\pi^0\) production ratio of 0.69±0.08, which we measured in the data using a sample of double conversion \((\pi^0/\eta \rightarrow \gamma \gamma \rightarrow e^+e^-e^+e^-)\) events, as shown in Figure 2. Fortunately, the \(E/p\) distributions of \(\pi^0\) and \(\eta\) are very similar (due to similar decay kinematics), so the production ratio used in the Monte Carlo has little effect on their combined \(E/p\) shape. We also use the double conversion events to measure the meson \(p_T\) spectrum to be used in the Monte Carlo. We find that a power law with an exponent of negative six gives a good description of the data.
We extract the number of signal candidates in each $p_T$ bin by performing a $\chi^2$ fit of the $E/p$ distributions observed in the data to the Monte Carlo signal and background templates. In the fit only the normalizations of the signal and background are allowed to float. Examples of two fits are shown in Figure 3 and the number of signal candidates found in each $p_T$ bin is listed in Table III.

As seen in Figure 3, the narrow signal peak is quite distinct from the broad background distribution, and in general the fits to the data are reasonable. In some fits, however, the signal peak is shifted slightly with respect to the Monte Carlo prediction. This effect is due to a $p_T$ bias associated with conversion tracking which occurs when the spatial separation of the two tracks in the inner layers of the CTC is below the hit resolution. A hit level simulation of the tracking system reproduces this effect, but it is not simulated by our fast Monte Carlo, so the templates do not reproduce this. Studies show that the $E/p$ shift is no larger than 1% in the 8 GeV electron data, and 2% in the 23 GeV photon data.

To determine a systematic uncertainty on the background subtraction due to this effect, we multiply the $E/p$ of each event in the 8 GeV electron data by a scale factors of 1.01 and 0.99. We then perform the $\chi^2$ fit again, and we take the change in the number of signal candidates as a systematic uncertainty. Similarly we use scale factors of 1.02 and 0.98 in the 23 GeV data to determine the uncertainty. For the 8 GeV electron data this error is $+12/-10\%$ at 10 GeV and decreases to less than $\pm 5\%$ above 20 GeV, while the error is less than $\pm 5\%$ for the 23 GeV electron data.

B. Other backgrounds

We consider two other potential sources of background. The first is fake conversions, where two random tracks satisfy the conversion identification requirements. In this case the soft conversion track is likely to be a hadron. A study of the $E/p$ of the soft conversion tracks finds no evidence for hadronic contamination, so we neglect this background.

A second source of background is due to high $p_T$ prompt electrons, such as those produced in $W \rightarrow e\nu$ events. These electrons often have a co-linear bremsstrahlung photon, and this photon may convert in the detector material and produce one or two soft tracks. The soft tracks can form a high $p_T$ conversion candidate when combined with the prompt electron. This background is the motivation for the $E_T$ requirement applied to the 8 GeV electron data, which would otherwise have significant $W \rightarrow e\nu$ contamination above 25 GeV. In the 23 GeV photon data this background is less significant because these events are unlikely to satisfy the 1-tower topology.

To account for remaining prompt electron backgrounds in both datasets, including any remaining $W$ electrons, we have searched for hits in the SVX and VTX detectors in events where the conversion occurs outside these detectors. These studies have indicated that in the 8 GeV electron data there is no significant prompt electron contamination below 25 GeV, and above 25 GeV we adopt a one sided 10% systematic uncertainty. In the 23 GeV photon data we adopt a one sided 3% systematic uncertainty in all $p_T$ bins.

IV. ACCEPTANCE AND EFFICIENCY

The acceptance is evaluated with the PYTHIA direct photon Monte Carlo, and includes the fiducial requirements, the 1-tower and 2-tower topological requirements, and the $E_T$ and $p_T$ requirements on the CEM clusters and tracks. For the 2-tower data (8 GeV electron trigger), the acceptance is 33% at 10 GeV, and decreases to 6.5% at 65 GeV. In the 1-tower data (23 GeV photon trigger) the acceptance increases from 35% at 30 GeV to 43% at 65 GeV.

The efficiency of the remaining selection requirements are measured in the data with a variety of complementary datasets. The efficiency of the event $z_0$ requirement is measured to be $93.7 \pm 1.1\%$ in minimum bias data. The conversion identification efficiency is measured using a loose sample of conversions occurring in and around the CTC inner cylinder material. We find an efficiency of $97.4 \pm 2.0\%$, where the uncertainty is determined by variations seen when dividing the data into $p_T$ bins. The 8 GeV electron trigger efficiency is measured with a pre-scaled 5 GeV electron trigger and an inclusive muon dataset, and has an asymptotic efficiency of $91.4 \pm 0.9\%$. The 23 GeV photon trigger efficiency is measured with pre-scaled 10 GeV and 23 GeV photon triggers, and has an efficiency of $91.4 \pm 4.3\%$. The electron identification efficiency is measured with the non-trigger electron in $Z \rightarrow e^+e^-$ data, and is found to be $84.3 \pm 3.0\%$. The efficiency is measured with a track embedding study, and has a plateau value of $96 \pm 2\%$ per track above 400 MeV. The isolation requirement efficiency is measured by choosing random locations in the calorimeter in minimum bias data and adding up the energy found within a cone radius of 0.4. The efficiency is found to be $85.9 \pm 0.4\%$. The no-extra-track requirement efficiency is evaluated with electrons in $Z \rightarrow e^+e^-$ data, and is found to be $89.6 \pm 0.5\%$. The missing energy efficiency is evaluated with unisolated conversion candidates. These events are predominantly di-jet events where the true $E_T$ is zero, so the measured $E_T$ is due to the calorimeter resolution. The efficiency decreases from 1.0 at 20 GeV to 89% at 65 GeV.

The efficiencies are summarized in Table IV. The total acceptance times efficiency for the two datasets is plotted in Figure 4.
16.5 GeV < \pT < 18 GeV

\[ \pi^0, \eta \]

\[ \gamma + \pi^0, \eta \]

- data

30 GeV < \pT < 34 GeV

\[ \pi^0, \eta \]

\[ \gamma + \pi^0, \eta \]

- data

FIG. 3: An example of the $E/p$ background subtraction fit in two $p_T$ bins. Left: the 16.5 to 18 GeV bin from the 8 GeV electron (2-tower) data. Right: the 30 to 34 GeV bin from the 23 GeV photon (1-tower) data.

| source               | 8 GeV electron | 23 GeV photon | efficiency        |
|----------------------|----------------|---------------|-------------------|
| $\pi^0$              | *              | *             | 0.937 ± 0.011     |
| Conversion ID        | *              | *             | 0.974 ± 0.020     |
| Level 1 trigger      | *              | *             | 1.0               |
| Level 2 trigger (8 GeV) | *          | *             | 91.4 ± 0.9 % above 16 GeV |
| Level 2 trigger (23 GeV) | *          | *             | 0.914 ± 0.043     |
| Level 3 electron ID  | *              | *             | 0.849 ± 0.030     |
| Tracking (CTC)       | *              | *             | 0.96 ± 0.02 per track |
| Isolation            | *              | *             | 0.859 ± 0.004     |
| No extra tracks      | *              | *             | 0.896 ± 0.005     |
| $E_T$                | *              |               | 1.0 below 20 GeV, 0.89 at 65 GeV |

TABLE I: Summary of signal efficiencies. The asterisks indicate to which dataset each efficiency applies.

V. TOTAL CONVERSION PROBABILITY

The final element of the photon cross section measurement with conversions is the total probability that the photon converts in the CDF inner detector. The conversion probability has been evaluated in several ways. The standard technique relies on a material map measured in the data with an inclusive conversion dataset, calibrated with an a priori determination of the amount of material in the CTC inner cylinder. This method gives a conversion probability of 5.17 ± 0.28%, and we refer to this result as the standard material scale. Other material measurements based on the hard bremsstrahlung rate in $W \rightarrow e\nu$ and $J/\psi \rightarrow e^+e^-$ events give results in agreement with this number \[14\].

A second technique compares the number of $\pi^0$ Dalitz decays ($\pi^0 \rightarrow e^+e^-\gamma$) to the number of $\pi^0 \rightarrow \gamma\gamma$ decays. In some Dalitz events the on shell photon subsequently converts in the inner detector material. Then the event has a four-track topology, with the invariant mass being the $\pi^0$ mass. Similarly, in some $\gamma\gamma$ events both photons convert in the detector material, giving the same four-track signature. In the four-track event sample, the Dalitz events can be separated from the $\gamma\gamma$ events because two of the Dalitz electrons are prompt. Since the four-track Dalitz events undergo one conversion in the detector material, while the four-track $\gamma\gamma$ events undergo two conversions, the Dalitz-to-$\gamma\gamma$ ratio gives the conversion probability, after accounting for the branching ratios of the two decays. This method gives a conversion probability of $8.02 \pm 0.73(stat) \pm 0.73(sys)\%$, which is significantly higher than the standard result quoted above.

Several other datasets also give evidence for a larger conversion probability. At CDF the reconstructed mass of di-muon resonances such as the $J/\psi$, $\psi(2s)$, $T(1s),(2s)$, and $(3s)$ depend on the amount of material in the inner detector due to muon $dE/dx$ energy losses. We correct the muon momenta for the ex-
expected energy loss by assuming the standard material scale. However, after the correction the reconstructed masses are less than the PDG masses for all five resonances. For the $J/\psi$ the mass shift is more than twenty times larger than the statistical error, while for the $\Upsilon(3s)$ the shift is only 1.2 times the statistical error. The dominant systematic uncertainty is due to the fact that the reconstructed $J/\psi$ mass depends on the amount of material the muons pass through. After adopting a systematic uncertainty to account for this, the measured value of the $J/\psi$ mass agrees with the PDG value within errors. These effects do not prove that the standard material scale is too small, but they are consistent with that hypothesis.

There is also some evidence from W electrons for a larger material scale. In Run 1b the peak of the $E/p$ distribution in W electrons in the data is shifted to the right with respect to the Monte Carlo simulation when assuming the standard material scale. Although this effect is not adequately understood, the Monte Carlo $E/p$ peak can be made to agree with the data by increasing the material.

In summary, the evidence concerning the total conversion probability is ambiguous. Rather than choose between two conflicting results, we adopt the approach of choosing a central value and systematic uncertainty which encompasses all possibilities. This value is $6.60 \pm 1.43\%$. We make one adjustment to the conversion probability to account for the effective loss of material due to the requirement on the radial location of the conversion ($r_{cnv} > 2.0$ cm). The final value of the effective conversion probability is $6.40 \pm 1.43\%$. The uncertainty on the conversion probability dominates all other errors on the photon cross section. However, while the conversion probability affects the overall normalization of the cross section, it does not affect the shape of the cross section as a function of $p_T$.

This is assured by the fact that the pair-production cross section does not vary significantly over the $p_T$ range considered here.

VI. SYSTEMATIC UNCERTAINTIES

In this section we briefly summarize the systematic uncertainties on the photon cross section measurement with conversions. (A detailed discussion is given in Ref. [12].) In Section II we discussed the systematic uncertainties we adopt to account for shortcomings in the Monte Carlo $E/p$ model, and backgrounds due to prompt electrons. Both of these uncertainties depend on $p_T$.

For the 8 GeV electron data the remaining $p_T$ dependent systematic uncertainties are as follows. We take a systematic uncertainty to account for a possible time dependence on the trigger efficiency. This uncertainty is determined by counting the fraction of events in our final sample which occur before the midpoint of Run 1b. This fraction is 53.6%, and depends on $p_T$. We take 3.6% as the uncertainty. Secondly, the conversion identification efficiency varies by 2.0% when dividing the data into $p_T$ bins, and we take this as a systematic uncertainty.

We also adopt the following $p_T$ independent systematic uncertainties. The cross section uncertainty due to the total conversion probability is $+27/-17\%$. The CEM energy scale uncertainty results in an cross section error of $3.0\%$. The integrated luminosity is measured to 4.1%, and the asymptotic trigger efficiency is known to 1.4%. There are also uncertainties due to the tracking efficiency (2.0%), the electron identification efficiency (3.5%), and the $z_0$ requirement efficiency (1.2%).

The systematic uncertainties on the 23 GeV photon data sample are similar, except there is no trigger time dependence, no electron identification uncertainty, and the asymptotic trigger efficiency is known to 4.7%.

The total $p_T$ independent systematic uncertainty is $+28/-18\%$ for both datasets. The total $p_T$ dependent systematic uncertainty in each $p_T$ bin is listed in Table III. The total systematic uncertainty is listed in Table III.

VII. CROSS SECTION MEASUREMENT

The cross section is calculated according to
TABLE II: The $p_T$ dependent systematic uncertainty for all $p_T$ bins. The correlated systematic uncertainty is $+28/-18\%$ for both datasets.

| $p_T$ (GeV) | $p_T$ dep. sys. err. (%) |
|------------|--------------------------|
| 8 GeV electron (2-tower) data: |
| 10-11      | $+10.6/-12.8$            |
| 11-12      | $+9.3/-11.6$             |
| 12-13      | $+9.4/-9.3$              |
| 13-14      | $+8.5/-8.6$              |
| 14-15      | $+6.7/-7.3$              |
| 15-16.5    | $+6.7/-6.9$              |
| 16.5-18    | $+5.7/-6.0$              |
| 18-20      | $+7.6/-7.8$              |
| 20-22      | $+7.0/-6.1$              |
| 22-24.5    | $+4.3/-5.8$              |
| 24.5-27    | $+5.1/-11.9$             |
| 27-30      | $+5.7/-11.3$             |
| 30-34      | $+4.1/-11.1$             |
| 34-39      | $+4.1/-11.0$             |
| 39-45      | $+5.6/-11.5$             |
| 45-52      | $+4.1/-10.8$             |
| 52-65      | $+8.8/-13.3$             |

23 GeV photon (1-tower) data:

| $p_T$ (GeV) | $p_T$ dep. sys. err. (%) |
|------------|--------------------------|
| 30-34      | $+2.3/-4.9$              |
| 34-39      | $+2.8/-4.9$              |
| 39-45      | $+3.9/-5.6$              |
| 45-52      | $+5.0/-4.7$              |
| 52-65      | $+4.7/-8.2$              |

$A \cdot \epsilon$ is the acceptance times efficiency shown in Figure 4 multiplied by the effective conversion probability of 6.40%. We measure the average cross section between -0.9 < $\eta$ < 0.9, so $\Delta \eta$ is 1.8. $\Delta p_T$ is the bin width, and $\int L$ is the integrated luminosity of 73.6 pb$^{-1}$ for the 8 GeV electron data and 83.7 pb$^{-1}$ for the 23 GeV photon data.

The final result for both datasets is listed in Table III. In the $p_T$ region where the datasets overlap (30 GeV < $p_T$ < 65 GeV) the two measurements are in good agreement with each other. This comparison is an important cross check on the acceptance and efficiency calculations of the two datasets, since they differ by up to a factor of nine.

Since the two datasets are in agreement we can combine the measurements in the region of overlap. However, the 23 GeV photon data would dominate the combined cross section (due to much smaller errors), so instead we simply adopt the 23 GeV photon data above 30 GeV. This hybrid cross section is compared to NLO QCD and the standard CDF measurement (referred to as CES-CPR) in Figure 5. The theory curve is taken from the authors of Reference [2]. The calculation uses the CTEQ5M parton distribution functions with the all scales set to the $p_T$ of the photon. Only the statistical error bars are shown here.

The CES-CPR measurement and the conversion measurement agree with each other both in shape and in normalization. The total systematic uncertainty on the conversion measurement is larger ($+30\%/-20\%$) than the CES-CPR measurement (18% at 10 GeV and 11% at 115 GeV) due to the large uncertainty on the total conversion probability. Nevertheless, for both measurements the total systematic uncertainties are primarily $p_T$ independent, so that both techniques give a much more precise measurement of the shape of the cross section as a function of $p_T$. The agreement of the conversion and CES-CPR measurements on the shape is remarkable, since the two techniques have little in common with each other. They use independent data samples, independent background subtraction techniques, and have different acceptances, efficiencies, and systematic uncertainties.

Figure 6 shows the conversion measurement alone as (data-theory)/theory. To compare the shape of the data to the calculation, the uncertainty bars in this plot are the combined statistical and $p_T$ dependent systematic uncertainties. The data show a steeper
TABLE III: Summary of the conversion cross section measurement in both datasets. The 8 GeV electron data has an integrated luminosity of $73.6\text{pb}^{-1}$, and the 23 GeV photon data has an integrated luminosity of $83.7\text{pb}^{-1}$. $\Delta\eta$ is 1.8, and the effective conversion probability, which is not included in the acceptance $\times$ efficiency shown here, is 6.40%. The NLO QCD theory was calculated by the authors of Reference [2], and uses the CTEQ5M parton distribution functions with all scales set to the $p_T$ of the photon.

| $p_T$ (GeV) | $\langle p_T \rangle$ (GeV) | $A \cdot \epsilon$ | $N_{\text{signal}}$ (pb/GeV) | stat error (%) | sys error (%) | $\frac{d\sigma}{dp_T d\eta}$ (pb/GeV) |
|-------------|----------------|----------------|-----------------|---------------|-------------|----------------|
| 10-11 | 10.5 | 0.067 | 7152 | 12590 | 2.2 | +30/-22 | 10968 |
| 11-12 | 11.5 | 0.094 | 7761 | 9771 | 2.1 | +29/-22 | 7434 |
| 12-13 | 12.5 | 0.106 | 6111 | 6773 | 2.2 | +29/-20 | 5203 |
| 13-14 | 13.5 | 0.109 | 4320 | 4659 | 2.6 | +29/-20 | 3743 |
| 14-15 | 14.5 | 0.108 | 3195 | 3483 | 2.9 | +29/-20 | 2758 |
| 15-16.5 | 15.7 | 0.105 | 3059 | 2289 | 2.8 | +29/-20 | 1963 |
| 16.5-18 | 17.2 | 0.096 | 1846 | 1509 | 3.5 | +29/-19 | 1328 |
| 18-20 | 18.9 | 0.086 | 1391 | 950 | 4.1 | +29/-20 | 888 |
| 20-22 | 20.9 | 0.077 | 863 | 658 | 5.1 | +29/-19 | 577 |
| 22.4-24.5 | 23.2 | 0.068 | 596 | 413 | 6.0 | +29/-20 | 369 |
| 24.5-27 | 25.7 | 0.063 | 344 | 258 | 6.7 | +29/-20 | 238 |
| 27-30 | 28.3 | 0.056 | 272 | 207 | 7.7 | +28/-22 | 158 |
| 30-34 | 31.9 | 0.047 | 136 | 90 | 8.8 | +28/-21 | 158 |
| 34-39 | 36.3 | 0.041 | 101 | 65 | 13.5 | +28/-21 | 158 |
| 39-45 | 41.6 | 0.036 | 63.9 | 41 | 14.4 | +28/-21 | 158 |
| 45-52 | 48.1 | 0.032 | 21.7 | 15 | 18.7 | +28/-21 | 158 |
| 52-65 | 57.8 | 0.030 | 16.6 | 12 | 33.5 | +28/-21 | 158 |

| $p_T$ (GeV) | $\langle p_T \rangle$ (GeV) | $A \cdot \epsilon$ | $N_{\text{signal}}$ (pb/GeV) | stat error (%) | sys error (%) | $\frac{d\sigma}{dp_T d\eta}$ (pb/GeV) |
|-------------|----------------|----------------|-----------------|---------------|-------------|----------------|
| 30-34 | 31.9 | 0.212 | 723 | 88.4 | 4.8 | +28/-19 | 94.6 |
| 34-39 | 36.3 | 0.220 | 564 | 53.1 | 5.3 | +28/-19 | 49.1 |
| 39-45 | 41.6 | 0.238 | 316 | 22.9 | 7.4 | +28/-20 | 26.2 |
| 45-52 | 48.1 | 0.250 | 225 | 13.3 | 8.5 | +29/-19 | 13.4 |
| 52-65 | 57.8 | 0.261 | 131 | 4.0 | 11.3 | +29/-21 | 5.7 |

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FIG. 6: The isolated photon cross section from conversions compared to NLO QCD. The error bars shown here are the combined statistical and $p_T$ dependent systematics, in order to compare the shape of the measured cross section to theory.

Direct photon cross-section ($pp \rightarrow \gamma X$) 
$|\eta| < 0.9$, $\sqrt{s} = 1.8$ TeV

Conversion data only
Error bars are stat. $\oplus$ $p_T$ depen. sys
Data norm. error is +28/-18%
Theory is NLO QCD, CTEQ5M, $\mu = p_T$

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