A Measurement of The Isolated Direct Photon Cross Section at 630 GeV

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Abstract

The inclusive cross section for isolated photons at $\sqrt{s} = 630$ GeV (Run 1C) is measured for the central ($|\eta| < 0.9$) and forward ($1.6 < |\eta| < 2.5$) rapidity regions. We compare the result with next to leading order QCD predictions using CTEQ parton distibution functions.

1 Introduction

The present analysis has been developed along the lines of the published Run 1A/1B cross section data [1], described in greater detail in a DØ note by S. Linn [2]. Other techniques are from previous isolated photon analysis at 1800 GeV/c^2 [3, 4, 5] and at 630 GeV/c^2 [6, 7]. This note supercedes and expands on the previous 630 GeV/c^2 analyses. The differential cross section for the process $p\overline{p} \rightarrow \gamma + X$ can be written as

$$\frac{d^2\sigma}{dE_T d\eta} = \frac{N\mathcal{P}}{L\Delta\eta\Delta E_T A\epsilon_s\epsilon_d\epsilon_t} \tag{1}$$

where N is the number of photon candidates (one or two per event), $\mathcal{P}$ is the photon purity (the fraction of direct photons in the sample), L is the integrated luminosity, $\Delta\eta$ and ΔE_T are the bin sizes in pseudorapidity and E_T , A is the geometric acceptance, ϵ_s is the efficiency of the selection criteria, ϵ_d is the efficiency of the charged track cut, and ϵ_t is the efficiency of the trigger.

Previous measurments of the isolated single photon cross section at collider energies by UA2 and CDF showed a discrepency between the theory and the data, particularly in the low E_T regions as shown in Fig. 1 [8, 9]. The CDF data has never been published.

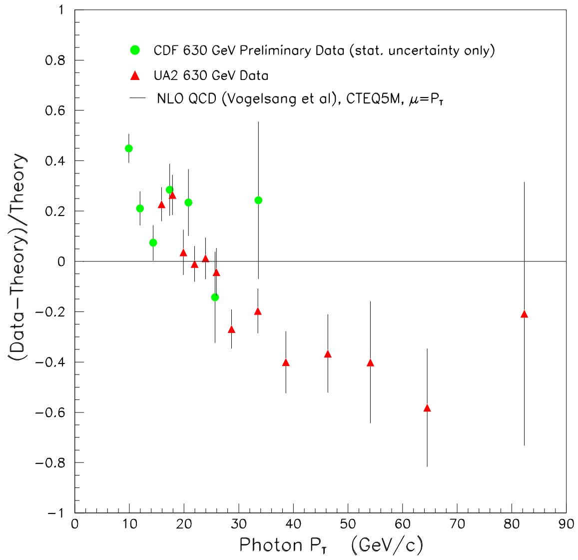


Figure 1: Production of direct photons at 630 GeV from UA2 and CDF. The data is normalized to CTEQ5 as implemented by Vogelsang.

2 Data and Monte Carlo Sample

2.1 The Direct Photon Data Set

The data in this analysis were taken at 630 GeV during the last part of Run 1C, with three dedicated isolated photon triggers, as summarized on Table 1. The respective luminosities, number of events successfully reconstructed, and events used in the analysis after all selection criteria, is also shown. The error on the luminosity is 5%.

2.2 Monte Carlo Sample

The analysis depends heavily on the Monte Carlo to determine efficiencies and background from neutral mesons. The MC sample, generated in the Florida State University farm, consists of full PYTHIA photon and electromagnetic jet events generated at $\sqrt{s} = 1.8$ TeV, with zero bias events

L1 Trigger	**L2 Filter**	**Thresh. (GeV)**	$\int L\,dt$ (nb^{-1})	**Events**	**Events Used**
em_1_2_lnr	gam_4_iso5	4.5	2.021	52771	1890
em_1_3_lnr	gam_8_iso3	8	17.22	20597	1169
em_1_7_lnr	gam_14_iso	14	520.5	24362	3161

Table 1: 630 GeV isolated photon triggers

superimposed. To minimize computing time, most of these events had only the particles and energy in a cone of $R = 0.7$ around each photon or jet simulated through DØGEANT, using plate level calorimeter geometry. These events were used to estimate the photon purity, $\mathcal{P}$ (see Section 4). A smaller number of events had the entire event simulated in the detector and were used for determining selection efficiencies, (Section 3.4).

In an attempt to maximize MC statistics within the allotted cpu budget, about ten different zero bias events were overlayed for the same PYTHIA event. Although the events in this MC sample are clearly not independent, studies have indicated only a moderate degree of correlation [10]. This point is addressed further in Appendix A. The number of available MC events is summarized in Tables 2 and 3 for six E_T ranges, in the central and forward regions, respectively

E_T **Range**	*Before All Cuts*			*After All Cuts*		
	Data	**MC** γ	**MC Jets**	**Data**	**MC** γ	**MC Jets**
6 – 8	6681	12746	32061	908	6262	7144
8 – 13	8817	26199	42169	742	14862	9495
13 – 18	5719	15731	22566	967	10015	6038
18 – 23	3091	17694	15017	865	12188	4559
23 – 33	1516	19423	15977	377	13074	4908
>33	432	41442	24578	67	29542	8078

Table 2: Number of Data and MC events in central rapidity region as a fundtion of E_T , used for calculating photon purity.

The ability of the MC to model the data was tested by comparing 40 GeV simulated electrons with electron candidates from $W \rightarrow e\nu$ Run 1B events [5].

E_T Range	*Before All Cuts* Data	MC γ	MC Jets	*After All Cuts* Data	MC γ	MC Jets
6 – 8	4614	2590	14081	599	1625	3674
8 – 11	5734	13903	17244	313	9188	3880
11 – 15	3036	16830	15914	238	11255	3590
15 – 20	5246	16293	18104	821	11239	4187
20 – 26	1361	17873	12162	256	12501	3129
>26	334	36490	27848	67	25544	7389

Table 3: Number of Data and MC events in forward rapidity region as a function of E_T , bin used for calculating photon purity.

As there are very few W events for the 630 GeV sample, this comparison could not be performed with the runs corresponding to the data used for the present analysis. A comparison of the effect of selections on data and fully simulated Monte Carlo photons demonstrated that within statistical accuracy, the two samples were affected in a similar manner.

Because the Monte Carlo data set was generated at $\sqrt{s}$ = 1.8 TeV a comparison of the distribution of the selection variables between the Monte Carlo and the data was made to confirm that the Monte Carlo adequately described the 630 GeV data. The details of this comparison are covered in Appendix B.

2.3 Event Selection

The selections used on the MC sample (where applicable) and data are:

- $|\eta| < 0.9$ $(1.6 < |\eta| < 2.5)$ for the central (forward) region.
- $|\eta^{det}| < 9$ $(16 < |\eta^{det}| < 25)$ for the central (forward) region.
- $|Z_{vertex}| < 50\,cm$
- For the central region, $0.1 < \mathrm{mod}(16\phi/\pi) < 0.9$.
- No track in the CDC pointing to the EM cluster within $\delta\phi \times \delta\theta$ of 0.2 $\times$ 0.2
- $\frac{EM\,E^{R\leq0.2}}{Total\,E^{R\leq0.2}} > 0.96$

- Isolation cut: $E_T^{R\leq 0.4} - E_T^{R\leq 0.2} < 2.0\,GeV$.
- H-matrix $\chi^2 < 150$

The first four cuts are labeled acceptance cuts because they constrain the candidate photon and its surrounding cone of isolation to the geometric regions where the detector is well understood. The last three, collectively named selection criteria, are tuned to selectively reject QCD jet contamination in the candidate sample.

3 Calculation of efficiencies

3.1 Trigger Efficiency

The trigger efficiency for the high and medium energy triggers has been determined from the data, while the low-energy trigger efficiency has been determined using Monte Carlo events. The inability to determine the low-energy trigger efficiency with data is one of the weaknesses of this analysis. The sensitivity of the cross section to the correct efficiency from Run 1A is shown in Fig. 2. The isolation requirements and trigger efficiency correction are different for Run 1A at 1800 GeV and Run 1C at 630 GeV, so the correction used in Run 1A is not applicable in this analysis. To minimize the effect of the uncertainty in the low-energy triggers, we have chosen not to use the lowest threshhold data in the final cross section.

This analysis relies on a common method to determine the high energy (14 GeV) and medium energy (8.0 GeV) trigger efficiencies, and on a complementary method to check the high energy trigger efficiency. The results from the two methods are averaged together and their difference is taken as a measure of the systematic uncertainty.

The common method used by the medium and high energy triggers simply takes the ratio of the number of 14 GeV (8.0 GeV) triggers divided by the number of 8.0 GeV (4.5 GeV) triggers, with both triggers scaled by the appropriate luminosity factors taken from the run. The trigger turn on ratios are shown in Fig. 3 and Fig. 4 for the CC and EC, respectively. We have estimated systematic uncertainties in the medium energy regime from those determined in the high energy regime.

The alternative method for finding the high energy efficiency uses all events that fired the medium energy trigger as tagged events. The fraction of these tagged events that also fired the high trigger defines the efficiency. This alternative method can only be used for the 14.0 GeV trigger because it

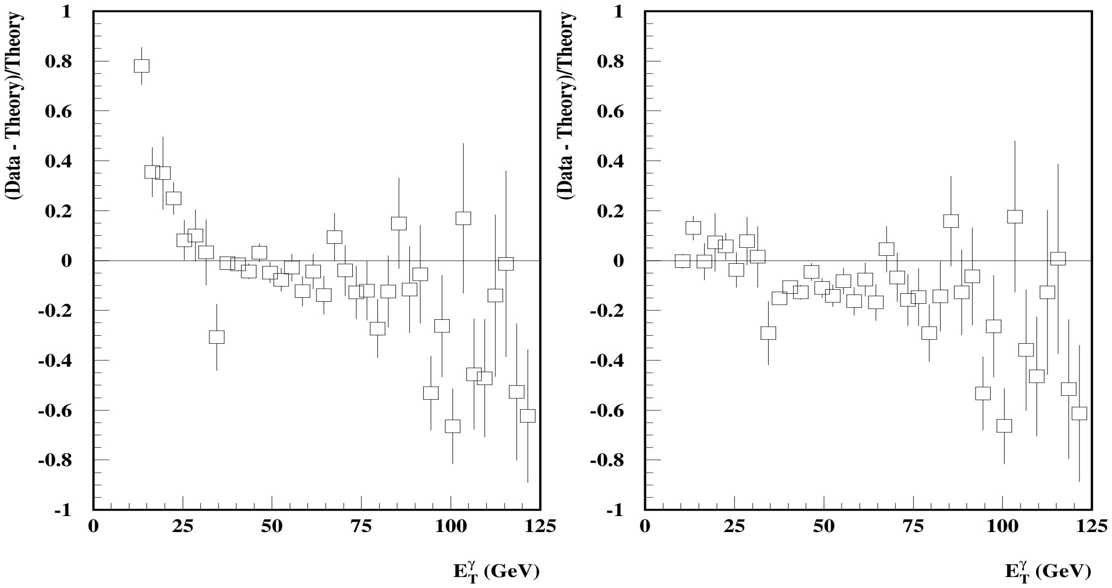


Figure 2: Effect of trigger efficiency on Run 1A data. *Left*: Published result for the CC region. *Right*: Same data, but without the correction for trigger efficiency.

requires that all tagged events have the potential of firing the higher energy trigger; a criteria that is only satisfied if the higher energy trigger is not prescaled. This alternative method is also shown in Fig. 3 and Fig. 4. Note that for the EC, the two methods of determining the high energy trigger efficiency give almost identical results, while for the CC, the fit results differ by 1.3σ.

The points were fitted with a functional form

$$\epsilon_t = 1 - e^{(b-E_T)/a} \tag{2}$$

where a and b are free parameters, with b approximately equal to the trigger threshold energy.

It is not possible to determine the low energy efficiency from the data, so instead we have used results of a MC study carried on by A. Schaffer in 1995 [11], with events generated for the Run 1A analysis, both for the central and forward rapidity regions.

The low energy trigger efficiency is shown in Fig. 5. The points have been fitted with the functional form in Eq. 2 with $a = 1.97 \pm 0.32$ (1.80 ± 0.30) in the central (forward) region and b set to the threshold energy of 4.5 GeV. The error bands have been enlarged to account for other possible functional

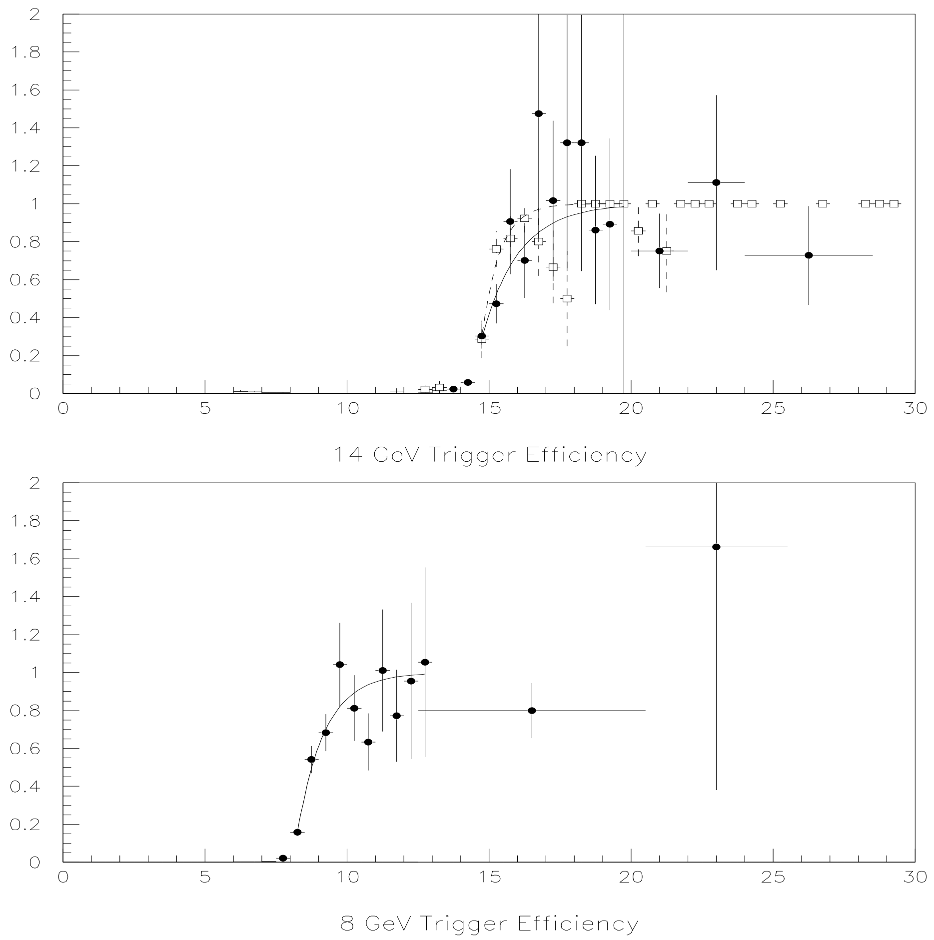


Figure 3: Trigger efficiency for the central region. The black circles show the efficiency determined from the luminosity corrected data described in the text, and the open squares show the efficiency determined from the direct method that is only applicable to the high energy trigger.

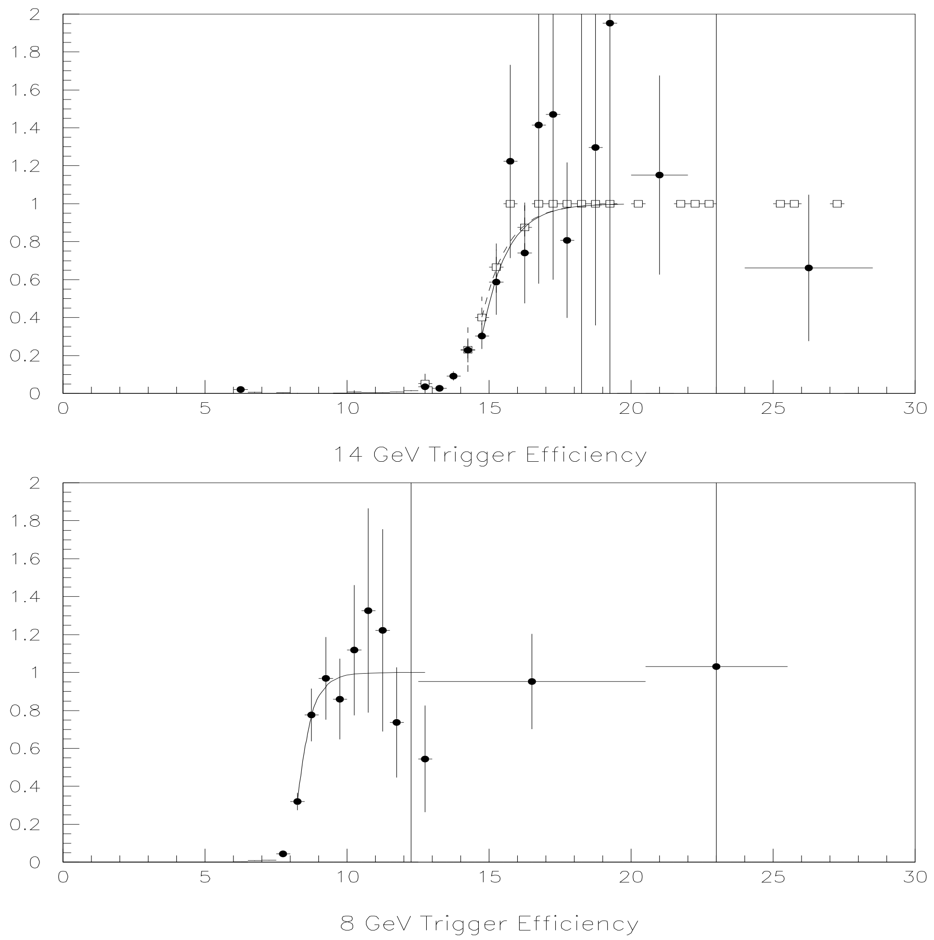


Figure 4: Trigger efficiency for the forward region. The black circles show the efficiency determined from the luminosity corrected data described in the text, and the open squares show the efficiency determined from the direct method only applicable to the high energy trigger.

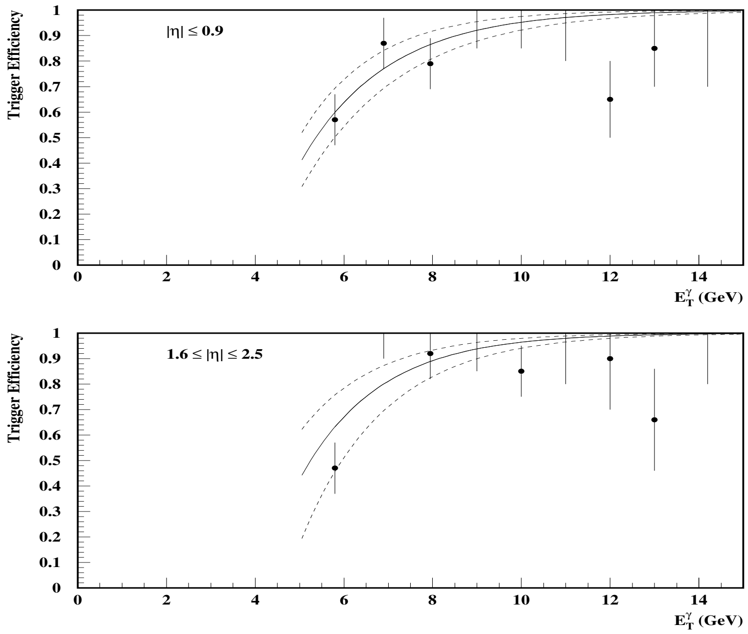


Figure 5: Low energy trigger efficiencies for the central and forward regions.

Threshold	Region	a	b
4.5 GeV	CC	1.97 ± 0.32	4.5
8.0 GeV	CC	$0.98 \pm 0.16 \pm 0.08$	$8.08 \pm 0.04 \pm 0.04$
14.0 GeV	CC	$0.96 \pm 0.33 \pm 0.32$	$14.40 \pm 0.18 \pm 0.10$
4.5 GeV	EC	1.80 ± 0.32	4.5
8.0 GeV	EC	$0.45 \pm 0.14 \pm 0.07$	$8.07 \pm 0.05 \pm 0.04$
14.0 GeV	EC	$0.89 \pm 0.43 \pm 0.05$	$14.36 \pm 0.25 \pm 0.08$

Table 4: Trigger efficiency used for this analysis fit to the functional form $\epsilon_t = 1 - e^{(b-E_T)/a}$. The first error is statistical and the second is systematic.

dependences. The trigger efficiencies used in this analysis are summarized in Table 4. The uncertainty in the determination of the trigger efficiency below 10 GeV is one of the very large systematic uncertainties that affect the low-E_T region. In addition, there is a large background fraction and the determination of the purity in the low-E_T data is imprecise, (Section 4). Also, the selection efficiency is not well determined below 8 GeV (section 3.4). Because of these three problems, we have chosen 8 GeV as the minimum E_T for quoting a cross section.

To check that the various tiggers are consistent with each other, we have plotted the number of events satisfying the selections divided by the luminosity, as a function of E_T for the central and forward regions in Fig. 6. In Fig 7 the normalized difference is plotted. As expected if there are no inconsistencies between triggers, each ratio moves from a value of 1 to a value of zero at an energy of about 2 GeV over the trigger threshhold. We use events that fired the 8 (14) GeV trigger if they have $E_T > 10$ (16) GeV. With these threshholds, no systematic problems in the trigger are apparent.

3.2 Acceptance cuts

The acceptance A takes into account the events lost due to the cuts in the cracks of ϕ module (20% in the CC), in the Z_{vertex} distribution, and in η.

The acceptance in Z_{vertex} was estimated by taking the ratio of events with and without the Z_{vertex} requirement and found to be .848 (.846) for the CC (EC). The vertex distribution is shown in Fig. 8 fitted to a Gaussian function.

The acceptance in η_d was taken from the Run 1B analysis, and is 0.917 ± 0.007 (0.930 ± 0.007) in the central (forward) region [5]. It was calculated from a MC simulation, using an η distribution modeled by Owens et al. [12]. The systematic uncertainty corresponds to the difference obtained for a flat distribution in physics η and the above distribution. This systematic uncertainty is large enough to encompass any minor differences in shape between the 1800 and 630 GeV distributions.

Combining the three separate sources of loss, the total acceptance is $A = 0.622 \pm 0.007$ (0.787 ± 0.007) in the central (forward) pseudorapidity region.

3.3 Charged Track Cut

The presence of a charged track near a shower distinguishes electrons from photons. By removing EM objects with an associated charged track extrapolated from the wire chambers, contamination of the photon signal by

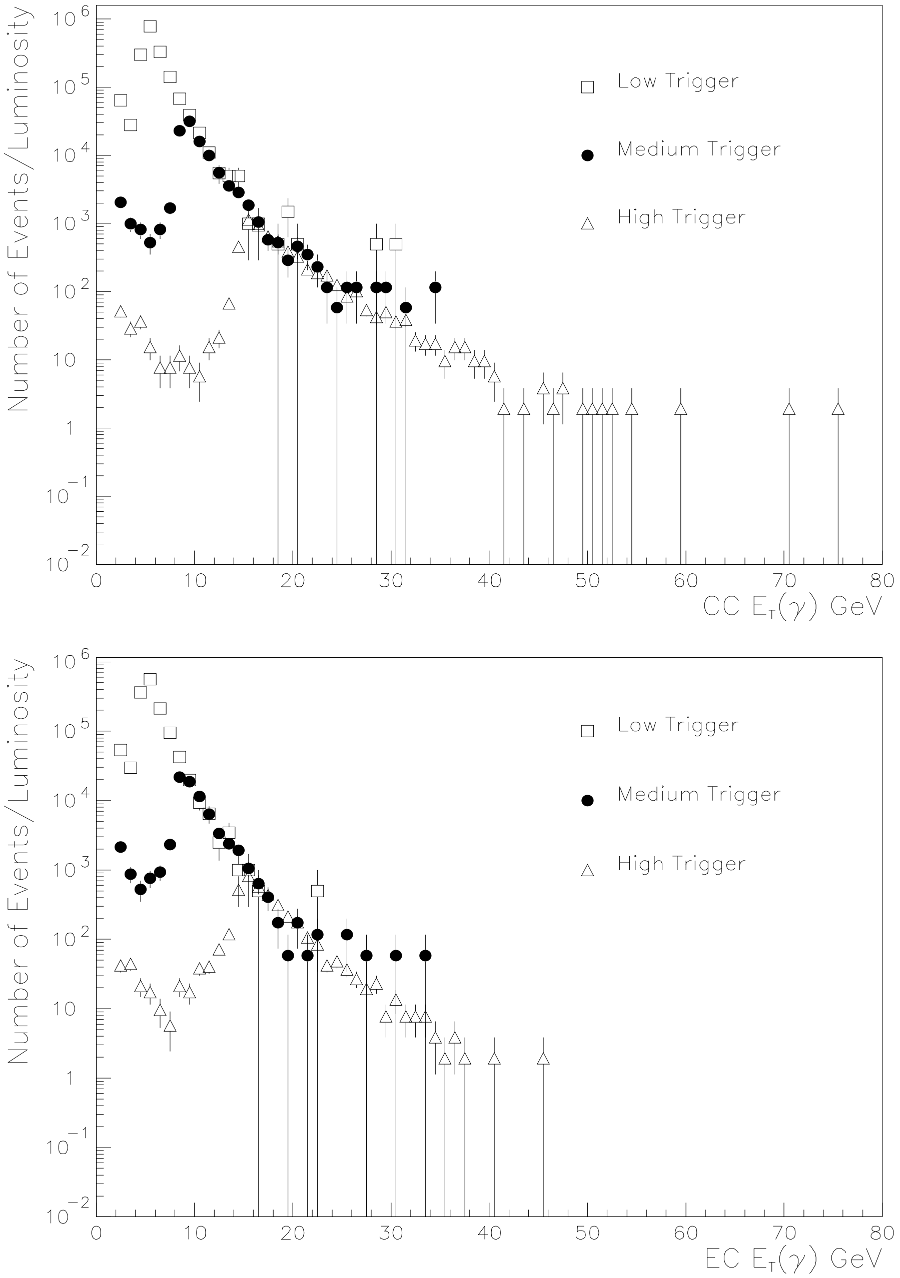


Figure 6: Luminosity-corrected yields for the central and forward region as a function of E_T.

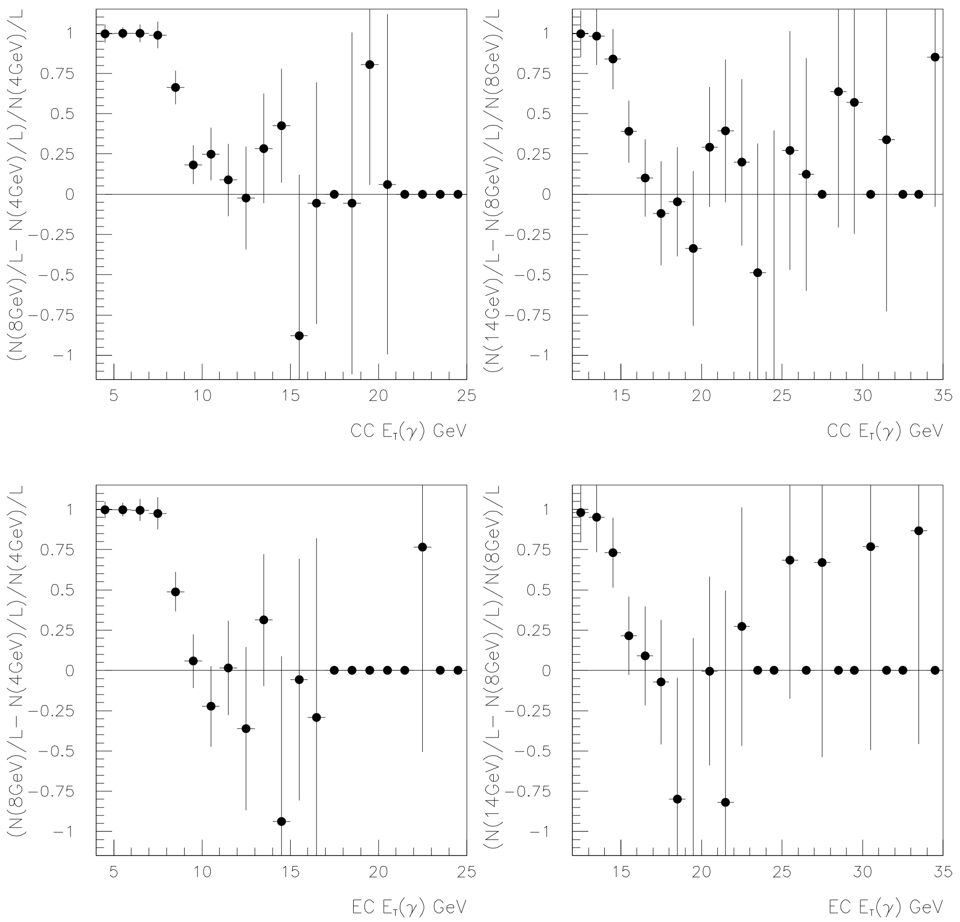


Figure 7: Normalized luminosity-corrected yields for the central and forward region as a function of E_T The analysis described in this note requires a threshhold of 10 (16) GeV for events that fired the 8 (14) GeV trigger .

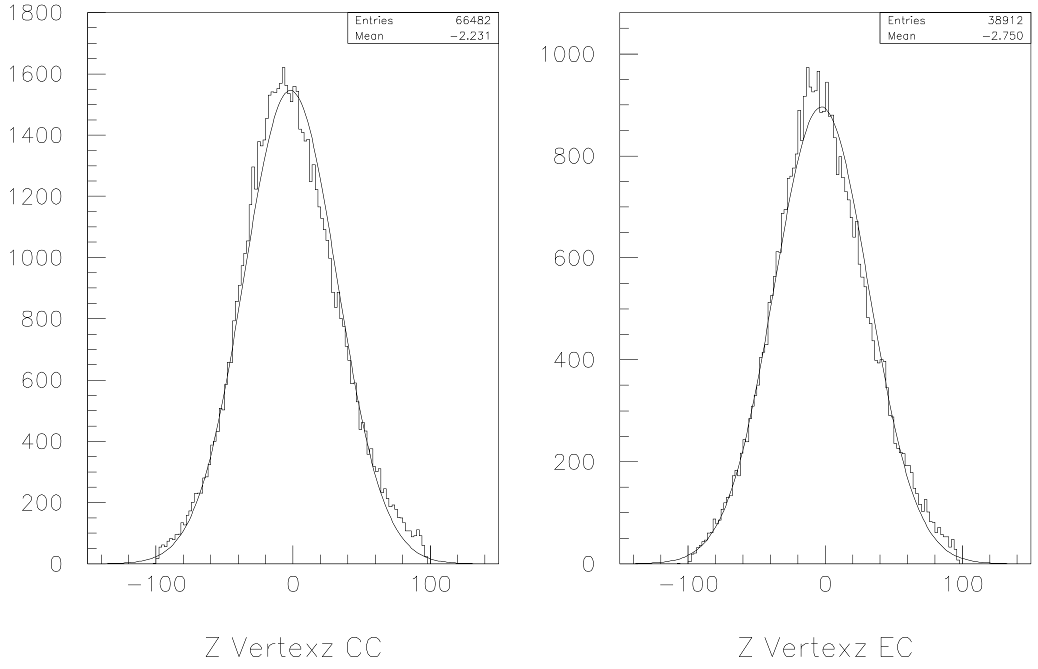


Figure 8: Vertex distribution of isolated photon events

electrons was greatly reduced. However, this can lead to rejection of signal if a direct photon has converted or has an unrelated overlapping charged track. The effect is more important in the EC due to the higher track density and the larger amount of material for the γ to convert.

The overall tracking efficiency is parameterized as

$$\epsilon_d = (1 - pt)(1 - \psi)$$

where p is the probability that a photon will convert before the tracking chambers, t is the probability that a track in the detector will be reconstructed, and ψ is the probability that a reconstructed track from the underlying event will be found in the tracking road of a good photon.

The parameter p has been determined previously to be 0.095 ± 0.010 (0.386 ± 0.041) for the CC (EC)[4]. To determine the other parameters, we used a sample of $Z^0 \rightarrow e^+e^-$ events from Run 1C (at 1.8 TeV) because the number of Z^0 events at 630 GeV was found insufficient. Z^0 events with no jets in the event were chosen to avoid electrons that may have overlapped a jet, and to ensure a topology similar to that of photon events where any jets are generally in the opposite hemisphere from the photon. Both EM clusters where also required to have a reconstructed E_T above 25 GeV.

To determine t, both electrons from the Z^0 decay were checked against the following requirements:

- $\eta < 0.9$
- At least one track in the road $\delta\phi \times \delta\theta = 0.2 \times 0.2$.
- Track match significance $\sigma_t < 5$ (10) in the CC (EC).
- EM fraction $> 95\%$
- Isolation fraction $< 20\%$
- Hmatrix $\chi^2 < 100$.

Each EM shower passing these requirements was tagged as a good electron, and the other electron from Z^0 decay was considered unbiased and usable for determining the tracking efficiency. Photon selections, except the tracking cut, were applied to the unbiased sample and any candidate that passed these cuts was checked for $\sigma_t < 5$ (10) in the CC (EC). Invariant mass distributions were calculated for all candidates passing the photon selections, both with and without the tracking criteria. The tracking efficiency was determined by calculating how many electrons from $Z^0 \rightarrow e^+e^-$ events passed the tracking requirement. The number of events in the Z^0 signal region (N_S) was determined from events having an invariant mass between 86 and 96 GeV/c^2. The background was defined in two regions on either side of the Z^0 peak from 61 to 71 GeV/c^2 and from 111-121 GeV/c^2, with the number of background events (N_B) being half of the total number in these two regions. Events with and without tracks in the CC and EC are shown in Fig. 9. The tracking efficiency is given by

$$t = \frac{N_{TS} - N_{TB}}{N_S - N_B}$$

where the subscript T indicates the number of events with associated tracks. The tracking efficiency is estimated as $t = .769 \pm .024 \pm .017$ ($.683 \pm .042 \pm .002$) in the CC (EC), where the first error is statistical and the second systematic, the latter estimated by the difference in efficiency with and without background subtraction.

The track overlap probability, ψ, was obtained using the same method described above for determining t, but with an additional track in the road pointing to the EM cluster. The estimated track overlap probability is $\psi = .074 \pm .014 \pm .008$ ($.195 \pm .033 \pm .044$) in the CC (EC), where the

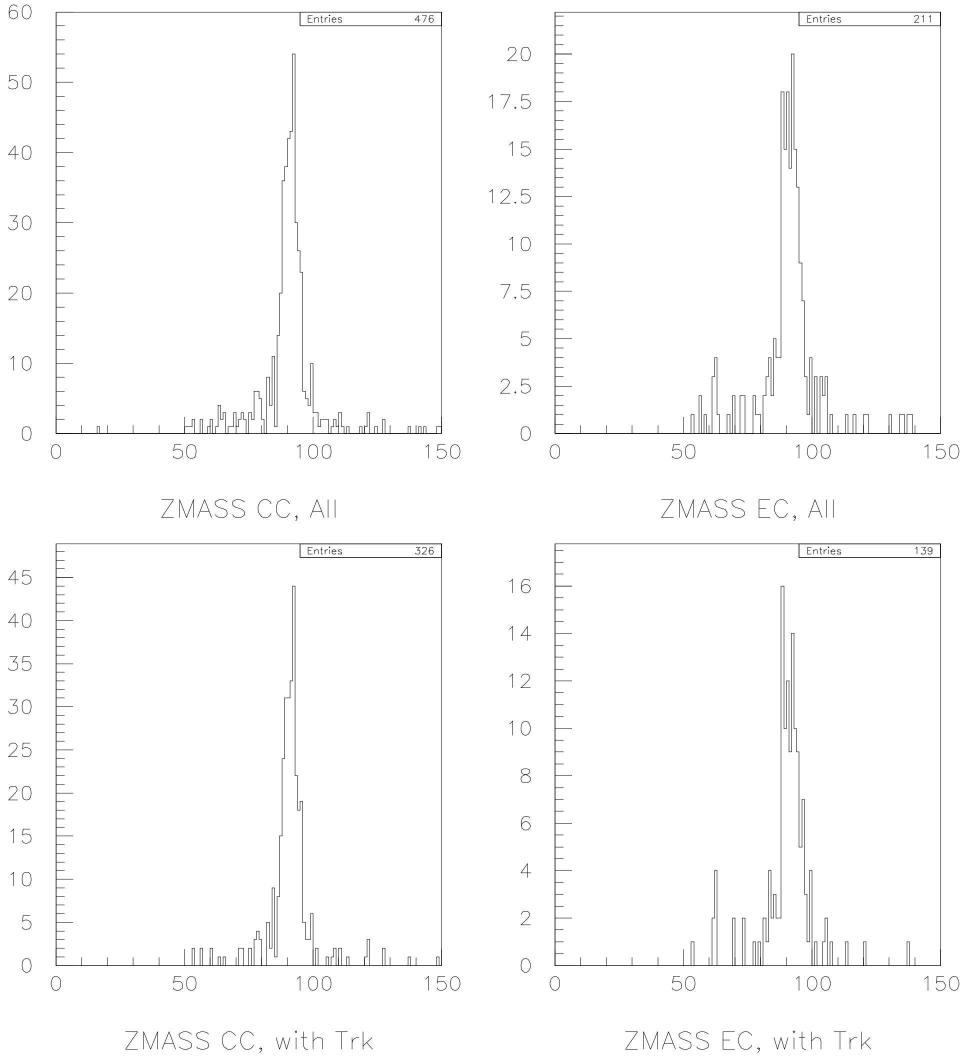


Figure 9: Invariant mass peaks for events with an unbiased EM cluster passing photon selections and for the same events also passing electron tracking requirements in the CC and EC.

first error is statistical and the second is systematic. The systematic uncertainty is estimated from a comparison of two different methods used in the Run 1A analysis to determine ψ. One of the methods is the same as used in this analysis, and the other uses very clean photons and any tracks in the road pointing to the cluster[5]. The percent difference between the two methods for the Run 1A analysis was used as the systematic uncertainty in this analysis.

Combining the values for p, t, and ψ, the total tracking efficiency is found to be $\epsilon_d = 0.858 \pm 0.018$ (0.593 ± 0.079) in the central (forward) region. The Monte Carlo tracking efficiency is adjusted to match these values.

3.4 Selections

The selections listed in Section 2.3 are applied to remove most of the multi-particle background. The isolation, EM fraction, and H-matrix χ^2 cuts select EM objects consistent with being single particle showers.

For the Run 1A analysis [3] and for Jerger's thesis [5], the fully simulated photon events were used to determine selection efficiencies. For the new combined Run 1A/B analysis, the larger data set of single photons was used [2]. For energies above 10 GeV, these two efficiencies are comparable, but for lower energies, they are very different, as shown in Fig. 10. The final cross section does not use the lowest bins in these plots. Because the full Monte Carlo is expected to give a more accurate result, we use the efficiencies determined from the fully simulated events. A fuller discussion on how the MC simulation of efficiencies was verified at 40 GeV, using electrons from W decay, can be found in References [4, 5].

4 Photon Purity

4.1 Purity Determination

The isolated direct photon sample is contaminated with a background arising from jets that have fluctuated into isolated EM objects. It consists mainly of single or multiple isolated π^0 and η mesons which decay into photons not resolved because of the calorimeter granularity. This background cannot be singled out on an event by event basis, and is corrected instead in each E_T region by means of an average photon fraction, or purity ($\mathcal{P}$), defined as the ratio $\mathcal{P} = \gamma/(\gamma\text{+jet})$, where γ and jet, respectively, correspond to the number of direct photons and background jets that survive the selection

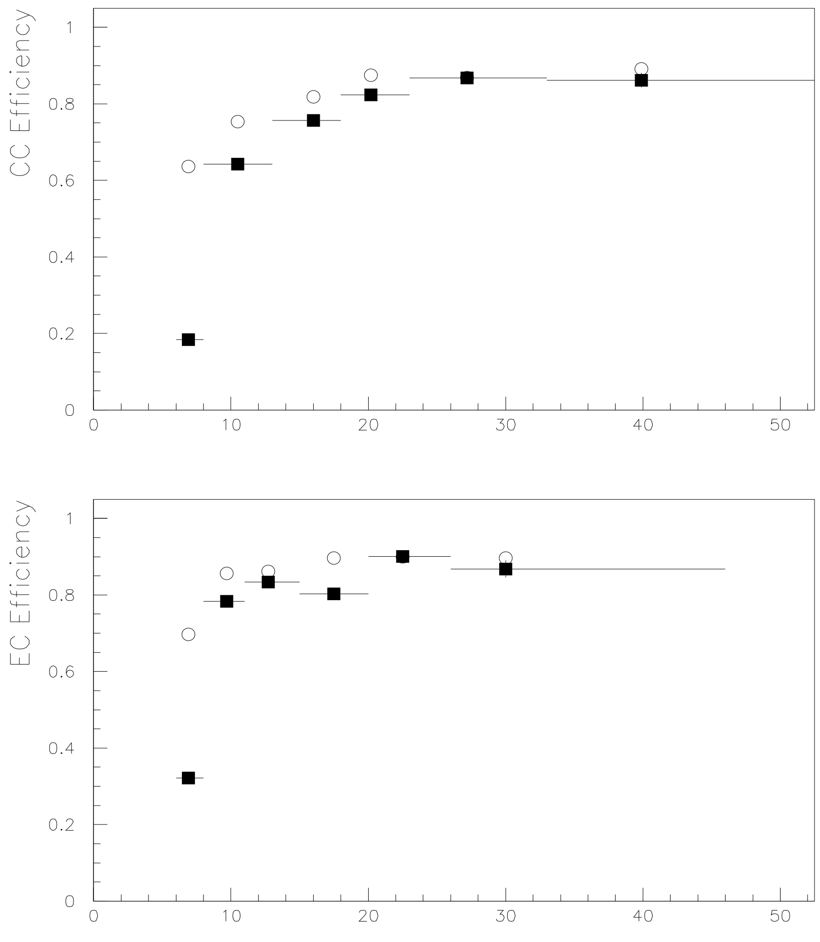


Figure 10: Selection efficiencies for the central and forward η regions. The squares use the full Monte Carlo with fewer events while the circles use the single-photon Monte Carlo, only simulating the event in an $R = 0.7$ cone around the photon.

criteria.

The photon purity is estimated by comparing the distributions of different observables in the data with MC predictions for photons and jets. Variables sensitive to the difference between single and multi-photon showers, and well reproduced by the MC simulation, are particularly suitable for this analysis. Following analyses in Run 1A and Run 1B, we investigated the fraction of energy deposited in the first layer of the EM calorimeter (E_1). Single photon showers are less likely to convert early, and thus deposit a smaller E_1 fraction on average. A discriminant that enhances the sensitivity to the small E_1 region where the difference between single and multi-photon events is largest must be used.

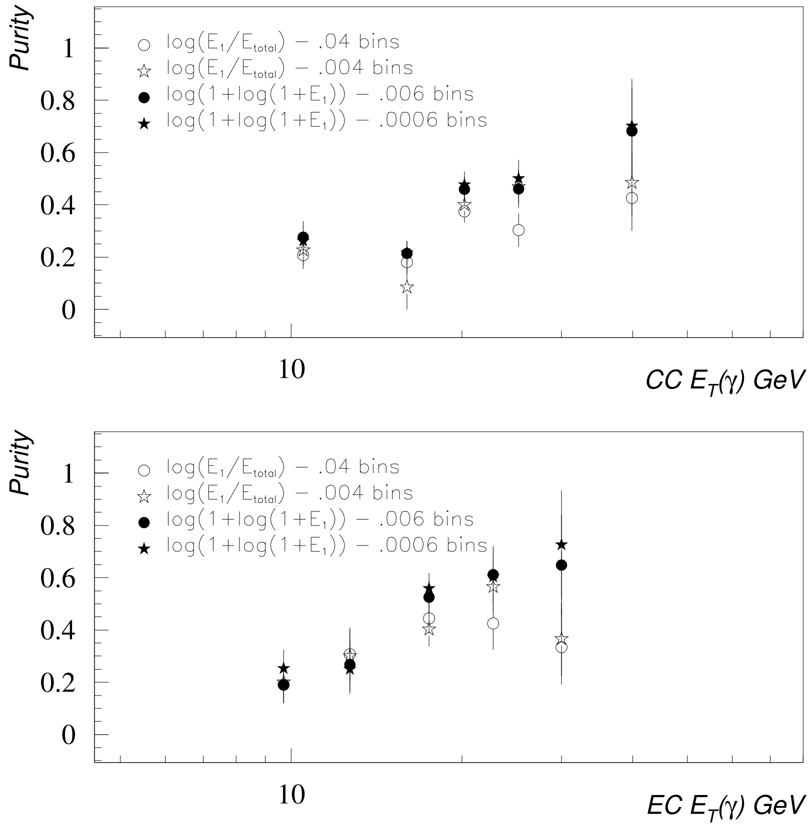


Figure 11: Photon purity using different discriminants, showing the bin size for each discriminant.

We have compared two discriminants to determine the purity, $\log(E_1/E_{total})$ and $\log(1+\log(1+E_1))$, the former used in the Run 1A analysis and the latter used in the combined Run 1A/1B analysis. It was found that the results obtained from $\log(E_1/E_{total})$ were somewhat dependent on the size of the histogram bins used in the fit, while the results obtained from $\log(1+\log(1+E_1))$ were much less dependent on bin size and well behaved. As a general rule, the purity determined from $\log(E_1/E_{total})$ moves closer to the value determined from $\log(1 + \log(1 + E_1))$ as the bin size in the first discriminant decreases. Fig. 11 shows the fitted purity for the two different discriminants and different histogram bin sizes.

Fig. 12 presents the data vs. $\log(1+\log(1+E_1))$ for the central region of rapidity with E_T bins of 8–13, 13–18, 18–23, 23-33, and >33 GeV, together with MC contributions from photons and jets. The Monte Carlo distributions were fitted to the data using the HBOOK routine HMCMLL, which correctly incorporates statistical errors in both the data and the MC histograms. The mean photon fraction is then obtained by fitting the data to a combination of photons and jets. As with the Run 1A/1B analysis, a systematic uncertainty was assigned to the use of PYTHIA to model jets. This uncertainty was estimated by varying the multiplicity of neutral mesons in the core of the jet by ±10% [1].

Figure 13 presents the EC data vs. $\log(1 + \log(1 + E_1))$. The routine HMCMLL is used, and the purity is determined from the same fit as that used in the CC. Tables 5 and 6 give the numerical results of the fits shown in Figs. 12 and 13.

E_T Range (GeV)	E_T (GeV)	HMCMLL Fit
8-13	10.5	27.6 ± 6.2
13-18	16.0	21.3 ± 4.7
18-23	20.2	45.9 ± 5.0
23-33	25.2	46.1 ± 7.3
>33	39.9	68.2 ± 16.8

Table 5: Results for photon purity in the CC.

4.2 Monte Carlo Energy Scale

For the forward region, the MC distributions have an offset in $\log(1+\log(1+E_1))$ with respect to the data, which has been shown to be due to incor-

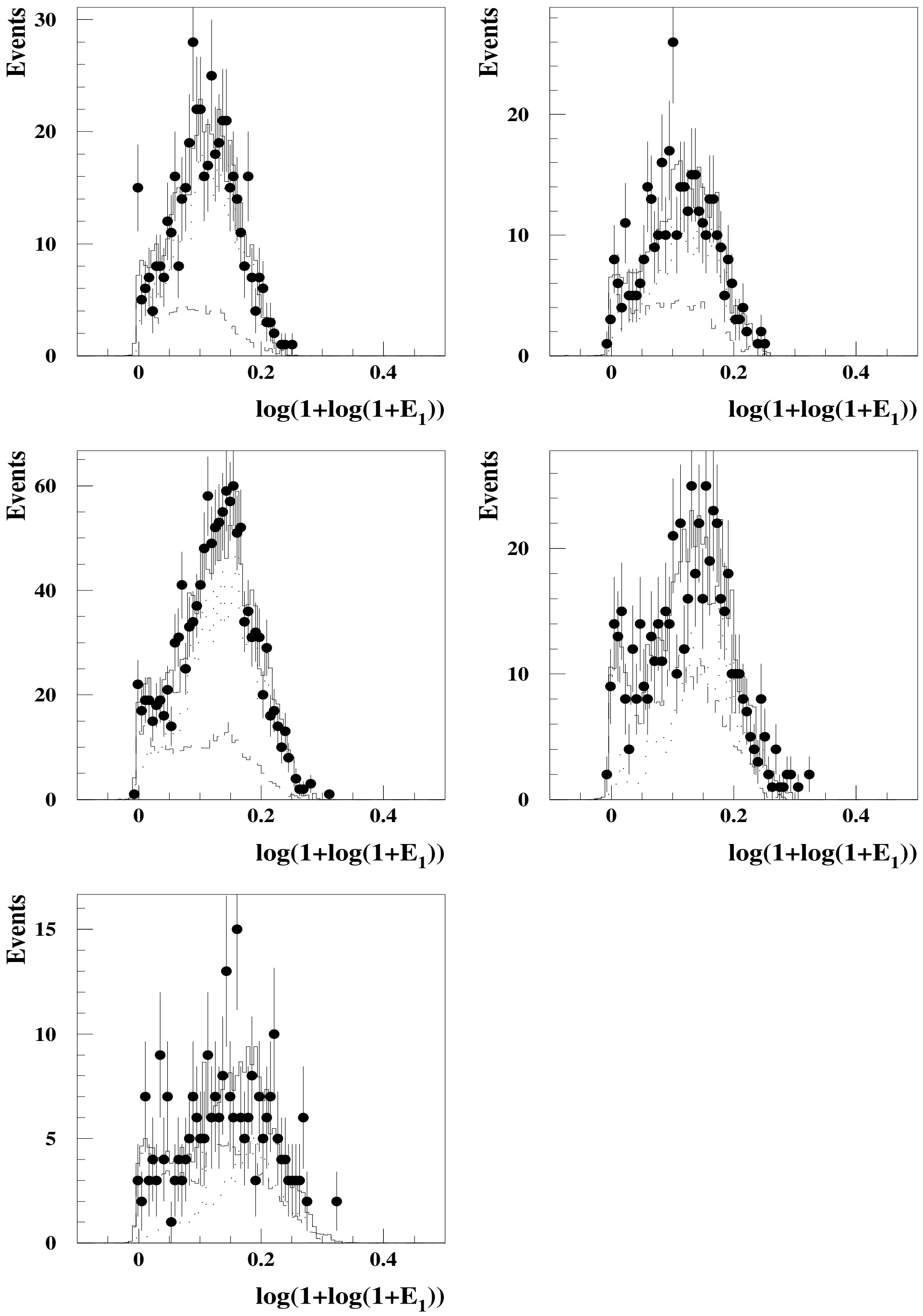


Figure 12: Distributions of $\log(1 + \log(1 + E_1))$ for the central η region in E_T bins of 8–13, 13–18, 18–23, 23–33, and >33 GeV. The solid line is total MC fit to the data. The dashed line is the photon contribution, and the dotted line is the background contribution.

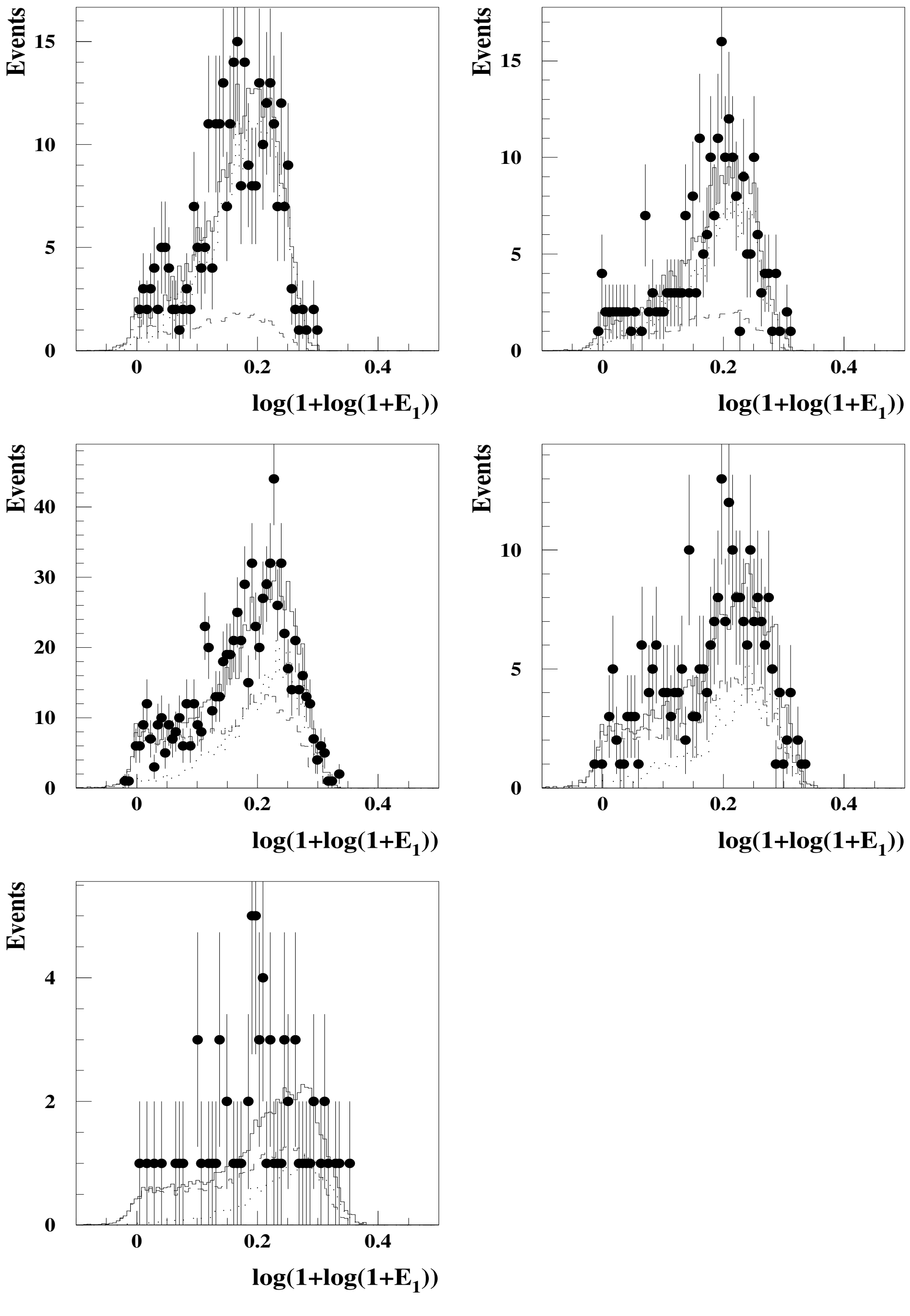


Figure 13: Distributions of $\log(1 + \log(1 + E_1))$ for the forward η region in E_T bins of 8–11, 11–15, 15–20, 20–26, and >26 GeV. The solid line is total MC fit to the data. The dashed line is the photon contribution, and the dotted line is the background contribution.

E_TRange (GeV)	E_T(GeV)	HMCMLL Fit
8-11	9.7	18.9 ± 6.8
11-15	12.7	26.7 ± 10.2
15-20	17.5	52.5 ± 6.2
20-26	22.7	61.2 ± 10.9
>26	30.0	64.8 ± 19.2

Table 6: Results for photon purity in the EC.

rect sampling fraction used in the simulation [4, 5]. This offset was studied extensively in the Run 1A and Run 1B data.

We have chosen to parameterize this offset using the same method as the Run 1A/1B analysis. [2] We assume that the parameterization is of the form $E_1^{MC} = \alpha + \beta E_1$ where α and β are determined from the data. We use the same value of β as the Run 1A/1B publication which was determined from the $W \to e\nu$ sample: 1.203 for $\eta > 1.6$ and 1.364 for $\eta < 1.6$ with a 10% error [10]. The Run 1A/1B analysis extracted the value of α to be 0.112 MeV by fitting the purity $\mathcal{P}$ for various values of α and choosing the value of α with the lowest global χ^2, the sum of the χ^2 value from the fit to each energy bin.

Because the fit of the two Monte Carlo distributions to the data is dependent on many kinematic variables which determine the shape of the curves and affect the χ^2, it is unclear that simply maximizing the likelihood (minimizing the χ^2) by changing one variable, α necessarily determines the correct value of α. If this method is correct, then different purity discriminants should choose the same value for α. Therefore, we have investigated this likelihood method for determining the value of the linear term α in more detail by comparing two different discriminants which give almost identical results and are both valid, $\log(E_1/E_{total})$ using bin sizes of .004 and $\log(1 + \log(1 + E_1))$ using bin sizes of .006 (see Section 4.1). The maximum likelihood as a function of the value of α is plotted using the two different discriminants in Fig. 14. We see that both discriminates behave in a similar manner. However the "global" maximum of the two discriminates are at different values. For the discriminant $\log(1 + \log(1 + E_1))$ the maximum likelihood is .120 MeV, while for the discriminant $\log(E_1/E_{total})$ the value is near -.050 MeV. There is no reason to believe that either of these values is actually the true global maximum or that this method is necessarily a valid method for determining the correct value of α. Consequently, there is no

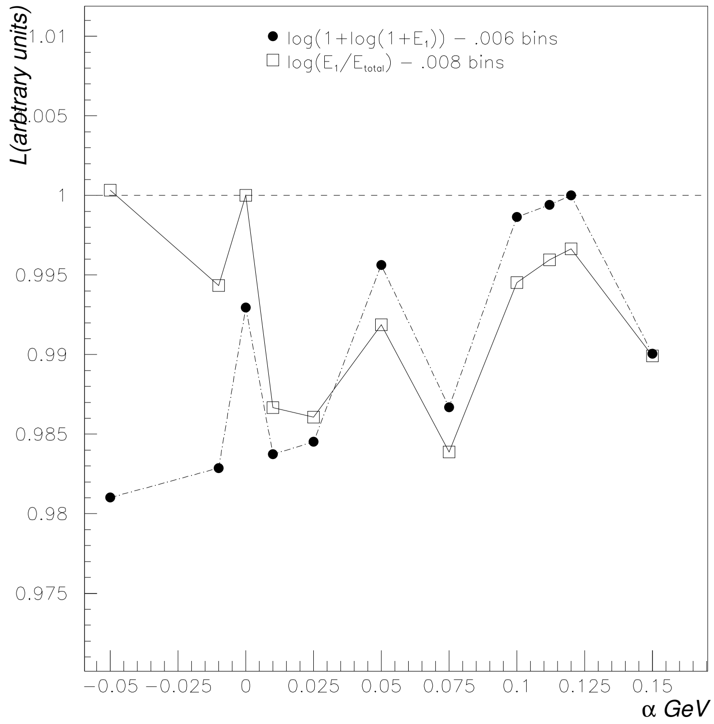


Figure 14: Likelihood of the Purity fit in the EC as a function of the linear energy shift α.

compelling reason to include a linear term for the MC energy shift, so we have set $\alpha = 0$.

4.3 E_T Dependent Fit

The photon fractions were combined with the selection efficiencies (calculated under the same binning) and fitted vs. E_T using a two-parameter functional form:

$$\mathcal{P}/\epsilon_s = \frac{1}{1 + a(E_T)^b}.$$

The fit, shown in Fig. 15 with its statistical uncertainty, assures that $\mathcal{P}/\epsilon_s$ is a smooth function of E_T. This functional form is chosen because it satisfies the boundary conditions of low purity at low E_T and high purity at high E_T (approaching a value near 1), and because we expect the data to be a sum of two falling cross sections (photons and jets) roughly of the form aE_T^b.

In order to estimate the uncertainty from our choice of E_T binning and fitting function, we have used three alternative functions to fit the data, and two other choices of E_T binning. The alternative fitting functions are

$$\mathcal{P}/\epsilon_s = 1 - e^{-(a+bE_T)},$$

$$\mathcal{P}/\epsilon_s = a + bE_T,$$

and

$$\mathcal{P}/\epsilon_s = a + b\log E_T.$$

The results of these alternative fits are shown in Tables 7 and 8 and Figs. 16-18.

E_T **Bins**	Fit	**Fitting Functions** $\frac{1}{1+ax^b}$	$1 - e^{-(a+bx)}$	$a + bx$	$a + b\log x$
6-8-13-18-23-33	a	53 ± 45	$.053 \pm .18$	$.14 \pm .12$	$-.39 \pm .34$
	b	$-1.3 \pm .30$	$.029 \pm .010$	$.016 \pm .006$	$.29 \pm .11$
6-7-10-16-20	a	66.5 ± 85.2	$-.058 \pm .217$	$.087 \pm .15$	$-.52 \pm .37$
	b	$-1.52 \pm .44$	$.046 \pm .03$	$.025 \pm .008$	$.37 \pm .13$
6-8-11-15-20-26	a	74 ± 82	$.017 \pm .22$	$.14 \pm .14$	$-.49 \pm .38$
	b	$-1.5 \pm .37$	$.035 \pm .012$	$.018 \pm .007$	$.34 \pm .13$

Table 7: Fitting the Purity in the central region, using different functions and different binning with $x = E_T$.

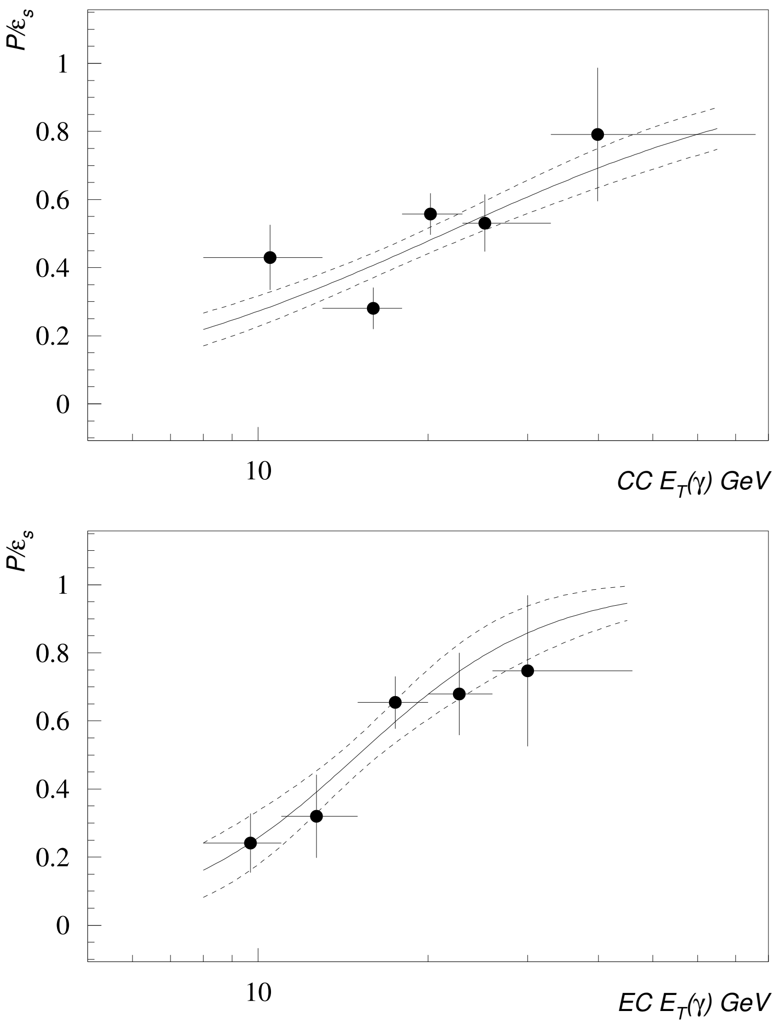


Figure 15: Photon purity divided by the selection efficiency for the central and forward regions. The dashed line shows the statistical uncertainty in the fit.

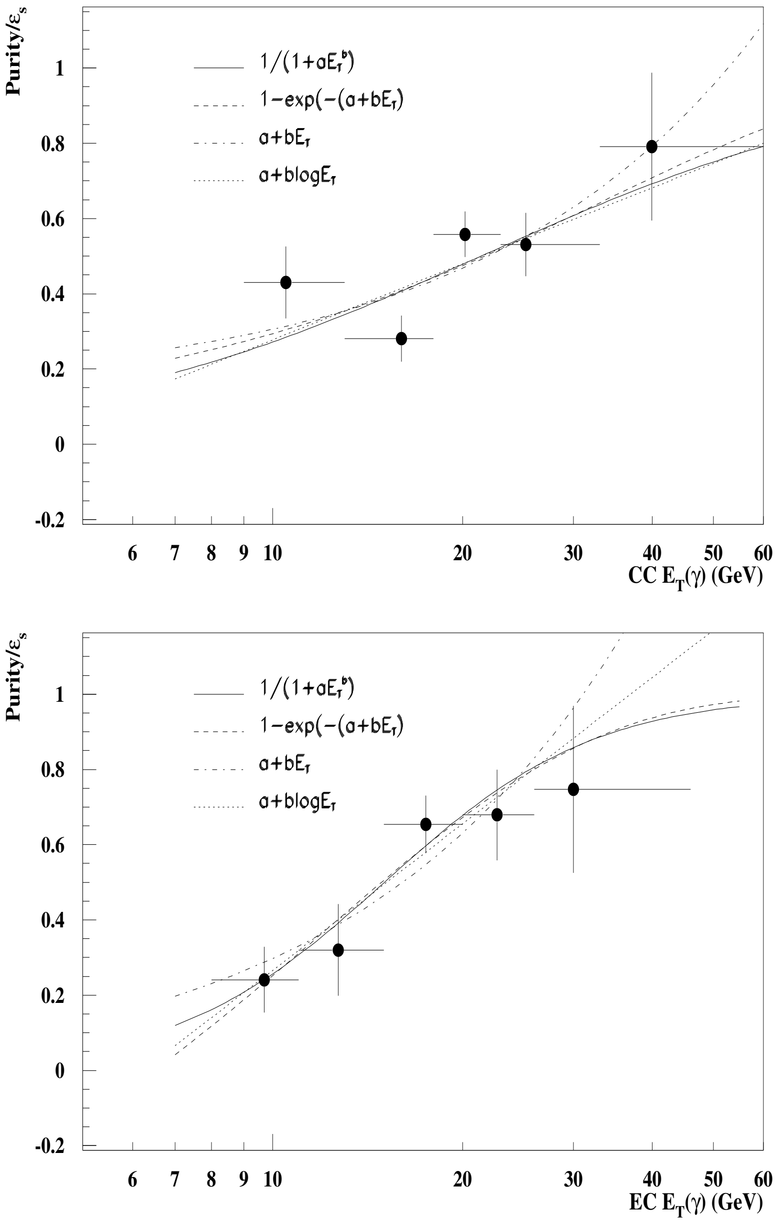
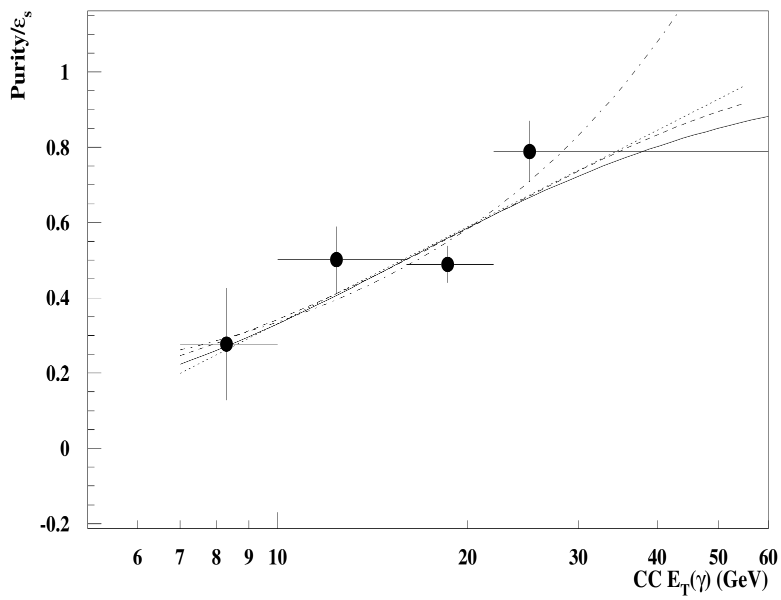


Figure 16: $\mathcal{P}/\epsilon_s$ using different fitting functions (a) CC and (b) EC.



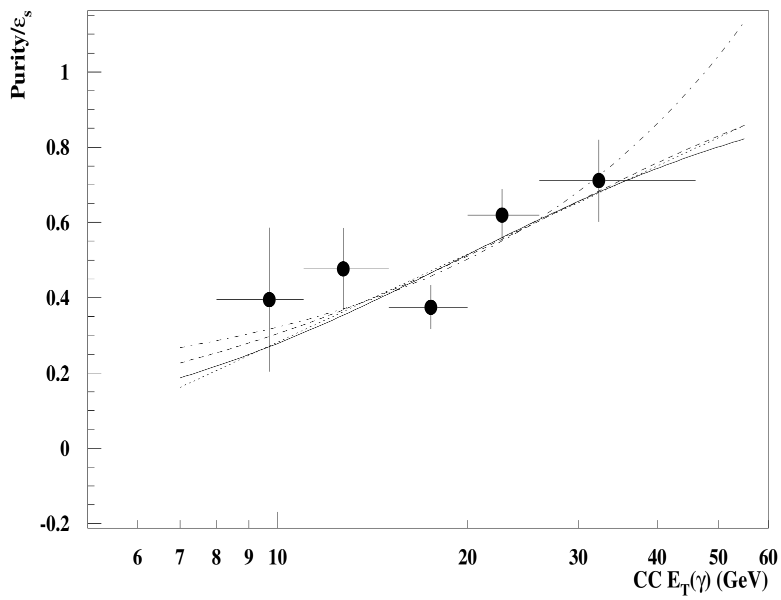


Figure 17: $\mathcal{P}/\epsilon_s$ with alternative E_T bins and four different fitting functions in the central rapidity region. The legend is the same as in Fig. 16.

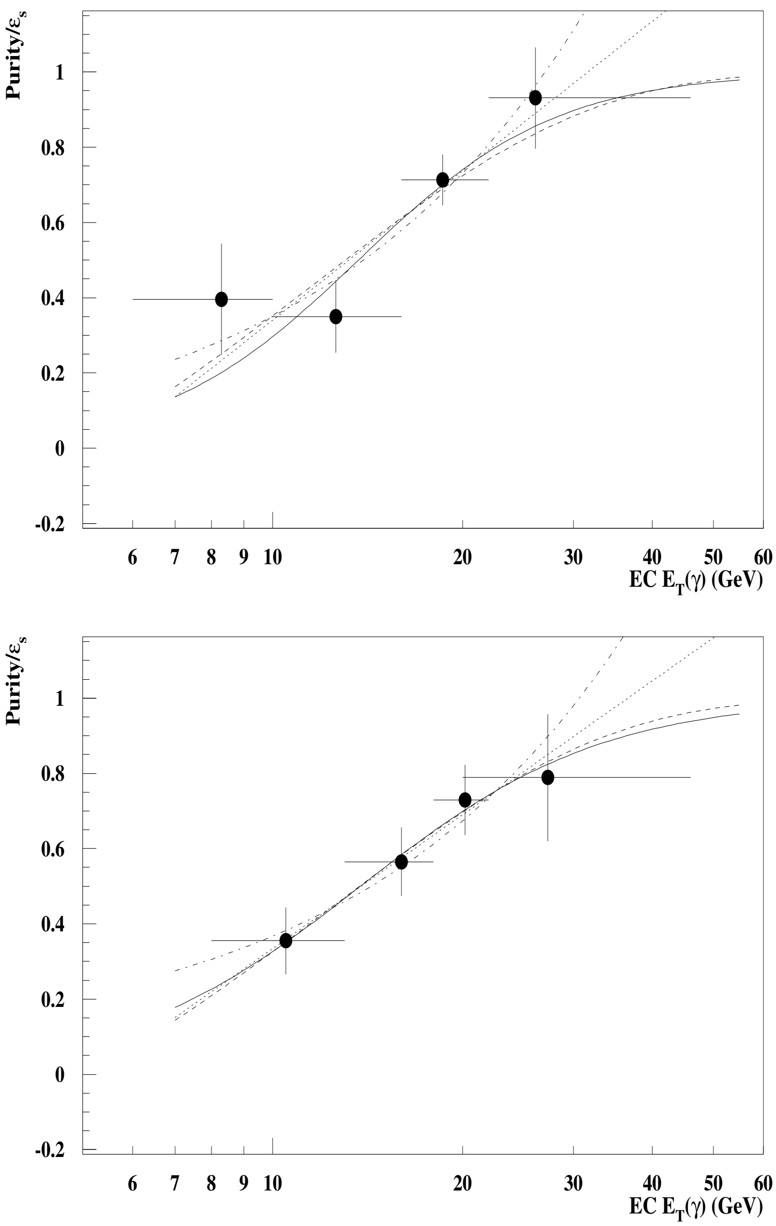


Figure 18: $\mathcal{P}/\epsilon_s$ with alternative E_T bins and four different fitting functions in the forward rapidity region. The legend to is the same as in Fig. 16.

E_T **Bins**	Fit	**Fitting Functions**			
		$\frac{1}{1+ax^b}$	$1-e^{-(a+bx)}$	$a+bx$	$a+b\log x$
6-8-13-	a	375 ± 960	$-.40 \pm .34$	$.061 \pm .17$	$-.85 \pm .45$
18-23	b	$-2.3 \pm .94$	$.08 \pm .025$	$.031 \pm .01$	$.51 \pm .16$
6-7-10-	a	1363 ± 5053	$-.42 \pm .28$	$-.03 \pm .17$	$-.98 \pm .42$
16-20	b	-2.76 ± 1.33	$.085 \pm .02$	$.038 \pm .01$	$.57 \pm .15$
6-8-11-	a	1175 ± 2787	$-.53 \pm .26$	$-.04 \pm .14$	$-1.03 \pm .38$
15-20-26	b	$-2.6 \pm .87$	$.082 \pm .020$	$.033 \pm .009$	$.56 \pm .14$

Table 8: Fitting the Purity in the forward region, using different functions and different binning with $x = E_T$.

Except for in the very high E_T regions, a comparison of the fit parameters in Tables 7 and 8, and the curves in Figs. 16-18 indicate that the spread on all of the alternative fits for different binning is comparable to the individual errors on the data points. The fitted function is smooth and does not exhibit the statistical fluctuations inherent in the data. The systematic uncertainty is determined by calculating the rms value of the different fits and different binning from the default choices, setting an upper limit of $\mathcal{P}/\epsilon_s = 1.1$ on each fit due to physical considerations. In Fig. 19, we have plotted the systematic band in uncertainty determined from the rms, using all of the alternative fits and binning, as well as the default fit and its statistical error.

5 Cross Sections and Comparison to Theory

Using the selections, efficiencies and photon purity discussed in the previous sections, we can evaluate the cross section using equation 1. If an event had more that one photon candidate, the two most energetic ones were selected, and the selection criteria applied to each separately. Table 9 shows the number of candidates surviving each step. The last cut, indicated as Filter, assures that there is a one to one correspondence between the energy of the photon candidate and the trigger energy range. For example, an event that fired the low energy trigger but whose photon candidate is above the threshhold for the medium energy trigger acceptance would not be used to determine the cross section.

Figure 20 displays the isolated photon cross sections for the central and forward rapidity regions, together with the theoretical prediction from Owens,

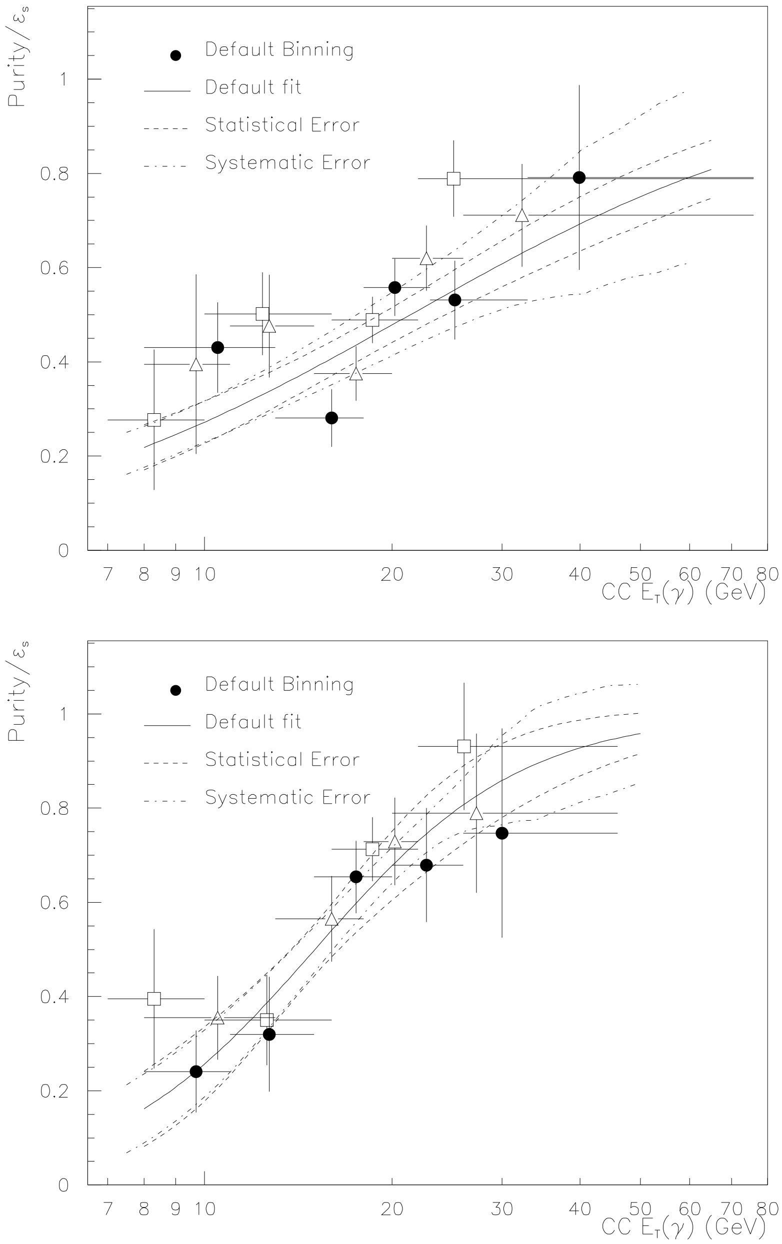


Figure 19: Statistical error from the default fit and band in systematic uncertainty from four possible fitting functions and three different bin selections for CC and EC data.

Cut	$\|\eta\| < 0.9$ Number of candidates	Lost events %	$1.6 < \|\eta\| < 2.5$ Number of candidates	Lost events %
Initial	64809	–	37960	–
$E_T > 6.0$ GeV	28239	56.4	20583	45.8
Vertex	23803	15.7	17304	15.9
$\eta^{det} + \phi$ crack	18378	22.8	16286	5.9
Track Veto	11486	37.0	6566	59.6
EM Fraction	9521	17.1	6293	4.2
χ^2	6553	31.2	4074	35.3
Isolation	5807	11.4	3884	4.7
Filter	3926	32.4	2294	40.9
Final Sample	**3926**	**93.9**	**2294**	**94.0**

Table 9: Number of photon candidates after each selection step for the CC and EC data.

$\boldsymbol{E_T}$**Range (GeV)**	$\boldsymbol{< E_T >}$	$\frac{d\sigma}{dE_T}(\frac{\text{pb}}{\text{GeV}})$	$\boldsymbol{\delta\sigma}_{\text{stat}}$(%)	$\boldsymbol{\delta\sigma}_{\text{syst}}$(%)
8-11	9.8	11500	4.6	56
11-14	12.1	2160	5.6	42
14-17	16.4	779	4.2	45
17-20	18.3	255	3.5	30
20-23	21.3	127	5.1	23
23-26	24.3	72.7	7.1	21
26-29	27.3	40.6	9.8	21
29-32	30.4	27.0	12	21
32-35	33.5	12.9	18	22
35-38	36.6	10.3	21	23
38-41	39.4	7.83	24	24
41-47	44.4	1.68	39	25
47-80	58.2	.569	29	25

Table 10: Differential cross section in the CC ($|\eta| < 0.9$) with systematic and statistical uncertainties.

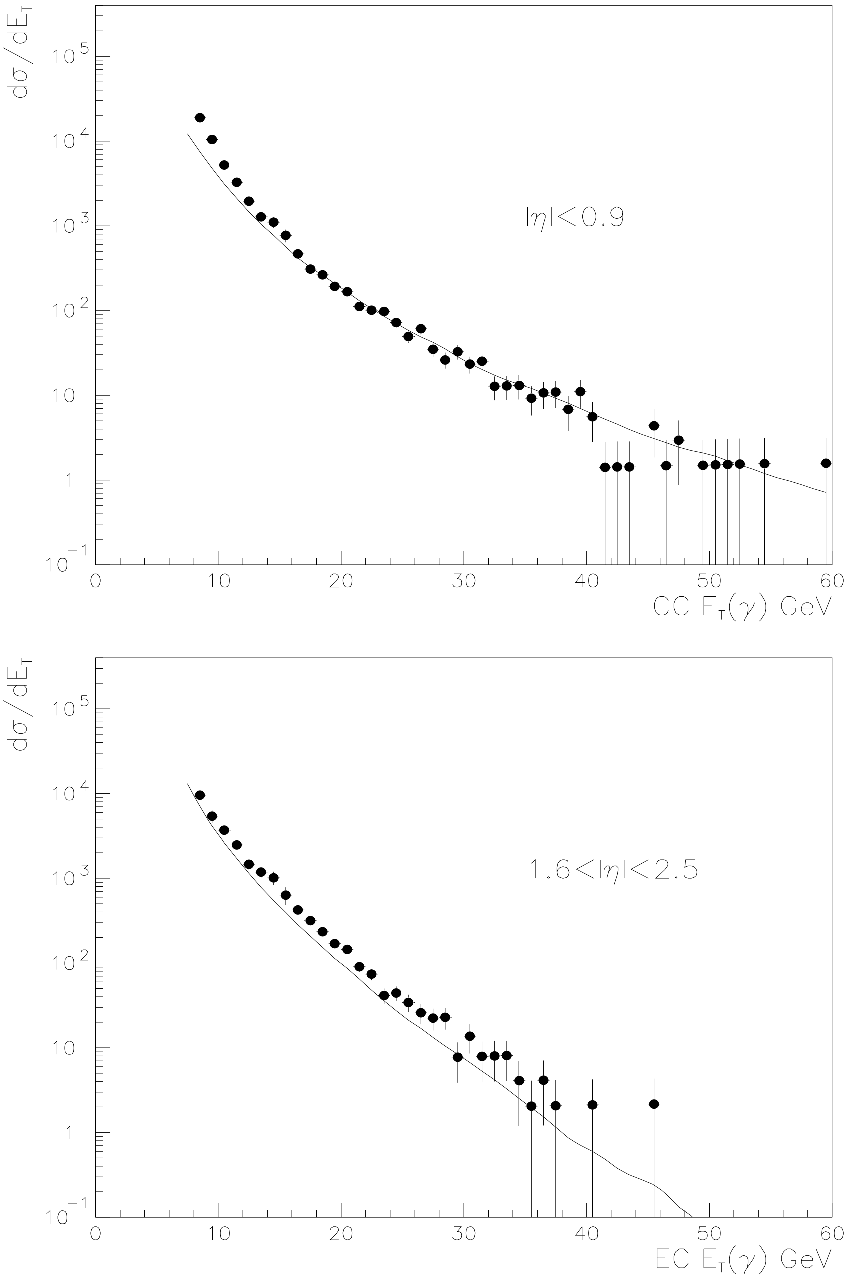


Figure 20: The isolated photon cross section, $d\sigma/dE_T\ d\eta$ vs. photon E_T for the central and forward rapidity regions. The errors are statistical and the curve is the theoretical prediction of CTEQ4M.

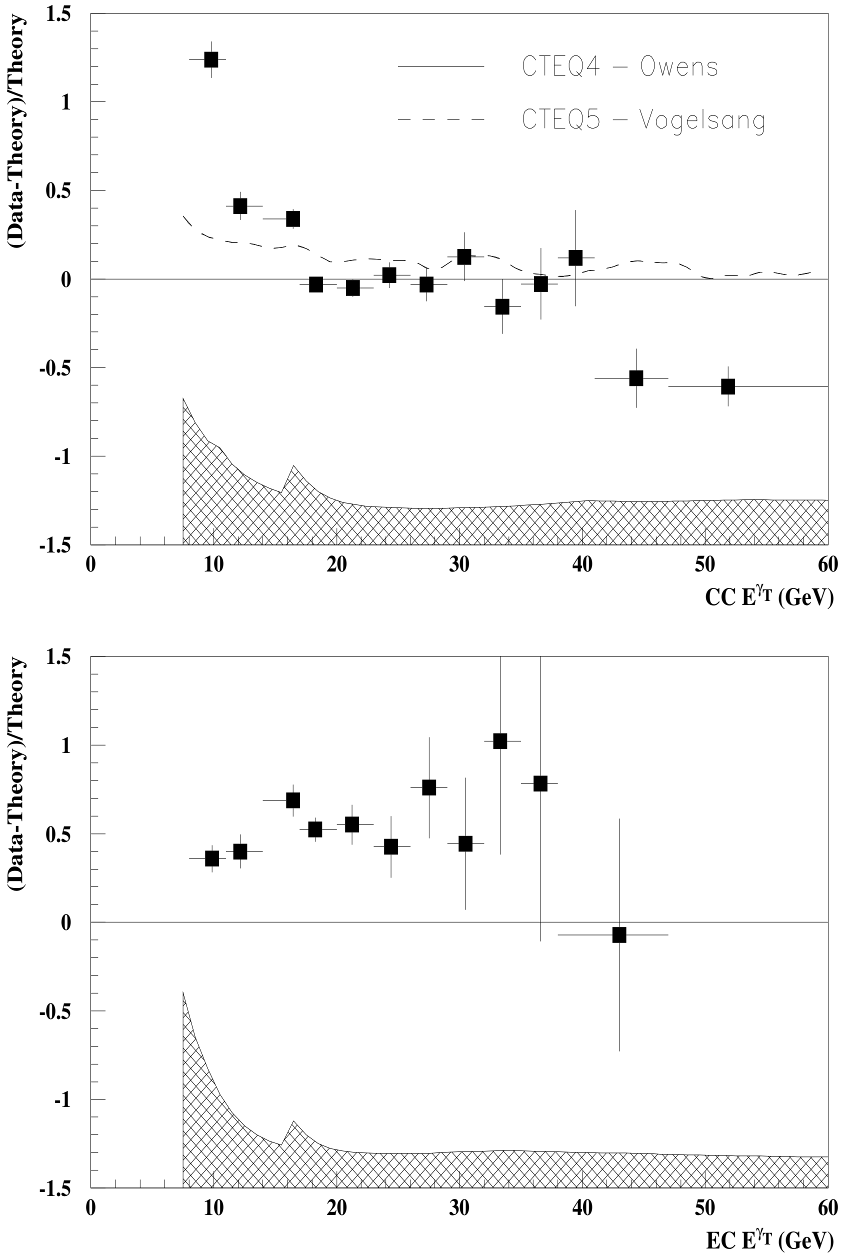


Figure 21: (Data-Theory)/Theory for the central (top) and forward (bottom) rapidity regions. The hatched region shows the systematic uncertainty.

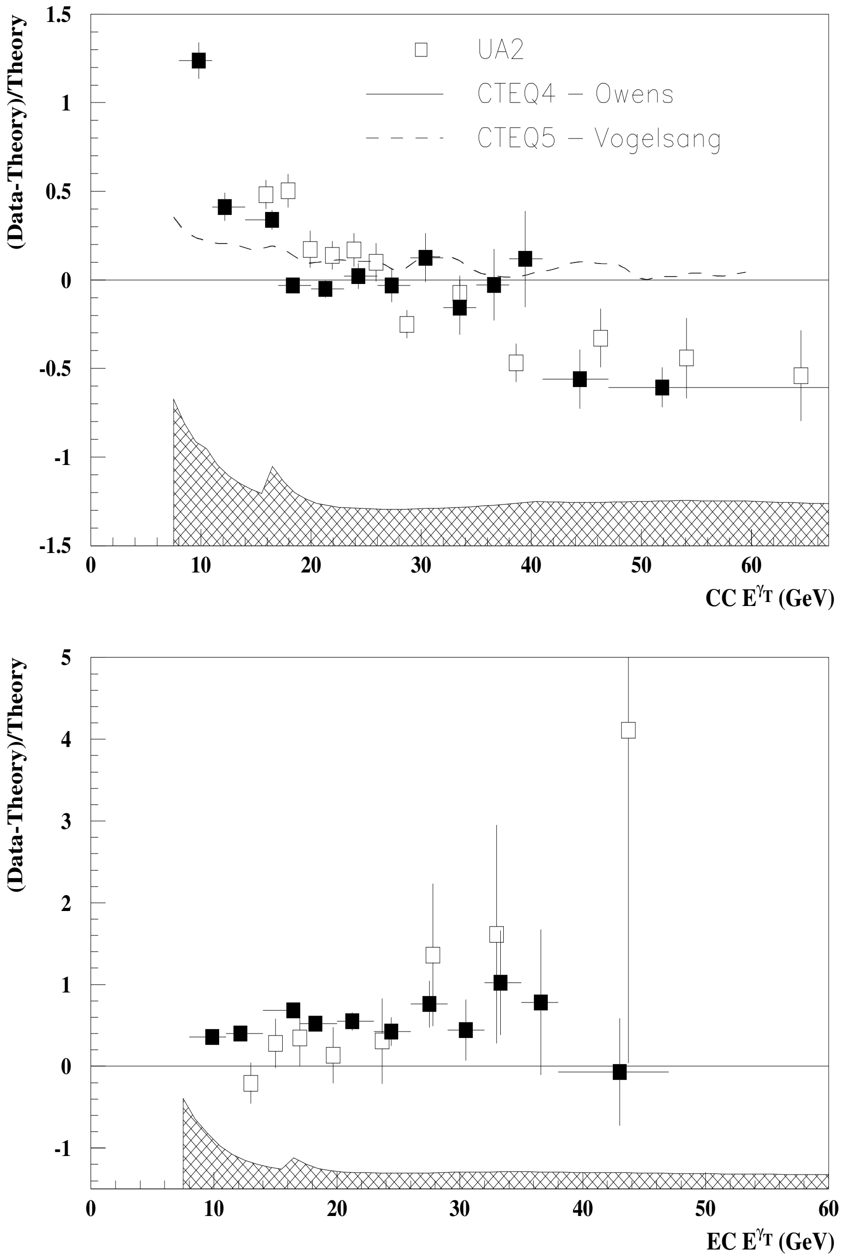


Figure 22: (Data-Theory)/Theory for the central (top) and forward (bottom) rapidity regions comparing to results from UA2. The errors on the UA2 data are statistical only.

E_TRange (GeV)	$< E_T >$	$\frac{d\sigma}{dE_T}(\frac{\text{pb}}{\text{GeV}})$	$\delta\sigma_{\text{stat}}(\%)$	$\delta\sigma_{\text{syst}}(\%)$
8-11	9.9	6260	5.6	60
11-14	12.2	1710	6.9	37
14-17	16.4	693	5.3	38
17-20	18.3	240	4.5	25
20-23	21.3	103	7.2	20
23-26	24.4	40.2	12	19
26-29	27.5	23.8	16	20
29-32	30.5	9.82	26	21
32-35	33.3	6.75	32	21
35-38	36.6	2.76	50	21
38-47	43.0	.195	71	20

Table 11: Differential cross section in the EC ($1.6 < |\eta| < 2.5$) with systematic and statistical uncertainties.

Baer and Ohnemus [12], using the CTEQ4M parton distribution functions, smeared with DØ photon energy resolutions. The results are tabulated in Tables 10 and 11. Fig. 21 compares the data to the theoretical prediction in terms of the quantity (Data-Theory)/Theory. The theoretical prediction of Vogelsang *et. al.* using CTEQ5M and setting all fragmentation scales equal to E_T is also shown for comparison [13]. This analysis is compared to results from UA2 in Fig. 22 with only the statistical uncertainty shown for the UA2 data [8].

6 Run 1A/1B Analysis Method

We have also performed this analysis with modifications which make it more convenient to compare with the published 1800 GeV cross section. The primary difference between the method described in this note and the 1800 GeV measurement is that this analysis fits curves to purity/efficiency ($\mathcal{P}/\epsilon_s$) because of the statistical fluctuations (Section 4.3) of the data, while the 1800 GeV analysis used a bin-by-bin analysis. The larger data set at 1800 GeV ensures smaller statistical fluctuations. Here we describe the result of measuring the cross section at 630 GeV without fitting $\mathcal{P}/\epsilon_s$. In order to further facilitate comparison with the 1800 GeV analysis, we have used x regions that correspond to those used in the published 1800 GeV measurement, .012 $< x <$ .014 (7.35 GeV $< E_T <$ 9.10 GeV), .014 $< x <$ .020 (9.10 GeV $< E_T <$ 12.6 GeV), .020 $< x <$ .023 (12.6 GeV $< E_T <$ 14.7 GeV), .023 $< x <$ .030 (14.7 GeV $< E_T <$ 18.9 GeV), .030 $< x <$ .042 (18.9 GeV $< E_T <$ 26.3 GeV), and .042 $< x$ (26.3 GeV $< E_T$). The selection efficiencies determined using this binning are shown in Fig. 23

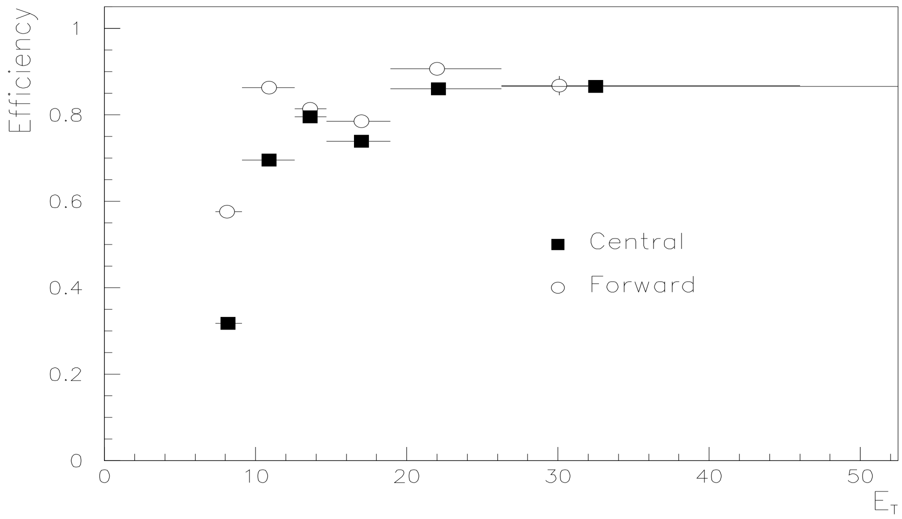


Figure 23: Photon selection efficiency for the central and forward regions in bins that correspond to the same x regions as the published 1A/1B data.

Figs. 24 and 25 present the Monte Carlo fractional fits to the data in these E_T regions using the variable $\log(1 + \log(1 + E_1))$ as the discriminant in the CC and EC, respectively. Table 12 and Fig. 26 tabulate the results of the fits.

For the published 1A/1B analysis, the uncertainty was quoted as a correlated and an uncorrelated uncertainty rather than as a statistical and a systematic uncertainty. Most of the uncorrelated uncertainty in this analysis comes from the purity divided by the selection efficiency as shown in Fig. 27.

The cross section derived using the 1A/1B analysis method is shown in Fig. 28. The low energy cross section in the central rapidity region is much higher using the 1A/1B 1800 GeV analysis method than that extracted from the default 630 GeV analysis method (see Section 5). In the lowest E_T bin (7.35-9.10 GeV) this is due to the low (and very uncertain) value of ϵ_s

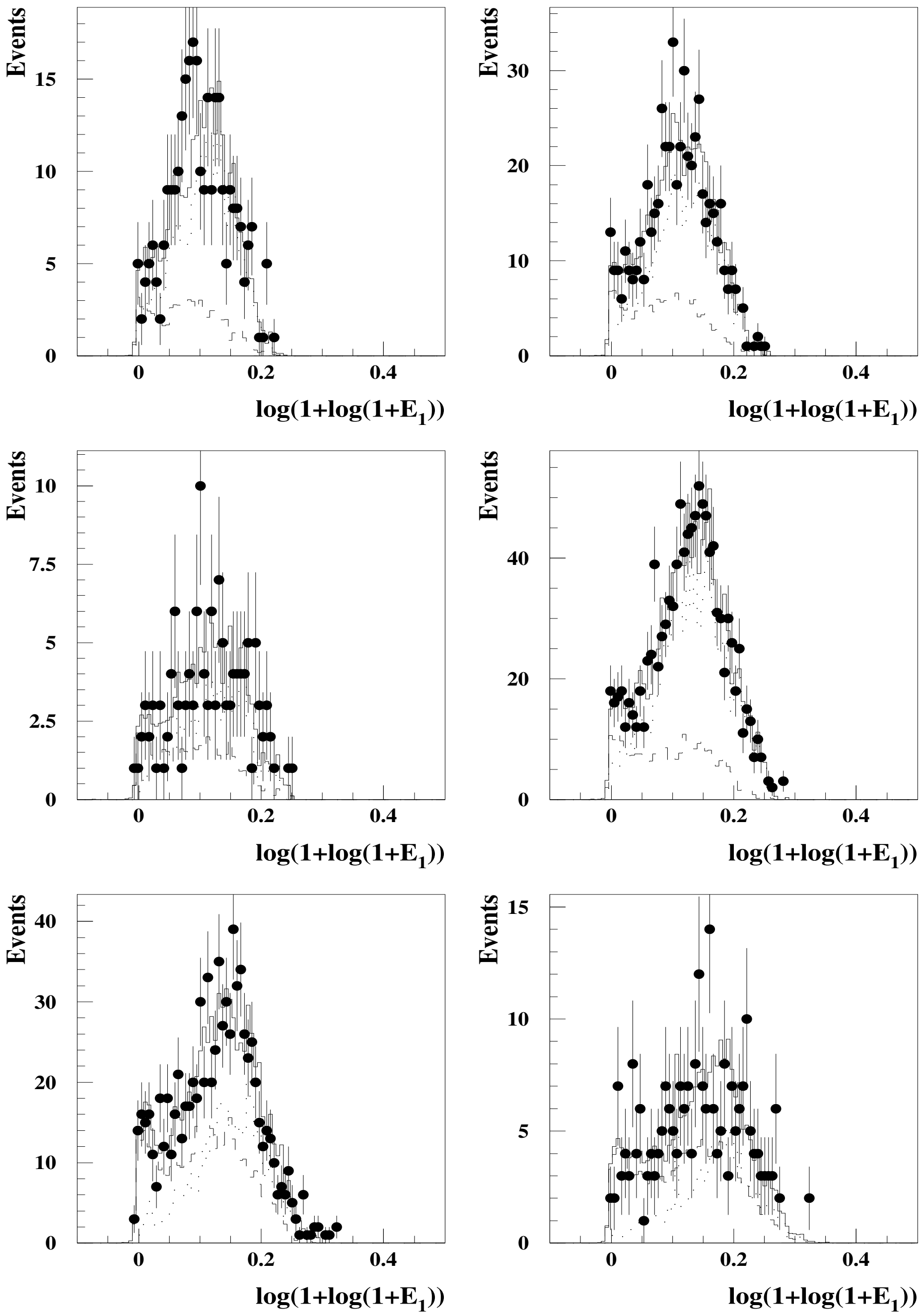


Figure 24: Distributions of $\log(1 + \log(1 + E_1))$ for the central η region in E_T bins of 7.35–9.10, 9.10–12.6, 12.6–14.7, 14.7–18.9, 18.9–26.3, and >26.3 GeV. The solid line is total MC fit to the data. The dashed line is the photon contribution, and the dotted line is the background contribution.

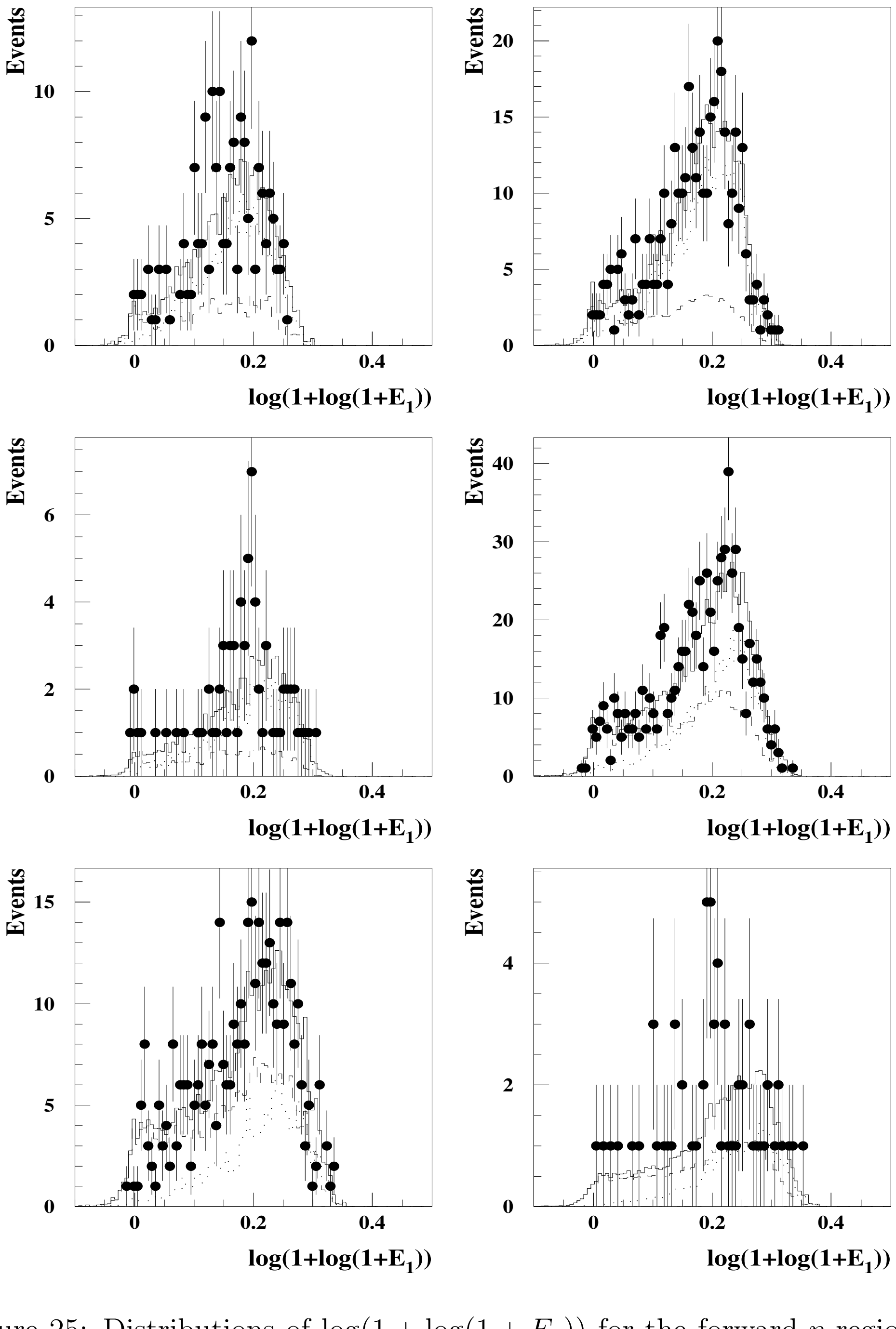


Figure 25: Distributions of $\log(1+\log(1+E_1))$ for the forward η region in E_T bins of 7.35–9.10, 9.10–12.6, 12.6–14.7, 14.7–18.9, 18.9–26.3, and >26.3 GeV. The solid line is total MC fit to the data. The dashed line is the photon contribution, and the dotted line is the background contribution.

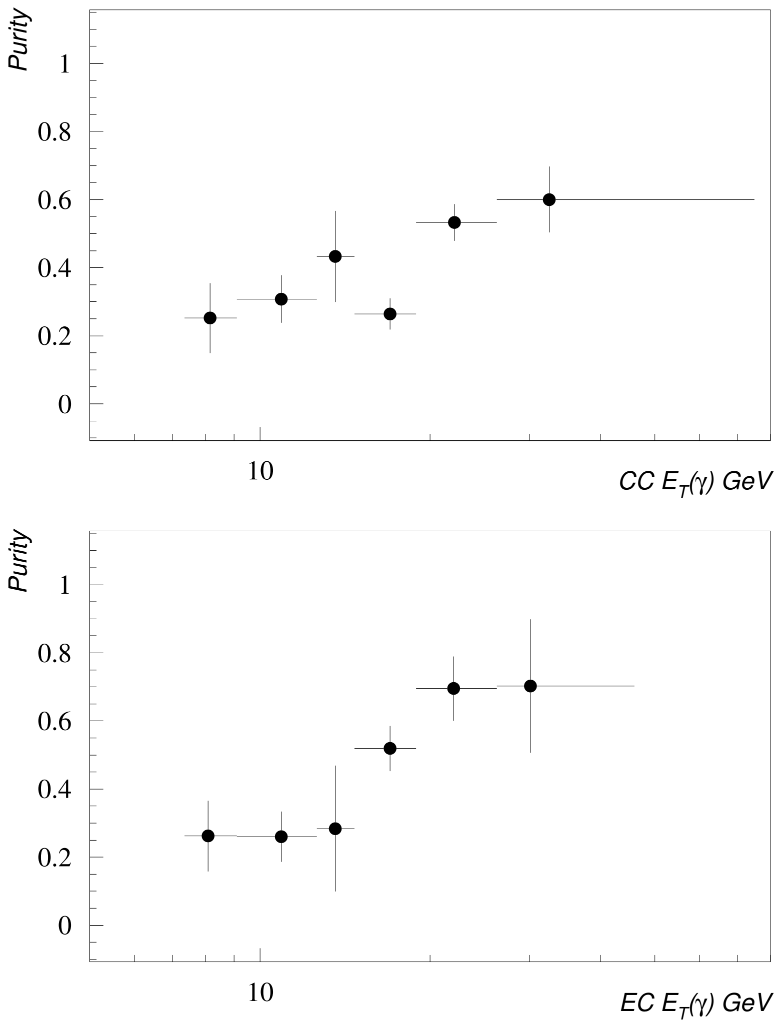


Figure 26: Photon purity for the central and forward regions using x regions that correlate with the published Run 1A/1B 1800 GeV data.

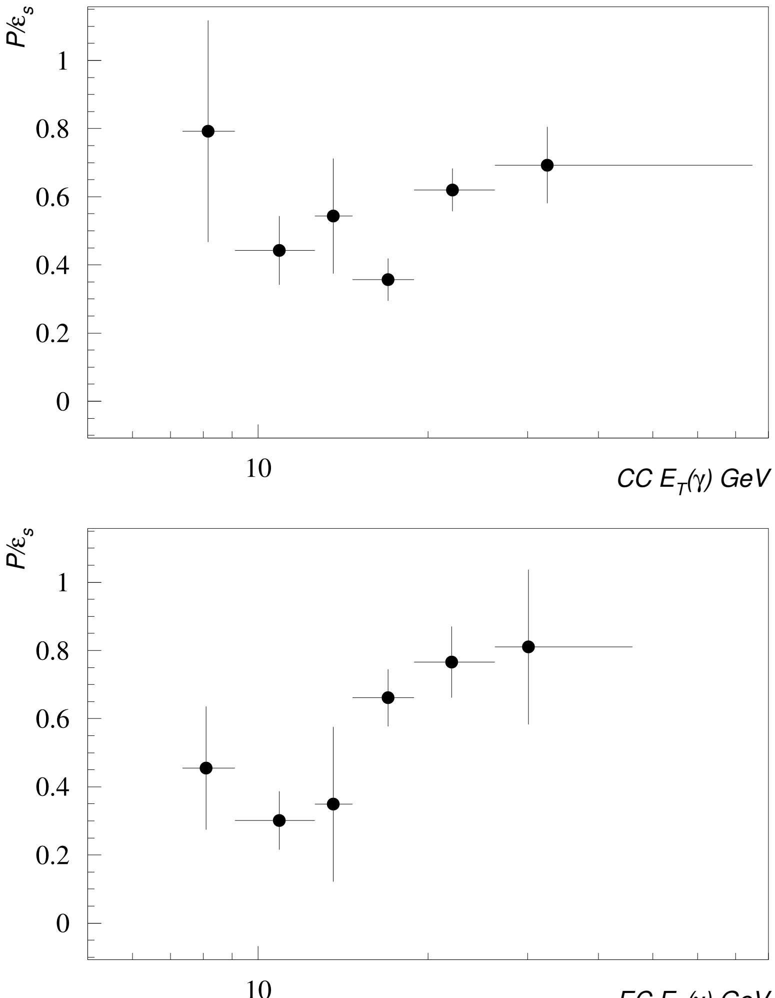


Figure 27: Photon purity divided by selection efficiency for the central and forward regions using x regions that correlate with the published Run 1A/1B 1800 GeV data.

E_TRange (GeV)	CC Fit	EC Fit
7.35-9.10	25.2 ± 10.3	26.2 ± 10.4
9.10-12.6	30.8 ± 7.0	26.0 ± 7.4
12.6-14.7	43.3 ± 13.4	28.4 ± 18.5
14.7-18.9	26.4 ± 4.6	51.9 ± 6.6
18.9-26.3	53.3 ± 5.4	68.5 ± 9.5
>26.3	60.0 ± 9.7	70.3 ± 19.6

Table 12: Photon purity in the same x regions as the 1800 GeV published data.

derived from the Monte Carlo below 8 GeV. For the next E_T bin (9.10-12.6 GeV) the main reason for the large value is that the $\mathcal{P}/\epsilon_s$ value fitted from the data fluctuates statistically to a higher value around 10 GeV. This local fluctuation is smoothed and minimized in the default analysis method becase a smooth function of E_T is fit to the $\mathcal{P}/\epsilon_s$ points. Without this fitting, the high statistical fluctuation of the $\mathcal{P}/\epsilon_s$ point around 10 GeV causes a significant increase in the measured cross section. The results are tabulated in Tables 13 and 14.

E_T Range (GeV)	$< E_T >$	$\frac{d\sigma}{dE_T}(\frac{\text{pb}}{\text{GeV}})$	$\delta\sigma_{\text{uncor}}(\%)$	$\delta\sigma_{\text{cor}}(\%)$
7.35- 9.1	8.2	80900	48	65
9.1-12.6	10.9	8110	31	40
12.6-14.7	13.6	2090	33	29
14.7-18.9	17.0	426	29	21
18.9-26.3	22.1	139	12	15
26.3-75.0	32.5	7.05	17	9

Table 13: Differential cross section in the CC with correlated and uncorrelated errors.

Fig. 29 shows the difference between the experimental and theoretical differential cross sections using the theory of Owens *et. al.* The correlated uncertainty includes contributions from the uncertainty on the geometric acceptance, the luminosity, the tracking efficiency, the fragmentation model and the energy scale (independent of energy) in the Monte Carlo. The uncorrelated uncertainty includes the uncertainties due to statistics, purity fitting,

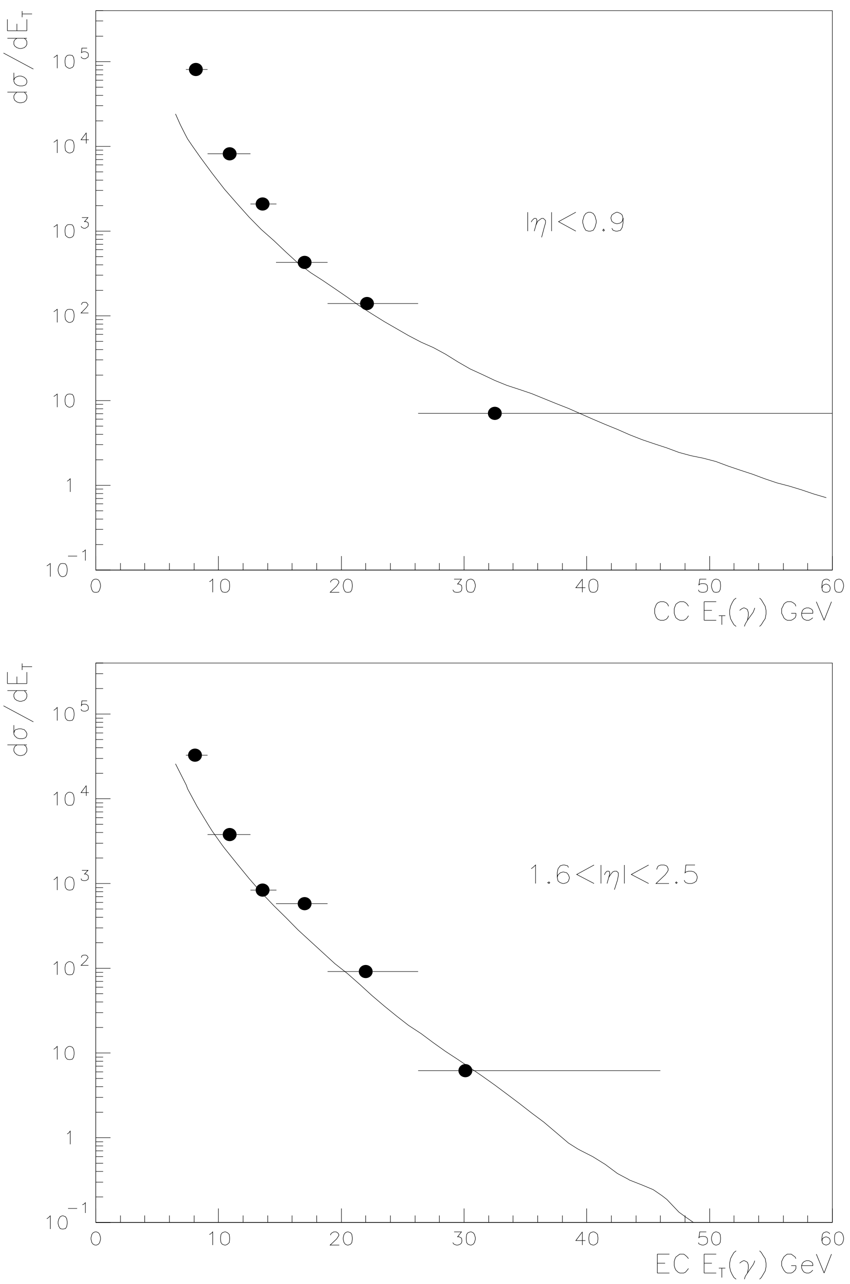


Figure 28: The isolated photon cross section, $d\sigma/dE_T\ d\eta$ vs. photon E_T for the central and forward rapidity regions using the 1A/1B analysis method. The errors are statistical and the curve is the theoretical prediction of CTEQ4M.

E_T Range (GeV)	$< E_T >$	$\frac{d\sigma}{dE_T}(\frac{\text{pb}}{\text{GeV}})$	$\delta\sigma_{\text{uncor}}(\%)$	$\delta\sigma_{\text{cor}}(\%)$
7.35- 9.1	8.0	33000	47	67
9.1-12.6	10.9	3810	31	34
12.6-14.7	13.6	839	66	24
14.7-18.9	17.2	578	24	17
18.9-26.3	22.0	91.4	15	16
26.3-46.0	30.1	6.19	31	15

Table 14: Differential cross section in the EC with correlated and uncorrelated errors.

the efficiency of the selection criteria, and the trigger efficiency. The lowest energy bin in this plot is in a range of $7.35 < E_T < 9.10$ GeV/c. Because this is lower than the minimum energy for which a reasonable uncertainty can be calculated, (see Sections 3.1 and 3.4), Fig. 29 is replotted in Fig. 30 without the lowest energy bin.

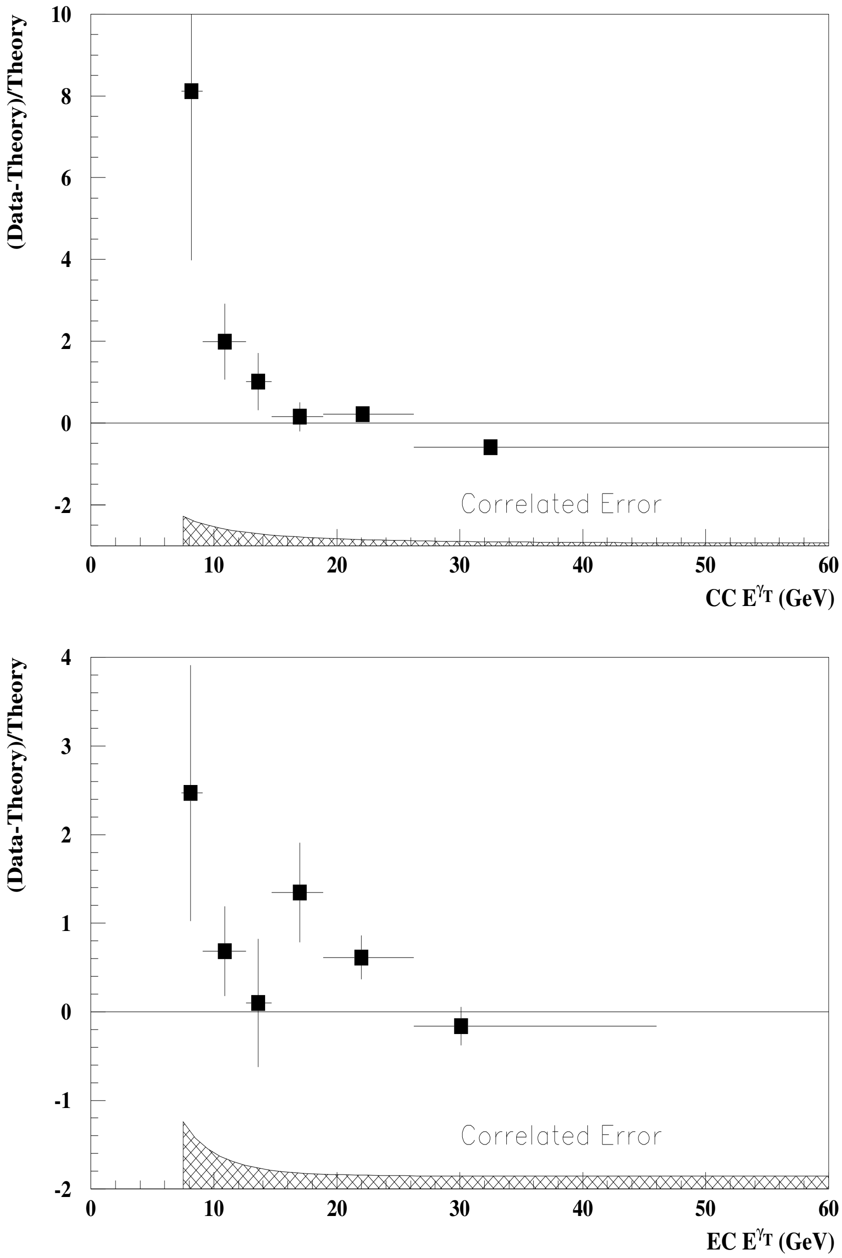


Figure 29: (Data-Theory)/Theory for the central (top) and forward (bottom) rapidity regions. The error bars indicate the uncorrelated uncertainty and the hatched region shows the correlated uncertainty.

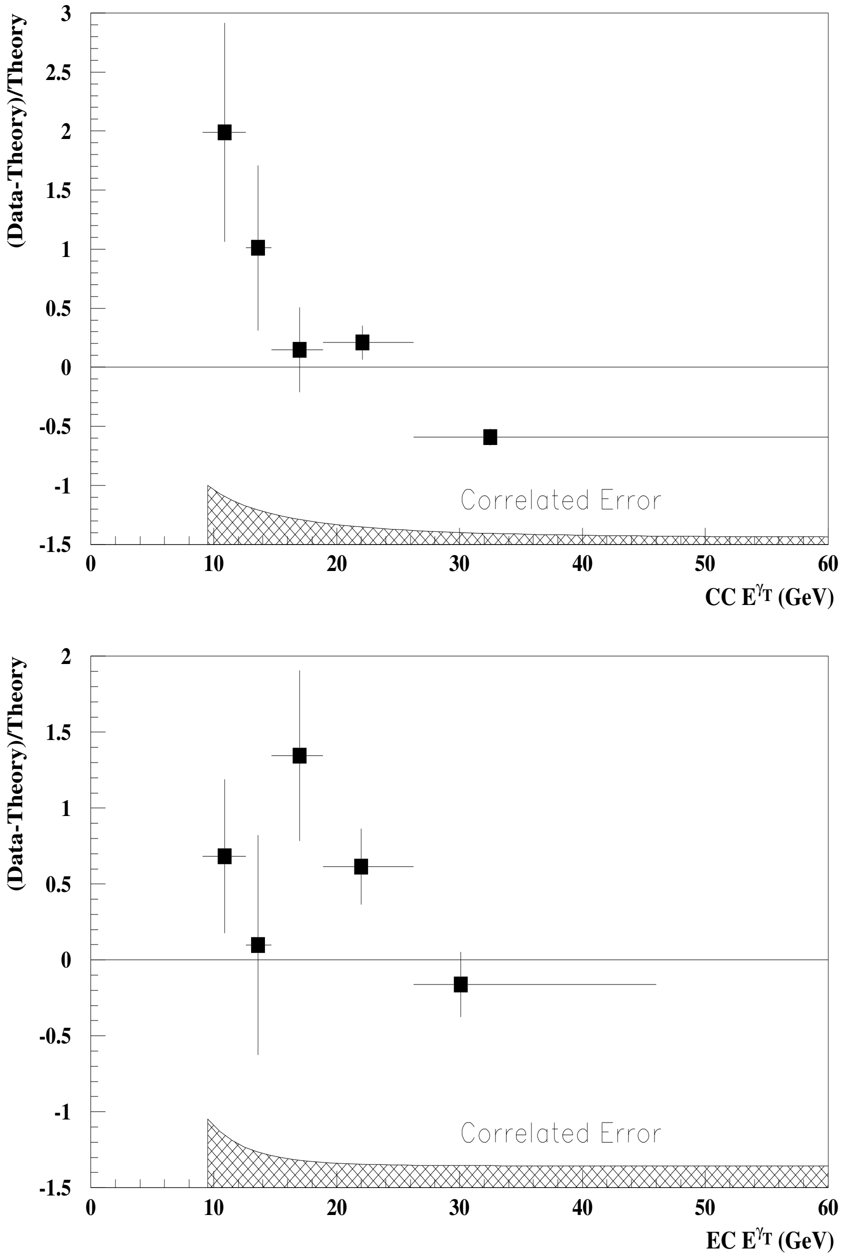


Figure 30: Same as Fig. 29 but without the lowest energy bin plotted.

A Monte Carlo Statistics

It was mentioned in Section 2.2, that the MC statistics were increased by overlaying eight to ten different zero bias events onto the same GEANT event. We have recalculated the photon purities for the central regions, but allowing each PYTHIA event to be used only once in the analysis. The comparison of results with the enlarged MC sample is summarized in Table 15. The tests in this appendix were performed by fitting the purity distributions in the CC region using smoothed HBOOK Monte Carlo distibutions and MINUIT [6].

$\boldsymbol{E_T}$**Bin (GeV)**	$\boldsymbol{E_T}$**(GeV)**	**Case A**	**Case B**
8-13	10.6 ± 1.2	14.8 ± 5.70	20.2 ± 5.2
13-18	16.5 ± 1.1	9.4 ± 4.8	12.9 ± 4.5
18-23	19.9 ± 1.4	32.2 ± 4.9	27.8 ± 4.5
23-33	26.3 ± 2.6	37.5 ± 7.7	28.4 ± 7.1
>33	37.6 ± 3.8	69.8 ± 20.6	72.4 ± 25.8

Table 15: Purity results with (case A) and without (case B) several noise files overlayed for the same PYTHIA event.

B Center of Mass Energy

The selection efficiency and the purity for this analysis is somewhat dependent on the Monte Carlo simulation. We expect that the Monte Carlo generated at 1800 GeV should adequately describe the data for these variables. This appendix investigates, in more detail, how well the Monte Carlo, generated at 1.8 TeV describes the data at 630 GeV.

B.1 Calorimeter Energy

The deteremination of the purity is very dependent on E_1, the energy deposited in the first electromagnetic section of the calorimeter. A comparison of the mean E_1 of Run 1B at 1800 GeV and Run 1C at 630 GeV before and after imposing selection requirements, is shown in Figs. 31 and 32. Except for high transverse energies in the EC before selections, there is good agreement between the two data sets. Since the correction is applied after cuts, and since most of the photons lie below 20 GeV, we expect that the Run 1B Monte Carlo adequately simulates the E_1 energy distributions in Run 1C.

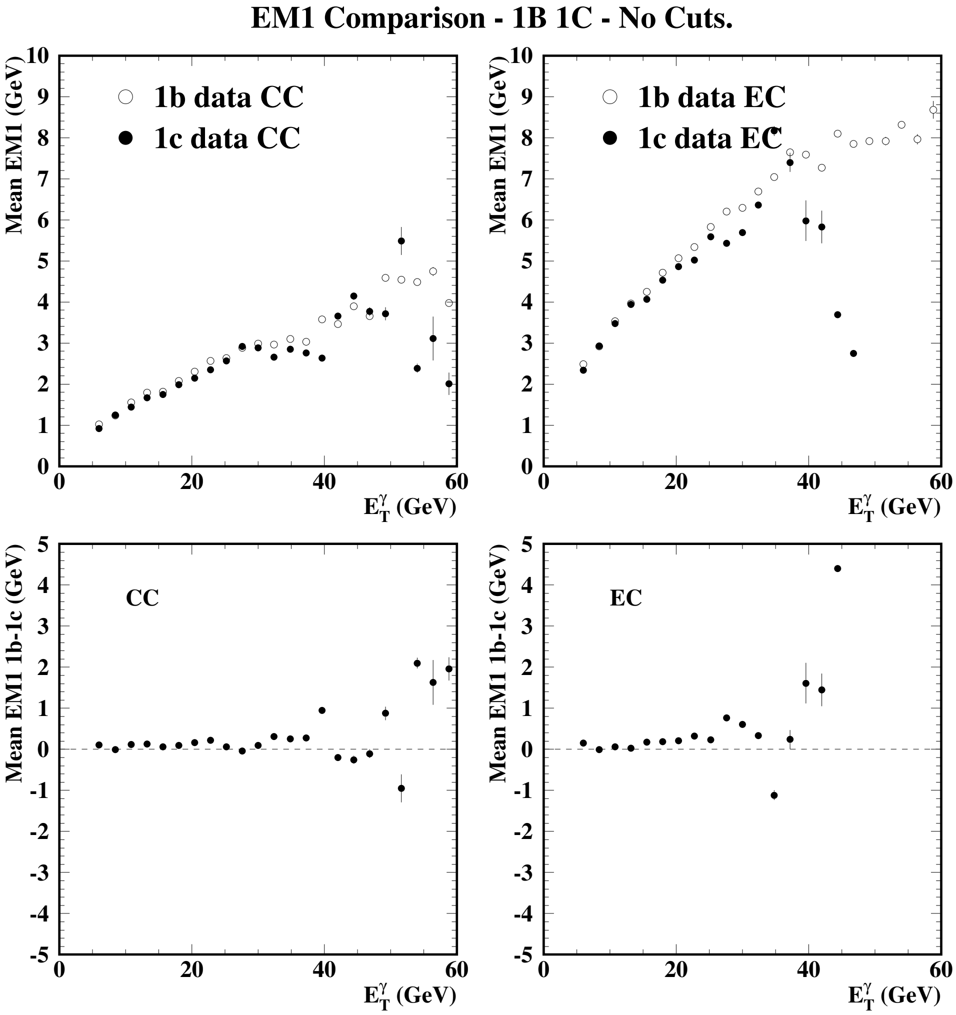


Figure 31: Comparison of E_1 energy for Run 1B at 1800 GeV and Run 1C at 630 GeV, before imposing photon selection criteria.

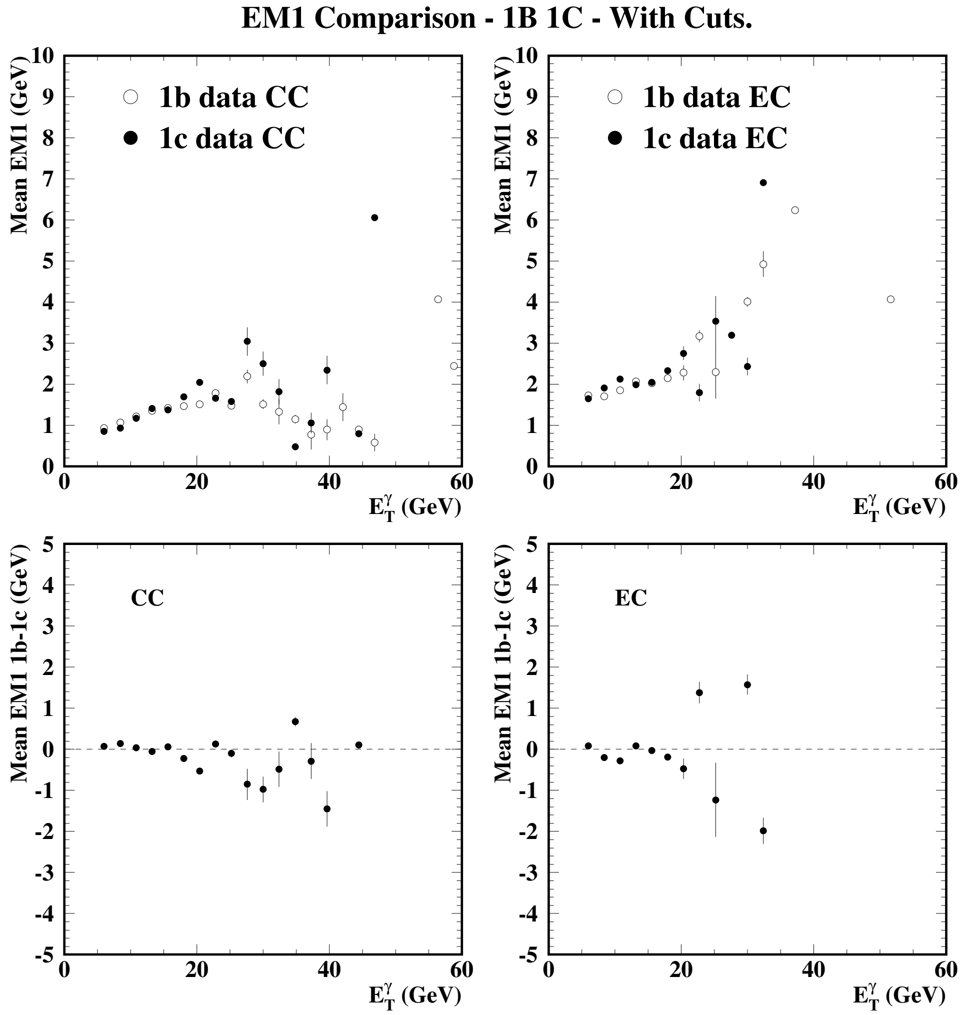


Figure 32: Comparison of E_1 energy for Run 1B at 1800 GeV and Run 1C at 630 GeV, after imposing photon selection criteria.

B.2 Selection Distributions

We have also compared various Monte Carlo and data variables used for selecting events. The comparison is made in six E_T regions that do not cross any trigger boundaries or any MC generation boundaries (7–8–10–14–16–20–40 GeV). The lowest E_T region is not used in the cross section measurement and so agreement is less important than in the higher regions. For each variable we have plotted the data along with the Monte Carlo photons and jets scaled to have the same number of events as the data in each particular E_T region as shown in Figs. 33 through 38. A minimum requirement for the Monte Carlo to accurately describe the data is that the distribution of data points should fall somewhere between the photon and the jet distributions since the data is a mixture of the two. Two sets of photon Monte Carlo are compared with the data: the fully simulated events used for efficiency studies, and the events fully simulated only in a cone of $R = 0.7$ around each electromagenetic cluster used for the purity determination. It is expected that the latter should not adequately describe certain kinematic variables, such as missing E_T. The Monte Carlo jet data has been fully simulated only in a cone of $R = 0.7$ around each electromagenetic cluster. The Monte Carlo photons and jets have considerable more events than the data and, consequently, have statistical uncertainties much smaller than the data. The fully simulated events vary from one-sixth the number of data events in the lowest $E - T$ bin to ten times the number of data events in the highest E_T bin.

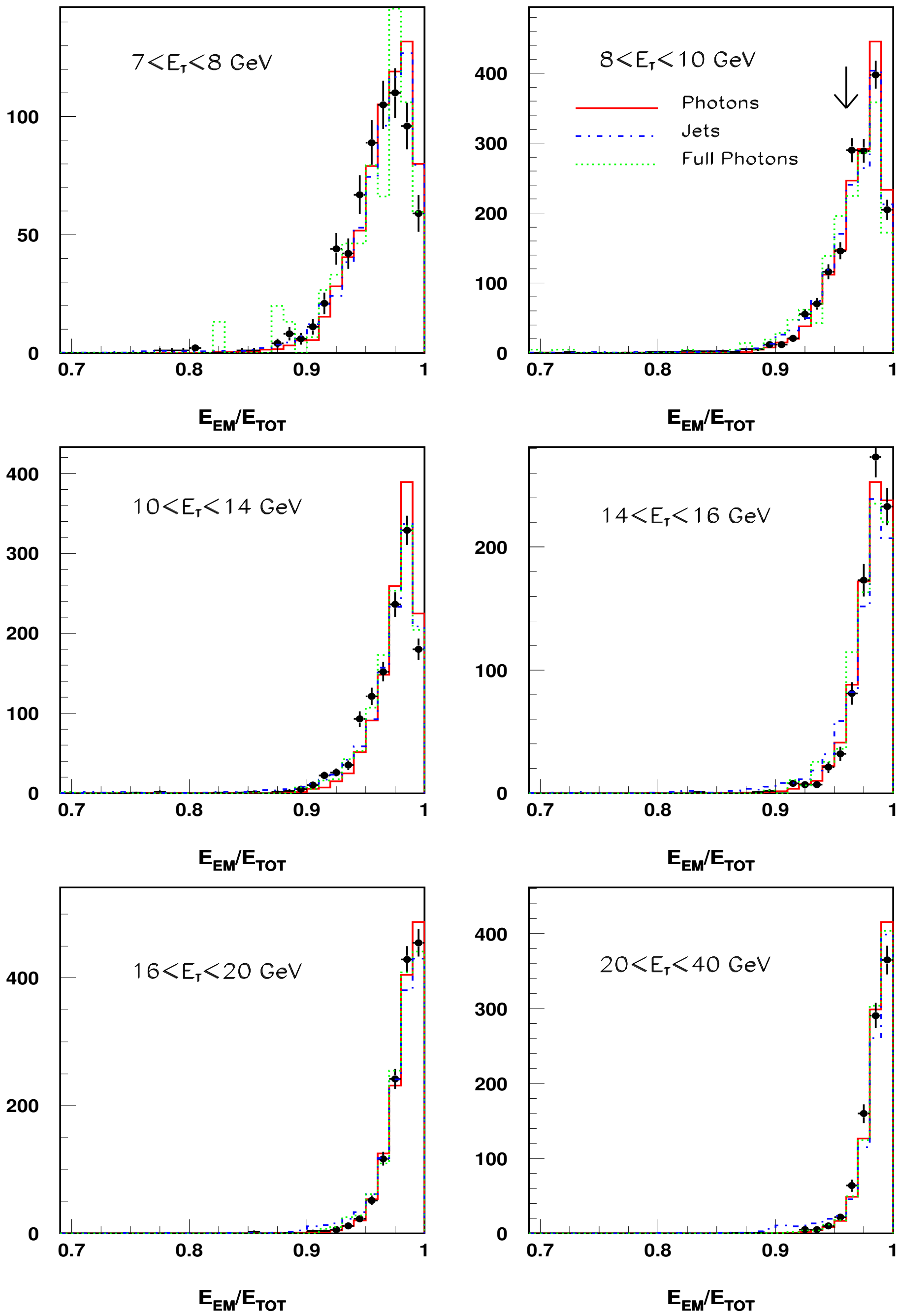


Figure 33: Comparison of Monte Carlo and data for the electromagnetic fration in the CC. The key and selection criteria (indicated with an arrow) shown in one E_T region is identical for all E_T regions.

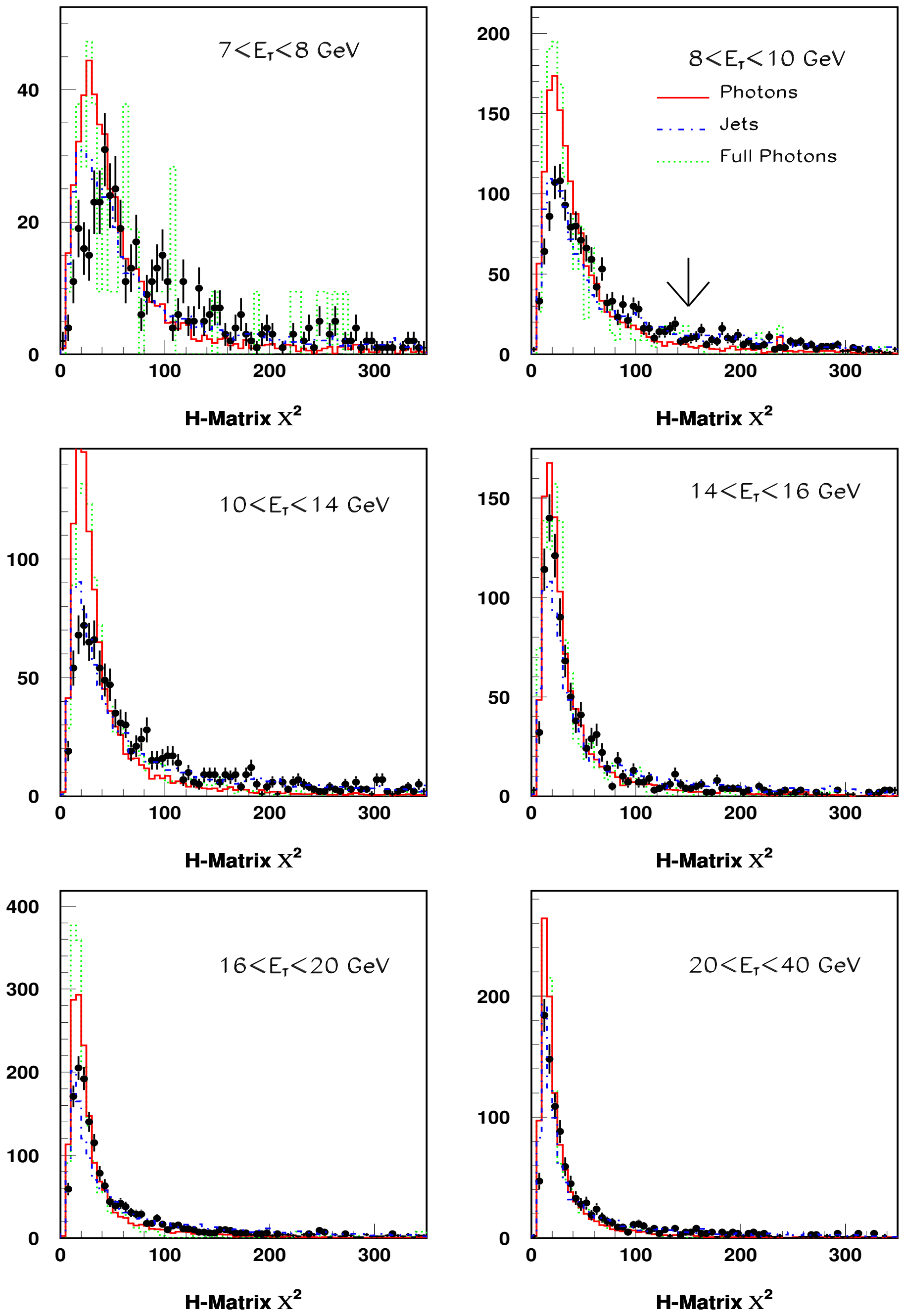


Figure 34: Comparison of Monte Carlo and data for the H-Matrix χ^2 in the CC. The key and selection criteria (indicated with an arrow) shown in one E_T region is identical for all E_T regions.

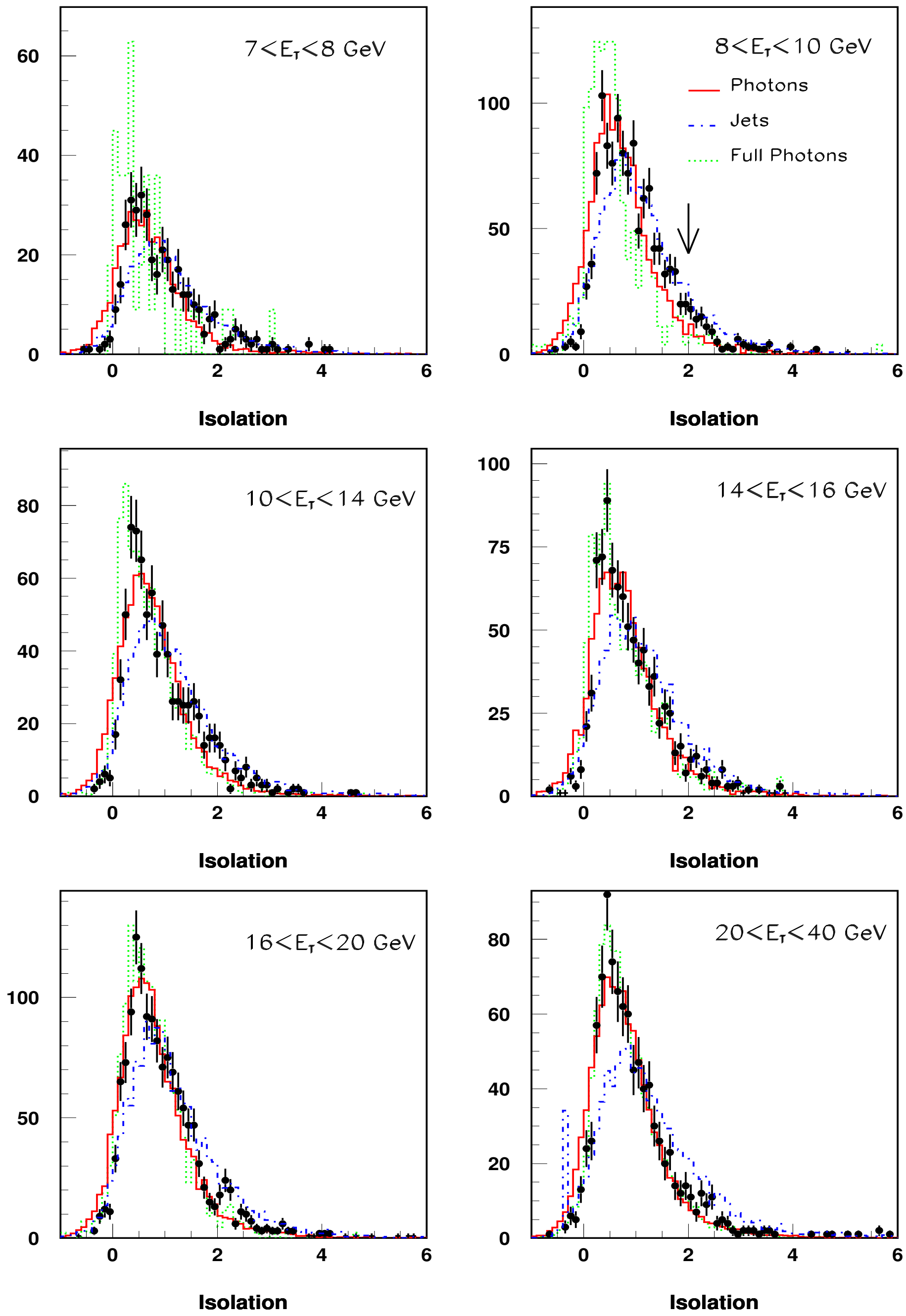


Figure 35: Comparison of Monte Carlo and data for the Isolation in the CC. The key and selection criteria (indicated with an arrow) shown in one E_T region is identical for all E_T regions.

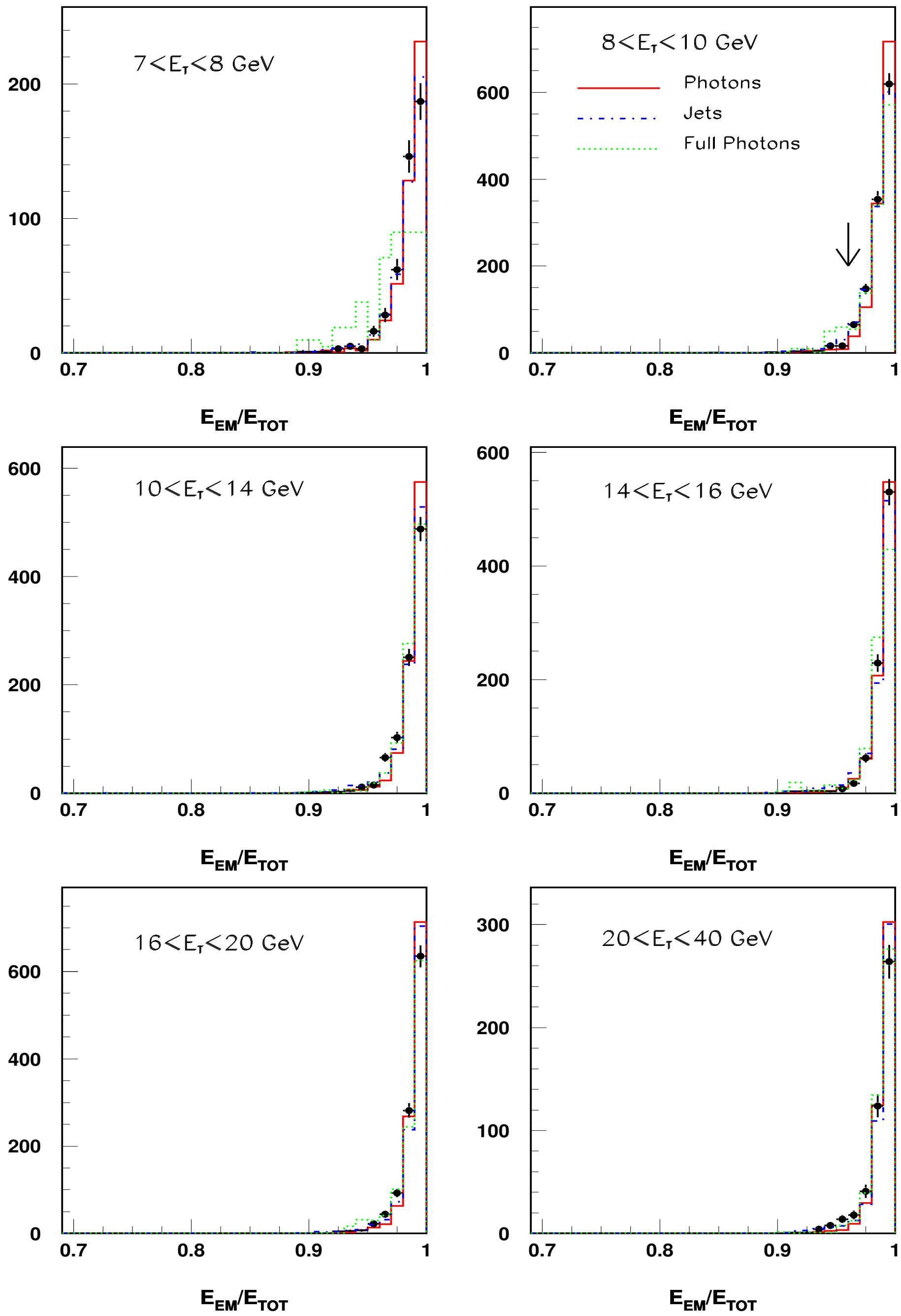


Figure 36: Comparison of Monte Carlo and data for the electromagnetic fration in the EC. The key and selection criteria (indicated with an arrow) shown in one E_T region is identical for all E_T regions.

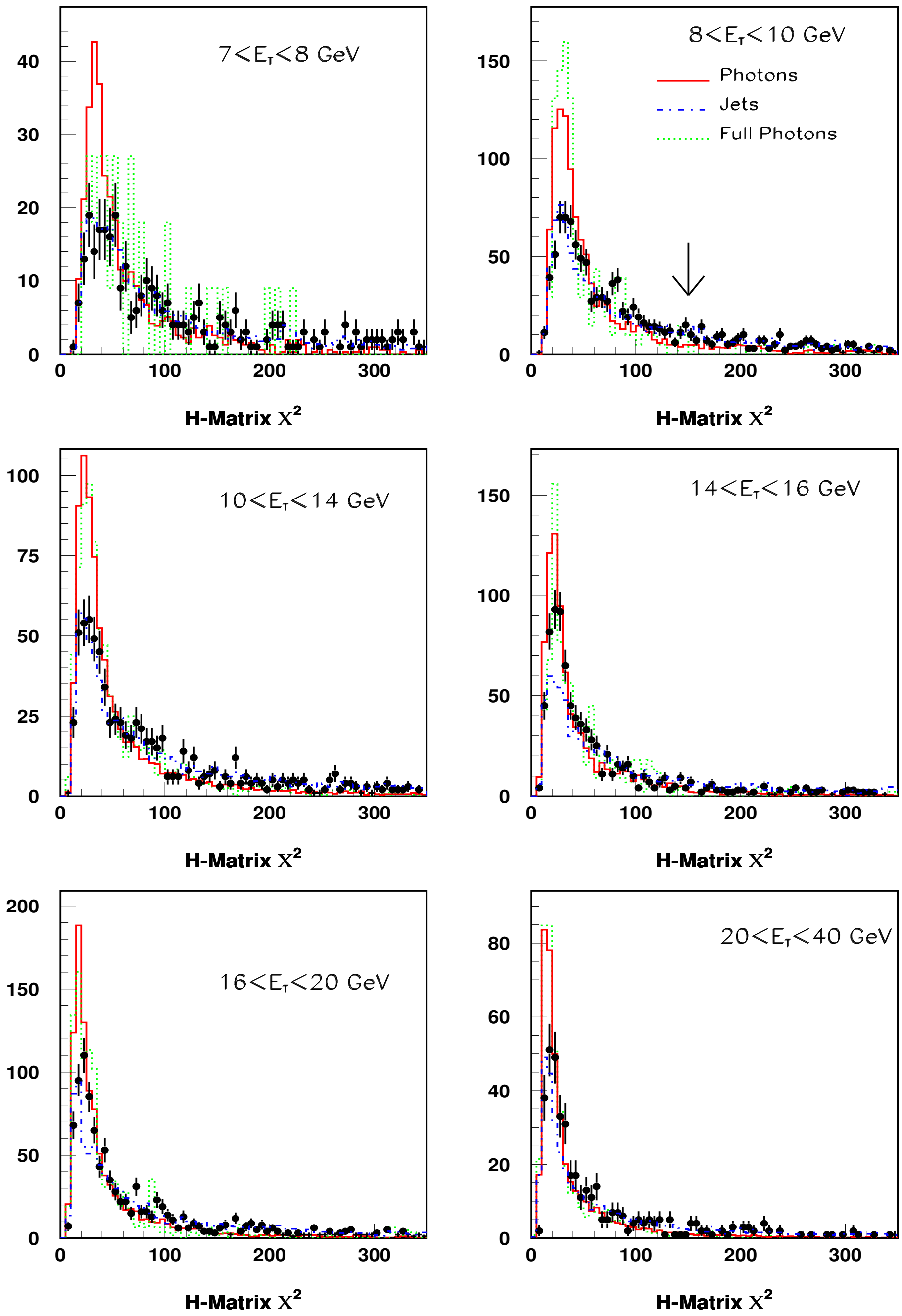


Figure 37: Comparison of Monte Carlo and data for the H-Matrix χ^2 in the EC. The key and selection criteria (indicated with an arrow) shown in one E_T region is identical for all E_T regions.

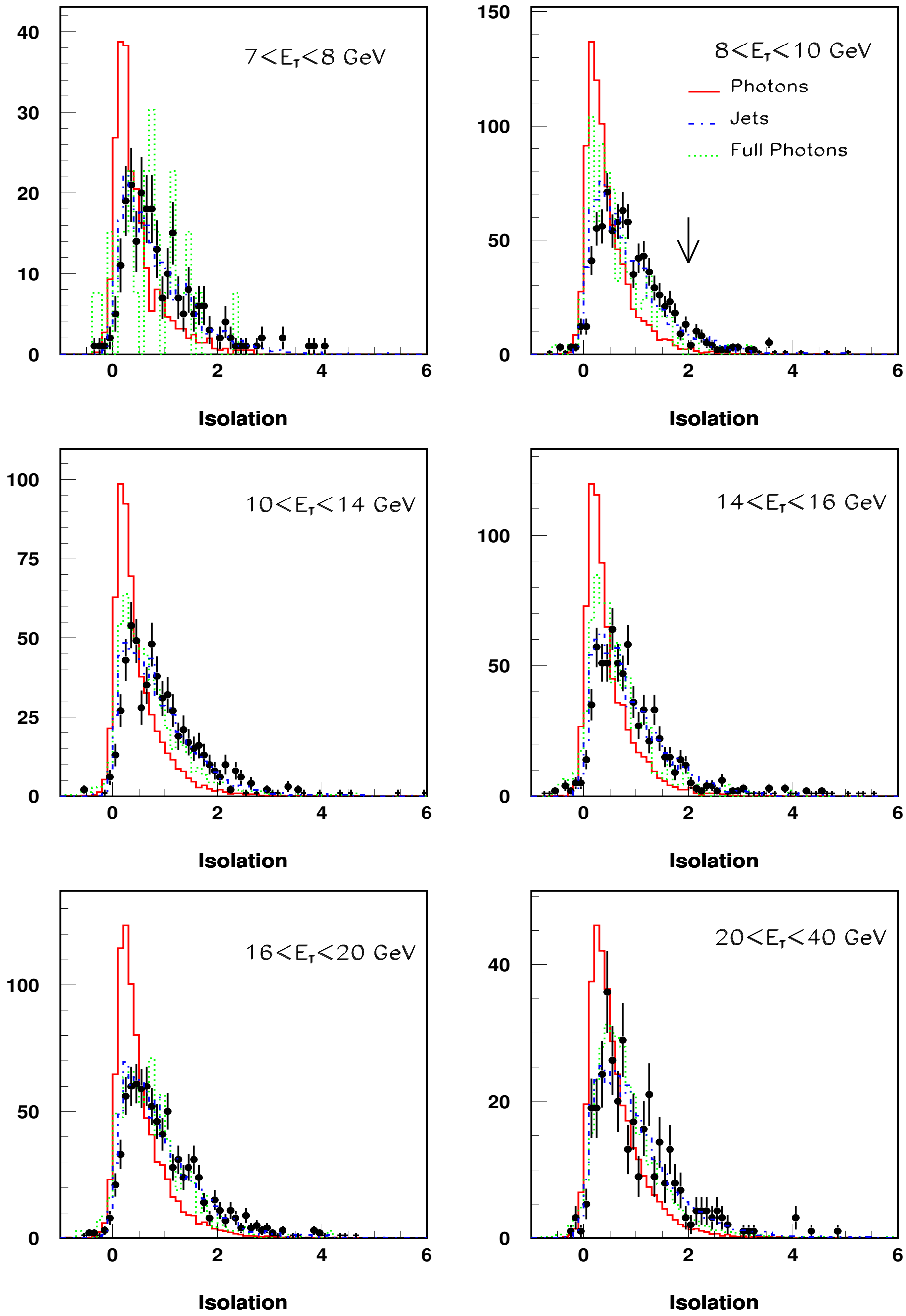


Figure 38: Comparison of Monte Carlo and data for the Isolation in the EC. The key and selection criteria (indicated with an arrow) shown in one E_T region is identical for all E_T regions.

References

[1] "The Isolated Photon Cross Section at $\sqrt{s} = 1.8$," DØ Collaboration, *Phys. Rev. Lett.*, **84**, 2786, 2000.

[2] "The Isolated Photon Cross Section at $\sqrt{s} = 1.8$ TeV Using the Combined Run 1A/B Data Sample
S.L. Linn,DØ Note ♯ 3564, 1999.

[3] "The Isolated Photon Cross Section in the Central and Forward Rapidity Region in $p\bar{p}$ Collisions at $\sqrt{s}$=1.8 TeV".
D0 Collab., Phys. Rev. Letters (77), 5011, (1996)

[4] "The Inclusive Cross Section for Isolated Photons in Run 1a",
S.L. Linn, DØ Note ♯ 2745, 1995.

[5] "Inclusive Direct Photon Production in the Central and Forward Rapidity Regions in Proton-Antiproton Collisions at a Center of Mass Energy of 1800 GeV",
S.A. Jerger, Ph.D. Thesis, Michigan State University, 1997.

[6] "The 630 GeV Isolated Direct Photon Cross Section",
S. Grinstein, R. Piegaia, DØ Note ♯ 3350, 1997.

[7] "Producción de Fotones Directos en Colisiones $p\bar{p}$ a 630 GeV",
S. Grinstein, Tesis de Licenciatura, Universidad de Buenos Aires, 1997.

[8] UA2 Collaboration, J. Alitti *et. al.,* Phys. Lett. **B288** (1992) 386, UA2 Collaboration, J. Alitti *et. al.,* Phys. Lett. **B283** (1991) 554, UA2 Collaboration, Ansari *et. al.,* Z. Phys. **C41** (1988) 395.

[9] CDF Collaboration, F. Abe *et. al.,* Phys. Rev. Lett. **73** (1994) 2662; http://www-cdf.fnal.gov/physics/new/qcd/QCD.html.

[10] S.L. Linn, private communication.

[11] A. Schaffer and S.L. Linn, private communication.

[12] D. Owens, Phys. Rev, **D42**, (1990) 61

[13] W. Vogelsang and A. Vogt, Nucl. Phys. **B453**, (1995) 334