Photon Production

at the Fermilab Tevatron

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for the DØ and CDF Collaborations

Recontres de Moriond '99
QCD and Hadronic Interaction
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Outline

I. Motivation

II. Detectors

- The DØ Detector
- The CDF Detector

III. Data Analysis

- Event Selection
- Backgrounds
- DØ Photon Purity
- CDF Efficiency and Calibration

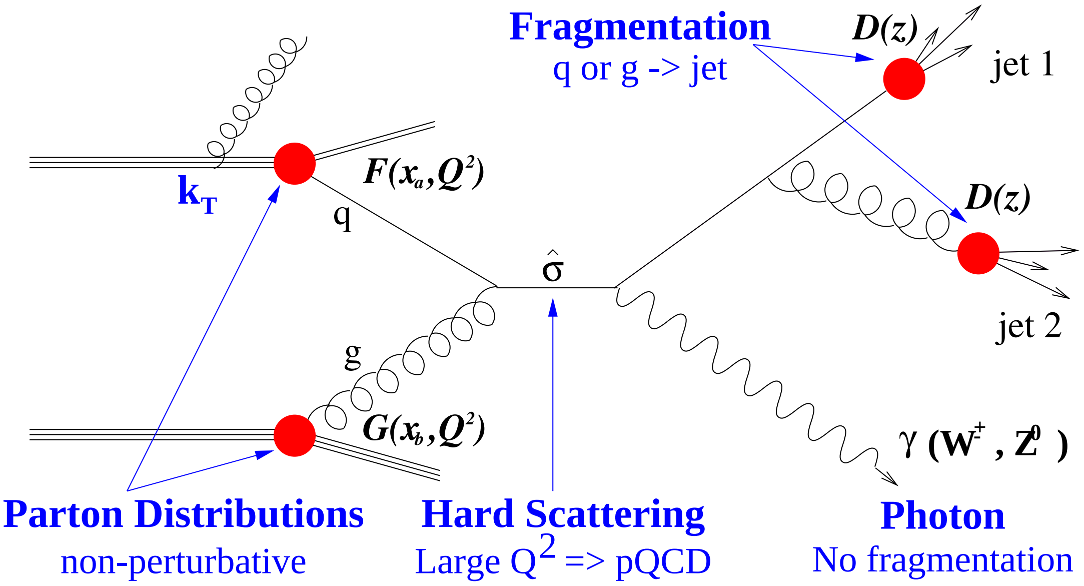
IV. New Physics Results

- Isolated Photon Cross Section
- $\gamma + \mu$ Peoduction Cross Section

V. Conclusions

Theoretical Motivation

Comparison of Measurement and Theory:



$$E\frac{d^3\sigma}{dp^3} = \sum_{a,b} x_a F(x_a)\ x_b G(x_b) \frac{d\hat{\sigma}}{d\hat{t}}(a\ b \to \gamma\ jet)$$

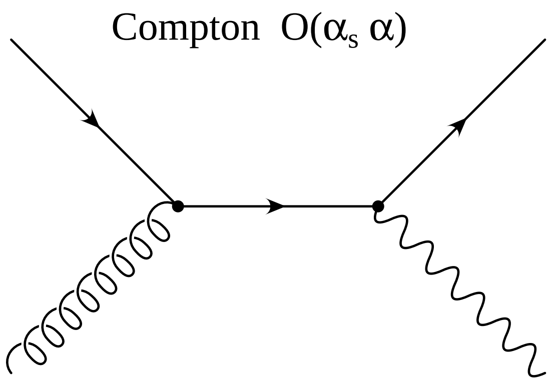
$$= \frac{\partial^3\sigma}{\partial\ \cos\theta^*\ \partial x_a\ \partial x_b} \longrightarrow \text{physics variables are } \cos\theta^* \text{ and } x$$

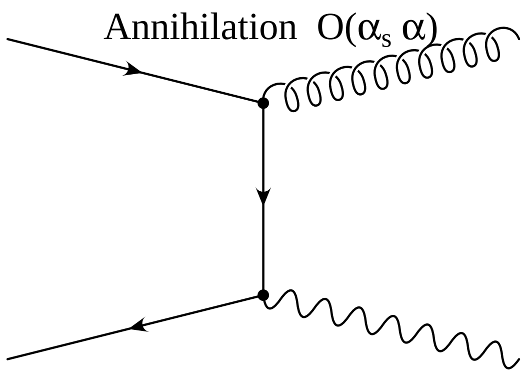
$$= \frac{\partial^3\sigma}{\partial E_T\ \partial\eta_\gamma\ \partial\eta_{jet}} \longrightarrow \text{detector measures energy and position}$$

Theoretical Motivation

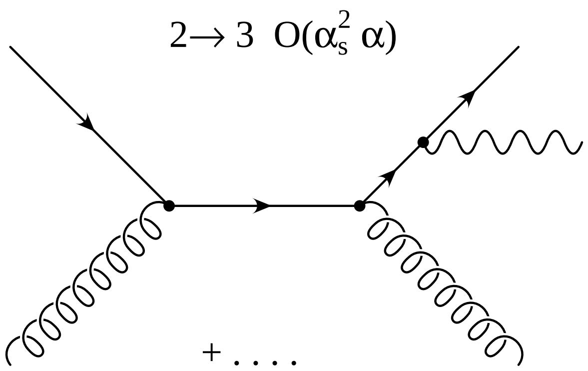
Sources of Direct Photons:

Leading Order:



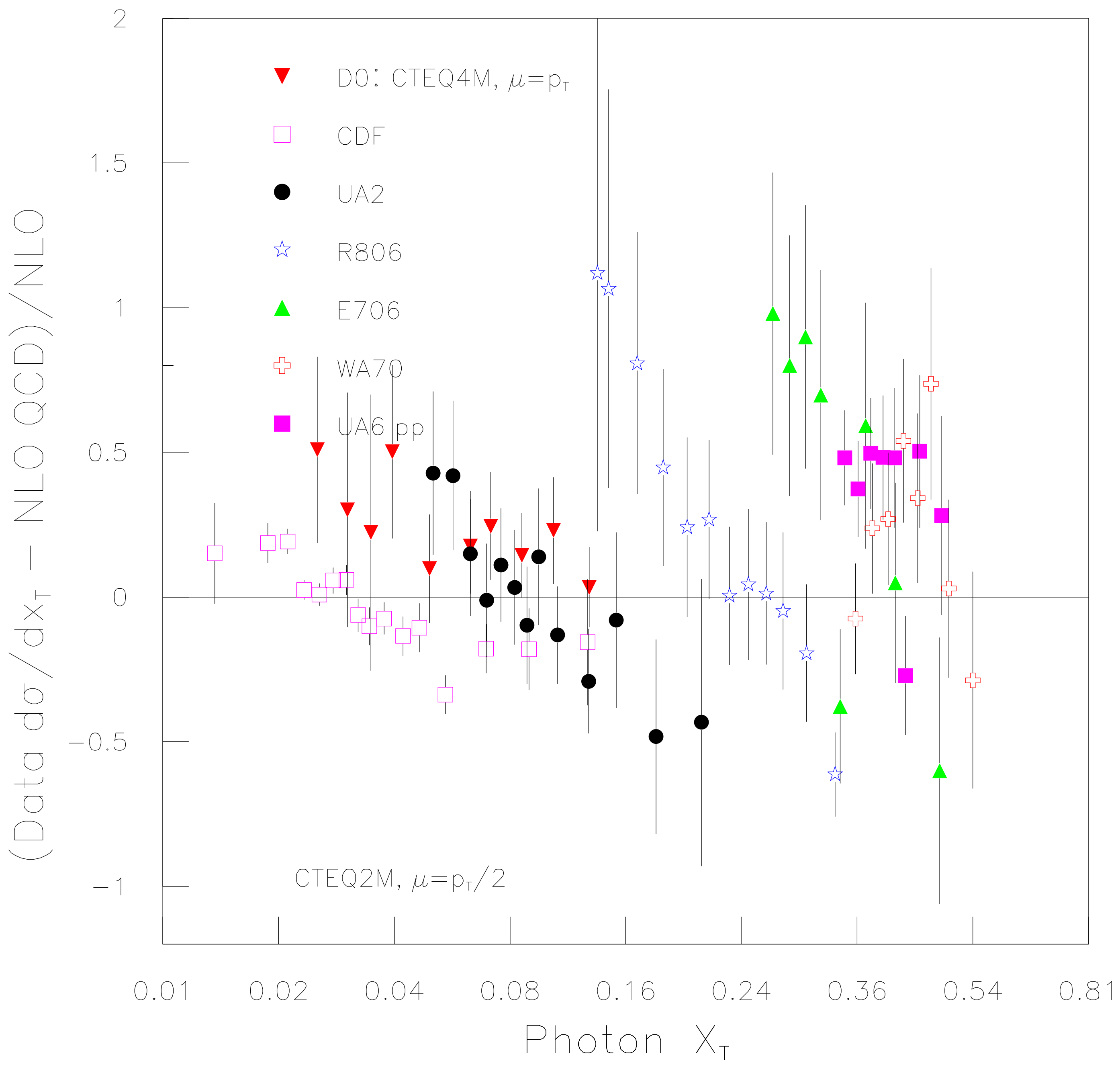


Higher Order:



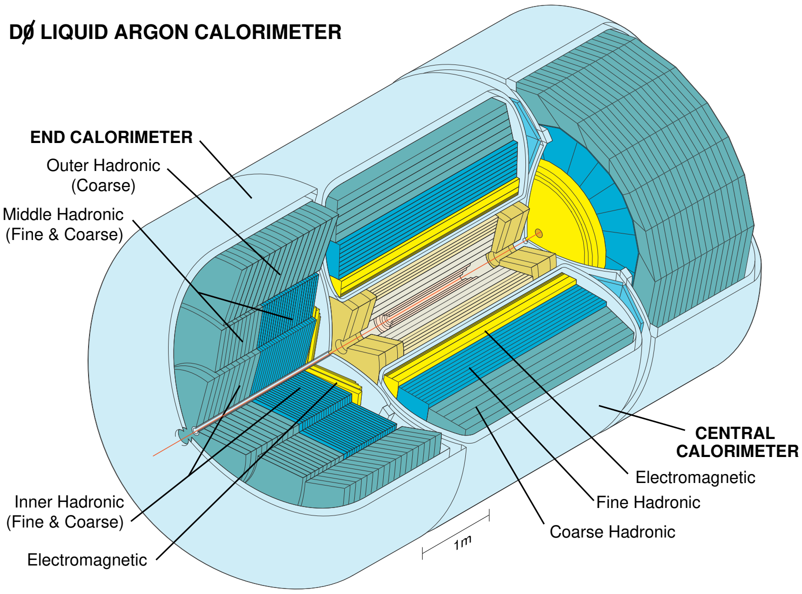
Motivation

History of cross section measurement shows discrepency between data and theory



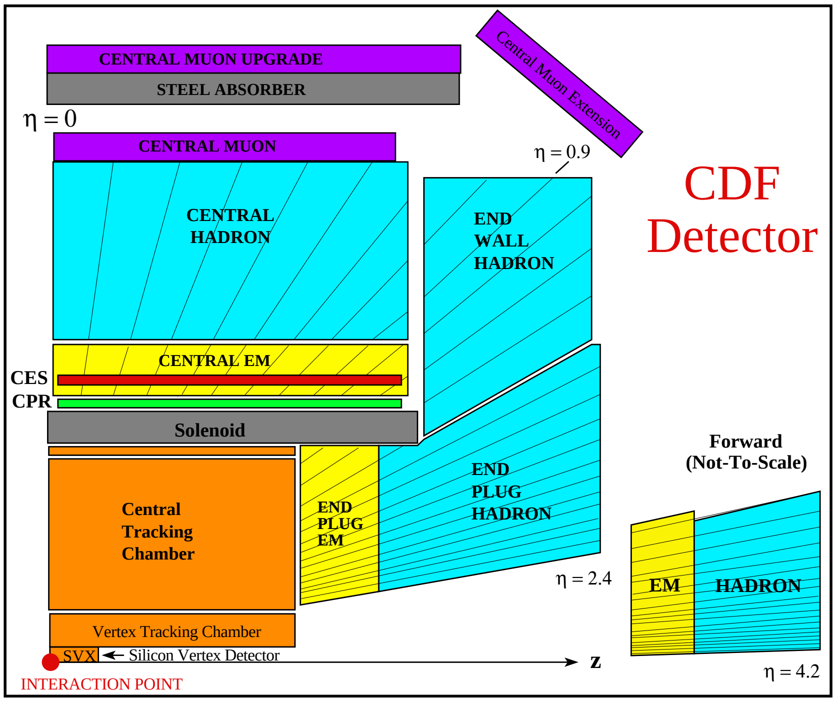
Comparison of $d\sigma/dx_T$ for different experiments

Experimental Apparatus: The DØ Calorimeter



- Liquid Argon - Uranium calorimeter
- e/π Response: 1.02 — 1.09
- $|\eta| \leq 4.2$
- Longitudinal Segmentation:
  - 4 EM layers (2,2,7,10)X_0, 4-5 Hadronic layers (6λ)
- Transverse Segmentation:
  - $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ or 0.05×0.05 in EM_3
- Energy Resolution (%):
  - Electrons: $\frac{15}{\sqrt{E}} + 0.3$, Hadrons: $\frac{50}{\sqrt{E}} + 4$

Experimental Apparatus:The CDF Detector



- Central: Lead(Steel)-Scintillator for EM(Hadronic)
- Central Preradiator (CPR): $|\eta| < 1.1$ and $1.075 X_0$
- Central EM Strip Chamber (CES):
- $|\eta| < 4.2$
- Thickness: 18-25 X_0 (EM) , 5-8 λ (Hadronic)
- Transverse Segmentation $(\Delta\eta \times \Delta\phi)$: $0.1 \times 15^\circ$ (Central)
- Energy Resolution (%)
  - Electrons: $\frac{13.5}{\sqrt{E}} + 1.7$,
  - Hadrons: $\frac{80.0}{\sqrt{E}} + 3.0$

$\boxed{\text{DØ Offline Photon Selection}}$

- Fiducial Cuts
  - $|\eta| \leq 0.9$ in central cryostat (CC)
  - $1.6 \leq |\eta| \leq 2.5$ in forward cryostats (EC)
  - ϕ cut in CC to avoid module edges
  - $|z| \leq 50.0$ cm
- No charged track pointing to cluster ($\Delta\theta \times \Delta\phi = 0.2 \times 0.2$)
- EM Fraction of $E_{total} \geq 96\%$
- Isolation E_T: $E_T^{R<0.4} - E_T^{R<0.2} < 2.0$ GeV, ($R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2}$)
- Reconstructed shower shape matches test beam shower shape. ($\chi^2_{H-Matrix} < 150$)
- Selection cuts give an E_T dependent efficiency (ϵ) averaging $\sim 50\%$($\sim 40\%$) in the CC (EC).

CDF Offline Photon Selection

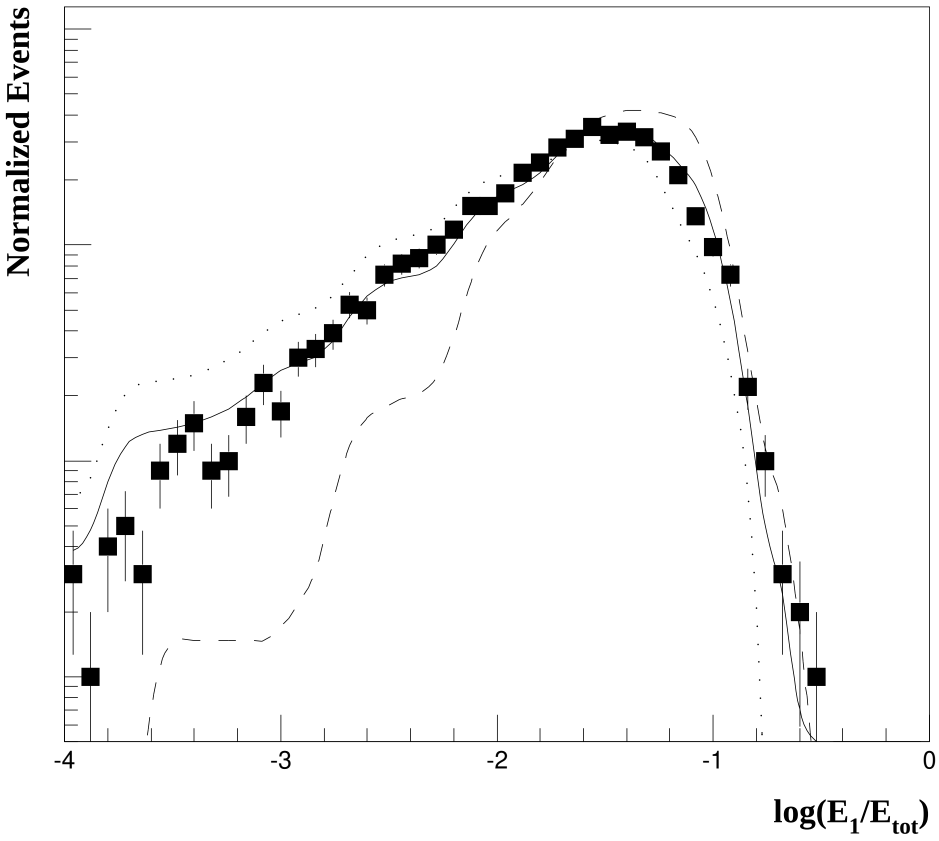
- Fiducial Cuts
  - $|\eta| \leq 0.9$ in CEM
  - Avoid module edges of CES and CEM
  - $|z| \leq 60.0$ cm
- No CTC tracks pointing toward calorimeter clusters
- Only 1 EM cluster with $E_T > 1$ GeV in the CES per detector wedge
- Isolation E_T: Unassociated $E_T < 1$ GeV within $R < 0.4$
- Reconstructed shower matches single photon shower shape within the CES. ($\chi^2 \leq 20.0$)

Data Analysis: Backgrounds

- Primary background due to η^0 and π^0 production
  - $\sigma_{jet}/\sigma_\gamma \sim 10^3$ at low E_T
  - Jets fluctuate to a single π^0 or η with probability of 10^{-3}
  - For $E_T > 10.0$ GeV, $\eta^0 \rightarrow \gamma\gamma$ and $\pi^0 \rightarrow \gamma\gamma$ appear as single photon.
- Background subtracted out statistically

DØ Data Analysis: Photon Purity

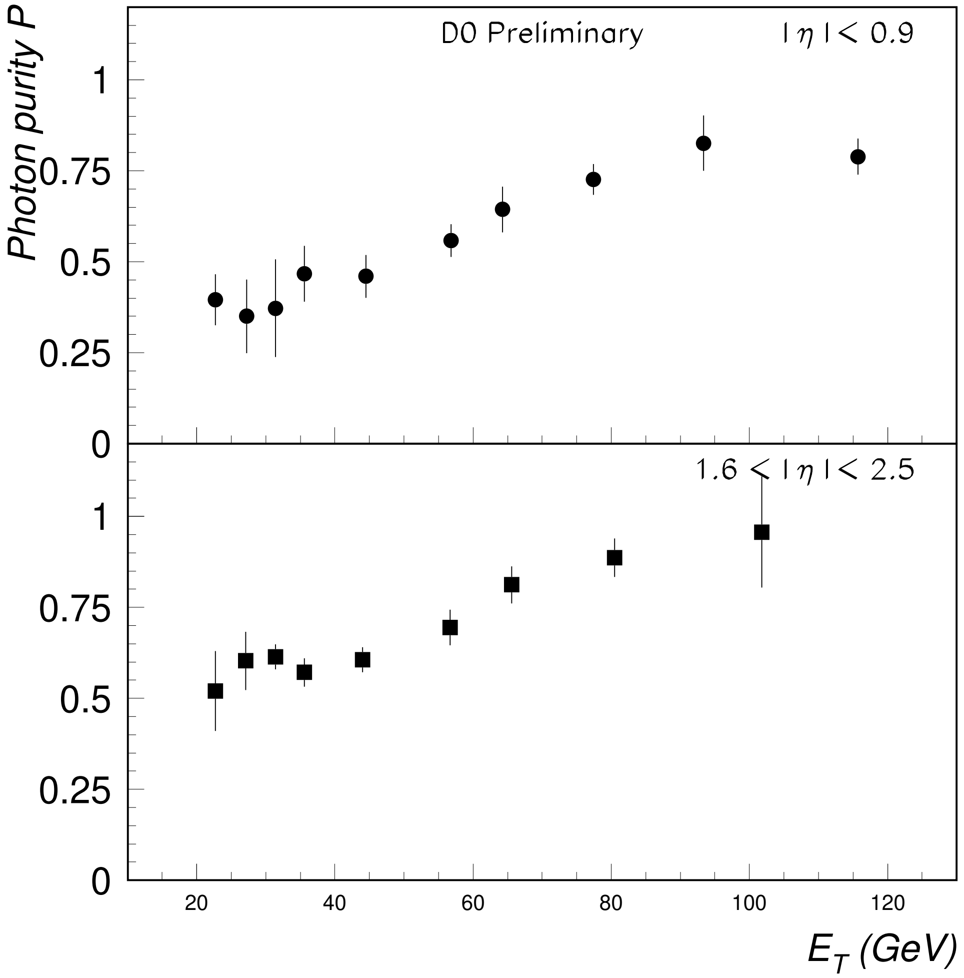
- Exploit the longitudinal segmentation of the calorimeter
- $\mathcal{P}(\pi^0/\eta \to (\geq 2)\gamma \to e^{\pm}) > \mathcal{P}(\gamma \to e^{\pm})$ in E_1
- Use $\log(E_1/E_{total})$ as γ-meson discriminant.



Data: Points
MC Signal: Dots
MC Background: Dashed

DØ Cross Section Data Analysis

Photon Purity: $P = \frac{N_\gamma}{N_\gamma + N_{(\pi^0,\eta^0)}}$



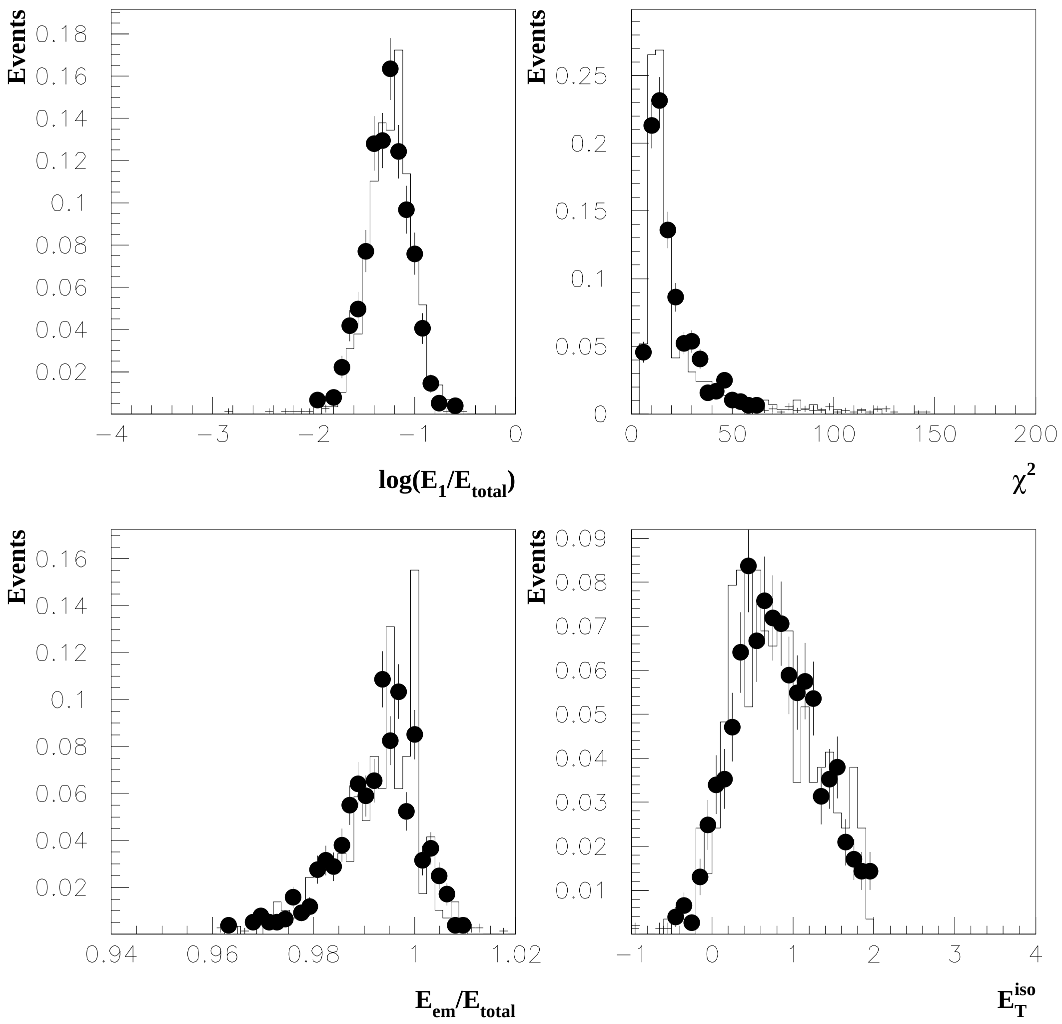
$$\frac{d^2\sigma}{dE_T d\eta} = \frac{NP}{\mathcal{L}\epsilon\Delta\eta\Delta E_T}$$

N = Number of Photon Candidates
P = Purity
$\mathcal{L}$ = Luminosity
ϵ = Selection Cut Efficiencies

DØ Data/Monte Carlo Comparisons

Use electrons from $W \to e\nu$ events:

- $\log\left(E_1/E_{total}\right)$ - discriminant
- $\chi^2_{H-Matrix}$ - Shower shape
- E_{EM}/E_{total} - EM fraction
- Isolation cone $E_T^{R\leq 0.4} - E_T^{R\geq 0.2}$



Data: Histogram

MC: Points

CDF Data Analysis: Photon Identification

Two methods are used to determine the photon fraction:

- Profile Method
  - Compare shower shape in CES to test beam electron showers
  - Showers from π^0 and η are wider than single γ showers
  - Used in low E_T region (below 36 GeV/c)
- Conversion method
  - Greater chance that 1 of 2 photons will convert in CPR for background than for single γ.
  - Used in high E_T region (above 36 GeV/c).

CDF Cross Section Data Analysis:

- Photon cross section calculated using:

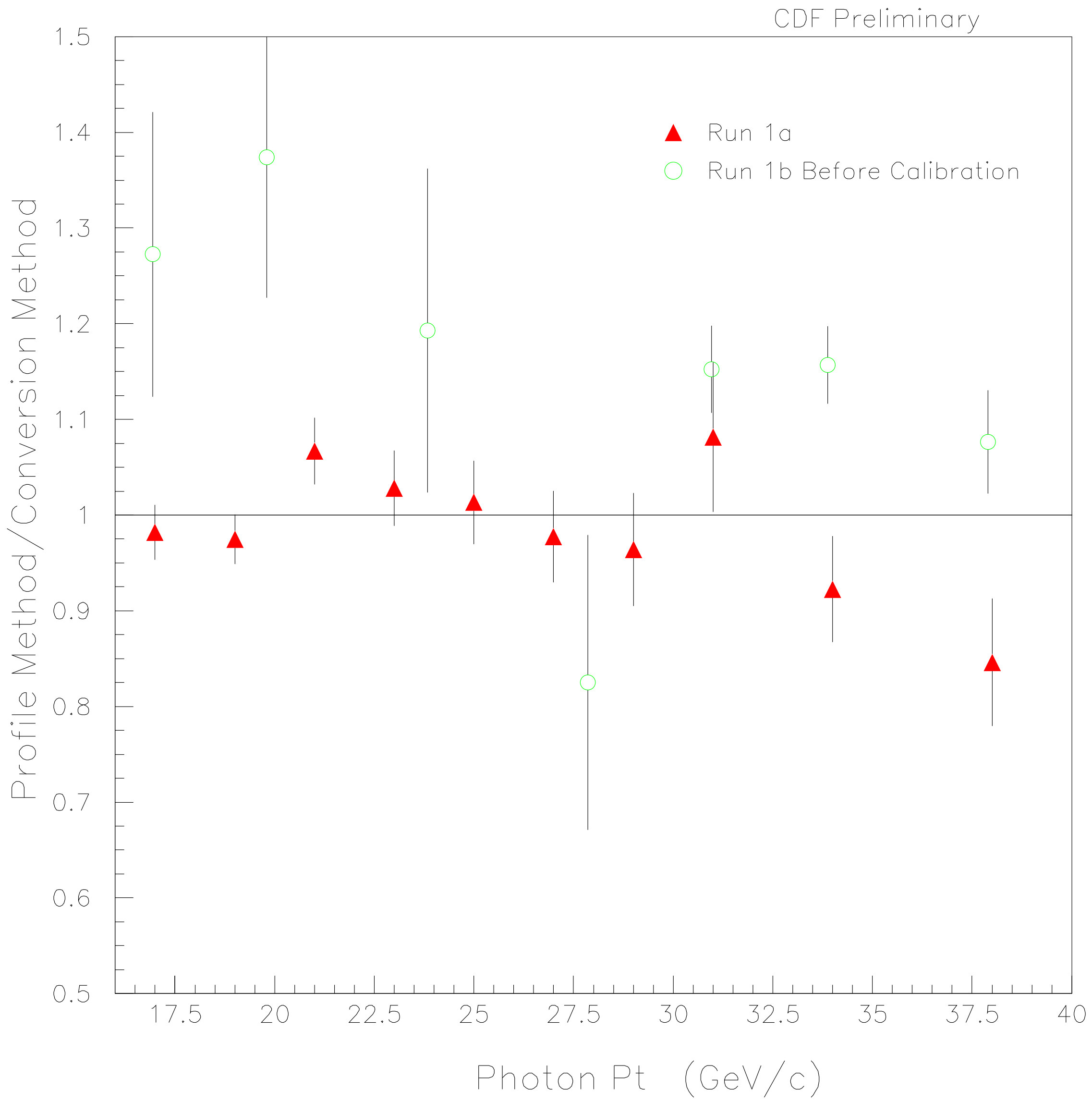
$$N_\gamma = \left(\frac{\epsilon - \epsilon_b}{\epsilon_\gamma - \epsilon_b}\right) N$$
$$\epsilon N = \epsilon_\gamma N_\gamma + \epsilon_b N_b$$
$$N_b = N - N_\gamma$$

ϵ = measured data efficiency for either method
ϵ_γ = signal efficiency from Monte Carlo
ϵ_b = background efficiency from Monte Carlo
N = number of photon candidates

- Both identification methods should give the same cross section
- Run 1A cross sections agreed to 2%
- Run 1B DID NOT before recalibration

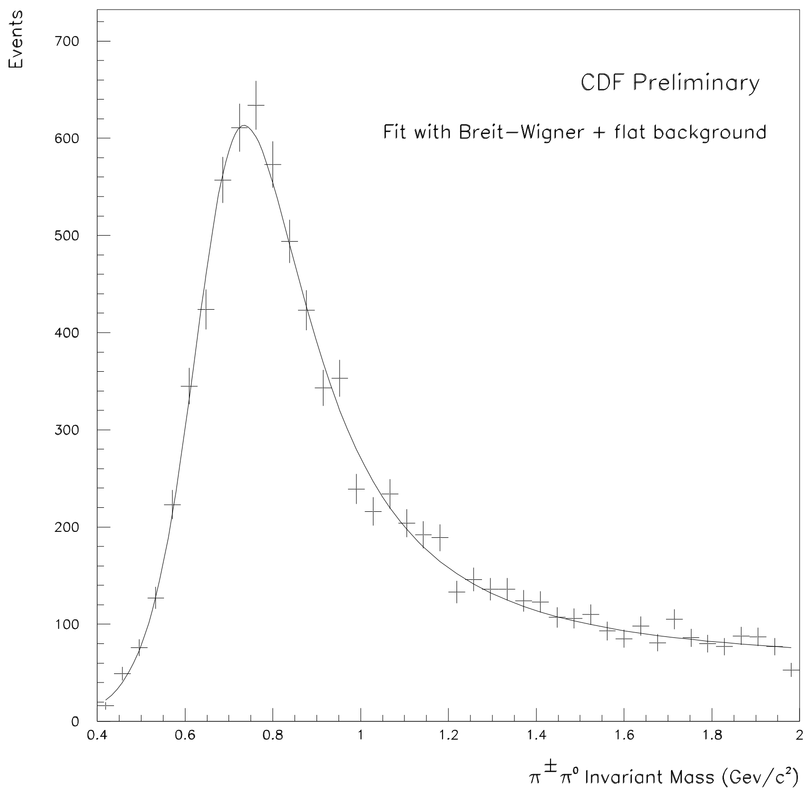
CDF Data Analysis: Before Calibration

Ratio of Profile to Conversion Methods



CDF Data Analysis: Calibration

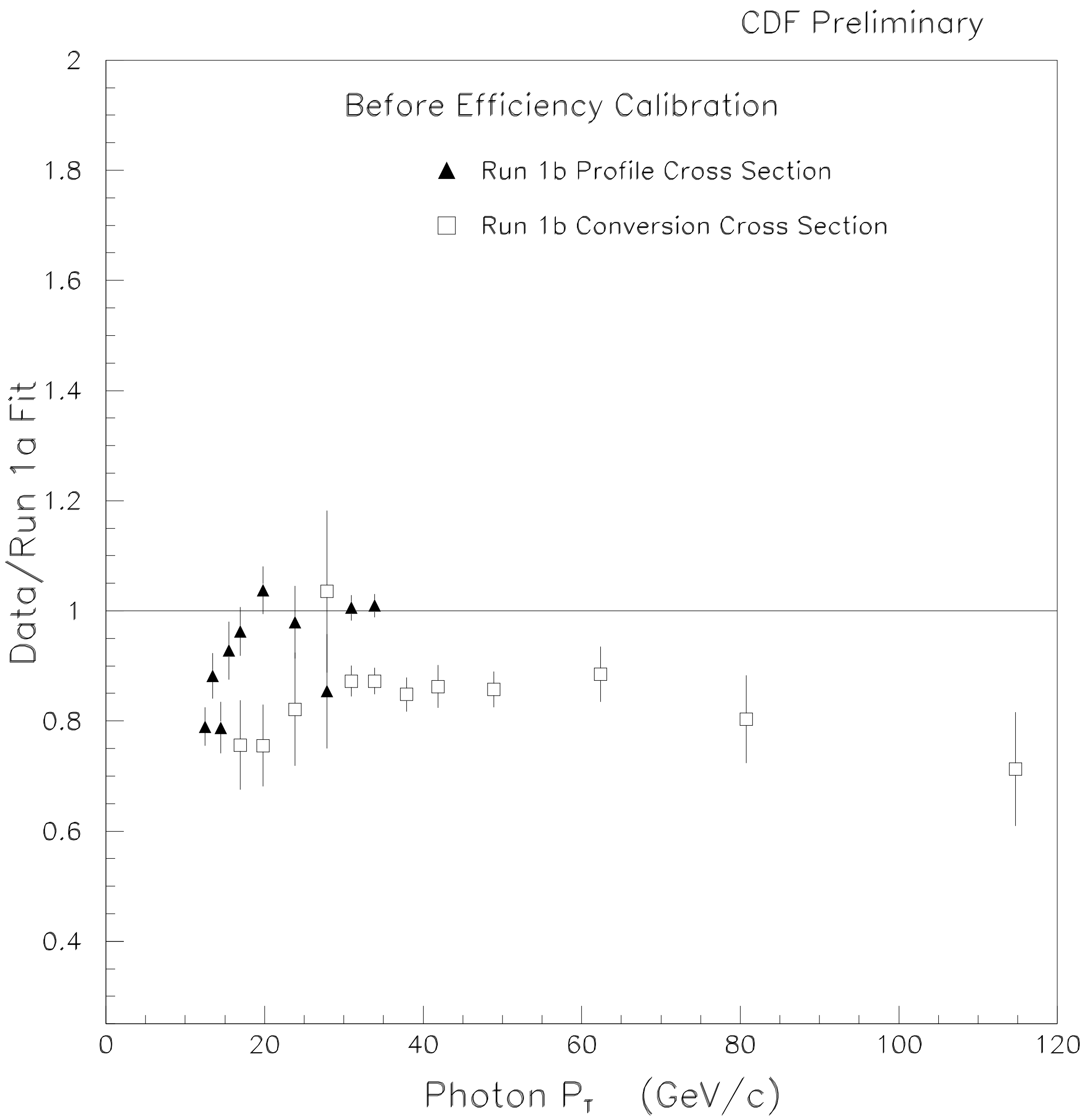
- Use $\rho^{\pm} \rightarrow \pi^{\pm}\pi^{0} \rightarrow \pi^{\pm}\gamma\gamma$ to check efficiencies
- Compare efficiencies from ρ peak to expected efficiencies
- Change both signal and background efficiencies to correct for discrepencies



	Measured	Expected	Difference
Profile	0.458 ± 0.009	0.472	-2.97%
Conversion	0.866 ± 0.006	0.838	+3.34%

CDF Data Analysis: Calibration

Profile and Conversion cross sections before recalibration (normalized to 1A fit).



CDF Data Analysis: Calibration

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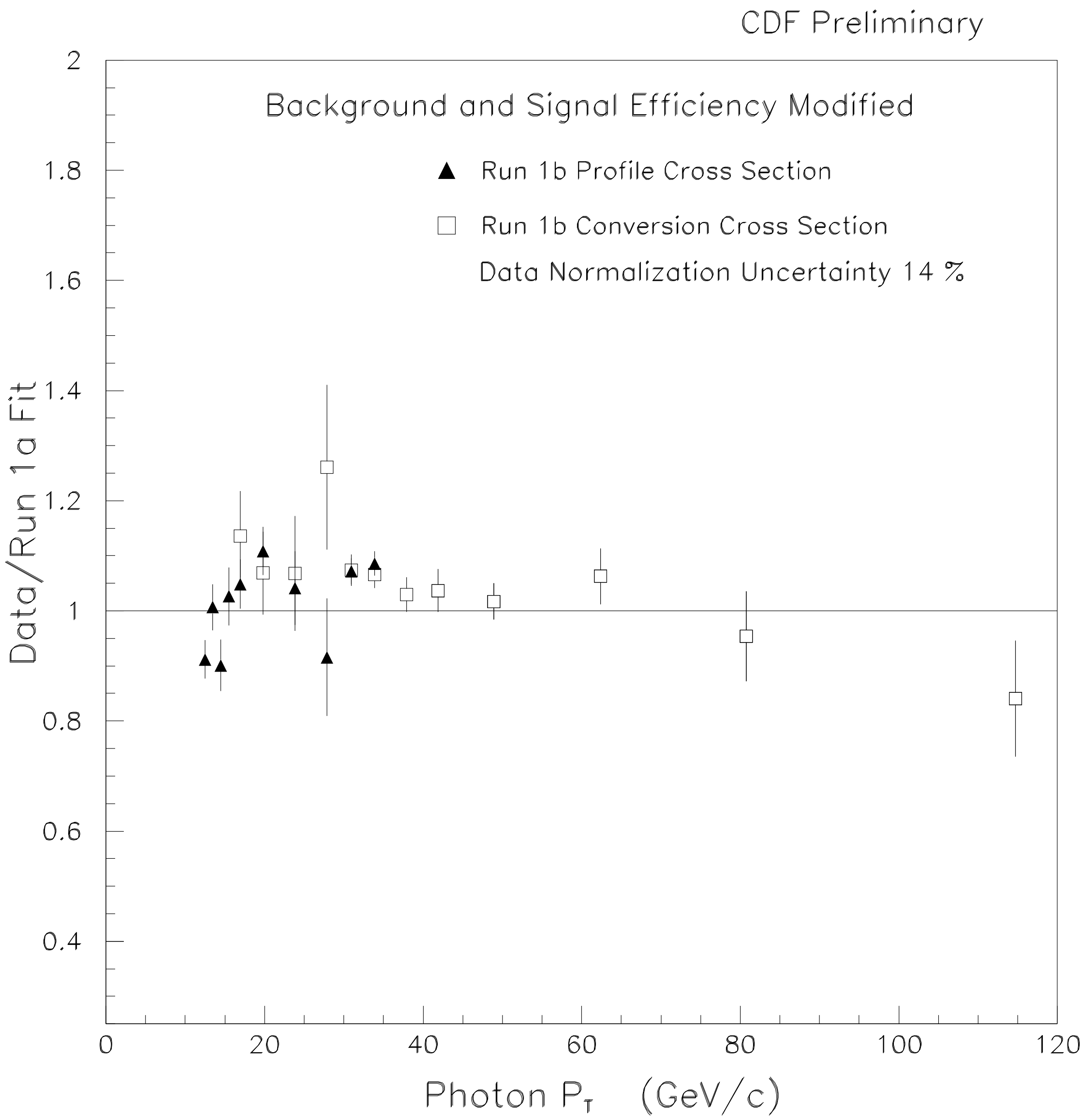
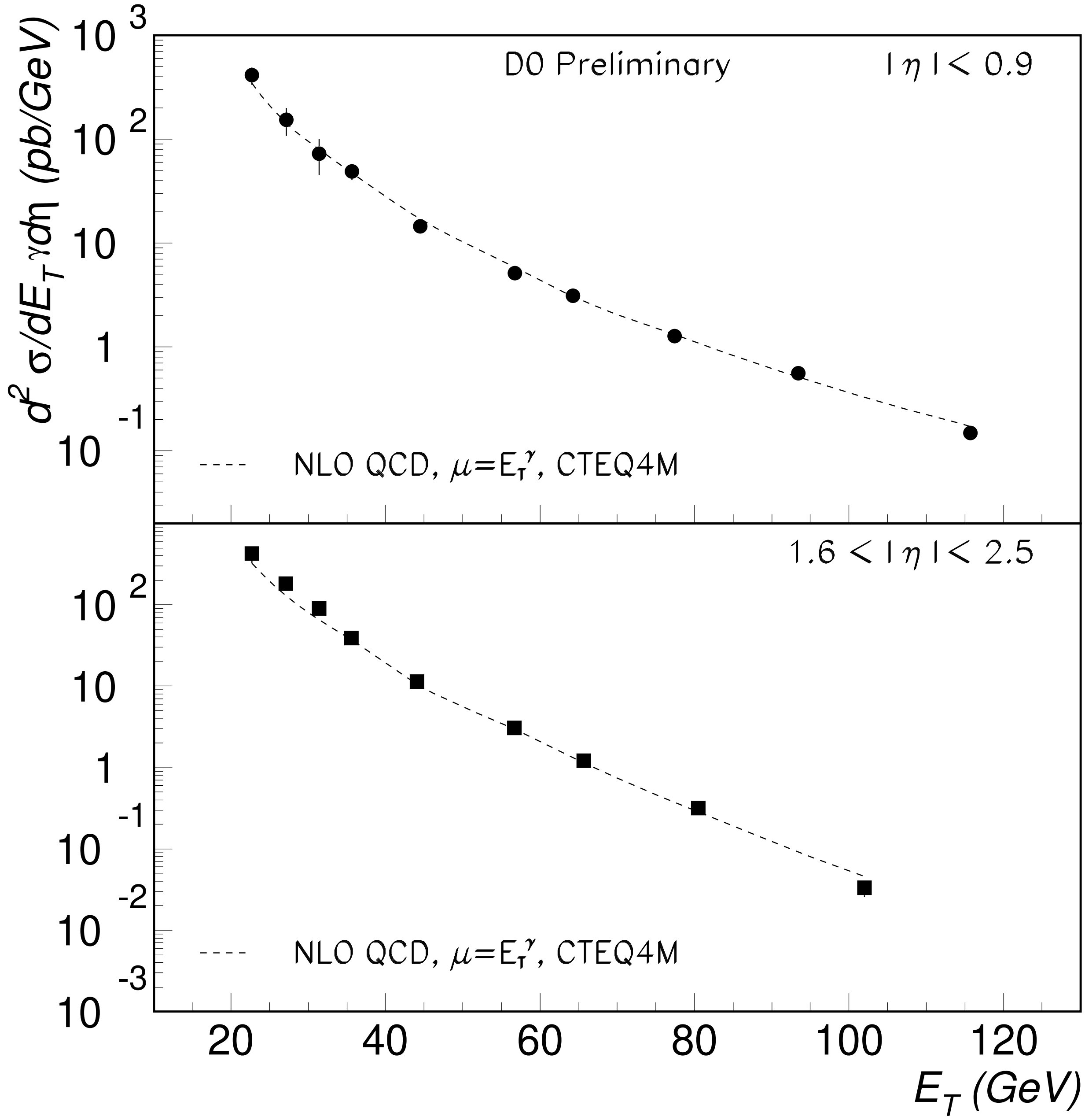


DØ Inclusive Photon Cross Section

The resulting cross section is compared to NLO predictions of Baer, Ohnemus, and Owens.



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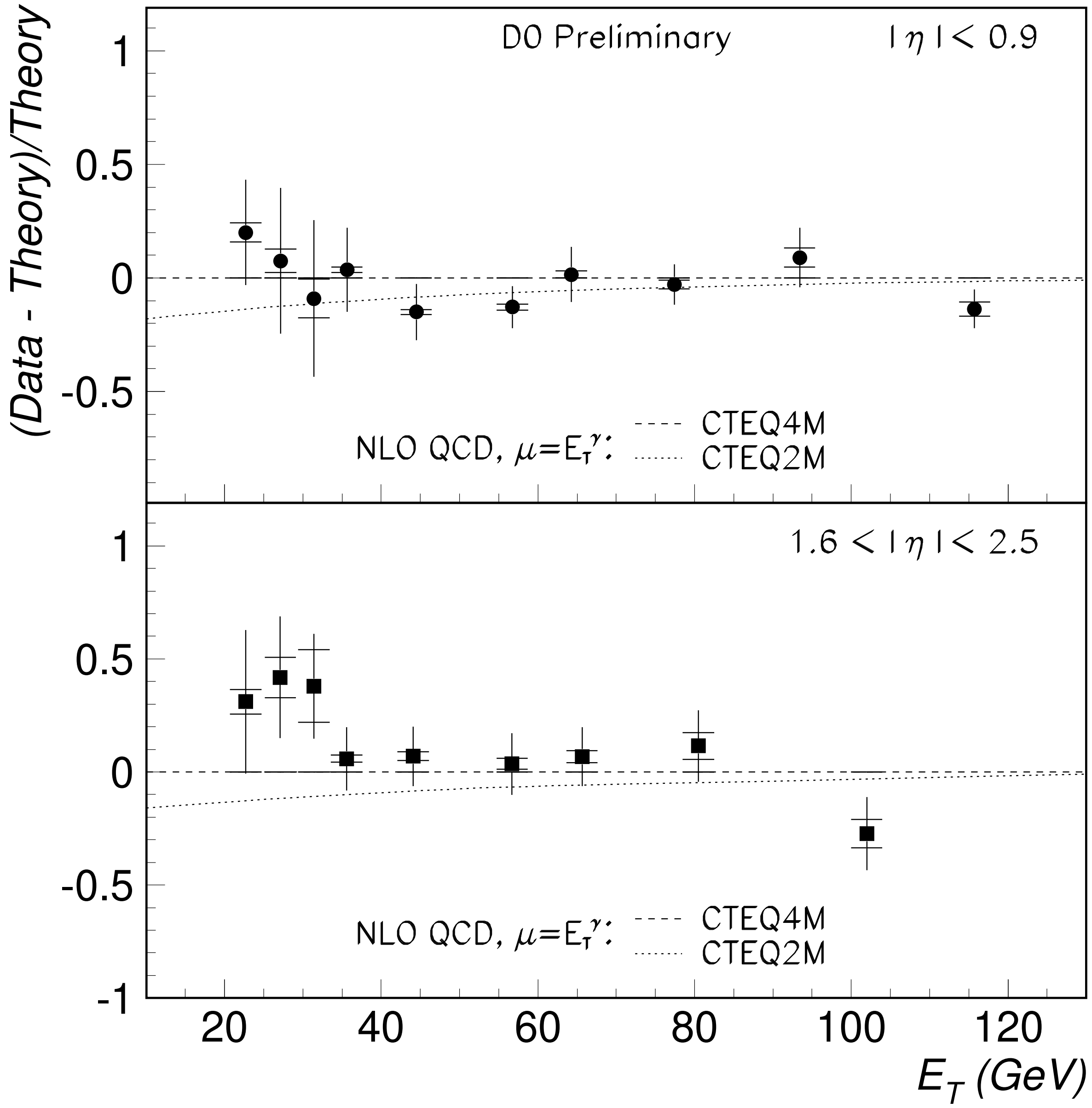
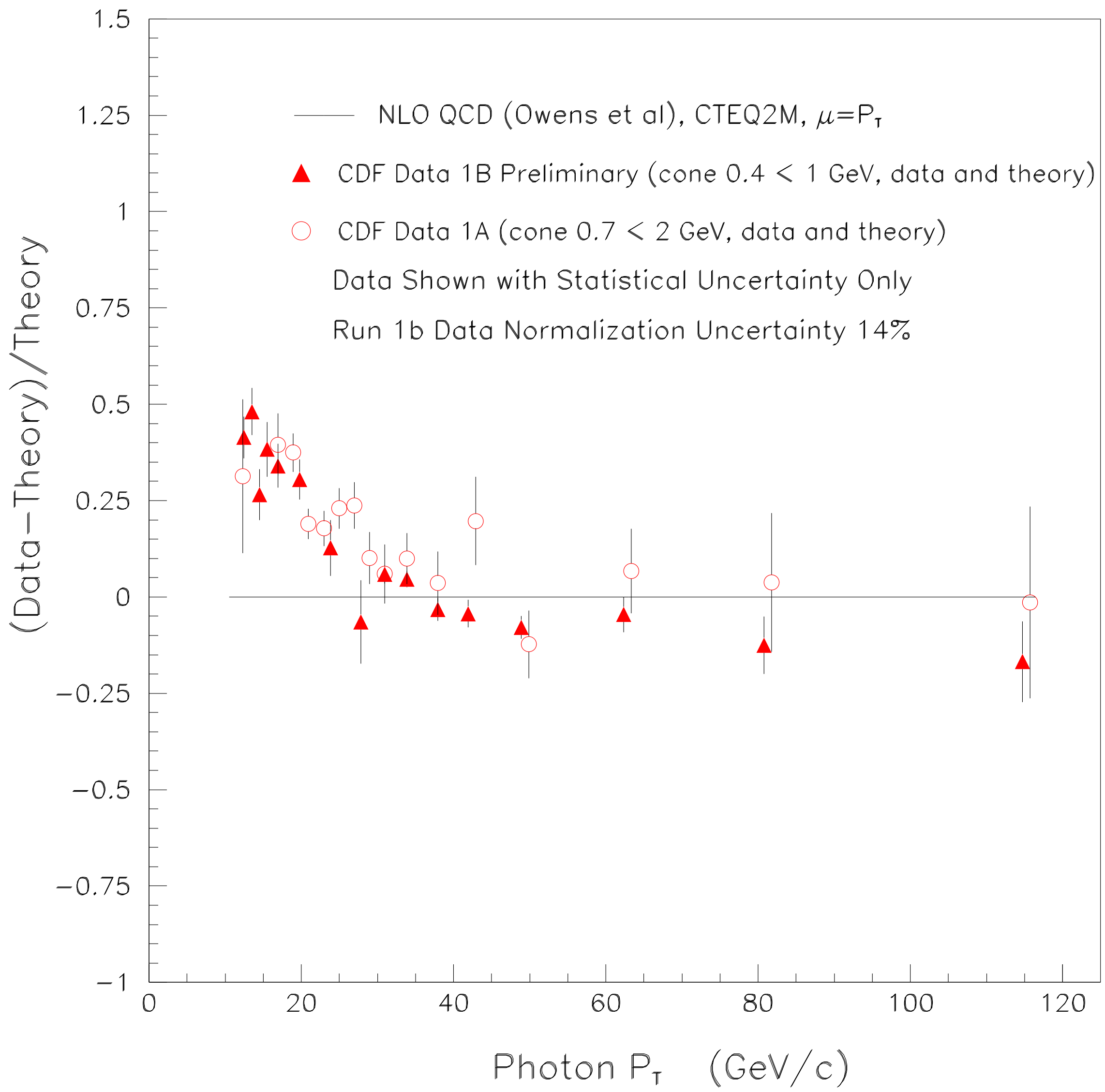


CDF Inclusive Photon Cross Section

Comparison of 1A and 1B data to theory used for original 1A analysis (CTEQ2M)



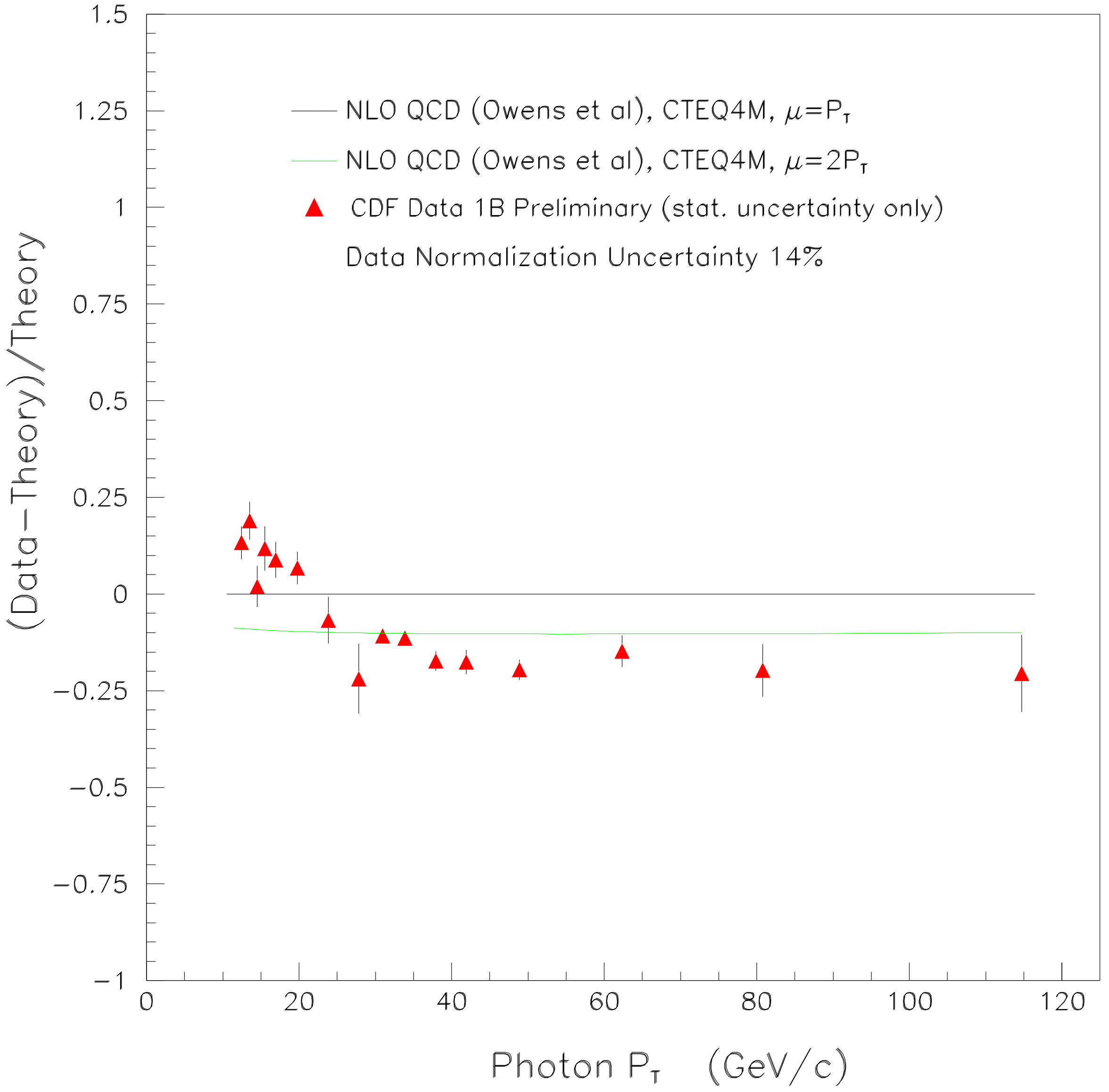
CDF Inclusive Photon Cross Section

Evolution of Theoretical Calculations Since Run 1A

- Changes in Owens et.al.
  - Changing isolation cut increased normalization by 10%
  - Lowering the cutoff of 2 $\rightarrow$ 3 body interaction increased normalization by 5 %
  - CTEQ2M to CTEQ4M increases slope by 15%
- Changes by Vogelsang et.al.
  - NLO fragmentation
  - Allow three theory scales to change

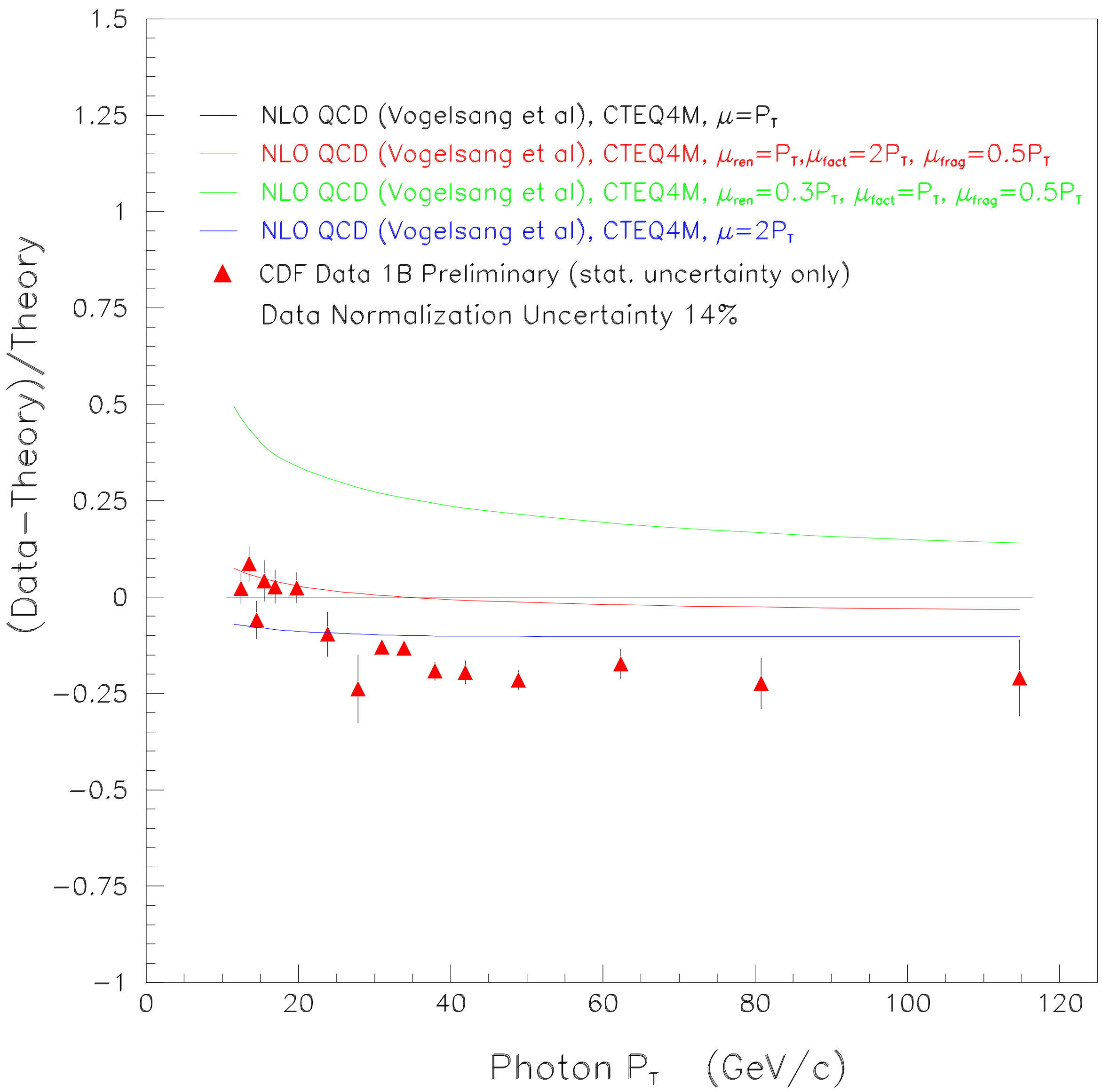
CDF Inclusive Photon Cross Section

Renormalization Scale Effects



CDF Inclusive Photon Cross Section

Theory Scale Effects



CDF Inclusive Photon Cross Section

Photon Selection and Background Subtraction
Systematic Uncertainties

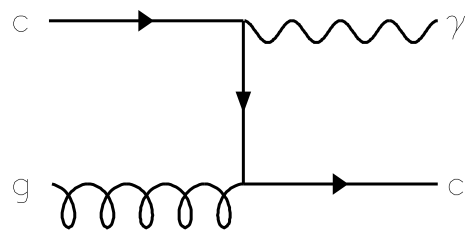
Systematic Uncertainty	
Trigger	5.0%
No track	1.0%
No CPR track	0.4%
$\lvert Z_{\text{vertex}}\rvert < 60$ cm	3.1%
Isolation	0.3%
Extra strip/wire cluster	3.1%
Missing E_T/E_T	1.3%
Luminosity	7%
Total	9.3 %

CES and CPR Efficiency Systematic Uncertainties

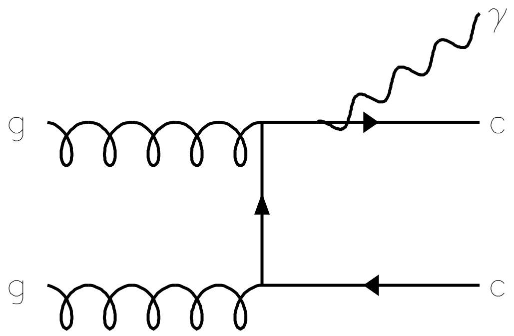
P_T	16 GeV/c	100 GeV/c
CPR and CES efficiencies	7%	4.5%
Backscatter	2%	2%
η/π^0	2%	0.2%
Back only/Sig+Back	5%	10%
Total	9%	13%

CDF Photon + Muon

Photon + Muon Production



$cg \to \gamma c \to \gamma \mu X$



$gg \to \gamma c\bar{c} \to \gamma \mu X$

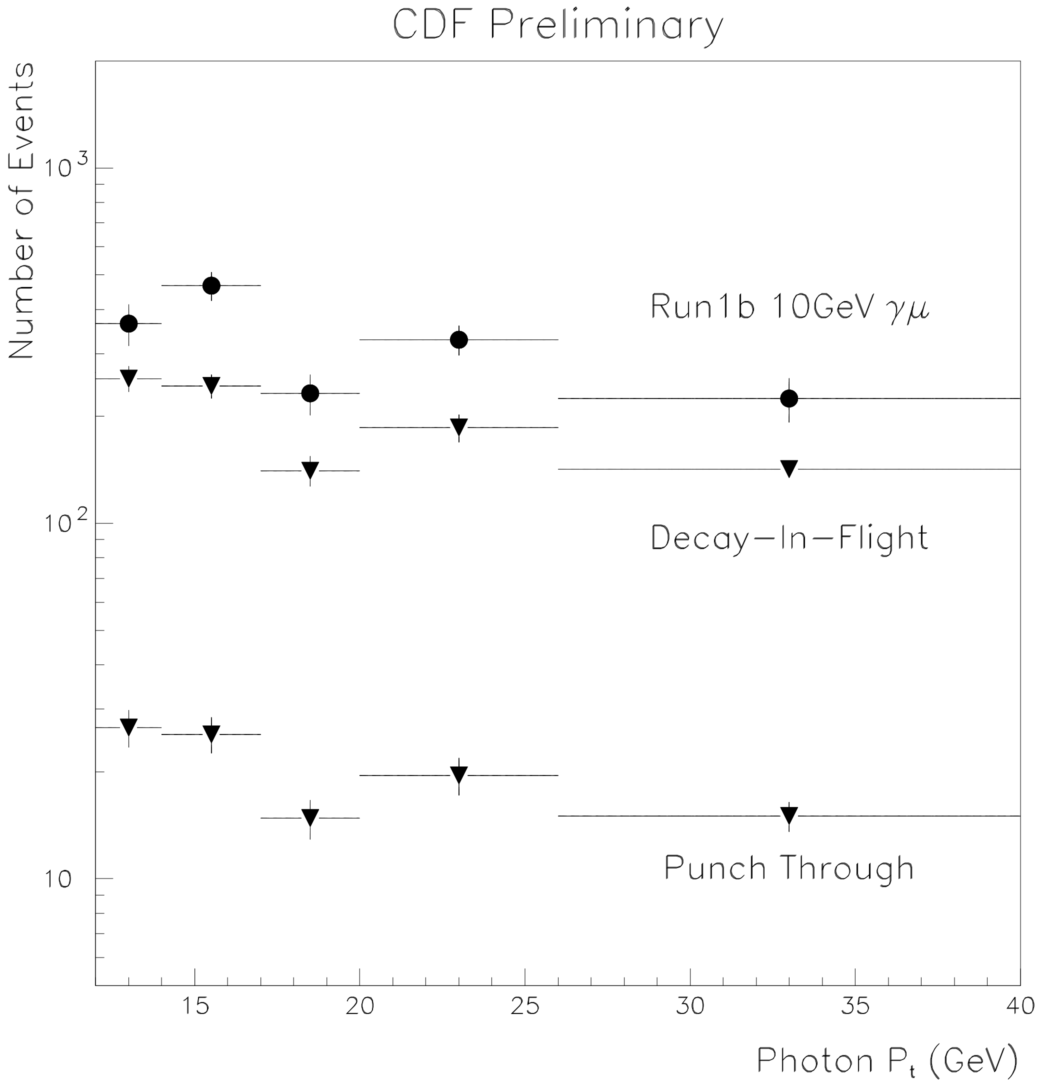
- Motivation is to measure the charm content of the proton
- NLO corrections are large due to $gg \to c\bar{c} \to c\bar{c} + \gamma$, where c-quark radiates a photon

CDF Photon + Muon

- Photon Selection:
  - $12 < P_T^\gamma < 40$ GeV
  - $|\eta^\gamma| < 0.9$
- Muon Selection:
  - Charged track in central trackin chambers matched to track in muon chambers
  - $P_T^\mu > 4.0$ GeV
  - $|\eta^\mu| < 1.0$

CDF Photon + Muon

Muon Backgrounds



- Muon Backgrounds from two sources
  - K/π Decay-In-Flight
  - Hadron Punch Through
- Backgrounds estimated from Monte Carlo
  - Use $K/\pi/P = 20/60/20$ (from E735, Tevatron, LEP)

CDF Photon + Muon

γ Efficiencies

Cuts	Efficiency
10 GeV photon trigger	0.86
Acceptance and cuts	0.41

μ Efficiencies

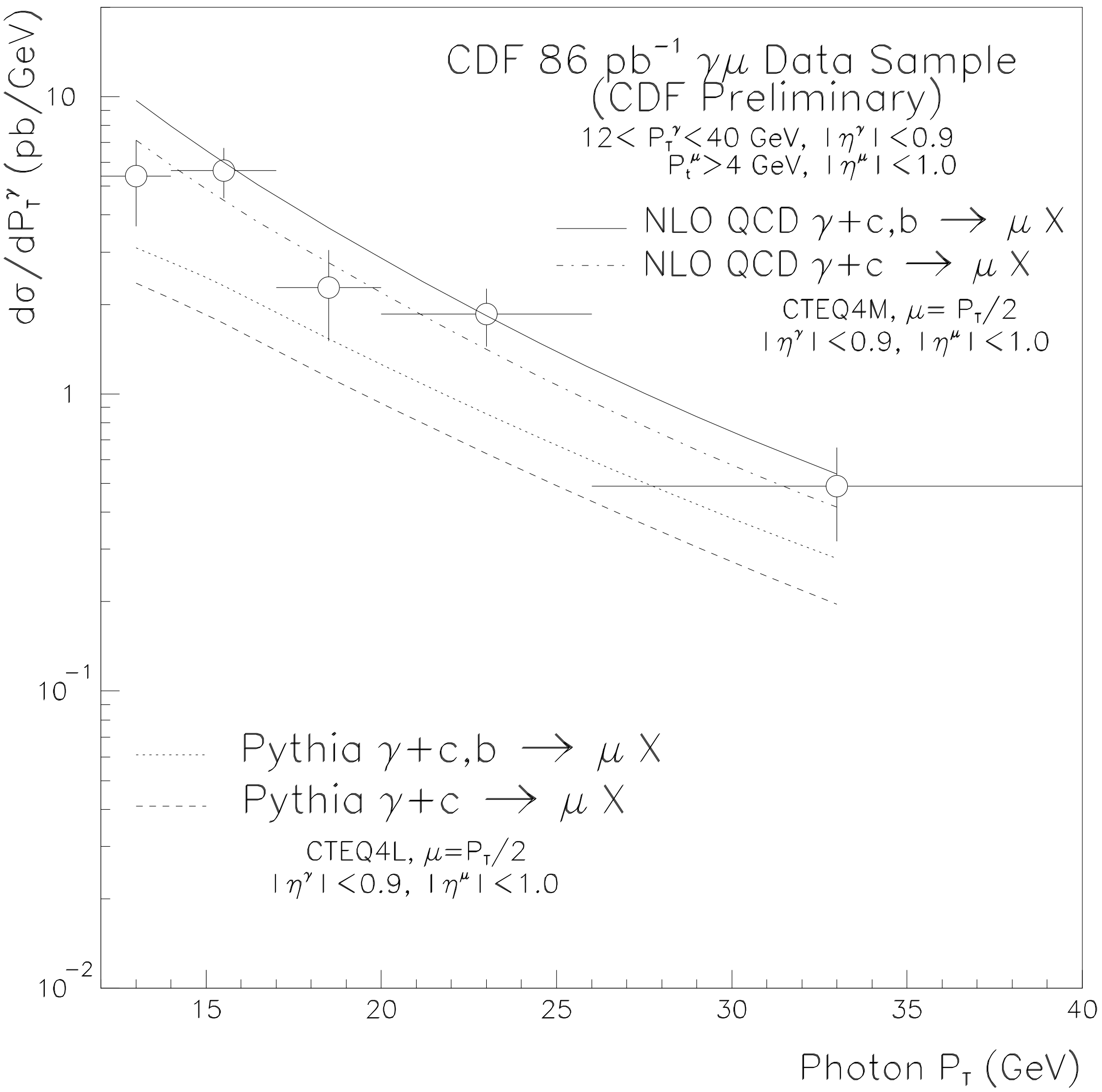
Cuts	Efficiency
Muon trigger	0.89
Acceptance and cuts	0.57

Systematic Uncertainties

Systematic Uncertainty	Errors
γ trigger, acceptance, and efficiency	5.3%
γ background subtraction	5.4%
μ trigger, acceptance, and efficiency	4.7%
μ background subtraction	4.6%
γ background subtraction (particle fraction)	14.5%
CDF Luminosity Measurement	4.3%
Total	17.2%

CDF Photon + Muon

Cross Section



Conclusions

- Single Photon Production
  - DØ and CDF produce consistent measurements
  - Data and NLO QCD agree for $E_T >\sim 30$ GeV
  - Data lie above theory at low E_T
  - Changing theory scales does not resolve low E_T problem
- Photon + Muon Production
  - Charm content of proton agrees with NLO QCD with current statistics
- Still have discrepencies between experiment and theory
- Photon production continues to be a fruitful arena for exploring QCD

Thanks to:

- CDF: Steve Kuhlmann, Dana Partos
- DØ: John Womersley, Pierrick Hanlet