Global Photon Summary

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(for the CDF/DØ/ZEUS/H1/E706 Experiments)

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Outline

- Physics Motivations for Prompt Photon Production
- Production Mechanisms for Prompt Photons
- Measurement Techniques for Isolated Photons
- Experimental Results
  - Part I. Prompt Photon Production at Tevatron
    - Summary of **CDF/DØ** Run 1 Photon Results and kT issues
  - Part II. Prompt Photon Productions at HERA
    - Summary of **ZEUS/H1** Photon Results and kT issues
- Summary and Outlook

Why High Energy Photons?

- Photons have a point-like coupling to the hard interaction, allowing for direct probes and precision tests of perturbative QCD

- As long as 20 years ago, prompt photon measurements were promoted as a way to:
  - avoid all the systematics associated with jet ID and measurement
    - Photon can be measured more precisely than jet.
    - emerge directly from the hard scattering without fragmentation
  - allows the potential for measuring the gluon distribution in the proton

- Photons have not been a simple test of QCD and have not given input to parton distributions, and they continue to challenge our ability to calculate within QCD

- In addition, we can search for new physics with photons in the final states
  - Higgs: H ® gg is a discovery channel at LHC
  - Recent SUSY Models: Supergravity Model (mSUGRA), GMSB Model
  - Technicolor: Photon + dijet signatures, Diphoton resonances
  - Large Extra Dimensions, etc ...

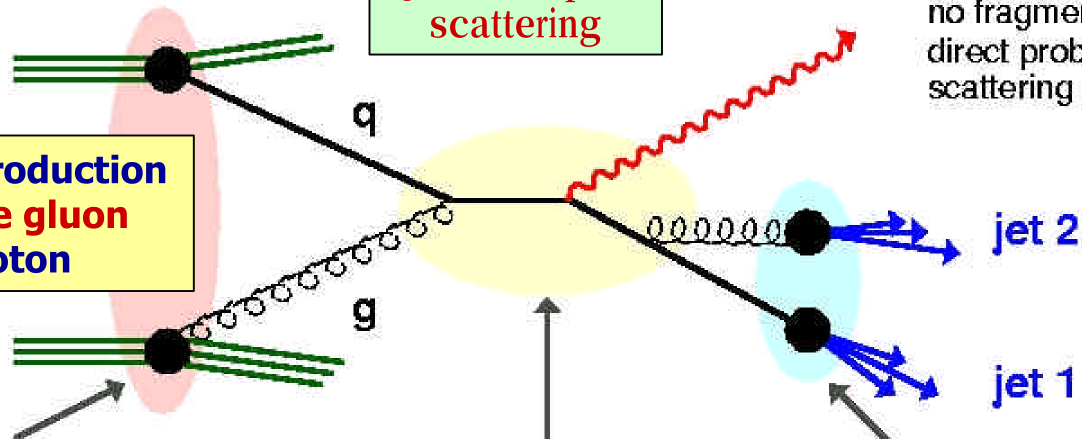
Prompt Photon Production at the Tevatron

e.g. $\bar{p}p \rightarrow \gamma + jet + X$

QCD Compton scattering

photon
no fragmentation $\rightarrow$ direct probe of the hard scattering process

Prompt photon production is sensitive to the gluon distribution in proton



Both the initial and final states can be colored and can radiate gluons

Parton Distributions
Non-perturbative, must be experimentally determined, but are universal

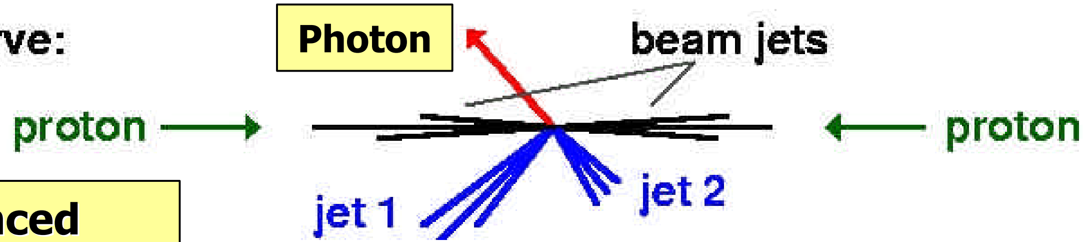
Hard scattering
High momentum transfer
Perturbative QCD

Fragmentation
(quark, gluon) $\rightarrow$ jet

Hadron collider is a broad-band quark and gluon collider

What we observe:

Photon



Recoil Jets

Photon is balanced by 1 or 2 jets in final state

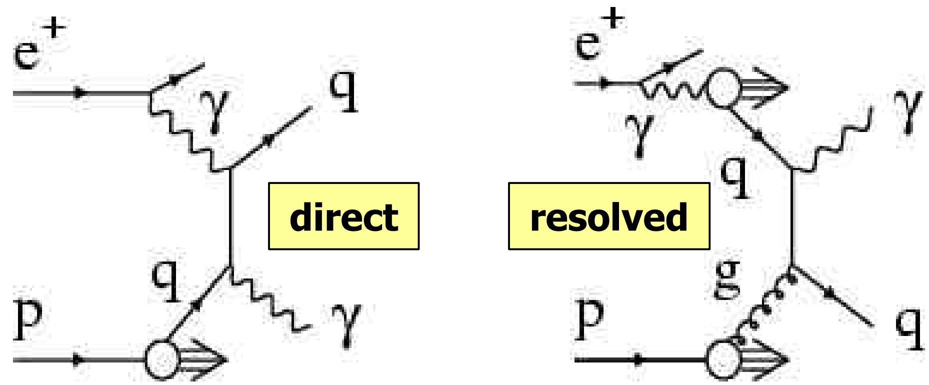
Prompt Photon Production at HERA

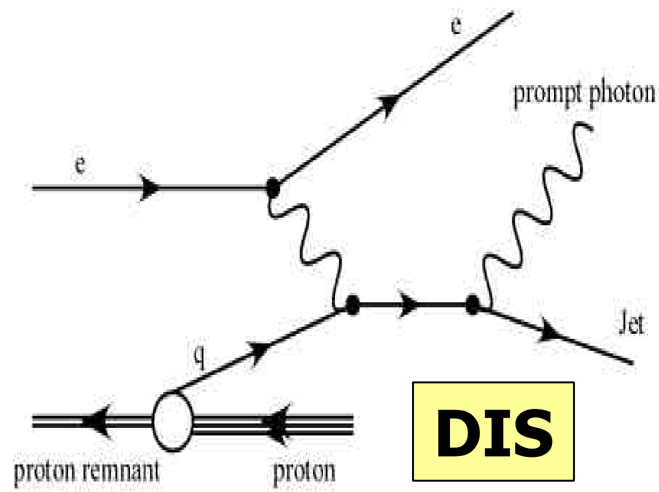
- Prompt photons can be produced in direct and resolved interactions.
- In photoproduction, only one LO direct process: "Direct Compton"
- HERA kinematics favor gluon from proton and quark from incoming photon (see resolved process)

- In DIS, prompt photons emitted by the direct process with no resolved contribution

- Sensitive to quark densities in photon at HERA
- The clean signature of the prompt photon can provide a good means to test QCD; photon structure, intrinsic parton momentum(k_T), NLO etc …

Photoproduction





* prompt photon is produced directly in the hard scattering

Photon Identification

- **Usually jet contains one or more π^0 mesons which decay to photons**
  - **we are really interested in <u>direct</u> photons (from the hard scattering)**
  - **but what we usually have to settle for is <u>isolated</u> photons (a reasonable approximation)**

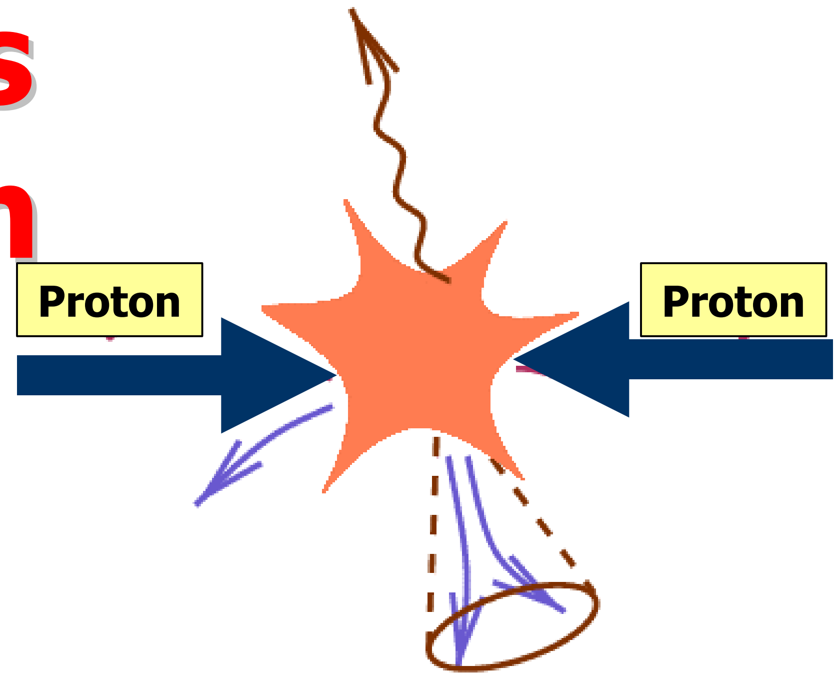
    Isolation: require less than e.g. 2 GeV within e.g. $\Delta R = 0.4$ cone

- **This rejects most of the jet background, but leaves those cases where a single π^0 or η meson carries most of the jet's energy**

- **This happens perhaps 10^{-3} of the time, but since the jet cross section is 10^3 times larger than the isolated photon cross section, we are still left with a signal to background of order 1:1**

- **There are a number of different technique to distinguish photons from π^0 backgrounds.**
  - **Conversion Probability: γ's to convert in a preshower detector**
  - **Shower Profile: 2 γ's from π^0 will produce EM showers with broader lateral and smaller longitudinal profiles**
  - **Reconstruction: requires good EM/angular resolution (fixed target)**

Prompt Photons at Tevatron



Probing QCD

- CDF/DØ Background Subtraction Methods
- Summary of CDF/DØ Run 1 Photon Results
- New puzzles from Tevatron photons
- Run 2a Photon Results, so far ...

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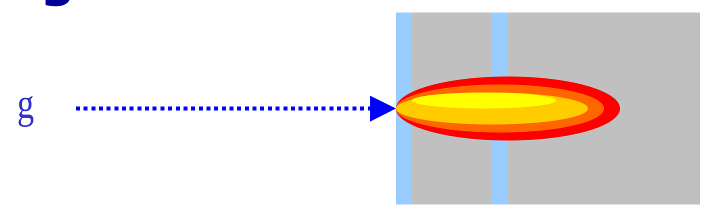
Signal and Background

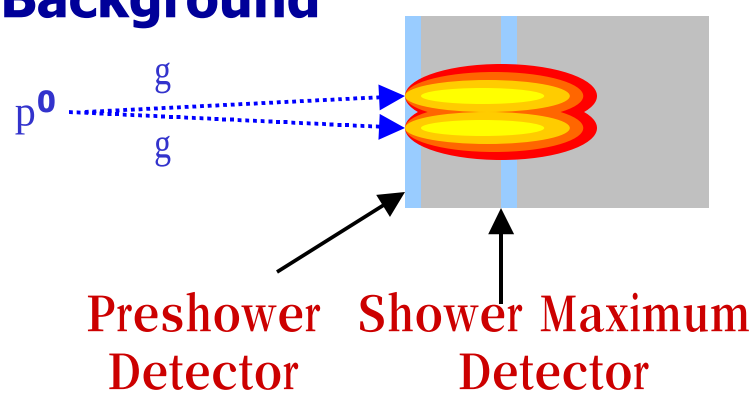
Photon candidates: isolated electromagnetic showers in the calorimeter, with no charged tracks pointing at them

Experimental Techniques in Run 1

- **Signal**



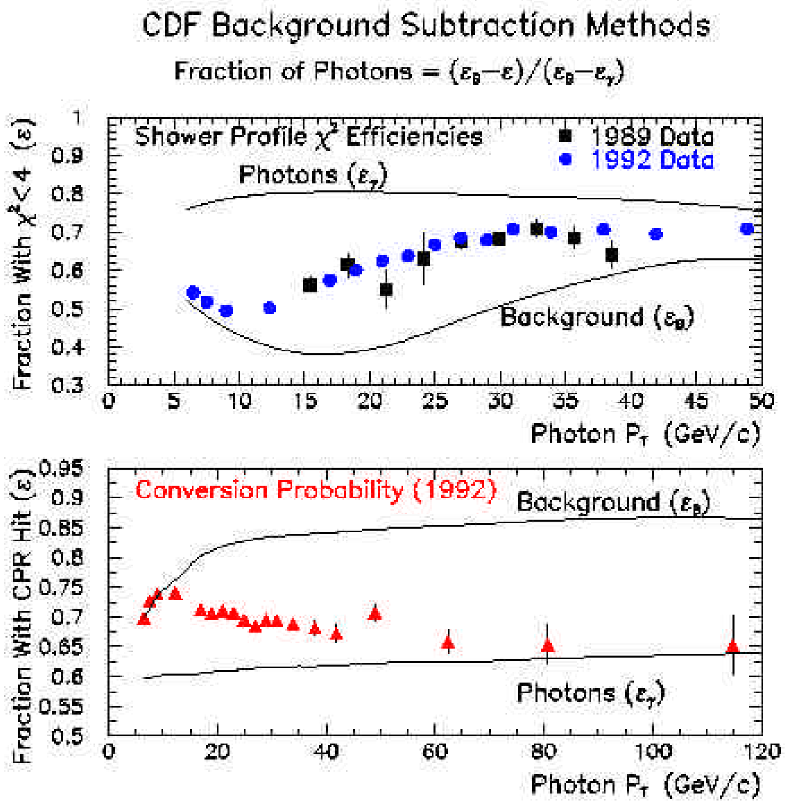
- **Background**



- **CDF/DØ** uses two techniques for determination of photon signal;
  1. EM Shower width
  2. Conversion Probability
- **CDF measures the transverse profile at start of shower (preshower detector) and at shower maximum**
- **DØ measured longitudinal shower development at start of shower**

Photon Purity Estimators

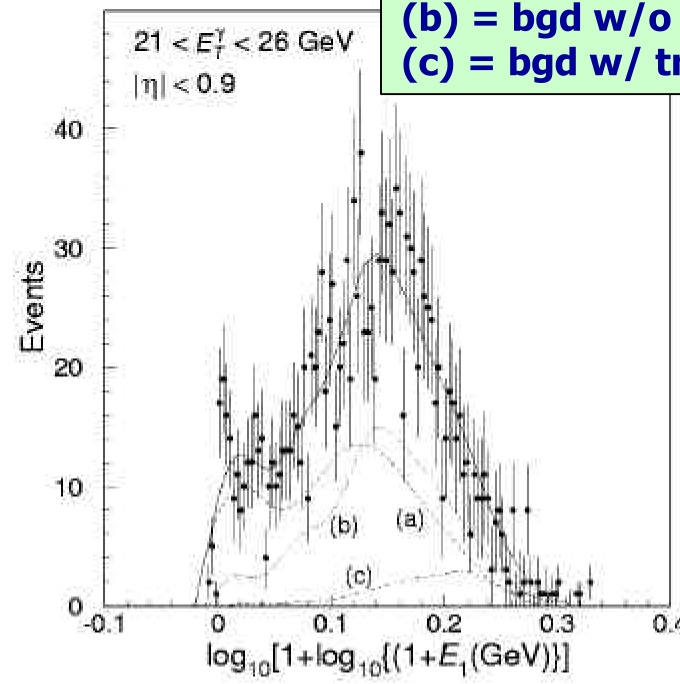
- **CDF**



For every photon, using the conversion and profile info., CDF find the fraction of candidates with this info. (extracted signals statistically)

- **DØ**

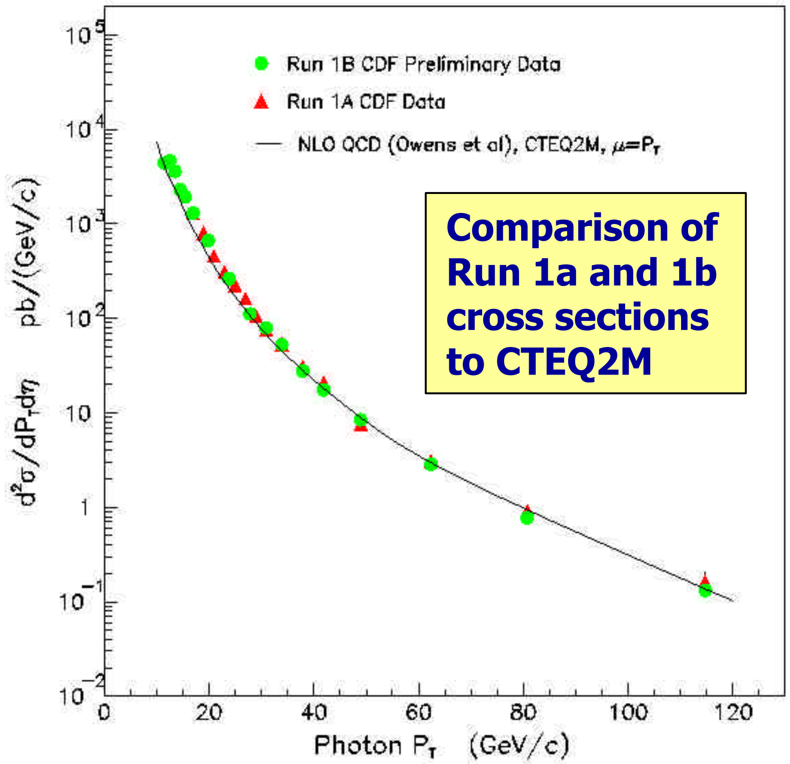
Each E_T bin fitted as sum of:
(a) = photons
(b) = bgd w/o tracks
(c) = bgd w/ tracks



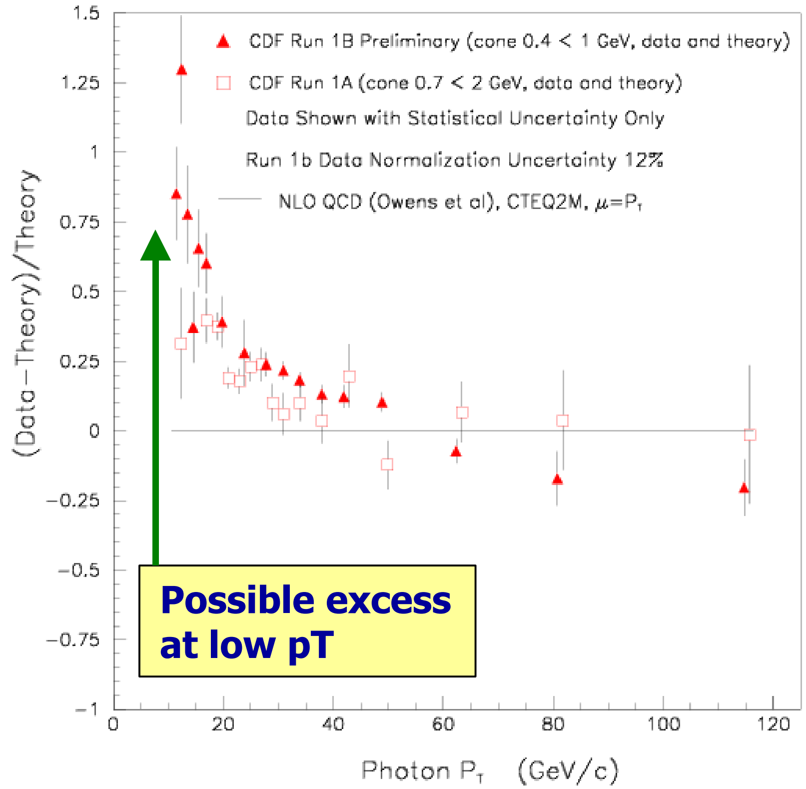
DØ model longitudinal energy depositions of photon's and jets and perform a statistical comparison to data using the discriminant variable to determine the photon purity.

CDF Photon Cross Sections at 1.8 TeV

- **CDF, PRD 65 (2002) 112003**



(Data - Theory)/Theory

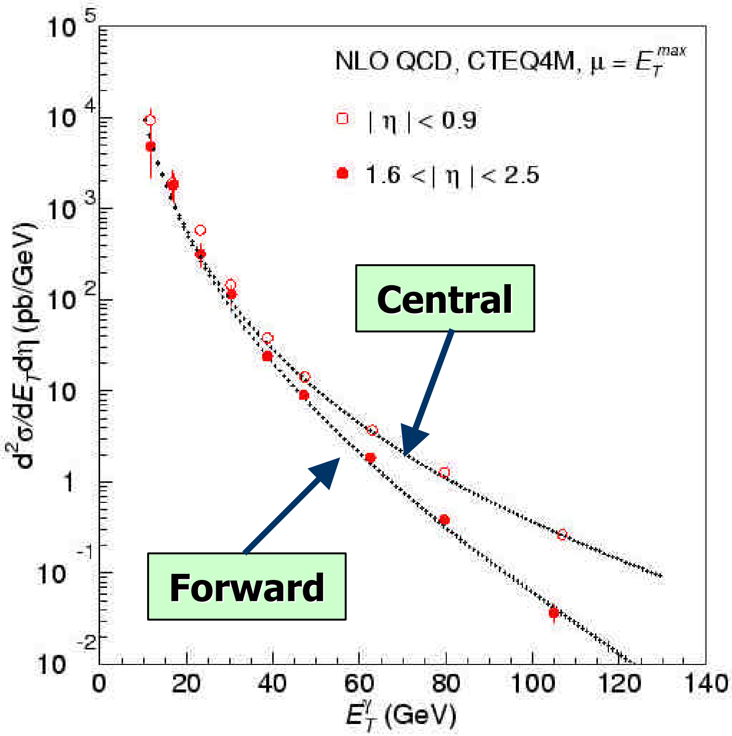


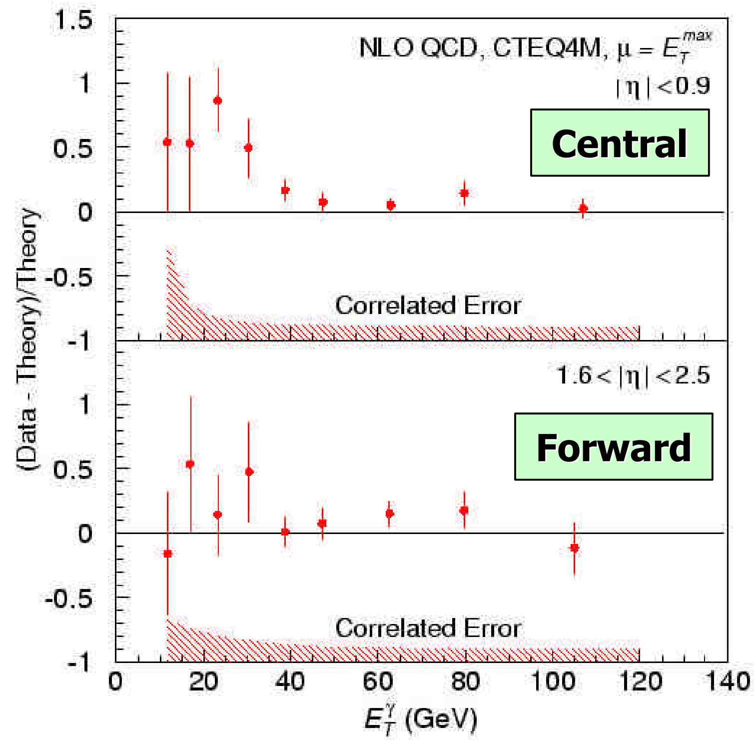
- **CDF data from Run 1b agrees with that from 1a and probe both low Et and high Et region in more detail. Results show agreement with NLO, but shape at low p_T is suggestive. What causes the apparent shape at low pT?**

DØ Photon Cross Sections at 1.8 TeV

- DØ, PRL 84 (2000) 2786

(Data - Theory)/Theory



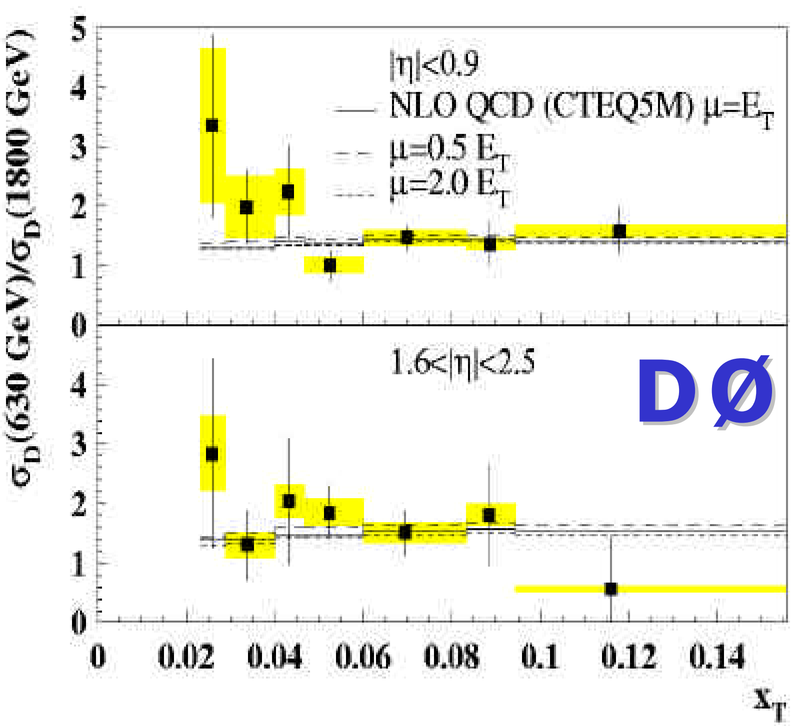


- The measured cross sections is in good agreement with NLO for Et > 36GeV
- The differences between the data and NLO for Et < 36 GeV suggests that a more complete theoretical understanding of the processes is needed.

DØ Prompt Photons at 630 GeV

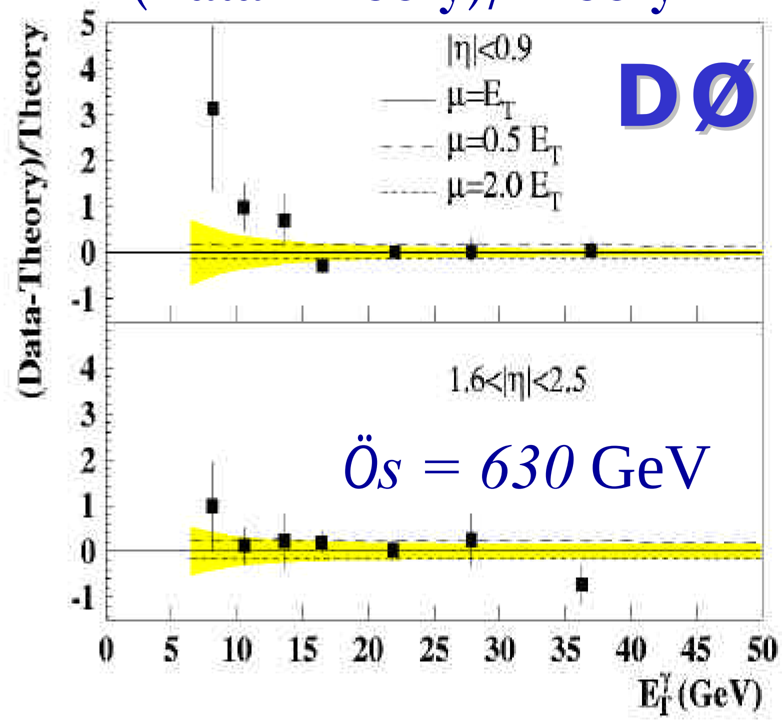
- **At the end of Run 1, CDF and DØ both took data at lower CM energy, Ös = 630 GeV**
- **DØ measured the photon x-sec at 630 GeV and compared to 1800 GeV photon x-sec.**

- Low xT deviations are not significant due to experimental uncertainties
- Good overall agreement with NLO pQCD



DØ, PRL 87 (2001) 251805

(Data - Theory)/Theory

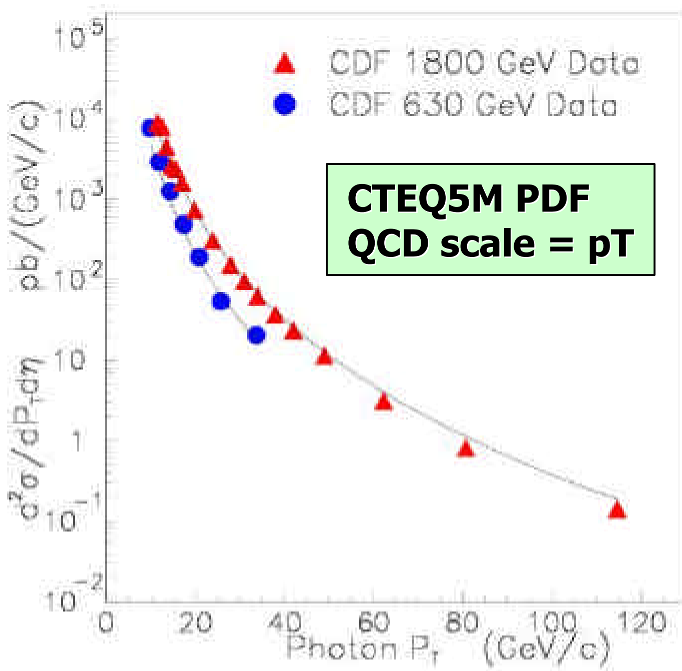


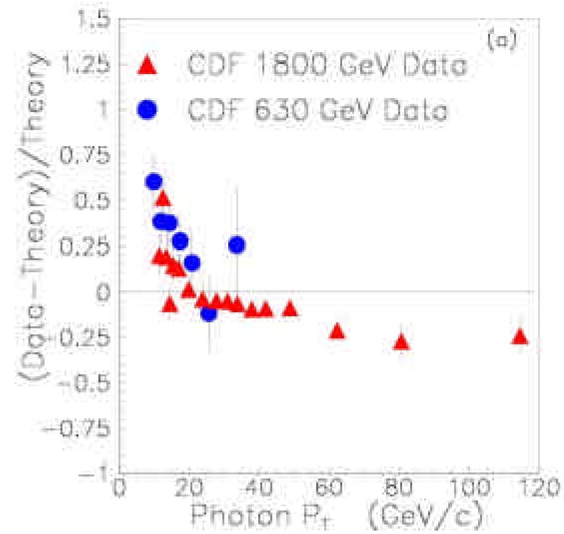
Measurement is higher than NLO at low Et in the central region but agrees at all other Et and in the forward region.

Comparison of Photons at 1.8 TeV and 0.63 TeV

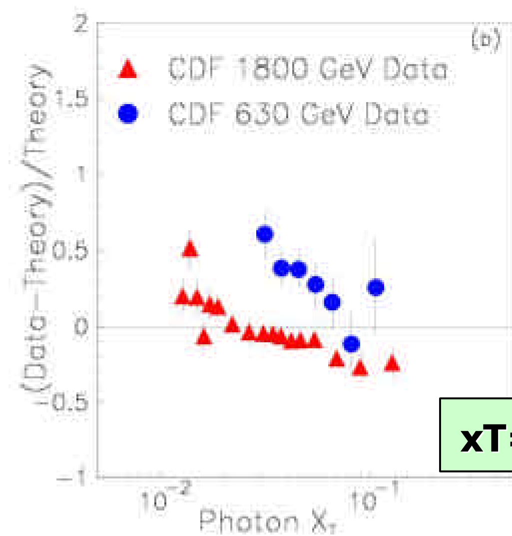
PRD 65, 112003 (2002)

- Inclusive photon cross section at the different Ös compared to NLO QCD predictions
- A comparison of the 1.8 TeV and 0.63 TeV data to a NLO QCD as a function of pT and xT





CDF

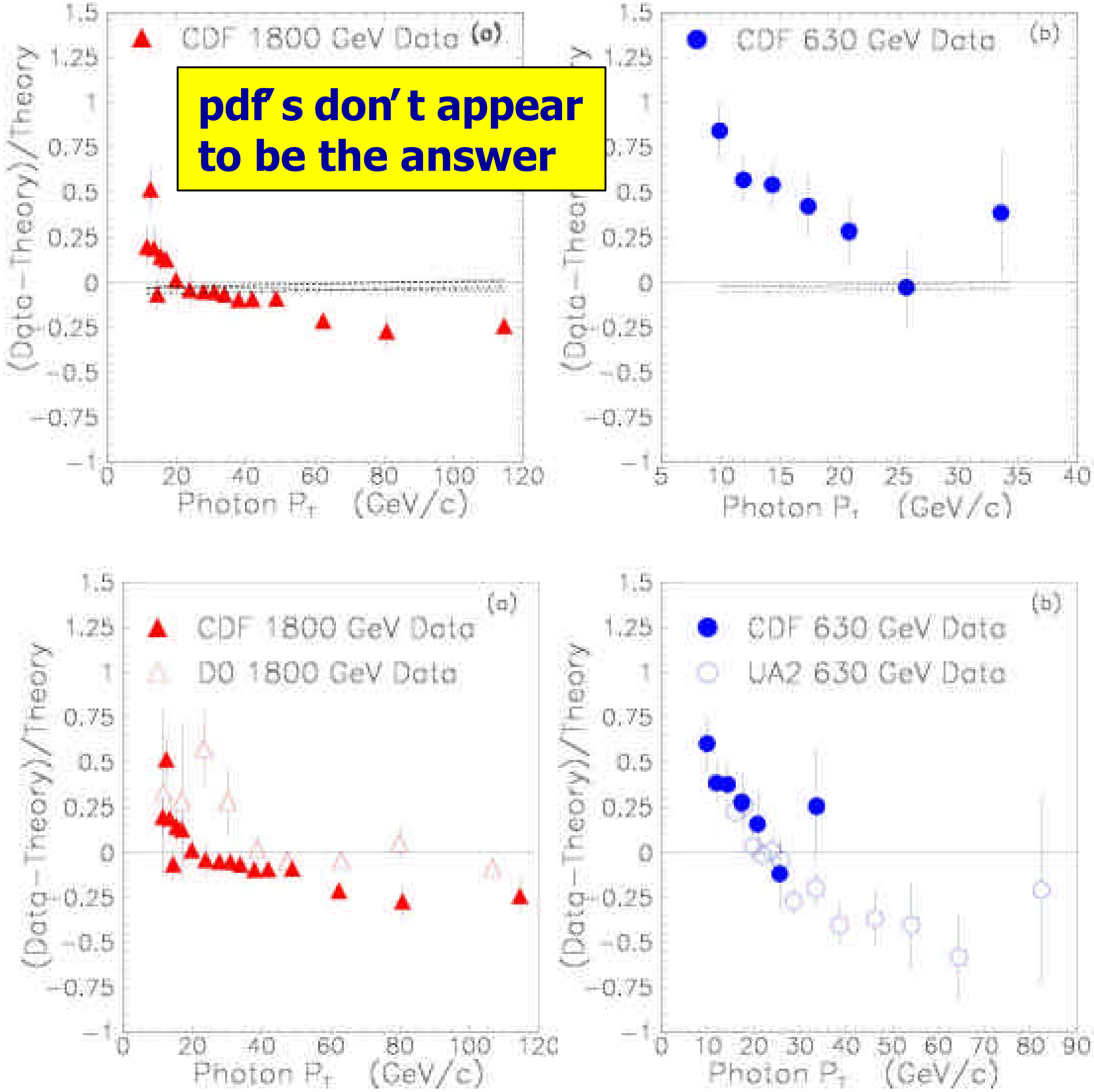


CDF

xT=2pT/Ös

- Deviations from predictions of NLO QCD
  - steeper slope at low p_T
  - normalization problem at high p_T at 1.8 TeV

CDF Results consistent those from DØ/UA2



A comparison of the 1.8 TeV and 0.63 TeV cross sections to NLO QCD using different PDFs;
CTEQ5M (Solid)
CTEQ5HJ, MRST99

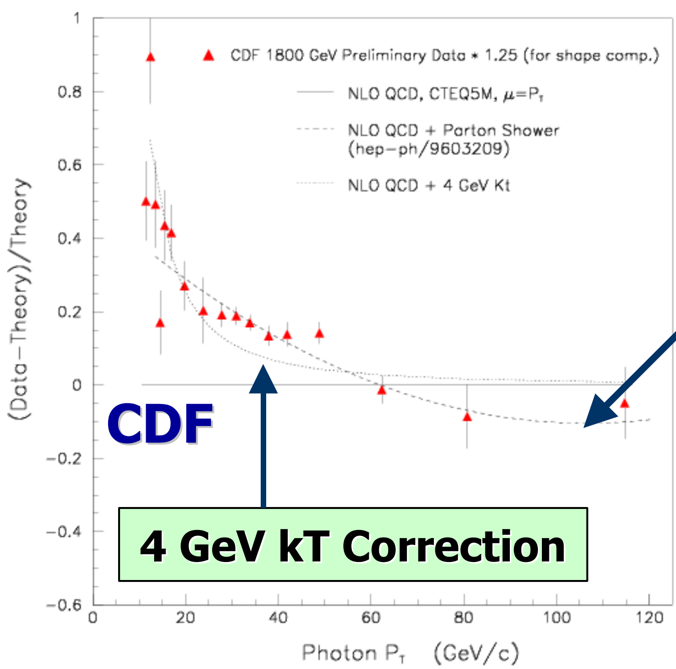
Many combinations of PDF and scales have been tried and none has been found that match the shape of data

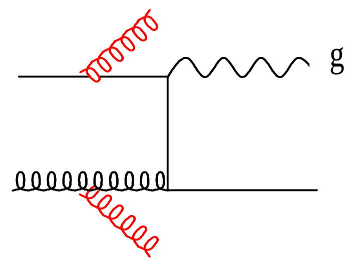
- CDF data agree well with the corresponding DØ and UA2 measurements.
- CDF and DØ data differ in normalization by ~20%, consistent with systematic uncertainties of measurement.

What's Happening at Low pT?

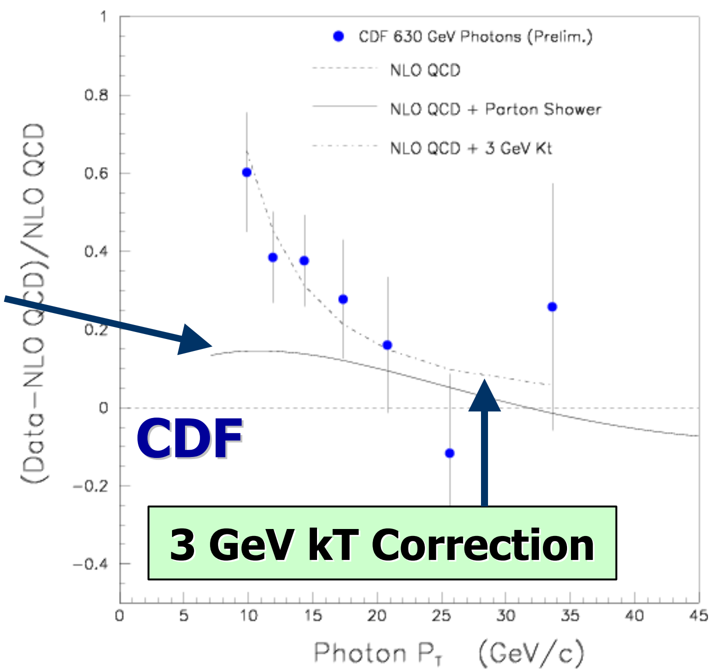
One possibility is an incomplete description of the initial state parton shower in NLO QCD calculation with possible kT recoil effect.
(see k_T Effects in Direct-Photon Production, PRD59 (1999) 074007)

kT denotes the magnitude of the effective transverse momentum of the colliding partons; Gaussian smearing of the transverse momenta by a few GeV can model the rise of cross section at low E_T



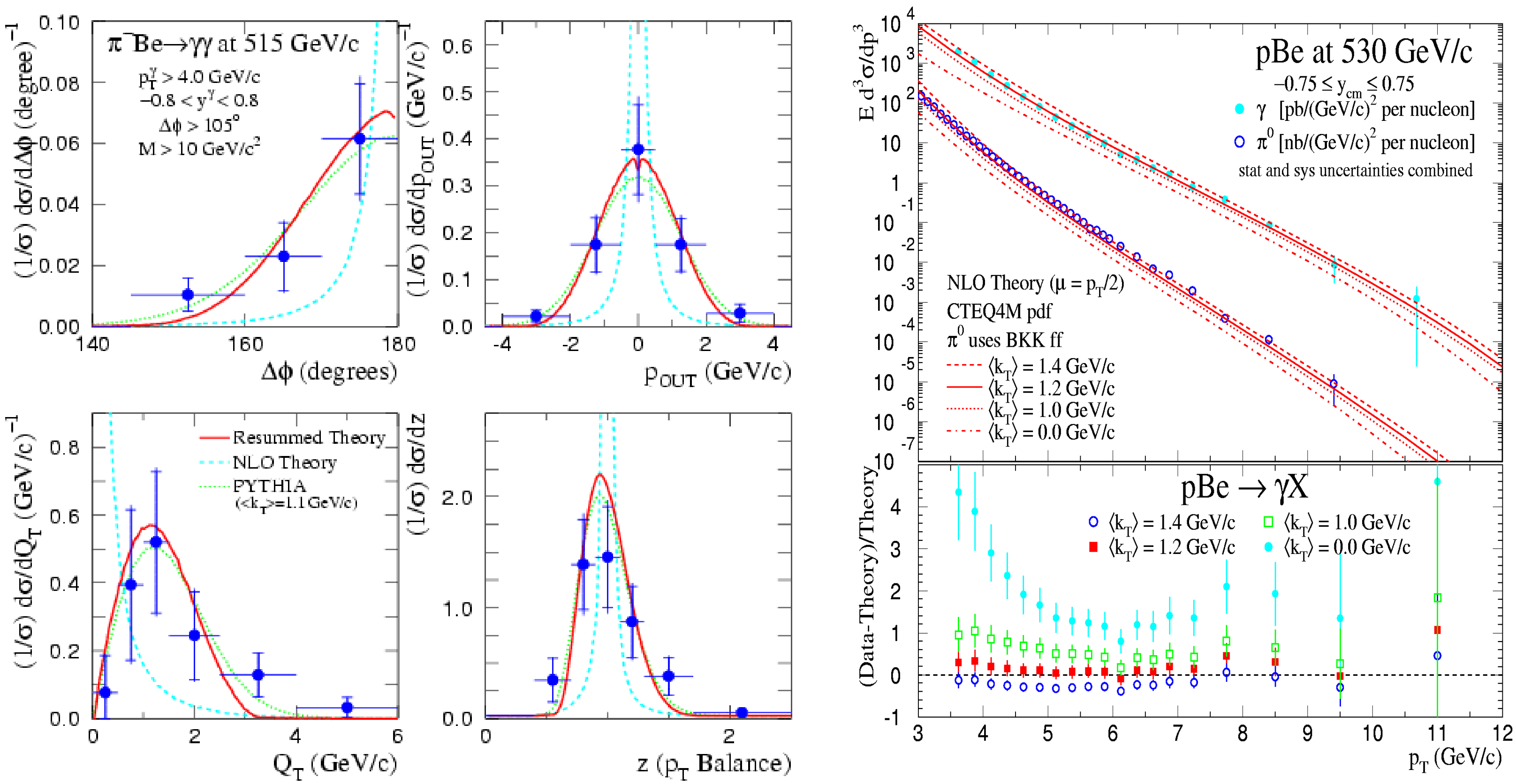


Parton shower (Baer and Reno)



Fixed Target Photon Production

- **Even larger deviations from QCD observed in fixed target (E706)**

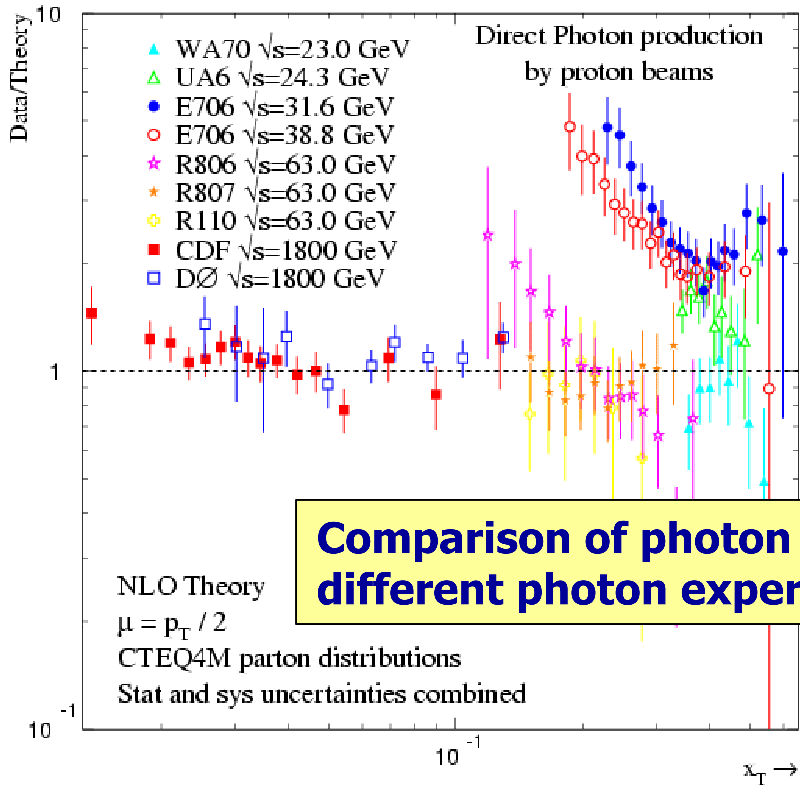


- **Again, Gaussian smearing (~1.2 GeV) can account for the data.**
- **Theoretical uncertainties are too large to use prompt photons to determine the gluon distribution.**

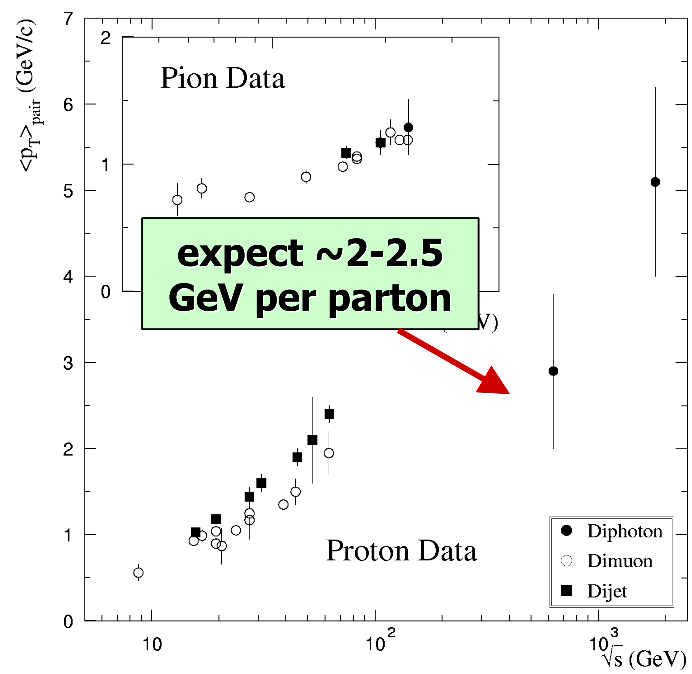
Direct Photons and Parton k_T

- The Tevatron exp. highlight serious limitations of current QCD description of prompt photon production
- One offered explanation is that the partons in the proton may have a considerably higher kT **due to soft gluon radiation at low pT**

- $<k_T>$ increase as approximately logarithmic with Ös
  - 1 GeV for fixed target
  - 2.5 GeV at Ös = 630 GeV
  - 3~4 GeV for TeVatron at Ös = 1.8



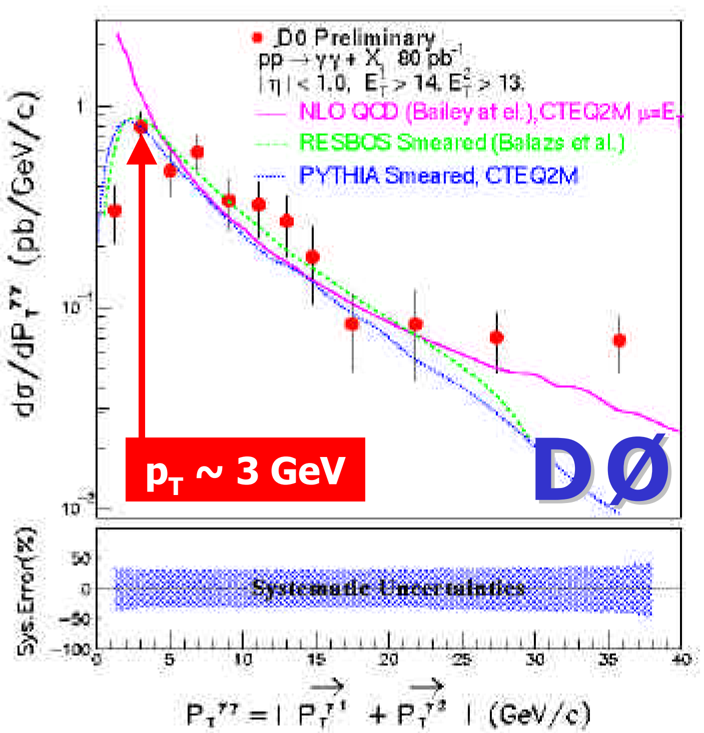
Comparison of photon XT for different photon experiments

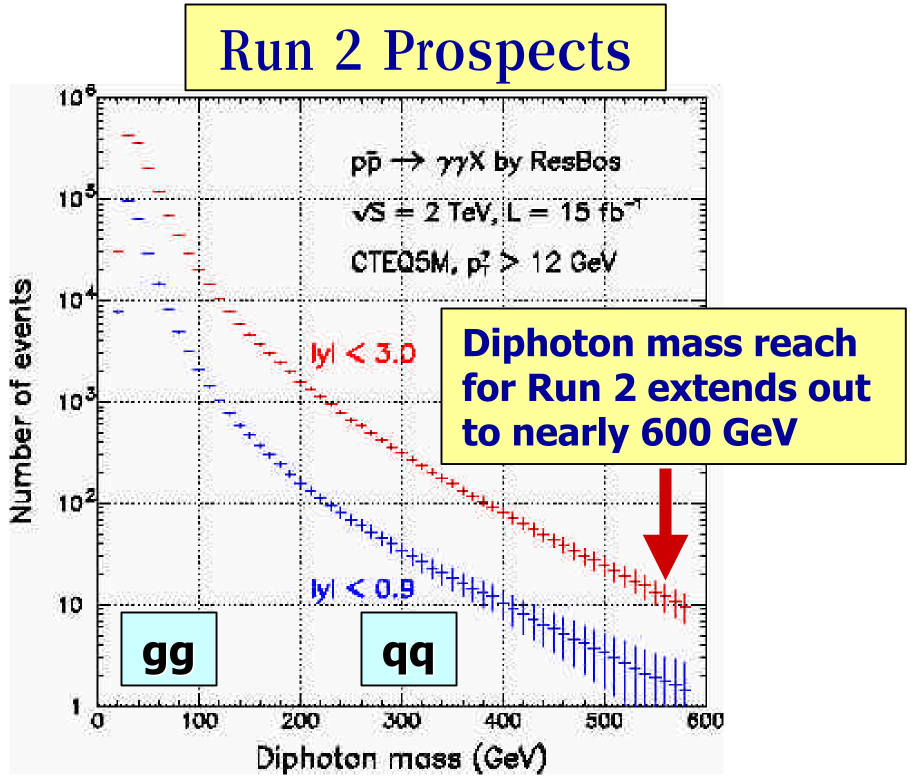


Gaussian smearing of kT gives good agreement with Tevatron photon data

Diphoton Production at the Tevatron

- **Diphoton production is interesting both for QCD tests and searches for new phenomena, but rate is very small (few hundred events in Run I)**
- **The final state kinematics can be completely reconstructed (mass, p_T and opening angle of gg system)**



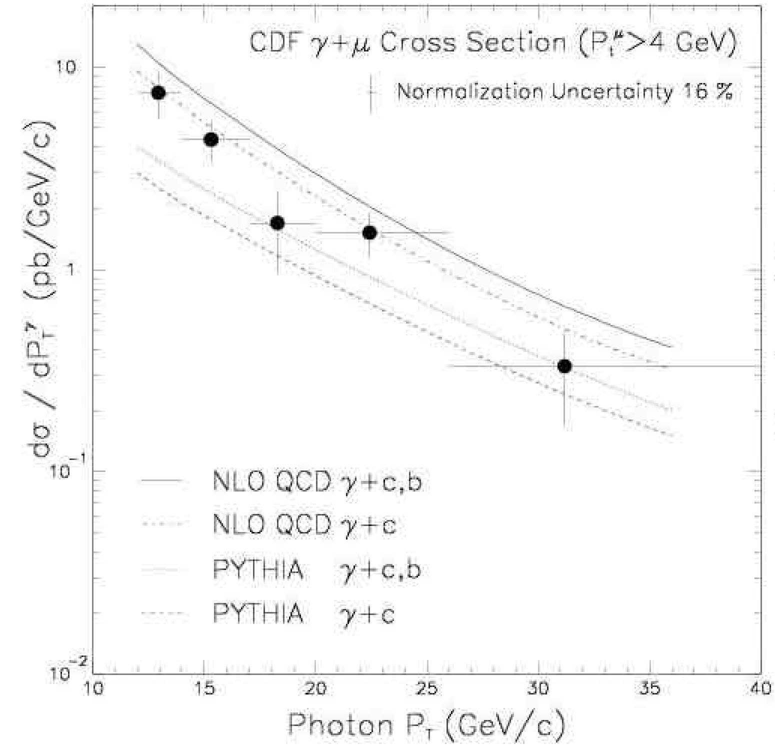


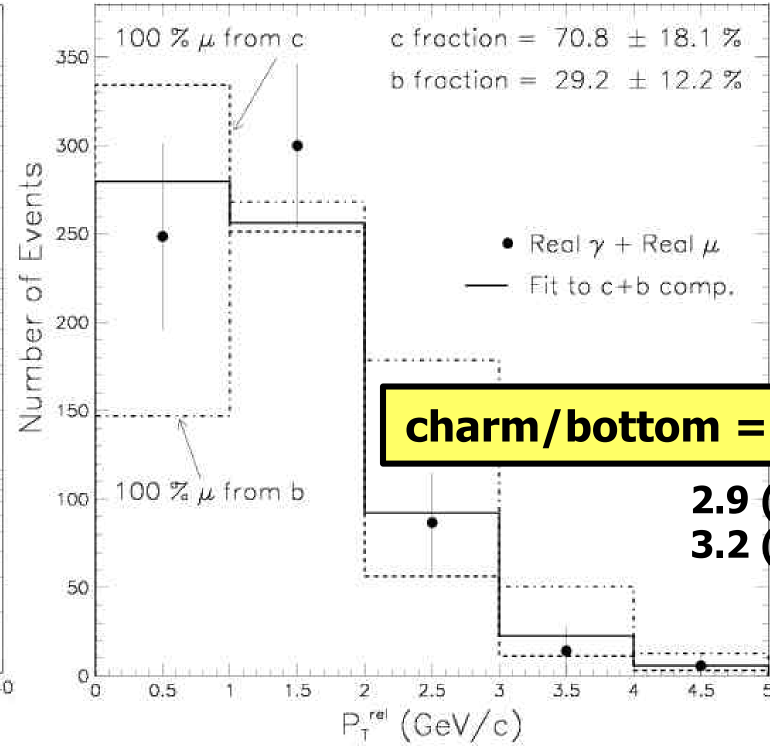
- **Need a resummation approach (RESBOS) or parton shower MC (PYTHIA) or ad hoc few-GeV k_T smearing**

PRD 65, 012003 (2002)

CDF Photon + Heavy Quark

- The 1st measurement of Heavy flavor contents of associated photon+muon events
- The events are due to Compton Scattering process cg->c(->m) + g





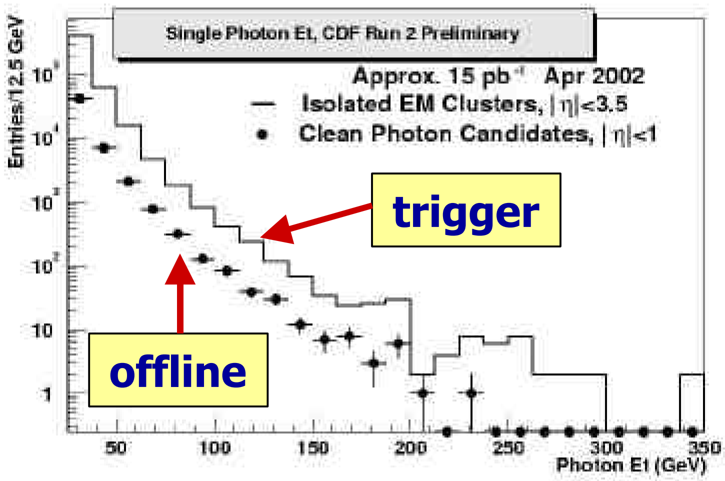
charm/bottom = 2.4 ± 1.2

2.9 (PYTHIA)
3.2 (NLO QCD)

The shape of the data agree with theory predictions, but fall below the theory in normalization by 2 standard deviations.

A significant fraction of the events contain a final-state b quark. The ratio of c to b is in good agreement with QCD

Run II CDF Photons

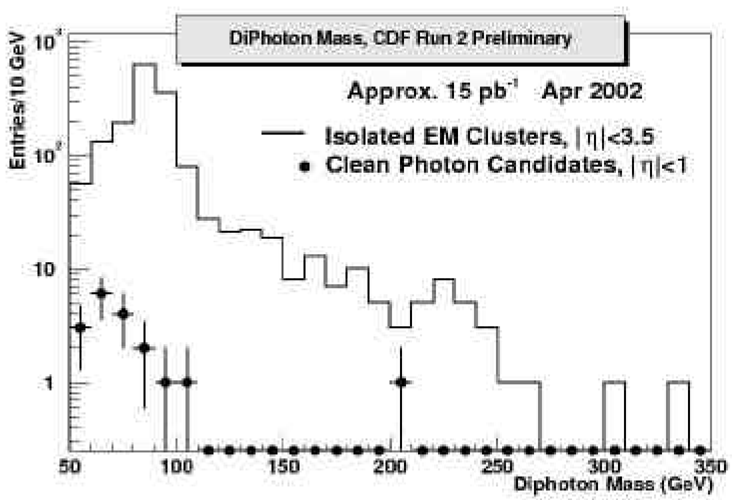


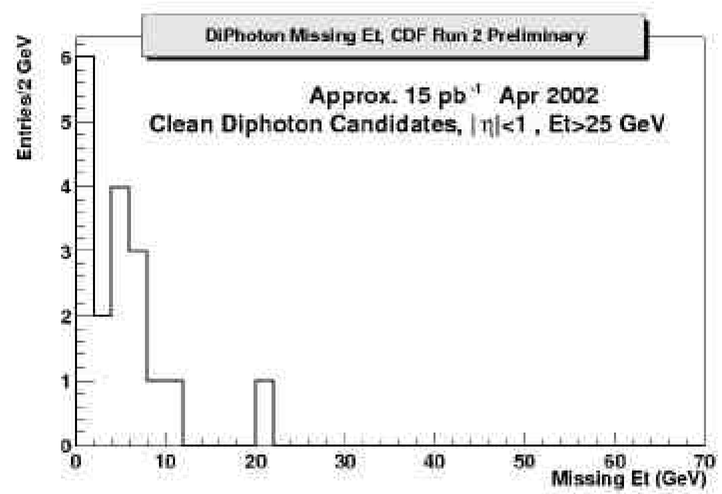
Data from Aug 8 – Apr 5 (15 pb^{-1})

Inclusive photon sample
- cal/tracking Iso, HAD/EM cuts
- results are similar to Run 1B

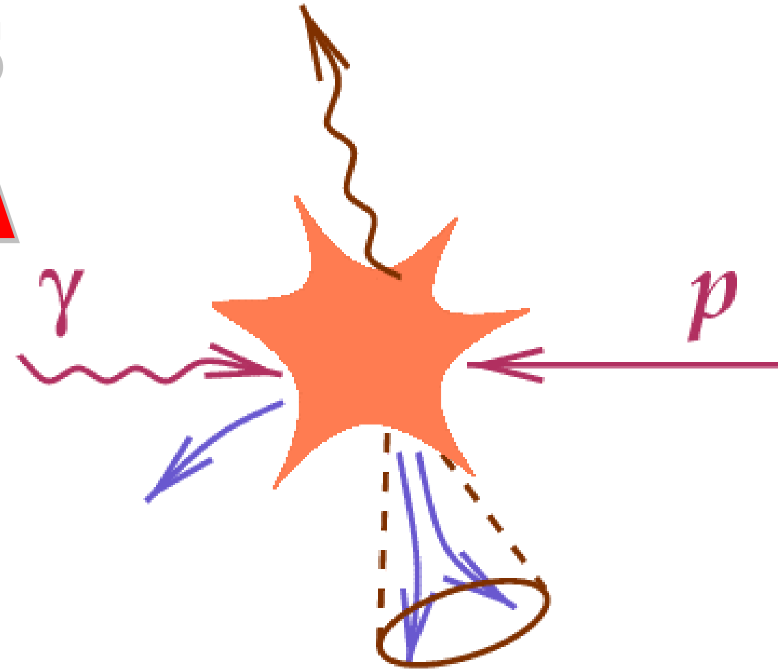
Inclusive diphoton sample
- require 2 photons
- same requirement as single photon

Diphoton is an interesting QCD measurement but is also a great place to look for new physics





Prompt Photons at HERA



Probing QCD

- Background Subtraction Methods
- Summary of ZEUS Prompt Photon Results
- ZEUS Determination of Parton kT
- New H1/ZEUS Photon Results – Preliminary

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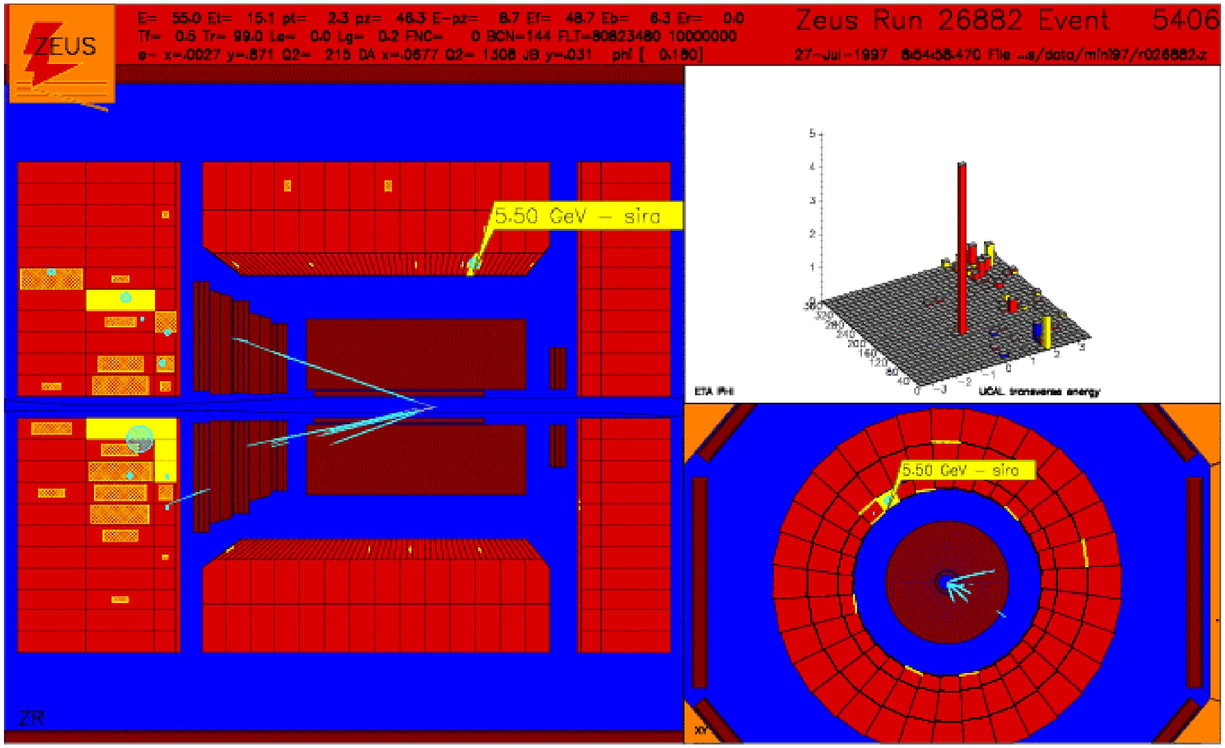
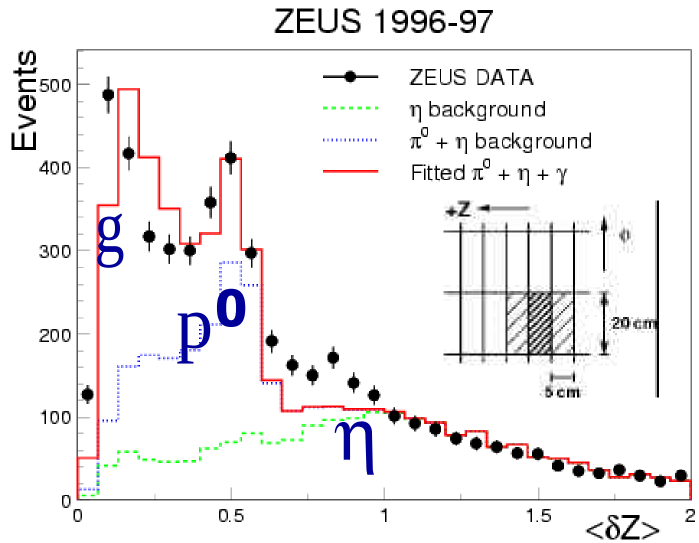
Prompt Photon Measurement at HERA

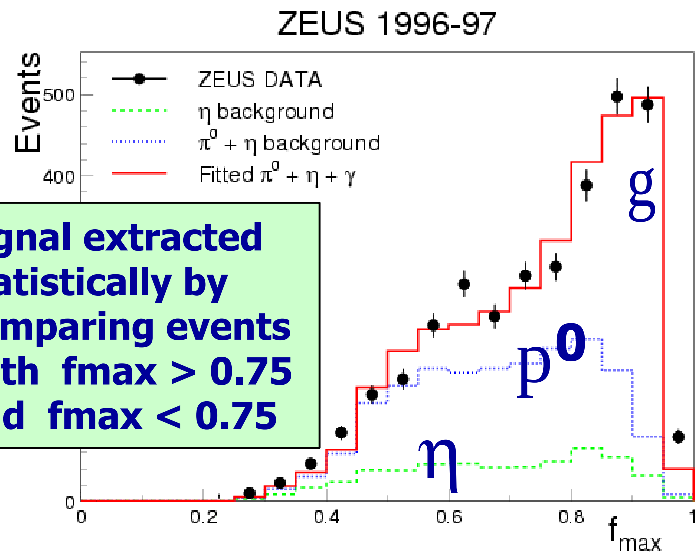


- Example of prompt photon production in the direct process at ZEUS
  - Clearly identified in calorimeter and well isolated
  - ZEUS BCAL has good granularity to separate high E_T photon from neutral pion and eta meson backgrounds
- Potentially significant backgrounds from jet fragments in dijet
  - Isolation cuts and Shower shape cuts are required to remove these

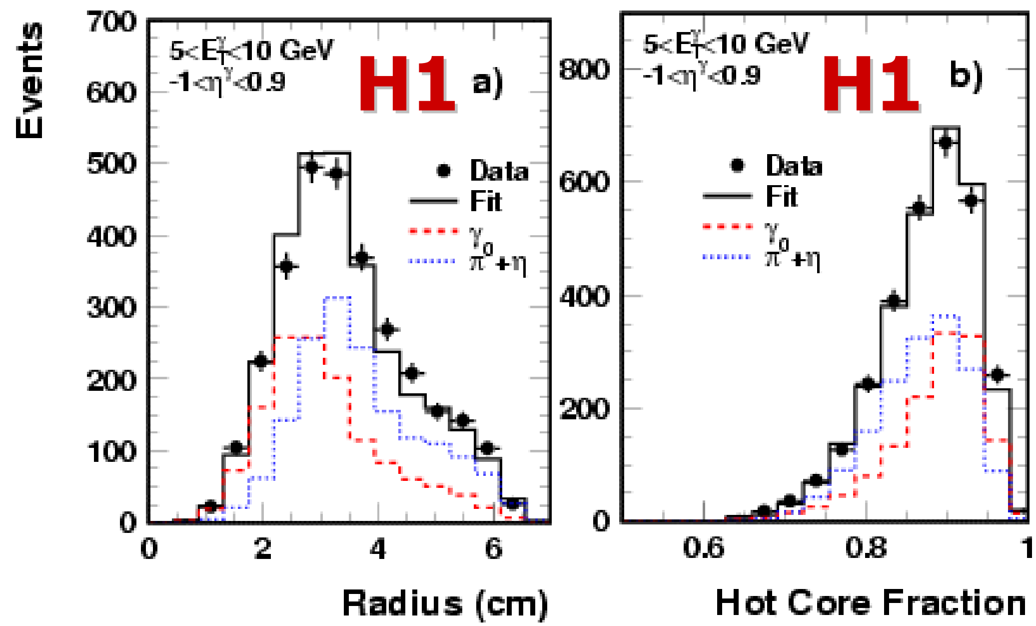
Identification of Photon Signal at ZEUS/H1

Topological shower shape quantities are used to separate 2 nearby photons





Signal extracted statistically by comparing events with fmax > 0.75 and fmax < 0.75



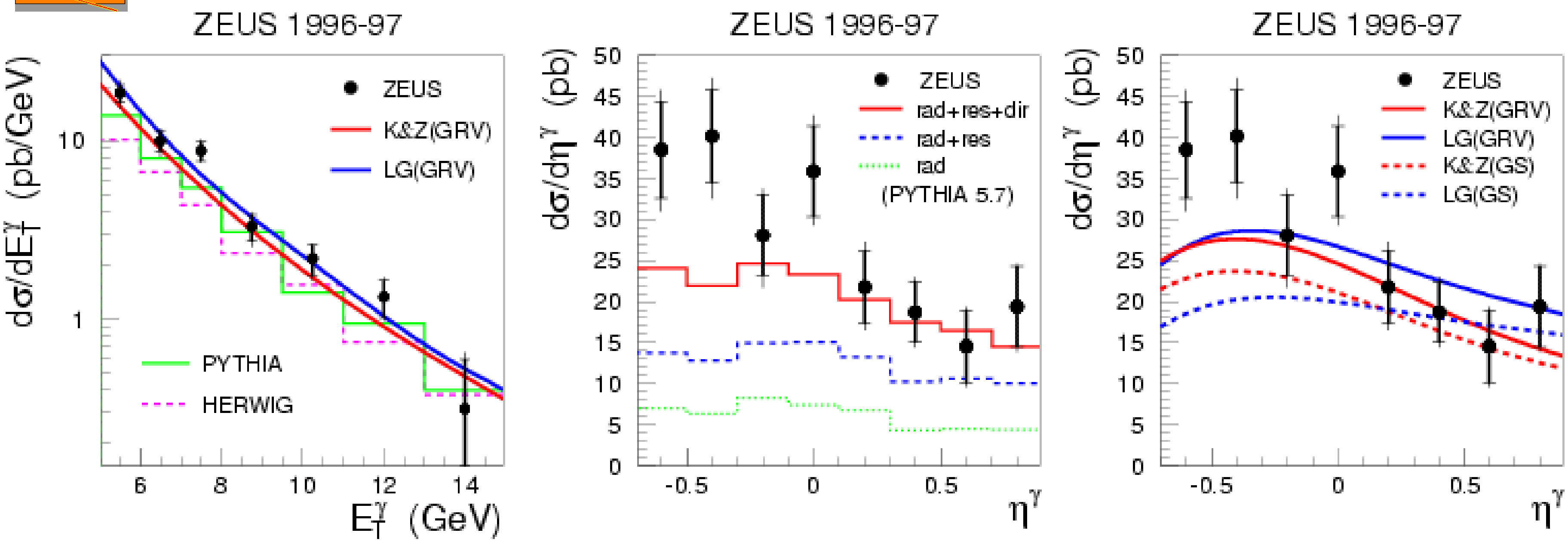
1. **Width of photon candidate in Z**
2. **Fraction of total photon energy in most energetic calorimeter cell**

1. **Mean transverse shower radius**
2. **Shower hot core fraction**

ZEUS Inclusive Photon Cross Sections

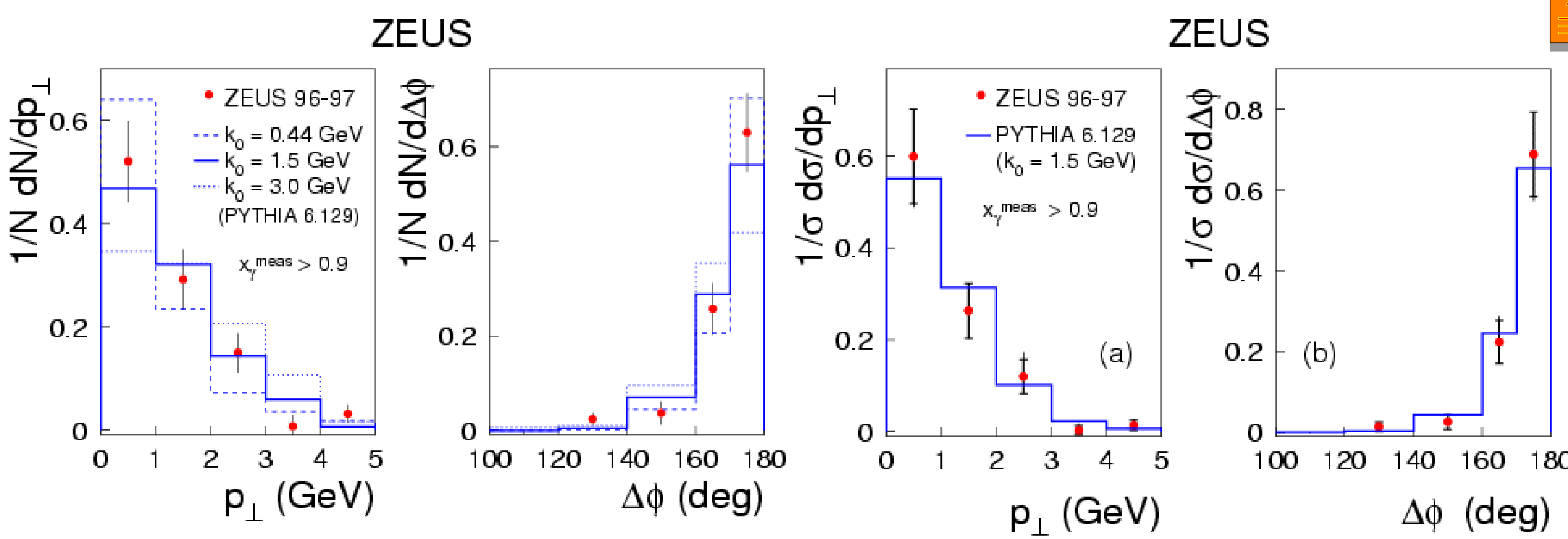
ZEUS, PLB 472 (2000) 175

Photoproduction



- $d\sigma/dE_T^\gamma$: **all theoretical models describe the shape of the data well**
  PYTHIA does fairly well, HERWIG is a little low in magnitude
- $d\sigma/d\eta^\gamma$: **generally described by LO and NLO over forward rapidities,**
  but there is a possible discrepancy in the rear region
- **Given the discrepancies also seen in HERA dijet, there would appear a need to review the present theoretical modelling of the photon parton structure**

ZEUS Determination of Parton <kT>



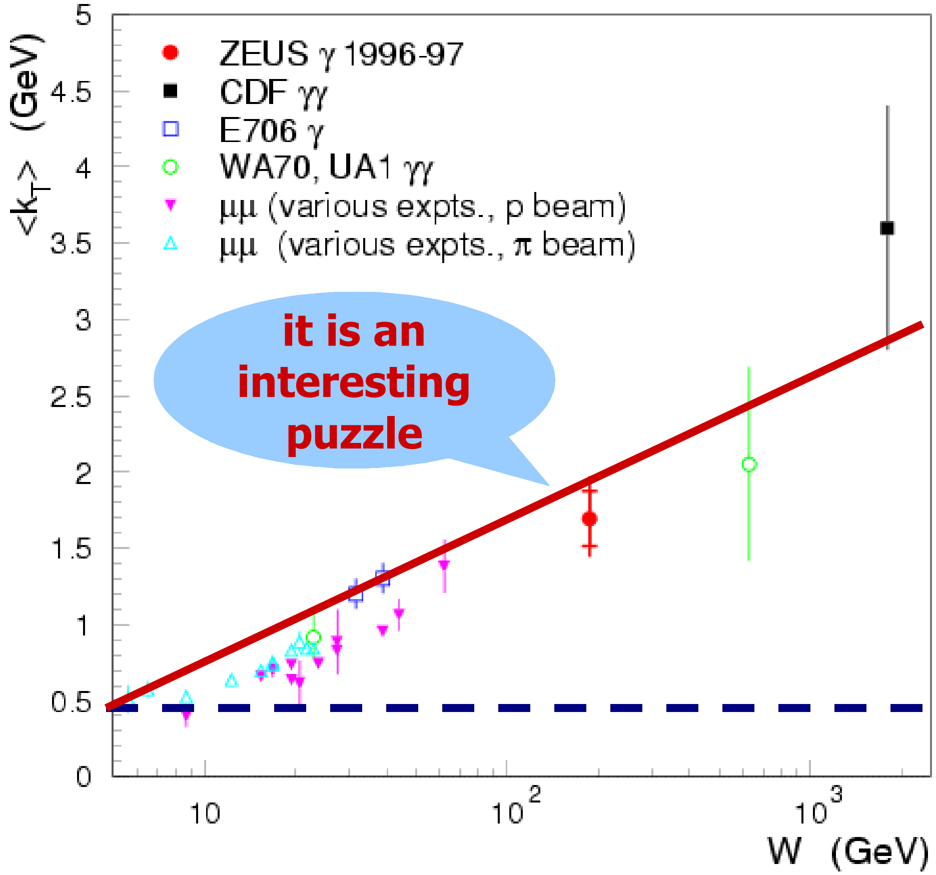
Photoproduction

Procedure to evaluate <kT>

- Select a highly direct-enhanced sample to minimize effects of photon structure
- Modeling kT: Vary 'intrinsic' contribution, k0, in PYTHIA parton shower model
- Fit pT distribution using series of k0 values
- Determine <kT>intr from a fit at the detector level with extra k0 points
- Use PYTHIA again at parton level to incorporate parton shower effects

$\langle kT \rangle = 1.69 \pm 0.18\ (+0.18, -0.20)$ [GeV]

A Consistent Picture of kT

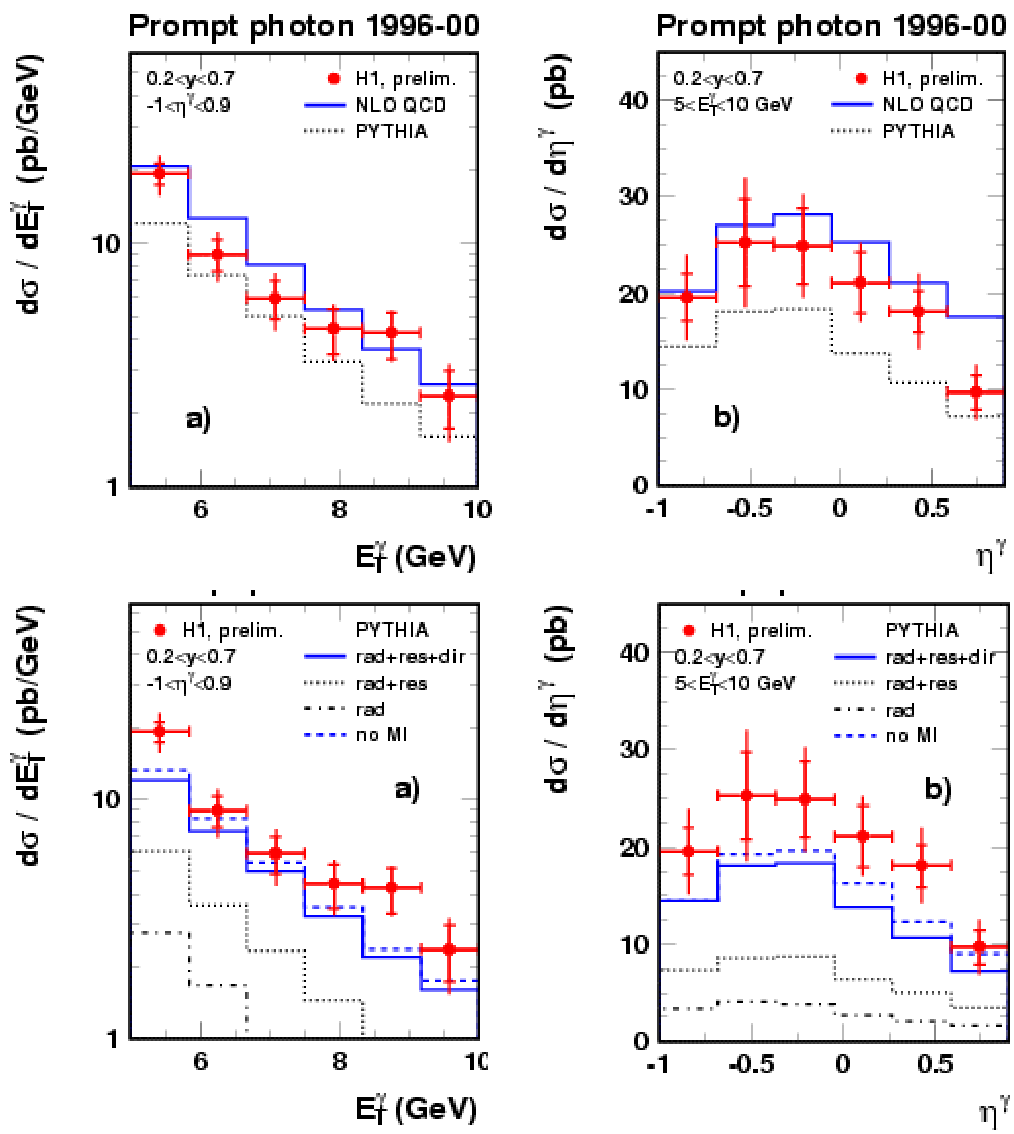


- Many experiments have made measurement of the effective parton kT in the proton
- Lower energies: expect a value ~ 0.5 GeV corresponding to size of the proton
- Higher energies: higher values obtained – initial state parton showers?
- Different exp. use different methods, but the trend is evident
- ZEUS result consistent with this trend

W = invariant mass of photon + jet final state

- **There may be an interesting connection between the Tevatron and HERA**
- **The new CDF/DØ Run2 measurement could add additional info to help interpret the kT effects and test theoretical models ...**

H1 Inclusive Photon Cross Sections



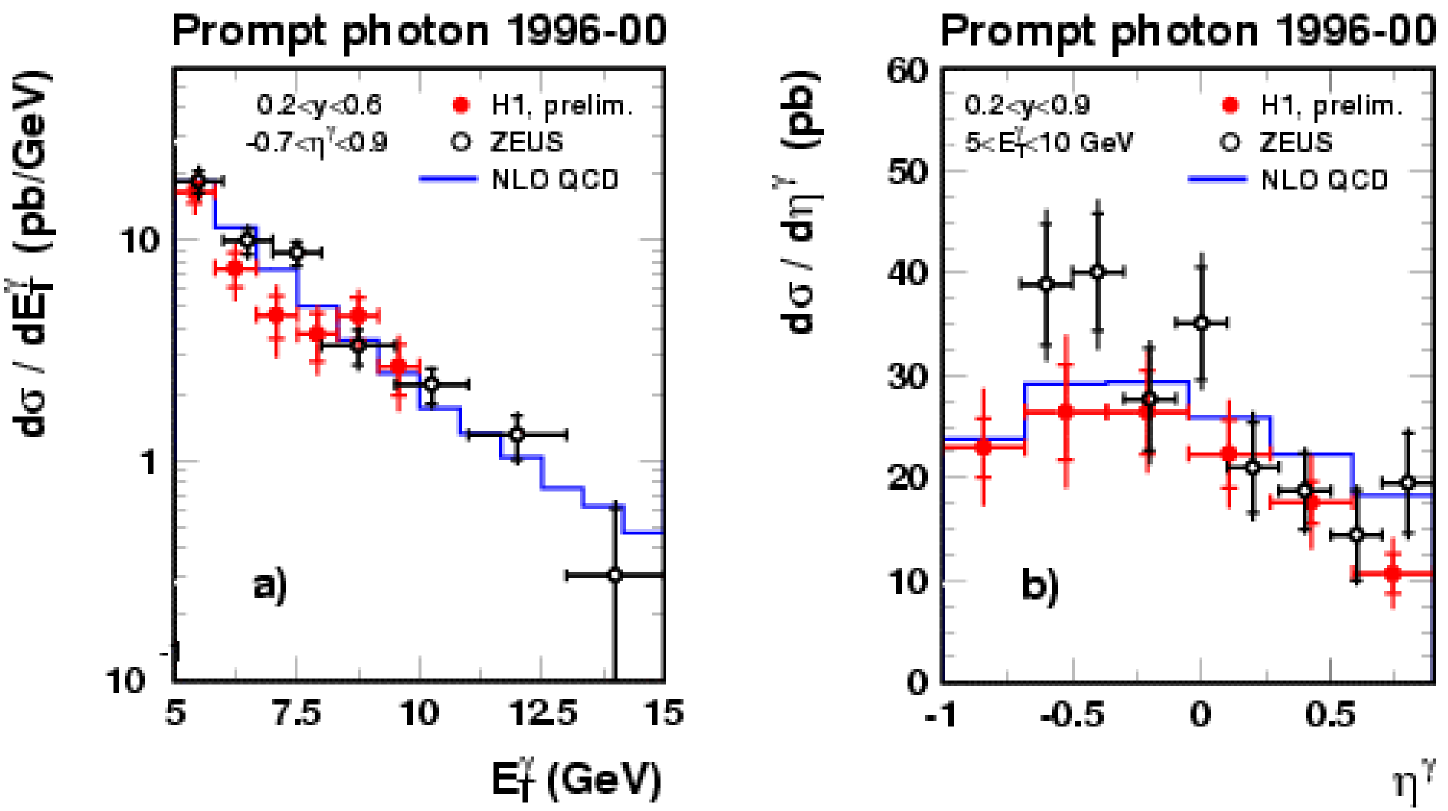
Photoproduction

- **NLO describes the H1 data quite well, but is above the data in the forward region.**
- **PYTHIA, shape is OK, but low in normalization(30%)**
- **PYTHIA indicates effect of MI at large rapidity; would reduce NLO prediction**

- **NLO pQCD calculation**
  Fontannaz , Guillet, Heinrich
  AFG/MRST2
- **PYTHIA**
  GRV(LO), MI, ISR/FSR

ZEUS Photon vs. H1 Photons

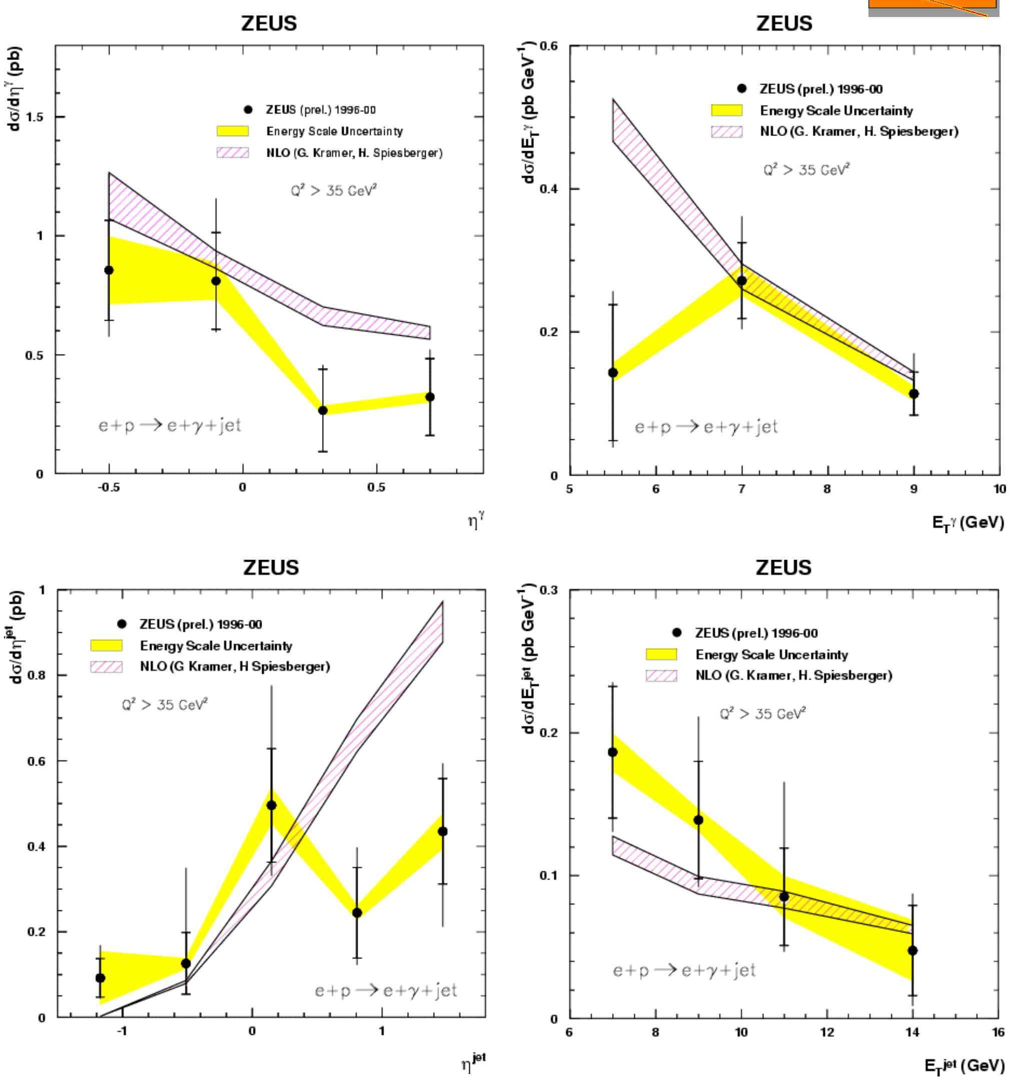
Photoproduction



The H1 data are compared to the results of the ZEUS at $\sqrt{s}$ = 300 GeV
The data are consistent, but the H1 data are somewhat lower at small rapidity, where the ZEUS results appear to exceed the NLO.

Prompt Photon Production in DIS at ZEUS

photon + jet

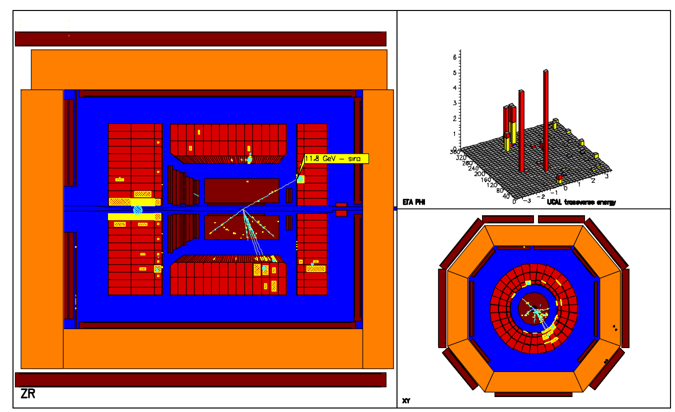


First Observation of prompt photon in DIS at HERA

Total measured cross sections

- **Inclusive photon**
  5.95 ± 0.61 (+0.19,–0.26) pb
- **Photon + Jet**
  0.90 ± 0.15 (+0.19,–0.08) pb

Reasonable agreement between the ZEUS data and NLO QCD calculations (by Kramer and Spiesberger)



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Summary and Outlook

- Prompt photon results from Hadronic collisions are generally consistent with NLO QCD.
- Recent Run 1 measurements of inclusive photon production at the Tevatron experiments indicate discrepancies with NLO QCD. kT smearing effects in a simple Gaussian model works fine, though for gluon distribution studies one needs more fundamental approaches. Improved theoretical predictions are being developed.
- From ZEUS prompt photon results, there are indications that our current understanding of the photon structure is lacking; It is time to review the current parametrization of the photon parton densities.
- Prompt photon analyses at the Tevatron/HERA are well underway and high luminosity photon data should provide experimental guidance to a better theoretical modeling of prompt photon production.
- It is important to understand QCD photon production in order to reliably search for new physics with photons in the final states.