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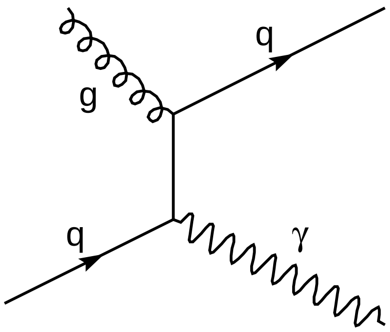
Observation of Isolated High-E_T Photons in Photoproduction at HERA

ZEUS Collaboration

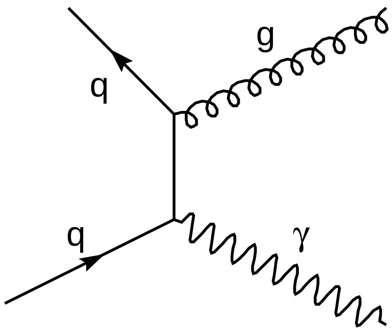
- introduction
- prompt photons in photoproduction at HERA
- event selection
- rejecting π^o / η background using shower shapes
- results and conclusions

What are prompt ('direct') photons?

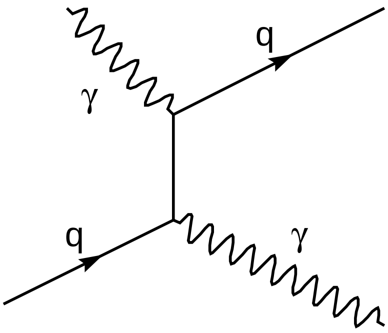
- photon is generated in hard scatter, not from parton fragmentation



QCD Compton



annihilation



photoproduction

Why are prompt photons interesting?

- pointlike coupling of photon to quark → direct link to parton level of interaction
- free from ambiguities caused by hadronization and jet identification and energy measurement
- gluon distribution enters in lowest order
- gluon measurement in Deep Inelastic Scattering (DIS) is indirect (gluons don't couple to lepton probe)
- more sensitive to gluon distribution at higher x values (compared to DIS)
- fewer leading order subprocesses than in jet measurements (only 1 kind of photon)
- background to exotic searches

disadvantages

- large background from mesons in jets
- small production rate relative to jets

Where have they been measured before?

A list of selected previous measurements

1979--1982: CERN Intersecting Storage Rings (ISR)

- proton-proton collisions
- P_T up to 12 GeV
- dominant process yielding high P_T photons is $gq \rightarrow \gamma q$ (annihilation channel $q\bar{q} \rightarrow \gamma g$ involves anti-quarks from sea)
- This observation of prompt photons can be interpreted as some of the first evidence for the existence of gluons.
- P_T curve in data is steeper than the theoretical calculation (lowest order QCD diagrams + soft gluon corrections)

1985: NA14 Collaboration at CERN SPS

- fixed target experiment using 50-150 GeV photon beam
- First results on inclusive photoproduction of high P_T prompt photons. $1.5 < P_T < 4.5$ GeV
- Cross section as function of P_T agrees with QCD calculation though errors are rather large

1988: WA70 Collaboration at CERN SPS

- fixed target experiment using 280 GeV protons
- pp $\rightarrow \gamma X$
- $4 < P_T < 6.5$ GeV
- data are compared to NLO QCD predictions using two sets of structure functions $\rightarrow$ incompatible with the set with harder gluon component

1991-93: UA1, UA2 Collaborations at CERN $p\bar{p}$ collider

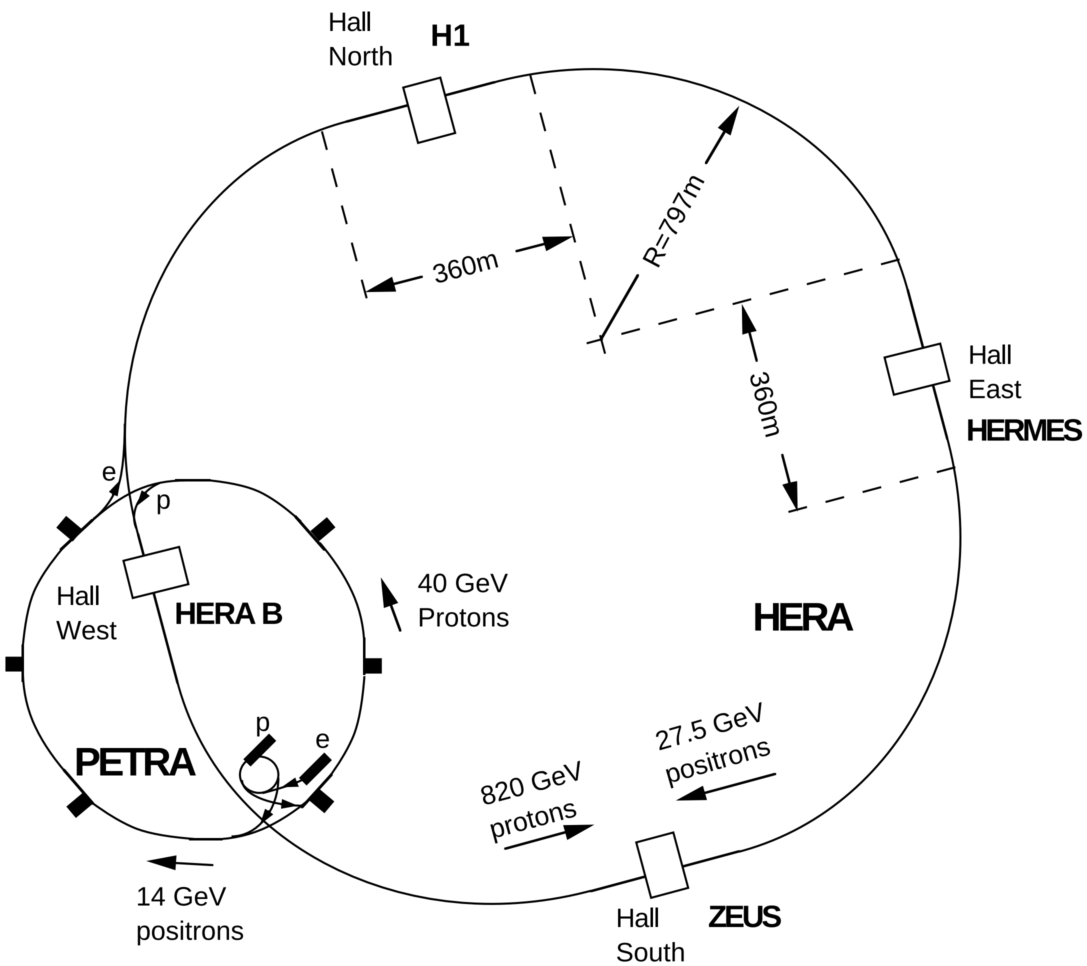
- center of mass energy = 630 GeV
- $16 < P_T < 82$ GeV
- 'Within uncertainties the data agree well with the QCD predictions'
- also measured photon + jet final state

HERA

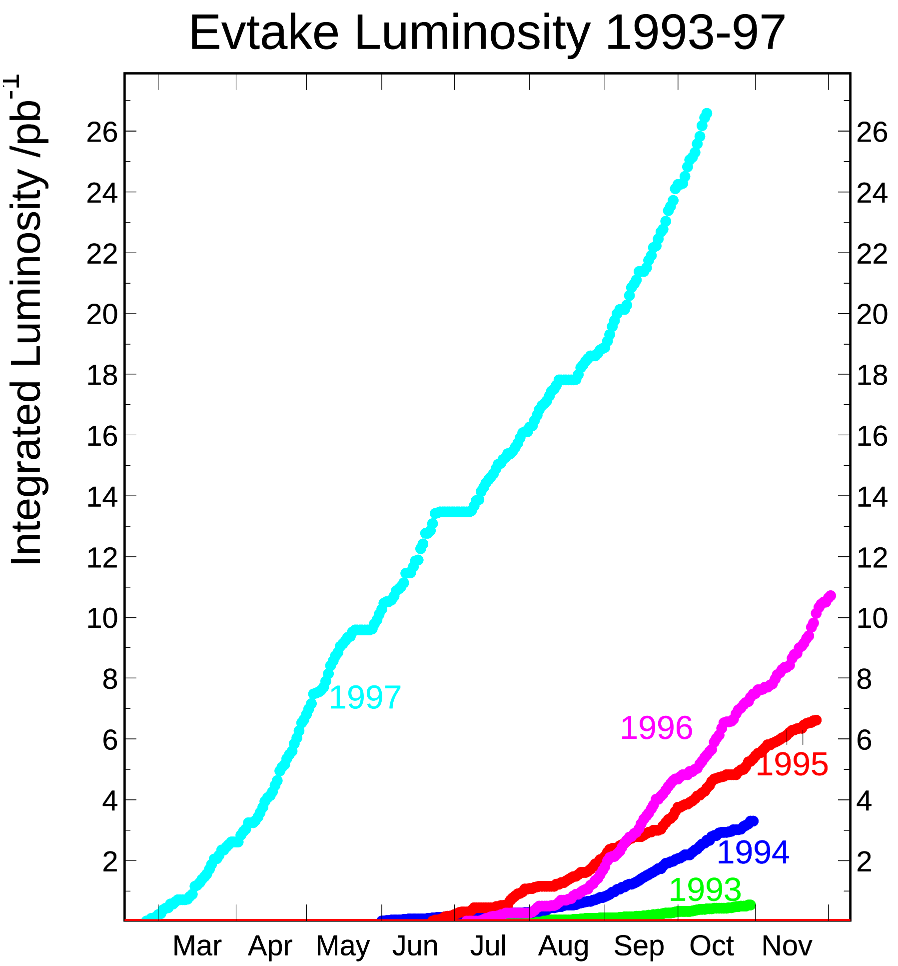
(at DESY laboratory in Hamburg, Germany)

e x p

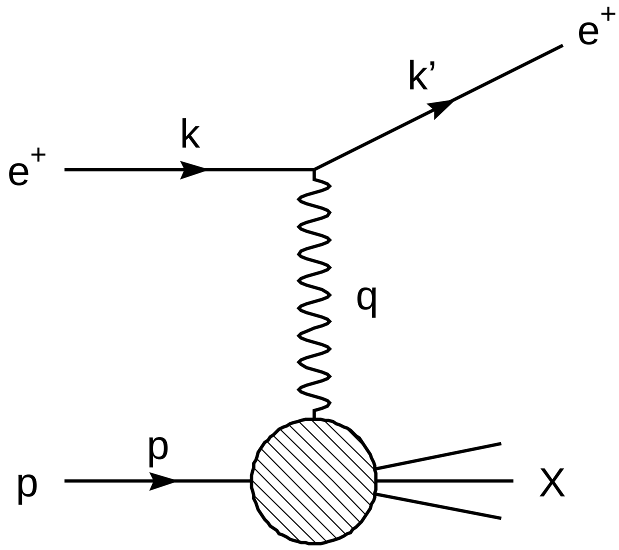
27.5 GeV x 820 GeV



Useful luminosity at ZEUS



Kinematic Variables



$Q^2 = -q^2 = -(k-k')^2$ square of four momentum transfer

$s = (p + k)^2 \cong 4E_eE_p = (300\ \mathrm{GeV})^2$

square of total center of mass energy

$x = Q^2 / (2p{\cdot}q)$ $0 \leq x \leq 1$

fraction of proton momentum carried by struck parton

$y = (p{\cdot}q) / (p{\cdot}k)$ $0 \leq y \leq 1$

fraction of positron energy carried by photon (E_γ / E_e)

a major aim of HERA physics: measure parton distributions of proton using large Q^2 virtual photons emitted from incident positron beam

ep cross section is highest when Q^2 is small

→ most events at HERA are mediated by almost real photons ($Q^2 \sim 0$) ‘photoproduction’

→ think of HERA as photon-proton collider

photon beam energy range: 0 -- 27.5 GeV

equivalent fixed target photon beam energy = 15 TeV

At LO, photoproduction in which high P_T particles are produced can be divided into two groups:

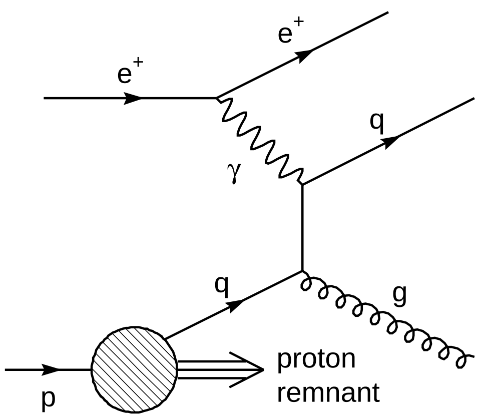
- 'direct' = entire photon interacts ($X_\gamma = 1$)
- 'resolved' = photon provides a quark or gluon which interacts ($X_\gamma < 1$)

X_γ is fraction of photon momentum involved in the hard scatter.

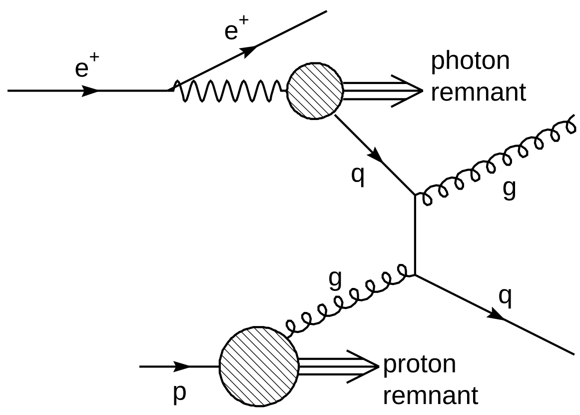
Well defined only at LO. Use estimator X_γ^{meas}

$$X_\gamma^{meas} = \Sigma_{\text{two jets}}(E\text{-}P_z) \,/\, \Sigma_{\text{event}}(E\text{-}P_z)$$

direct



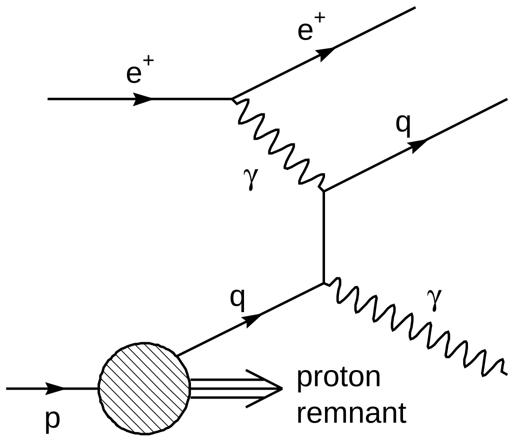
resolved

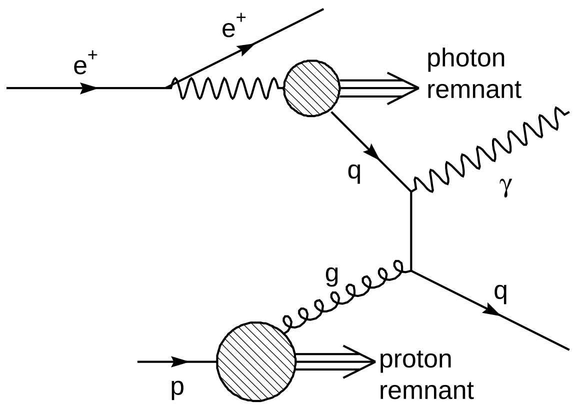


Replace outgoing gluon in dijet processes above with photon to get prompt photon diagrams...

LO Prompt Photon Diagrams

direct | resolved

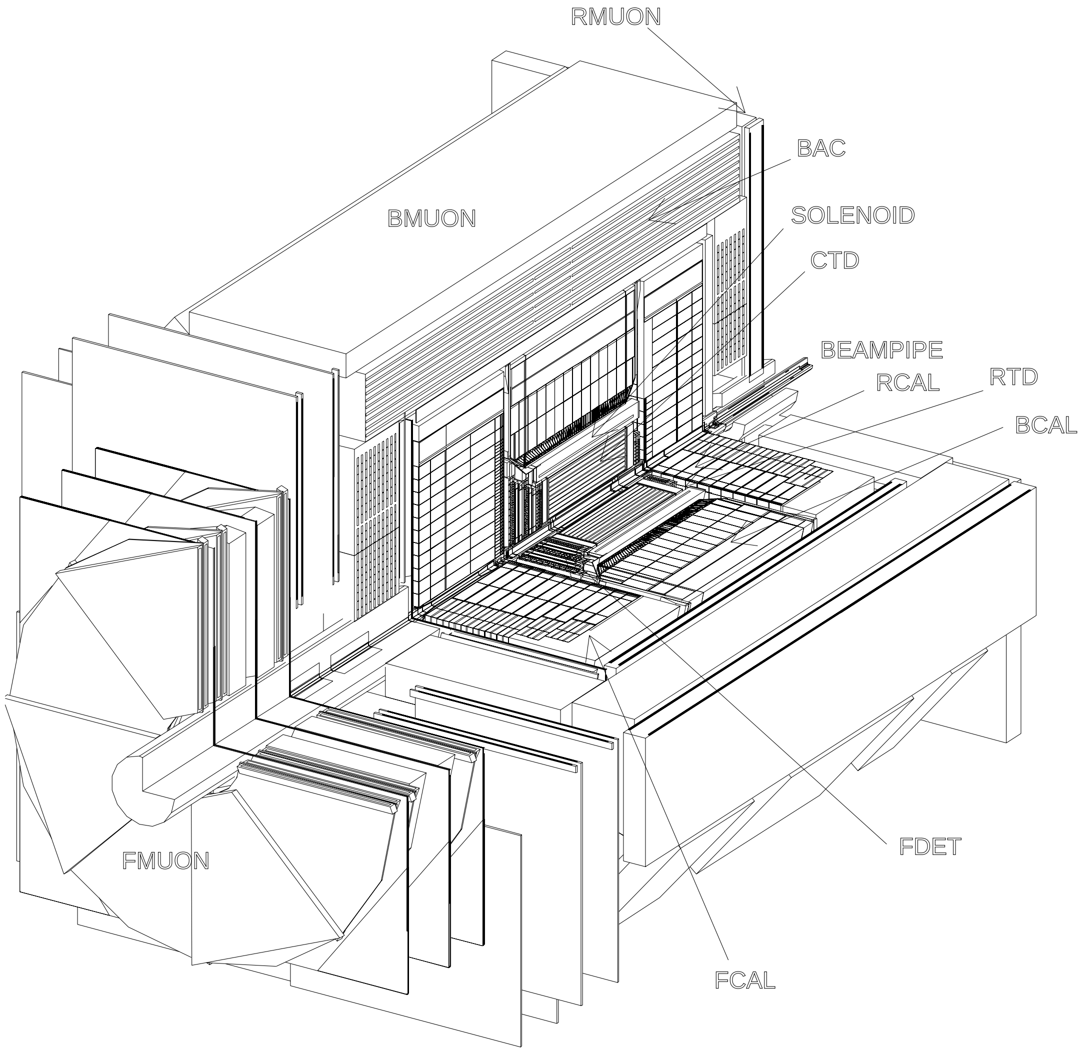




Dijet process can be a serious background to prompt photon process if one jet's energy is carried mostly by a π^o or η or if an outgoing quark radiates a high P_T photon.

Expect a jet opposite the photon $\rightarrow$ search for photon + jet final state.

ZEUS Detector



depleted uranium-scintillator calorimeter:

$$\sigma_{em} / E = 18\% / \sqrt{E(GeV)}$$

$$\sigma_{had} / E = 35\% / \sqrt{E(GeV)}$$

Central Tracking Detector (CTD) sits in 1.4 T B field

Event Selection

1995 data sample:

integrated luminosity = 6.4 pb^{-1}

‘photon + jet’ analysis

1996-1997 data sample:

integrated luminosity = 37 pb^{-1}

‘photon + jet’ and ‘inclusive photon’ analyses

preliminary results shown at ICHEP’98 (Vancouver)

quick overview

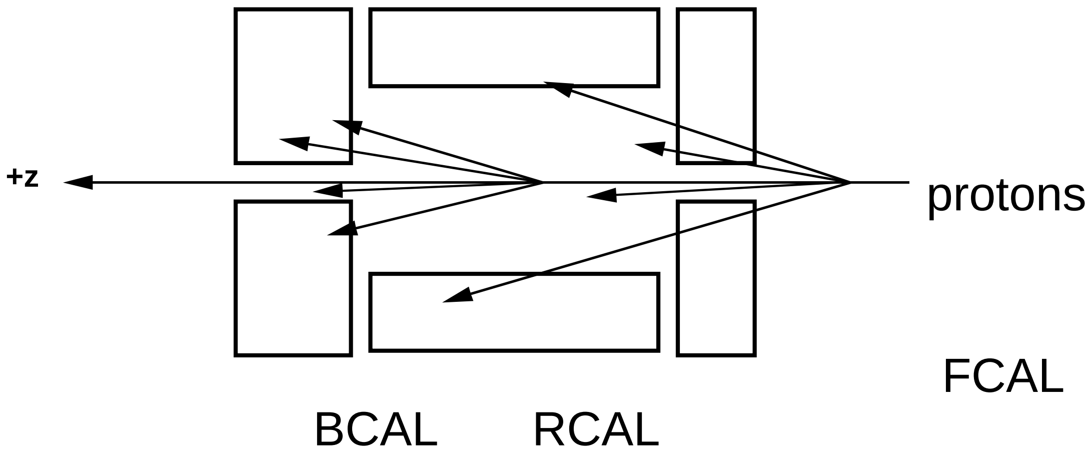
- remove beamgas and DIS to get photoproduction sample
- use em cluster finder to find photon candidates
- find jet using a cone algorithm
- require photon candidate to be isolated
- use shower shapes in calorimeter to further reject π^0,η background
- statistically subtract background based on shower shape variables

Cleaning Cuts

- reject beamgas events

Only 96 ns between bunch crossings!

beamgas: proton hits particle inside beampipe vacuum instead of hitting a positron



beamgas vertex inside detector:

$\Sigma(E-P_z)$ is small. Reject with $\Sigma(E-P_z) > 8$ GeV cut

beamgas vertex outside detector:

$\Sigma(E-P_z)$ may not be small. RCAL time is too early. Reject with timing cut.

- reject DIS events

Final state is scattered positron and a jet (from struck quark).

use track veto since positron leaves a track (see isolation cuts below)

For DIS, $\Sigma(E-P_z) = (E_p-E_p) + (E_e+E_e) = 2E_e = 55$ GeV

For photoproduction (low Q^2), scattered positron escapes down beam pipe reducing $\Sigma(E-P_z)$ by twice the scattered positron energy.

Reject DIS with $\Sigma(E-P_z) < 38$ GeV cut.

If there is an identified positron in calorimeter that has energy and angle consistent with a DIS event, reject event. effectively: $Q^2 < \sim 1$ GeV^2

Selection Cuts

- Use electromagnetic cluster finder to find photon candidates

$$5 \text{ GeV} \leq E_T^{\gamma} < 10 \text{ GeV}$$

For E_T above 10 GeV, opening angle of $\pi^o \rightarrow \gamma\gamma$ is too small to be resolved.

Only candidates in barrel calorimeter are considered (best spatial resolution). This is effective pseudorapidity cut in central region:

$$-0.7 \leq \eta^{\gamma} \leq 0.8$$

- Find jet using a cone algorithm (Snowmass convention) with radius 1.0 in η,ϕ

$$E_T^{jet} > 4.5 \text{ GeV}$$

$$-1.5 \leq \eta^{jet} \leq 1.8$$

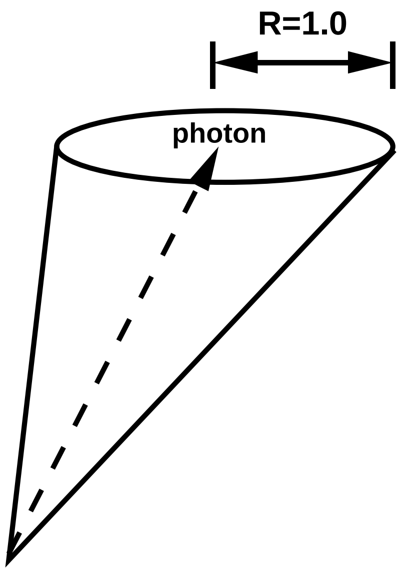
$\Delta\phi > 140^o$ between photon and jet

Isolation Cuts

- energy isolation cone

$\Sigma_{\text{NOT } \gamma}(E_T^{\text{CAL+TRACKS}}) < 0.1\ E_T^{\gamma}$

Require > 90% of E_T in cone of radius 1.0 around photon to be associated with photon.

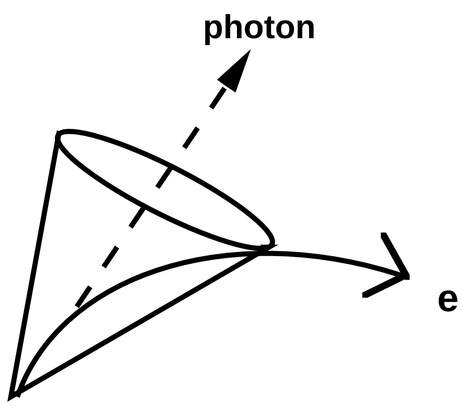


Rejects dijet events with part of one jet misidentified as a single photon.

- track isolation cone

Photon candidate is rejected if there is a track pointing ‘close’ to photon

$\sqrt{[(\delta\phi)^2 + (\delta\eta)^2]} < 0.3$



Background rejection using shower shape in calorimeter

Main background is neutral mesons in jets

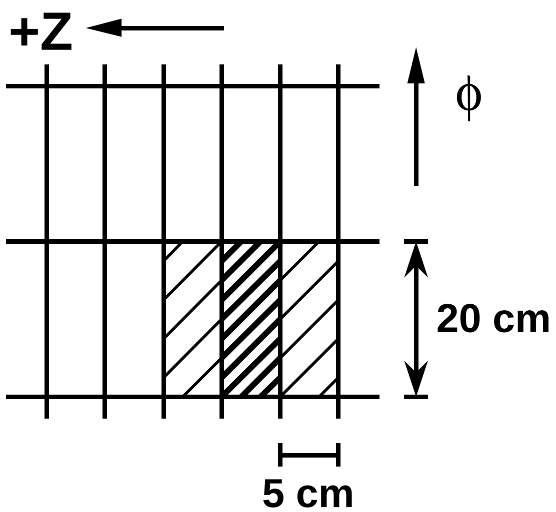
$$\pi^o \rightarrow \gamma\gamma \qquad \eta \rightarrow \gamma\gamma,\ 3\pi^o$$

Opening angle of photons, $\alpha \sim$ resolution of electromagnetic section of barrel calorimeter (5 x 20 cm cells). Reconstruction is not possible.

$$\alpha \sim 1/E_\pi$$

Single photons deposit most of their energy in 1 cell.

π^o, η energy deposit is more evenly distributed over two or more cells.



Look at two shower shape quantities to distinguish γ from π^o, η: Zwidth, Fmax

“energy weighted width in z”

Zwidth $= \Sigma_i |z_i - z^{avg}| E_i / \Sigma_\iota E_i$

$z^{avg} = \Sigma_i (z_i E_i) / \Sigma_i E_i$

Σ_i = cells attached to photon candidate (from finder)

0.0 = all energy deposited in 1 cell (γ)

0.5 = energy ~evenly deposited in 2 cells (π^o)

“fraction of total photon energy which is in the most energetic cell”

$$\text{Fmax} = \frac{\text{energy of highest energy cell}}{\text{total energy of photon}}$$

$0 \leq \text{Fmax} \leq 1$

1.0 = all energy is in 1 cell

0.5 = 50% of energy is in 1 cell

Comparison of π^o shower shape in DATA with single π^o Monte Carlo

Difficult to find high energy ($E_T > 5$ GeV) π^os in the ZEUS data.

Use process

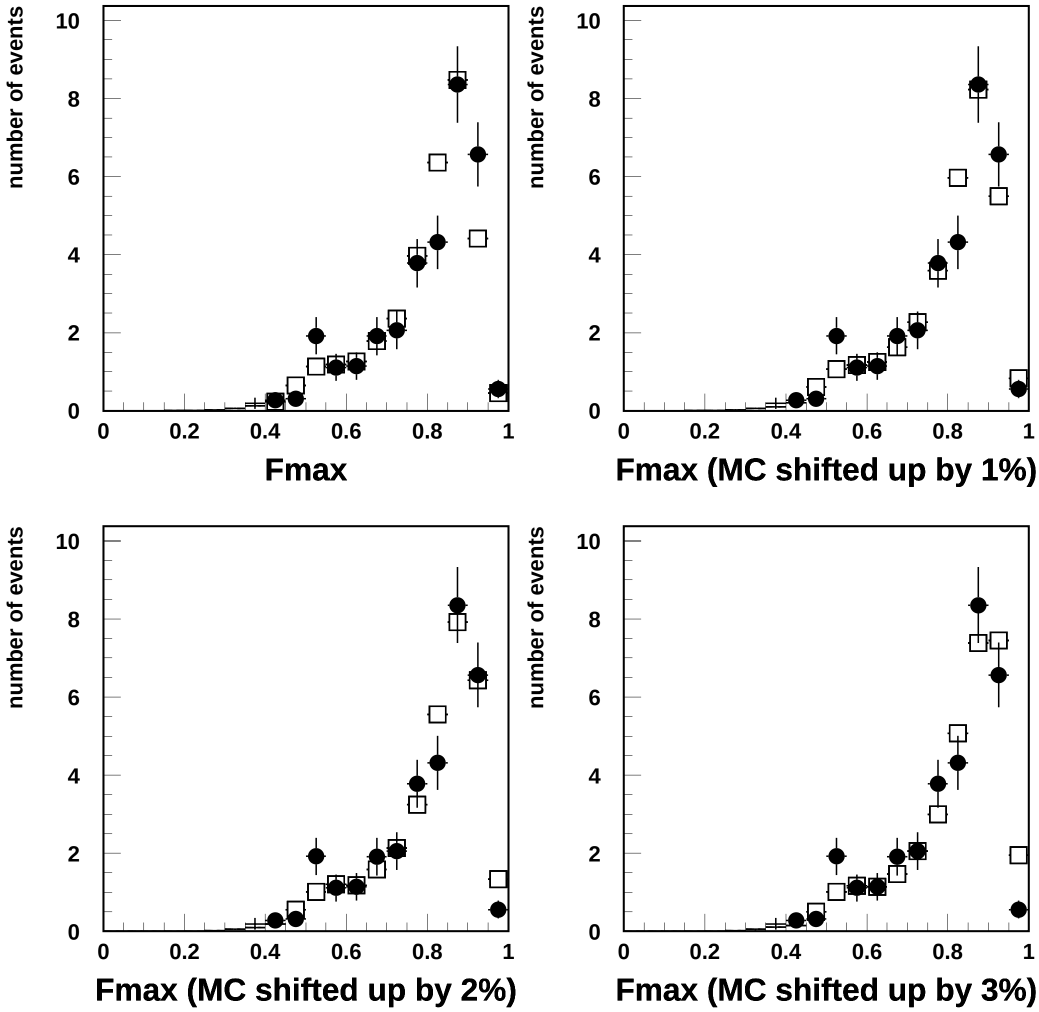
$$\rho^{\pm} \rightarrow \pi^o \pi^{\pm}$$

Fmax

Reasonable agreement.

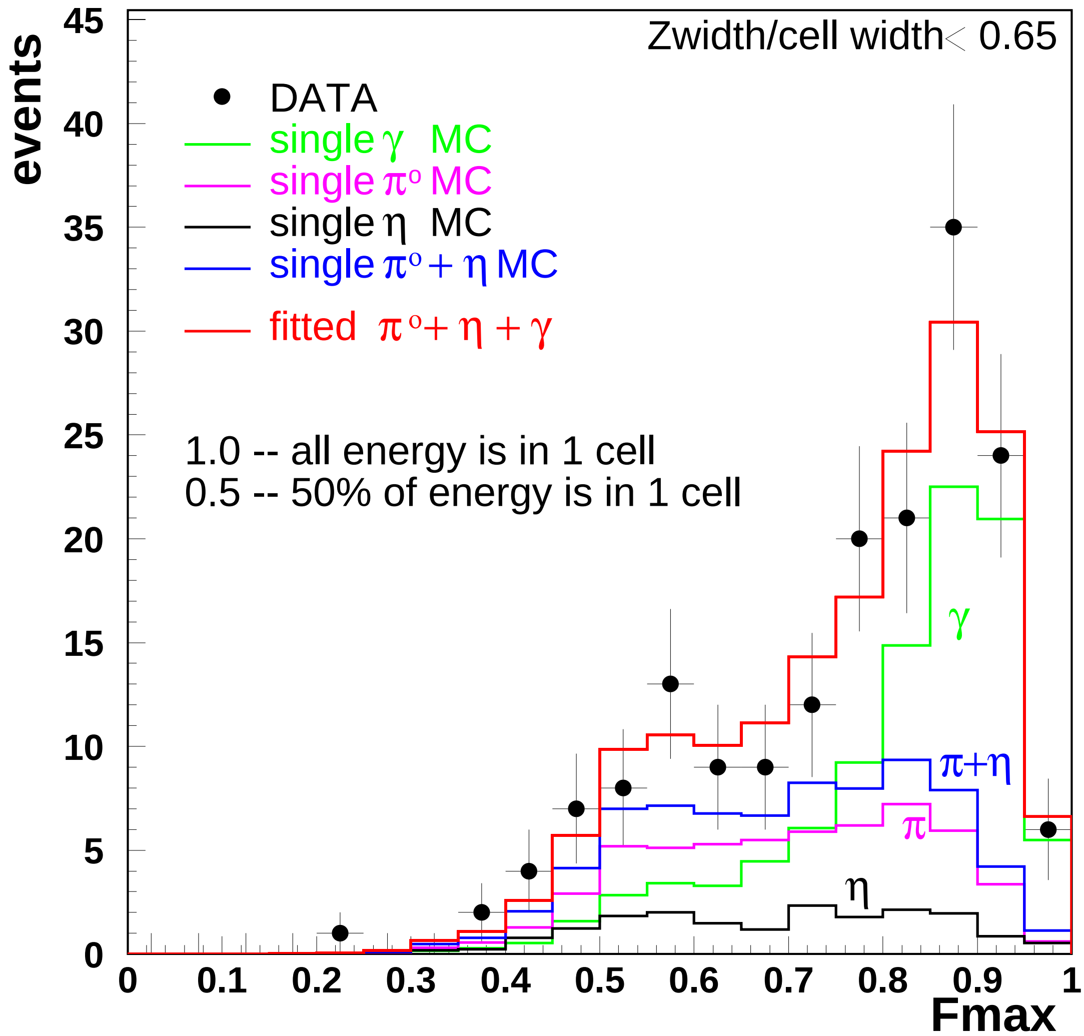
Data based verification of MC

Comparison of Fmax for single photon Monte Carlo (open) and data positrons (filled)



Best agreement if MC Fmax values are multiplied by 1.025

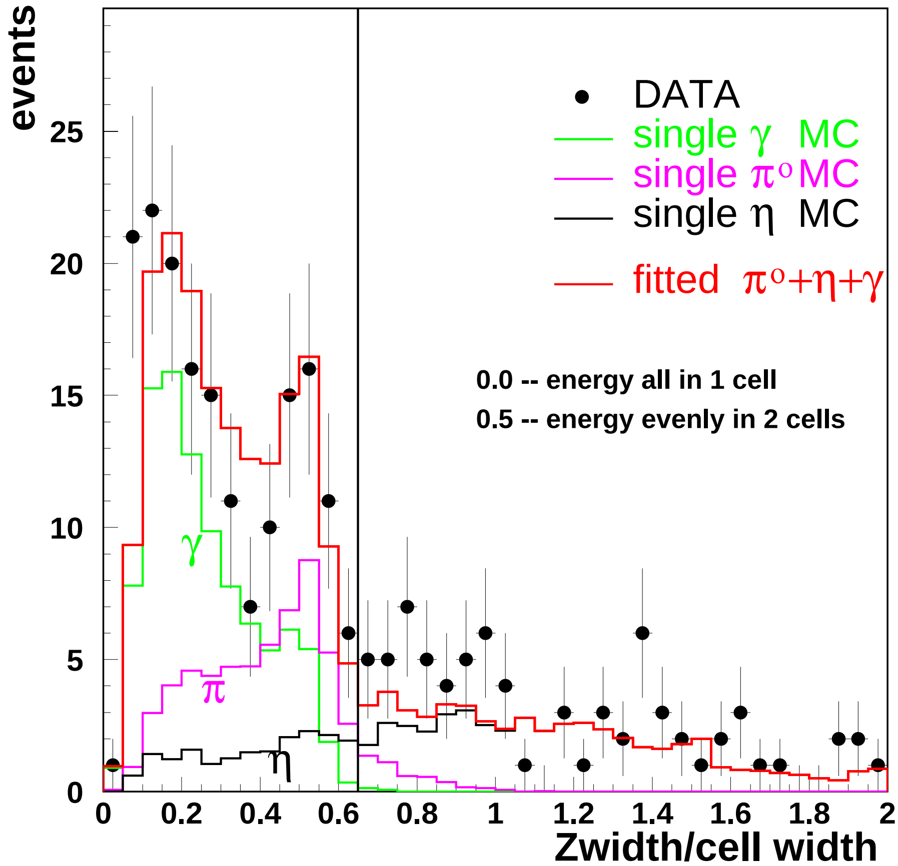
“fraction of total photon energy which is in the most energetic cell”



Result of fit for Fmax (174 data events)

- large γ component demanded (~60%)
- $\gamma + (\pi^{o} + \eta)$ gives a good fit
- π^{o}, η shape very similar

“energy weighted width in z”



Fit the relative amounts of γ, π^o, and η Monte Carlo to data for Zwidth > 0.65 (get η component) and all Fmax bins.

Fitted Zwidth curve satisfactorily describes data, even in Zwidth < 0.65 region which was not part of fit.

- γ and π^o have different peaks, η describes long tail
- apply Zwidth < 0.65 cut before plotting Fmax

‘Background’ Monte Carlo

Create enriched background sample of dijet events using Pythia 5.7 Monte Carlo generator.

enrichment: at least 1 jet has at least 80% of its P_T carried by the types of particles which can mimic a single photon in detector (γ, π^o, η, K_s^o)

This algorithm was chosen after examining standard dijet MC events which passed all prompt photon cuts.

Zwidth

background MC is described by single π^o, η MC

Fmax shape in background MC

Fmax

background MC Fmax shape is described by single π^0, η MC

→ It is reasonable to use single π^0 and η MC to represent background in shower shape plots.

Background subtraction using Fmax plot

Assume data in Fmax plot may be expressed as sum of two parts: photon signal plus neutral meson background.

Goal: plot any quantity of interest for photon signal part of Fmax plot.

example of interesting quantity: X_γ

Plot X_γ^{meas} for each of two subsamples:

Fmax > 0.75 signal enriched

Fmax ≤ 0.75 background dominant

Estimate number of signal events, N_{sig}, and number of background events, N_{bgd}, in each bin:

$N(\text{Fmax} > 0.75) = \alpha\, N_{sig} + \beta\, N_{bgd}$

$N(\text{Fmax} \leq 0.75) = (1-\alpha)\, N_{sig} + (1-\beta)\, N_{bgd}$

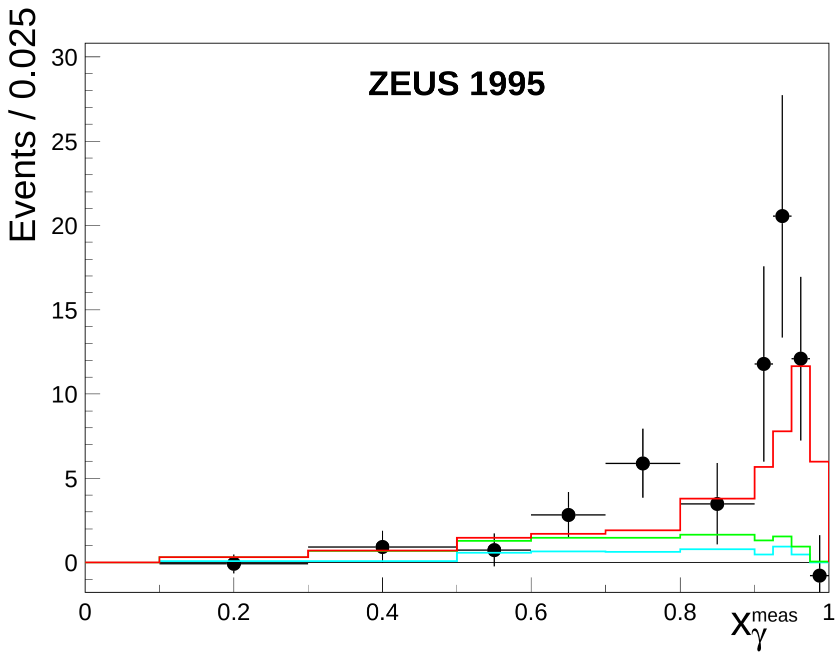
α (β) is probability that a signal (background) event will have Fmax > 0.75 (based on MC Fmax shape)

X_γ is fraction of photon momentum carried by its parton into the hard scatter

$X_\gamma^{meas} = \Sigma_{photon+jet}(E\text{-}P_z) \,/\, \Sigma_{event}(E\text{-}P_z)$

$X_\gamma^{meas} > 0.8$ direct process dominates

$X_\gamma^{meas} < 0.8$ resolved process dominates



Pythia 5.7 MC (direct + resolved + radiative)

Pythia 5.7 MC (resolved + radiative)

Pythia 5.7 MC radiative (i.e. quark radiates high P_T photon)

- peak corresponds to direct process
- resolved component is small
- background distribution is consistent with zero above 0.9

Cross section (1995 data)

$$\gamma\, p \rightarrow \gamma_{prompt} + \text{jet} + x$$

$0.16 < y < 0.8$	$Q^2 \leq 1\ \text{GeV}^2$
$5\ \text{GeV} \leq E_T^{\gamma} < 10\ \text{GeV}$	$-0.7 \leq \eta^{\gamma} \leq 0.8$
$E_T^{jet} > 5\ \text{GeV}$	$-1.5 \leq \eta^{jet} \leq 1.8$
$X_{\gamma} > 0.8$	photon is isolated

acceptance correction from Pythia MC = 1.69 +/- 0.09

57 data events

systematic errors:

- 8% -- vary calorimeter energy scale by +/- 3%
- 3% -- vary rapidity distributions of single particle MC
- < 2% -- vary E_T weighting of single particle MC, artificially halve number of fitted ηs, luminosity uncertainty

σ = 15.3 +/- 3.8 (stat.) +/- 1.8 (sys.) pb

NLO calculation (L. Gordon)

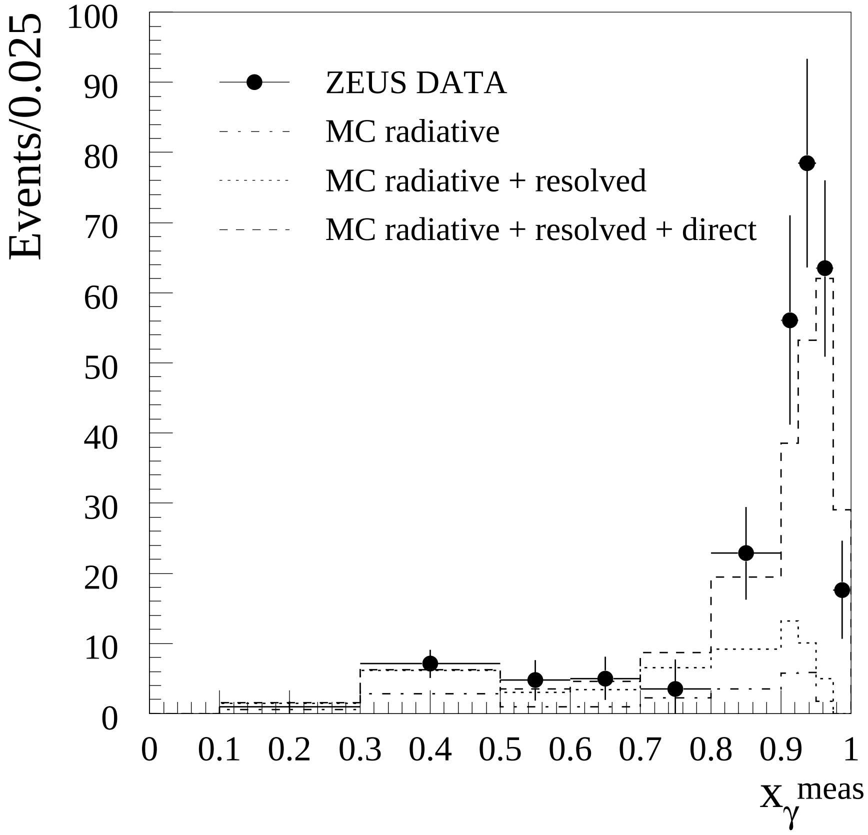
QCD scale	GS^{γ}	GRV^{γ} ← photon parton density
$(E_T^{\gamma})^2$	13.2	16.6 pb
$0.25(E_T^{\gamma})^2$	14.1	17.9 pb

experiment and theory are in good agreement

ZEUS 1996/7 preliminary

> 5 times the 1995 statistics (37 pb^{-1})

jet + photon

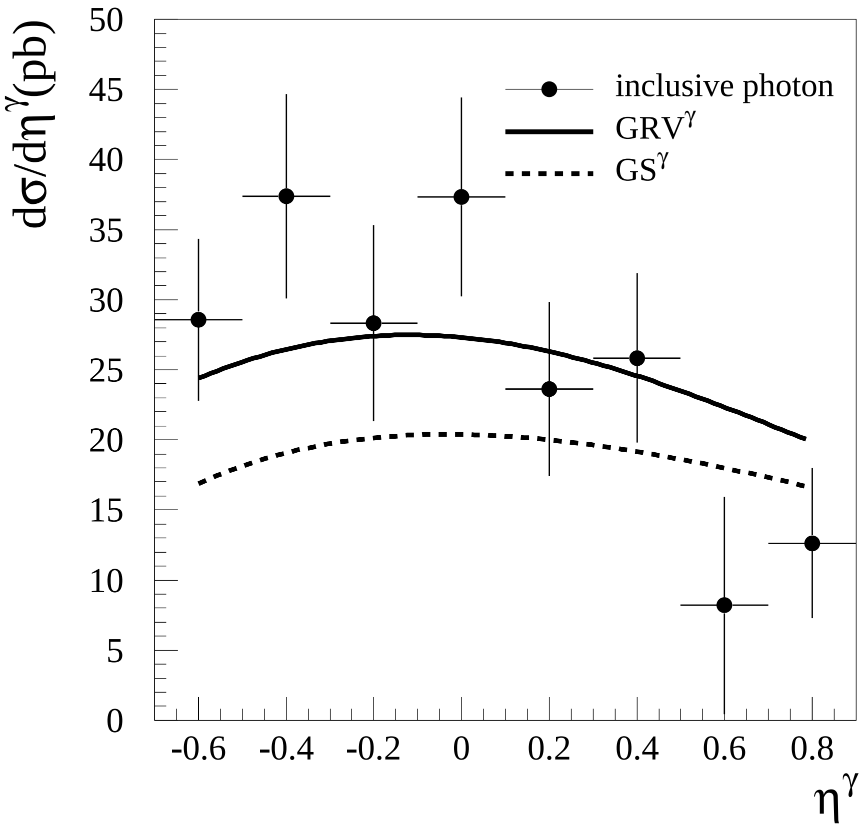


As for 1995 data, reasonable agreement with LO MC.

Cross section for X_γ > 0.8 consistent with 1995.

ZEUS 1996/7 preliminary

inclusive photon



systematic uncertainty of ~14% is not included

GRV prediction gives reasonable description of data.

Conclusions

- For the first time at HERA, an isolated high E_T photon signal has been observed (in 1995 ZEUS data) in the process

$$\gamma\, p \rightarrow \gamma_{prompt} + jet + x$$

- The observed X_γ distribution is consistent with LO QCD expectations (from Pythia Monte Carlo)
- Measured cross section for $X_\gamma > 0.8$ is in agreement with a NLO QCD prediction:

$$\sigma = 15.3 \pm 3.8\ (stat.) \pm 1.8\ (sys.)\ pb$$

- Preliminary measurement of $d\sigma/d\eta^{\gamma}$ in 1996-1997 inclusive photon sample is consistent with a NLO QCD calculation. GRV is favored over GS photon pdf.

Outlook

- Extend measurement to more forward rapidities to see more resolved photon events.
- look forward to more data from 1998 and from the HERA luminosity upgrade

Independent Check of Background

- much background due to photoproduction dijet processes (one of the jets mimics a photon in detector)
- amount of background was estimated using Monte Carlo shower shapes (verified with actual data)
- a further, independent check of the background magnitude was performed using a completely separate data sample --> Deep Inelastic Scattering (DIS) events

background =(# dijet events) x (photon/jet)

dijet events = number of dijet events in 1995 data passing all cuts of prompt photon analysis except those cuts involving the found emc object

photon/jet = probability that a jet will mimic a photon (i.e. apply em cluster finder, E_T isolation cone, track isolation cone, shower shape cut)

DIS provides a source of jets (from the struck quark) with known energy and angular distribution if scattered e^+ is measured.

Result: this study predicts a background (for $X_\gamma > 0.8$) of 52 events (with an upper limit of 80 at 95% C.L.) due to jets being misidentified as single photons.

actual analysis: bgd = 36 +/- 14   sig + bgd = 90 events

What is main background?

neutral mesons in jets:

$\pi^o \rightarrow \gamma\gamma$ (B.R. = 99%)

$\eta \rightarrow \gamma\gamma$ (B.R. = 39%)

$\eta \rightarrow 3\pi^o$ (B.R. = 32%)

multiple photons can mimic single photon in detector

Strategies to minimize these backgrounds:

- reconstruction

  Measure position and energy of each photon from meson decay. Detector spatial resolution may not be good enough.

- shower profiles

  π^o/η showers are broader than single photon shower. Two photon opening angle ~ 1/E

- conversions

  π^o/η decay is twice as likely to produce a $\gamma \rightarrow e^+e^-$ conversion pair which can be identified with preshower detector

- isolation cuts

  Require photon to be isolated within cone of radius R (typically 0.5-1.0). factor 10-100 rejection

Prompt Photons at HERA

- NLO calculations are available for ‘inclusive photon’ as well as ‘photon plus jet’
- a measurement at forward pseudorapidities would be particularly sensitive to the resolved photon contribution

resolved + direct
resolved
direct

- With cuts like those used at ZEUS, the NLO calculations are sensitive to the photon distributions but not to different proton distributions

  → may potentially be used to distinguish between different models of the photon structure function

LEP (e^+e^-)

Hadronic Z decays are used. Data is

- compared with parton level QCD calculations
- used to test detailed predictions of parton shower models

1990: OPAL makes first measurement at LEP of isolated prompt photon production

1996: ALEPH is first LEP experiment to measure non-isolated photons inside jets to extract quark-to-photon the fragmentation function

Tevatron ($p\bar{p}$)

- Compton process ($gq \rightarrow \gamma q$) dominates
- some excess above NLO is seen at low end of E_T^γ range in isolated photon cross section
- high precision CDF data dominate a recent global QCD fit of prompt photon data
- also measured diphoton events, the angular distribution in photon + jet events, photons at forward rapidities

Can prompt photons be seen at HERA?

Where have they been measured before?

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- dominant process yielding high P_T photons is $gq \rightarrow \gamma q$
- can be interpreted as some of the first evidence for the existence of gluons.

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- fixed target, 50-150 GeV photon beam
- First results on inclusive photoproduction of high P_T prompt photons. $1.5 < P_T < 4.5$ GeV
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- cm energy = 630 GeV, $16 < P_T < 82$ GeV

- ‘Within uncertainties the data agree well with the QCD predictions’

1993: E706 Collaboration at Fermilab

- fixed target, pBe and π^-Be, 3.5 - 10 GeV photons
- data higher than NLO QCD at low P_Ts

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