Prompt Photons in Photoproduction at HERA

Preliminary Examination

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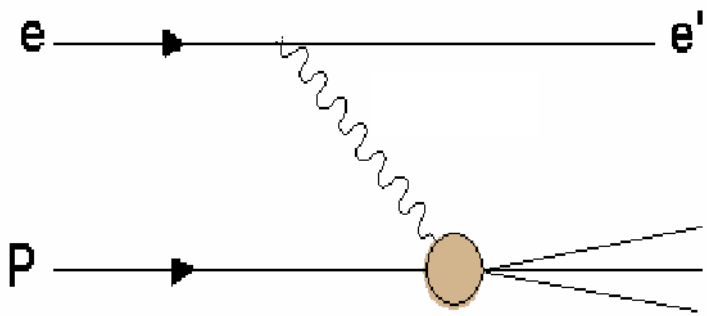
Outline

- Introduction
- HERA and ZEUS
- Kinematics
- Prompt Photon Events
- Related Experimental Results
- MC Generation and Usage
- Event Sample and Cuts
- Summary and Plan for the Future

Structure Of The Proton



- Studied via Probe Exchange
  - Wavelength of probe: $\lambda = h/Q$
    - h: Planck's constant
    - Q: Related to the probe's momentum
    - A smaller wavelength means greater resolution
- HERA Collisions
  - E_e=27.5 GeV , E_p=920 GeV
  - HERA provides ep collisions with CMS energy ~ 300 GeV
  - Provides γ or W/Z as probes
  - Deep Inelastic Scattering (DIS): $1 < Q^2 < 40{,}000\ GeV^2$
  - Probe to .001 fm (Proton is 1 fm)

Quark-Parton Model

- **Hadrons: particles that interact strongly**
  - Bound states of structure-less particles (quarks)
- **Quark-parton model**
  - Quark properties: mass, electric charge, spin
  - Quarks treated as point-like, non-interacting

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

Quark-Parton Model

- **Proton contains only valence quarks**
  - **Partons considered point-like particles**
  - **Structure functions describing individual particles' momenta distribution depend only on x_{Bj}**
    - x_{Bj} is the fraction of the proton's momentum carried by the parton
    - No Q^2 dependence (Bjorken scaling):

$$F_i(x_{Bj}, Q^2) \rightarrow F_i(x_{Bj}) \qquad F_2 = \sum_i e_i^2 x_{Bj} f_i(x_{Bj})$$

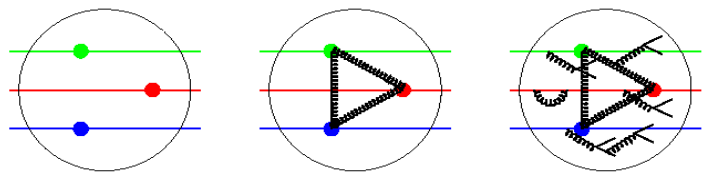
- **$f_i(x) \rightarrow$ Parton density functions (PDF's)**
  - **Must be experimentally determined**

QCD and Colored Gluons

Problems with Quark-Parton Model

- **Statistics for fermion Δ^{++}**
  - Δ^{++} comprised of 3 *u* quarks
  - Violation of exclusion principle under QPM
- **Sum rule for F_2**
  - If QPM correct: $\int_0^1 F_2(x_{Bj})dx_{Bj} = 1$
  - Value of integral shown to be ~0.5 by experiment
    - **Quarks carry roughly half proton momentum**
- **Single quarks never observed**

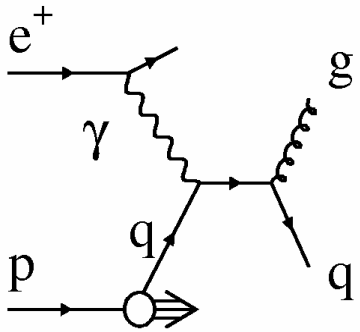
Quantum Chromodynamics: gluons with color quantum number



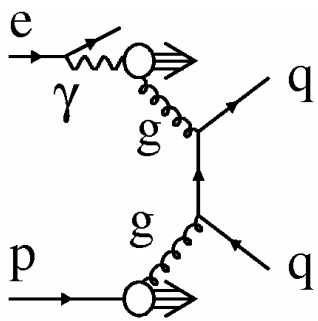
- **Δ^{++} quark composition: $u_R u_B u_G$**
- **Mediator of strong force → gluon**
  - Gluons carry roughly half proton momentum
- **Observed particles "colorless" → color conservation**
  - Isolated quarks not observed → Confinement

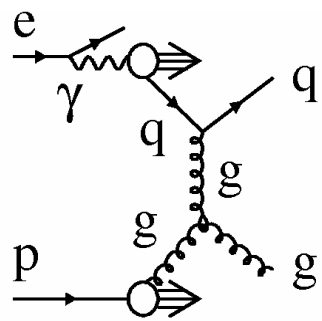
Photoproduction

Direct:



Resolved:





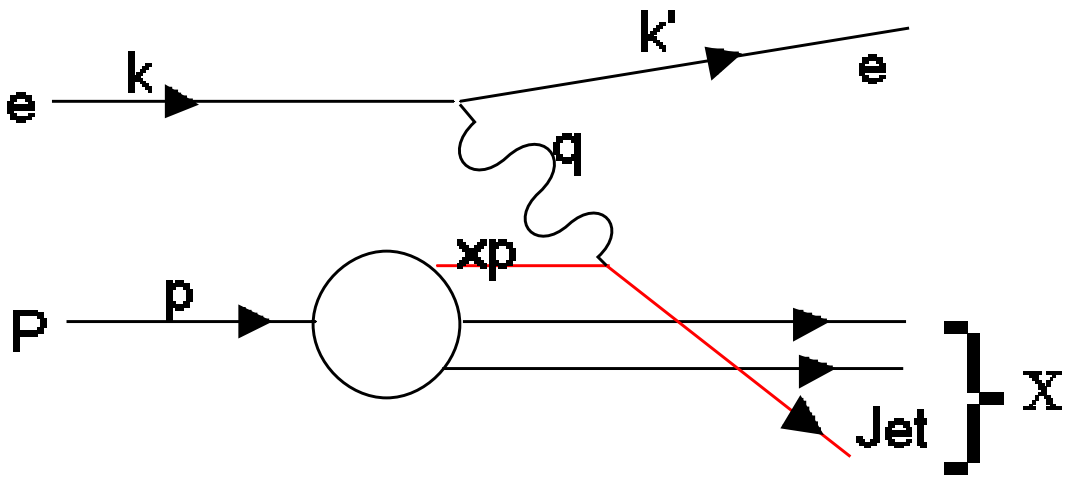
Photon carries very little 4-momentum

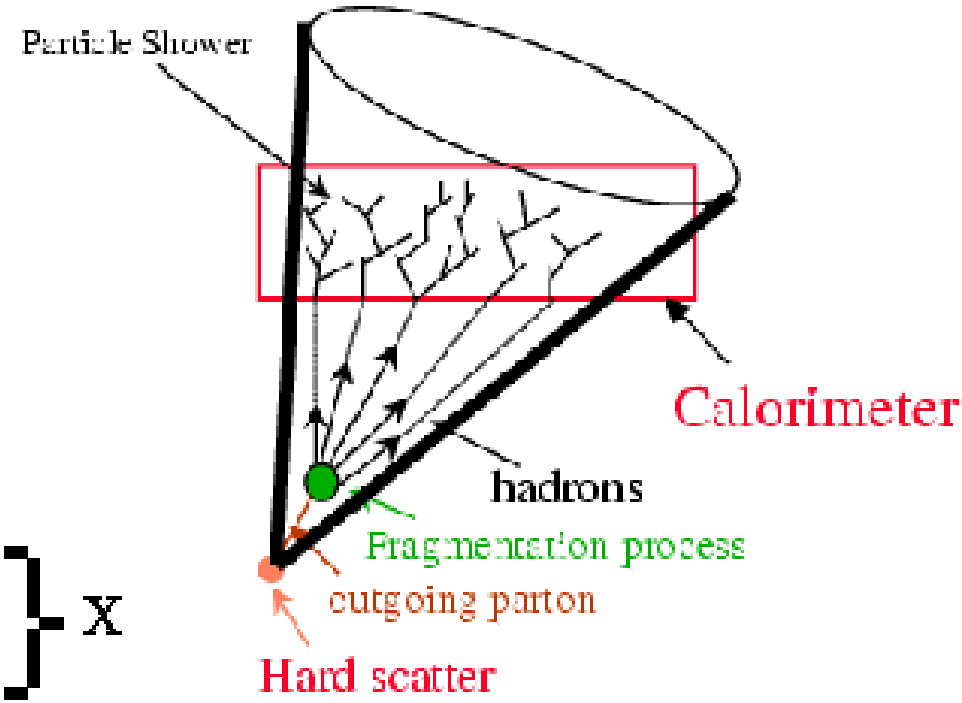
- Photon is almost real
- Photoproduction ($Q^2 \sim 0$)
- DIS ($Q^2 > 1$)

- Most ep events are photoproduction
  - Cross section has a ($1/Q^4$) dependence
- Direct Photoproduction: Photon couples to a parton
- Resolved Photoproduction: Photon fluctuates into partonic state

Jets and Hadronization

Struck Parton → Jet





- Colored partons produced in the interaction → "Parton Level"
- Colorless hadrons form via hadronization → "Hadron Level" (Fragmentation)
- Collimated "spray" of particles → "Jets"
- Particle showers observed as energy deposits in detectors → "Detector Level"

Jets in Resolved & Direct Photoproduction

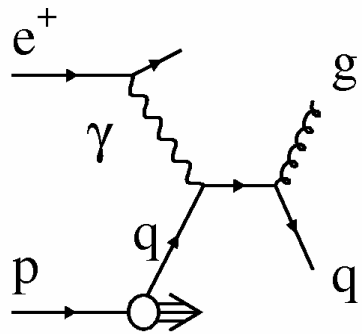
For direct and resolved either a quark or a gluon emerges from the proton

This struck quark or gluon will hadronize and form a jet …

Direct Photoproduction:

→Virtual photon scatters off of one of the quarks

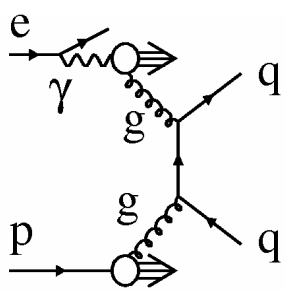
→This leads to a sensitivity to the quark distribution

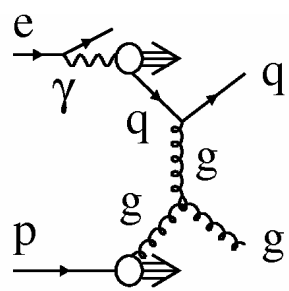


Resolved Photoproduction:

→A quark or gluon from the resolved virtual photon strikes a gluon from the proton

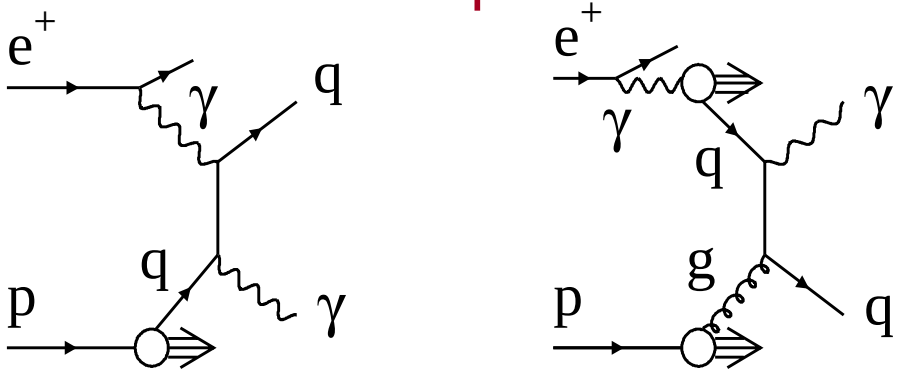
→This leads to a sensitivity to the gluon distribution





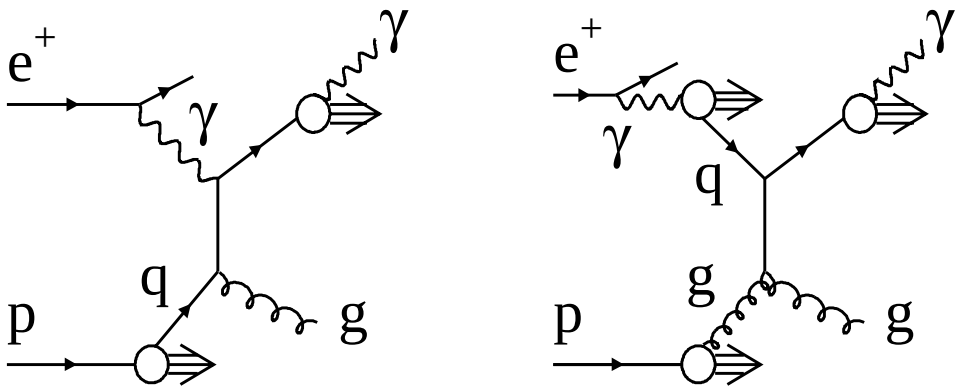
Prompt Photons

Prompt:



(a) Direct (b) Resolved

Radiative:



(c) Direct (d) Resolved

Prompt Photon

- γ is produced at the initial interaction point
  - → Carries information about the struck parton
  - → No hadronization

Non-Prompt Background

- Radiative events, The photon is radiated after the interaction
- Neutral mesons, The photon originates from a decay of hadron

$$\pi^0 \rightarrow 2\gamma$$

Mean Intrinsic Transverse Momentum, $\langle k_T \rangle$

Confinement

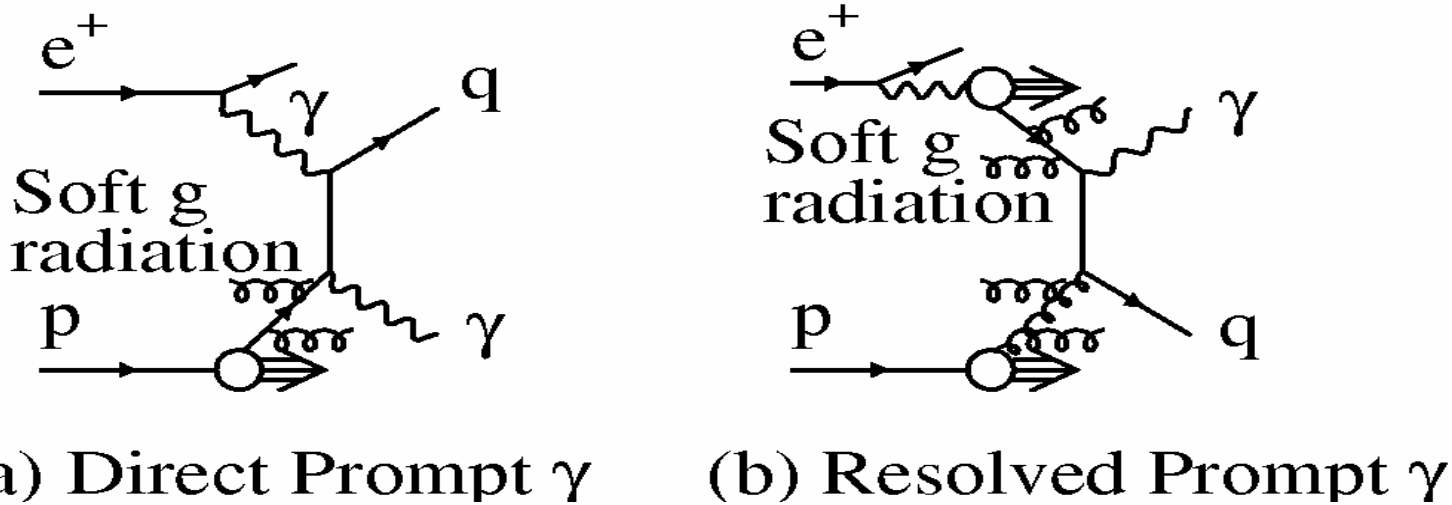
Heisenberg Uncertainty Principle,

$$(\Delta x)(\Delta p) \geq \hbar$$

- **Initial state gluon radiation**

  No transverse momentum from the electron

  But there is from gluons → $\langle k_T \rangle$ provides information about the gluons



(a) Direct Prompt γ (b) Resolved Prompt γ

Photoproduction of Prompt γ + Jet

Presence of a jet →

- Allows the underlying QCD process in the γp interaction to be identified more clearly

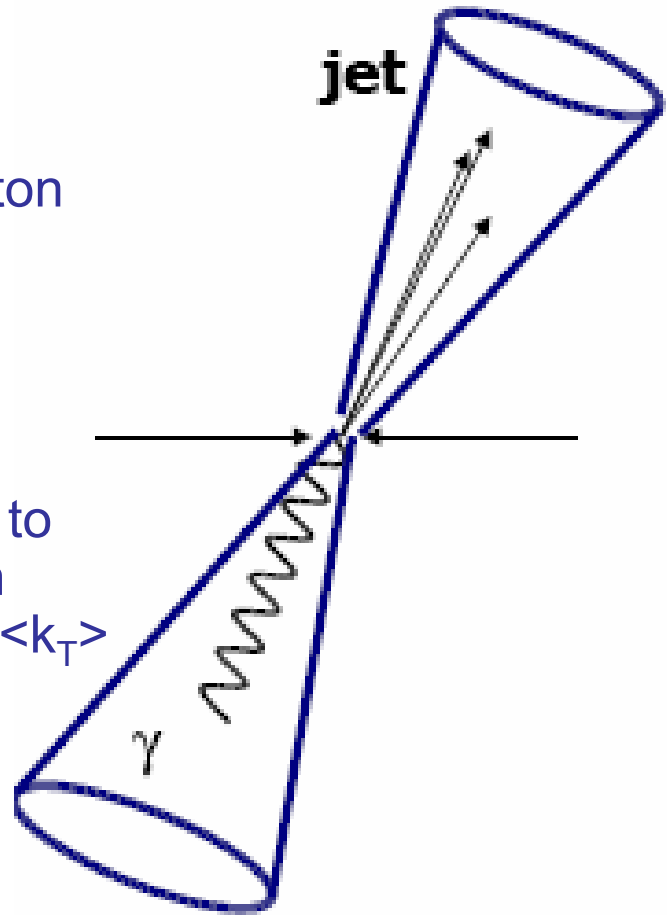
Presence of the prompt photon →

- Provide information about the underlying parton process that is relatively free of hadronization uncertainties

Photoproduction →

- No additional transverse momentum is given to the parton by the photon → The jet and photon should emerge with opposite p_T except for the $\langle k_T \rangle$ contribution

Reliable theoretical calculations available



HERA Description

DESY

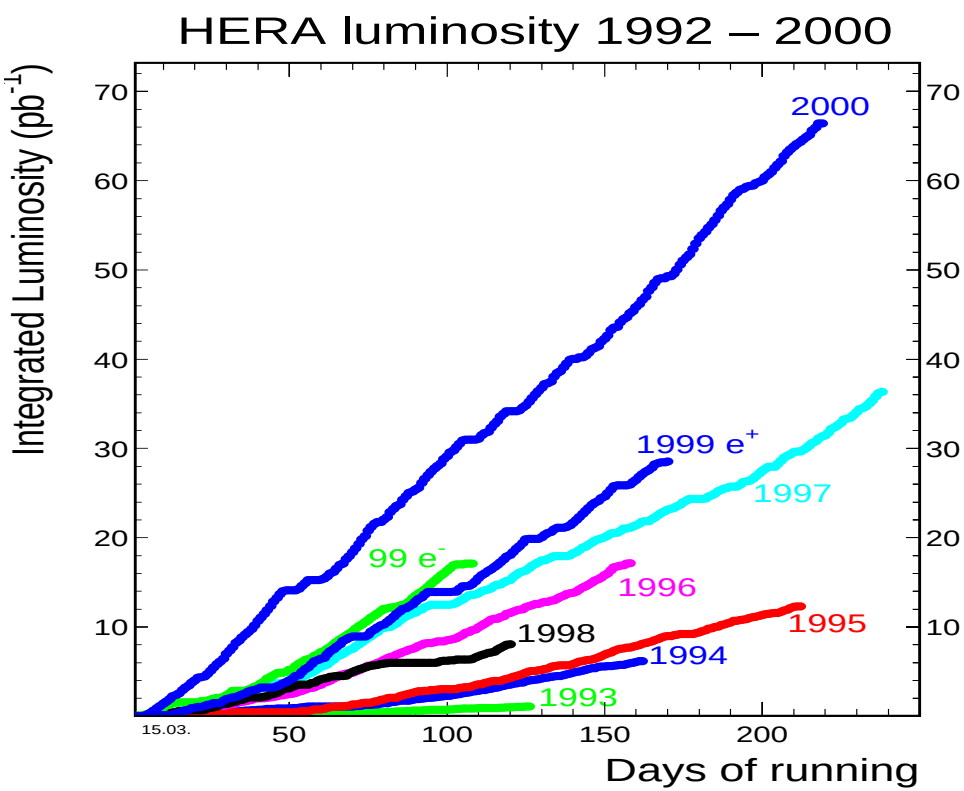
Hamburg, Germany

- 920 GeV protons
- 27.5 GeV e^- or e^+
- CMS energy 318 GeV
  - Equivalent to 50 TeV fixed target
- 220 bunches
  - Not all filled
- 96 ns crossing time
- Currents:
  - ~90mA protons
  - ~40mA positrons
- Instantaneous luminosity:
  - $1.8 \times 10^{31} cm^{-2} s^{-1}$

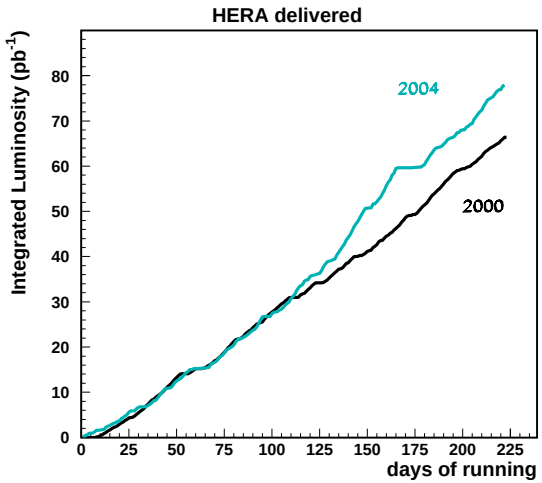
$$L = \frac{R_{tot} - (I_{tot} / I_{unp}) R_{unp}}{\sigma_{BH}}$$

H1 & ZEUS are general purpose detectors

HERA Luminosity

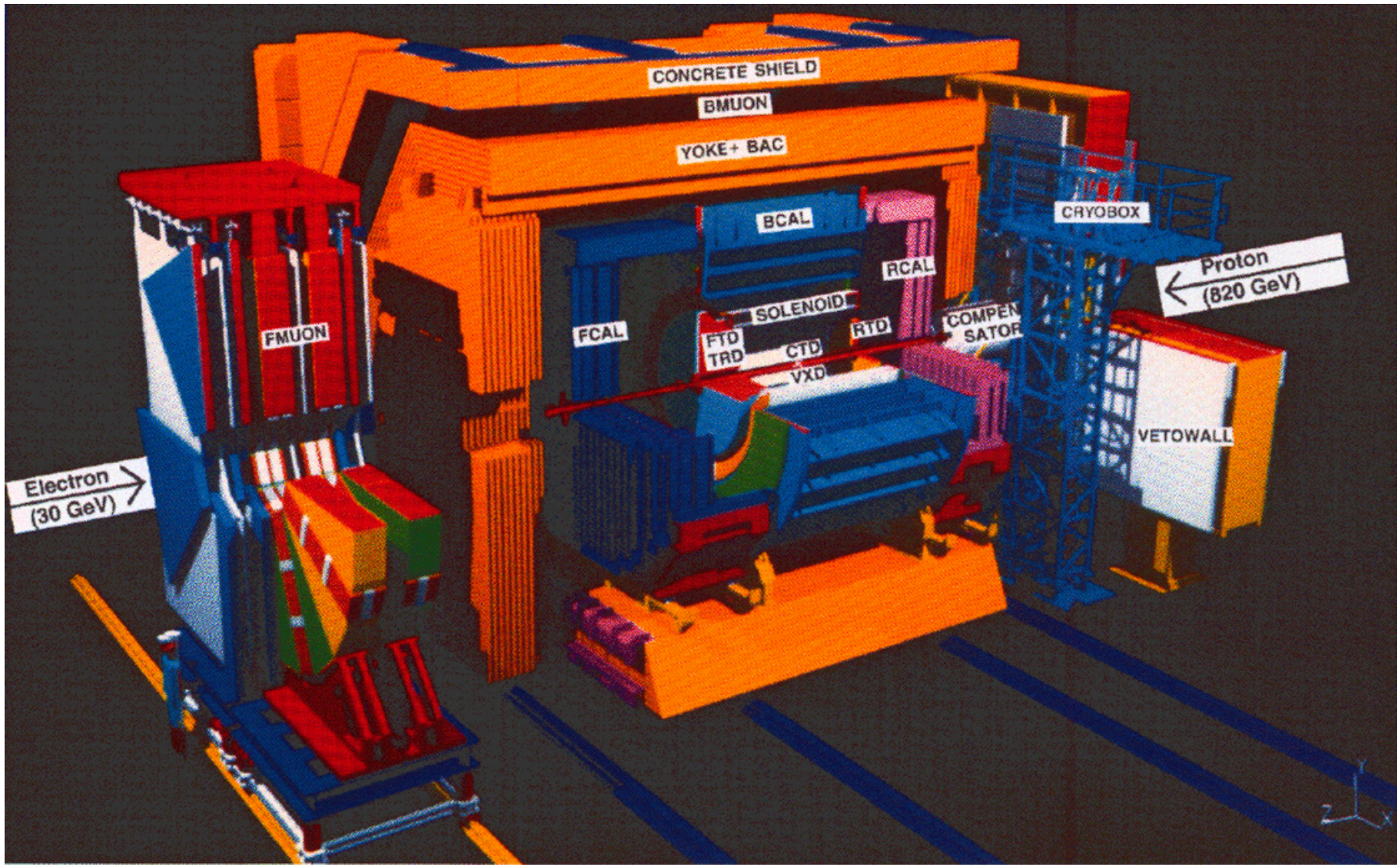


- Total integrated luminosity from '92 → '00: ~193 pb^{-1}
- Total from '02 → '04 : ~84 pb^{-1}
- Plan for '05-'07: 0.5 fb^{-1}

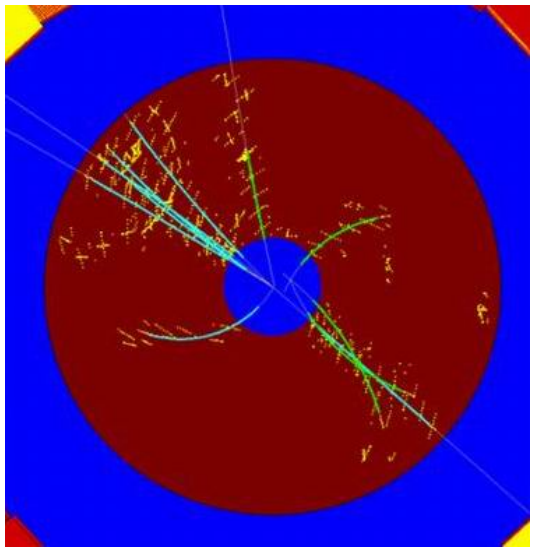


ZEUS Luminosities (pb^{-1})			# events (10^6)
Year	**HERA**	**ZEUS on-tape**	**Physics**
e$^-$: *93-94, 98-99*	27.37	18.77	32.01
e$^+$: *94-97, 99-00*	165.87	124.54	147.55

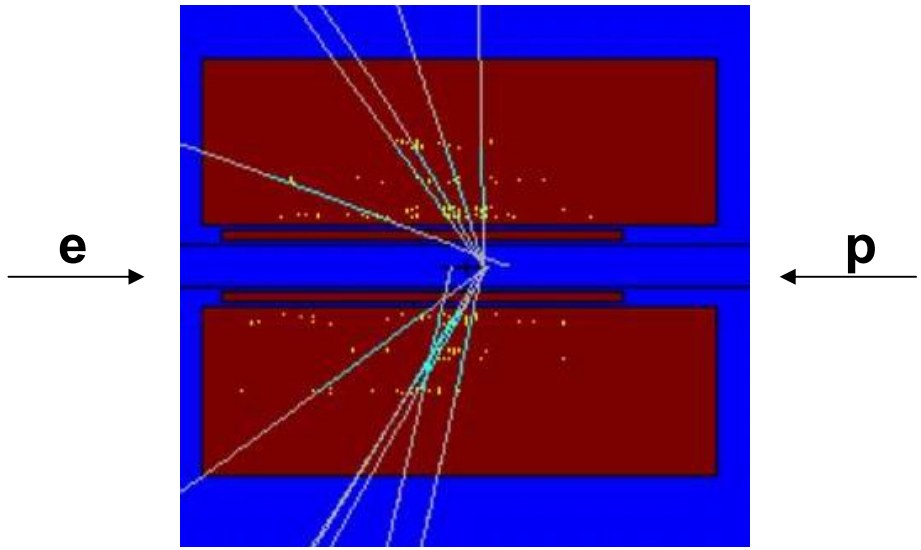
ZEUS Detector



Central Tracking Detector



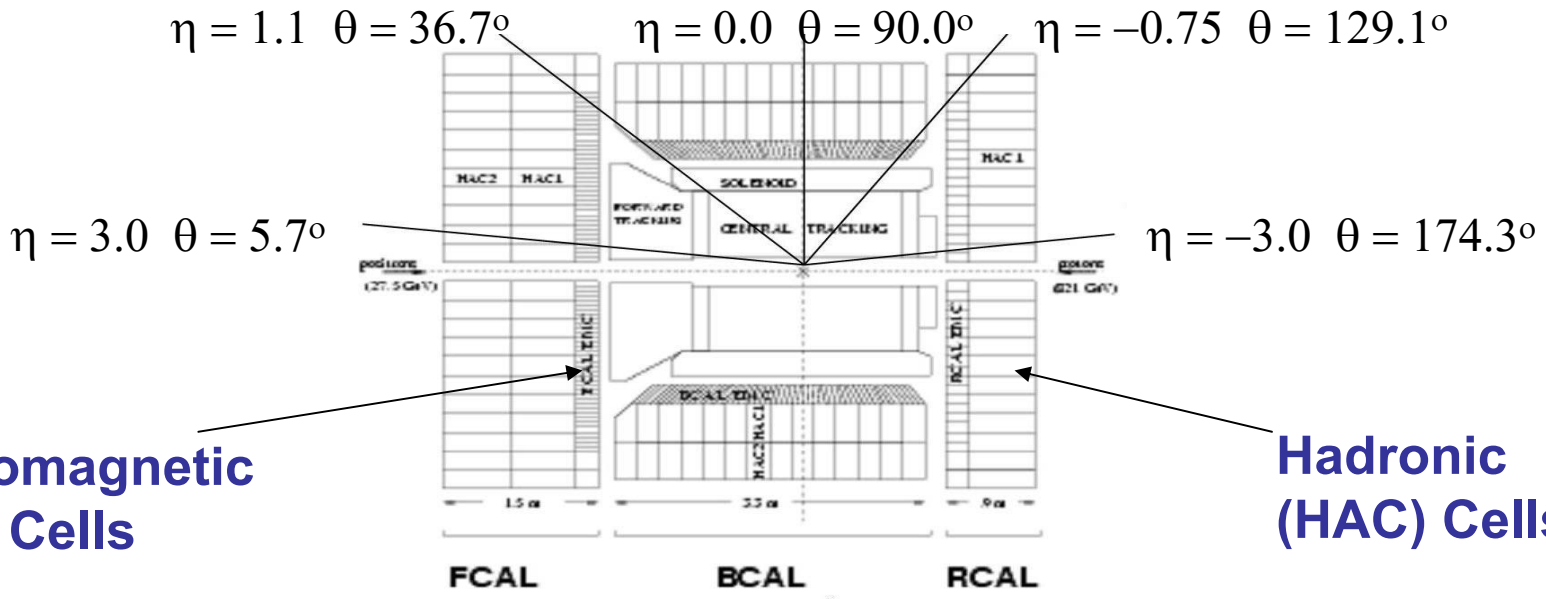
View Along Beam Pipe



Side View

- **Cylindrical Drift Chamber inside 1.43 T solenoid**
- **Measures event vertex**
- **Vertex resolution**
  - Transverse (x-y): 1mm
  - Longitudinal (z): 4mm

Uranium-Scintillator Calorimeter



Electromagnetic (EMC) Cells

Hadronic (HAC) Cells

Pseudorapidity

$$\eta = -\ln[\tan(\theta/2)]$$

Depleted uranium and scintillator

99.8% Solid angle coverage

Energy resolution (single particle test beam)

- **Electromagnetic:** $0.18/\sqrt{E(GeV)}$
- **Hadronic:** $0.35/\sqrt{E(GeV)}$

Measures energy and position of final state particles

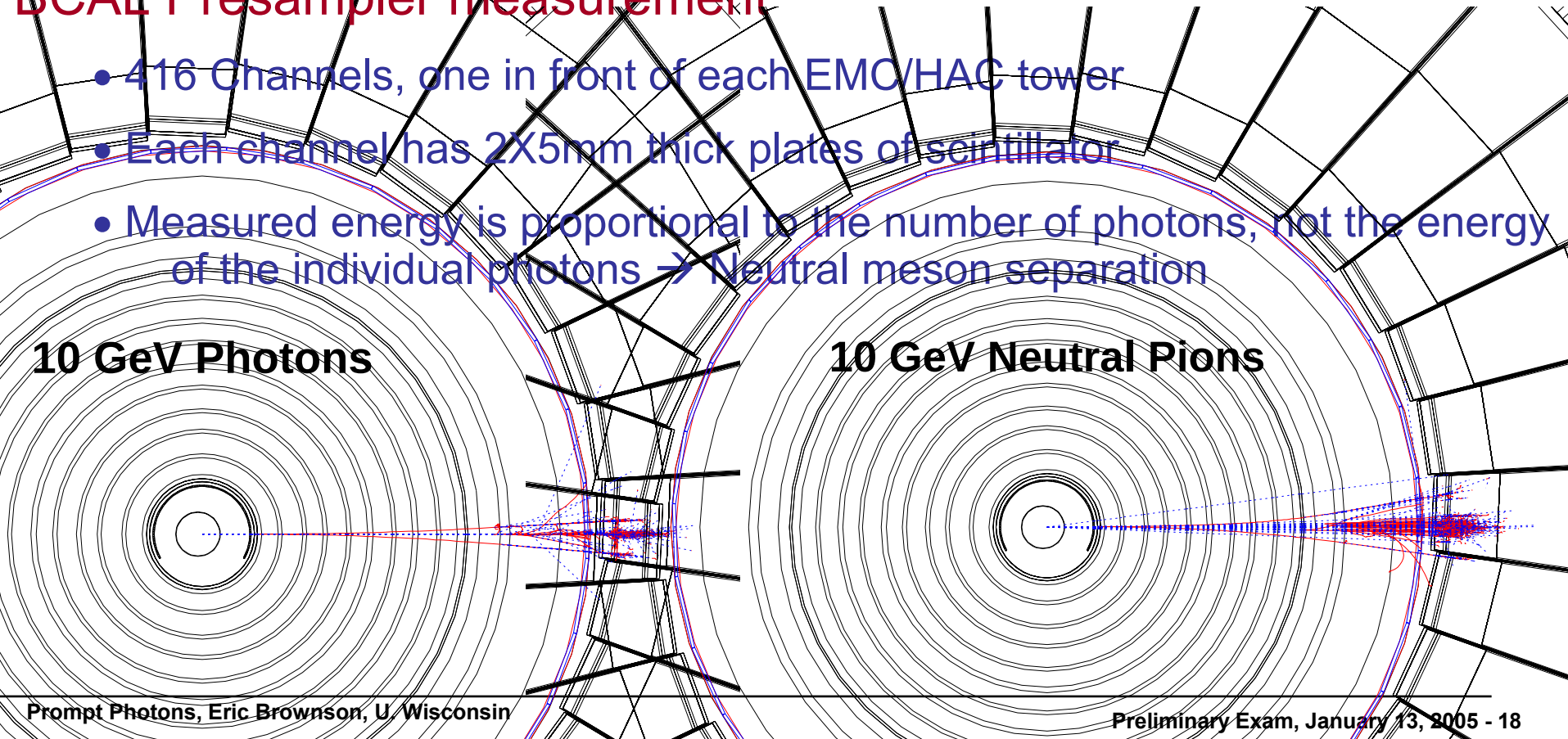
Barrel Presampler

As a particle moves from the interaction point it passes through dead material in front of the BCAL

- This leads to energy loss before measurement

BCAL Presampler measurement

- 416 Channels, one in front of each EMC/HAC tower
- Each channel has 2X5mm thick plates of scintillator
- Measured energy is proportional to the number of photons, not the energy of the individual photons → Neutral meson separation



Online Event Selection: ZEUS Trigger

10 MHz crossing rate, 100 kHz Background rate, 10Hz physics rate

First level: Use data subset: 10 MHz → 500 Hz

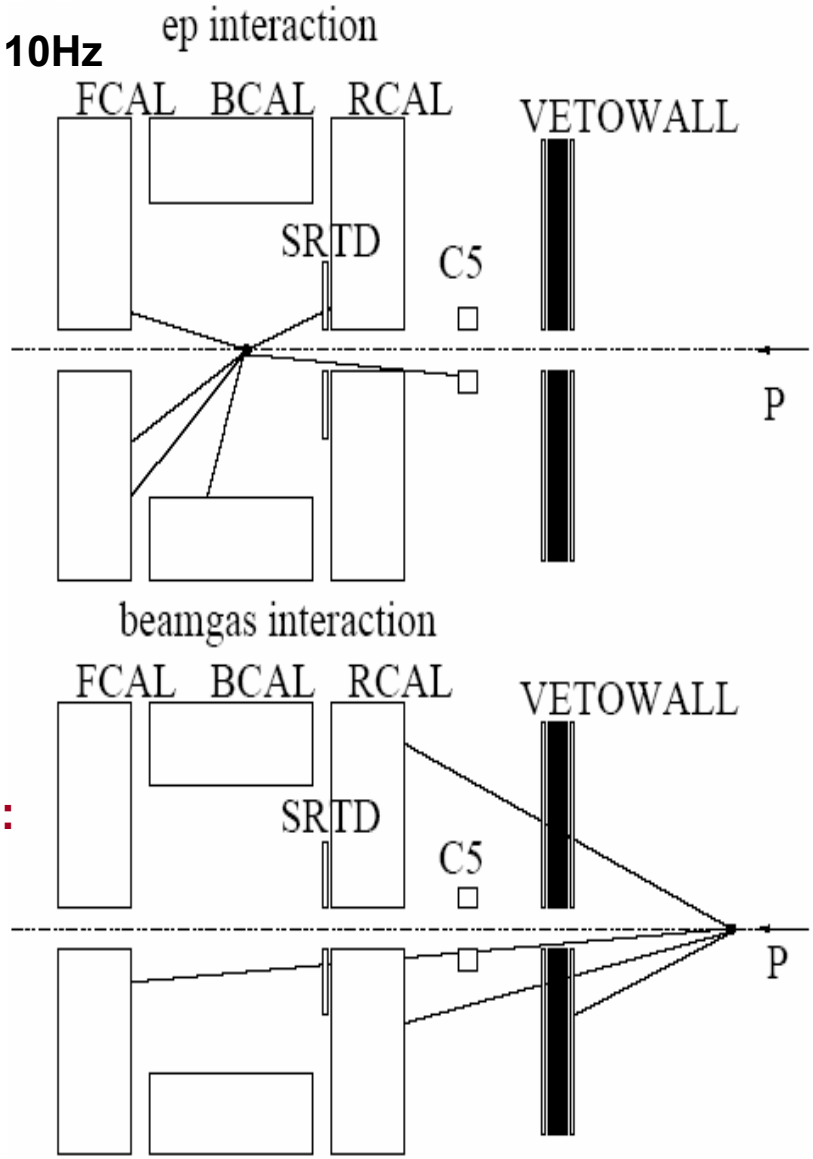
- Dedicated custom hardware
- Pipelined without deadtime
- Global and regional energy sums
- Isolated μ and e^+ recognition
- Track and vertex information

Second level: Use all data: 500 Hz → 100 Hz

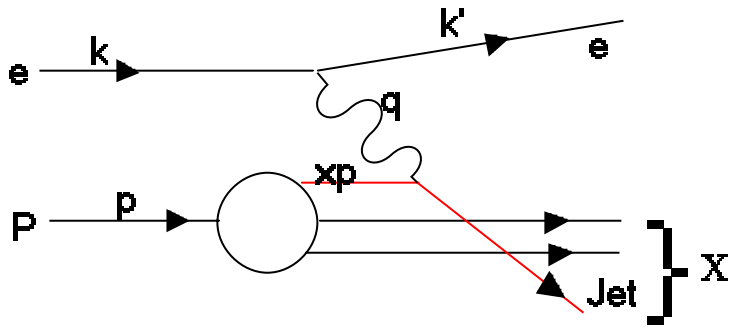
- Calorimeter timing cuts
- $E - p_z < 55$ GeV
  - Energy, momentum conservation
- Vertex information
- Simple physics filters
- Commodity transputers

Third level: Use full reconstruction information: 100 Hz → < 10 Hz

- Processor farm
- Full event information
- Refined jet and electron finding
- Complete tracking algorithms
- Advanced physics filters



Kinematic Variables



Center of Mass Energy of ep system squared

- $s = (p+k)^2 \sim 4E_pE_e$

Center of Mass Energy of γp system squared

- $W^2 = (q+p)^2$

Photon Virtuality (4-momentum transfer squared at electron vertex)

- $q^2 = -Q^2 = (k-k')^2$

Fraction of Proton's Momentum carried by struck quark

- $x = Q^2/(2p\cdot q)$

Fraction of e's energy transferred to proton in proton's rest frame

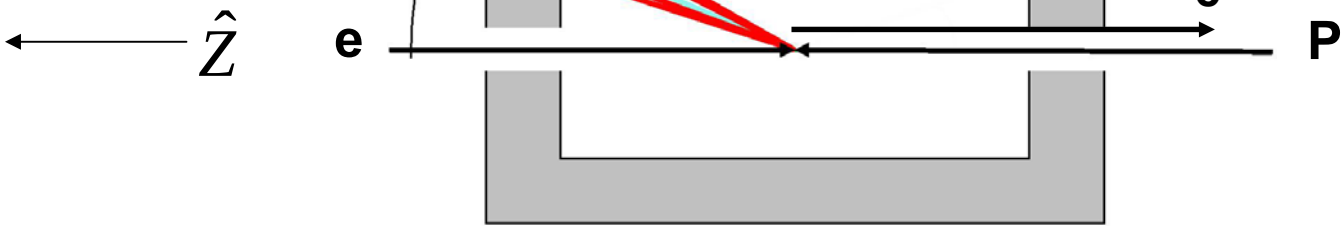
- $y = (p\cdot q)/(p\cdot k)$

Variables are related

- $Q^2 = sxy$

Kinematic Reconstruction

Photoproduction Topology:



Measured Quantities: E_h, p_z, p_T^2

Escapes down beam pipe

Luminosity Detectors

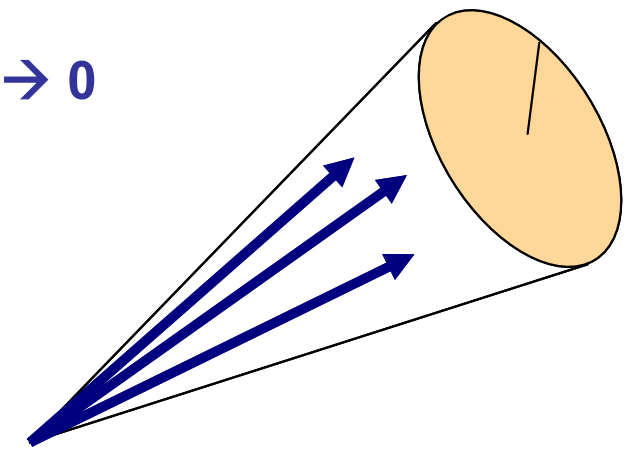
Variable	Jacquet-Blondel Method (E_h, p_z, p_T^2)
y	$\frac{E_h - p_{z,h}}{2E_e}$
Q^2	$\frac{p_{T,h}^2}{1 - y_{JB}}$
x	$\frac{Q_{JB}^2}{s \cdot y_{JB}}$

Jet Finding: Cone Algorithm

Maximize total E_T of hadrons in cone of Fixed size

- Procedure:
  - Construct seeds (starting positions for cone)
  - Move cone around until E_T is maximized
  - Determine the merging of overlapping cones
- Issues:
  - Overlapping
  - Seed , Energy threshold
  - Infrared unsafe , s→ ∞ as seed threshold → 0

$$R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

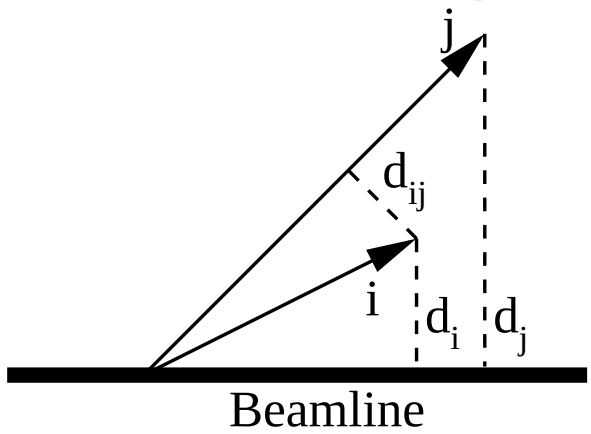


For the Jet:

$$E_T = \sum_i E_{T,i} \qquad \Phi = \frac{1}{E_T}\sum_i E_{T,i}\cdot\Phi_i$$

$$\eta = \frac{1}{E_T}\sum_i E_{T,i}\cdot\eta_i$$

Jet Finding: Longitudinally Invariant k_T Algorithm



In ep: k_T is transverse momentum with respect to beamline

For every object *i* and every pair of objects *i, j* compute

- $d_i = E^2_{T,i}$ (distance to beamline in momentum space)
- $d_{ij} = \min\{E^2_{T,i}, E^2_{T,j}\}[\Delta\eta^2 + \Delta\phi^2]$ (distance between objects)

Calculate min{ d_i , d_{ij} } for all objects

- If (d_{ij}/R^2) is the smallest, combine objects *i* and *j* into a new object
- If d_i is the smallest, then object *i* is a jet

Advantages:

- No ambiguities (no seed required and no overlapping jets)
- k_T distributions can be predicted by QCD

Model Events: PYTHIA Generator

Parton Level

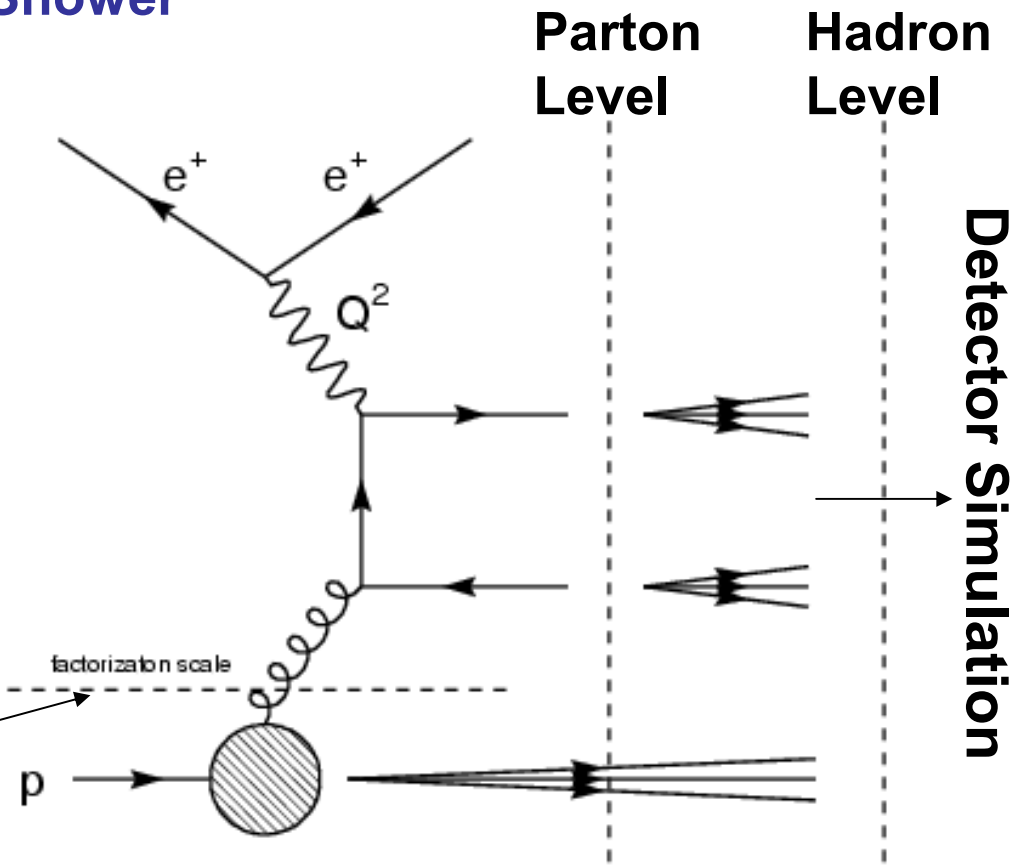
- Matrix Element + Parton Shower

Hadron Level Model

- Fragmentation Model
- Lund String (Next Slide)

Detector Level

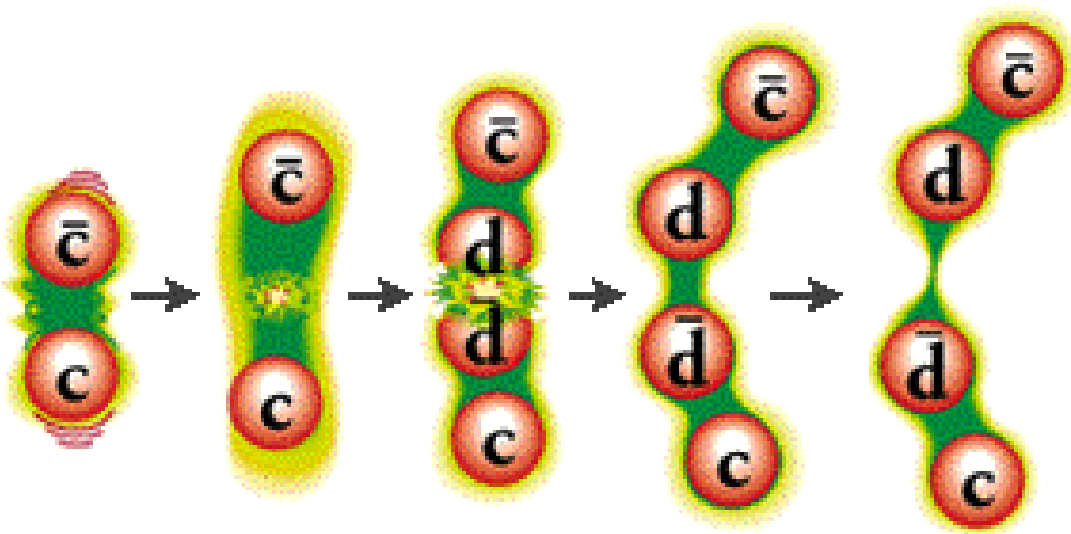
- Detector simulation based on GEANT

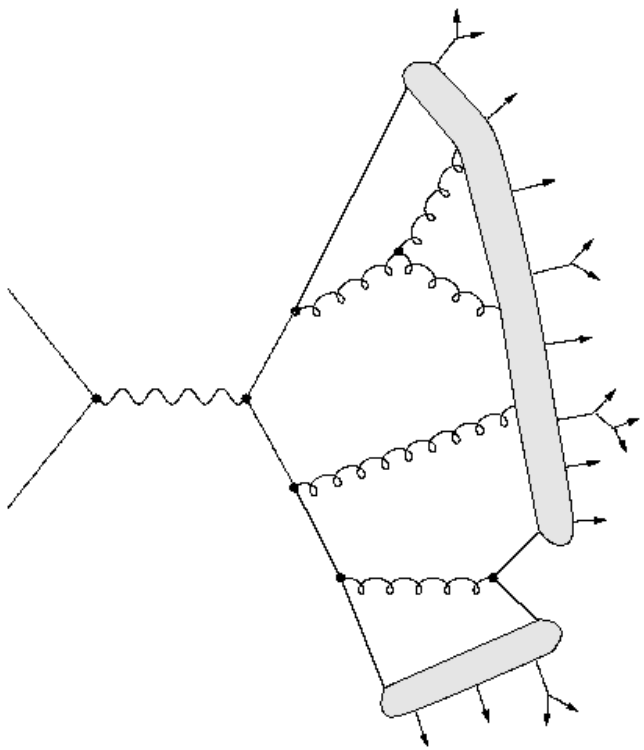


Factorization: Long range interactions below certain scale absorbed into proton's structure

Lund String Fragmentation

- Color “String" stretched between q and $\bar{q}$ moving apart
- Confinement with linearly increasing potential (1GeV/fm)
- String breaks to form 2 color singlet strings, and so on., until only on-mass-shell hadrons.



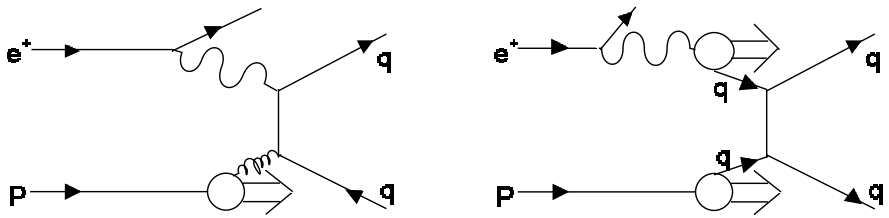


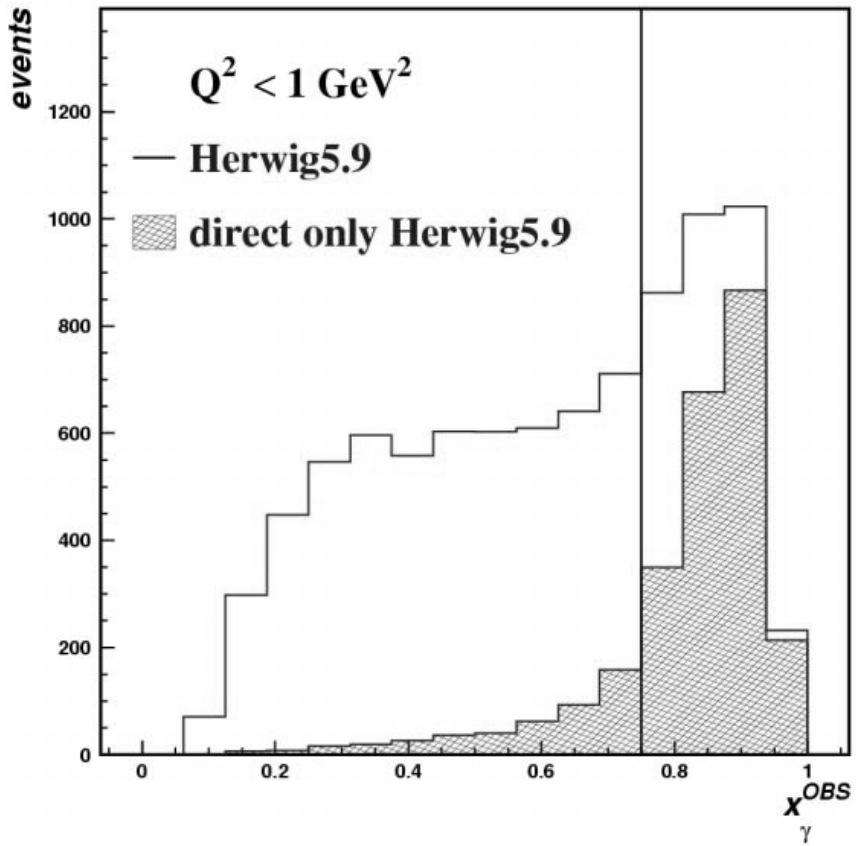
Photoproduction Observables: X_γ^{meas}, X_p^{meas}

X_γ^{meas}: Fraction of the photon's momentum involved in the collision

- Direct Photoproduction: $X_\gamma \sim 1$
- Resolved Photoproduction: $X_\gamma < 1$

$$X_\gamma^{meas} = \sum_{\gamma,Jet} \frac{(E - P_z)}{(2E_e Y_{jb})}$$

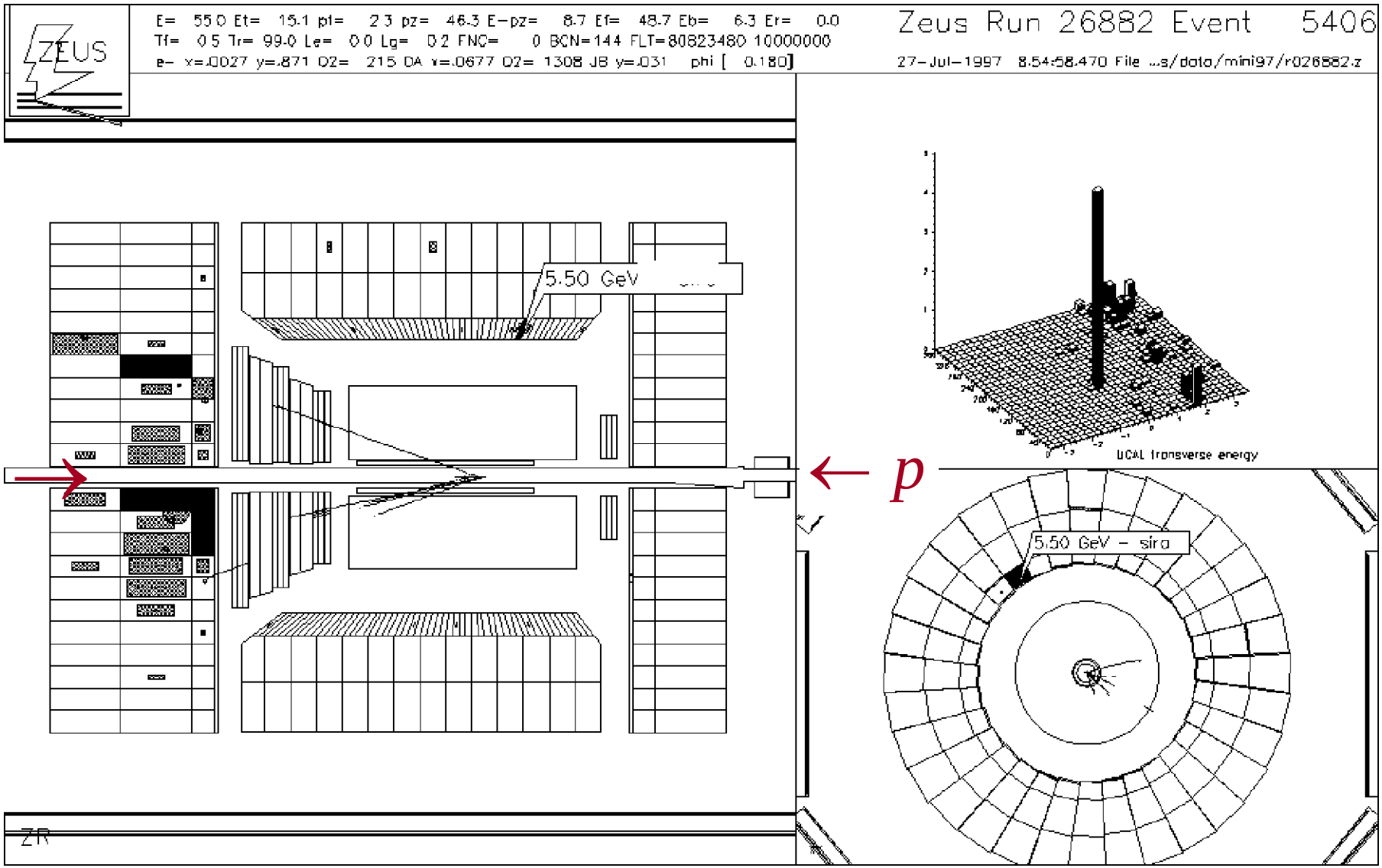




X_p^{meas}: Fraction of the proton's momentum involved in the collision

$$X_p^{meas} = \sum_{\gamma,Jet} \frac{(E + P_z)}{(2E_e)}$$

Prompt Photon Event

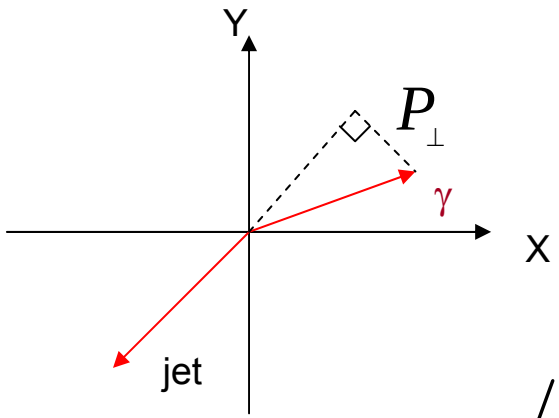


Prompt γ + Jet Photoproduction Observable: $P_\perp$ From ZEUS

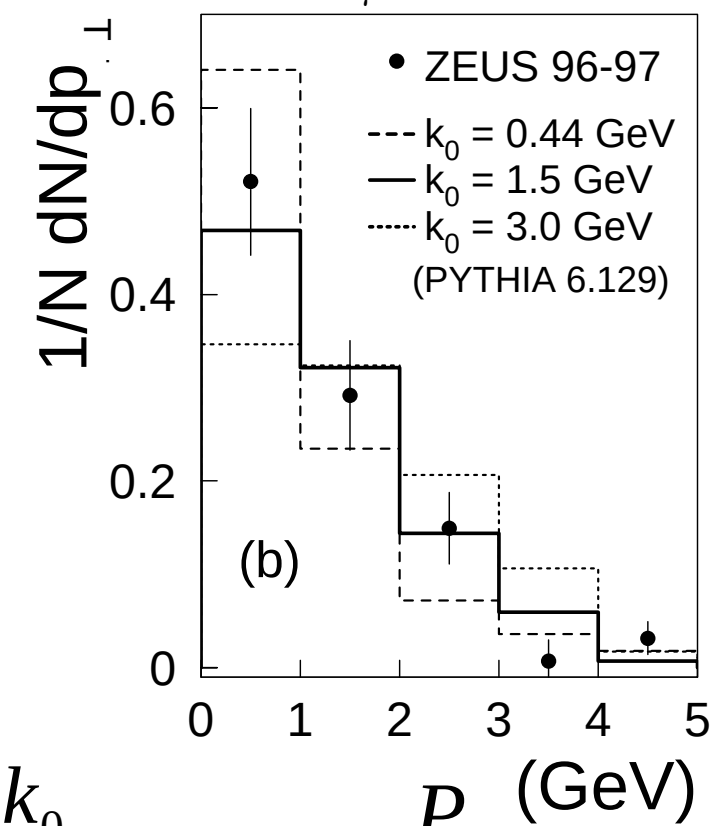
Momentum imbalances of the photon relative to the jet:

- Related to the intrinsic transverse momentum of the struck parton $\langle k_T \rangle$
- ZEUS previously measured $P_\perp$ from 0 to 5 GeV

$$P_\perp = \frac{|\, P_{xy,\,\gamma} \mathrm{X}\, P_{xy,\,jet}\,|}{P_{T,\,jet}}$$



(a)



$$\langle k_T \rangle_{2D-rms} = k_0$$

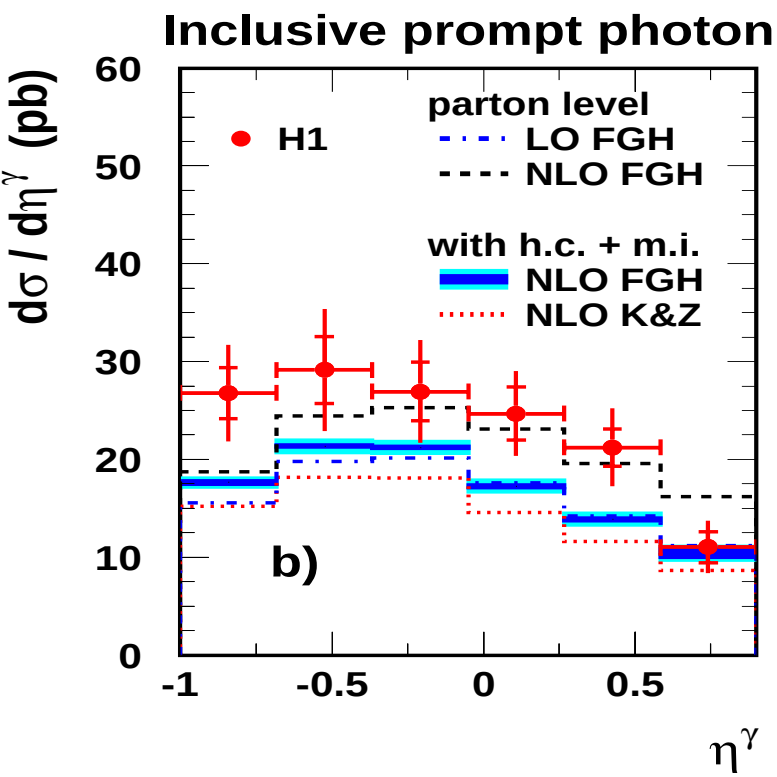
$E_T^\gamma + E_T^{jet} > 12.5$ GeV

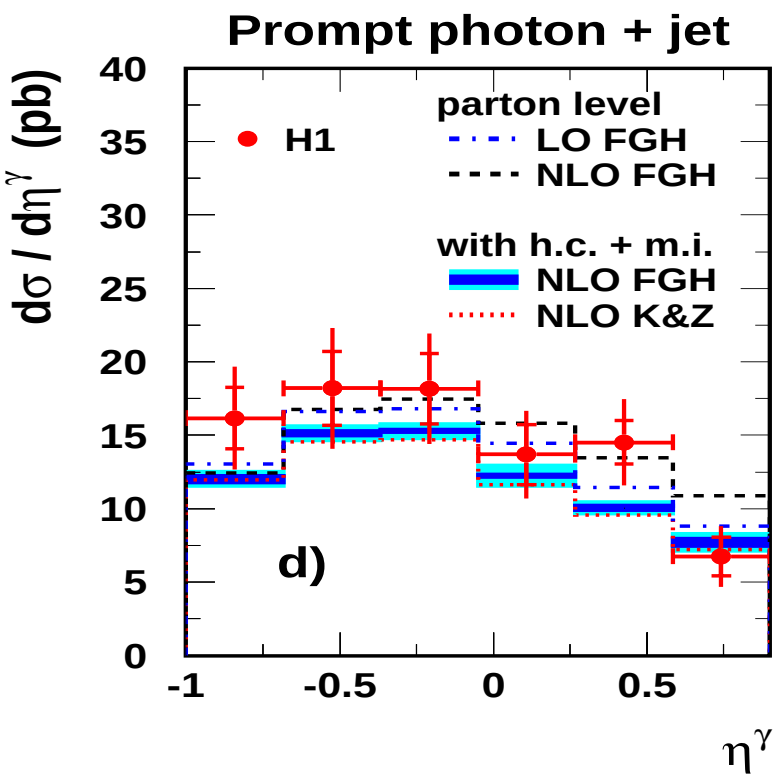
H1 Prompt Photons in Photoproduction: η^γ

"Measurement of Prompt Photon Cross Sections in Photoproduction at HERA"

DESY Preprint 04-118

- With and without the jet requirement, the two cross sections are about a factor of 2 apart
- With and without the jet, same qualitative shape of η^γ



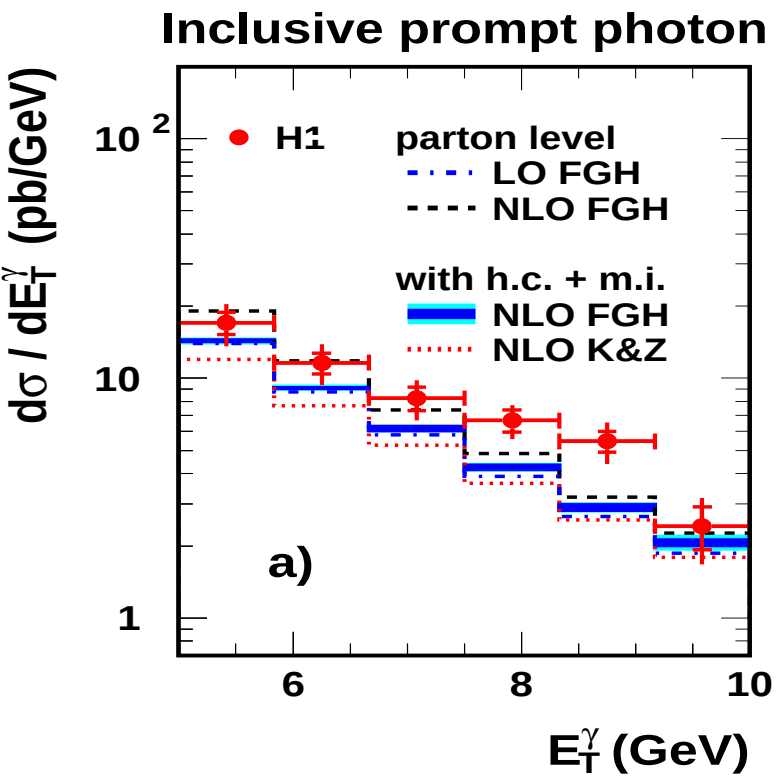


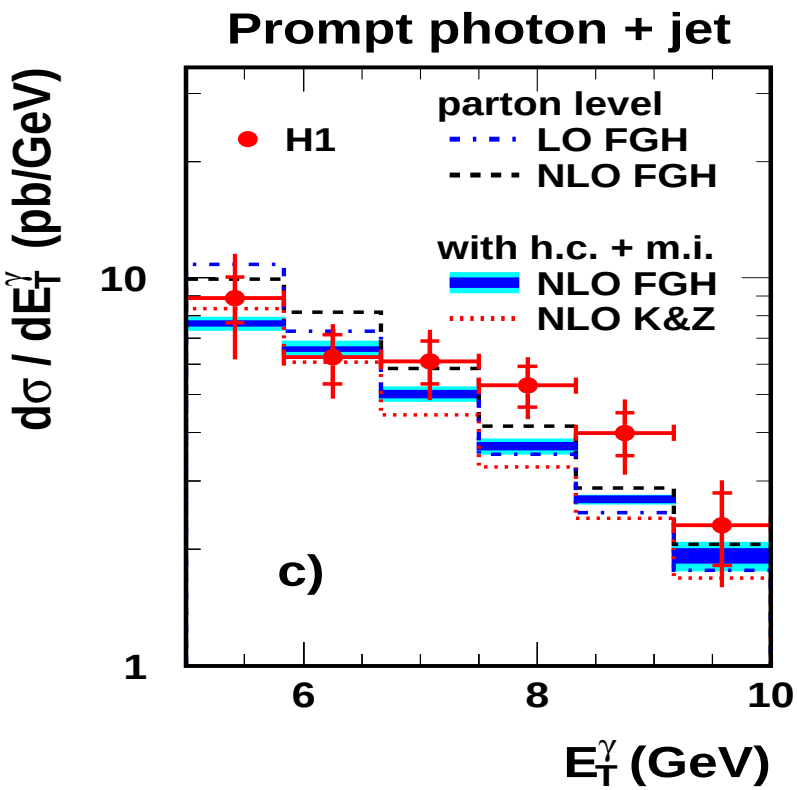
H1 Prompt Photons in Photoproduction: E_T^γ

"Measurement of Prompt Photon Cross Sections in Photoproduction at HERA"

DESY Preprint 04-118

- With and without the jet requirement, the two cross sections are about a factor of 2 apart (Note the log scale)
- With and without the jet, same qualitative shape of E^γ





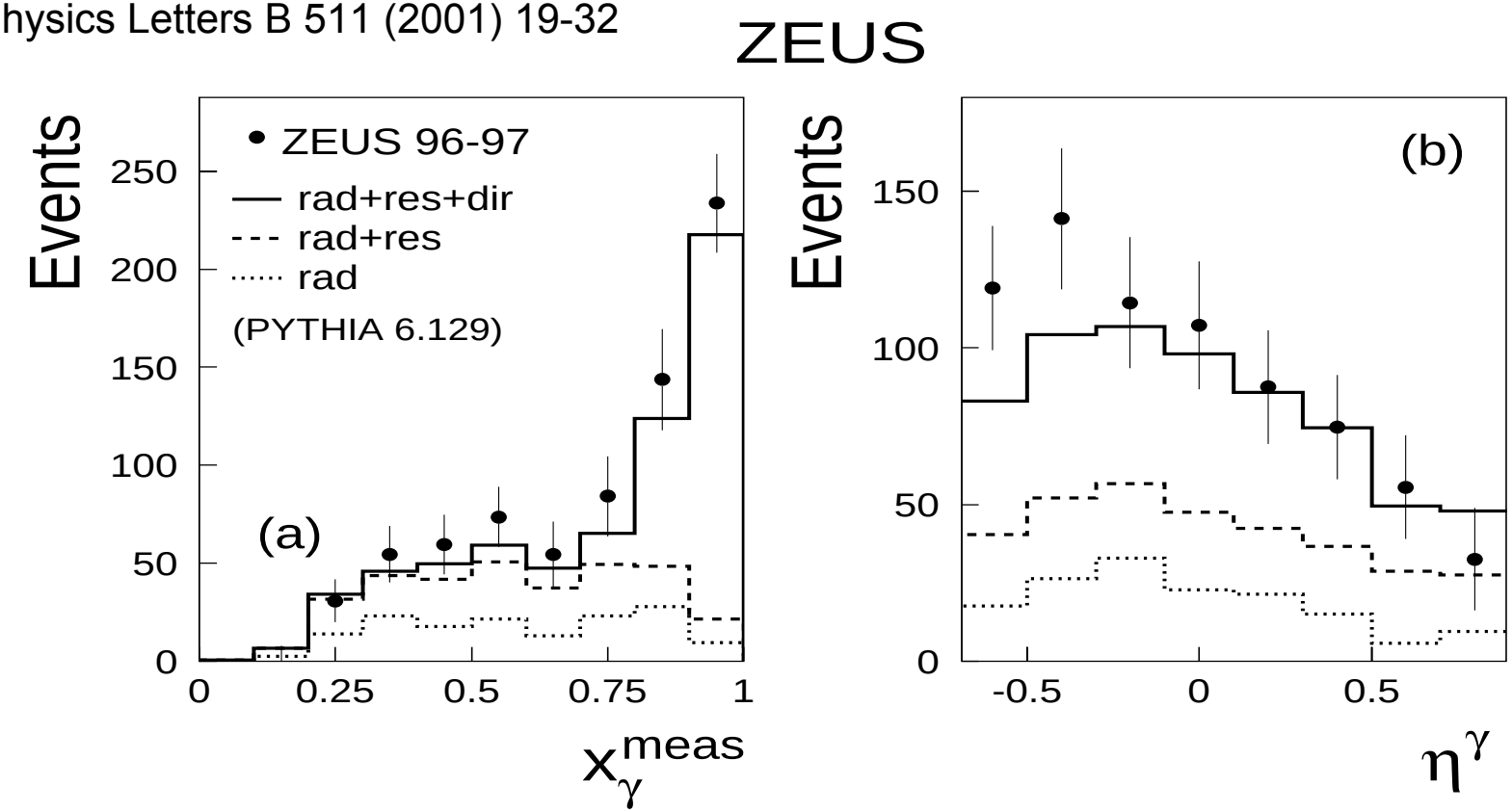
Previous ZEUS Prompt γ + Jet Photoproduction Analysis

"Study of the effective transverse momentum of partons in the proton using prompt photons in photoproduction at HERA"

Physics Letters B 511 (2001) 19-32

- Both direct and resolved events are present
- Uses '96-'97 Data

  → Barrel Presampler not available



Previous ZEUS Prompt γ + Jet Photoproduction Analysis

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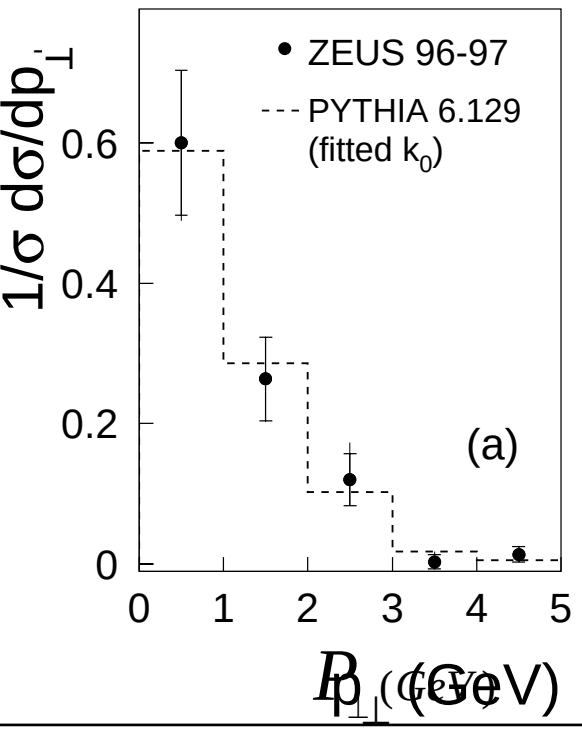
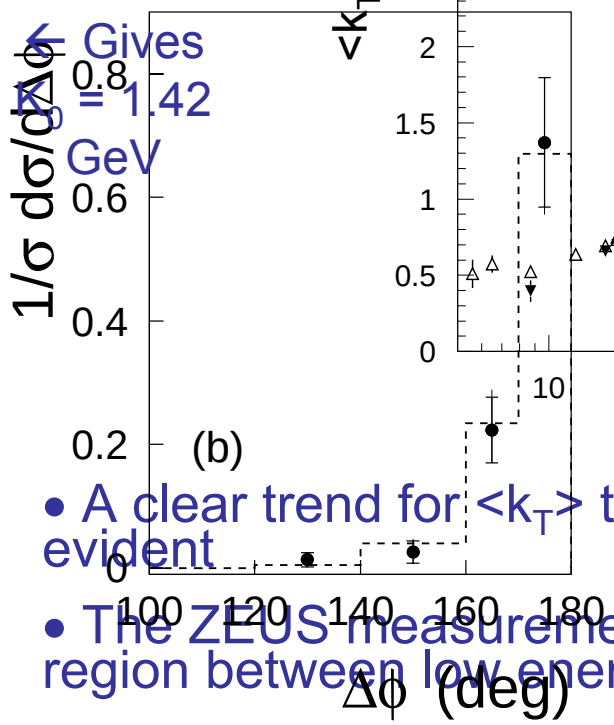
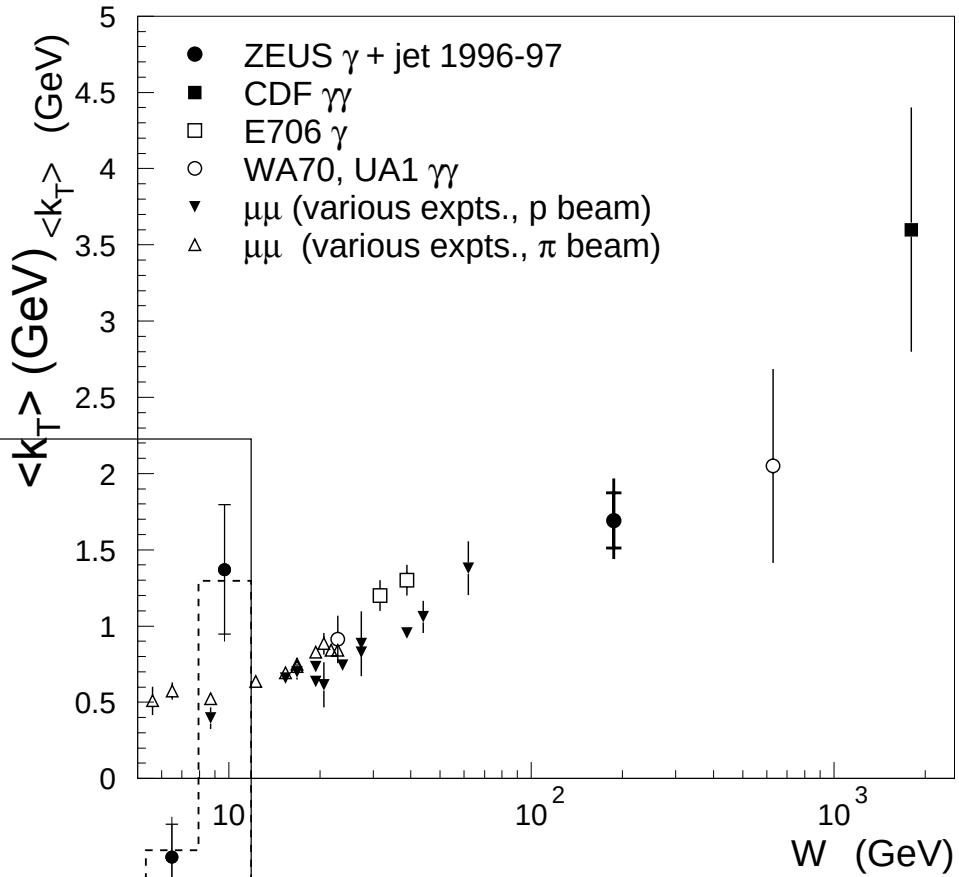




⇐ Gives k_0 = 1.42 GeV



- A clear trend for $\langle k_T \rangle$ to rise with increasing W is evident
- The ZEUS measurement is in an intermediate region between low energies and very high energies

New ZEUS Prompt γ + Jet Photoproduction Sample

Trigger Cuts:

FLT:

- EMC Energies > Threshold
- Total Cal. Energy > Threshold
- At least one good Track

SLT:

- $|Z_{vtx}| < 60$ cm
- $E\text{-}P_z$ > Threshold
- E_T(Box) > 8.0 GeV

TLT:

- Limit on the Number of Bad Tracks
- At least one electron candidate from the elec5 electron finder with,

$E_T^{\gamma} > 4.0$ GeV , $-3.0 < \eta^{\gamma} < 1.5$

Offline Cuts:

- $|Z_{vtx}| < 55$ cm
- No Scattered electron

  → Selects Photoproduction Events

- $0.2 < Y_{JB} < 0.8$

  →Lower: Remove Beam Gas

  →Upper: Remove DIS Events

- Photon Candidate: $-0.74 < \eta^{\gamma} < 1.1$

$$\frac{E_{emc}}{E_{tot}} > 0.9 \qquad E_T^{\gamma} > 5.0 GeV$$

- Hadronic Jet: $-1.6 < \eta^{Jet} < 2.4$

$$\frac{E_{emc}}{E_{tot}} < 0.9 \qquad E_T^{Jet} > 6.0 GeV$$

If Two Hadronic Jets are found the One with higher E_T is used

New Prompt γ + Jet Analysis

- Increased luminosity
  - Previous analysis → 38.6 pb^{-1}
  - '99-'00 → 77.1 pb^{-1} + Additional running periods
- BCAL Presampler
  - Commissioned in '98 → Improved background rejection
- New QCD calculations available
  - M. Krawczyk and A. Zembrzuski (2003)
  - M. Fontannaz, J.P. Guillet and G. Heinrich (2002)
- First look at new data → …

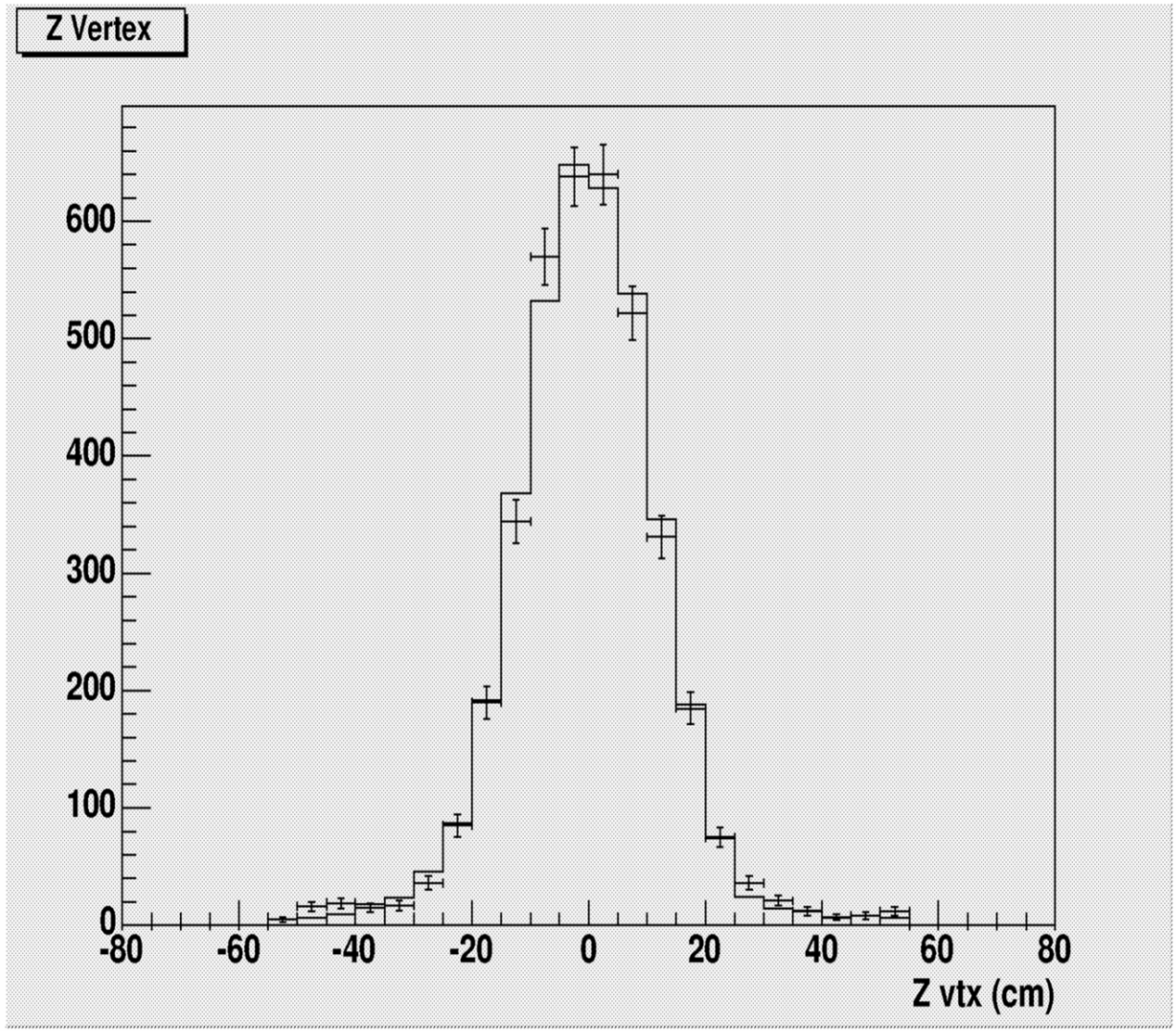
Photoproduction Prompt γ + Jet: Event Vertex

$|Z_{vertex}| < 55$ cm

→Excludes beam gas background

→ Needed to accurately reconstruct the event

P_T, E_T, η, etc …



Data are crosses

MC are solid line

Photoproduction Prompt γ + Jet: Y_{meas}

$0.2 < Y_{meas} < 0.8$

$$Y_{meas} = \sum_{Cal} \frac{E - p_z}{2E_e} \qquad P_z = E\cos\theta$$

Y > 0.2,

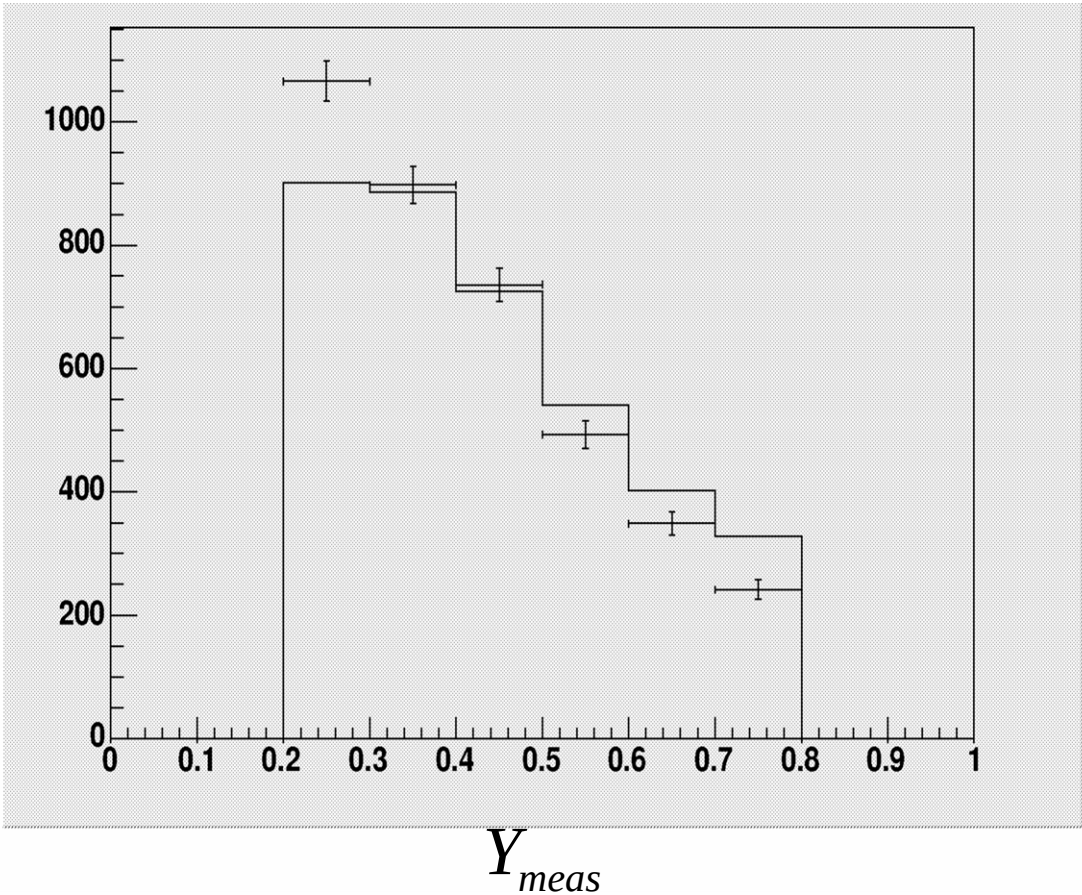
→Eliminate proton gas background

→Eliminate cosmic events

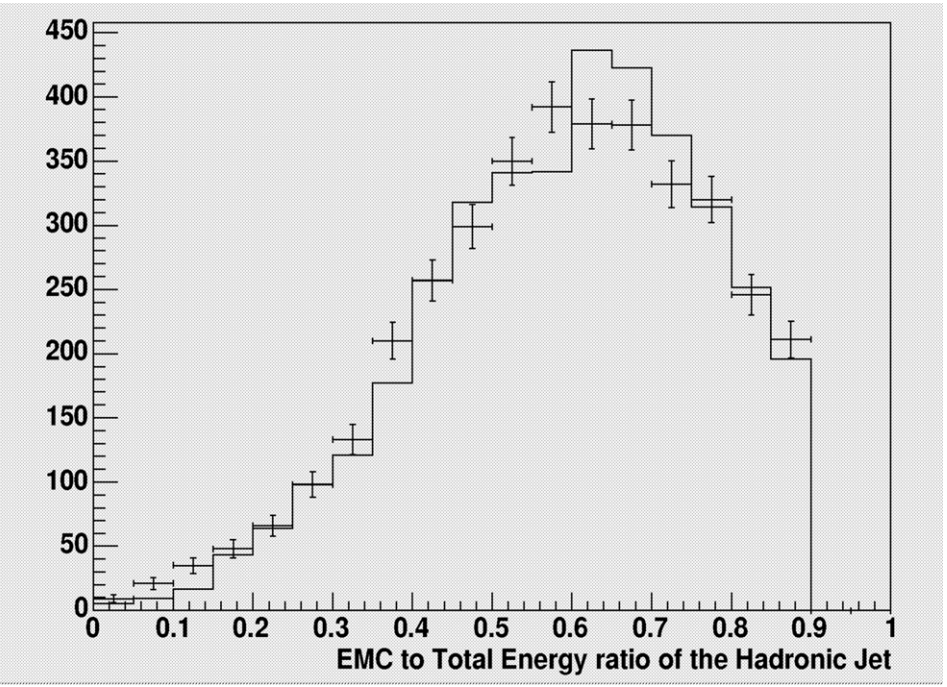
Y < 0.8,

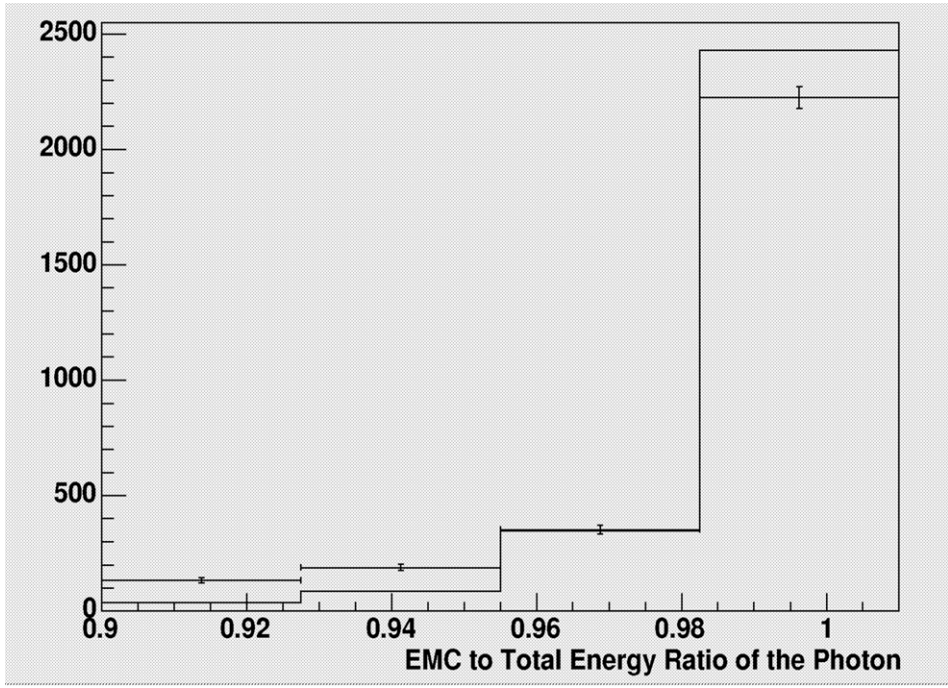
→Eliminate DIS events

i.e. Events where the photon is actually a misidentified electron



Photoproduction Prompt γ + Jet: Energy Deposit Ratio





Separating the photon and hadronic Jet, cut at 0.9

- Photons deposit almost all of their energy in the EMC section of the CAL
- Hadronic jets deposit more of their energy in the HAC section of the CAL than photons

Background & Neutral Mesons

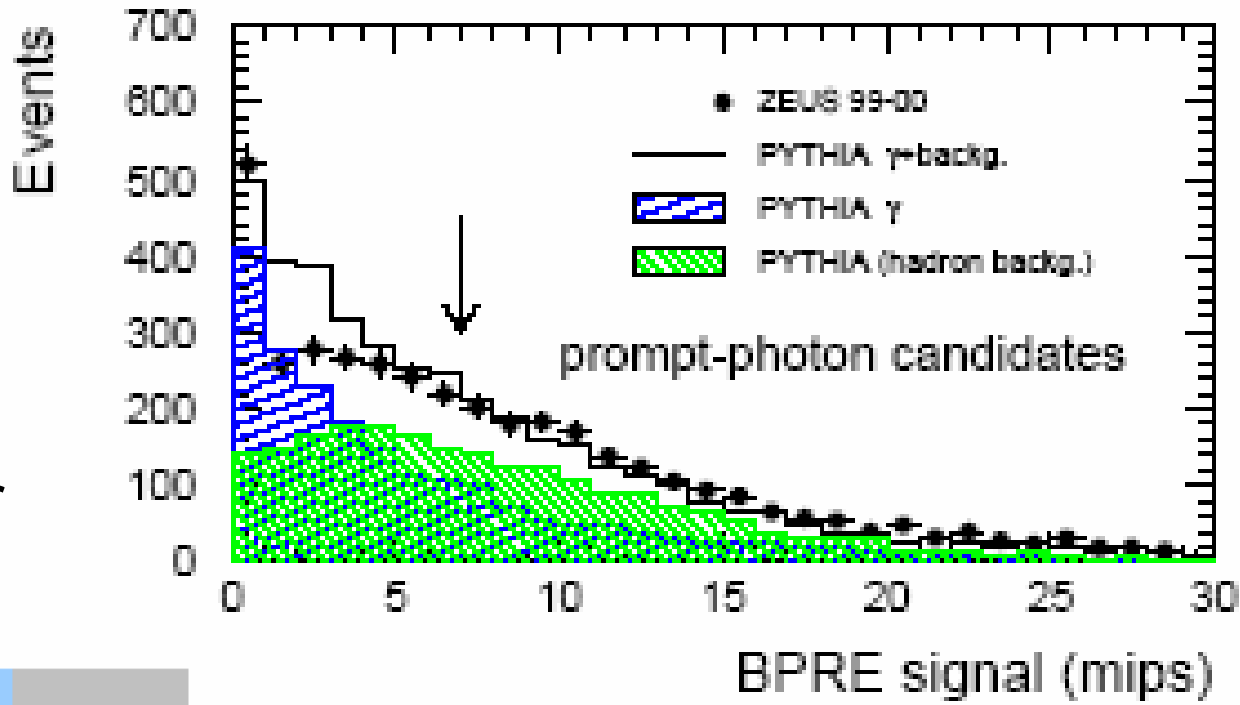
Background:

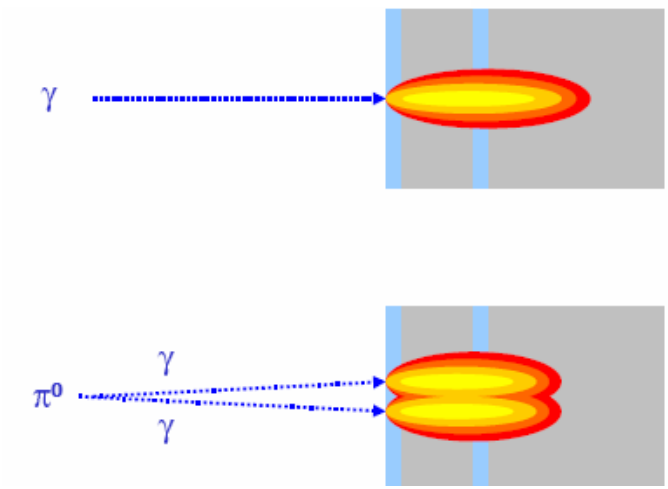
$$\eta \rightarrow (2\gamma) \cup (3\pi^0)$$

$$\pi^0 \rightarrow 2\gamma$$

Solution:

New Barrel Presampler





BPRE signal < 7 (mips)

- Reject events where the photon interacted with dead material
- Reject events with more photons

Photoproduction Prompt γ + Jet: E_T^{γ}, η^{γ}

The kinematics of the Photon

Photon cuts:

$E_{emc}/E_{tot} > 0.9$

$-0.74 < \eta_{\gamma} < 1.1$

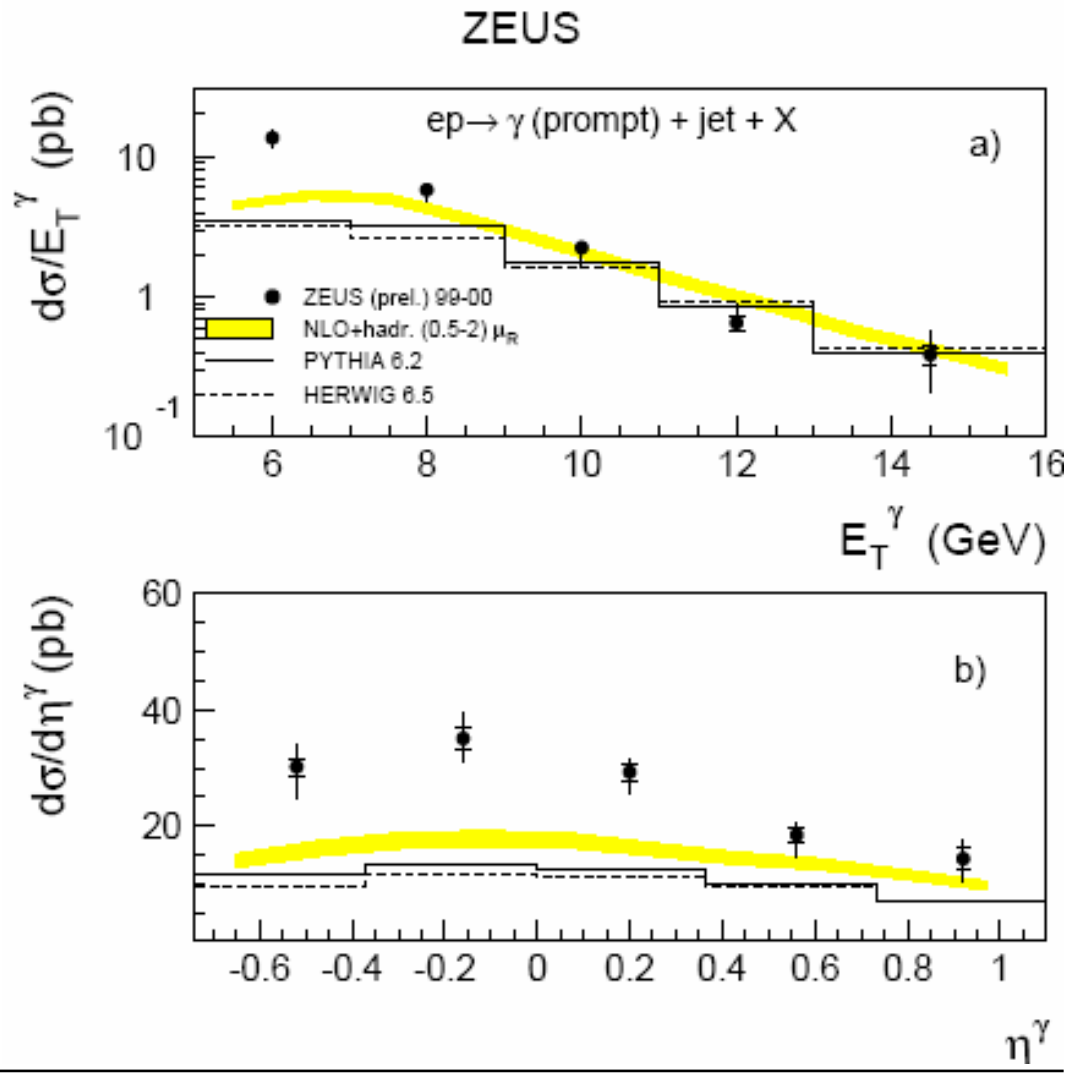
$E_T^{\gamma} > 5$ GeV

Hadronic jet cuts:

$E_{emc}/E_{tot} < 0.9$

$-1.6 < \eta_{\gamma} < 2.4$

$E_T^{jet} > 6$ GeV



Photoproduction Prompt γ + Jet: E_T^{jet}, η^{jet}

The kinematics of the Hadronic Jet found with the k_t Jet Finder

Photon cuts:

$E_{emc}/E_{tot} > 0.9$

$-0.74 < \eta_\gamma < 1.1$

$E_T^\gamma > 5$ GeV

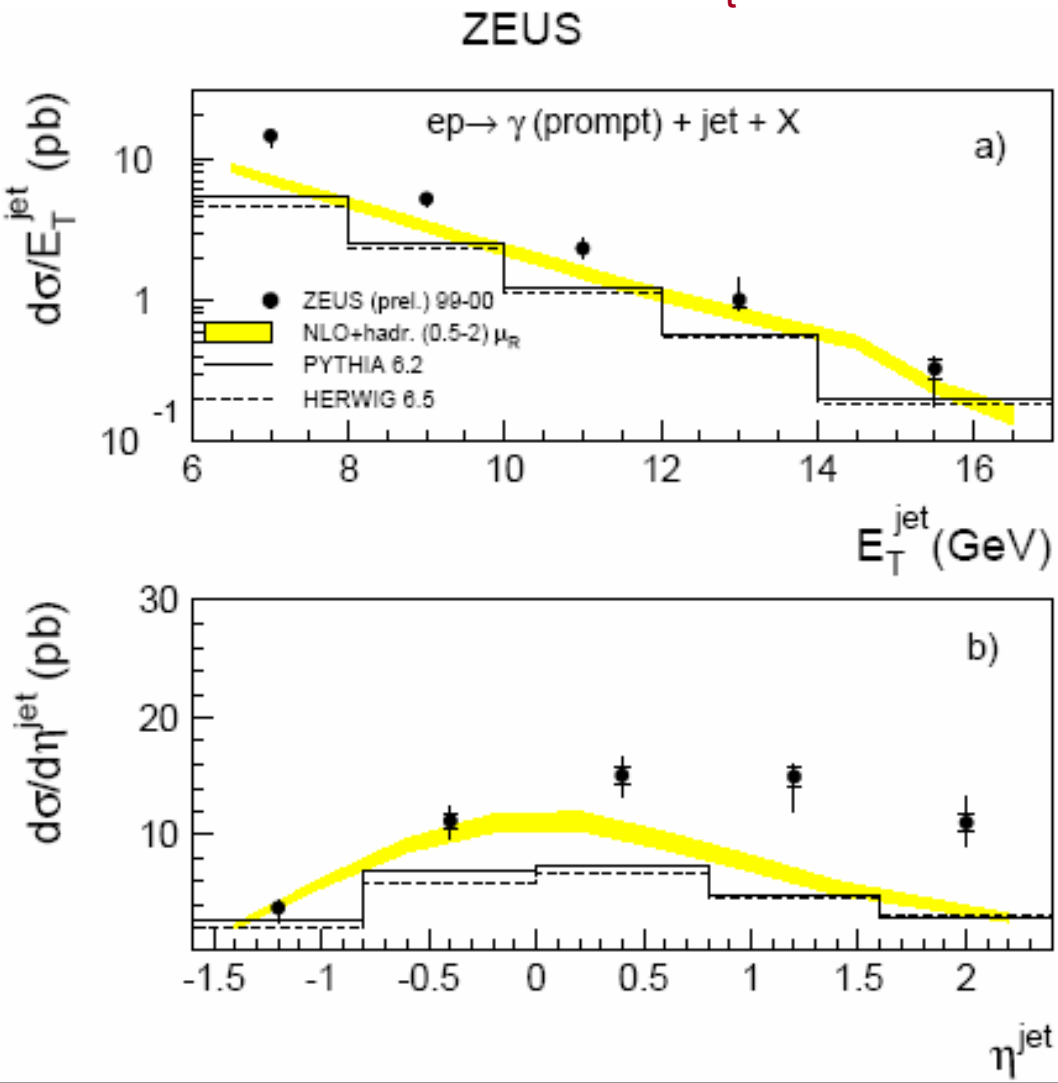
Hadronic jet cuts:

$E_{emc}/E_{tot} < 0.9$

$-1.6 < \eta_\gamma < 2.4$

$E_T^{jet} > 6$ GeV

If 2 jets were found the one with the highest E_T was used



Summary & Plan

Summary:

- Photoproduction of prompt photon + jet provides a hadronization correction free measurement of quark & gluon distributions
- Provides a method of measuring $\langle k_T \rangle$
- Barrel Presampler provides background rejection independent of the photon energy

Plan:

- Analyze new high luminosity sample, with the new Barrel Presampler
- Examine disagreement with model, try different models
- Systematic error study
  - Y_{meas} & Lower cuts on jet and photon E_T are of particular importance
- Refine $\langle k_T \rangle$ measurement