Rapidity Gaps in Photoproduction at HERA

Preliminary Examination

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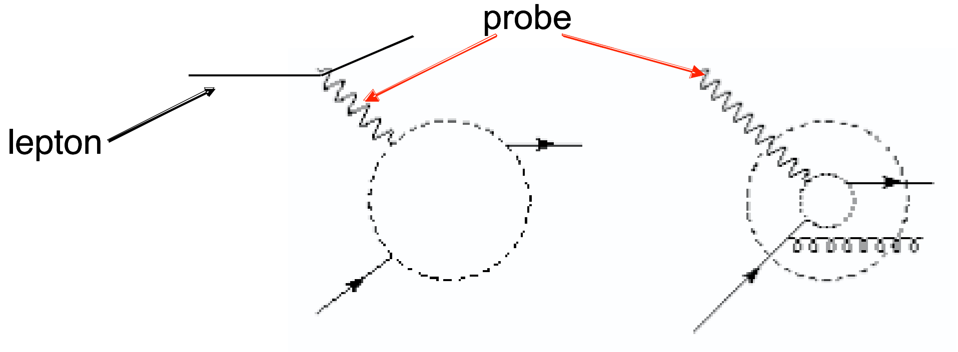
Outline of Talk

- Introduction
- HERA and ZEUS
- Photoproduction and Diffraction
- Rapidity Gaps
- Comparisons between Data and MC
- Event Sample and Cuts
- Summary

High Energy Collisions

- **Particle Scattering**
  - **Particles interact via probe exchange**
  - **Wavelength of probe: $\lambda = h/Q$**
    - h: Planck's Constant
    - Q: related to Photon Momentum
    - Smaller wavelength means greater resolution
- **Lepton-Proton Collisions**
  - **HERA: ep CMS Energy ~ 300 GeV**
    - Deep Inelastic Scattering: $Q^2 \sim 40{,}000\ \text{GeV}^2$
  - **Currently possible to probe to 0.001fm (Proton is 1fm)**



Quark Parton Model and QCD

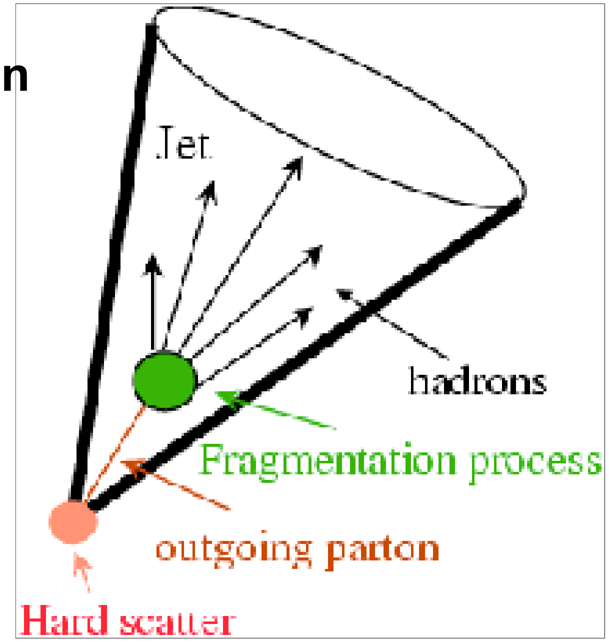
- Quarks and Gluons are colored objects called partons
- QCD describes “Strong” Interaction
  - Interactions between partons with strong coupling α_s
- Interaction mediated by exchange of gluons
  - Process called “Color Flow”
  - Multiple gluons can be exchanged
- Individual quarks have color, but only exist in colorless combinations (hadrons)
  - “Color Confinement”

Jets

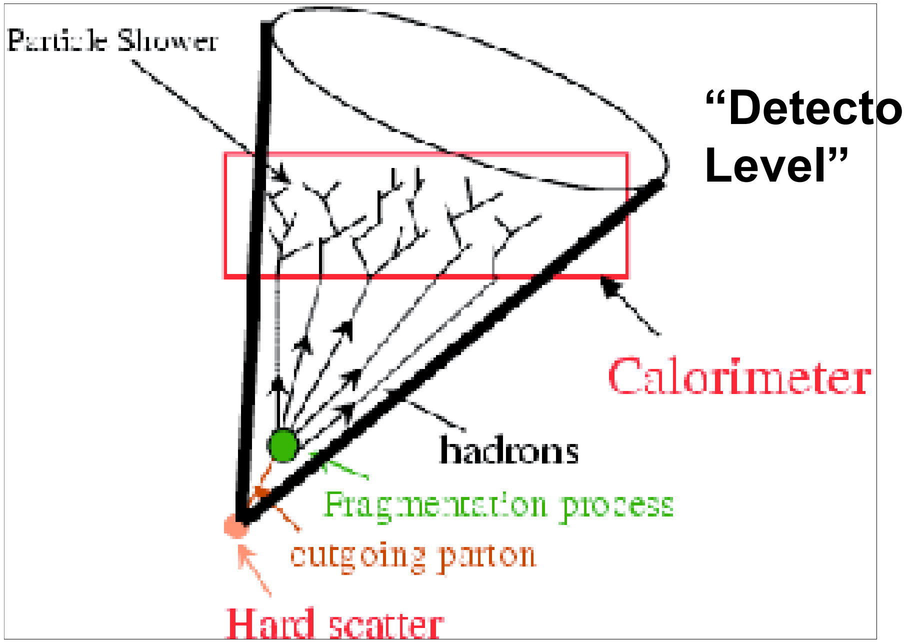
What is Produced

What is Observed in Detector

“Hadron Level”



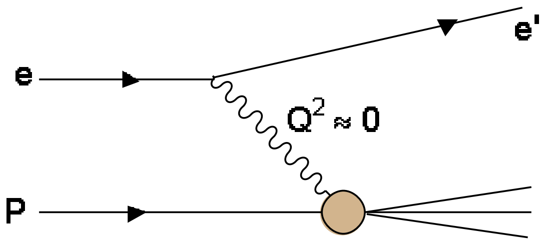
“Detector Level”



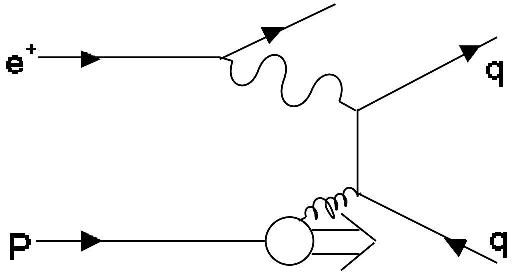
- Colored Partons produced in hard scatter
- Partons undergo hadronization to form colorless hadrons (Fragmentation)
- Colorless collimated “spray” of hadrons called a “Jet”
- Particle shower in calorimiter ➔ observe deposited energy

Photoproduction

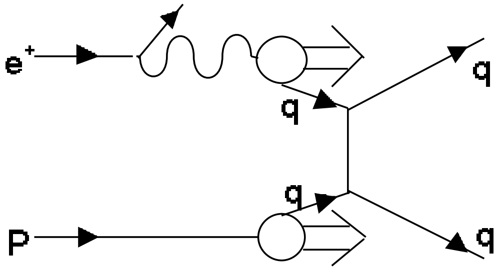
General Photoproduction



Direct



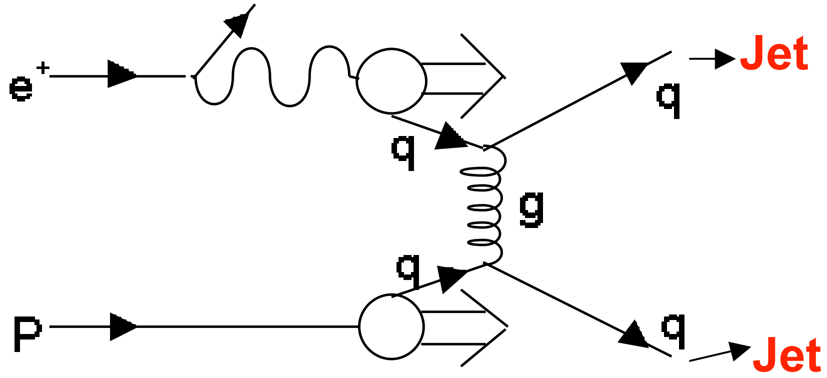
Resolved



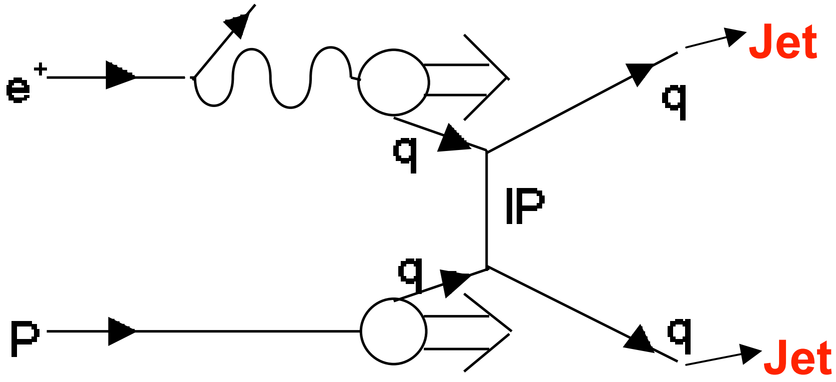
- Photon carries very little 4-momentum ($Q^2 \sim 0$)
- Photon is almost real
- Most ep events are photoproduction
  - Cross section has $1/Q^4$ dependence
- Direct: γ couples directly to a parton in proton
- Resolved:
  - Fluctuation of γ into partonic state
  - parton from γ couples to parton in proton

Color Non-Singlet and Singlet Exchange in Resolved γP

Color Non-Singlet Exchange



Color Singlet Exchange



•Color Non-Singlet Exchange:

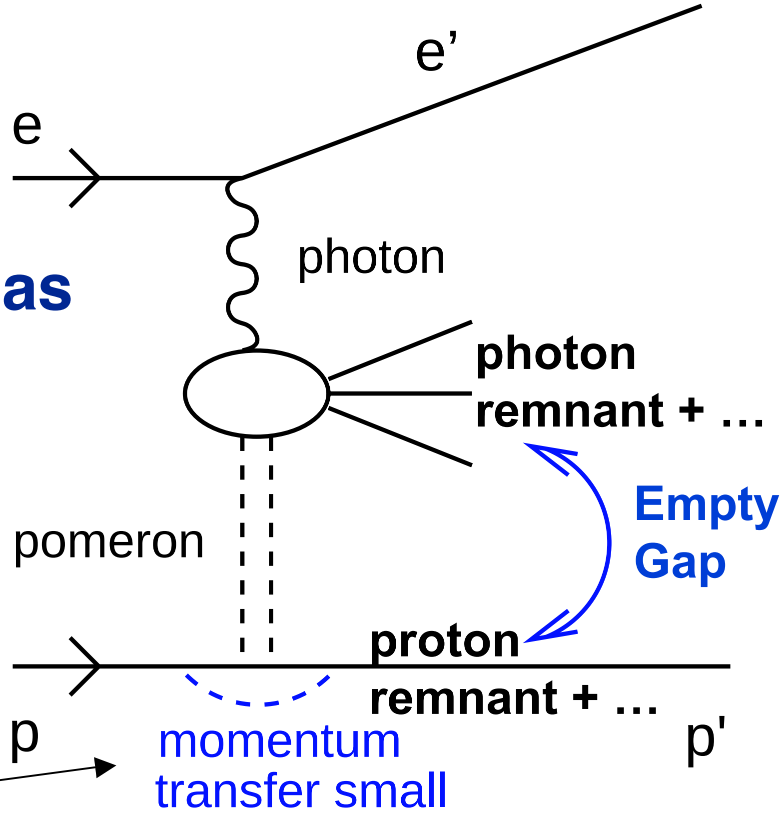
- Jets are color connected to each other
- Gap between jets filled with final state particles

•Color Singlet Exchange:

- Jets are not color connected to each other
- No final state particles between jets (Empty Gap)

Diffraction

- Final state particles preserve quantum numbers of associated initial state particles
- Characteristics of Diffraction
  - Small momentum transfer (t) at P vertex
  - Exchange object (Pomeron) has quantum numbers of vacuum
  - Absence of particles between P and γ remnants (to follow)



$t = (P-P')$

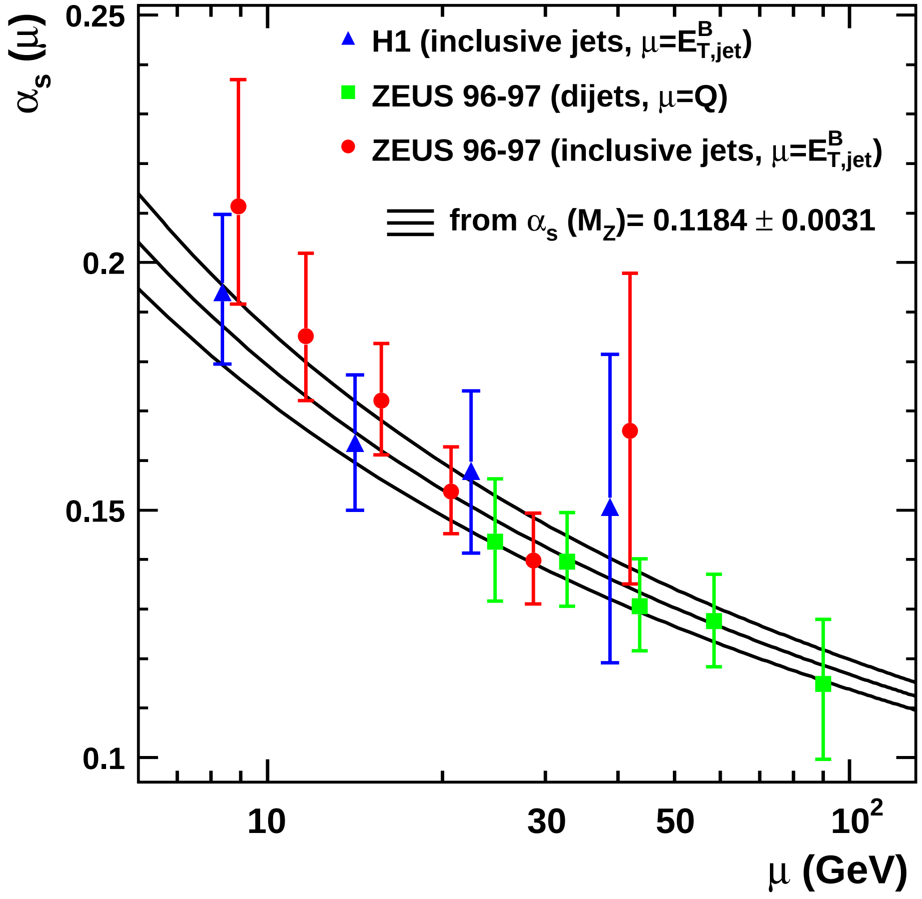
QCD Scale

Leading Order (LO) Next to Leading Order (NLO)

$$A = A_0 + A_1\alpha_S + A_2\alpha_S^2 + \dots$$

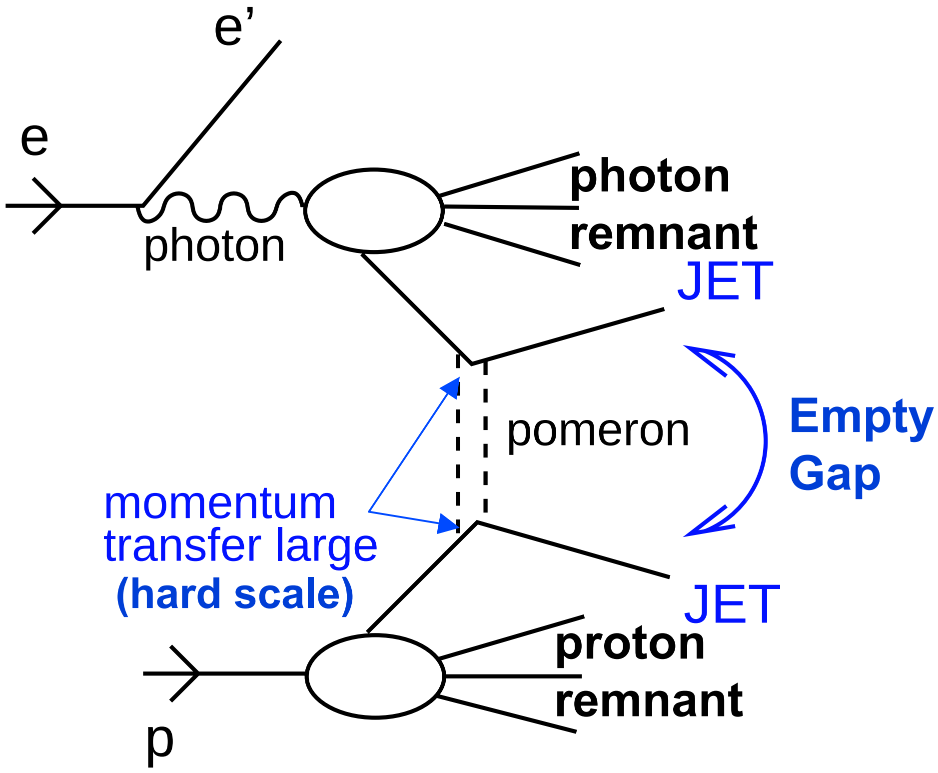
- Running of α_S
    - As scale μ increases, $\alpha_S(\mu)$ decreases ($\mu = E_T$ or Q)
- Perturbative QCD
    - Small $\alpha_S(\mu)$ (hard scale)
    - Series expansion used to calculate observables
- Nonperturbative QCD
    - Large $\alpha_S(\mu)$ (soft scale)
    - Series not convergent

HERA DIS Data: Running of $\alpha_S(\mu)$



Hard Diffractive Scattering in Photoproduction

- **Photoproduction: $Q^2 \sim 0$**
- **Diffraction: Absence of particles between jets, low t**
- **Hard process**
  - **High jet E_T ➔ hard scale**
  - **Hard QCD inside soft QCD process**
  - **pQCD applicable to a hard QCD process**



Sample contains more events with high E_T jets than predicted by diffraction without hard processes

HERA Description

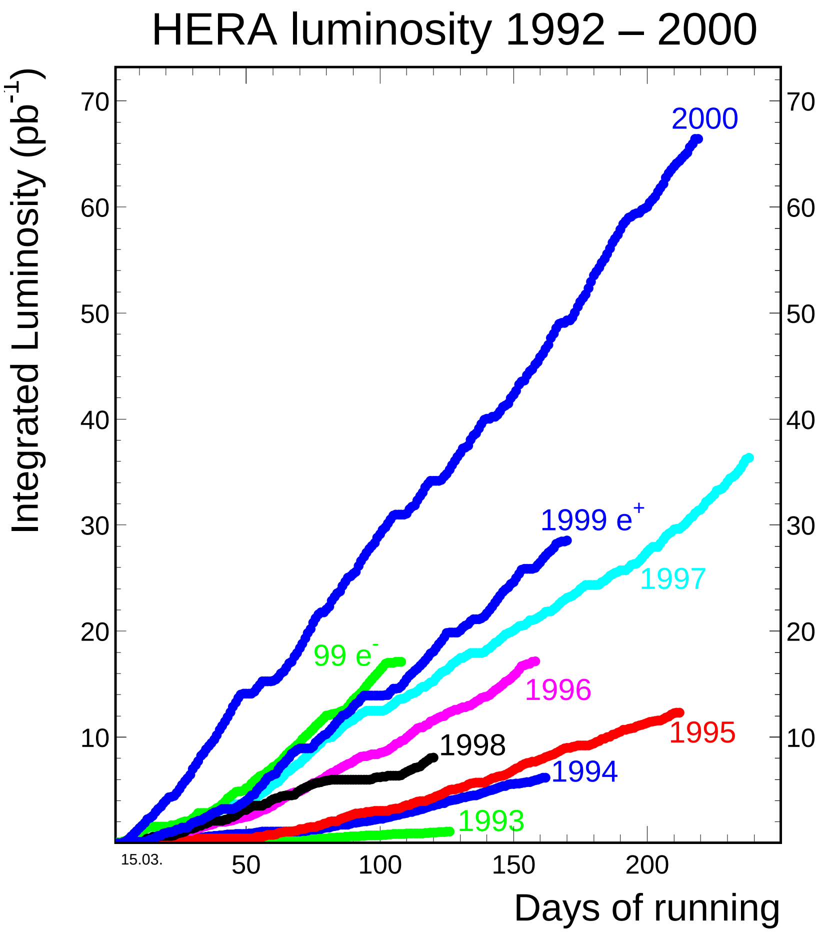
DESY

Hamburg, Germany

- 820/920 GeV Protons
- 27.5 GeV e^- or e^+
- CMS Energy 300/318 GeV
  - Equivalent to 50 TeV fixed target
- 220 bunches
  - Not all filled
- 96 ns crossing time
- Currents:
  - ~90mA protons
  - ~40mA electrons
- Instantaneous Luminosity:
  - $1.8\text{x}10^{31}\text{cm}^{-2}\text{s}^{-1}$

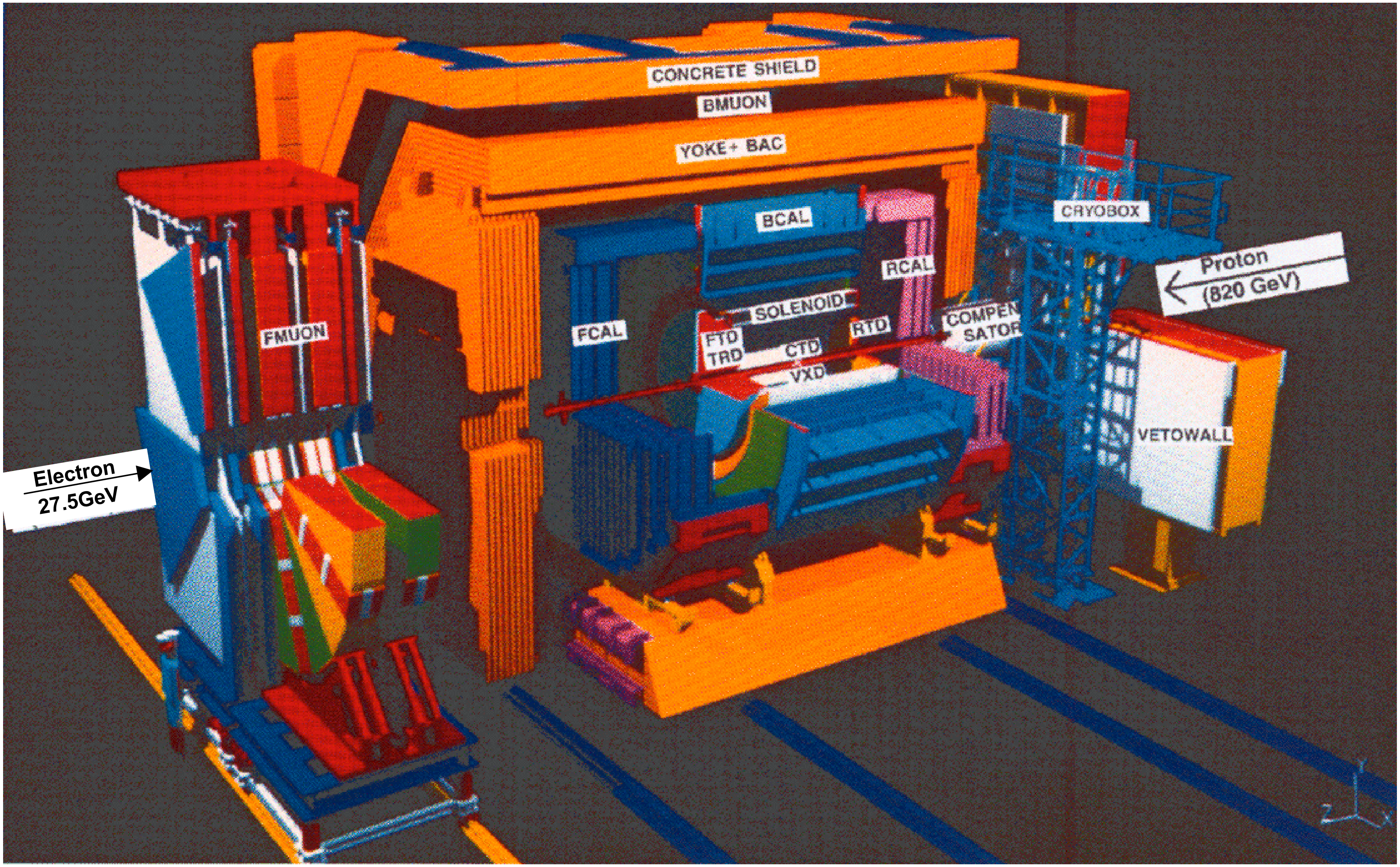
$$L = \frac{R_{tot} - (I_{tot}/I_{unp})R_{unp}}{\sigma_{BH}}$$

HERA Luminosity



- **Total Integrated Luminosity since 1992: ~193 pb^{-1}**
  - **e$^-$: ~27 pb^{-1}**
  - **e$^+$: ~165 pb^{-1}**
- **Luminosity upgrade recently completed**
  - **5x increase in Luminosity**
  - **Longitudinal polarization of e**
- **Starting up now**
  - **Goal: 1 fb^{-1} by end of 2006**

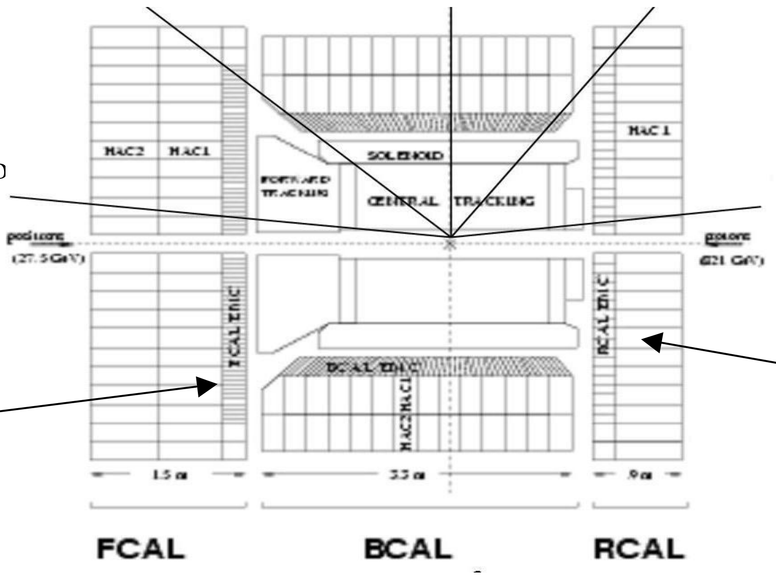
Zeus Detector



ZEUS Calorimeter

$\eta = 1.1 \;\; \theta = 36.7^{o}$ $\eta = 0.0 \;\; \theta = 90.0^{o}$ $\eta = -0.75 \;\; \theta = 129.1^{o}$

$\eta = 3.0 \;\; \theta = 5.7^{o}$ $\eta = -3.0 \;\; \theta = 174.3^{o}$



Electromagnetic (EMC) Cells

Hadronic (HAC) Cells

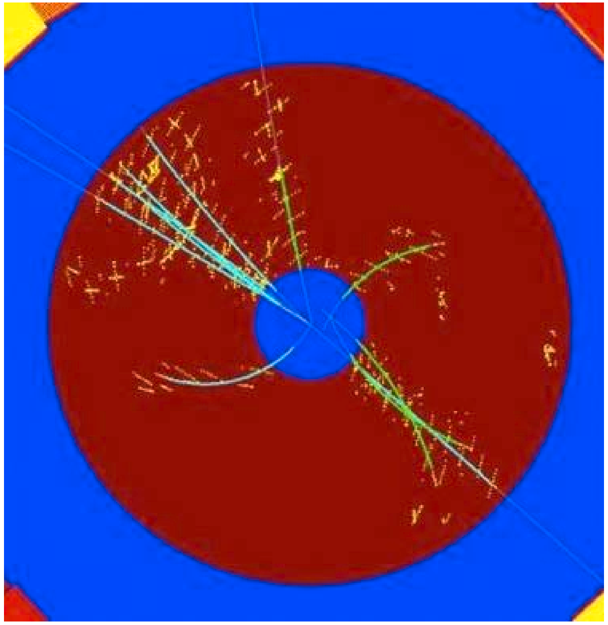
Pseudorapidity

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

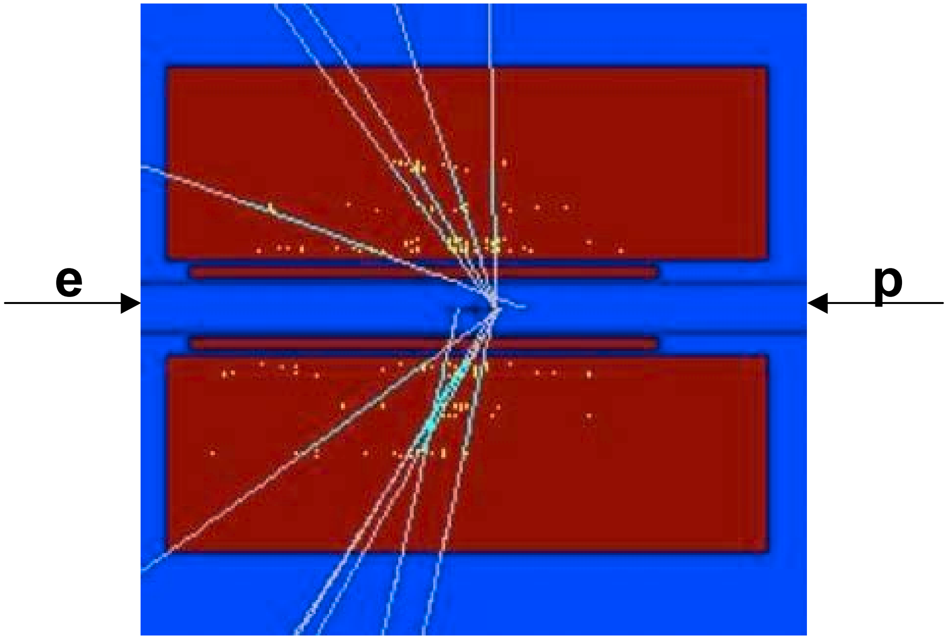
- **Depleted Uranium and Scintillator**
- **99.8% Solid Angle Coverage**
- **Energy Resolution (single particle test beam)**
  - **Electromagnetic:** $0.18/\sqrt{E(GeV)}$
  - **Hadronic:** $0.35/\sqrt{E(GeV)}$
- **Measures energy and position of final state particles**

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

ZEUS Trigger

•First Level

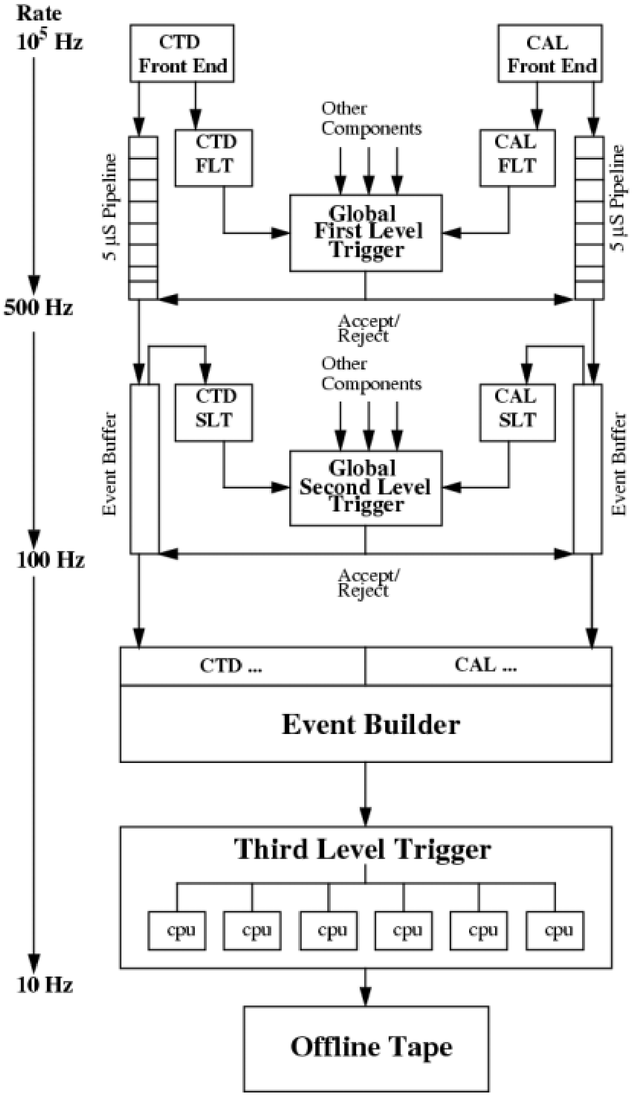
- Dedicated custom hardware
- Pipelined without deadtime
- Global and regional energy sums
- Isolated μ and e^+ recognition
- Track quality information

•Second Level

- Commodity Transputers
- Calorimeter timing cuts (next slide)
- $E - p_z$ cuts
- Vertex information
- Simple physics filters

•Third Level

- Commodity processor farm
- Full event info available
- Refined jet and electron finding
- Advanced physics filters



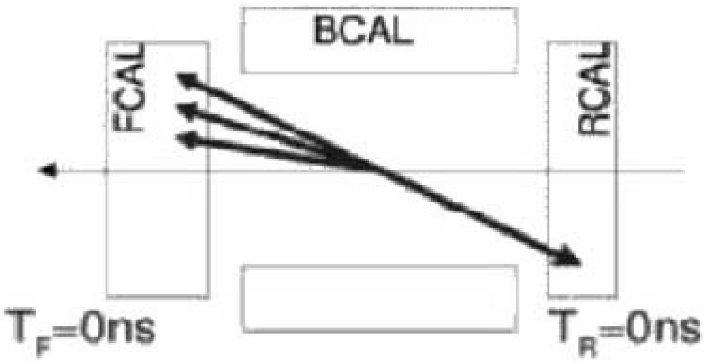
10^7 Hz Crossing Rate

10^5 Hz Background Rate

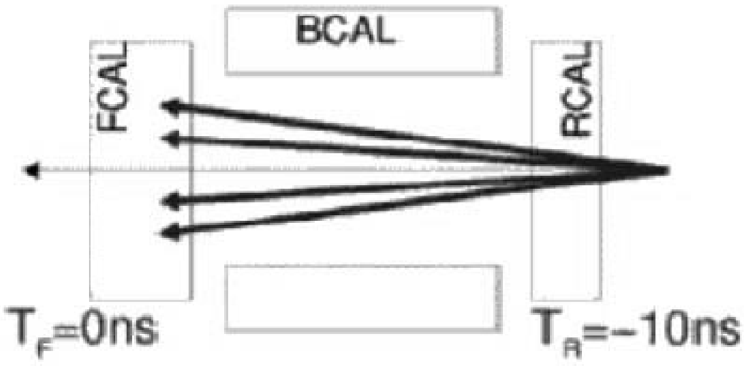
10 Hz Physics Rate

Background Rejection: Timing

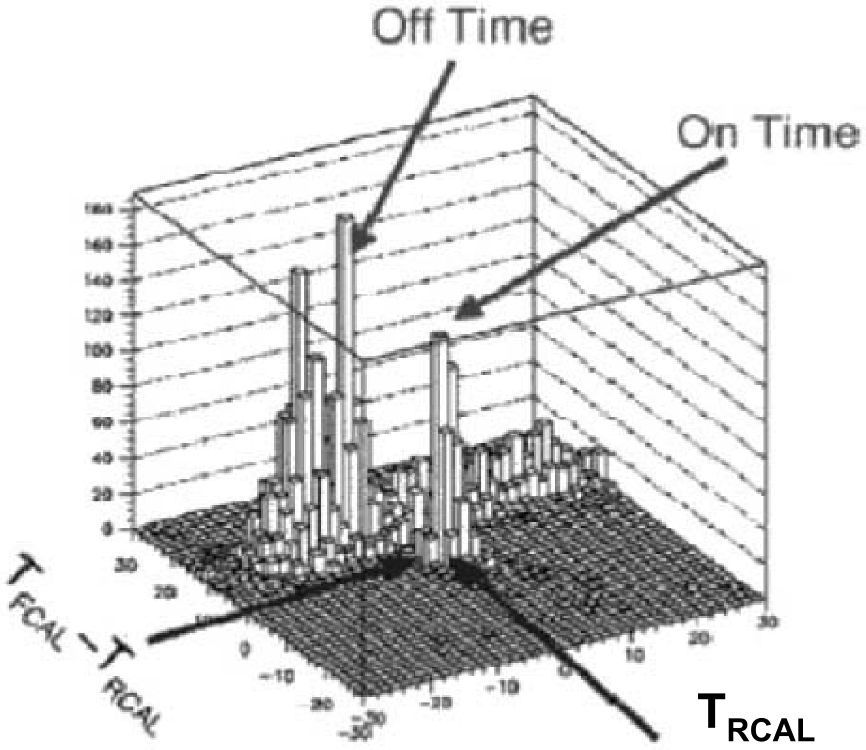
"Distance" between FCAL and RCAL is ~10ns



On Time Event



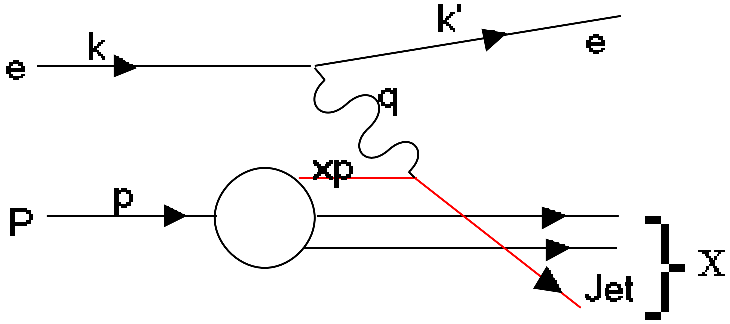
Beam Gas Event



Calorimeter timing at Level 2

ZEUS Calorimeter timing resolution <1 ns

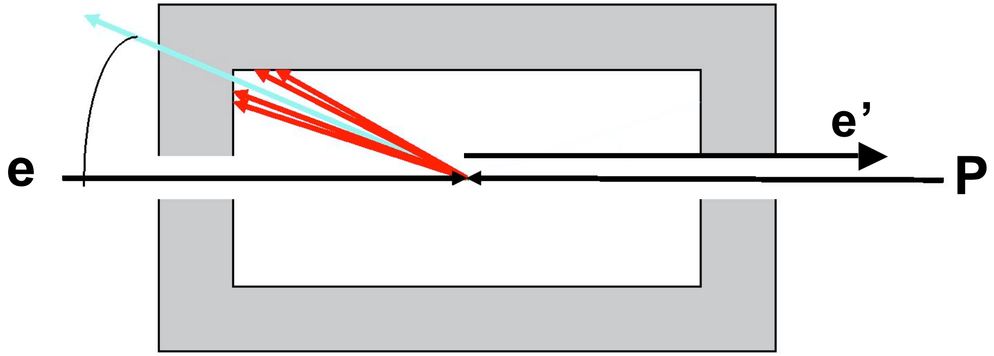
Kinematic Variables



- Center of Mass Energy of ep system squared
  - $s^2 = (p+k)^2 \sim 4E_pE_e$
- 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

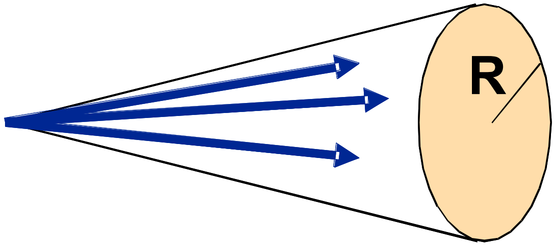
Measured Quantities: E_h, p_z, p_T^2



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

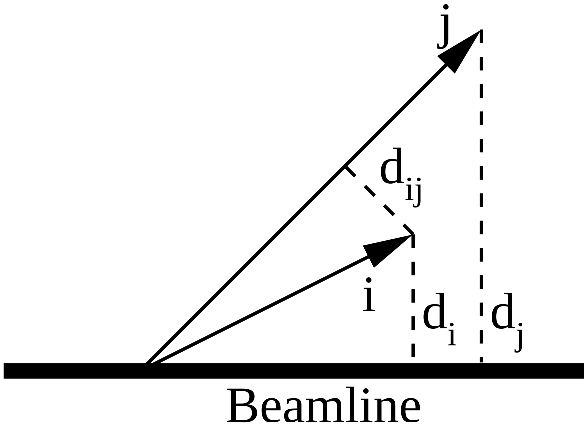
Particles close to each other in phase space used to retrace through hadronization to original parton



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

- Maximize total E_T of hadrons in cone of R=1
- Procedure
  - Construct seeds (starting positions for cone)
  - Move cone around until a stable position is found
  - Decide whether or not to merge overlapping cones
- Advantages:
  - Lorentz invariant along z axis
  - Conceptually simple

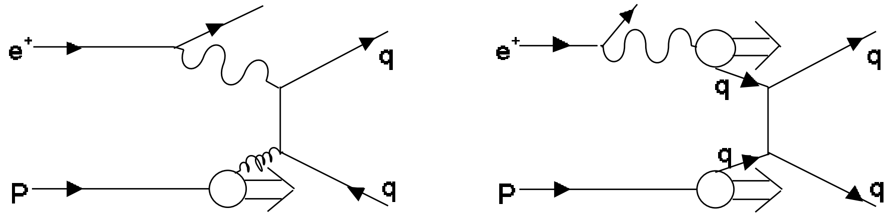
Jet Finding: Longitudinally Invariant K_T Algorithm



- In ep: k_T is transverse momentum with respect to beamline
- For every object *i* and every pair of objects *i, j* compute
  - $d^2_i = E^2_{T,i}$ (distance to beamline in momentum space)
  - $d^2_{ij} = \min\{E^2_{T,i}, E^2_{T,j}\}[\Delta\eta^2 + \Delta\phi^2]^{1/2}$ (distance between objects)
- Calculate min{ d^2_i , d^2_{ij} } for all objects
  - If d^2_{ij} is the smallest, combine objects *i* and *j* into a new object
  - If d^2_i is the smallest, the object *i* is a jet
- Advantages:
  - No ambiguities (no seed required and no overlapping jets)
  - k_T distributions can be predicted by QCD

Photoproduction Observables

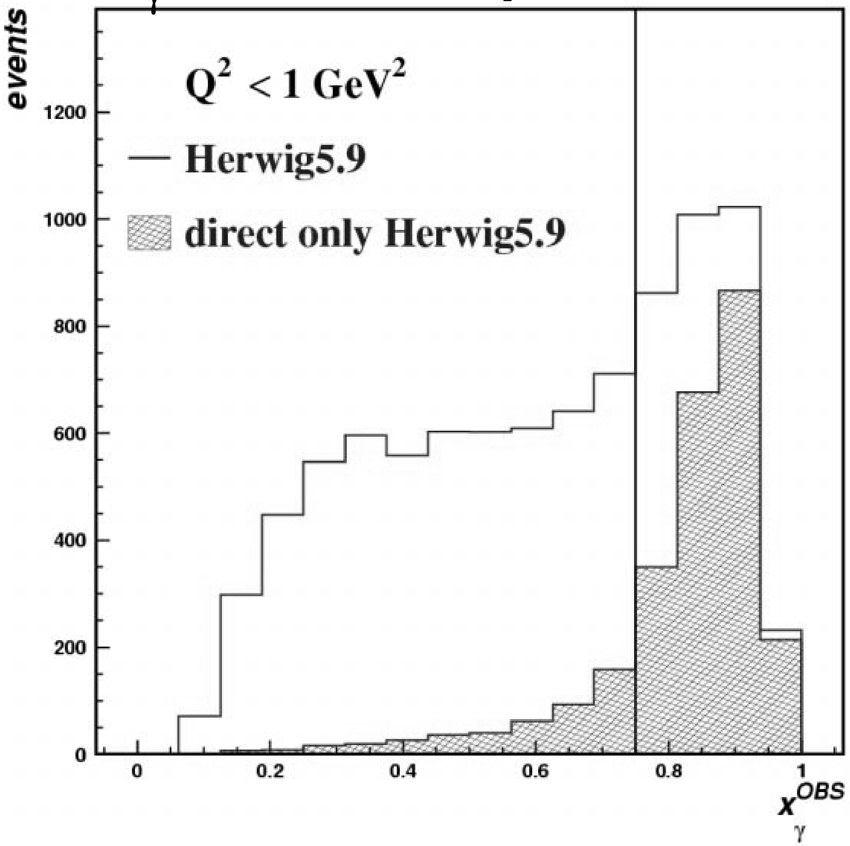
- **x_γ: Fraction of γ momentum involved in collision**
  - Direct Photoproduction: $x_\gamma \sim 1$
  - Resolved Photoproduction: $x_\gamma < 1$



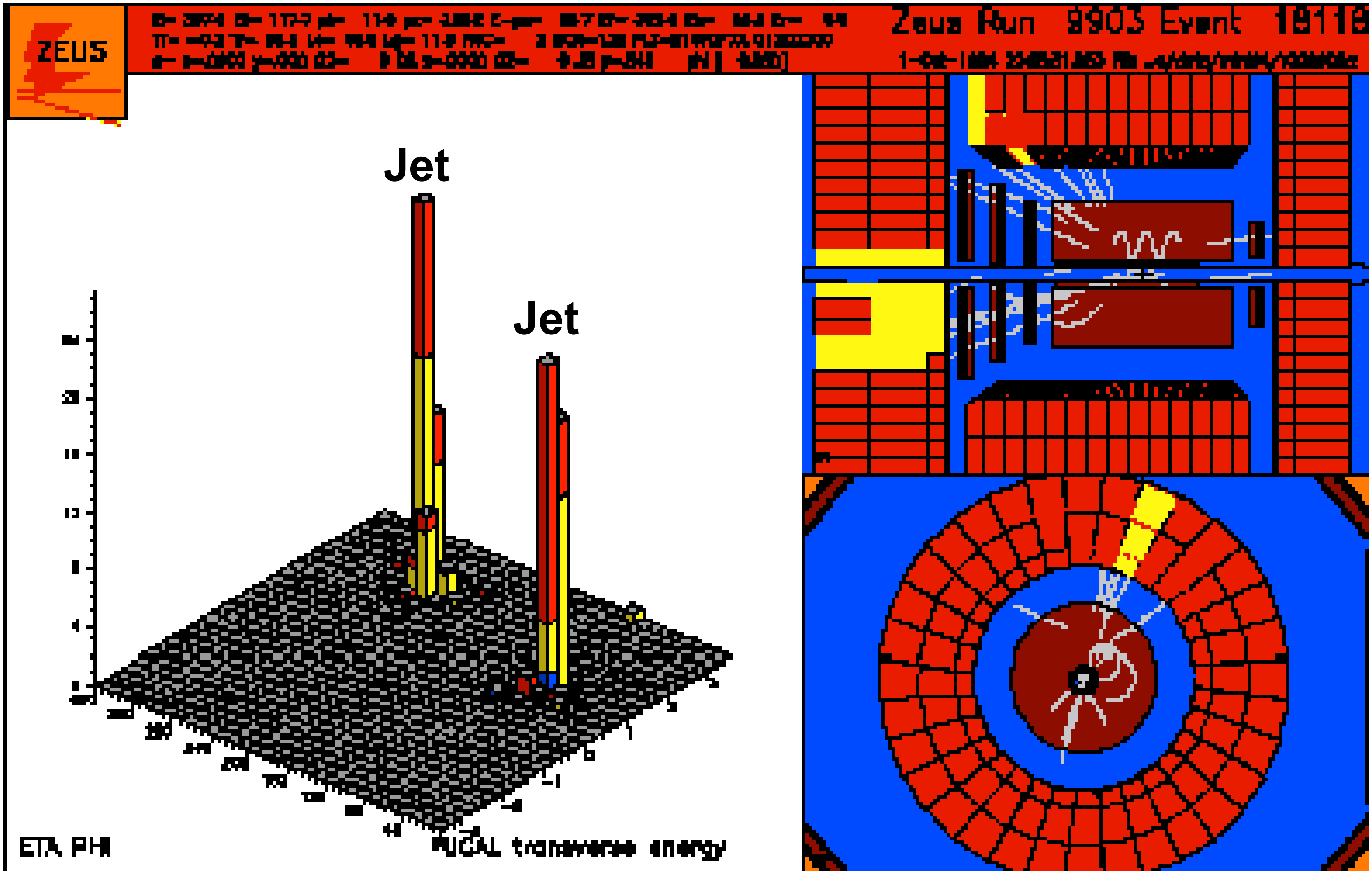
- **x_P: Fraction of P momentum involved in hard interaction**

$$x_\gamma^{OBS} = \frac{\sum_{jets} E_T e^{-\eta}}{2yE_e} \qquad x_P^{OBS} = \frac{\sum_{jets} E_T e^{\eta}}{2E_P}$$

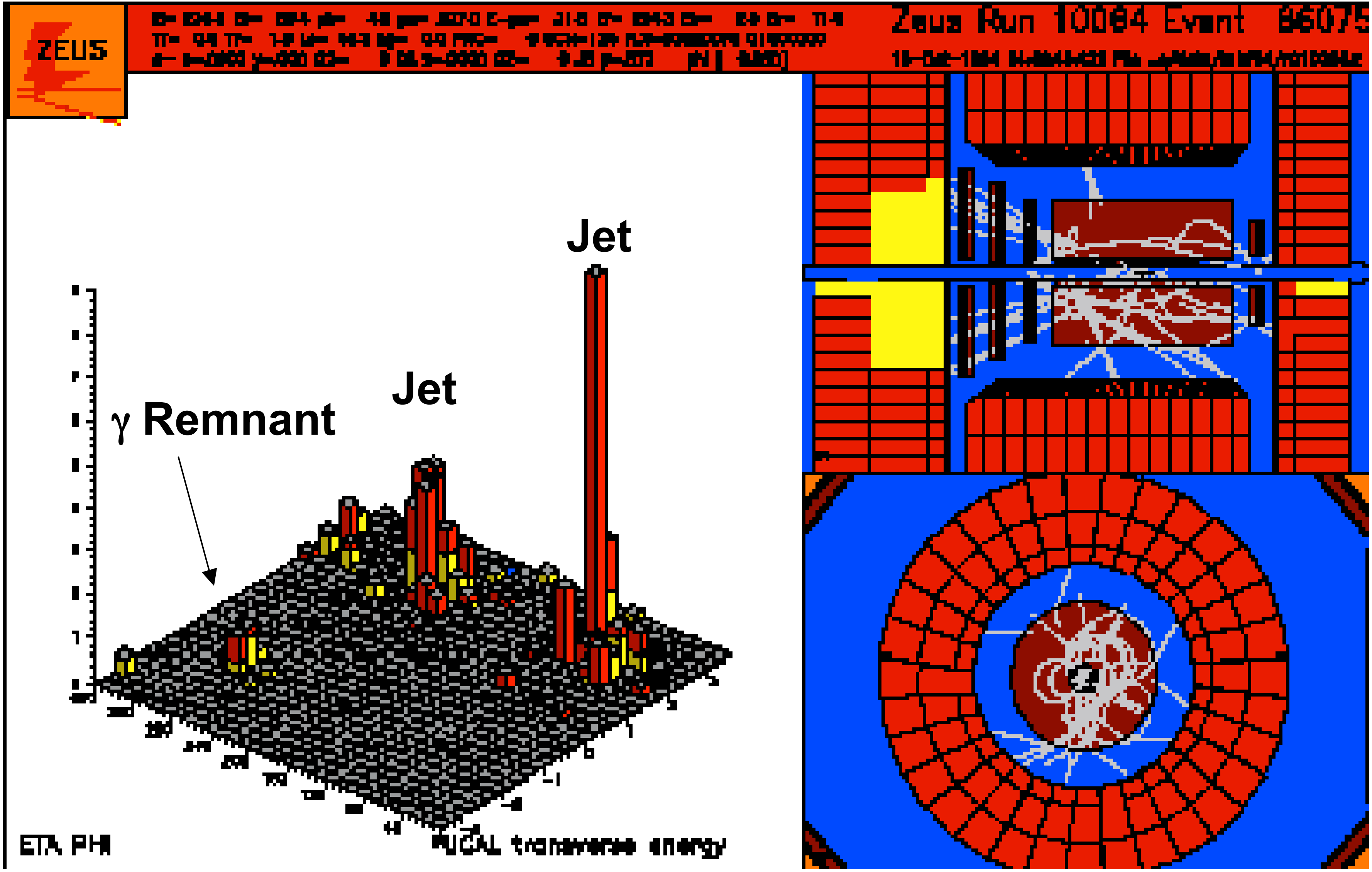
x_γ^{OBS} in Photoproduction



Direct Photoproduction Event

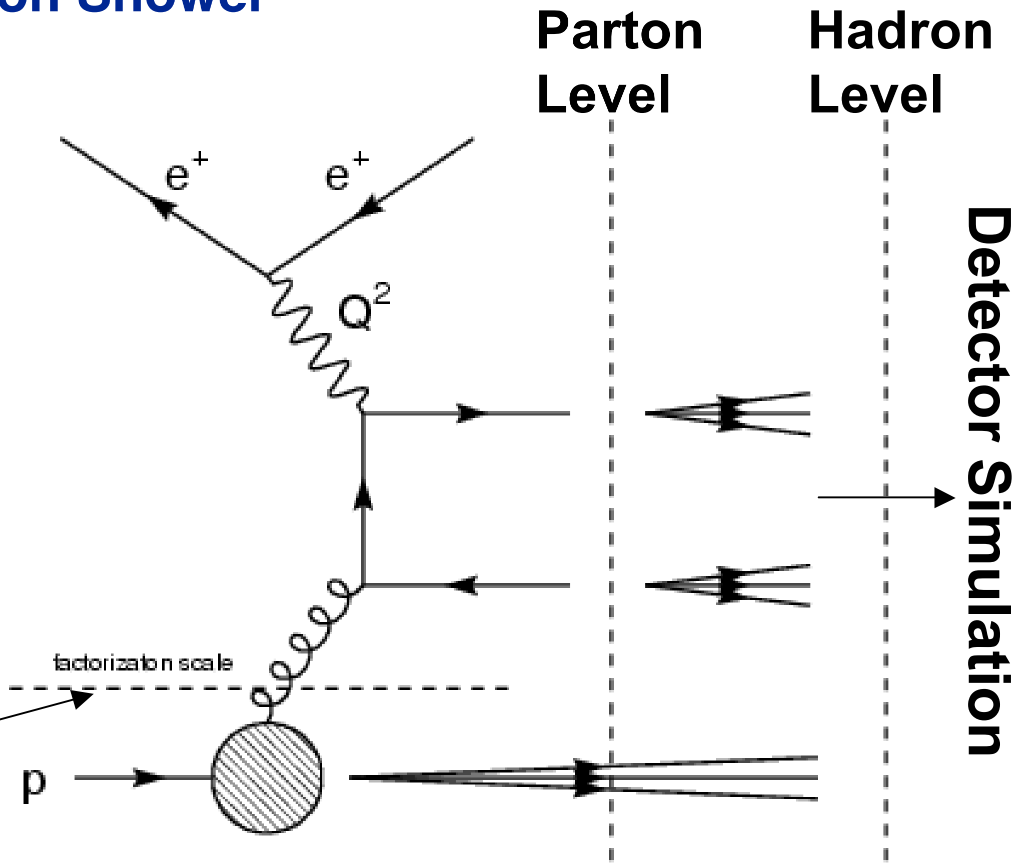


Resolved Photoproduction Event



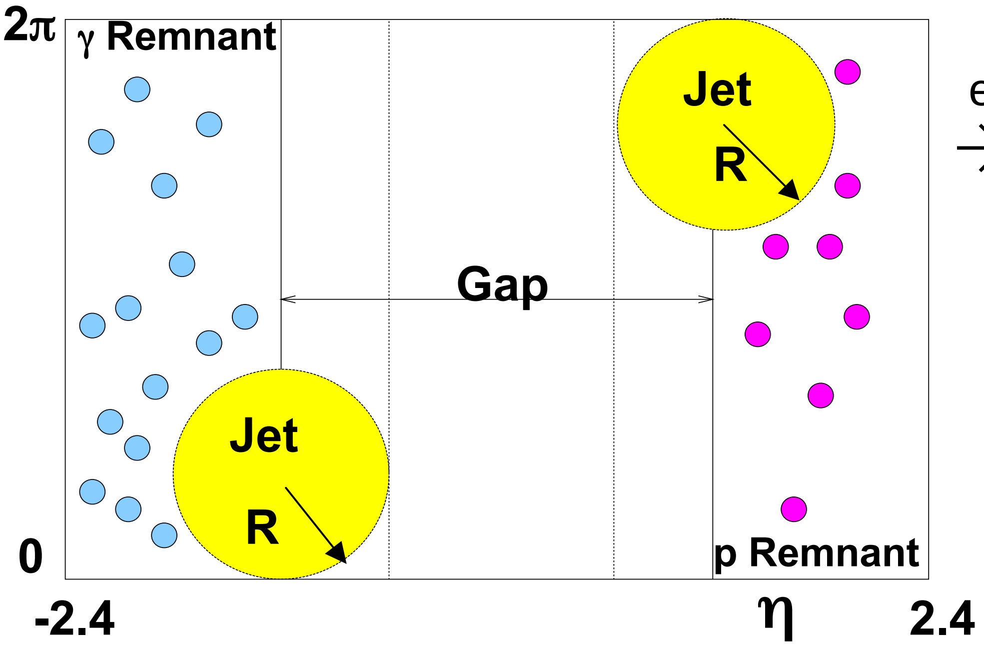
Model Events: PYTHIA Generator

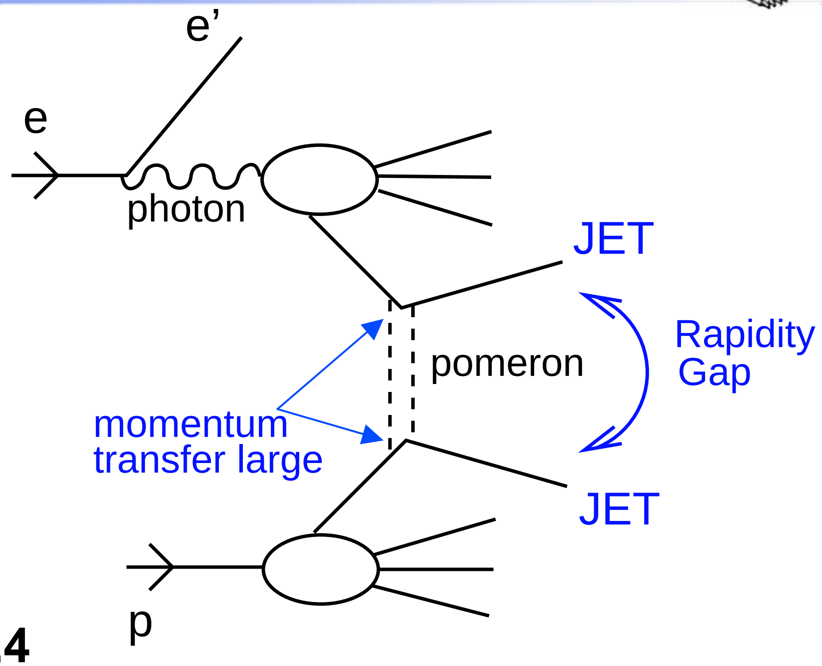
- Parton Level
  - LO Matrix Element + Parton Shower
- Hadron Level
  - Fragmentation Model
- Detector Level
  - Detector simulation based on GEANT



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

Topology of Rapidity Gaps





- **•2 jets represented as circles in (η,φ) phase space**
  - **Distance between jet centers: Δη**
  - **Radius of jet cone: R~1**
- **•Gap indicates color singlet exchange**
- **•No final state particles between jets (Rapidity Gap)**

The Gap Fraction

Dijet events with Rapidity Gap

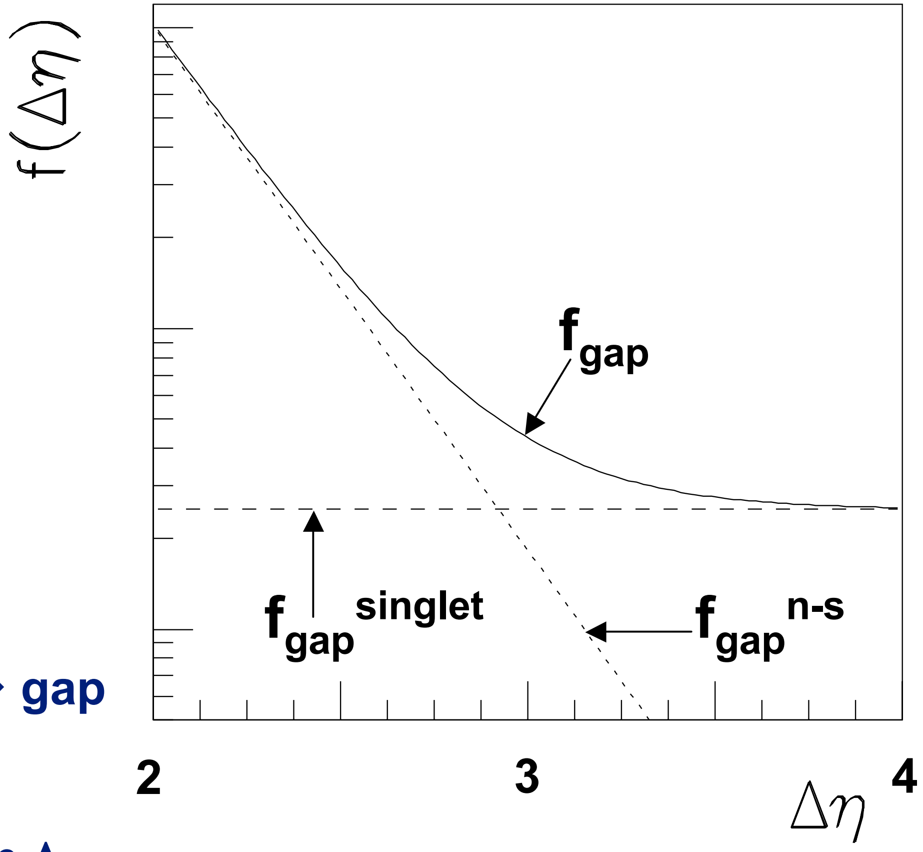
All Dijet Events

$$f(\Delta\eta) = \frac{d\sigma_{gap} / d\Delta\eta}{d\sigma / d\Delta\eta}$$

$$\sigma_{gap} = \sigma_{gap}^{\mathrm{singlet}} + \sigma_{gap}^{\mathrm{non-singlet}}$$

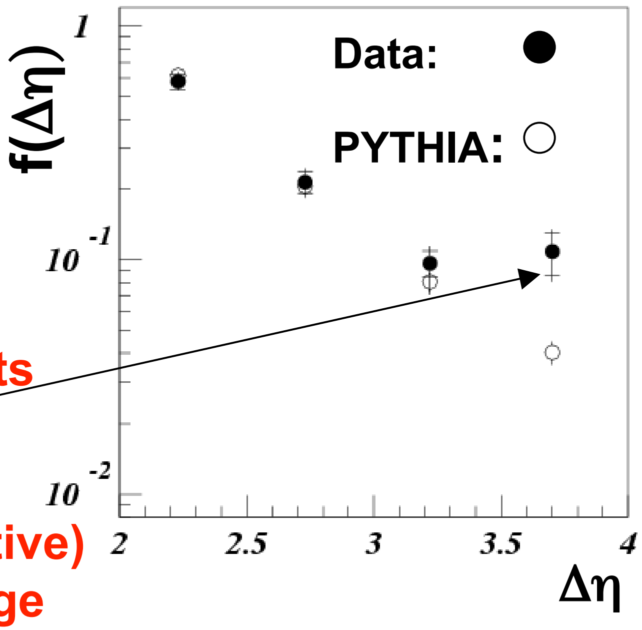
- **Singlet:**
  - **f(Δη) constant in Δη**
- **Non-Singlet:**
  - **Particle production fluctuations ➔ gap**
  - **Non-diffractive exchange**
  - **f(Δη) decreases exponentially with Δη**

Expectation for Behavior of Gap Fraction (J. D. Bjorken, V. Del Duca, W.-K. Tang)



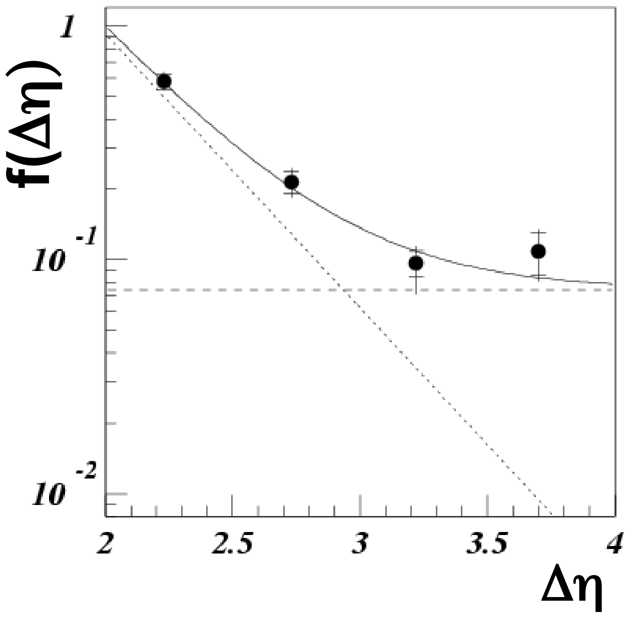
1994 ZEUS Results

Gap Fraction



Suggests Color Singlet (Diffractive) Exchange

Gap Fraction Fit



2 Jets With:

$E_T > 6$GeV,

$\eta < 2.5$,

$\Delta\eta > 2$,

$|\eta_{avg}| < 0.75$,

$0.15 \leq y \leq 0.7$

- Color singlet exchange not in ZEUS 1994 PYTHIA
- f(Δη) excess at high Δη suggests singlet contribution
  - Excess of Gap Fraction ~ 0.07
  - P and γ remnants limit size of measurable gap

2002 H1 (ep) Results

- Color Singlet exchange added in PYTHIA and HERWIG
  - PYTHIA: γ exchange
  - HERWIG: IP exchange
  - Now agrees with data at high $\Delta\eta$
- Low Statistics for large $\Delta\eta$

Jet Cuts:

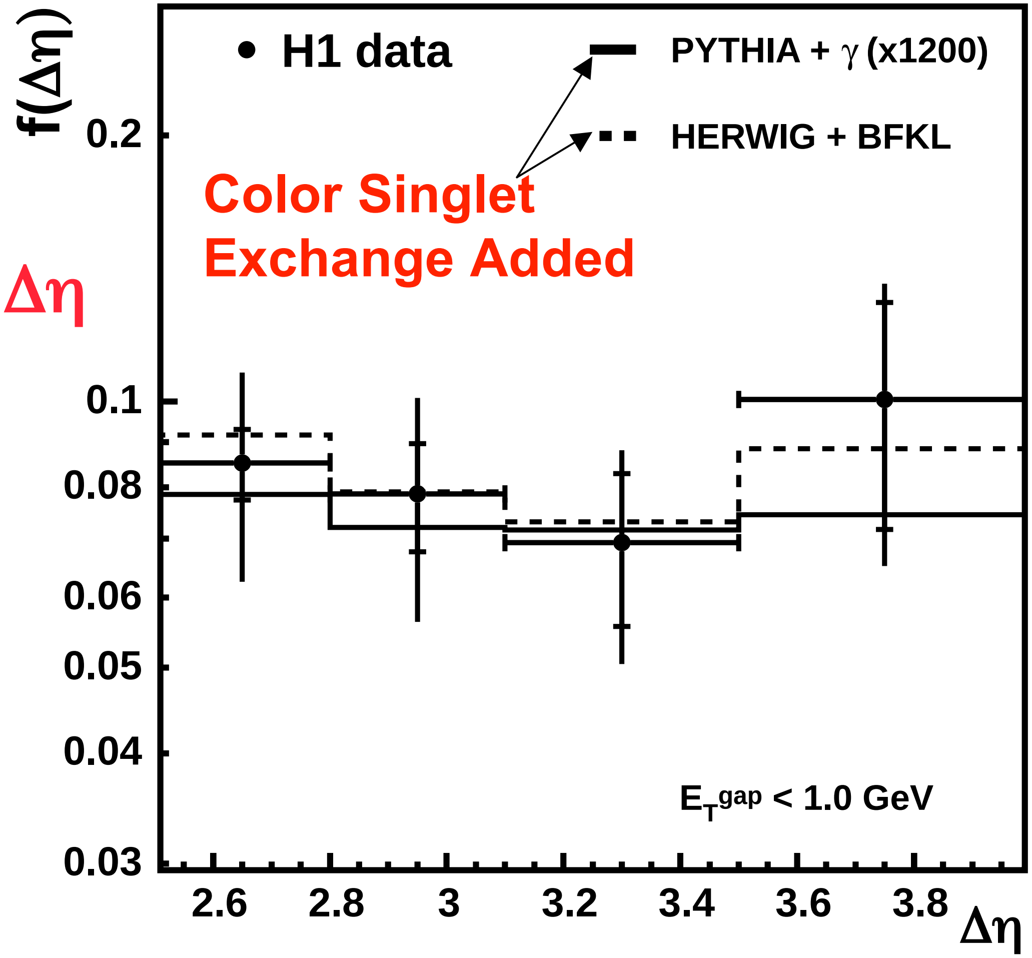
$E_T^{Jet\ 1} > 6.0$ GeV

$E_T^{Jet\ 2} > 5.0$ GeV

$\eta^{1,2} < 2.65$

$2.5 < |\Delta\eta| < 4.0$

$165 < W_{\gamma p} < 233$ GeV



Event Selection – 1996 ZEUS Data

Trigger Cuts

- **FLT**
  - **Total CAL energy > 14 GeV**
  - **Good Track**
- **SLT**
  - **$E-p_z > 8.0$ GeV**
    - Eliminates beam gas events
  - **$E_T^{Box} > 8.0$ GeV**
    - Sum of E_T in all CAL cells excluding 1st ring around FCAL beam pipe
    - Ensure energy is not from proton remnant
  - **At least one CAL SLT EMC cluster**
  - **Vert. Tracks/Tot. Tracks > 0.15**
- **TLT**
  - **>2 jets with $E_T \geq 4$ GeV, $|\eta| < 2.5$**
  - **$p_z/E < 1.0$**

Offline Cuts

- **$|z_{vtx}| < 40$cm**
  - **Region of best acceptance and prediction by MC**
- **No Scattered Electron**
  - **Select photoproduction events**
- **$0.2 < y_{JB} < 0.85$**
  - **Lower: Remove beam gas**
  - **Upper: Remove DIS events**

Work done this summer by P. Ryan

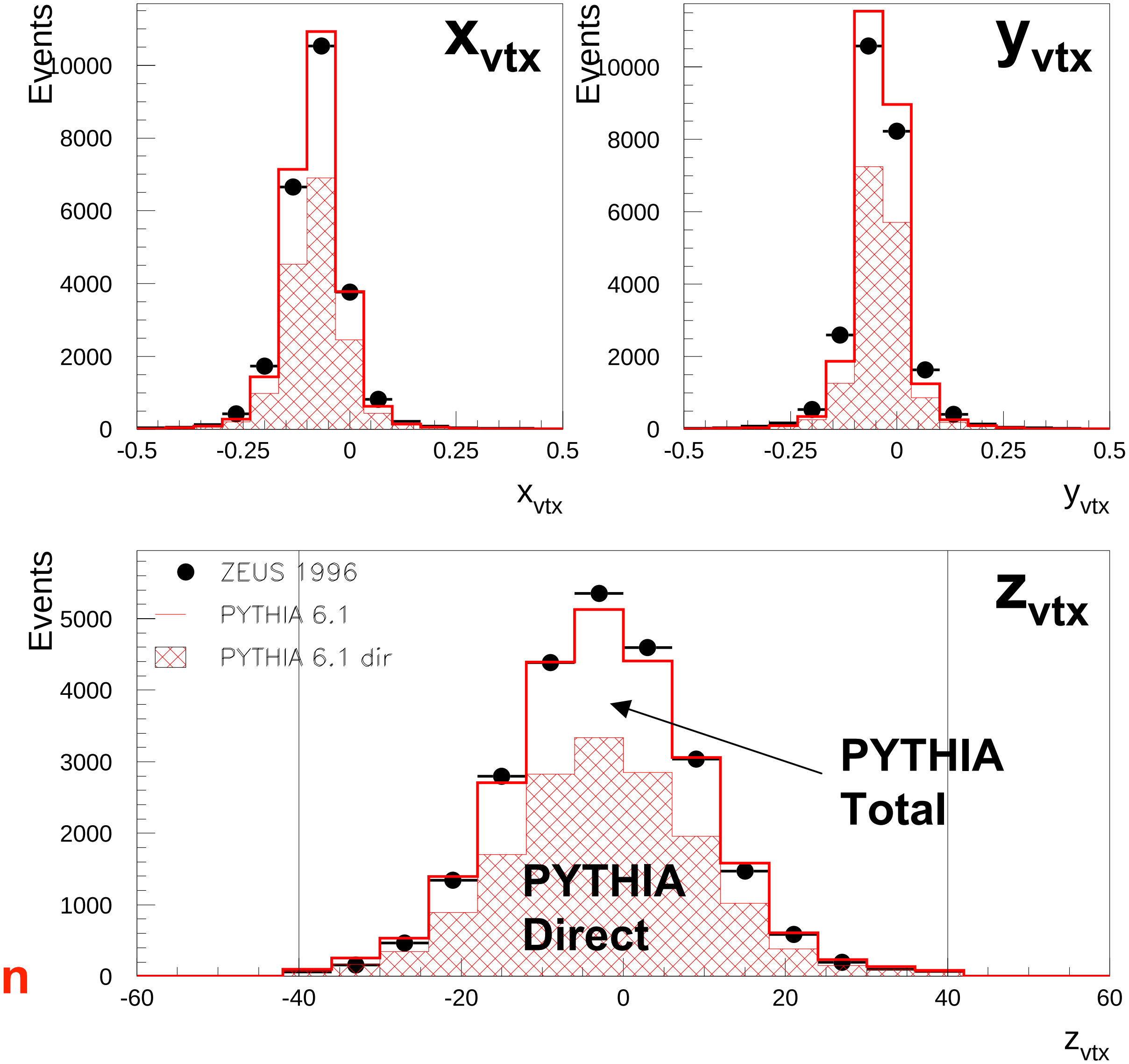
Jet Finding

- Jets built using calorimeter cells
- k_T Algorithm
- Jets ordered in decreasing E_T
- Cuts on Jets:
  - $E_T^{Jet\ 1} > 6$ GeV
  - $E_T^{Jet\ 2} > 5$ GeV
  - $|\eta^{Jet\ 1,2}| < 2.4$
  - $|\Delta\eta| > 2.0$

Jets Separated by a large rapidity gap

~25,000 Events passed cuts

Simulation of Event Vertex



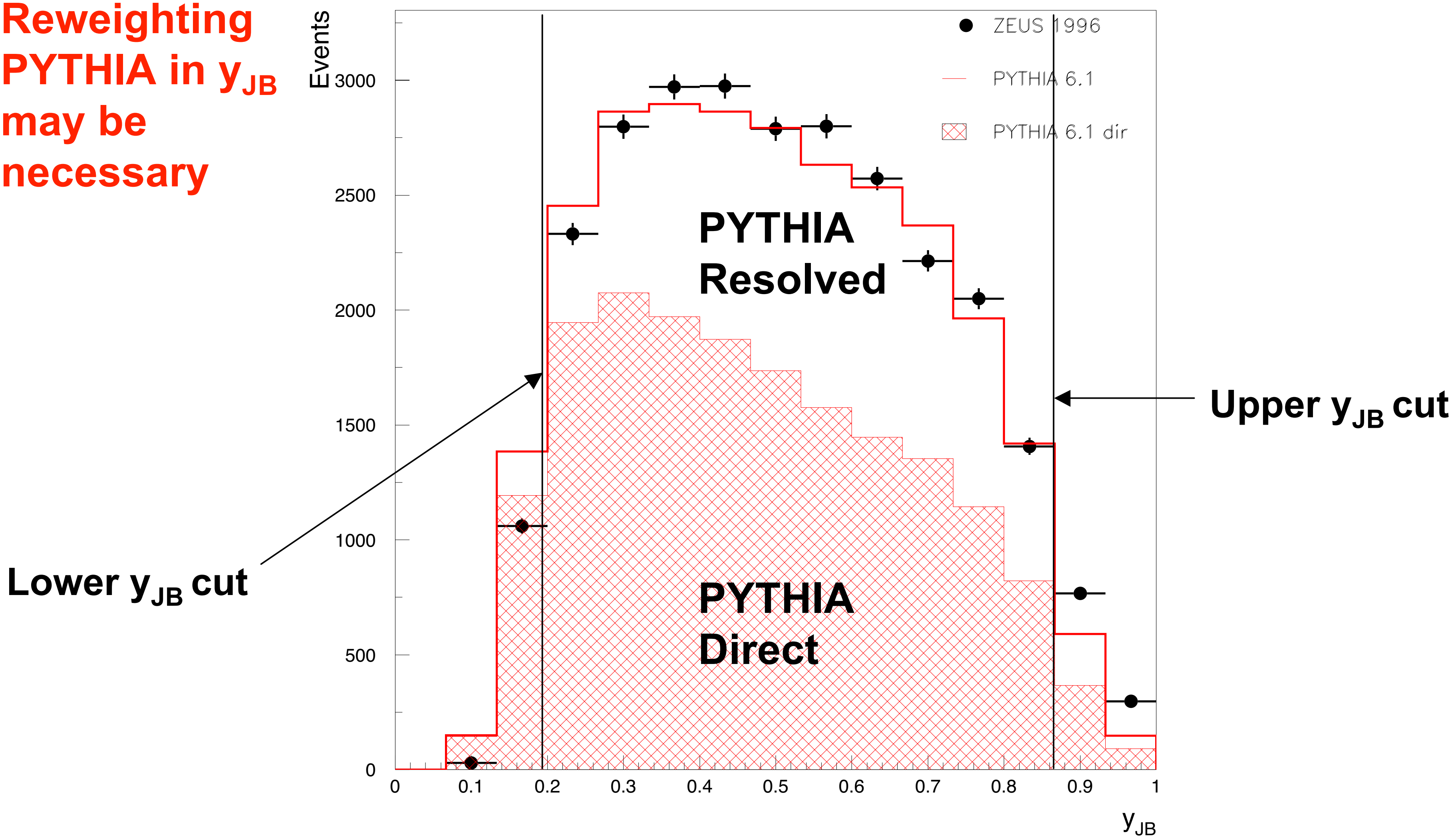
Position of interaction vertex well simulated.

Important as anchor of tracking reconstruction

Simulation of y_{JB}

y_{JB} = (E-p_z)/55 GeV

Reweighting PYTHIA in y_{JB} may be necessary



PYTHIA Resolved

PYTHIA Direct

Lower y_{JB} cut

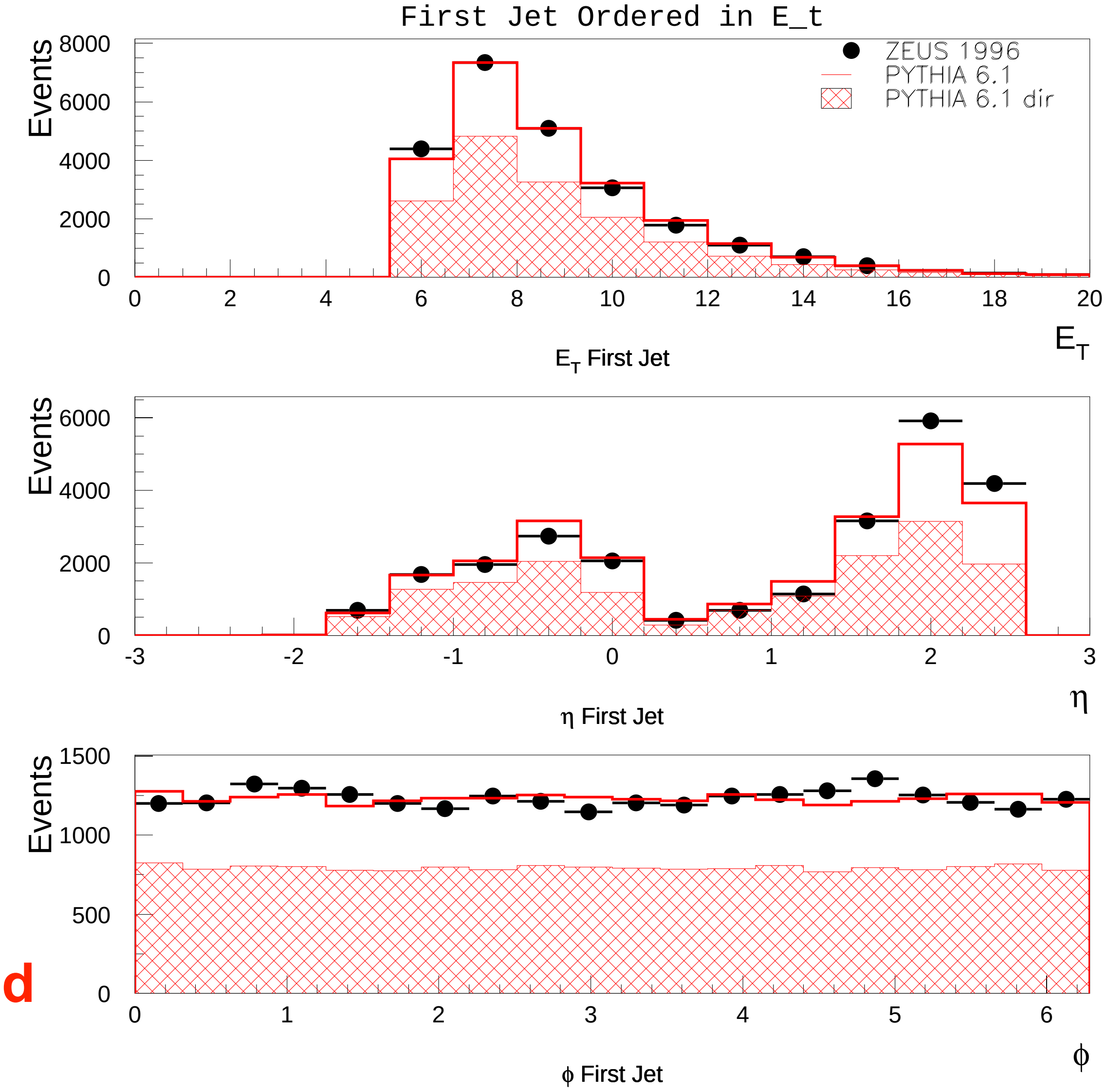
Upper y_{JB} cut

Jet Distributions: Highest E_T Jet

ZEUS Data vs. PYTHIA

Direction and energy of produced partons understood

Jet kinematics and detector effects well understood and simulated



E_T

η

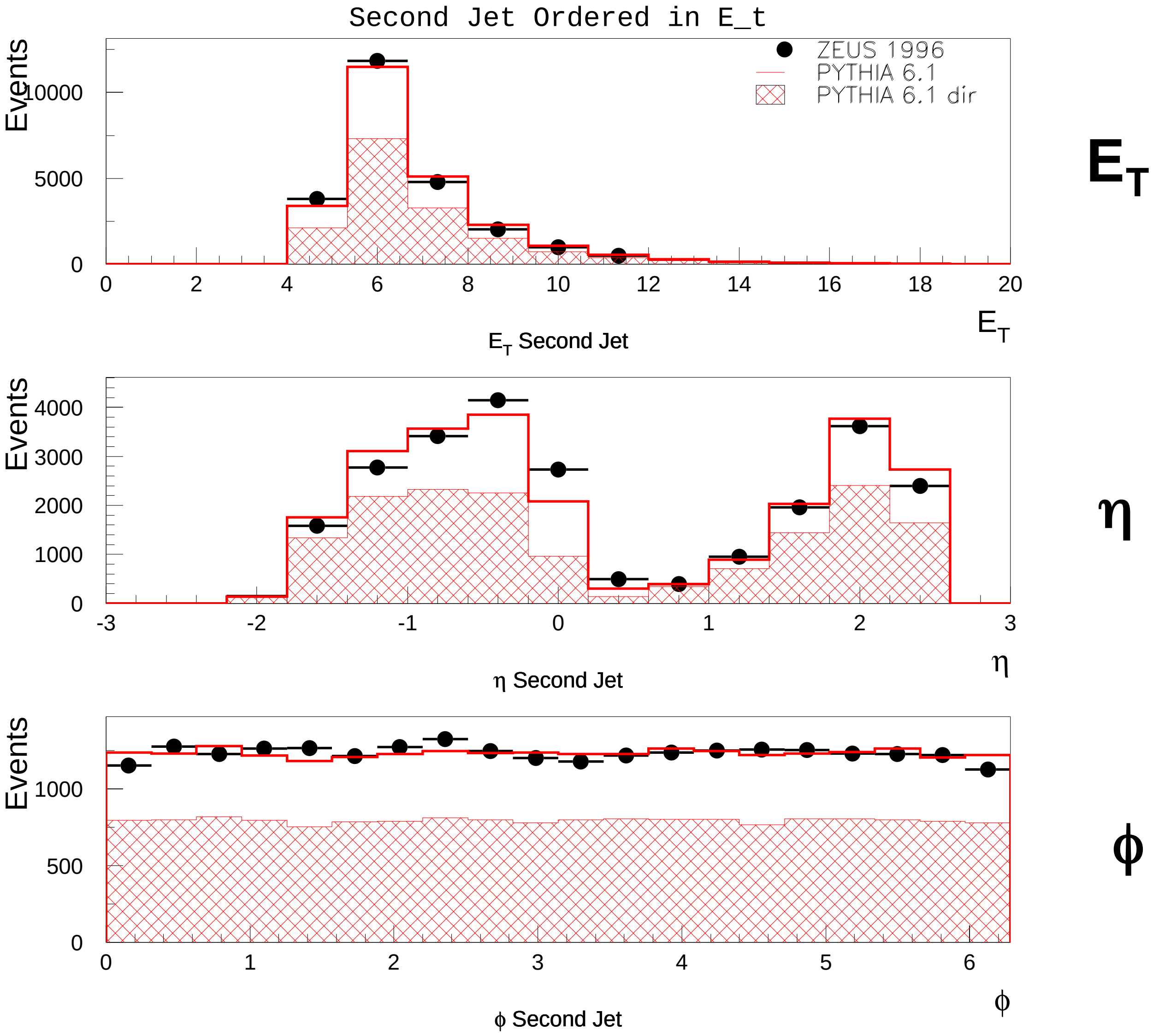
ϕ

Jet Distributions: 2^{nd} Highest E_T Jet

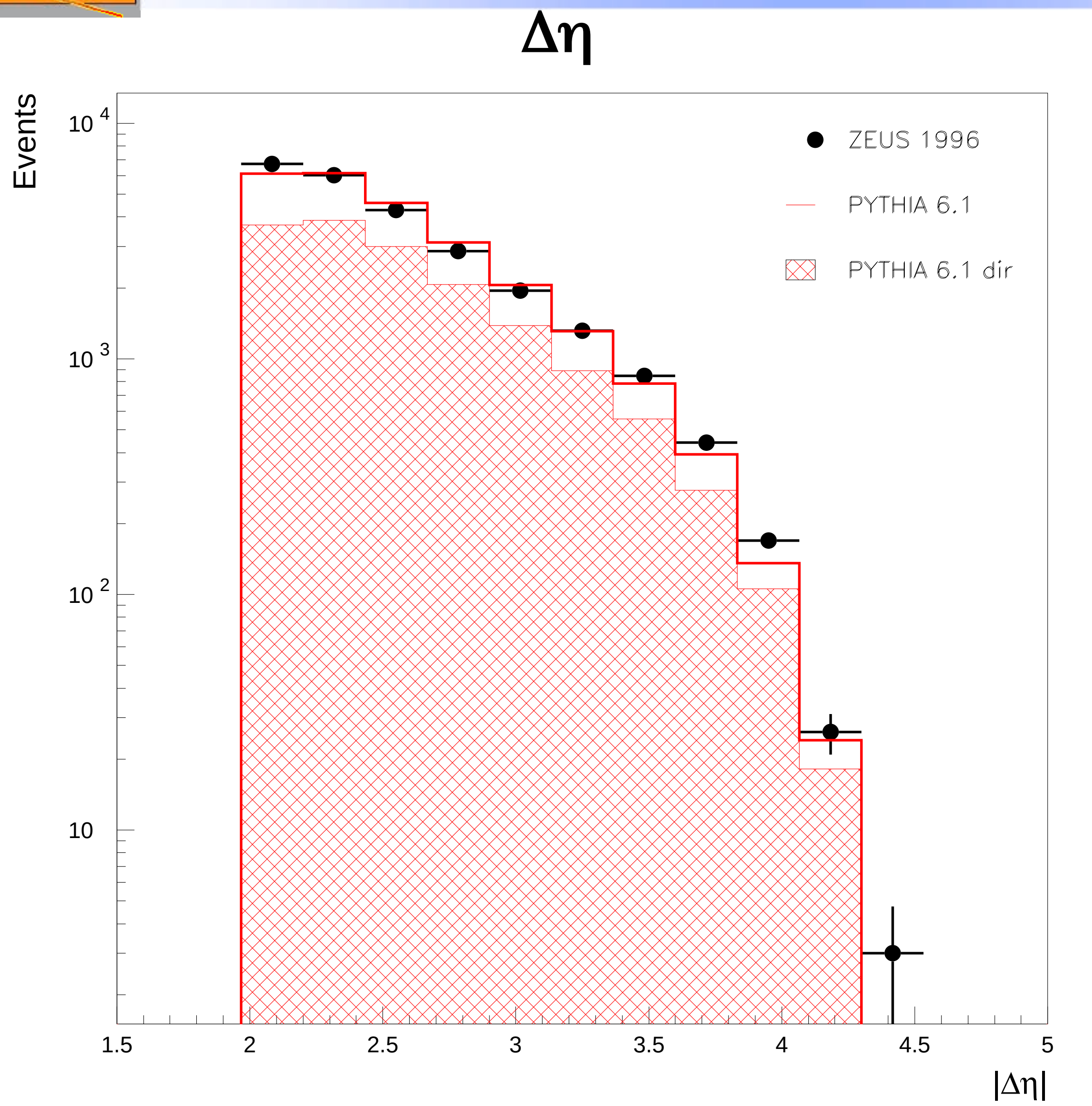
ZEUS Data vs. PYTHIA

2^{nd} Jet allows test of jet finding algorithms

Jet kinematics and detector effects well understood and simulated



Simulation of Δη

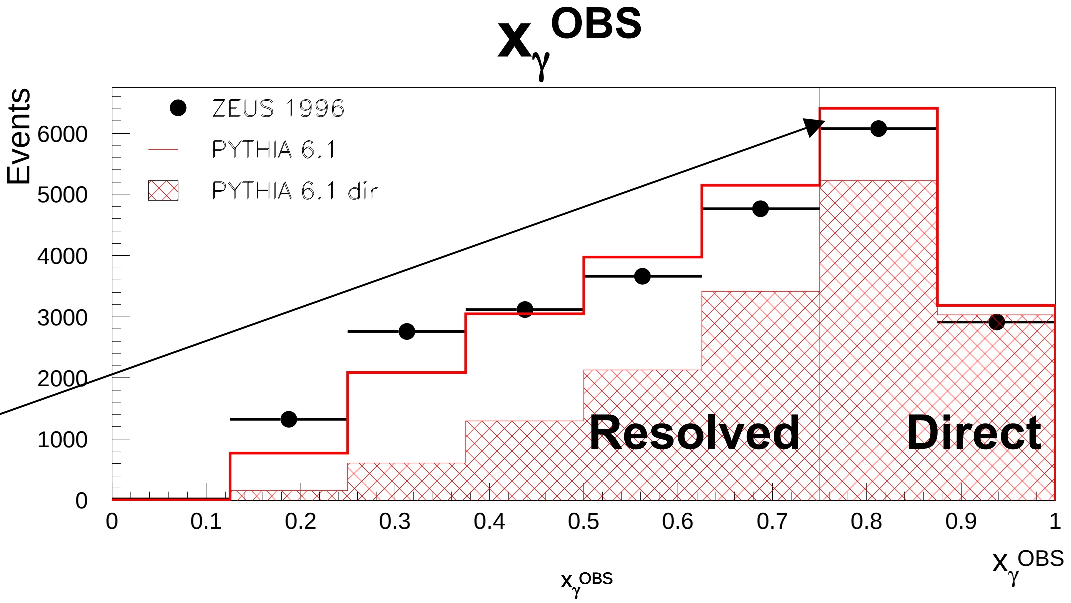


- **•Validates**
  - **Jet finding**
  - **Hadron models**
  - **Detector simulation**
- **•Distance in η between jets well simulated**
  - **Important for study of Rapidity Gaps**

Direct and Resolved Contributions

x_γ^{OBS} used to distinguish direct and resolved

Below 0.75 is resolved enhanced

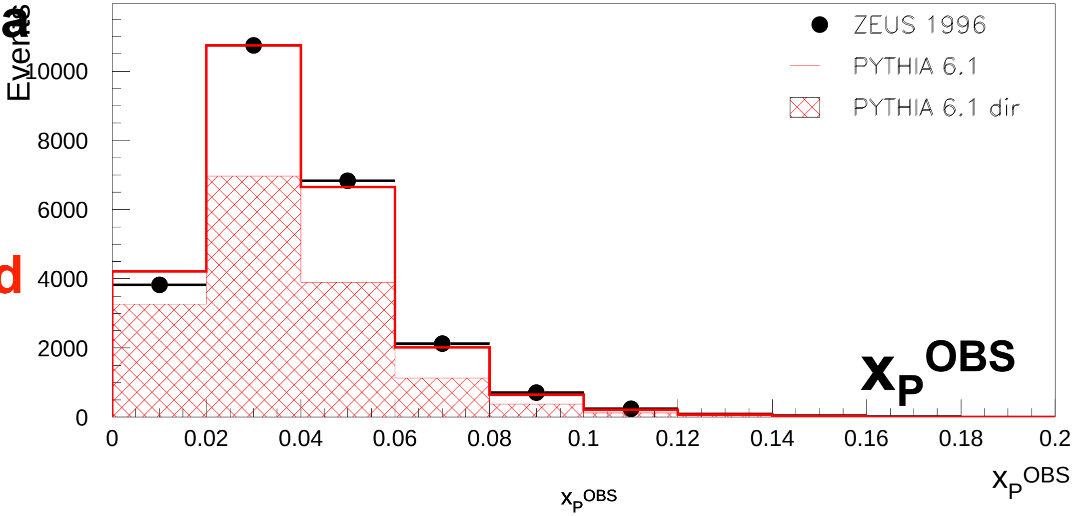


$$x_\gamma^{OBS} = \frac{\sum_{jets} E_T e^{-\eta}}{2yE_e}$$

Fit of MC to Data yields:

43% **Direct**

57% **Resolved**



$$x_P^{OBS} = \frac{\sum_{jets} E_T e^{\eta}}{2E_P}$$

Summary

- **Conclusions**
  - **Compare diffractive photoproduction events to pQCD predictions**
  - **First look at rapidity gaps in ZEUS 1996 Photoproduction Data**
  - **Jet kinematics are well understood and simulated and detector effects accounted for**
  - **Hard Scale in Soft Process ➔ pQCD applicable for a soft process**
- **Plans**
  - **First add 1997 Data and then 1999-2000 Data (~160,000 events)**
  - **Measure jet cross-sections and gap fraction**
  - **Understand systematic uncertainties**
    - Cuts on kinematic variables
    - Mixing of direct and resolved PYTHIA contributions
    - Calorimeter energy scale
    - Use of HERWIG instead of PYTHIA for acceptance corrections