Multiplicity Distributions in DIS at HERA

Preliminary Examination

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Outline

- Introduction
- HERA and ZEUS
- Kinematics
- Parton Shower & Hadronization Models
- Universality of Hadron Production
- Data Selection & Simulation of ZEUS Data
- Mean Charged Multiplicity vs. Effective Mass
- Summary and Plan

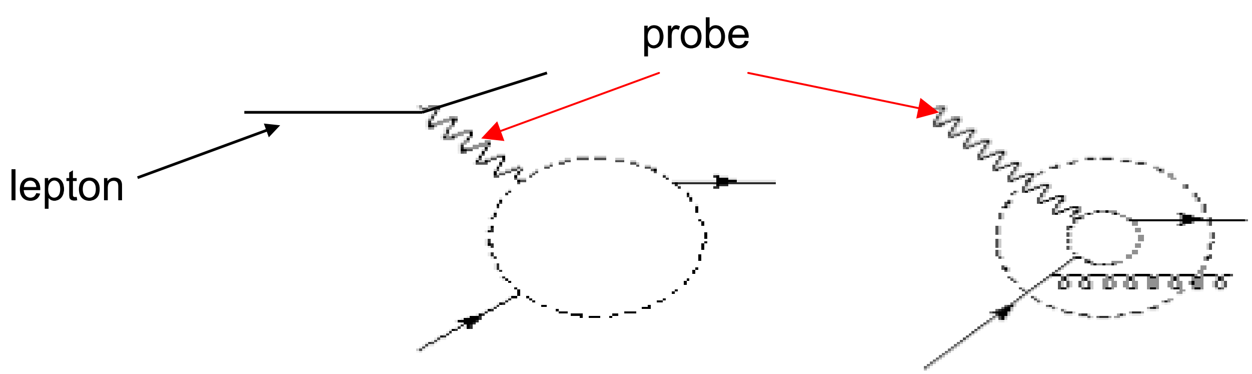
Particle Scattering

- Study structure of proton
- Scattering via probe exchange
  - Wavelength $\lambda = \frac{\hbar}{Q}$

h : Plank's Constant

Q^2: related to momentum of photon

- Deep Inelastic Scattering – Q^2 large
  - High energy lepton transfers momentum to a nucleon via probe



Size of proton ~ 1 fm   HERA Q^2 Range ~ 40,000GeV^2 HERA can probe to ~ 0.001 fm

Naïve Quark Parton Model

Parton Model

- Proton consists of pointlike non interacting constituents (partons)

Quark Parton Model

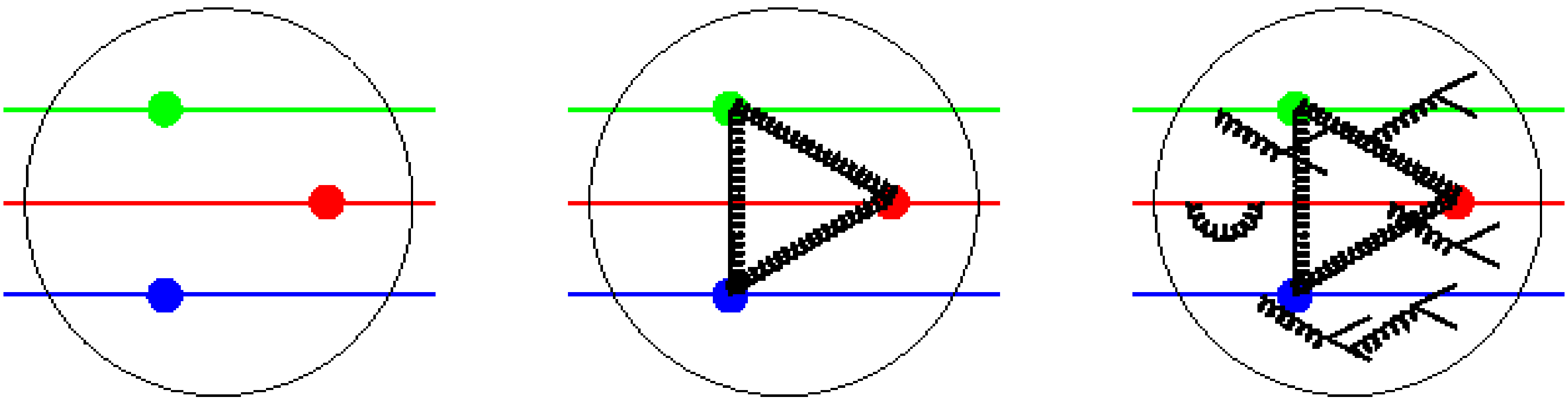
- 3 families of quarks ½ spin particles

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

QCD Theory

QCD Quantum Chromodynamics

- Strong force couples to color and is mediated by the gluon
- Gluon permits momentum exchange between quarks
- Gluons create quarks through pair production
- Color confinement: free partons are not observed, only colorless objects -hadrons
- Parton distribution function (PDF) gives probability of finding parton with given momentum within proton (experimentally determined)



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)

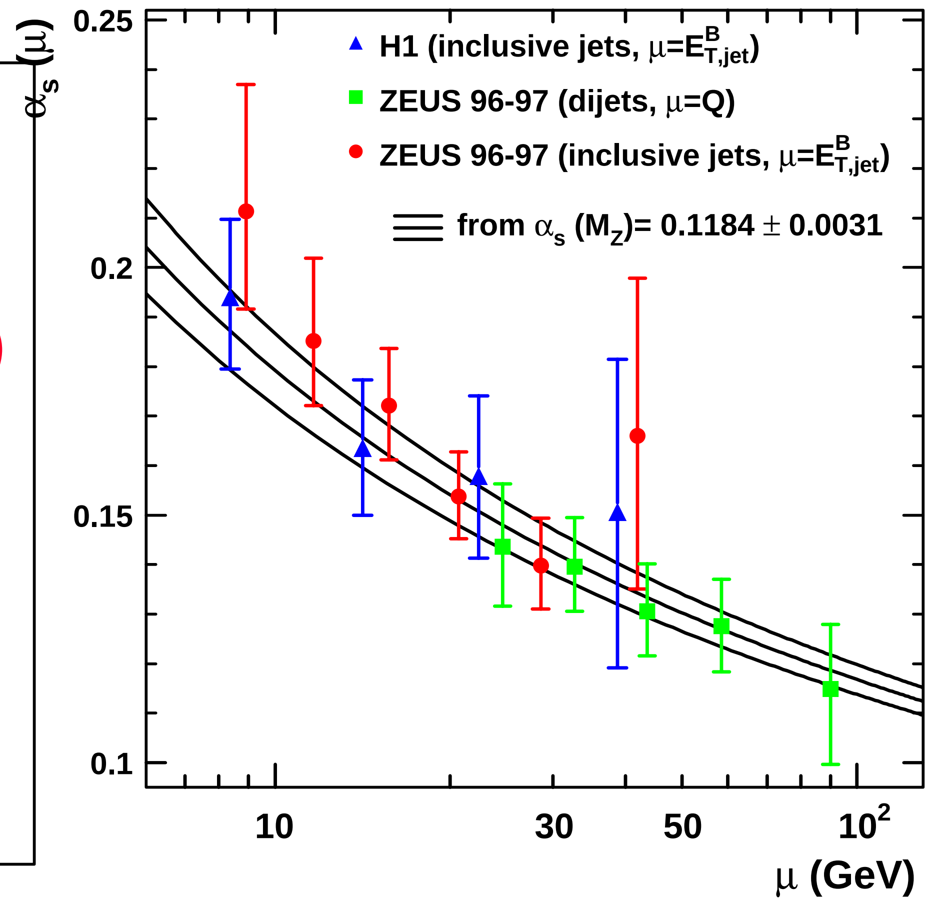
Perturbative QCD (pQCD)

- Small $\alpha_S(\mu)$ (hard scale)
- Series expansion used to calculate observables

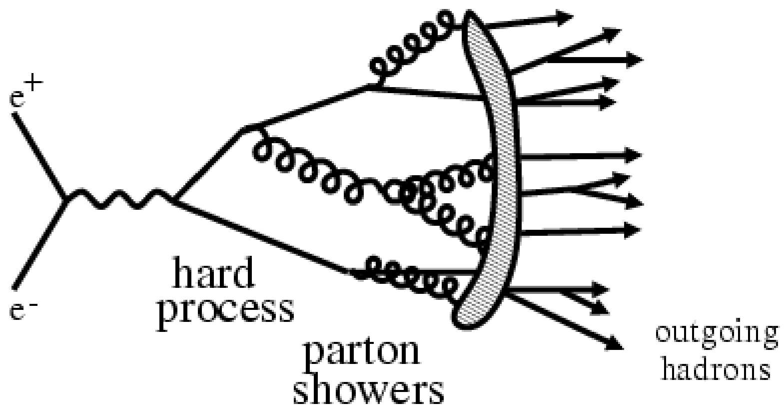
Nonperturbative QCD

- Large $\alpha_S(\mu)$ (soft scale)
- Series not convergent

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



From Partons to Hadrons



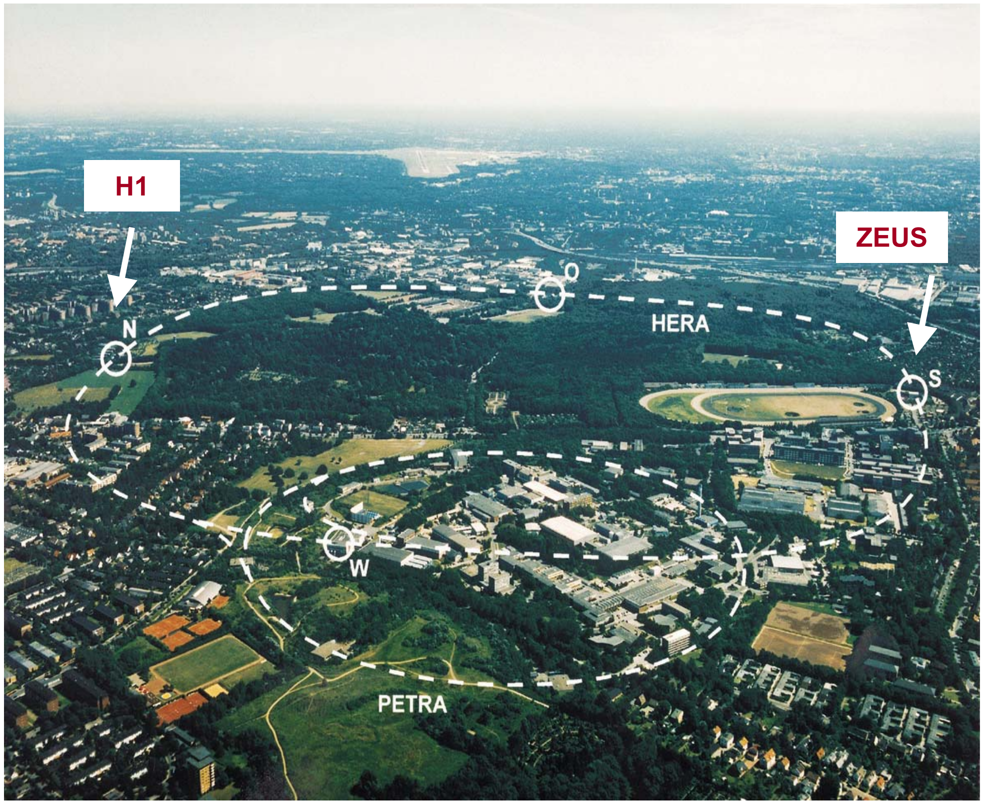
hard scattering ⊗ parton showers ⊗ hadronization

- Hard scattering: large scale (short distance) perturbative process
- Parton showers: initial QCD radiation of partons from initial partons
- Hadronization: colorless hadrons produced from colored partons
  soft process (large distance) - not perturbatively calculable
  phenomenological models and experimental input

Multiplicity and Energy Flow

- The hard scattering process determines the initial distribution of energy
- Parton Shower + Hadronization determine the number of charged particles produced
- Measure mean number of charged particles produced, (mean charged multiplicity, $<n_{ch}>$), versus the energy available for production of final state hadrons, study the mechanisms of hard scattering, parton showers and hadronization
- pQCD & universality of the hadronization process can be tested by comparison with data from e^+e^- and hadron colliders.

HERA Description



DESY Hamburg, Germany

Unique opportunity to study hadron-lepton collisions

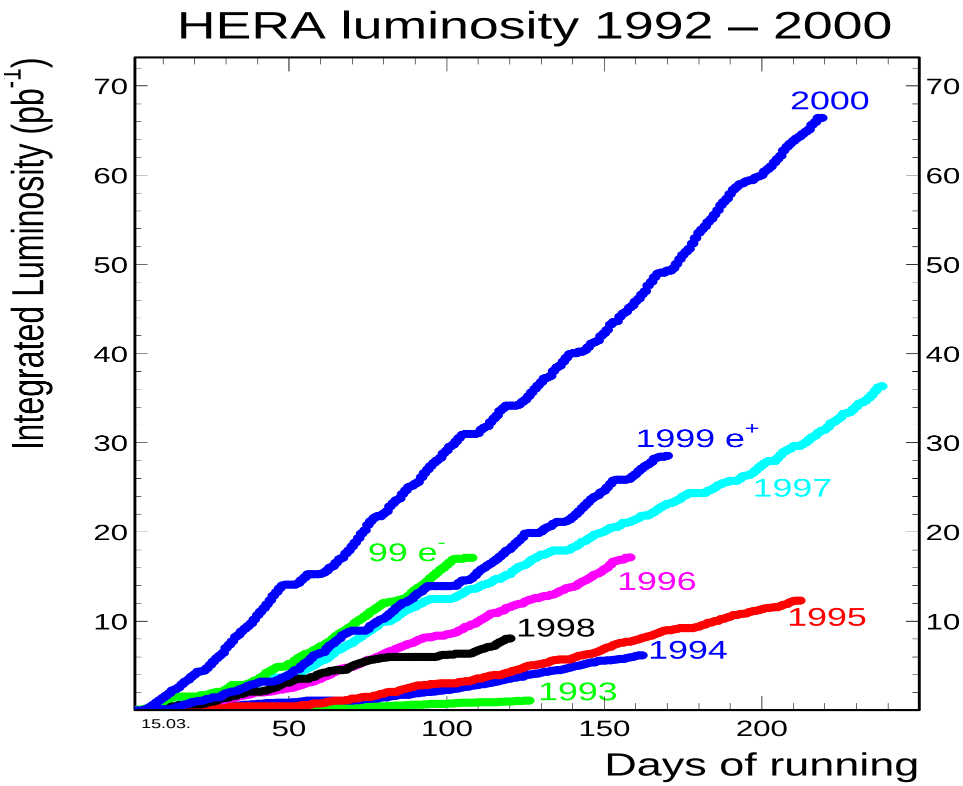
- **920 GeV p^+**
  (820 GeV before 1999)
- **27.5 GeV e^- or e^+**
- **318 GeV cms**
- **Equivalent to a 50 TeV Fixed Target**

Instantaneous luminosity max: $1.8 \times 10^{31}\ cm^{-2}s^{-1}$

- **220 bunches**
- **96 ns crossing time**

I_P~90mA p
I_e~40mA e^+

HERA Data



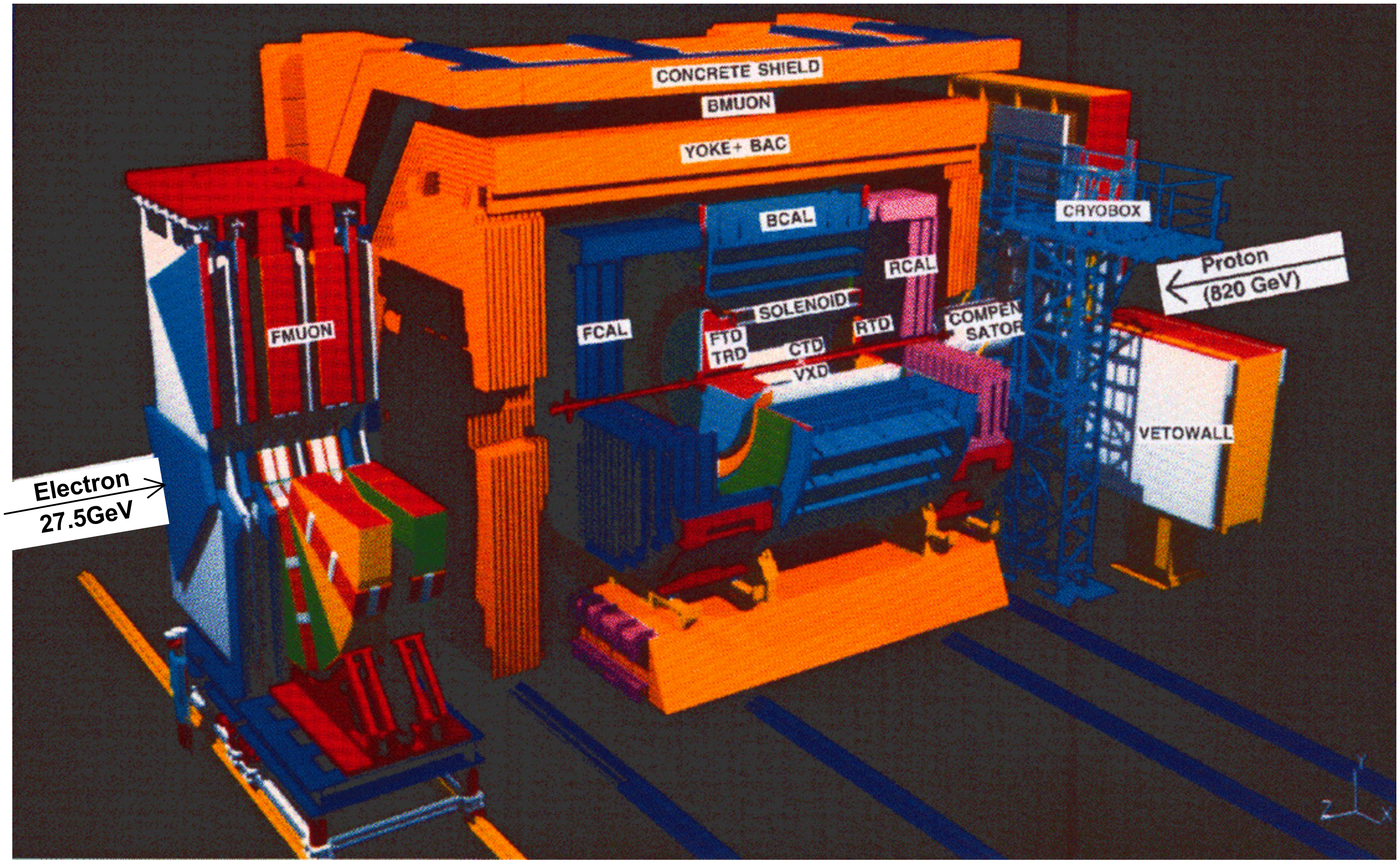
Luminosity upgrade

- 5x increase in Luminosity

⇒ **expect 1 fb^{-1} by end of 2006**

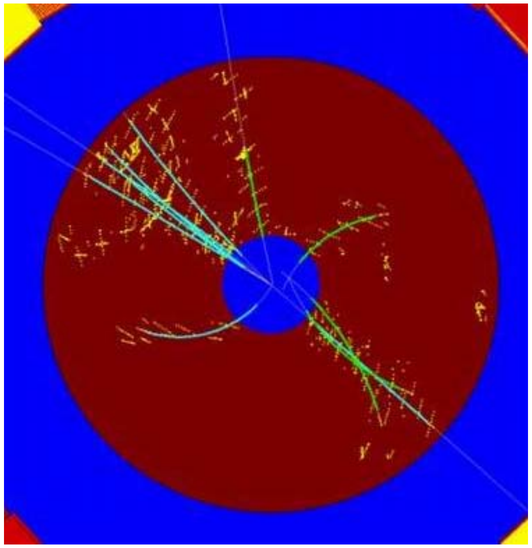
ZEUS Luminosities (pb^{-1})			# events (10^6)
Year	**HERA**	**ZEUS on-tape**	**Physics**
e$^-$: *93-94, 98-99*	27.37	18.77	32.01
e$^+$: *94-97, 99-00*	165.87	124.54	147.55

ZEUS Detector

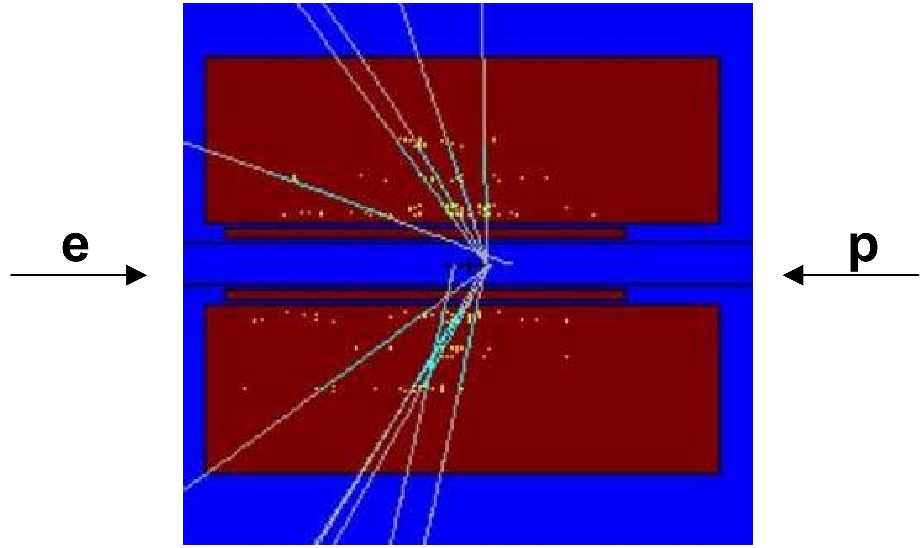


- General Purpose Detector
- Almost hermetic
- Measure ep final state particles: energy, particle type and direction

Central Tracking Detector



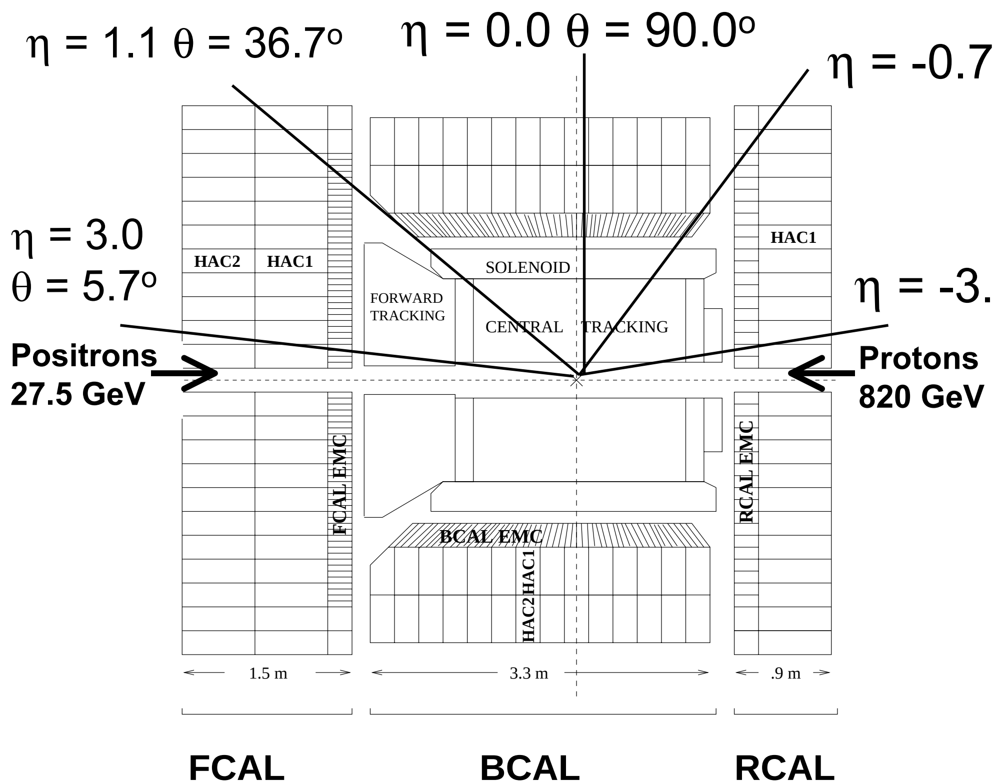
View Along Beam Pipe



Side View

- Drift Chamber inside 1.43 T Solenoid
- Can resolve up to 500 charged tracks
- Average event has ~20-40 charged tracks
- Determine interaction vertex of the event
- Measure number of charged particles (tracks)

Uranium-Scintillator Calorimeter



- alternating uranium and scintillator plates (sandwich calorimeter)
- compensating - equal signal from hadrons and electromagnetic particles of same energy - e/h = 1
- Energy resolution $\sigma_e/E_e = 18\% / \sqrt{E}$ $\sigma_h/E_h = 35\% / \sqrt{E}$, E in GeV
- Depth of FCAL > RCAL due to $E_p > E_e$
- covers 99.6% of the solid angle
- Used for measuring energy flow of particles.

$$\eta = -\ln(\tan(\frac{\theta}{2}))$$

ZEUS Trigger

10^7 Hz Crossing Rate, 10^5 Hz Background Rate, 10 Hz Physics Rate

•First Level

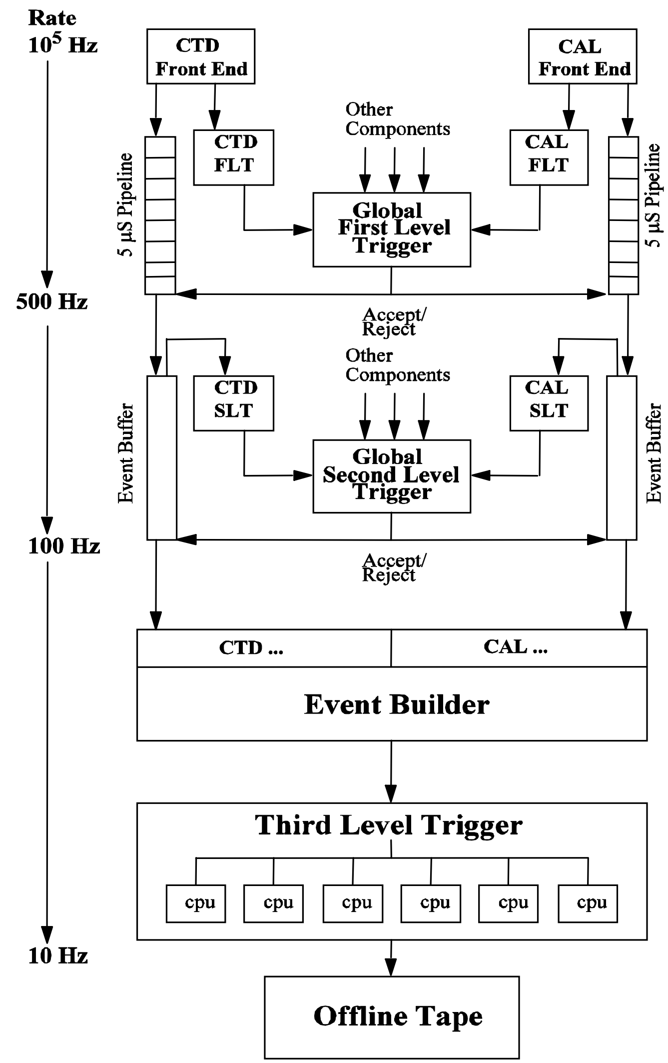
- Dedicated custom hardware
- Pipelined without deadtime
- Global and regional energy sums
- Isolated μ and e^+ recognition
- Track quality information

•Second Level

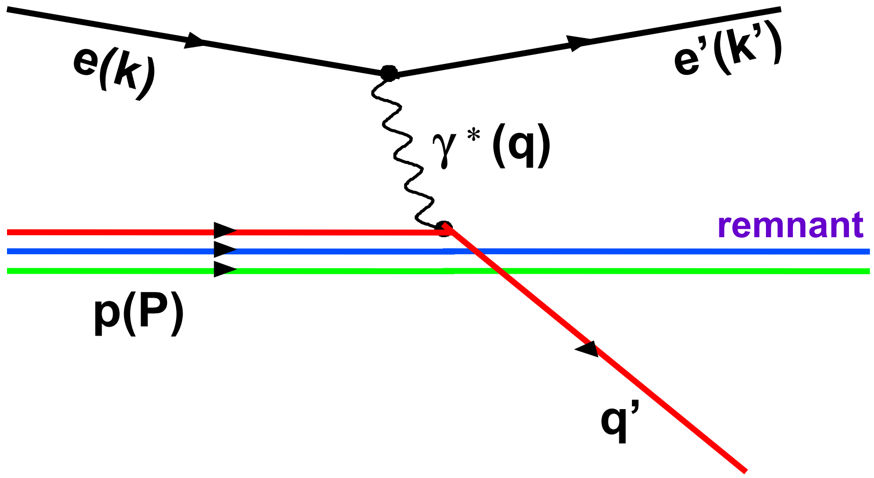
- "Commodity" Transputers
- Calorimeter timing cuts
- E - p_z cuts
- Vertex information
- Simple physics filters

•Third Level

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



Kinematic Variables



Virtuality of exchanged photon

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

Inelasticity: $0 \leq y \leq 1$ $\quad y = \dfrac{p \cdot q}{p \cdot k}$

Fraction of proton momentum carried by struck parton $\quad x = \dfrac{Q^2}{2q \cdot p}$

$0 \leq x \leq 1$

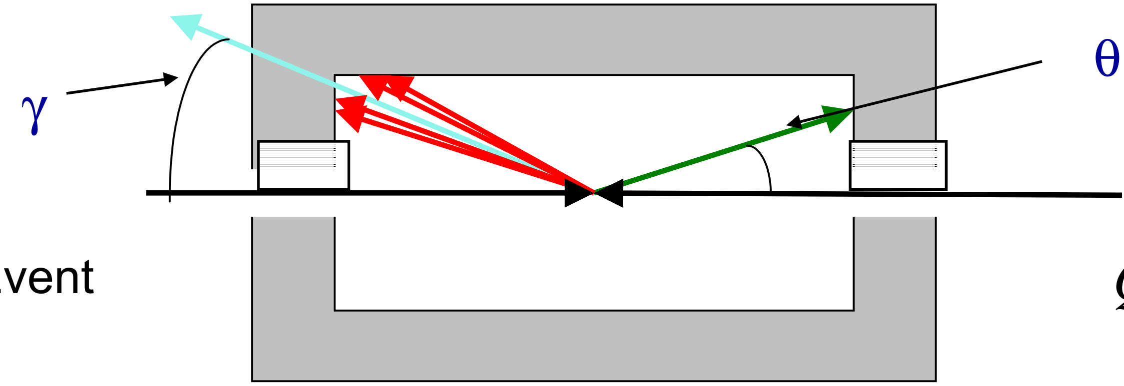
$\sqrt{s}$ **= Center of mass energy of the ep system** $\quad s = (p + k)^2 \cong 4E_e E_p$

Center of mass energy of the γ^*P system $\quad W^2 = (q + p)^2$

Only two independent quantities $\quad Q^2 = sxy$

Kinematic Reconstruction

Four Measured Quantities: E_e', θ_e, E_h, γ_h.



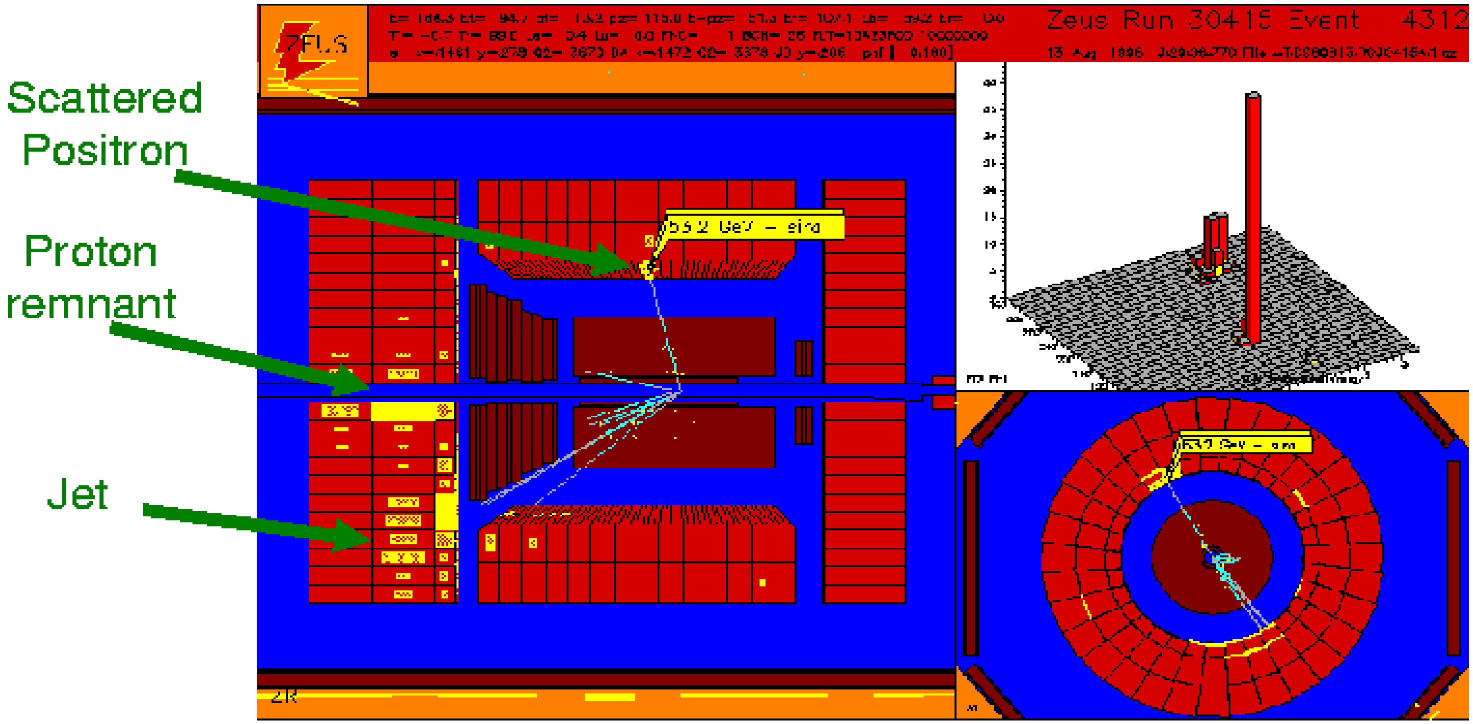
(p,E) conservation

DIS Event

$$Q^2 = sxy$$

Variable	Electron Method (E_e',θ)	Jacquet-Blondel (E_h,γ)	Double Angle (θ,γ)
Q^2	$2E_eE'(1+\cos\theta_e)$	$\frac{p_{T,h}^2}{1-y_{JB}}$	$4E_e^2\frac{(1+\cos\theta_e)\cdot\sin\gamma}{\sin\gamma+\sin\theta_e-\sin(\gamma+\theta_e)}$
x	$\frac{Q_{el}^2}{s\cdot y_{el}}$	$\frac{Q_{JB}^2}{s\cdot y_{JB}}$	$\frac{Q_{DA}^2}{s\cdot y_{DA}}$
y	$1-\frac{E'}{2E_e}(1-\cos\theta_e)$	$\frac{E_h-p_{z,h}}{2E_e}$	$\frac{(1-\cos\gamma)\cdot\sin\theta}{\sin\gamma+\sin\theta-\sin(\theta+\gamma)}$

Deep Inelastic Scattering

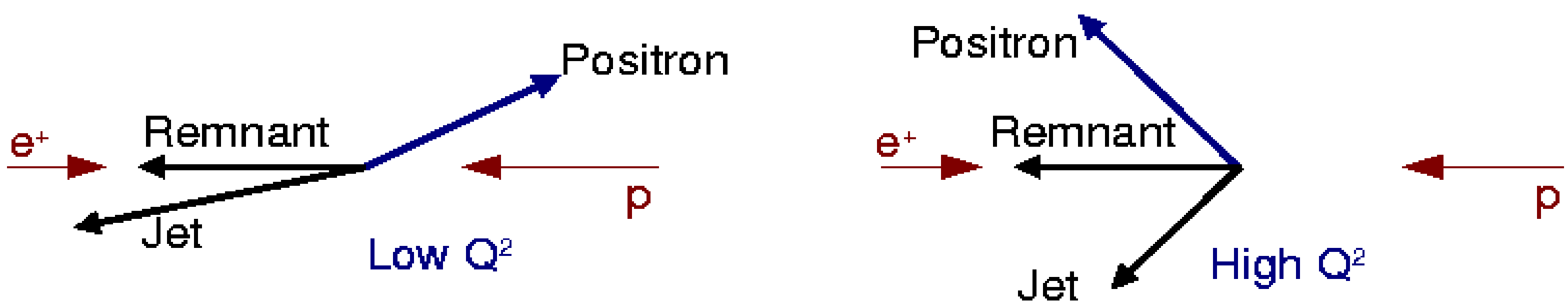


Q^2~3600GeV^2

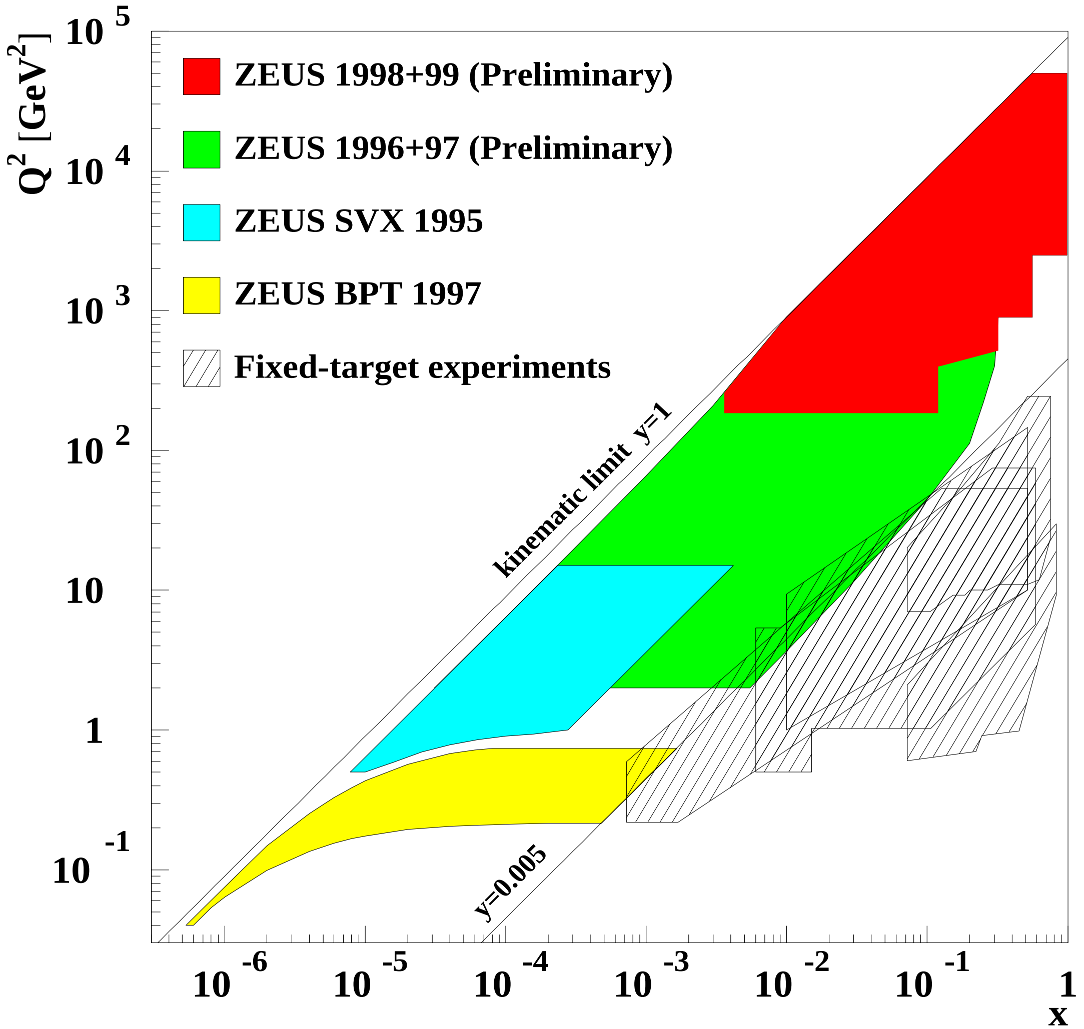
X ~0.15

Y ~0.20

(1+1) event



HERA Kinematic Range



$Q^2 = sxy$

$0.1 < Q^2 < 20000\ GeV^2$

$10^{-6} < x < 0.9$

Equivalent to a

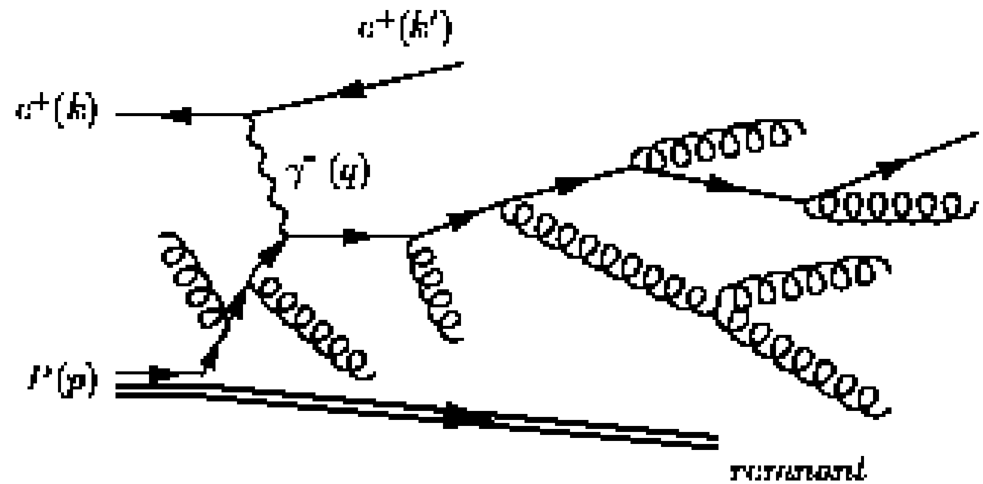
50 TeV Fixed Target Experiment

Modeling Multi-parton Production

- Model multiple parton emissions from partons produced in hard scattering
- Not possible to perform exact matrix element calculations
- Two approaches: Parton Shower and Color Dipole Model

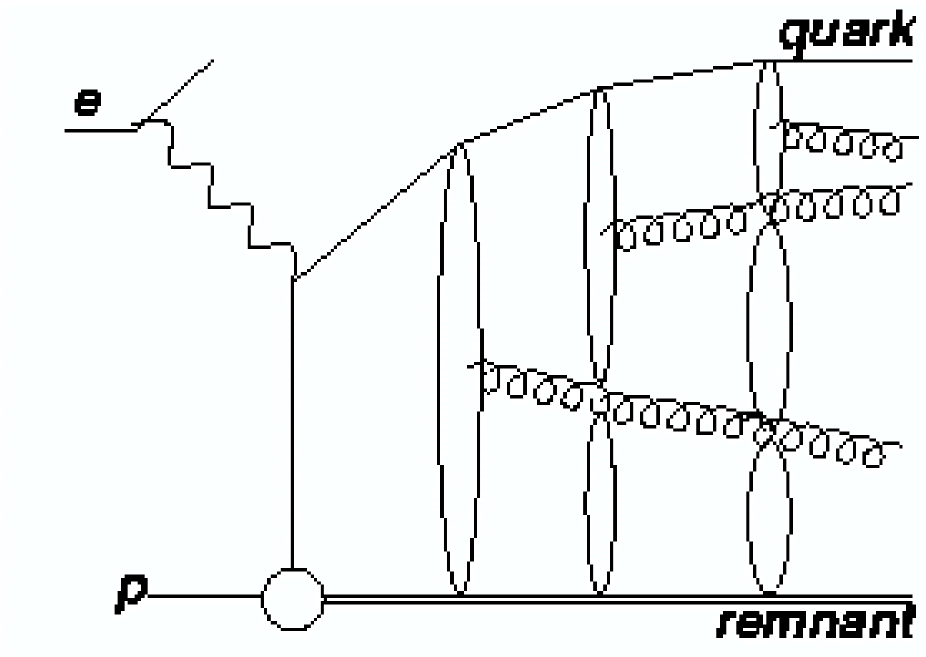
Parton Shower Model

- successive splitting process
- cascade of partons with decreasing virtuality
- cascade continues until a cut-off $\sim 1\ \text{GeV}^2$



Color Dipole Model

- Chain of independently radiating color dipoles
- ep: first dipole between struck quark and proton remnant
- gluon induced processes are added in "by hand“

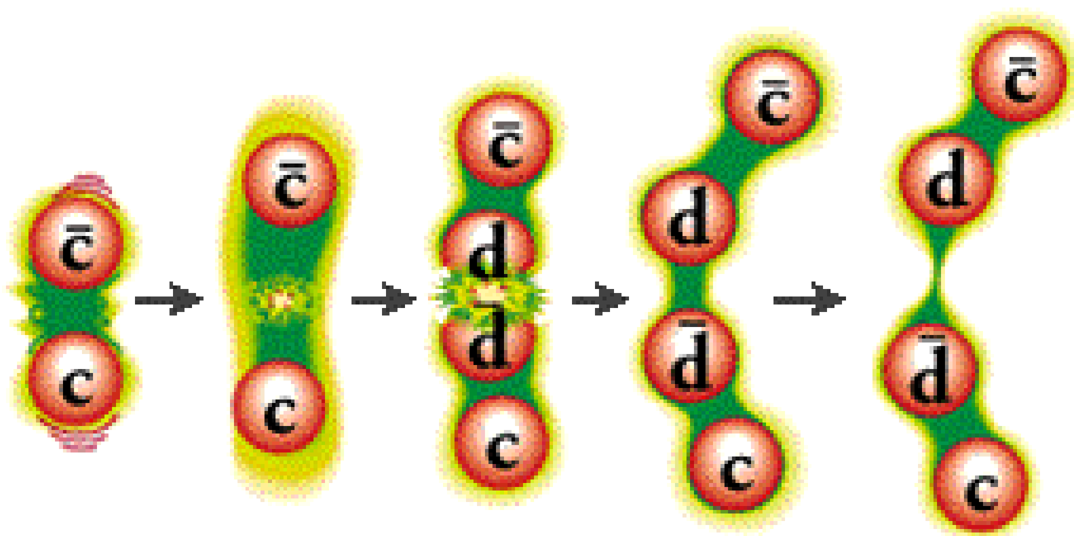


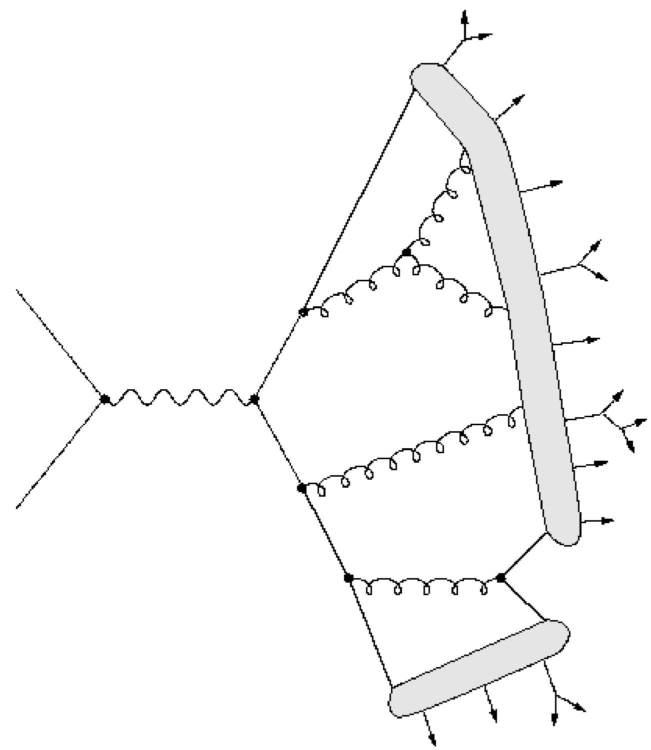
Hadronization Models

- Use phenomenological models because these processes aren't calculable in pQCD – low scale
  - Lund String Model and Cluster Fragmentation Models
- Start at low cut-off scale – set of partons from parton shower transformed into colorless hadrons
- Local parton-hadron duality
  - Long distance process involving small momentum transfers
  - Hadron level flow of momentum and quantum numbers follows parton level
  - Flavor of quark initiating a jet found in a hadron near jet axis

Lund String Fragmentation

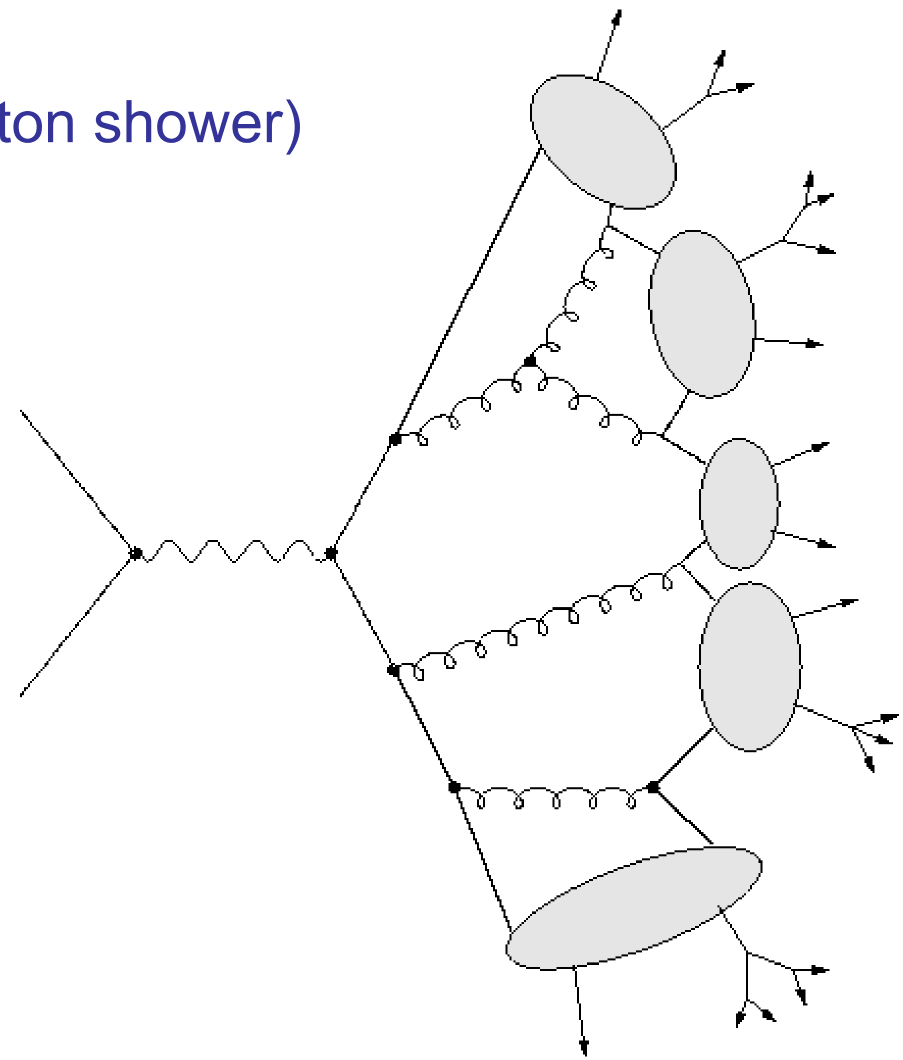
- color "string" stretched between q and $\bar{q}$ moving apart
- confinement with linearly increasing potential (1GeV/fm)
- string breaks to form 2 color singlet strings, and so on., until only on-mass-shell hadrons.



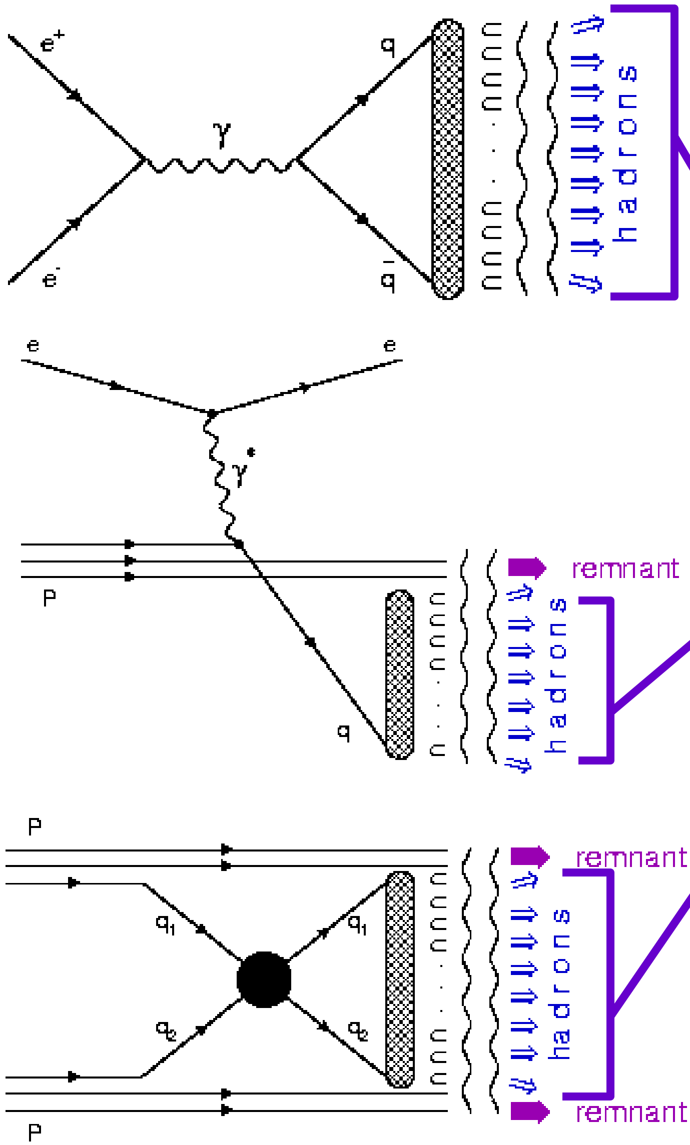


Cluster Fragmentation Model

- preconfinement of color (after parton shower)
- non-perturbative $g \rightarrow q\bar{q}$ splitting after parton shower
- color-singlet clusters of neighboring partons formed
- clusters decay into hadrons



Universality of Hadron Production



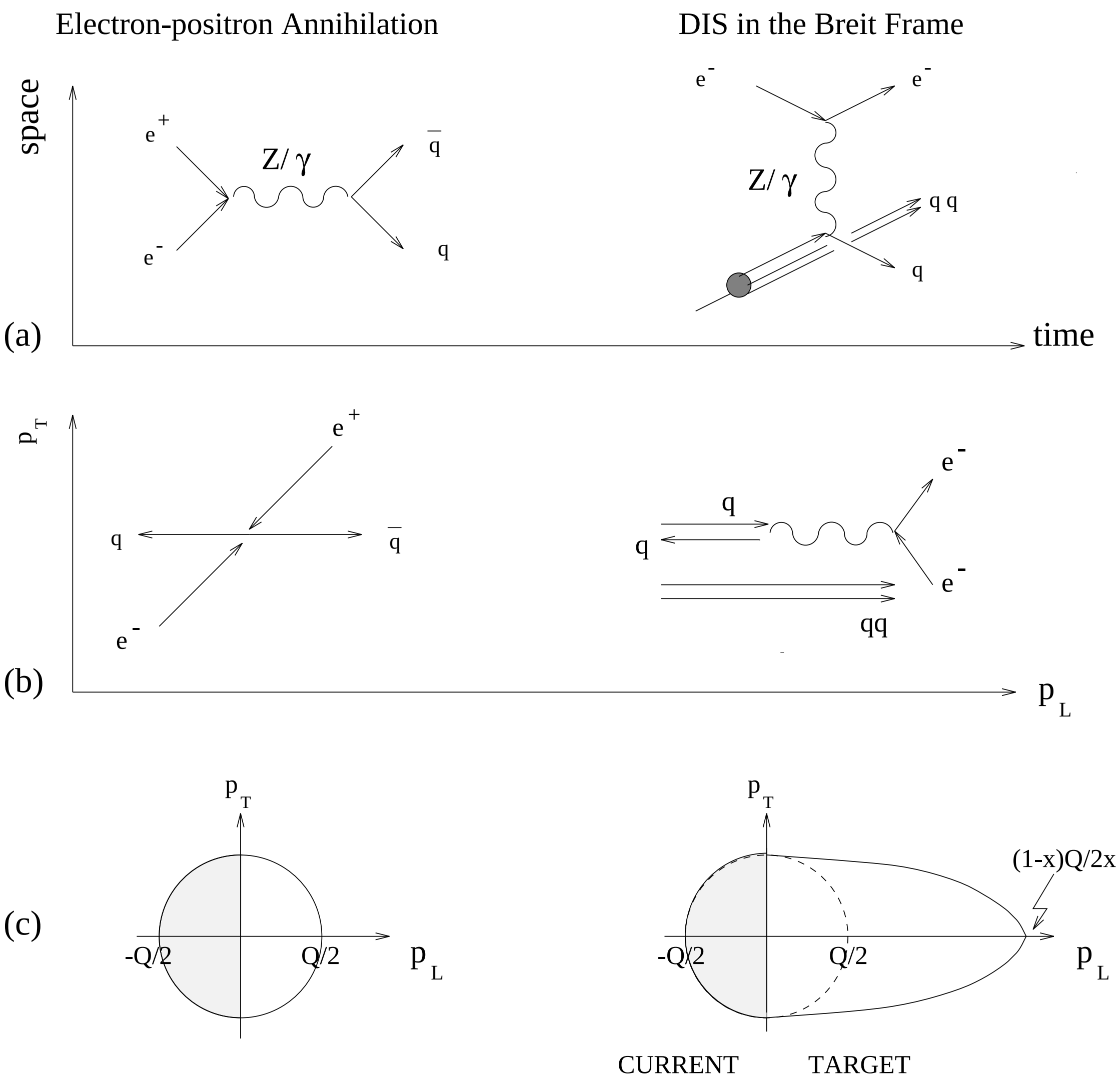
Can look at just part of the string: assumed to give final state particles proportional to logarithm of mass

Similarity of particle production at ee, ep and $p\bar{p}$ colliders

Aim: Test the universality of hadronization in QCD

n_{ch} ~ length of the string(s) ~ ln of energy available for hadron production

e^+e^- & ep : Breit Frame



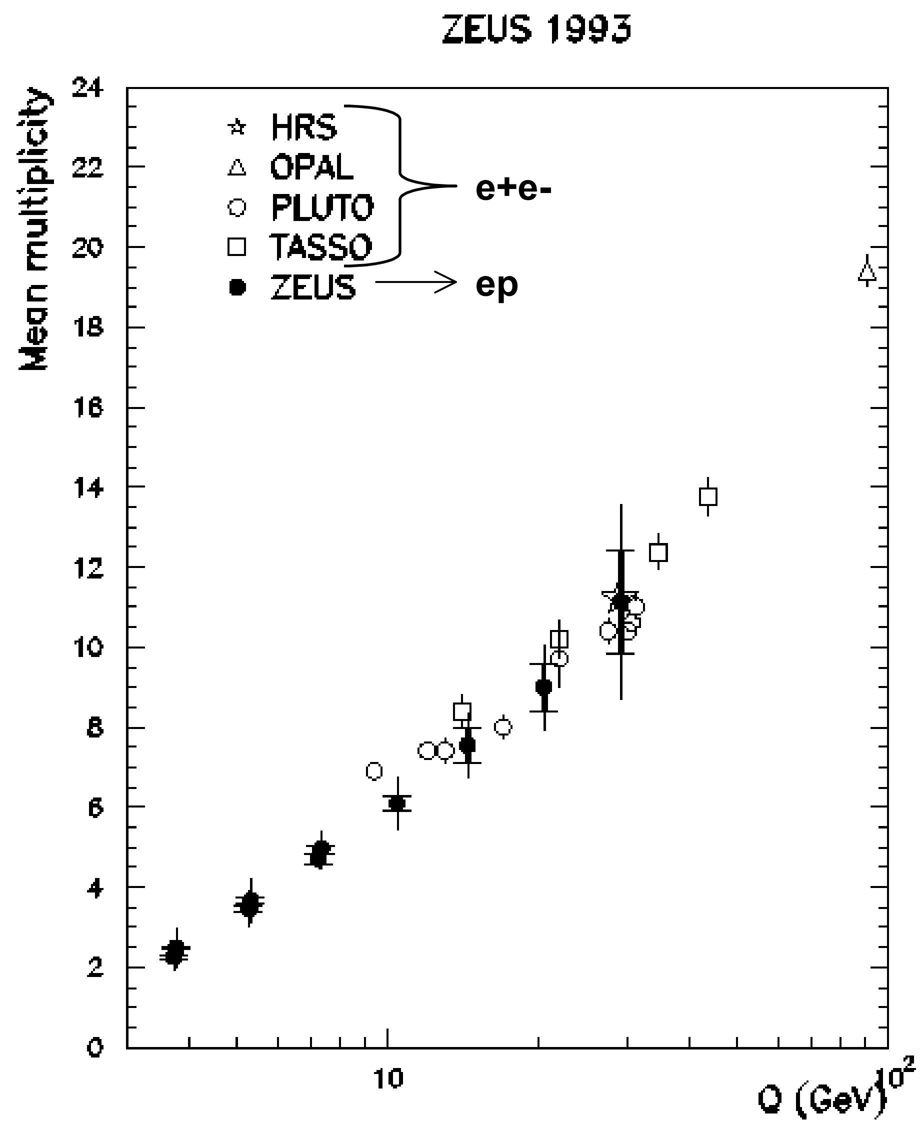
Phase space for e^+e^- annihilation evolves with $Q/2 = \sqrt{s}/2$

Current hemisphere of Breit frame evolves as Q/2

Current region $\cong e^+e^-$ annihilation

Early Experimental Evidence for Universality

- Mean charged multiplicity vs. Q in e^+e^- and current region of Breit frame at HERA
- Linear dependence vs. ln Q observed
- Data in e^+e^- and ep agree universality of hadronization process observed
- Also look at $<n_{ch}>$ as a function of energy available for particle production (slide to follow)



96-97 Data Sample

- **Event Selection**
  - Scattered positron found with $E > 12$ GeV
  - longitudinal vertex cut: $|Z_{vtx}| < 50$ cm
  - scattered positron position cut: $|x| > 15$ cm or $|y| > 15$cm (in RCAL) "Box cut"
  - 40 GeV < $E-p_z$ < 60 GeV
- **Track Selection**
  - Tracks associated with primary vertex
  - $|\eta| < 1.75$
  - $p_T > 150$ MeV
- **Physics and Kinematic Requirement**
  - Q^2 (from double angle) > 12 GeV^2
  - y (from scattered positron) < 0.95
  - y (from hadrons) > 0.04

95842 events before cuts
4798 events after all cuts

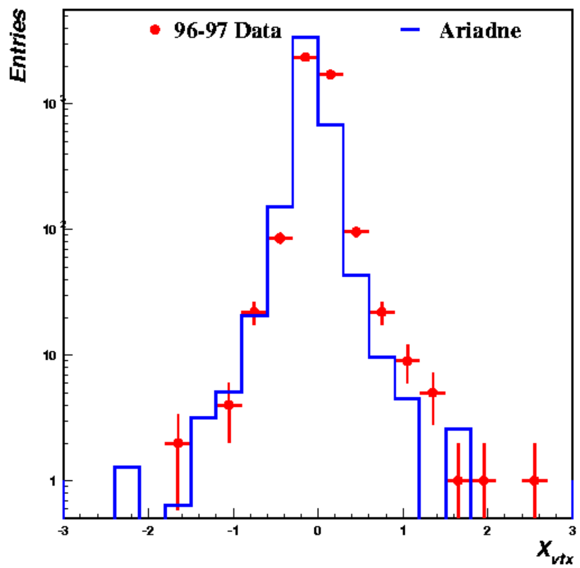
Event Simulation

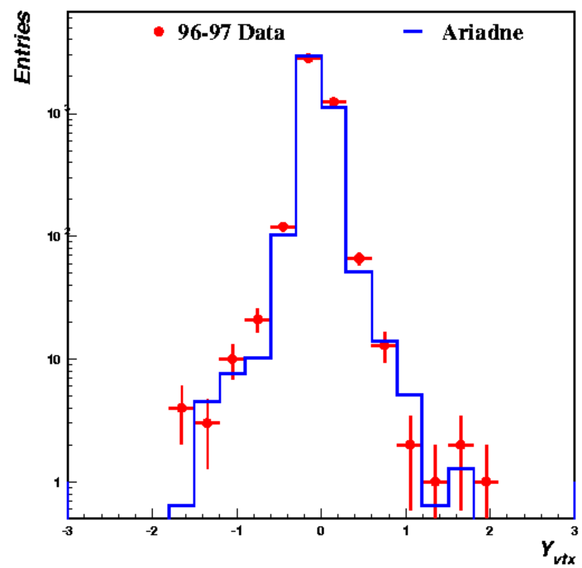
- **Ariadne '96 v2.0**
  - **Matrix elements at LO pQCD $\mathcal{O}(\alpha_s)$**
  - **Parton showers: CDM**
  - **Hadronization: String Model**
  - **Proton PDF's: GRV94 HO parameterization of experimental data***
- **$Q^2 > 10$ GeV^2**
- **Detector Simulation: software package based on GEANT**

19990 events before cuts
7058 events after all cuts

*M.Glück, E.Reya and A.Vogt, Phys. Lett. B306 (1993) 391

Zeus '96 Data vs. Ariadne

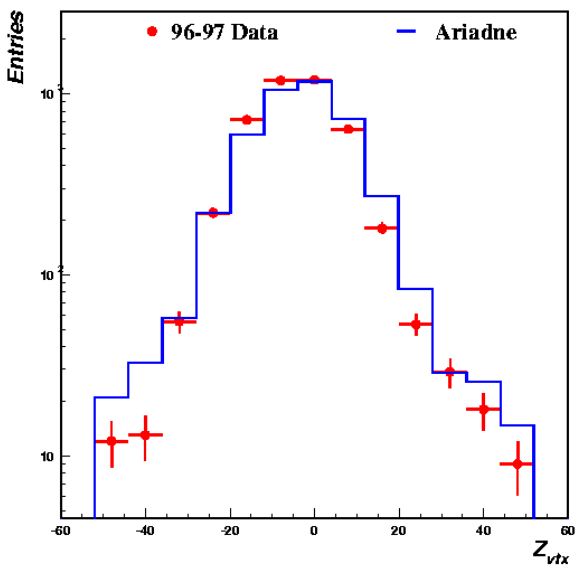




Vertex Position

⬅ X & Y vertex

- MC simulates transverse vertex well



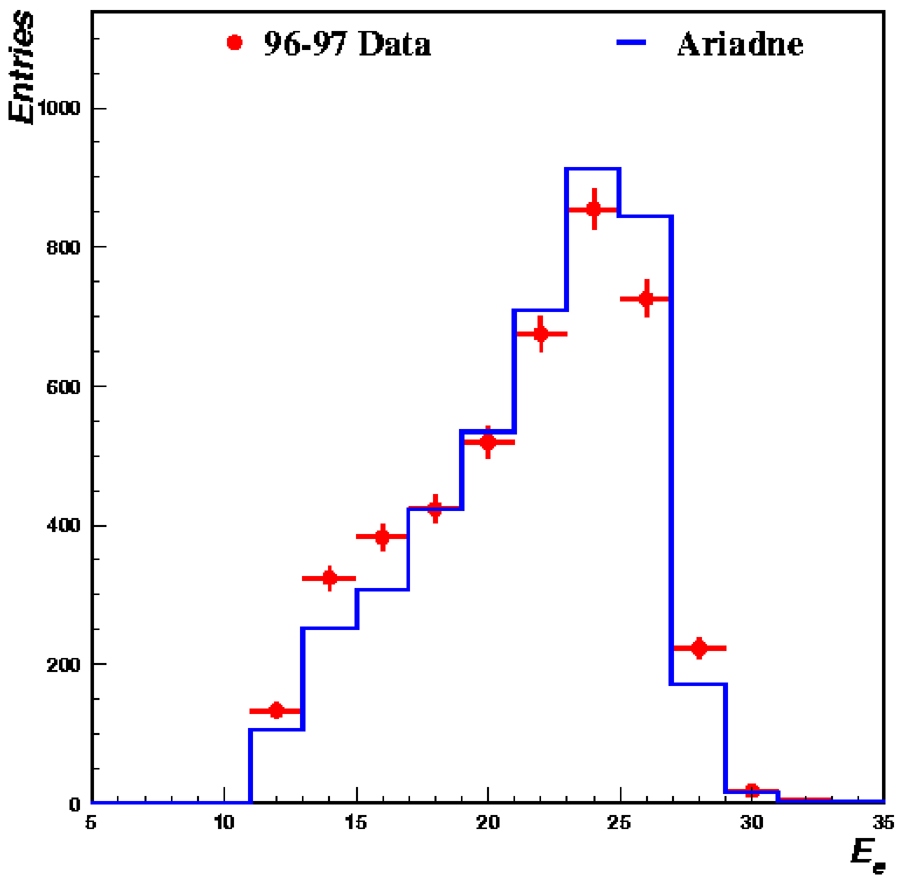
⬅ Z vertex

- Longitudinal vertex is shifted due to partial data

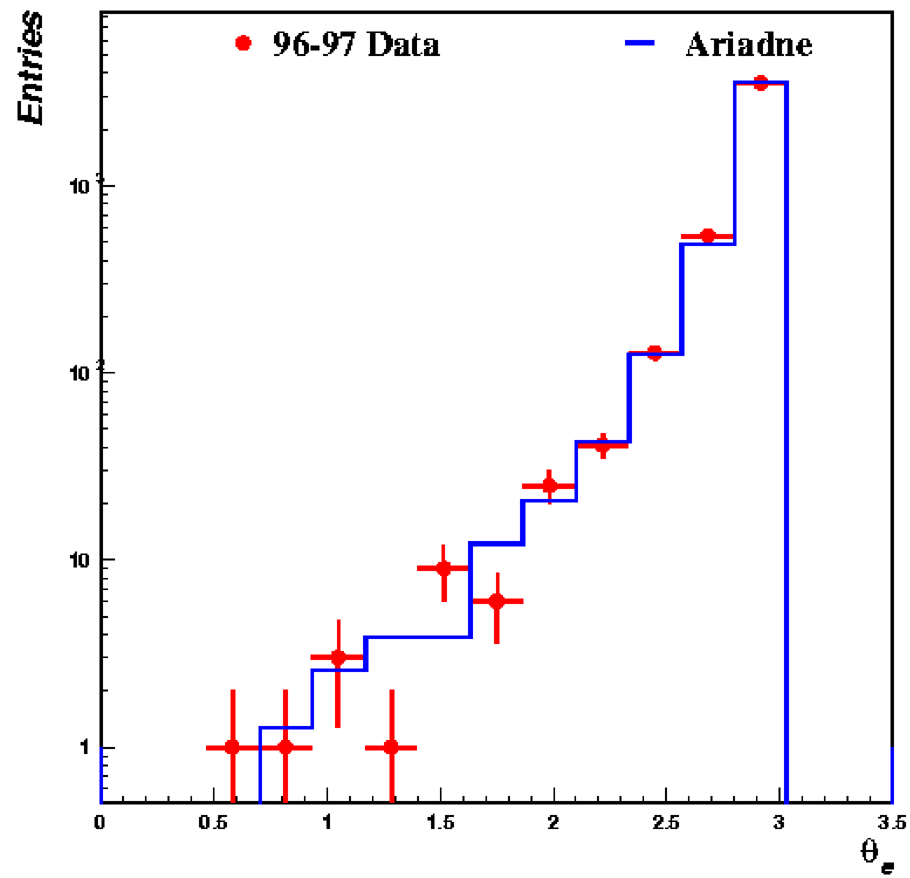
Work done by M.Sumstine
Summer 2002

Energy & Theta of Scattered Positron

Scattered Positron Energy

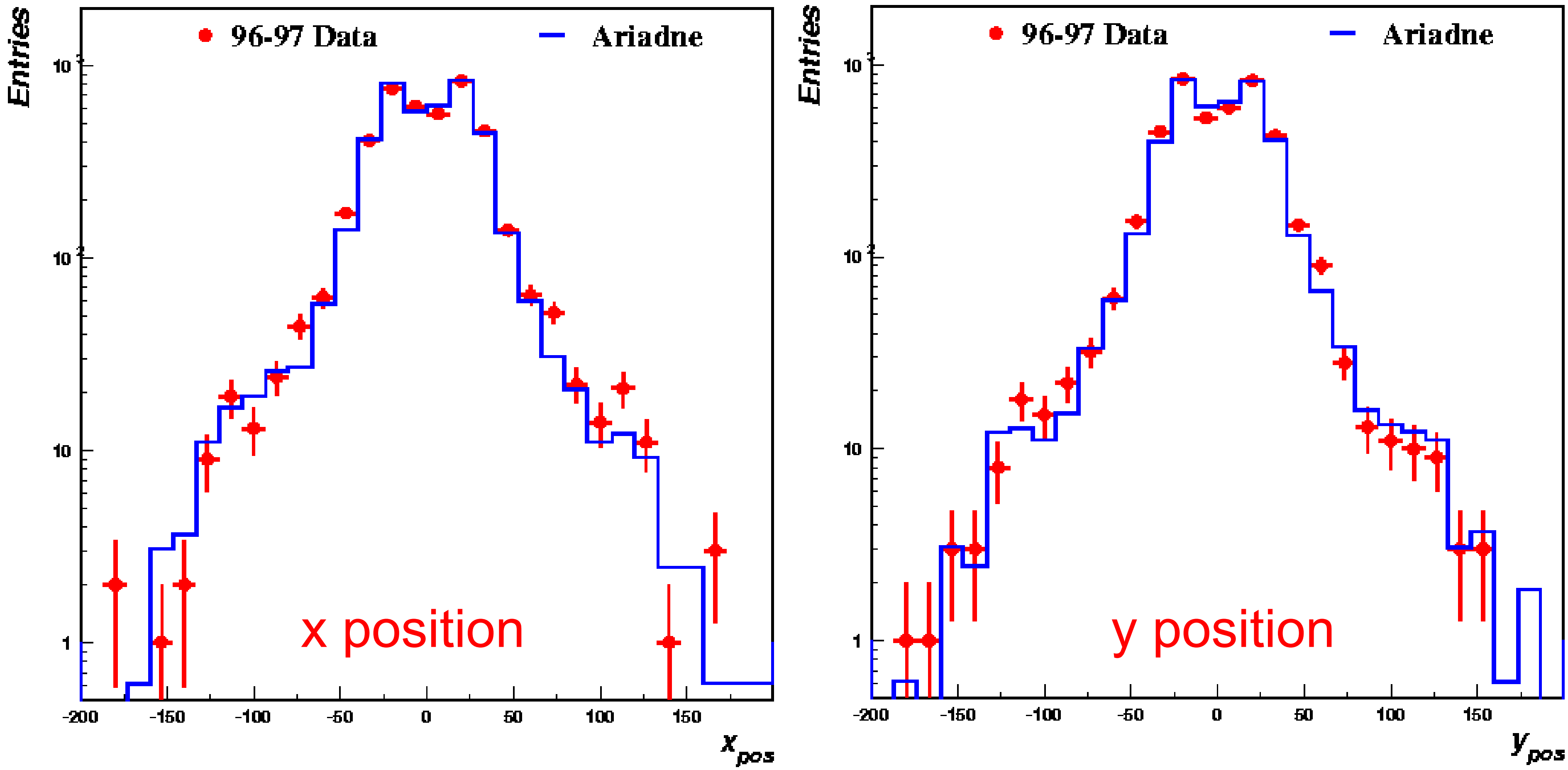


Polar Angle of Scattered Positron



Positron energy corrections needed – under study.

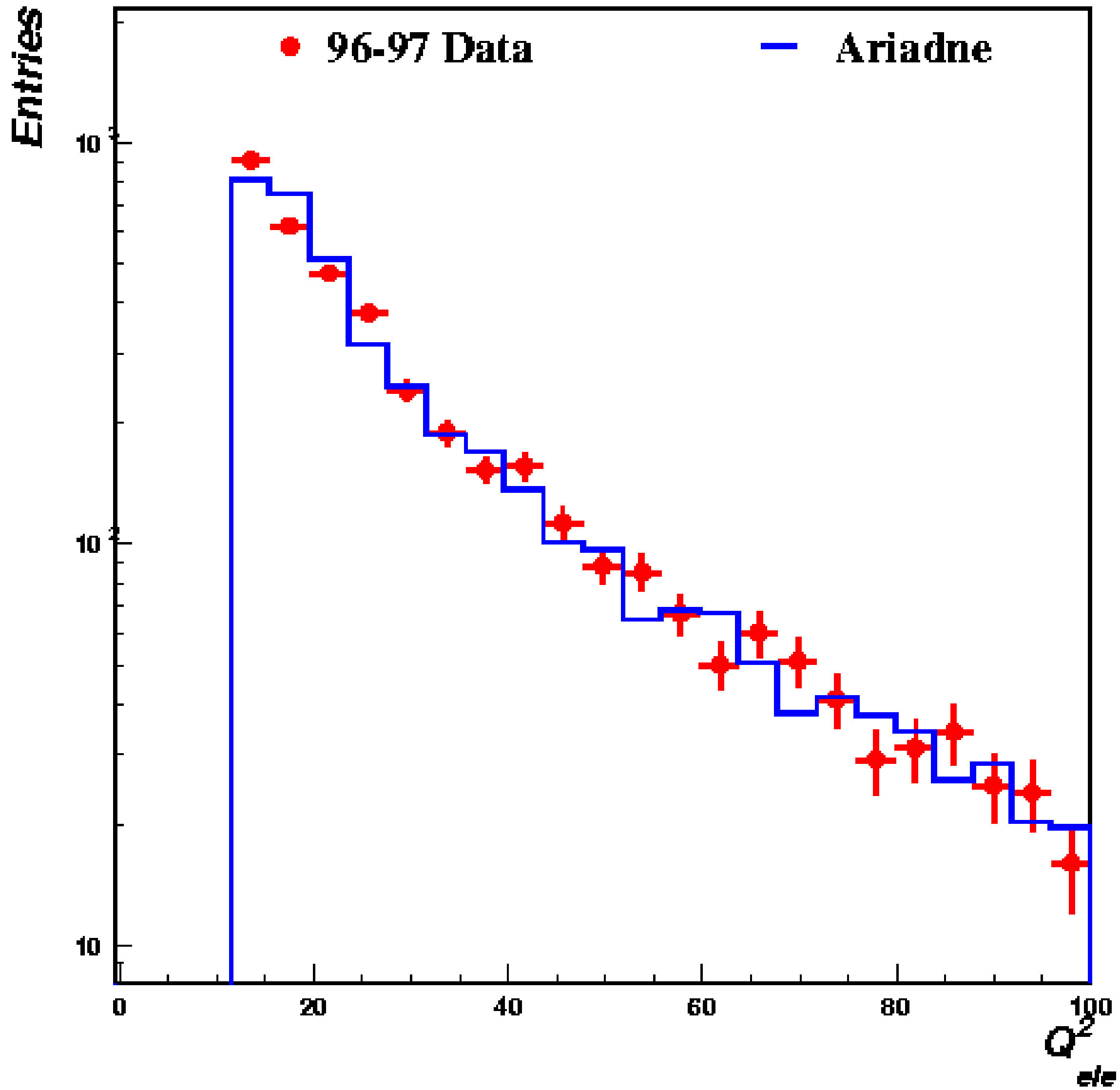
Position of Scattered Positron at RCAL



Important for reconstruction of Q^2

Cut: |x| or |y| > 15cm : Eliminates events close to beam pipe

Kinematics: Virtuality

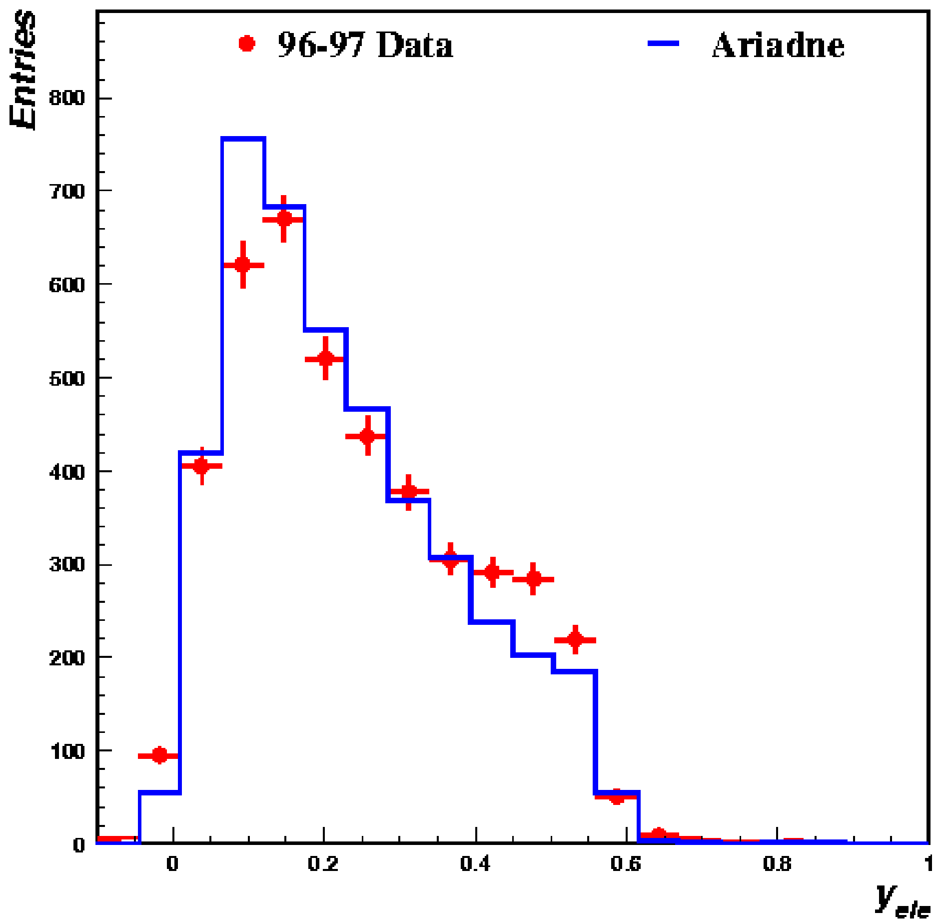


Q^2 electron method

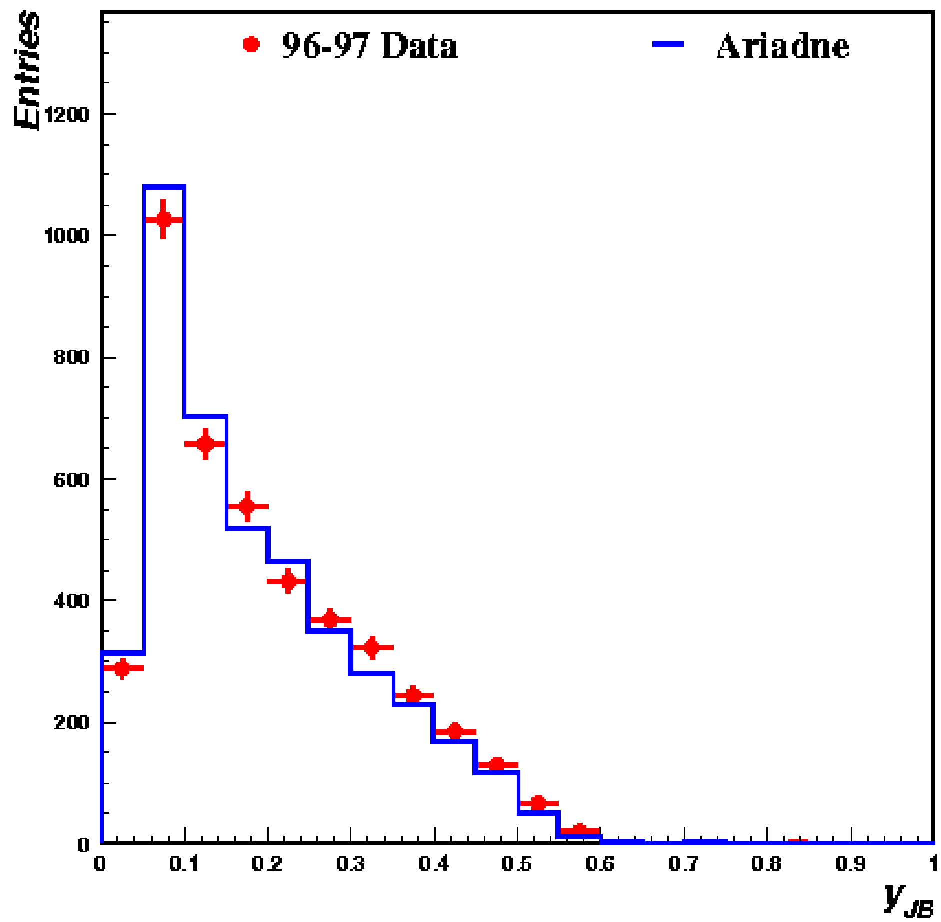
- Energy corrections not yet applied

Kinematics: Inelasticity

Y electron method

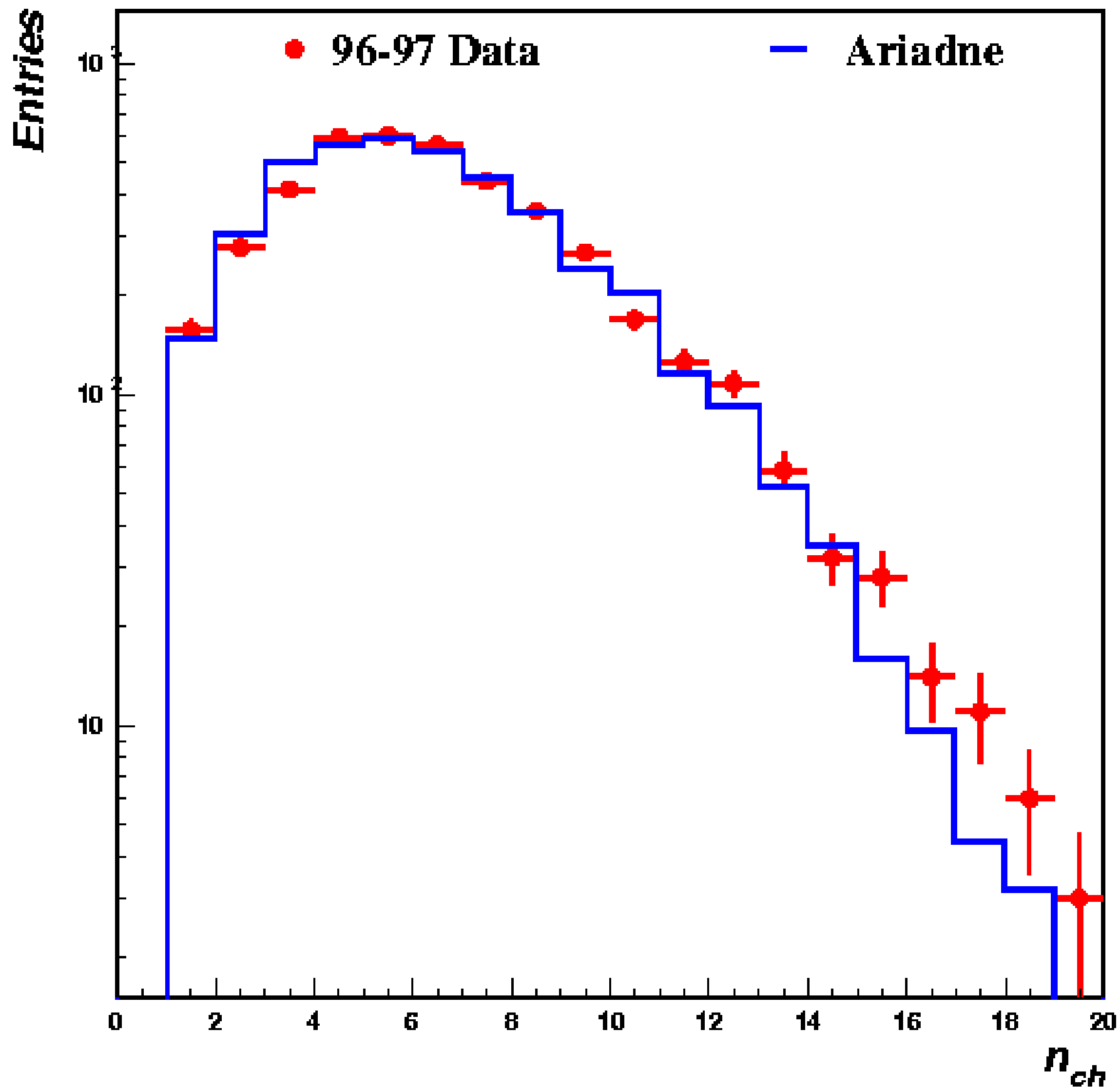


Y hadron method



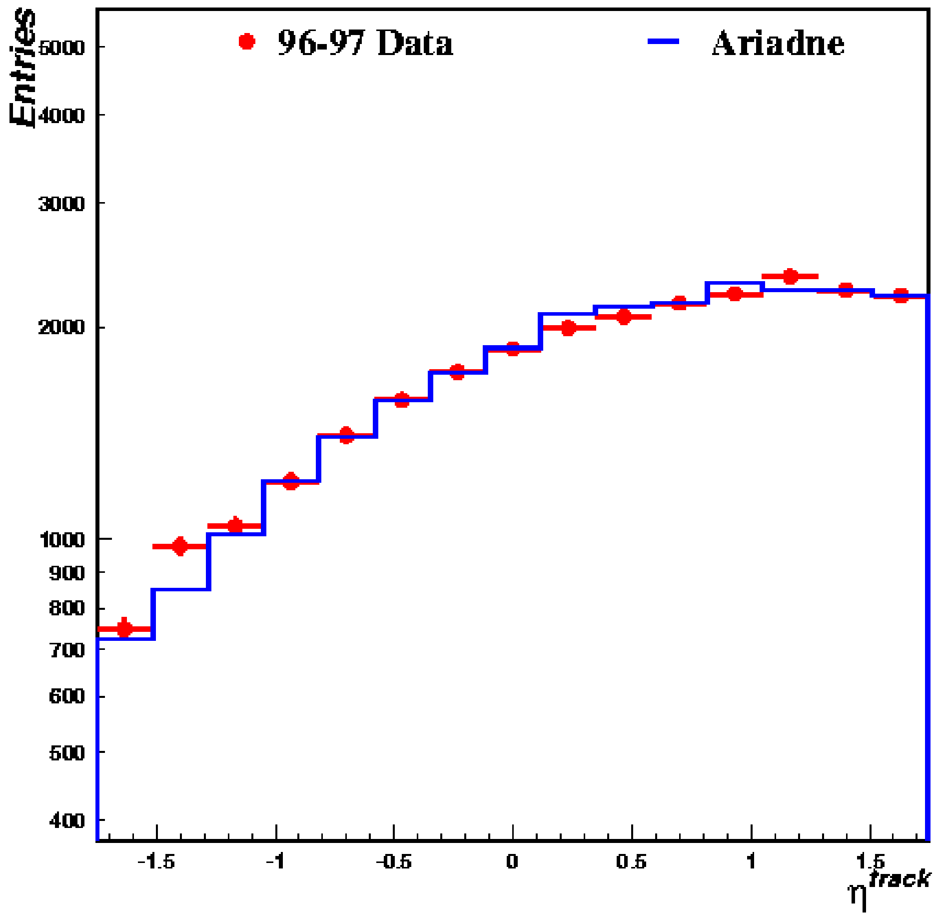
- needs electron energy corrections
- uses hadronic system variables

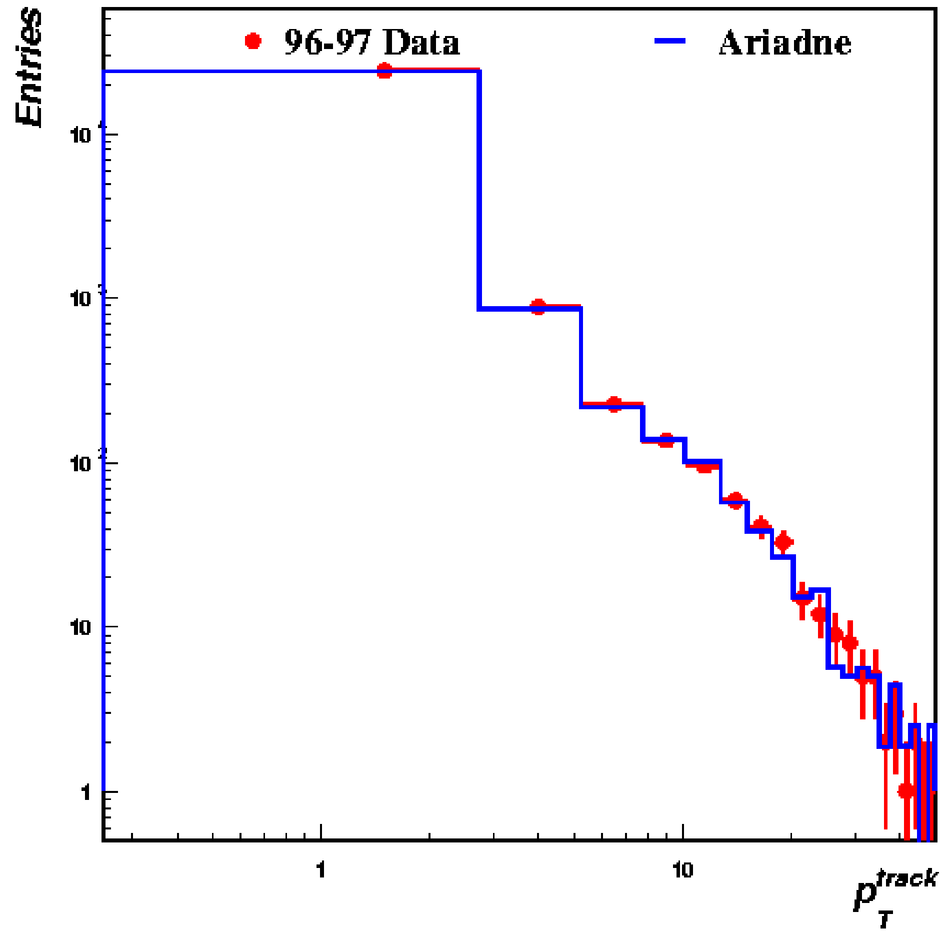
Tracking: # of Charged Tracks



- Number of tracks well described by Ariadne model over two orders of magnitude
- Validation of model & CTD tracking simulation

Tracking: η & p_T





First look at tracking, acceptable for use to correct for detector effects

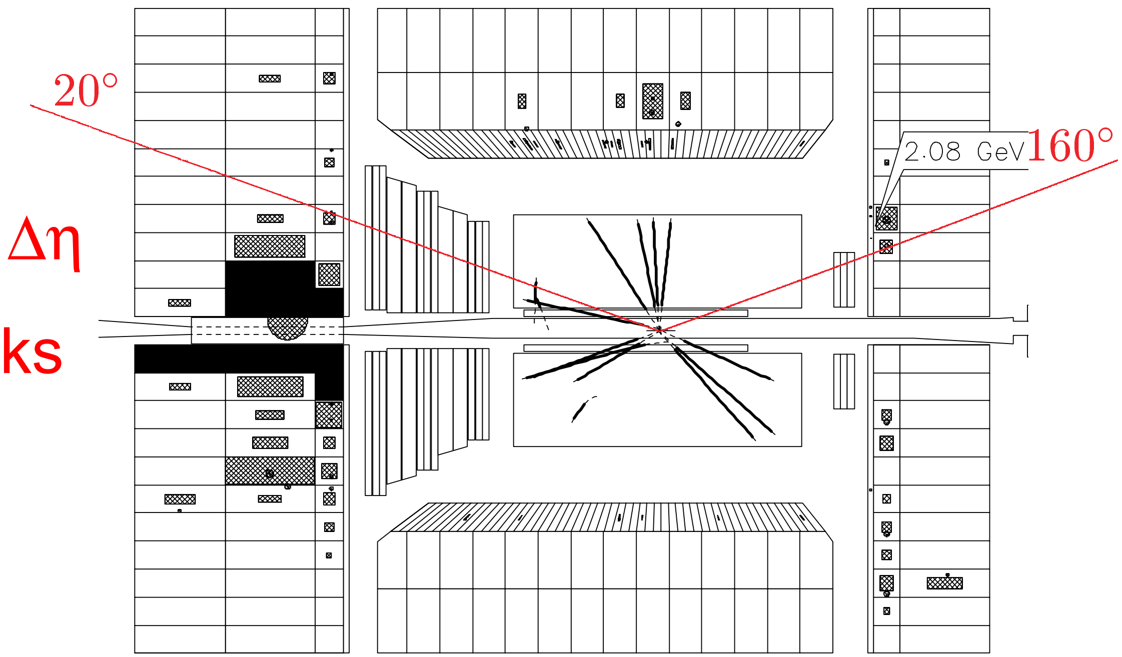
Effective Mass

$$M_{eff}^2 = (\sum_{i \neq e'} E^i)^2 - (\sum_{i \neq e'} p_x^i)^2 - (\sum_{i \neq e'} p_y^i)^2 - (\sum_{i \neq e'} p_z^i)^2$$

Study: $\langle n_{ch} \rangle$ vs. M_{eff}

CTD

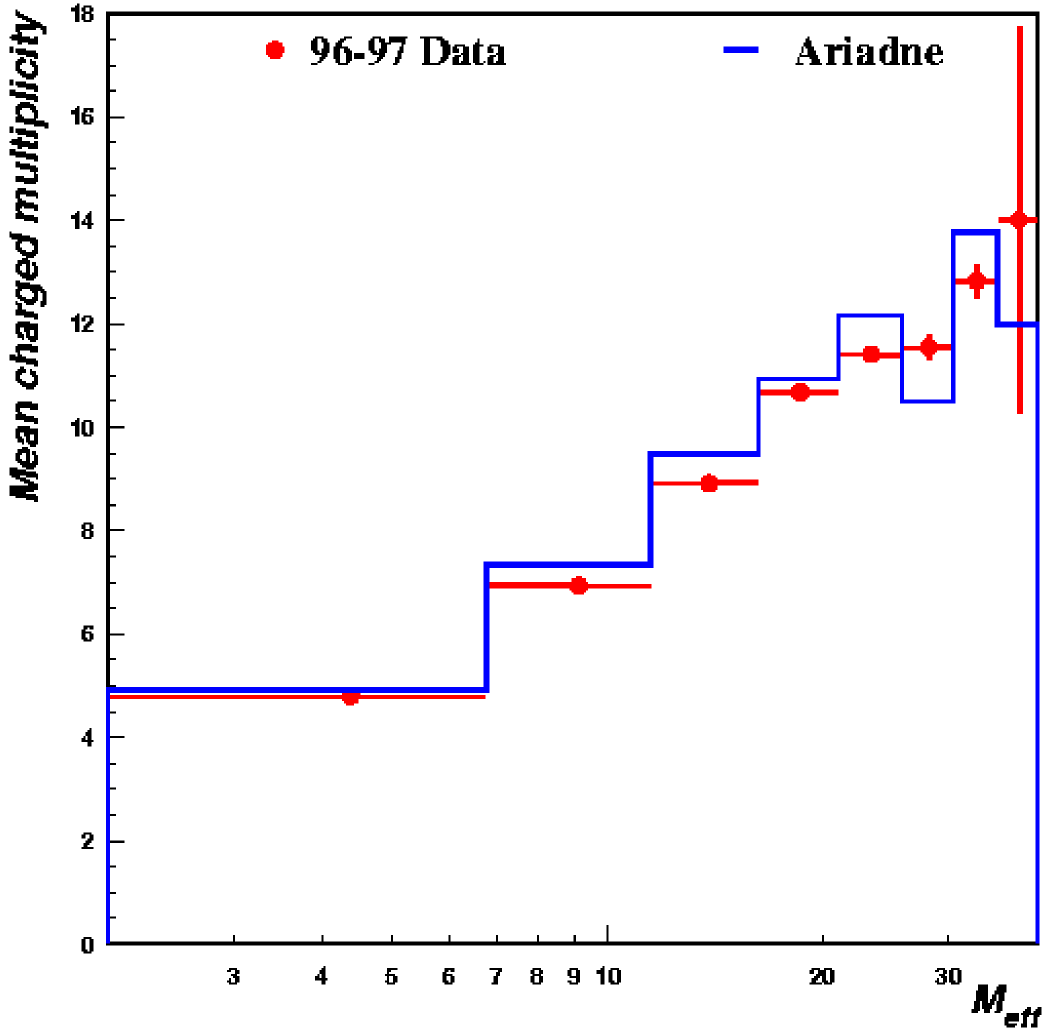
CAL within the CDT acceptance



- Hadronic final state within Δη
- Charged part seen as tracks
- Energy measured by calorimeter

Mean Charged Multiplicity vs. M_{eff}

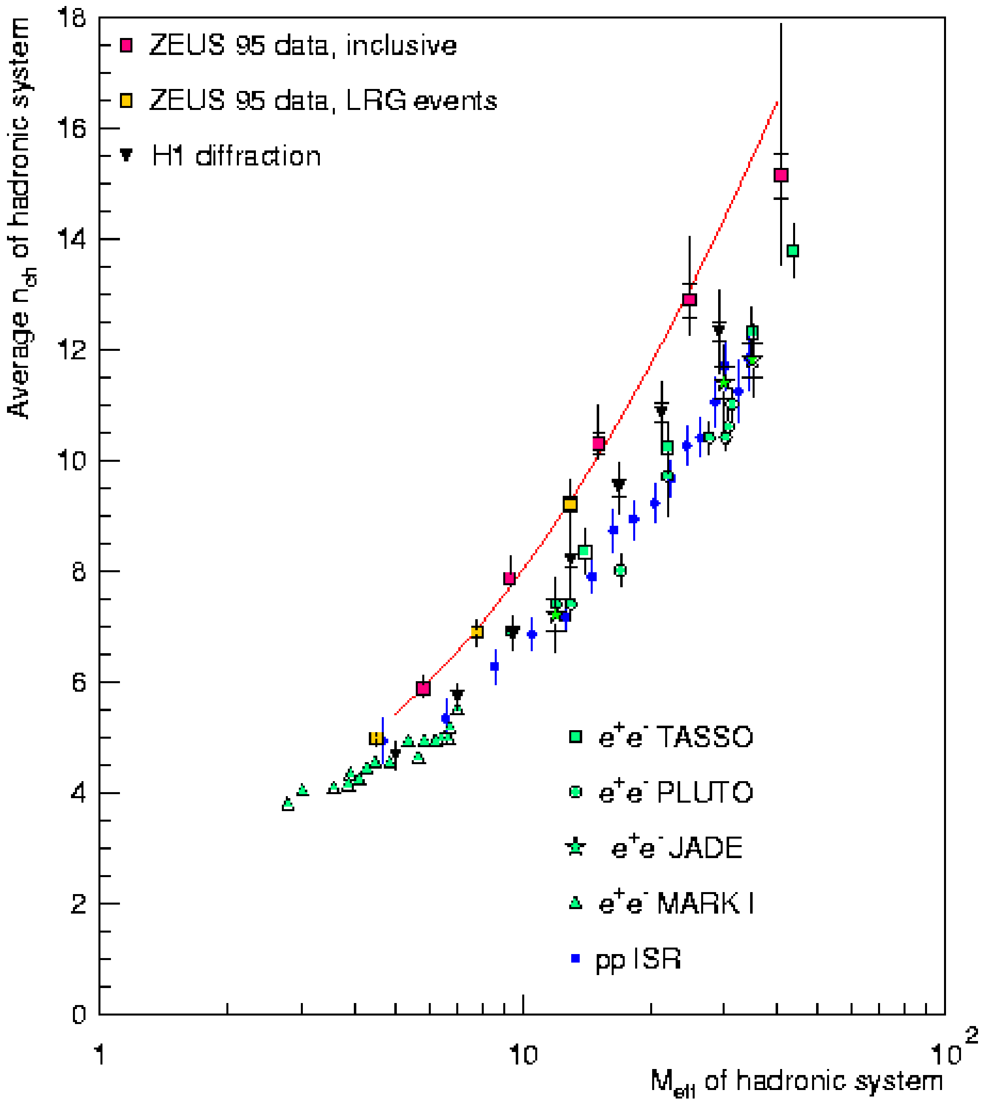
Average number of charged particles vs. effective mass



- Reasonable agreement for first look at partial data sample, statistics limited at high M_{eff}
- Uncorrected ZEUS '96 data compared to Ariadne
- proportional to ln (M_{eff})

ZEUS Measurement

- Investigation of degree of universality in particle production
- $\langle n_{ch} \rangle$ consistent with linear dependence vs. M_{eff}
- $\langle n_{ch} \rangle$ 15% above corresponding e^+e^-
- Understand color dynamics at the pre-hadronization stage at HERA



Summary

- First look at Multiplicity Distributions in DIS at HERA using 1996 data
- DIS data sample compared to pQCD + parton showers + hadronization models predictions
- Event kinematics and tracking well understood and simulated

Plan

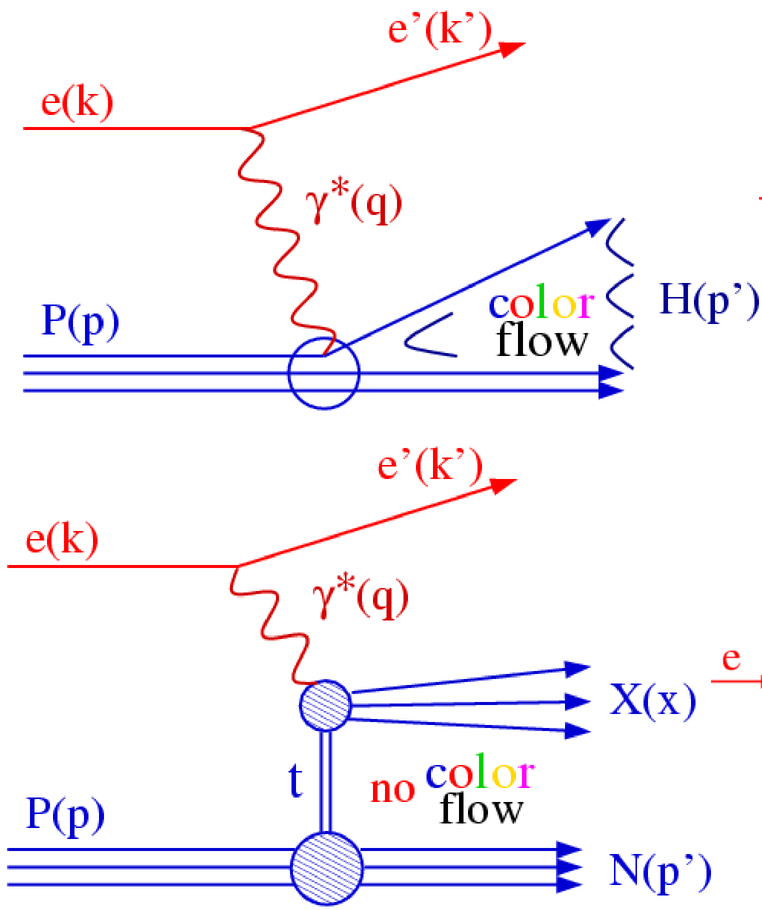
- Increase statistics of data and simulation events
  - include all 96 and 97 data
- Investigate diffractive effects
- Measure multiplicities vs. Q^2 in the current and target region of the Breit frame
- Measure momentum spectra
- Compare different models for parton showers and hadronization to data
- Evaluate systematic uncertainties

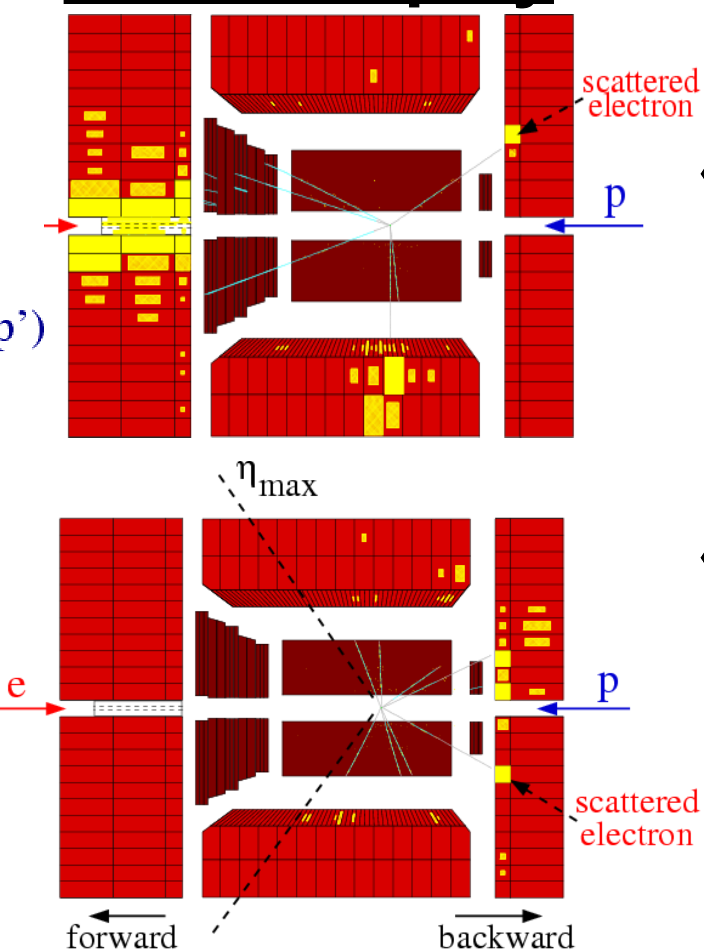
Diffraction & η_{max}

Diagram

Event Display

$$\eta = -\ln(\tan(\frac{\theta}{2}))$$





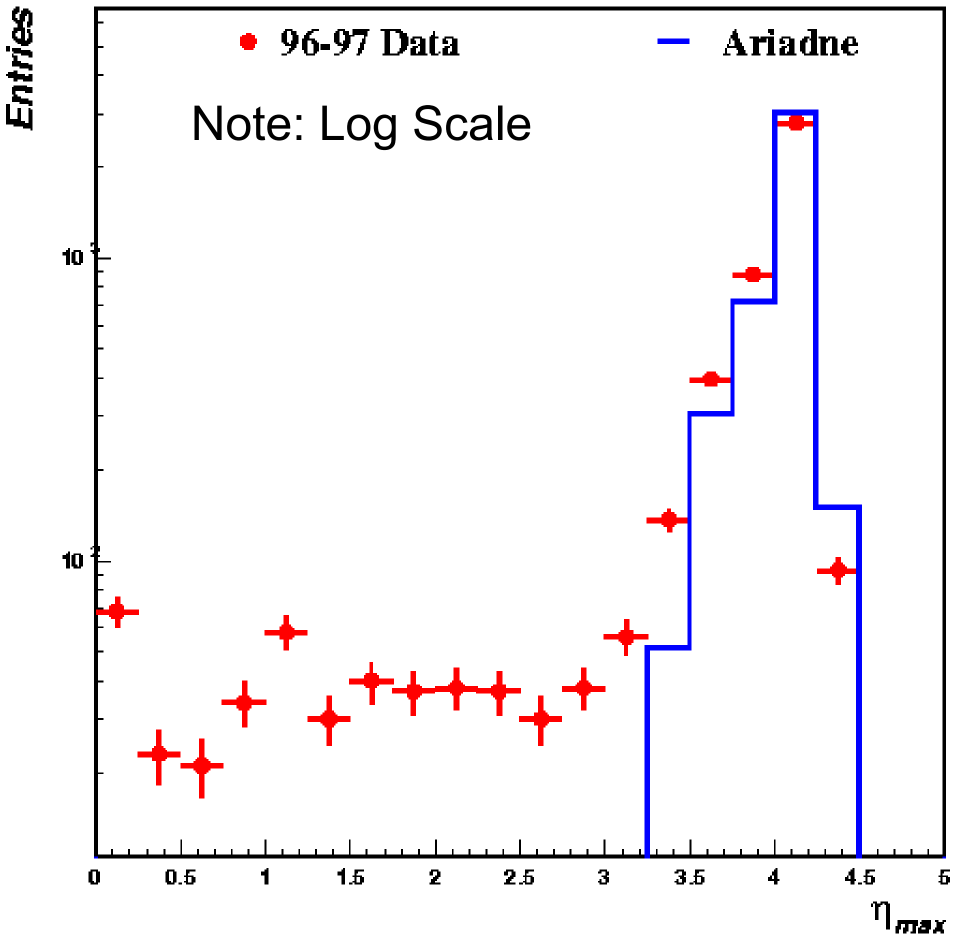
⬅ **DIS**

⬅ **Diffraction**

- 5-10% of events
- Not modeled by Ariadne

Diffractive events expected at large angles (low η_{max})

Look for Diffractive Events



Normalized above η_{max} = 3.2

- Only η_{max}>3.2 is described by Ariadne
- ~500 events out of total data sample (4798 events)
- These are diffractive events that are not simulated by the Ariadne Monte Carlo

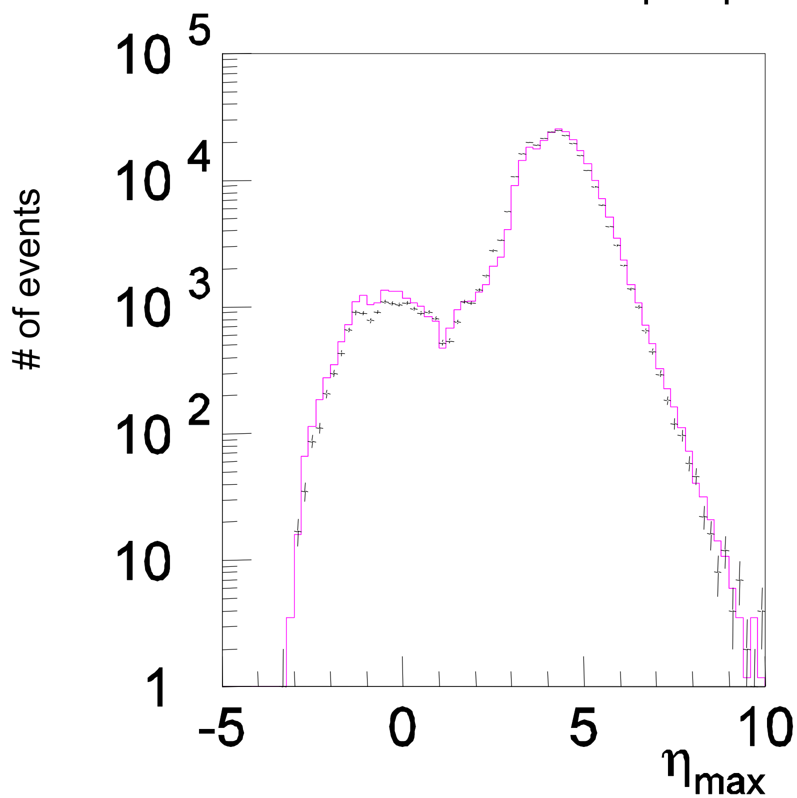
Solutions:

- (fast) Cut out diffractive events
- (better) Use mixture of diffractive & non-diffractive monte carlo.
- will do both

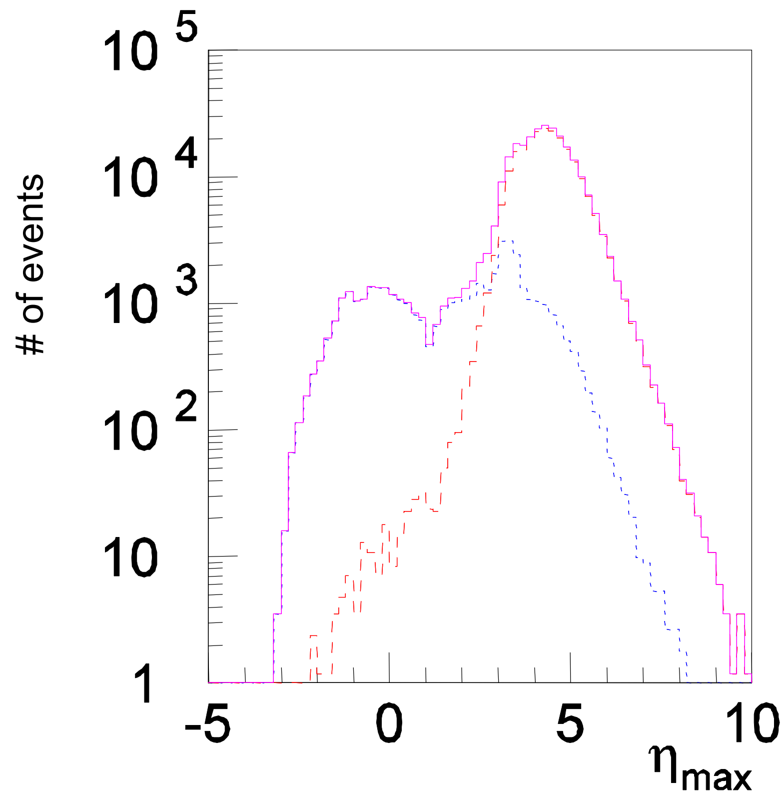
Mix Diffractive & Non-Diffractive Models

- RapGap contains diffraction; Ariadne does not
- A fit to a superposition of RapGap and Ariadne η_{max} distributions, determines relative contribution of each

RapGap + Ariadne 10<Q2<1200



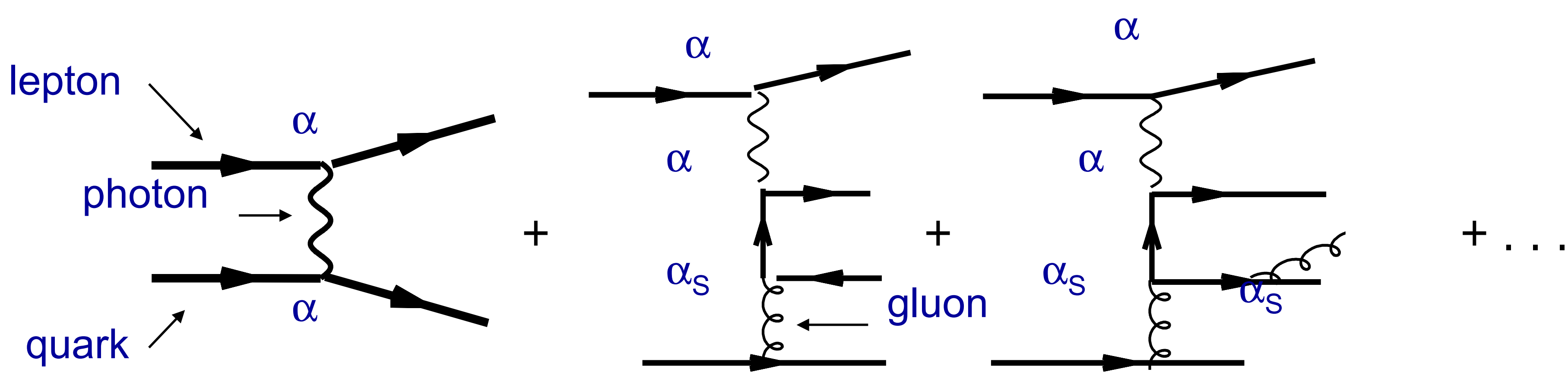
Data & fitted MC mixture



16% RAPGAP+ 84% Ariadne

pQCD series

Perturbative QCD (pQCD) series:



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

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