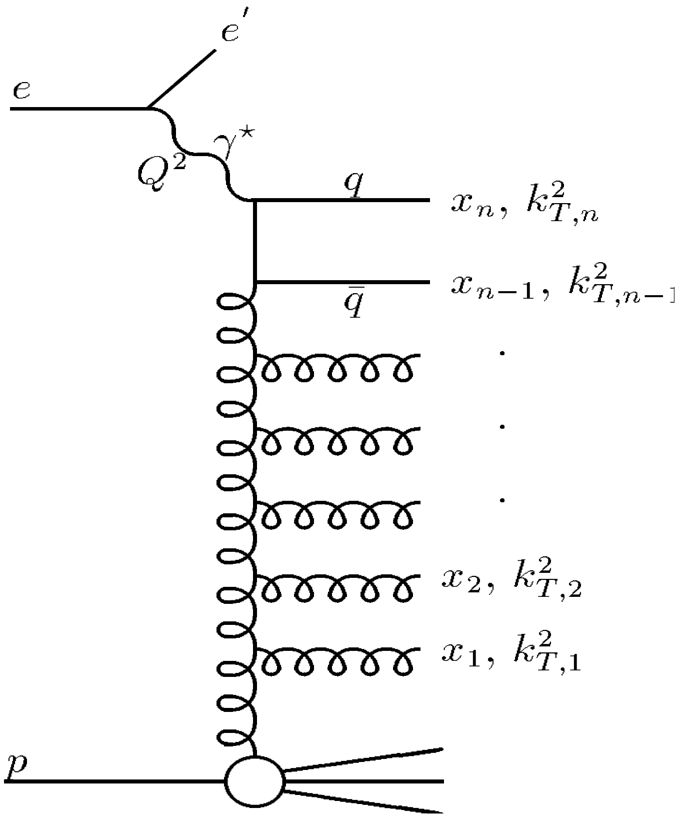
Search for BFKL Dynamics in Deep Inelastic Scattering at HERA

Preliminary Examination



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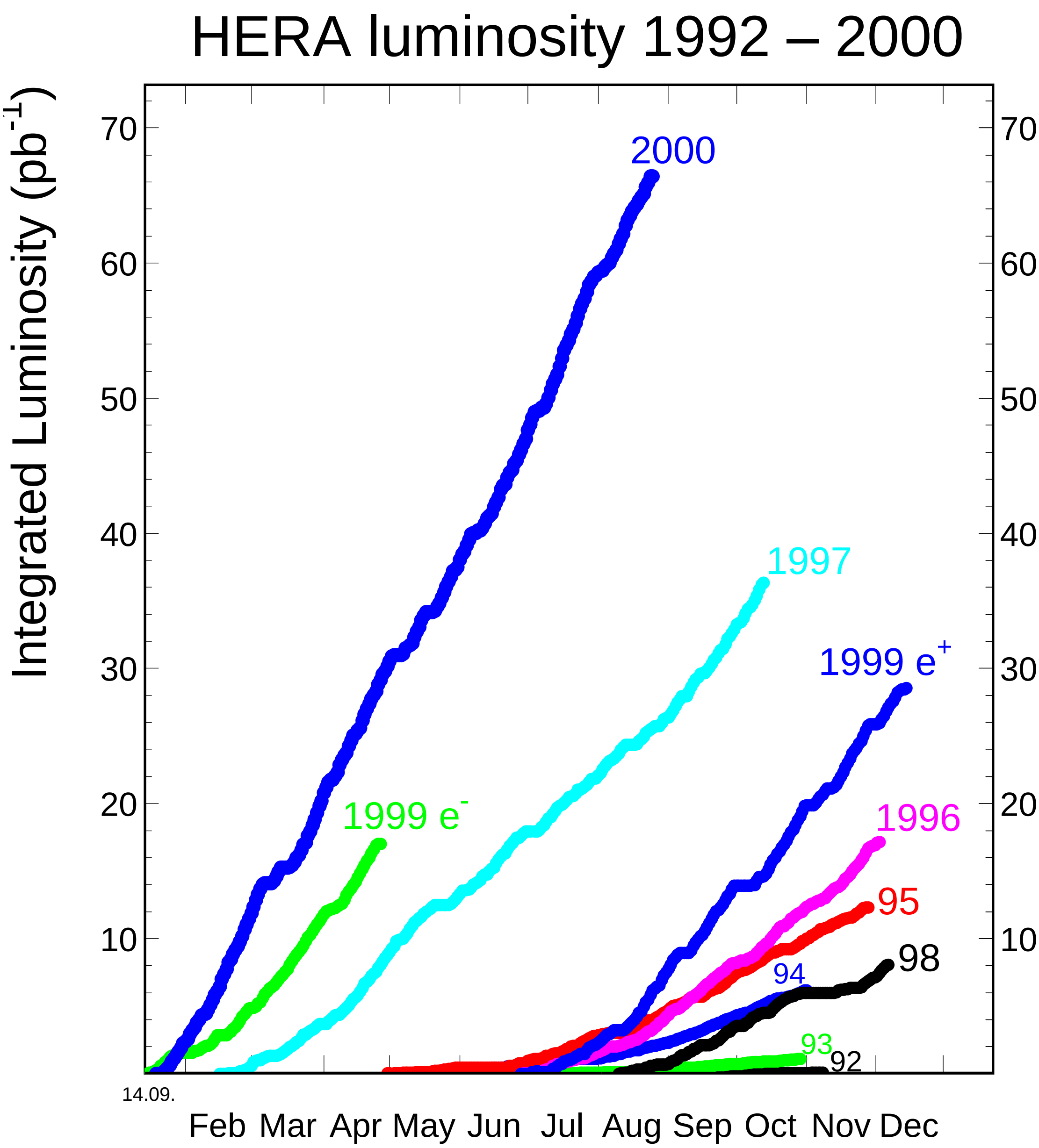
HERA Collider

HERA: an electron−proton accelerator at DESY

- 820/920 GeV proton
- 27.5 GeV electrons or positrons
- 300/318 GeV center of mass energy
- 220 bunches, 96 ns crossing time
- Instantaneous luminosity: 1.8 x 10^{31} $cm^{-2}s^{-1}$
- currents: ~90mA protons, ~40mA positrons

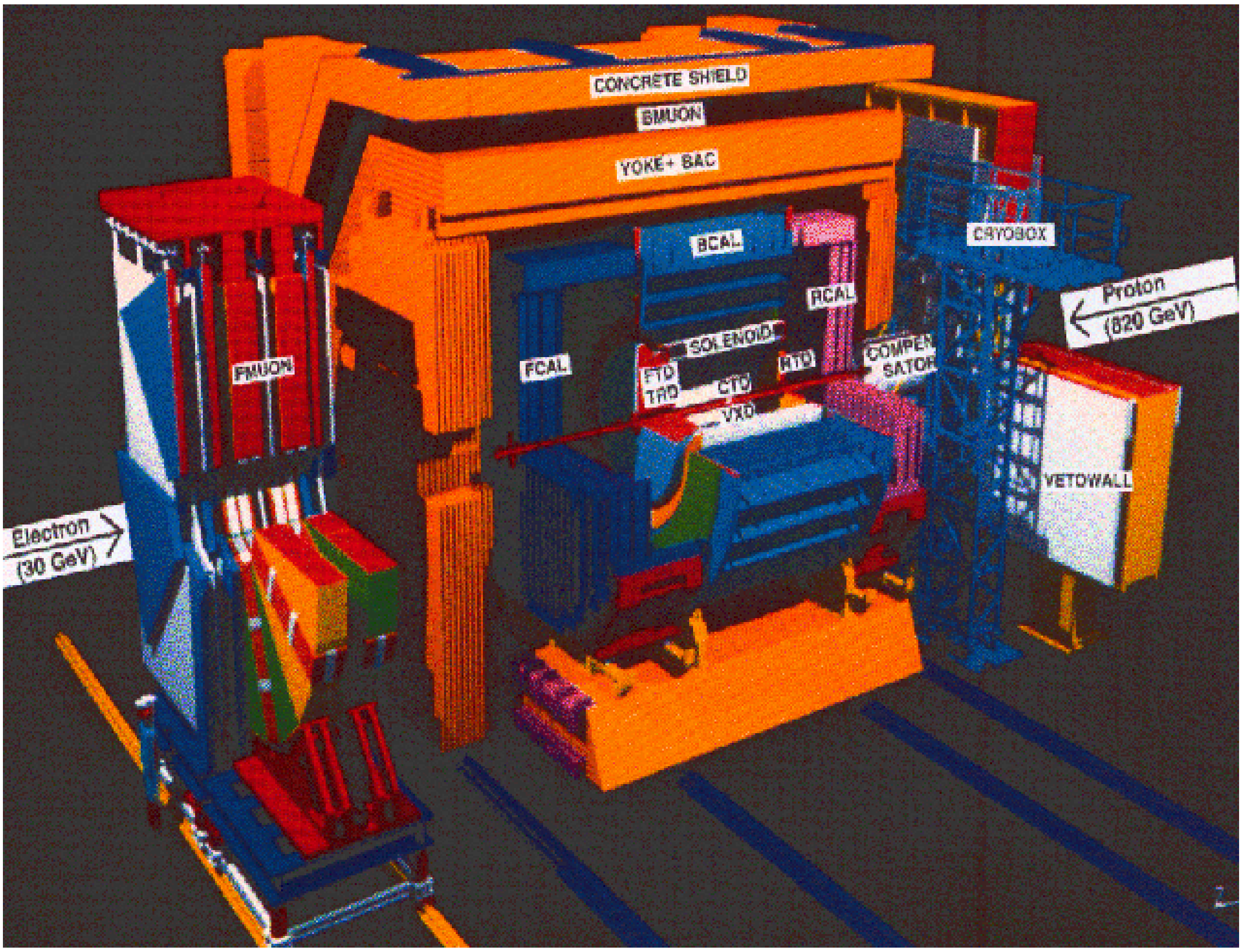
Luminosity



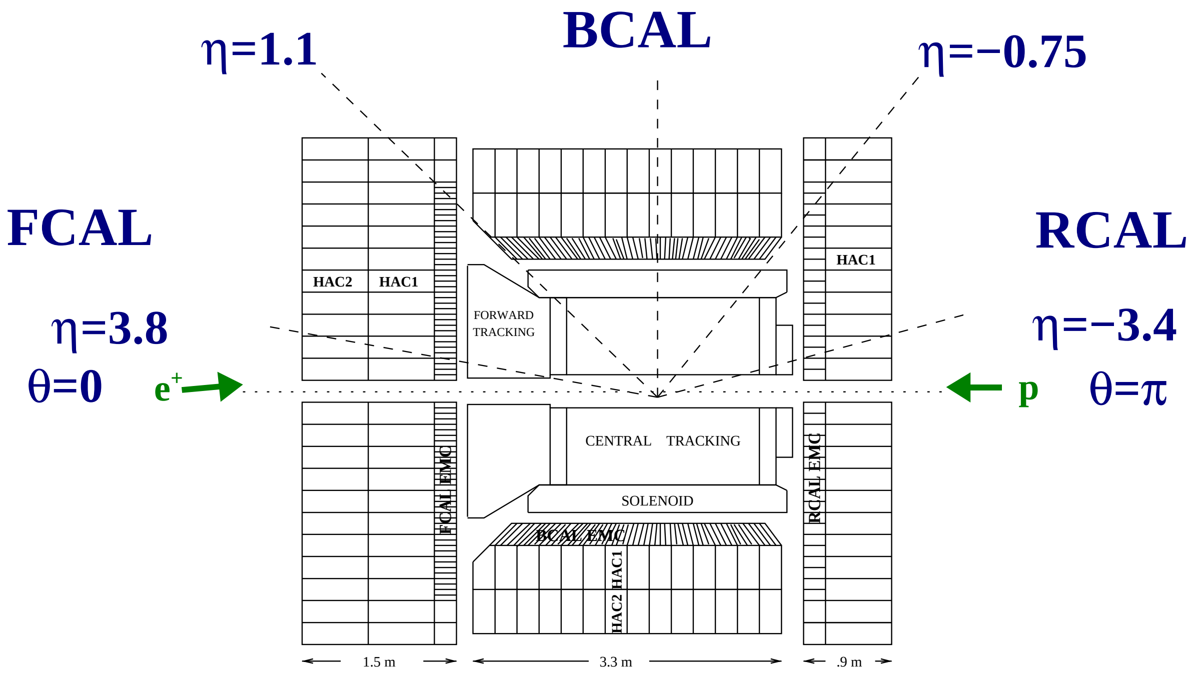
- total integrated luminosity: 185 pb^{-1}
- currently undergoing luminosity upgrade
  - 1 fb^{-1} expected by end of 2005

⇒ significant yearly improvement

Zeus Detector



Zeus Geometry



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

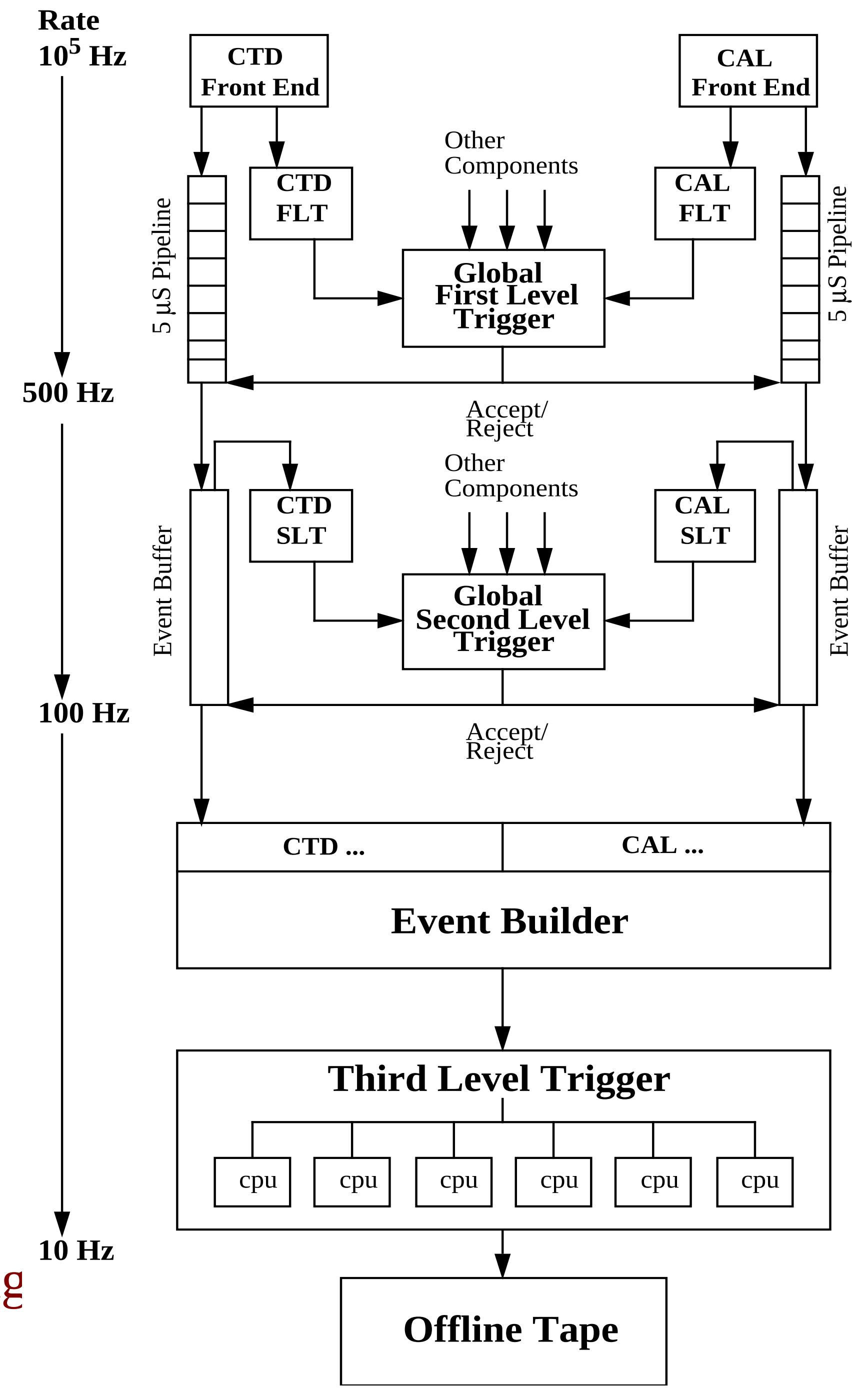
- Calorimeter: alternating layers of depleted uranium and scintillator.
  - 99.7% solid angle coverage
  - Energy resolution: $35\%/\sqrt{E}$ for hadronic section
    $18\%/\sqrt{E}$ for electromagnetic section

- Central Tracking Detector: drift chamber
  - 1.43 T solenoid
  - vertex resolution: 1mm transverse, 4mm in z

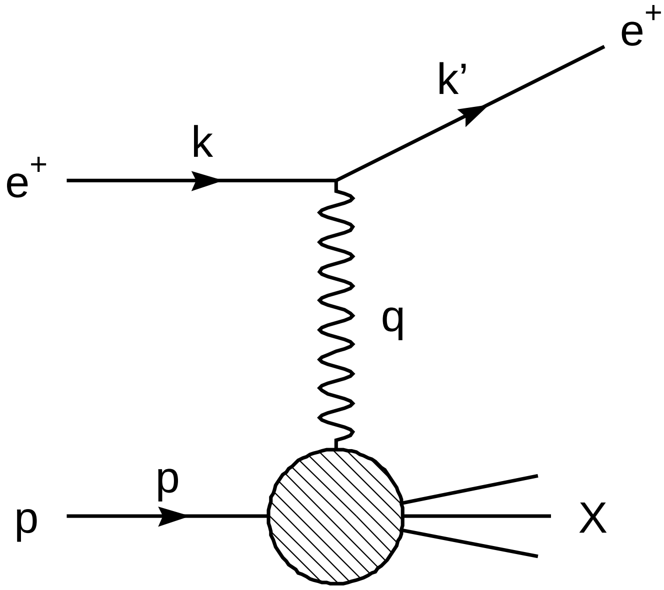
Zeus Trigger

- First level
  - dedicated hardware
  - no deadtime
  - global and regional energy sums
  - isolated muon and positron recognition
  - track quality information
- Second Level
  - timing cuts
  - $E-p_z$
  - simple physics filters
  - vertex information
- Third Level
  - full event information available
  - advanced physics filters
  - jet and electron finding

10^7 Hz crossing rate
10^5 Hz background rate
10 Hz physics rate



DIS Kinematics



$s^2 = (p+k)^2 \sim 4E_pE_e = (318\ \mathrm{GeV})^2$ center of mass energy

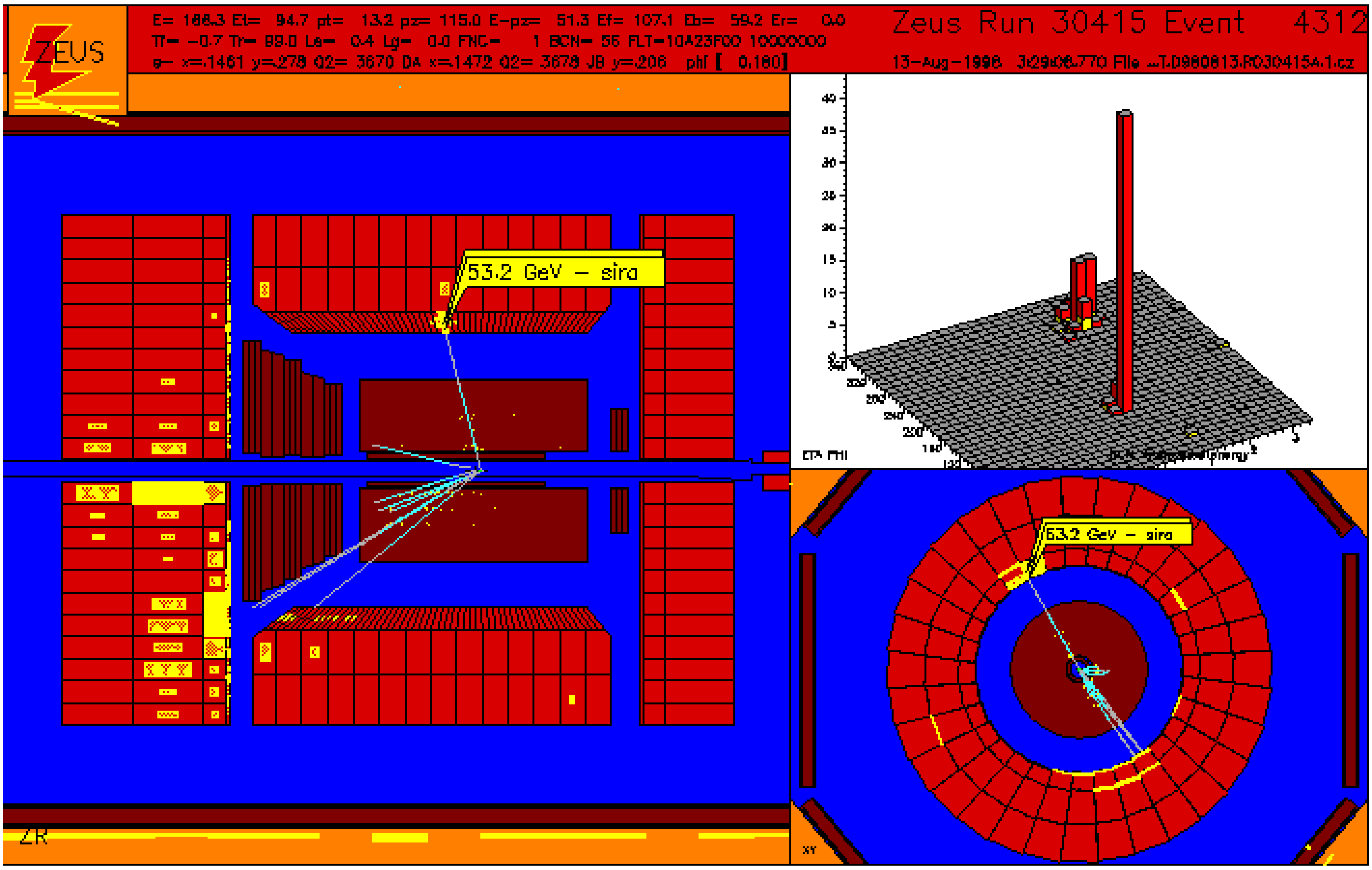
$Q^2 = -q^2 = -(k-k')^2$ the square of the four momentum transferred

$$x = \frac{Q^2}{2p\bullet q}$$ fraction of proton's momentum carried by the struck parton

$$y = \frac{p\bullet q}{p\bullet k}$$ fraction of positron's energy transferred to the proton in the proton's rest frame

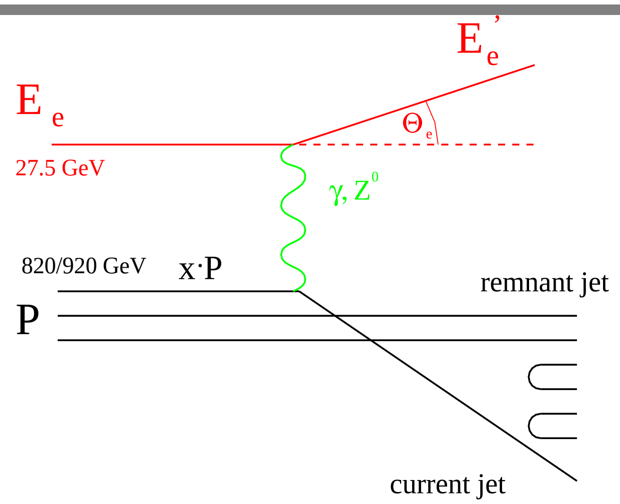
$Q^2 = sxy$

Deep Inelastic Scattering Event



$Q^2 \sim 3700$ $x \sim .15$ $y \sim .21$

Kinematic Reconstruction



- Electron Method − use scattered electron energy, angle

$$Q^2 = 2EE'(1+\cos\theta_e)$$

$$y = 1 - \frac{E'}{2E}(1-\cos\theta_e)$$

$$x = \frac{E}{P}\left(\frac{E'(1+\cos\theta_e)}{2E-E'(1-\cos\theta_e)}\right)$$

→ best resolution at high y and low Q^2

- Double Angle Method − use leptonic, hadronic angles

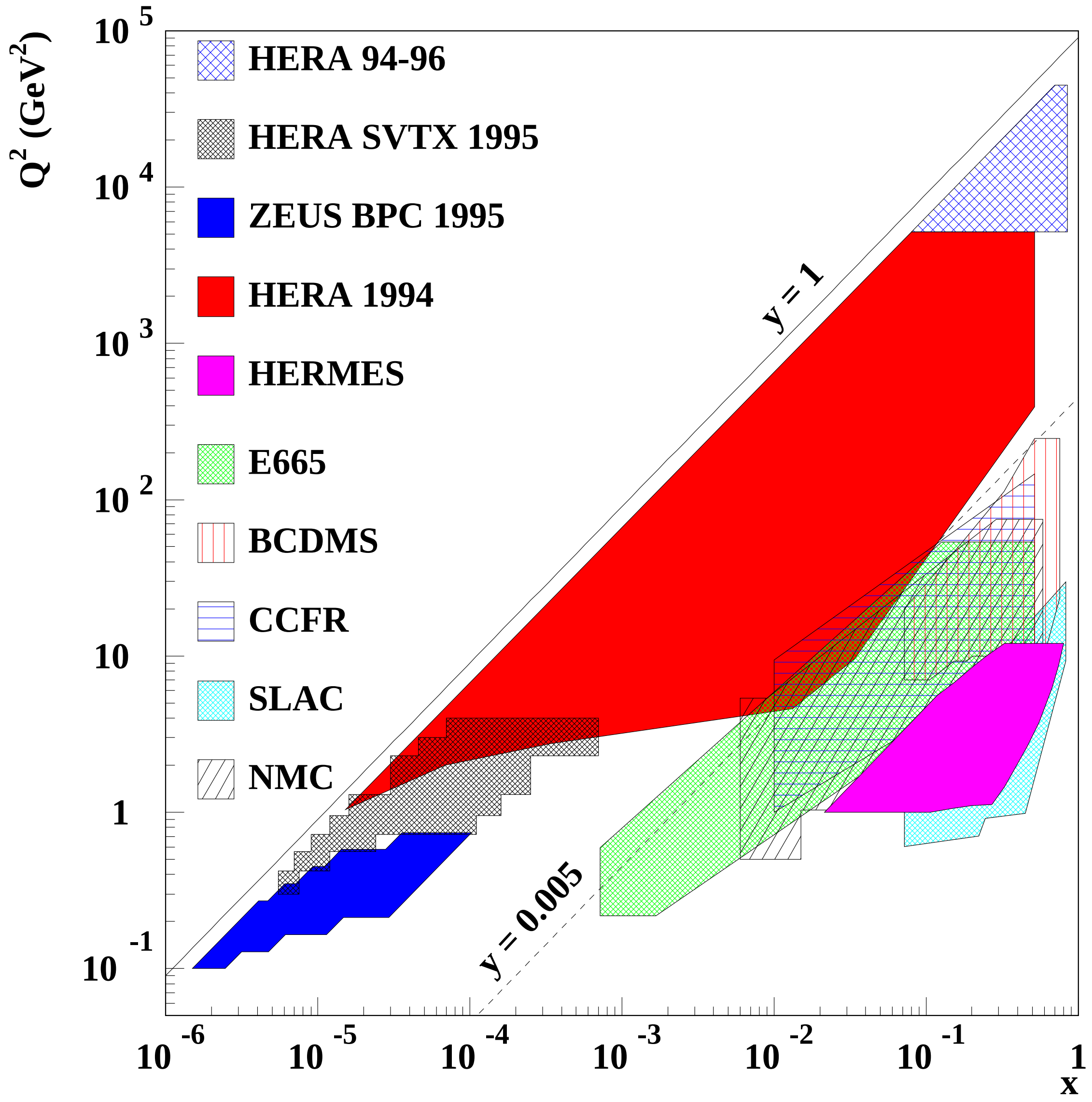
$$\cos\gamma_h = \frac{(\Sigma p_x)^2+(\Sigma p_y)^2-(\Sigma(E-p_z))^2}{(\Sigma p_x)^2+(\Sigma p_y)^2+(\Sigma(E-p_z))^2}$$

$$E'_{DA} = 2E\frac{\sin\gamma_h}{\sin\theta_e+\sin\gamma_h-\sin(\theta_e+\gamma_h)}$$

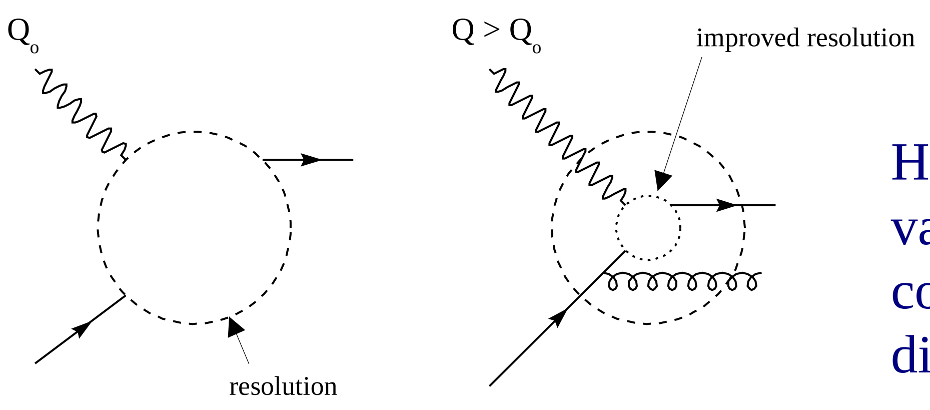
$$Q^2_{DA}=\frac{4E^2\sin\gamma_h(1+\cos\theta_e)}{\sin\gamma_h+\sin\theta_e-\sin(\theta_e+\gamma_h)} \quad y_{DA}=\frac{\sin\theta_e(1-\cos\gamma_h)}{\sin\gamma_h+\sin\theta_e-\sin(\theta_e+\gamma_h)} \quad x_{DA}=\frac{Q^2_{DA}}{s y_{DA}}$$

→ depends only on energy ratios ⇒
less sensitive to energy scale uncertainties

Kinematic Range

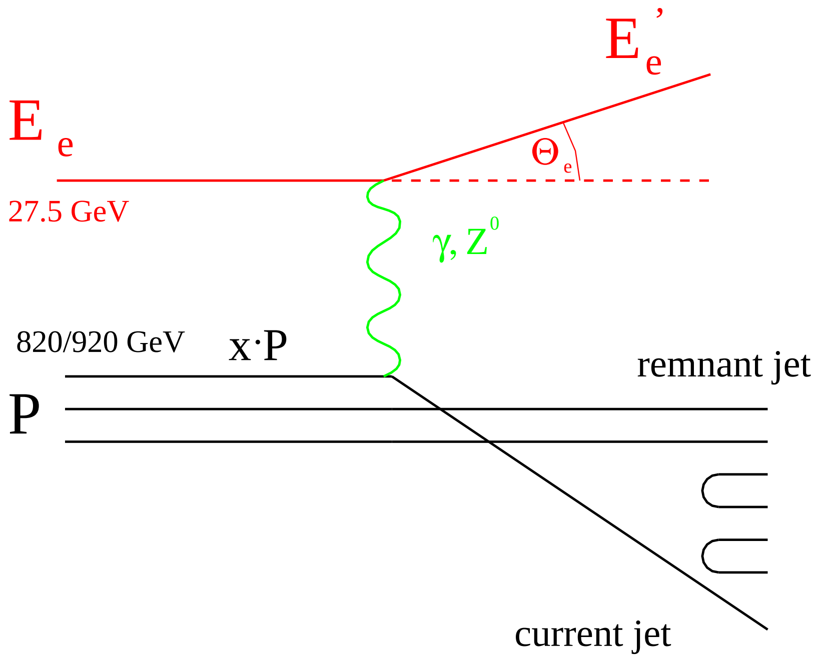


Q~1/λ describes our ability to "see" inside the proton.



HERA reaches values of Q that correspond to distances of ~.001 fm.

DIS Cross Section



For neutral current processes, the differential cross section is:

$$\frac{d^2\sigma(e^\pm p \rightarrow e^\pm X)}{dx\, dQ^2} = \frac{2\pi\alpha^2_{em}}{xQ^4}\left[Y_+ F_2(x,Q^2) \mp Y_- xF_3(x,Q^2) - y^2 F_L(x,Q^2)\right]$$

$$Y_\pm = 1 \pm (1-y)^2$$

The structure function F_2 parameterizes the interaction between transversely polarized photon and spin ½ partons.

The structure function F_L parameterizes the interaction between longitudinally polarized photons and the proton.

The structure function xF_3 is the parity violating term due to the presence of the weak interaction.

Quark Parton Model

The structure function F_2 can be expressed in terms of the quark distributions in the proton:

$$F_2(x,Q^2) = \sum_{\text{quarks}} A_q(Q^2) \cdot (xq(x,Q^2) + x\bar{q}(x,Q^2))$$

parton distribution functions

$q(x,Q^2)$ and $\bar{q}(x,Q^2)$, called parton distribution functions, are the average number of partons with momentum fraction between x and x+dx inside the proton.

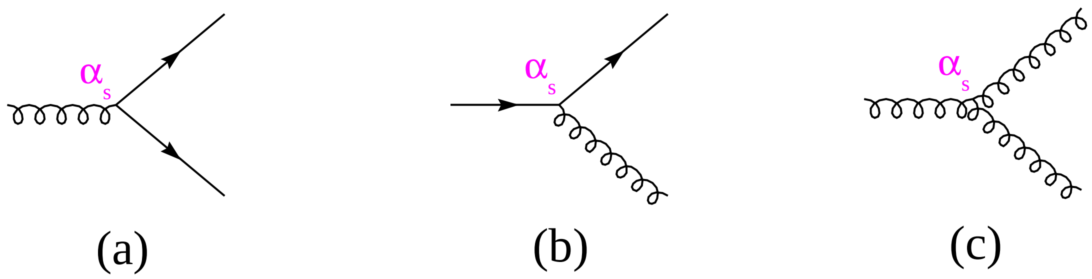
For $Q^2<M_Z^2$, the coefficient $A_q(Q^2)$ approaches e_q^2, the charge of the quarks, and F_2^{NC} reduces to F_2^{EM}.

- Naive Quark Parton Model
  - No interaction between the partons
  - Proton structure function independent of Q^2
  - Interpretation: partons are point−like particles

$\Rightarrow$ Bjorken Scaling $F_2(x,Q^2) \rightarrow F_2(x)$, $F_L=0$

QCD

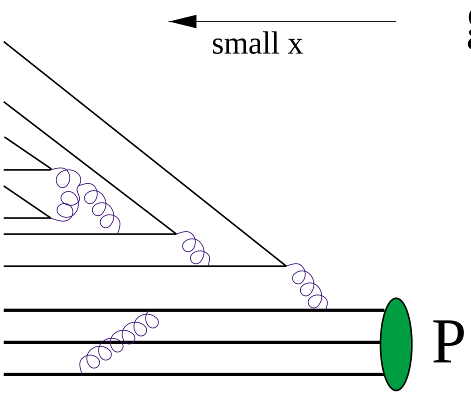
Quarks only account for half of the proton’s momentum
$\rightarrow$ introduce gluons



The relevant strong interactions are given by splitting functions, which are related to the probabilities that

(a) a gluon splits into a quark−antiquark pair
(b) a quark radiates a gluon
(c) a gluon splits into a pair of gluons

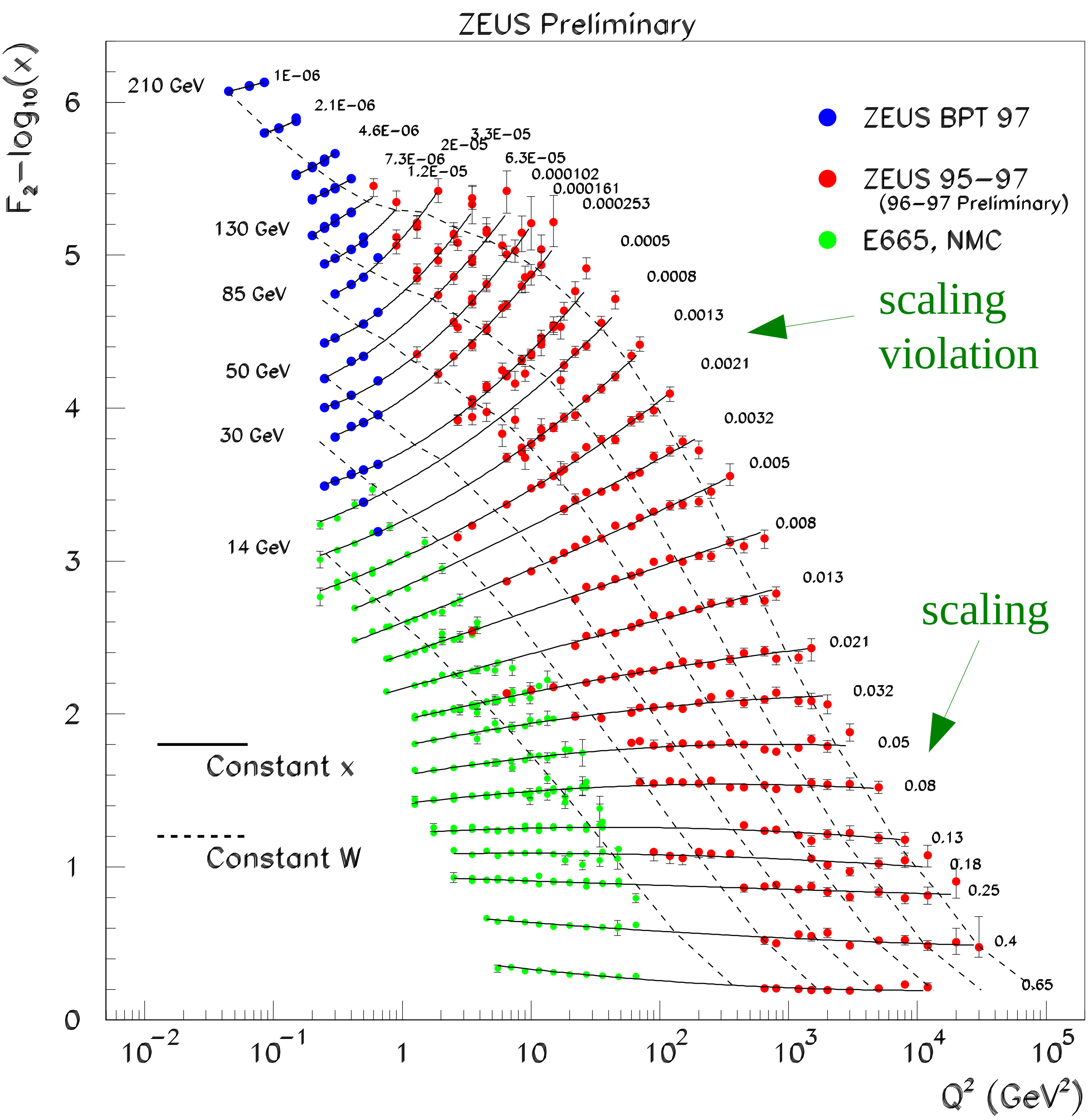
Prediction: presence of gluons will break Bjorken scaling



gluon driven scaling violation

Parton−parton interactions are mediated by gluons, generating transverse momentum of the partons.

Scaling Violation



- gluon density can be extracted from fits of F_2 along lines of constant x $g(x,Q^2) \sim \frac{dF_2(x,Q^2)}{d\ln Q^2}$
- gluons account for nearly half the momentum of the proton

QCD Evolution − DGLAP

A powerful mechanism in QCD is the ability to predict the PDF at a selected x and Q^2, given an initial parton density.

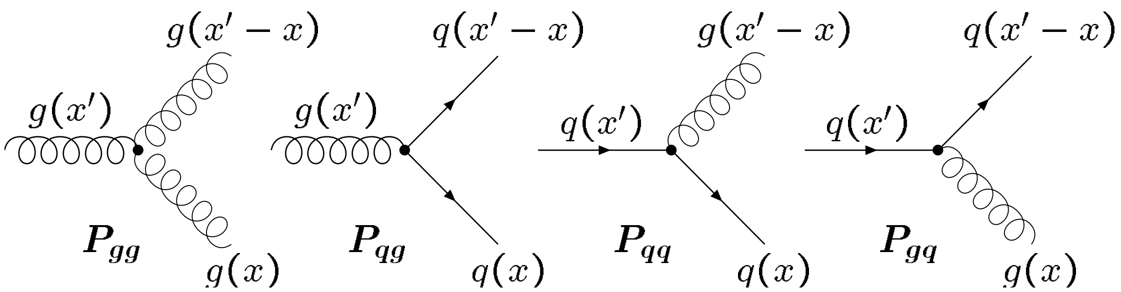
The DGLAP equations give the quark and gluon densities in the proton as follows:

$$\frac{dq_i(x,Q^2)}{d\,lnQ^2}=\frac{\alpha_s(Q^2)}{2\pi}\int_x^1\frac{dz}{z}[q_i(y,Q^2)P_{qq}(\frac{x}{z})+g(y,Q^2)P_{qg}(\frac{x}{z})]$$

splitting functions
−calculable by QCD

$$\frac{dg(x,Q^2)}{d\,lnQ^2}=\frac{\alpha_s(Q^2)}{2\pi}\int_x^1\frac{dz}{z}[\sum q_i(y,Q^2)P_{gq}(\frac{x}{z})+g(y,Q^2)P_{gg}(\frac{x}{z})]$$

The splitting functions are the probabilities for a quark or gluon to split into a pair of partons.



In the evolution of the PDF’s, there are terms proportional to $\ln Q^2$, $\ln(1/x)$, and $\ln Q^2 \ln(1/x)$.

DGLAP Approximation:

- sums terms $\ln Q^2$, $\ln Q^2 \ln(1/x)$
- limited range of validity

→ $\alpha_s(Q^2)\ln(Q^2)\sim O(1)$ $\alpha_s(Q^2)\ln(\frac{1}{x})\ll 1$

Dijet Processes

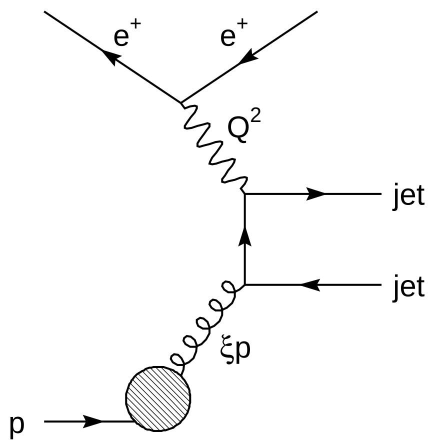
Direct measurement of the gluon distribution

− how well does perturbative QCD and DGLAP evolution describe events with jets?

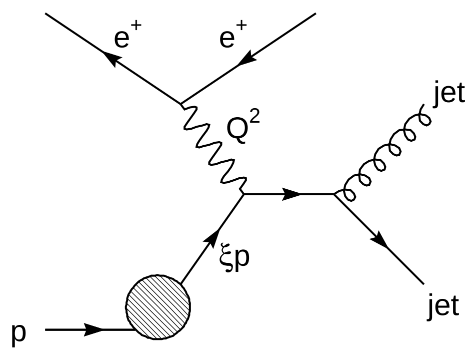
- investigate dijet production in DIS
- kinematic range easily accesible at HERA

Leading Order QCD Diagrams:

Boson−Gluon Fusion



QCD Compton



Now the fraction of the proton's momentum carried by the parton is:

$$\xi = x\left(1 + \frac{M_{jj}^{2}}{Q^{2}}\right)$$

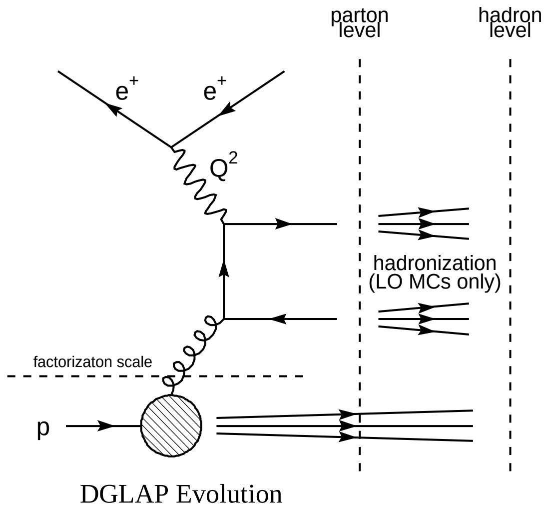
M_{jj} = dijet mass

LO Monte Carlo Models

"Monte Carlos" are event generators that attempt to reproduce theoretically predicted cross section distributions.

Dijet leading order monte carlo models include:

- LO matrix elements for two parton final state
- higher order effects
  - parton showers
- non−perturbative effects
  - hadronization

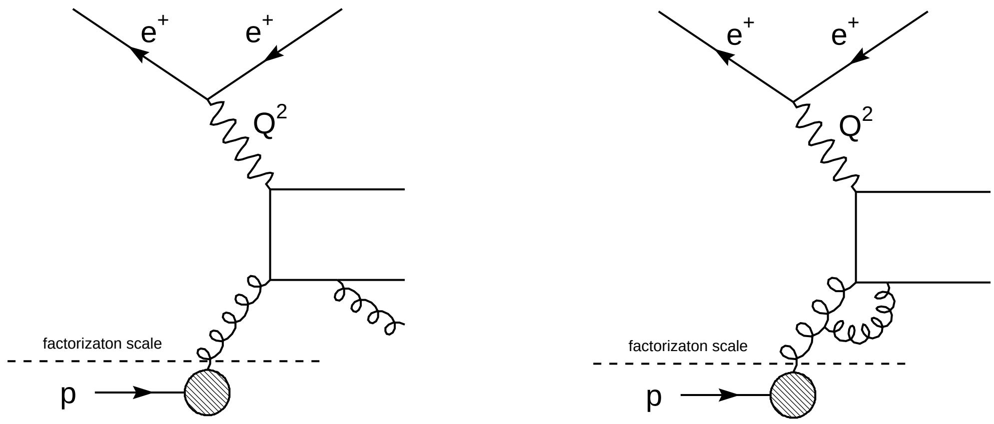


LO monte carlo programs: ARIADNE, LEPTO, HERWIG

- LO matrix element
  - ARIADNE, LEPTO and HERWIG use the Feynman inspired calculation of the matrix element
- Parton Showers
  - LEPTO, HERWIG use parton showers that evolve according to the DGLAP Equation
  - ARIADNE uses the color dipole model, in which each pair of partons is treated as an independent radiating dipole.
- Hadronization
  - LEPTO, ARIADNE use the Lund String Model
  - HERWIG uses Cluster Fragmentation

NLO Calculations

At next to leading order, a single gluon emission is included in the dijet final state



Next to leading order calculations include:

- matrix elements for three parton final states
  - soft/collinear gluon emissions
- virtual loops

They do not include:

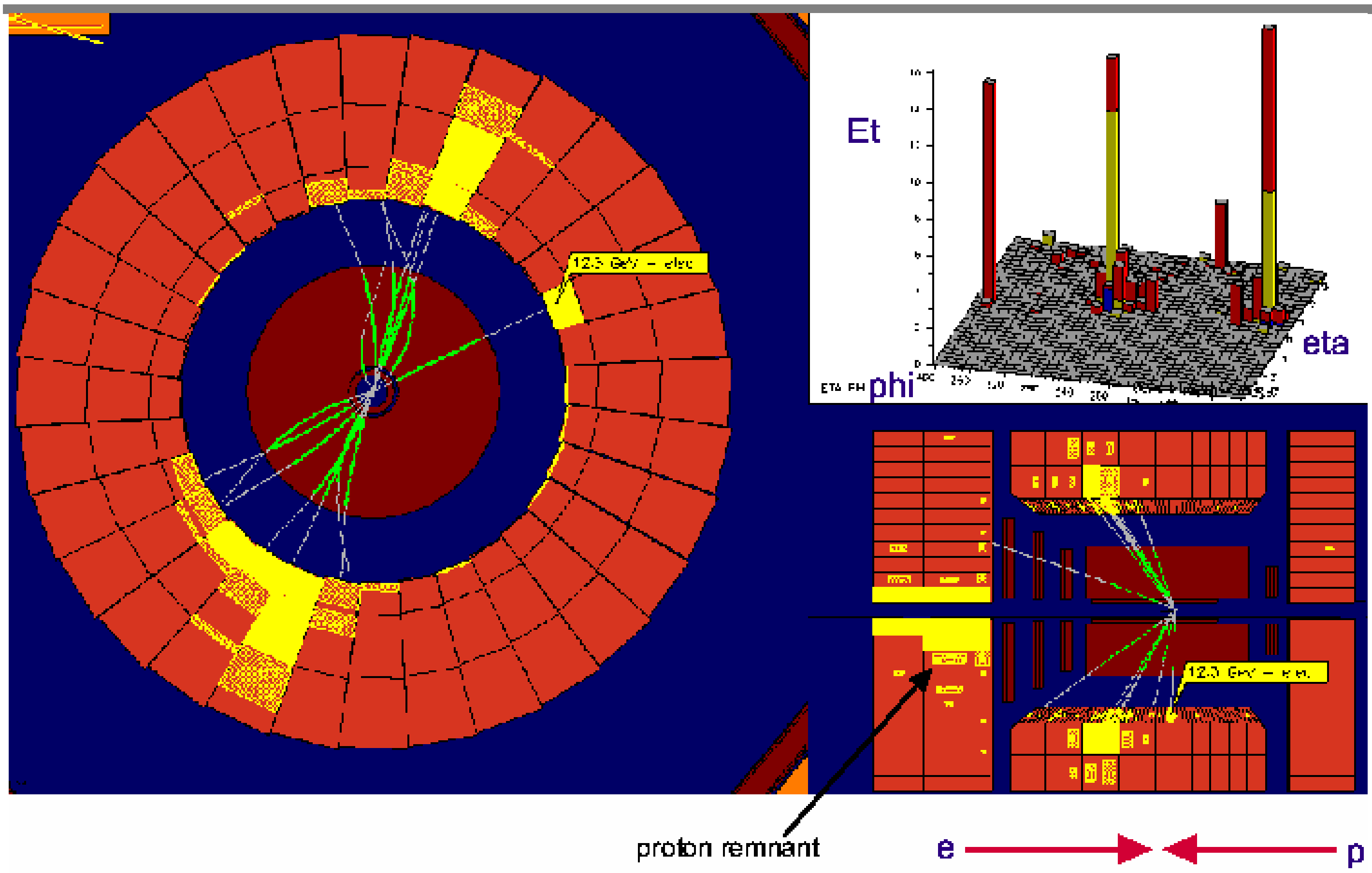
- parton showering
- hadronization

Uncertainties:

- renormalization scale: scale at which the strong coupling constant α_s is evaluated
- factorization scale: scale at which the parton densities are evaluated

NLO calculations: MEPJET, DISENT, DISASTER++

96/97 Dijet Cross Section Measurement



Data Sample: 38.4 pb^{-1} of data taken in 1996 and 1997

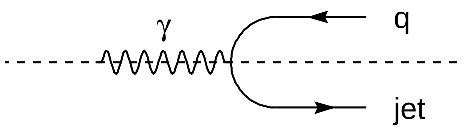
Event Selection Cuts: $10 < Q^2 < 10{,}000$
$y > 0.04$
electron energy > 10 GeV

Jet cuts: jet $E_T > 5$ GeV
$-2.0 < \eta < 2.0$
} Lab Frame

leading jet $E_T > 8$ GeV
subleading jet $E_T > 5$ GeV
} Breit Frame

Breit Frame

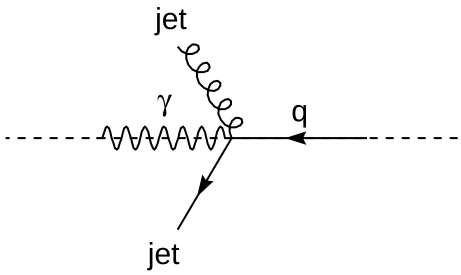
Dijet identification is easier in the Breit Frame



QPM event in
Breit Frame

Definition:

- quark rebounds off photon with equal and opposite momentum
- axis is the proton−photon axis
- photon is completely space−like: its 4−momentum has only a z−component
- outgoing jet has no E_T



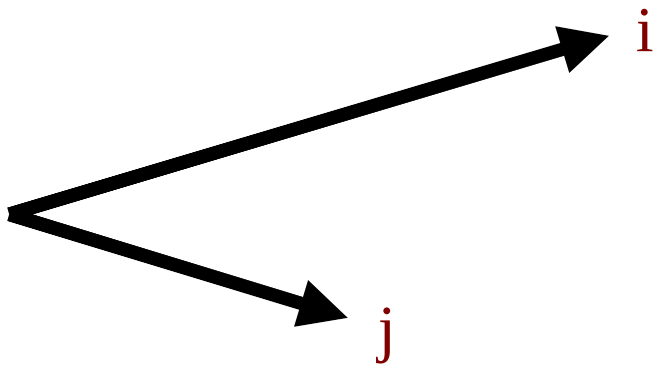
QCD Compton
event in Breit Frame

In dijet events, the outgoing jets are balanced in E_T

A cut on the jet E_T removes QPM events from the dijet sample

Jet Finder

Inclusive mode k_T cluster algorithm:



Combine particles i and j into a jet if $d_{i,j}$ is smaller of $\{d_i, d_{i,j}\}$.

$$d_i = E_{T,i}^{\,2}$$

$$d_{i,j} = \min\{E_{T,i}^{\,2}, E_{T,j}^{\,2}\}(\Delta\eta^2 + \Delta\varphi^2)/R^2$$

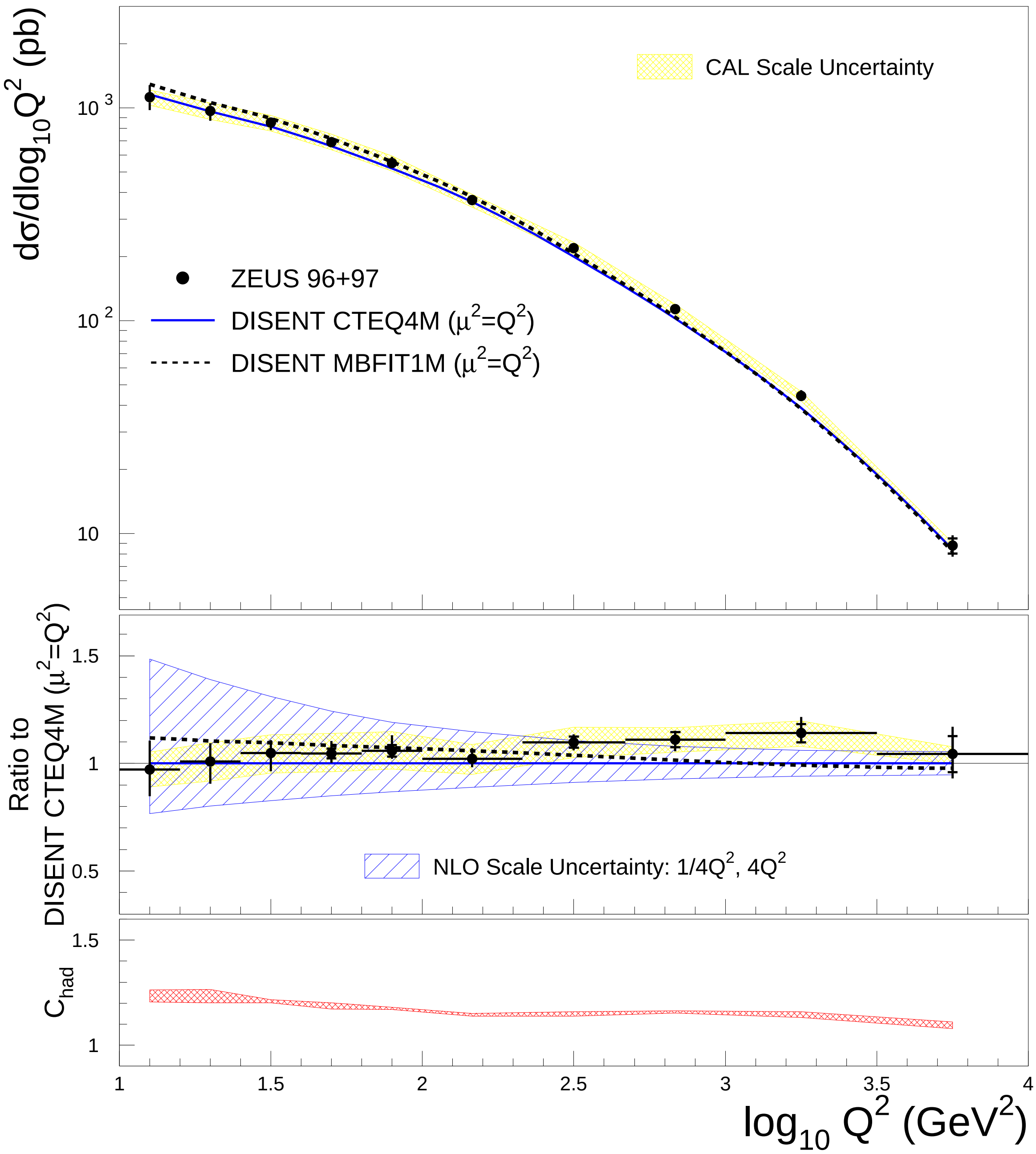
Repeat algorithm with all calorimeter cells.

Preferred over cone algorithms because:

- no seed requirements
- same application to cells, hadrons, partons
- no overlapping jets
- infrared safe to all orders

Agreement with DGLAP

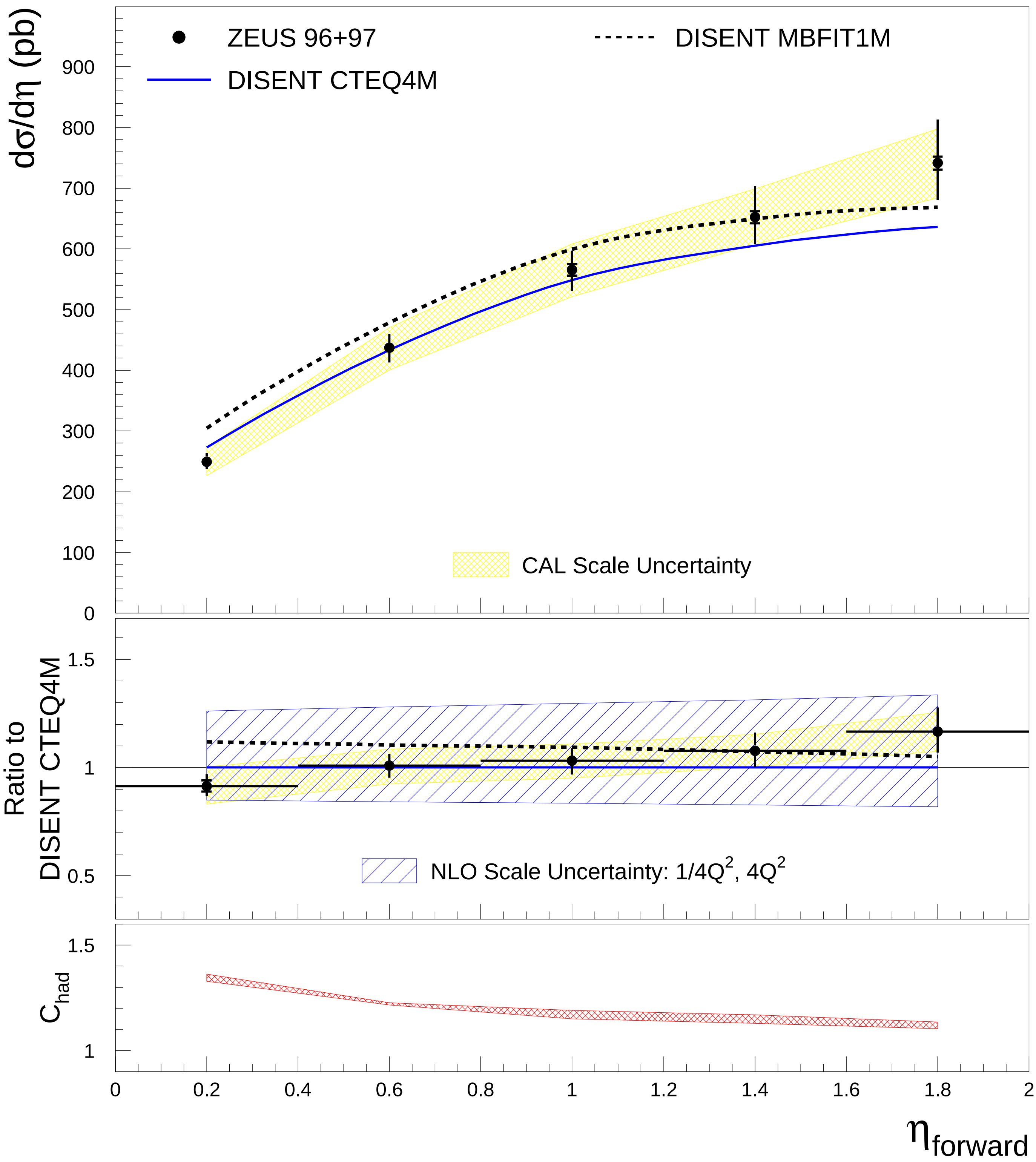
Comparison of the data with the NLO calculation that uses a DGLAP model for the PDF's has shown good agreement − a triumph for pQCD!



Questions remain:

- large renormalization scale uncertainty
- η > 2 region not investigated

Dijet cross section vs. η

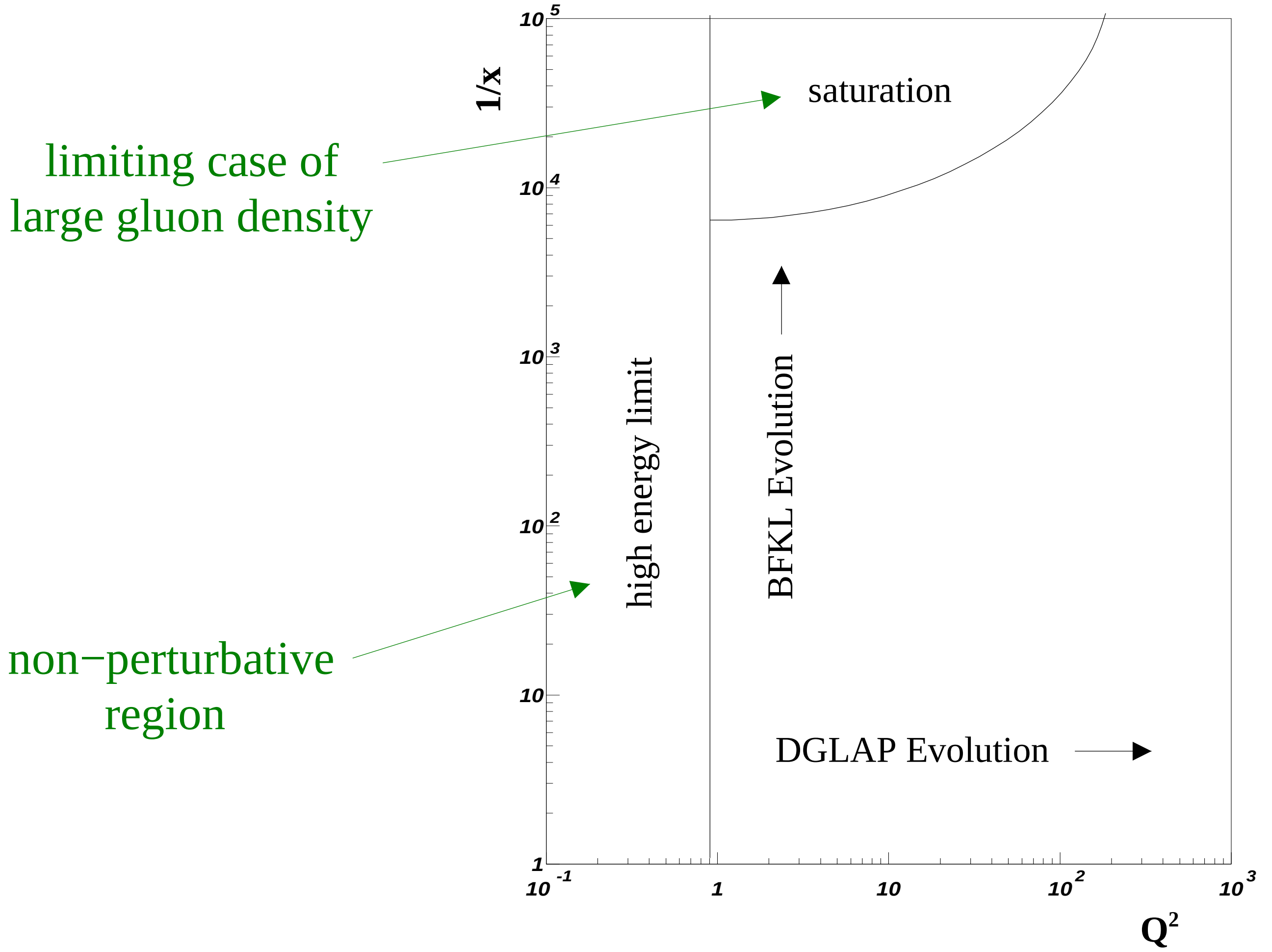


Why BFKL?

DGLAP: In the perturbative expansion of the parton densities, only terms proportional to $(\ln Q^2)^n$ are kept and summed to all orders.

At small values of x, terms in the evolution that contain $\ln \frac{1}{x}$ are no longer negligible.

BFKL, another evolution of the PDF's, includes terms $\ln \frac{1}{x}$ in its sum.



BFKL provides an evolution in x at fixed Q^2, given a starting distribution at x_o.

BFKL

The BFKL Equation is:

$$\frac{\partial f(x,k_T^2)}{\partial \ln \frac{1}{x}} = \frac{3\alpha_s}{\pi} k_T^2 \int_0^\infty \frac{k_T'^2}{k_T'^2} \left[\frac{f(x,k_T'^2) - f(x,k_T^2)}{|k_T'^2 - k_T^2|} + \frac{f(x,k_T^2)}{\sqrt{4k_T'^4 + k_T^4}} \right]$$

where the gluon density is defined to be:

$$xg(x,Q^2) = \int_0^{Q^2} \frac{dk_T^2}{k_T^2} f(x,k_T^2)$$

The forward jet cross section has been calculated:

$$\sigma_{forward\ jet} \sim \left(\frac{x_{jet}}{x}\right)^{4\ln 2\, \alpha_s \frac{N_c}{\pi}} \left(\frac{Q^2}{p_t^2}\right)^{\mu}$$

Expanding,

$$\left\{1 + \frac{\alpha_s N_c}{\pi} 4\ln 2 \log\left(\frac{x_{jet}}{x}\right) + \frac{1}{2}\left[\frac{\alpha_s N_c}{\pi} 4\ln 2 \log\left(\frac{x_{jet}}{x}\right)\right]^2 + \ldots\right\} \left(\frac{Q^2}{p_t^2}\right)^{1+\mu}$$

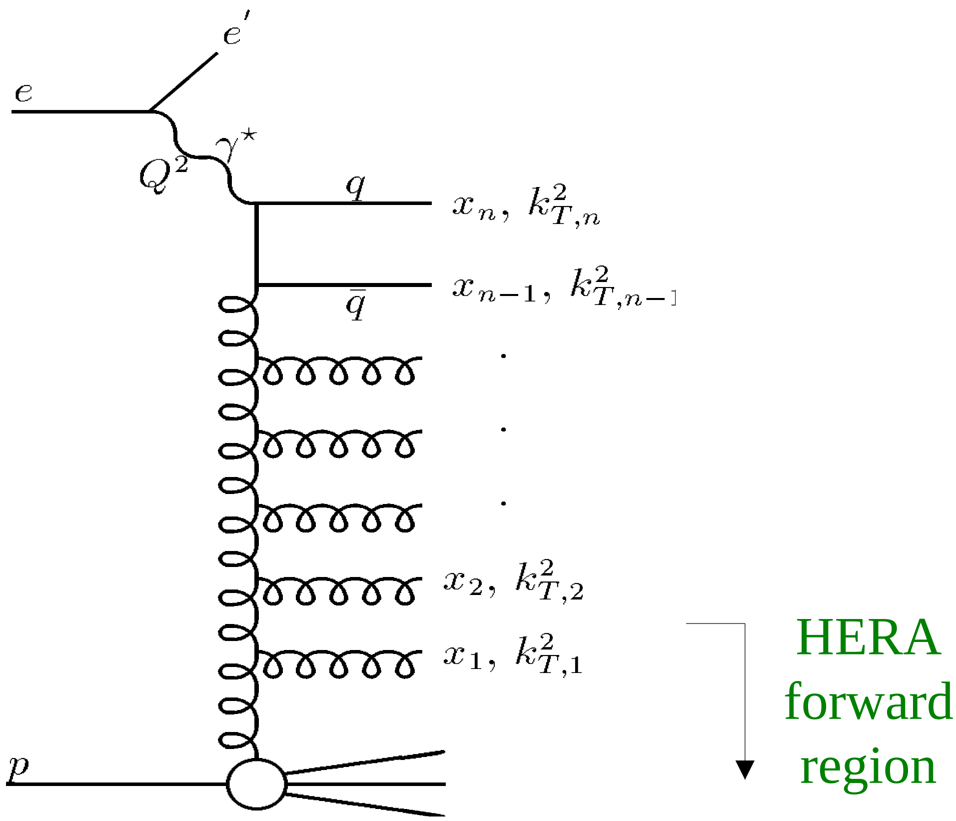
expansion in ln(1/x)

The first term of this expansion is similar to the NLO calculation in DGLAP perturbation theory.

The range of applicability is:

$$\alpha_s \ln(Q^2) \ll 1 \qquad \alpha_s \ln\frac{1}{x} = O(1)$$

Gluon Ladder



DGLAP: $x = x_n < x_{n-1} < \ldots < x_1$, $Q^2 = k^2_{T,n} \gg \ldots \gg k^2_{T,1}$

BFKL : $x = x_n \ll x_{n-1} \ll \ldots \ll x_1$, no ordering in k_T

If BFKL works, we should see additional contributions to the hadronic final state from high transverse momentum partons going forward in the HERA frame.

Forward Jets at Zeus

Previous Measurement

Data Sample: 6.36 pb^{-1} taken in 1995

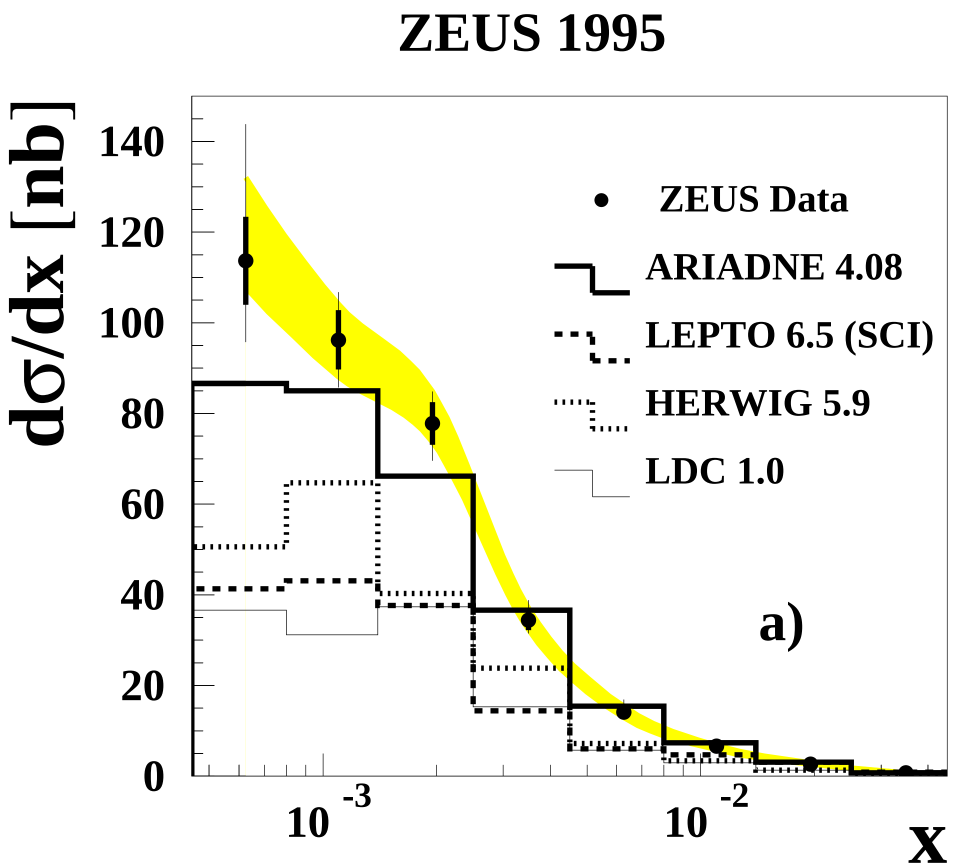
Analysis done in lab frame

Jet finding with cone algorithm

Selection Cuts

- $4.5 \times 10^{-4} < x < 4.5 \times 10^{-2}$ range in x limited by resolution and choice of binning
- $E_e > 10$ GeV good electron
- $y > 0.1$ sufficient hadronic energy away from forward region
- $0.5 < E^2_{T,Jet} / Q^2 < 2$ selects BFKL phase space
- $E_{T,Jet} > 5$ Gev good reconstruction of the jet
- $\eta_{Jet} < 2.6$ experimental limitations
- $x_{Jet} > 0.036$ selects high energy jets at the bottom of the gluon ladder
- $p_{Z,Jet}$ (Breit) > 0 rejects forward jets with large x_{Bj} (QPMevents) rejects leading order jets from the quark box

Results of the 1995 Forward Jets analysis



None of the models used describes the cross section over the entire x range investigated

Issues:

- all monte carlo models understimate the data at low x
- LO monte carlo models are not consistent with each other
- LDC underestimates measured forward jet cross section

→ results inconclusive

LDC, the Linked Dipole Chain model, implements the structure of the CCFM Equation, intended to reproduce DGLAP and BFKL in their respective ranges of validity.

Proposal

Proposal: Test perturbative QCD in a new kinematic range, applying knowledge acquired from the dijet analysis.

Challenges: find kinematic region where

- measurement uncertainties are small
- theoretical uncertainties are small
- BFKL effects potentially large
  - ➔ forward jet region

We expect a successful measurement because of:

- Increased statistics by 17x $\Rightarrow$ higher jet E_T
  - ➔ smaller hadronization corrections
  - ➔ improved jet purities and efficiencies
- Better understanding of DGLAP from dijet analysis
  - ➔ Jet finding in Breit Frame using k_T algorithm
- Better understanding of theoretical calculations

Analysis Method

Plan: Measure the forward jet rate and compare to QCD based Monte Carlo predictions and analytical calculations based on DGLAP, BFKL and CCFM evolution.

Data Sample: 1996,1997,1999,2000 data is available

Use leading order monte carlos for detector corrections

Studies needed:

- jet finding purities and efficiencies
- hadronizationl corrections
- systematic uncertainties
  - energy scale uncertainty

Compare forward jet cross section with NLO calculation, using jets found in the Breit Frame and reconstructed using the k_T method

→ look for excess

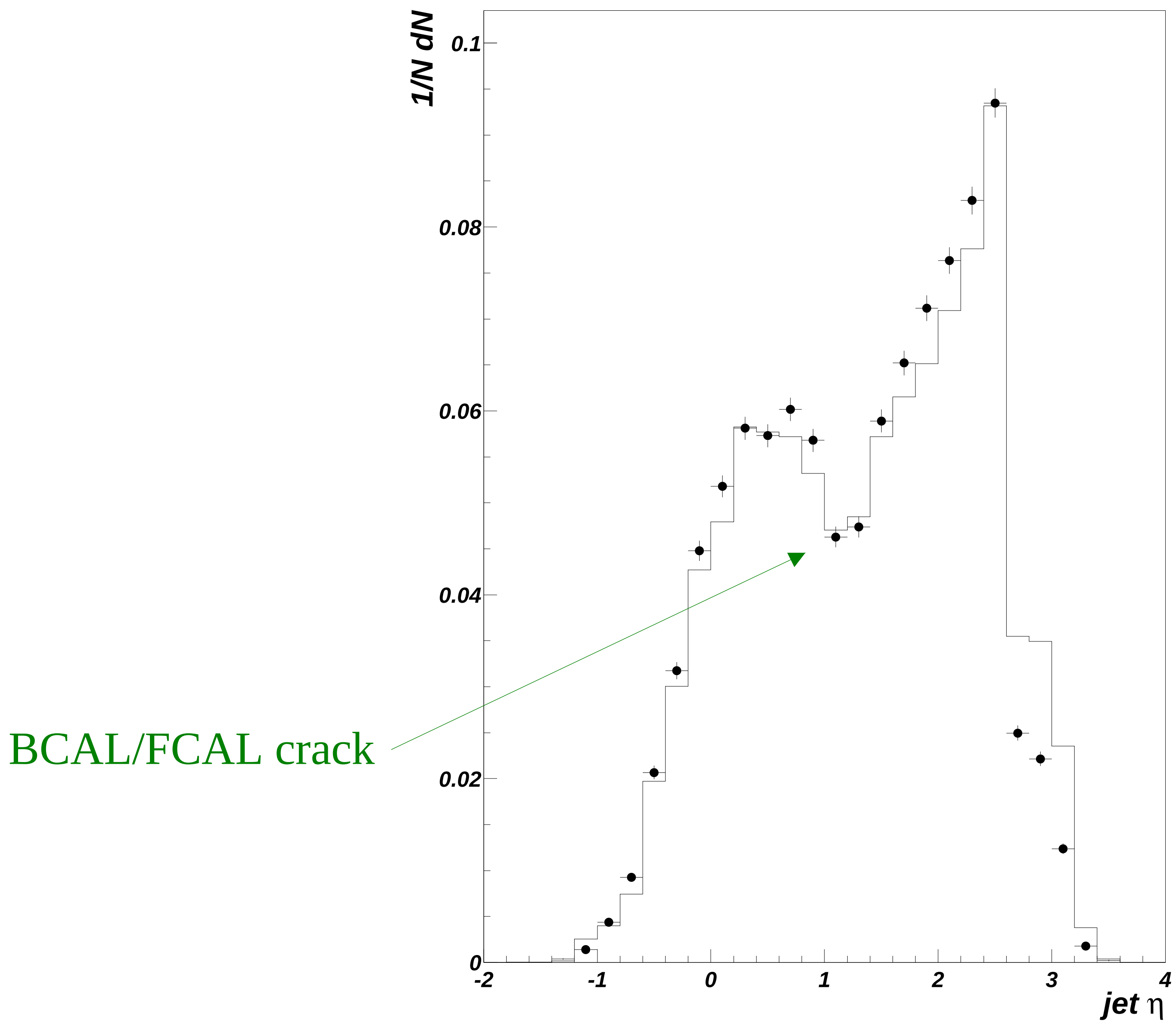
Data Sample

1996−1997 integrated luminosity = 38.4 pb^{-1}

1999−2000 integrated luminosity = 67.7 pb^{-1}

- new detector component: Forward Plug Calorimeter
  - increases eta range by 1 unit

1996 NC DIS

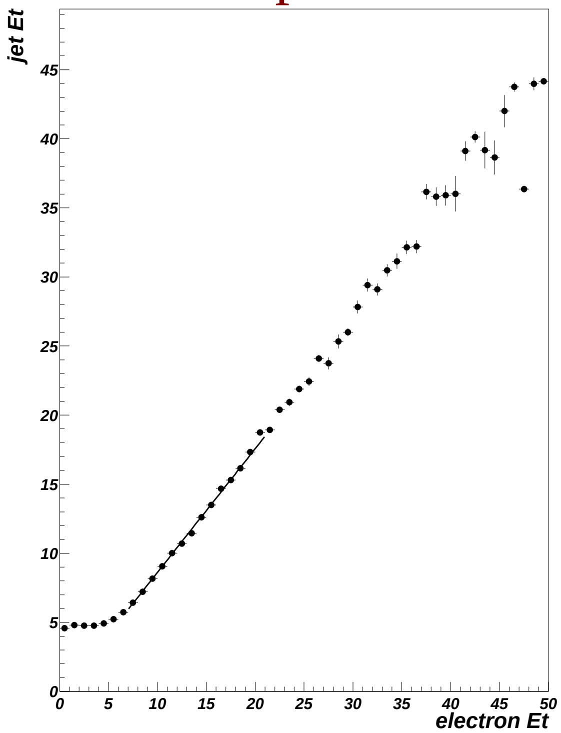


Calorimeter Energy Scale Uncertainty

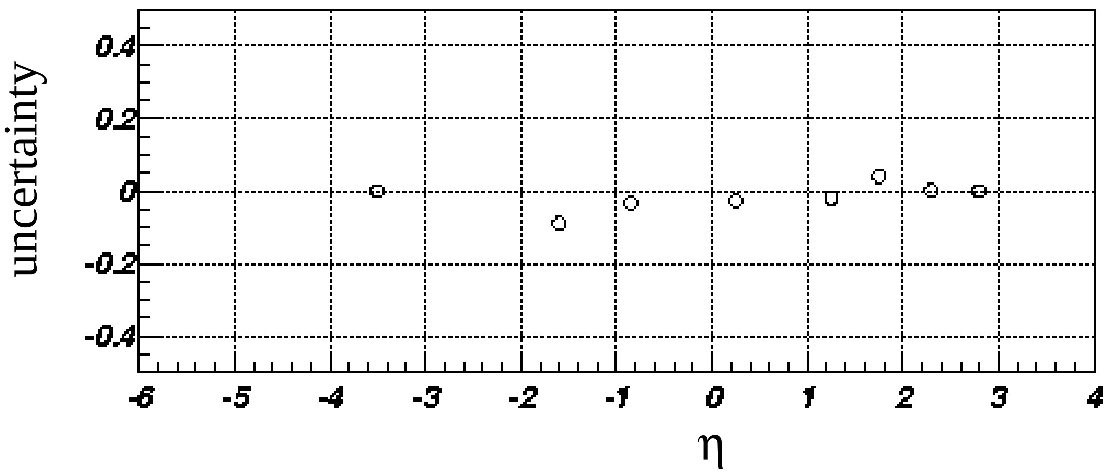
Scheme: In QPM events, the scattered positron and the jet are balanced in E_T in the laboratory frame.

Assuming the reconstructed electron energy is reliable, the jet transverse energy should be the same as the positron's.

$$uncertainty = \frac{slope^{data}_{E_t^{jet} vs E_t^e} - slope^{MC}_{E_t^{jet} vs E_t^e}}{slope^{MC}_{E_t^{jet} vs E_t^e}}$$



Preliminary Conclusion: energy uncertainty is within 3%



Summary

- A departure from parton evolution described by DGLAP at low x is theorized
- Forward region is the best place to look for low x, BFKL signature dynamics
- 96/97 dijets analysis laid out standards with which to make a solid cross section measurement
- data exists

Forward Jet	statistics	jet E_T	jet η	reference frame	jet finder	DGLAP
95 measurement	6.36 pb^{-1}	>5 GeV	<2.6	Lab	cone	LO
proposed mesurement	106 pb^{-1}	>>5 GeV	farther forward	Breit	k_T cluster	NLO

Conclusion: A measurement of forward jet cross section is warranted because we have the possibility to learn more about pQCD.

Pseudorapidity

$$rapidity = \frac{1}{2}\ln\left[\frac{E+p_{\parallel}}{E-p_{\parallel}}\right]$$

$$pseudorapidity = \eta = \frac{1}{2}\ln\left[\frac{|p|+p_{\parallel}}{|p|-p_{\parallel}}\right] = -\ln\left(\tan\frac{\vartheta}{2}\right)$$

Lorentz boost along the beam direction:

$\eta' = \eta + f(v)$

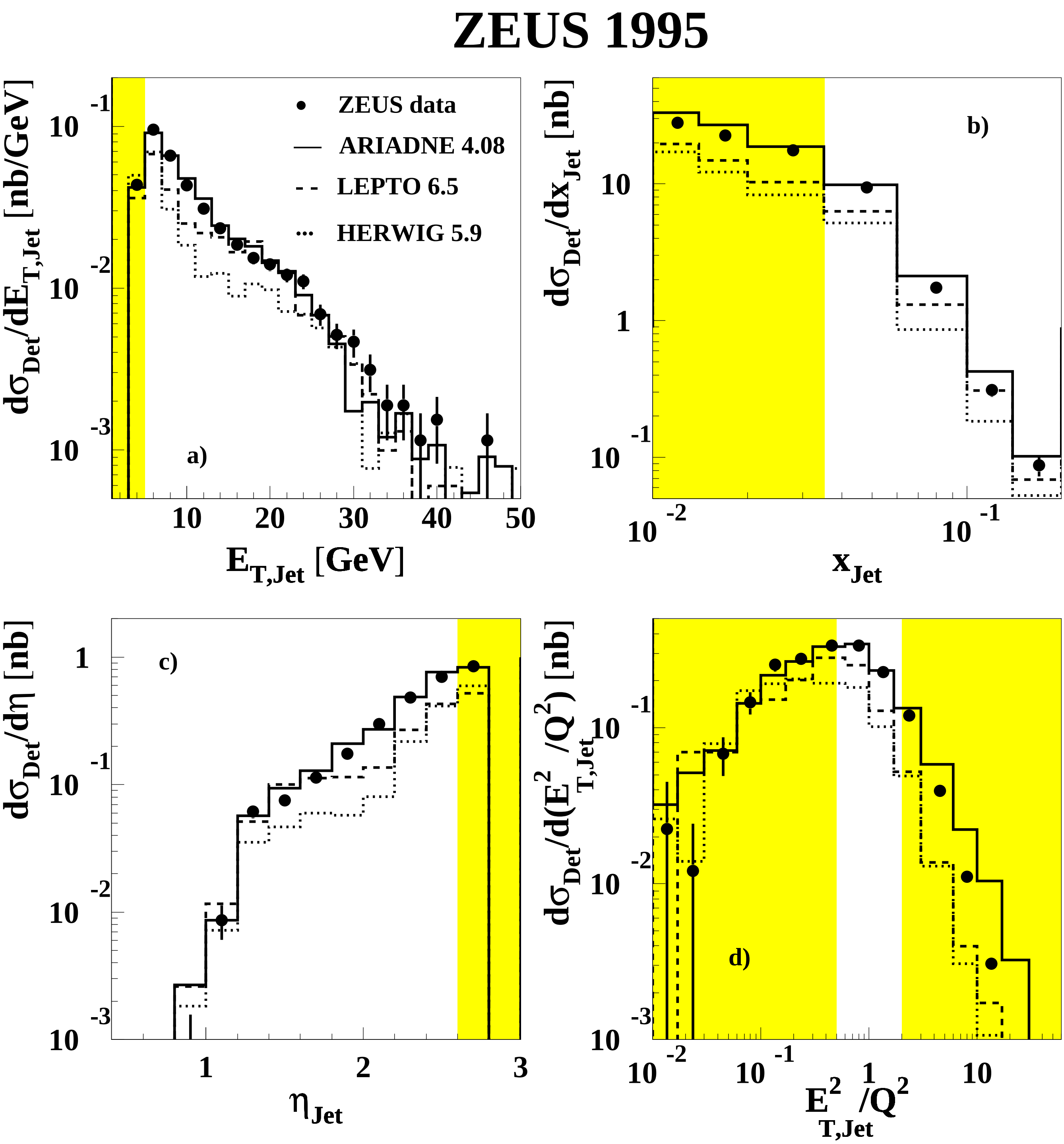
η is shifted by an additive constant

$\Delta\eta$ is unaffected

The form of the transverse energy distribution in $\eta-\varphi$ space is the same in all frames

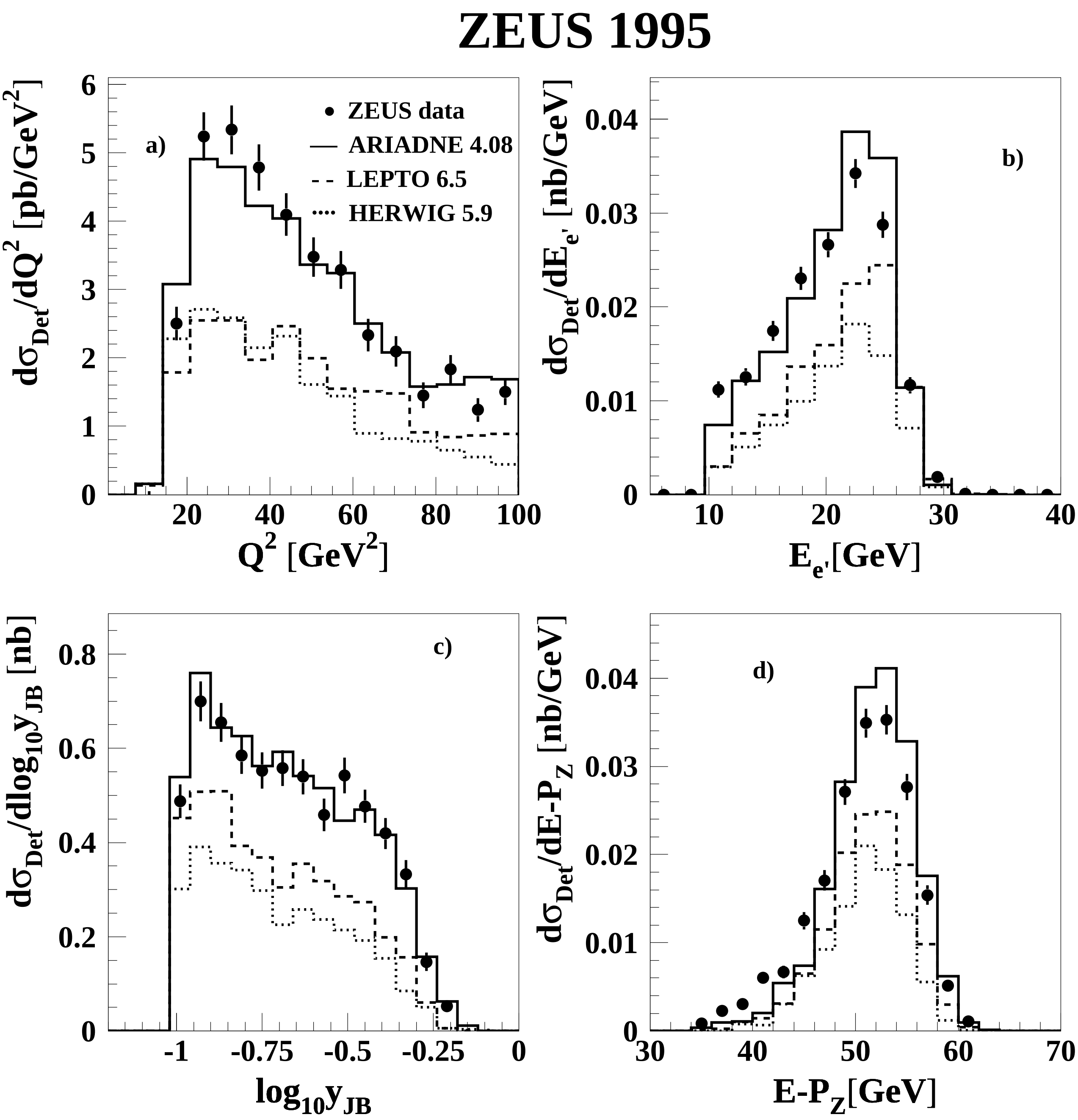
Comparison of Data and Monte Carlo Distributions

Jet quantities

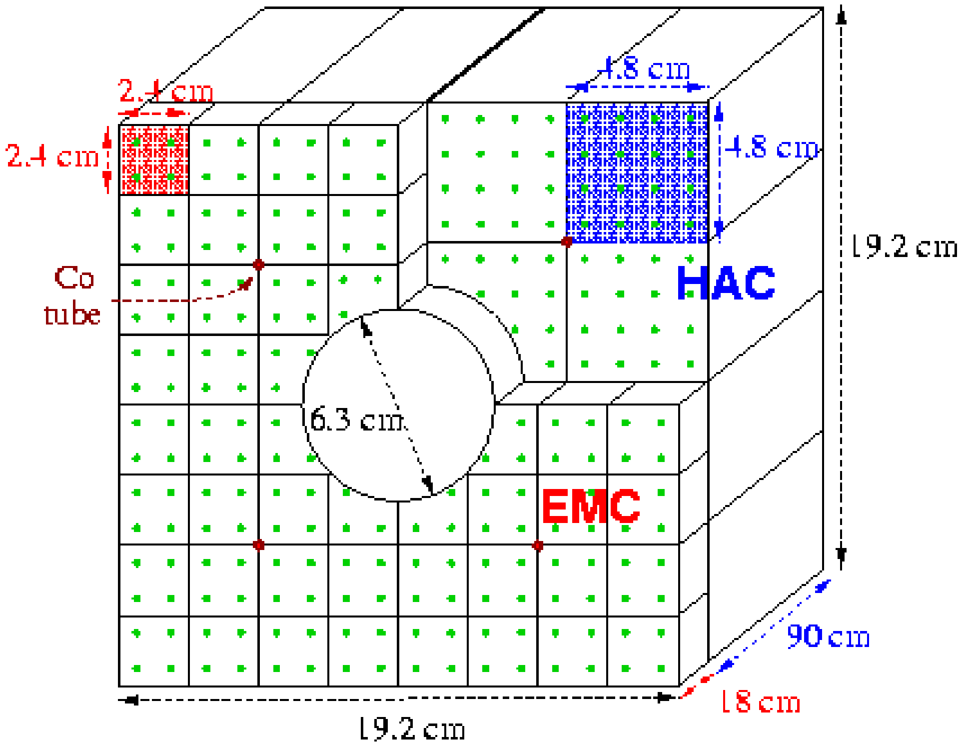


Comparison of Data and Monte Carlo Distributions

Event quantities



FPC



2.4 cm
2.4 cm
4.8 cm
4.8 cm
19.2 cm
Co
tube
HAC
6.3 cm
EMC
90 cm
18 cm
19.2 cm