Dijet Production in Charged Current ep Deep Inelastic Scattering with ZEUS at HERA

Preliminary Examination

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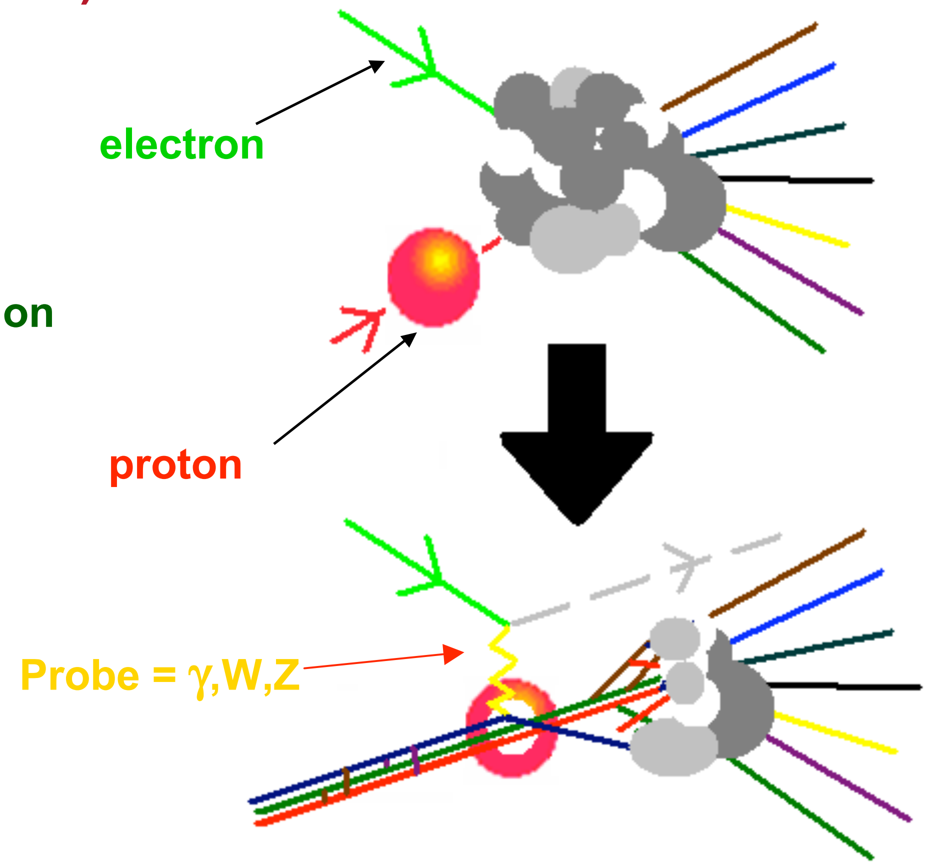
Outline

- Theoretical Background
  - Proton Structure
  - Quark-Parton Model
  - Color Charge and QCD
  - Charged Currents
- Goals for This Analysis
- Experimental Methods
  - HERA Accelerator
  - ZEUS Detector
  - Jets and Jet Finding
- Present Status
  - Previous H1 and ZEUS Dijet Results
  - Comparison of ZEUS Dijet and Monte Carlo
- Summary and Research Plan

Structure of the Proton

Scattering experiments give information about the components of the proton (partons).

- **Studied via Probe Exchange**
  - **Wavelength of probe:** $\lambda = h/q$
    - *h*: Planck's constant
    - *q: probe 3-momentum*
    - A smaller λ means better resolution
- **HERA Collisions**
  - HERA Collider provides *ep* collisions with Center of Mass Energy (CME) of 318 *GeV*
    - E_e=27.5 *GeV* , E_p=920 *GeV*
  - Provides γ/Z or *W* as probes
  - Deep Inelastic Scattering (DIS):
    - 1 $GeV^2 < Q^2$
  - Probe to .001 *fm*
    - (Proton has a radius of 1 *fm*)



Deep Inelastic Scattering (DIS)

CME of ep system squared

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

CME of photon-proton 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 parton

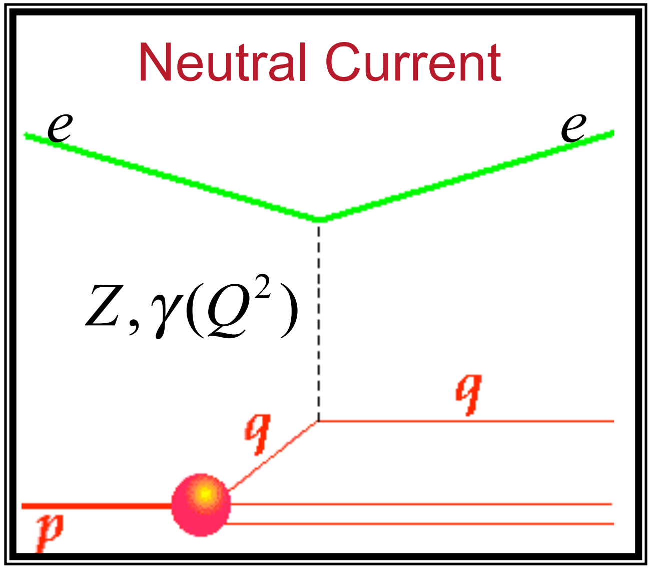
- $x = Q^2/(2p\cdot q)$

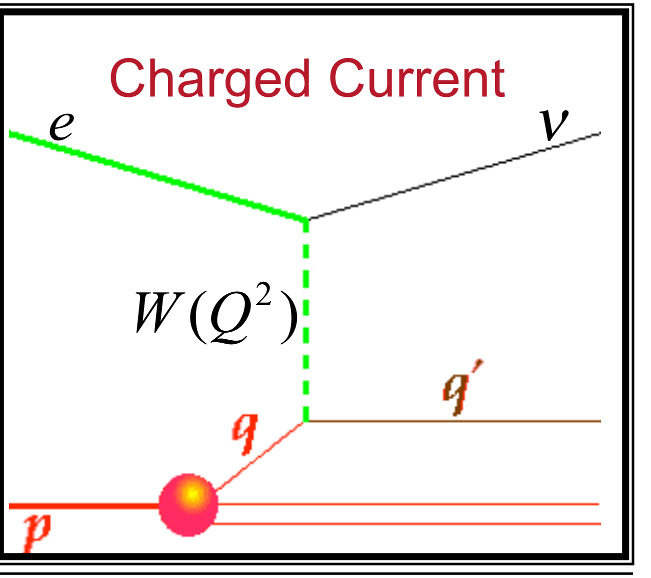
Fraction of e's energy transferred to proton in proton's rest frame

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

Variables are related

- $Q^2 = sxy$





Quark Parton Model (QPM)

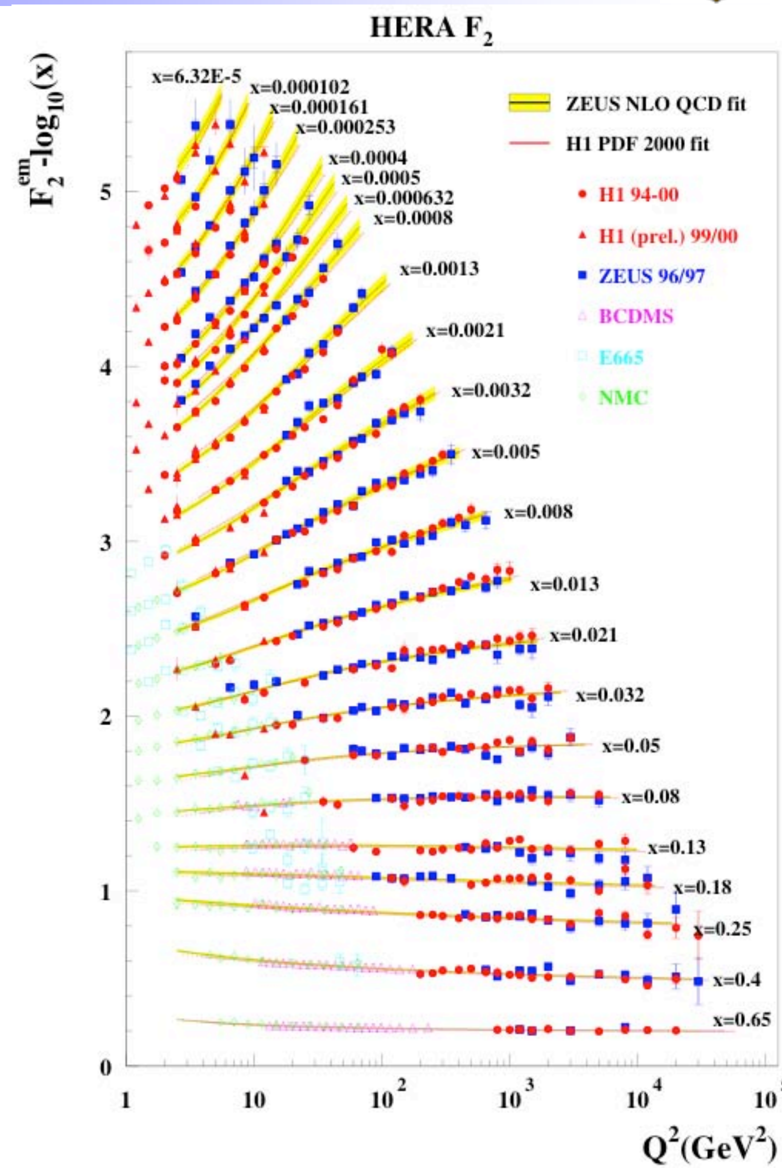
Introduced to characterize the classification of hadrons

- Hadrons:
  - Bound states of quarks
- Quark properties:
  - Point-like fermions,
  - Mass, electric charge, spin, flavor
    - Originally only u,d,s
  - Non-interacting
- Proton contains exactly 3 quarks (uud)

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

Structure Functions in QPM

- These distributions depend only on $\boldsymbol{x_{Bj}}$, *the* fraction of the proton's momentum carried by the quark.
- No Q^2 dependence (**Bjorken scaling**),
  but scaling violation (next slide) ⇒
- **Parton Distribution Functions** *(f_i)* can be interpreted as probability density of detecting a parton with flavor *i* and x_{Bj} in *$(x, x + dx)$*
  - must be experimentally determined.

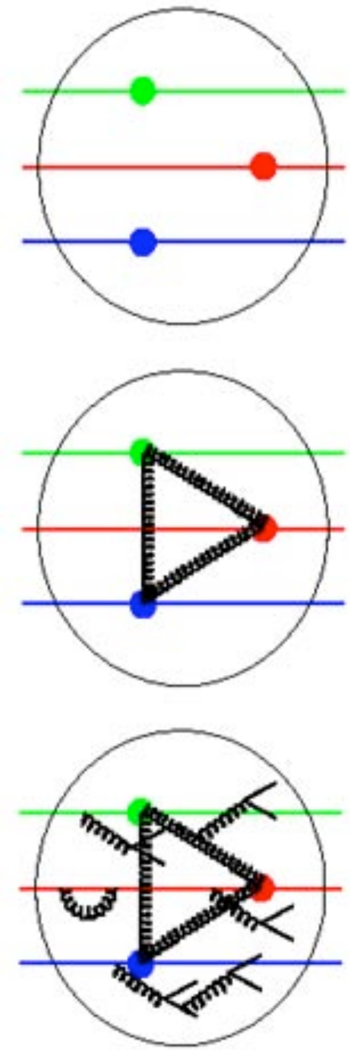


$$F_2 = \sum_i e_i^2 x_{Bj} f_i(x_{Bj})$$

Quantum Chromodynamics (QCD) and Color Symmetry

Limitations of QPM

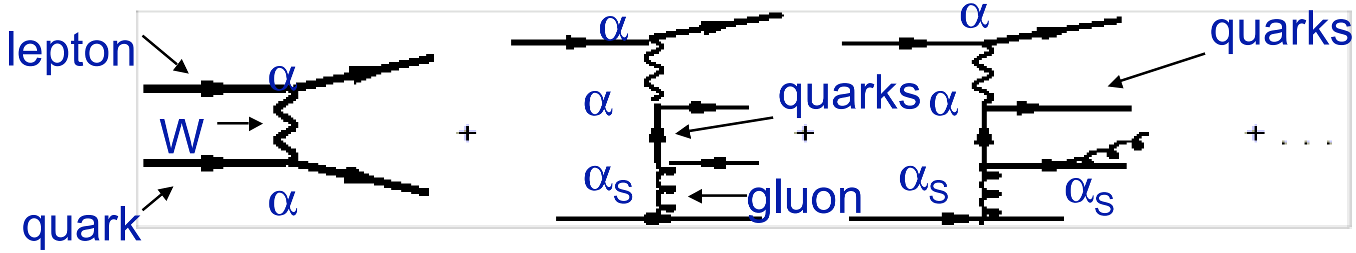
- **Scaling violation observed**
- **Sum rule for F_2**
  - If QPM correct: $\int_0^1 F_2(x_{Bj})dx_{Bj} = 1$
    - Value of integral shown to be ~0.5 by experiment
    - Quarks carry roughly half proton momentum
- **Statistics for fermion Δ^{++}**
  - Comprised of 3 u quarks:
    Violation of exclusion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



Gluons and Color Quantum Number

- **Mediator of strong force → gluon**
  - Introduces scaling violation
  - Gluons carry roughly half proton momentum
- **Δ^{++} valence quark composition: $u_R u_B u_G$**
- **Color force increases with distance**
  - Isolated quarks not observed → confinement

Perturbative QCD



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

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

Want to compute cross sections, etc

- **Write scattering amplitudes as a perturbative expansion of Feynman diagrams.**

Running of strong coupling constant α_S

- **As momentum transfer scale μ increases, $\alpha_S(\mu)$ decreases ($\mu = E_T$ or Q)**

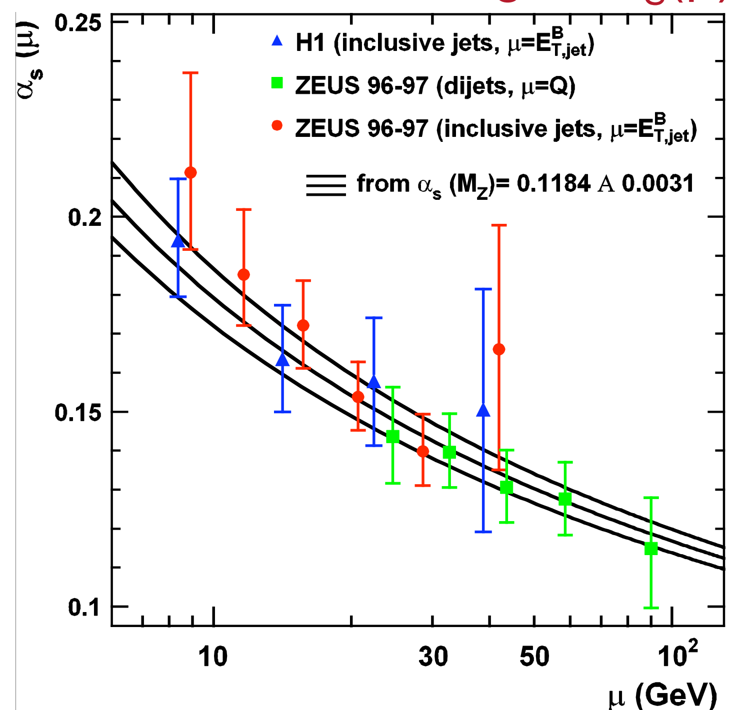
Perturbative QCD

- **Small $\alpha_S(\mu)$ (hard scale)**
  - Higher order terms can have significant contributionss
- **Cannot sum all terms**

Nonperturbative QCD

- **Large $\alpha_S(\mu)$ (soft scale)-Not convergent**

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



QCD Evolution

QCD evolution: $f(x_0, Q_0^2) \rightarrow f(x, Q^2)$

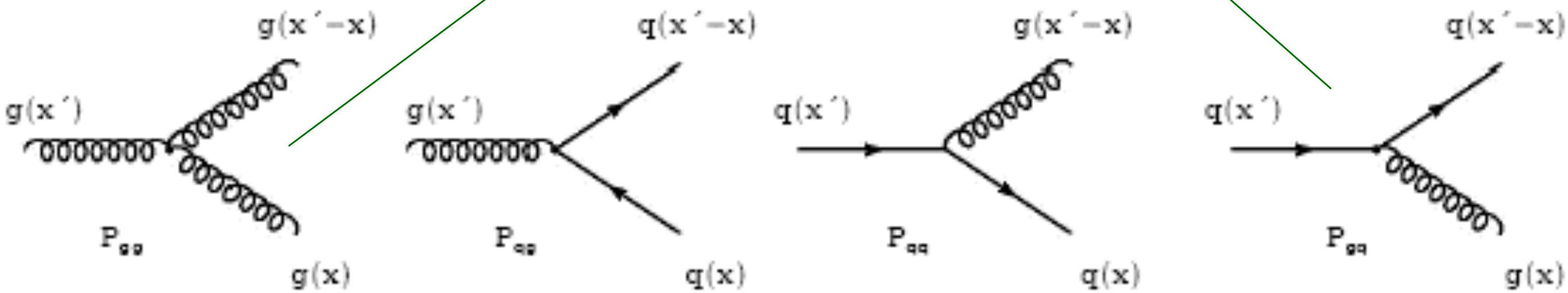
Computed by summing over diagrams

DGLAP Evolution: Sum over diagrams contributing *ln*(Q²) terms

- **Valid in region of high Q^2, x_{Bj}**

$$\frac{\partial g(x,Q^2)}{\partial \ln(Q^2)} = \frac{\alpha_S(Q^2)}{2\pi}\int_x^1 \frac{dz}{z}\left[P_{gg}\left(\frac{x}{z}\right)g(z,Q^2) + P_{gq}\left(\frac{x}{z}\right)q(z,Q^2)\right]$$

- **Splitting Functions**



LO DIS NC & CC Cross Sections

(Neutral Current)

$$e^- p \rightarrow e^- X$$

$$\frac{d^2\sigma_{NC}}{dxdQ^2} = \frac{2\pi\alpha_{QED}^2}{xQ^4} x \left[\begin{array}{c} \left(2-2y+y^2\left(1-4\frac{x^2 m_p^2}{Q^2}\right)\right) \\ \times \left(\begin{array}{c} (u+\bar{u})A_u + (d+\bar{d})A_d \\ +(s+\bar{s})A_s + (c+\bar{c})A_c \end{array} \right) \\ -\left(1-(1-y)^2\right)\left(\begin{array}{c} (u-\bar{u})B_u + (d-\bar{d})B_d \\ +(s-\bar{s})B_s + (c-\bar{c})B_c \end{array} \right) \end{array} \right]$$

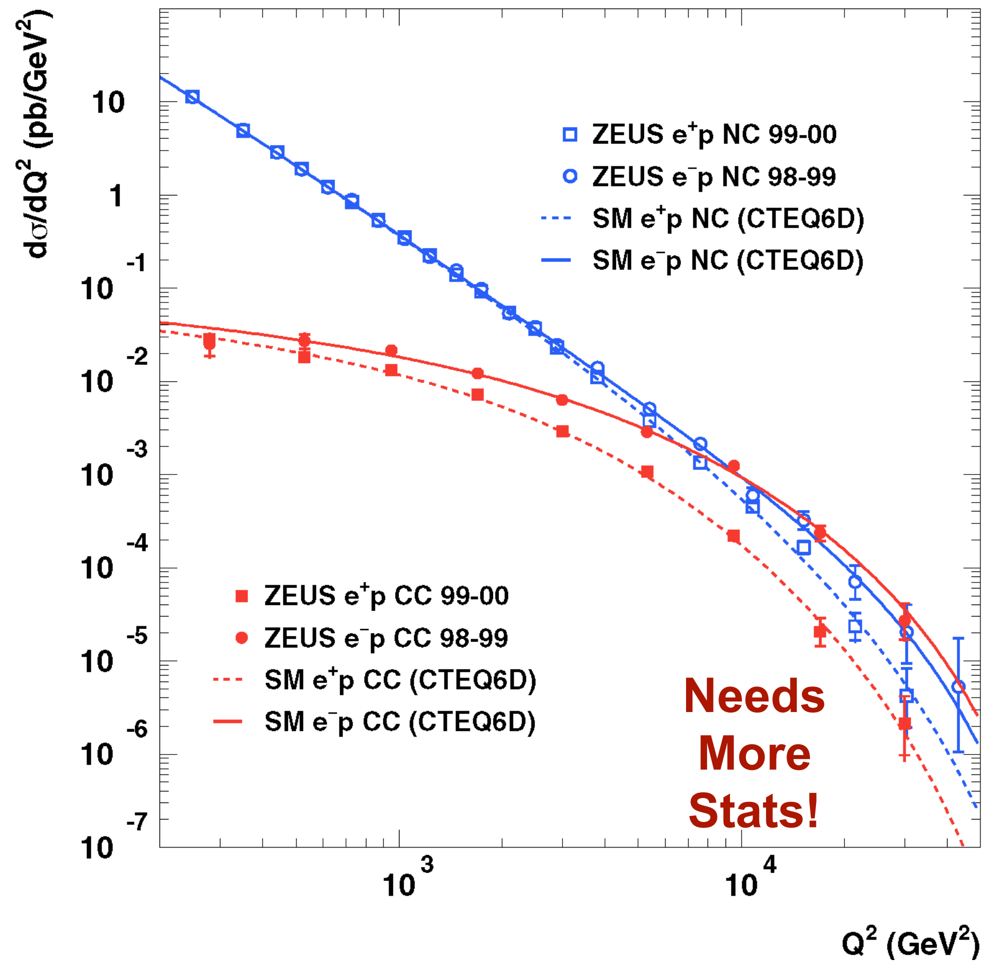
(Charged Current)

$$e^- p \rightarrow e^- X$$

$$\frac{d^2\sigma_{CC}}{dxdQ^2} = \frac{G_F^2}{2\pi}\left[\frac{M_W^2}{Q^2+M_W^2}\right]^2 \times \left[u + c + (1-y^2)(\bar{d}+\bar{s})\right]$$

$$e^+ p \rightarrow e^+ X$$

$$\frac{d^2\sigma_{CC}}{dxdQ^2} = \frac{G_F^2}{2\pi}\left[\frac{M_W^2}{Q^2+M_W^2}\right]^2 \times \left[\bar{u} + \bar{c} + (1-y^2)(d+s)\right]$$



CC DIS can individually probe the u, d structure functions!

Charged Current Processes

Neutrino escapes detector; missing p_T

A good Test of SM

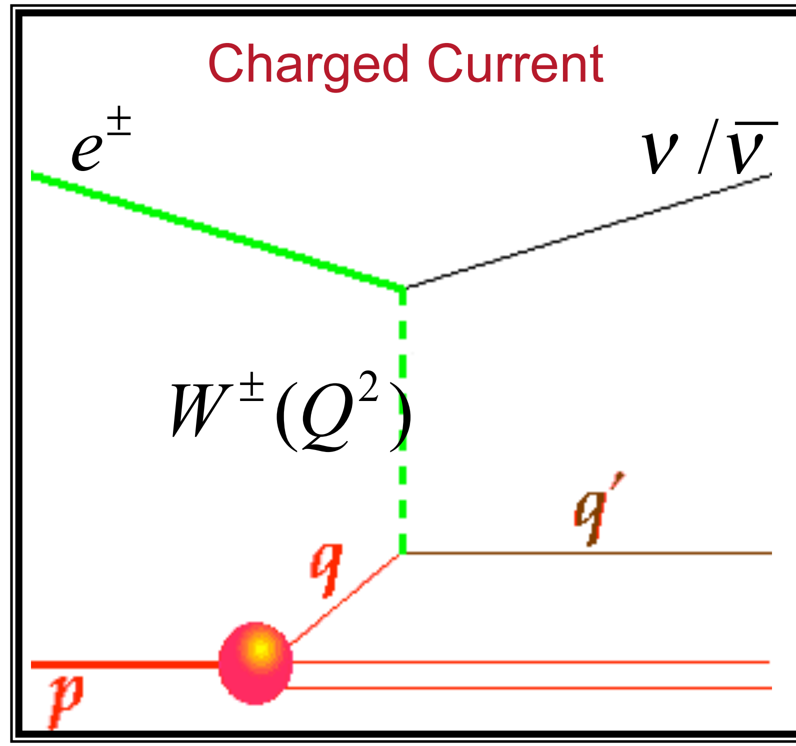
- $\frac{d^2\sigma}{dxdQ^2}$ sensitive to M_W
- e^-p and e^+p σ depend individually on *u(x)*, *d(x)*

Adds information to NC DIS.

- Both NC and CC needed to compute θ_W, the electroweak mixing angle.
- Uses weak probe only
- Flavor-specific to leading order
- Probes chiral structure of weak interaction

Many SM extensions have missing p_T signatures

- Leptoquarks
- Kaluza-Klein Theories



Goals for This Analysis

Improve Charged Current Measurement

- **Higher statistics**
  - Old Sample: ~193 pb^{-1}
    - e^- 27.4 pb^{-1}
    - e^+ 166 pb^{-1}
  - New Sample :~294 pb^{-1}
    - e^- 204 pb^{-1}
    - e^+ 89.4 pb^{-1}
- **Extend range of Q^2, x**
  - Previous range: $280 < Q^2 < 10{,}000$; $.008 < x < .42$
  - Increased statistics should improve this range

Examine possible dependences of Hadronic Final State (HFS) on the underlying electroweak process (W^+ or W^- exchange).

- **Energy flow of HFS**
  - Tracking + Calorimeter Information
- **Distribution of hadrons within final state**

HERA Description

920 GeV protons

27.5 GeV e

CMS energy 318 GeV

- **Equivalent to 50 TeV e on fixed target**

220 bunches

- **Not all filled**

96 ns crossing time.

Currents:

- **~100mA protons**
- **~40mA positrons**

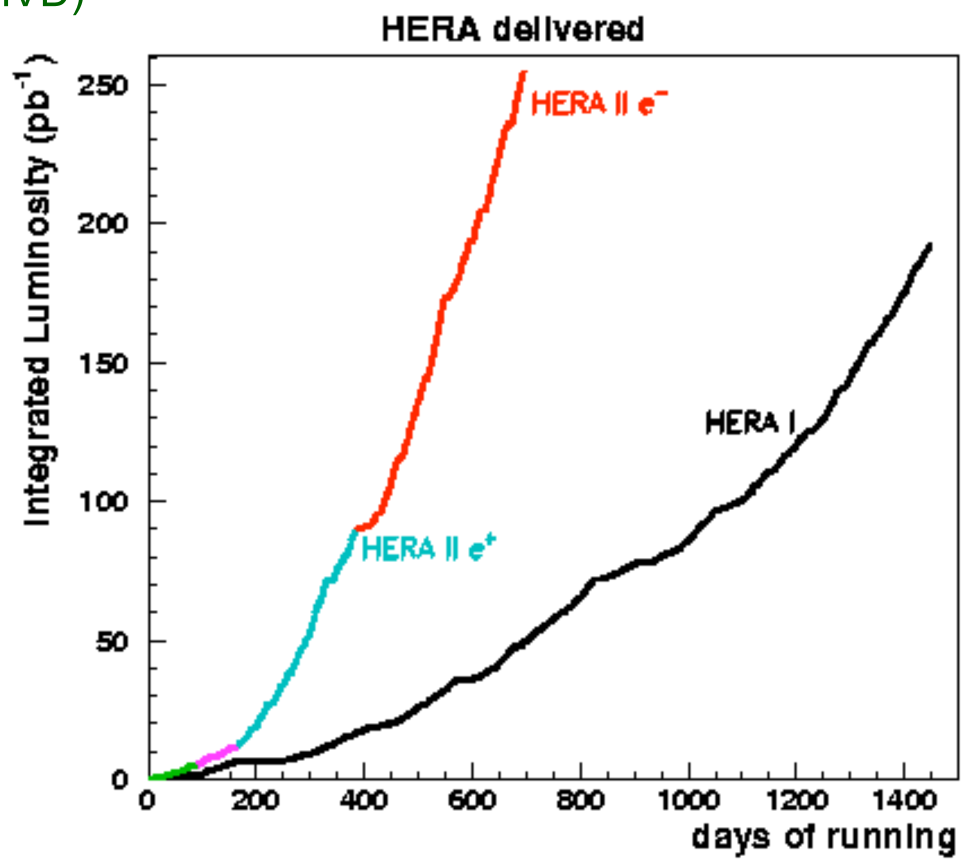
Luminosity:

- **~5x10^{31}cm^{-2}s^{-1}**
- **~pb^{-1}/day**

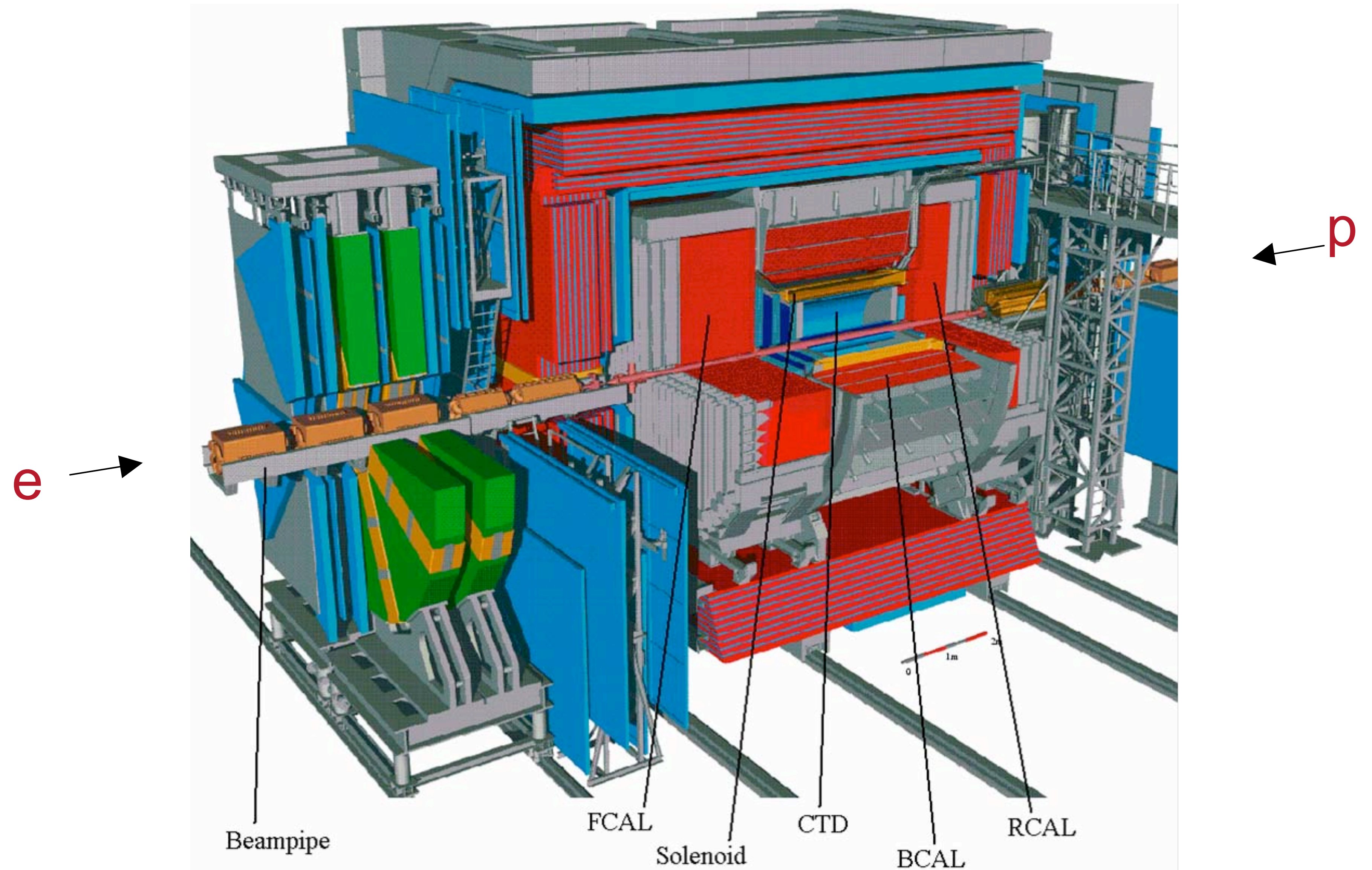
DESY Accelerator Complex, Hamburg, Germany

HERA Luminosity

- **Goals for HERA II upgrade:**
  - **ZEUS**
    - Add Micro Vertex Detector (MVD)
  - **HERA**
    - Achieve Higher Statistics
    - Perform Polarization Studies
  - **Total integrated luminosity**
  - **HERA I: '92- '00: ~193 pb^{-1}**
    - e^- 27.4 pb^{-1}
    - e^+ 166 pb^{-1}
  - **HERA II: '02- '05 :~294**
    - e^- 204 pb^{-1}
    - e^+ 89.4 pb^{-1}
    - Maximum Polarization: 50%
  - **More Lumi to Come**
    - up to 30 June 2007
    - ~250 pb $^{-1}$ more



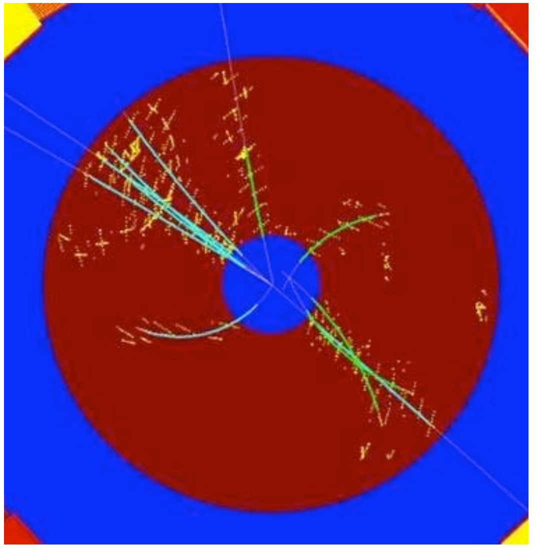
ZEUS Description

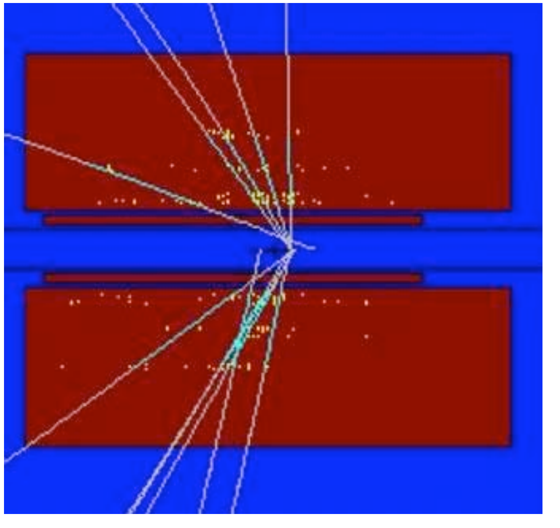


Central Tracking Detector (CTD)

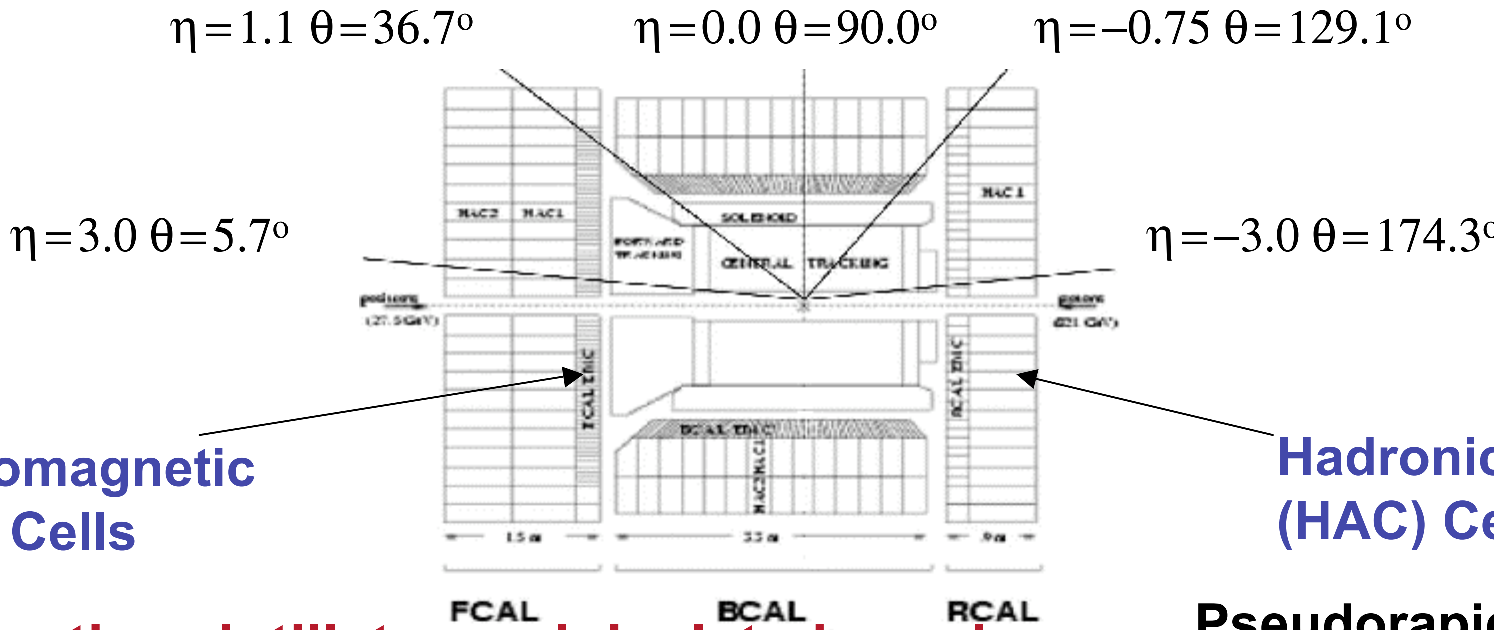
- Cylindrical Drift Chamber inside 1.43 T solenoid
- Angular coverage 15° < θ < 164 °
- 72 wire layers
- 9 superlayers
- Alternate layers at 5° to Beam Line
- Measures event vertex
  - Vertex resolution
    - Transverse (x-y): 1mm
    - Longitudinal (z): 4mm
- Measures Momentum Distribution

$$\sigma / p_T(GeV) = 0.005\, p_T(GeV) \oplus 0.004$$





Uranium-Scintillator Calorimeter



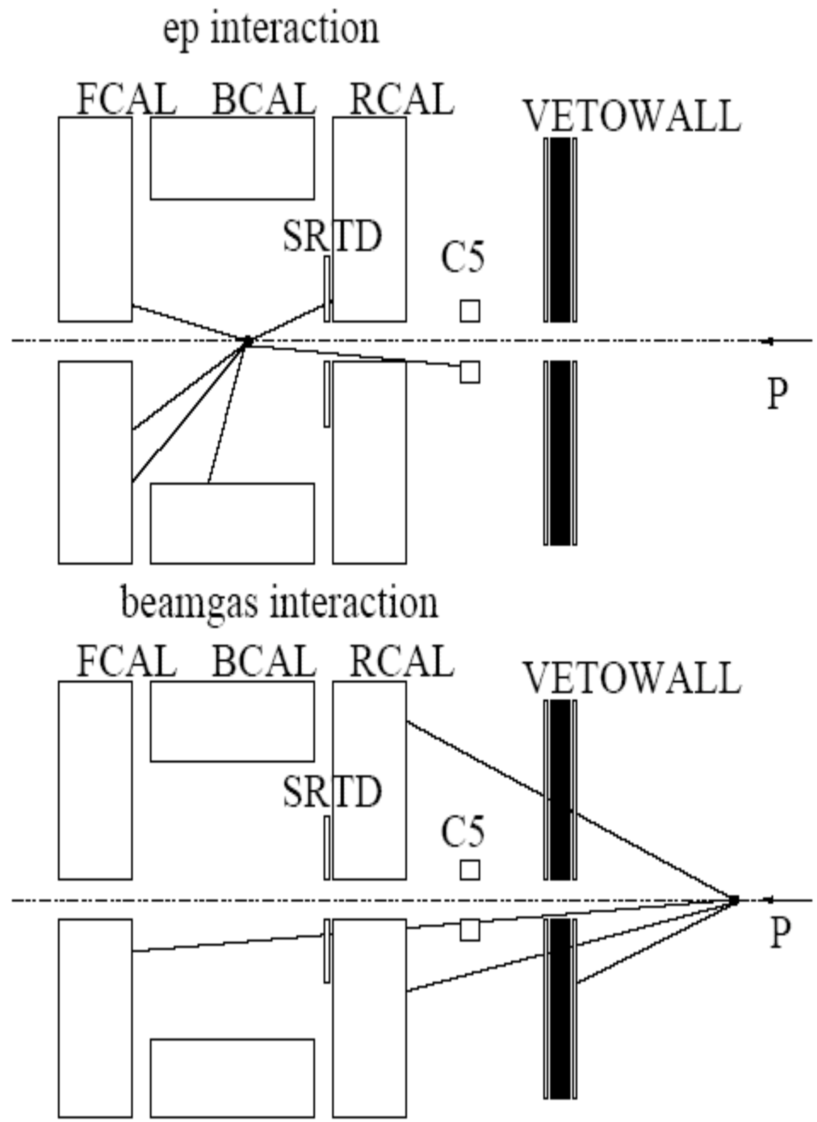
Pseudorapidity

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

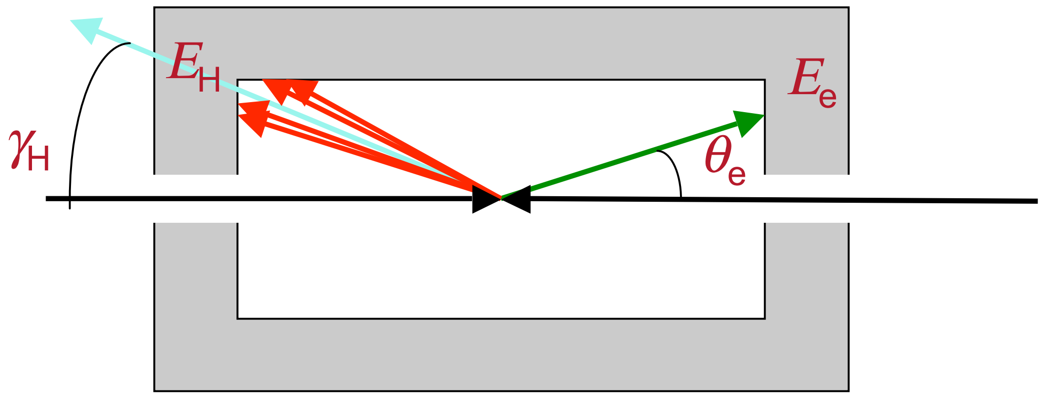
- **Plastic scintillator and depleted uranium**
- **99.8% Solid angle coverage**
- **Energy resolution (single particle test beam)**
  - **Electromagnetic: 18%/√ E(GeV)**
  - **Hadronic: 35%/√ E(GeV)**
    - Compare to 50%/√ E for H1
- **Measures energy and position of final state particles**

Online Event Selection: ZEUS Trigger

- **First level: Selects subset: 10 MHz → 500 Hz**
  - **Analyze every crossing**
  - **Reject Backgrounds:**
    - Beam-gas Events (99% 100-200kHz)
- **Second level: 500 Hz → 100 Hz**
  - **Calorimeter timing cuts**
  - **$E - p_z < 55$ GeV**
  - **Energy, momentum conservation**
  - **Vertex information**
- **Third level: 100 Hz → 1 Hz**
  - **Full event information**
  - **Refined jet and electron finding**
  - **Complete tracking algorithms**



NC Kinematic Reconstruction



Four Measured Quantities:

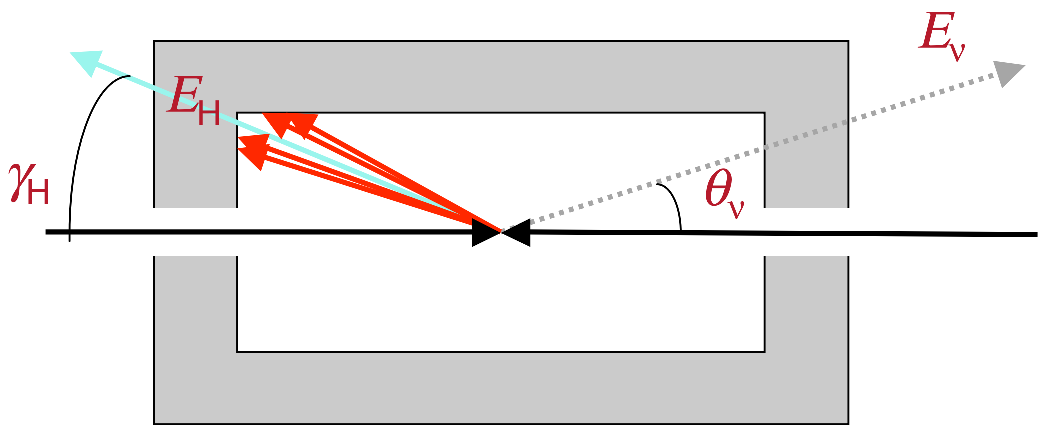
- E'_e : Electron Energy
- θ_e : Electron Angle
- E_H: Hadronic Energy
- γ_H: Hadronic Angle

Two Independent Variables

- Q^2,y (Q^2 = sxy)

Variable	Double angle method (γ_H,θ_e)	Electron method (E'_e,θ_e)
Q^2	$\frac{4E_e^2 \sin\gamma_H (1+\cos\theta_e)}{\sin\gamma_H + \sin\theta_e - \sin(\gamma_H+\theta_e)}$	$2E_e E'_e (1+\cos\theta_e)$
x	$\frac{Q^2_{DA}}{sy_{DA}}$	$\frac{Q^2_{EL}}{sy_{EL}}$
y	$4E_e^2 \frac{(1+\cos\theta_e)\sin\gamma_H}{\sin\gamma_H + \sin\theta_e - \sin(\gamma_H+\theta_e)}$	$1-\frac{E'_e}{2E_e}(1-\cos\theta_e)$

CC Kinematic Reconstruction



Two Measured Quantities:

- E_H: Hadronic Energy
- γ_H: Hadronic Angle

Two Independent Variables

- Q^2,y ($Q^2 = sxy$)

Variable	Jaquet-Blondel (E_H,γ_H)
Q^2	$\frac{p_{t,H}^2}{1-y_{JB}}$
x	$\frac{Q_{JB}^2}{sy_{JB}}$
y	$\frac{\sum_H (E_H - p_{z,H})}{2E_e}$

Zeus-H1 ep Kinematic Range

H1/ZEUS: General Purpose detectors at HERA

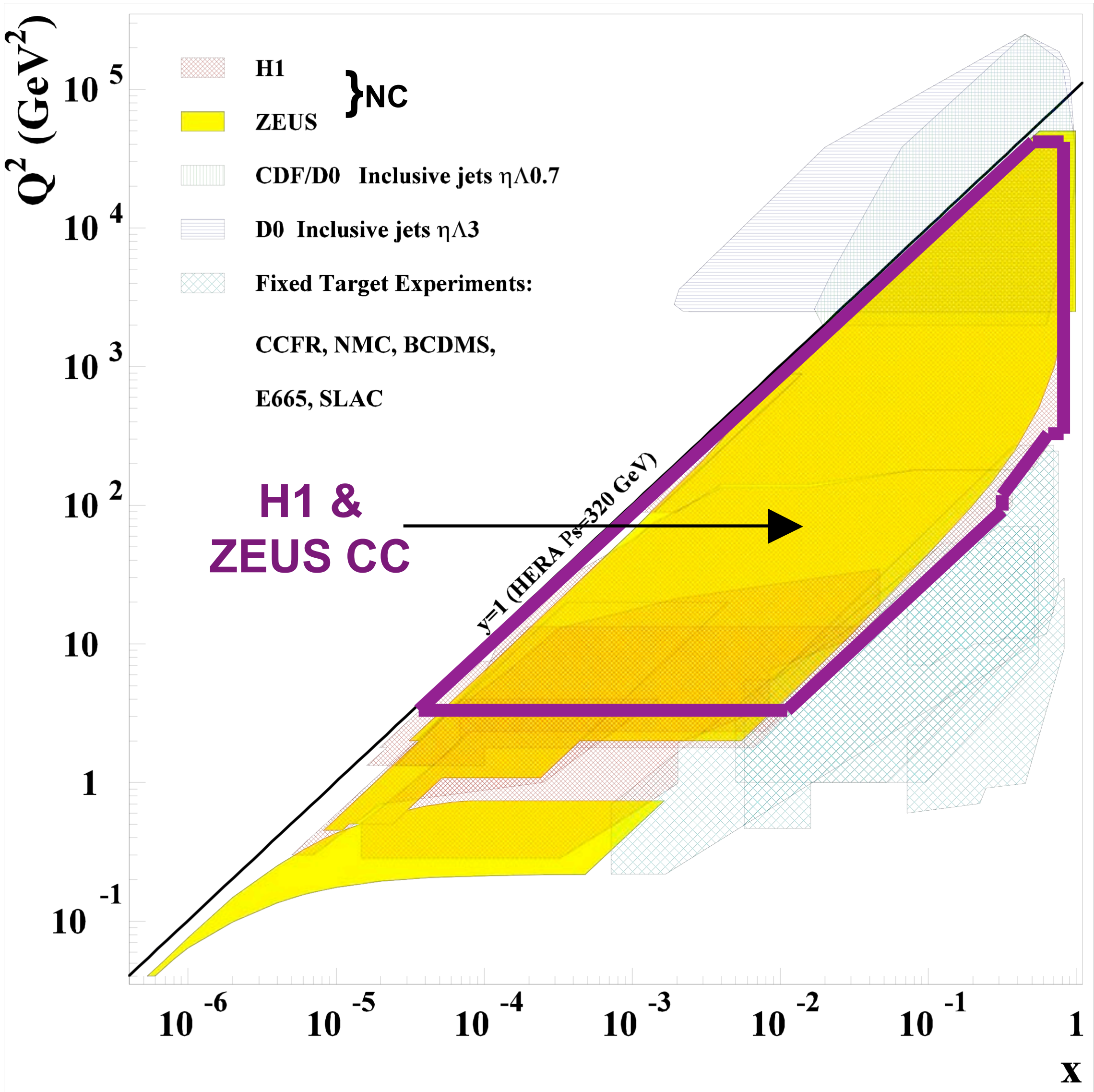
- ep at 318 GeV^2

CDF/D0: General Purpose Detectors at Tevatron

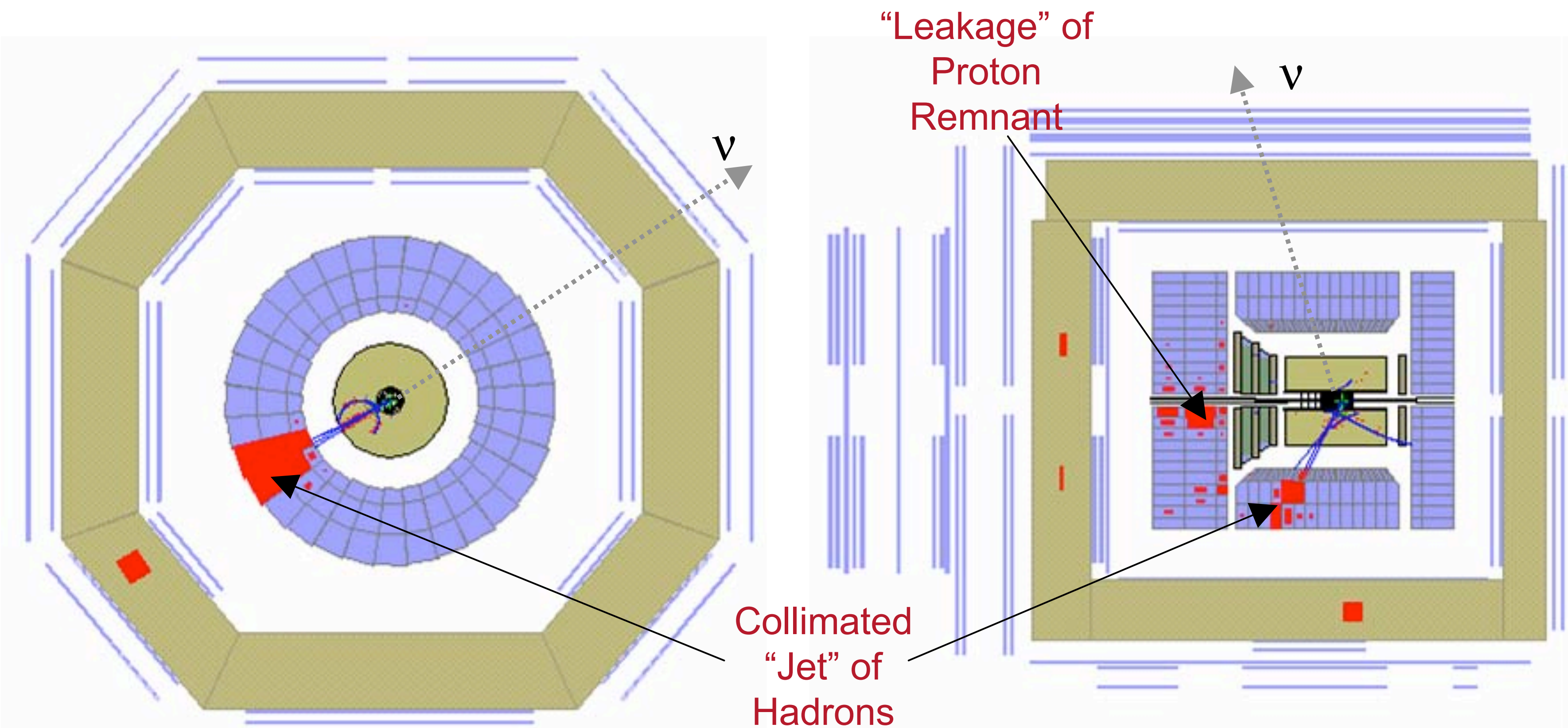
- $p\bar{p}$ at 1.8 TeV^2

Fixed target Experiments: Lower CME Experiments

- CCFR: Neutrino 600 GeV beam (Fermi)
  - $0.015 < x < 0.65$
  - $1.3 < Q^2 < 501$ GeV^2
- NMC: μ on p (CERN)
  - $0.002 < x < 0.60$
    $0.5 < Q^2 < 75$ GeV^2
- BCDMS μ on carbon
  - $0.2 < x < 0.7$
  - $25 < Q^2 < 200$ GeV^2
- E665 μ on p
  - $0.0008 < x < 0.06$
  - $0.2 < Q^2 < 75$ GeV^2
- SLAC E122 e on p,d
  - $.1 < x < .8$
  - $0.5 < Q^2 < 30$ GeV^2

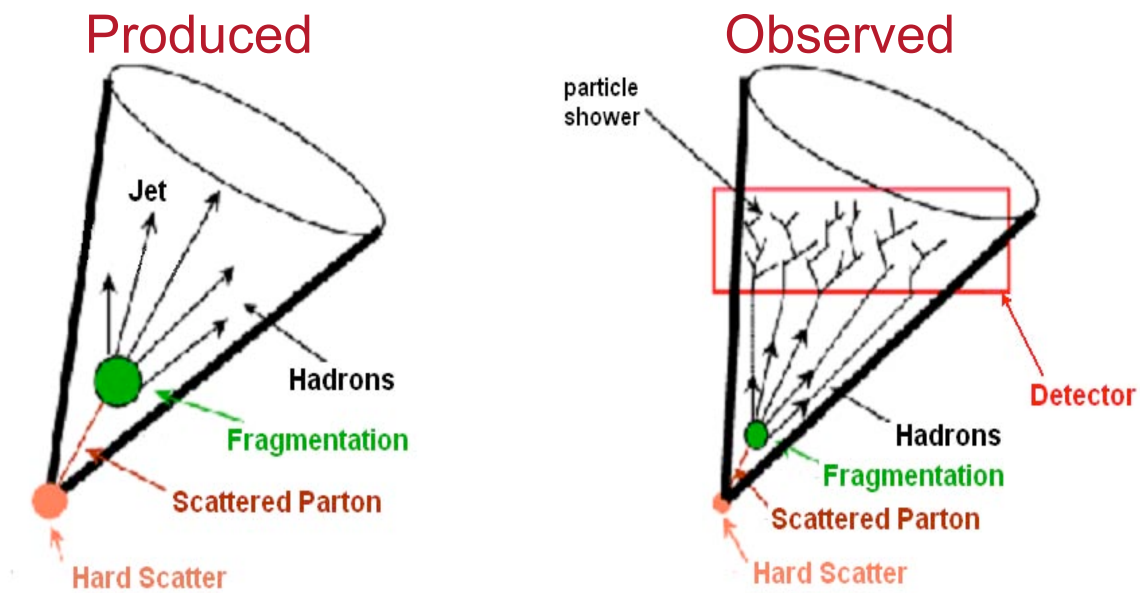


ZEUS CC DIS Event



- Proton remnant goes down beampipe
- Neutrino escapes detector, no electron detected.
- Net p_T detected
- Hadrons produced

Jets and Hadronization



Colored partons produced in hard scatter → "Parton level"

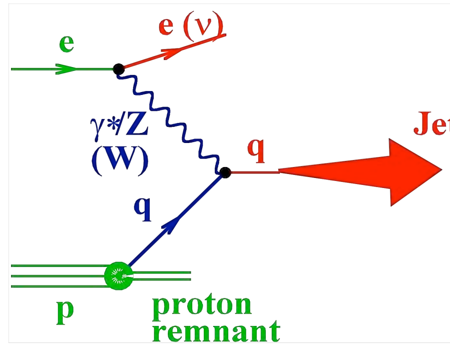
Colorless hadrons form through fragmentation → "Hadron level"

Collimated "spray" of real particles → Jets

Particle showers observed as energy deposits in detectors → "Detector level"

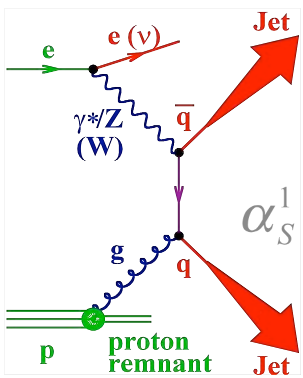
Jets at HERA

$O(\alpha^1 \alpha_S^0)$



1 jet

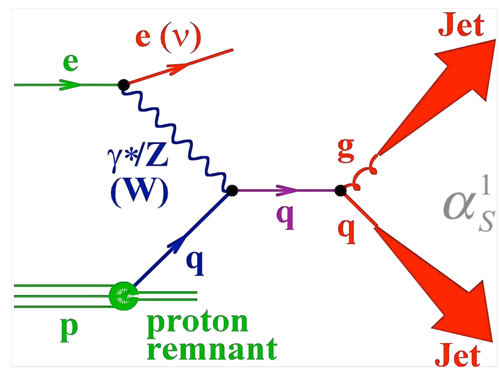
Boson-gluon fusion



$O(\alpha^1 \alpha_S^1)$

2 jets

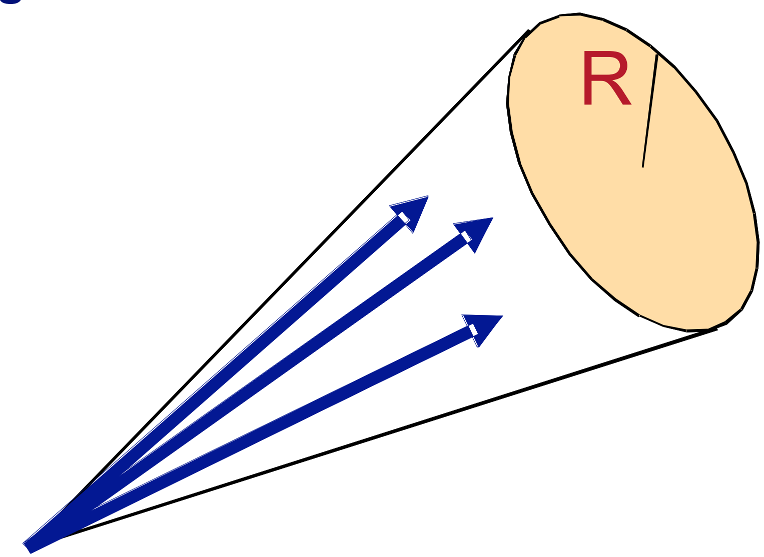
QCD Compton



- **To leading order, the jets in e^-p CC processes due to only to u quark, and only to d quark in e^+p CC processes.**
- **This creates a useful tool to test the SM predictions for individual flavor's splitting functions.**

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 in cone is maximized**
  - **Determine the merging of overlapping cones**
- **Issues:**
  - **Overlapping cones**
  - **Seed , Energy threshold**
  - **Infrared unsafe**
    - σ diverges as seed threshold → 0



Jet Finding: Longitudinally Invariant k_T Algorithm

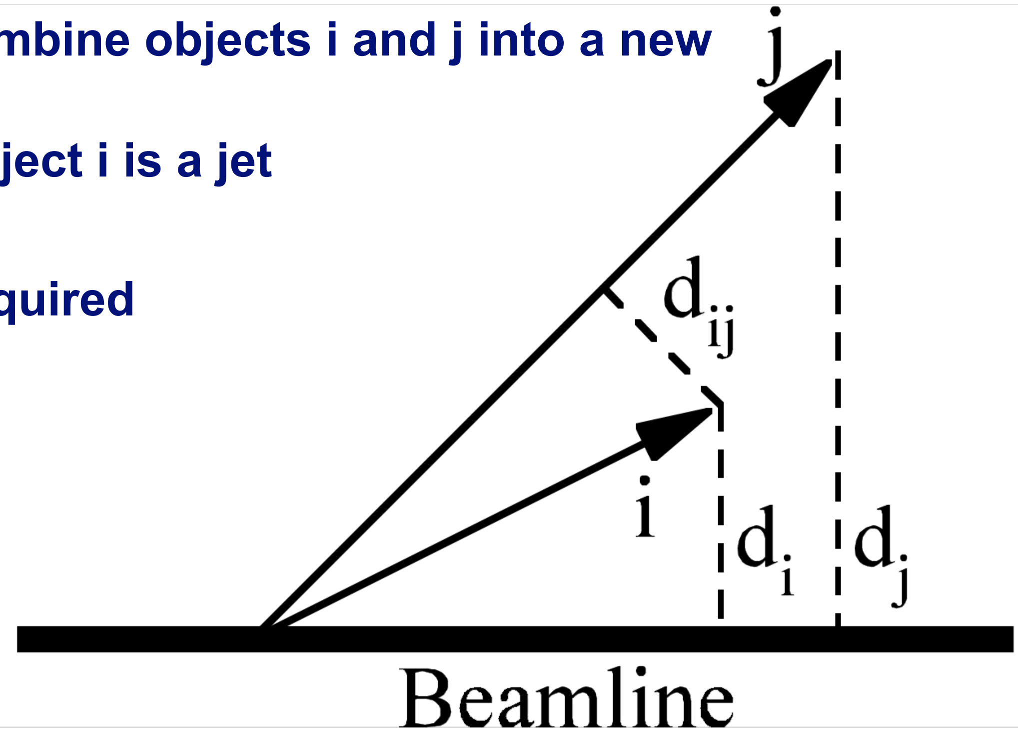
In ep: k_T is transverse momentum with respect to beamline

Algorithm

- **For every object i and every pair of objects i, j compute**
  - $d_i = E^2_{T,i}$ (distance to beamline in momentum space)
  - $d_{ij} = \min\{E^2_{T,i}, E_{2T,j}\}[D_h^2 + D_f^2]$ (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**



Monte Carlos (MCs)

Parton Level

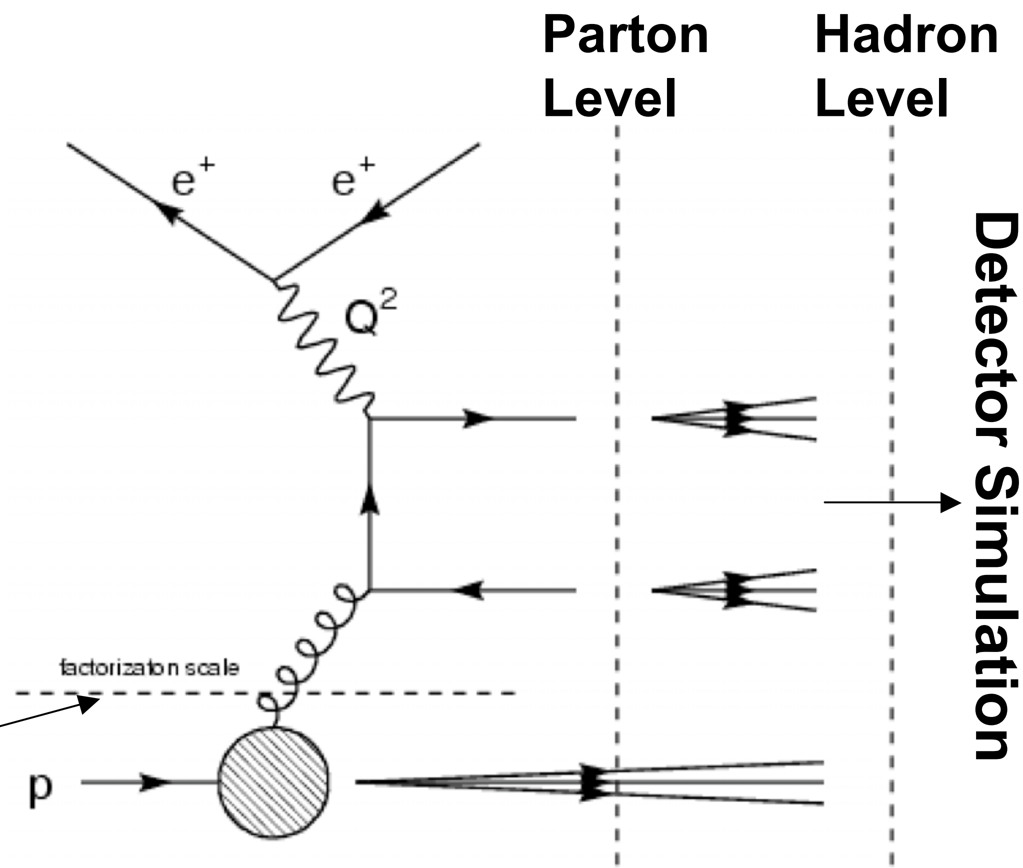
- QCD Crosssection

Hadron Level Model

- Fragmentation Model

Detector Level

- Detector simulation based on GEANT



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

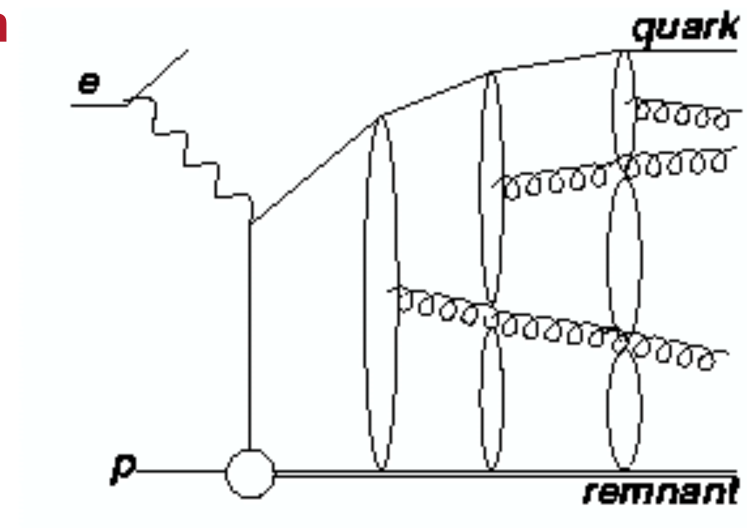
Leading Order (LO) MCs

Hard scatter calculated to leading order in pQCD. Higher order parton generation through approximations.

Two models used in this analysis:

ARIADNE: Color Dipole Model (CDM)

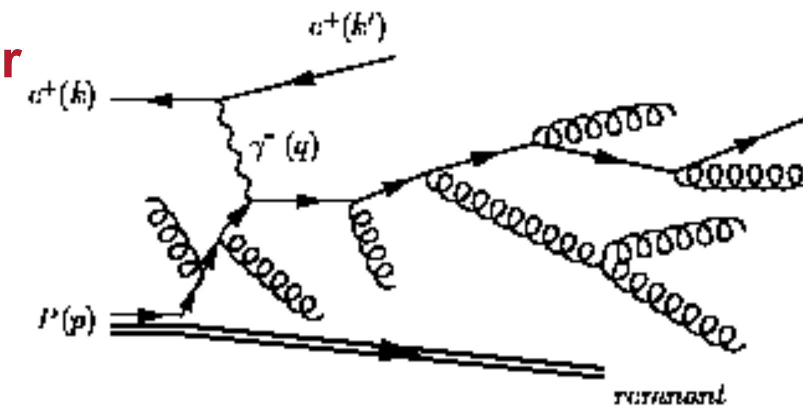
- **Gluons emitted from color field between quark-antiquark pairs**



CDM

LEPTO: Matrix Element + Parton Shower (MEPS)

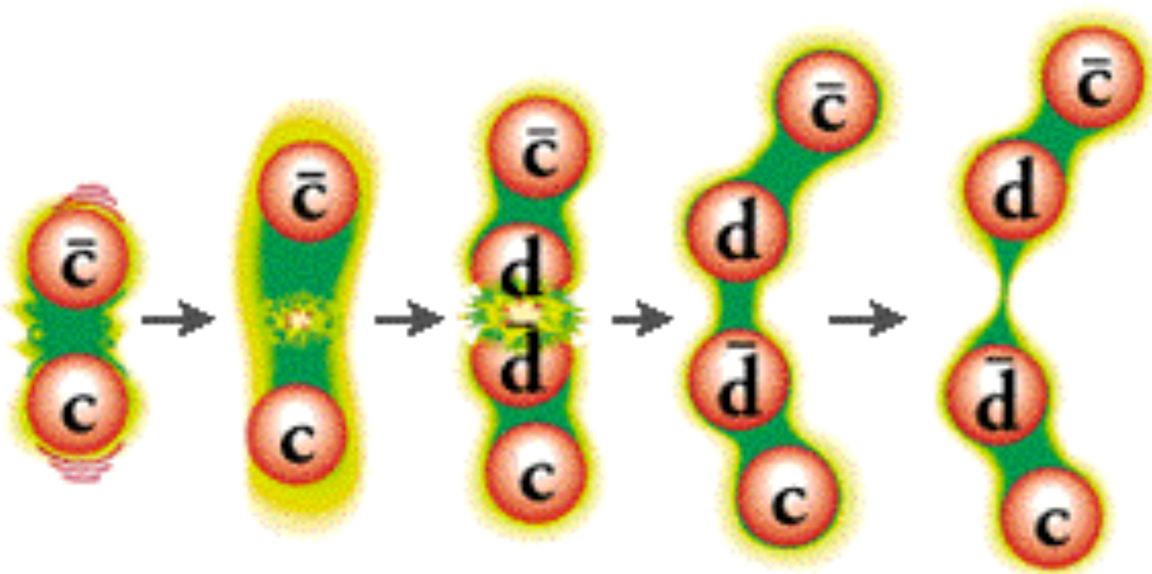
- **Parton cascade:**
- **Decreasing virtuality (q^2) as cascade progresses**

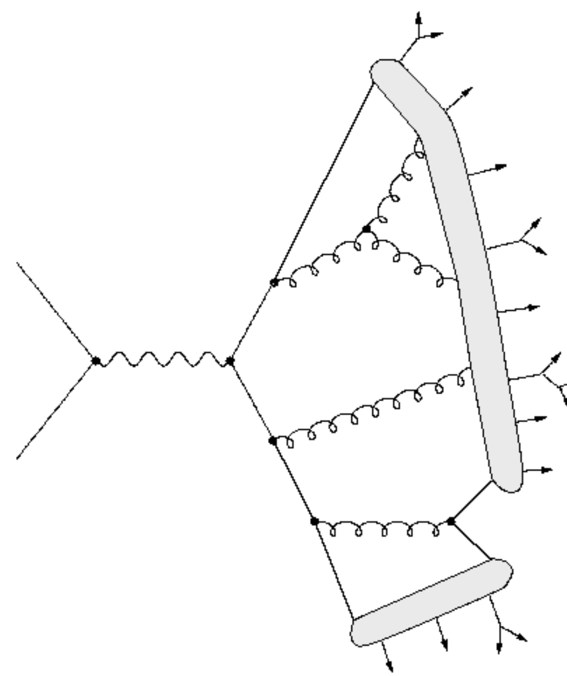


MEPS

Lund String Fragmentation

- Used by MCs to describe hadronization and jet formation.
- 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 remain.





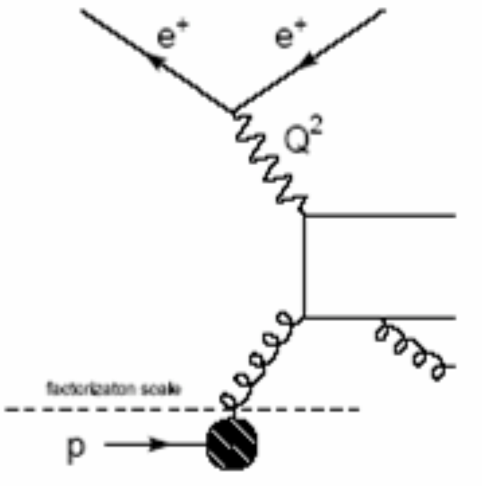
Next-to-Leading Order (NLO) Calculations: MEPJET

Inclusion of single gluon emission in dijet final state

- **Only terms of up to $O(\alpha_s^2)$ included for dijet calculations**
  - Exact calculation: does not include approx. for higher orders

NLO calculations include

- **One-loop corrections for virtual particles**
- **Correction for 3rd parton in final state (soft/collinear gluon emissions)**

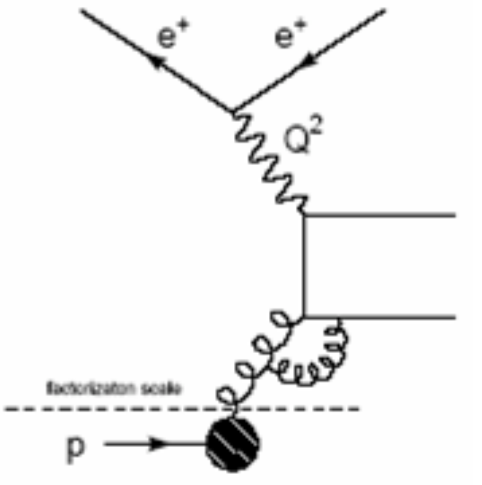


Corrections do not include

- **Parton showering**
- **Hadronization**
- **Corrections taken from Leading Order MC**

Uncertainties

- **Renormalization scale: scale for evaluating α_s**
- **Factorization scale: scale at which parton densities are evaluated**



ZEUS CC Dijet σ's

Calculations based on the SM (QCD+Electroweak) complemented with parton showers describe the behavior of jets in the region:

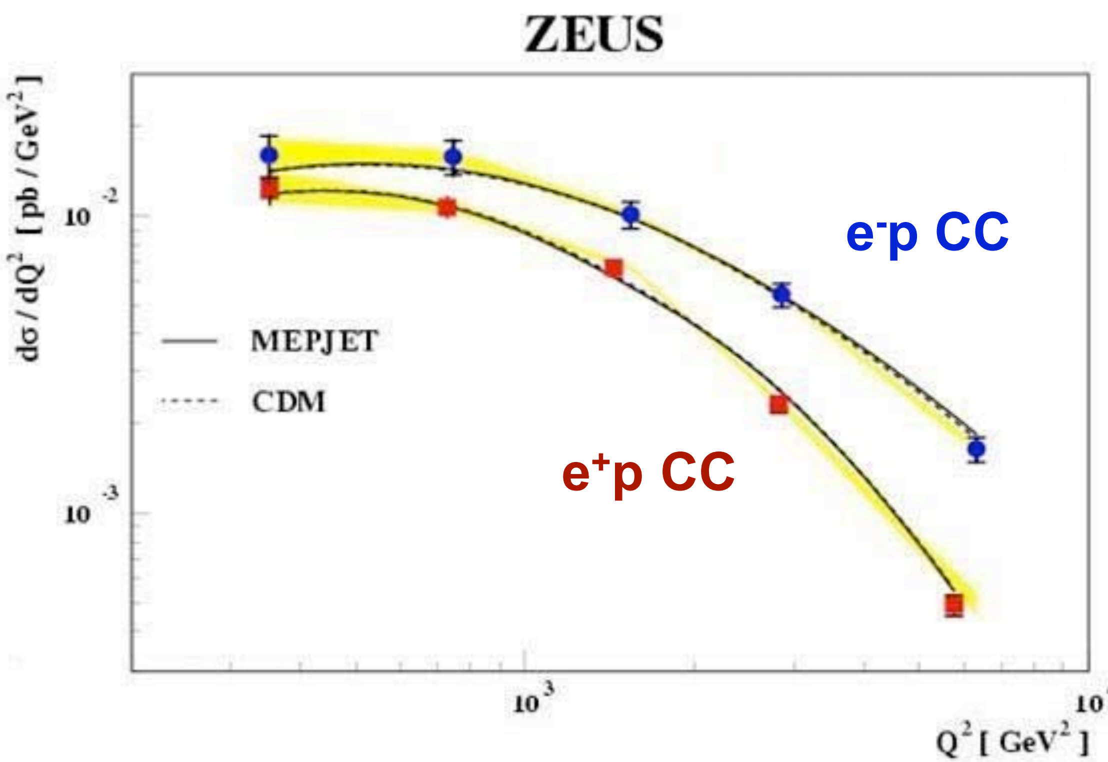
$Q^2 > 200 GeV^2$
$E_T^{jet1} > 14$ GeV(Lab)
$E_T^{jet2} > 5$ GeV(Lab)
$-1 < \eta^{jet} < 2$

I will use these established results to validate my analysis.

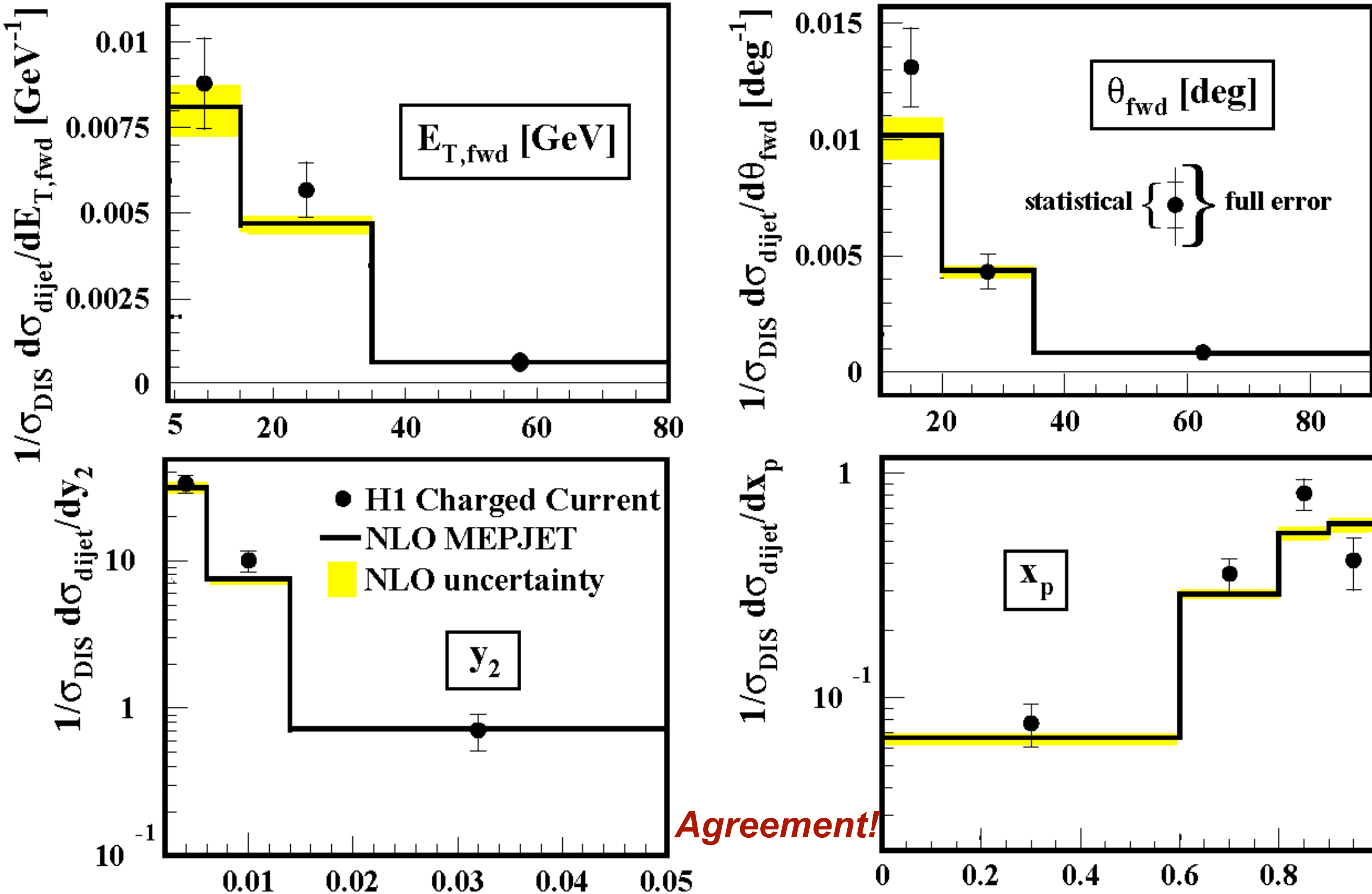
Eur.Phys.J. C31 (2003) 149-164:

Inclusive Dijet Cross-section vs. Q^2 for 98-00 ep CC Scattering

- 98-99 e-p CC (16.7pb)
- 99-00 e+p CC (65.5pb)



H1 CC Dijets vs. NLO



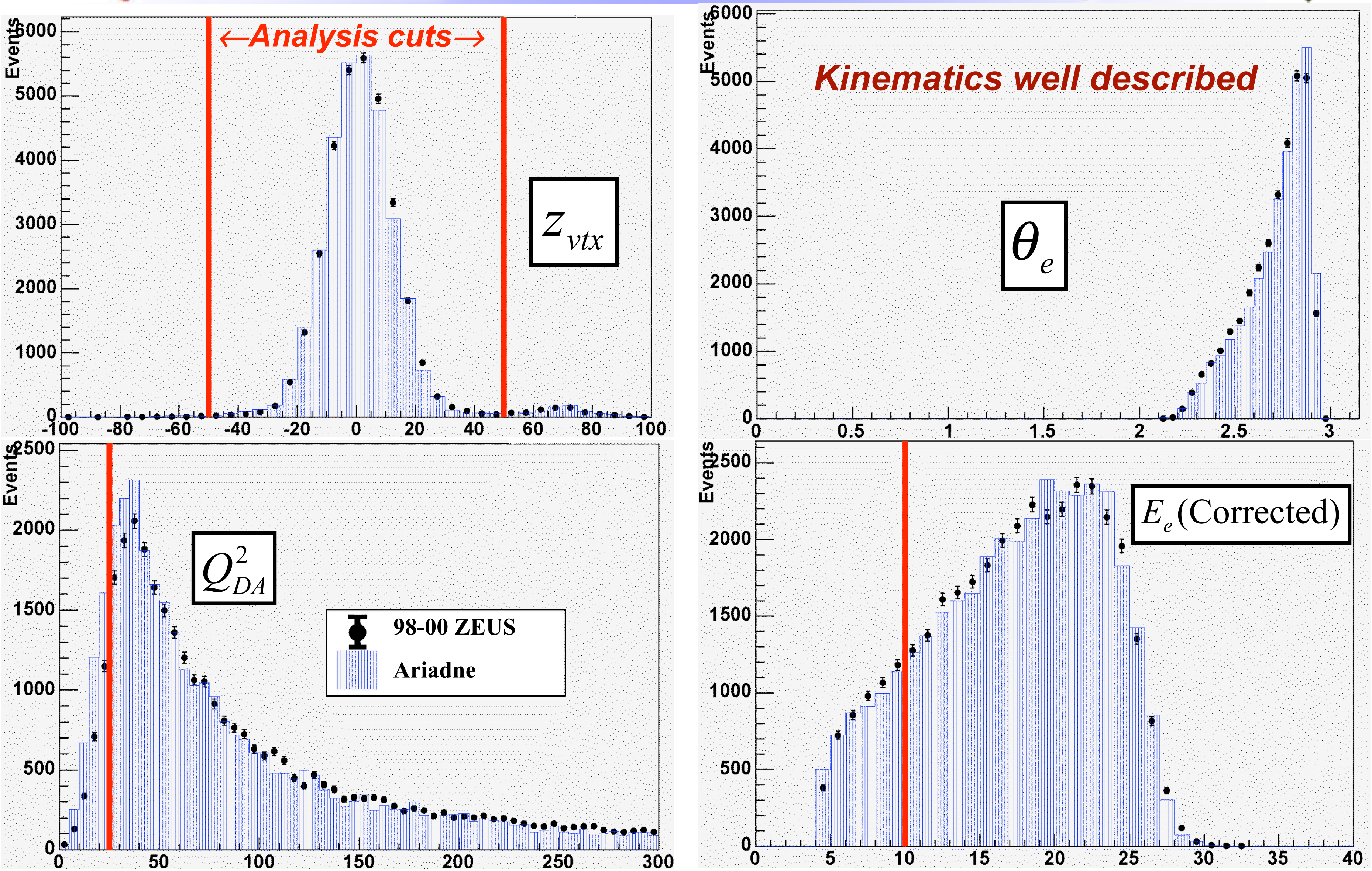
Agreement!

Validate Analysis: Previous ZEUS NC Dijets

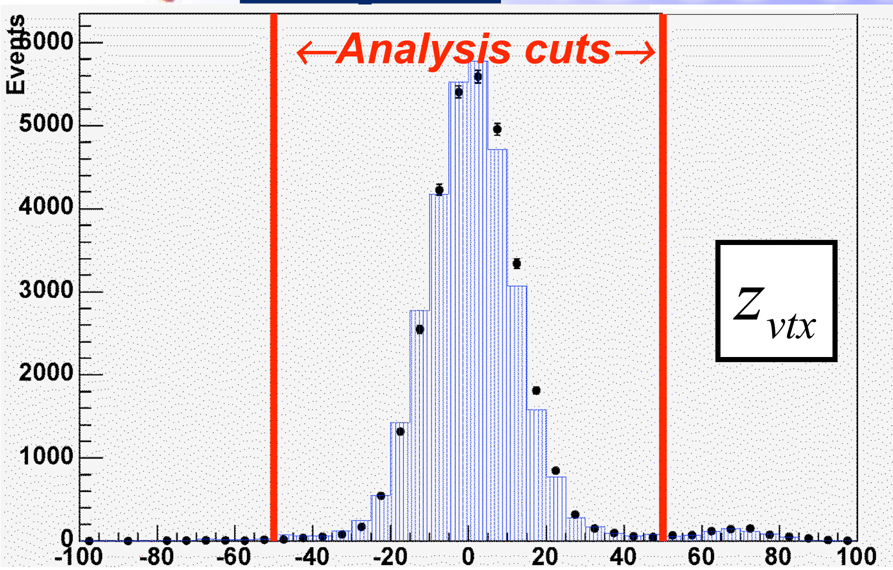
Data: 1998-2000 electron and positron: 82.2 pb-1

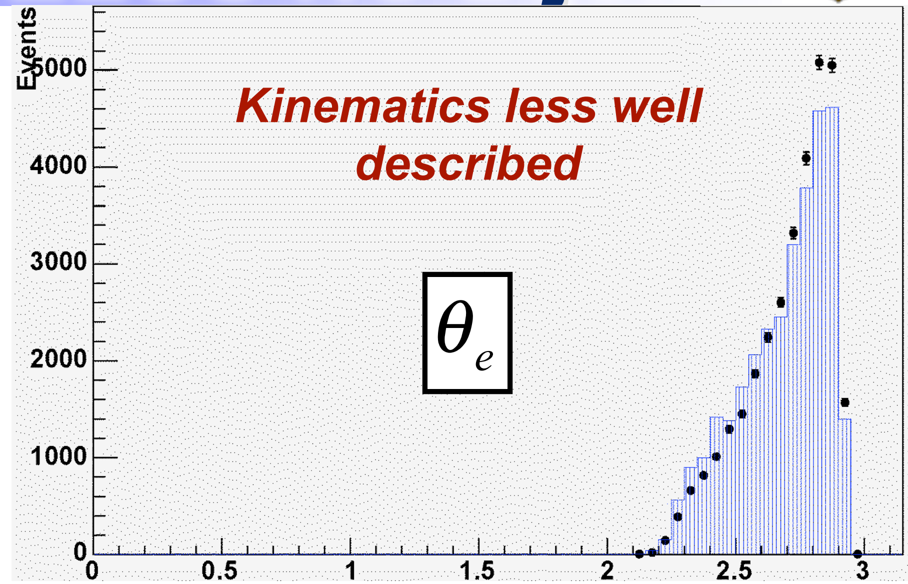
Remove background	
$|z\ \text{vertex}| < 50$ cm	Eliminate beam gas events
$40 < E - p_z < 60$ GeV	Eliminate cosmic, beam gas events
Select DIS	
$25\ \text{GeV}^2 < Q^2_{DA}$	
Select Dijets	
$y_{jb} > 0.04$	Requires minimum hadron energy
$y_{el} < 0.9$	Electron energy > 10 GeV
$|\eta_{jet}| > 2$ for both jets (lab frame)	Contained in calorimeter
$E_T > 5$ for both jets (lab frame)	Jet identification
$E_{T1} > 8$ $E_{T2} > 5$ (q-γ center of mass frame)	MC calculation region of validity

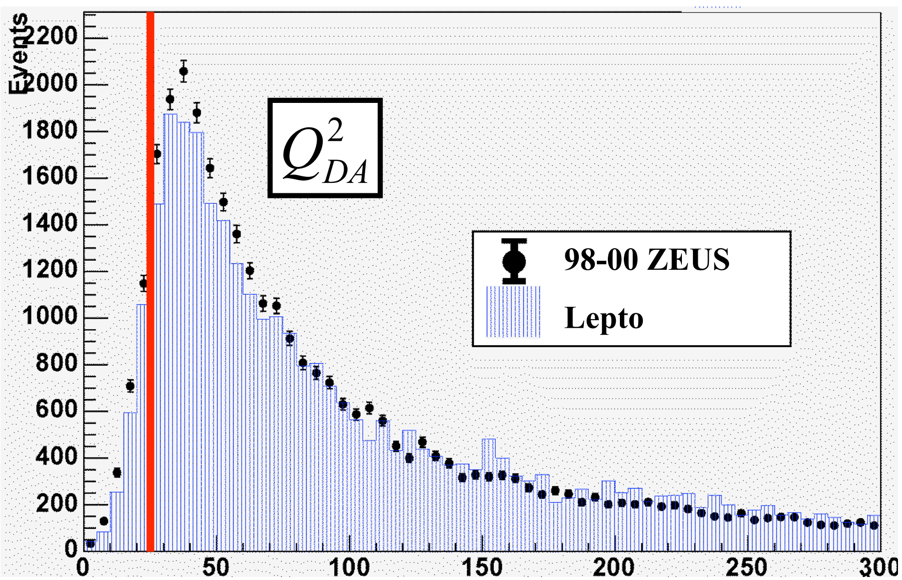
Event Kinematics: Ariadne vs 98-00 ZEUS NC Dijets

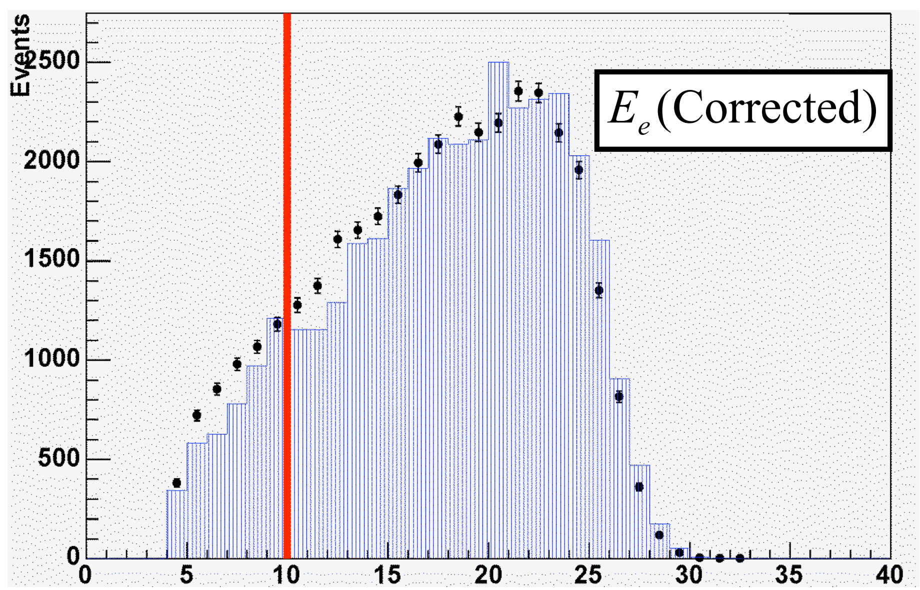


Event Kinematics: Lepto vs 98-00 ZEUS NC Dijets

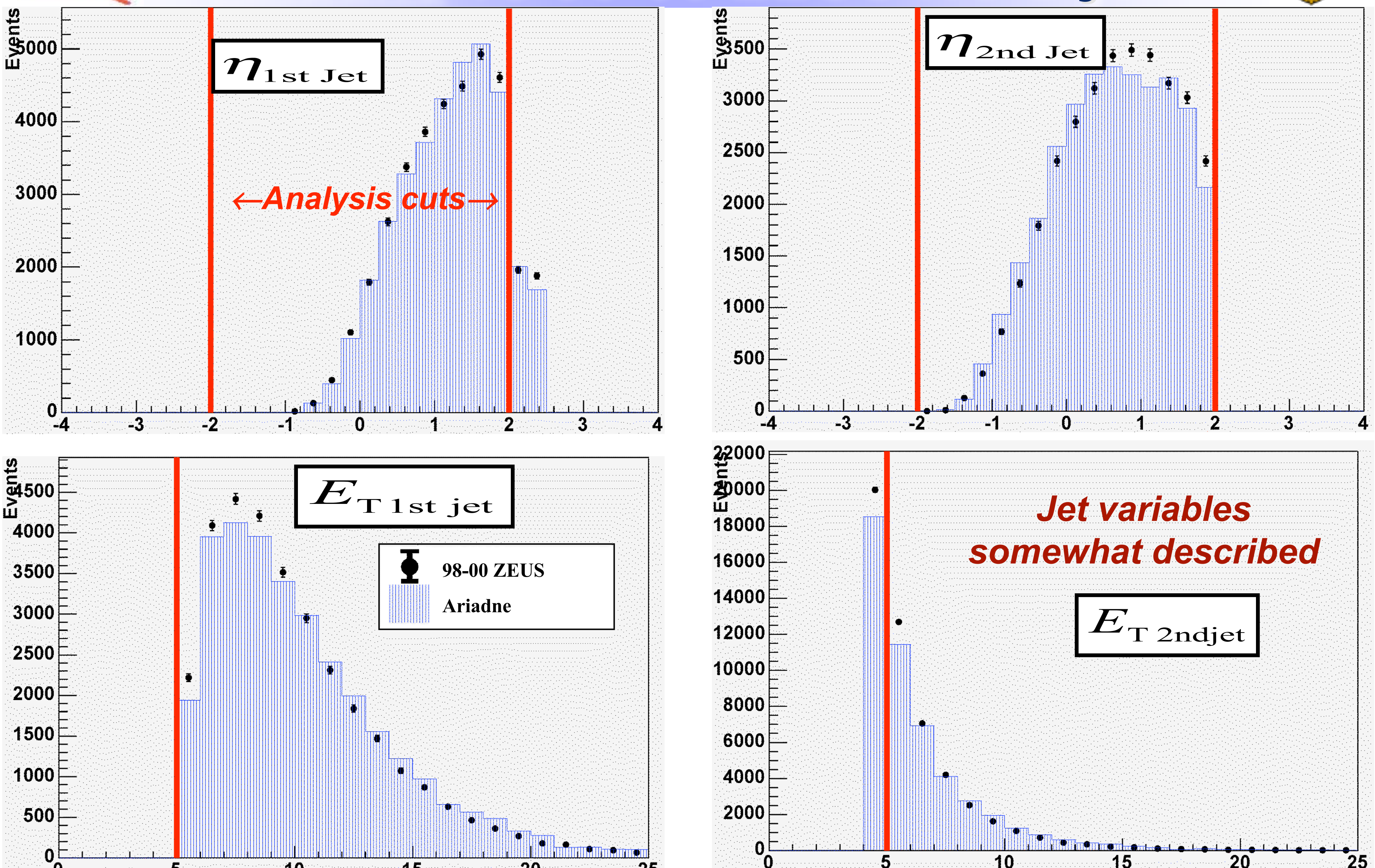




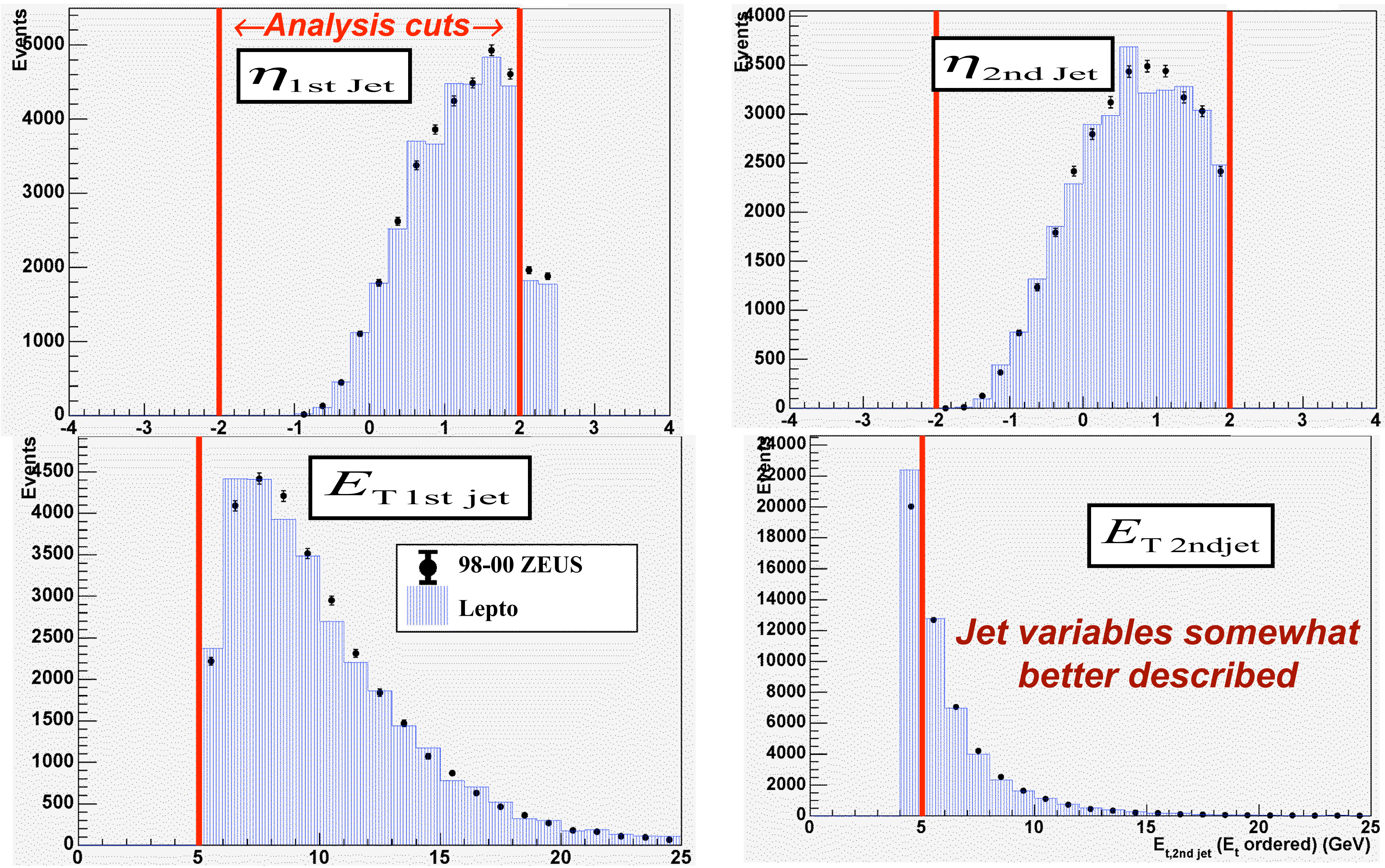




Jet Variables: Ariadne vs 98-00 ZEUS NC Dijets



Jet Variables: Lepto vs 98-00 ZEUS NC Dijets



New ZEUS CC Dijet Sample

Data: 2002-2005 electron and positron: 294 pb-1

Remove background	
|z vertex| < 50 cm	Eliminate beam gas events
Select DIS	
$200 < Q^2_{JB} < 17{,}000 GeV^2$	
Select Dijets	
p_T(CAL) > 11 GeV	Remove NC events
p_T(CAL) without 1st Ring>.8	Remove Beam Gas
n_{gt} ("good" tracks) > 0	Ensure good tracking
$n_{gt} / n_{tracks} > .2$	Remove Beam Gas
|φ(gt) - φ (CAL) |<1°; | p_T(gt)/ p_T(CAL)| >.1	Remove Beam Gas
Remove Events with "isolated CAL deposits"	Photomultiplier Discharge Sparks
-1 < η < 2 for both jets (lab frame)	Well Contained in Calorimeter
$E_{T1} > 14$, $E_2 > 5$ (lab frame)	Well reconstructed, MC region of validity

From prev analyses, we can estimate ~750 Dijets from 02-05 will be selected.

Summary & Plan

Summary

- CC jets offer a unique window into the SM and beyond.
- HERA II data offers chance to improve on previous measurements
  - higher statistics:
    - 02-05 e^-p > 7 x 98-00 e^-p.
    - 02-05 ep > 3.5 x 98-00 ep

Plan

- Analyze new high luminosity sample
- Compare with current pQCD calculations
- Systematic error study

Backup slides

DGLAP

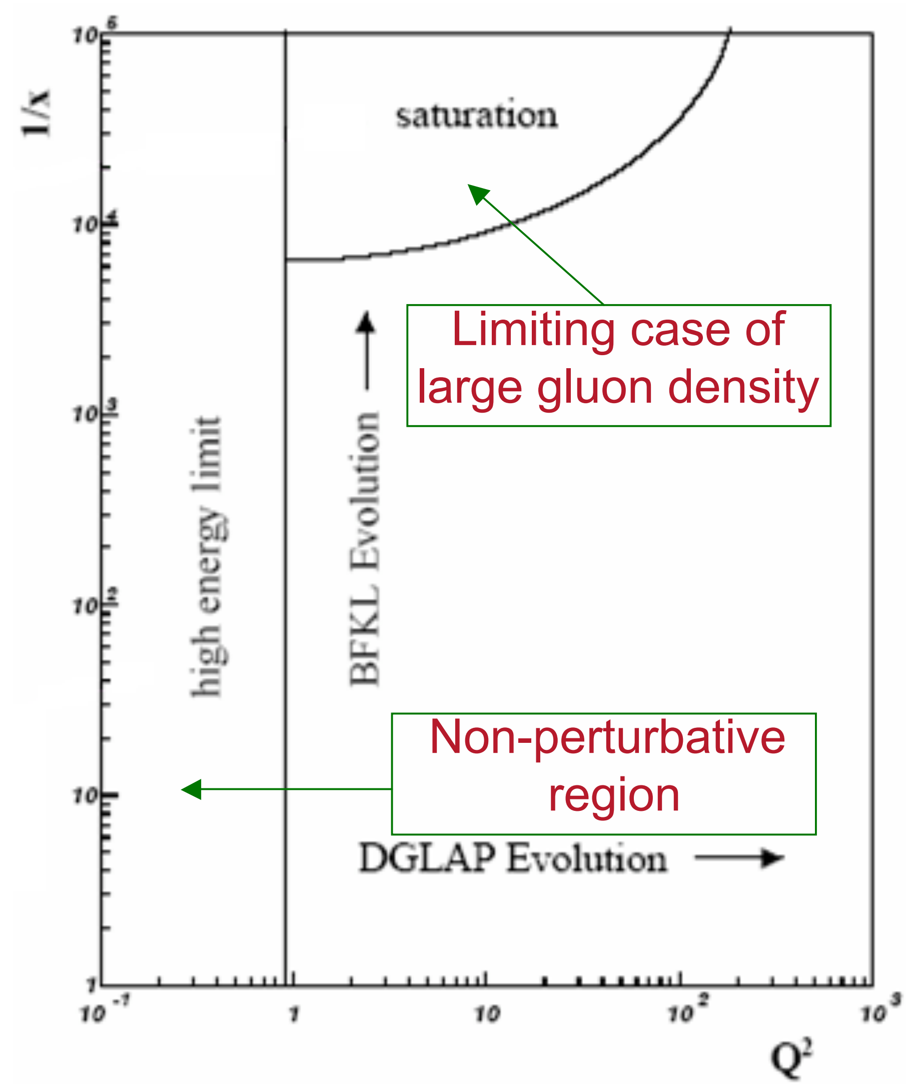
- Dokshitzer
- Gribov
- Lipatov
- Altarelli-Parisi

BFKL

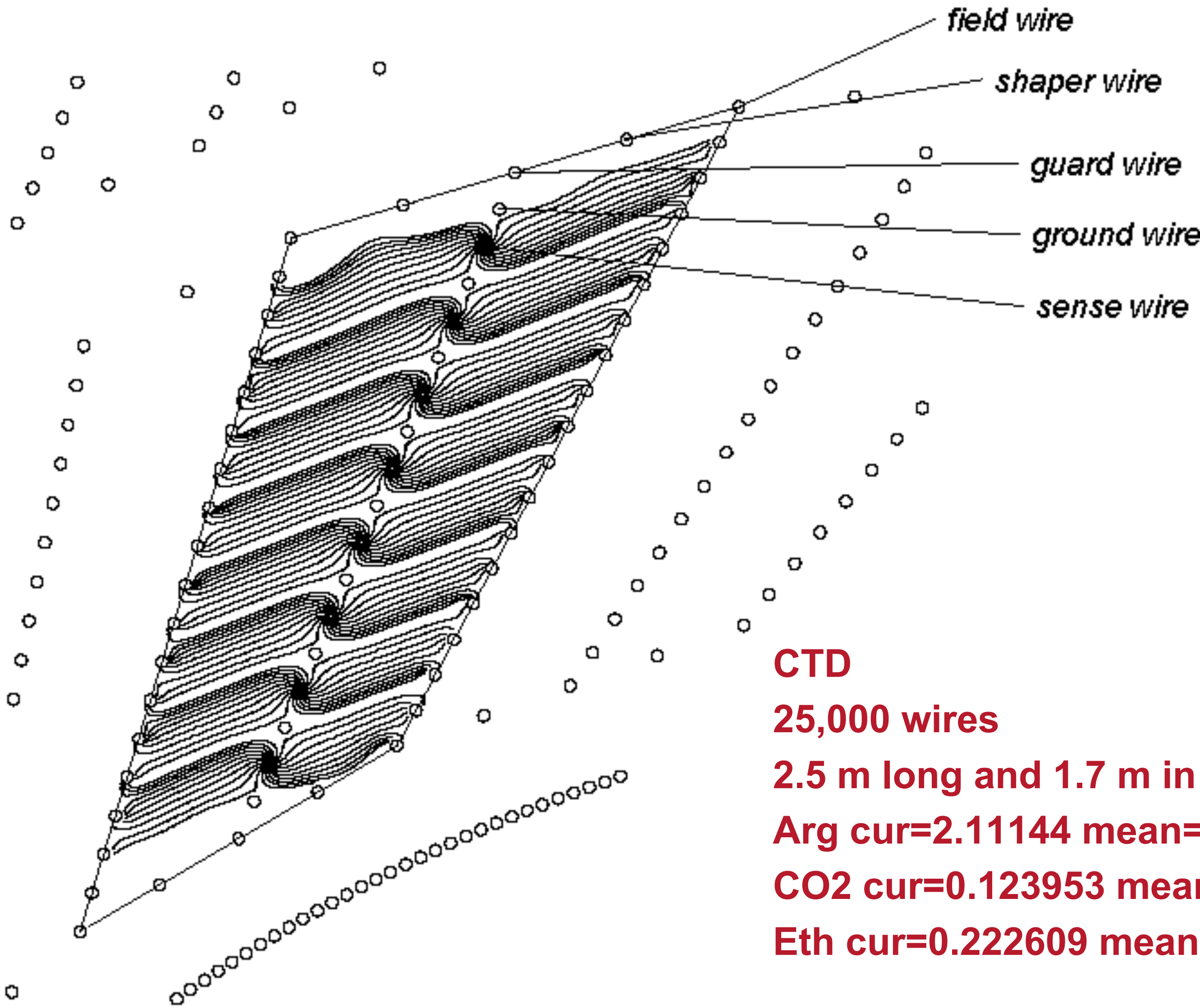
- Balitsky
- Fadin
- Kuraev
- Lipatov

BFKL and DGLAP apply in different kinematic regions

- DGLAP: high Q^2, x_{Bj}
  - Approximations do not include $ln(1/x_{Bj})$
- BFKL: low Q^2, x_{Bj}



CTD



CTD

25,000 wires

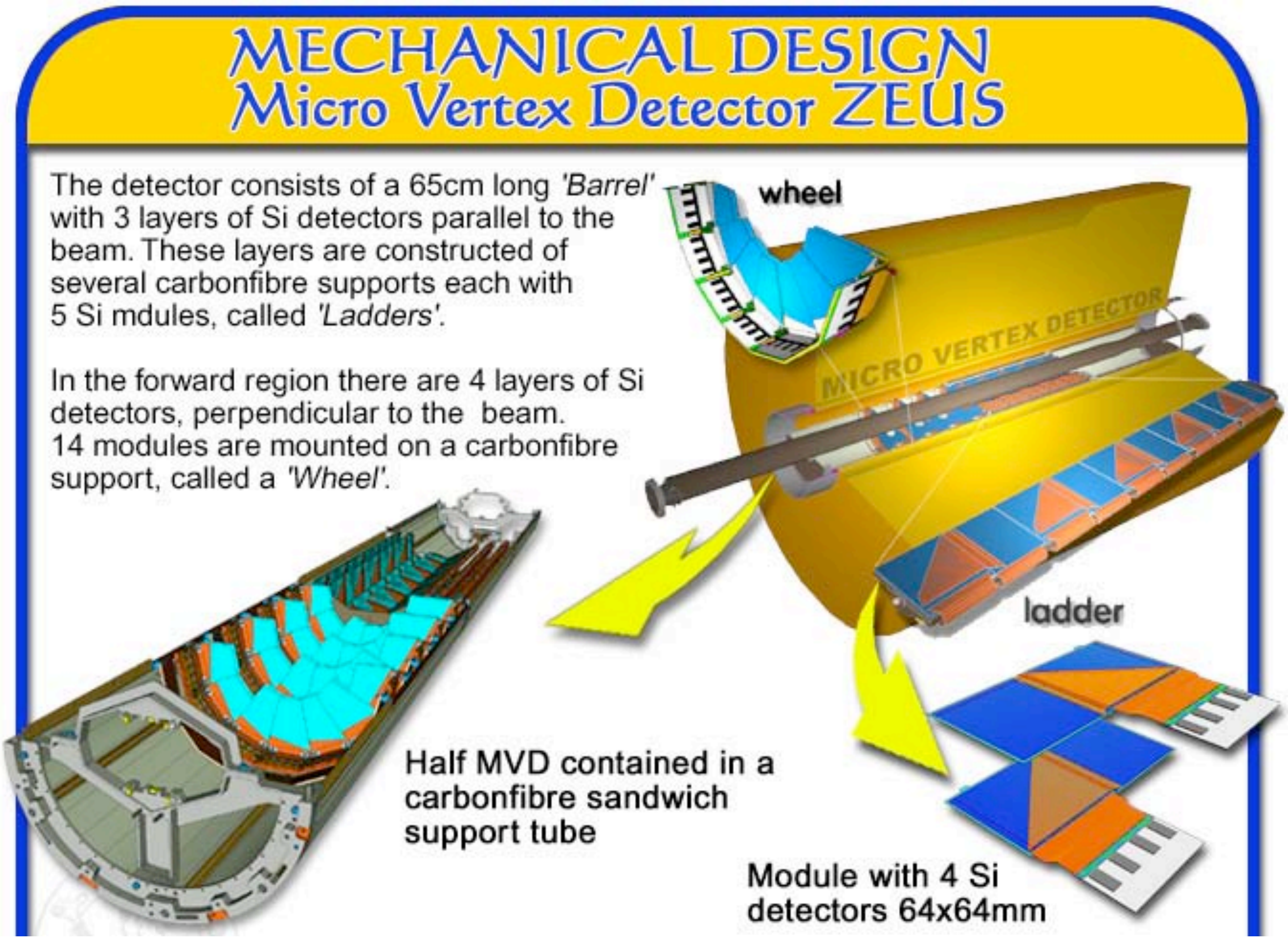
2.5 m long and 1.7 m in diameter

Arg cur=2.11144 mean=2.07625 L/m

CO_2 cur=0.123953 mean=0.125278 L/m

Eth cur=0.222609 mean=0.222669 L/m

MVD


MECHANICAL DESIGN
Micro Vertex Detector ZEUS
The detector consists of a 65cm long 'Barrel' with 3 layers of Si detectors parallel to the beam. These layers are constructed of several carbonfibre supports each with 5 Si mdules, called 'Ladders'.
In the forward region there are 4 layers of Si detectors, perpendicular to the beam. 14 modules are mounted on a carbonfibre support, called a 'Wheel'.
wheel
MICRO VERTEX DETECTOR
ladder
Half MVD contained in a carbonfibre sandwich support tube
Module with 4 Si detectors 64x64mm

Cal Specifics1

Cells in CAL?

Electroweak Mixing Angle

The coupling constants at γ, W+- and Z^0 vertices are not independent from each other.
In order for all infinities to cancel in electro-weak theory, the unification relation and the anomaly condition have to be fulfilled

The unification condition gives a relation between the coupling constants ($a_{em} = e^2/4pe_0$)

$$\frac{e}{2\sqrt{2\varepsilon_0}} = g_W \sin\theta_W = g_Z \cos\theta_W$$

q_w is the weak mixing angle or Weinberg angle

$$\cos\theta_W = \frac{M_W}{M_Z} \qquad M_W = 78.3 \pm 2.4 \quad GeV; \qquad M_Z = 89.0 \pm 2.0 \quad GeV$$

The anomaly condition relates electric charges: $\Sigma_l Q_l + 3\Sigma_q Q_q = 0$

M_W and M_Z were initially predicted for low energy interactions

$$\sin^2\theta_W = 0.227 \pm 0.014$$

$$\frac{G_Z}{G_W} = \frac{g_Z^2 M_W^2}{g_W^2 M_Z^2} = \sin^2\boldsymbol{\theta}_W$$

Boostin'

CMS energy 318 GeV

- Equivalent to 50 TeV fixed target

Luminosity

Luminosity is measured by ZEUS using the bremsstrahlung process.

The cross section of this process is very high, of the order of 20 mb, and it is known with an accuracy of 0.5%. The rate of photons produced with an angle smaller than 0.5 mrad with respect to the electron direction is measured by a lead-scintillator

electromagnetic calorimeter located at Z = -107m from the nominal interaction point. The calorimeter is shielded from the synchrotron radiation by a carbon-lead filter. The energy resolution is E = 23%=pE= GeV. The main source of background is the Bremsstrahlung of the electron in the residual gas present in the

beam pipe: the importance of this effect can be estimated using the pilot bunches.

The overall uncertainty on the luminosity measurement is in the range 1.5-2%

LUMI 92-05

- 92 e^- 0.03
- 93 e^- 1.09
- 94 e^+ 5.11
- 94 e^- 1.08
- 95e^+ 12.3
- 96e^+ 17.2
- 97e^+ 36.4
- 98e^- 8.08
- 99e^- 17.1
- 99e^+ 28.5
- 00e^+ 66.4

- 02-03e+ 5.20
- 03e+ 6.53
- 04e+ 77.9
- 04-05 e- 204

GEANT

Geant4 (for GEometry ANd Tracking) is a platform for "the simulation of the passage of particles through matter." It is the most recent in the GEANT series of software toolkits developed by CERN, and the first to use Object oriented programming (in C++). According to its website, "Its application areas include high energy physics and nuclear experiments, medical, accelerator and space physics studies."

Geant4 includes facilities for handling geometry, tracking, detector response, run management, visualization and user interface. For many physics simulations, this means less time need be spent on the low level

details, and researchers can start immediately on the more important aspects of the simulation.

Following is a summary of each of the facilities listed above:

- Geometry is an analysis of the physical layout of the experiment, including detectors, absorbers, etc., and considering how this layout will affect the path of particles in the experiment.
- Tracking is simulating the passage of a particle through matter. This involves considering possible interactions and decay processes.
- Detector response is recording when a particle passes through the volume of a detector, and approximating how a real detector would respond.
- Run management is recording the details of each run (a set of events), as well as setting up the experiment in different configurations between runs.
- Geant4 offers a number of options for visualization, including OpenGL, and a familiar user interface, based on Bash.

Luminosity

Luminosty

- N: events
- L: Integrated Lumi
- Luminosity:
- N_a:number of particles per bunch in beam a.
- U: circumference of ring
- n: bunches per beam
- V: velocity
- f: revolution frequency
- A: crossing cross section
- σ_x : stdev of beam profile

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

$$\frac{dN}{dt} \equiv \frac{dL}{dt} \bullet \sigma \qquad N = \sigma \int dt \left(\frac{dL}{dt}\right)$$

$$\Phi_a = \frac{dN_a/dt}{A} = \frac{N_a nv/U}{A} = \frac{N_a nf}{A}$$

$$\frac{dL}{dt} = f\frac{nN_aN_b}{A} = f\frac{nN_aN_b}{4\pi\sigma_y\sigma_x}$$

$$\frac{dL}{dt} \approx (50kHz)\frac{(200)(10^{10})(10^{10})}{(.01mm^2)}$$

$$= 10^{31}cm^{-2}s^{-1}$$

Calorimeter Specifics

Rapidity important because changes in rapidity are invariant under Lorentz boosts along the beam direction.

Pseudorapidity $\rightarrow$ Rapidity for m=0, β=1.

Rapidity. Calculate angles from the Energy and longitudinal momenta

$Y = 1/2 \log (E + p_z / E - p_z)$

Depleted Uranium, is 99.8% U^{238}, 0.25% U^{235}, and 0.001% U^{234} by Mass, Natural U has 0.72%U^{235}

So ours is depleted of U^{235}

e/h = 1

Calorimeter: EMC Depth : HAC Depth

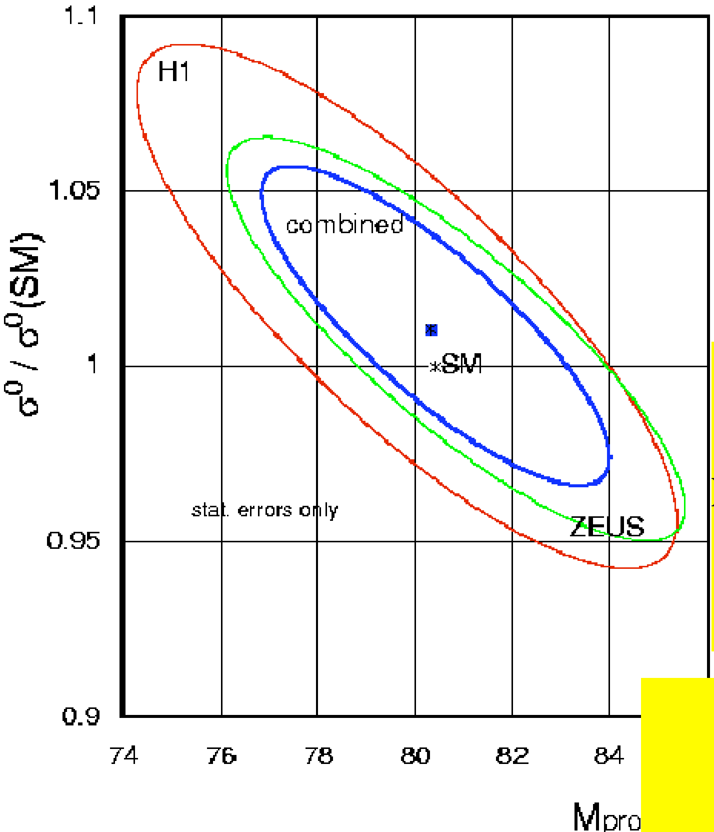
FCAL : 1λ : 6λ (6 nuclear interaction lengths)

BCAL : 1λ : 4λ

RCAL : 1λ : 3λ

λ=1 absorption length = 25 radiation lengths for electromagnetic particles

Backup Slides



Q² dependence of CC cross section includes propagator term

$$\sigma^0 = \sigma^{CC}\left(Q^2 = 0\right)$$

Charged Current DIS - Fitting M_W

$$\frac{d\sigma^{CC}}{dQ^2} \propto G_F^2 \left(\frac{M_W^2}{Q^2 + M_W^2} \right)^2$$

Fit shape of $\frac{d\sigma}{dQ^2}$ for M_W

$\mathrm{H1}: M_W = 80.9 \pm 3.3 \pm 1.7 \pm 3.7\ \mathrm{GeV}$

$\mathrm{Z}: M_W = 81.4 \pm 2.7 \pm 2.0 \pm 3.3\ \mathrm{GeV}$

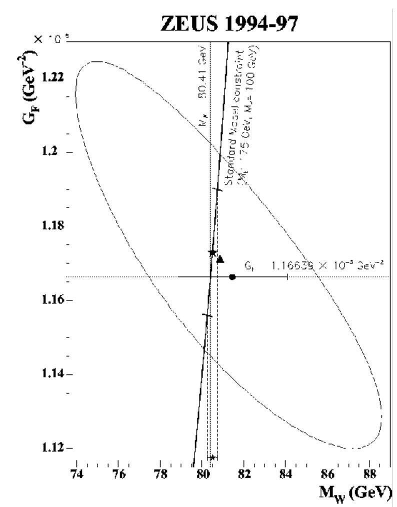
Errors : Stat.; Sys.; PDF

Standard Model constraint :

$$G_\mu = f\left(M_W; M_\mathrm{H}, M_Z, m_t\right)$$

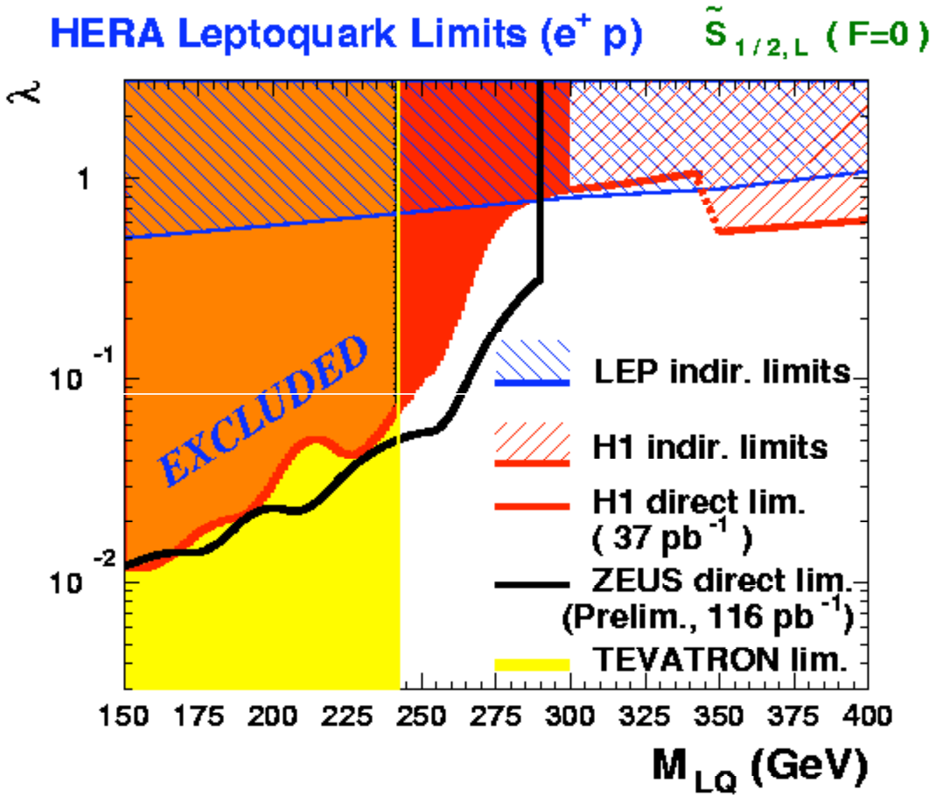
$$\mathrm{Z}: M_W = 80.50^{+0.24}_{-0.25}\,{}^{+0.13}_{-0.16}\,{}^{+0.30}_{-0.31}\,{}^{+0.03}_{-0.06}\ \mathrm{GeV}$$

Errors : Stat.; Sys.; PDF; $\Delta M_\mathrm{H}, \Delta M_Z, \Delta m_t$



Leptoquarks at HERA

Analysis of 1999 -2000 Data



LEP -Virtual effects to hadronic xsec

Tevatron - LQ produced via strong coupling

HERA - Stringent limits for intermediate mass range

Excess in old data not confirmed by New DATA H1 / ZEUS

→ Derive Limits on LQ couplings λ and Masses M_{LQ} (In BRW Model)

H1 Detector At HERA

Fine Grained Liquid Argon Calorimeter (~45,000 Channels)

EM section

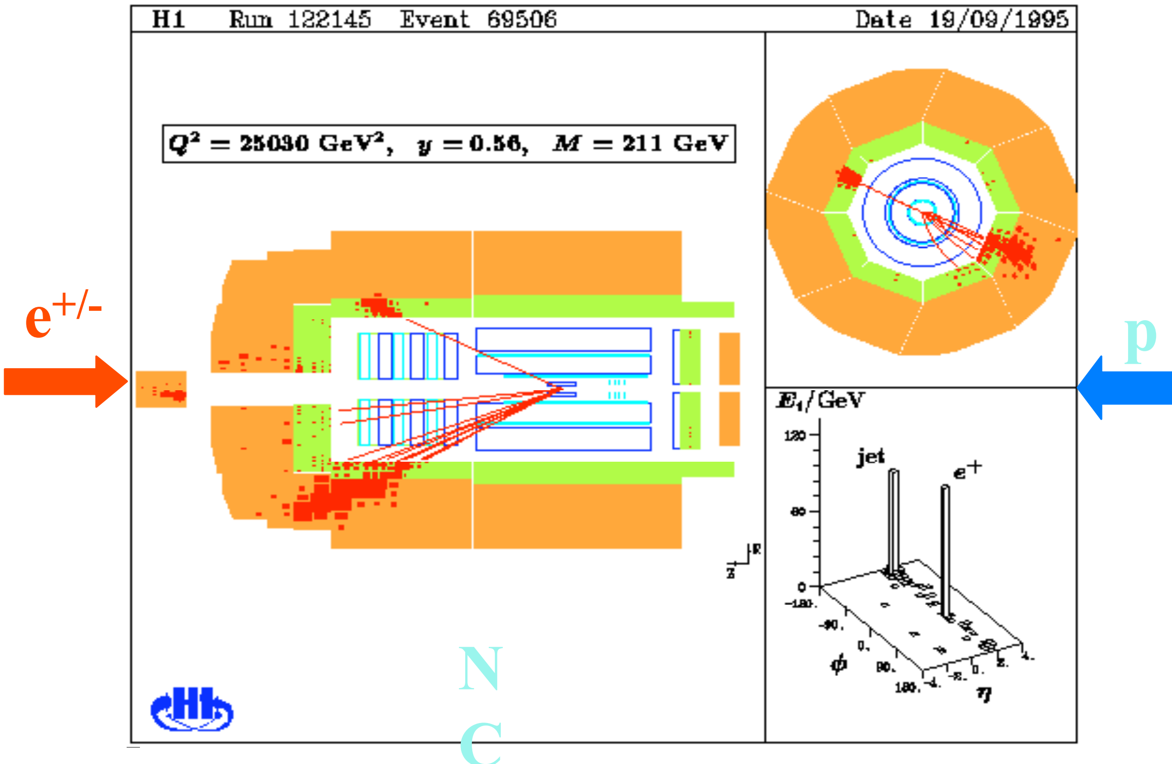
$$\frac{\delta E}{E} = \frac{12\%}{\sqrt{E}} \oplus 1\%$$

HAD section

$$\frac{\delta E}{E} = \frac{50\%}{\sqrt{E}} \oplus 1\%$$

Tracking Chambers

$$\sigma_p / p \approx 0.003p$$



Backup Slide

The history of particles

1911Ernest Rutherford* publishes his famous paper *The scattering of alpha and beta particles by matter and the structure of atoms*, in which measurements made by among others Hans Geiger and Ernest Marsden in 1909 were analysed. Rutherford explains the results of such measurements by the atom having all its mass concentrated to a nucleus of less than 10-14 m. This discovery marks the birth of nuclear physics.1919Ernest Rutherford demonstrates free protons by bombarding nitrogen with alpha particles. He concludes that nuclei have an inner structure.

1932James Chadwick* discovers the neutron and Werner Heisenberg* proposes that the nucleus consists of protons and neutrons, together termed nucleons.

1933-1934Otto Stern* and his co-workers discovers that the proton and the neutron have unexpectedly large (anomalous) magnetic moments. This is interpreted to mean that nucleons are not point-like, but occupy a certain volume, and can thus possess an inner structure.

1935A first model of how nucleons can form stable nuclei (strong interaction) is presented by Hideki Yukawa*.

1950sIt is discovered that the nucleon (like the atom and the nucleus) can be excited to higher energy levels. A large number of new particles, hadrons, related to the nucleon, are discovered. Robert Hofstadter* and his co-workers study the structure of protons and neutrons at the electron accelerator at Stanford. Using electron energies of up to 1 GeV (1 GeV is 109 eV) they measure how charge and magnetism are distributed within the nucleons. It is found that the distributions give a picture of the nucleons as "soft spheres".

1964Murray Gell-Mann* and Georg Zweig propose a model for the hadrons which, among other things, can theoretically describe the magnetic properties of the nucleon. The model requires three new elementary particles, which Gell-Mann calls quarks. But it is by no means clear that the quarks are true particles – they are perhaps only theoretical tools without experimental reality. Be that as it may, no free quarks are discovered.

1967The SLAC-MIT experiment starts at the new electron accelerator in Stanford. Jerome I. Friedman*, Henry W. Kendall*, Richard E. Taylor* and their co-workers obtain in 1968 the first indications that the nucleons have an inner structure with point-like scattering centres. These are later interpreted as being quarks.Since 1968, Intensive research into the inner structure of the nucleons starts all over the world, and is still continuing. * Nobel Laureates

HERA Specifics

HERA Circumference: 6336 m

Synchrotron radiation is lin. pol. in plane of acceleration.

Mean energy loss per revolution: for Electrons: ~8MeV

Fixed target: $E_{CM}=S=\sqrt{2E_1m_2}$

Colliding Beam: $E_{CM} = S=\sqrt{4E_1E_2}$

Luminosity: $L = f\, n_1\, n_2/4\pi\, \sigma_x\sigma_y$

N1,n2 number of particles in bunch

f=frequency

$\sigma_x\sigma_y$ characterize beam profiles in horizontal and vertical direction

~10^{11} Protons/Bunch

~3.5×10^{10} e/Bunch

Current: 1.6×10^{-19} q/C

Vacuum Pressure: 3×10^{-11} Torr

e+ beam: 0.165 T B field

P beam: 4.65 T B field

Spaces left in beam so kicker magnets can dump beam, study beamgas

Sokholov-Ternov Effect: e- polarized with spin antiparallel to dir. of bending field (transverse)

SLAC-MIT: First View of p Substructure

1968

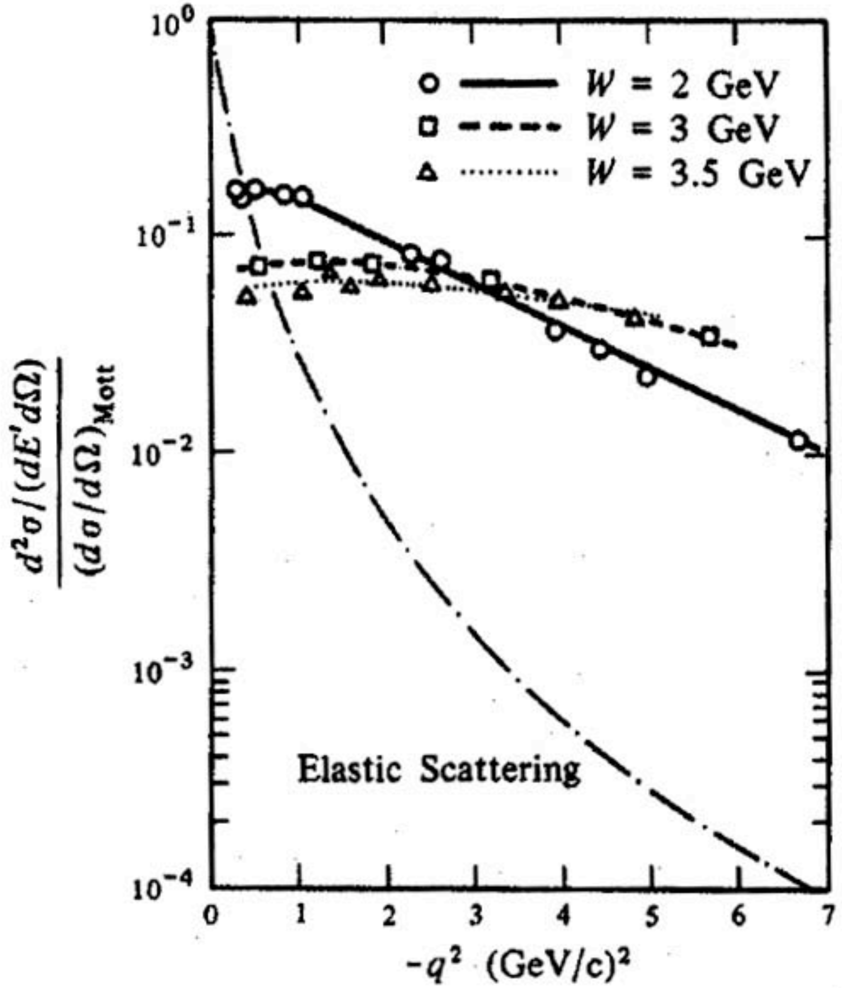
SLAC-MIT

Deep inelastic scattering of e^- of p, d
Observation of ~flat Q^2 dependence of
$R = \sigma_{inel}/\sigma_{Mott}$

R can be interpreted as form factor (describing form of scatterer)

R~const → pointlike scatterers inside proton

Partons later identified with quarks



LO Splitting Functions

$$P_{qq}(z) = \frac{4}{3}\frac{1+z^2}{1-z}$$

$$P_{qg}(z) = \frac{1}{2}(z^2 + (1-z)^2)$$

$$P_{gq}(z) = \frac{4}{3}\frac{1+(1+z)^2}{z}$$

$$P_{gg}(z) = 6\left(\frac{z}{1-z} + \frac{1-z}{z} + z(1-z)\right)$$

Extra-SM at HERA

Extra-SM

- Leptoquarks
  - Phys.Lett. B369 (1996) 173-185
- Kaluza-Klein Theories