Investigation of QCD Evolution through Jets with the ZEUS Detector at HERA

Preliminary Examination

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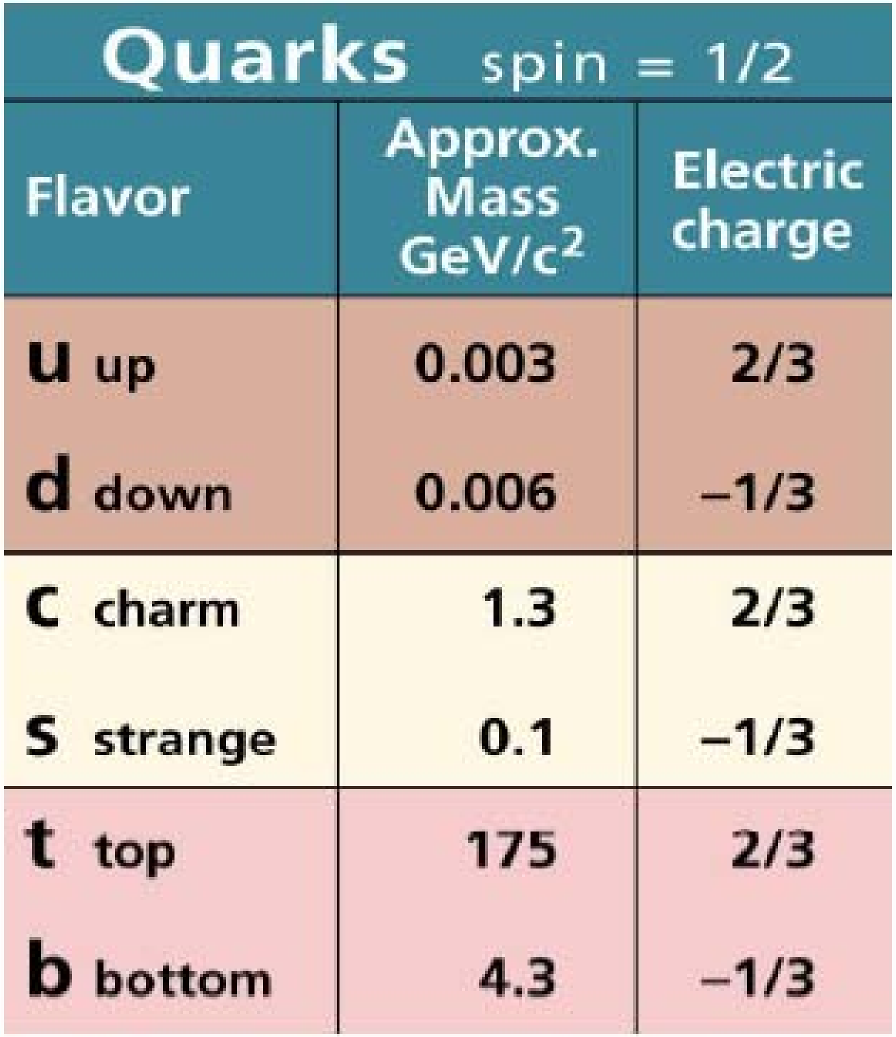
Outline

- Framework for QCD
    - Deep Inelastic Scattering and proton structure
    - Quark-parton model
    - Color charge and QCD
    - QCD Evolutions (DGLAP and BFKL)
- Methods for investigation
    - HERA accelerator
    - ZEUS detector
    - Jets and jet finding
    - Multiple jets
- Present Status
    - H1 and ZEUS Multijet results
    - Comparison between data and leading order Monte Carlo
- Conclusions and future plans

Classification of Particles

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



Quarks spin = 1/2

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

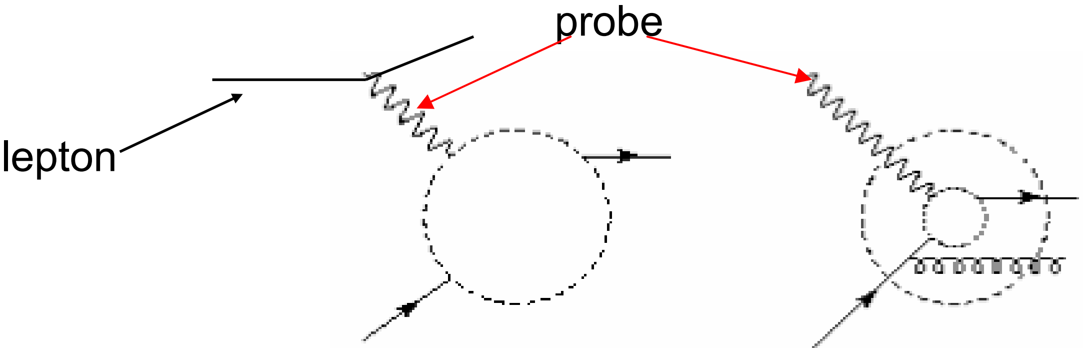
Parton Studies

Main objective: Study structure of particles

- **Scattering via probe exchange**
  - Photon → Electric charge
  - W, Z Bosons → Weak charge

  - Wavelength $\lambda = \frac{\hbar}{Q}$ Q: related to momentum of probe

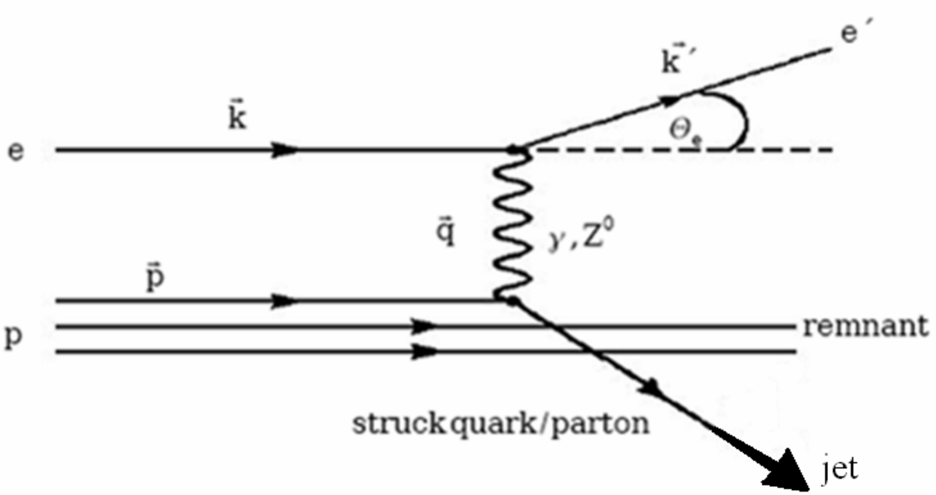
- **Special case: Deep Inelastic Scattering (DIS)**
  - High energy lepton transfers momentum to nucleon via probe



Size of proton ~ 1 fm

HERA can probe to ~ 0.001 fm

DIS Kinematics



$s = (p+k)^2$	Squared *ep* CM Energy
$Q^2 = -q^2 = (k-k')^2$	Photon virtuality
$x_{Bj} = \dfrac{Q^2}{2p \cdot q}$	Fraction of proton momentum carried by struck parton
$y = \dfrac{p \cdot q}{p \cdot k}$	Inelasticity
$Q^2 = sxy$	Only 2 independent quantities

DIS Cross Section

Express cross section in terms of DIS kinematics and proton structure

$$\frac{d^2\sigma(e^- p)}{dx_{Bj}\,dQ^2}(x_{Bj},Q^2)=\frac{2\pi\alpha_E^2}{x_{Bj}Q^4}\left[\mathrm{Y}_+F_2(x_{Bj},Q^2)-y^2F_L(x_{Bj},Q^2)-\mathrm{Y}_-x_{Bj}F_3(x_{Bj},Q^2)\right]$$

$$\mathrm{Y}_\pm=1\pm(1-y)^2$$

- **F_2, F_L, F_3 → proton structure functions**
  - F_2 → interaction between transversely polarized photon and partons
  - F_L → interaction between longitudinally polarized photon and partons
  - $x_{Bj}F_3$ → parity violating term from weak interaction

Quark-Parton Model

- **Proton contains only valence quarks**
  - **Partons considered point-like particles**
  - **Structure functions describing individual particles' momenta distribution depend only on x_{Bj}**
    - No Q^2 dependence (Bjorken scaling):

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

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

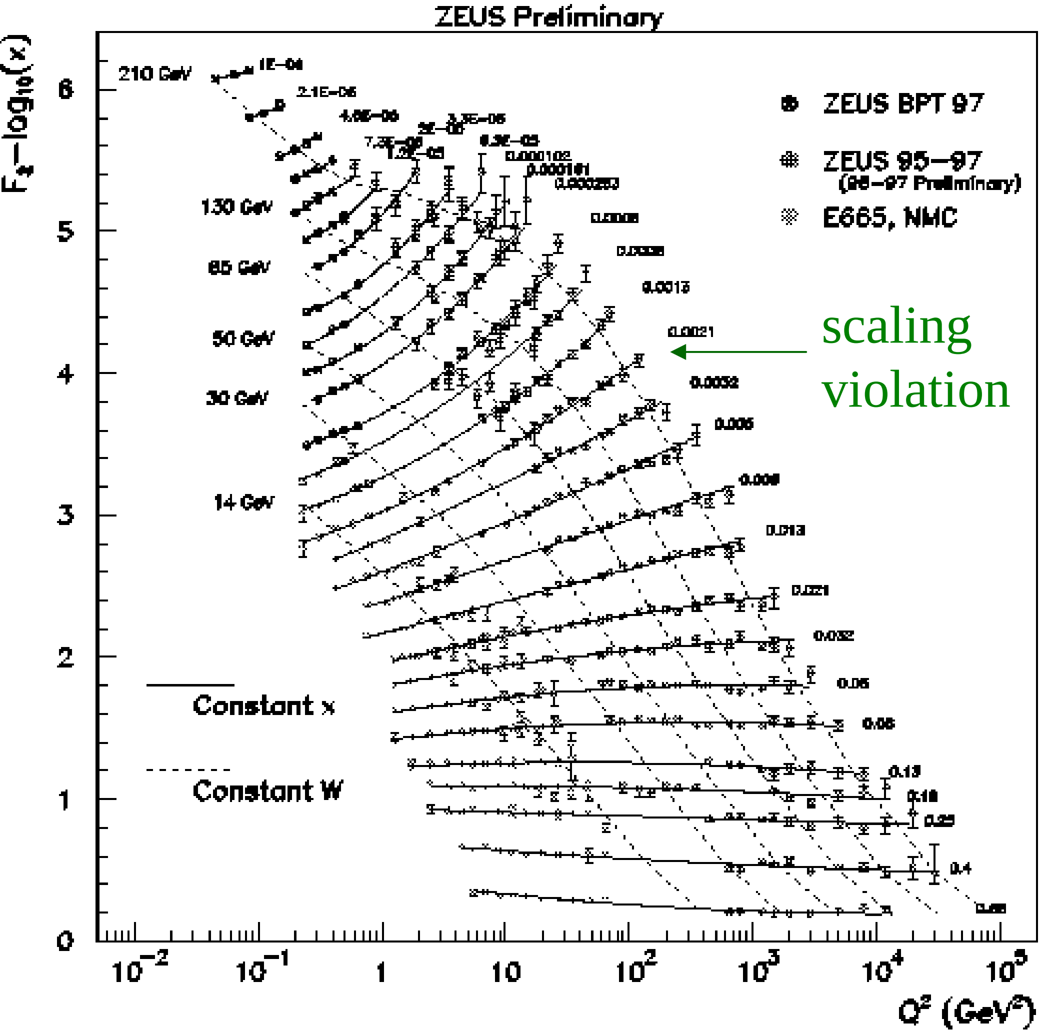
QCD and Colored Gluons

Problems with Quark-Parton Model

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

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

QCD and Scaling Violation



Quark-parton model: F_2 independent of Q^2

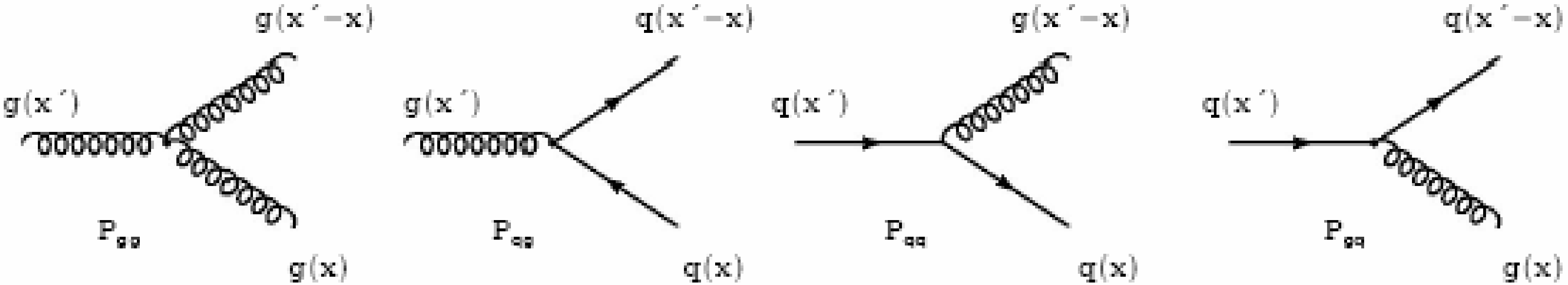
vs.

QCD: F_2 depends on Q^2

- **Slope of F_2 vs. Q^2 depends on x_{Bj}**
  - $x > \sim.25$: F_2 decreases as Q^2 increases
  - $x < \sim.25$: F_2 increases with Q^2
- **Prediction of QCD validated**

Perturbative QCD (pQCD)

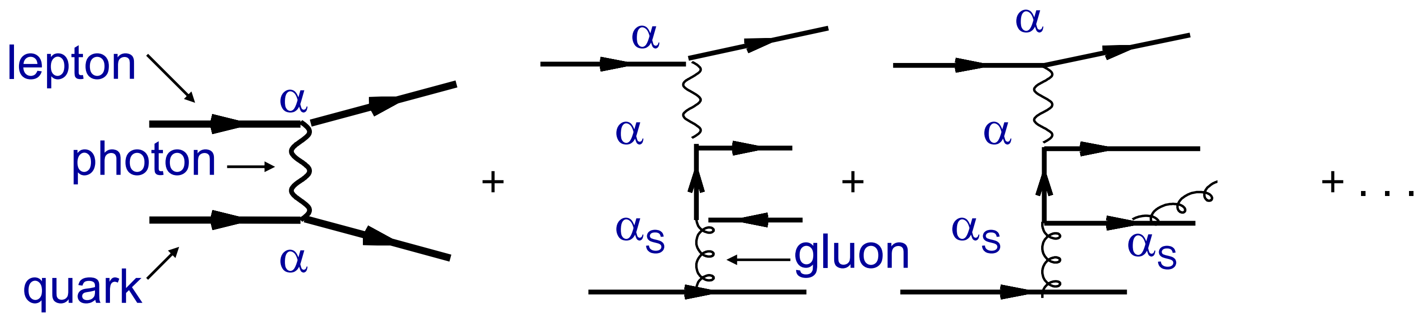
Splitting functions give probability quark or gluon to split into parton pair



- Leading Order quark and gluon splitting diagrams shown

pQCD–perturbative series summed over terms in expansion of α_s

- Methods of summation: next slide



BFKL and DGLAP Evolutions

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

Done by summing over diagrams

DGLAP: Sum over diagrams contributing *ln*(Q^2) terms

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

Splitting Functions

- **Widely used**

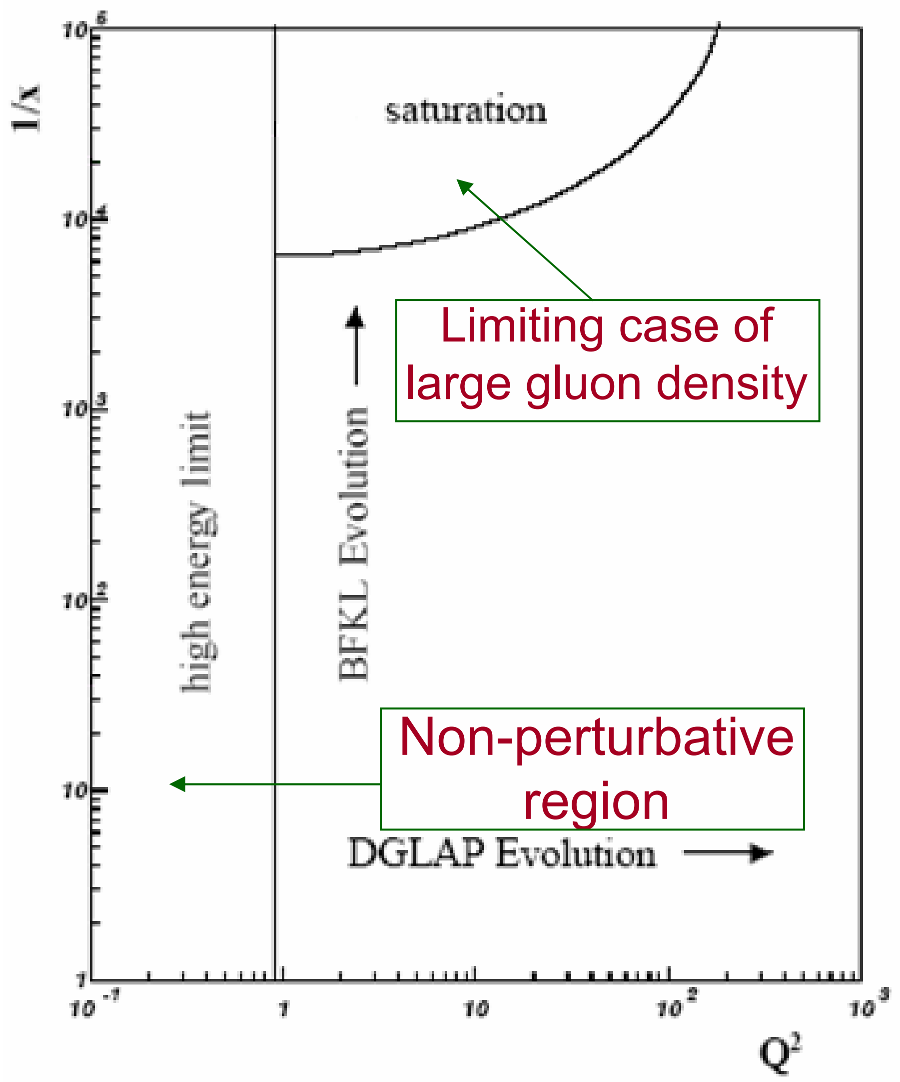
BFKL: Sum over diagrams contributing *ln*(1/x$_{Bj}$) terms

BFKL-DGLAP Applicability

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}**

Aim to study the ranges of validity



Limiting case of large gluon density

Non-perturbative region

Parton Energy and k_T Ordering

- **DGLAP: ordering in both k_T and x**

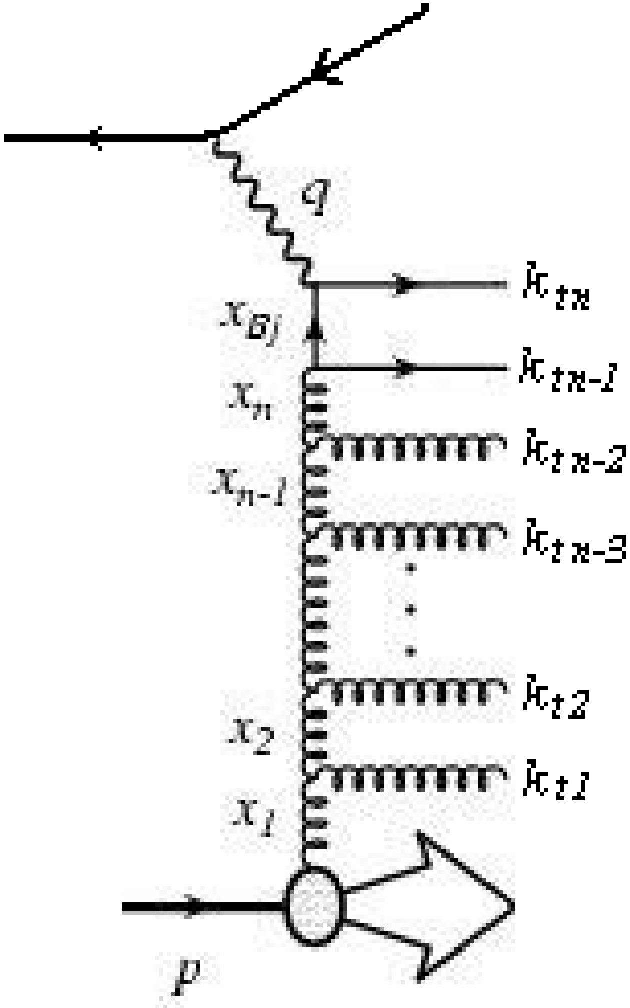
$$x_n < x_{n-1} < \ldots < x_2 < x_1$$

$$k_{t,n} > k_{t,n-1} > k_{t,n-2} > \ldots > k_{t,2} > k_{t,1}$$

- **BFKL: Strong ordering in *x,* but not ordered in k_T**

$$x_n << x_{n-1} << \ldots << x_2 << x_1$$

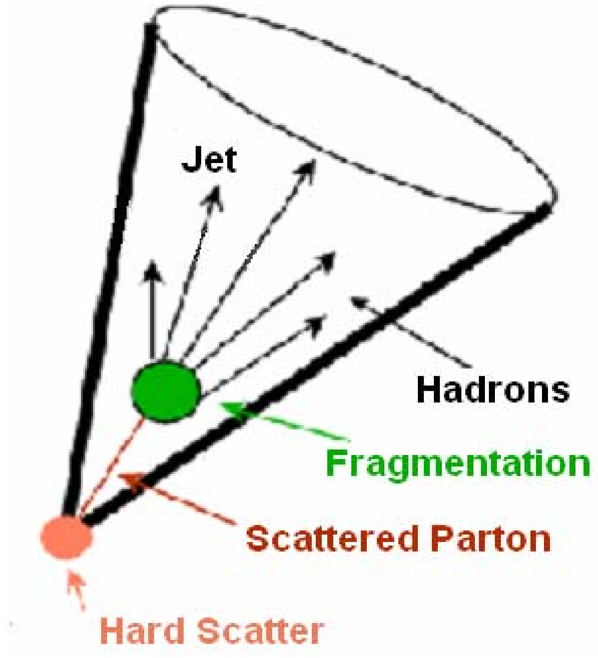
- **Differences**
  - **Expect more partons with higher k_t in forward region with BFKL than with DGLAP**
  - **DGLAP: Scattered partons correlated in Energy, azimuthal and polar angles**
  - **BFKL: Scattered partons not necessarily strongly correlated**



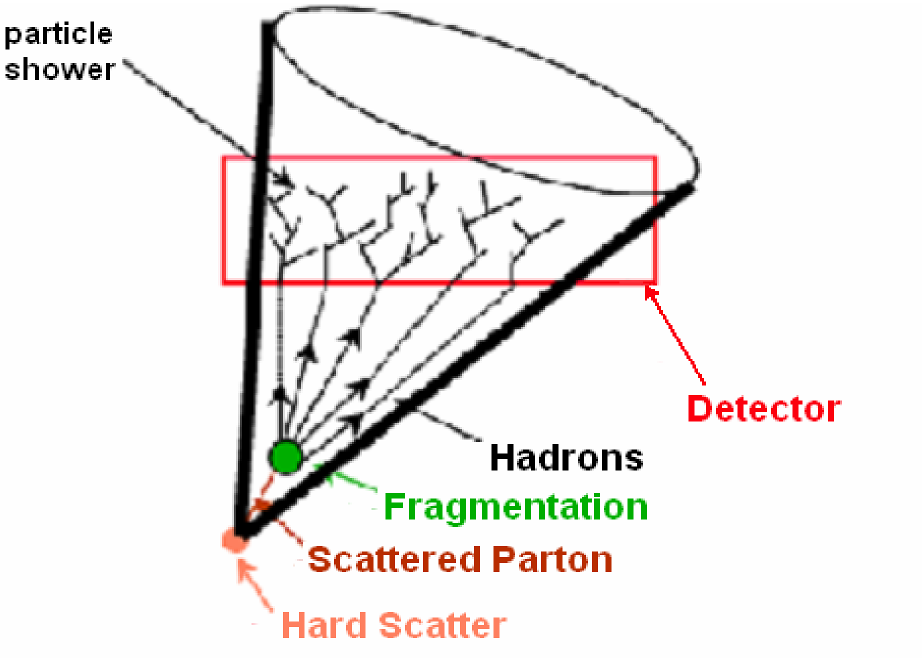
Jets

- **Colored partons produced in hard scatter → “Parton level”**
- **Colorless hadrons form through hadronization → “Hadron level”**
- **Collimated “spray” of particles → Jets**
- **Particle showers observed as energy deposits in detectors → “Detector level”**

Produced



Observed



HERA Collider at DESY

920 GeV protons

27.5 GeV e^- or e^+

318 GeV CMS Energy

- Equivalent to ~50 TeV fixed target

220 Bunches

- Not all filled

Beam Currents

- Proton: 140 mA
- Electron: 58 mA

Instantaneous Luminosity

- 1.8 x 10^{31}cm^{-2}s^{-1}

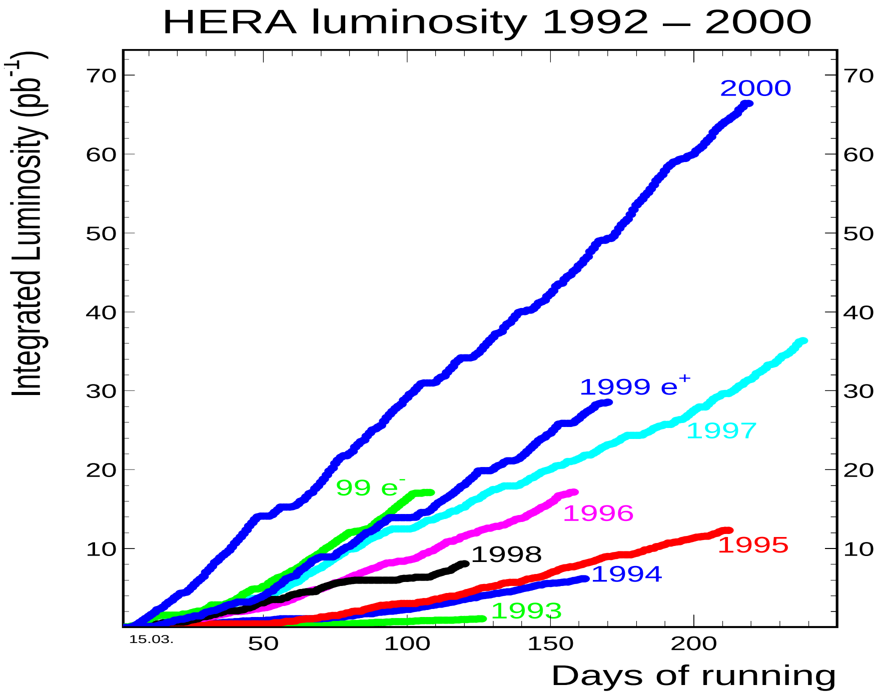
$$L = \frac{R_{tot} - (I_{tot}/I_{unp})R_{unp}}{\sigma_{BH}}$$

DESY
Hamburg, Germany

HERA Luminosity

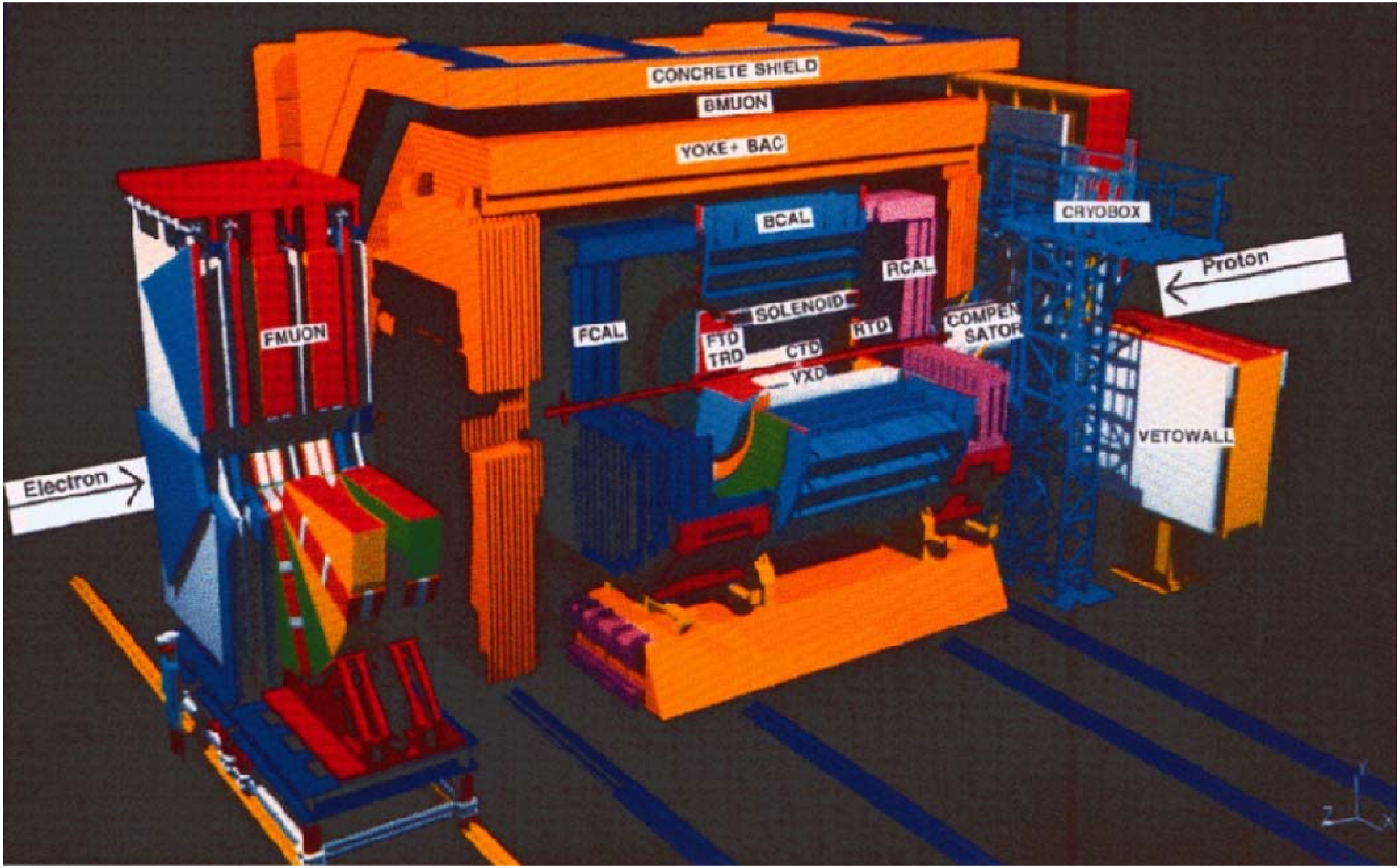
1992 – 2000 total integrated luminosity: 193 pb^{-1}

2002 – 2004 total integrated luminosity: 84 pb^{-1}

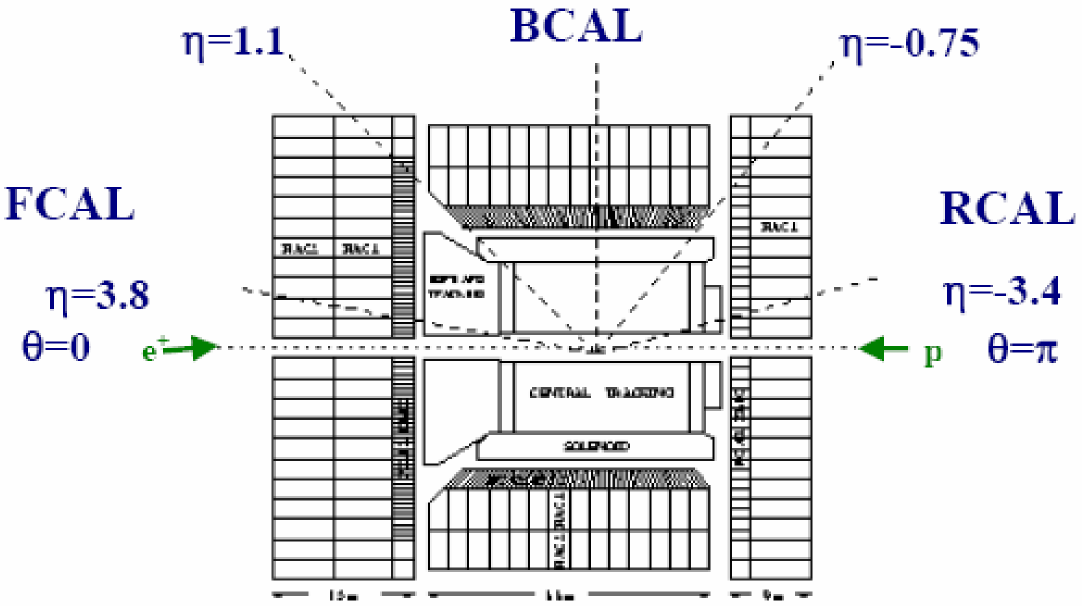


ZEUS Luminosities (pb^{-1})			# events (10^6)
Year	HERA	ZEUS on-tape	Physics
e^-: *93-94, 98-99*	27.37	18.77	32.01
e^+: *94-97, 99-00*	165.87	124.54	147.55

ZEUS Detector



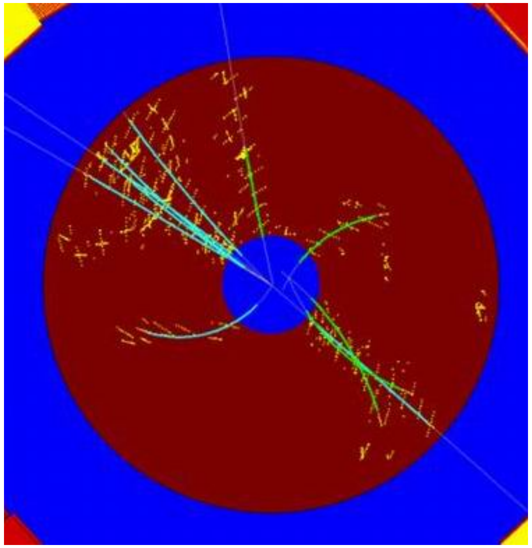
ZEUS Calorimeter



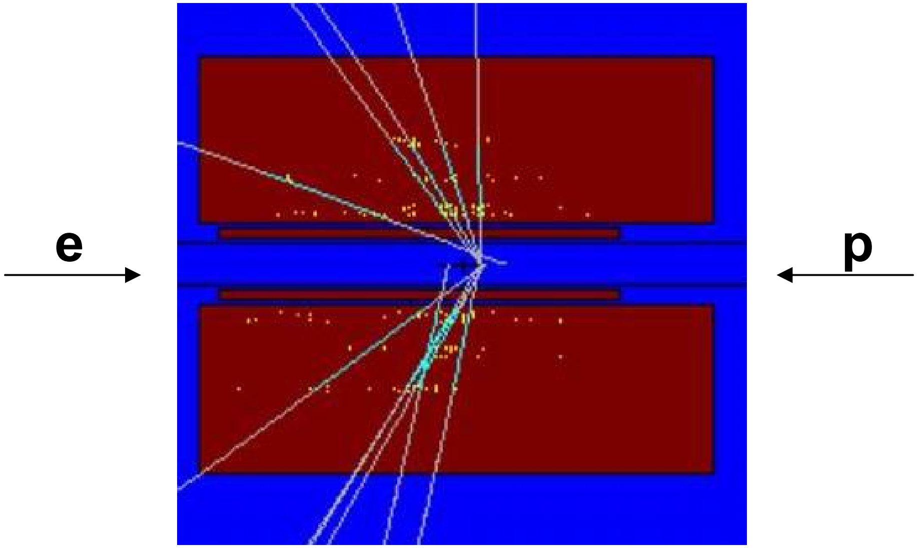
$$\eta = -\ln[\tan(\theta/2)]$$

- Alternating layers of depleted uranium and scintillator
- Energy resolutions in test beam
  - Electromagnetic: 18% / √E
  - Hadronic: 35% / √E
- 99.7% solid angle coverage ($-3.5 < \eta < 4.0$)

Central Tracking Detector (CTD)



View Along Beam Pipe



Side View

Drift chamber inside 1.43 T solenoid

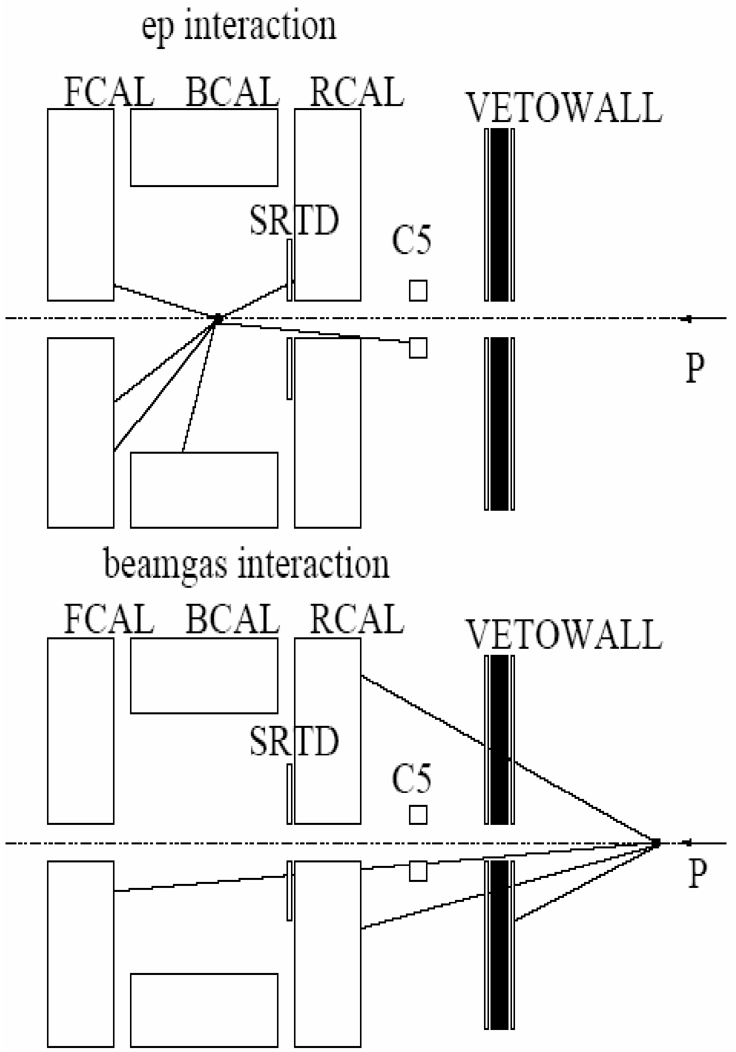
Measures event vertex

Vertex resolution

- longitudinal (z): 4mm
- transverse (x-y): 1mm

ZEUS Trigger

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



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

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

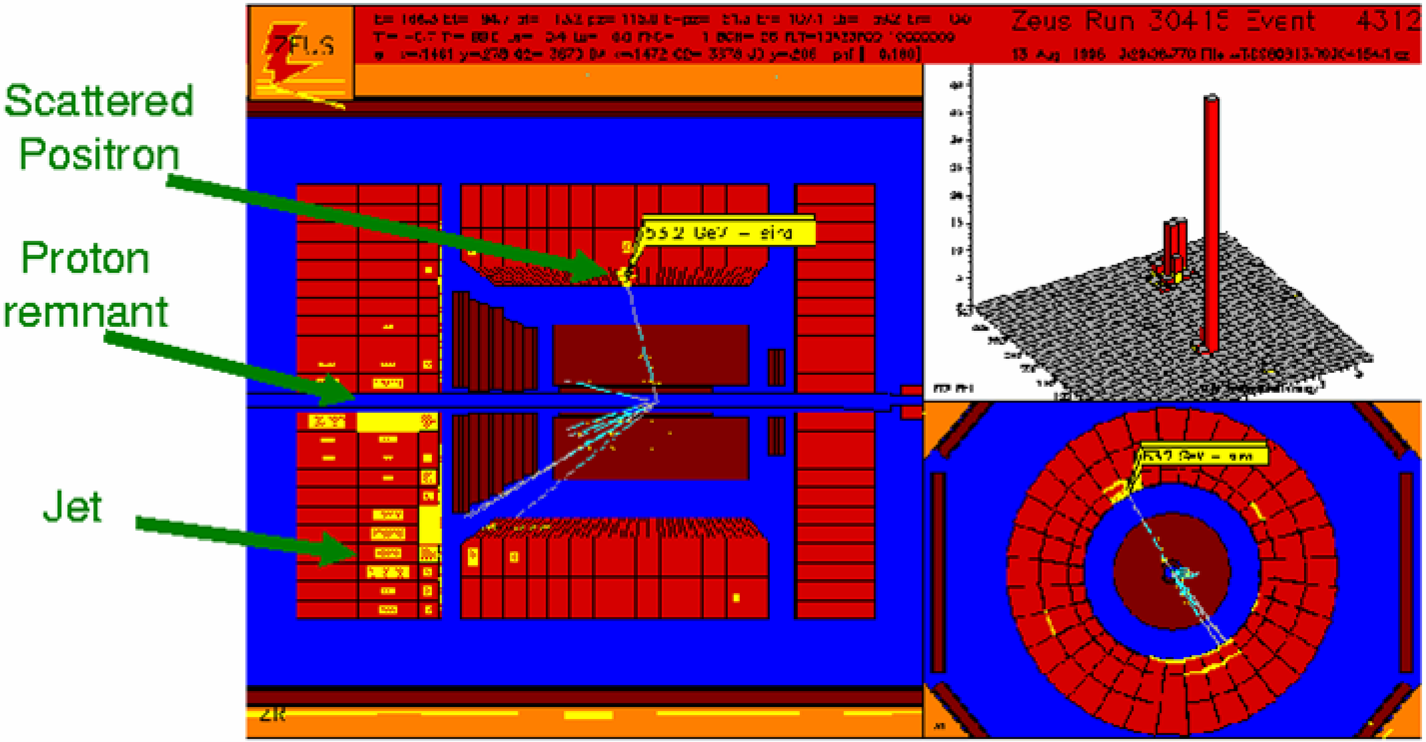
Second level: Use all data: 500 Hz → 100 Hz

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

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

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

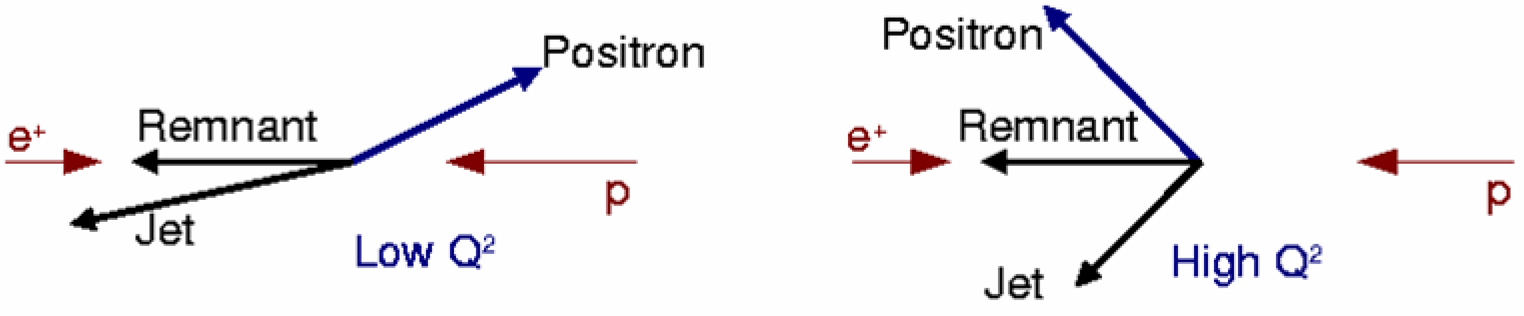
ZEUS DIS Event



$Q^2 \sim 3600 \, GeV^2$

$X \sim 0.15$

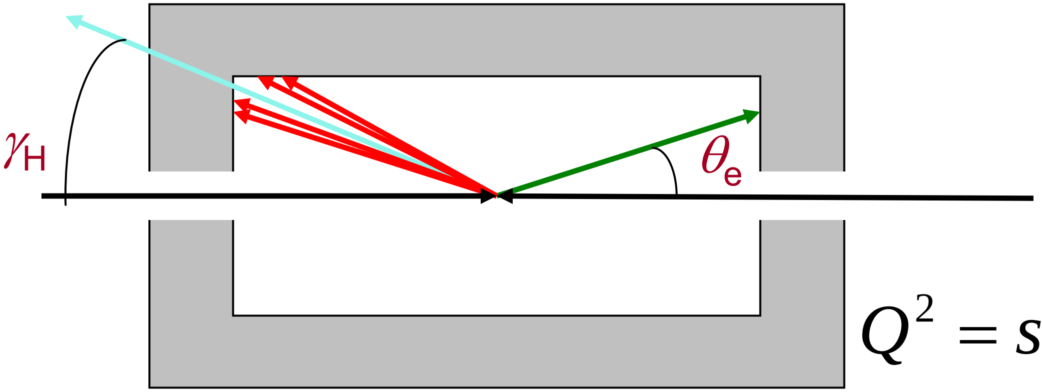
$Y \sim 0.20$



Kinematic Reconstruction

Four measured quantities: E_H, γ_H, E'_e, θ_e

Three reconstruction methods used: Double angle, Electron method, Jaquet-Blondel



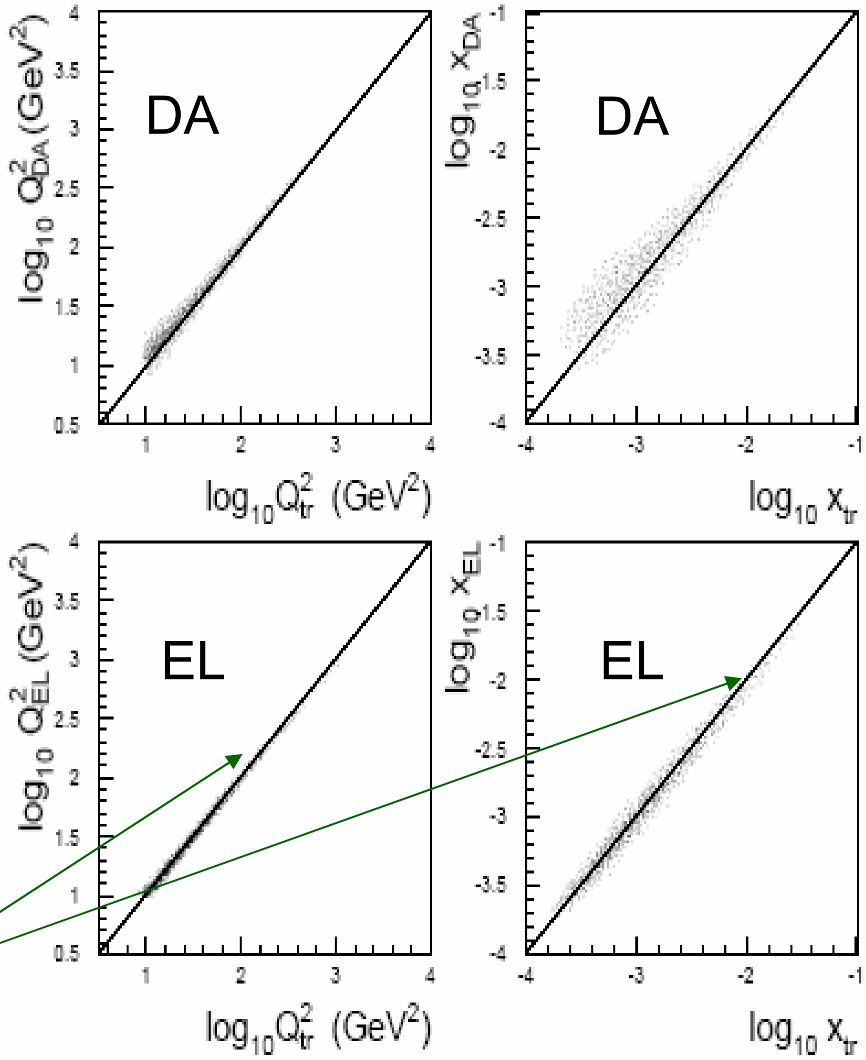
$$Q^2 = sxy$$

Methods have different resolutions over different kinematic regions

Variable	**Double angle method** **(γ_H,θ_e)**	**Electron method** **(E'_e,θ_e)**	**Jaquet-Blondel** **(E_H,γ_H)**
Q^2	$\frac{4E_e^2\sin\gamma_H(1+\cos\theta_e)}{\sin\gamma_H+\sin\theta_e-\sin(\gamma_H+\theta_e)}$	$2E_eE'_e(1+\cos\theta_e)$	$\frac{p_{t,H}^2}{1-y_{JB}}$
x	$\frac{Q^2_{DA}}{sy_{DA}}$	$E'_e\frac{1+\cos\theta_e}{2y_{el}E_p}$	$\frac{Q^2_{JB}}{sy_{JB}}$
y	$4E_e^2\frac{(1+\cos\theta_e)\sin\gamma_H}{\sin\gamma_H+\sin\theta_e-\sin(\gamma_H+\theta_e)}$	$1-\frac{E'_e}{2E_e}(1-\cos\theta_e)$	$\frac{\sum_H(E_H-p_{z,H})}{2E_e}$

ZEUS Data Reconstruction

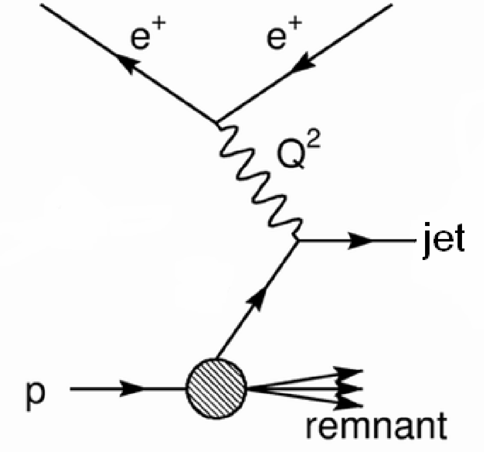
- **Use reconstruction methods that minimize resolution and systematic errors in different kinematic regions**
  - **Double Angle (DA) method**
    - Resolution worse than electron method at low x_{Bj}, Q^2
    - Resolution comparable to electron method at higher x_{Bj}, Q^2
  - **Electron (EL) method**
    - Good resolution in general
    - Underestimates slightly at higher x_{Bj}, Q^2



Single Jets and Dijets

Leading order: one hard scattered parton

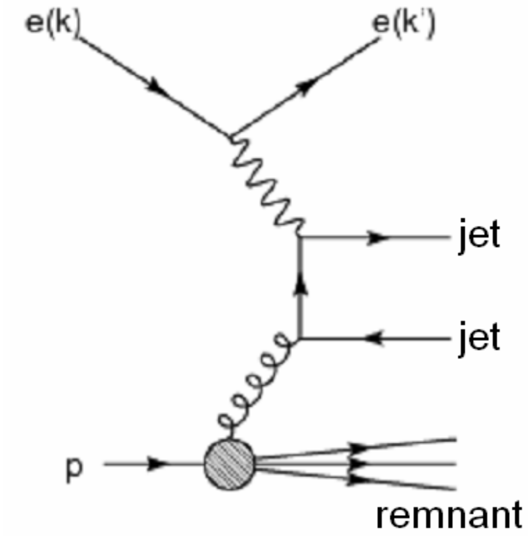
- **Single jet event**
- **Leading order diagrams O(α^0_s)**



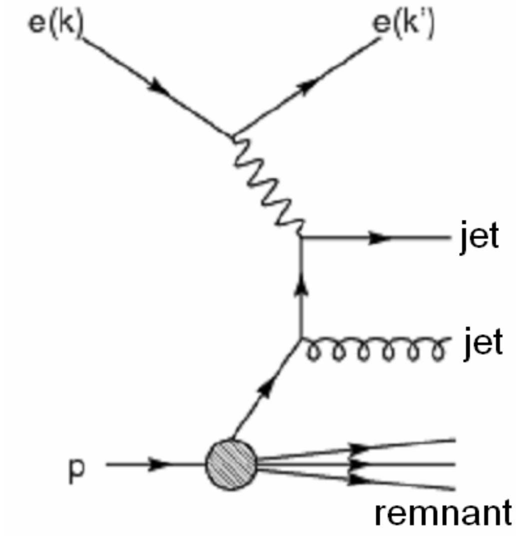
Dijets

- **Leading-Order diagrams O(α^1_s)**
- **Direct coupling to gluon**

Boson-Gluon Fusion (BGF)



QCD Compton

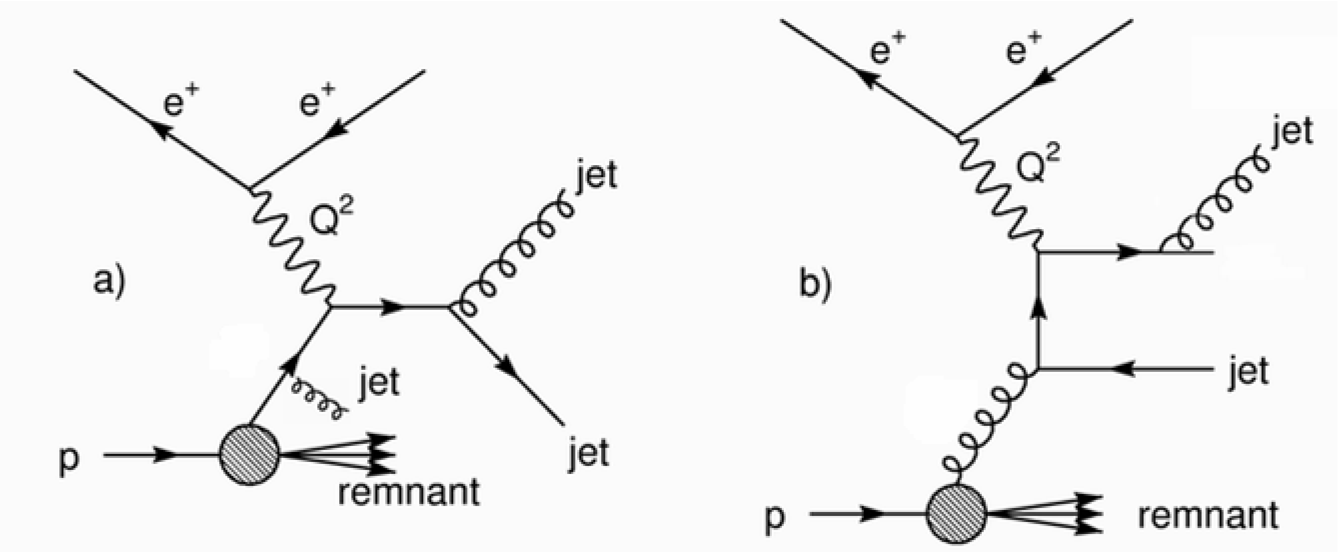


Multiple Jets

Trijet:

- **Radiated gluons from dijets**
  - Correction to leading-order dijet
- **Leading Order: O(α^2_s)**

- **Advantages of using multiple jets**
  - **Account for corrections beyond leading order dijet**
    - Further in pQCD perturbation series



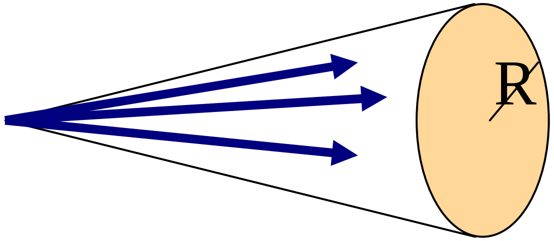
Jet Finding: Cone Algorithm

Maximize E_T of hadrons in cone of fixed size

- Construct seeds from energy deposits in cells
- Move cone until stable position found
- Decide whether to merge overlapping cones

- **Issues**
  - Overlapping
  - Seed – Energy threshold
  - Infrared unsafe – $\sigma \to \infty$ as seed threshold → 0

For the jet:

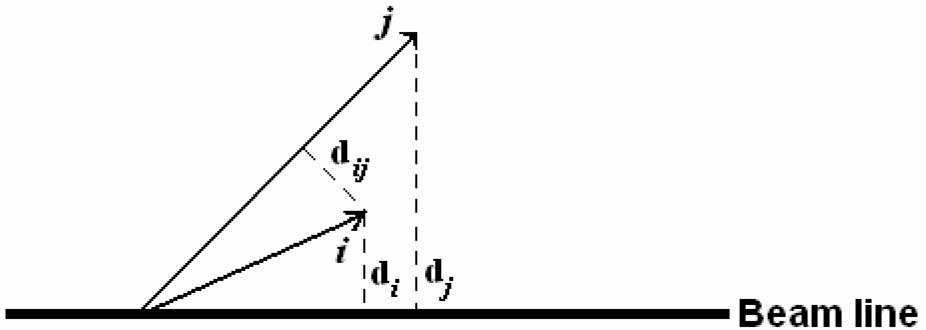


$$E_T = \sum_j E_{T,j}$$

$$\eta = \frac{1}{E_T}\sum_j E_{T,j}\eta_j \qquad \phi = \frac{1}{E_T}\sum_j E_{T,j}\phi_j$$

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

Jet Finding – k_t Algorithm



k_t: In *ep* transverse momentum with respect to beam line

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

- $d_i = (E_{T,i})^2 \rightarrow$ Distance to beam line in momentum space
- $d_{ij} = \min\{E^2_{T,i}, E^2_{T,j}\}[(\Delta\eta)^2 + (\Delta\phi)^2] \rightarrow$ Distance between objects
- Combine all d_i, d_{ij} into set

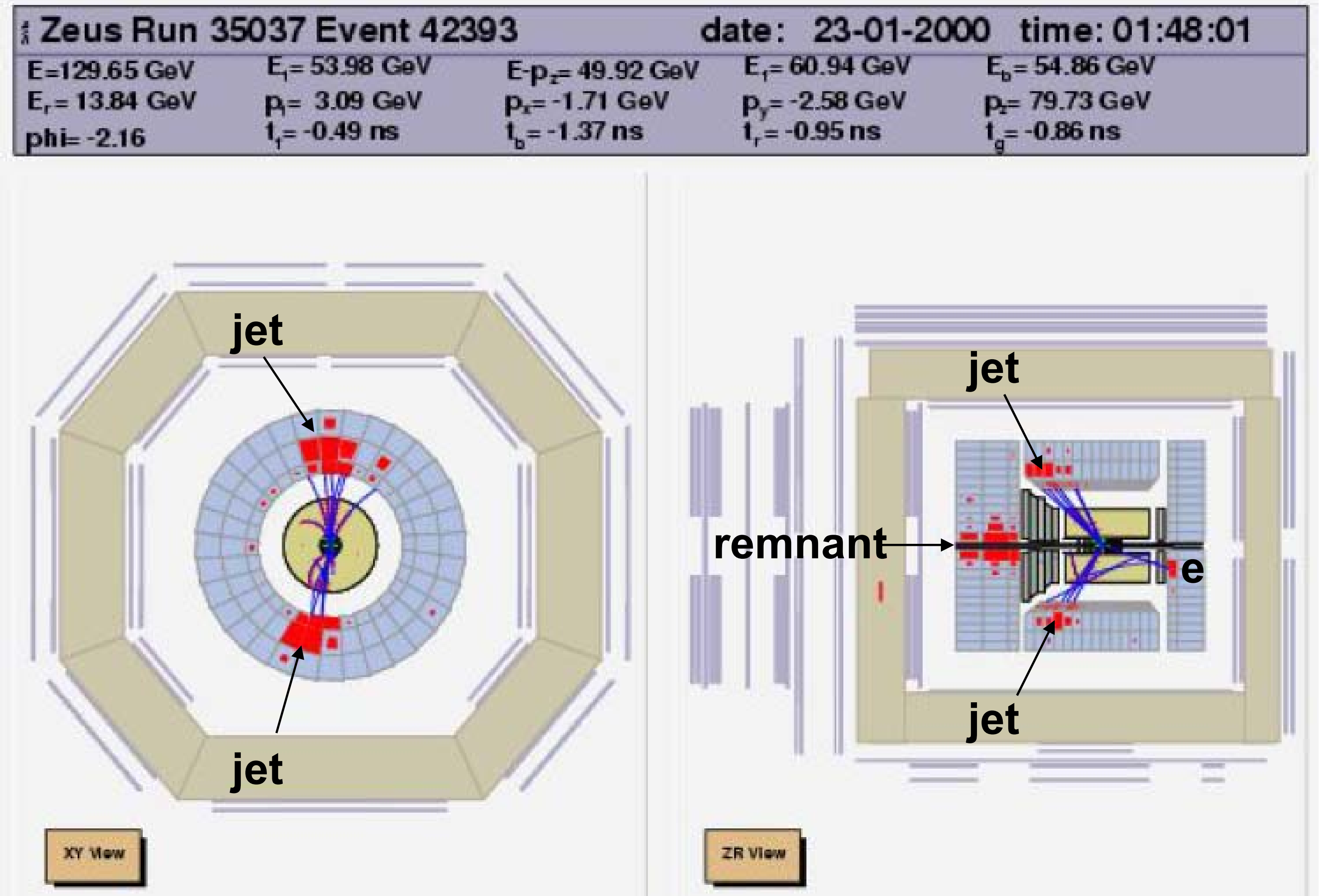
Calculate $\min\{d_i, d_{ij}\}$ for each object and pair of objects

- If minimum of set corresponds to $d_i \rightarrow$ Object for d_i taken as jet
- If minimum of set corresponds to $d_{ij} \rightarrow$ Combine objects *i* and *j*

Advantages

- No seed required and no overlapping jets
- Suitable for beyond-NLO pQCD calculations

Dijet Event at ZEUS



Zeus Run 35037 Event 42393 date: 23-01-2000 time: 01:48:01

E=129.65 GeV	E_t= 53.98 GeV	E-p_z= 49.92 GeV	E_f= 60.94 GeV	E_b= 54.86 GeV
E_r= 13.84 GeV	p_t= 3.09 GeV	p_x= -1.71 GeV	p_y= -2.58 GeV	p_z= 79.73 GeV
phi= -2.16	t_f= -0.49 ns	t_b= -1.37 ns	t_r= -0.95 ns	t_g= -0.86 ns

Two “back to back” jets

Breit Frame

Select a frame to optimize jet finding

$$\mathbf{q}+2x\mathbf{p}=0$$

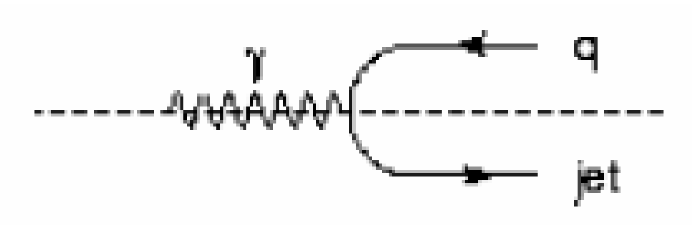
Single jet event

- **Struck quark rebounds with equal and opposite momentum**
- **Zero transverse energy (E_T)**

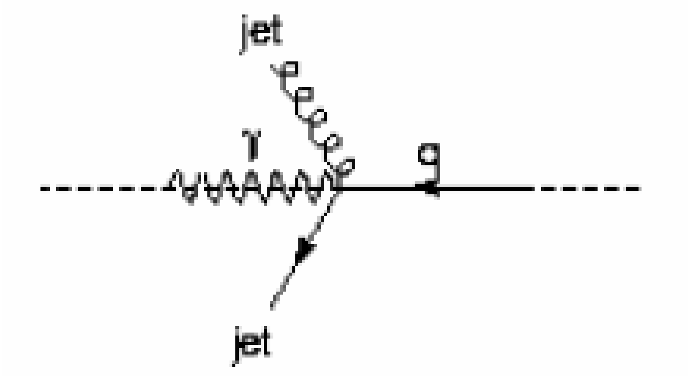
Dijet event

- **Jets balanced in E_T**

Requiring minimum jet $E_{T,\ \mathrm{Breit}}$ selects multijet events



“Brick wall” frame similar to $ee\rightarrow q\bar{q}$



Leading Order Monte Carlo

Simulate events to leading order (O(α_s) for dijets)

- **Leading Order Matrix elements**
- **Parton showering**
- **Hadronization**

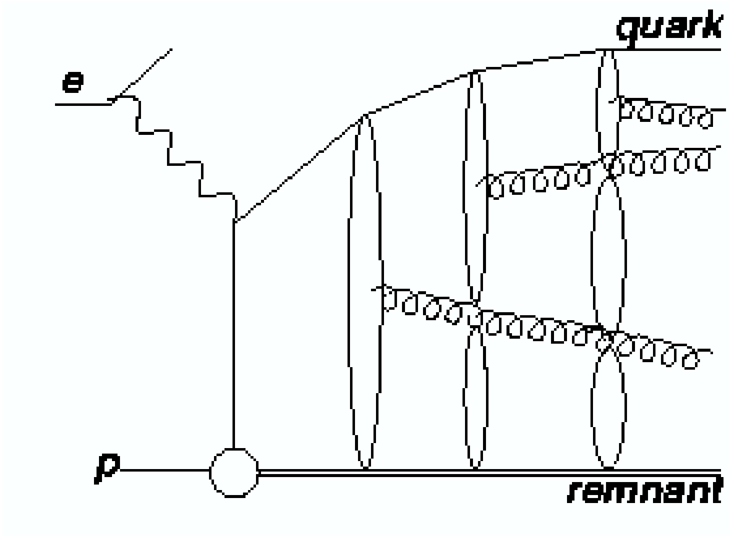
ARIADNE v4.08

- **Color Dipole Model (CDM)**
  - Gluons emitted from color field between quark-antiquark pairs
  - Supplemented with boson-gluon fusion processes
  - Gluons not necessarily k_t ordered (BFKL-like)

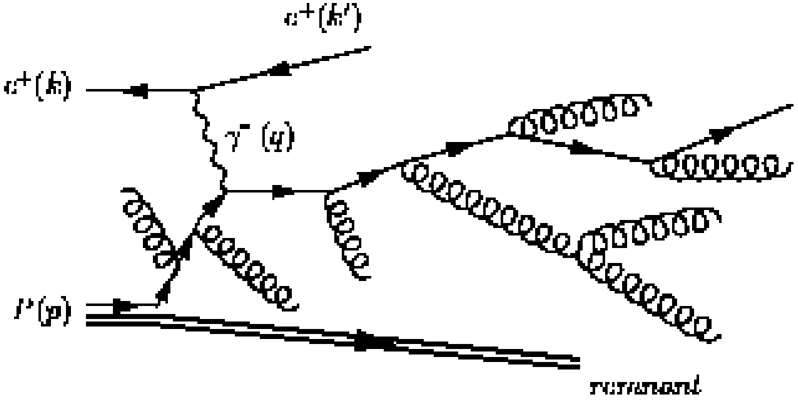
LEPTO v6.5.1

- **Matrix Element + Parton Shower (MEPS)**
  - Parton cascade: approximate higher orders in LO calc
  - Decreasing virtuality (q^2) as cascade progresses
  - Radiated gluons k_t-ordered (DGLAP-based)

Both use Lund String Model to simulate hadronization



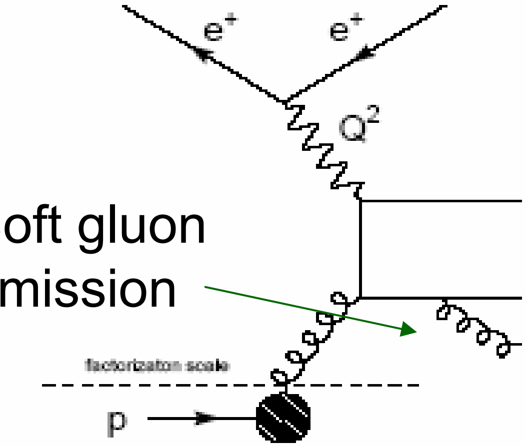
CDM



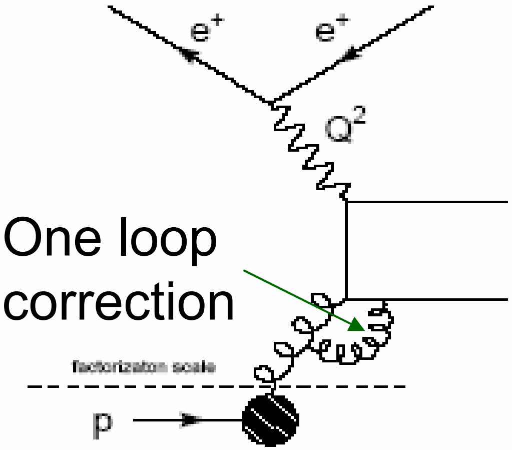
MEPS

Next-to-Leading-Order (NLO) Calculations

Soft gluon emission



One loop correction



Programs for DIS

- **DISENT**
- **MEPJET**
- **DISASTER++**
- **NLOJET**

Inclusion of single gluon emission in dijet final state

- **Only terms of up to $O(\alpha^2_s)$ 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**

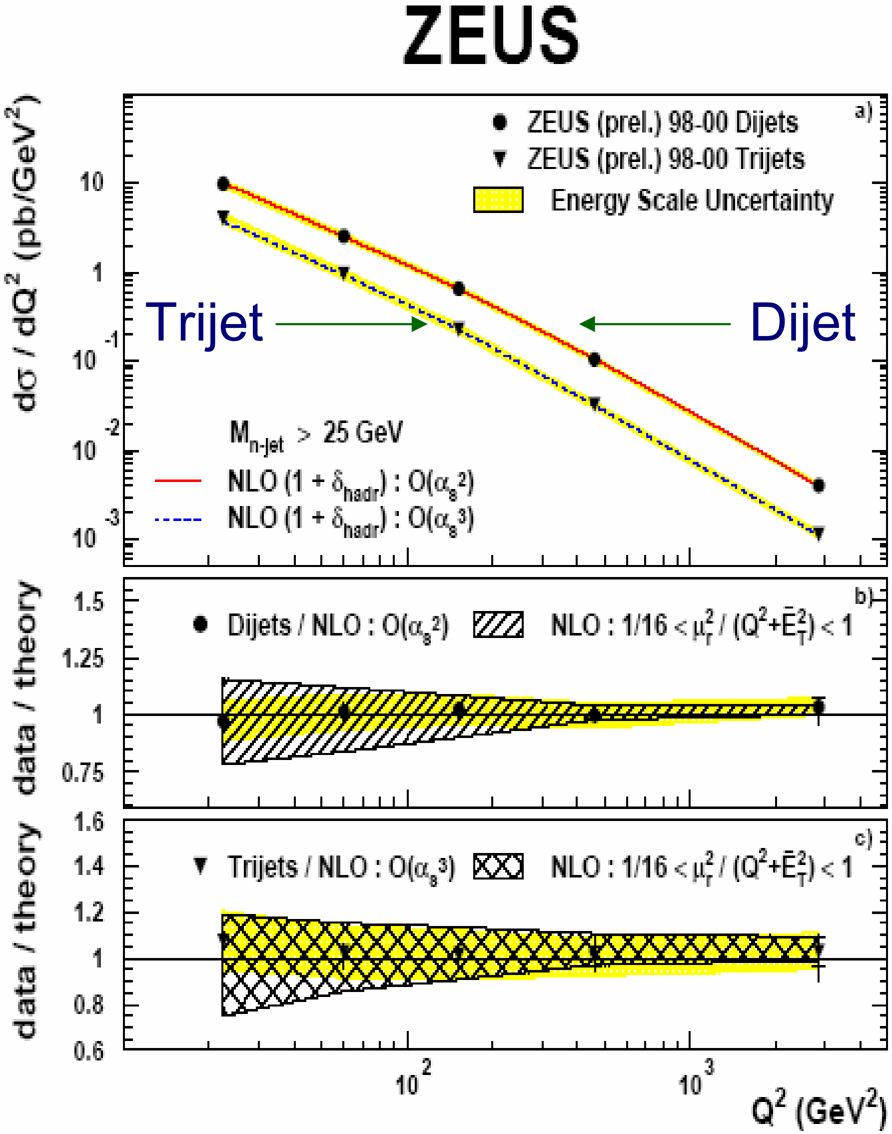
Uncertainties

- **Renormalization scale: scale for evaluating α_s**
  - Indicates size of contributions from higher order diagrams.
- **Factorization scale: scale at which parton densities are evaluated**

Present ZEUS Multijet Results

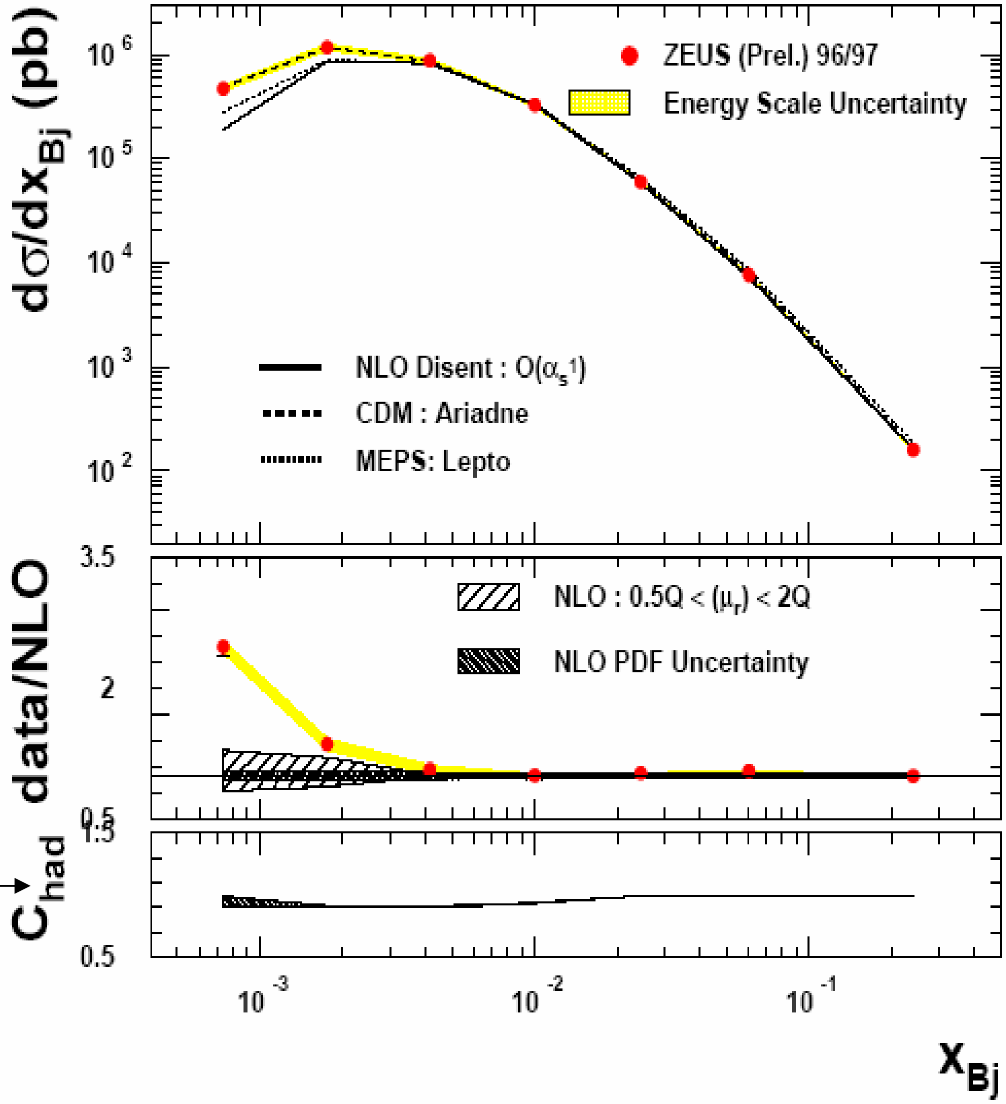
ZEUS inclusive dijet and trijet measurements well understood and modeled

- **Multijet cross sections vs. NLO calculations**
  - Dijet: UW PhD student D. Chapin (2001)
  - Trijet: UW PhD student L. Li, defends Jan 12, 2005
- **DGLAP NLO dijet and trijet calculations describe data well in general**
- **Examine if agreement extends to "BFKL" kinematic regions**



ZEUS Inclusive Jets

- Start with event cross section where at least one jet required
  - Former UW PhD student S. Lammers, graduated 2004
- Low x_{Bj} disagreement between data and DISENT
- Examine low x_{Bj} contribution from multijet events



Hadronization correction factor taken from Ariadne

BFKL/DGLAP vs. Jet Angles

- **Examine jet ϕ and E_T at low x_{Bj} and low Q^2**
  - **$x_{Bj} < 10^{-2}$**
  - **$Q^2 < 150$ GeV^2**
  - **DGLAP: Jet E_T and angles strongly correlated**
    - "Back to back" in ϕ
    - k_t ordering of scattered partons: jets with highest E_T should have similar η
  - **BFKL: Jet E_T and angles not strongly correlated**
    - More jets with high E_T expected in forward region than with DGLAP

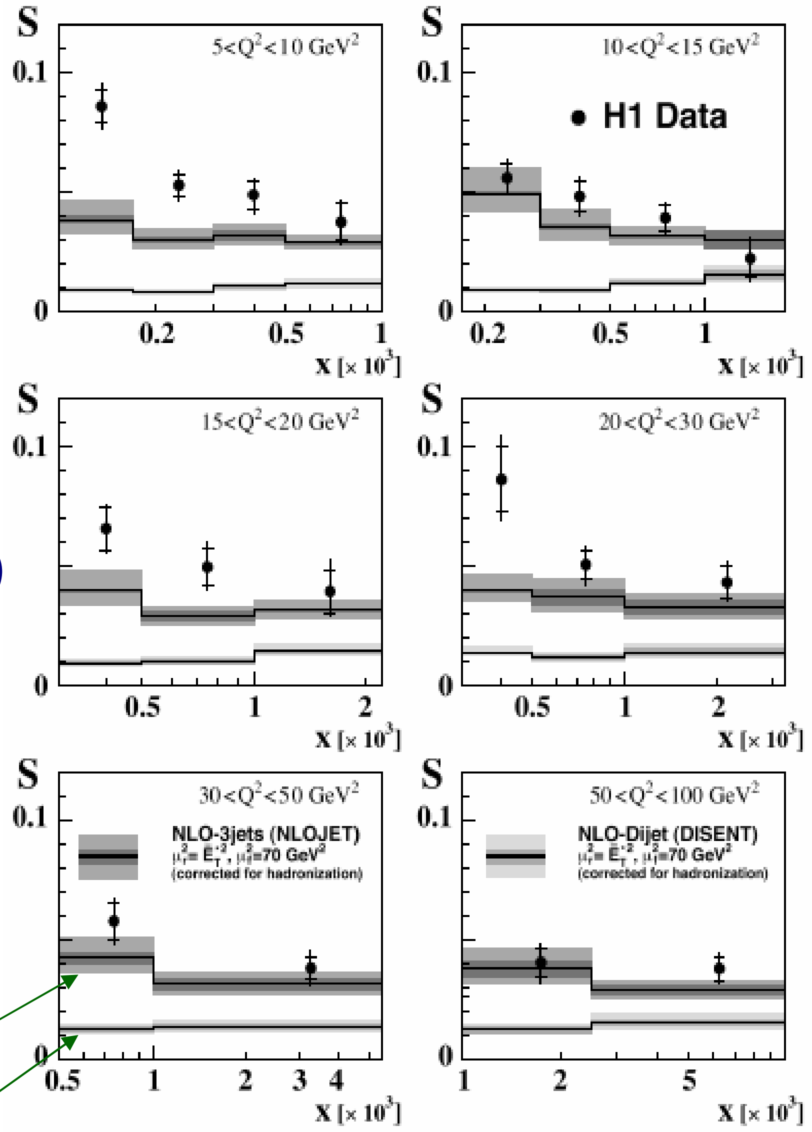
H1 Inclusive Dijet Events

ϕ correlation of two most energetic jets in multijet events

- **1996-1997 H1 data: Jet E_T > 7 GeV**

$$S = \frac{N_{Dijet}(\Delta\phi < 120°)}{N_{Dijet}}$$

- **Compare to DGLAP for NLO O(α_s^2) and NLO O(α_s^3)**
    - O(α_s^2): Data not described
    - O(α_s^3): Agreement at high x_{Bj} Still excess at low Q^2 and x_{Bj}
- **Excess events with small ϕ separation of highest E_T jets**



NLO: O(α_s^3)

NLO: O(α_s^2)

DESY–03–160
October 2003

ZEUS DIS Data Sample

Data: 1998-2000 electron and positron: 82.2 pb^{-1}

<table>
<tr><th colspan="2">Remove background</th></tr>
<tr><td>$|z \text{ vertex}| < 50$ cm</td><td>Eliminate beam gas events</td></tr>
<tr><td>$40 < E - p_z < 60$ GeV</td><td>Eliminate cosmic, beam gas events</td></tr>
<tr><th colspan="2">Select DIS</th></tr>
<tr><td colspan="2">$10 < Q^2_{DA} < 5000$ GeV^2</td></tr>
<tr><th colspan="2">Improve precision</th></tr>
<tr><td>$y_{jb} > 0.04$</td><td>Requires minimum hadron energy</td></tr>
<tr><td>$y_{el} < 0.6$</td><td>Electron energy > 10 GeV</td></tr>
<tr><td>$\cos(\gamma_h) < 0.7$</td><td>Breit Frame jet finding</td></tr>
<tr><td>$(E - p_z)_e < 54$ GeV</td><td>Electron E, p conservation</td></tr>
<tr><td>$\eta_{max} > 2.5$</td><td>Eliminate diffractive events</td></tr>
</table>

Dijet and BFKL Analysis Sample

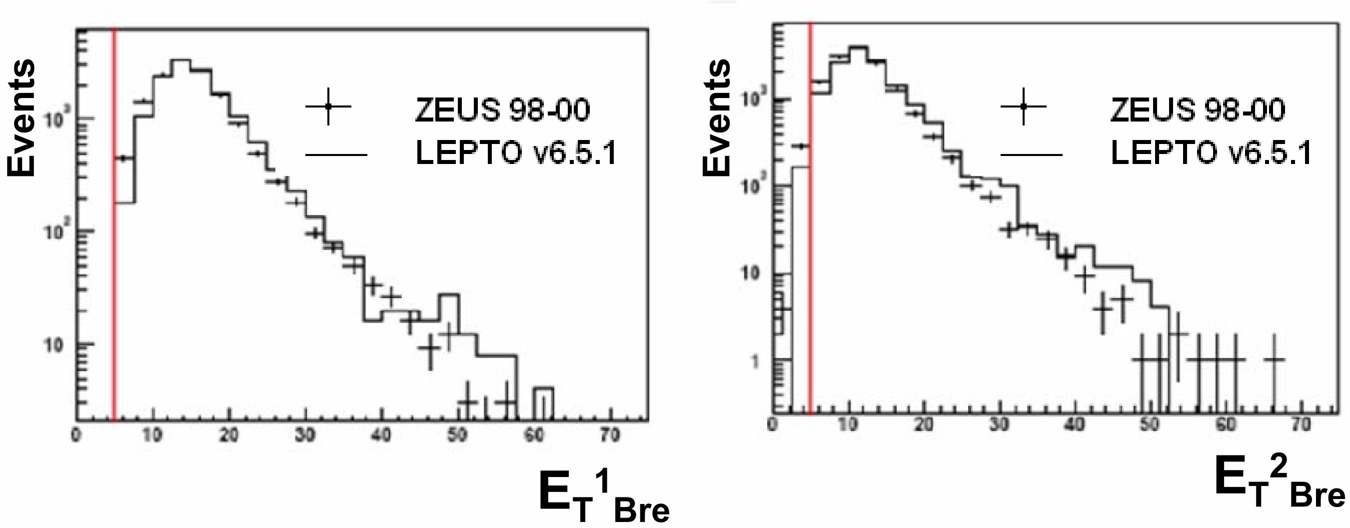
Inclusive dijets	
$E^{1,2}_{T,Breit} > 5$ GeV	Well-resolved jets
$-1 < \eta_{Lab} < 2.5$	Jet η in well-understood region
Mass dijet system > 25 GeV	NLO calculations
Above plus BFKL Dijets: Low x, Q^2	
$Q^2_{DA} < 150\ \mathrm{GeV}^2$	
$10^{-4} < x_{DA} < 10^{-2}$	

Dijet Data vs. LEPTO MC

First look:
Inclusive dijets

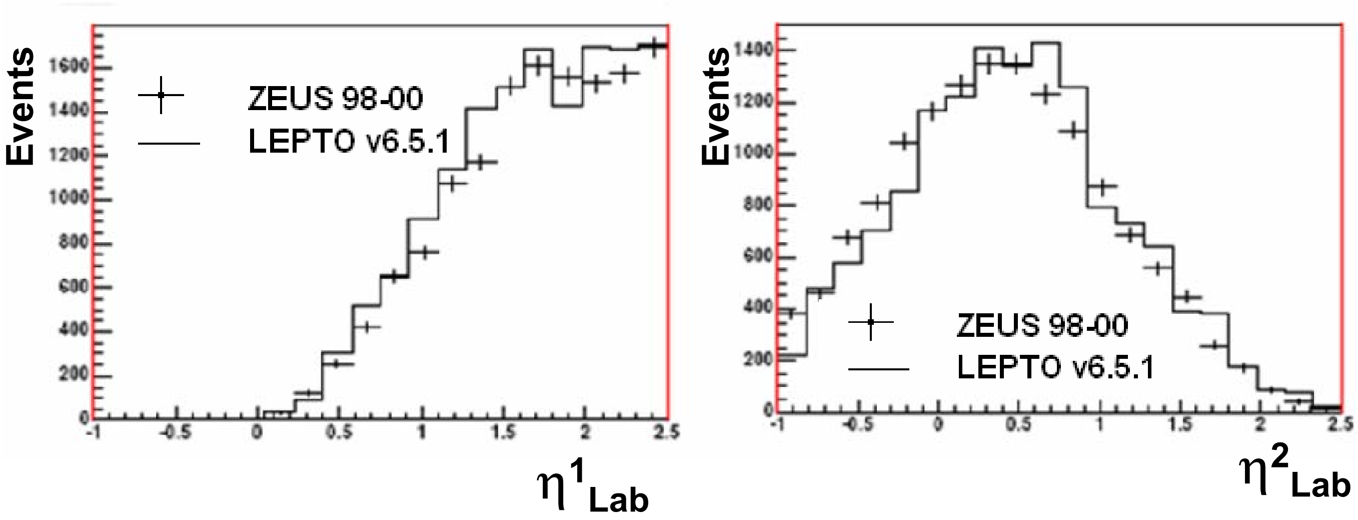
E_T in Breit Frame of 2 highest E_T jets

- Ordered in E_T
- Area normalized



η in lab frame of 2 highest E_T jets

- Ordered in η



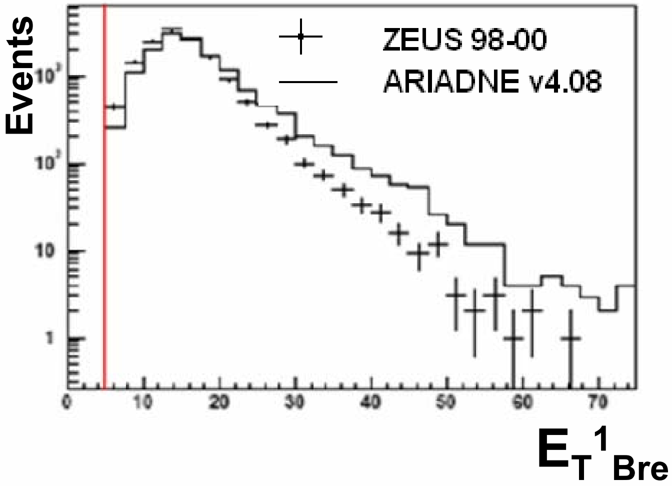
Reasonable agreement overall

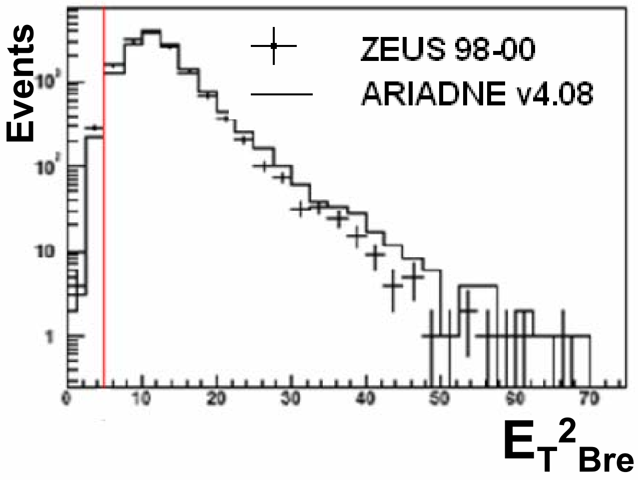
Dijet Data vs. ARIADNE MC

First look: inclusive dijets

E_T in Breit Frame of 2 highest E_T jets

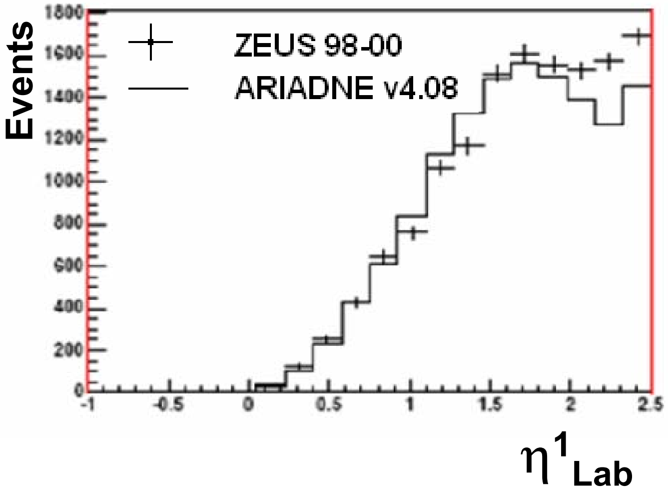
- **Ordered in E_T**
- ***Area normalized***

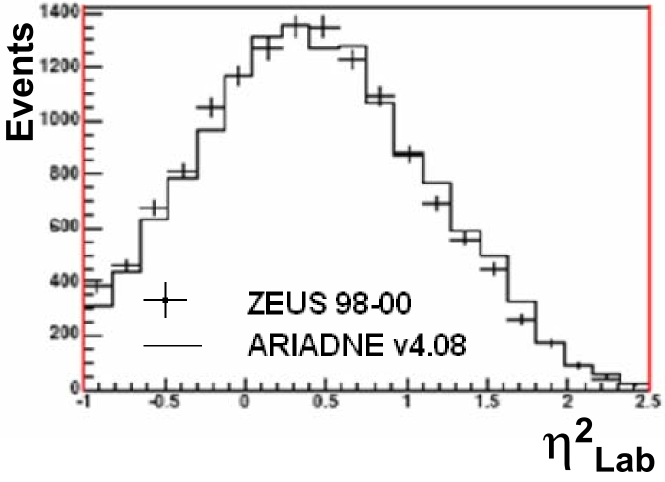




η in lab frame of 2 highest E_T jets

- **Ordered in η**





Need to investigate discrepancies with ARIADNE

Summary

QCD evolution studies with ZEUS at HERA

- **Good understanding of inclusive multijet events at ZEUS**
- **DGLAP NLO discrepancy with event cross sections with at least one jet, jet azimuthal separation at low x_{Bj}, Q^2**
- **Reasonable agreement between ZEUS 98-00 inclusive dijet sample and LEPTO**
- **Disagreement between ZEUS 98-00 inclusive dijet sample and ARIADNE needs investigation**

Plans

- Examine ϕ separation of two most energetic jets in multijet events, compare to DGLAP NLO, other calculations
  - See if H1 result consistent with higher statistics and other models
    - H1 luminosity 21 pb^{-1} from 96/97
    - ZEUS 98-00: 82.2 pb^{-1}
- Examine kinematics and variables that enhance differences between BFKL and DGLAP.
  - Focus on jet pseudorapidities