Parton Dynamics at Low Bjorken x in Deep Inelastic Scattering at HERA

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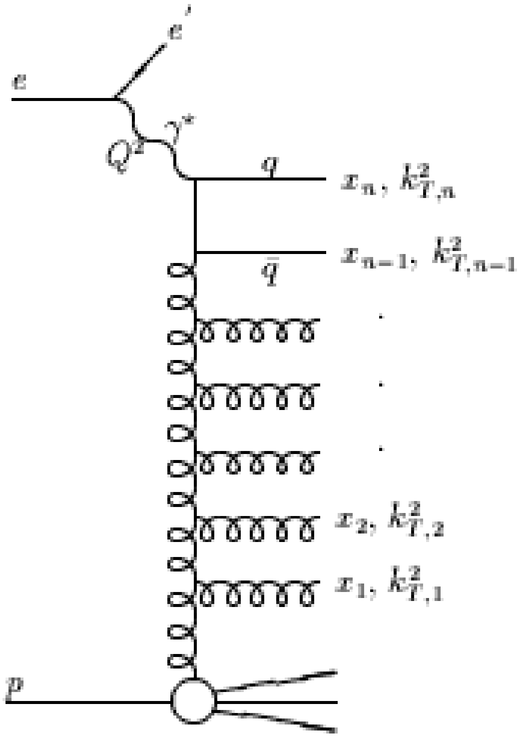
Columbia University, HEP Seminar



- HERA and ZEUS
- Parton Evolution: DGLAP, BFKL
- Forward Jet Measurement
- Summary
- HERA II

HERA Accelerator

HERA: an electron-proton collider at DESY in Hamburg, Germany

2 collider experiments
--> H1 and ZEUS
2 fixed target experiments
--> HERA-B and HERMES

HERA I: 1992-2000

~130 pb-1 taken by ZEUS, H1

2000-2002 Luminosity Upgrade

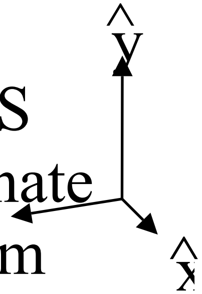
HERA II: 2003-2007

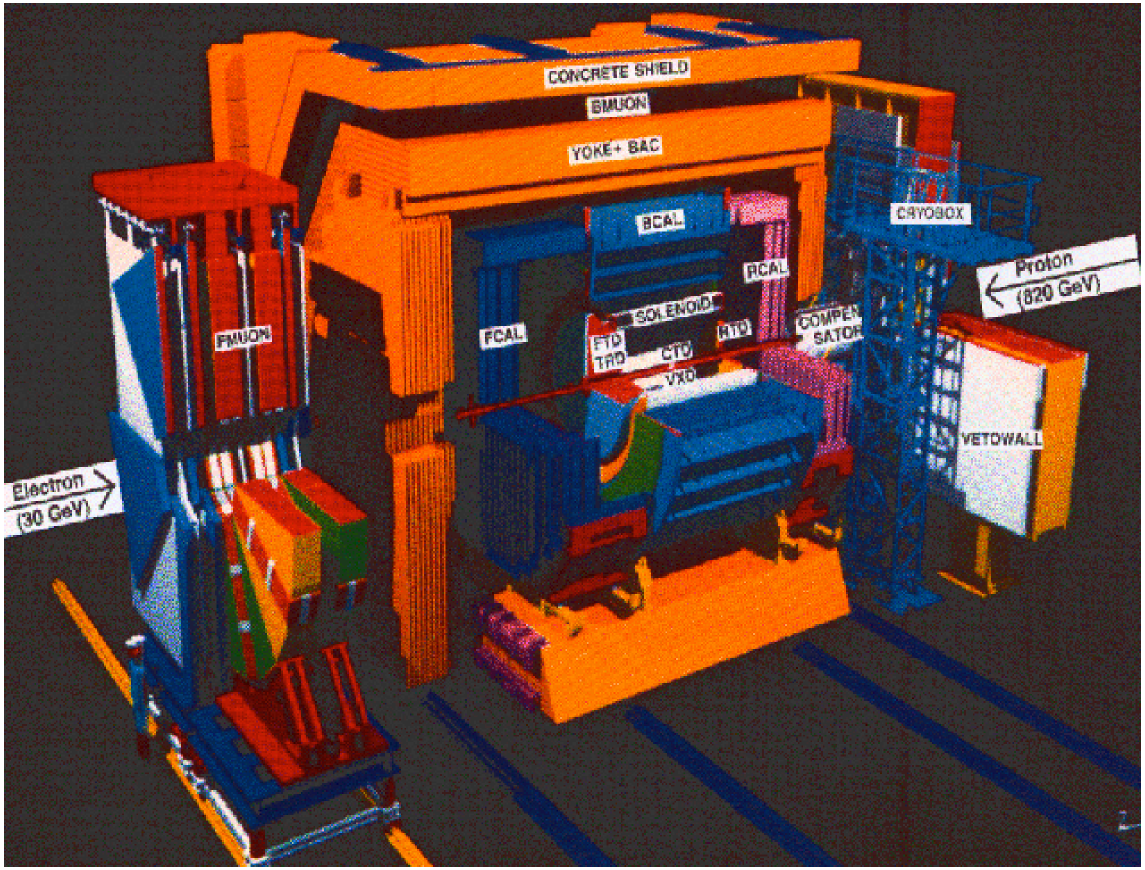
Projected Luminosity: $L^{sum} \ldots 500\ pb^{1}$

- 820/920 GeV protons
- 27.5 GeV e±
- 300/318 GeV c.o.m. energy
- 220 bunches, 96ns. crossing time
- 90 mA protons,40 mA positrons
- Instantaneous luminosity: $L^{inst} = 1.8\text{\AA}10^{31}\ cm^{2}\ s^{1}$

ZEUS Detector

ZEUS Coordinate System





820/920 GeV protons

27.5 GeV positrons

99.7% solid angle coverage

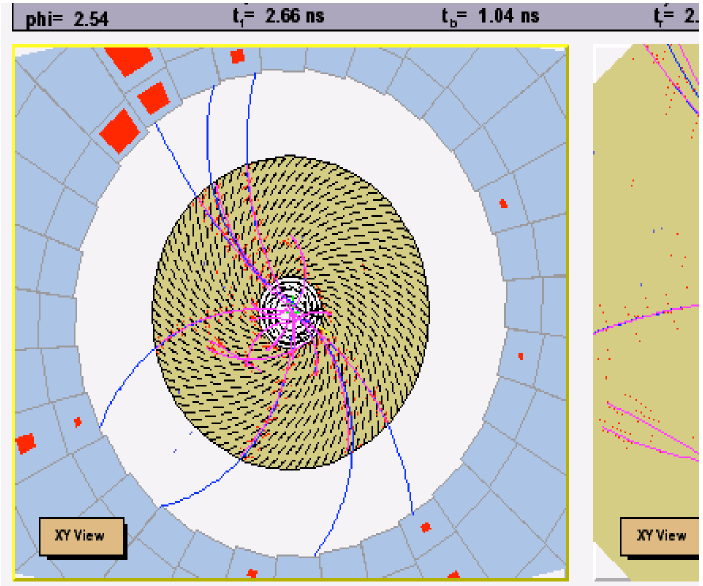
! uranium-scintillator calorimeter sandwich design, compensating
longitudinal segmentation: electron/hadron separation
transverse segmentation: position detection

! argon-ethane central tracking drift chamber
operates in 1.4T magnetic field

ZEUS Central Tracker and Calorimeter

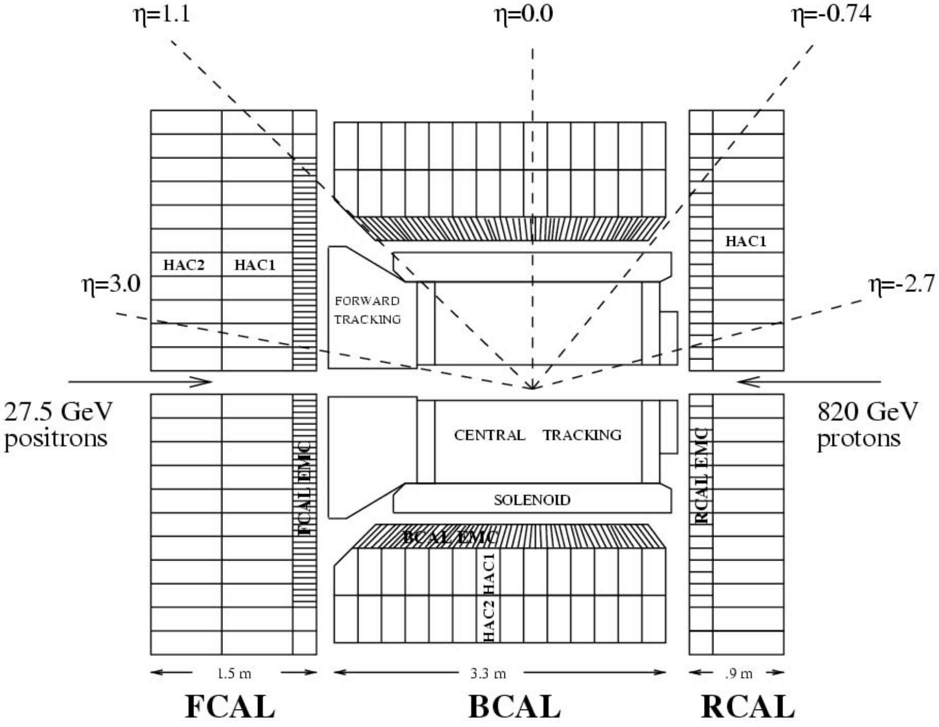
CTD

Drift chamber inside 1.4T solenoid
Vertex Resolution: 4mm in z
1mm transv



view down beampipe

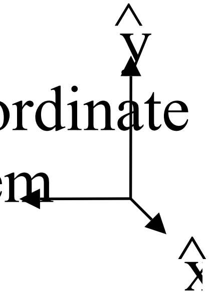
CAL:



½= ln tan(¾/2)

Energy Resolution
35% / ÖE for HAC
18% / ÖE for EMC
Cell geometries:
EMC: 10x20cm. (RCAL), 5x20cm (B/FCAL)

ZEUS Coordinate System



Deep Inelastic Scattering

$$Q^2 = \quad q^2 = (k \quad k')^2$$

Momentum transfer

Resolution variable q = 1/l

$$x_{Bj} = \frac{Q^2}{2p\text{Å}q}$$

fraction of proton's momentum carried by the struck parton

$$y_{Bj} = \frac{p\text{Ă}q}{p\text{Å}k}$$

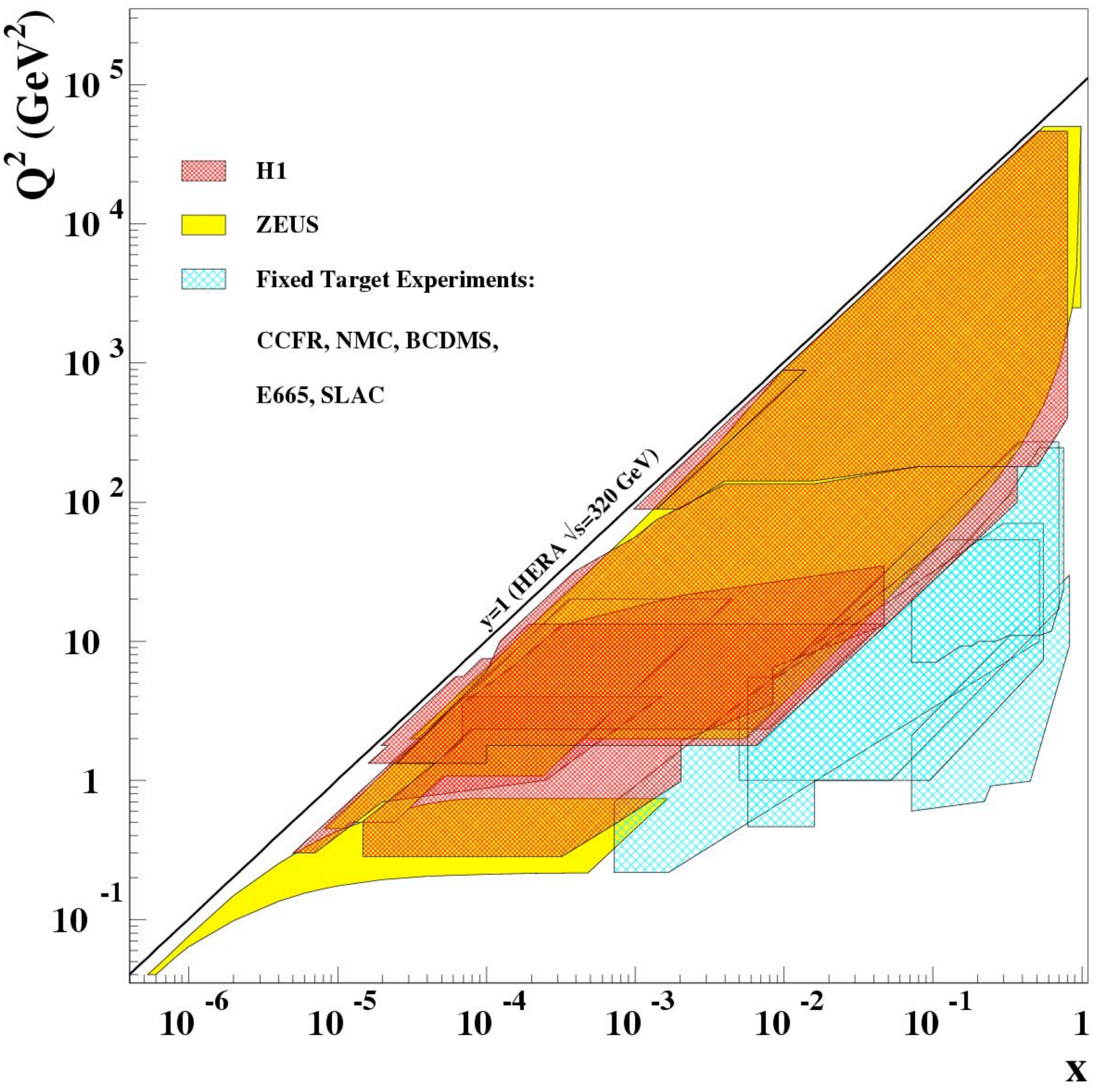
fraction of electron's energy transferred to the proton in the proton's rest frame

e-p scattering mediated by a
g,Z0 (Neutral Current), W±(Charged Current)

Ös = center-of-mass energy

$$Q^2 = s\text{Å}x\text{Å}y$$

Kinematic Coverage



HERA extends kinematic reach well beyond fixed-target experiments

$0.45\,GeV^{2}$ „ Q^{2} „ $20000\,GeV^{2}$

$10\ ^{6}$ „ x „ 0.9

At Ös = 320 GeV, HERA equivalent to 50TeV fixed-target experiment

Deep Inelastic Scattering Cross Section

NC DIS Cross section made up of:

- matrix element calculation
- propagator
- parton density function (PDF)

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

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

F2 parameterizes interaction between photon and spin ½ partons; can be written in terms of the quark densities :

$$F_2(x,Q^2) = \sum_{quarks} A(Q^2)\left[xq(x,Q^2) + x\bar{q}(x,Q^2)\right]$$

Quantum Chromodynamics

Quark-parton model:
valence quarks are free
F2 independent of Q2 -> scaling

Quarks account for only half the momentum in the proton

Pij – QCD Splitting Functions – probability for
a mother parton i to emit a daughter parton j

low x =>
increasing gluon

Gluons impart transverse energy to quarks ® scaling violation

DIS Processes and Orders of as

Quark-parton model
(QPM) events:

Dominant contributor
to inclusive cross section

zeroth-order as process
in QCD (no gluons)

2-parton final states:
Boson-Gluon Fusion
& QCD Compton

first-order as processes
in QCD (1 gluon vertex)

BG
F

QCDC

Factorization

Factorization of DIS cross section: $\text{È}_{DIS} = {}_{i}\, q_i\left(x,\text{Â}_F^2\right) \circ \text{È}^{part}\left(x,\text{Â}_F^2\right)$

i = gluons, all quark flavors

mF -- factorization scale: parameter introduced for handling divergence in calculation

kTparton > mF: parton is included in partonic cross section
kTparton < mF: parton is “absorbed” into parton distribution

$$\frac{d\text{È}_{DIS}}{d\ln \text{Â}_F} = 0 \longrightarrow \frac{dq_i}{d\ln \text{Â}_F} = \frac{\cdot_s}{2\text{Æ}}\ {}_{j} + \frac{d\text{»}}{\text{»}} P_{ij}\left(\text{»},\text{Â}_F^2\right) q_j\left(\text{»},\text{Â}_F^2\right)$$

splitting functions

The splitting functions can be expanded in a perturbation series in as , yielding terms (aslnQ2)n, (asln(1/x))n and (aslnQ2ln(1/x))n

DGLAP Evolution Equations

Quark and gluon parton distribution functions (PDF's) are predicted at a certain x and Q2, given an initial distribution at x0 and Q02.

$$\frac{dq_i(x,Q^2)}{d\,lnQ^2}=\frac{\cdot_s(Q^2)}{2Æ}+_x^1\frac{dz}{z}\left[q_i(y,Q^2)P_{qq}\left(\frac{x}{z}\right)ƒ\;g(y,Q^2)P_{qg}\left(\frac{x}{z}\right)\right]$$

splitting functions
-calculable by QCD

$$\frac{dg(x,Q^2)}{d\,lnQ^2}=\frac{\cdot_s(Q^2)}{2Æ}+_x^1\frac{dz}{z}\left[q_i(y,Q^2)P_{gq}\left(\frac{x}{z}\right)ƒ\;g(y,Q^2)P_{gg}\left(\frac{x}{z}\right)\right]$$

In the perturbation series calculation of the evolution of the PDF's with x and Q2,
there are terms proportional to (aslnQ2)n, (asln(1/x))n and (aslnQ2ln(1/x))n,

DGLAP Approximation:
sums terms aslnQ2, ignores asln(1/x)
has limited applicability ---> $\cdot_s\ln(Q^2)\sim 1$ $\cdot_s\ln\frac{1}{x}\text{i}\;1$

DGLAP = Dokshitzer,
Gribov,
Lipatov,
Altarelli, Parisi

BFKL Evolution

An alternate resummation scheme
for determining the parton densities

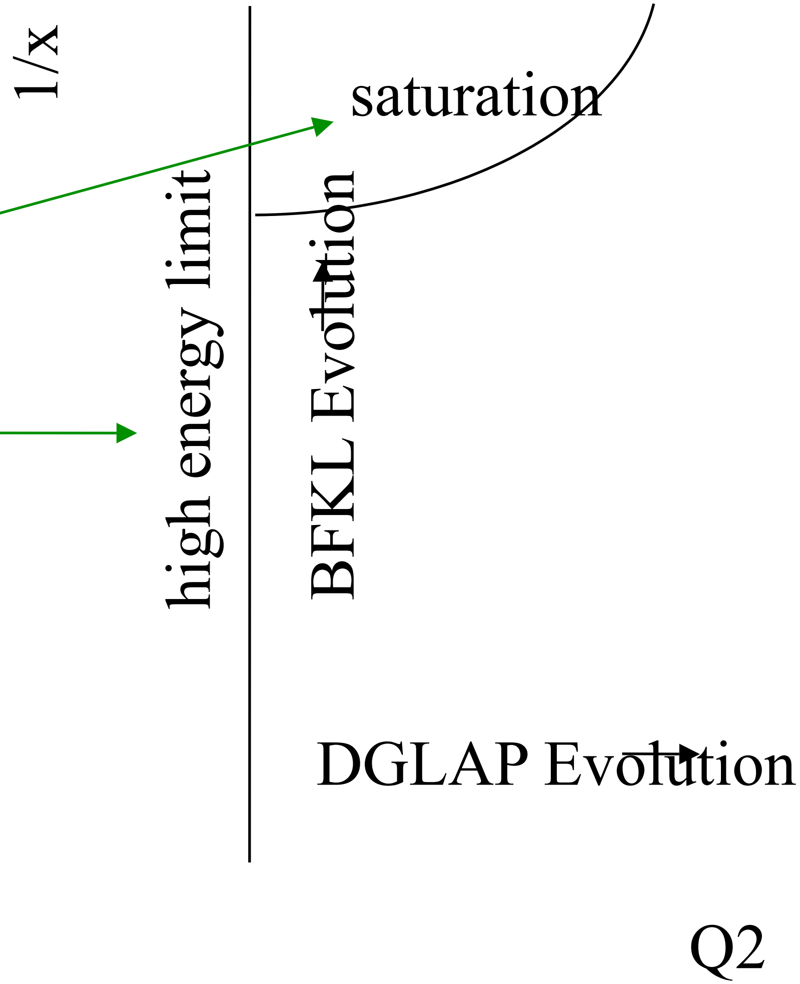
limiting case of large
gluon density

non-perturbative region

At small x, ln(1/x) terms in
perturbation series not negligible.

BFKL approximation:
sums terms asln(1/x), ignores aslnQ2
has limited applicability --->

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


1/x

saturation

high energy limit

BFKL Evolution

DGLAP Evolution

Q2

BFKL = Balitzki, Fadin, Kuraev,
Lipatov

Gluon Ladder

DGLAP: x = xn < xn-1 < ... < x1, Q2 = k2T,n >> ... >> k2T,1
BFKL : x = xn << xn-1 << ... << x1, no ordering in kT

forward fadeout
h democracy

BFKL Þ additional hadrons from high transverse momentum forward partons, above the DGLAP prediction.

DGLAP kT ordering

HERA forward region

Monte Carlo

- Parton Distribution Function
- LO QCD Matrix Elements --> hard subprocess
- Parton Showering
- Hadronisation

} model-dependent
(non-perturbative)

Parton Showering Models:
Color-Dipole (CDM): Ariadne (BFKL-like)
MEPS: Lepto (DGLAP-like)

MC used for:
detector acceptance
hadronization corrections
ISR/FSR corrections

→ detector simulation
& reconstruction

Monte Carlo (II)

LEPTO:

- kT-ordered parton shower - DGLAP
- Hadronization: Lund String Model

ARIADNE:

- Parton showering with CDM
  (Color Dipole Model: BFKL-like)
  Hadronization: Lund String Model

Lund String Model: Color string stretched across pairs of final state partons.
Energy stored in the string gives rise to hadrons.

Detector acceptance estimated with LO Color Dipole Model (CDM) implemented with Ariadne , which has the best description of data

Next-to-Leading-Order

NLO calculations give partonic level cross sections for one higher order in as
--no attempt at modeling higher order contribution

Programs for DIS:
DISENT (Seymour and Catani)
DISASTER++ (Graudenz)
MEPJET (Mirkes, Zeppenfeld)

For comparison with data, NLO cross sections need to be corrected from parton to hadron level – Ariadne.

2 implementations of NLO calculation by DISENT

Inclusive Jet (QPM) Phase Space

$$d\text{È}_{LO} = A_0$$

$$d\text{È}_{NLO} = A_1 ƒ\ B_1 \cdot {}^{1}_{s}$$

explained in more detail later

QPM Suppressed (Dijet) Phase Space

$$d\text{È}_{LO} = C_1 \cdot {}^{1}_{s}$$

$$d\text{È}_{NLO} = C_2 \cdot {}^{1}_{s} ƒ\ D_2 \cdot {}^{2}_{s}$$

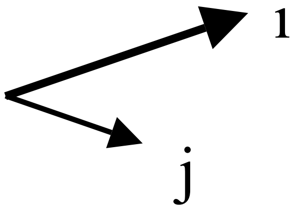
Renormalization Scale μR: Scale at which the strong coupling constant is evaluated

Renormalization scale uncertainty determined by effect on cross section by scale variation: $\frac{Q}{2}„\ \text{Â}_{R}„\ 2Q$ -- dominant theoretical uncertainty

Jets

Jets are selected in the lab frame using the longitudinally invariant kT-cluster algorithm:

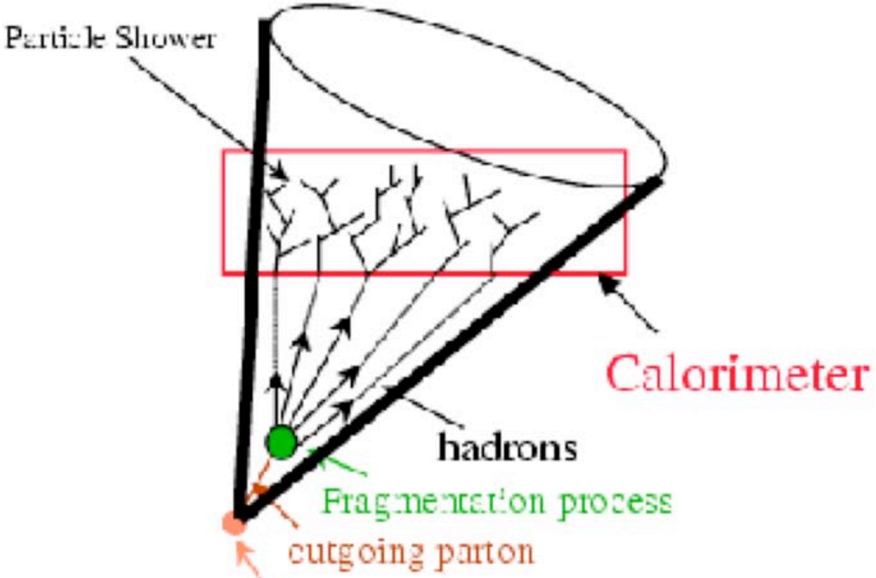
Catani et.al.; Ellis & Soper

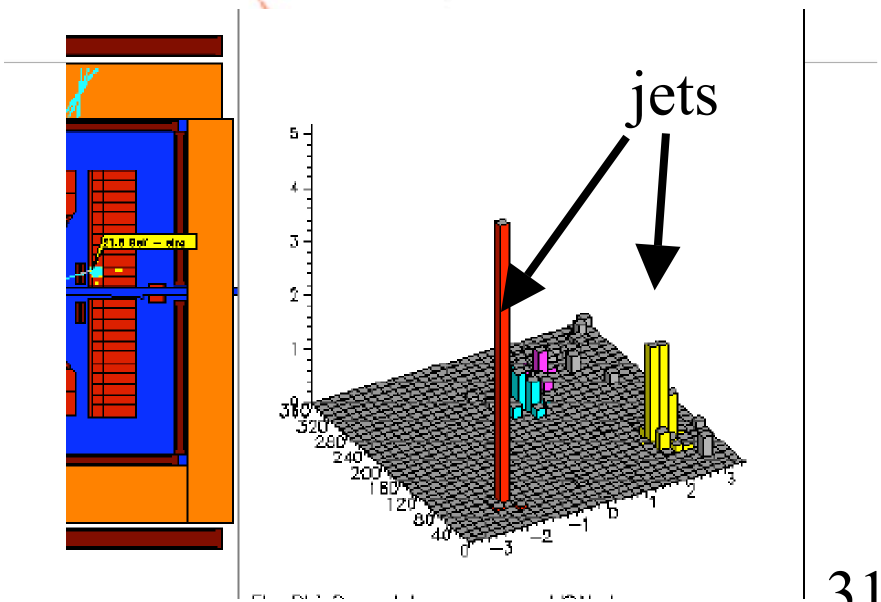


⇓

Combine particles i and j into a jet if di,j is smaller of {di,di,j}.

Can be applied to partons, hadrons and detector quantities in the same way





Data Selection: Inclusive Jets

Data Set: ZEUS 96/97 (~38.6 pb-1)

Phase space selection

! Q2 > 25 GeV --- region of high trigger and detector acceptance
y > 0.04 --- good reconstruction of hadronic system
E´el > 10 GeV --- high purity DIS sample
ET,jet > 6 GeV --- ensures a hard jet is measured
-1 < hjet < 3 --- detector acceptance

$$½= \ln\left(\tan\frac{¾}{2}\right)$$

DIS selection made by requesting high-energy positron in the final state with additional cuts applied to reject background.

Inclusive Jet Cross Section vs. hjet

Cross section drops in forward region due to y-cut

- Significant discrepancy with NLO at high h,

Ariadne (BFKL-like LO MC) can describe the data

Lepto (DGLAP-like LO MC) gives fairly good description

Cross section dominated by QPM events - should be well understood! NLO is O(as)

BFKL?
Parton shower missing from NLO?

Inclusive Jet Cross Section vs. Q2, x

Discrepancy between data and NLO localized in lowest xBj and Q2 bins, regions where BFKL may be important

Inclusive Jet Cross Sections vs. total Inclusive Cross Sections using DISENT

Inclusive jet phase space

! Q2 > 25 GeV2 ! ET,jet > 6 GeV
y > 0.04 ! -1 < hjet < 3

Fully inclusive DIS phase space

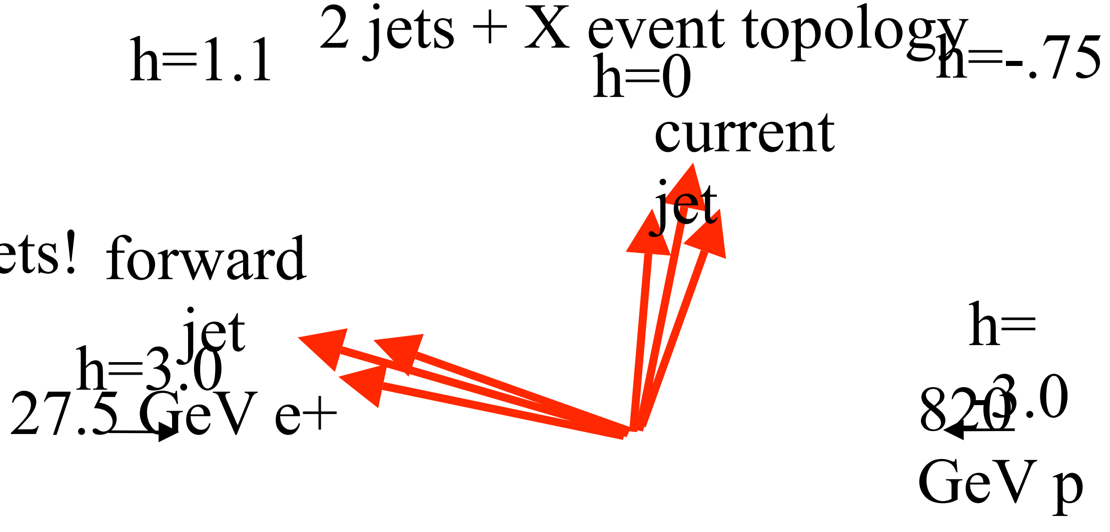
! Q2 > 25 GeV2 no jet
y > 0.04 selected!

A hard lower cut-off in the jet ET significantly limits the phase space
Þ inclusive jet cross section does not dominate
inclusive DIS cross section at low xBj and Q2

Event Topology: Isolating the Signal

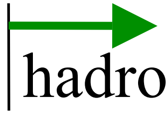
Remember that our signal events are Boson-Gluon Fusion and QCDC events with high-ET forward going jets!

2 jets + X event topology



In QPM events, only 1 jet =>
hadronic angle = jet angle

To enhance our “signal-to-background” rati
(reject QPM), we restrict our phase space:
events must have hadronic angle > 90o
jet h must be in forward half of detector



hadronic angle
gh > 90º

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

Reselection of Phase Space

Inclusive Jet Phase Space

! Q2 > 25 GeV
y > 0.04
Eel > 10 GeV
ET,jet > 6 GeV
-1 < hjet < 3

to suppress QPM

"QPM Suppressed" Phase Space

! Q2 > 25 GeV
y > 0.04
Eel > 10 GeV
ET,jet > 6 GeV
0 < hjet < 3
cos (ghad) < 0

Disent Calculations:
LO = O(as0) = QPM
NLO = QPM + corrections

2 orders in the series of as

with hadronic angle requirement
QPM = 0 for h > 0
BGF + QCDC for h > 0

Just 1 order in the series of as

Disent Calculations:
LO = O(as1) = BGF + QCDC
NLO = O(as2) = BGF + QCDC

2 orders in the series of as + corrections

Inclusive Jet Cross Section vs. hjet for "QPM Suppressed" Phase Space

For our signal events, agreement with NLO within errors.

NLO now includes terms O(as2)

Ariadne gives good description of data

Lepto gives fair description of data

Renormalization scale uncertainty grows in the forward region

Inclusive Jet Cross Section vs. Q2,x for QPM Suppressed Phase Space

NLO based on DGLAP agrees with data within errrors.

BFKL Phase Space

Further restrictive phase space
suggested by Mueller, Navalet

limitation on Q2/E2T,jet suppresses
events exhibiting DGLAP evolution

$Q^2 \sim E^2_{T,\ jet}$

Inclusive Sample:

! Q2 > 25 GeV
y > 0.04
Eel > 10 GeV
ET,jet > 6 GeV
-1 < hjet < 3

QPM Suppressed Sample:

! Q2 > 25 GeV
y > 0.04
Eel > 10 GeV
ET,jet > 6 GeV
0 < hjet < 3
cos(gh) < 0

BFKL Jets Sample:

! Q2 > 25 GeV
y > 0.04
Eel > 10 GeV
ET,jet > 6 GeV
0 < hjet < 3
cos(gh) < 0
0.5 < Q2/ET,jet2 < 2

Inclusive Jet Cross Section vs hjet for BFKL Phase Space

Data shows excess over NLO

Large renormalization scale uncertainty persists

Ariadne (BFKL-like MC) gives excellent description of data over entire region

Lepto (DGLAP-like MC) cannot describe data

Inclusive Jet Cross Section vs Q2,x for BFKL Phase Space

NLO Calculation can describe the data.

Summary

- Inclusive jet cross sections at Q2 > 25 GeV2 , y >0.04 have been measured over the full rapidity acceptance region in three phase space regions

	NLO Calculation	Ariadne (BFKL-like MC)	Lepto (DGLAP-like MC)
Inclusive PS	cannot describe data in forward	good description	good description
QPM Suppressed PS	data above NLO; agreement w/in errors	good description	fair description
BFKL PS	data above NLO	excellent description	data above Lepto

Conclusions

- Large renormalization scale uncertainty indicates higher order contributions are important for obtaining an accurate prediction from the theory.

A resummed NLO calculation, perhaps using the BFKL implementation, would be interesting to compare to the data, both for its cross section predictions and as a measure of the renormalization scale uncertainty in the low-xBj and high-hjet region

Experimental improvements:

A forward jet analysis is in progress that measures farther forward using an additional forward plug calorimeter.
New forward tracking detectors have been installed, and should improve reconstruction in the forward region for HERA II
With improved jet reconstruction, measure at lower jet transverse energy

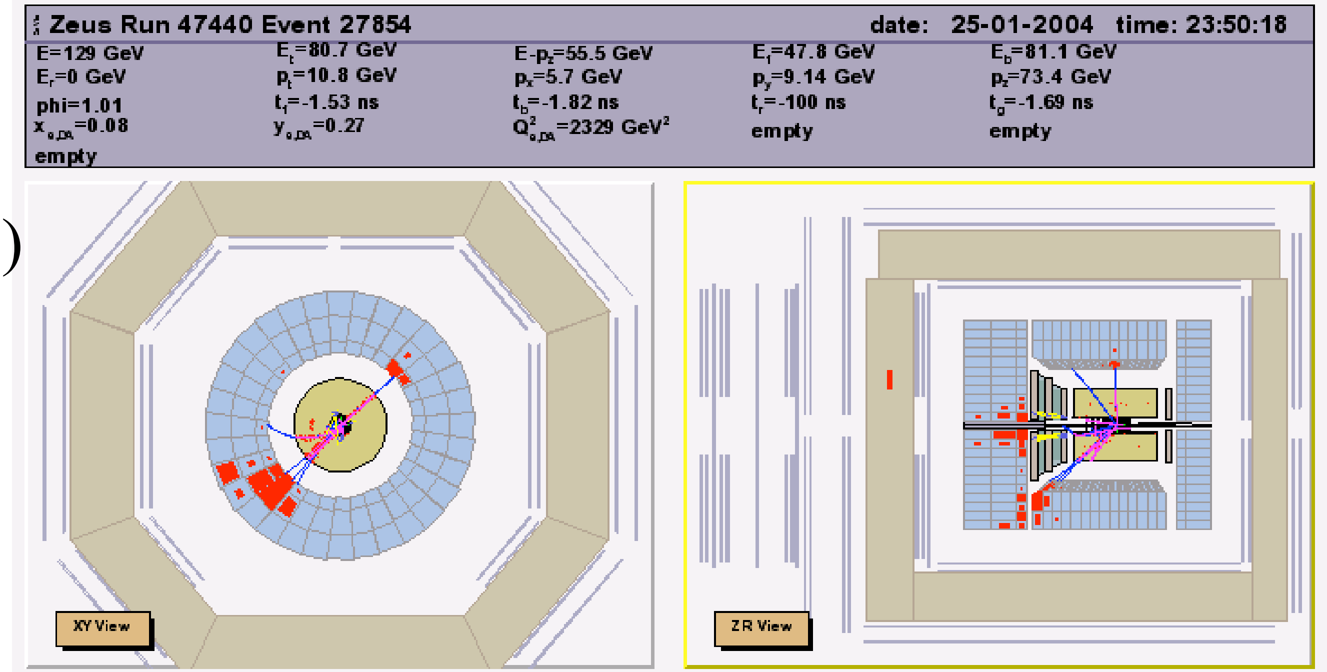
HERA II

HERA II goals and accomplishments:
Increase instantaneous luminosity over 1.8x10-31 cm-1s-1 by factor 3-5
specific luminosity reached, beam currents gradually ramped
1 fb-1 total integrated luminosity – factor 5-10 over HERA I
HERA delivers stable lumi, with each experiment taking 5-10 pb-1
70% longitudinal polarization of e± beams → achieved 50% with e+

Detector upgrades:
tracking chambers:
    silicon vertex (ZEUS) and forward/backward tracking (both)
forward proton spectrometer (H1)
luminosity detectors (both)
triggers (both)

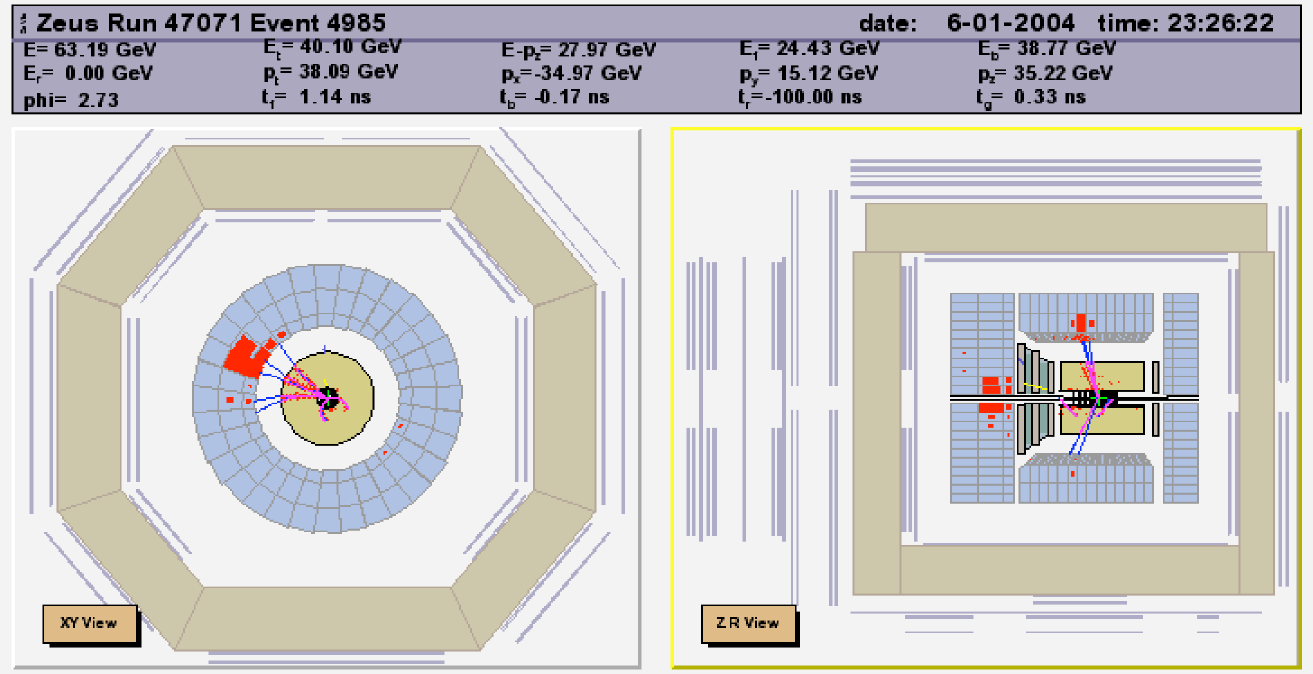
HERA II Events

Neutral Current DIS
e± p ® e± X (g,Z0 exchange)
Q2 = 2325 GeV2
x = 0.08



Zeus Run 47440 Event 27854 date: 25-01-2004 time: 23:50:18

E=129 GeV
E_t=80.7 GeV
E-p_z=55.5 GeV
E_f=47.8 GeV
E_b=81.1 GeV
E_r=0 GeV
p_t=10.8 GeV
p_x=5.7 GeV
p_y=9.14 GeV
p_z=73.4 GeV
phi=1.01
t_f=-1.53 ns
t_b=-1.82 ns
t_r=-100 ns
t_g=-1.69 ns
$x_{e,DA}$=0.08
$y_{e,DA}$=0.27
$Q^2_{e,DA}$=2329 GeV^2
empty
empty
empty



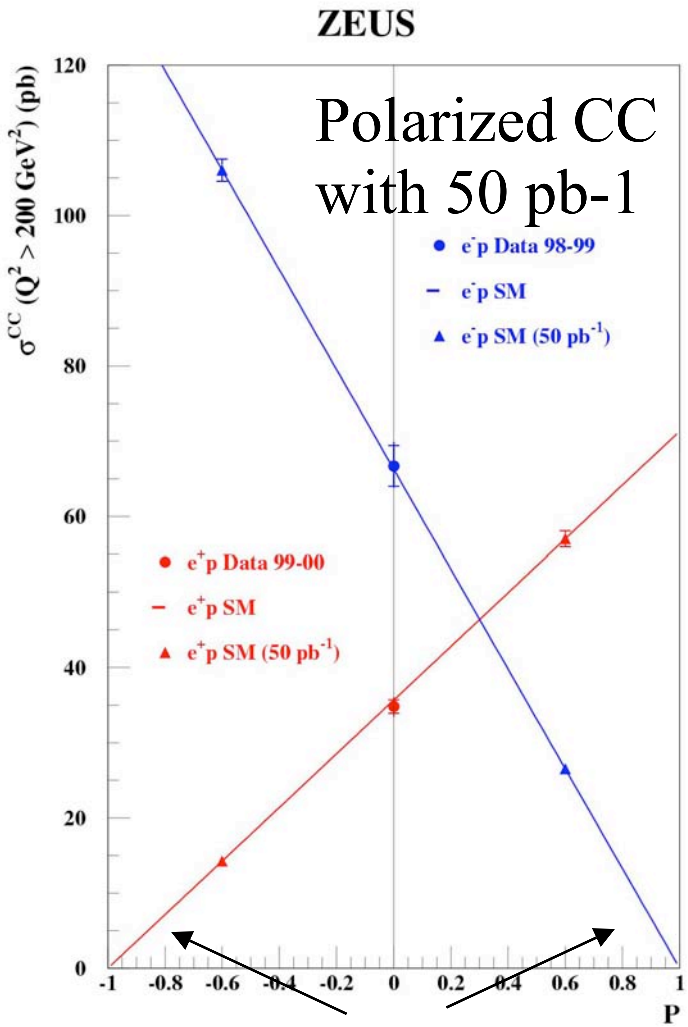
Zeus Run 47071 Event 4985 date: 6-01-2004 time: 23:26:22

E= 63.19 GeV
E_t= 40.10 GeV
E-p_z= 27.97 GeV
E_f= 24.43 GeV
E_b= 38.77 GeV
E_r= 0.00 GeV
p_t= 38.09 GeV
p_x=-34.97 GeV
p_y= 15.12 GeV
p_z= 35.22 GeV
phi= 2.73
t_f= 1.14 ns
t_b= -0.17 ns
t_r=-100.00 ns
t_g= 0.33 ns

Charged Current DIS
e± p ® n X (W± exchange)
Q2 = 2800 GeV2
pT = 38

HERA II Analyses

Structure Function Measurements:
more accurate CC, NC ! xF3, FL
polarized cross section
charm, bottom contributions
parton density functions

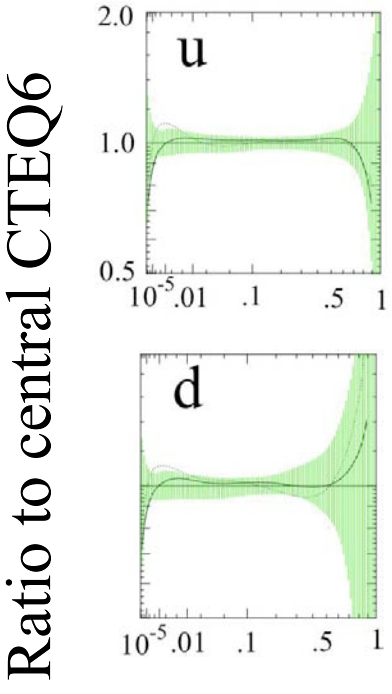


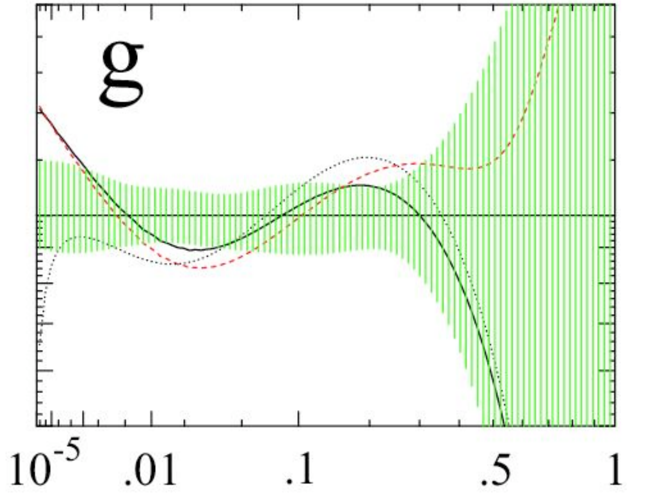
Polarized CC with 50 pb-1

extrapolation

sensitivity to new physics

Uncertainty estimates by CTEQ at Q2 = 10 GeV2





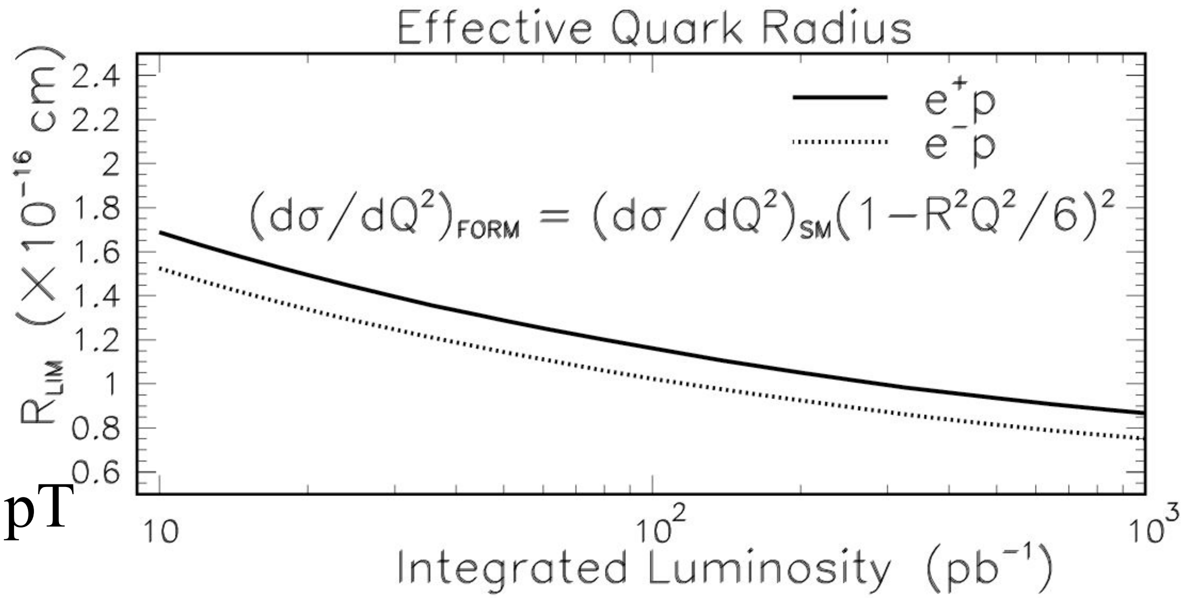
u density most constrained

gluon density poorly constrained at high x

HERA II Analyses

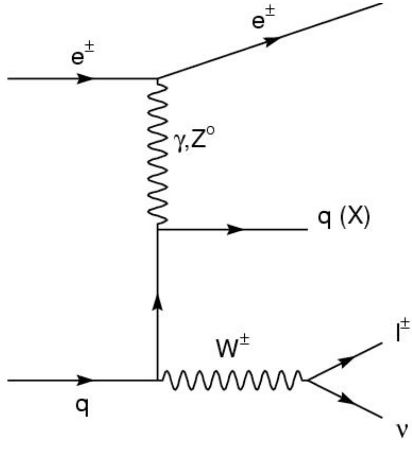
New Physics Searches:

- Quark Substructure →
- Leptoquarks
- Contact Interactions
- SUSY
- Large Extra Dimensions
- Isolated Leptons and missing pT



H1 observe an excess in HERA I of events with a high pT isolated lepton and missing pT

e.g.



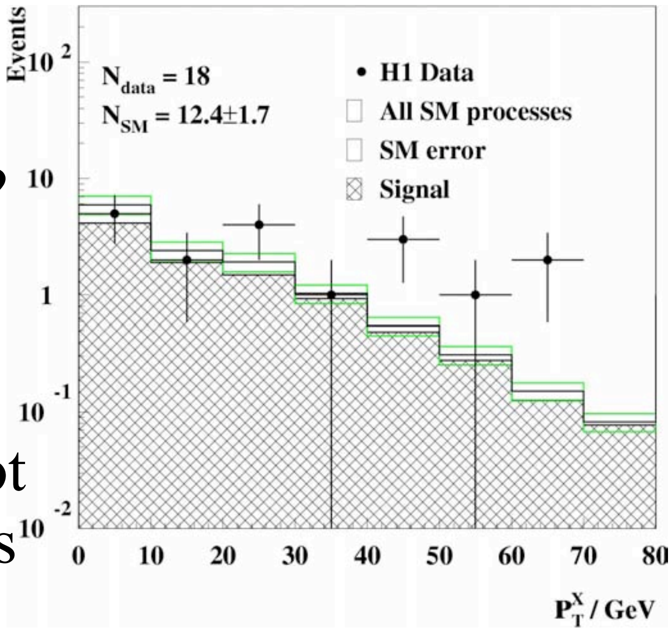
jet

isol. lepton

missing pT

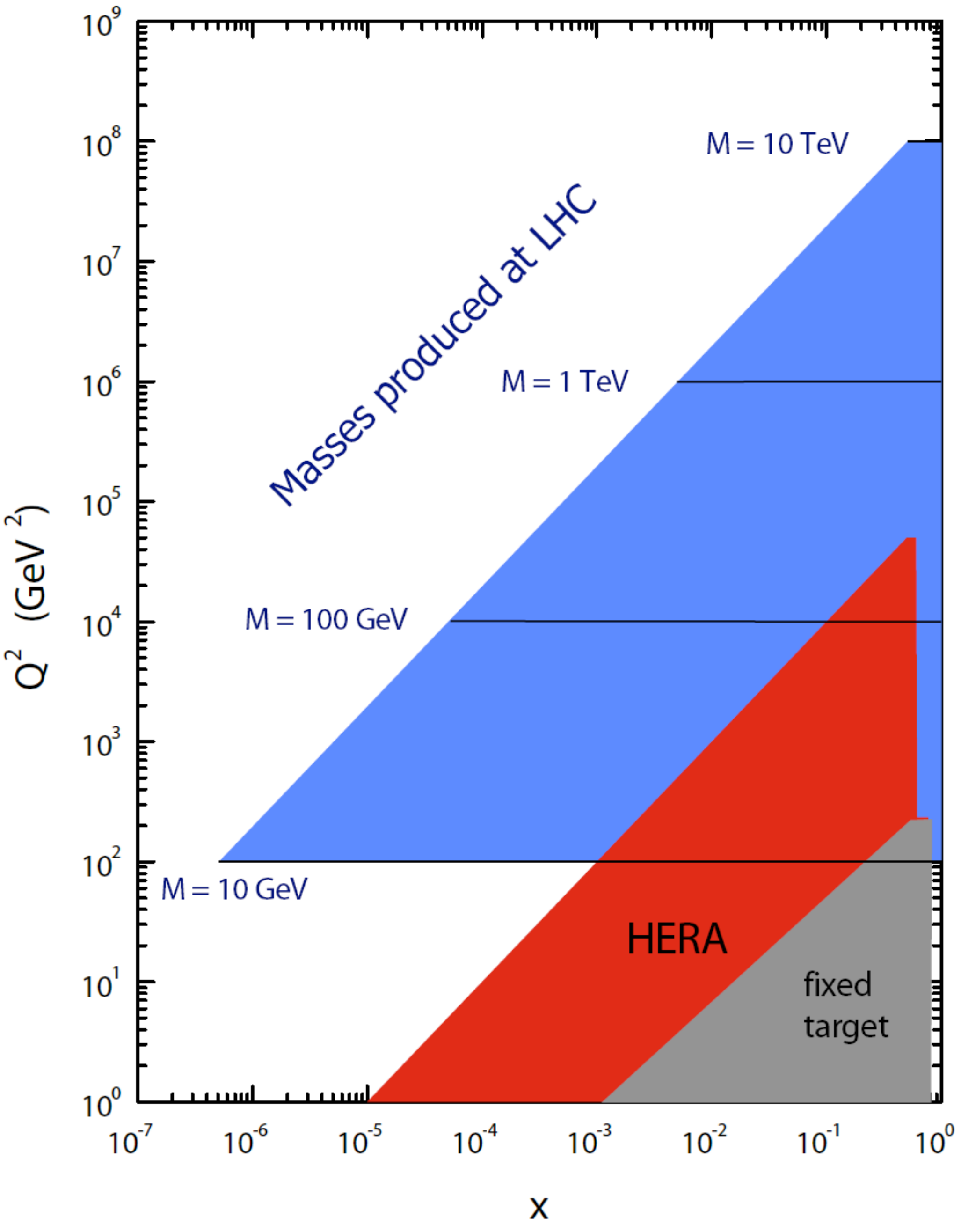
Excessive W production?
Supersymmetry?
Excited quarks?

ZEUS does not observe excess



Look for new results from HERA II in this year's spring and summer conferences

HERA ® LHC



HERA densities extrapolate into
LHC region

DGLAP parton densities,
QCD knowledge from HERA
↓
LHC measurements

HERA measurements crucial for
understanding signal + background
at LHC!

End of Talk

HERA Luminosity

Steady increase of luminosity accumulation
during HERAI, with ZEUS taking 130 pb-1

- 17 pb-1 of e-
- 115pb-1 of e+
- 820 GeV protons through 1997
- 920 GeV protons 1998-present

Post-upgrade:

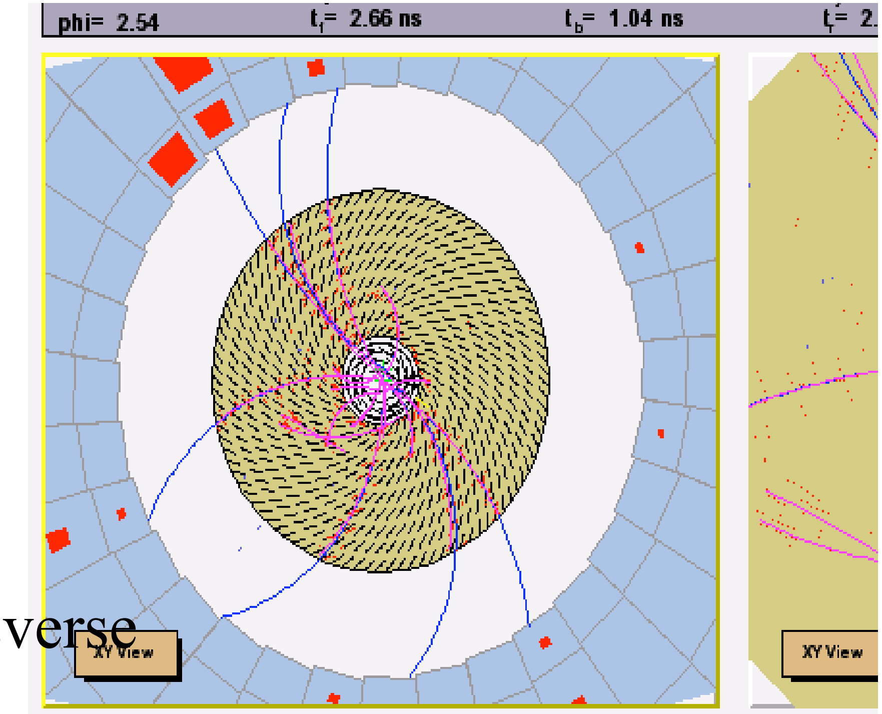
Several sources of background delayed delivery of lumi, most problems solved, now stable running

Projected Total HERAII Luminosity:

$$L^{\text{sum}} \ldots 500\ pb^{1}$$

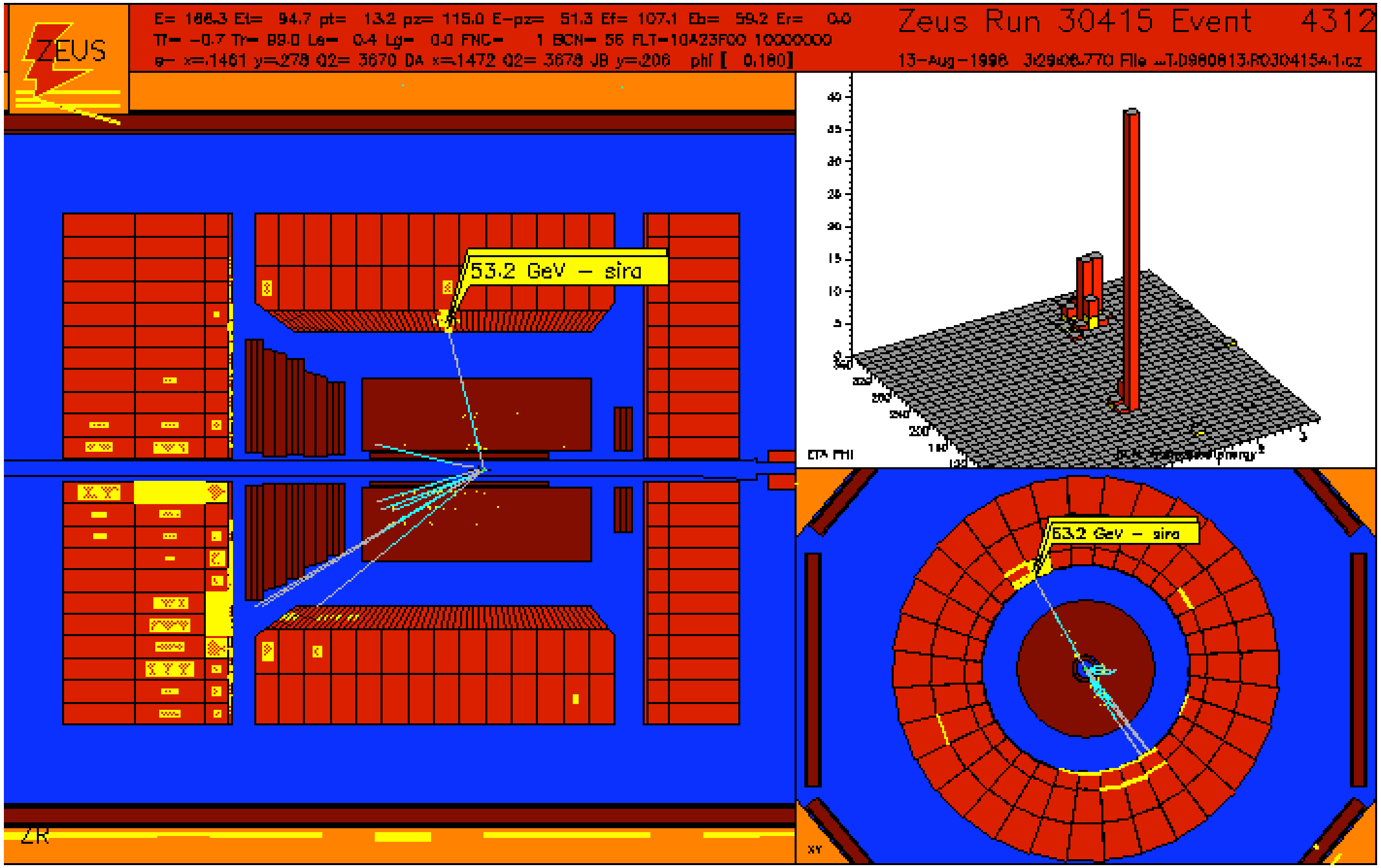
Central Tracking Detector

CTD: drift chamber inside 1.4T solenoid
Vertex Resolution: 4mm in z
1mm transverse



views down the beampipe in x-y

Deep Inelastic Scattering Event

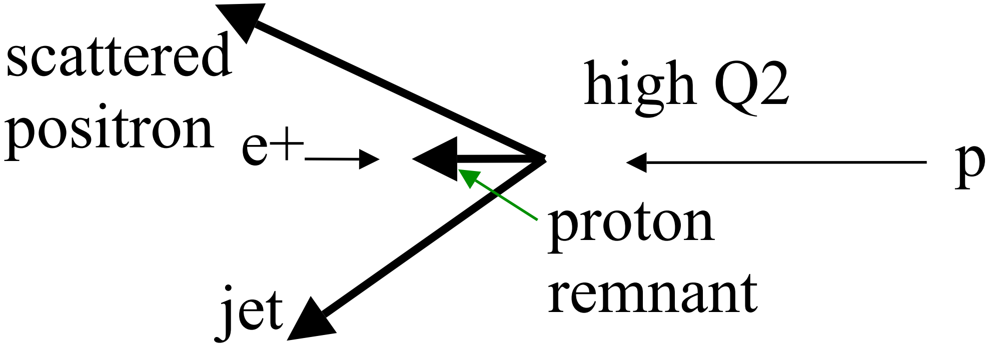


```
E= 168.3 Et=  94.7 pt=  13.2 pz= 115.0 E-pz=  51.3 Ef= 107.1 Eb=  59.2 Er=   0.0
Tf= -0.7 Tr= 89.0 Le=  0.4 Lg=  0.0 FNC=    1 BCN= 56 FLT=10A23F00 10000000
e- x=.1461 y=.278 Q2= 3670 DA x=.1472 Q2= 3678 JB y=.206   phi [  0.180]
```

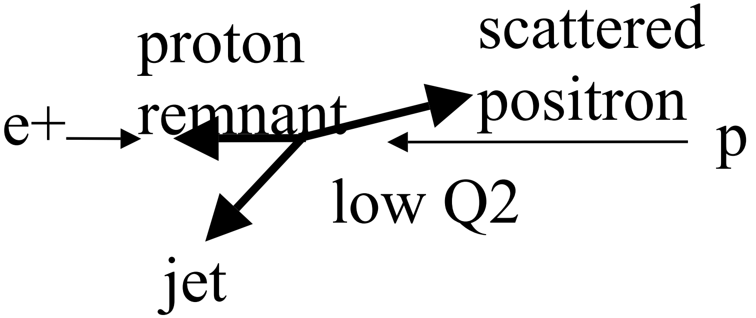
820/920 GeV p on
27.5 GeV e+ Þ
large forward boost

Q2 correlated to scattered positron angle

This event:
Q2~3600 GeV2
x ~0.15
y ~ 0.2



scattered positron
e+
high Q2
p
proton remnant
jet



e+
proton remnant
scattered positron
p
low Q2
jet

Scaling Violation

scaling
violatio
n

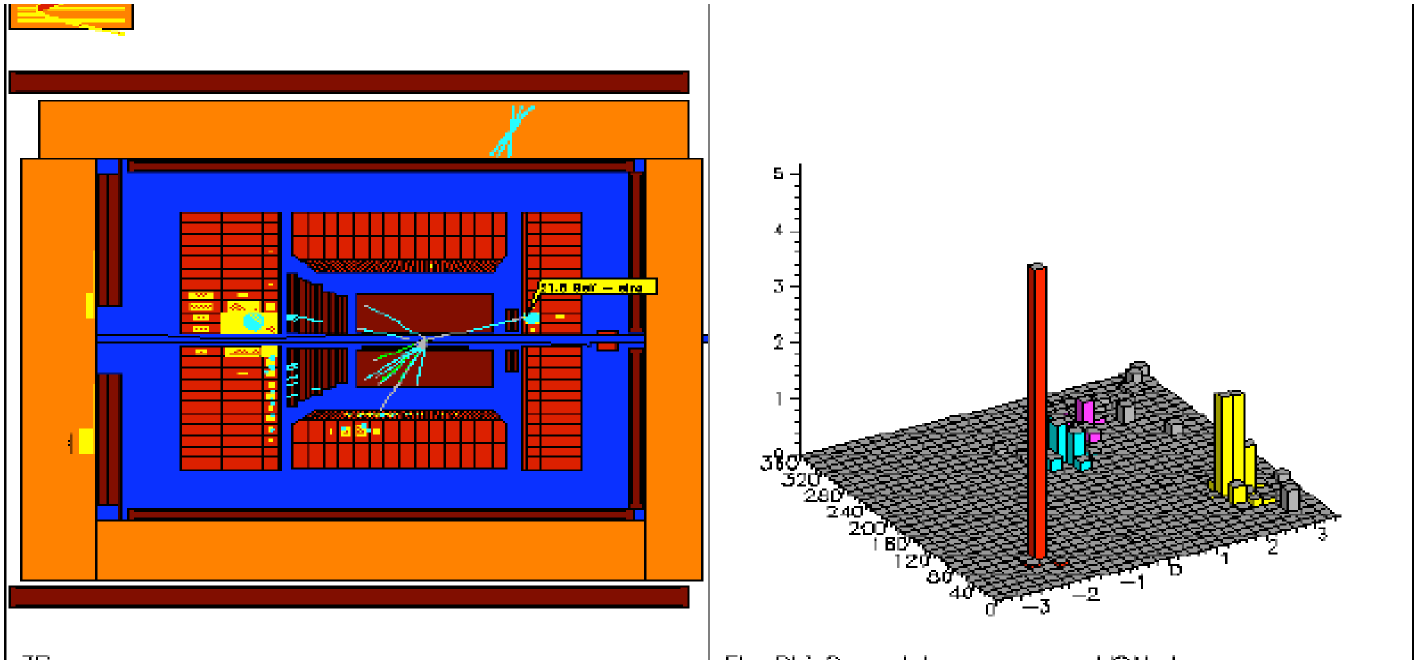
scalin
g

Gluon density can be extracted from fits to F2 along lines of constant x

$$g(x,Q^2) \sim \frac{dF_2(x,Q^2)}{d\ln Q^2}$$

F2 increasing at lower x
Þ increasing gluon

Dijet Event



Looking for presence of strong forward jets accompanied by hadronic activity in central and/or rear parts of the detector

Previous ZEUS Measurement

Issues:

- all monte carlo models understimate the data at low x

LO monte carlo models are not consistent with each other

Improvements:

- new data set: 6x more statistics
- new calculation: NLO
- higher reach in h

jet finding with kT-algorithm

Jet and event reconstruction

Experimental challenges:
need good description of data by MC
need high jet finding purity and efficiency

• Data
– Ariadne

Data is well described by Ariadne

Purities and efficiencies ~60%, except at high h and low ET.

Systematic Uncertainties

Systematic uncertainties arise from
data measurement resolution
poor description of data by MC at cut boundary
model dependencies in MC

Systematic Checks	Typical/Maximal (in a bin) Variation
1. Lepto instead of Ariadne	6% / 15%
2.Calorimeter Energy Scale ±3%	5% / 23%
3. Jet Et cut variation ± 1GeV	2% / 13%
4. Jet h cut (forward) variation ± 0.2	1% / 5%
5. Electron energy cut variation ± 1 GeV	2% / 5%
6. Q2 cut variation ± 2 GeV	1% / 3%
7. Vtx cut variation ± 10 cm.	1% / 2%
8. High E-pz cut variation ± 3 GeV	1% / 1%
9. Low E-pz cut variation ± 3 GeV	1% / 1%
10. Hadronic angle cut variation ± 0.1	3%/ 12%