An Introduction to HERA Physics

DESY Summer Student Program
23 August, 2005
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DESY, Hamburg

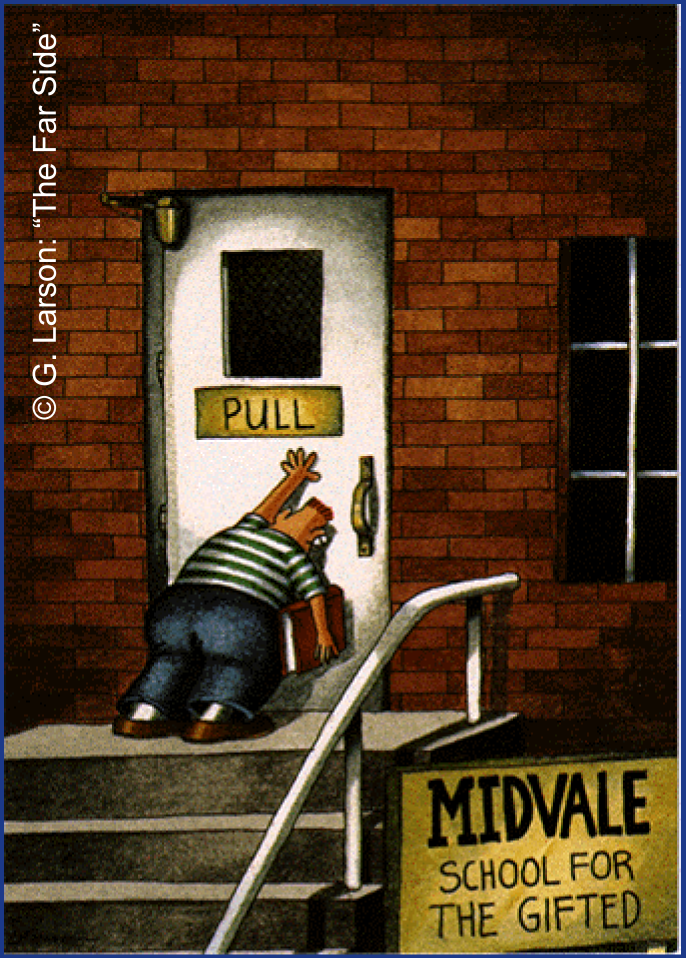
Overview

Part 1:

- What is HERA?
- Kinematics
- Structure Functions and QCD evolution

Part 2:

- Selected HERA Results:
  - Structure Functions
  - High Q^2 and EW precision measurements
  - Jets and the strong coupling α_S
  - Exotics (Pentaquarks et al…)

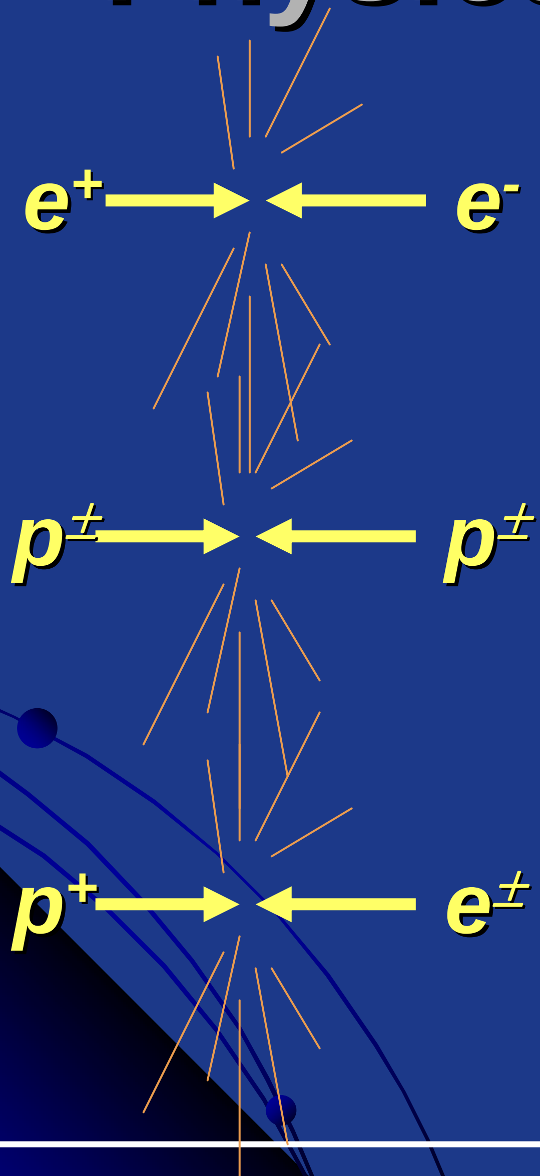


Part 1

What is HERA?

"I've got it, too, Omar … a strange feeling like we've just been going in circles."

Physics @ Colliders



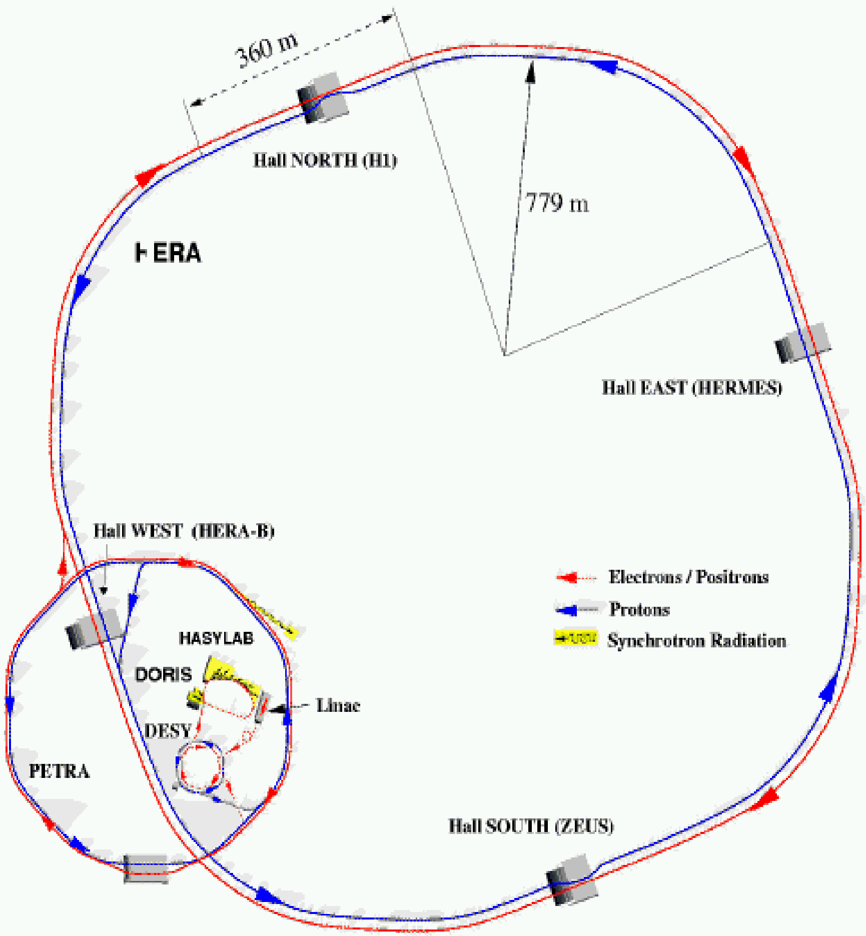
+ Simple initial state
+ Clean final states
+ Little background
- Limited energy
• e.g. LEP(200 GeV), *ILC(1 TeV)*

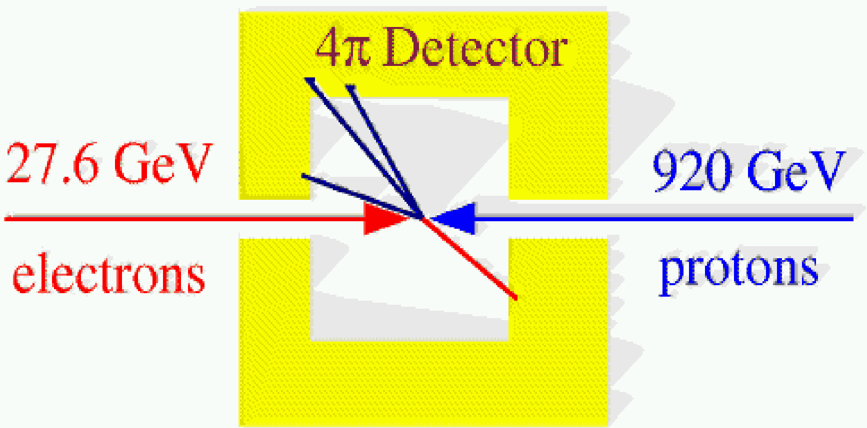
+ High energy (no synch rad)
- Complicated initial state
- Large and complicated backgrounds
- e.g TEVATRON(2 TeV), *LHC(14 TeV)*

+ Unique initial state
- two accelerators
- HERA (300 GeV)


H1
hermes
ZEUS
©stadionwelt.de
HERA
B
PETRA

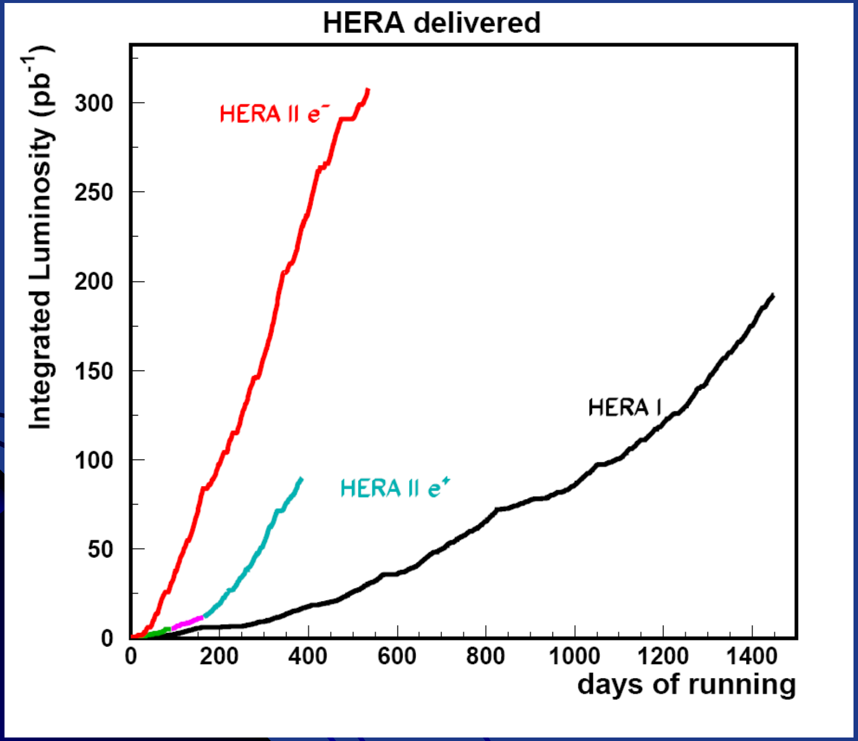
HERA: The only *ep* Collider on the Planet





$$\sqrt{s} \approx 320\ \text{GeV}$$

HERA



- Highlights:
  - Started operation in 1992
  - 4 Experiments:
    - H1 and ZEUS (ep)
    - HERMES (e)
    - HERA-B (p) (until 2003)
  - $\sqrt{s}$ = *300 GeV* (→1997)
  - $\sqrt{s}$ = *318 GeV* (1998 →)
  - *e*$^+$ and *e*$^-$ beams
  - up *to 60%* lepton polarization
  - > 600 Mio *ep* collisions recorded per experiment

Physics Topics of HERA

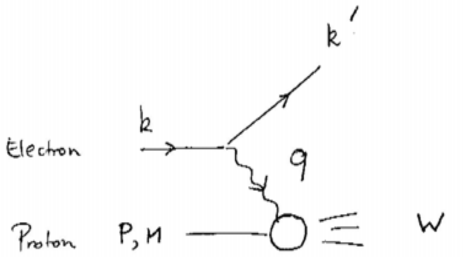
- Proton Structure
  - Parton densities
    - gluon density (xg(x))
    - Valence quark distributions
  - QCD evolution
  - Different evolution schemes (e.g. BFKL)
  - Strangeness and charm
  - α_S
- Perturbative QCD
  - Jets
    - Gluon density
    - α_S
  - Multiparticle Observables:
    - Multiplicity distributions
    - Event chapess
    - Multiparticle Correlations
- Border between pQCD and non-perturbative QCD
- Photon Structure
- Diffraction
- EW
- BSM and Exotics
  - Leptoquarks
  - Excited Quarks and Fermions
  - FCNC
  - MSSM Searches
  - R-parity violation SUSY
  - Contact Interactions
  - …
- Spectroscopy

Kinematics


Yakity yak yak yak!..
yakity yak yak yak!..
© Gary Larson, The Far Side

①

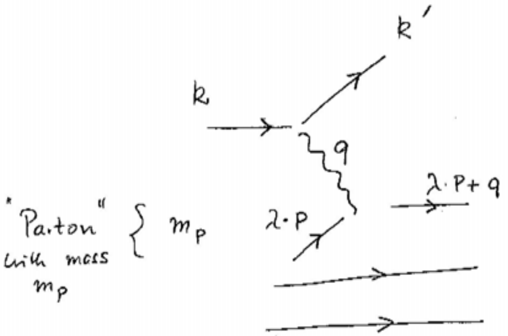
Kinematics of Deep Inelastic Scattering:



$$q = k - k'$$

$$W^2 = (P+q)^2$$

We want to view this process like this



This condition assumes that the parton is "point-like"

$$(\lambda \cdot p)^2 = \lambda^2 p^2 = m_p^2 = (q + \lambda \cdot P)^2$$

$$m_p^2 = q^2 + 2\lambda\, p \cdot q + (\lambda \cdot p)^2$$

$$q^2 = -Q^2$$

Note: Since q is space-like ($q^2 < 0$) we choose a positive quantity $Q^2 = -q^2$

$$\cancel{m_p^2} = -Q^2 + 2\lambda\, p \cdot q + \cancel{m_p^2}$$

$$\Rightarrow \lambda = \frac{Q^2}{2\, p \cdot q}$$

②

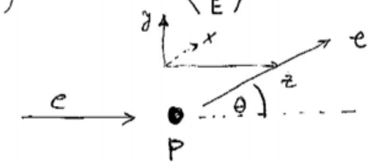
This quantity λ is the fractional momentum of a parton inside the proton. We call this quantity x_{Bj}

Note that with these two Lorentz-invariant quantities (x_{Bj}, Q^2) the "inclusive" scattering process is completely described.

Properties of x and Q^2:

go to the proton rest frame: metric: $g = \begin{pmatrix} 1 & & & \\ & -1 & & \\ & & -1 & \\ & & & -1 \end{pmatrix}$

$$P = \begin{pmatrix} M_p \\ 0 \\ 0 \\ 0 \end{pmatrix}, \quad k = \begin{pmatrix} E \\ 0 \\ 0 \\ E \end{pmatrix}, \quad k' = \begin{pmatrix} E' \\ 0 \\ E' \sin\theta \\ E' \cos\theta \end{pmatrix}$$



$$q = k - k' = \begin{pmatrix} E - E' \\ 0 \\ -E' \sin\theta \\ E - E' \cos\theta \end{pmatrix}$$

$$P \cdot q = M_p (E - E')$$

The electron looses energy to the proton, so

$$E' < E \quad \Rightarrow \quad P \cdot q > 0$$

~~energy loss : E' = 0 (ignore mass)~~

~~Minimum energy loss : E' = E~~

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(3)

$$0 \le x \le 1$$

One more variable

$$y = \frac{P \cdot q}{P \cdot k}$$

Properties of y

Proton rest frame:

$$p = \begin{pmatrix} M_p \\ 0 \\ 0 \\ 0 \end{pmatrix} ; \quad k = \begin{pmatrix} E \\ 0 \\ 0 \\ E \end{pmatrix} ; \quad k' = \begin{pmatrix} E' \\ 0 \\ +E'\sin\theta \\ E'\cos\theta \end{pmatrix}$$

$$q = k - k' = \begin{pmatrix} E - E' \\ 0 \\ -E'\sin\theta \\ E - E'\cos\theta \end{pmatrix}$$

$$y = \frac{P \cdot q}{P \cdot k} = \frac{M_p (E - E')}{M_p \cdot E} = \frac{E - E'}{E}$$

'Scaled momentum transfer'

$$0 \le y \le 1$$

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(3b)

$$W^2 = (P + q)^2$$

$$= P^2 + 2P \cdot q - Q^2$$

$$= M_p^2 + \frac{Q^2}{x} - Q^2$$

~ 0 ← (deep inelastic)

$$W^2 = Q^2 \left(\frac{1}{x} - 1 \right)$$

At Hera where x is small $(\sim 10^{-3})$

$$W^2 \sim \frac{Q^2}{x}$$

Deep inelastic means:

$$\frac{Q^2}{x} \gg M_p^2 \sim 1\,\text{GeV}^2$$

(4)

... and one more useful relationship.

total energy:

$$s = (P+k)^2$$

$$s = \underbrace{P^2}_{=m_p^2} + 2P.k + \underbrace{k^2}_{=m_e^2}$$

ignore masses

$$s = 2 \cdot P.k$$

$$y \cdot x = \frac{P.q}{P.k} \cdot \frac{Q^2}{2P.q} = \frac{Q^2}{2 \cdot P.k}$$

$$P.k = \frac{Q^2}{2 \cdot y \cdot x}$$

$$s = \frac{Q^2}{y \cdot x}$$

$$Q^2_{max} \Leftrightarrow y = x = 1$$

$$Q^2_{max} = s$$

For Hera: Calculate in lab frame

$$P = \begin{pmatrix} E_p \\ 0 \\ 0 \\ E_p \end{pmatrix} \qquad k = \begin{pmatrix} E_e \\ 0 \\ 0 \\ -E_e \end{pmatrix}$$

$E_p = 920$ GeV

(5)

$$s = 2P.k$$

$$= 4\, E_p \cdot E_e = 101\,200 \text{ GeV}^2$$

$$\Rightarrow Q^2_{max} \sim 0\,000 \text{ GeV}^2$$

Now we come back to inclusive deep inelastic scattering:

Cross section for deep inelastic electron-proton scattering is given by

$$\frac{d^2\sigma}{dx\,dy} = \frac{4\pi\alpha^2 s}{Q^4}\left((1-y)\,F_2(x,Q^2) + xy\,F_1(x,Q^2)\right)$$

I shall not derive this result but a simple motivation is given in my slides which will be on the web.

Note: Details of the proton internal structure are hidden in F_2 and F_1

$\Rightarrow$ Structure functions

In general F_1 and F_2 depend on x and Q^2

(6)

If you assume that there is incoherent scattering on constituent quarks in the proton

$\Rightarrow F_1, F_2$ do not depend on Q^2

$\Rightarrow$ Scaling

Crucial observation at SLAC 1969

Interpretation:

Q^2 corresponds to the resolution according to the Heisenberg uncertainty principle

$$\Delta x \cdot \Delta p \geq \hbar$$

Something which shows no structure independent of the resolution must be pointlike.

At Hera $Q^2_{max} = 100\,000\ \text{GeV}^2$

$$\Rightarrow \Delta Q \sim 300\ \text{GeV}/c$$

$$\hbar c \sim 200\ \text{MeV fm}$$

$$\Delta x \geq \frac{200\ \text{MeV fm}}{300\ \text{GeV}} \sim 10^{-3}\ \text{fm}$$

proton radius 0.8 fm.

(7)

$\Rightarrow$ HERA can check the size of the proton's constituents down to $1/1000$ of the proton size: $\sim 10^{-18}$ m.

Remark on F_1:

F_1: related to the scattering on the magnetic moment.

For Spin $1/2$ partons $F_2(x) = 2x F_1(x)$

"Callan-Gross" relation.

For spin $\emptyset$ partons: $F_1(x) = 0$

F_2 and parton content:

xF_2 is the density of partons in momentum space:

$$F_2(x) = \sum_{i\ \text{quark species}} e_i^2 \left(q_i(x) + \bar{q}_i(x)\right)$$

"Bj"
(aka James Daniel Bjorken)

... a guided tour around the HERA phase space ...

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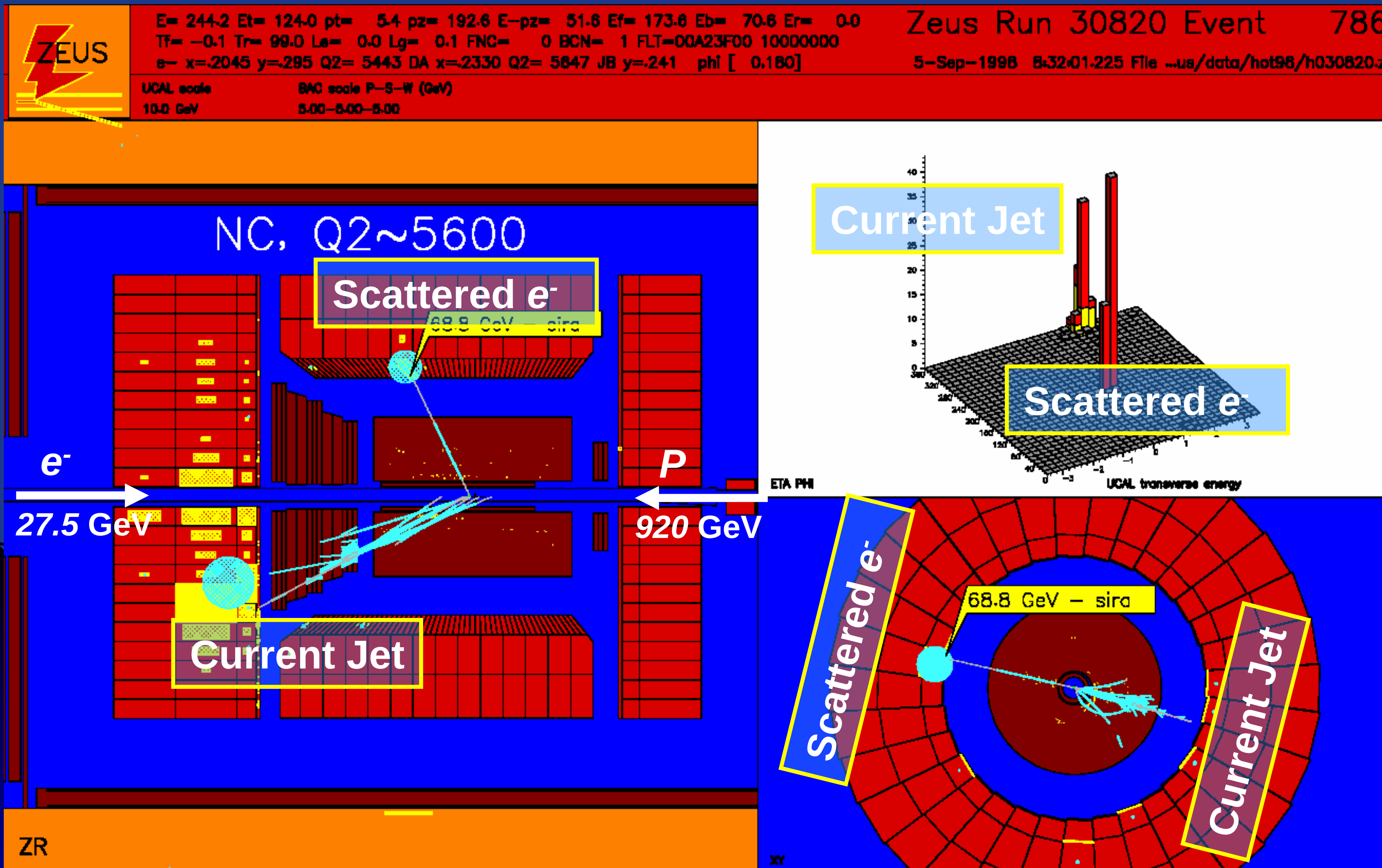
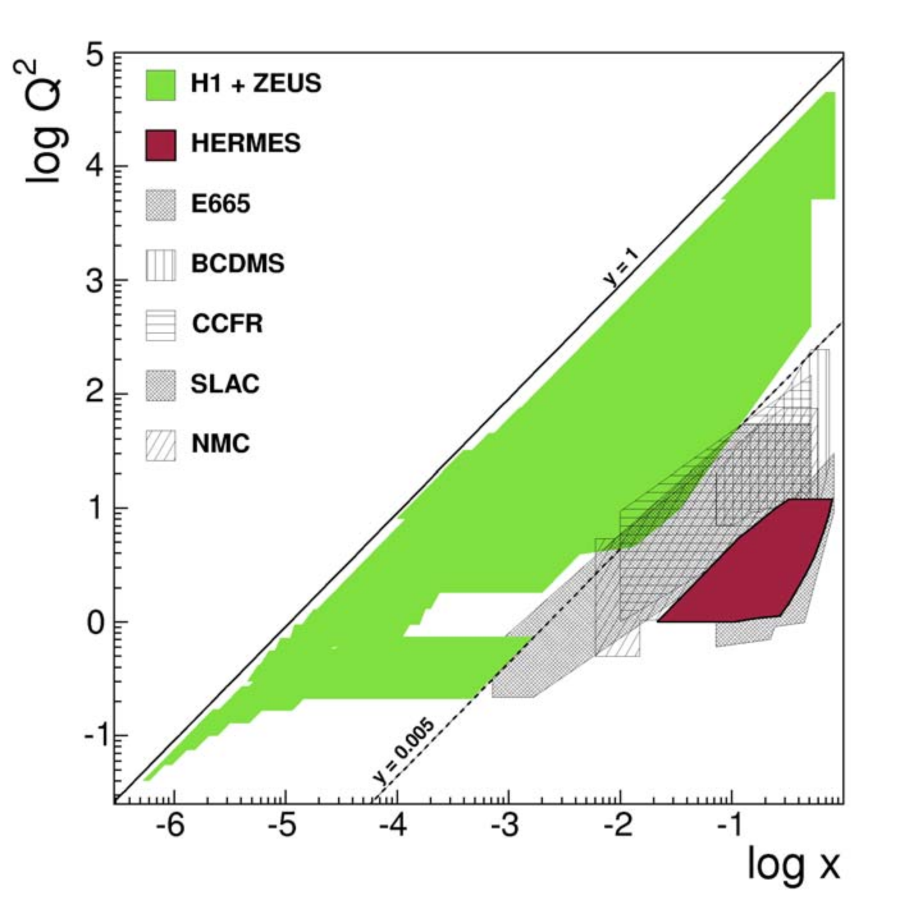
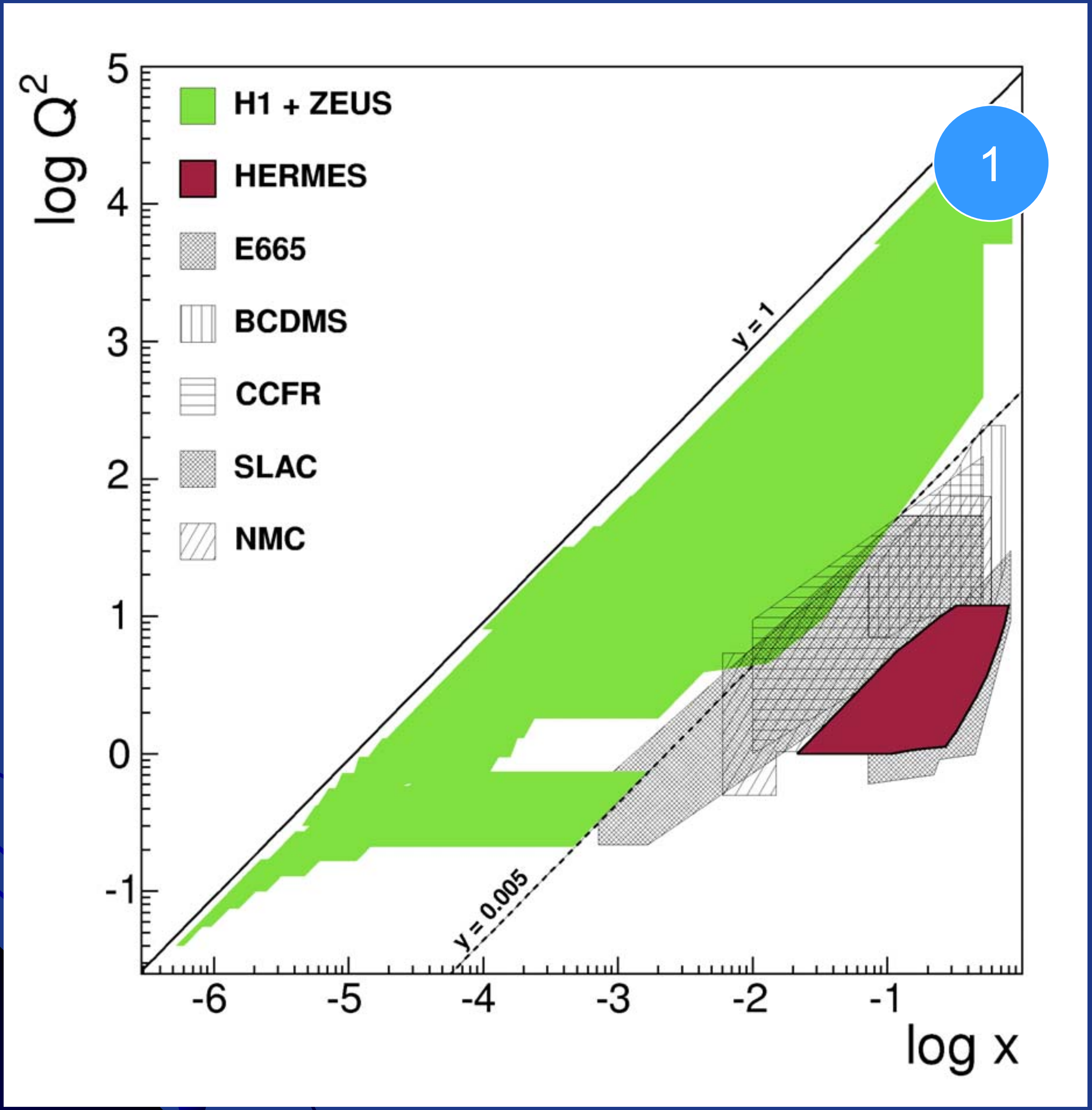

ZEUS
E= 244.2 Et= 124.0 pt= 5.4 pz= 192.6 E-pz= 51.6 Ef= 173.6 Eb= 70.6 Er= 0.0
Tf= -0.1 Tr= 99.0 Le= 0.0 Lg= 0.1 FNC= 0 BCN= 1 FLT=00A23F00 10000000
e- x=.2045 y=.295 Q2= 5443 DA x=.2330 Q2= 5647 JB y=.241 phi [0.160]
Zeus Run 30820 Event 786
5-Sep-1998 8:32:01.225 File ...us/data/hot98/h030820.z
UCAL scale
10.0 GeV
BAC scale P-S-W (GeV)
5.00-5.00-5.00
NC, Q2~5600
Scattered e-
68.8 GeV - sira
e-
27.5 GeV
P
920 GeV
Current Jet
ZR
Current Jet
Scattered e-
ETA PHI
UCAL transverse energy
Scattered e-
68.8 GeV - sira
Current Jet
XY

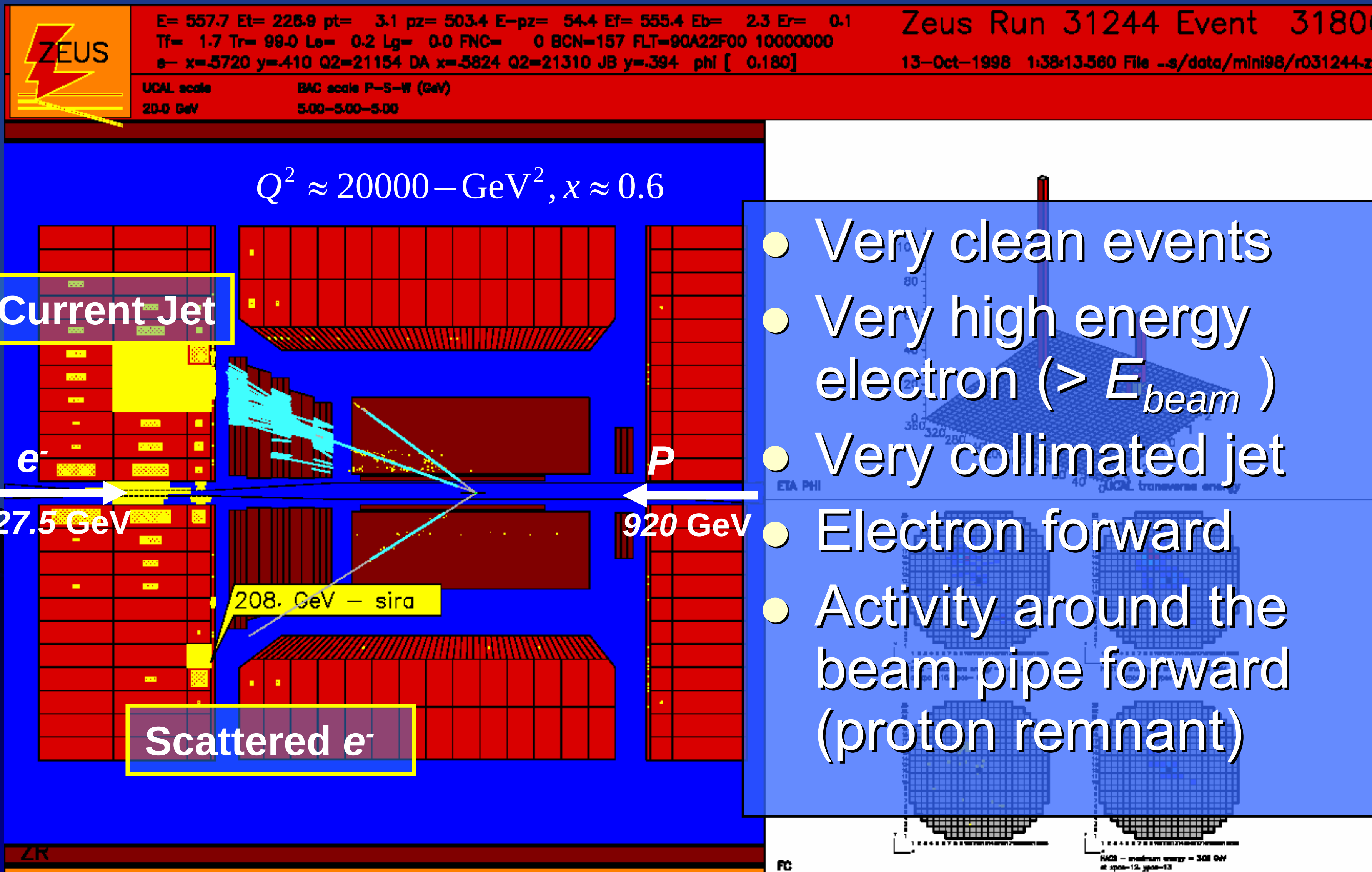
HERA I Kinematic Range



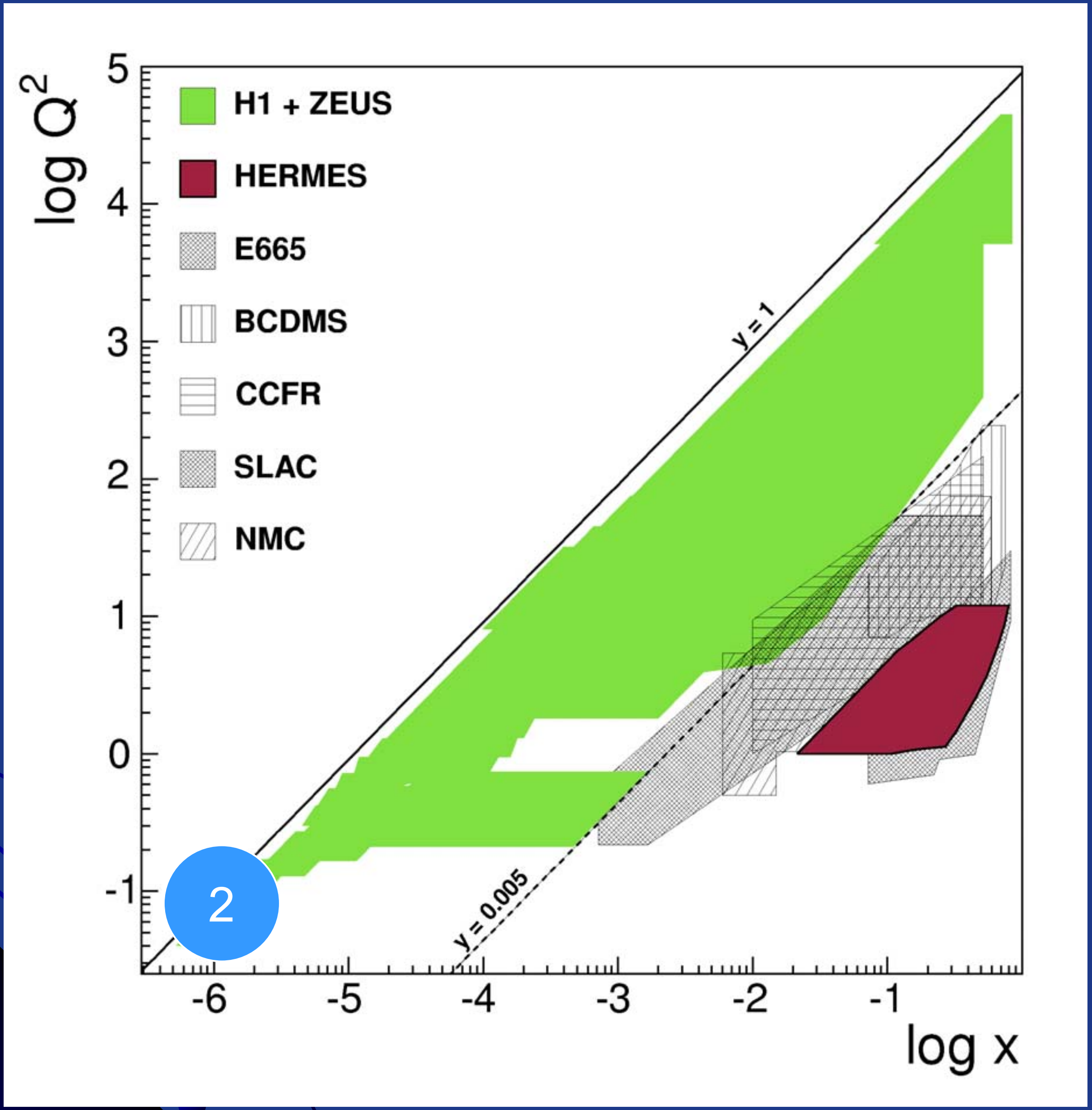
- Huge extension of kinematic reach:
  - x_{Bj}: 6 orders
  - Q^2: 6 orders
- Overlap with previous (fixed target) experiments


H1 + ZEUS
HERMES
E665
BCDMS
CCFR
SLAC
NMC
y = 1
y = 0.005
log Q^2
log x
5
4
3
2
1
0
-1
-6
-5
-4
-3
-2
-1
1

Very High Q^2



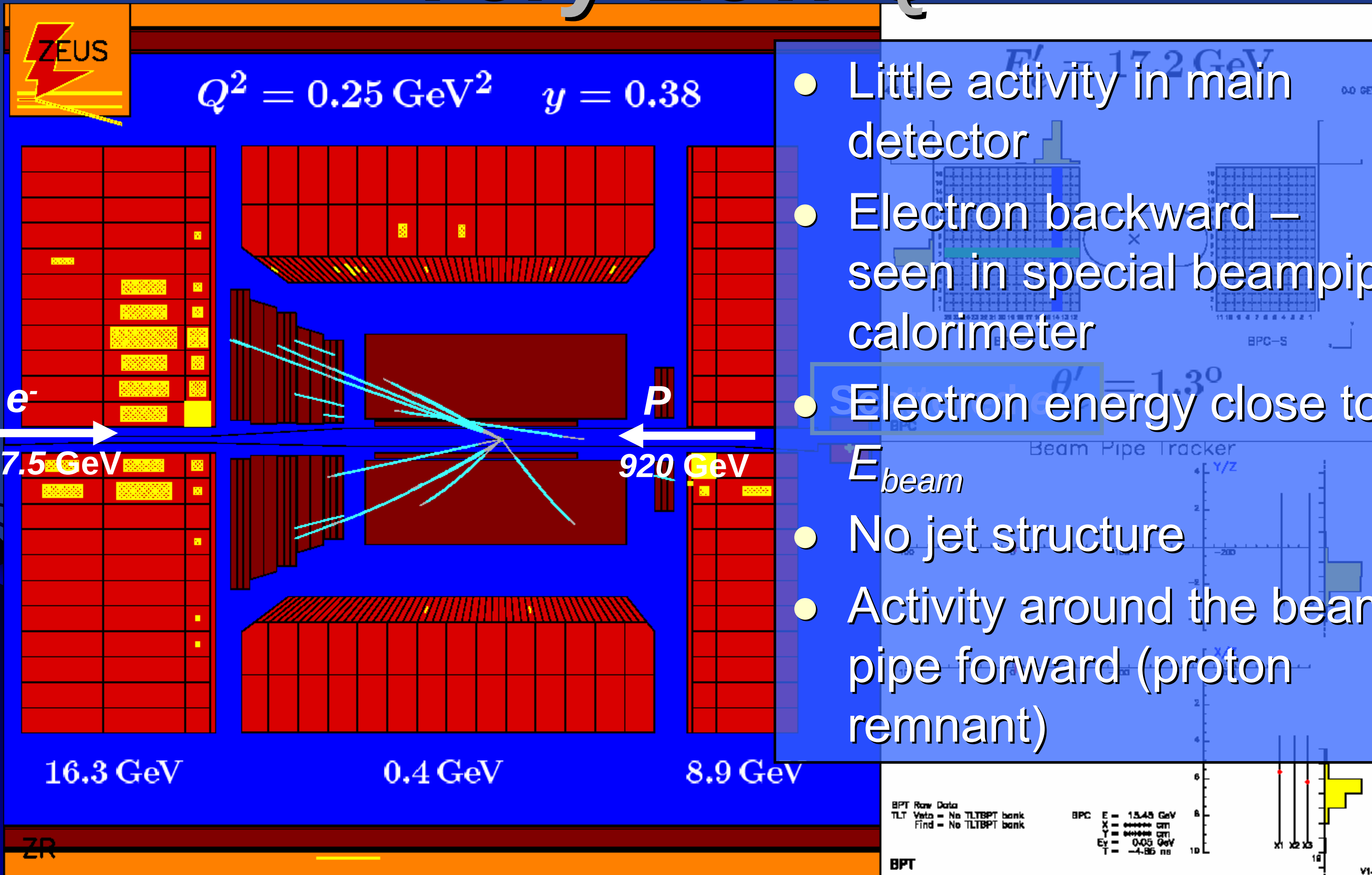
- Very clean events
- Very high energy electron (> E_{beam})
- Very collimated jet
- Electron forward
- Activity around the beam pipe forward (proton remnant)



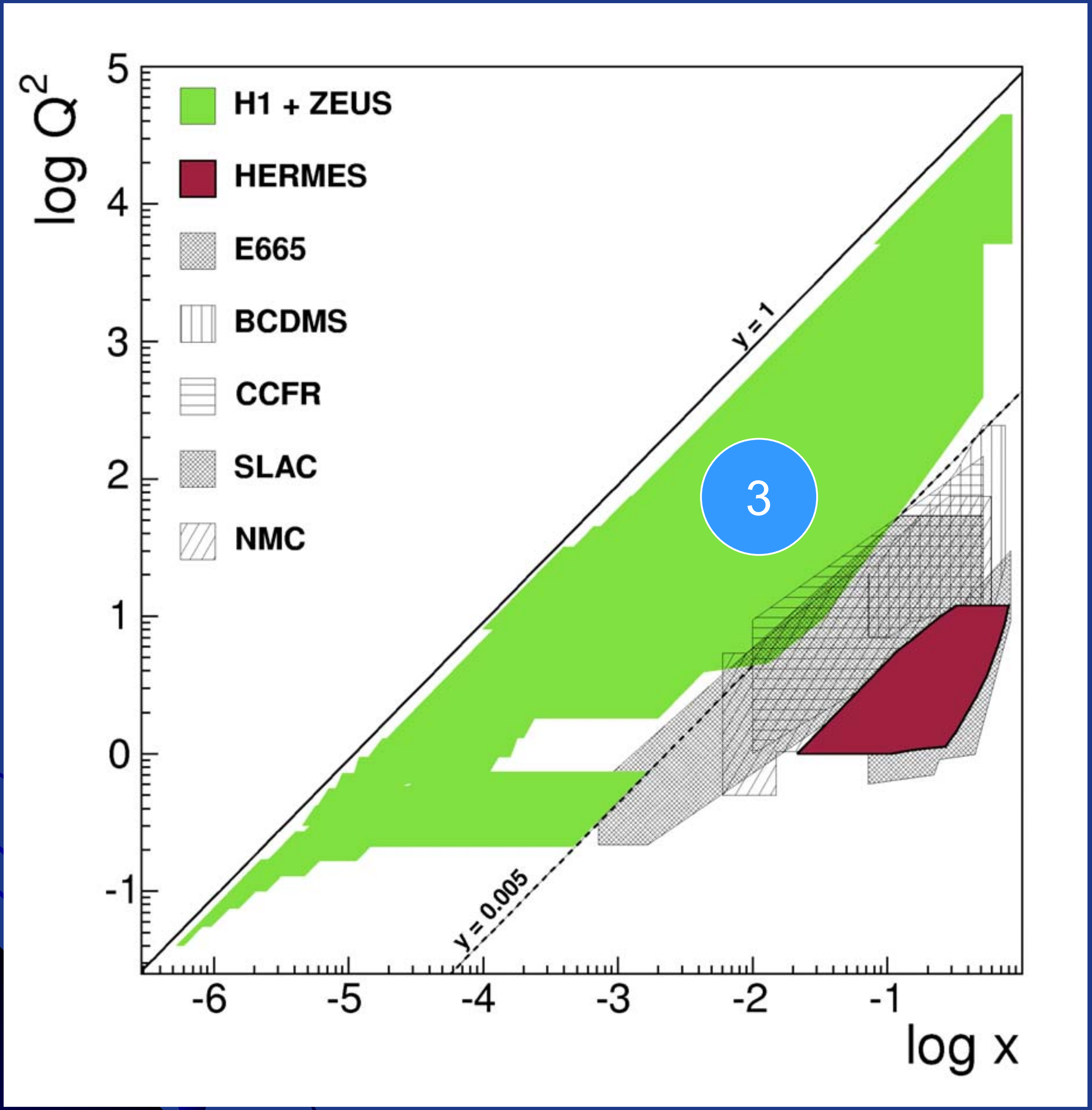
H1 + ZEUS
HERMES
E665
BCDMS
CCFR
SLAC
NMC
y = 1
y = 0.005
log Q²
log x
5
4
3
2
1
0
-1
-6
-5
-4
-3
-2
-1

2

Very Low Q^2

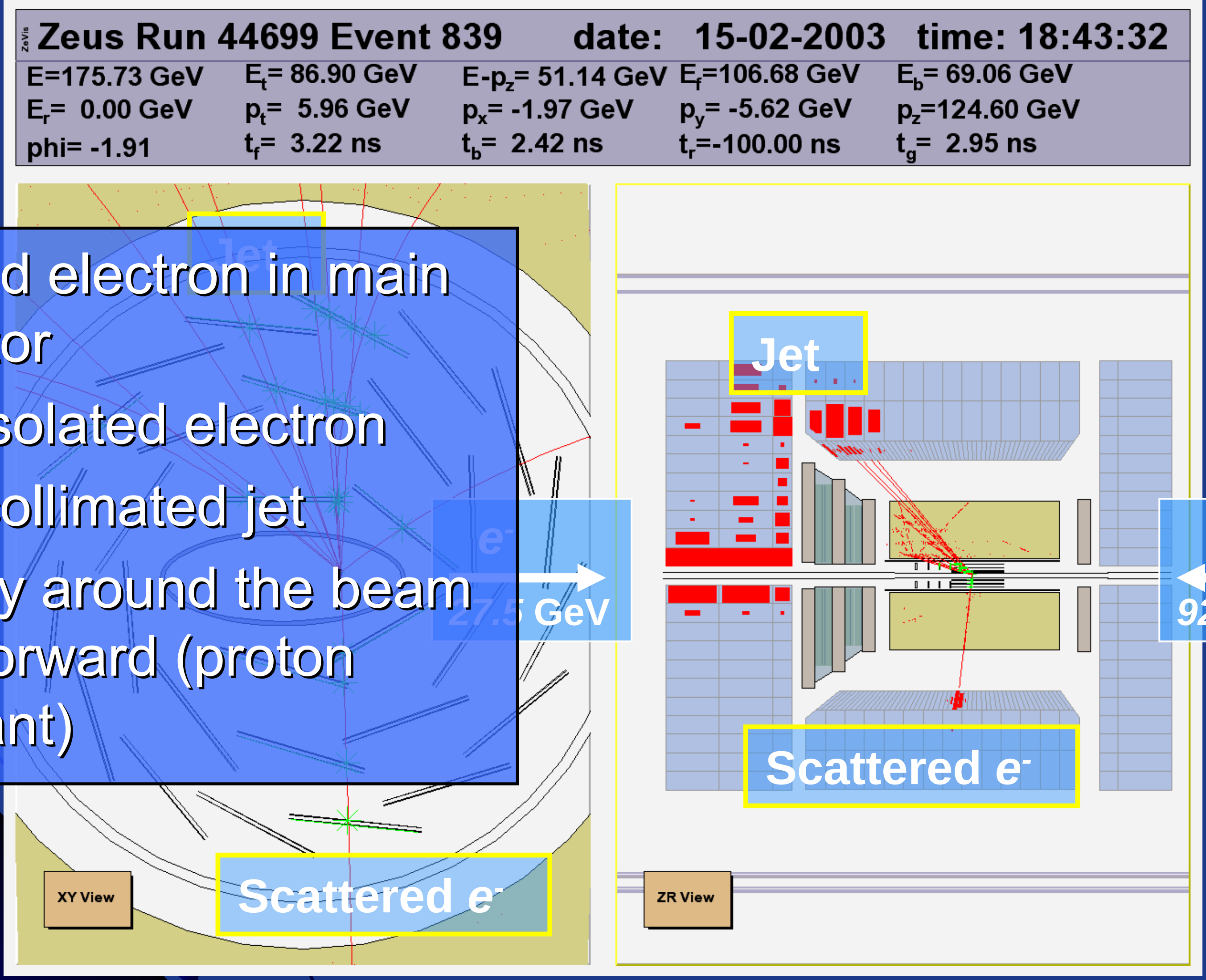


- Little activity in main detector
- Electron backward – seen in special beampipe calorimeter
- Electron energy close to E_{beam}
- No jet structure
- Activity around the beam pipe forward (proton remnant)



log Q²
H1 + ZEUS
HERMES
E665
BCDMS
CCFR
SLAC
NMC
y = 1
y = 0.005
3
5
4
3
2
1
0
-1
-6
-5
-4
-3
-2
-1
log x

Medium Q^2



- Jet and electron in main detector
- Well isolated electron
- Well collimated jet
- Activity around the beam pipe forward (proton remnant)

Structure Function Formalism

See e.g. David J Griffiths: “Introduction to elementary particles”, New York, 1987

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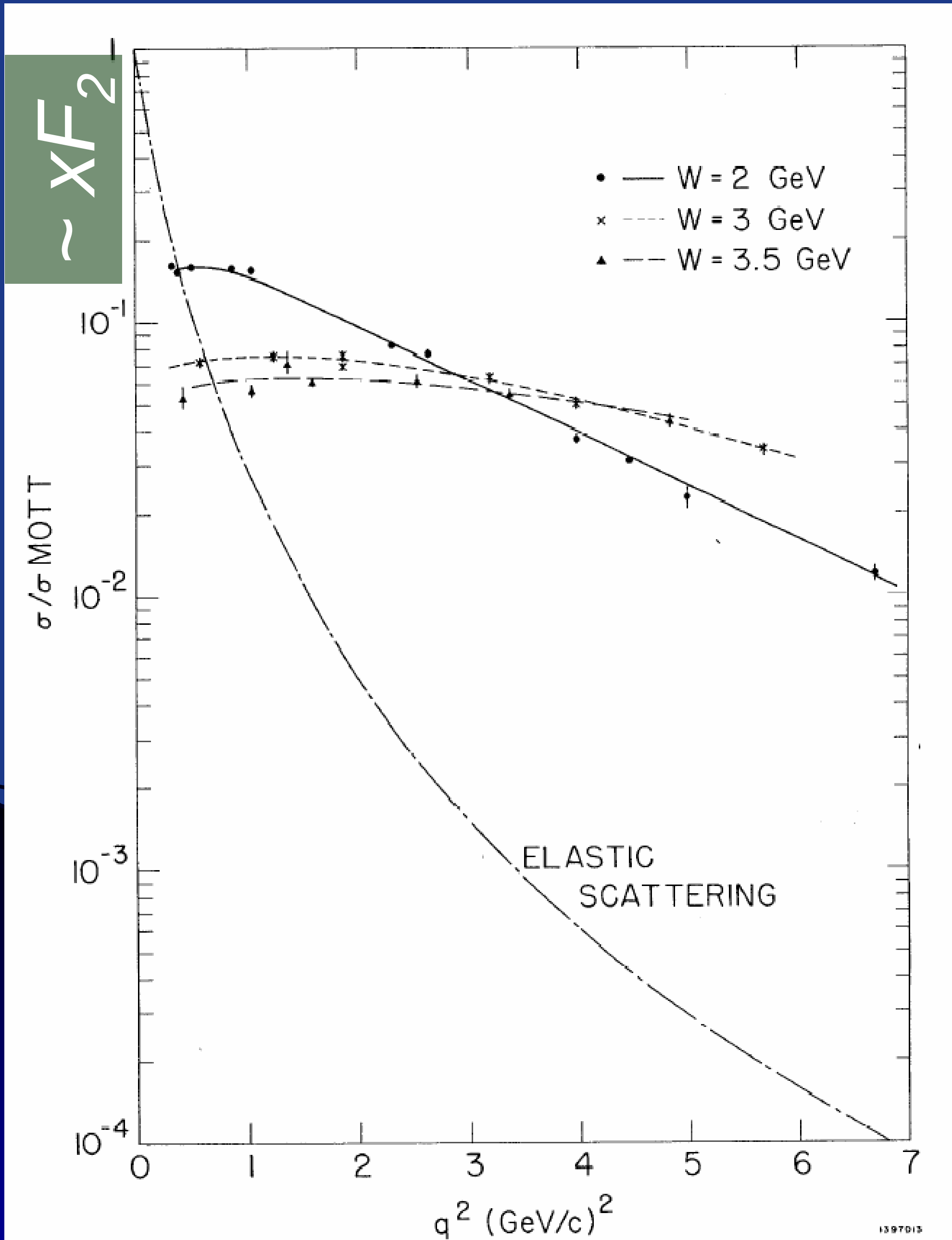
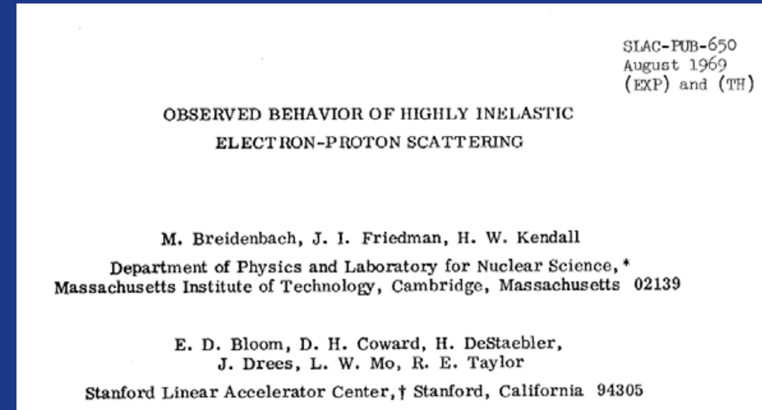



SLAC-PUB-650
August 1969
(EXP) and (TH)

OBSERVED BEHAVIOR OF HIGHLY INELASTIC ELECTRON-PROTON SCATTERING

M. Breidenbach, J. I. Friedman, H. W. Kendall
Department of Physics and Laboratory for Nuclear Science,*
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

E. D. Bloom, D. H. Coward, H. DeStaebler,
J. Drees, L. W. Mo, R. E. Taylor
Stanford Linear Accelerator Center,† Stanford, California 94305

- Deep inelastic:
  - $W >> M_P$
- $xF_2 \approx const.$

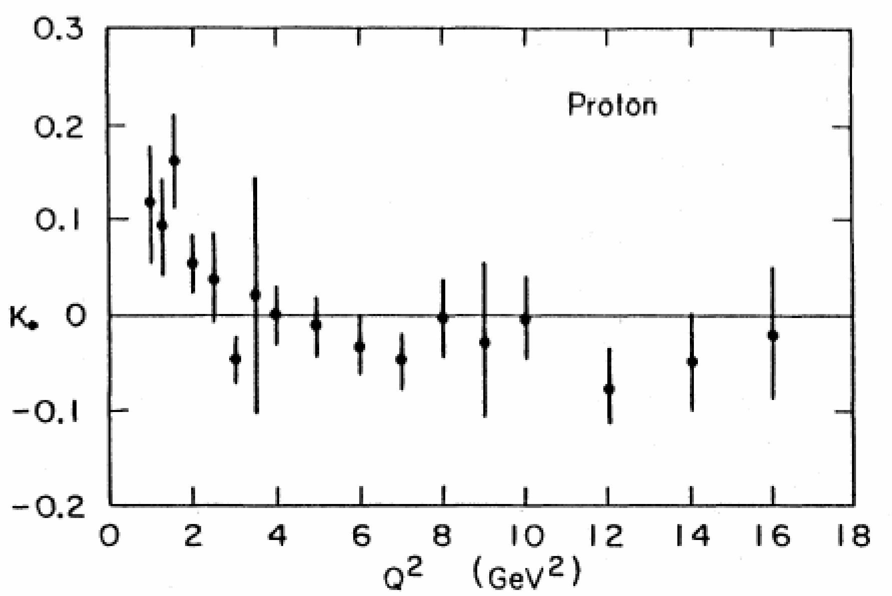
VOLUME 22, NUMBER 4 PHYSICAL REVIEW LETTERS 27 JANUARY 1969

HIGH-ENERGY ELECTROPRODUCTION AND THE CONSTITUTION OF THE ELECTRIC CURRENT*

C. G. Callan, Jr.,† and David J. Gross‡
Lyman Laboratory, Harvard University, Cambridge, Massachusetts
(Received 18 November 1968)

The asymptotic behavior of electroproduction cross sections is shown to contain information about the constitution of the electric current.

$$K_0 = F_2/(xF_1) - 1$$



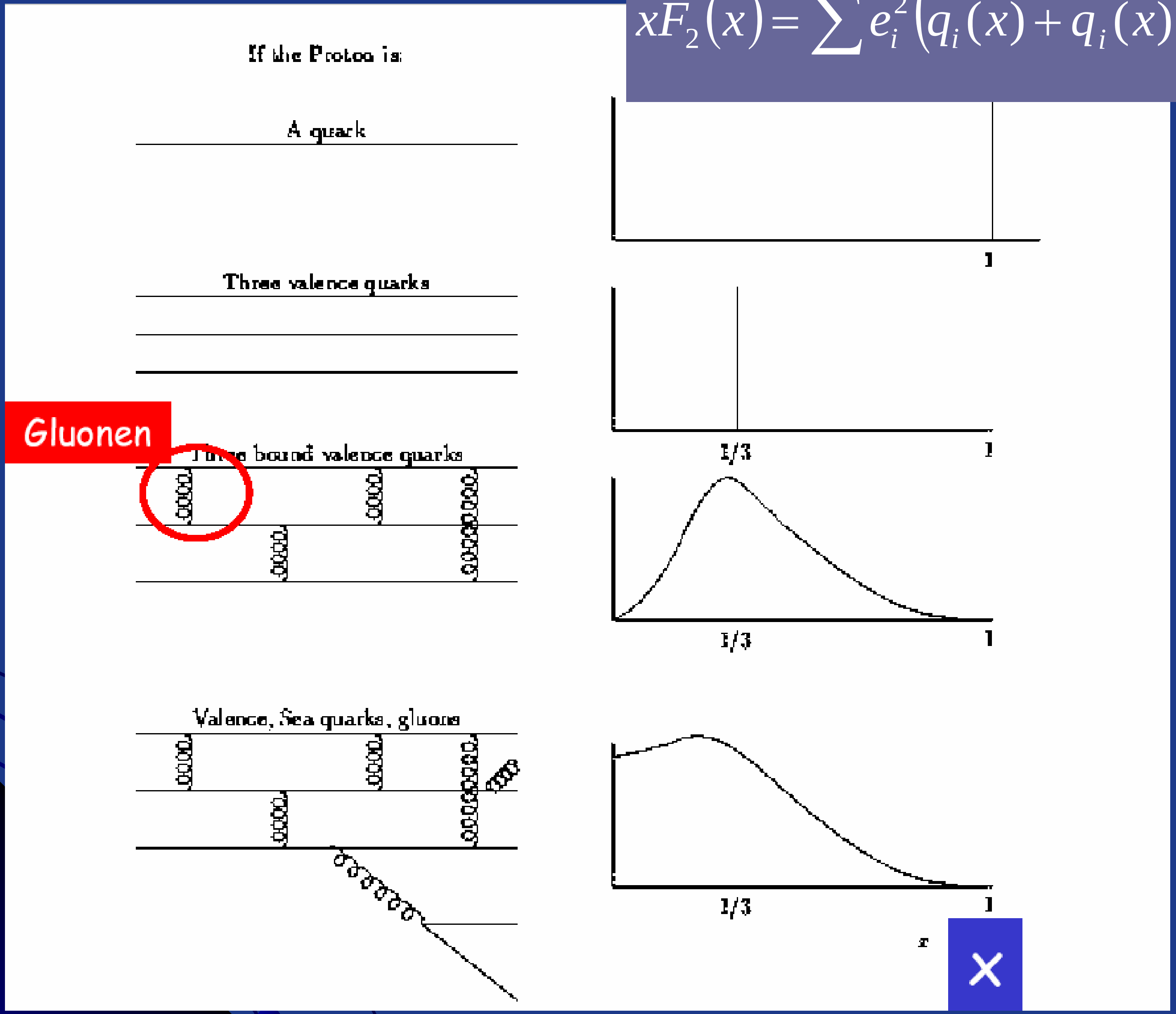
PHYSICAL REVIEW D VOLUME 20, NUMBER 7 1 OCTOBER 1979

Experimental studies of the neutron and proton electromagnetic structure functions

A. Bodek,* M. Breidenbach,† D. L. Dubin, J. E. Elias,‡ J. I. Friedman, H. W. Kendall, J. S. Poucher,§
E. M. Riordan,‖ and M. R. Sogard¶
Physics Department and Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

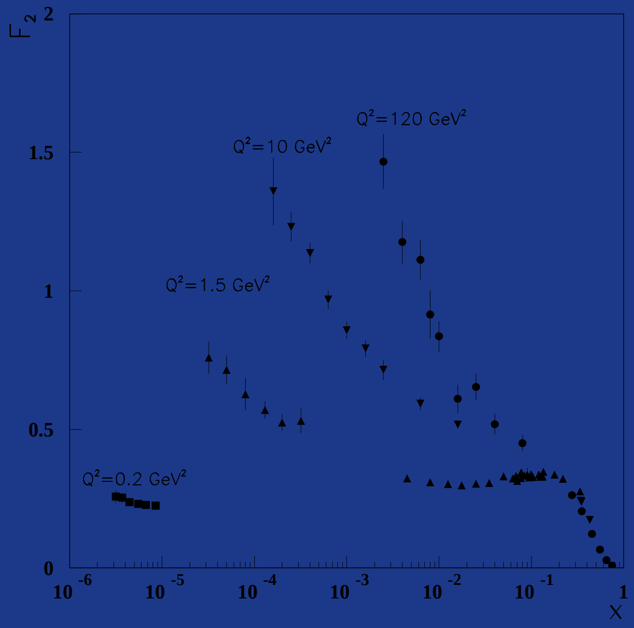
D. H. Coward and D. J. Sherden
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
(Received 23 March 1979)

$$xF_2(x) = \sum e_i^2 \left(q_i(x) + \overline{q}_i(x)\right)$$



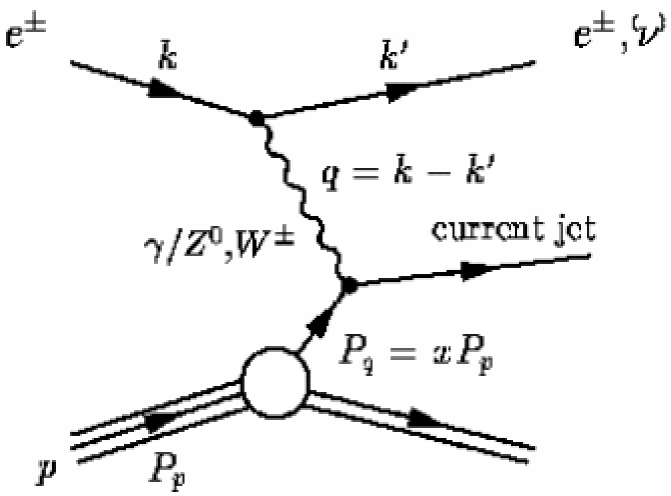
HERA Results for F_2

Sample F_2 data



Dramatic Scaling Violations!

NC Cross Section and Structure Functions



$Q^2 = -q^2 = -(k-k')^2$
x: momentum fraction of the struck parton
$y = Q^2/xs$

NC Reduced cross section: $\tilde{\sigma}_{NC}(x, Q^2)$

NC Cross Section:

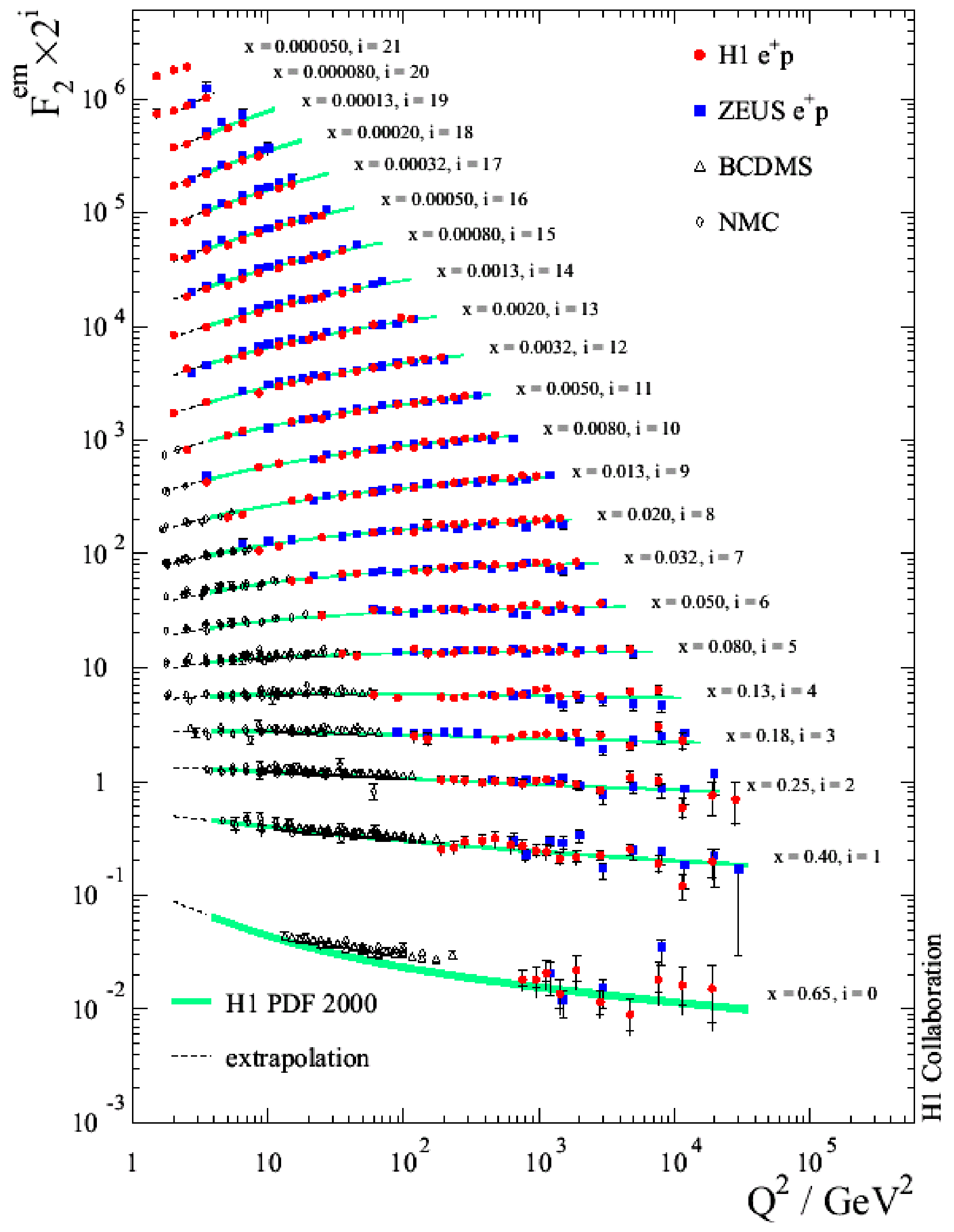
$$\frac{d^2\sigma_{NC}(e^\pm p)}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4} Y_+ \left[F_2 - \frac{y^2}{Y_+} F_L \mp \frac{Y_-}{Y_+} xF_3 \right]$$

Dominant contribution

Sizeable only at high y (y>~0.6)

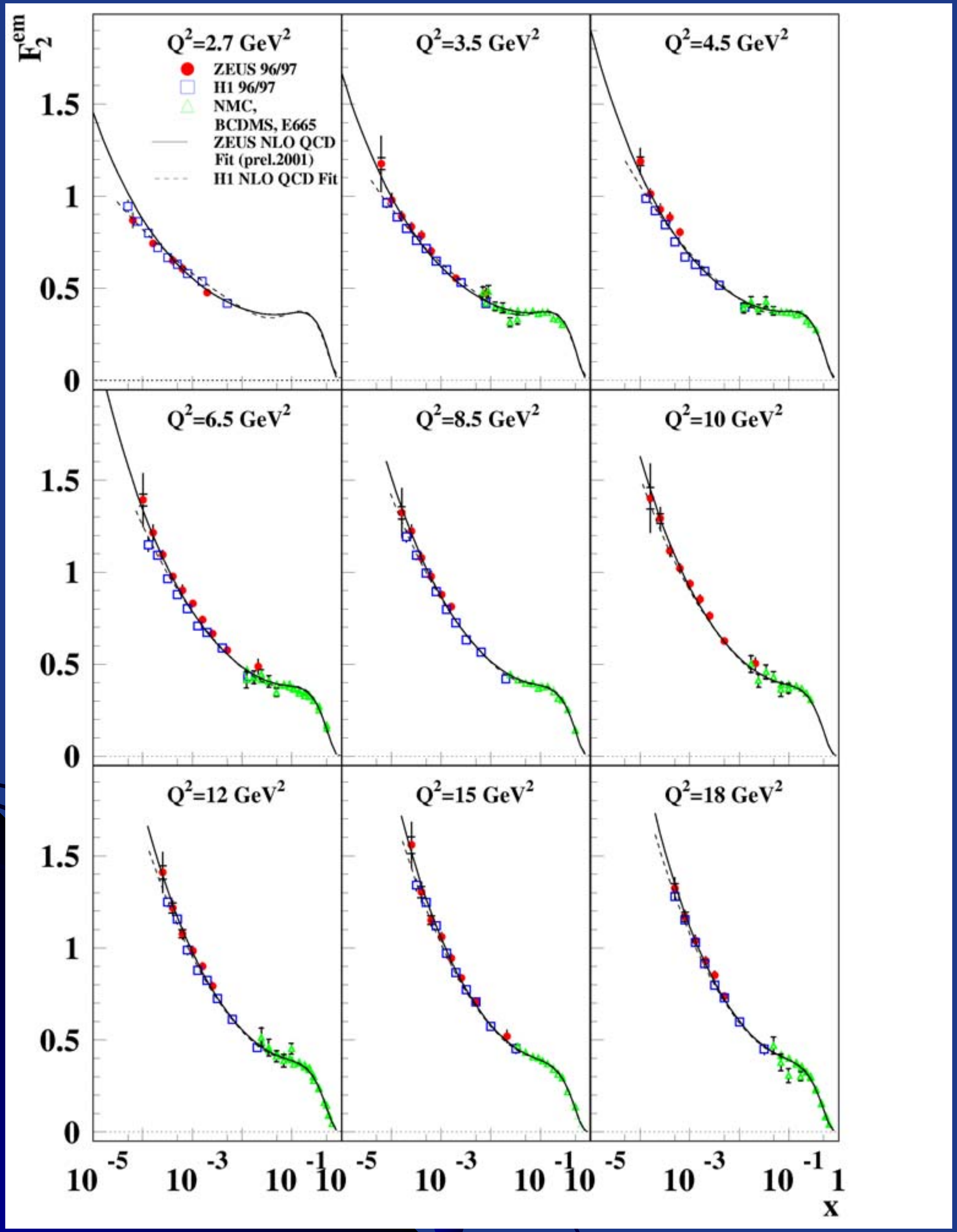
Contribution only important at high Q^2

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



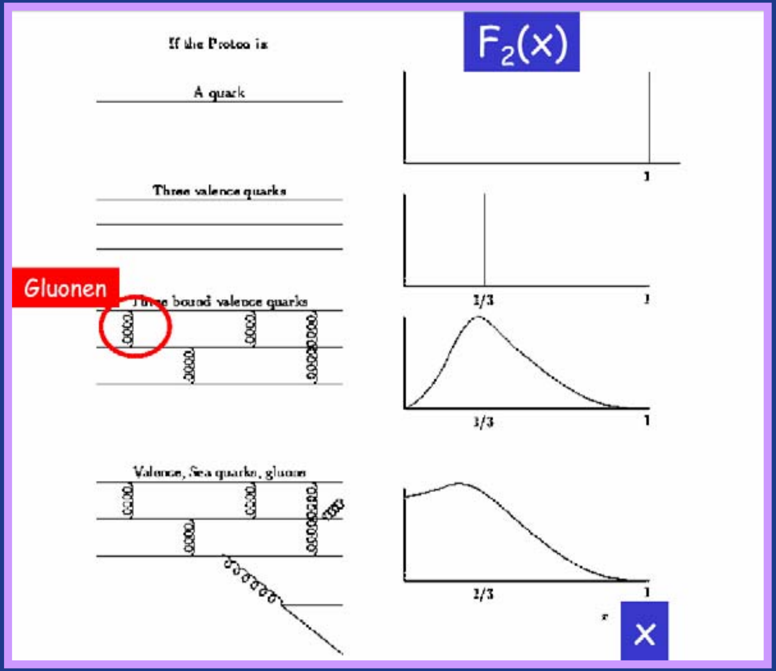
F_2 vs Q^2

- Note:
  - Enormous range of data (5 orders in Q^2 and 8 orders in x)
  - Approximate scaling at high Q^2
  - Scaling violations at low Q^2



F_2 vs x_{Bj}

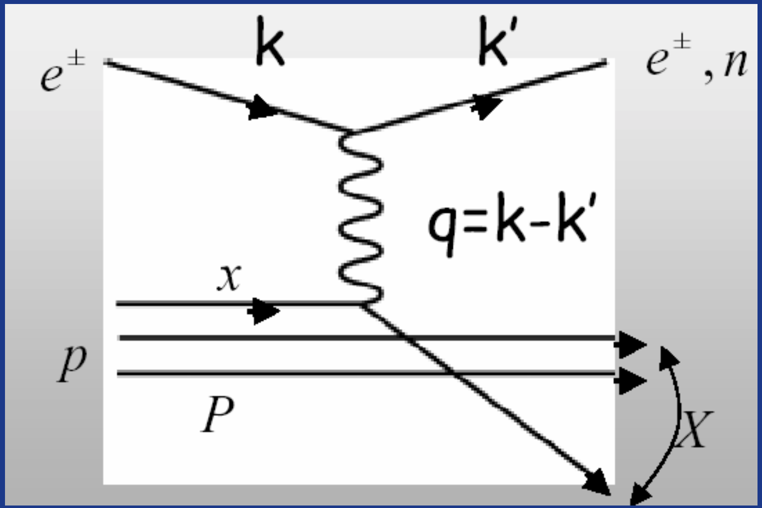
- Dramatic rise a low x_{Bj}
- Note previous picture:



Structure Function Evolution

Laboratory peer pressure

Reminder: Nomenclature/Kinematics



$$Q^2 = -(k-k')^2$$
$$= -q^2$$
$$y = \frac{P \cdot q}{P \cdot k}$$
$$x = \frac{Q^2}{2P \cdot q}$$
$$s = (k+P)^2$$
$$W^2 = M_X^2$$
$$= (q+P)^2$$
$$F_L = F_2 - 2xF_1$$
$$Y_{\pm}(y) = 1 \pm (1-y)^2$$

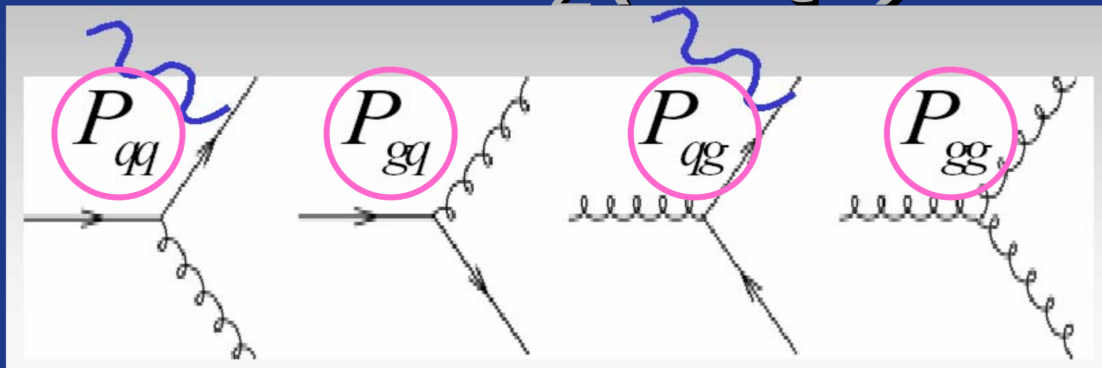
$$\frac{d^2\sigma}{dxdQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left\{-y^2 F_L(x,Q^2) + Y_+ F_2(x,Q^2) - Y_- xF_3(x,Q^2)\right\}$$

= 0 in the QPM

$$F_2(x) = x \cdot \sum_f z_f^2 (q_f(x) + \overline{q}_f(x))$$

Z^0 Exchange

What QCD tells about $F_2(x,Q^2)$?



Splitting functions:
Can be calculated in pQCD

$$\frac{d}{d\ln Q^2}\begin{pmatrix} q(x,Q^2) \\ g(x,Q^2) \end{pmatrix} = \frac{\alpha_s(Q^2)}{2\pi}\begin{pmatrix} P_{qq} & P_{qg} \\ P_{gq} & P_{gg} \end{pmatrix} \otimes \begin{pmatrix} q \\ g \end{pmatrix}$$

DGLAP Equation:

- Integral-Differential equation for the dependence of $q(x,Q^2)$, $g(x,Q^2)$ on Q^2
- Need an initial condition!

$$(a\otimes b)(x) = \int_0^1 dy\, a\left(\frac{x}{y}\right)\frac{b(x)}{y}$$

QCD Fits

- Make an ansatz at a fixed value of $Q^2 = Q_0^2$

$$xq(x,Q_0) = Ax^B(1-x)^C\left[1 + D\sqrt{x} + Ex\right]$$

- Write F_2 simpler:

$$F_2 \sim 4/9\,(U+\bar{U}) + 1/9\,(D+\bar{D})$$

with

$\bar{D} = \bar{d}+\bar{s}$ $\quad\bar{U} = \bar{u}+\bar{c}$

$U = u+c$ $\quad D = d+s$

- Ignore F_3 and F_L (for the moment)

Parton Distribution Functions

QCD fits to structure functions:

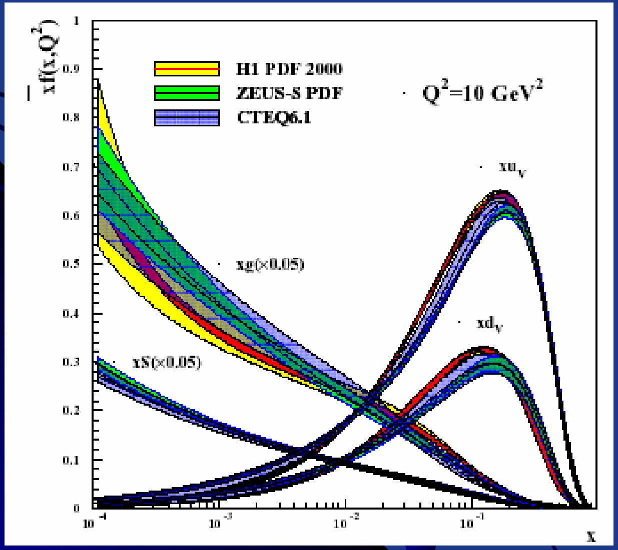
$F_2 \sim 4/9\,(U+\bar{U}) + 1/9\,(D+\bar{D})$

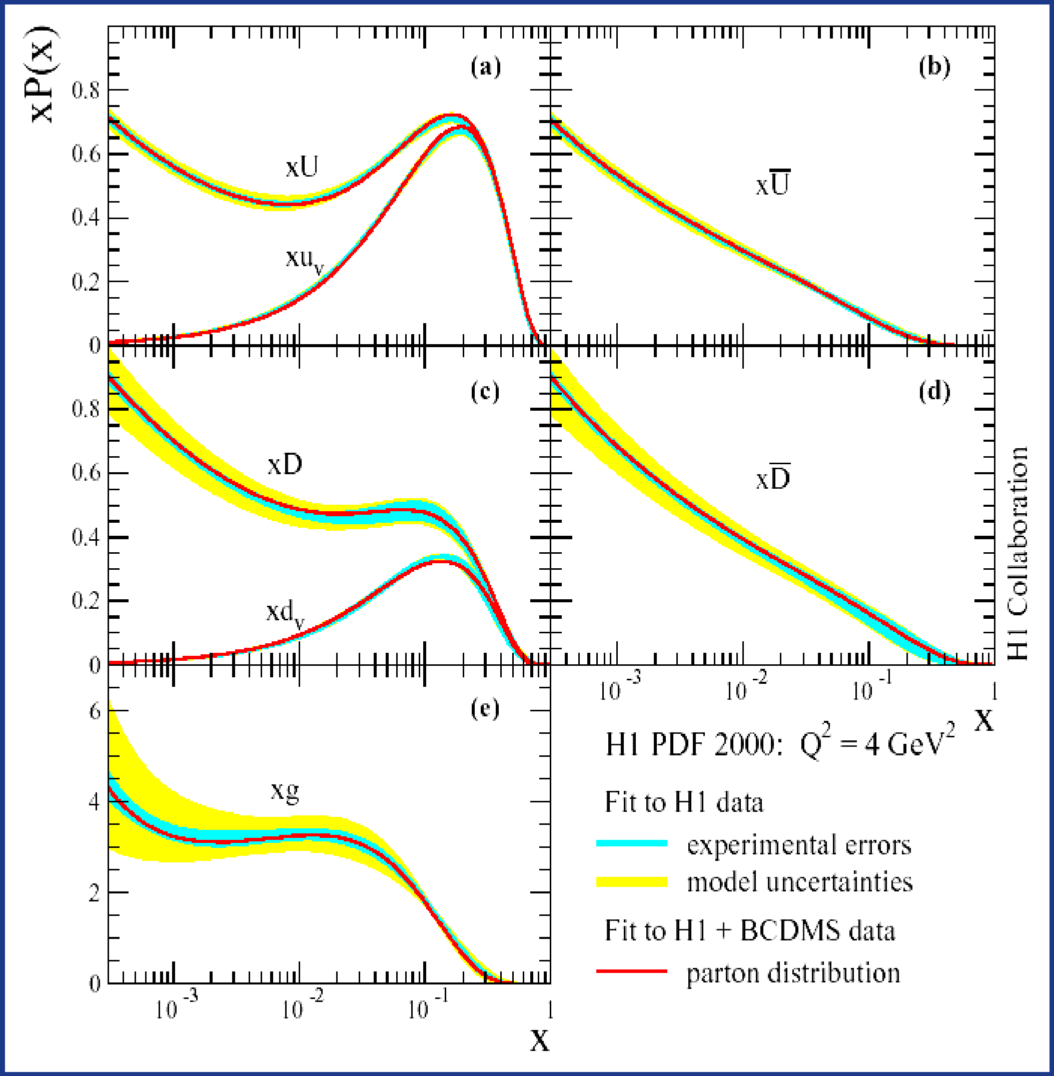
Valence quarks:

$2\,(U-\bar{U}) + \quad (D-\bar{D})$

$\bar{D} = \bar{d}+\bar{s} \qquad \bar{U} = \bar{u}+\bar{c}$

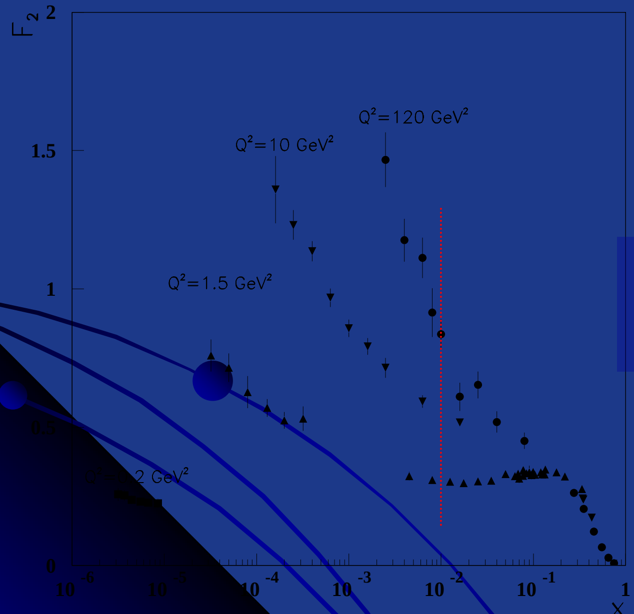
$U = u+c \qquad D = d+s$





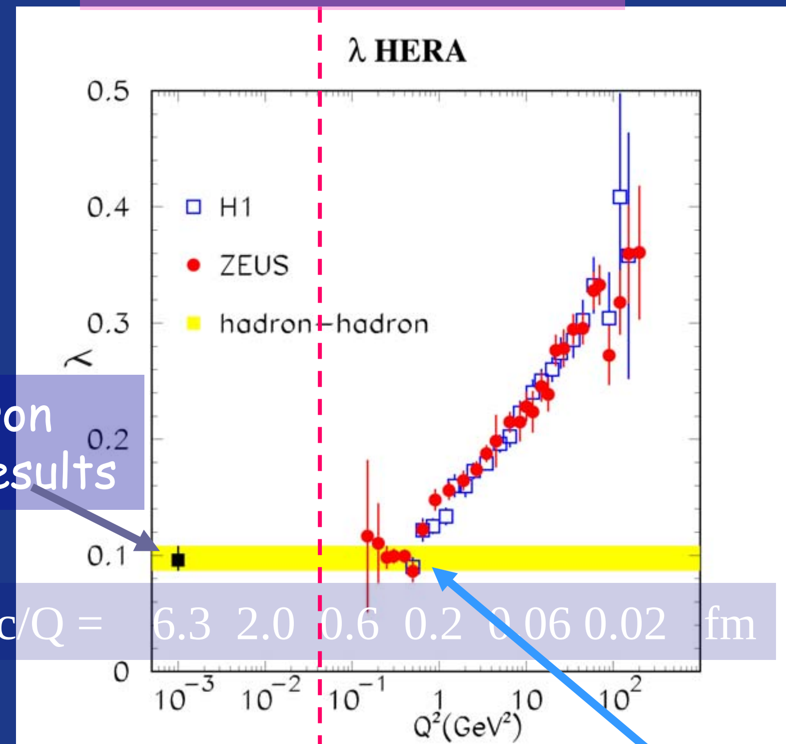
… another way to look at it …

Sample F_2 data



$F_2 \propto x^{-\lambda}$ at small x

Proton Charge radius



Hadron-hadron scattering results

$\hbar c/Q$ = 6.3 2.0 0.6 0.2 0.06 0.02 fm

Observation of hadron to parton transition