Physics at HERA

Summer Student Lectures
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Katja Krüger
Kirchhoff-Institut für Physik
H1 Collaboration
email: katja.krueger@desy.de

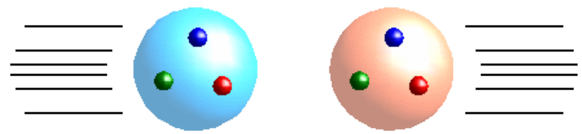
Overview

- Introduction to HERA
- Inclusive DIS & Structure Functions
  - formalism
  - HERA results
- High Q^2 & Electroweak Physics
- QCD: Jet Physics, Heavy Flavour Production
- Beyond the Standard Model
- (Diffraction)

Collider Types

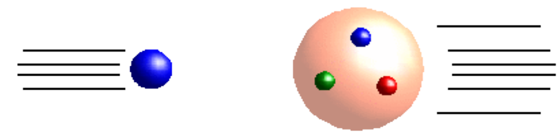
e^+e^-

+ clean initial and final state
+ small background
– limited energy
• LEP (200 GeV) ILC (1 TeV)



$p^{\pm}p^{\pm}$

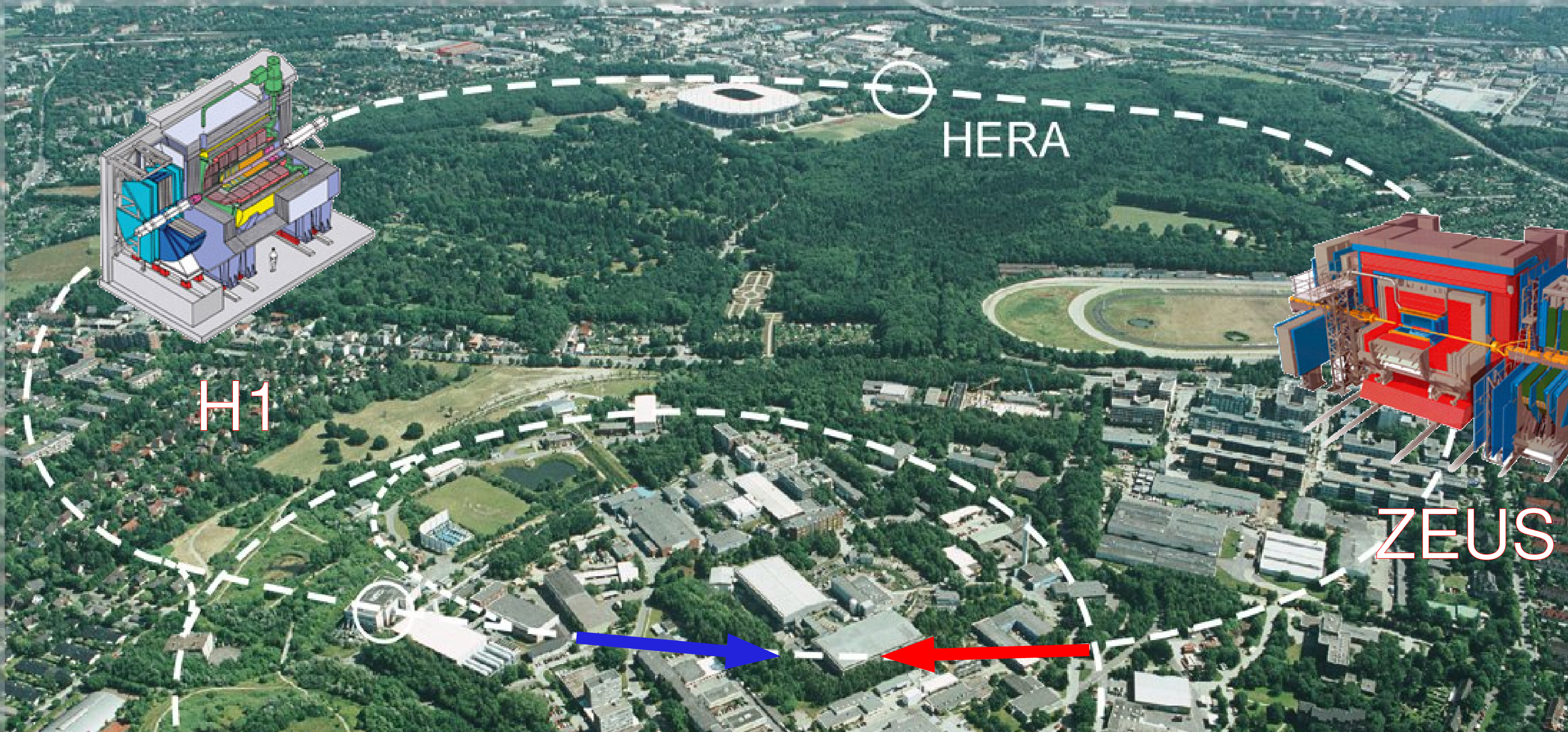
+ high energy
– complicated final state
– large background
• Tevatron (2 TeV) LHC (14 TeV)



ep

+ unique initial state
+ electron as probe of proton structure
– two accelerators
• HERA (300 GeV)

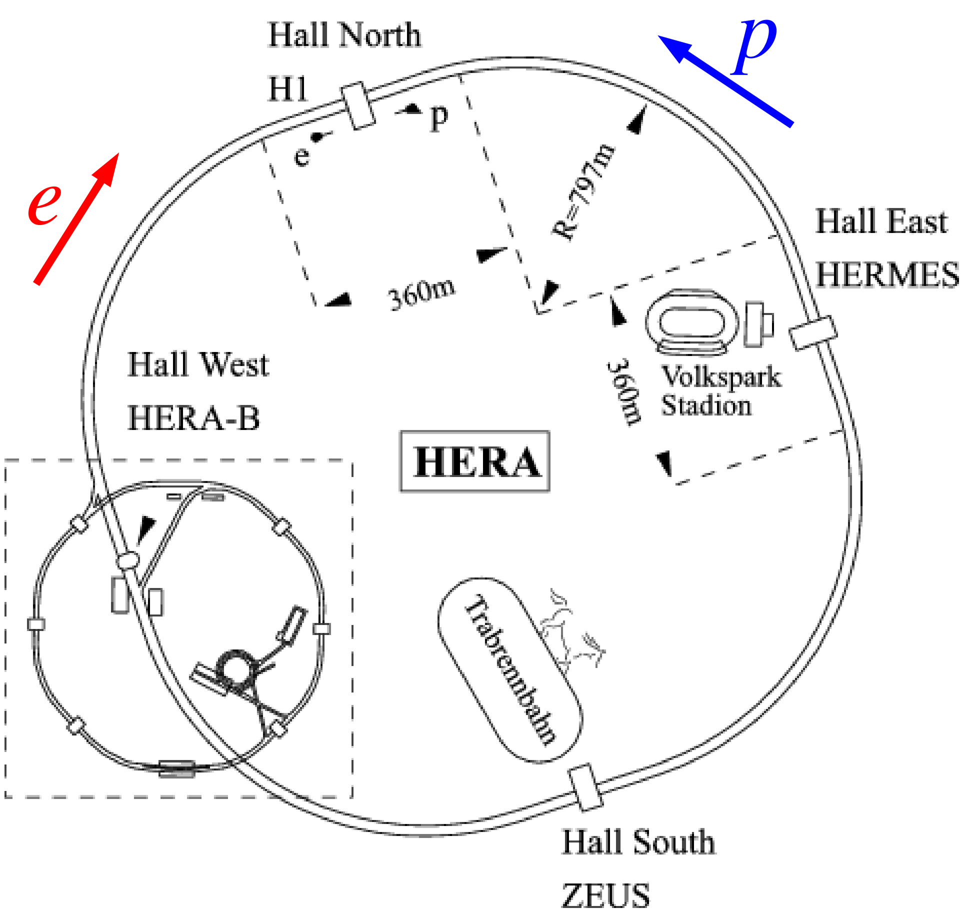
HERA

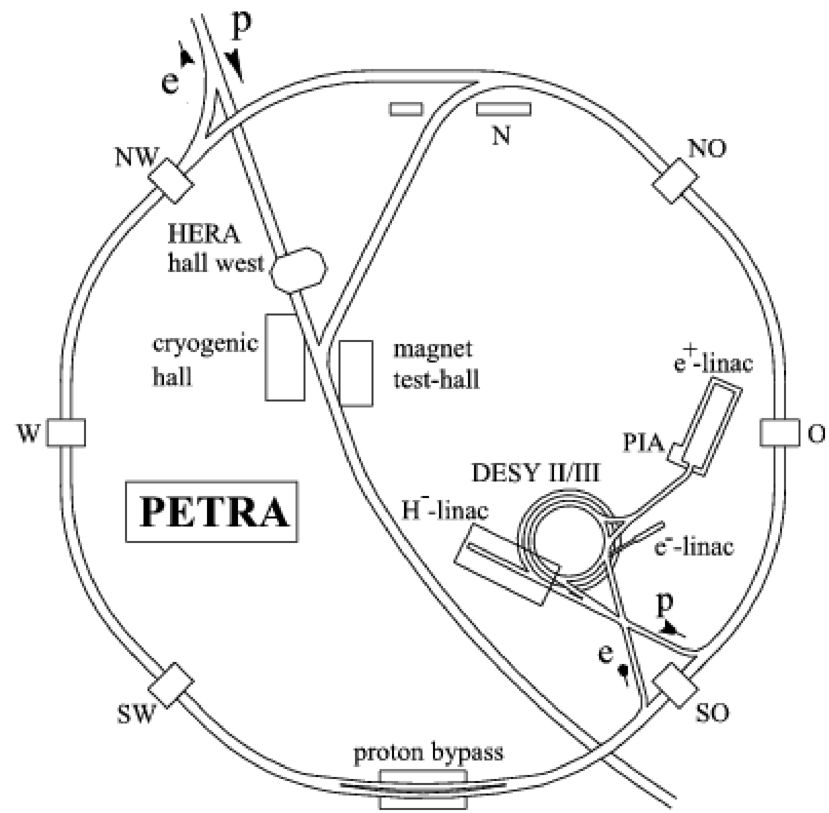


p **e**

920 GeV **27.6 GeV**

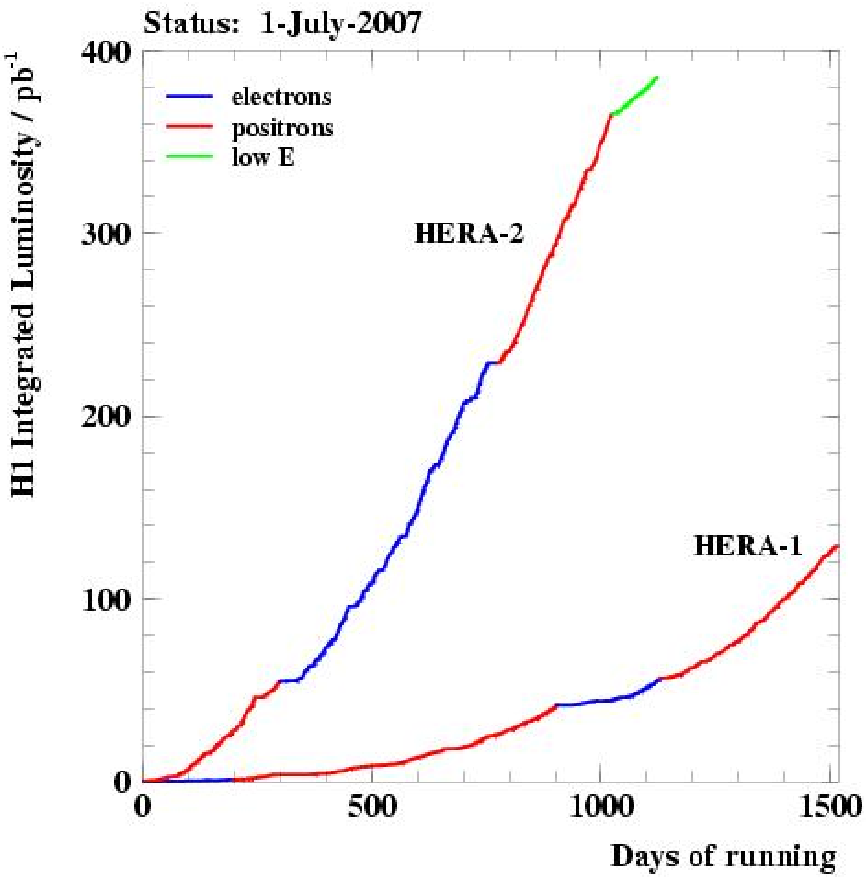
HERA & its Pre-Accelerators





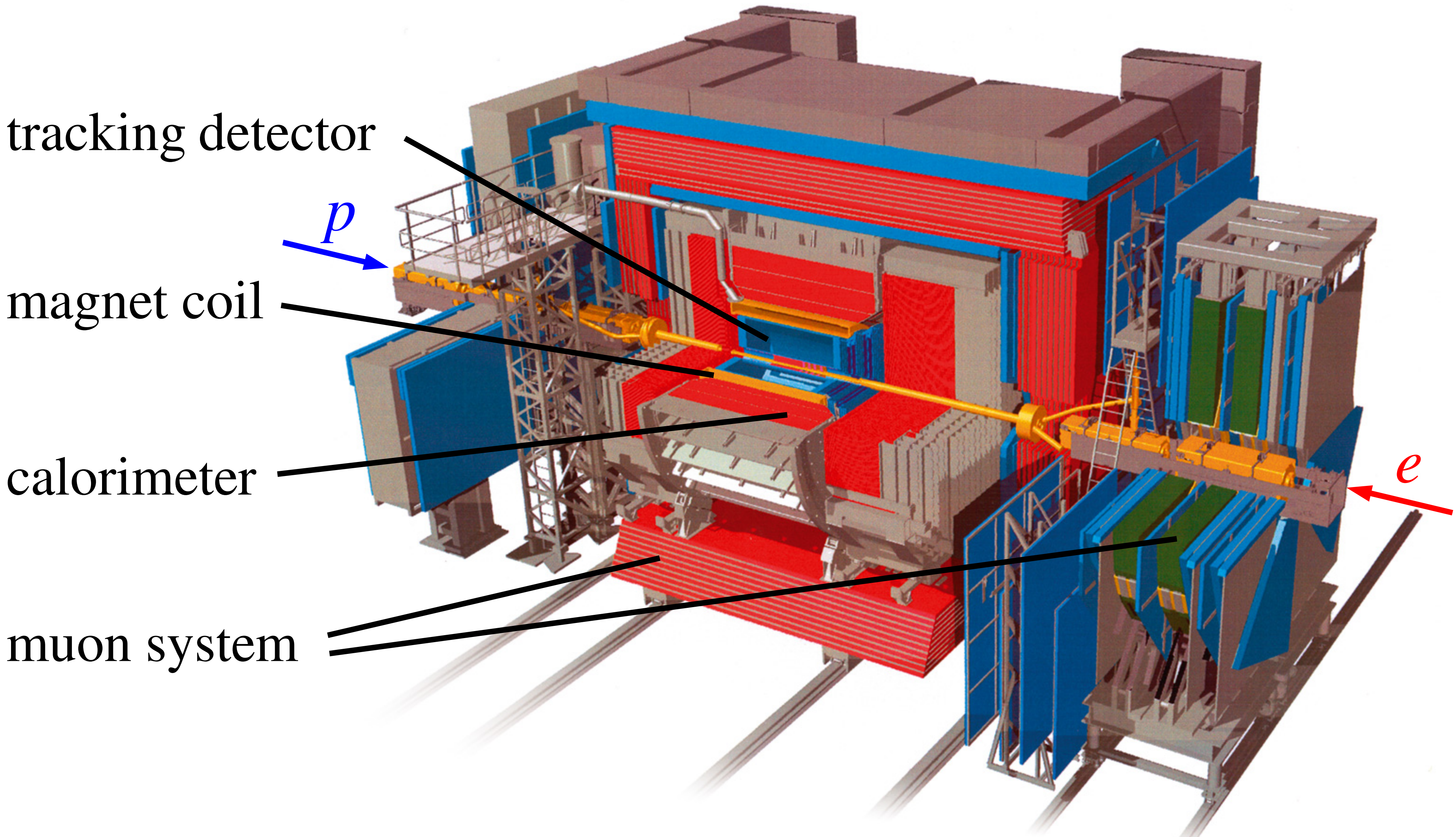
circumference: 6.3 km bunch crossing rate: 10.4 MHz

Collected Luminosity

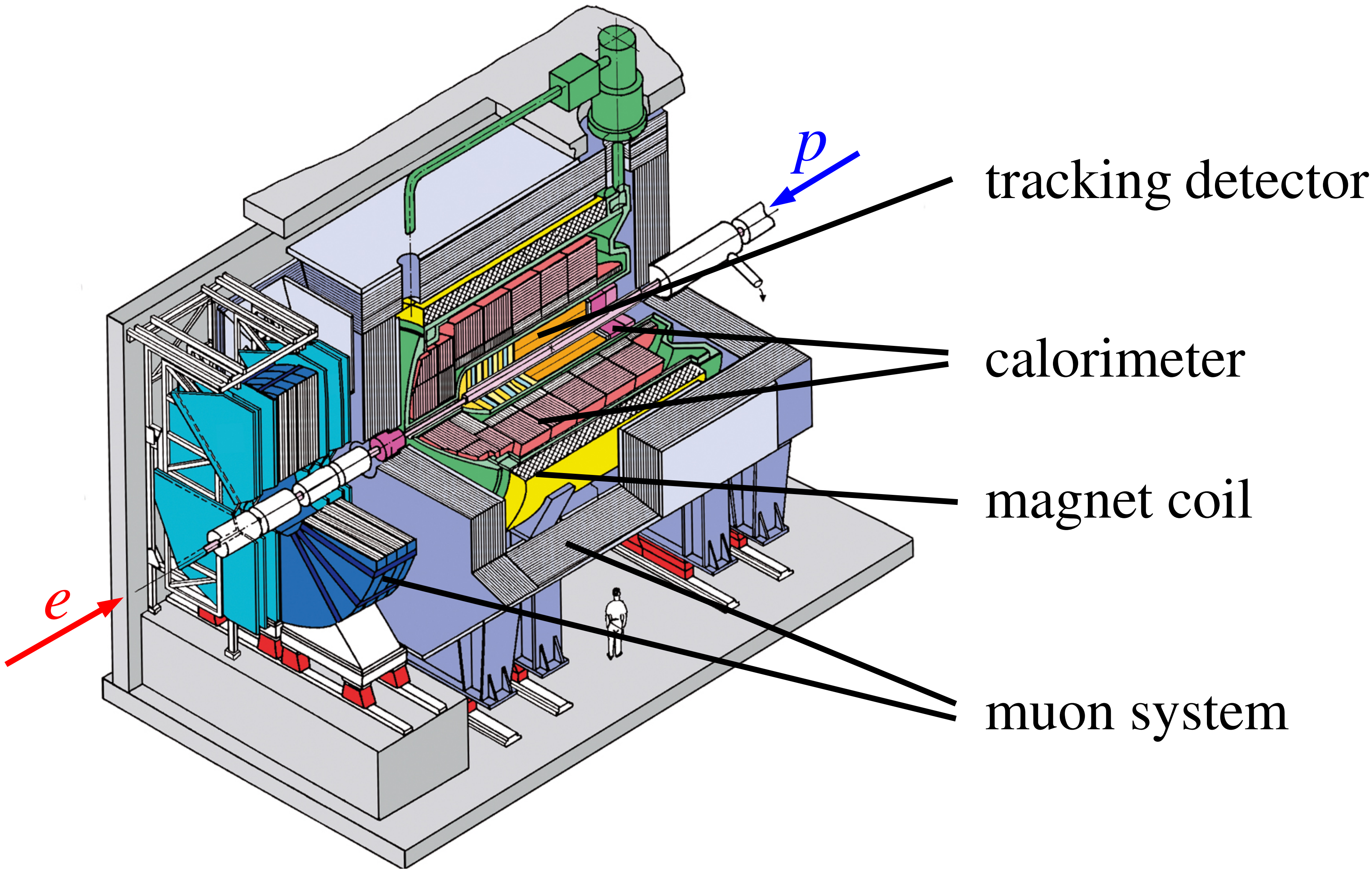


- HERA operated 1992-2007
- lumi upgrade in 2001
  - higher luminosity
  - *e* polarization
  - detector upgrades
- in total ~500 pb^{-1} of high energy data collected per experiment
- last months devoted to low *e* energy

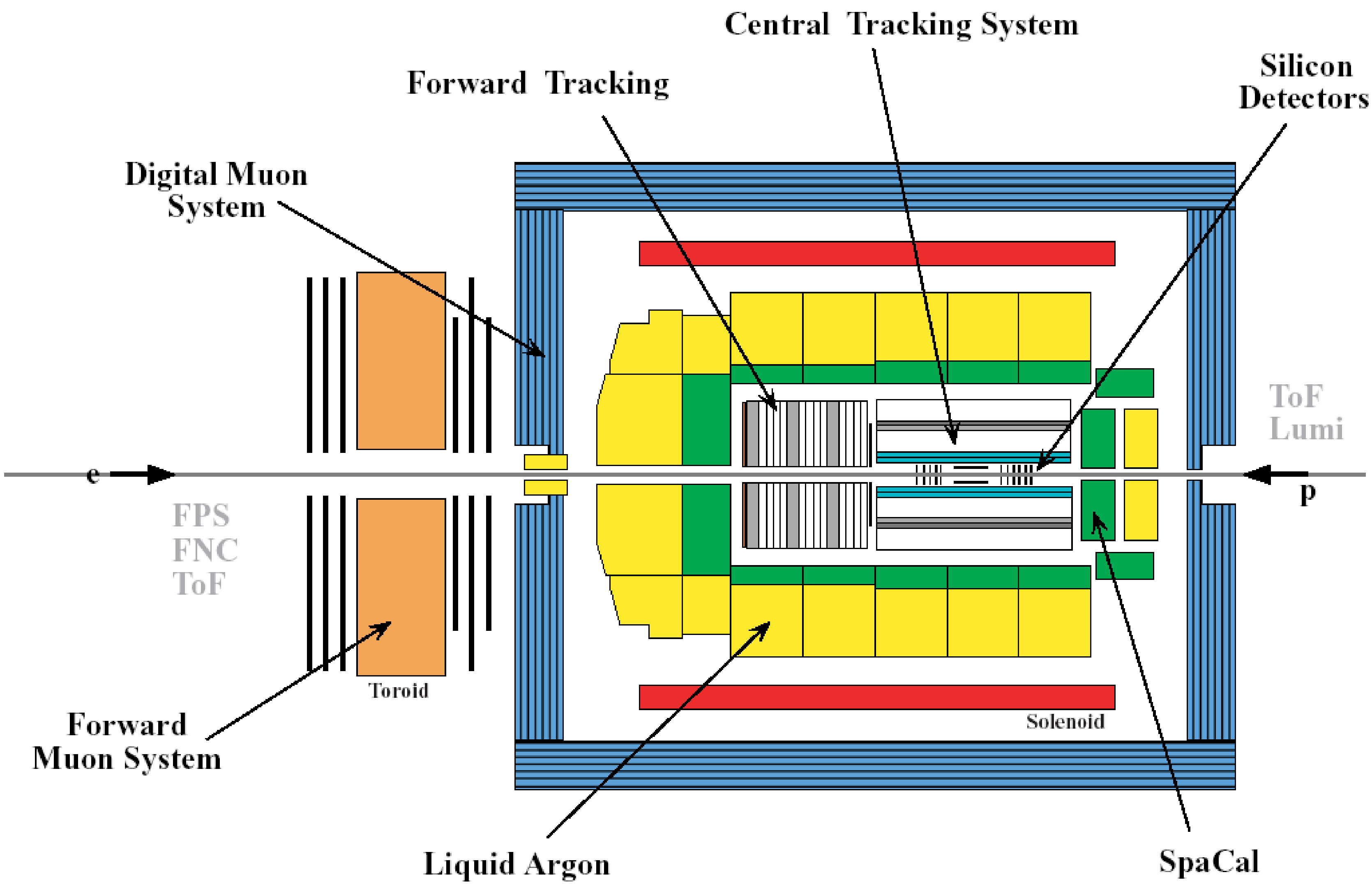
ZEUS Detector



H1 Detector



Schematic View of the H1 Detector



Physics Topics at HERA

expected

- proton structure
  - structure functions
  - parton densities
  - alpha_s
- photon structure
- perturbative QCD
  - jets
  - heavy quarks
- electroweak

not (so) expected

- exotics (beyond the standard modell)
  - SUSY
  - leptoquarks
  - ...
- diffraction

ep Scattering & Structure Functions

Elastic Electron Scattering

variables:

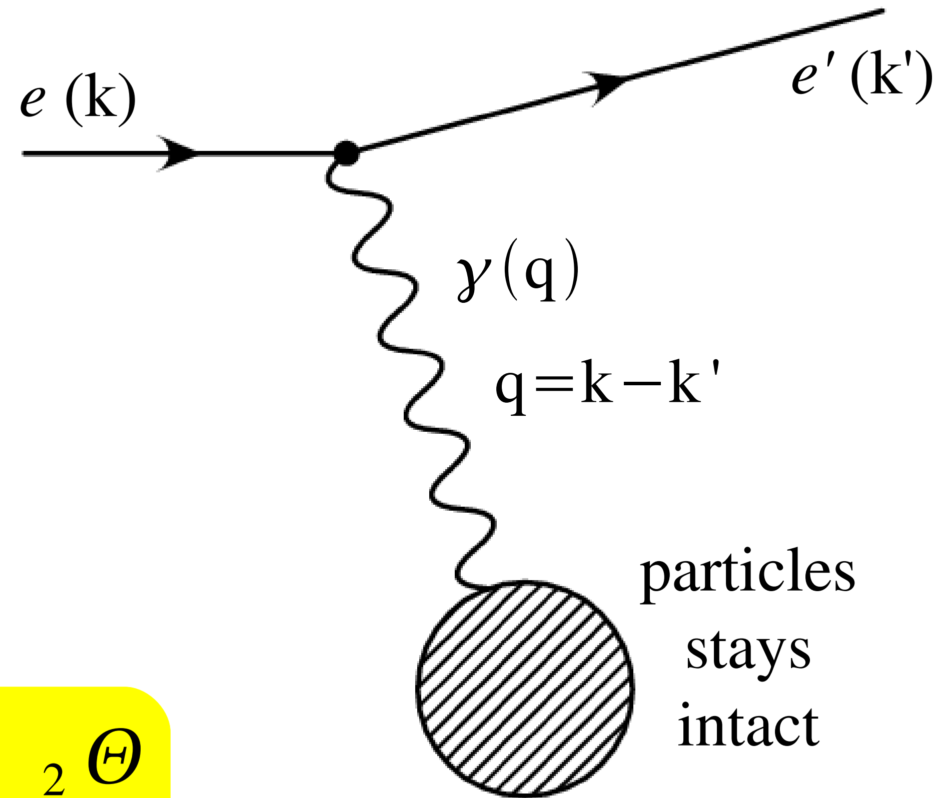
- $q \;= k - k'$
- $Q^2 = -q^2$
  $= 4\, E\, E' \sin^2(\Theta/2)$
- $E' = \dfrac{E}{1 + (2E/M)\sin^2(\Theta/2)}$

➔ only one independent!

$$\frac{d\sigma}{dQ^2} = \frac{4\pi\alpha^2 z^2}{Q^4}\left(\frac{E'}{E}\right)^2 \cos^2\frac{\Theta}{2}$$

Coulomb-
Potential ~1/r

recoil

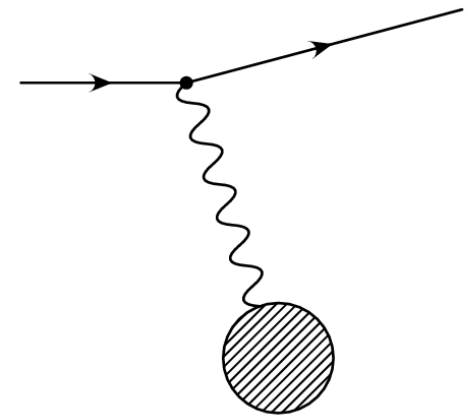


mass M,
charge z,
spin 0

Elastic Electron Scattering: Cross Section

- Mott Scattering: electron on a pointlike charged particle with spin 0

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}Q^2}\right)_{\mathrm{Mott}} = \frac{4\pi\alpha^2}{Q^4}\left(\frac{E'}{E}\right)^2 \cos^2\frac{\Theta}{2}$$



- Dirac Sacttering: electron on a pointlike charged particle with spin ½

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}Q^2}\right)_{\mathrm{Dirac}} = \left(\frac{\mathrm{d}\sigma}{\mathrm{d}Q^2}\right)_{\mathrm{Mott}}\left[1+2\tau\tan^2\frac{\Theta}{2}\right] \quad \text{with} \quad \tau=\frac{Q^2}{4M^2}$$

- electron on proton: „form factors“ needed:

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}Q^2}\right)_{ep} = \left(\frac{\mathrm{d}\sigma}{\mathrm{d}Q^2}\right)_{\mathrm{Mott}}\left[\frac{G_E^2(Q^2)+\tau G_M^2(Q^2)}{1+\tau} + 2\tau\, G_M^2(Q^2)\tan^2\frac{\Theta}{2}\right]$$

  - ➔ protons are not pointlike!

Electric Form Factor of the Proton

- describes the charge distribution in the proton (Fourier transform)
- measured:
  - $G_E(0) = 1$
  - $G_M(0) = 2.79$
  - $G_E(Q^2),\ \ G_M(Q^2) \ \propto \ \left(1+\frac{Q^2}{0.71\,\mathrm{GeV}^2}\right)^{-2}$

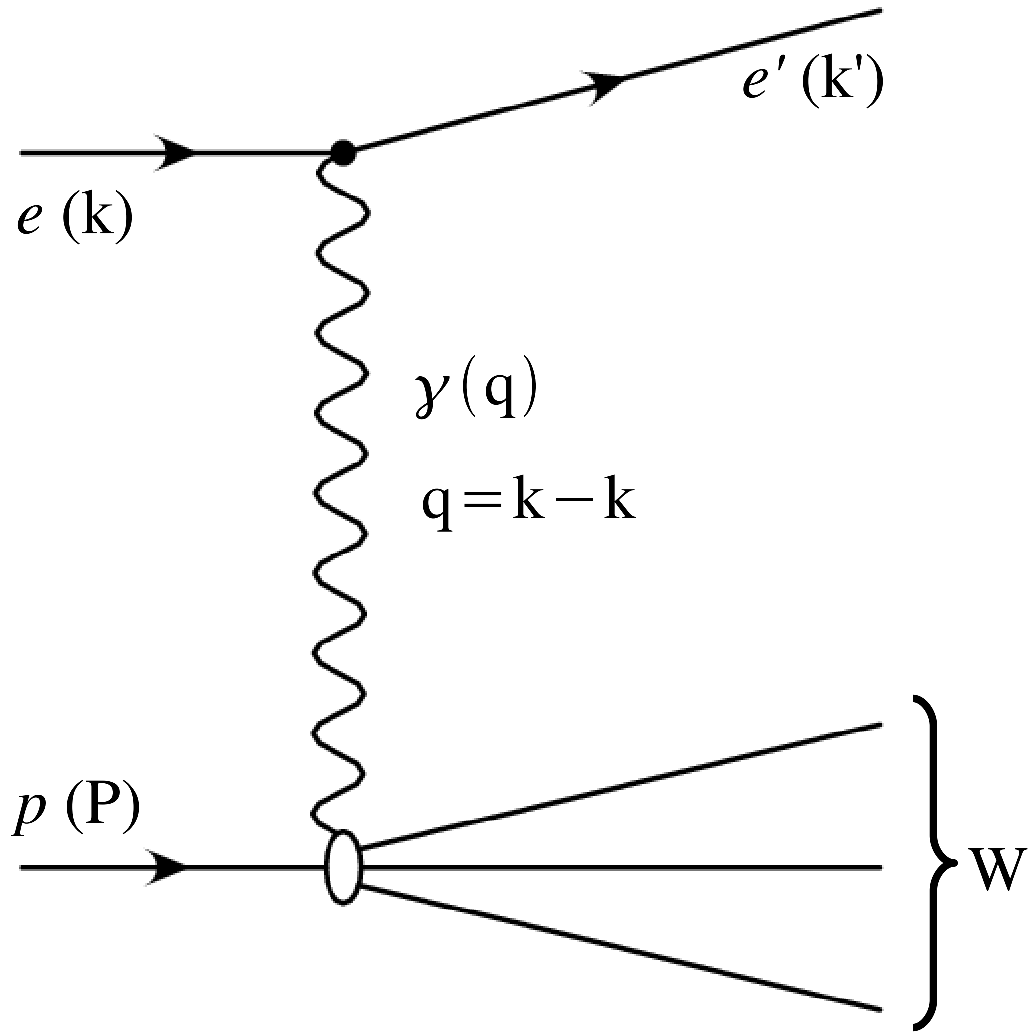
➔ elastic scattering only import at low Q^2

Inelastic Electron Scattering

variables:

- $q \quad = k - k'$
- $Q^2 \ = -q^2$
- $s \quad = (P + k)^2$
- $W^2 = (P + q)^2$
  $\qquad = M^2 + 2q \cdot P - Q^2$
- $y \quad = q \cdot P / k \cdot P$

➔ two independent!



elastic: $W = M$ inelastic: $W > M$

Inelastic Electron Proton Scattering

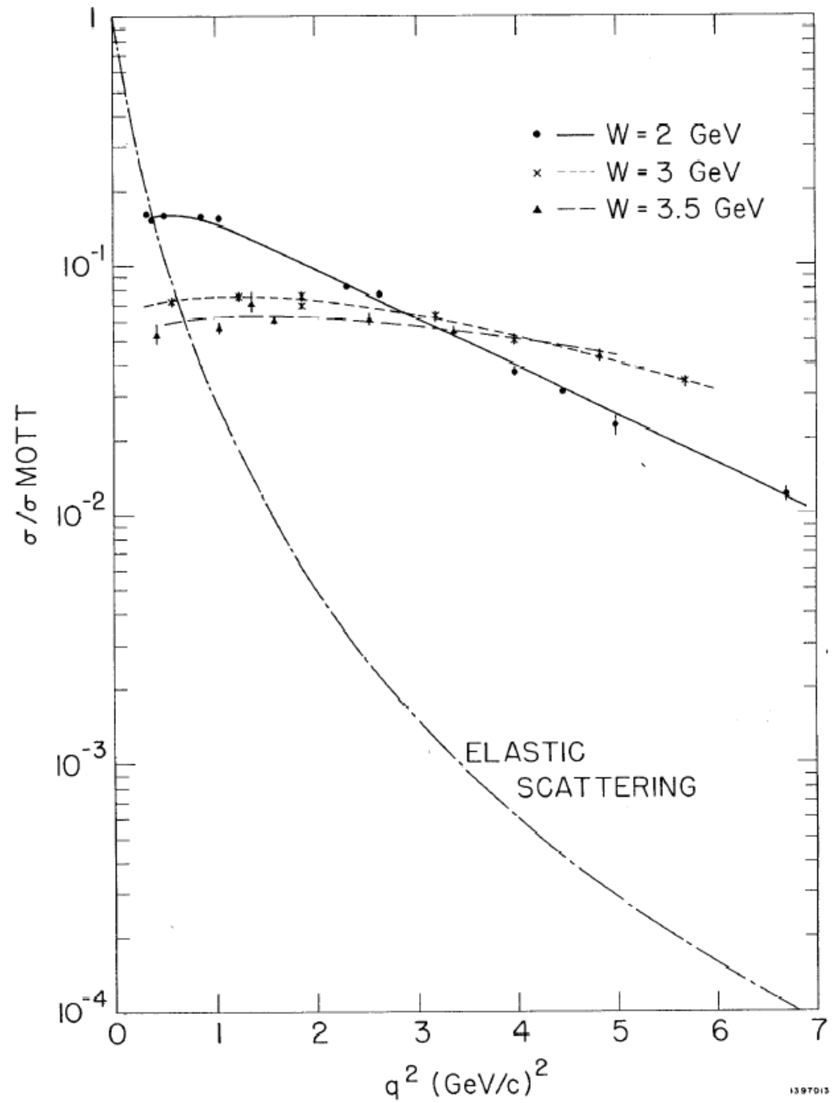
- inelastic scattering:
  $W > M_p$
- ratio to Mott cross section nearly flat in Q^2

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

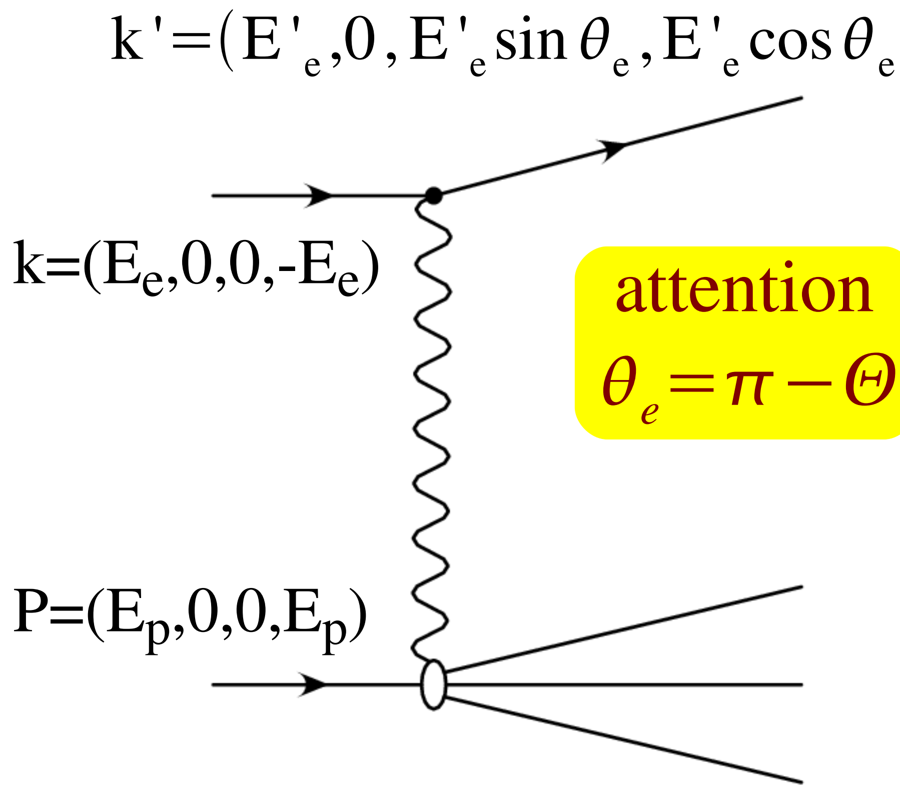
E. D. Bloom, D. H. Coward, H. DeStaebler,
J. Drees, L. W. Mo, R. E. Taylor
Stanford Linear Accelerator Center,† Stanford, California 94305



Deep Inelastic Scattering (DIS)

- deep: $Q^2 > M_p$
- inelastic: $W > M_p$
- for HERA: m_e, M_p << W

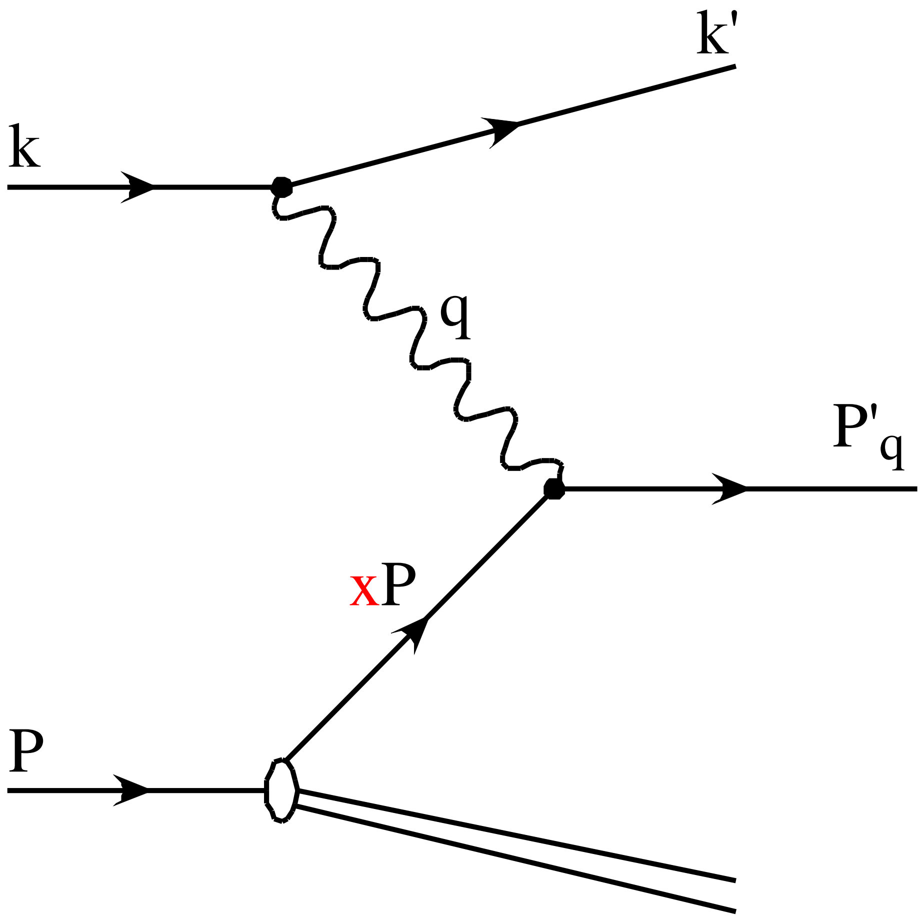
  → neglect m_e, M_p
  - $s = 4\, E_p\, E_e$
  - $Q^2 = 2\, E_e\, E'_e (1 + \cos\theta_e)$
  - $y = 1 - \frac{E'_e}{E_e} \sin^2 \frac{\theta_e}{2}$
  - $W = y \sqrt{s} - Q^2$



attention
$\theta_e = \pi - \Theta$

- one more variable: $x = Q^2 / (2\, P \cdot q) = Q^2 / ys$

DIS: What is x?



x can be interpreted as the momentum fraction of the struck parton of the proton:

$$P'_q = q + xP$$

$$(q + xP)^2 = -Q^2 + 2x\, q \cdot P + (xP)^2$$

$$(q + xP)^2 = (xP)^2$$

$$x = \frac{2\, q \cdot P}{Q^2}$$

Structure Functions F_1 & F_2

- the DIS cross section can be written as

$$\frac{d^2\sigma}{dx\,dQ^2}=\frac{4\pi\alpha^2}{Q^4}\frac{1}{x}\left[(1-y)\,F_2(x,Q^2)+\frac{y^2}{2}\,2x\,F_1(x,Q^2)\right]$$
$$=\frac{4\pi\alpha^2}{Q^4}\frac{1}{x}\frac{E'}{E}\left[F_2(x,Q^2)\,\cos^2\frac{\Theta}{2}+\frac{Q^2}{2x^2M_p^2}\,2x\,F_1(x,Q^2)\,\sin^2\frac{\Theta}{2}\right]$$

- comparison with Dirac formula

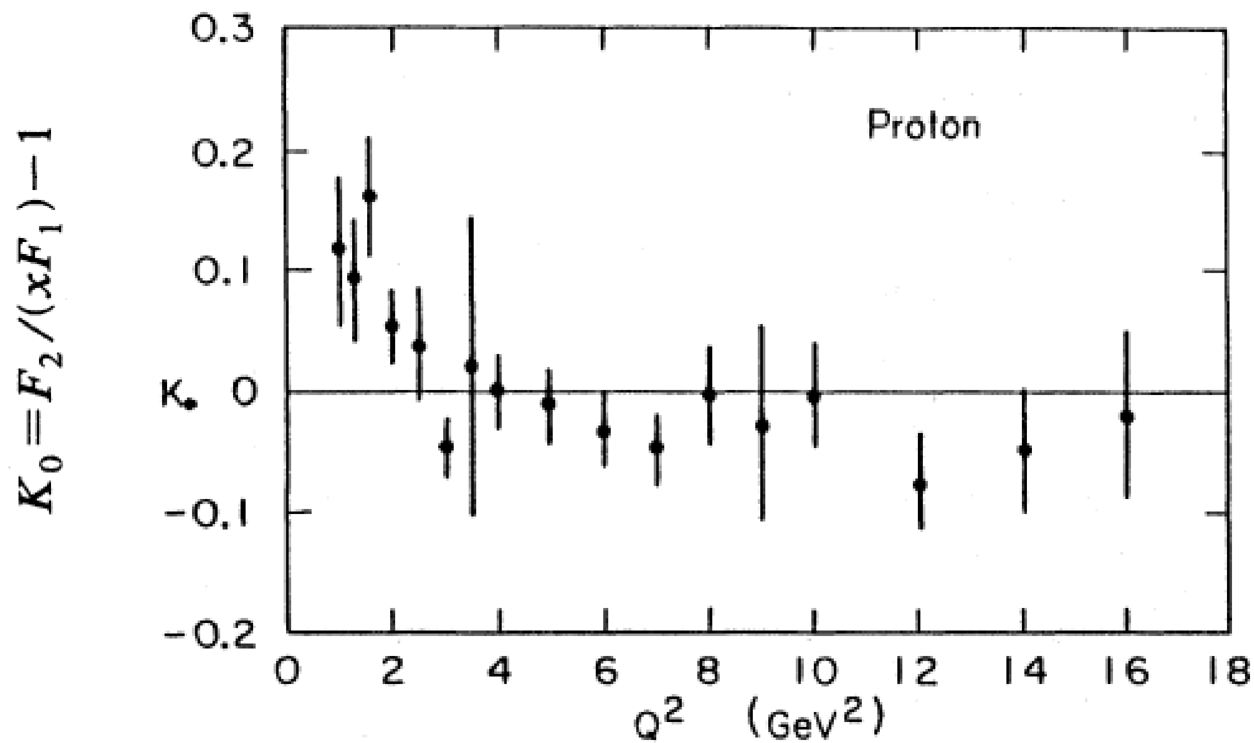
$$\left(\frac{d\sigma}{dQ^2}\right)_{\text{Dirac}}=\frac{4\pi\alpha^2z^2}{Q^4}\left(\frac{E'}{E}\right)^2\left[\cos^2\frac{\Theta}{2}+\frac{Q^2}{2M^2}\sin^2\frac{\Theta}{2}\right]$$

➔ F_2 corresponds to electric field of the parton

➔ F_1 corresponds to spin of the parton

Parton Spin

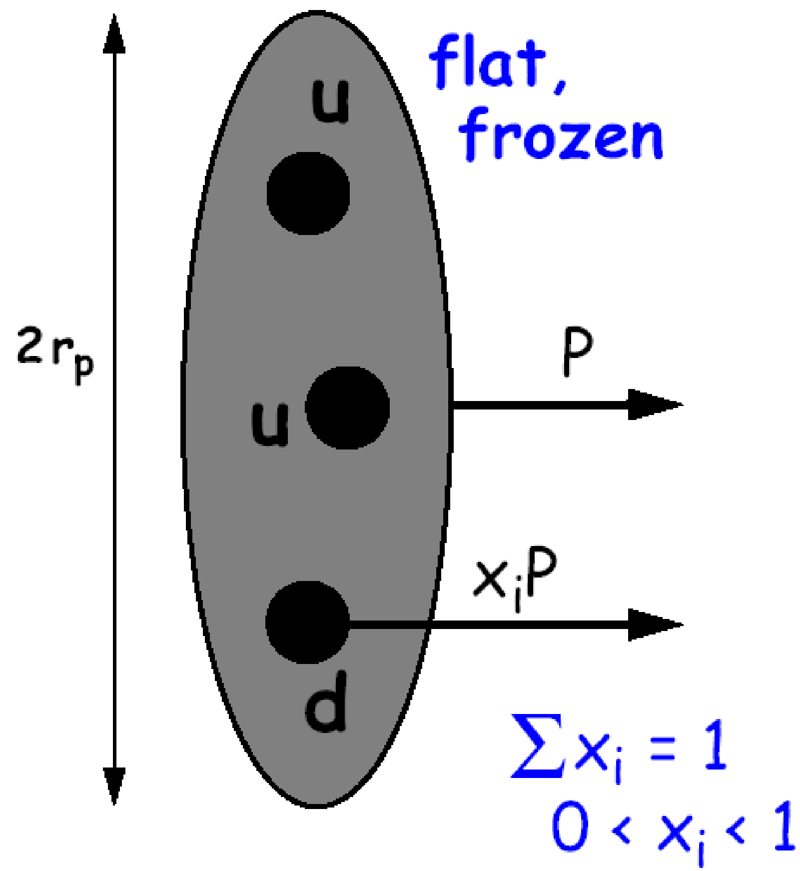
- parton spin ½: $2 \times F_1 = F_2$ (Callan Gross)
- parton spin 0: $2 \times F_1 = 0$



partons have spin ½

(Naive) Quark Parton Model

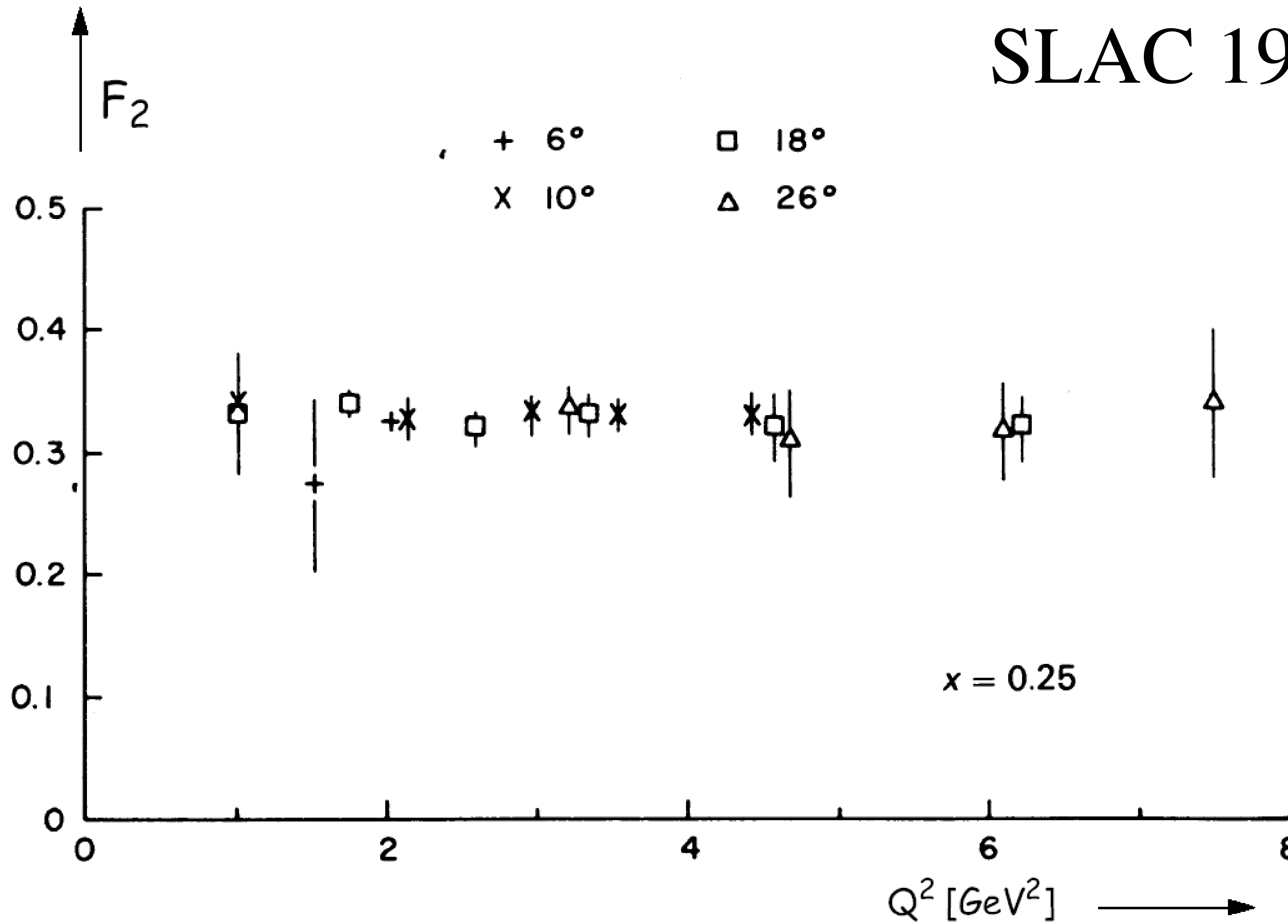
- proton consists of 3 partons, identified with the QCD quarks
- during the interaction proton is „frozen“
- electron proton scattering is sum of incoherent electron quark scatterings
- proton structure is defined by parton distributions



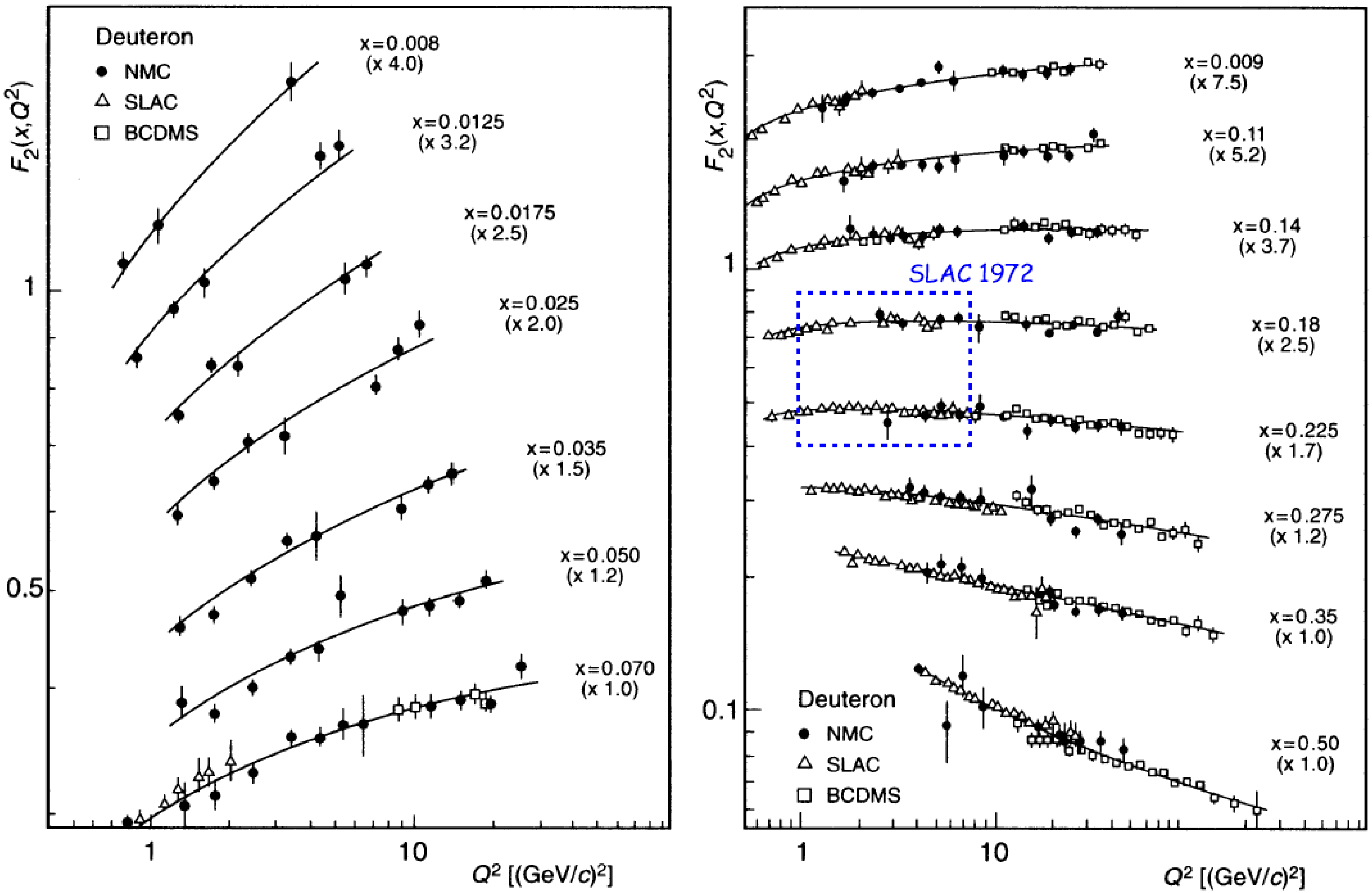
$$F_2(x, Q^2) = x \sum e_q^2 q(x)$$

Scaling: F_2 independent of Q^2

SLAC 1972

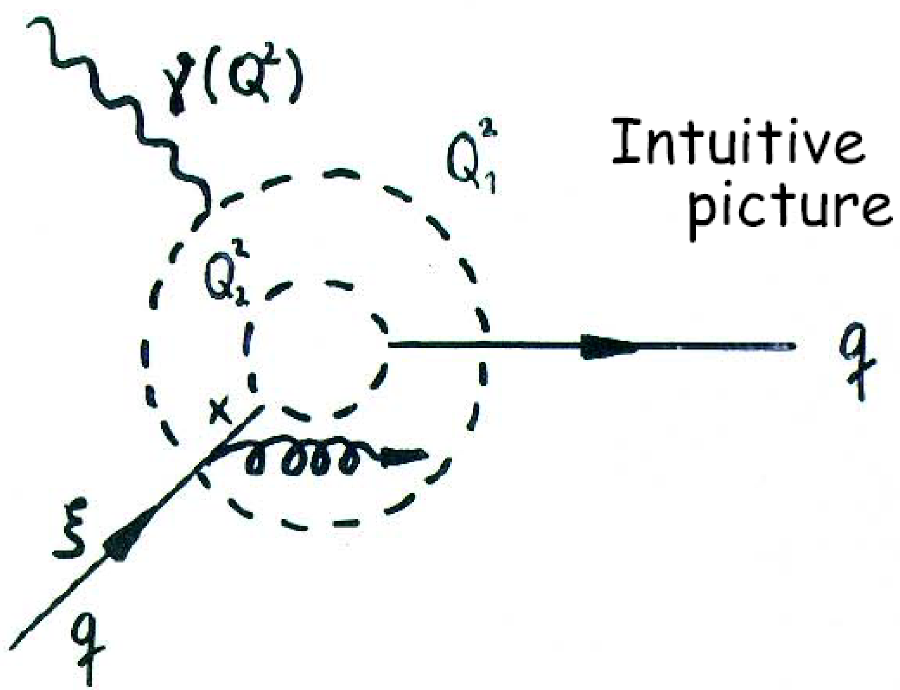


Scaling Violations



Parton Evolution

- number of partons changes with Q^2
- Q^2 can be interpreted as resolving power: $Q^2 \propto (\hbar / \lambda)^2$



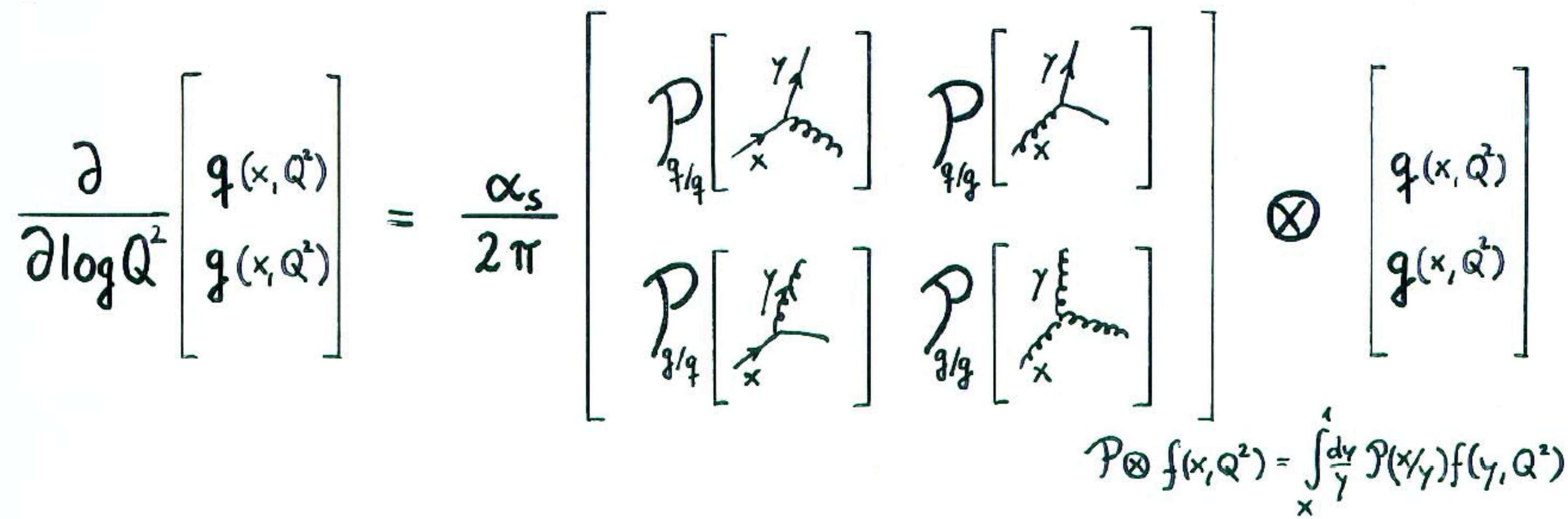
small Q^2:

- many partons with large x
- (nearly) no partons at low x

large Q^2:

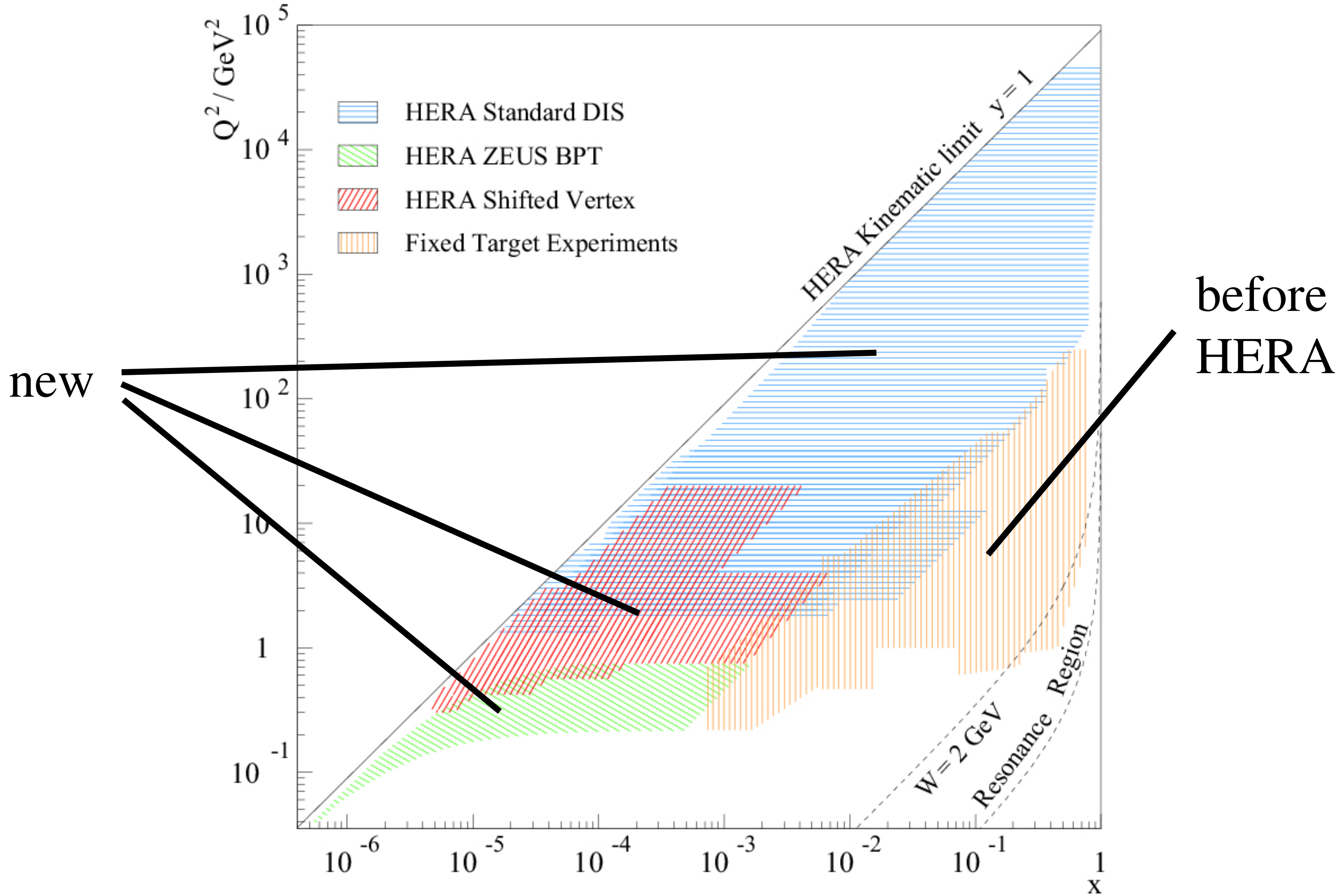
- less partons with large x
- more partons at low x

DGLAP Evolution Equations

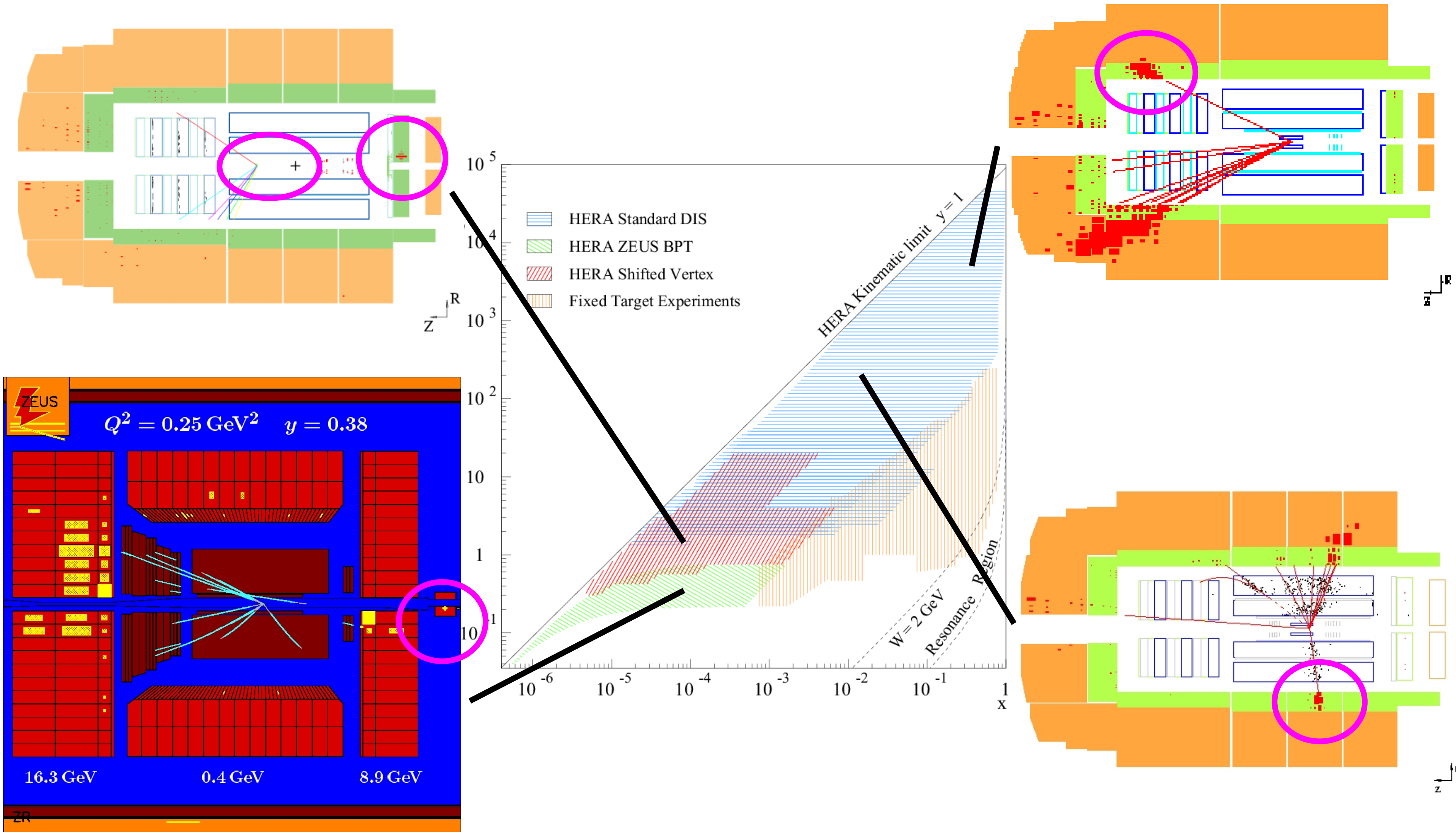


- Q^2 dependence of quark densities $q(x,Q^2)$ and gluon density $g(x,Q^2)$ is predicted
- no prediction for the x dependence → initial condition needed

HERA Kinematic Range

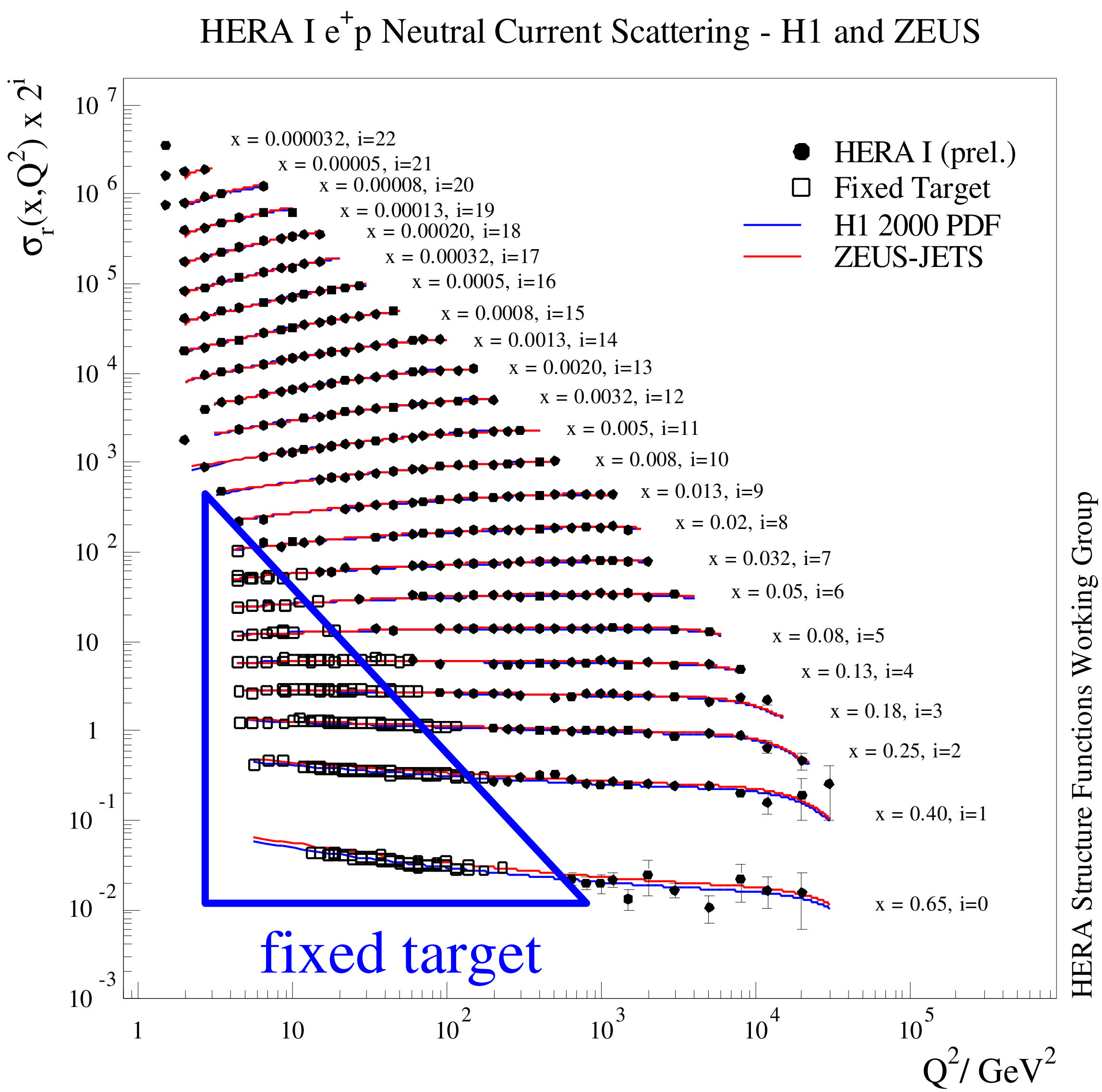


Events in Different Regions

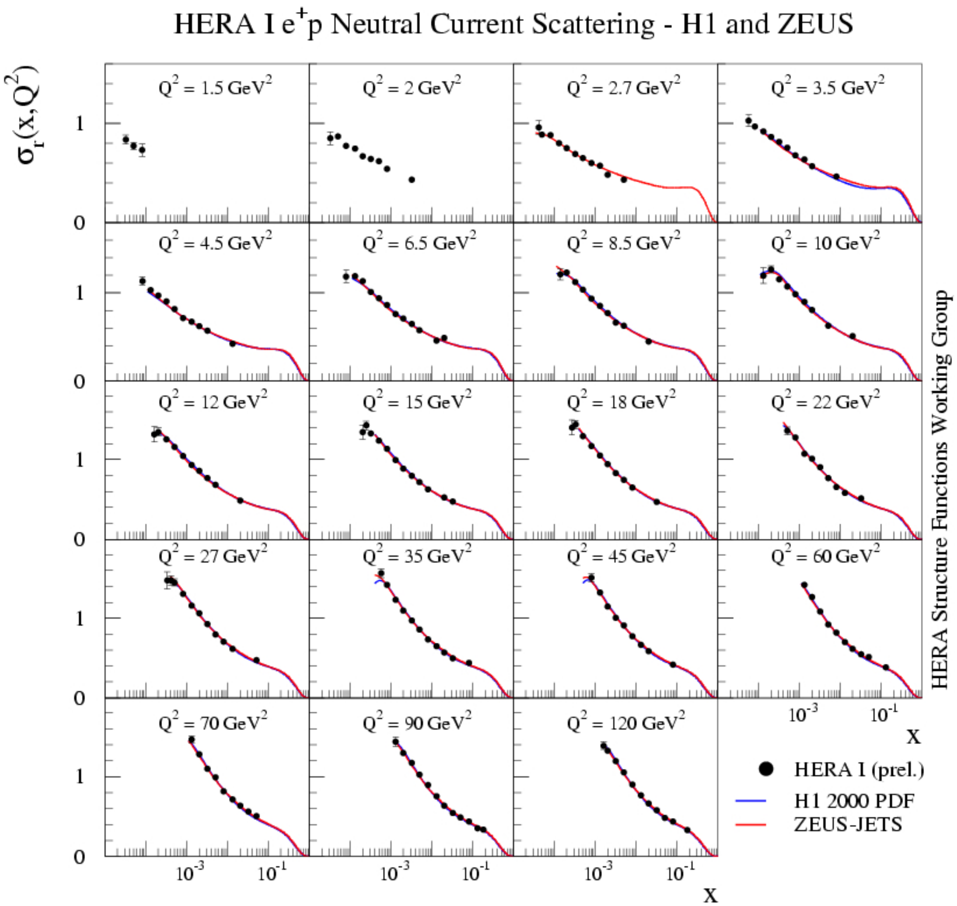


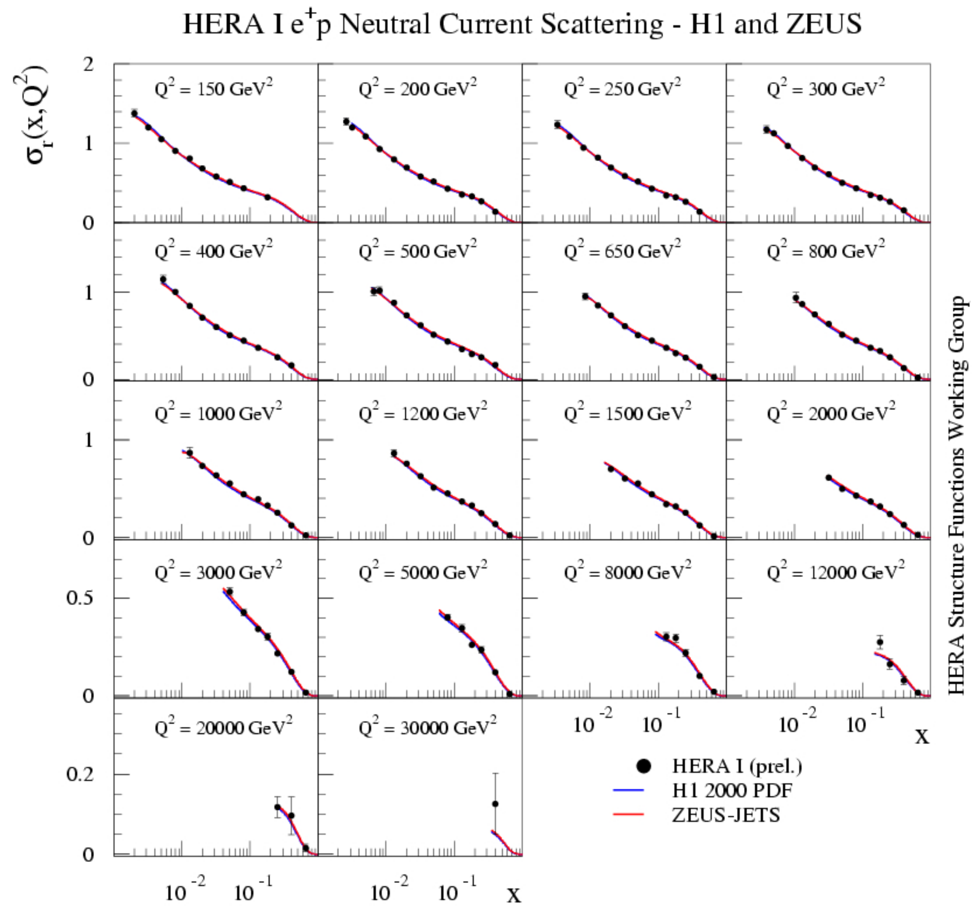
F_2 vs. Q^2

- HERA data cover huge range: 5 orders in Q^2 and 4 orders in x
- approximate scaling at large x
- clear scaling violations at small x



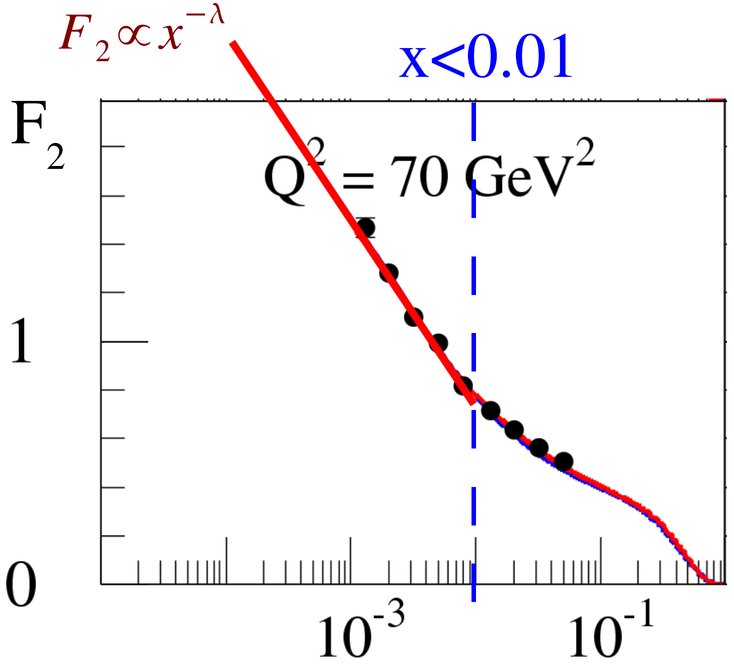
F_2 vs. x

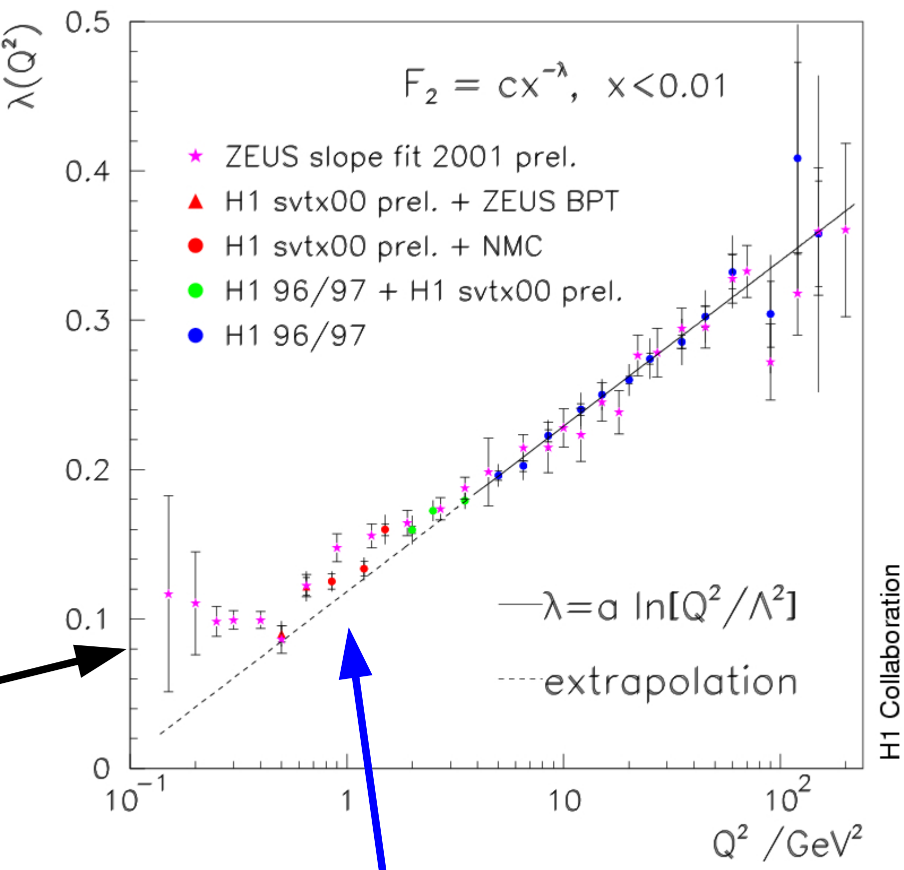




strong rise towards low x, steepness rising with Q^2

Hadrons vs. Partons





0.08 correponds to hadron-hadron scattering

transition from hadronic to partonic bahaviour