Physics at HERA

Summer Student Lectures
10-13 August 2009

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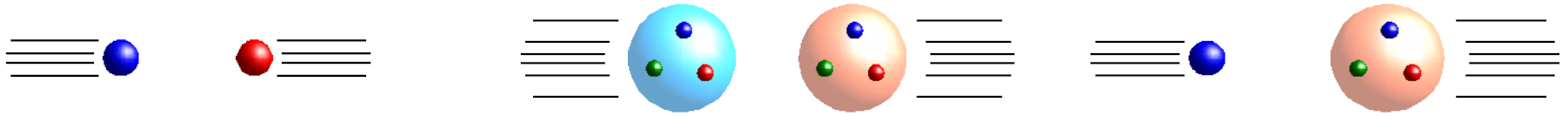
Overview

- 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)

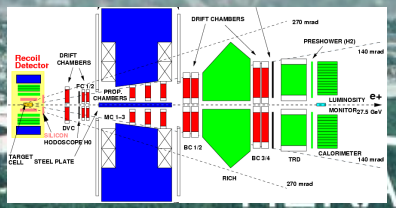
$p^\pm p^\pm$

+ 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



HERMES

H1

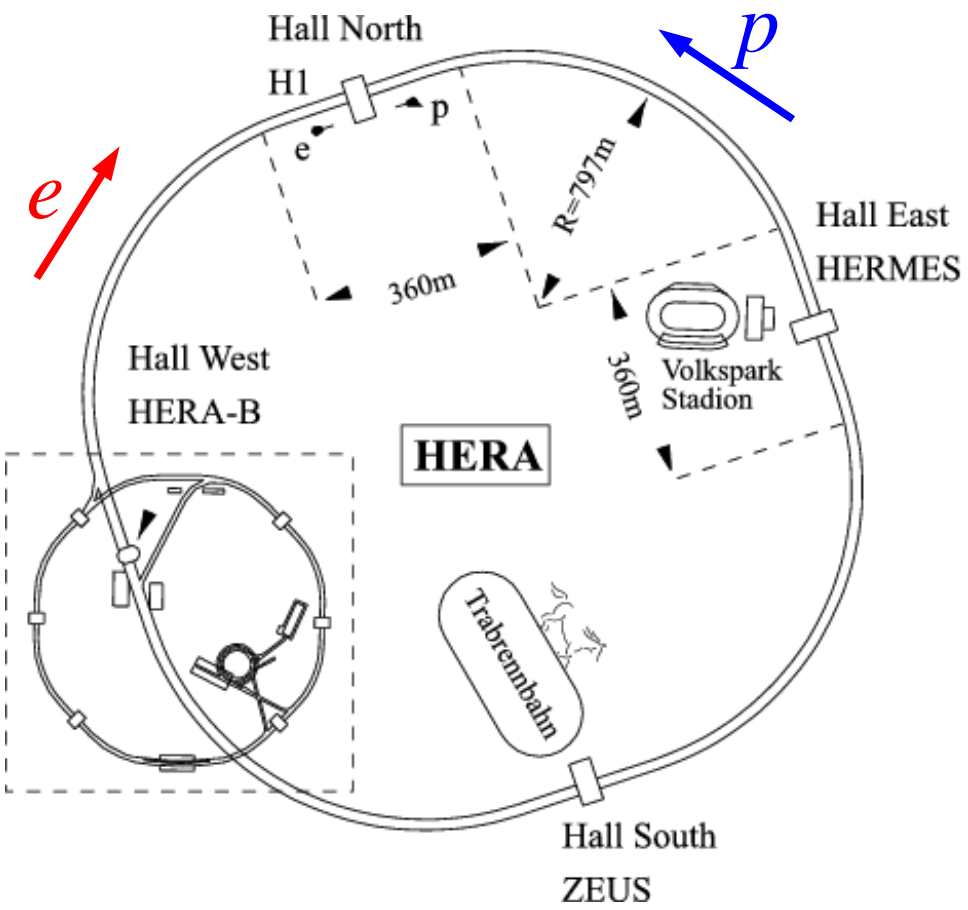
ZEUS

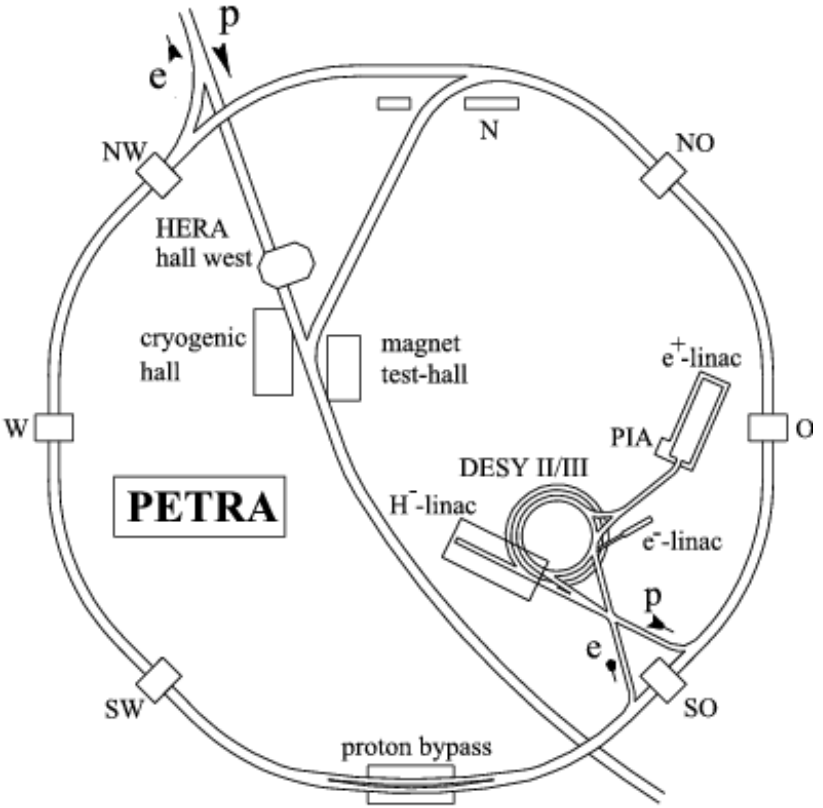
p **e**

920 GeV **27.6 GeV**

PETRA

HERA & its Pre-Accelerators

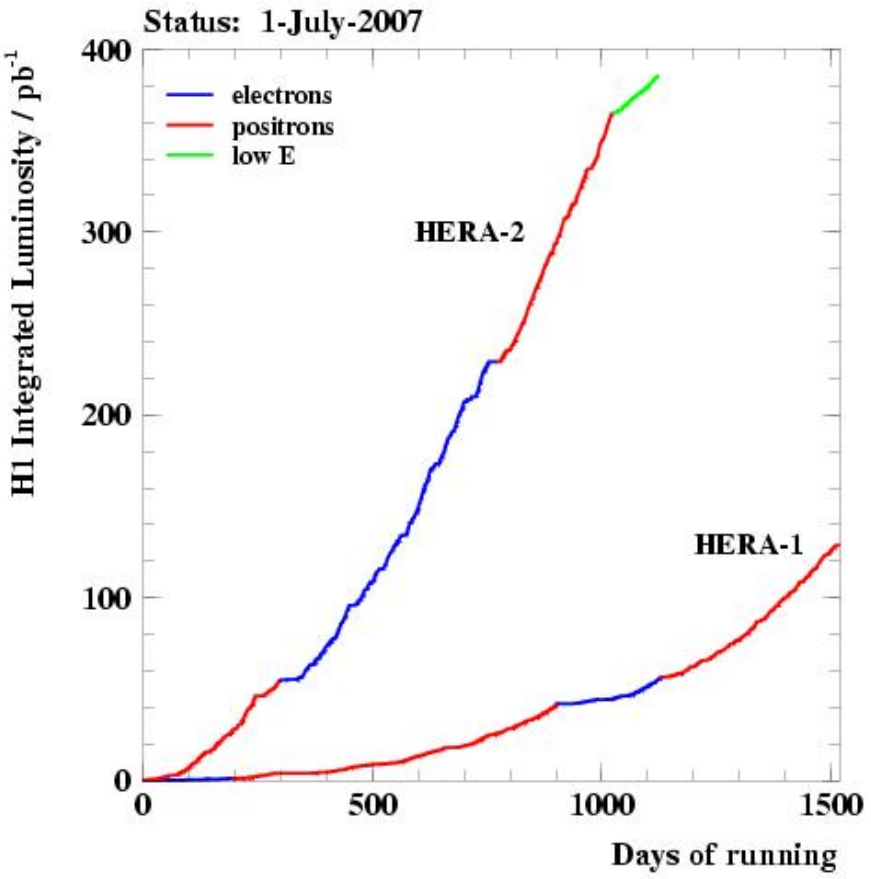




circumference: 6.3 km

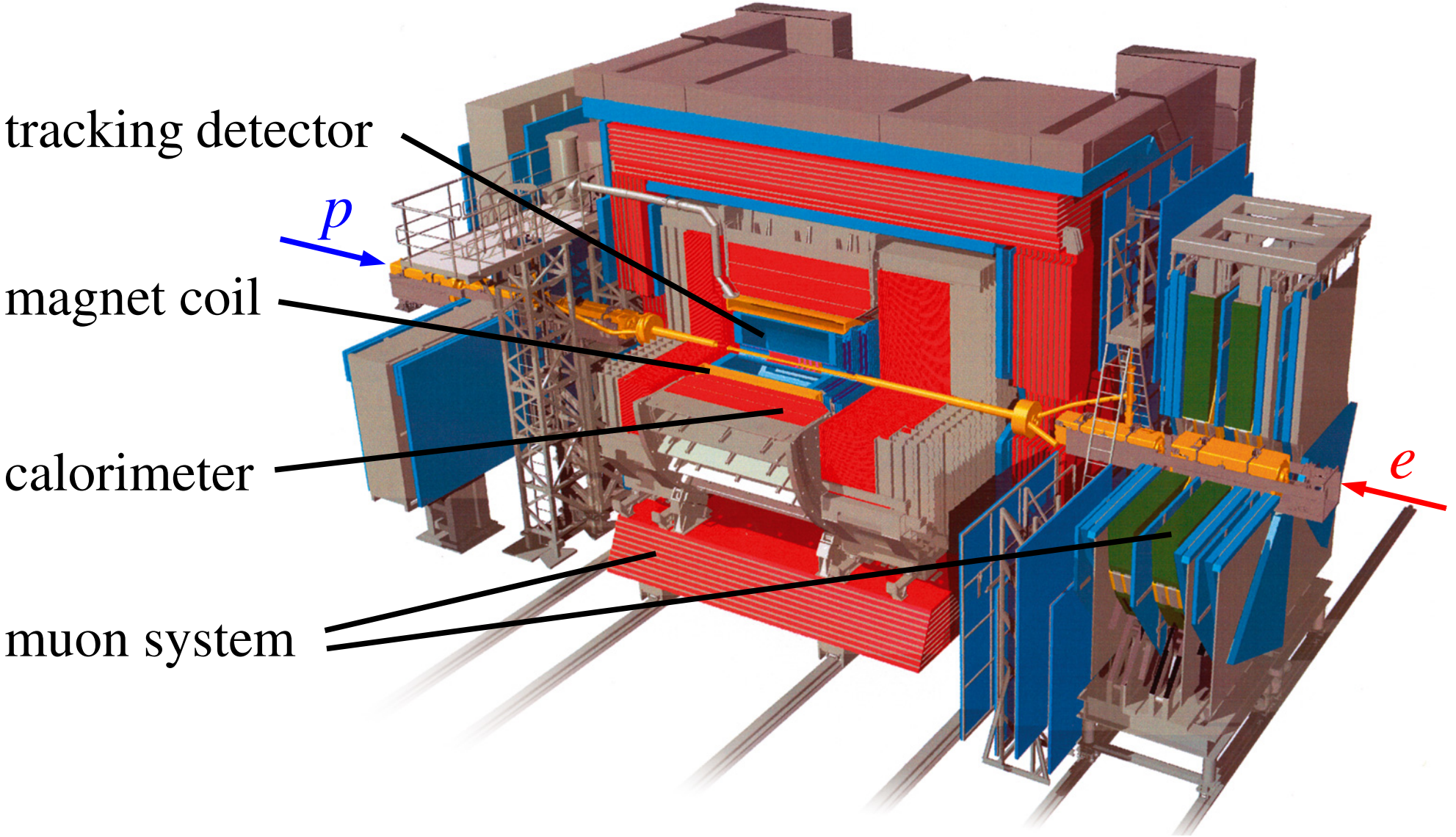
bunch crossing rate: 10.4 MHz

Collected Luminosity

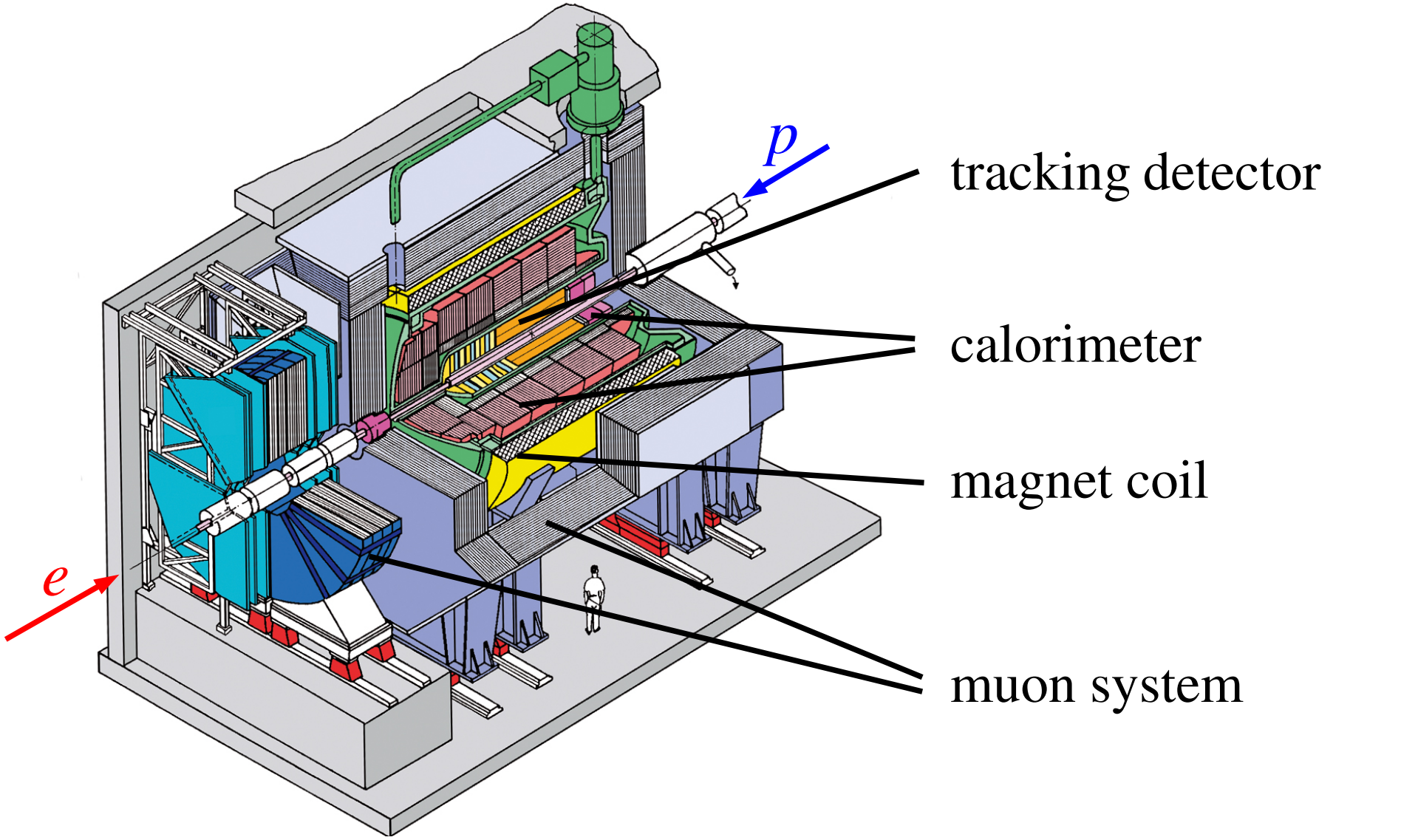


- HERA operated 1992-2007
- lumi upgrade in 2001
  - higher luminosity
  - *e* polarization for H1 & ZEUS
  - detector upgrades
- in total ~500 pb^{-1} of high energy data collected per experiment
- last months devoted to low *p* energy (460, 575 GeV)

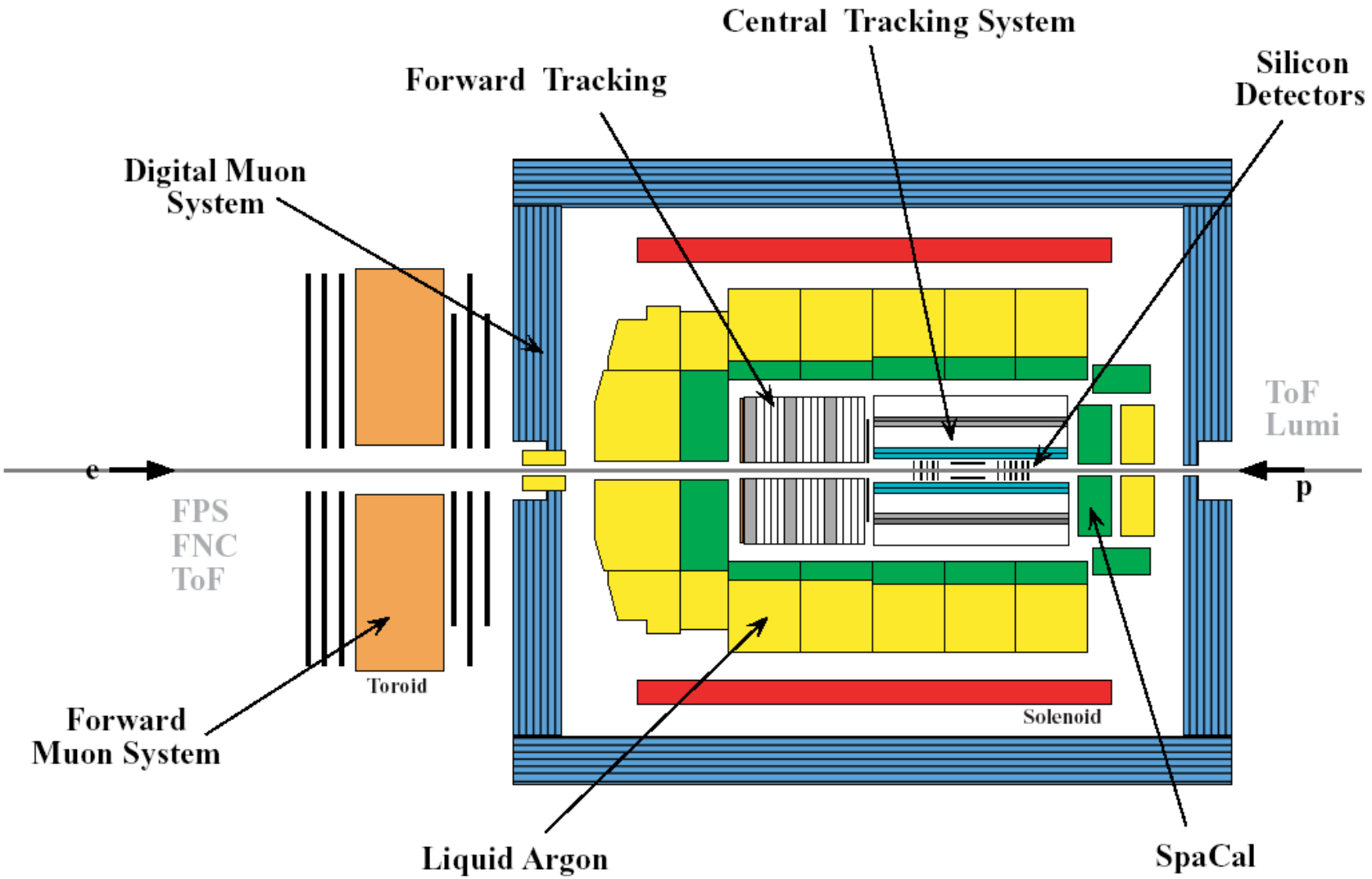
ZEUS Detector



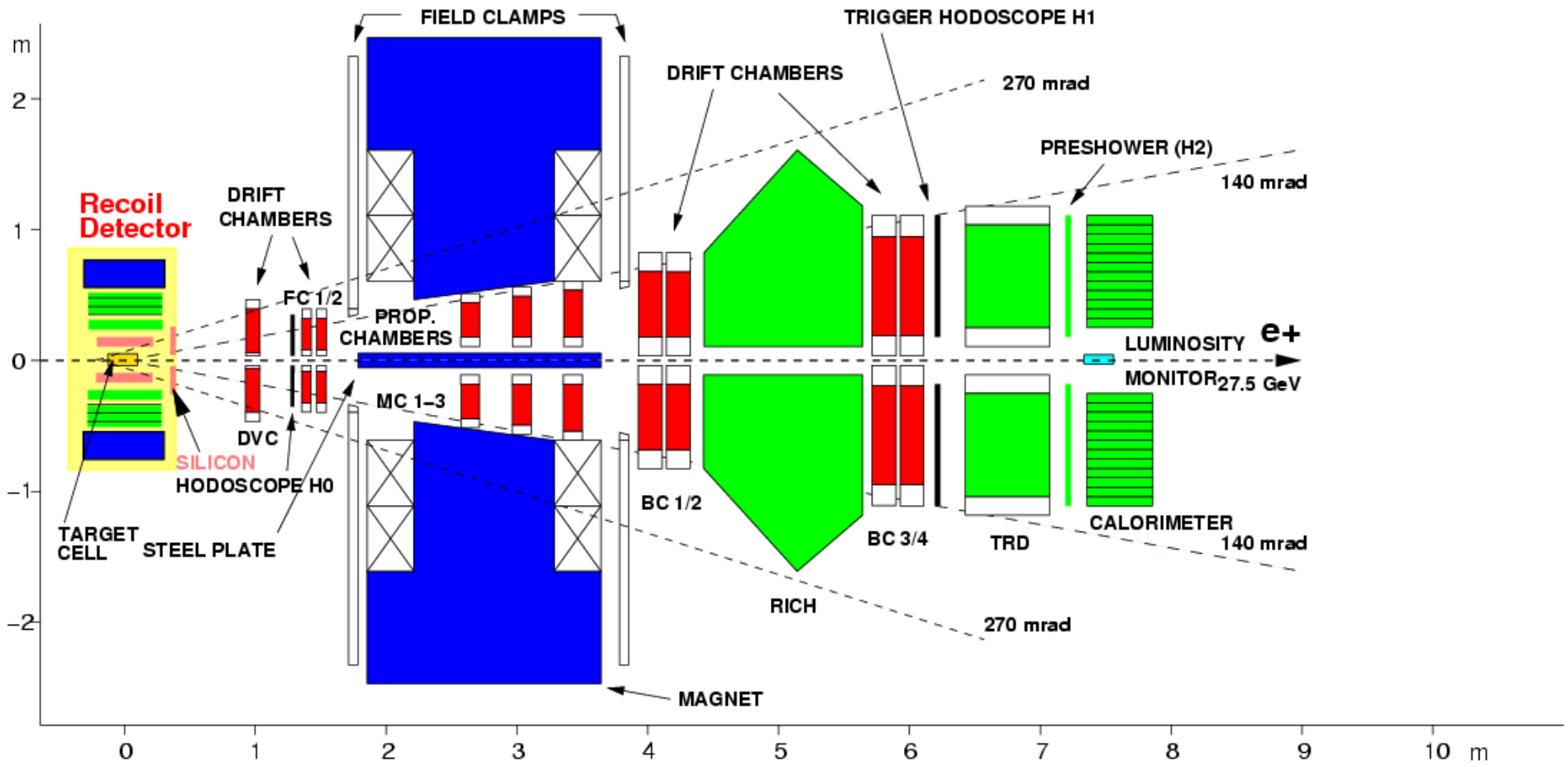
H1 Detector



Schematic View of the H1 Detector



HERMES Detector



- HERMES used electron beam on polarised gas target
- spectrometer covering region around electron beam direction

Physics Topics at HERA

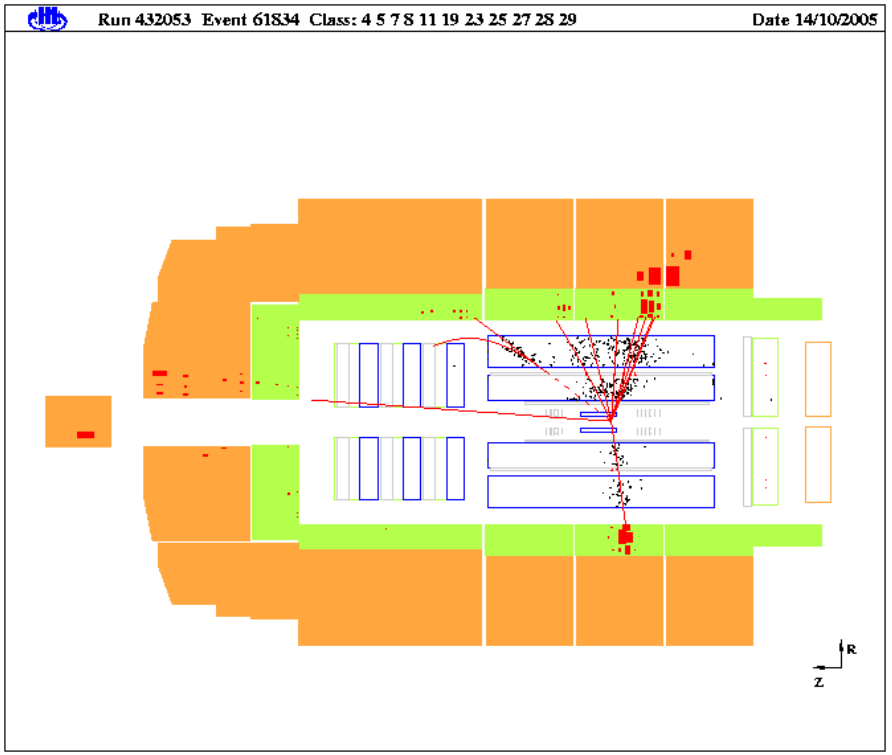
expected

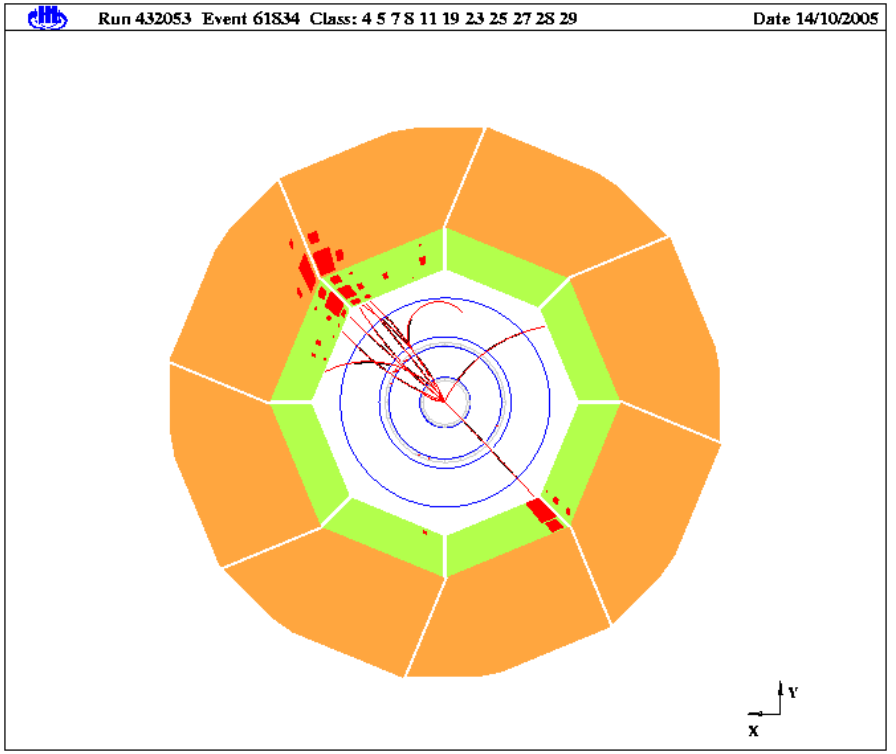
- proton structure
  - structure functions
  - parton densities
- photon structure
- perturbative QCD
  - jets
  - α_s
  - heavy quarks
- electroweak

not (so) expected

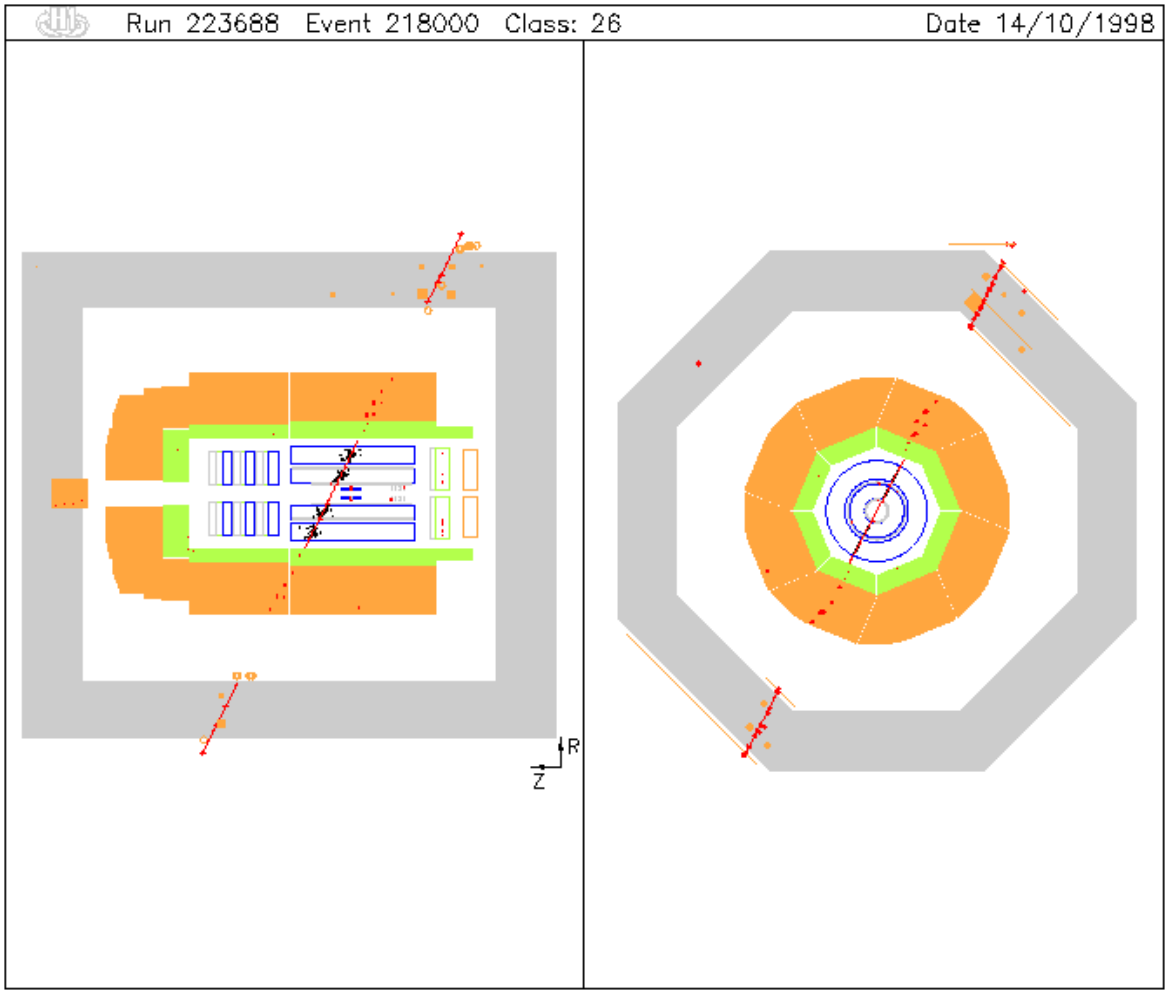
- exotics (beyond the standard modell)
  - SUSY
  - leptoquarks
  - ...
- diffraction

Some Events...

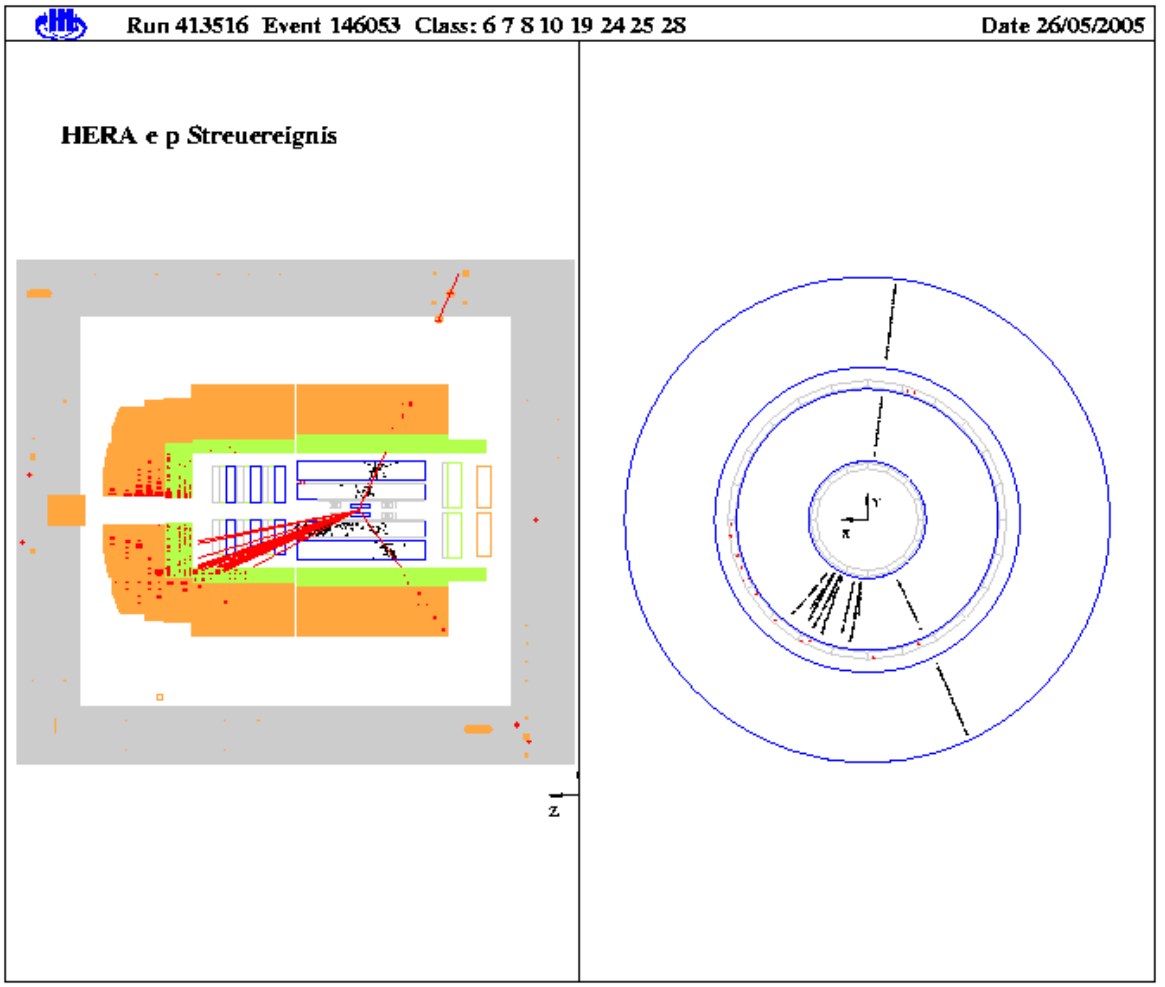

Run 432053 Event 61834 Class: 4 5 7 8 11 19 23 25 27 28 29
Date 14/10/2005
R
z


Run 432053 Event 61834 Class: 4 5 7 8 11 19 23 25 27 28 29
Date 14/10/2005
Y
x

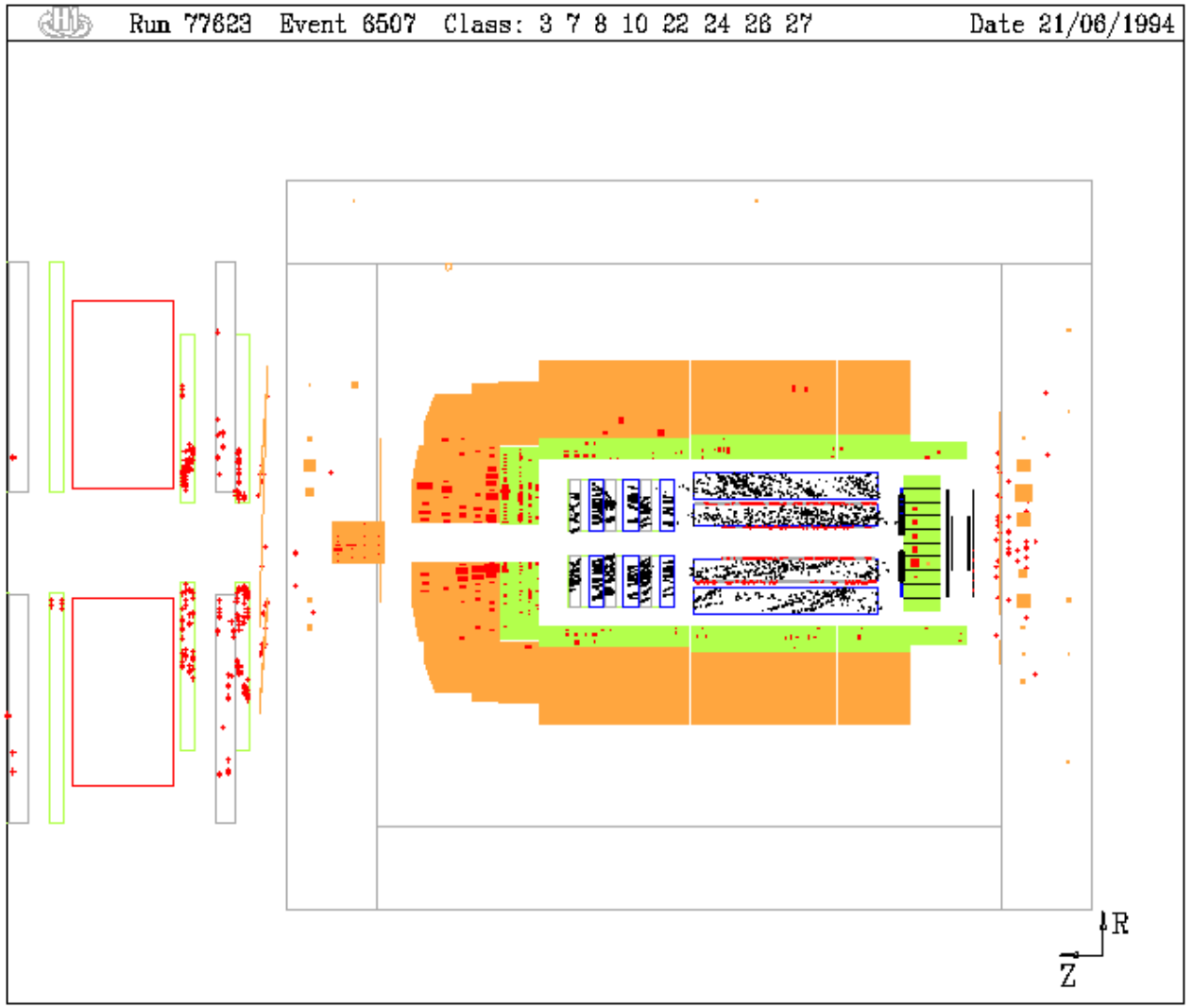
Some Events...



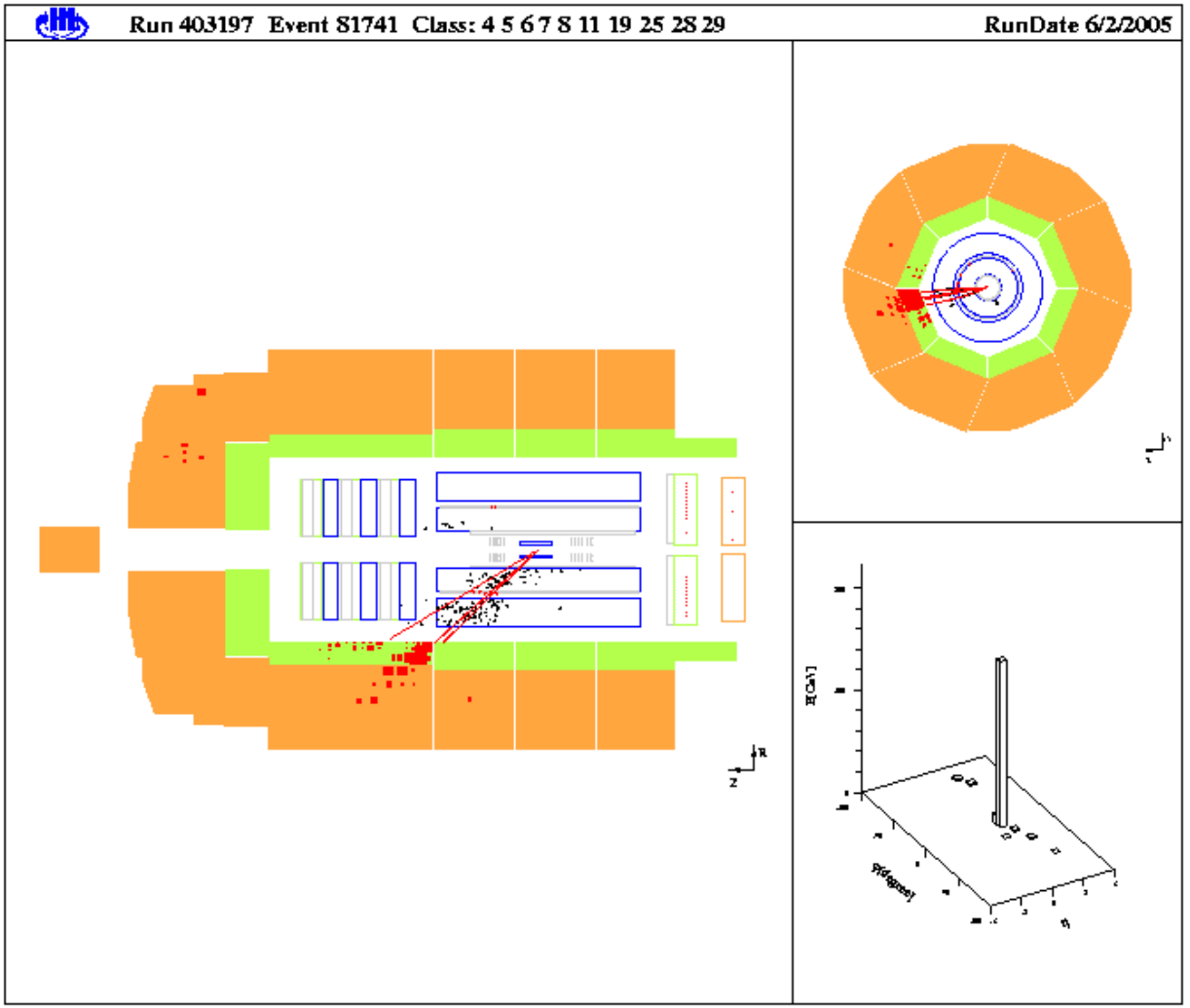
Some Events...


Run 413516 Event 146053 Class: 6 7 8 10 19 24 25 28
Date 26/05/2005
HERA e p Streuereignis
z
y
x

Some Events...



Some Events...


Run 403197 Event 81741 Class: 4 5 6 7 8 11 19 25 28 29
RunDate 6/2/2005

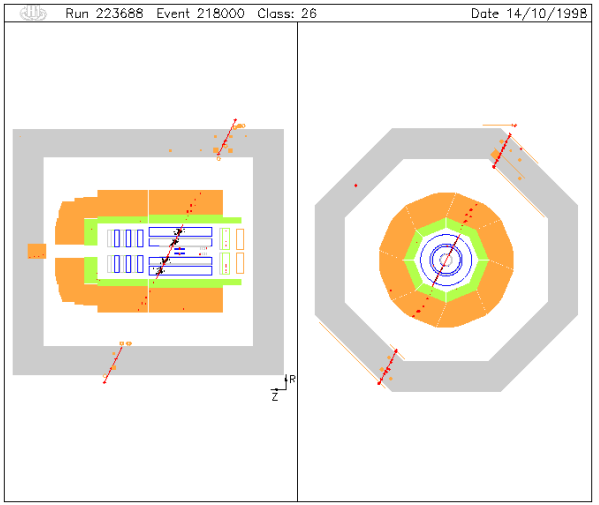
Event Rates

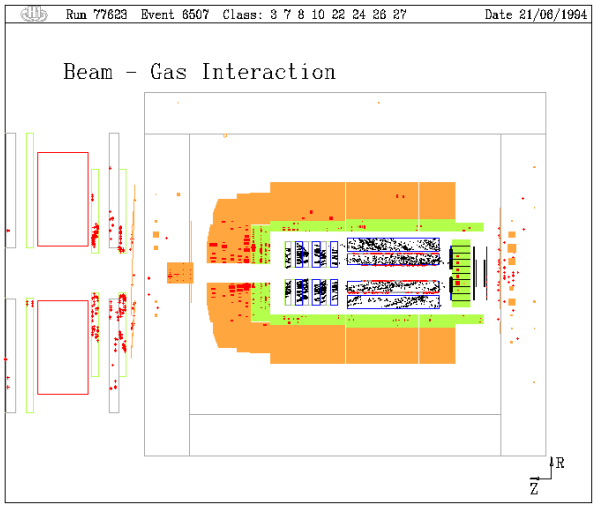
some kHz

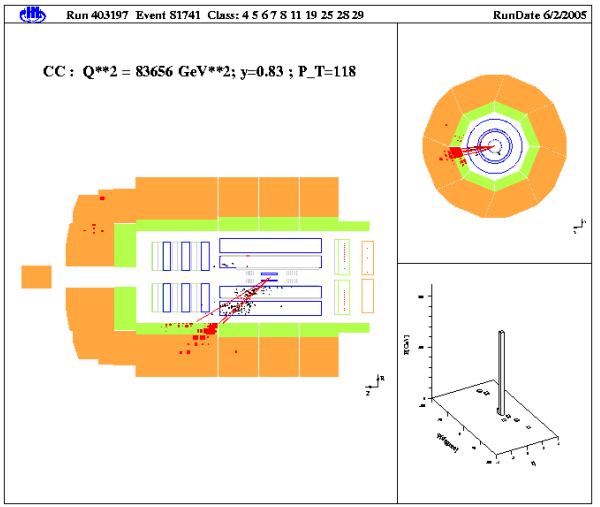
some Hz

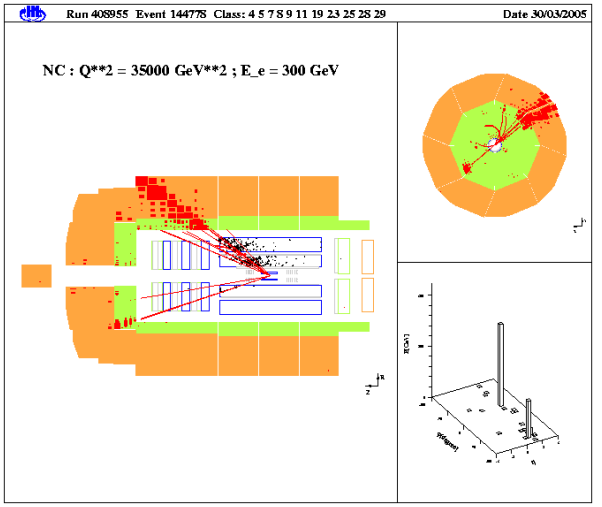
some min^{-1}

some $hour^{-1}$





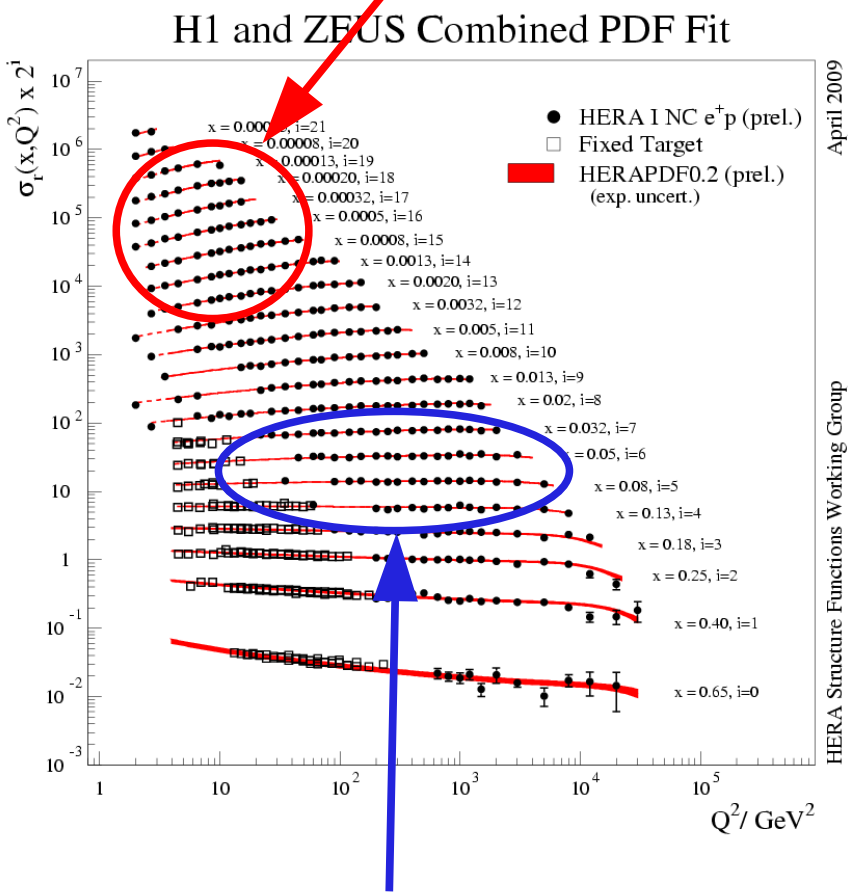




ep Scattering & Structure Functions

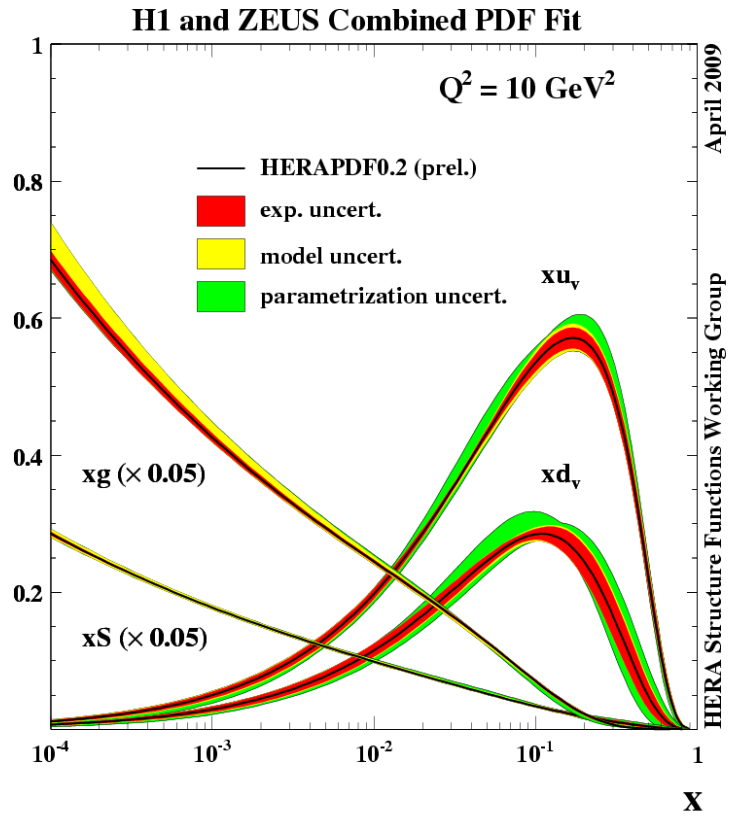
„The“ HERA Textbook Plots

gluons ?



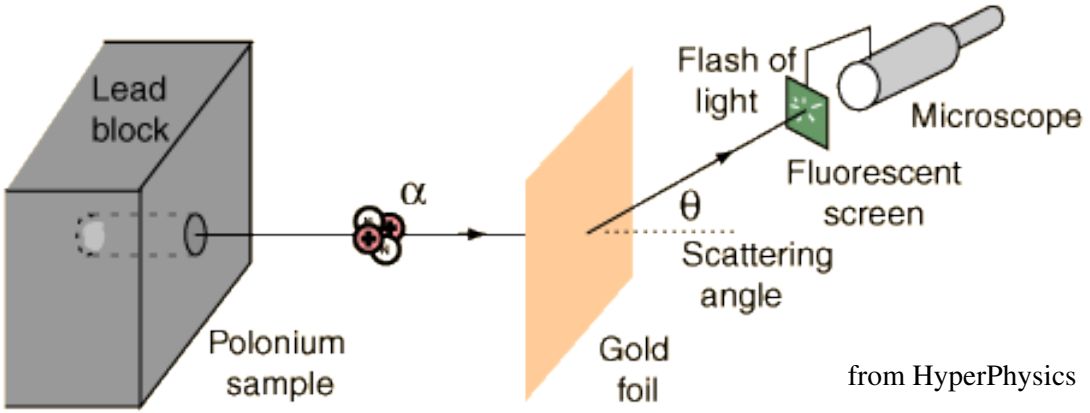
quarks ?

?



Rutherford Scattering

- first scattering experiment
- ➔ existence of the nucleus



$$\frac{d\sigma}{d\Omega} = \left(\frac{1}{4\pi\epsilon_0} \frac{Z_1 Z_2 e^2}{4 E_{kin}} \right)^2 \frac{1}{\sin^4 \frac{\Theta}{2}}$$

assumes

- Coulomb potential
- no spins
- no recoil

Elastic Electron Scattering

variables:

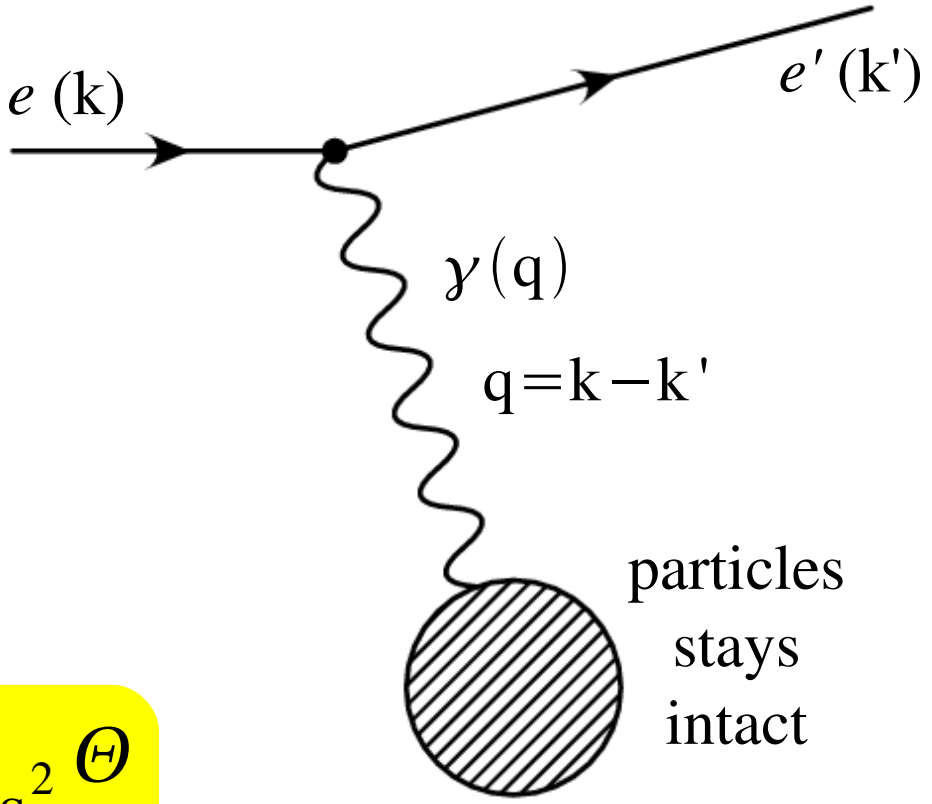
- $q = k - k'$
- $Q^2 = -q^2$
  $= 4\,E\,E'\sin^2(\Theta/2)$
- $E' = \dfrac{E}{1+(2E/M)\sin^2(\Theta/2)}$

➔ only one independent!

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

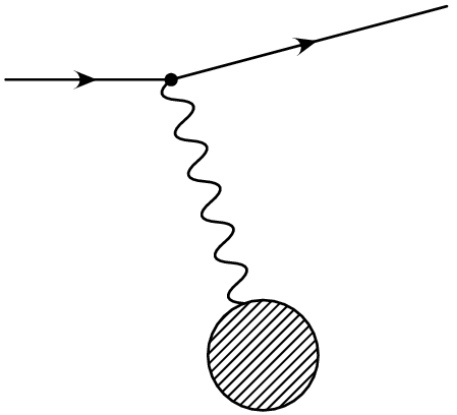
Coulomb-Potential ~1/r

recoil



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

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

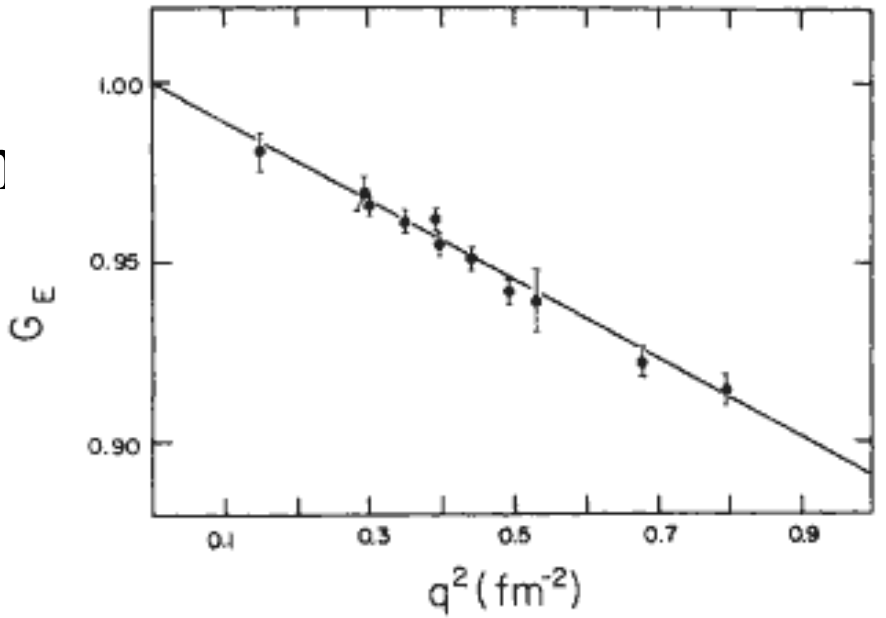
- electron on proton: „form factors“ needed:

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

  → protons are not pointlike!

Electric Form Factor of the Proton

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



fromJ.J. Murphy et al., „Proton form factor from 0.15 to 0.79 fm^{-2}

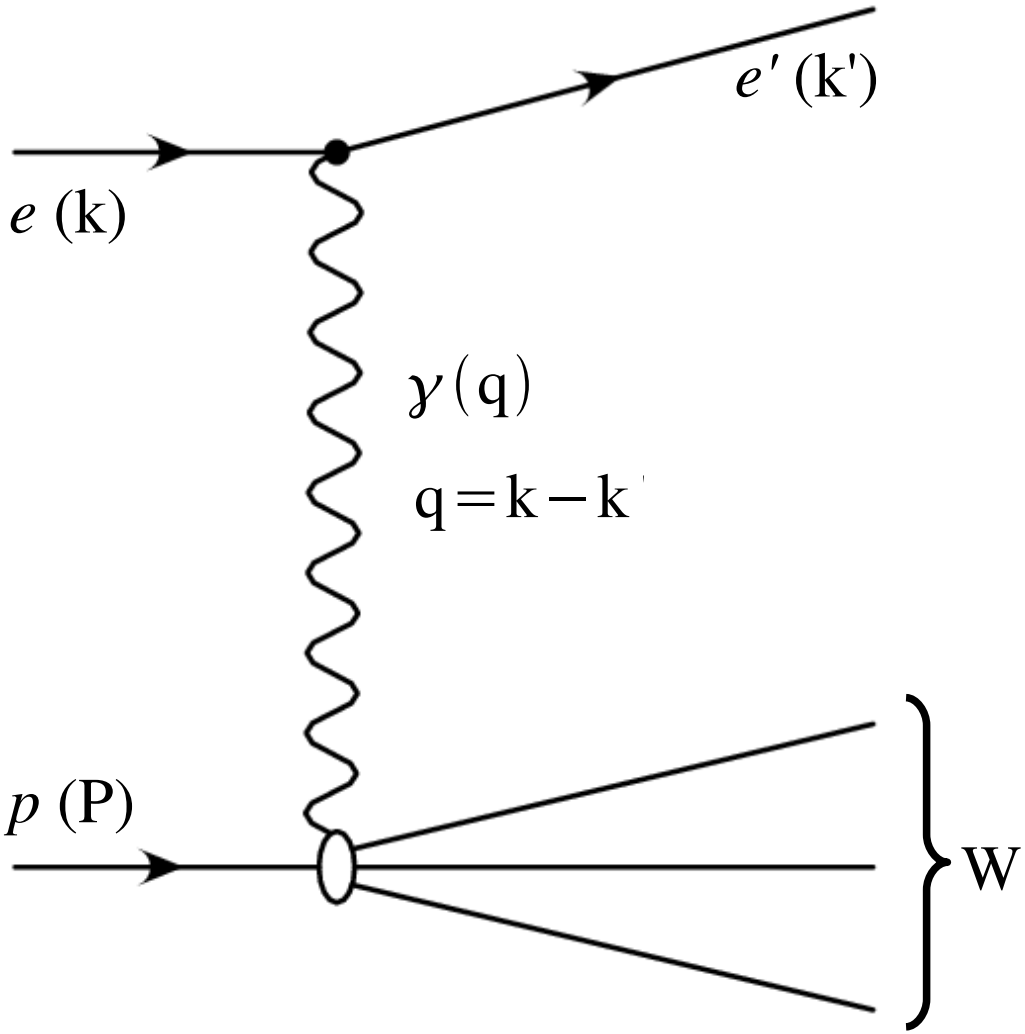
➔ elastic scattering only import at low Q^2

Inelastic Electron Scattering

variables:

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

➔ two independent!



elastic: W = M

inelastic: W > M

Inelastic Electron Proton Scattering

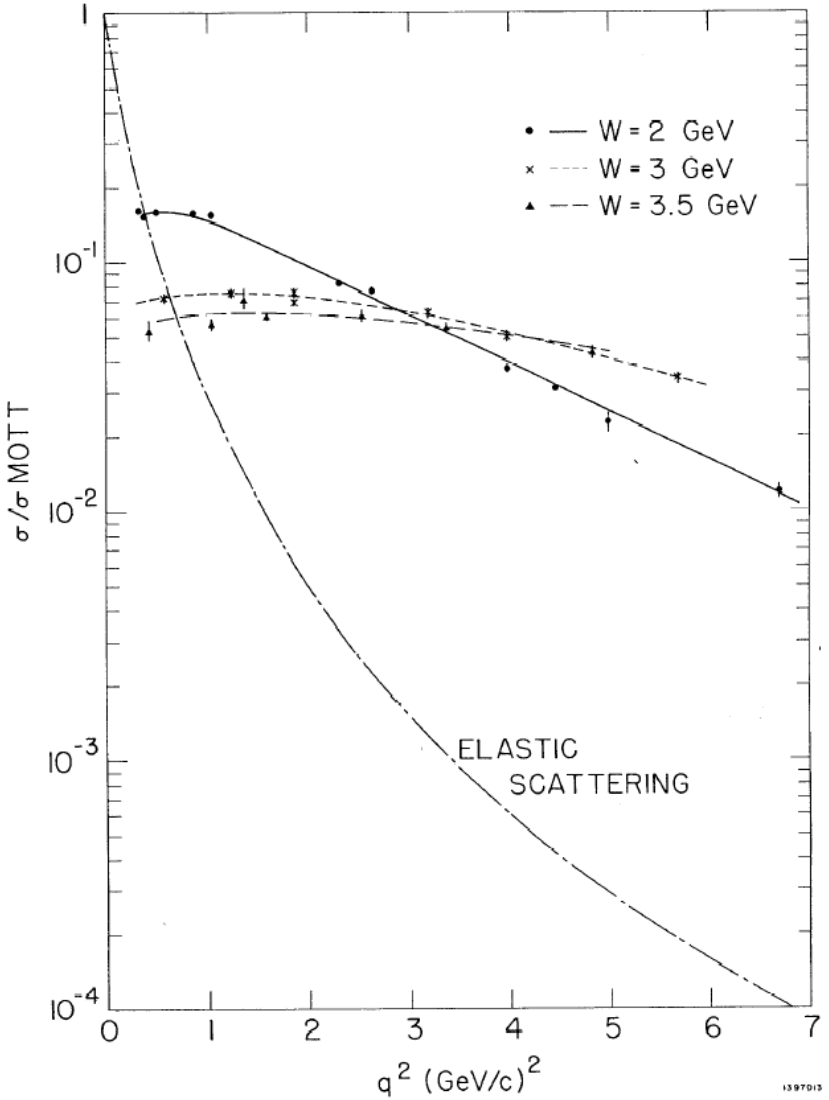
- inelastic scattering: $W > M_p$
- ratio to Mott cross section nearly flat in Q^2

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

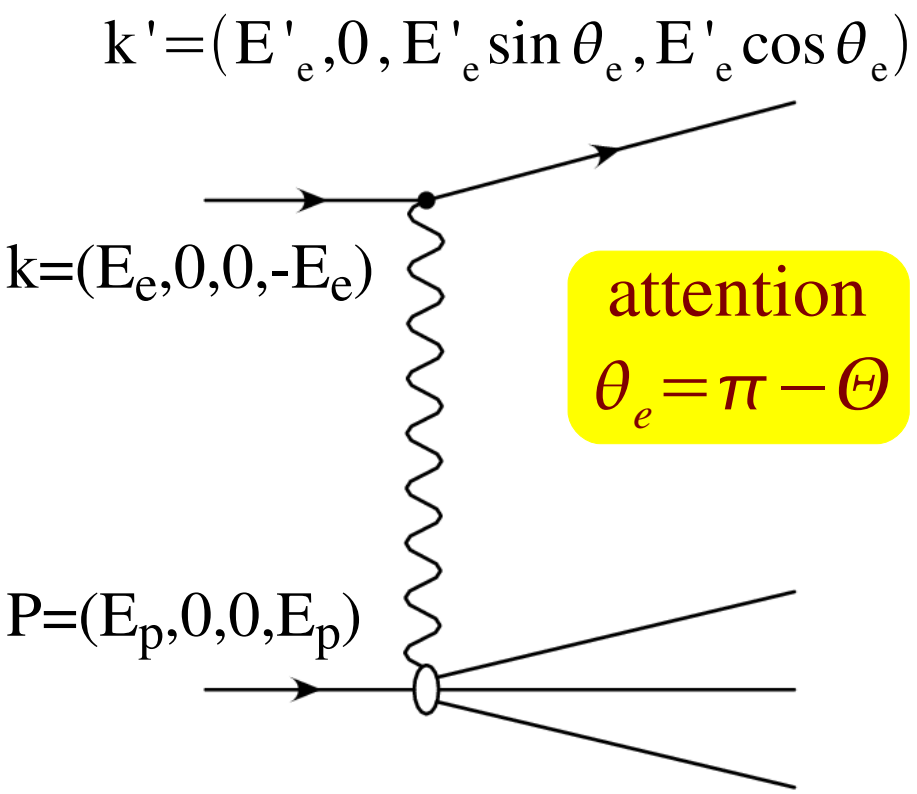


Deep Inelastic Scattering (DIS)

- deep: $Q^2 > (M_p)^2$
- inelastic: $W > M_p$
- for HERA: $m_e, M_p \ll W$

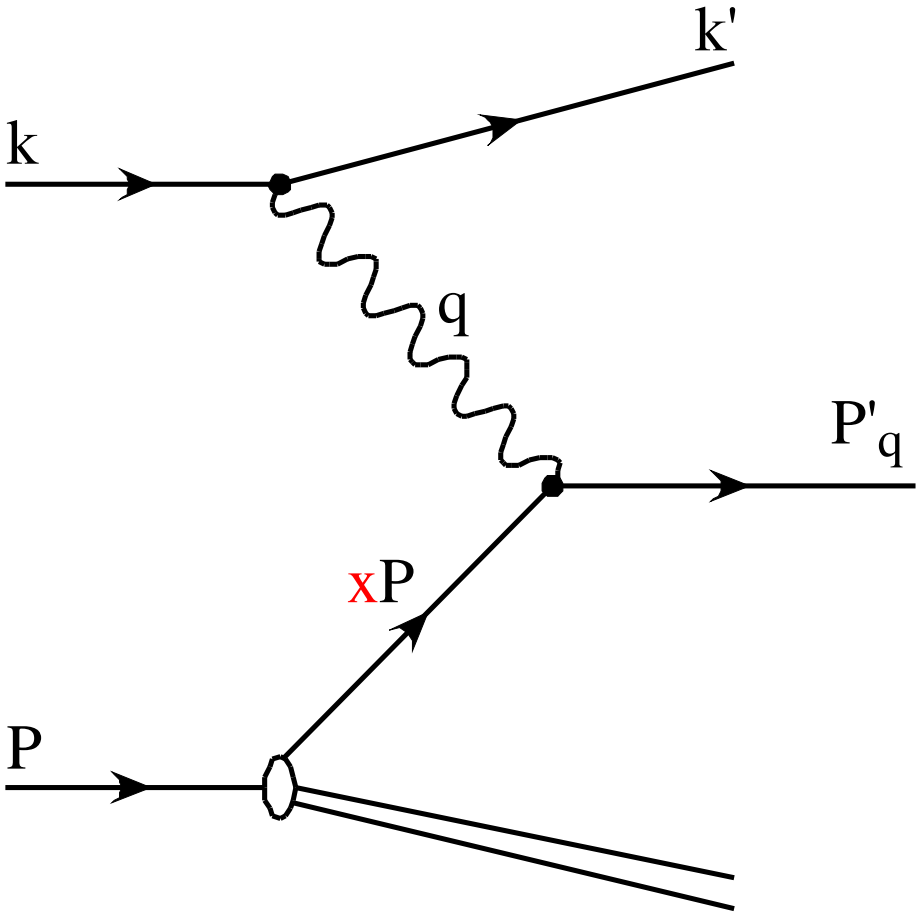
  → neglect m_e, M_p

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



- 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:

$$P'_q = q + xP$$

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

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

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

inelastic proton scattering is scattering on a parton of the proton!

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

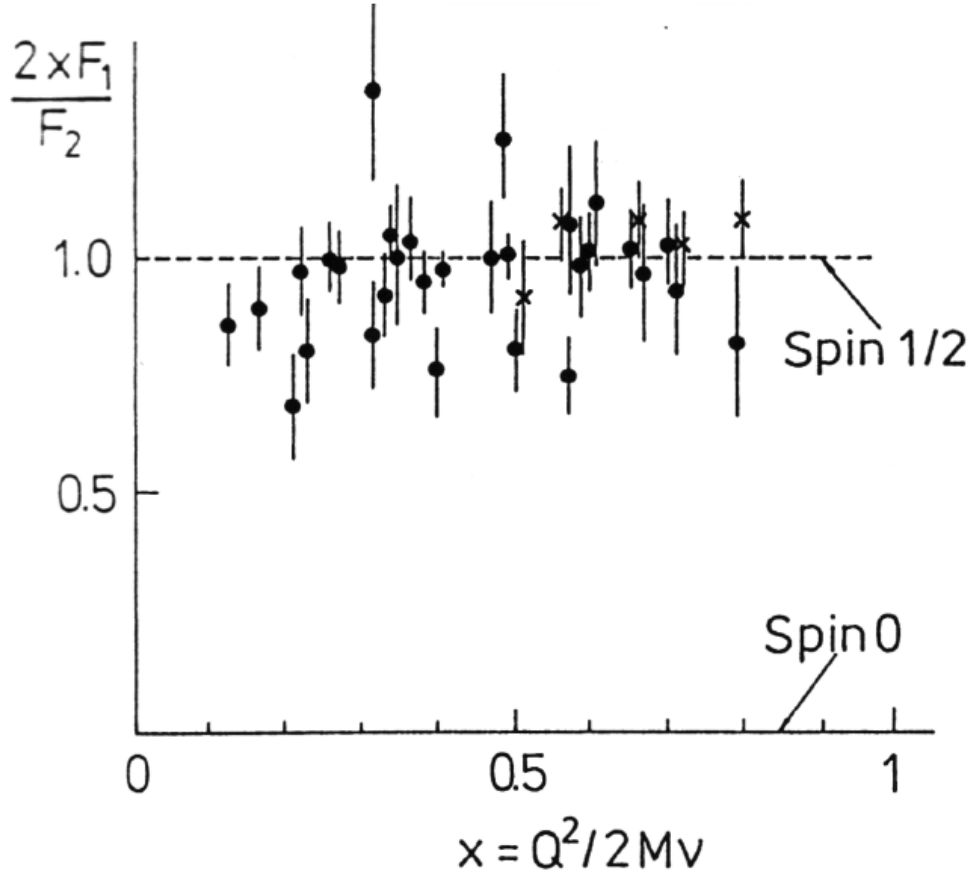
$$\left(\frac{d\sigma}{dQ^2}\right)_{\text{Dirac}} = \frac{4\pi\alpha^2 z^2}{Q^4}\left(\frac{E'}{E}\right)^2\left[\cos^2\frac{\Theta}{2} + \frac{Q^2}{2M^2}\sin^2\frac{\Theta}{2}\right]$$

➔ 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: $2 \times F_1 = 0$

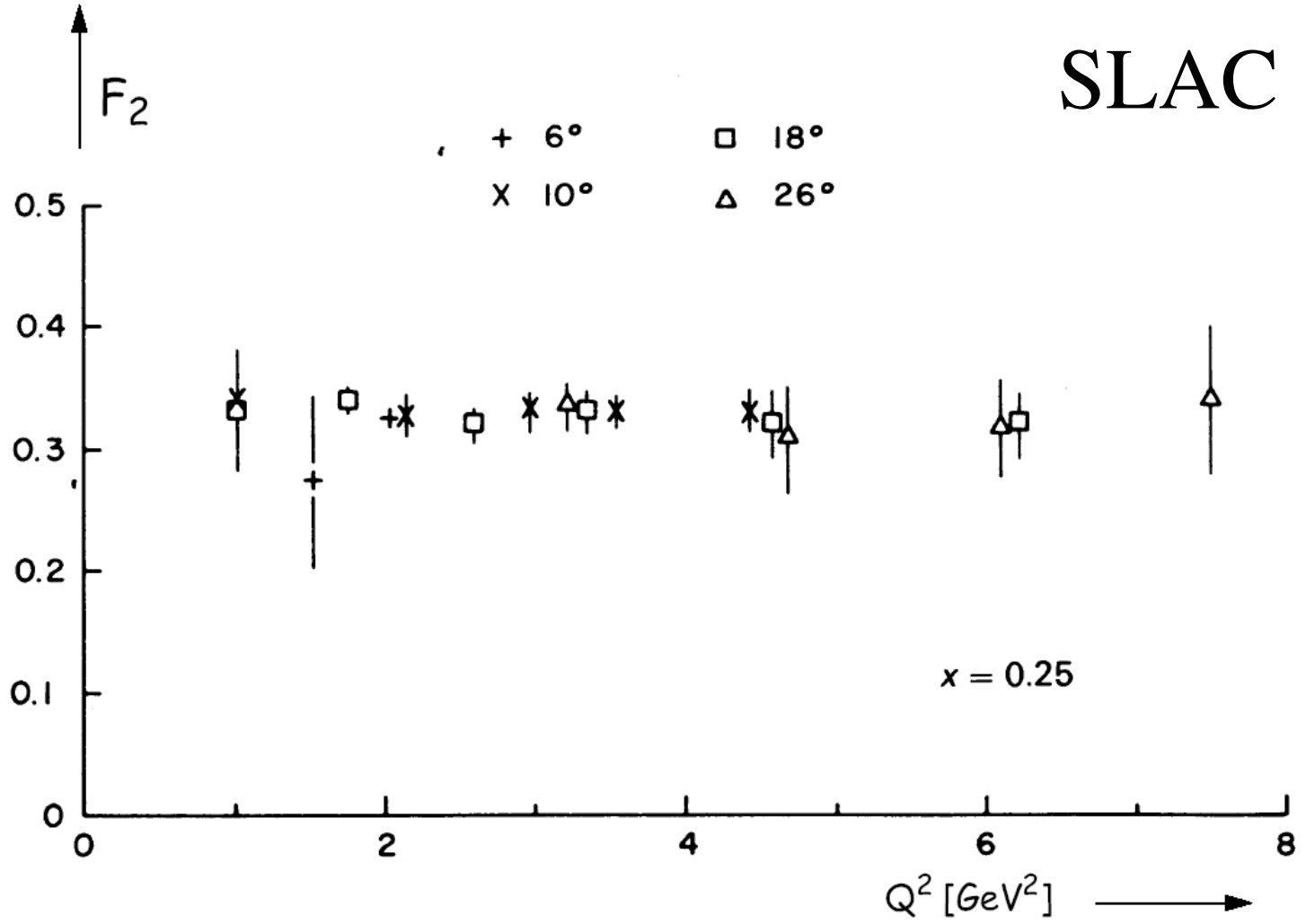


from P. Schmüser, „Feynman-Graphen und Eichtheorien für Experimentalphysiker“

partons
have spin ½

Scaling: F_2 independent of Q^2

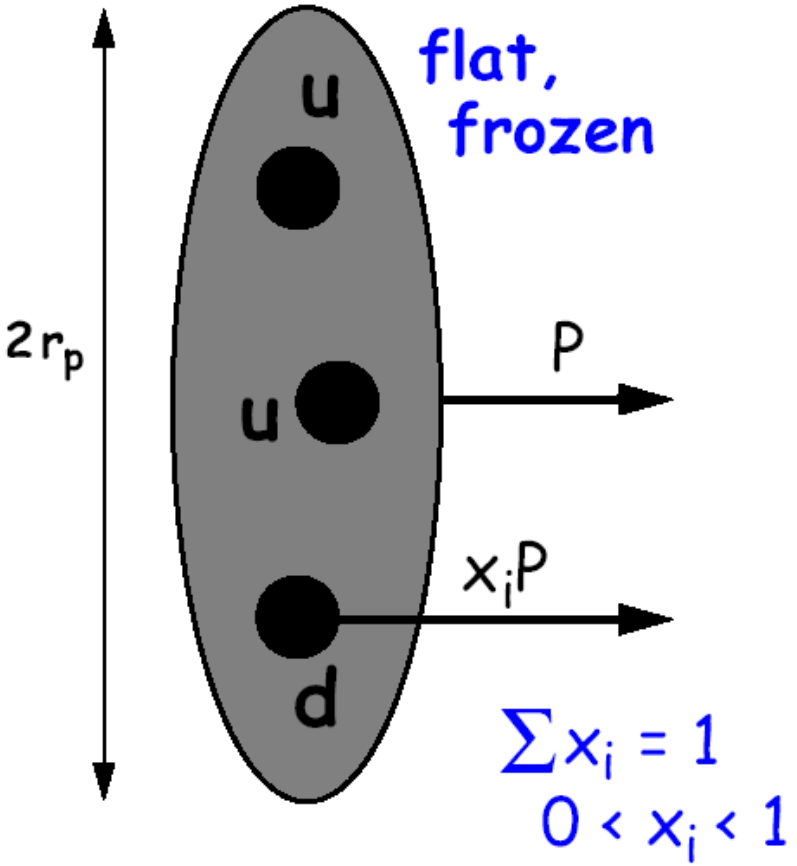
SLAC 1972



independent of Q^2, we always see the same partons (=quarks)

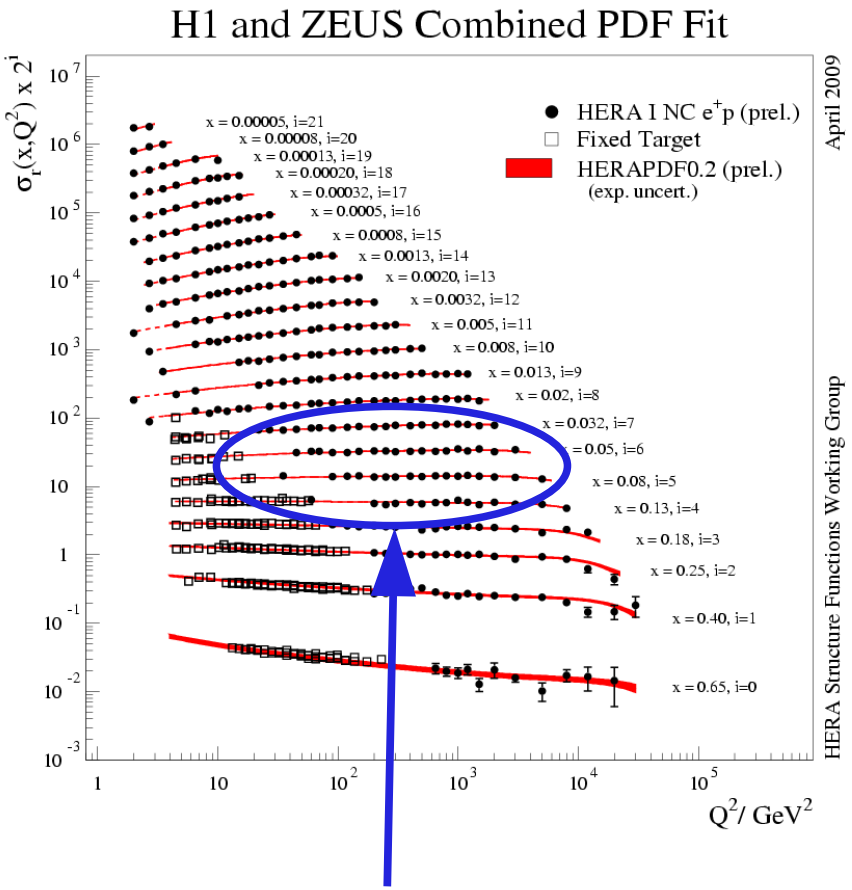
(Naive) Quark Parton Model

- 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



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

„The“ HERA Textbook Plots



quarks ✓