Physics at HERA

Summer Student Lectures
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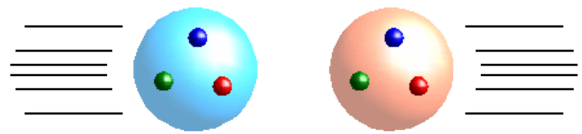
Overview

- 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

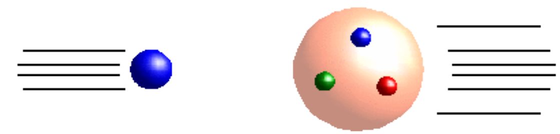
e^+e^-

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



$p^\pm p^\pm$

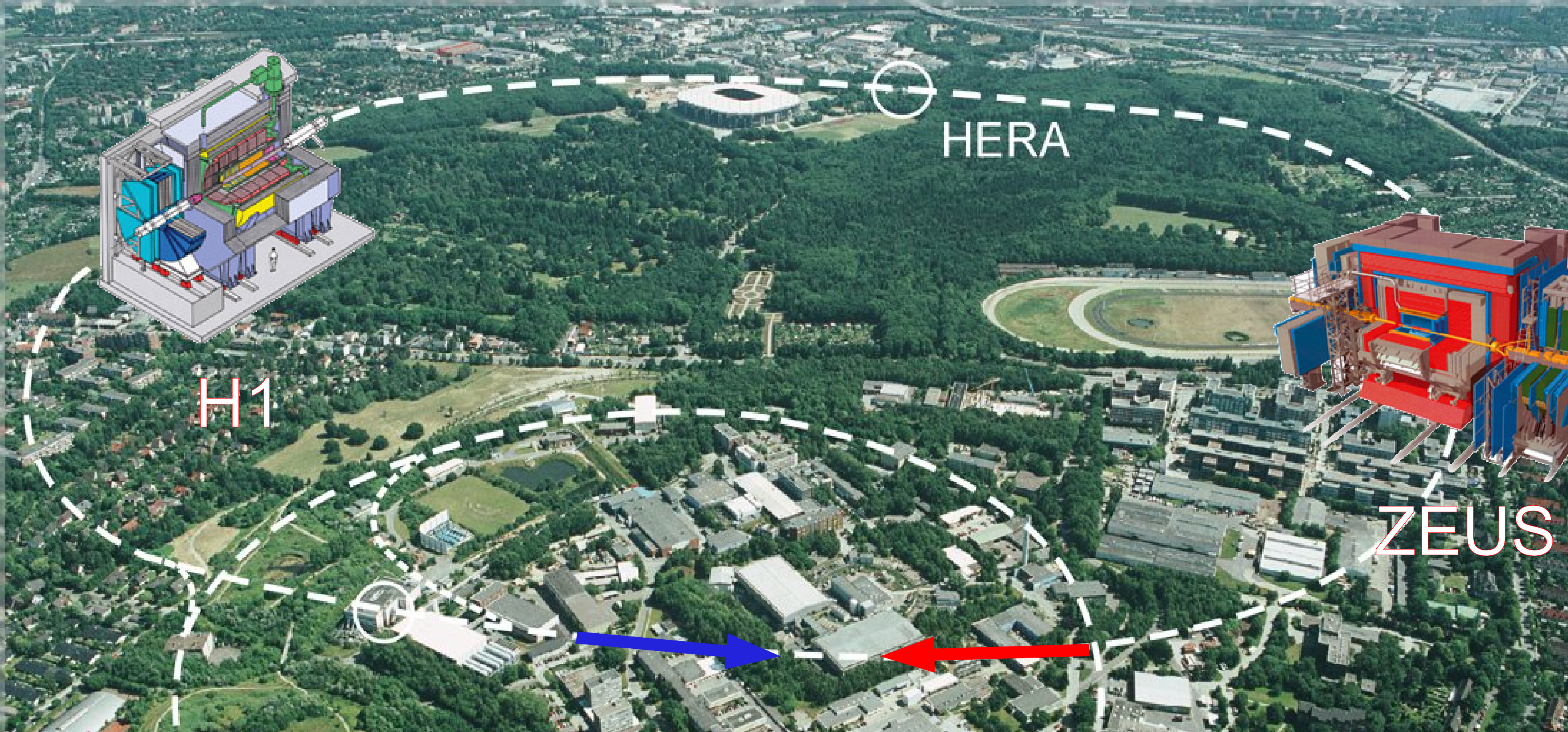
+ high energy
– complicated final state
– large background
• Tevatron (2 TeV)
  LHC (14 TeV)



ep

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

HERA

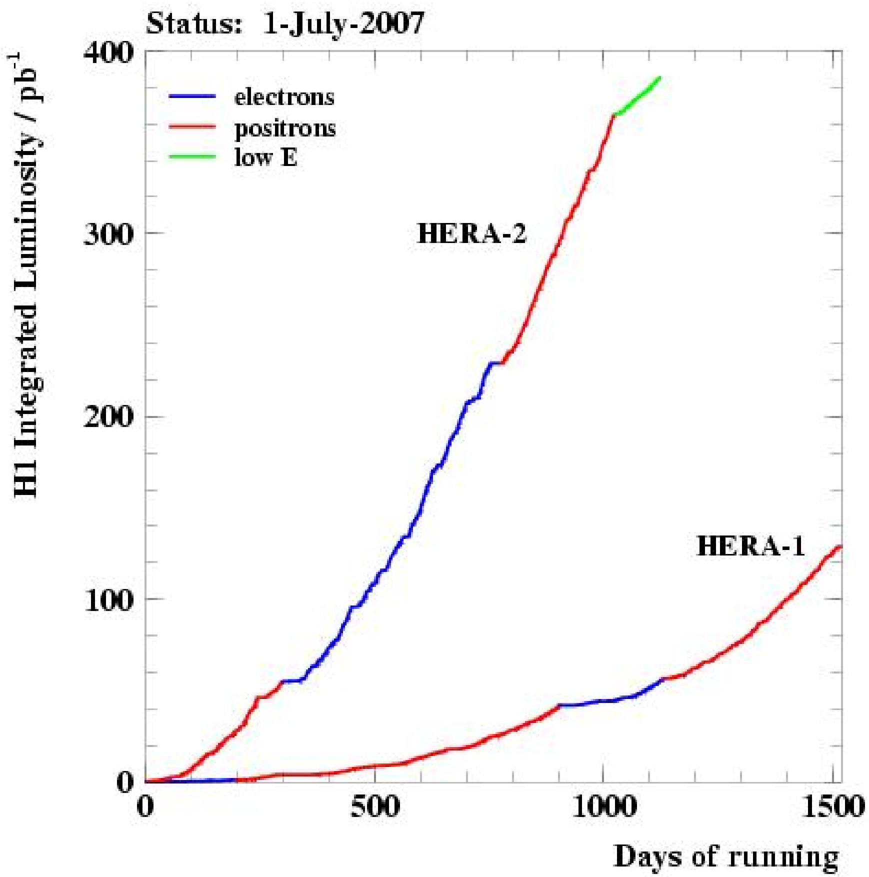


p
920 GeV

e
27.6 GeV

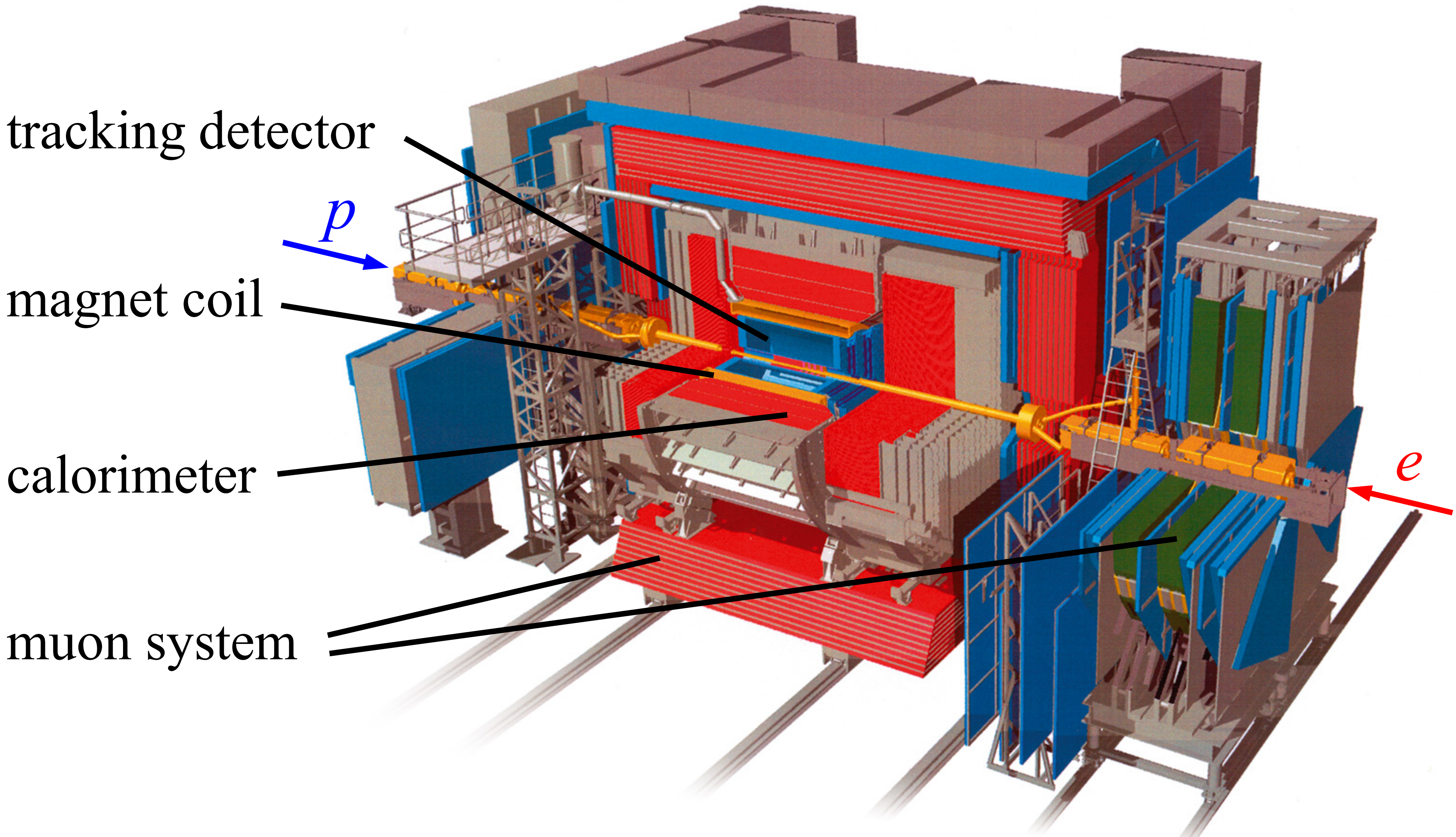
PETRA

Collected Luminosity

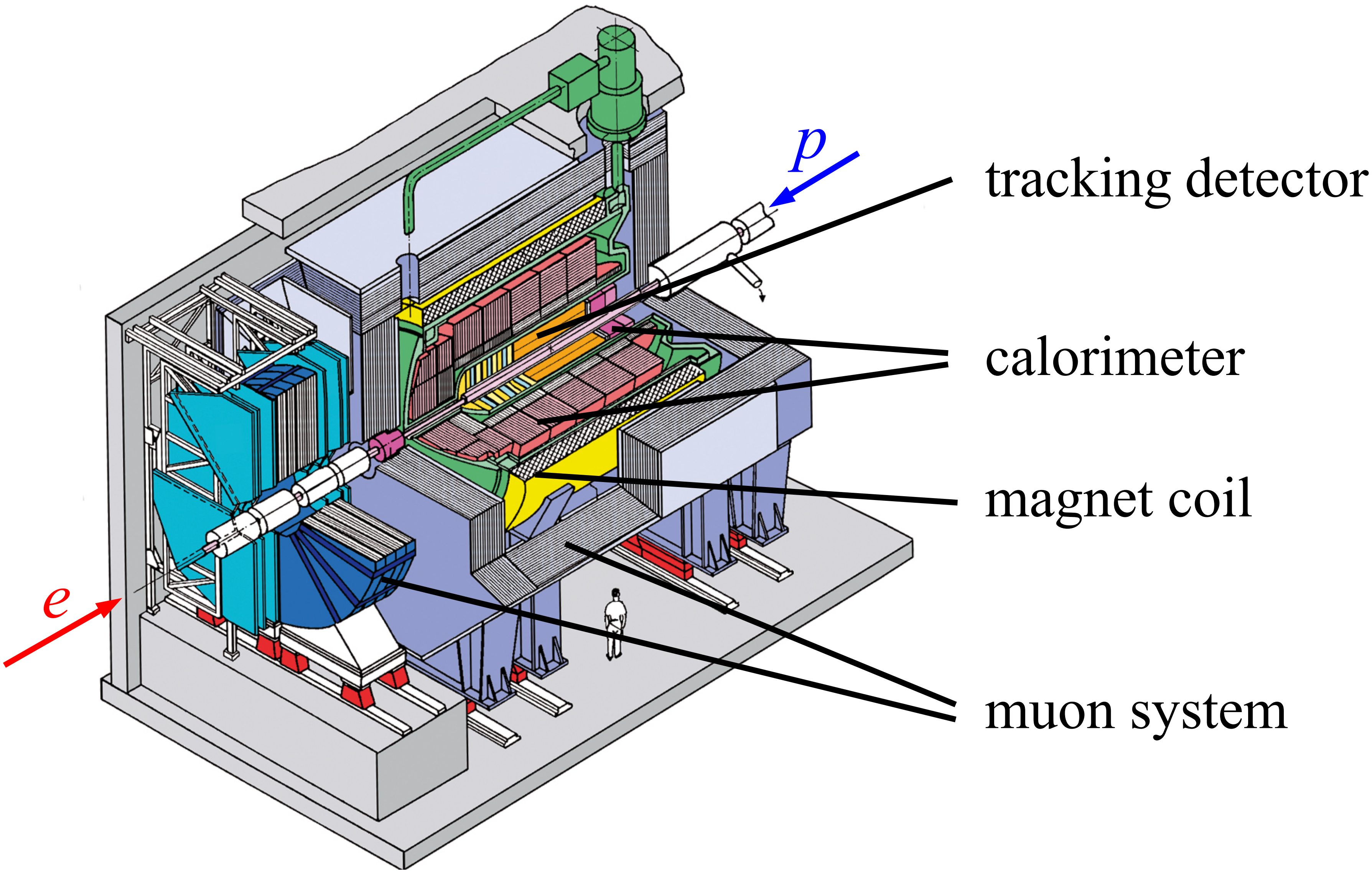


- HERA operated 1992-2007
- lumi upgrade in 2001
  - higher luminosity
  - *e* polarization for H1 & ZEUS
  - detector upgrades
- in total ~500 pb^{-1} of high energy data collected per experiment
- last months devoted to low *p* energy (460, 575 GeV)

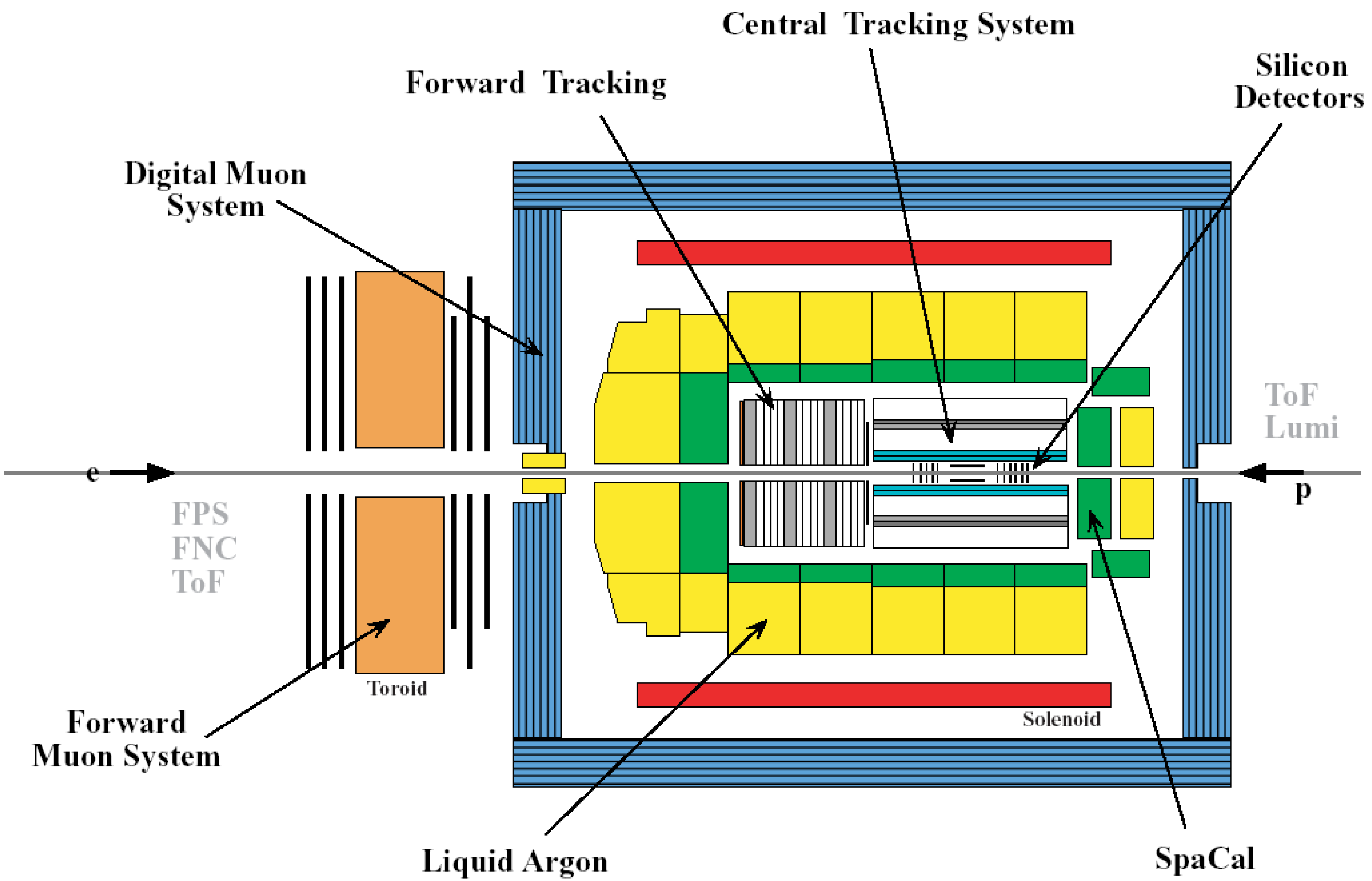
ZEUS Detector



H1 Detector



Schematic View of the H1 Detector



Physics Topics at HERA

expected

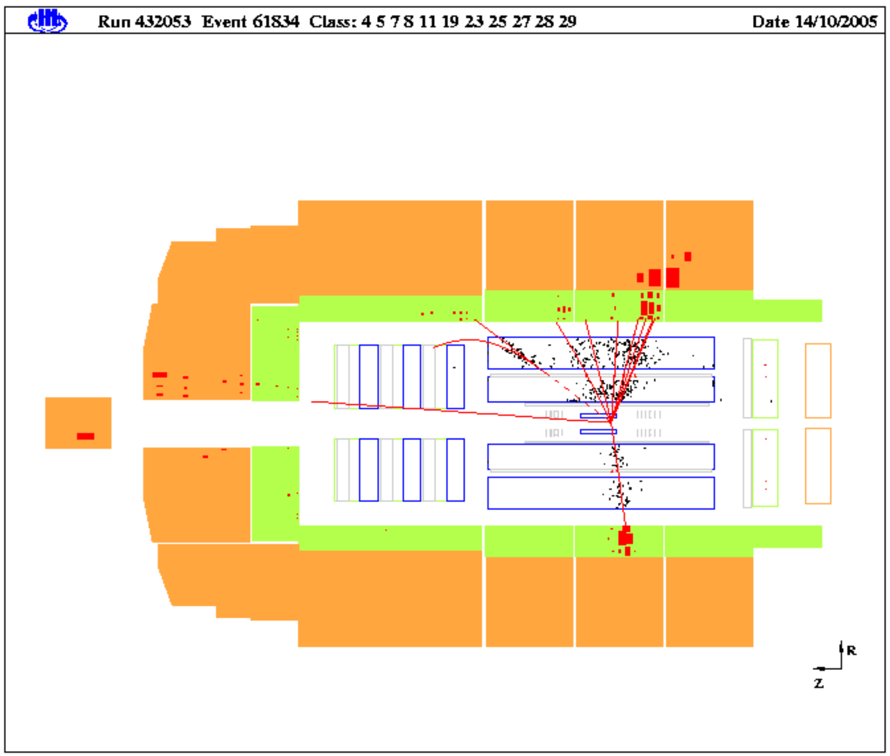
- proton structure
  - structure functions
  - parton densities
- photon structure
- perturbative QCD
  - jets
  - α_s
  - heavy quarks
- electroweak

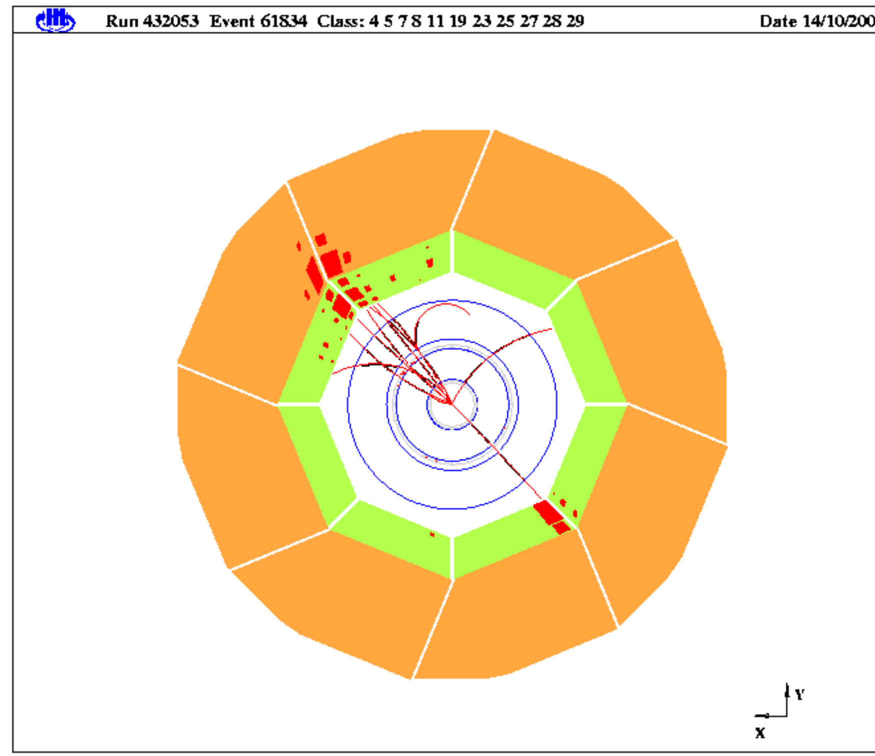
not (so) expected

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

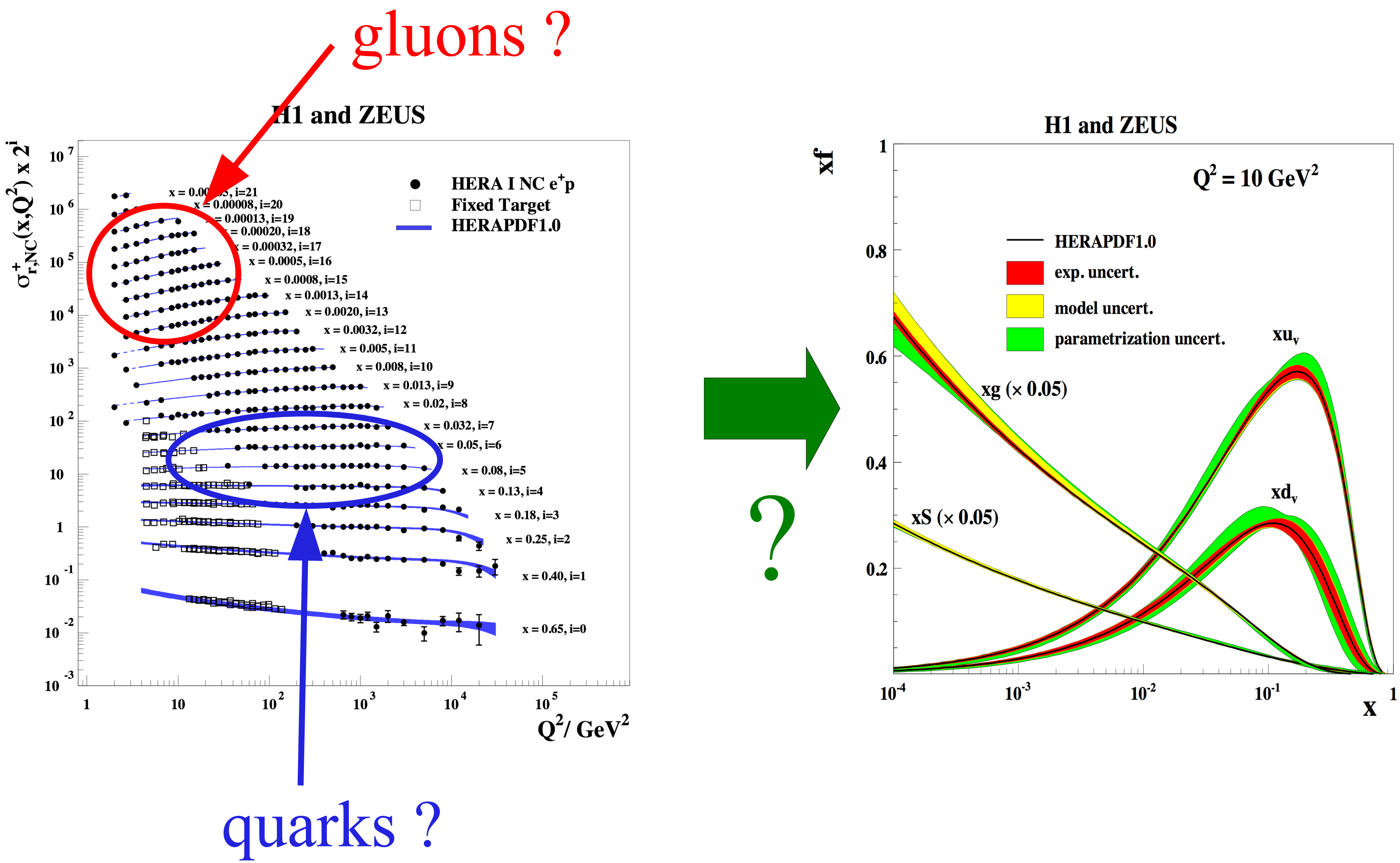
ep Scattering & Structure Functions

An *ep* scattering event





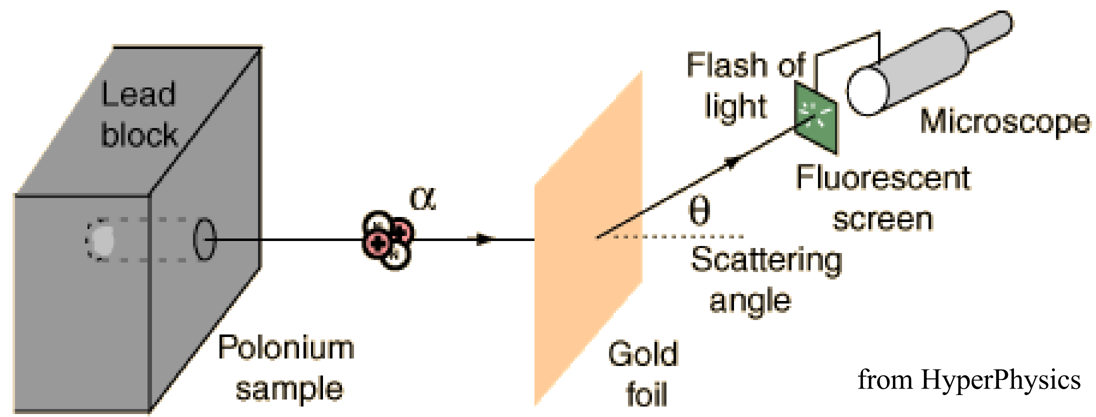
„The“ HERA Textbook Plots



Rutherford Scattering

- first scattering experiment

➔ existence of the nucleus



from HyperPhysics

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

assumes

- Coulomb potential
- no spins
- no recoil

Elastic Electron Scattering

variables:

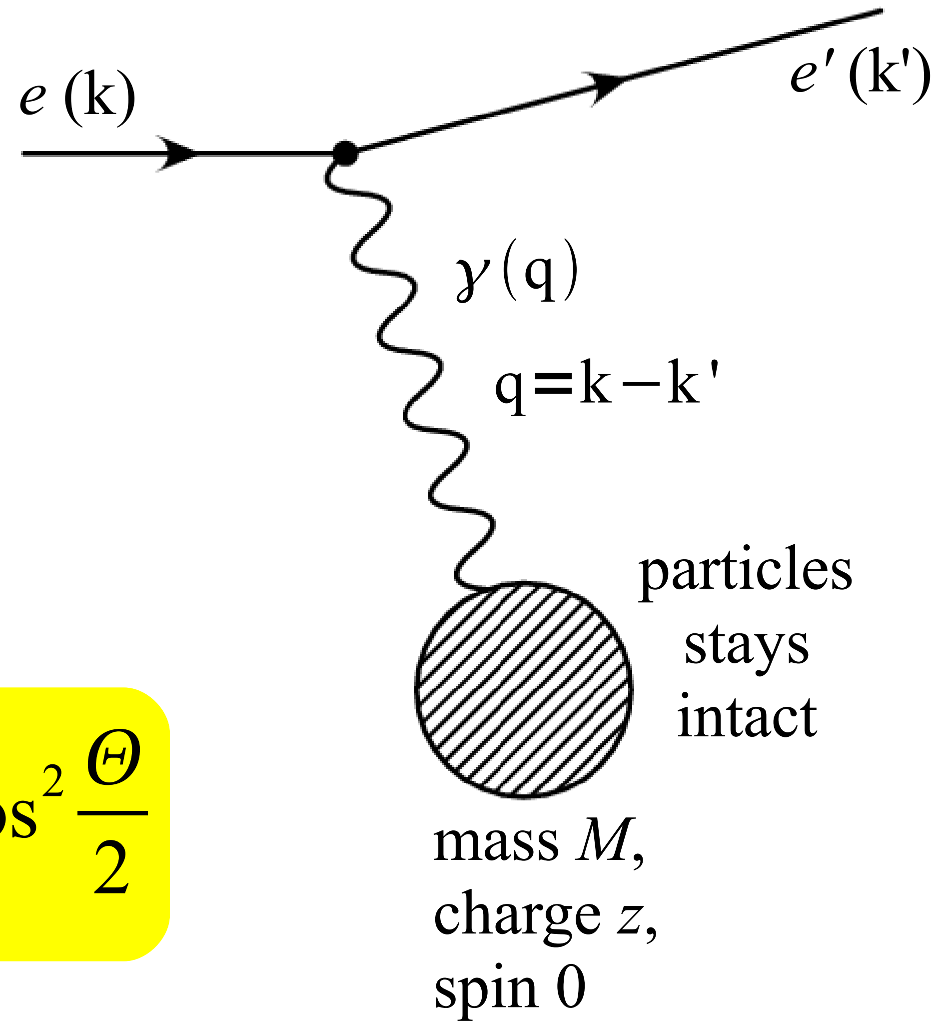
- $q = k - k'$
- $Q^2 = -q^2$
  $= 4\,E\,E'\sin^2(\Theta/2)$
- $E' = \dfrac{E}{1+(2E/M)\sin^2(\Theta/2)}$

➔ only one independent!

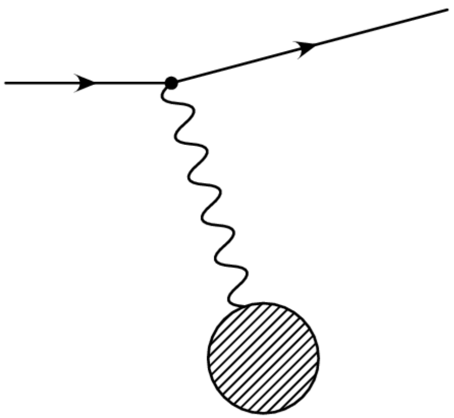
$$\frac{d\sigma}{dQ^2} = \frac{4\pi\alpha^2 z^2}{Q^4}\left(\frac{E'}{E}\right)^2 \cos^2\frac{\Theta}{2}$$

Coulomb-Potential ~1/r

recoil



Elastic Electron Scattering: Cross Section



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

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

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

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

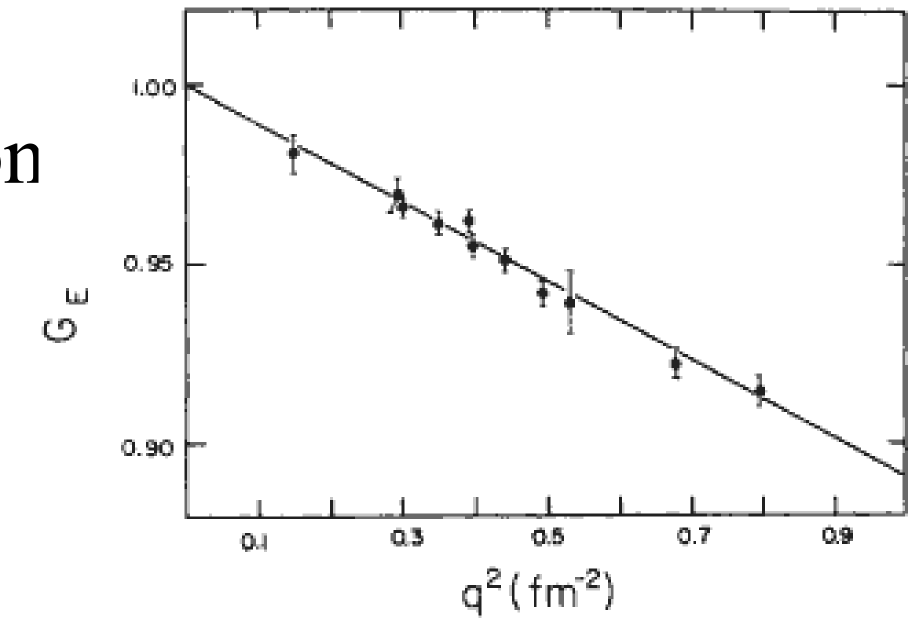
- electron on proton: „form factors" needed:

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

  ➔ 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 $^{-2}$

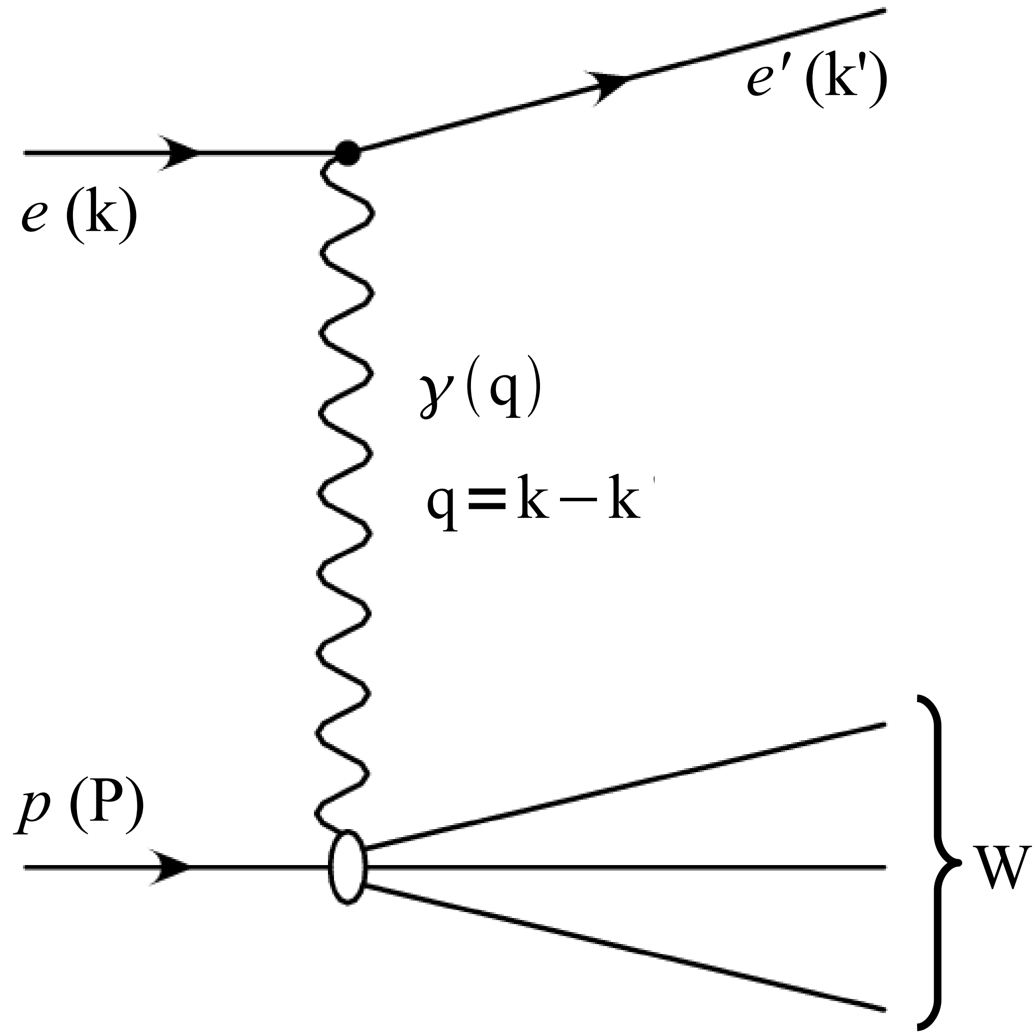
➔ elastic scattering only import at low Q^2

Inelastic Electron Scattering

variables:

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

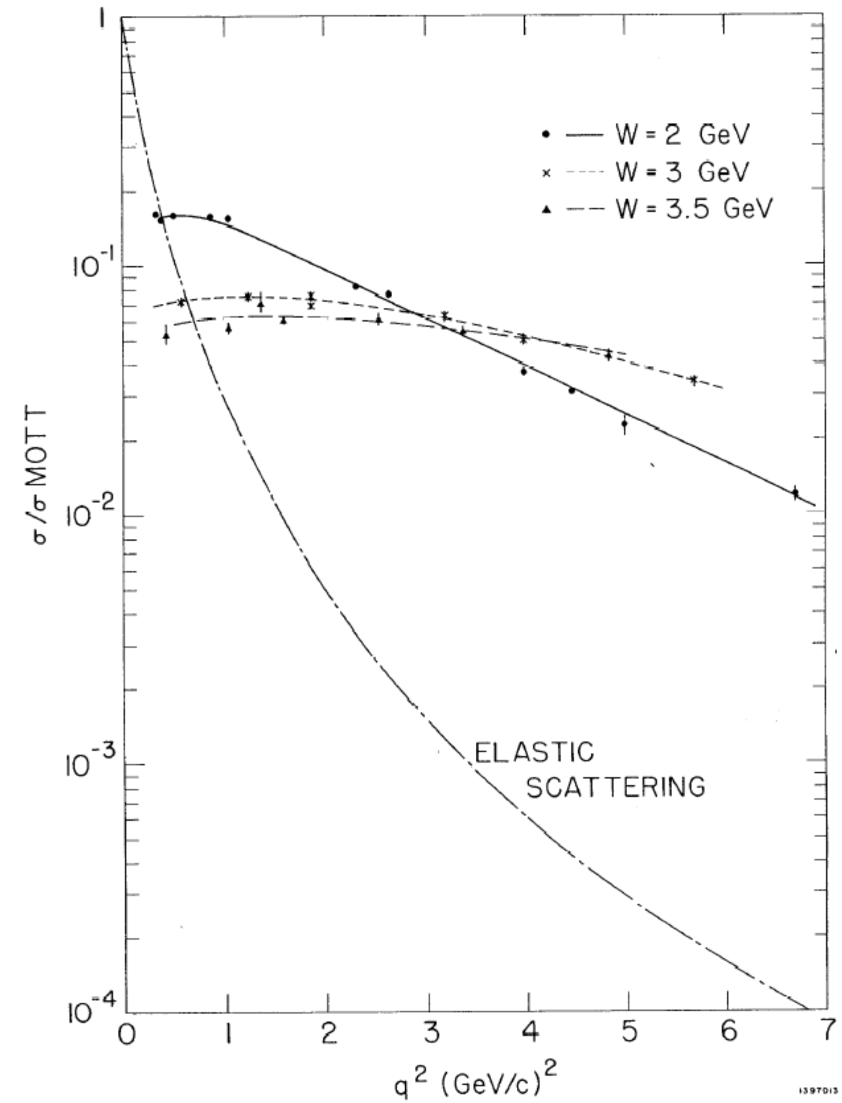
➔ two independent!



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

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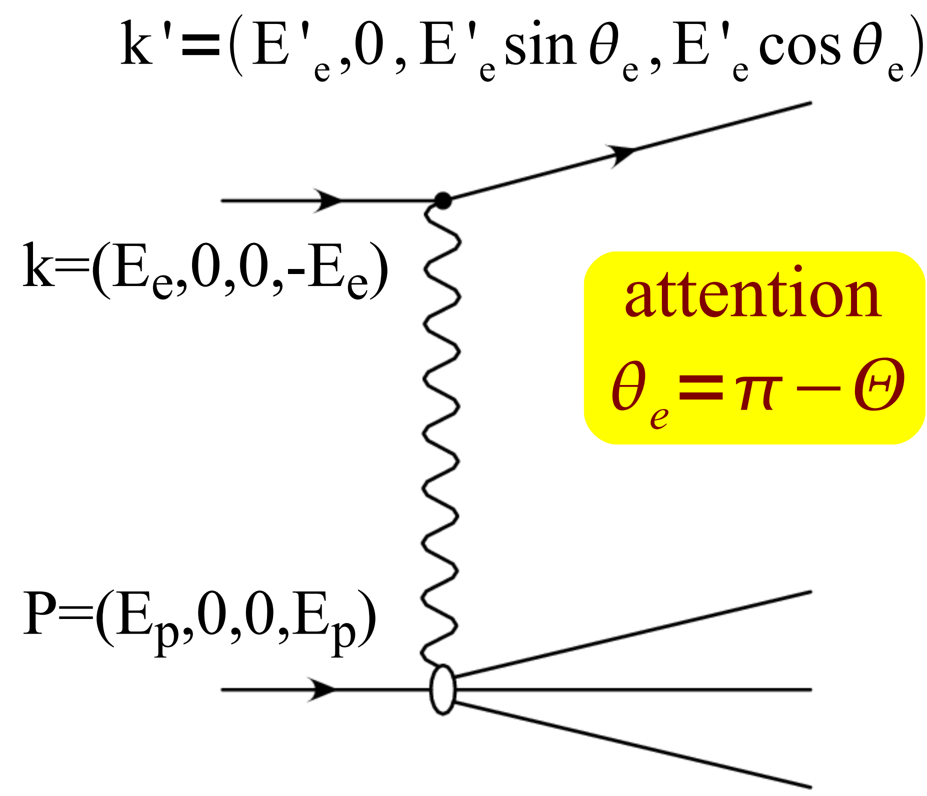
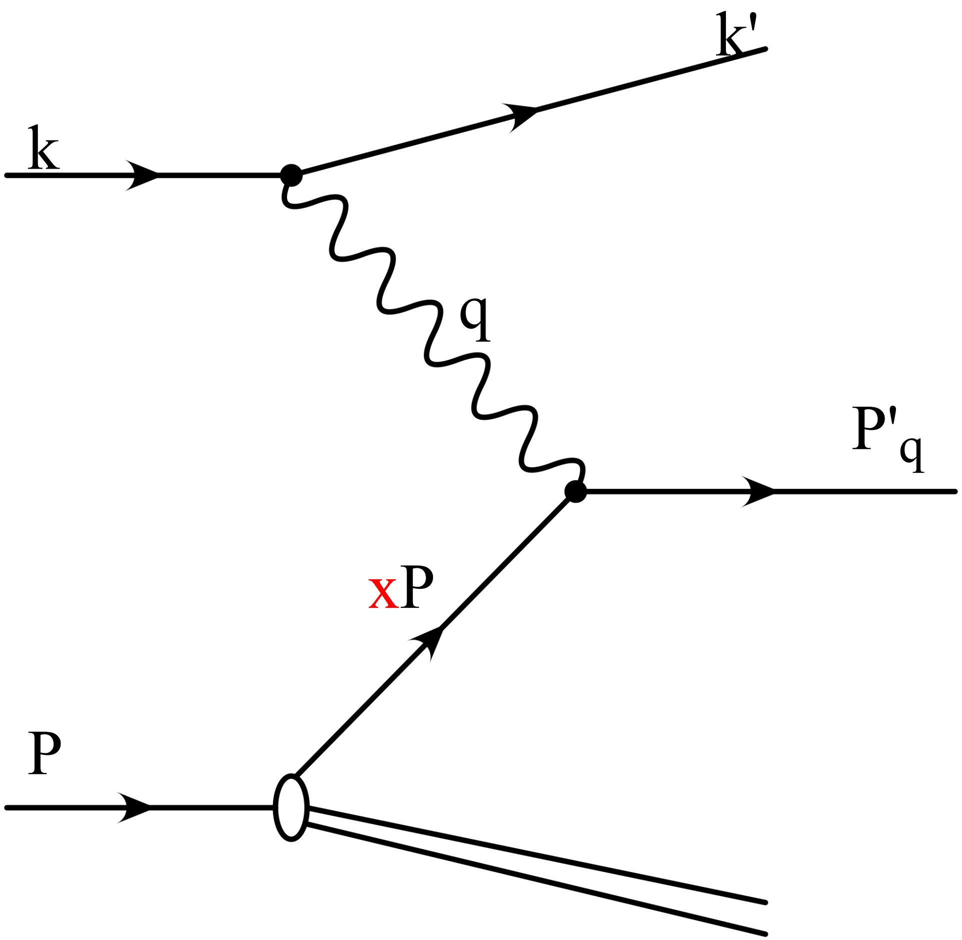
Deep Inelastic Scattering (DIS)

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



attention
$\theta_e = \pi - \Theta$

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

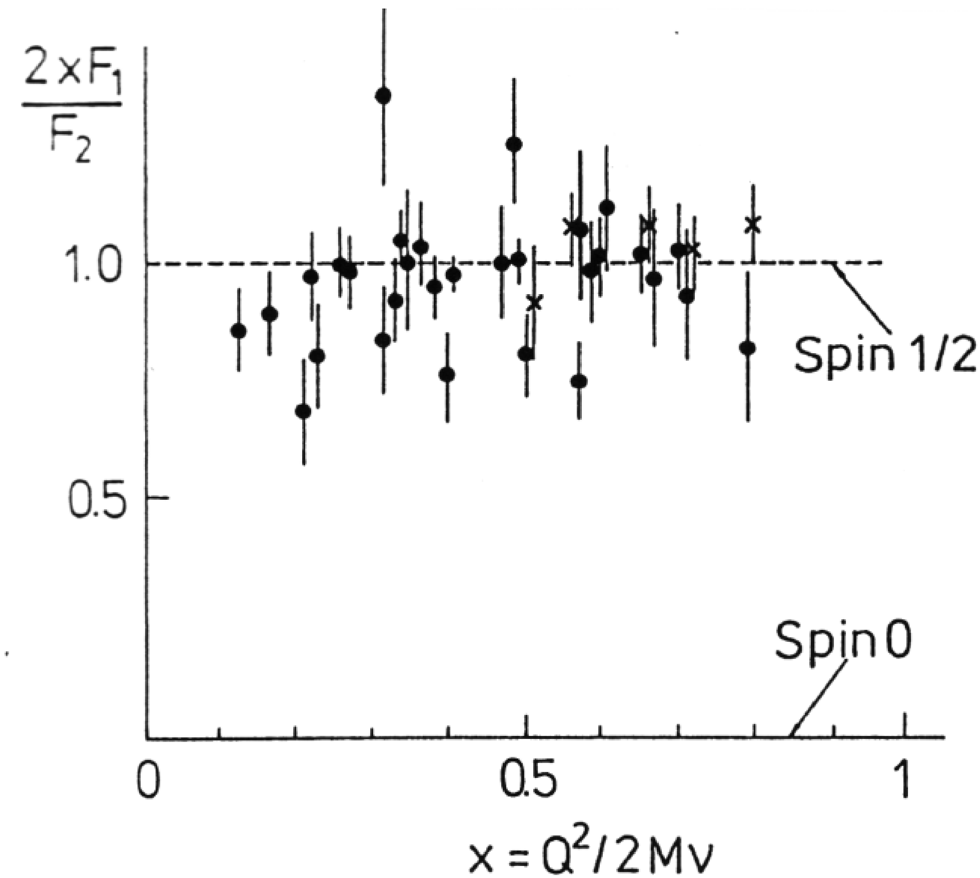
$$\left(\frac{d\sigma}{dQ^2}\right)_{\text{Dirac}}=\frac{4\pi\alpha^2}{Q^4}\left(\frac{E'}{E}\right)^2\left[\cos^2\frac{\Theta}{2}+\frac{Q^2}{2M^2}\sin^2\frac{\Theta}{2}\right]$$

➔ F_2 corresponds to electric field of the parton

➔ F_1 corresponds to spin of the parton

Parton Spin

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

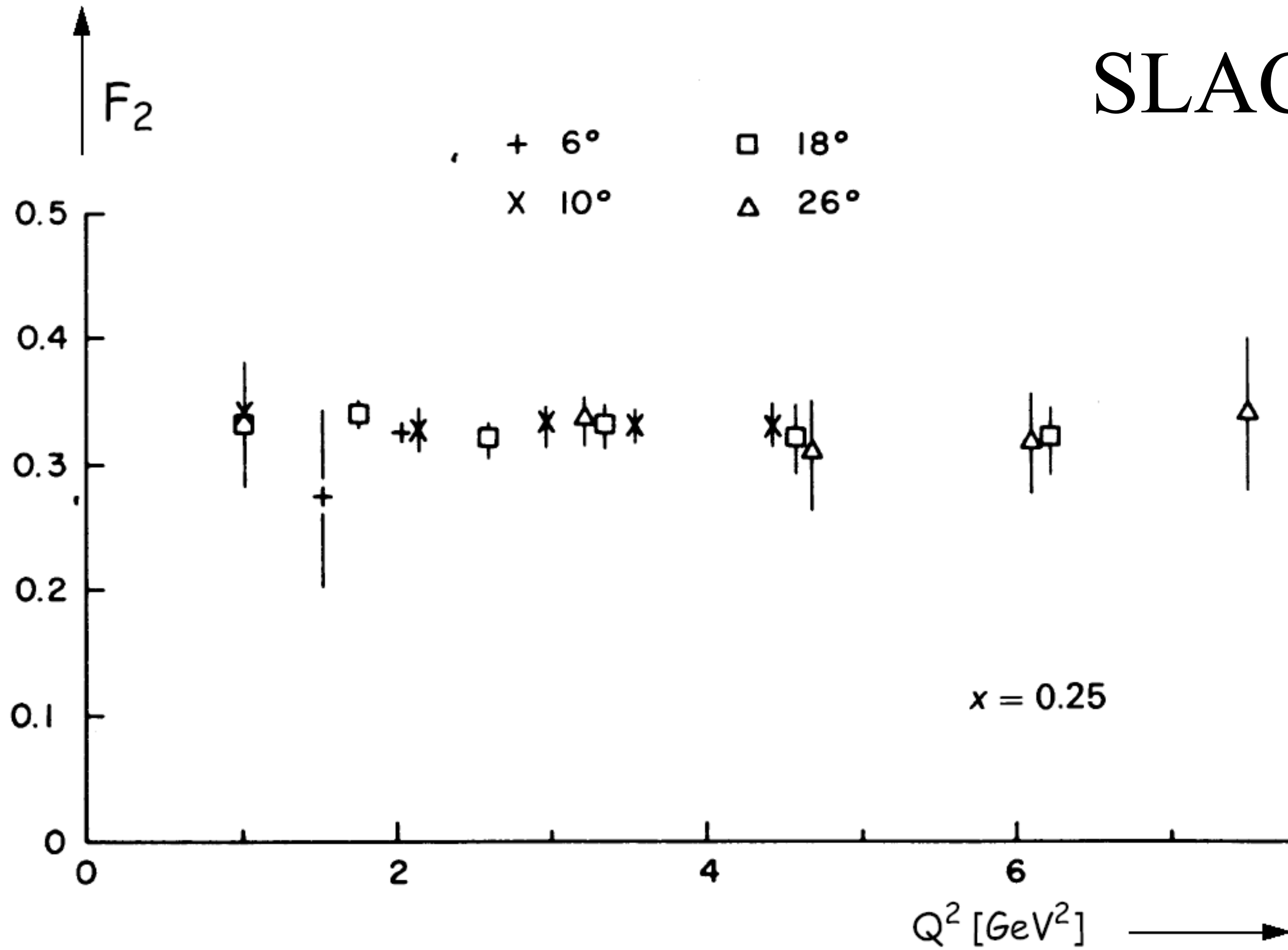


partons have spin ½

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

Scaling: F_2 independent of Q^2

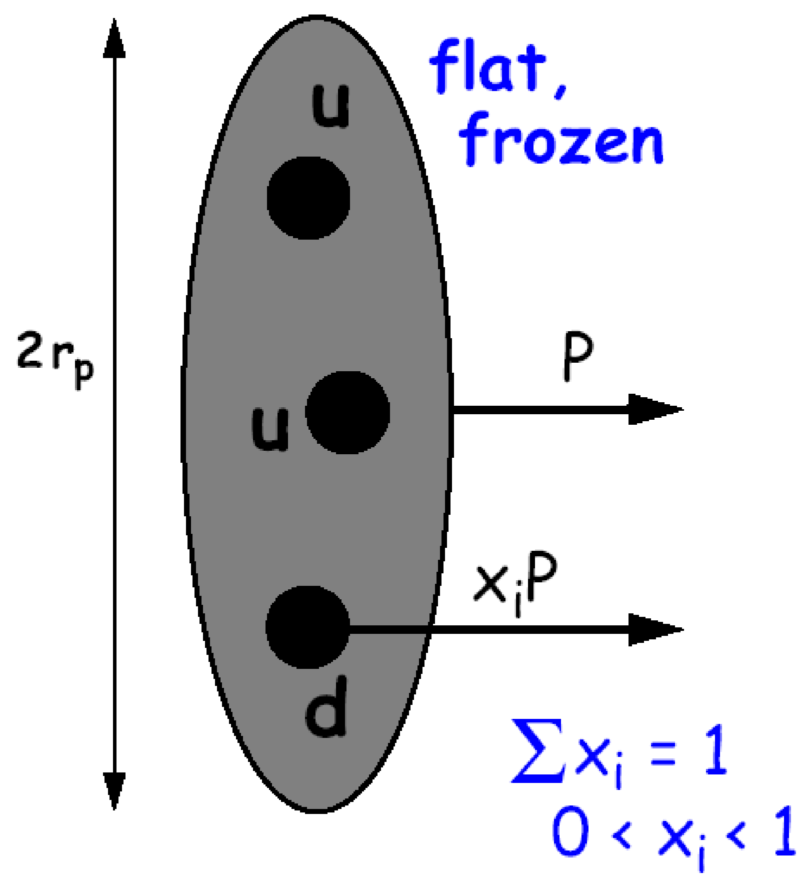
SLAC 1972



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

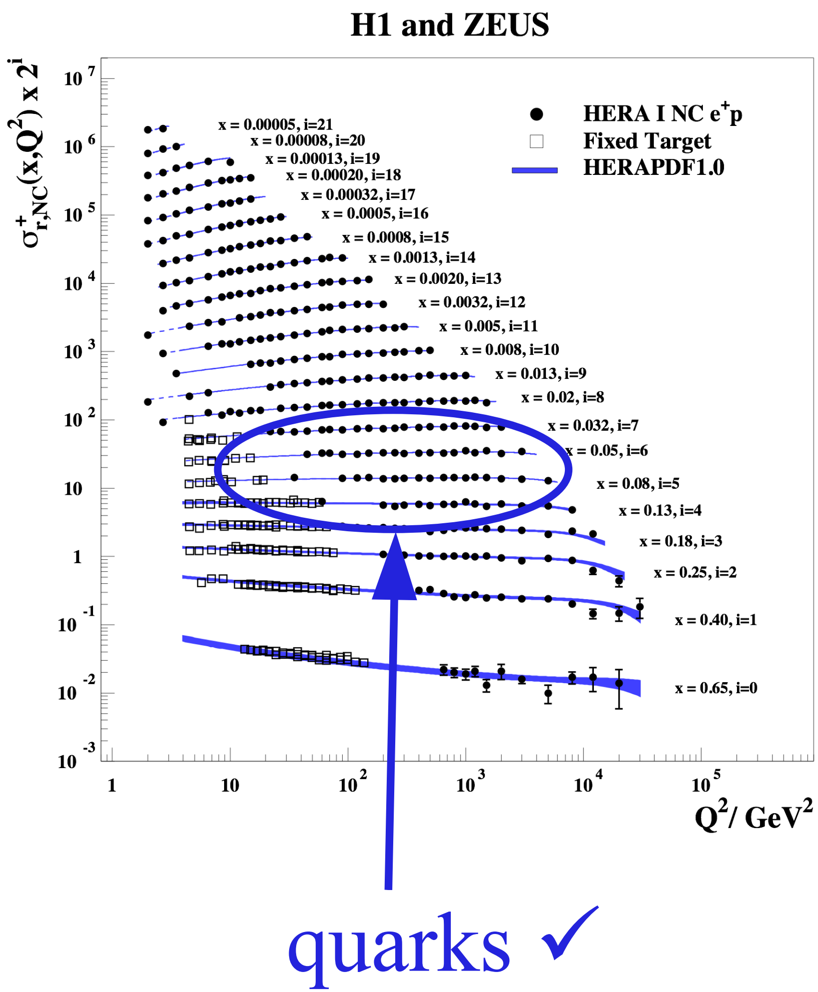
(Naive) Quark Parton Model

- 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



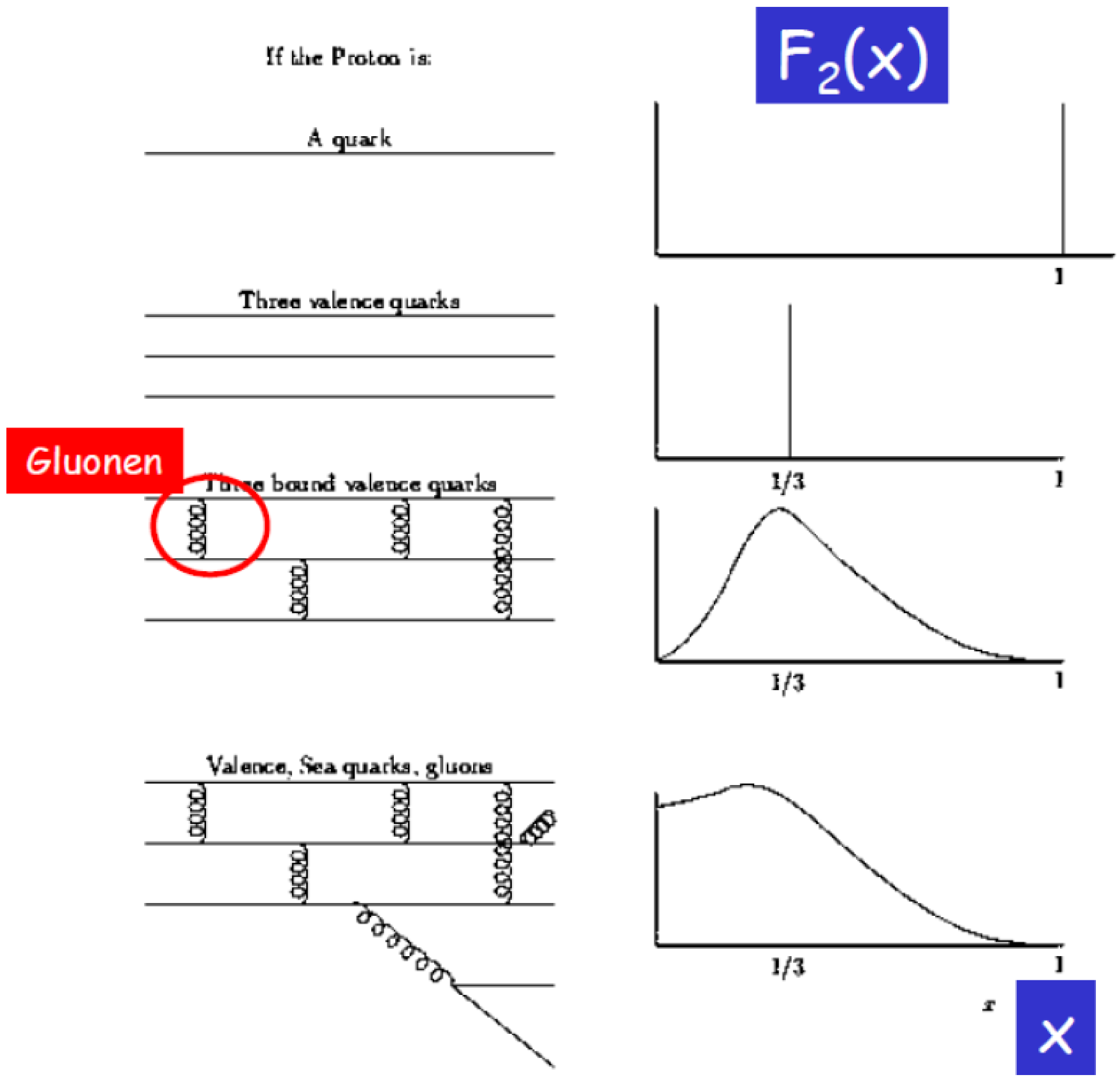
$$F_2(x, Q^2) = x \sum e_q^2 q(x)$$

„The“ HERA Textbook Plots



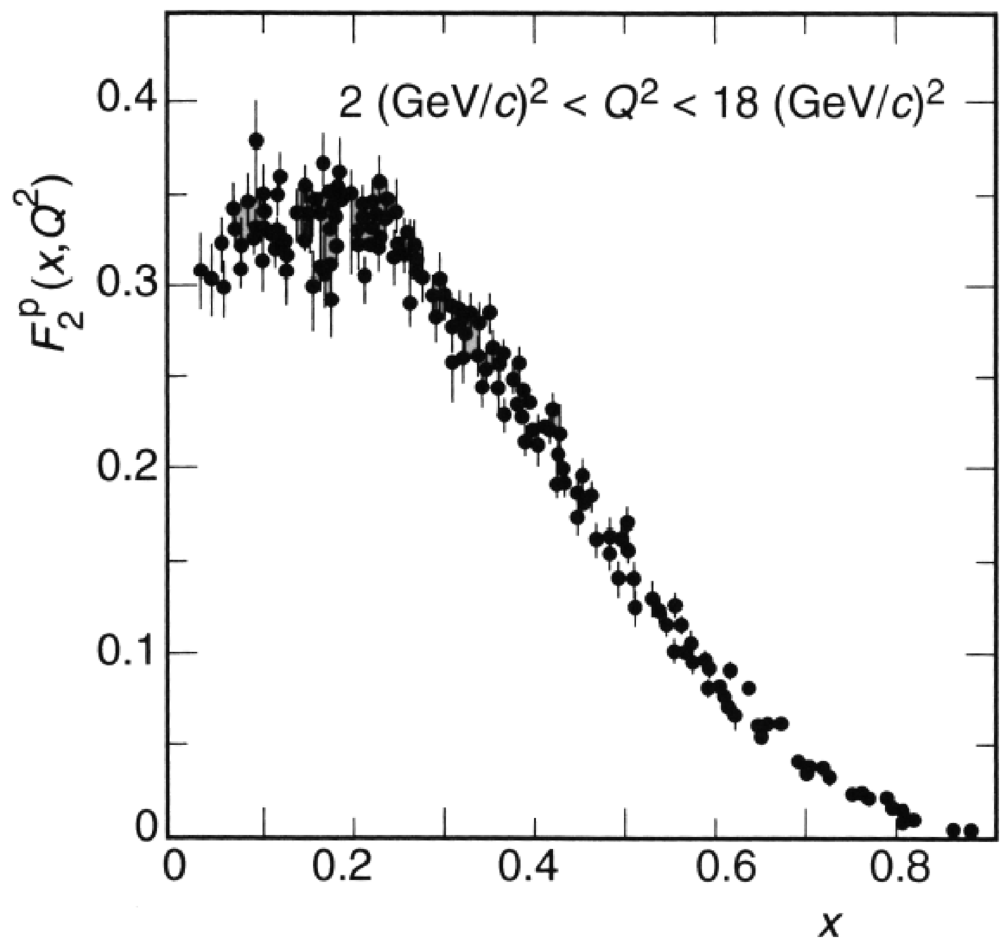
How does $F_2(x)$ look like?

How do we expect $F_2(x)$ to look like?



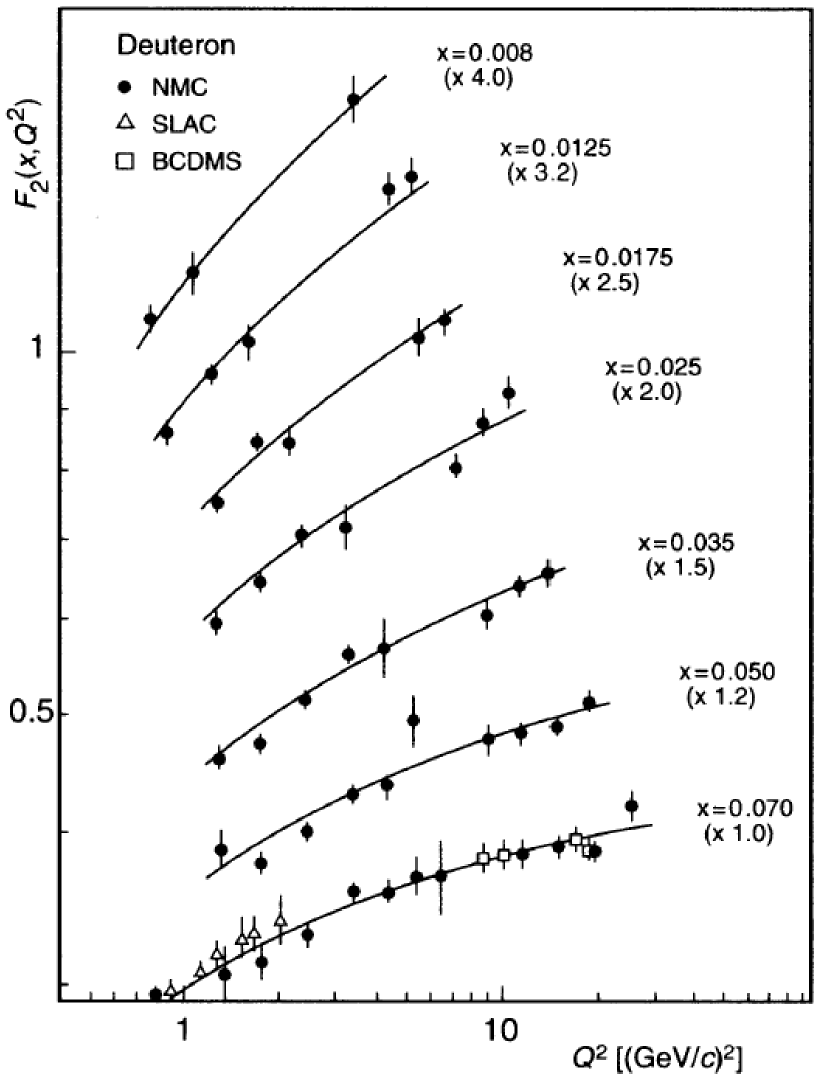
How does $F_2(x)$ look like?

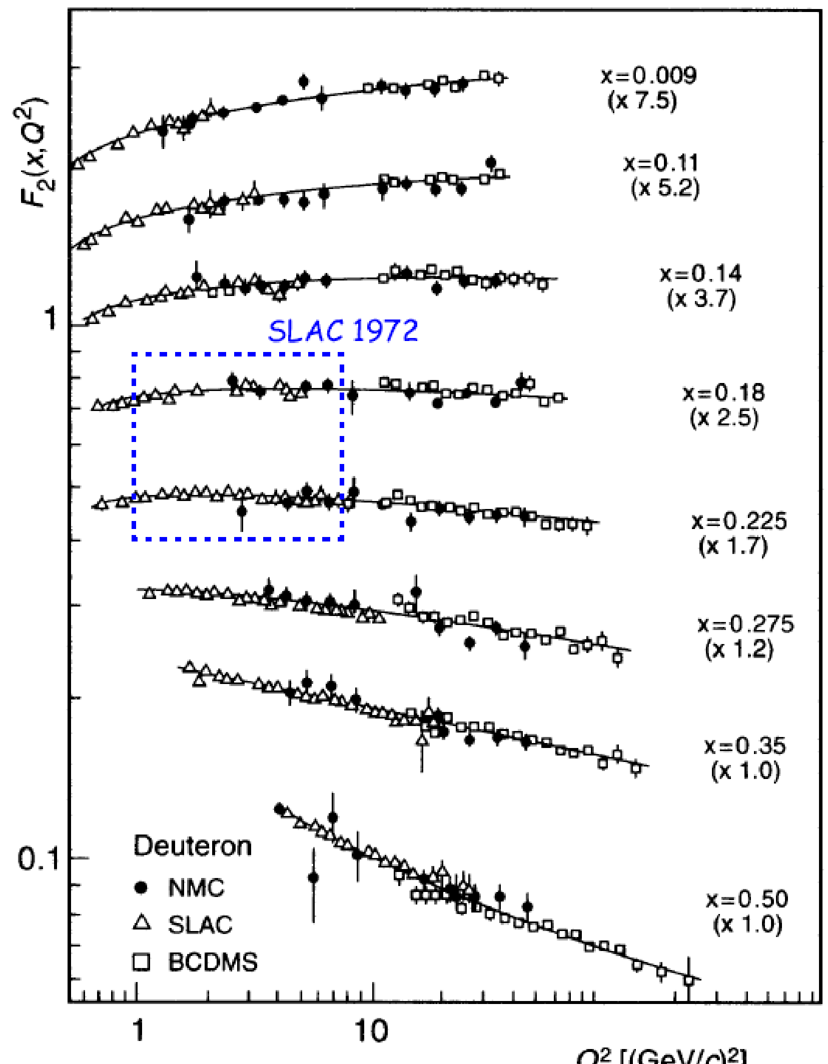
what happens at low x?



from Povh et al., „Teilchen und Kerne“

Scaling Violations

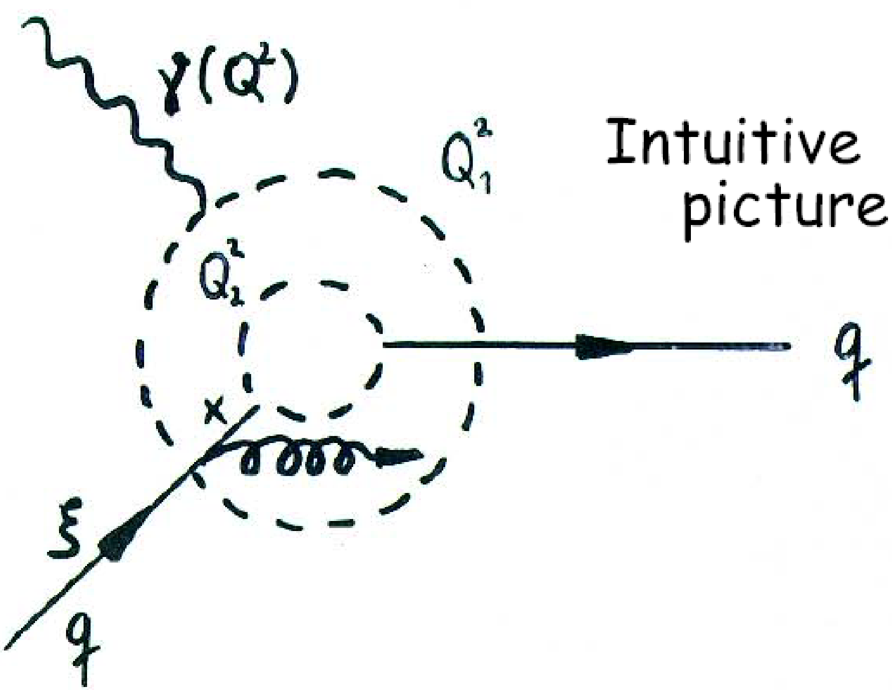




at smaller & larger x, the amount of quarks depends on Q^2!

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

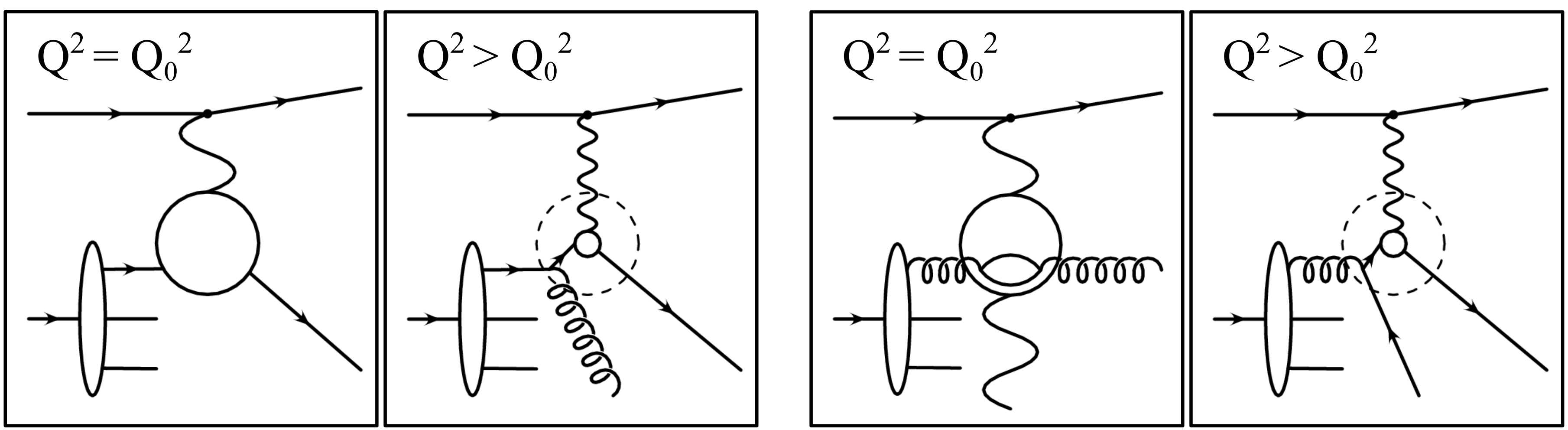
large Q^2:

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

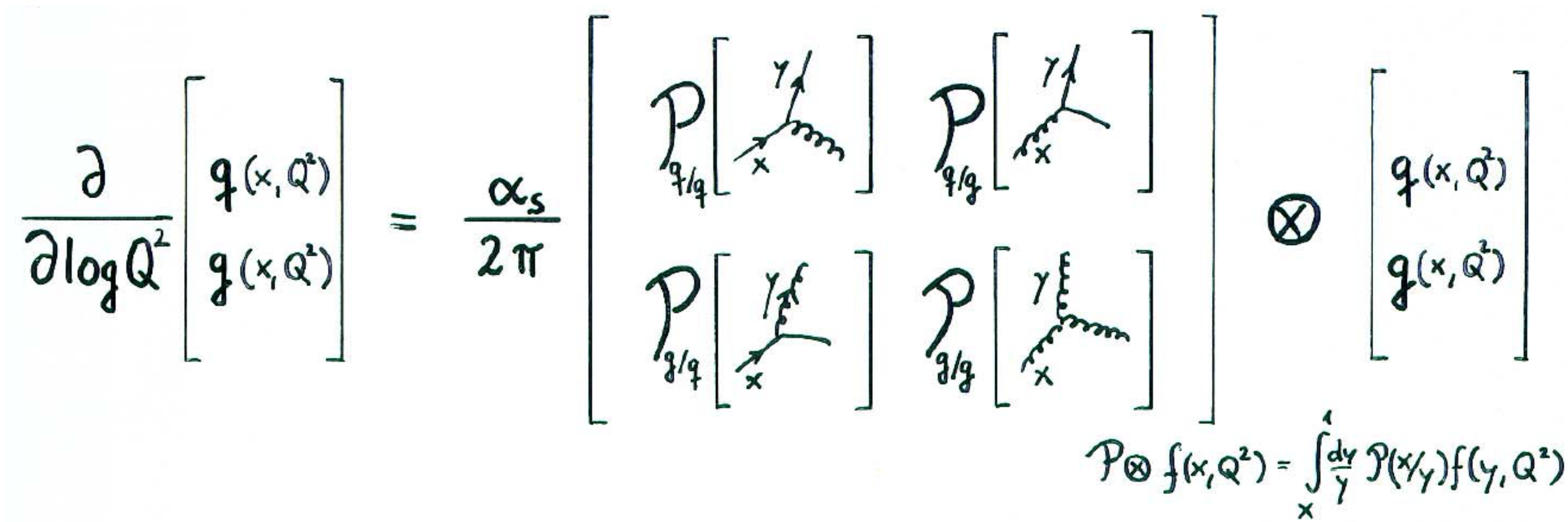
Scaling Violations

large x:
quarks radiate gluons,
so the studied x decreases
→ F_2 decreases with increasing Q^2

small x:
gluons split into seaquarks,
so more quarks become visible
→ F_2 increases with increasing Q^2

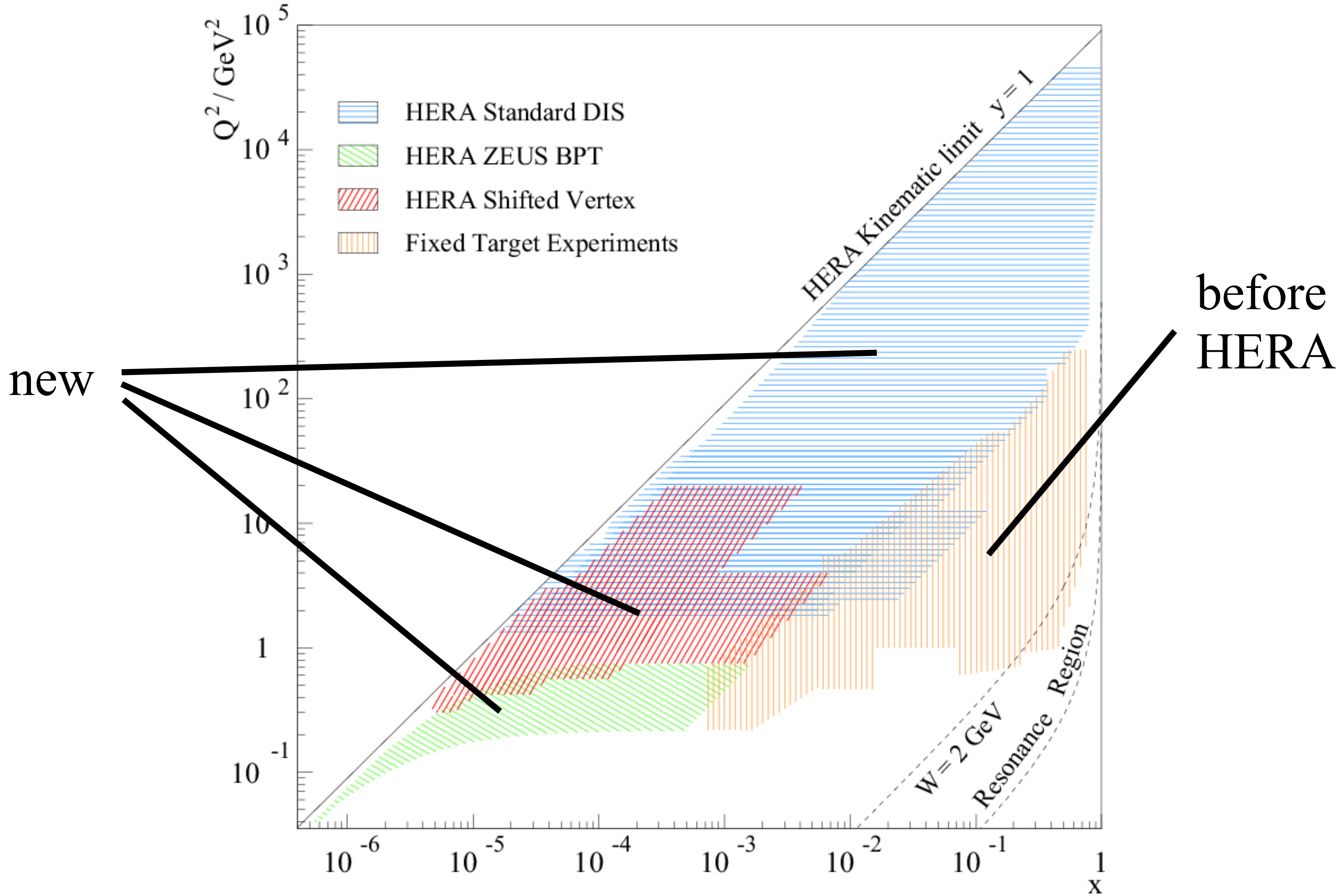


DGLAP Evolution Equations



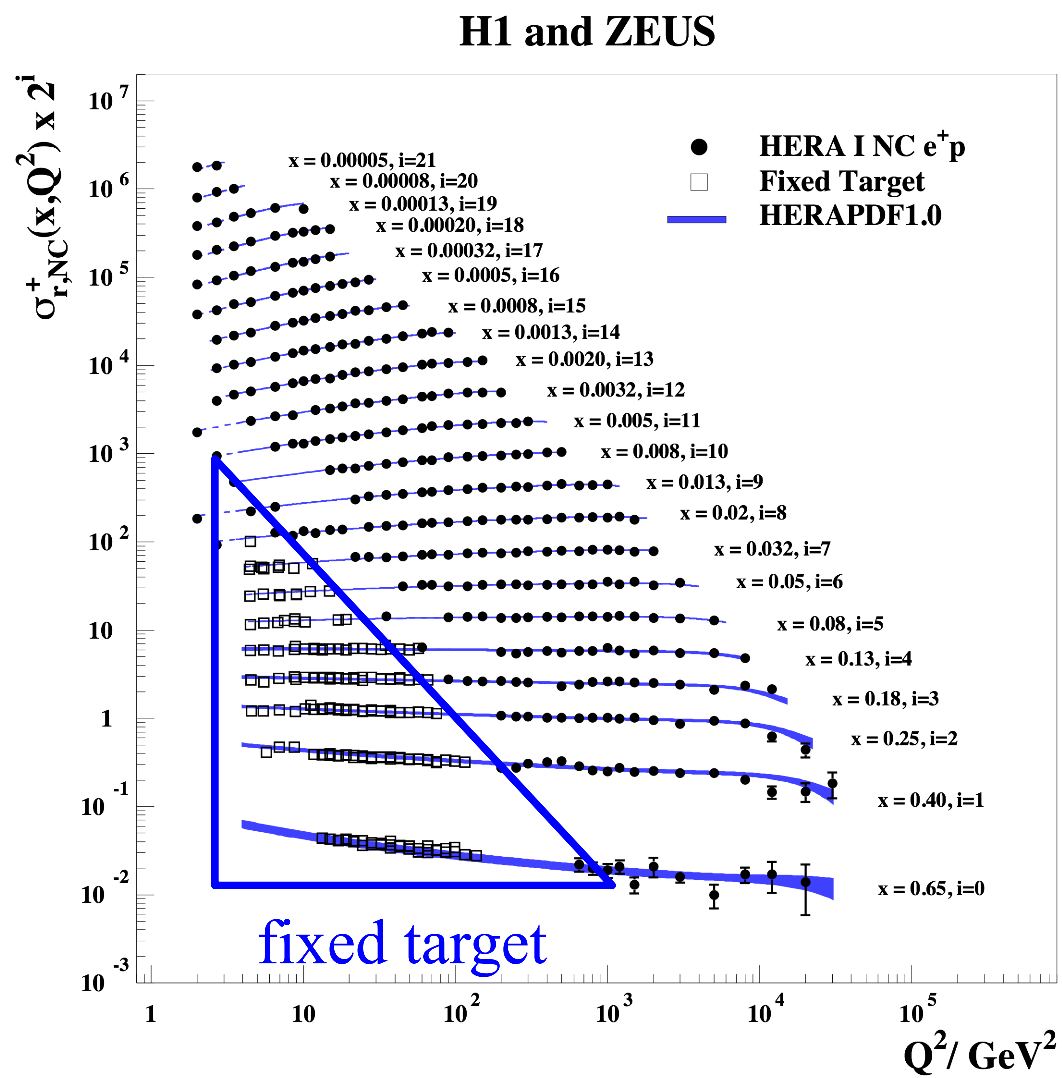
- Q^2 dependence of quark densities $q(x,Q^2)$ and gluon density $g(x,Q^2)$ is predicted
- no prediction for the x dependence $\rightarrow$ initial condition needed

HERA Kinematic Range



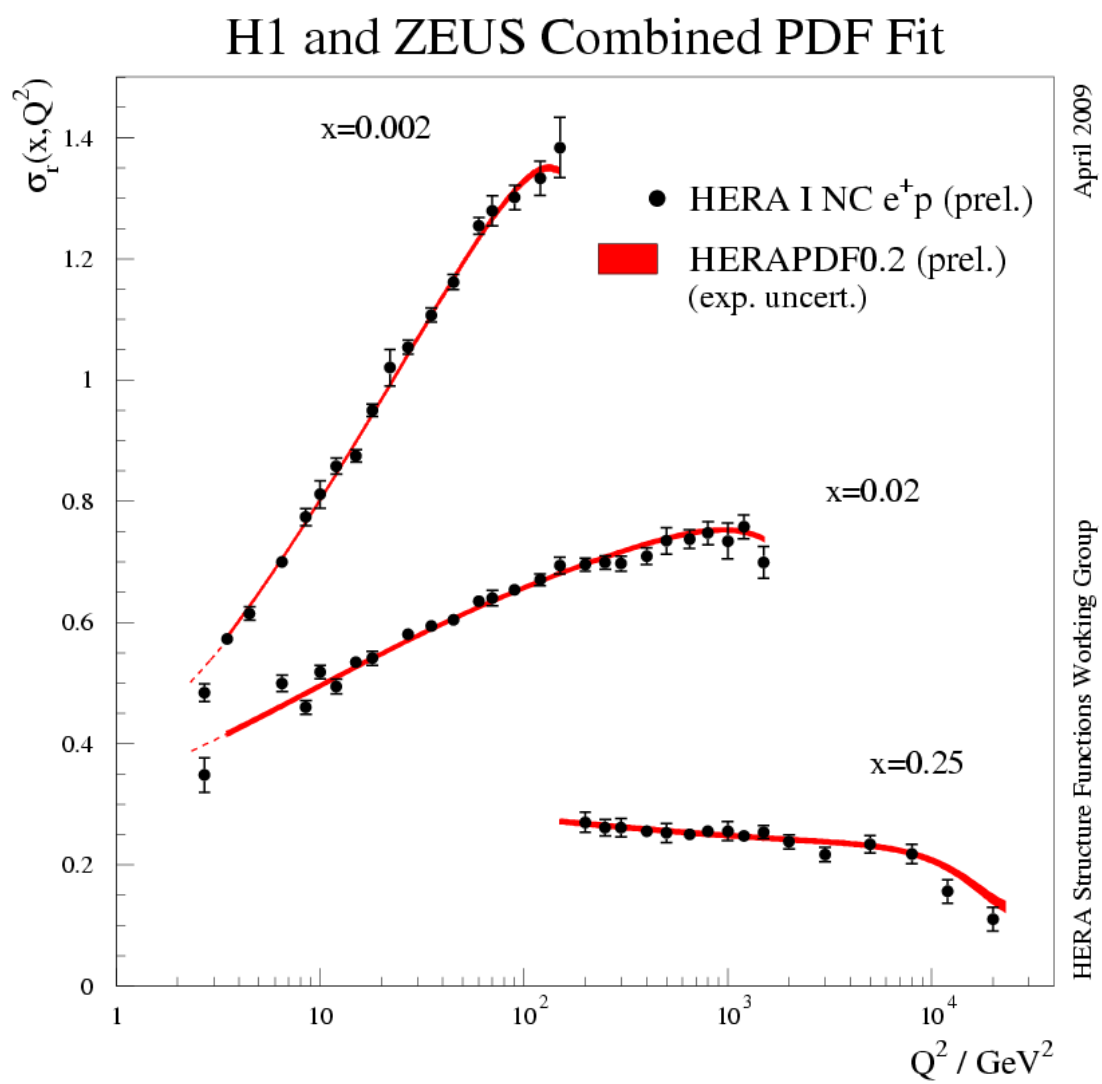
F_2 vs. Q^2

- 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

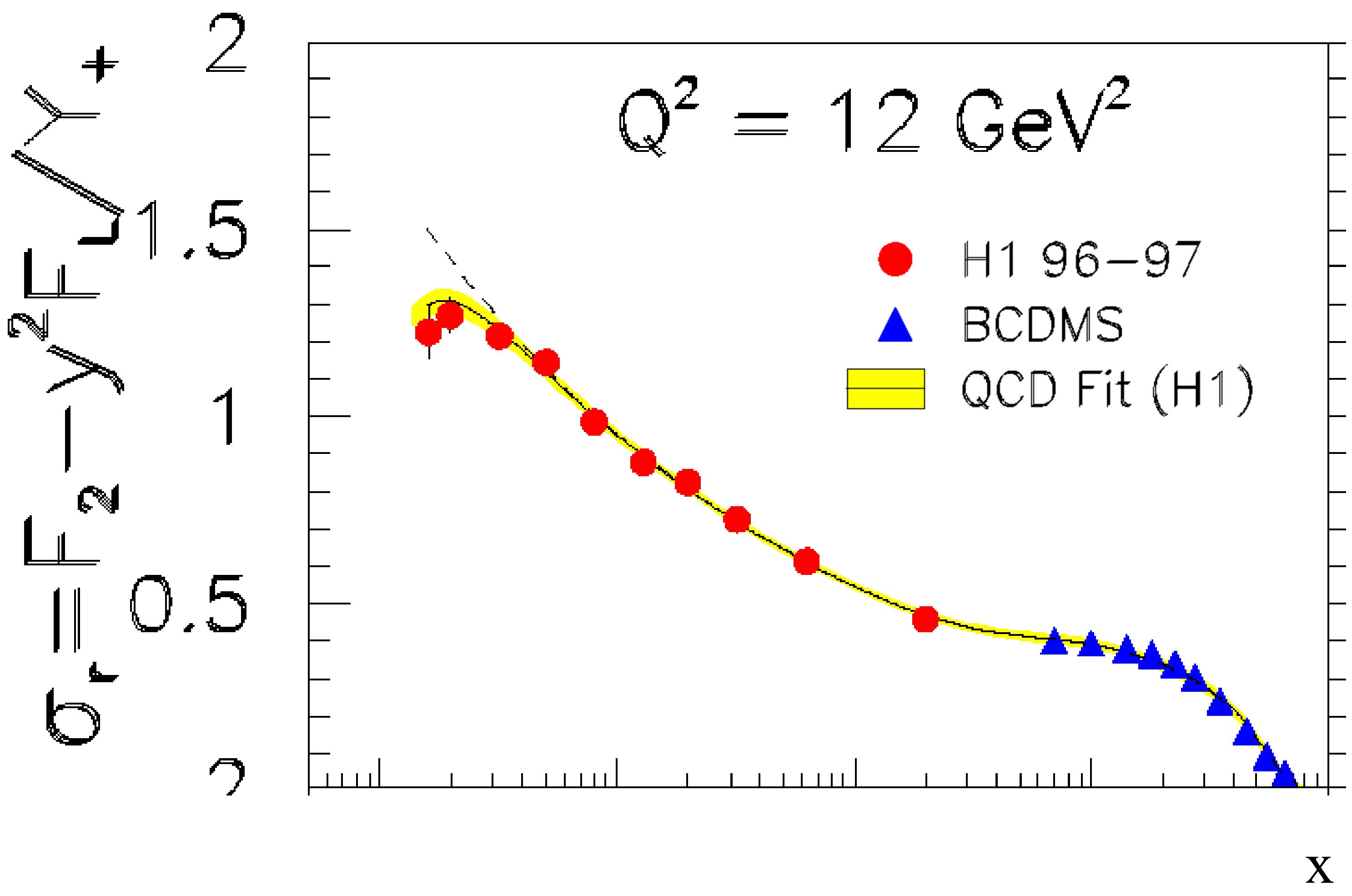


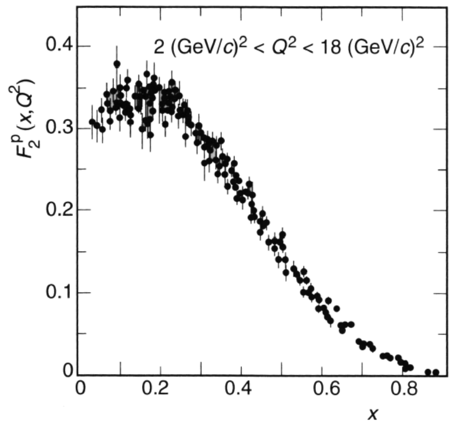
F_2 vs. Q^2: example bins

- clear scaling violations at small x
- approximate scaling at large x

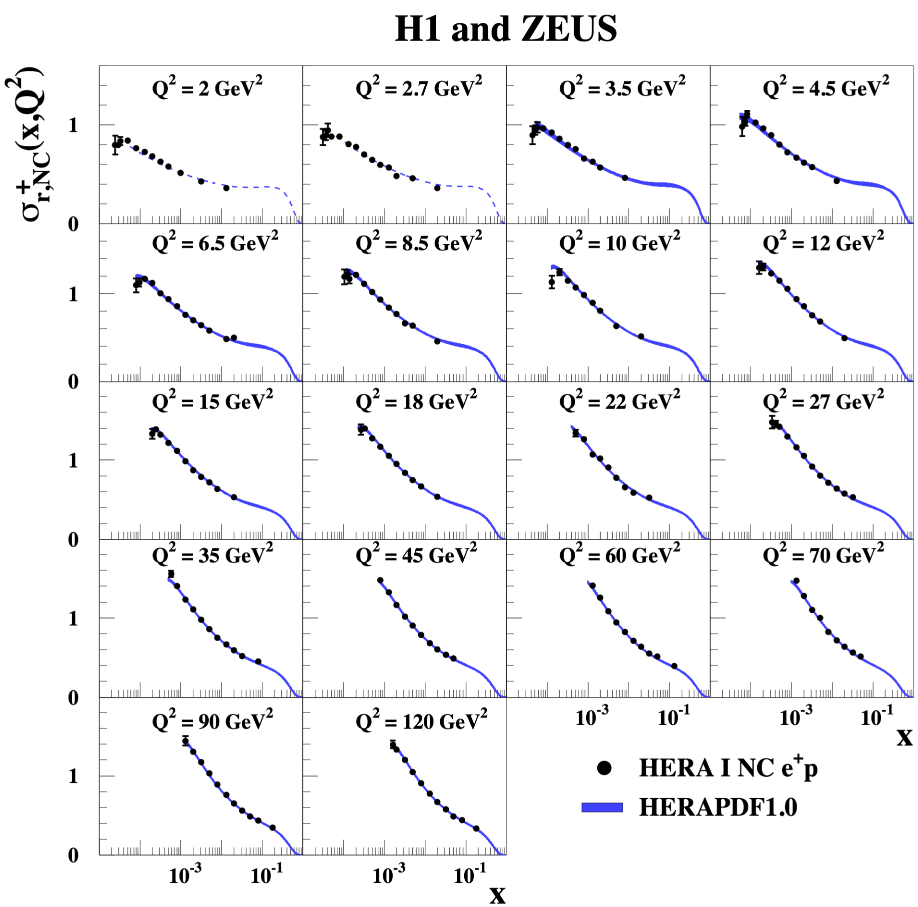


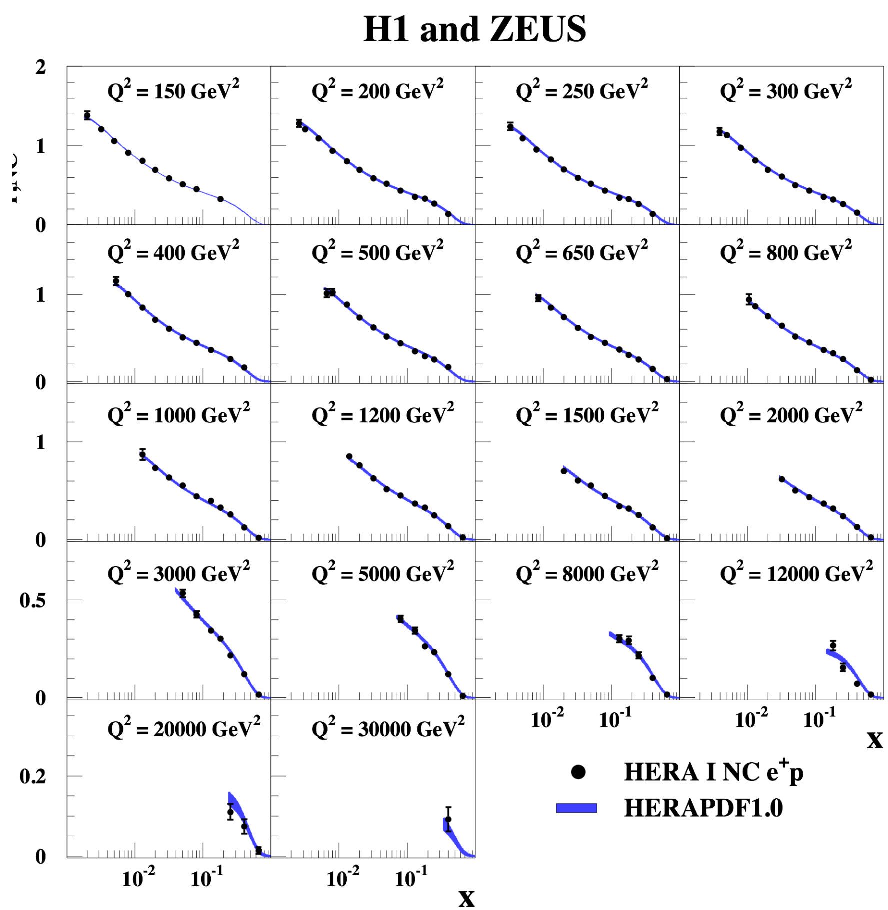
How does $F_2(x)$ look like at low x?





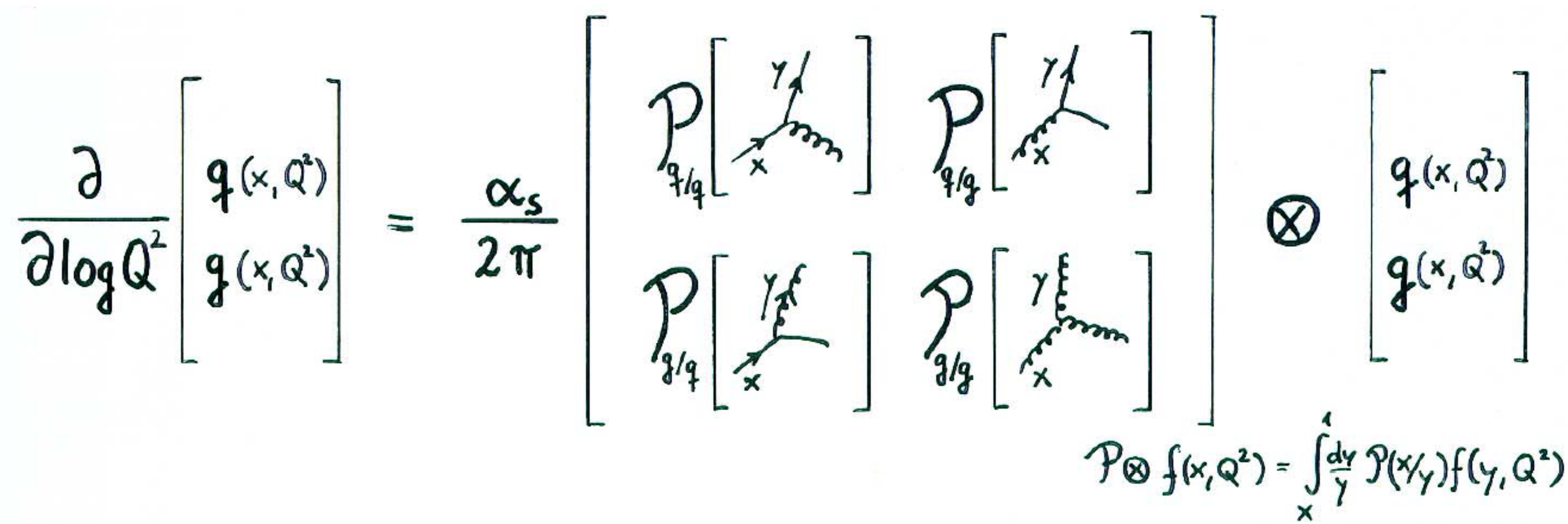
F_2 vs. x





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

DGLAP Evolution Equations



- Q^2 dependence of quark densities $q(x,Q^2)$ and gluon density $g(x,Q^2)$ is predicted

Parton Density Fits

DGLAP predicts only Q^2 dependence

- ➔ assume parametrisation of the parton density functions (PDFs) as a function of x at a starting scale Q_0^2 (typically around 2 - 7 GeV^2):

  $$x\ q(x, Q_0^2) = A x^B (1-x)^C \left[1 + D x + E x^2 + F x^3\right]$$

- ➔ evolve the PDFs to all measured Q^2, calculate F_2, and fit the parameters to match the data

- some freedom in the procedure!
  - how many parameters, which Q_0^2?
  - how to combine quark and antiquark densities?

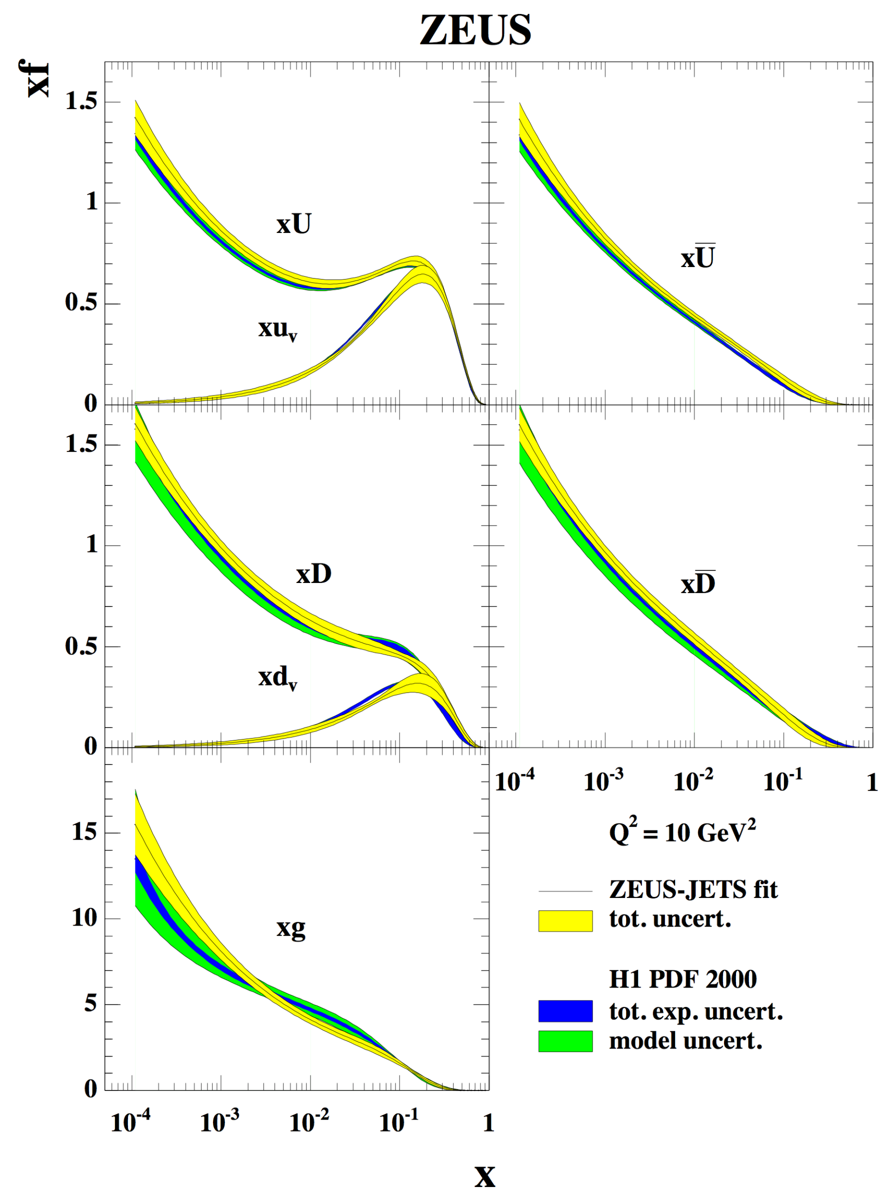
Parton Density Fits

quark and antiquark densities:

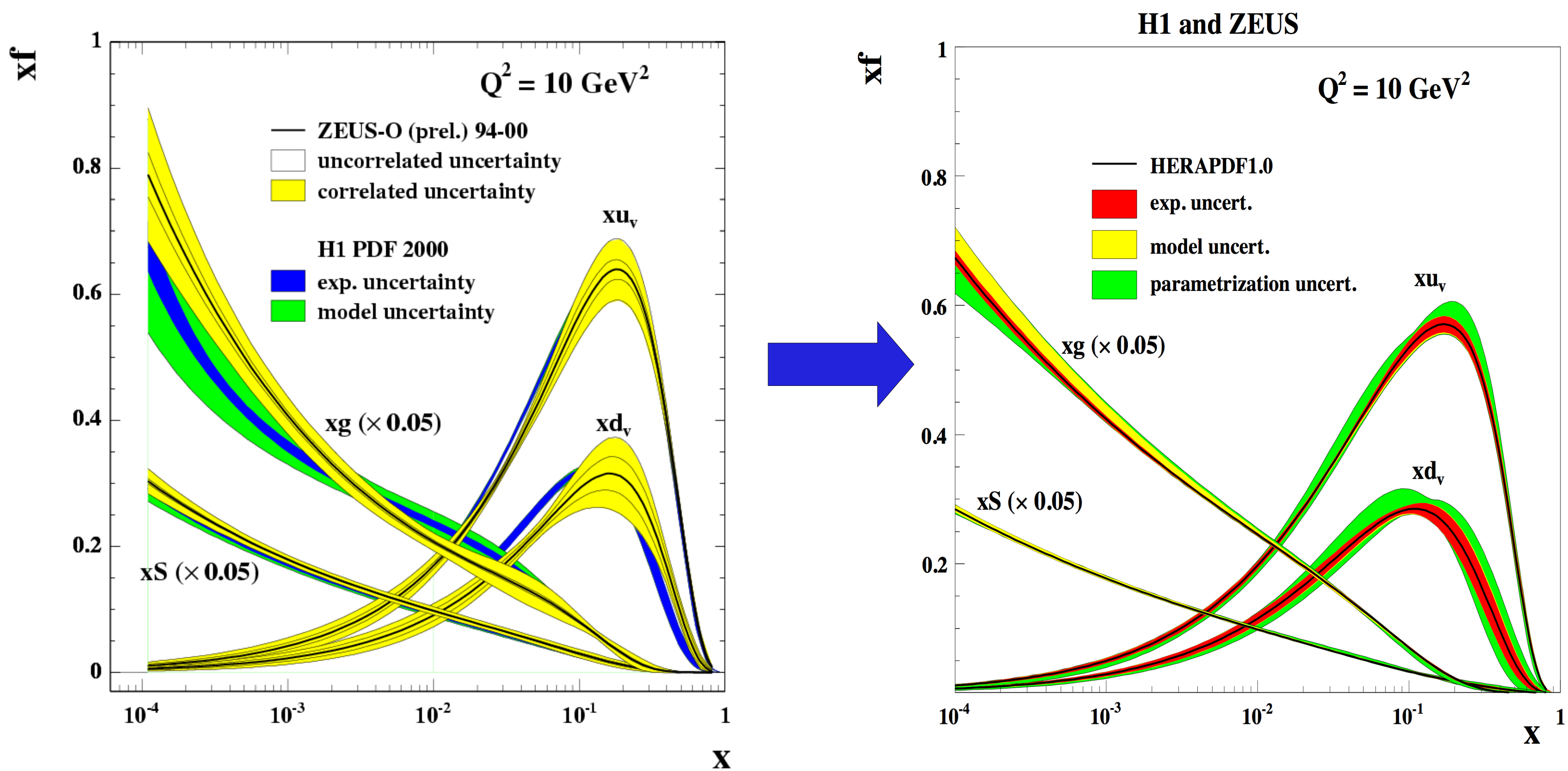
- most general: $u, \bar{u}, d, \bar{d}, s, \bar{s}, c, \bar{c}, (b, \bar{b})$
- distinguish valence and sea quarks (ZEUS):

  $u_v, d_v, Sea, \bar{d}-\bar{u}$
- distinguish *up*-type and *down*-type quarks (H1):

$$U = u + c, \quad D = d + s\,(+b)$$
$$\bar{U} = \bar{u} + \bar{c}, \quad \bar{D} = \bar{d} + \bar{s}\,(+\bar{b})$$
$$\rightarrow u_v = U - \bar{U}, \, d_v = D - \bar{D}$$



Combined H1 & ZEUS Parton Density



combination of data from H1 and ZEUS
gives big improvements!

Longitudinal Structure Function F_L

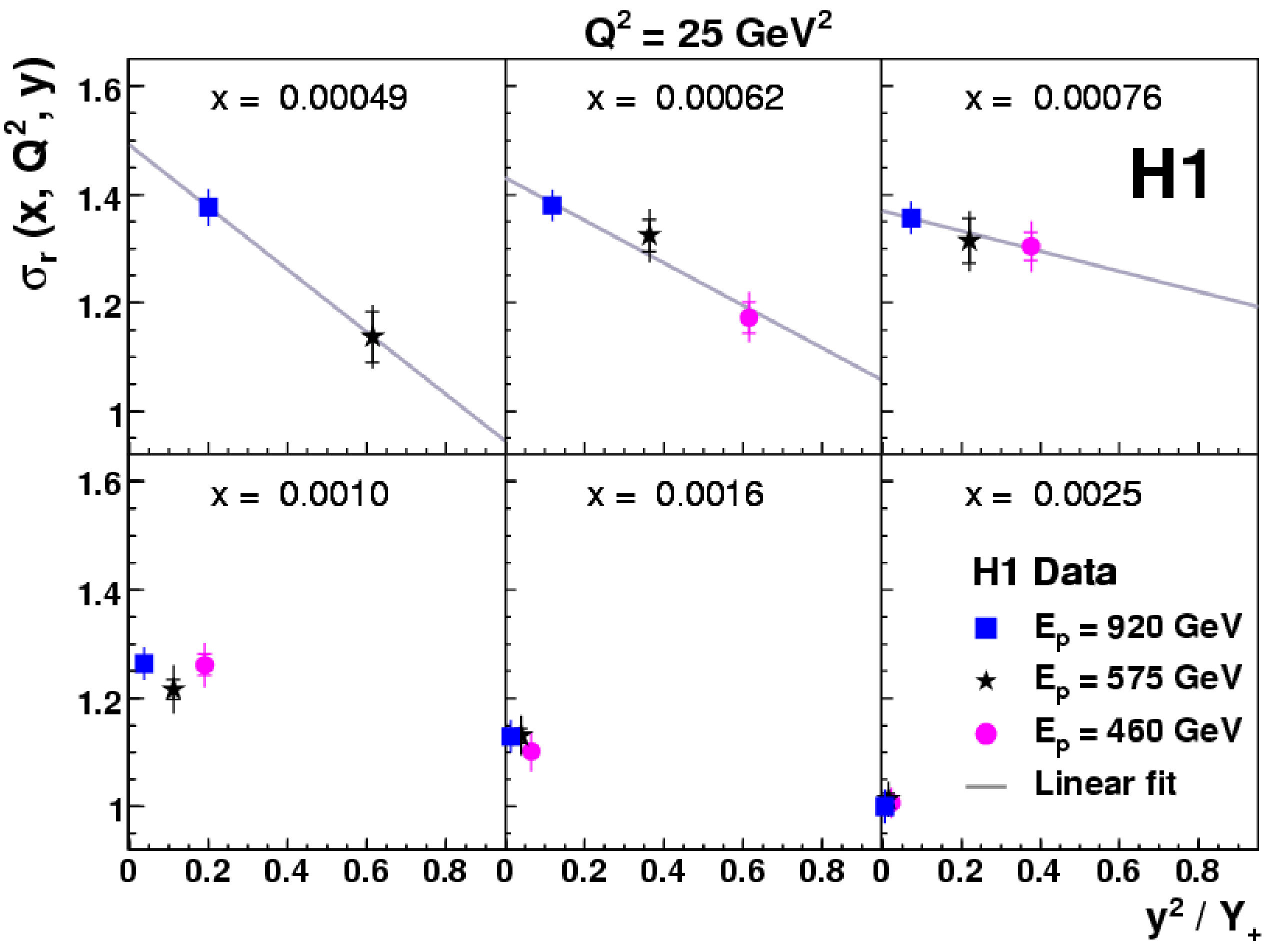
- Callan-Gross relation $2\,x\,F_1 = F_2$ only true in naive Quark-Parton-Model
- the longitudinal structure function F_L is defined as $F_L = F_2 - 2\,x\,F_1$
- F_L is directly proportional to the gluon density
- for a measurement of F_L one needs data at the same x and Q^2, but different y

$$\frac{d^2\sigma}{dx\,dQ^2} = \frac{4\pi\alpha^2}{Q^4}\frac{1}{x}\left(1-y+\frac{y^2}{2}\right)\left[F_2(x,Q^2) - \frac{y^2/2}{1-y+y^2/2}F_L(x,Q^2)\right]$$

- only possible with different s because $Q^2 = xys$

➔ measure at different beam energies!

Longitudinal Structure Function F_L



$$\sigma_r = \frac{x Q^4}{2\pi\alpha^2} \frac{1}{Y_+} \frac{d^2\sigma}{dx\,dQ^2}$$

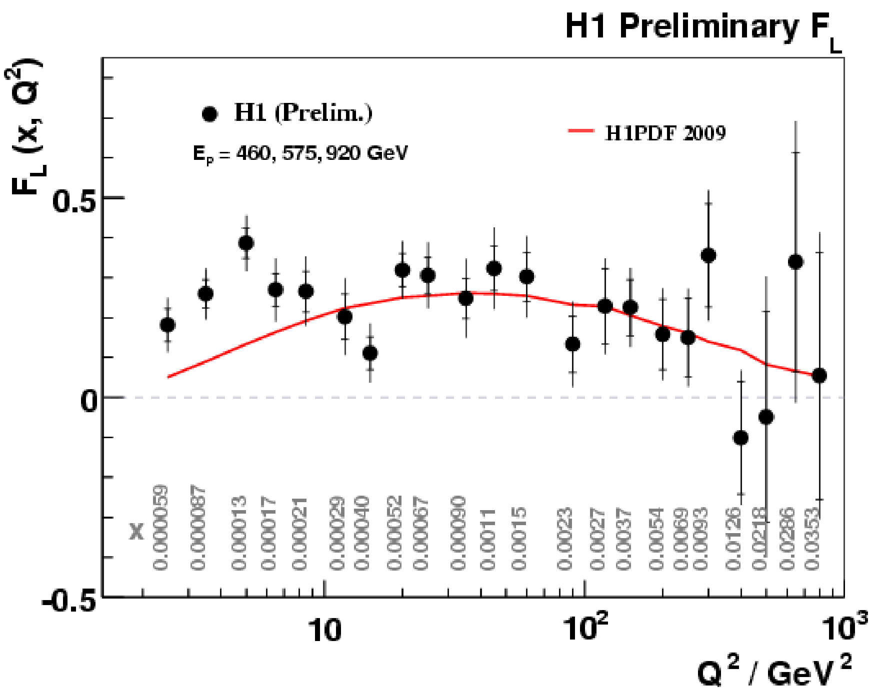
$$= F_2(x, Q^2) - \frac{y^2}{Y_+} F_L(x, Q^2)$$

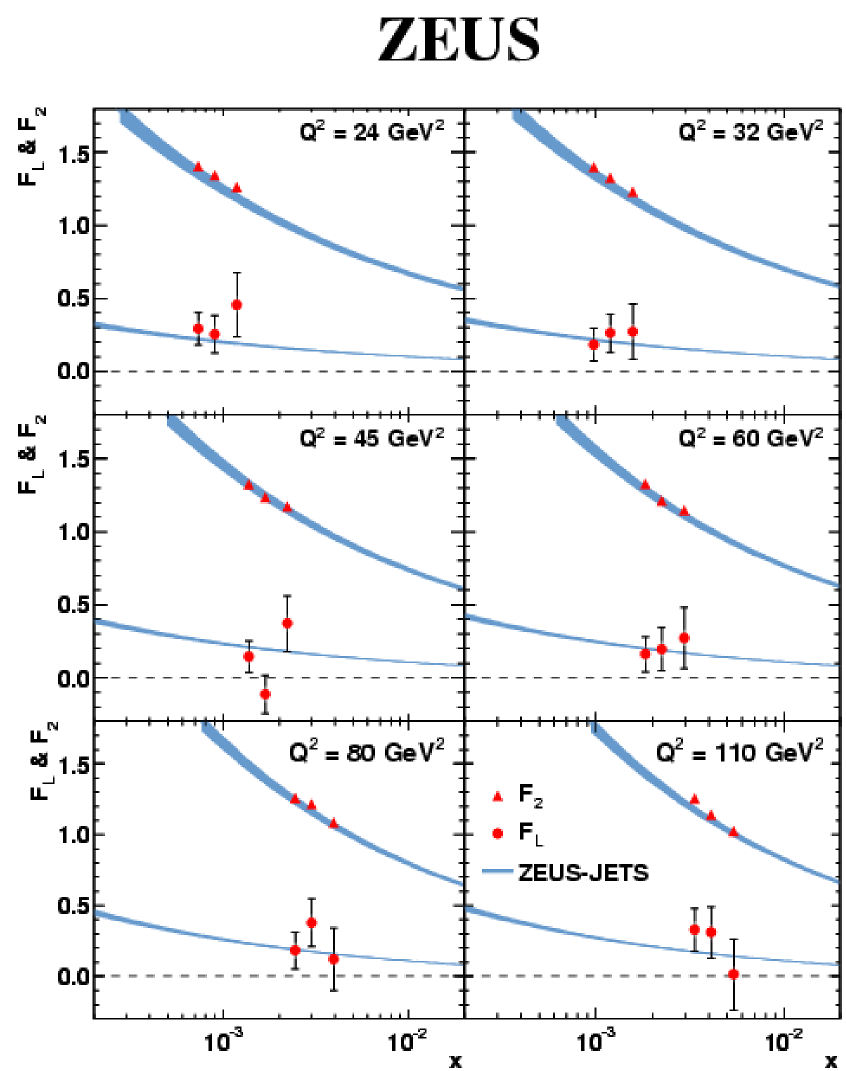
with $Y_+ = 1 + (1-y)^2$

- linear expression in y^2/Y_+

➔ use linear fits in y^2/Y_+ and determine F_L from slope

Longitudinal Structure Function F_L





- ZEUS: simultaneous determination of F_2 and F_L
- consistent with PDF fit to F_2
- most precise information on gluon still from scaling violations

„The“ HERA Textbook Plots