Physics at HERA

Summer Student Lectures
18 + 19 August 2008

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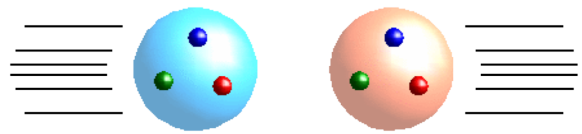
Overview

- 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

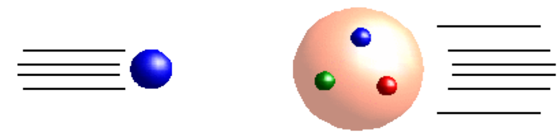
e^+e^-

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



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

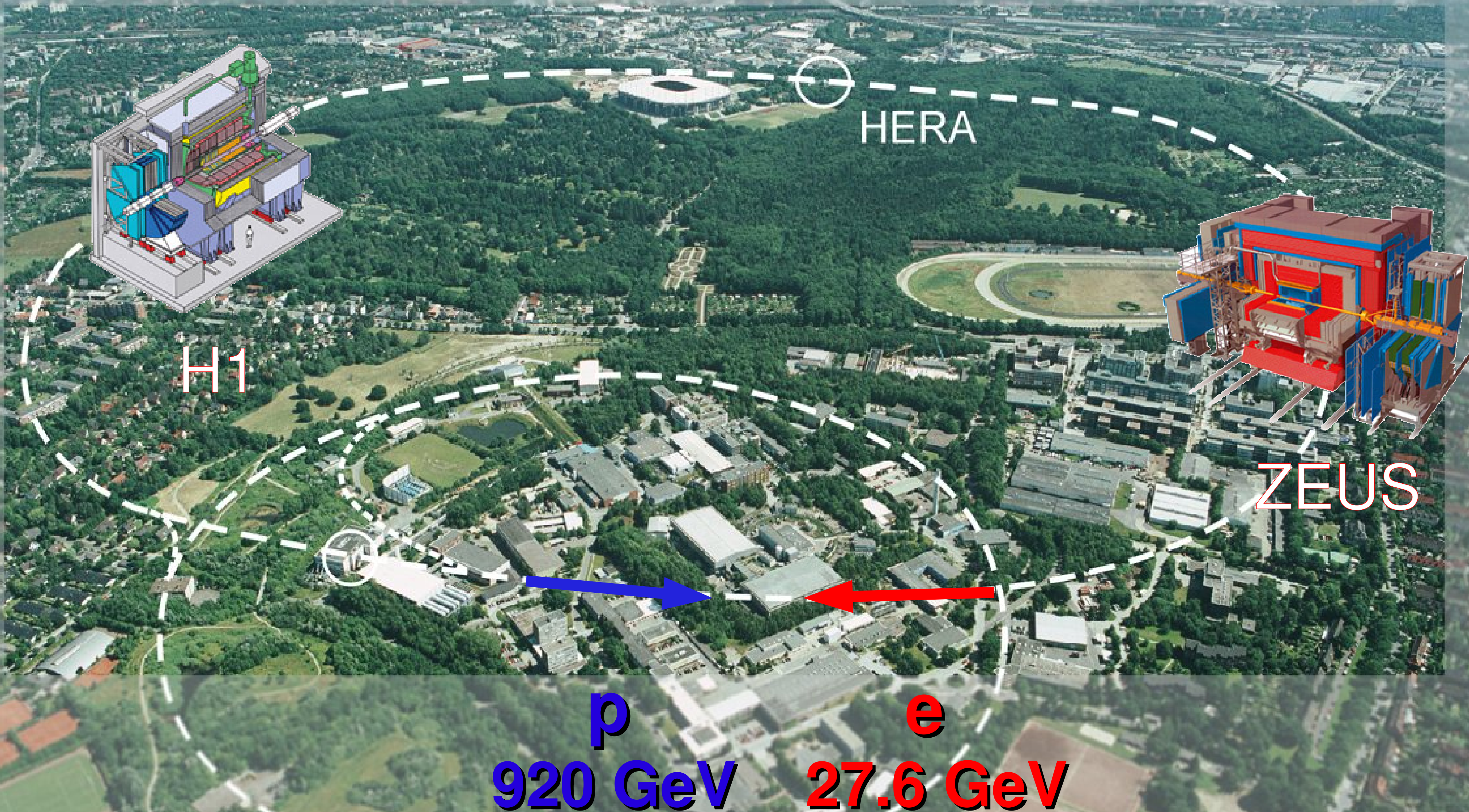
- + high energy
- – complicated final state
- – large background
- • Tevatron (2 TeV)
  LHC (14 TeV)



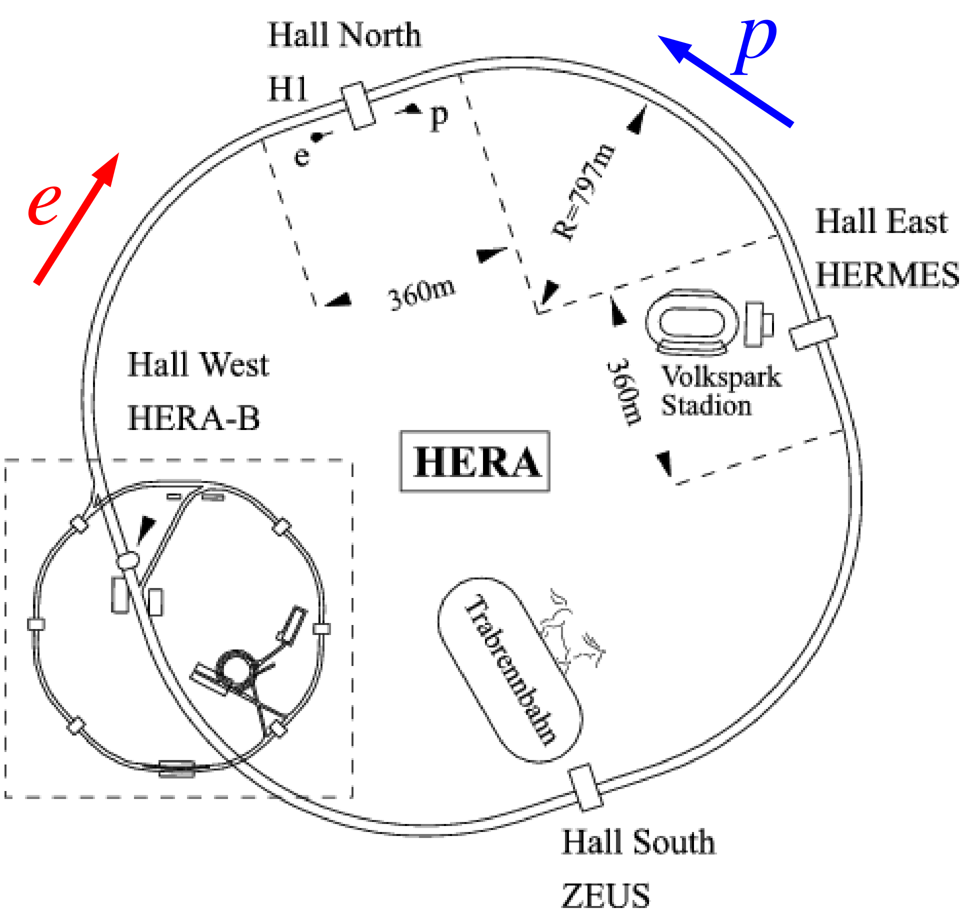
ep

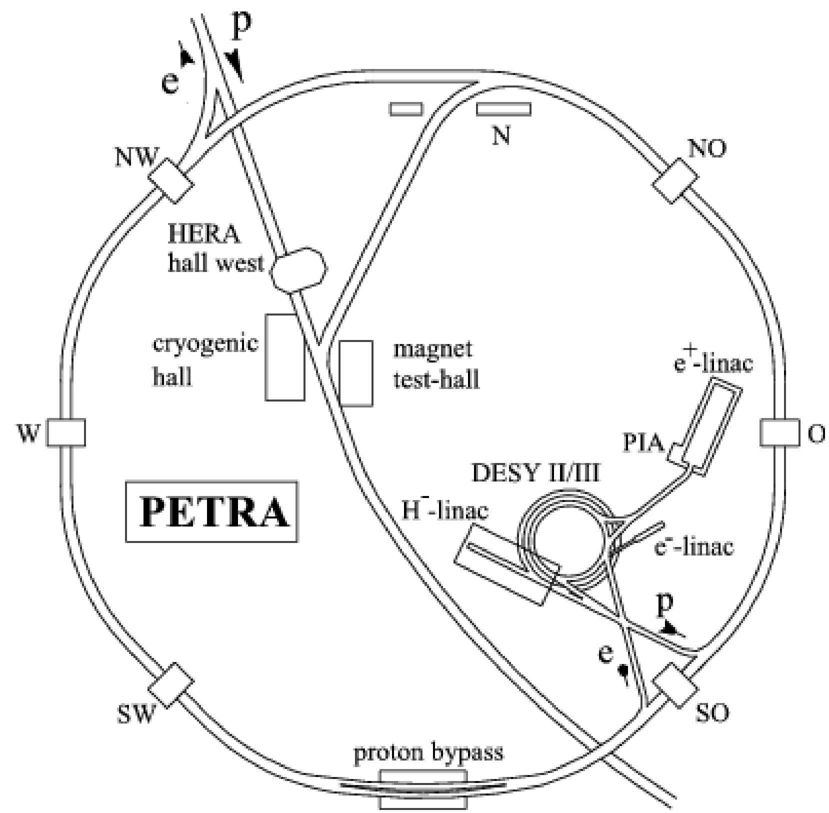
- + unique initial state
- + electron as probe of proton structure
- – two accelerators
- • HERA (300 GeV)

HERA



HERA & its Pre-Accelerators

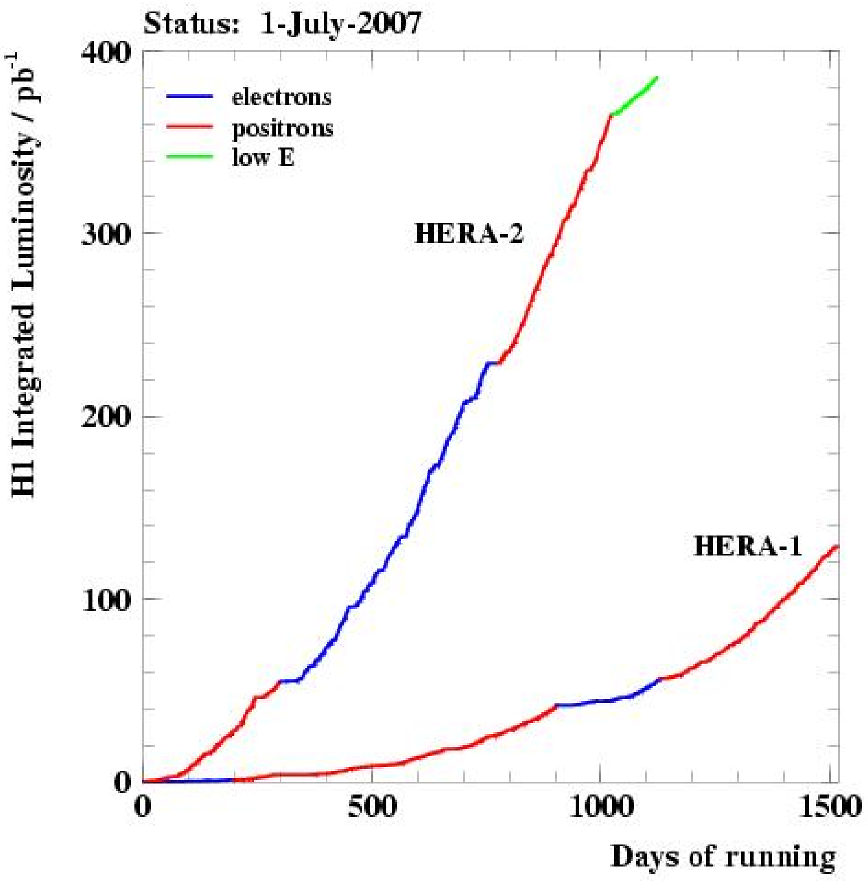




circumference: 6.3 km

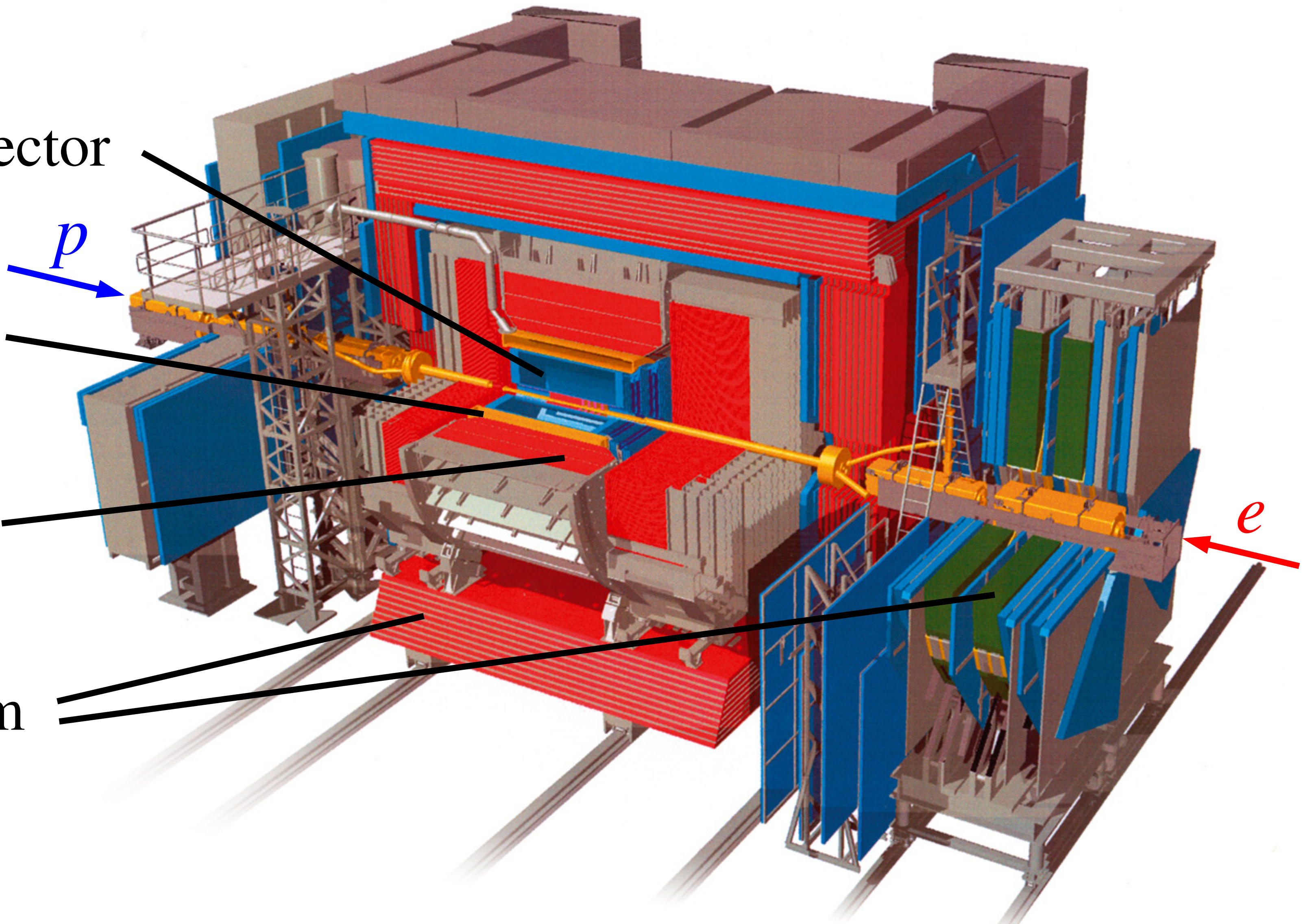
bunch crossing rate: 10.4 MHz

Collected Luminosity

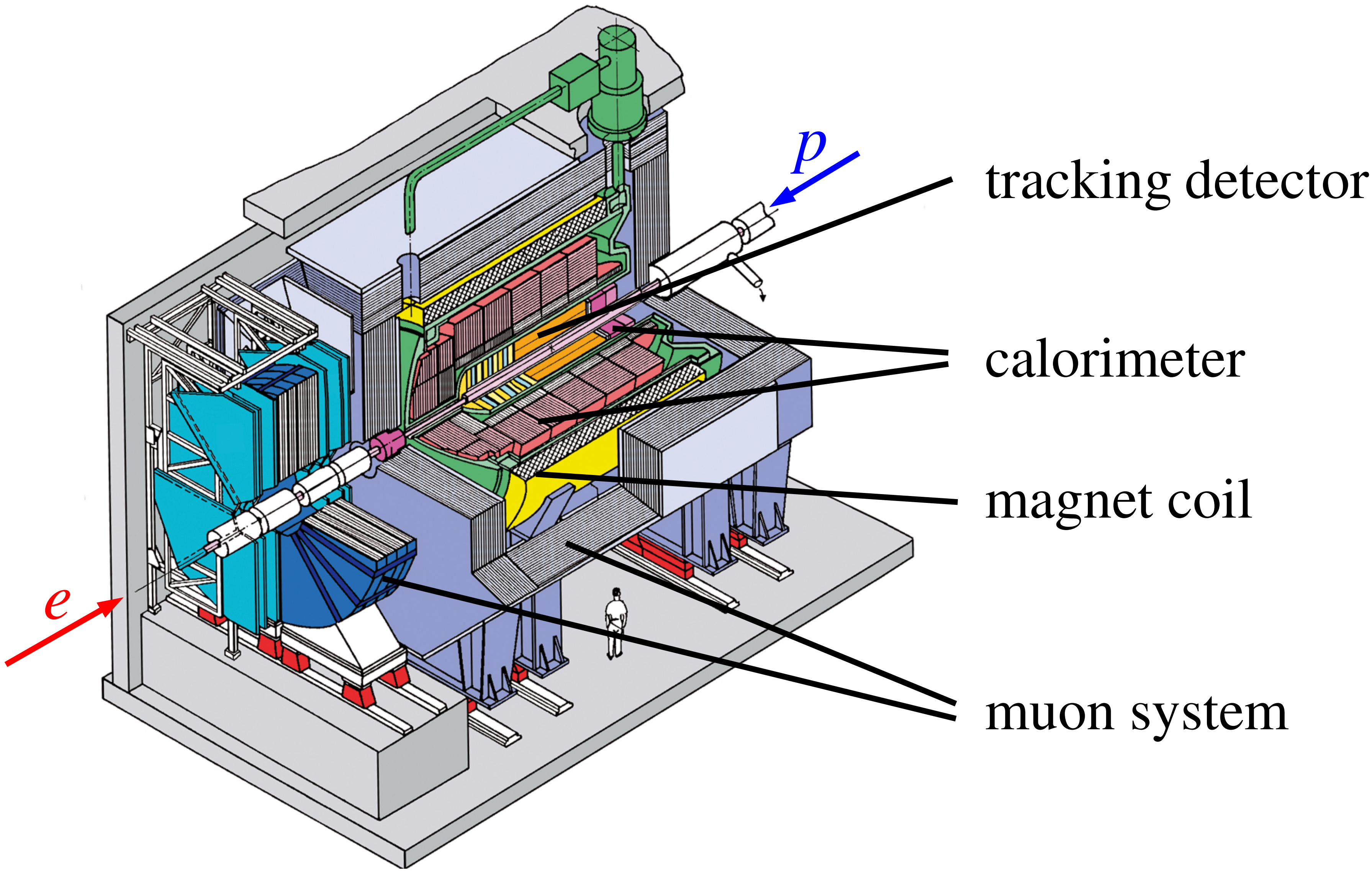


- HERA operated 1992-2007
- lumi upgrade in 2001
  - higher luminosity
  - *e* polarization
  - detector upgrades
- in total ~500 pb^{-1} of high energy data collected per experiment
- last months devoted to low *p* energy (460, 575 GeV)

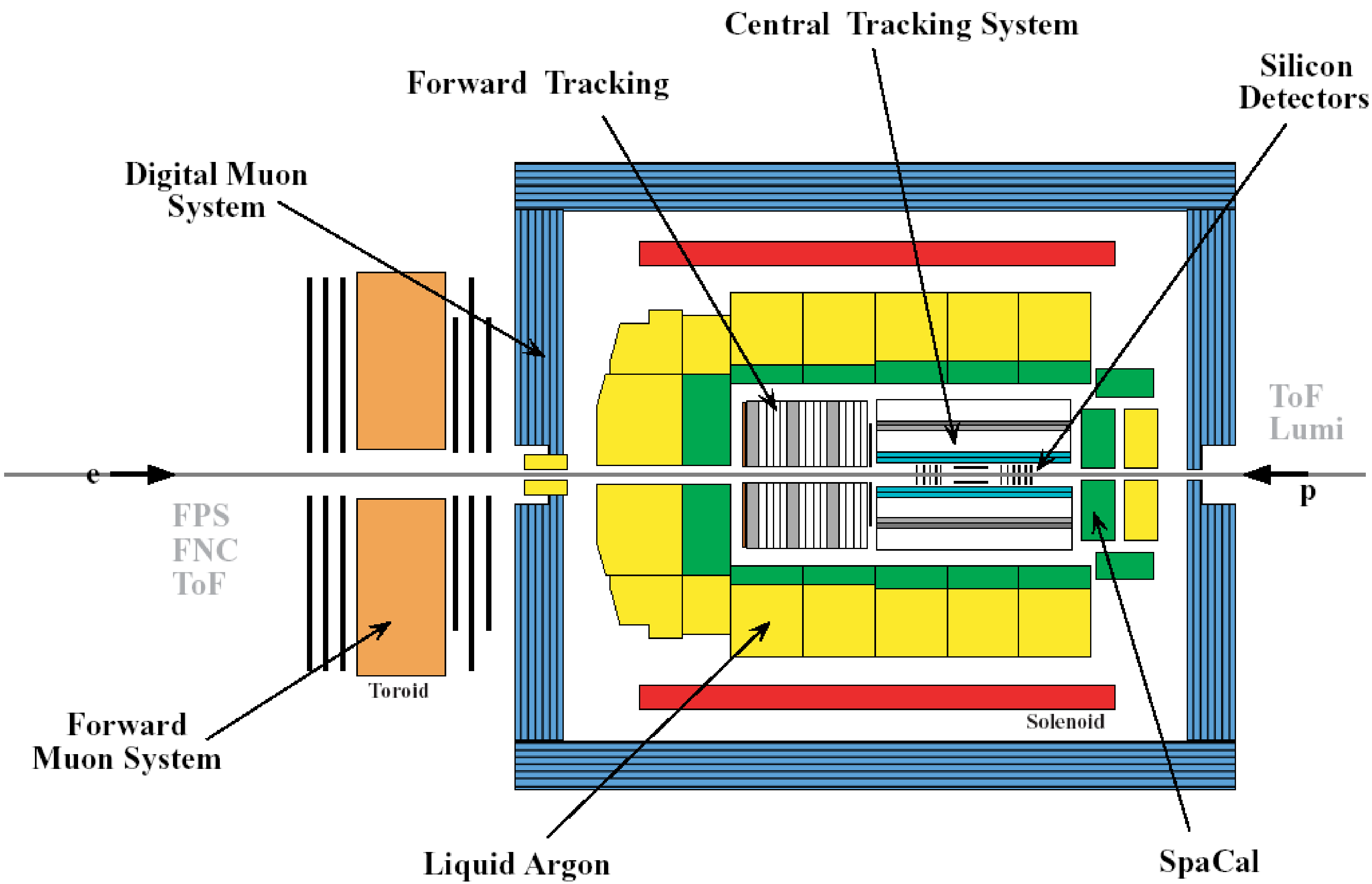
ZEUS Detector



H1 Detector



Schematic View of the H1 Detector



Physics Topics at HERA

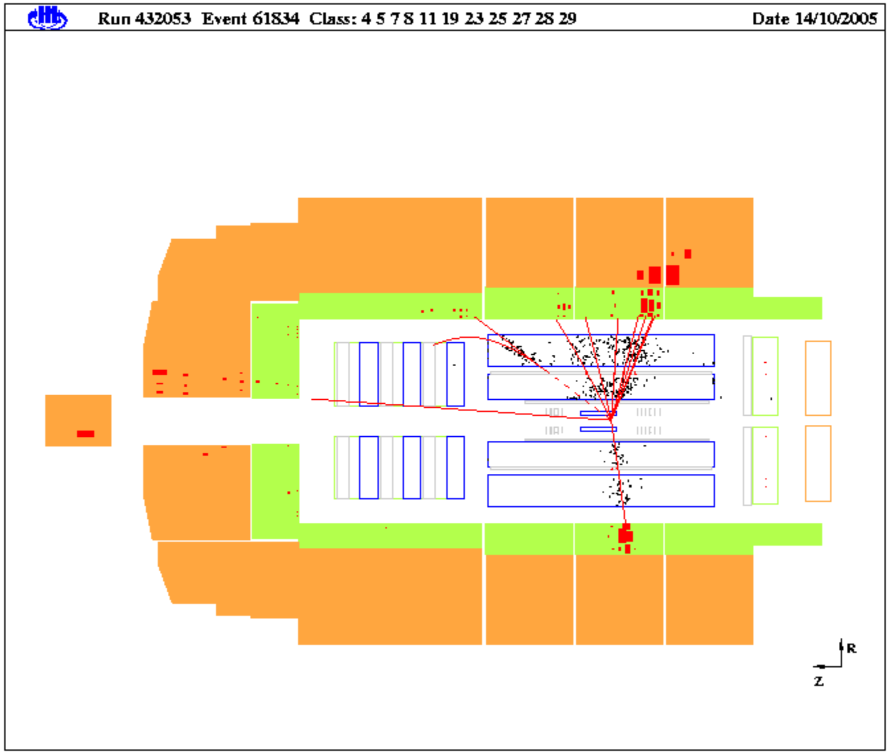
expected

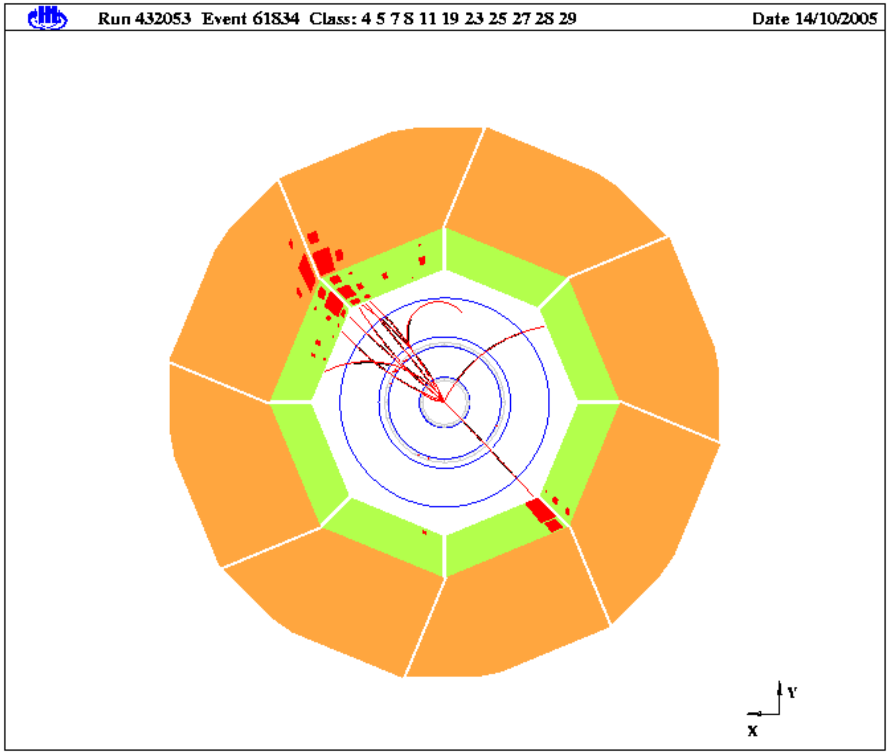
- proton structure
  - structure functions
  - parton densities
  - α_s
- photon structure
- perturbative QCD
  - jets
  - heavy quarks
- electroweak

not (so) expected

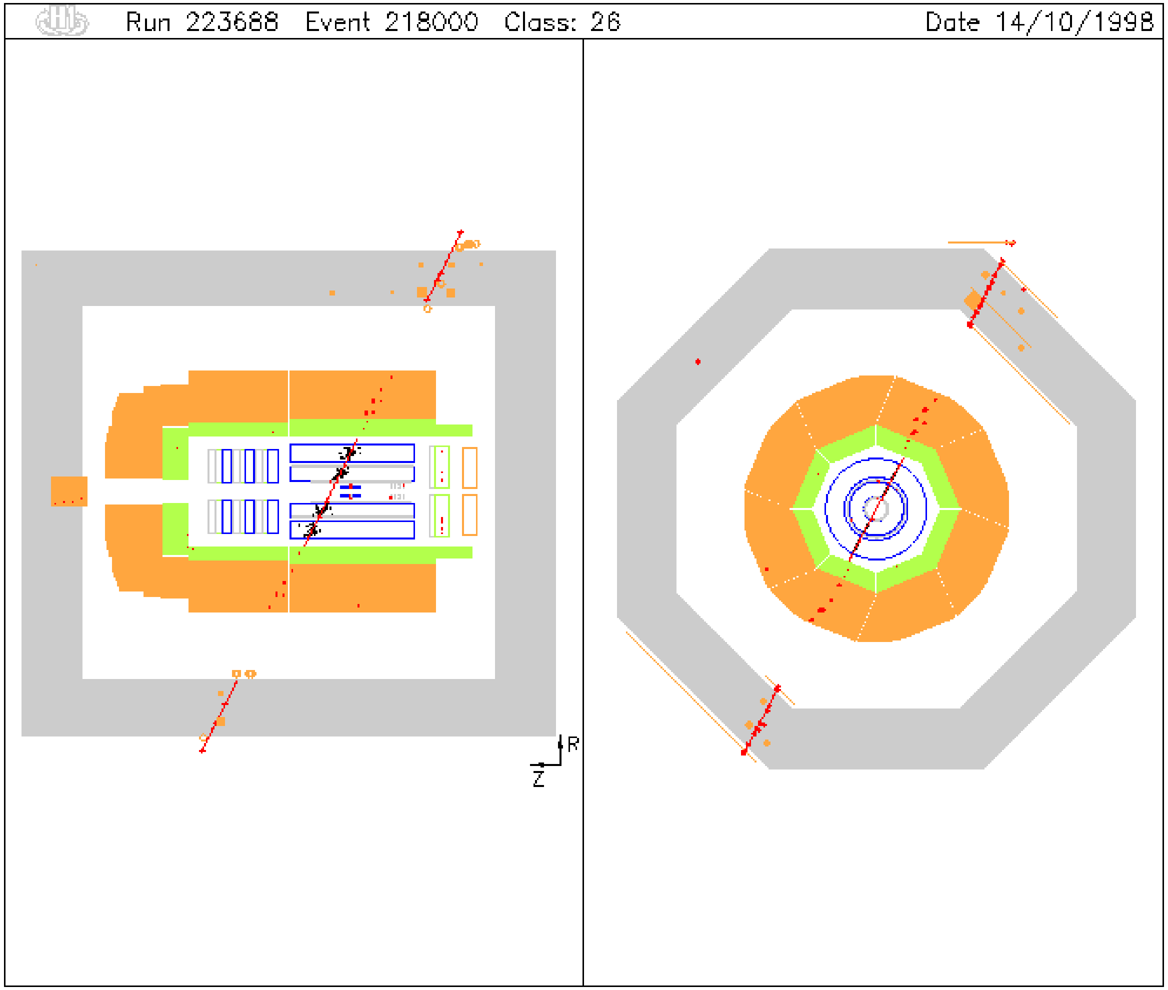
- exotics (beyond the standard modell)
  - SUSY
  - leptoquarks
  - ...
- diffraction

Some Events...

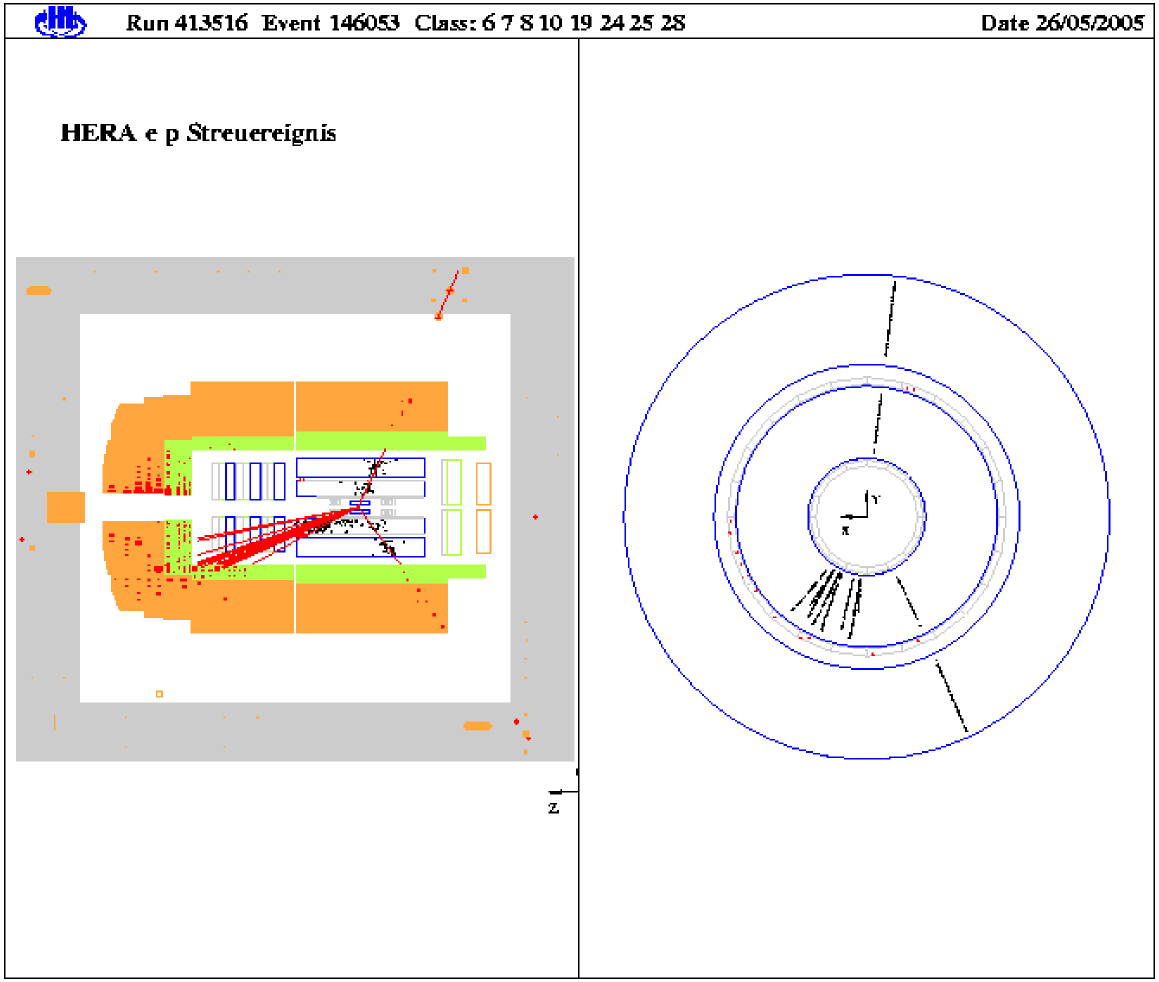

Run 432053 Event 61834 Class: 4 5 7 8 11 19 23 25 27 28 29
Date 14/10/2005
R
Z


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

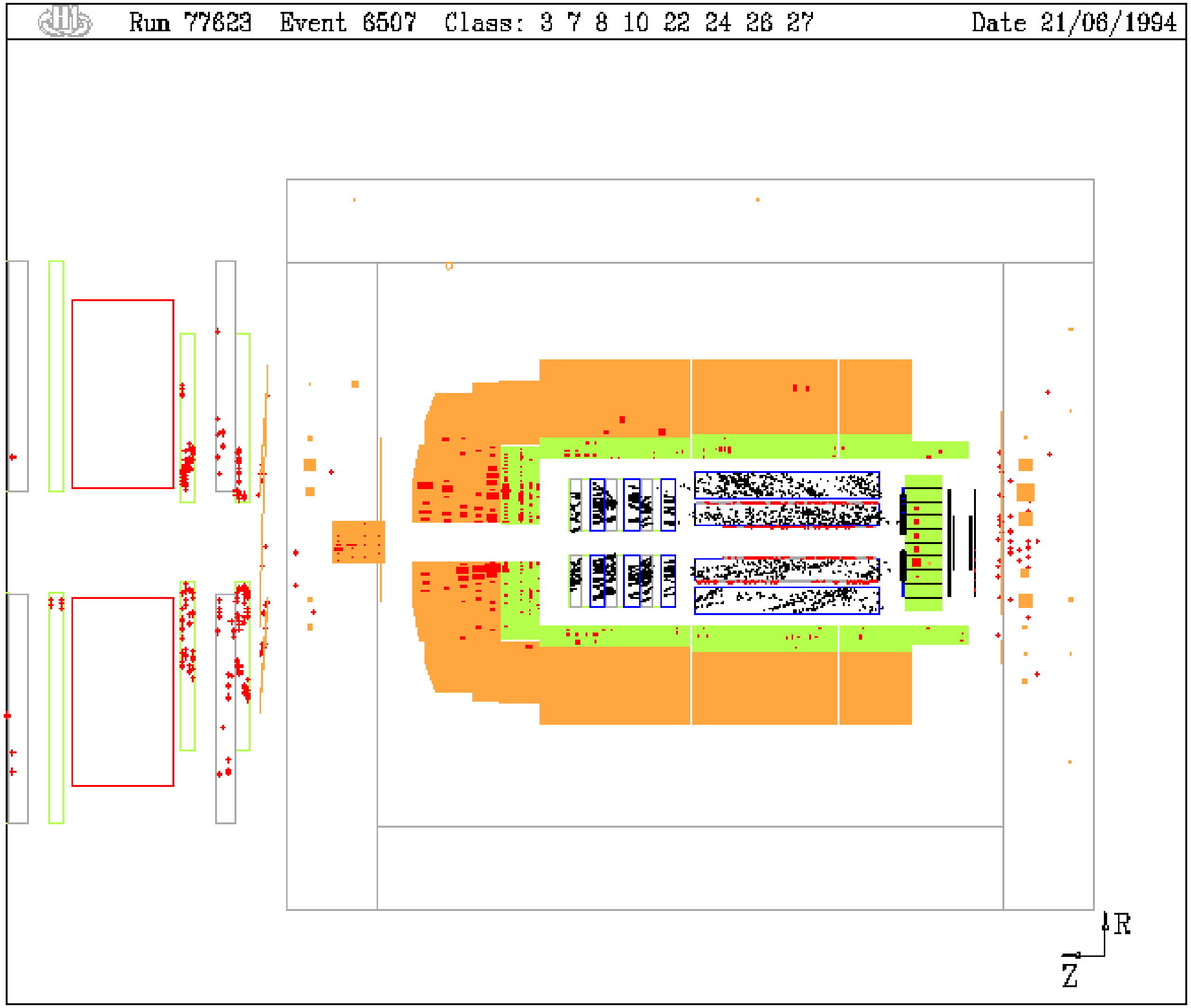
Some Events...



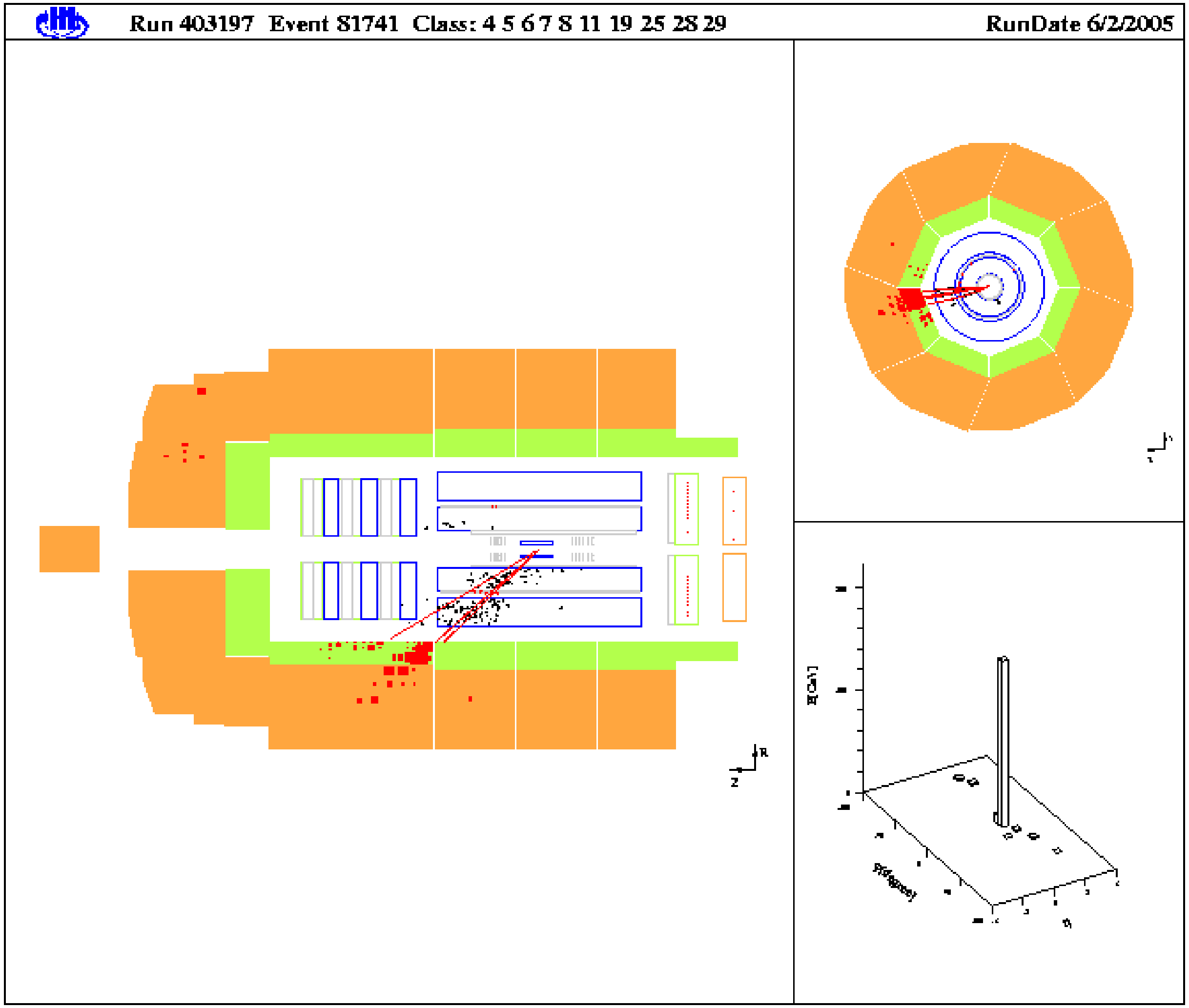
Some Events...


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

Some Events...



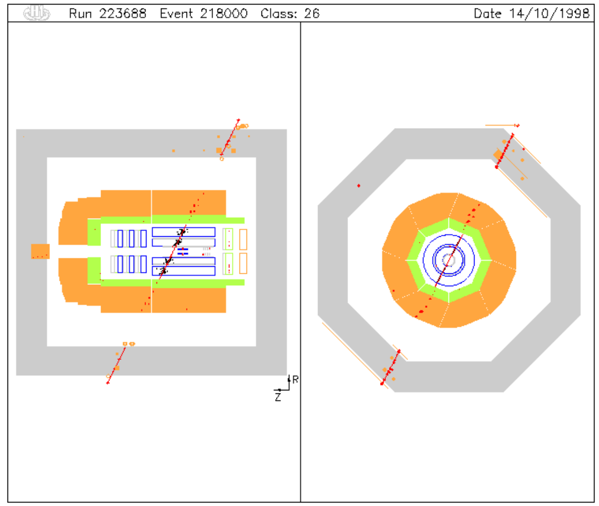
Some Events...

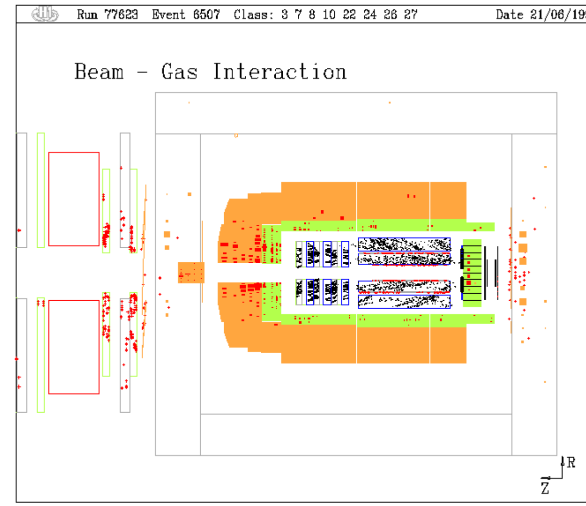

Run 403197 Event 81741 Class: 4 5 6 7 8 11 19 25 28 29
RunDate 6/2/2005

Event Rates

some kHz

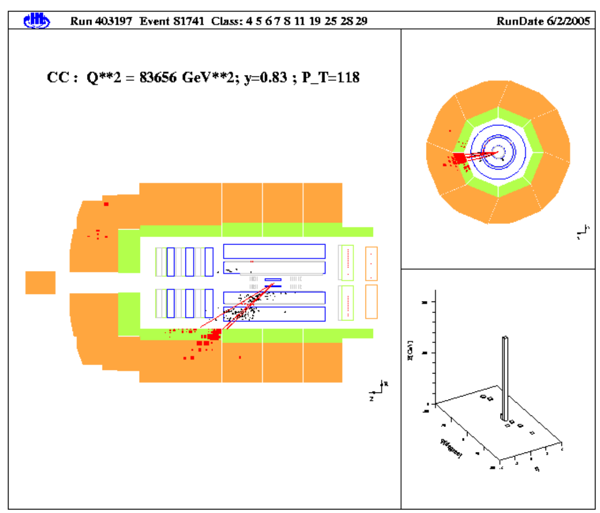
some Hz

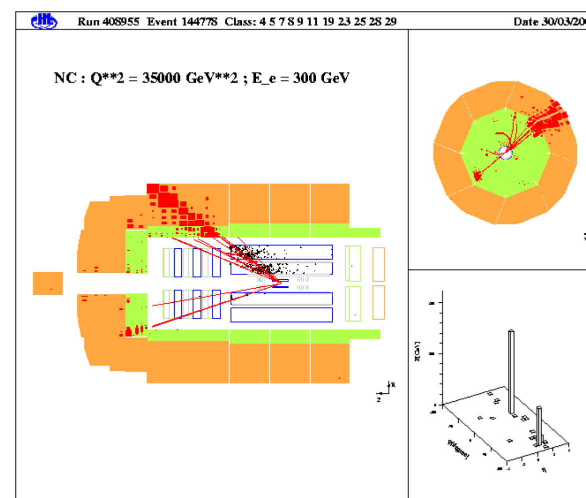




some min^{-1}

some hour^{-1}

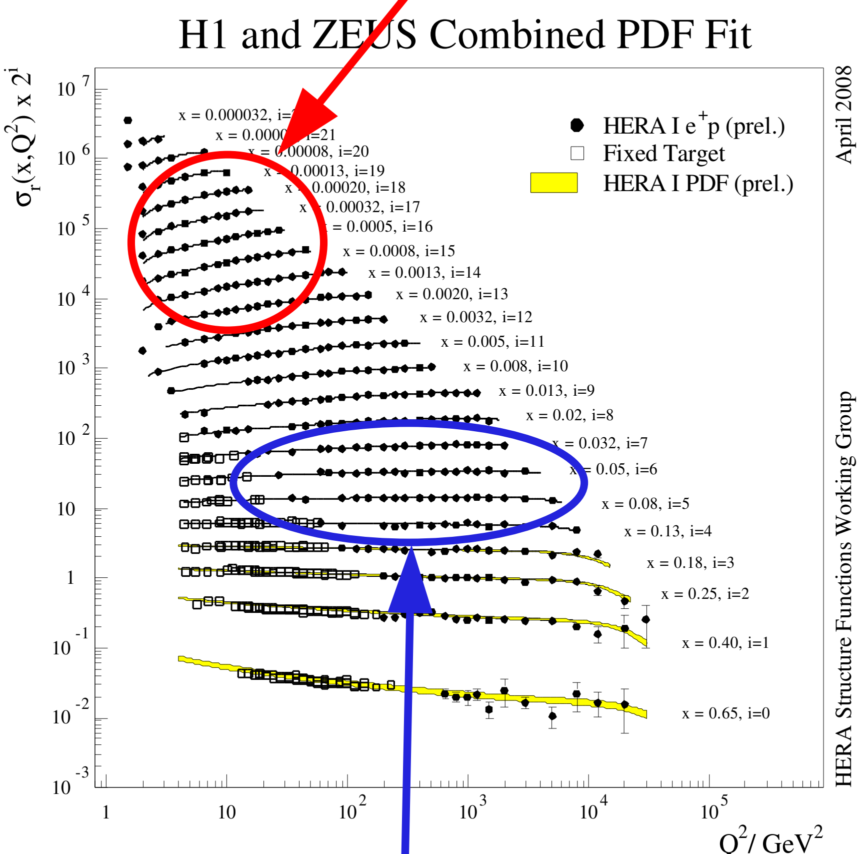




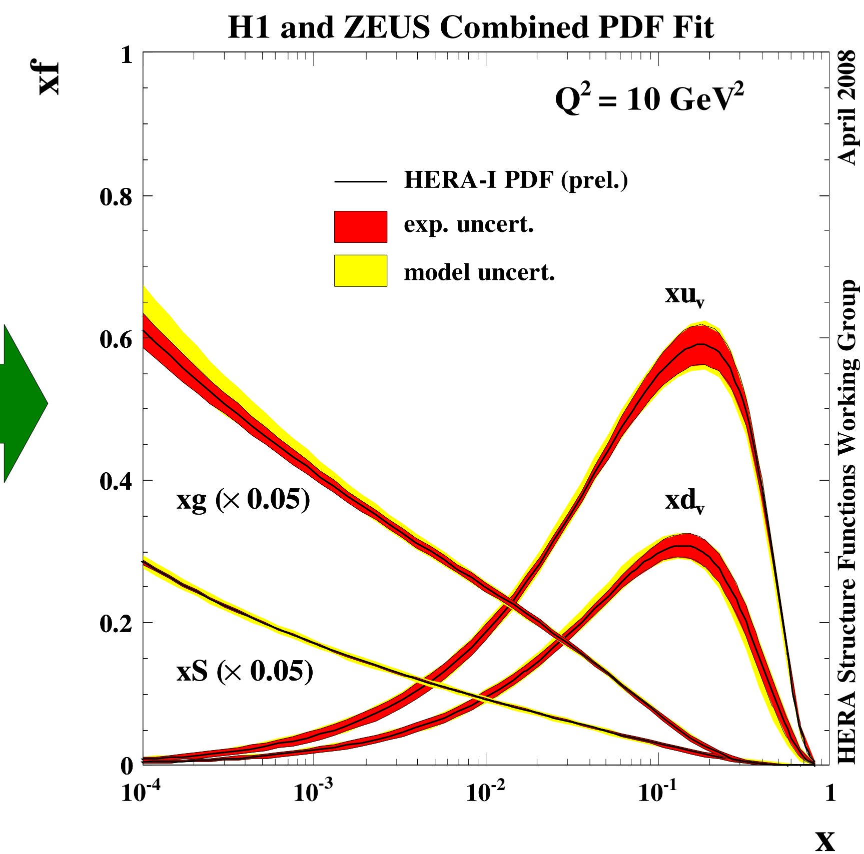
ep Scattering & Structure Functions

„The“ HERA Textbook Plots

gluons ?



?

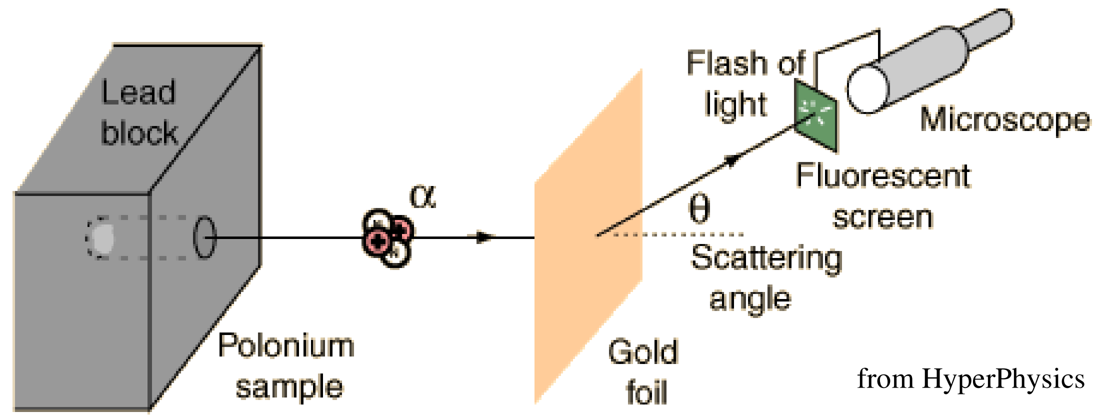


quarks ?

Rutherford Scattering

- first scattering experiment

➔ existence of the nucleus



from HyperPhysics

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

assumes

- Coulomb potential
- no spins
- no recoil

Elastic Electron Scattering

variables:

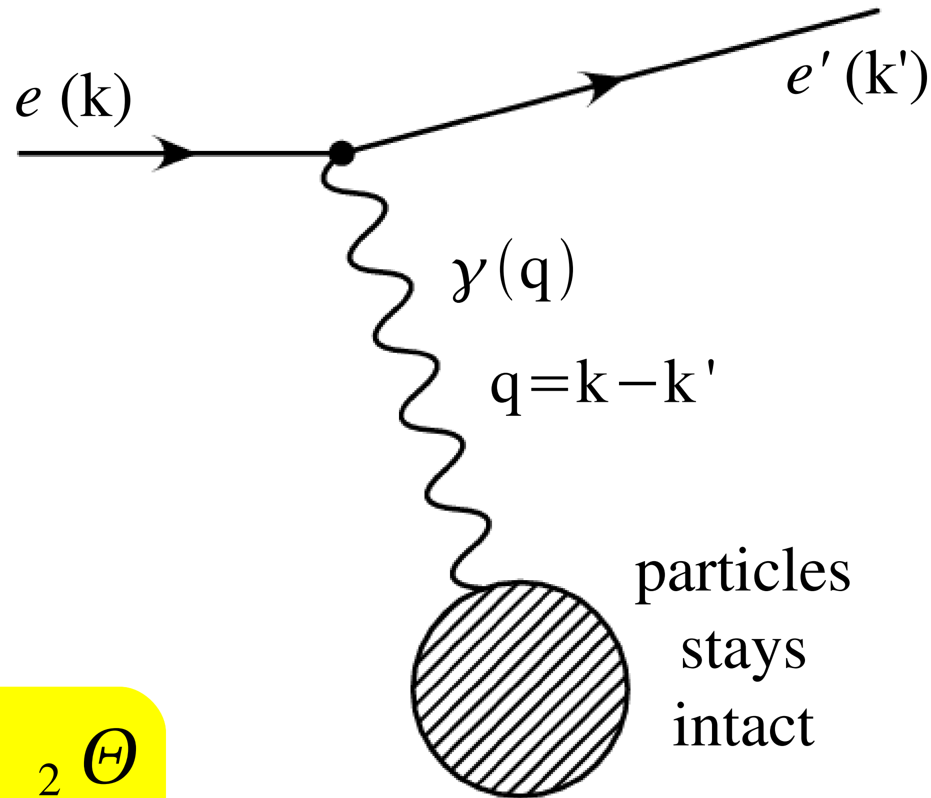
- $q \;\; = k - k'$
- $Q^2 = -q^2$
  $= 4\,E\,E'\sin^2(\Theta/2)$
- $E' = \dfrac{E}{1 + (2E/M)\sin^2(\Theta/2)}$

➔ 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

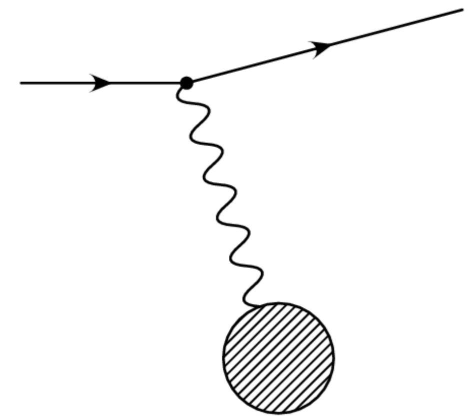
recoil



mass M,
charge z,
spin 0

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 Sacttering: electron on a pointlike charged particle with spin ½

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

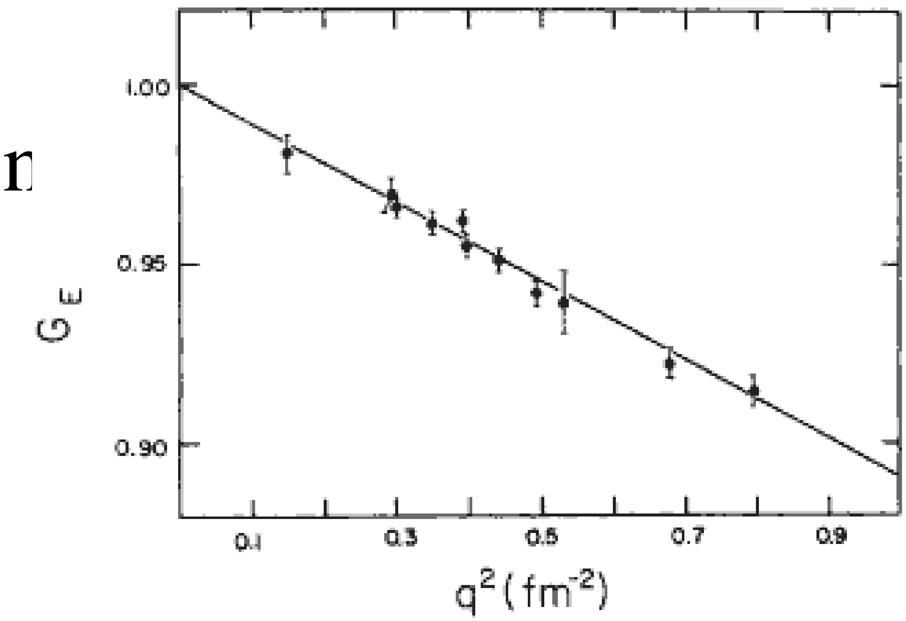
- electron on proton: „form factors“ needed:

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

  - → protons are not pointlike!

Electric Form Factor of the Proton

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



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

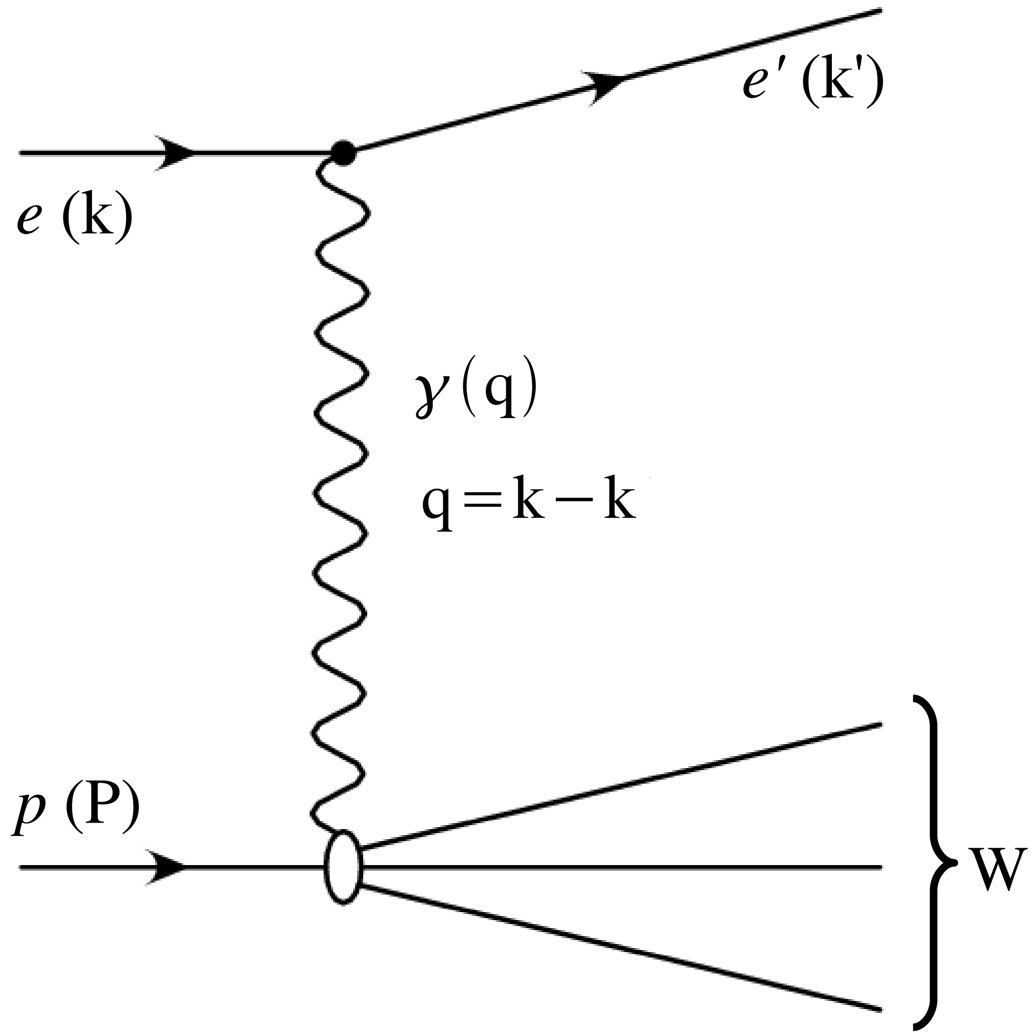
➔ elastic scattering only import at low Q^2

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!

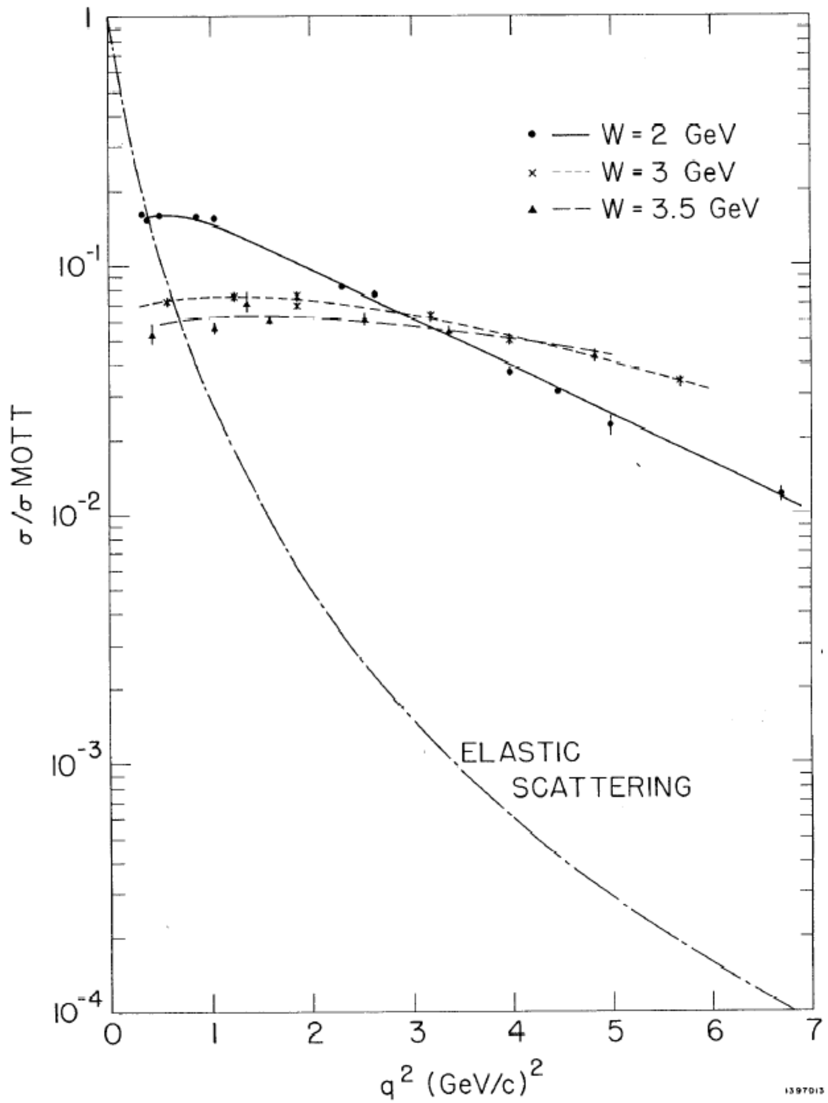


elastic: W = M

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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Department of Physics and Laboratory for Nuclear Science,*
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

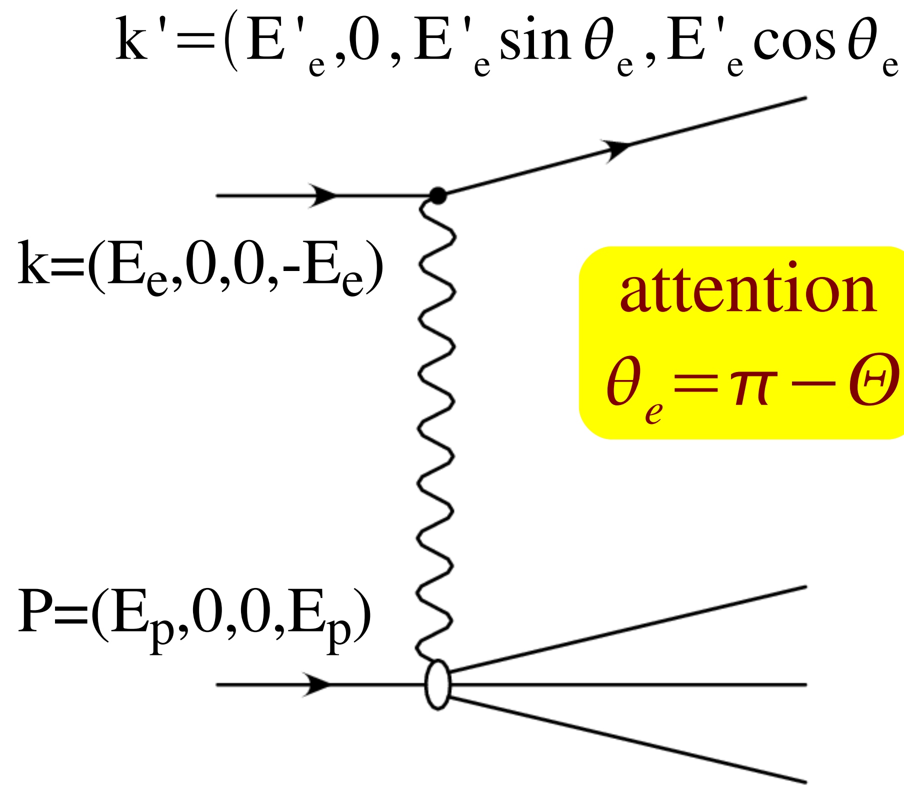
E. D. Bloom, D. H. Coward, H. DeStaebler,
J. Drees, L. W. Mo, R. E. Taylor
Stanford Linear Accelerator Center,† Stanford, California 94305

Deep Inelastic Scattering (DIS)

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

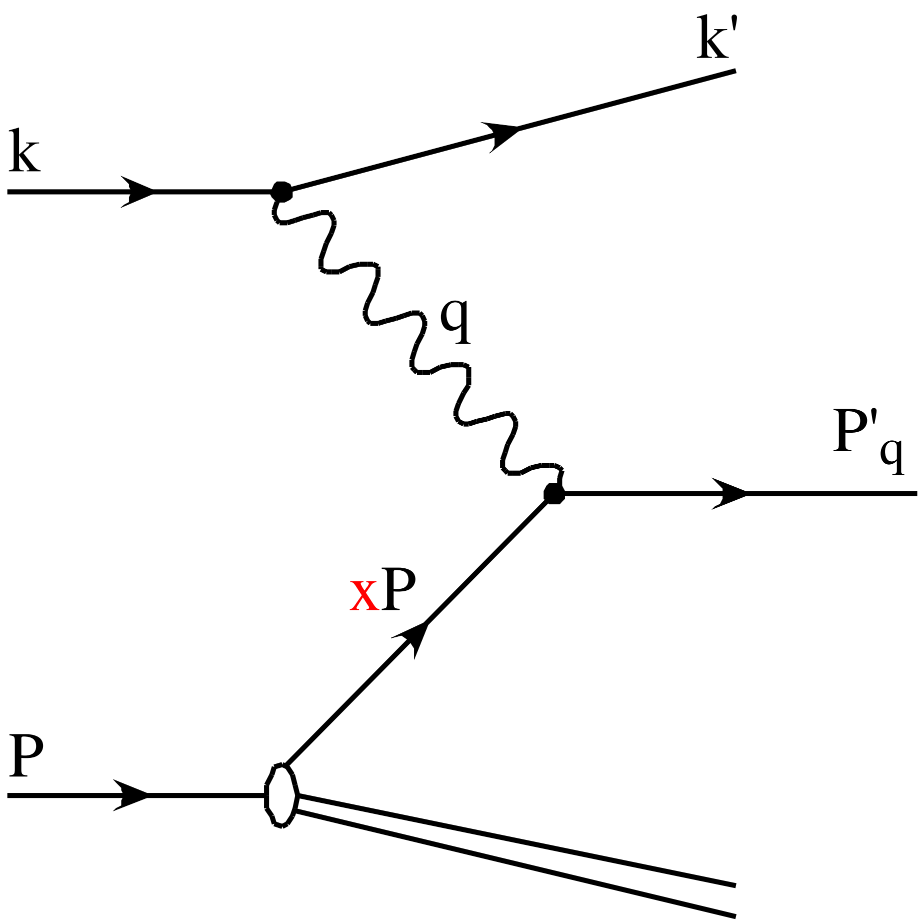
  → neglect m_e, M_p

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



- 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

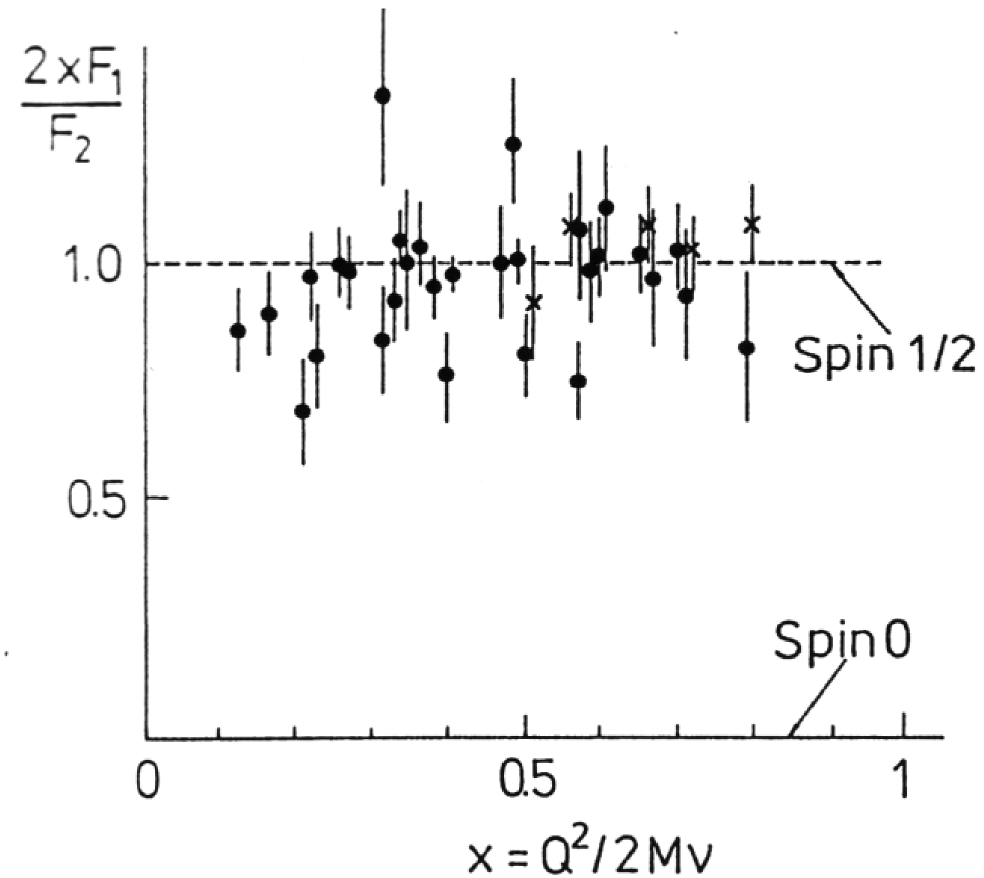
$$\left(\frac{d\sigma}{dQ^2}\right)_{\text{Dirac}} = \frac{4\pi\alpha^2 z^2}{Q^4}\left(\frac{E'}{E}\right)^2\left[\cos^2\frac{\Theta}{2} + \frac{Q^2}{2M^2}\sin^2\frac{\Theta}{2}\right]$$

➔ F_2 corresponds to electric field of the parton

➔ F_1 corresponds to spin of the parton

Parton Spin

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

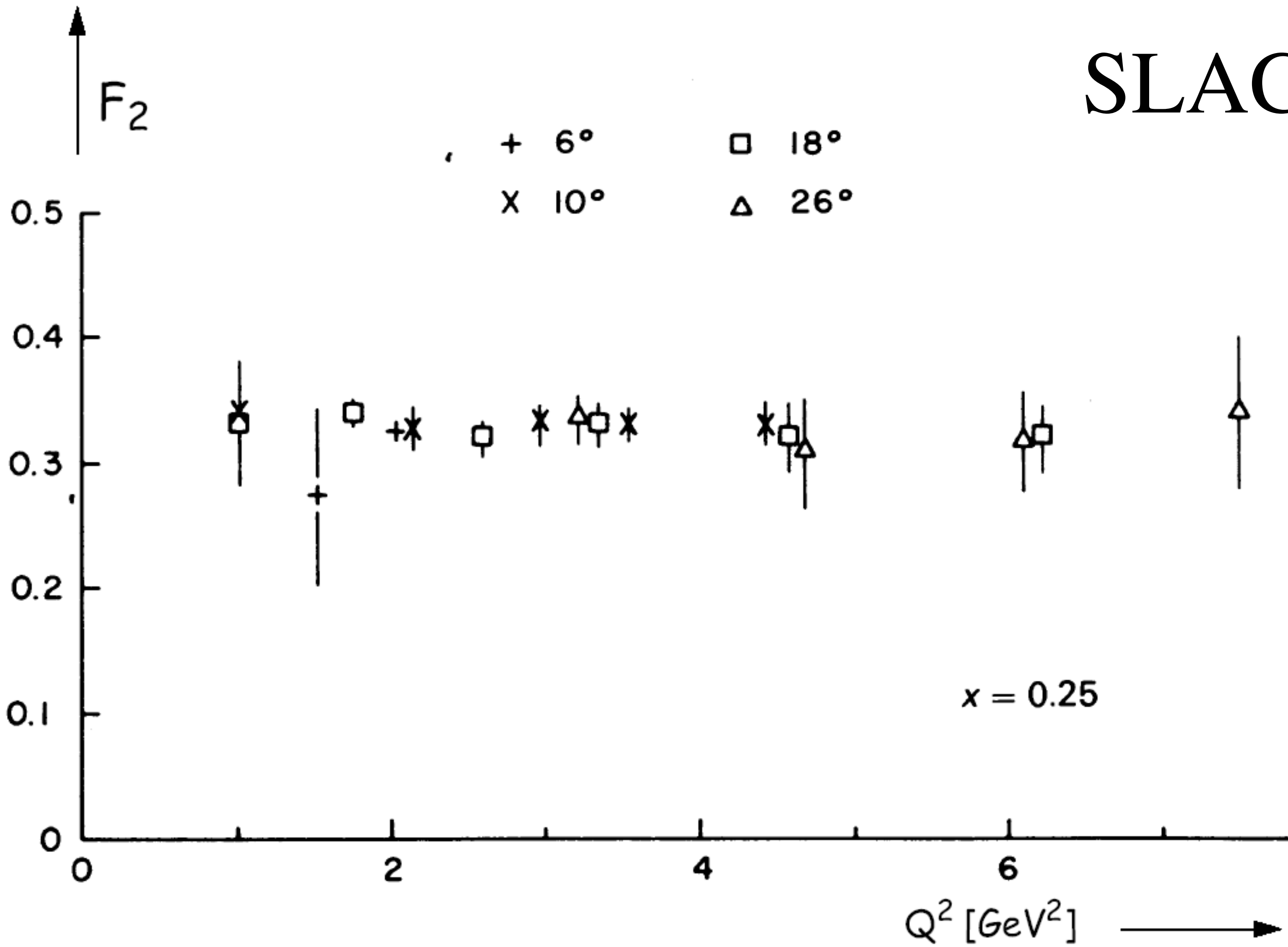


partons
have spin ½

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

Scaling: F_2 independent of Q^2

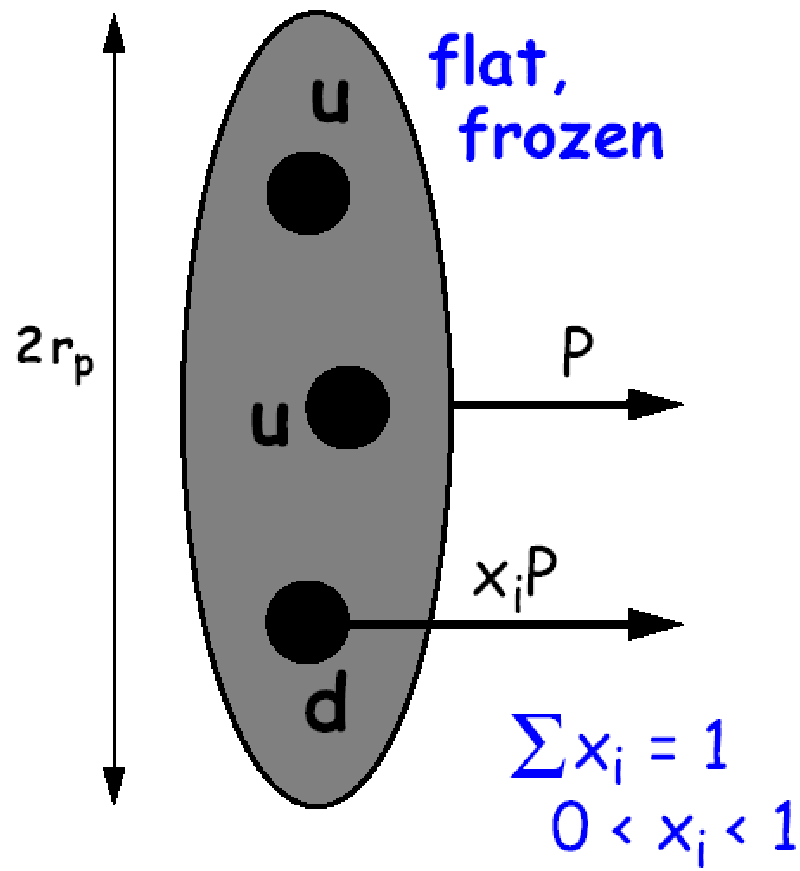
SLAC 1972



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

(Naive) Quark Parton Model

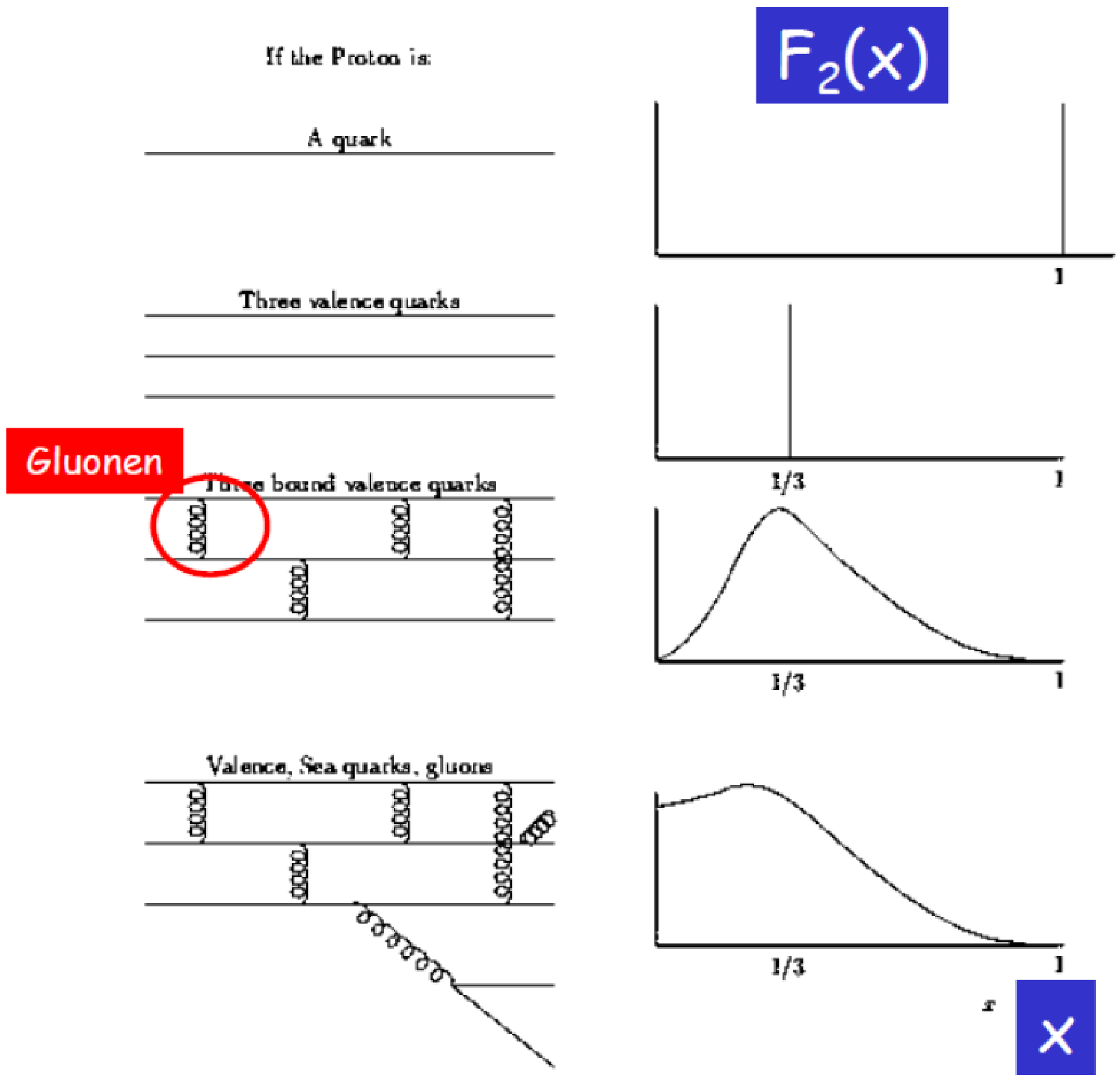
- proton consists of 3 partons, identified with the QCD quarks
- during the interaction proton is „frozen“
- electron proton scattering is sum of incoherent electron quark scatterings
- proton structure is defined by parton distributions



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

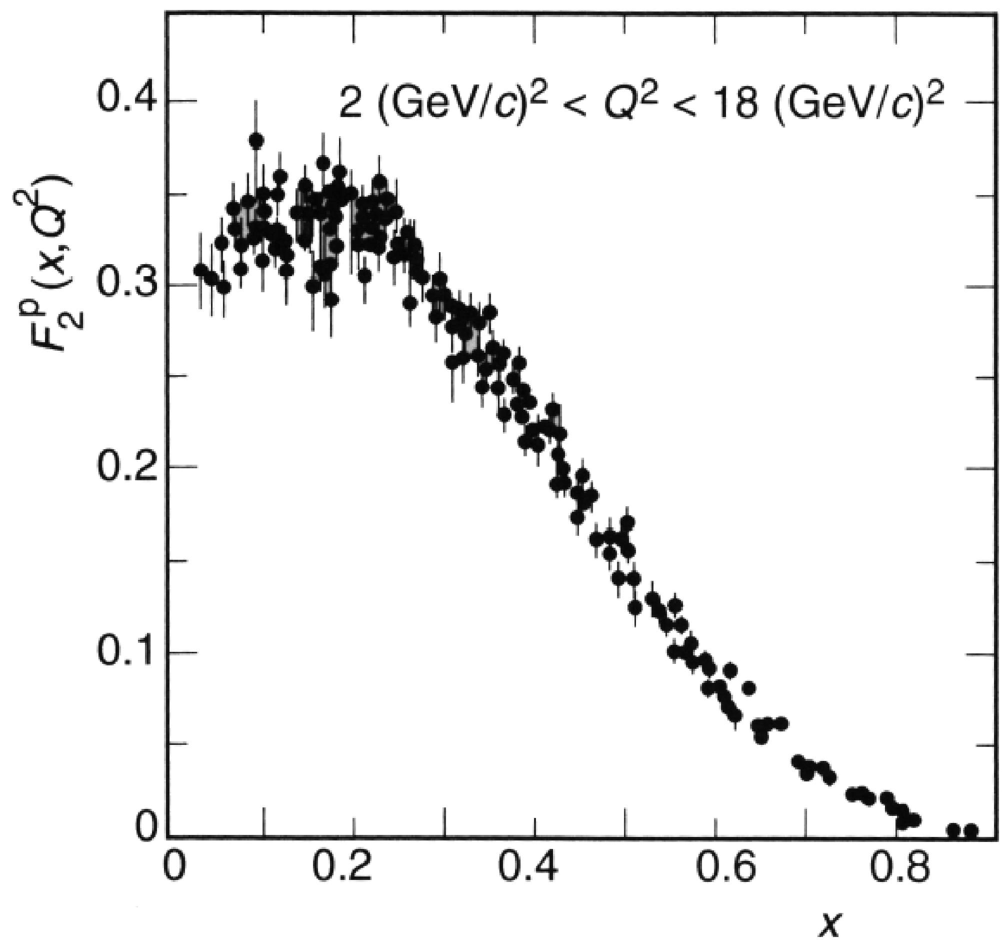
How does $F_2(x)$ look like?

How does $F_2(x)$ look like?



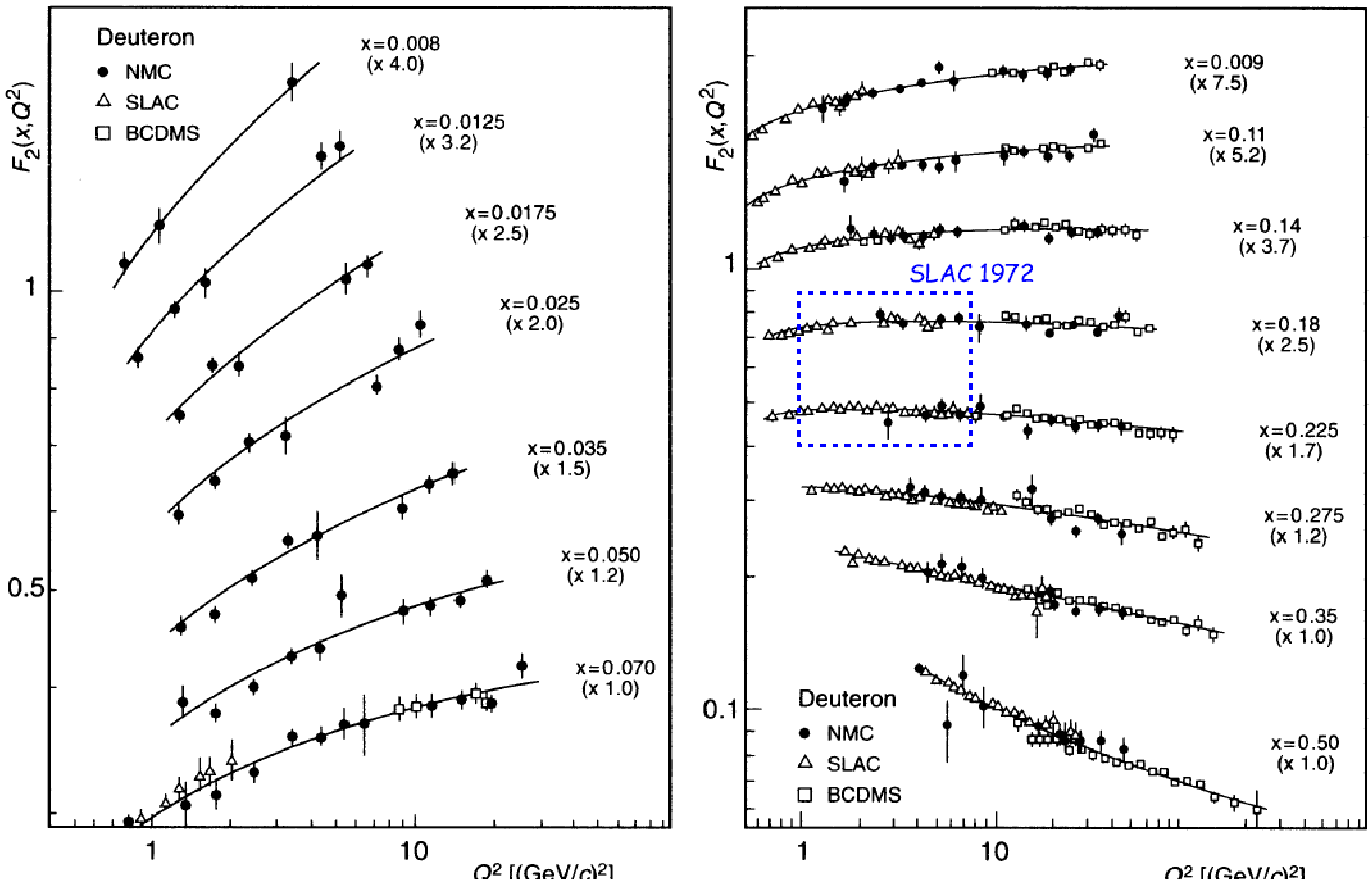
How does $F_2(x)$ look like?

what happens at low x?



from Povh et al., „Teilchen und Kerne“

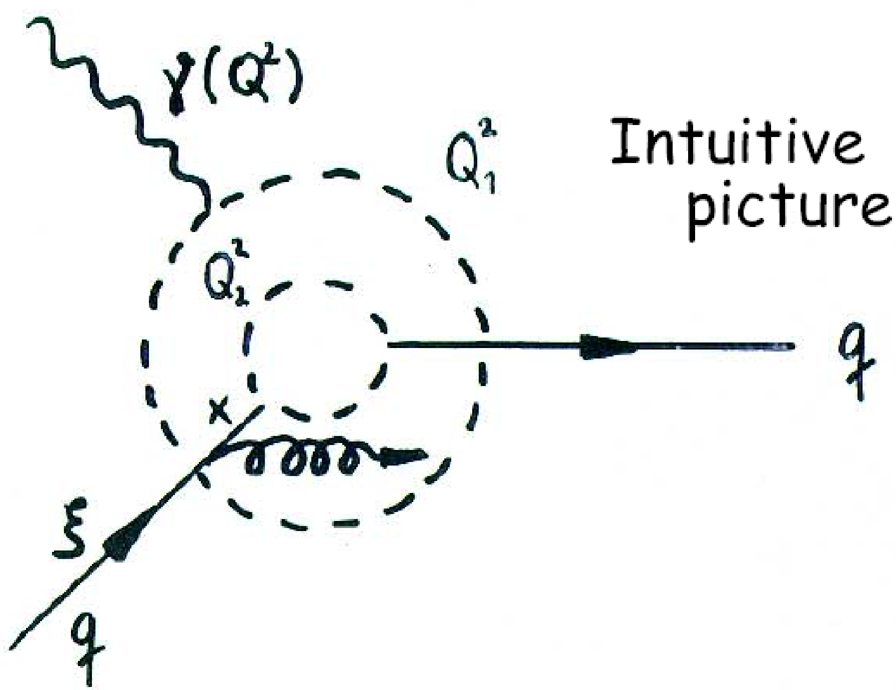
Scaling Violations



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

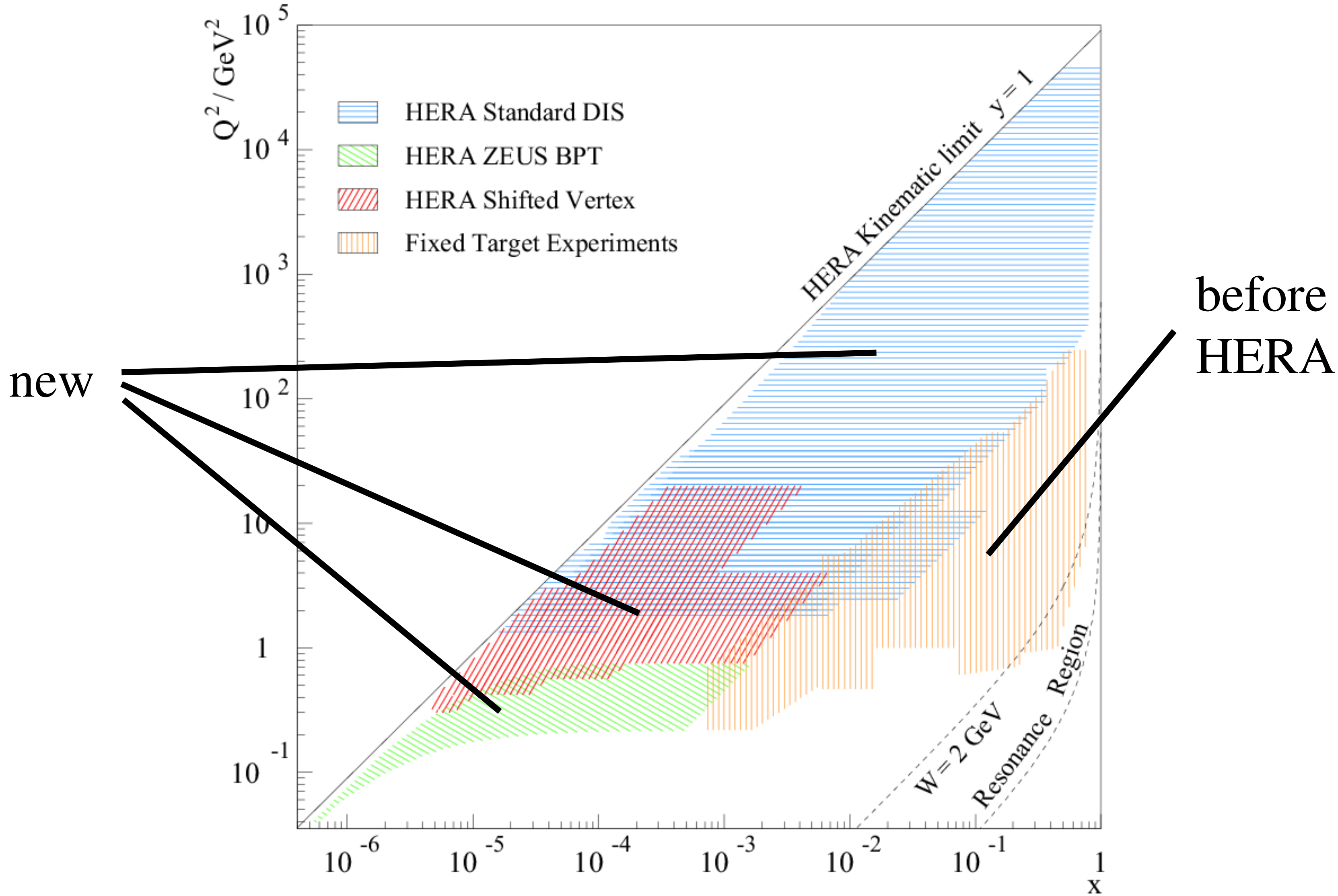
DGLAP Evolution Equations

$$\frac{\partial}{\partial \log Q^2}\begin{bmatrix} q(x,Q^2) \\ g(x,Q^2) \end{bmatrix} = \frac{\alpha_s}{2\pi}\begin{bmatrix} \mathcal{P}_{q/q} & \mathcal{P}_{q/g} \\ \mathcal{P}_{g/q} & \mathcal{P}_{g/g} \end{bmatrix} \otimes \begin{bmatrix} q(x,Q^2) \\ g(x,Q^2) \end{bmatrix}$$

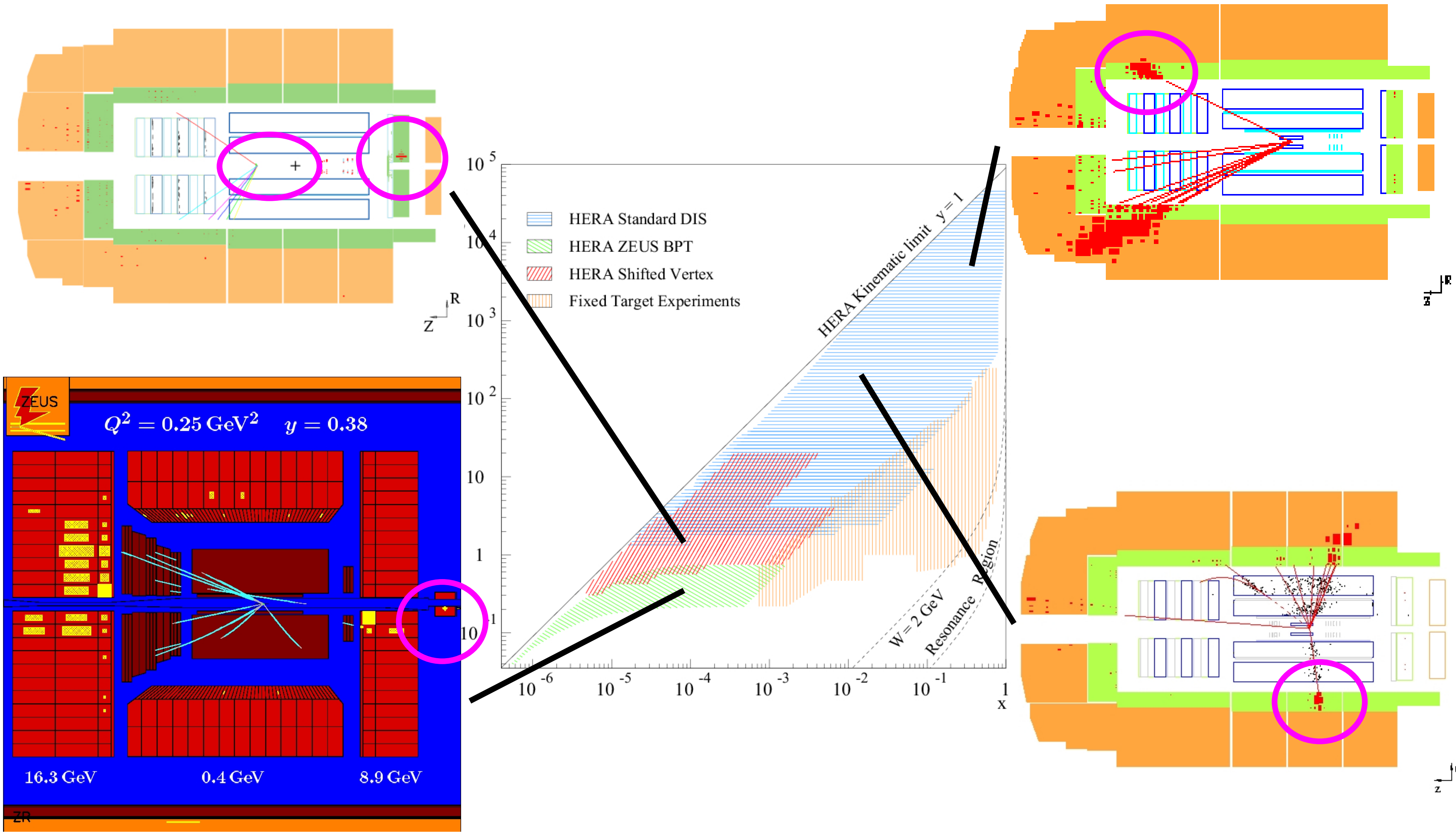
$$\mathcal{P} \otimes f(x,Q^2) = \int_x^1 \frac{dy}{y}\, \mathcal{P}(x/y)\, f(y,Q^2)$$

- 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 $\longrightarrow$ initial condition needed

HERA Kinematic Range

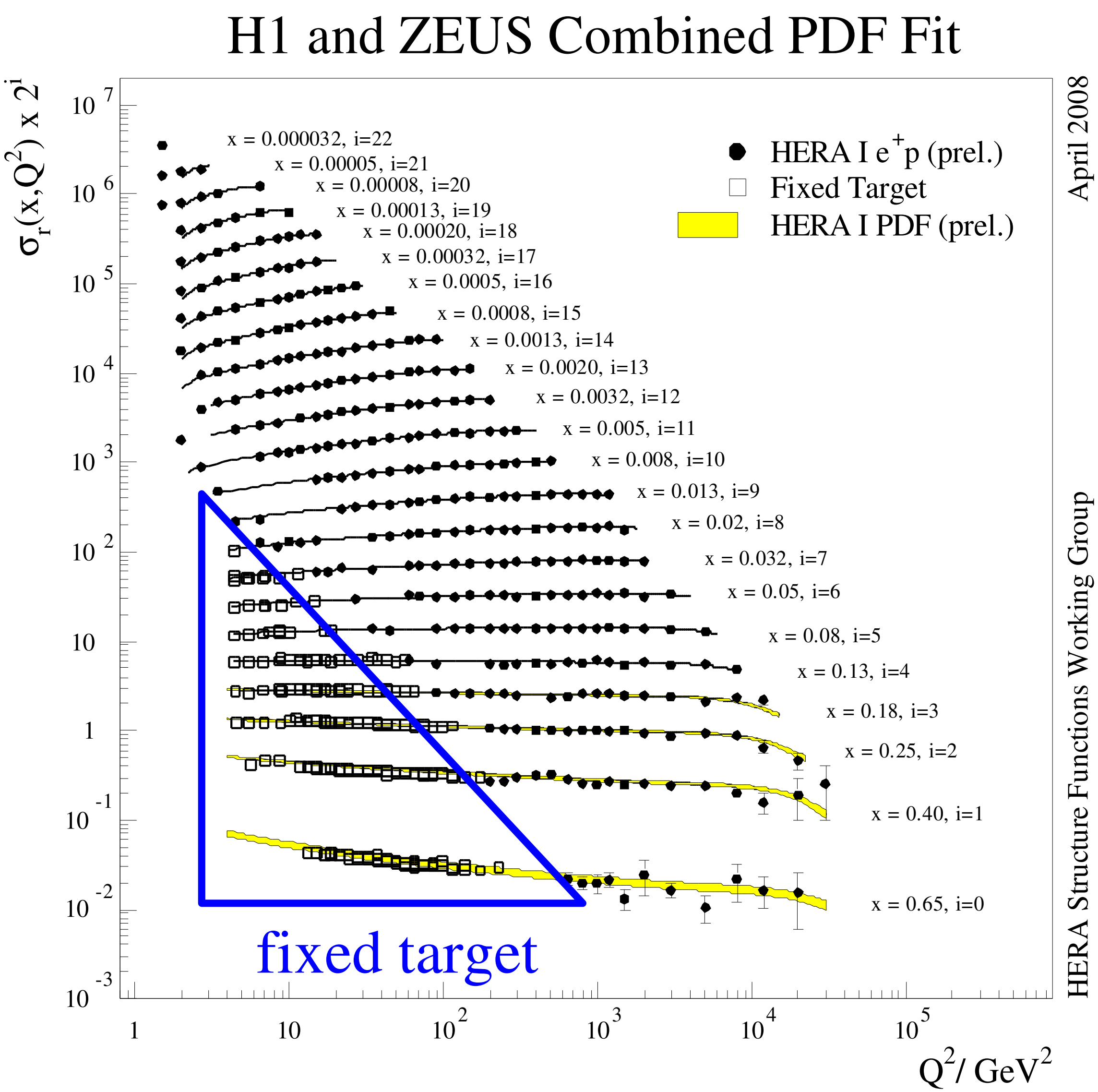


Events in Different Regions



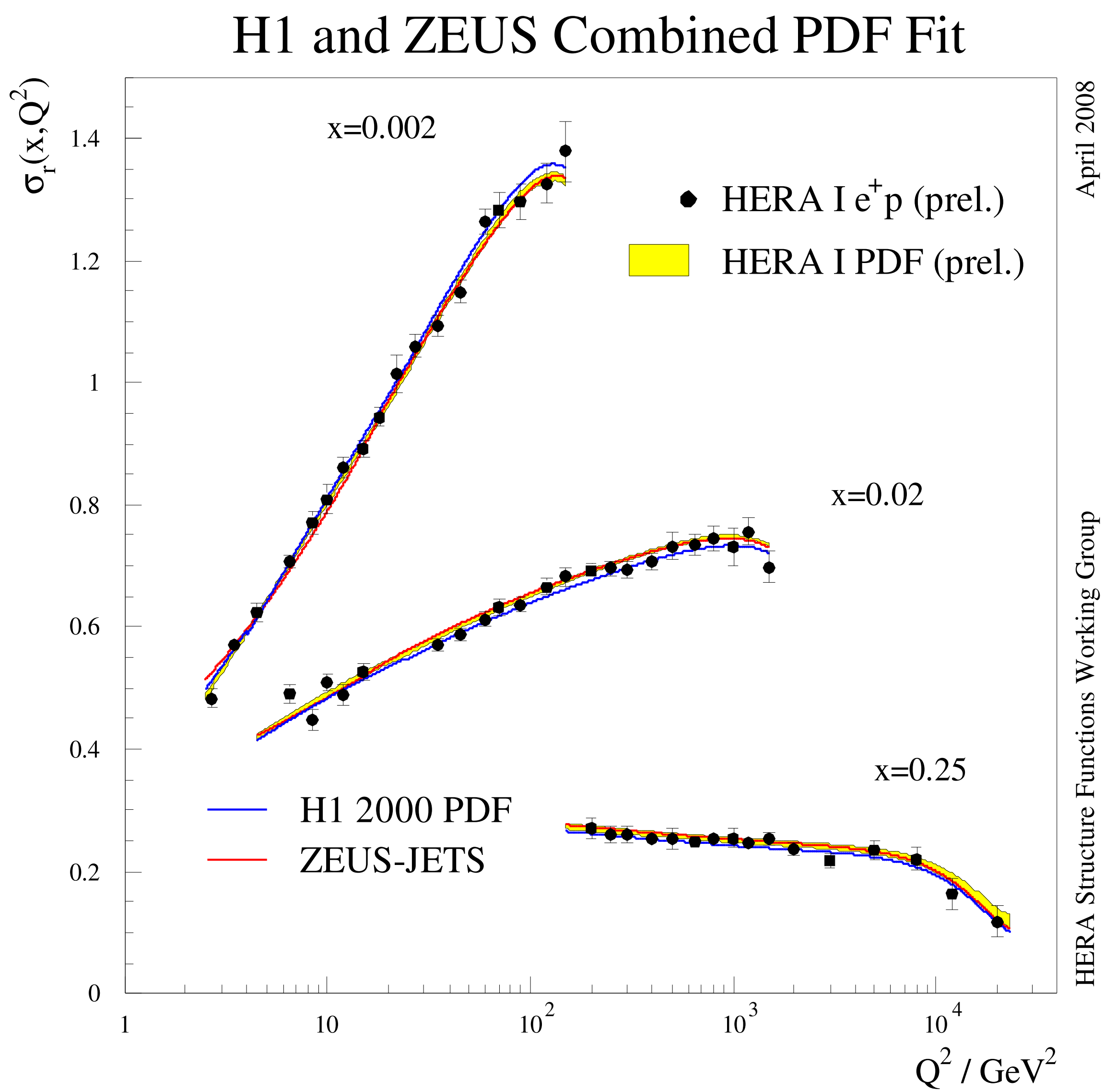
F_2 vs. Q^2

- 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

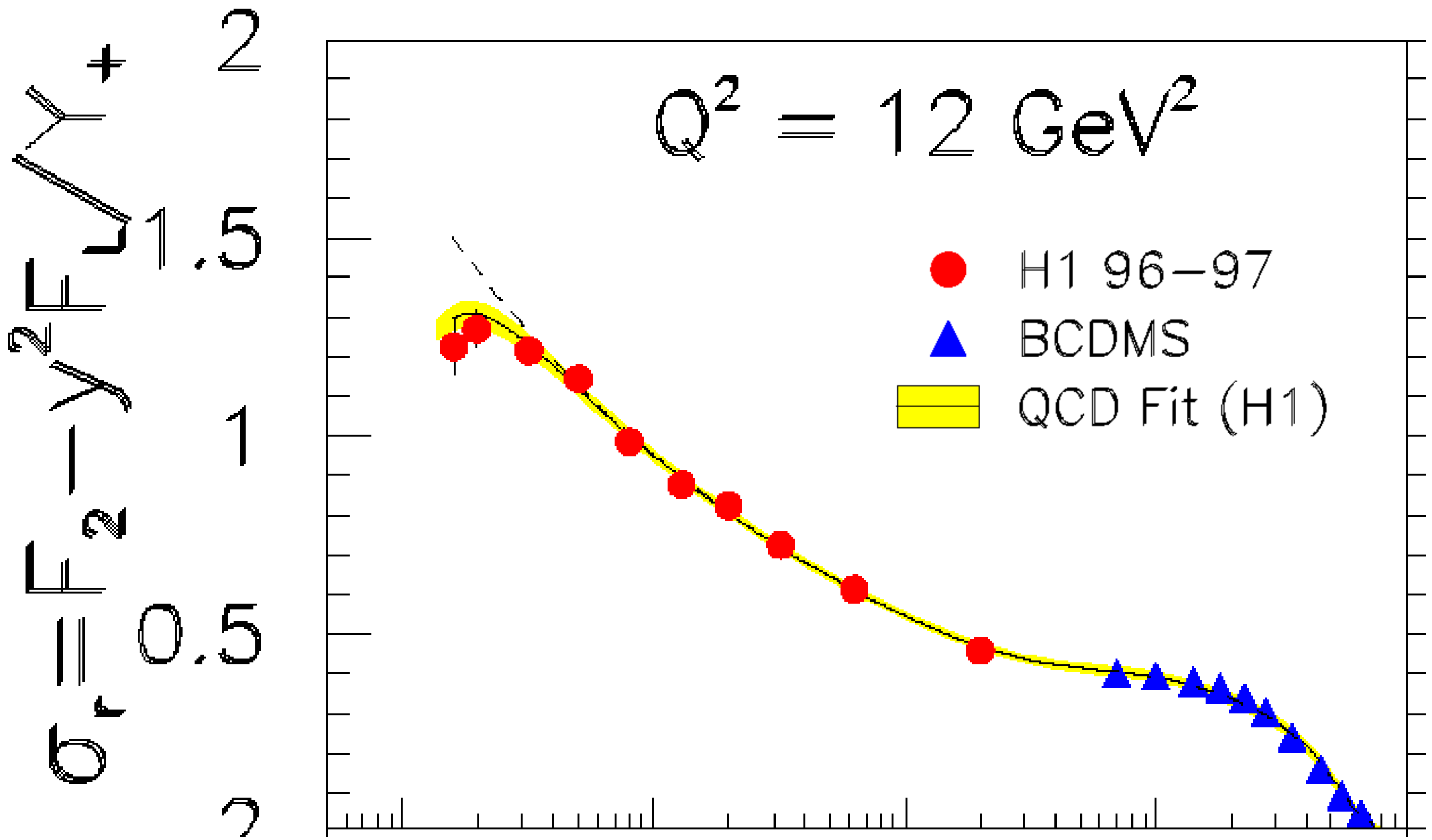


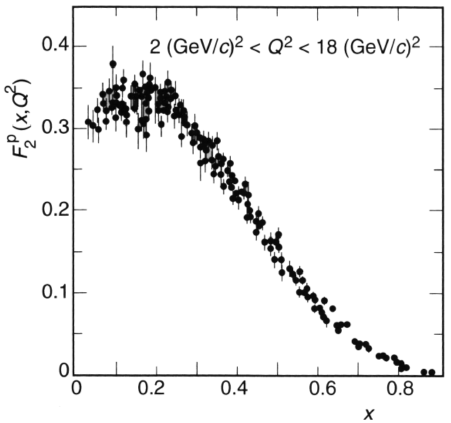
F_2 vs. Q^2: example bins

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

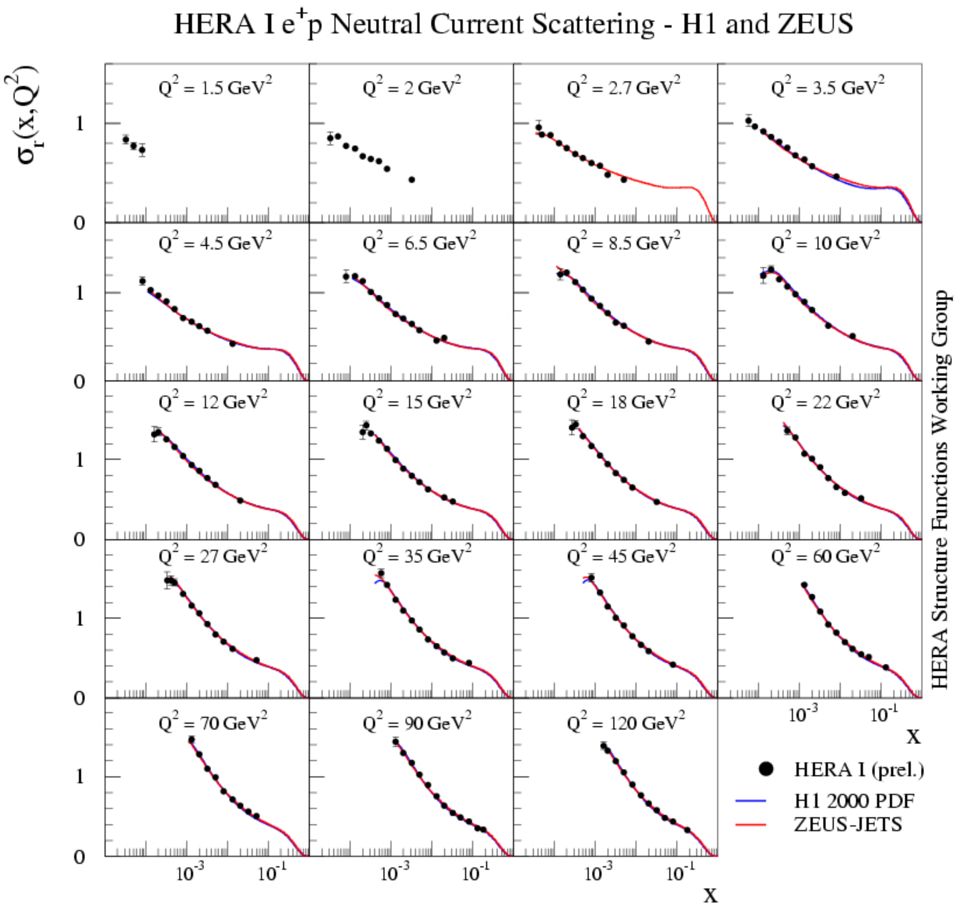


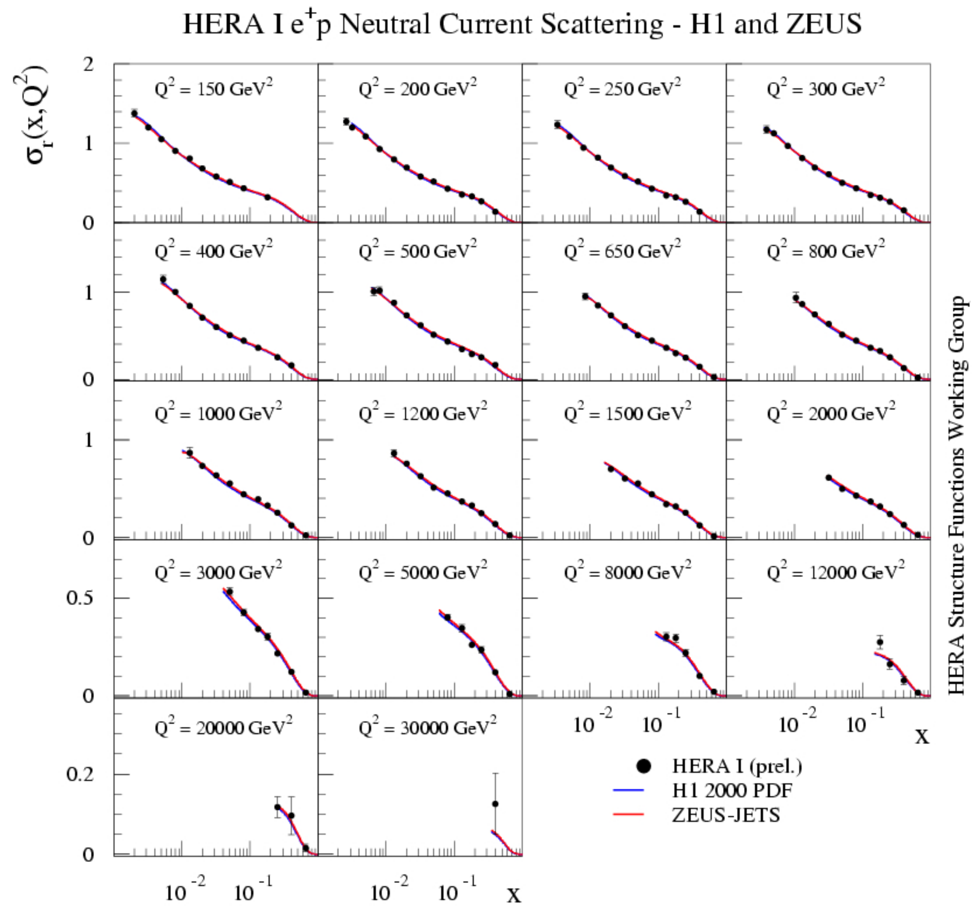
How does $F_2(x)$ look like?





F_2 vs. x





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

DGLAP Evolution Equations

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- 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

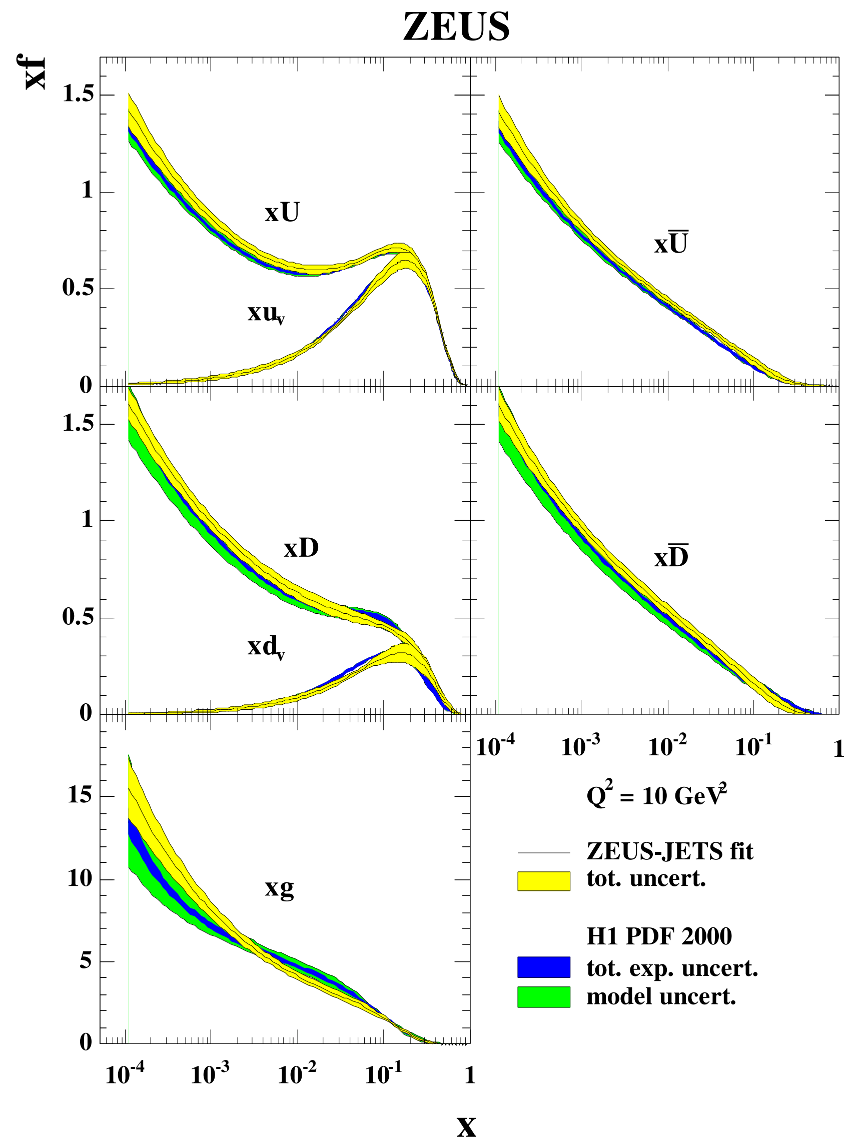
- ➔ assume parametrisation of the parton density functions (PDFs) as a function of x at a starting scale Q_0^2 (typically around 4 - 7 GeV^2):
  $$x\, q(x, Q_0^2) = A\, x^B (1-x)^C \left[1 + D\,x + E\,x^2 + F\,x^3\right]$$
- ➔ evolve the PDFs to all measured Q^2, calculate F_2, and fit the parameters to match the data

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

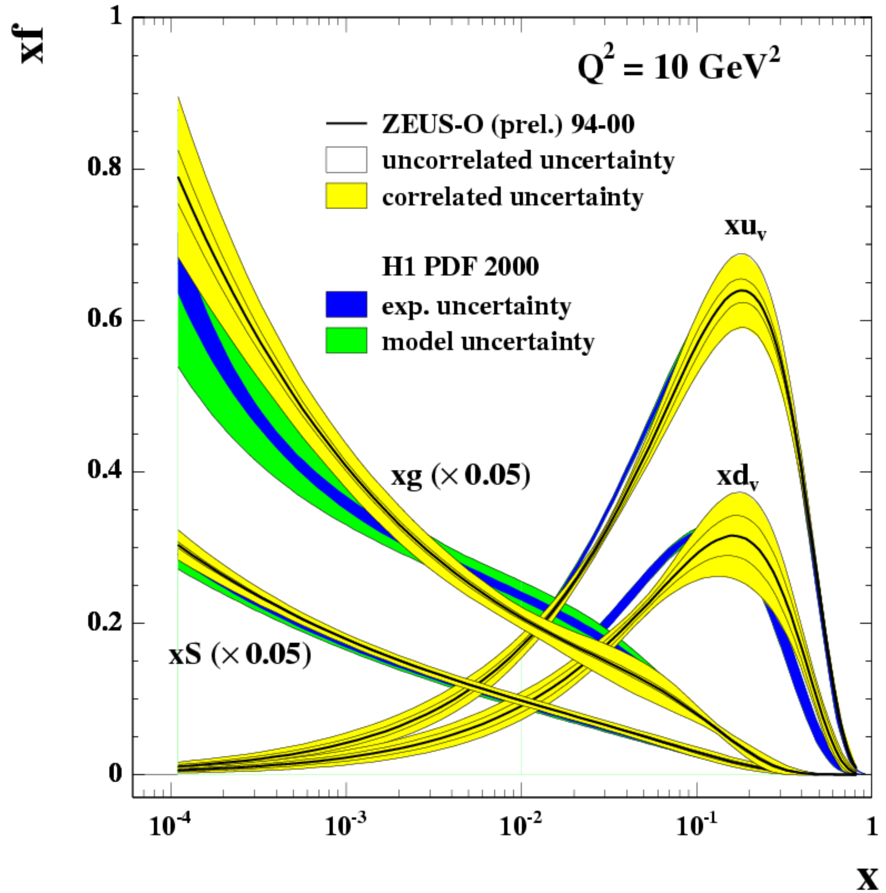
Parton Density Fits

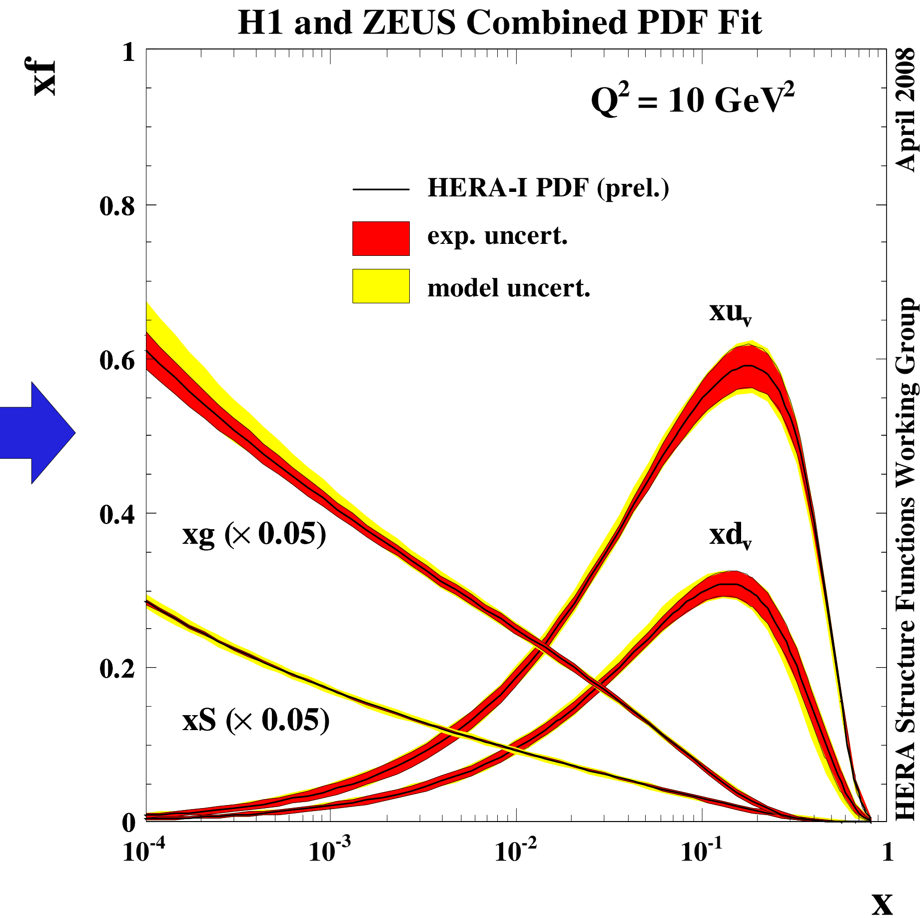
quark and antiquark densities:

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



Combined H1 & ZEUS Parton Density





combination of data from H1 and ZEUS
gives big improvements!

Longitudinal Structure Function F_L

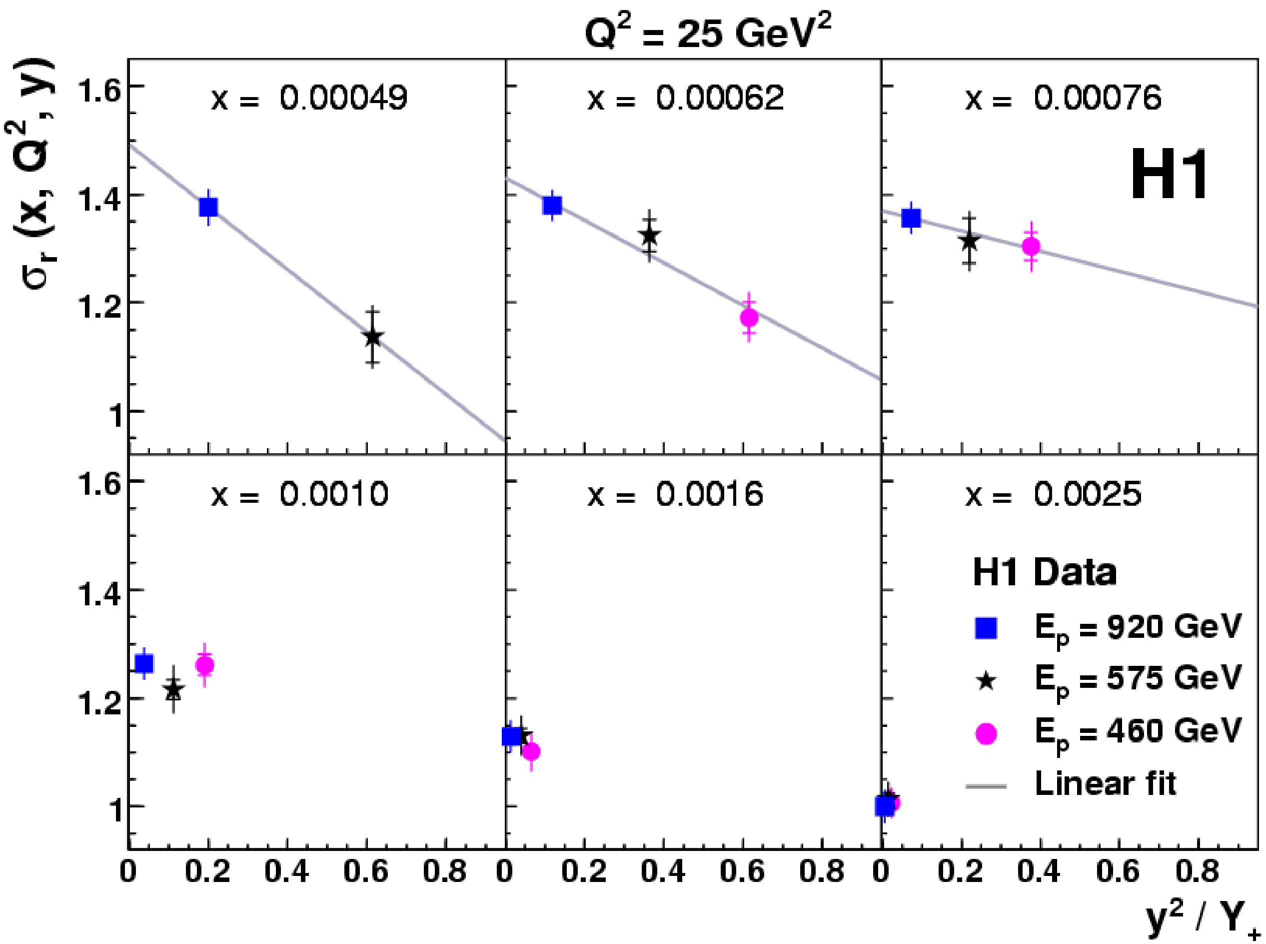
- Callan-Gross relation $2\,x\,F_1 = F_2$ only true in naive Quark-Parton-Model
- the longitudinal structure function F_L is defined as $F_L = F_2 - 2\,x\,F_1$
- F_L is directly proportional to the gluon density
- for a measurement of F_L one needs data at the same x and Q^2, but different y

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

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

➔ measure at different beam energies!

•Longitudinal Structure Function F_L



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

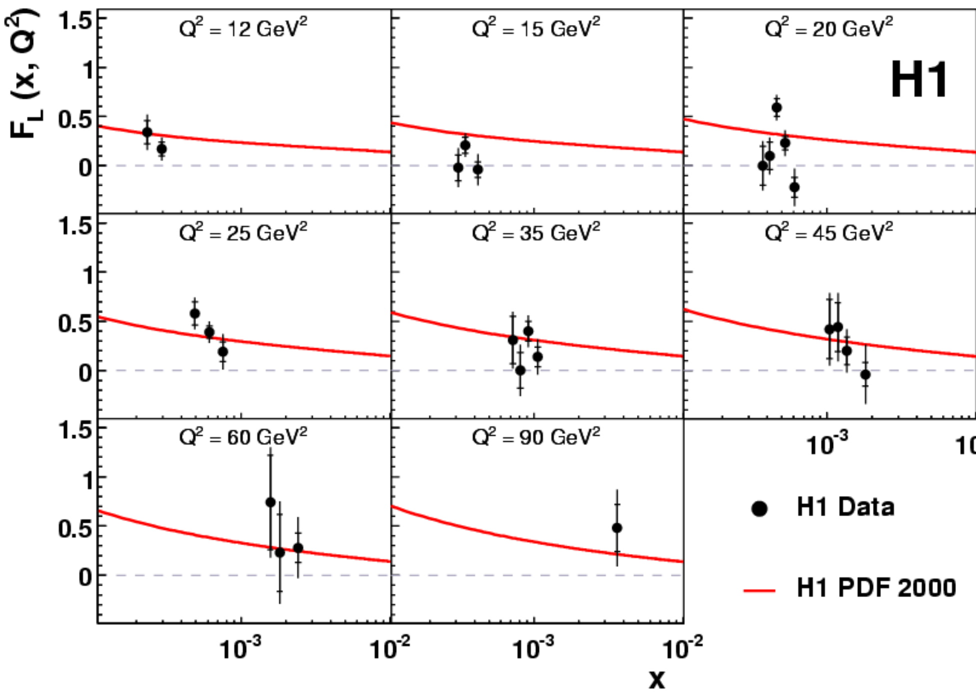
$$= F_2(x, Q^2) - \frac{y^2}{Y_+} F_L(x, Q^2)$$

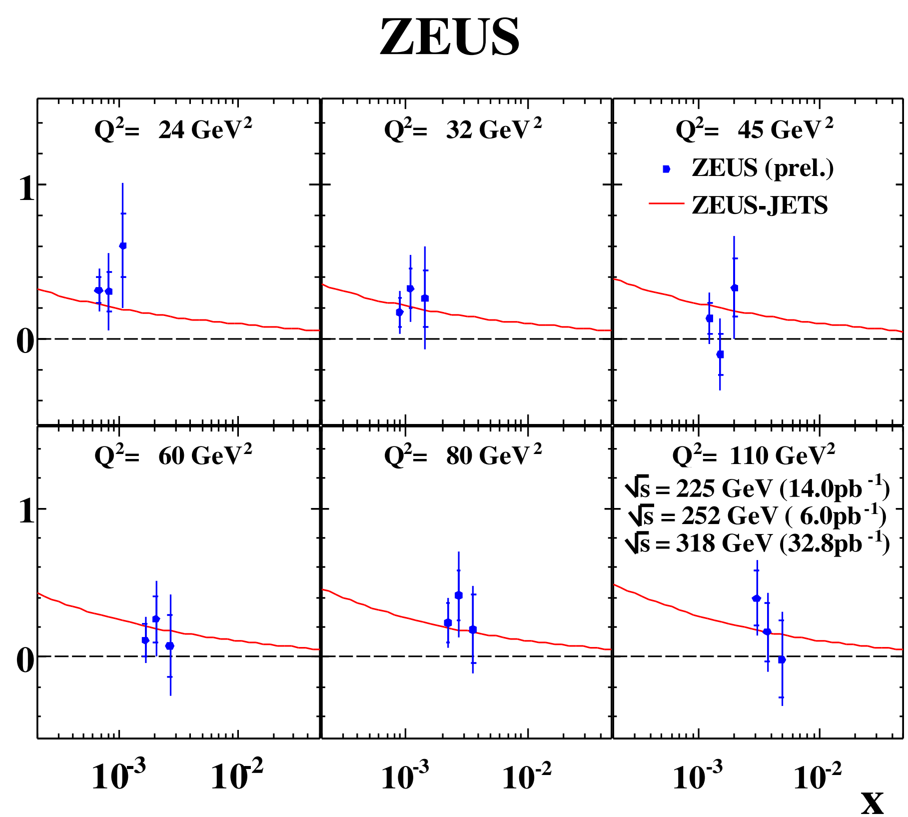
with $Y_+ = 1 + (1-y)^2$

- linear expression in y^2/Y_+

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

Longitudinal Structure Function F_L





- consistent with PDF fit to F_2
- most precise information on gluon still from scaling violations

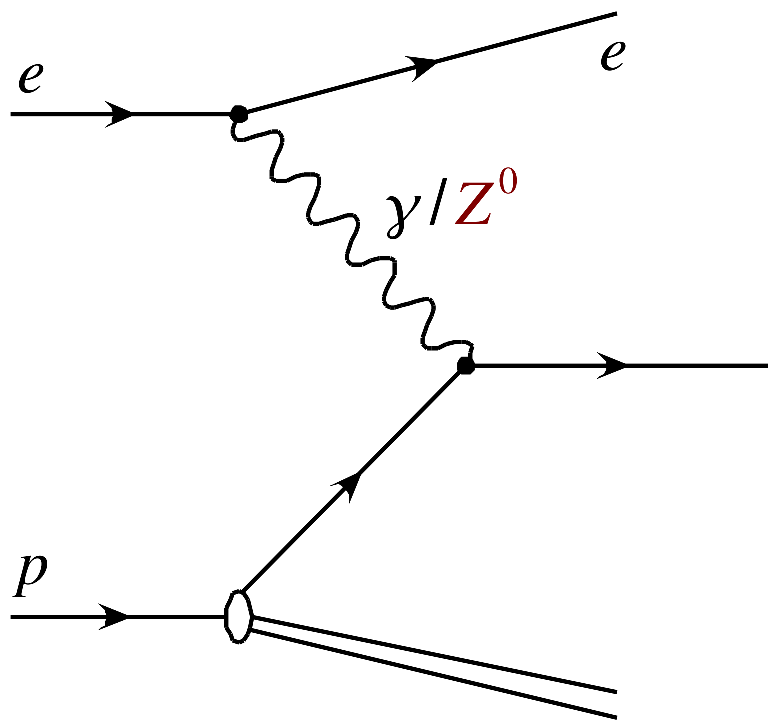
High Q^2 & Electroweak Physics

More Structure Functions

$F_L = F_2 - 2xF_1 = 0$ in the QPM

$$\frac{d^2\sigma^{\pm}_{NC}}{dx\,dQ^2} = \frac{2\pi\alpha^2}{Q^4}\frac{1}{x}Y_+\left[F_2(x,Q^2) - \frac{y^2}{Y_+}\boxed{F_L(x,Q^2)} \mp \frac{Y_-}{Y_+}x\boxed{F_3(x,Q^2)}\right]$$

$F_3: \gamma - Z^0 -$ interference



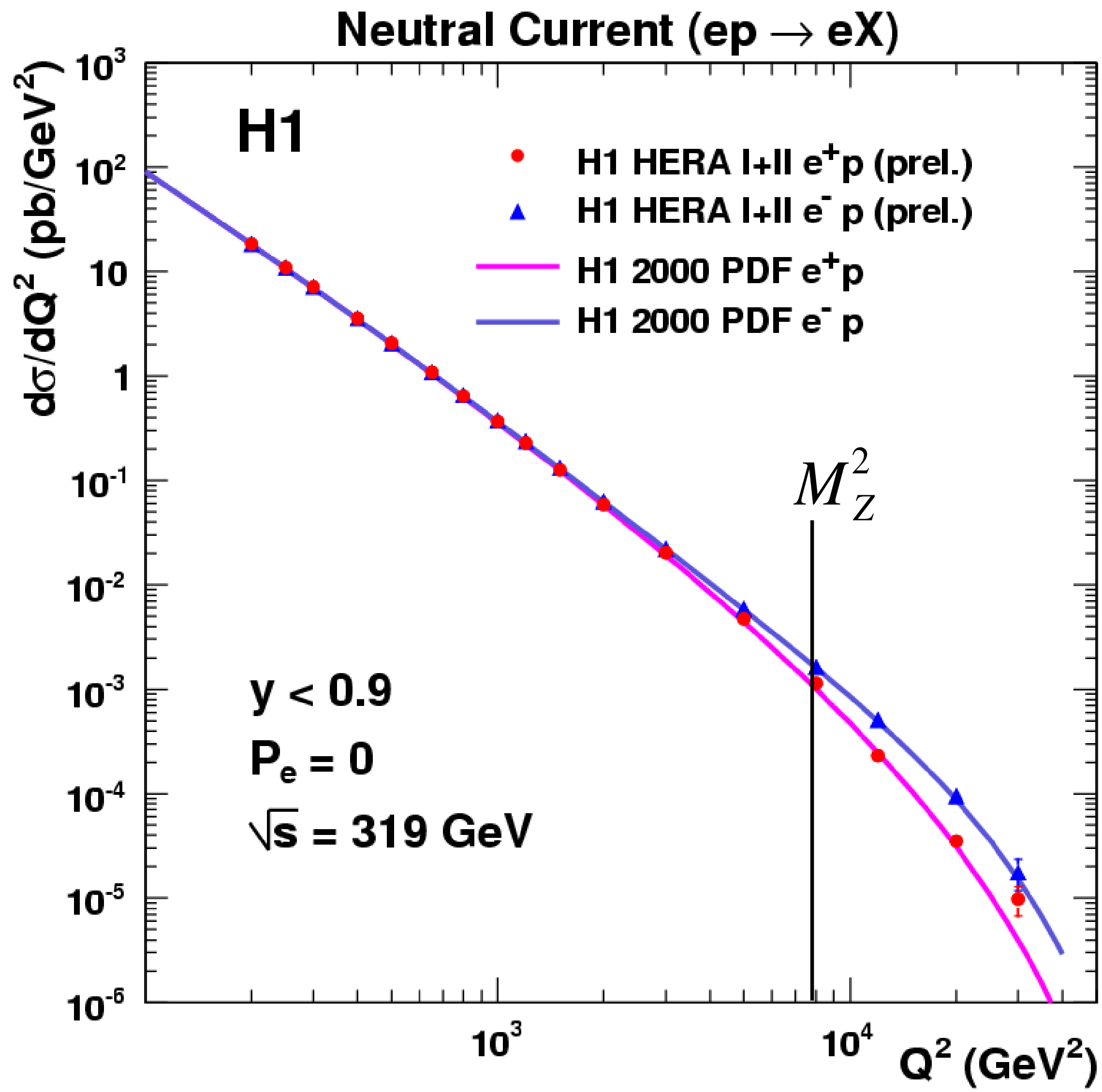
$$Y_\pm = 1 \pm (1-y)^2$$

- F_L relevant only at large y
- F_3 relevant only at large Q^2, different sign for e^+ and e^-

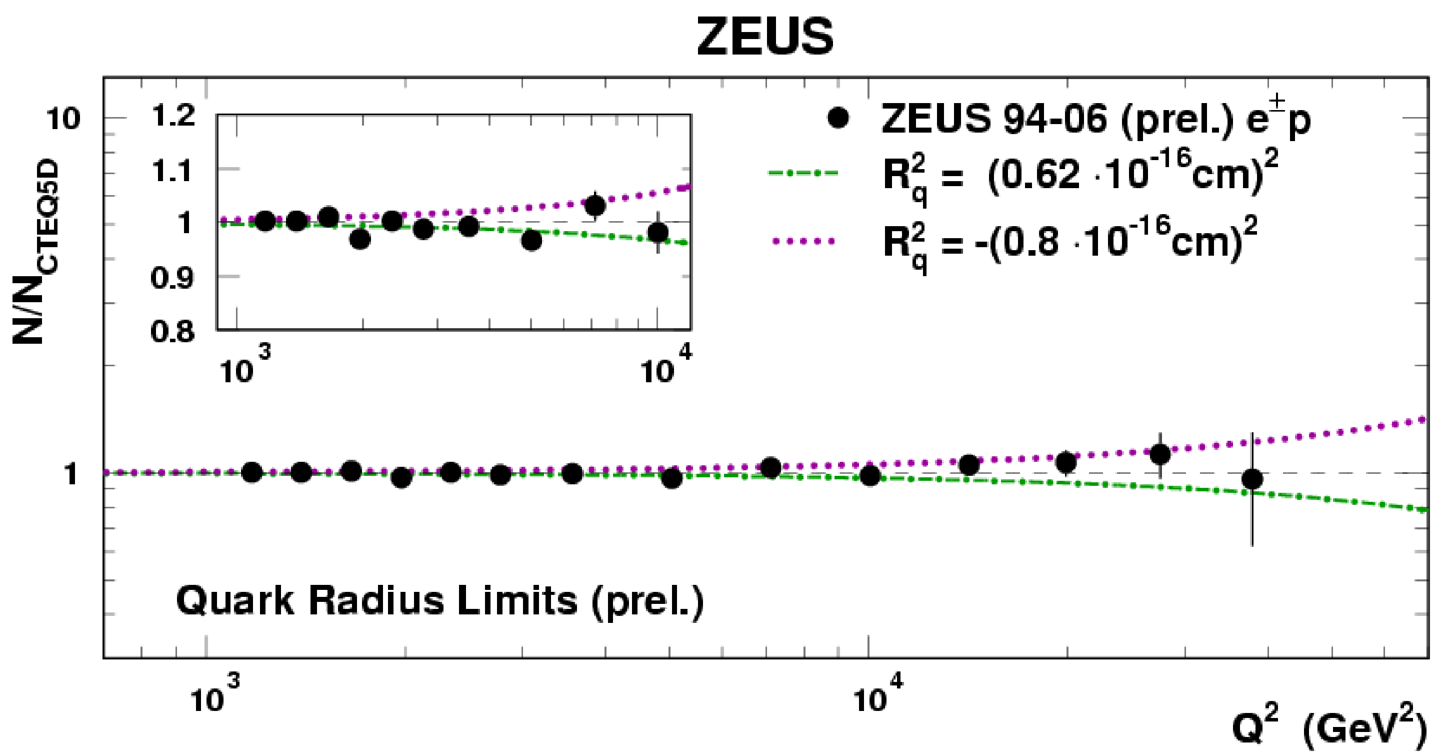
High Q^2 Neutral Current

- difference between e^+p and e^-p only at large $Q^2 \approx M_Z^2$

➔ $\gamma - Z^0 -$ interference

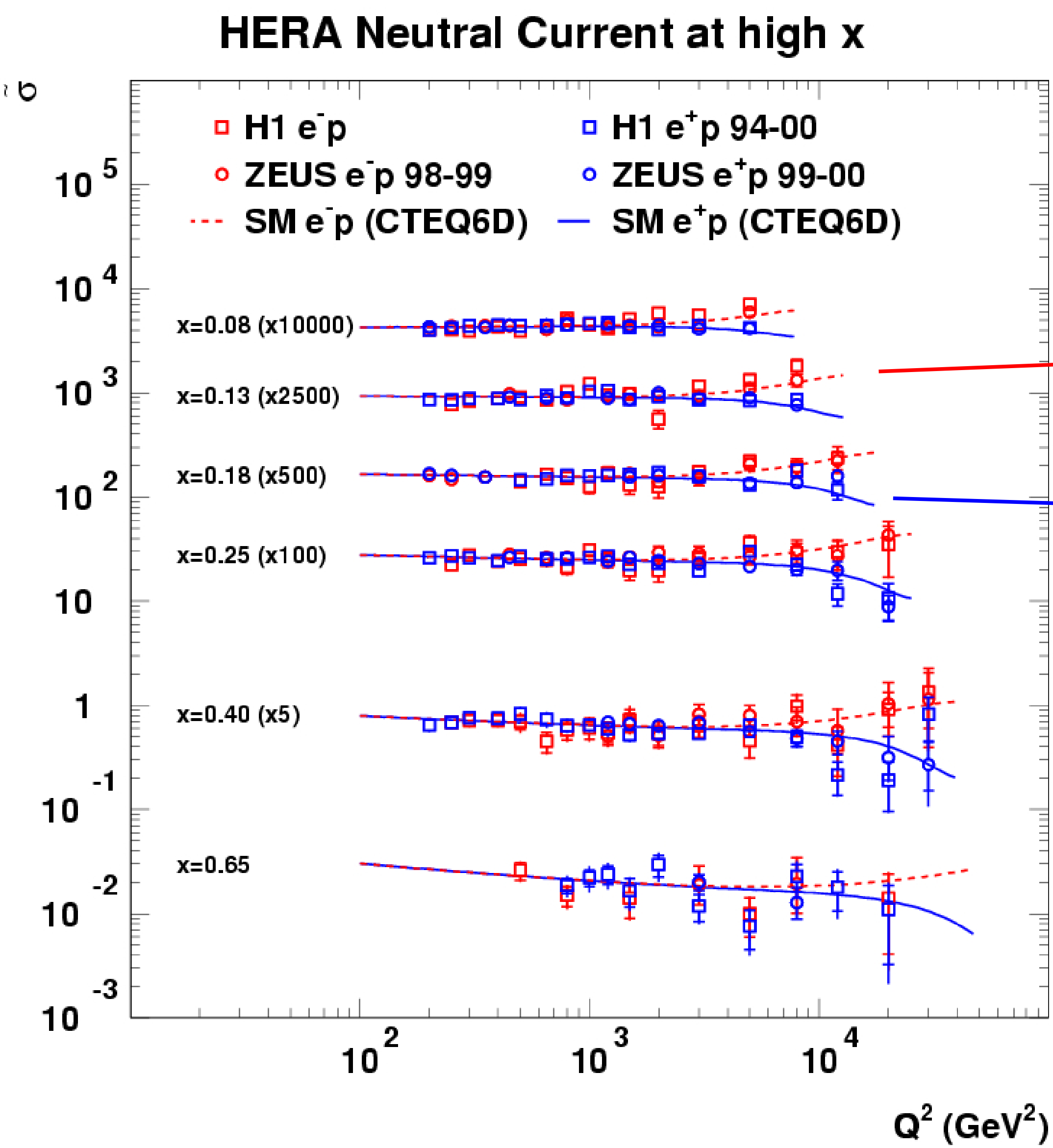


High Q^2 Neutral Current



- no significant deviation from Standard Model Fit at high Q^2
- can be interpreted as limit on quark size

High Q^2 Neutral Current



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

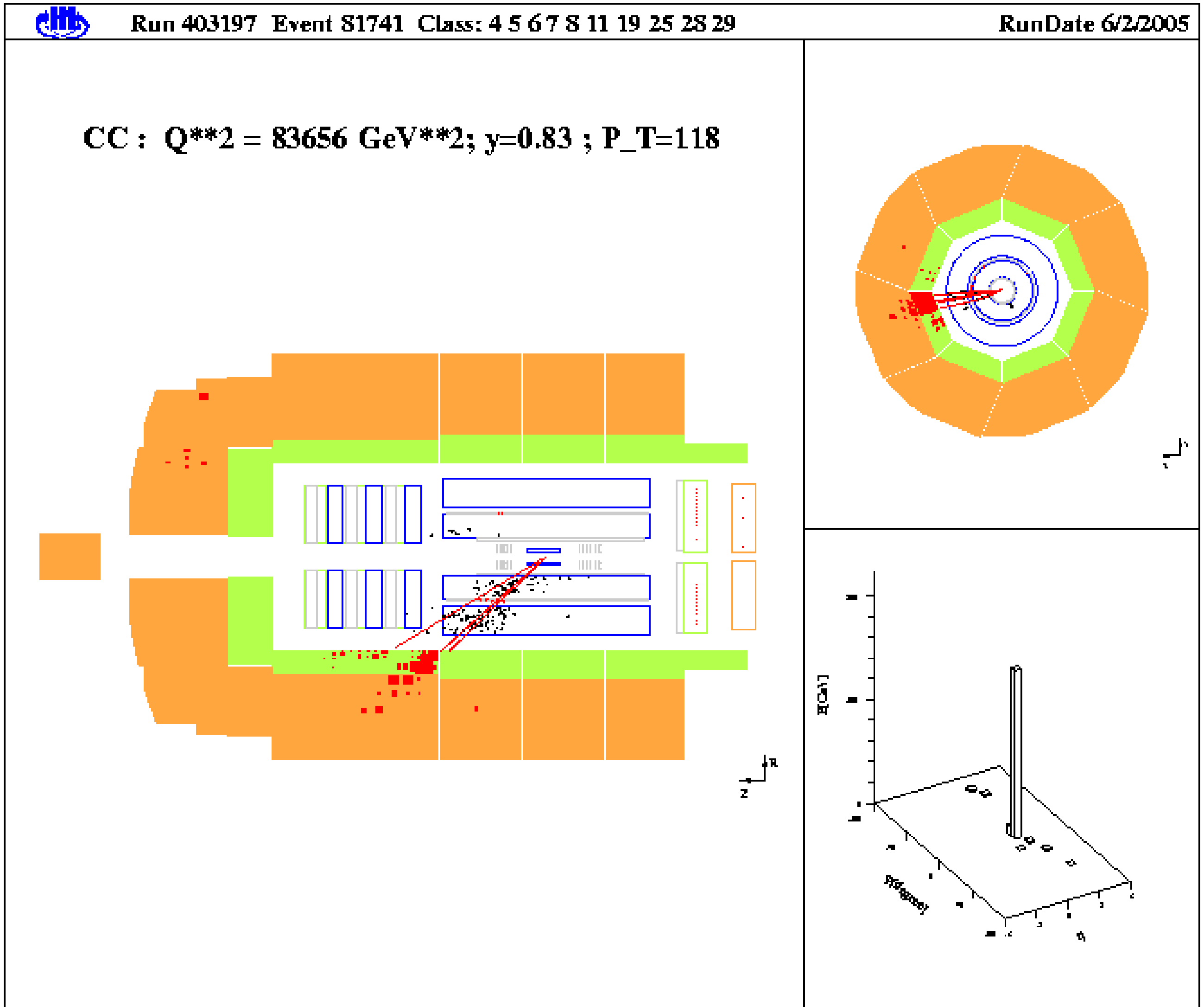
e^- positive interference

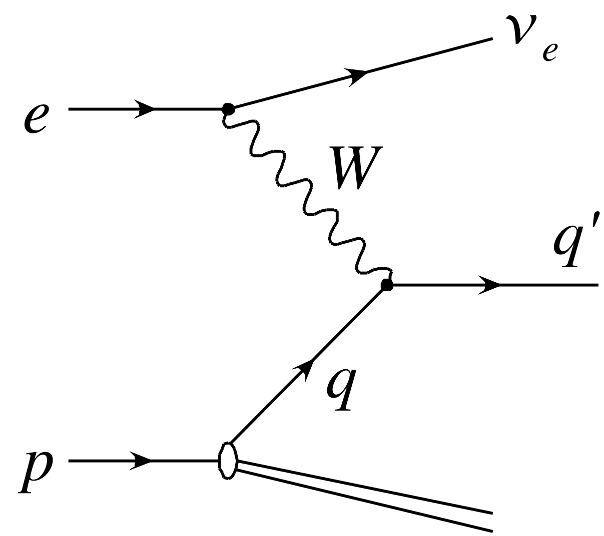
e^+ negative interference

$$x\,F_3 \propto x \sum e_q^2 (q - \bar{q})$$

direct handle on valence quark distribution!

Charged Current Interactions





neutrino not visible in detector

→ imbalance in transverse plane

Charged Current Cross Section

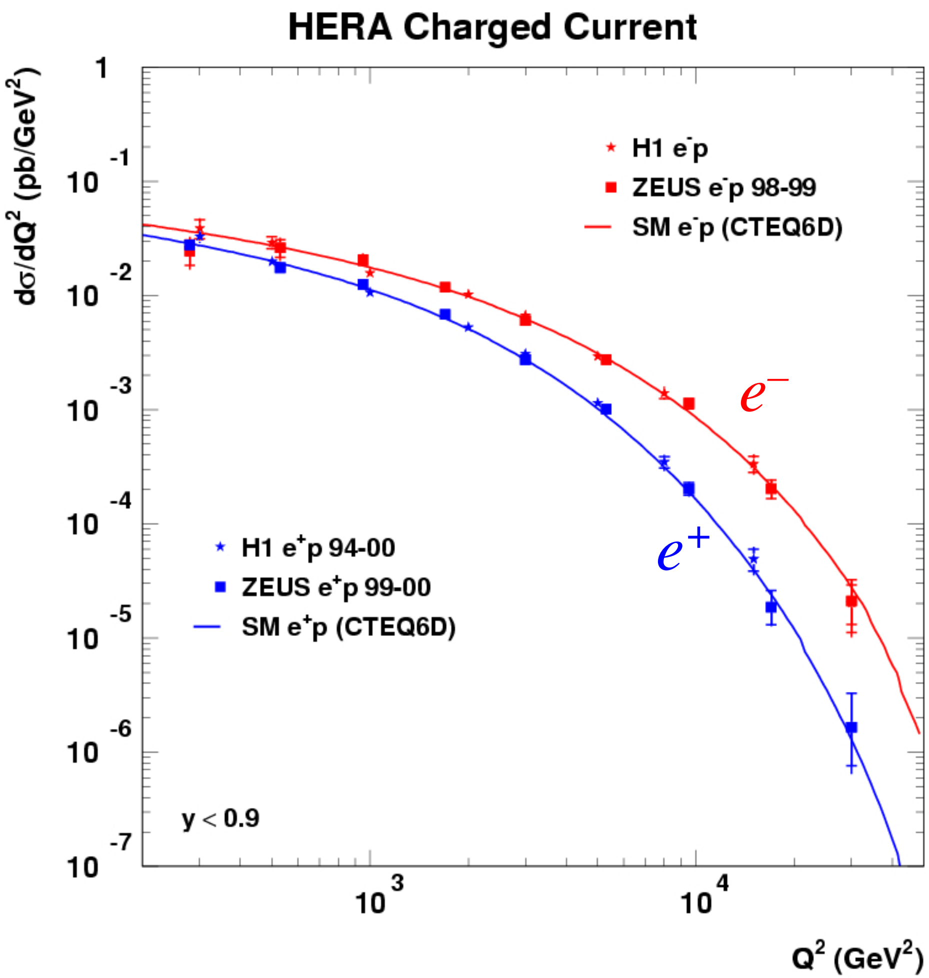
$$\frac{d^2\sigma^{\pm}_{CC}}{dx\,dQ^2} = \frac{G_F^2}{4\pi x}\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2 Y_+\left[W_2^{\pm} - \frac{y^2}{Y_+}W_L^{\pm} \mp \frac{Y_-}{Y_+}x\,W_3^{\pm}\right]$$

- W bosons couple differently to *up*- and *down*-type quarks
- in the QPM:

$$W_2^- = x(U+\overline{D}), \quad x W_3^- = x(U-\overline{D})$$
$$W_2^+ = x(\overline{U}+D), \quad x W_3^+ = x(D-\overline{U})$$
$$W_L^{\pm} = 0$$

→ $\sigma^-_{CC} \propto x\left[U + (1-y)^2\,\overline{D}\right]$

$\sigma^+_{CC} \propto x\left[\overline{U} + (1-y)^2\,D\right]$



Comparison NC vs. CC

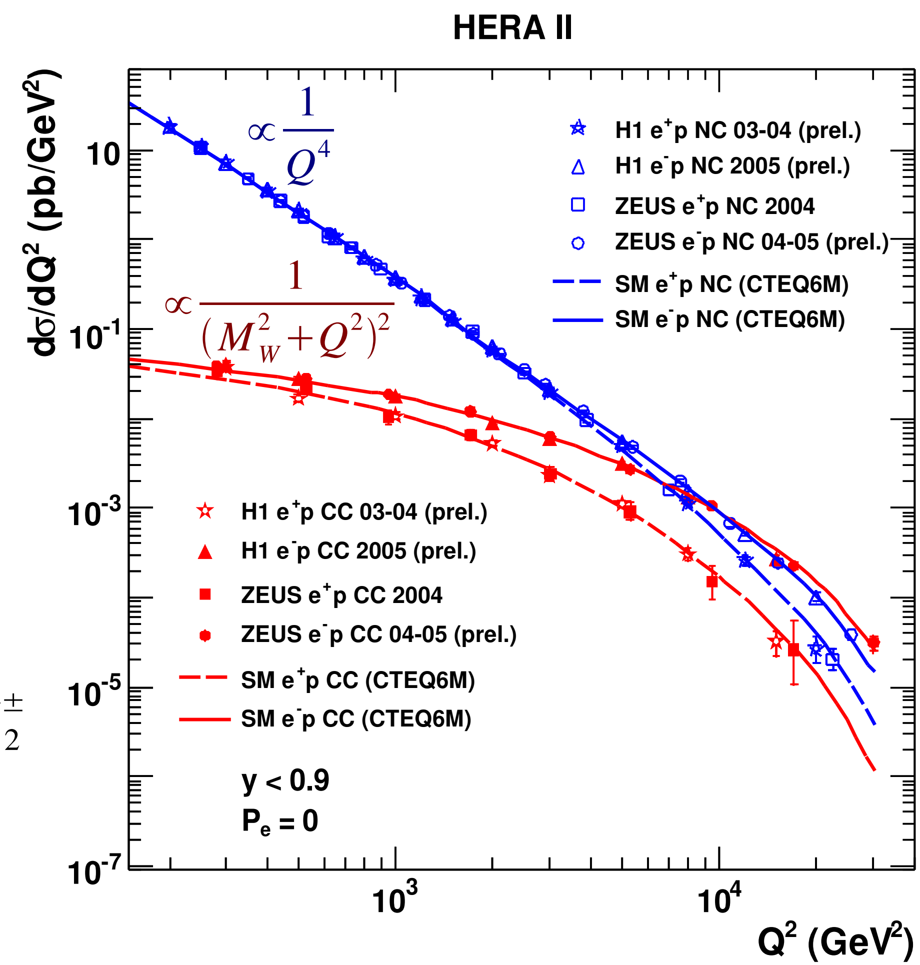
- at low Q^2: different dependences because of photon in NC
- at high Q^2: „electroweak unification“

but:

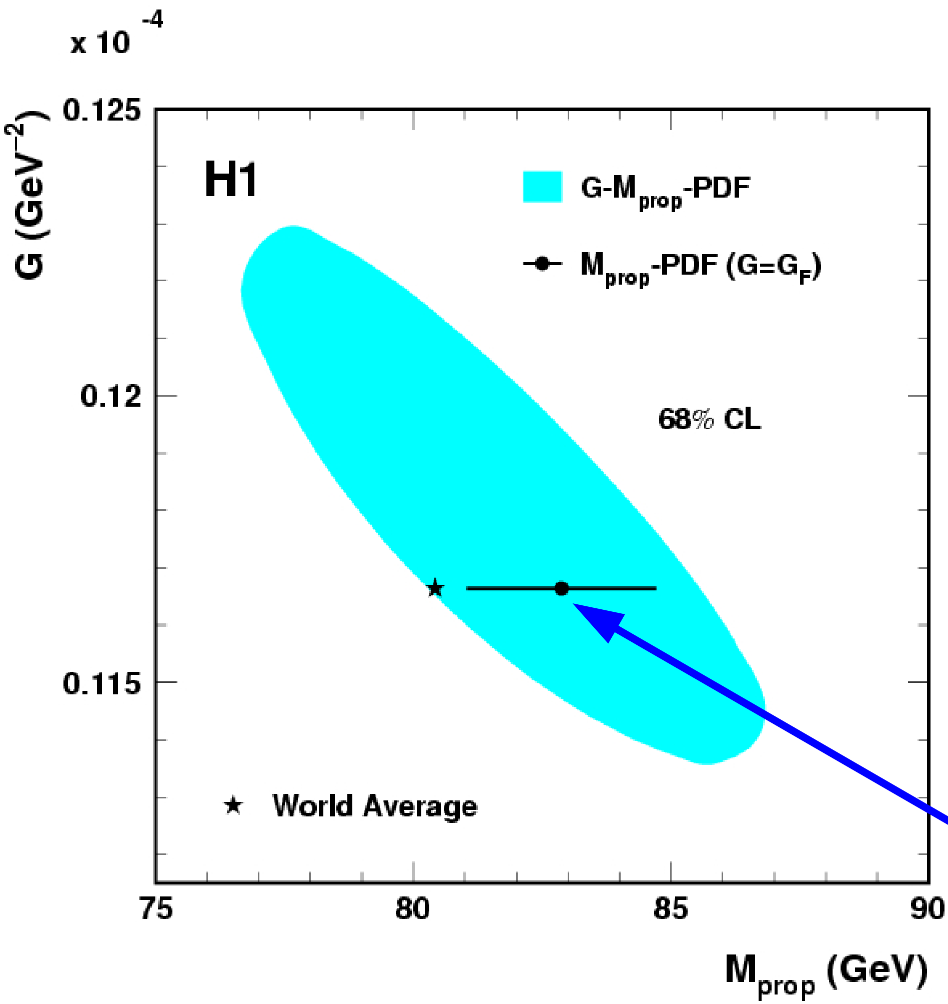
$$\frac{d^2\sigma_{CC}^{\pm}}{dx\,dQ^2} \approx \frac{G_F^2}{4\pi x}\cdot\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2 \cdot Y_+ W_2^{\pm}$$

$$\frac{d^2\sigma_{NC}^{\pm}}{dx\,dQ^2} \approx \frac{2\pi\alpha^2}{x}\cdot \frac{1}{Q^4} \cdot Y_+ F_2$$

similar because $G_F \approx \frac{4\pi\alpha}{\sqrt{2}M_W^2}$



Electroweak Parameters: *W* Mass



- $G = G_F$ determined by normalization of the CC cross section
- $M_{prop} = M_W$ determined by the Q^2 dependence of the CC cross section

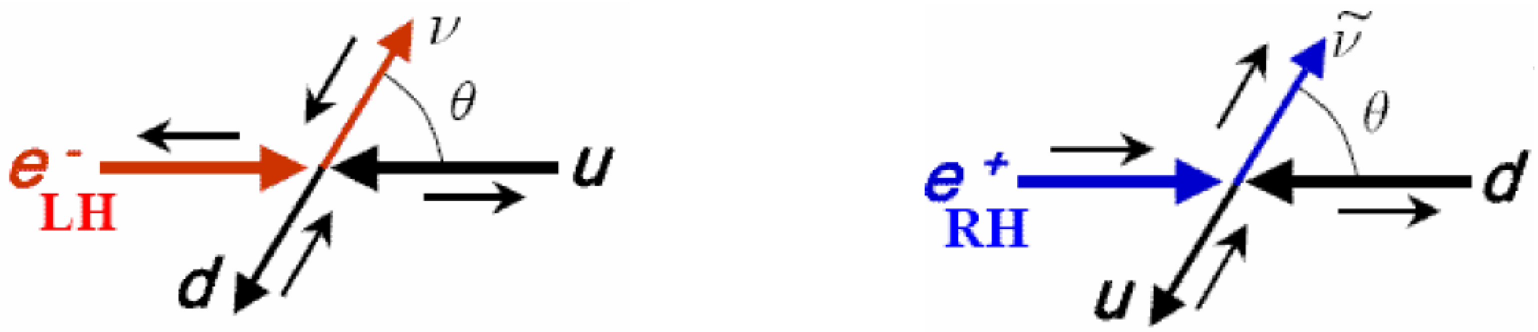
$$82.87 \pm 1.82_{\text{exp}} \left(\begin{matrix} +0.30 \\ -0.16 \end{matrix} \right)_{\text{model}} \text{GeV}$$

CC & Polarization

- CC cross section depends on longitudinal electron/positron polarization P_e

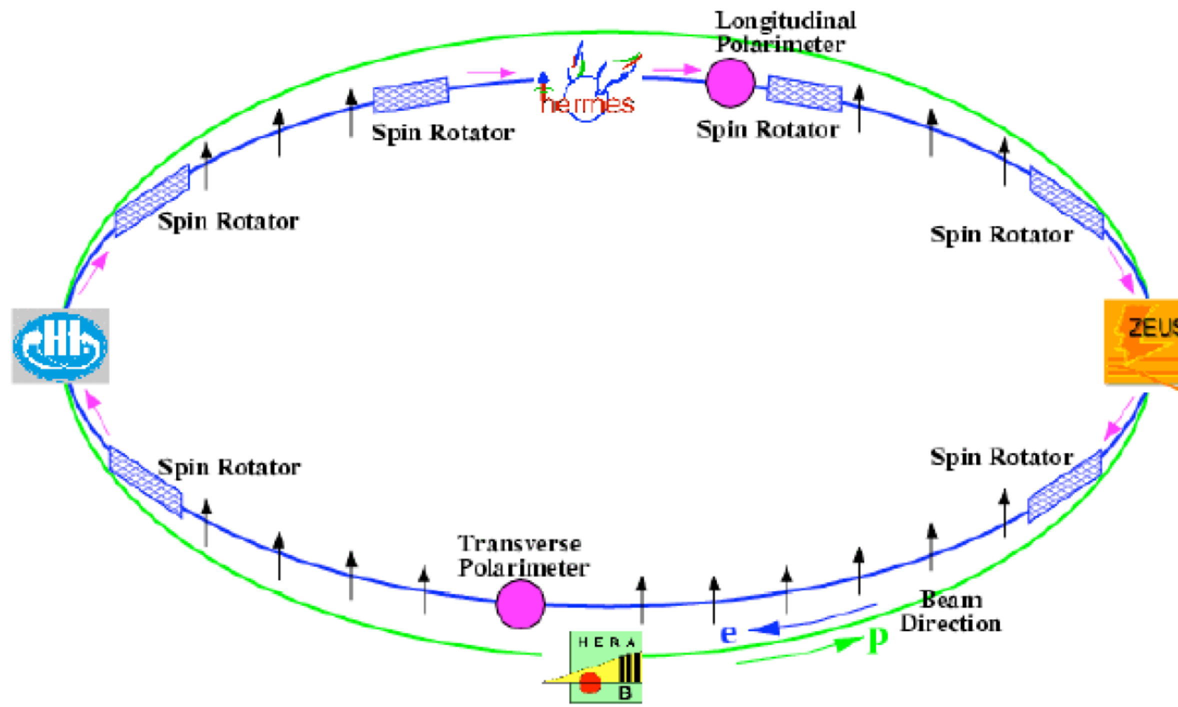
$$\frac{d^2\sigma_{CC}^{\pm}}{dx\,dQ^2}(P_e) \approx (1 \pm P_e)\frac{G_F^2}{4\pi x}\cdot\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2 \cdot Y_+ W_2^{\pm}$$

- reason: W boson couples only to left-handed (LH) particles and right-handed (RH) antiparticles:



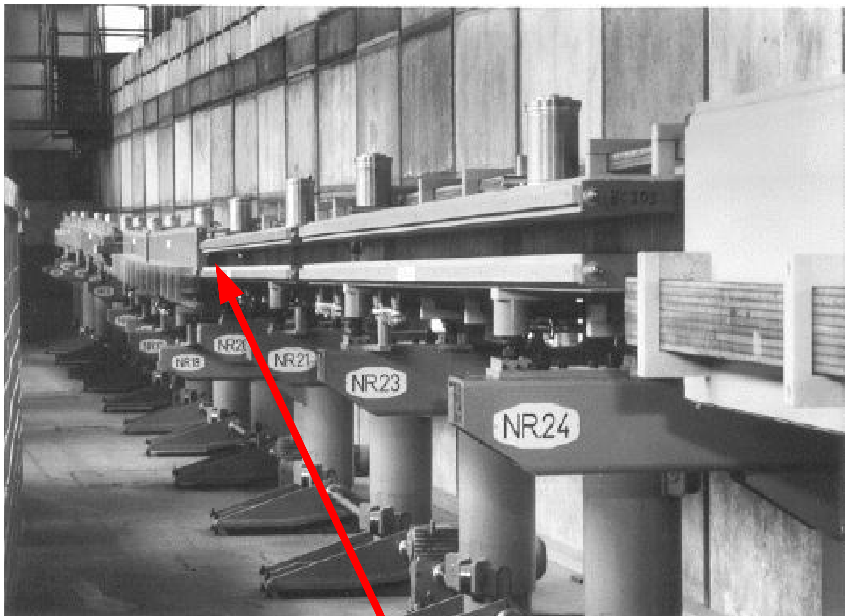
Polarization @ HERA

$$P_e = \frac{N_{RH} - N_{LH}}{N_{RH} + N_{LH}}$$



- transverse polarization builds up in ~40 minutes through synchrotron radiation (Sokolov-Ternov effect)
- spin rotators flip transverse $\longrightarrow$ longitudinal before experiments and back after

Polarization @ HERA



spin rotator

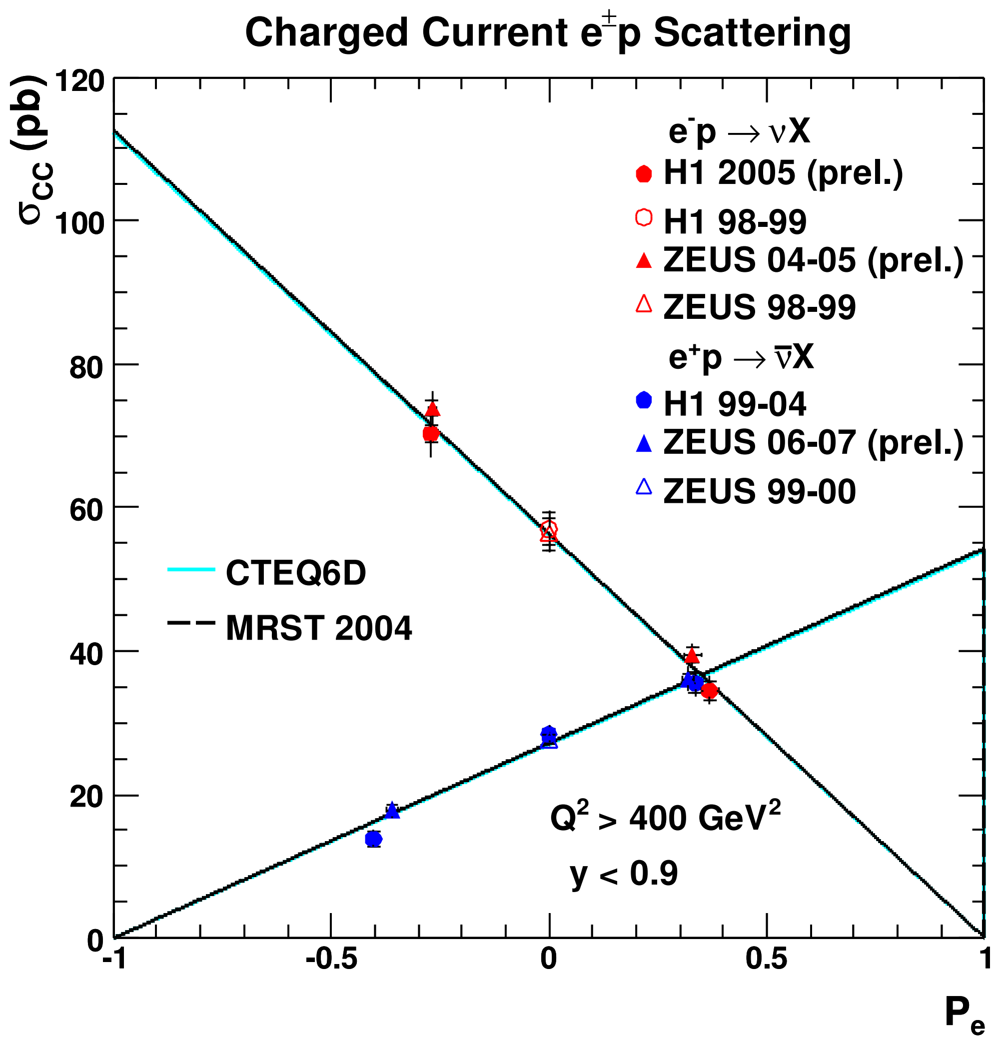
CC: Polarization Dependence

- Standard Modell expectation:

$$\sigma^{-}_{CC}(P_e=+1) = 0$$
$$\sigma^{+}_{CC}(P_e=-1) = 0$$

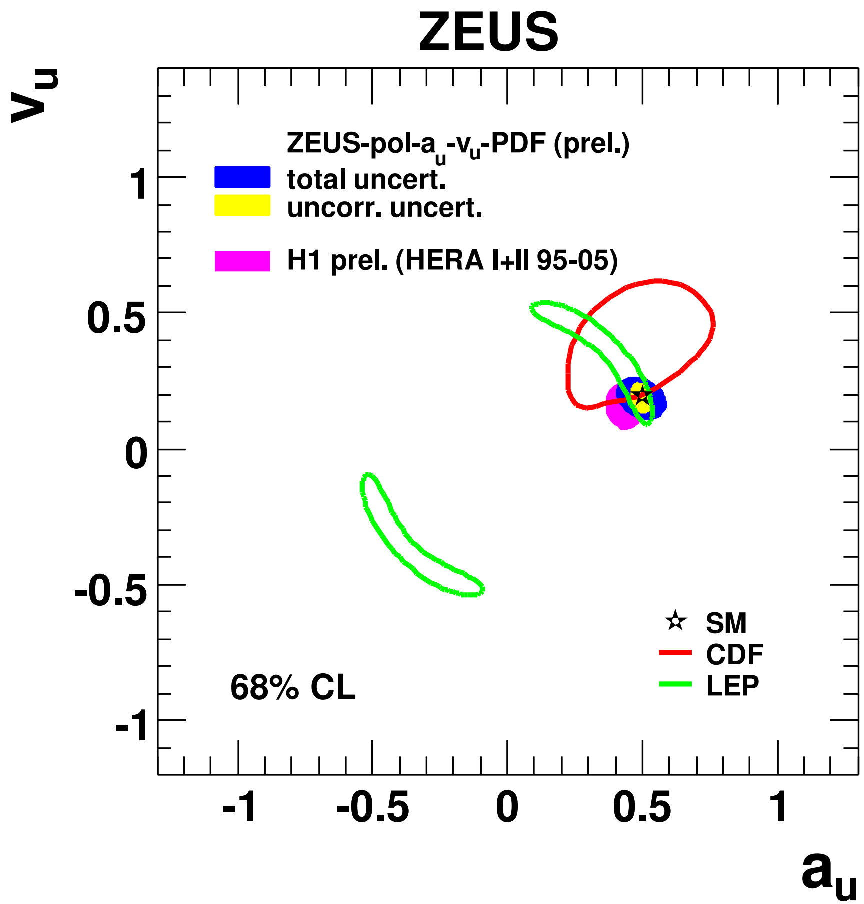
- experimental result: (H1)

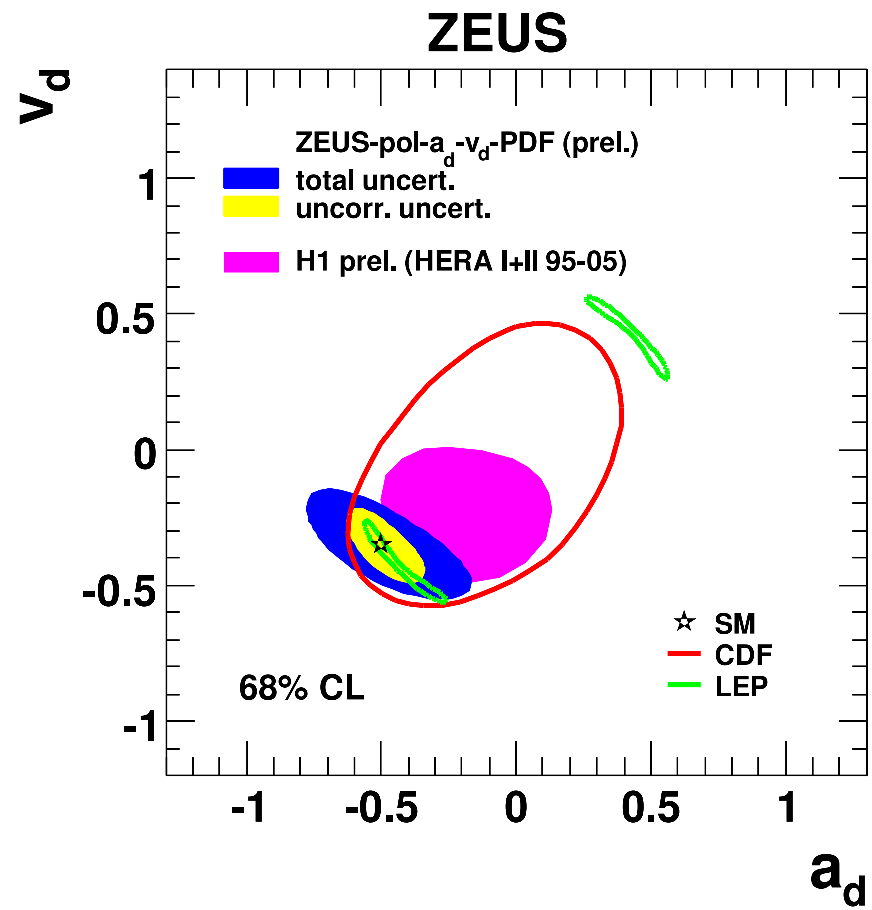
$$\sigma^{-}_{CC}(+1) = -0.9 \pm 2.9_{stat} \pm 1.9_{syst} \pm 1.9_{pol} \text{ pb}$$
$$\sigma^{+}_{CC}(-1) = -3.9 \pm 2.3_{stat} \pm 0.7_{syst} \pm 0.8_{pol} \text{ pb}$$



Electroweak Parameters: Z^0 Couplings

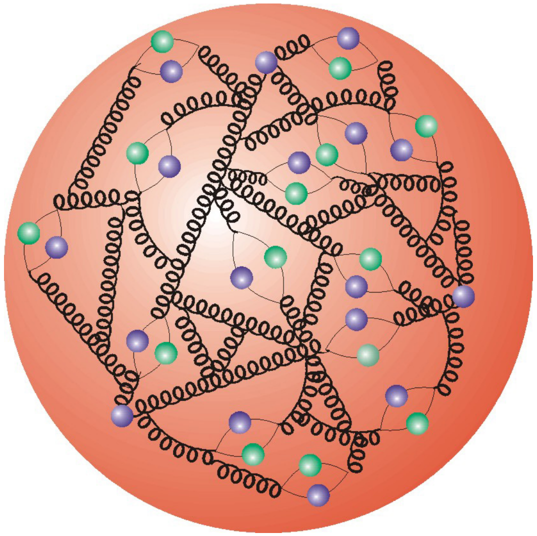
polarization also allows better sensitivity to vector and axial-vector couplings of *up*- and *down*-type quarks to the Z^0

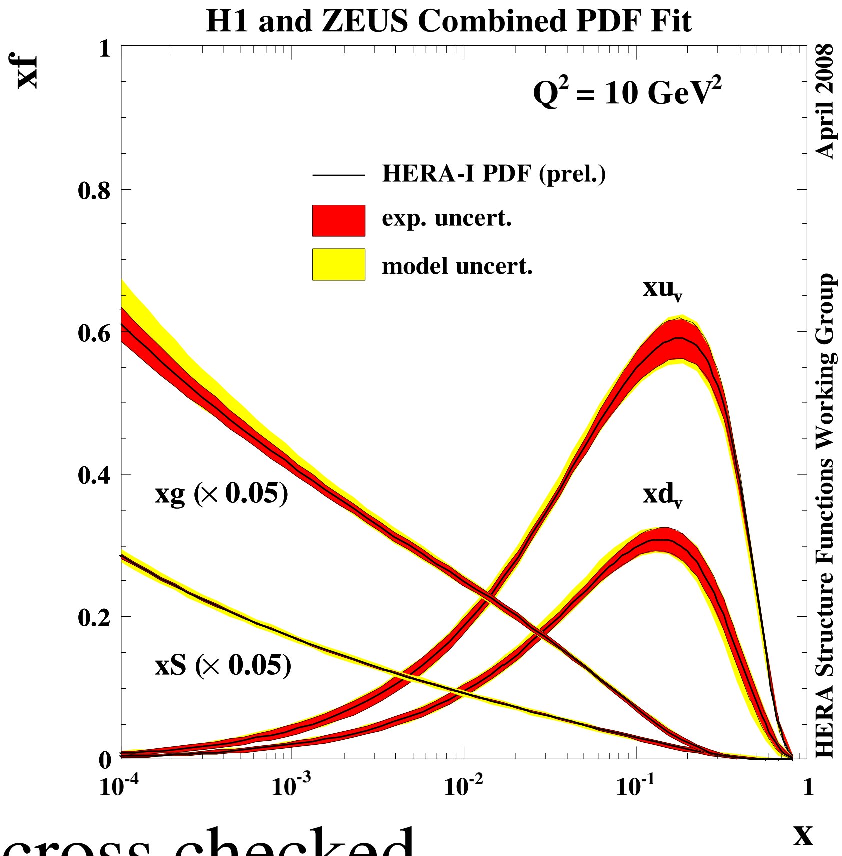




Summary

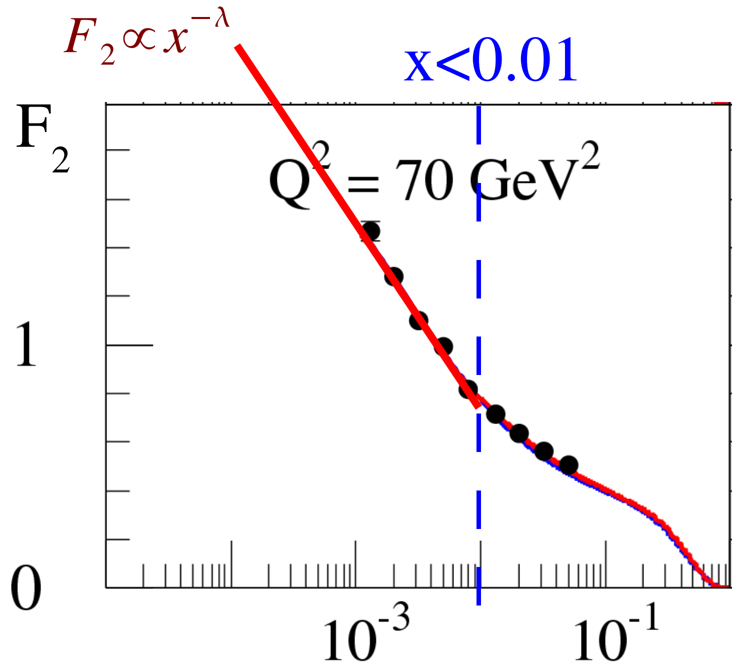
- inclusive *ep* scattering reveales structure of the proton
- large amount of gluons in the proton

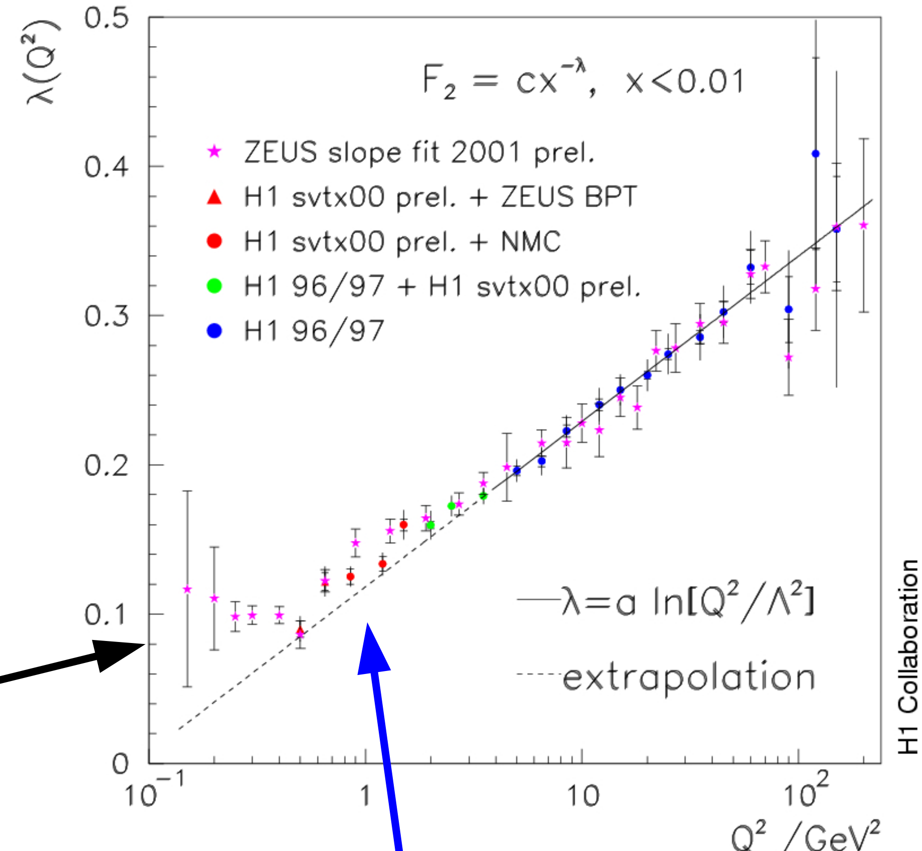




- Standard Modell can be cross checked

Hadrons vs. Partons





0.08 correponds to hadron-hadron scattering

transition from hadronic to partonic bahaviour