Physics at HERA

Summer Student Lectures
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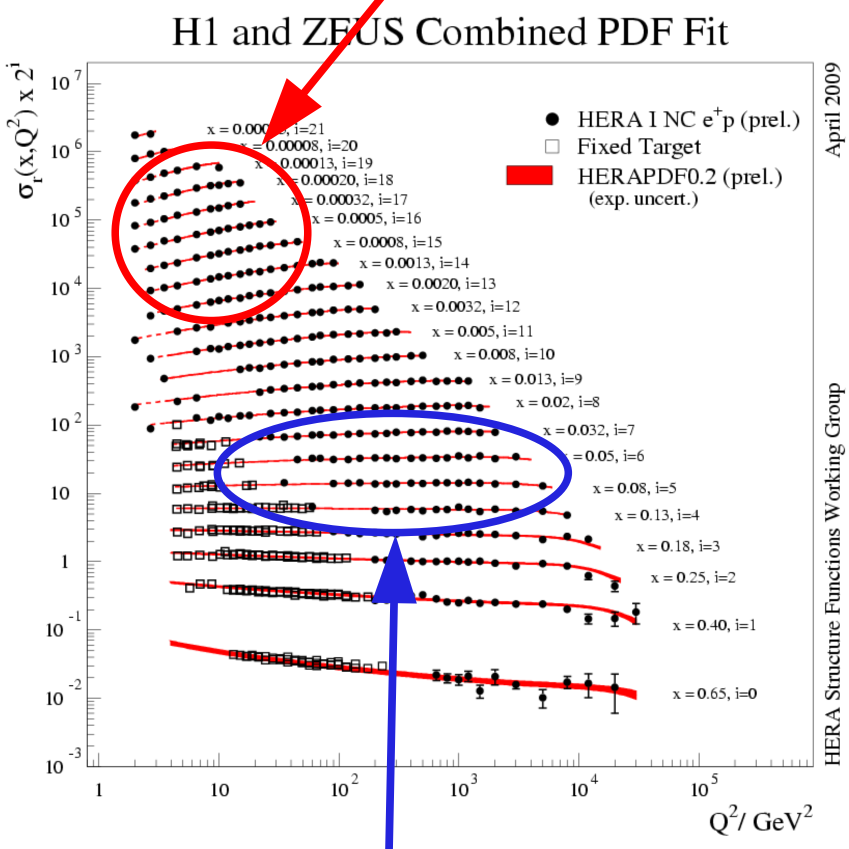
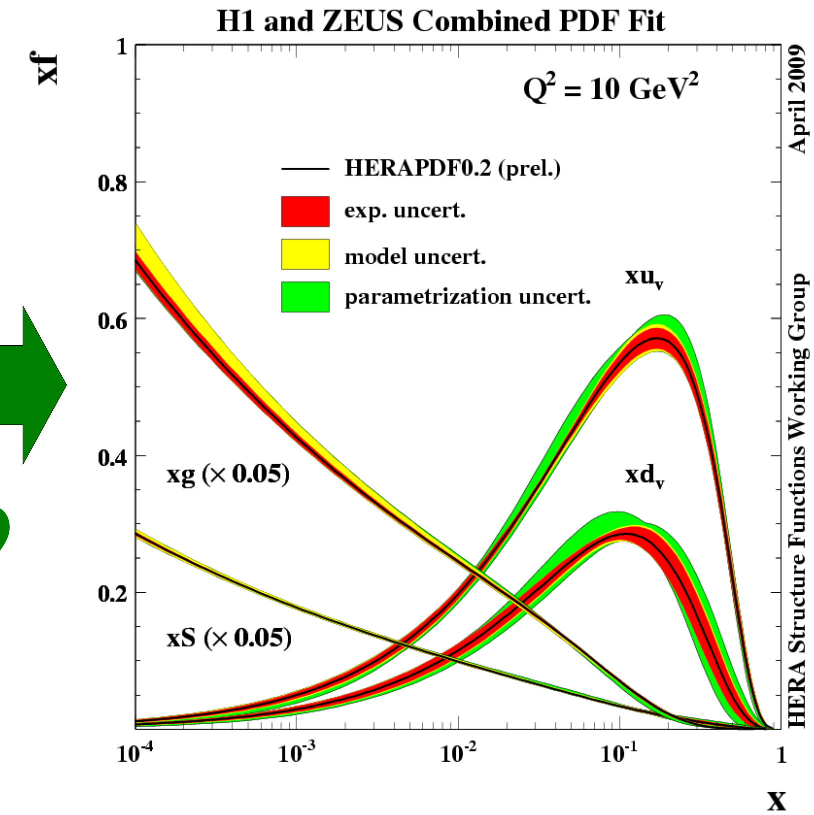
ep Scattering & Structure Functions

„The“ HERA Textbook Plots

gluons ?



?



quarks ?

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

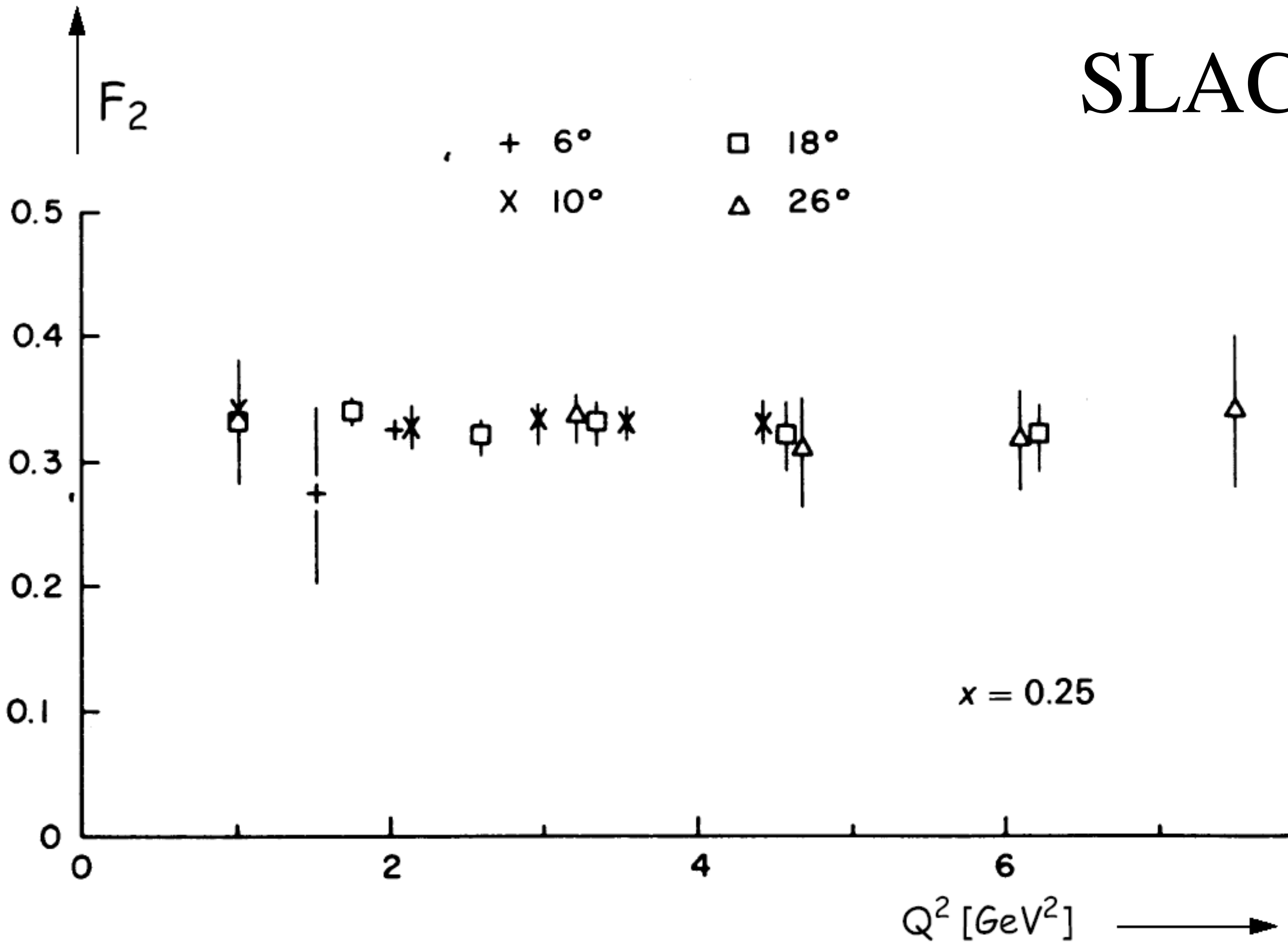
$$\left(\frac{d\sigma}{dQ^2}\right)_{\text{Dirac}} = \frac{4\pi\alpha^2 z^2}{Q^4}\left(\frac{E'}{E}\right)^2\left[\cos^2\frac{\Theta}{2} + \frac{Q^2}{2M^2}\sin^2\frac{\Theta}{2}\right]$$

➔ F_2 corresponds to electric field of the parton

➔ F_1 corresponds to spin of the parton

Scaling: F_2 independent of Q^2

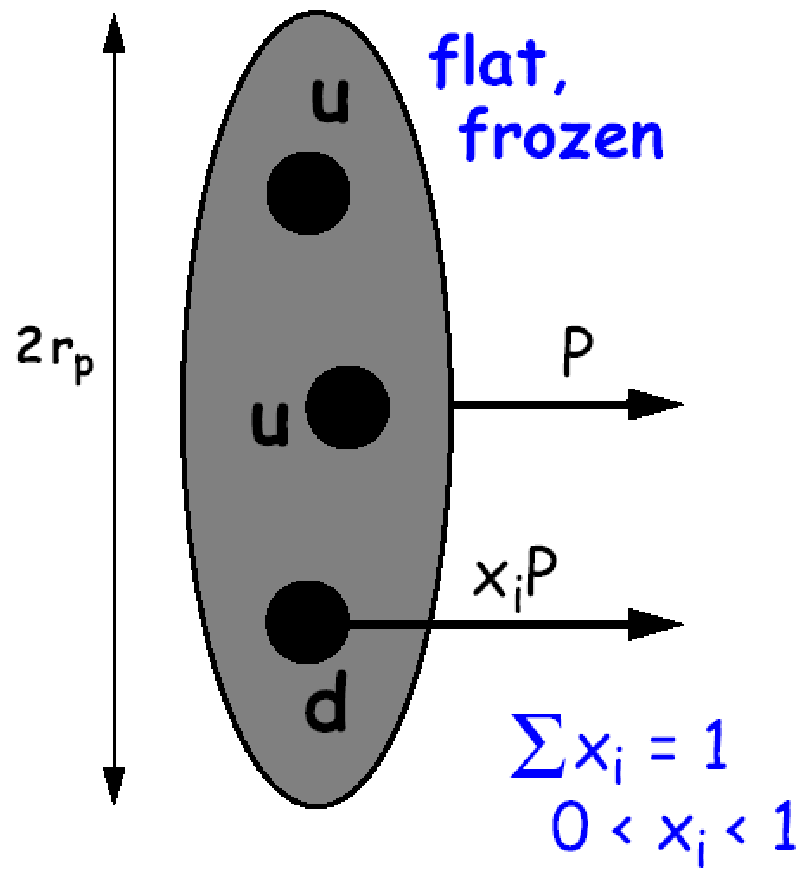
SLAC 1972



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?

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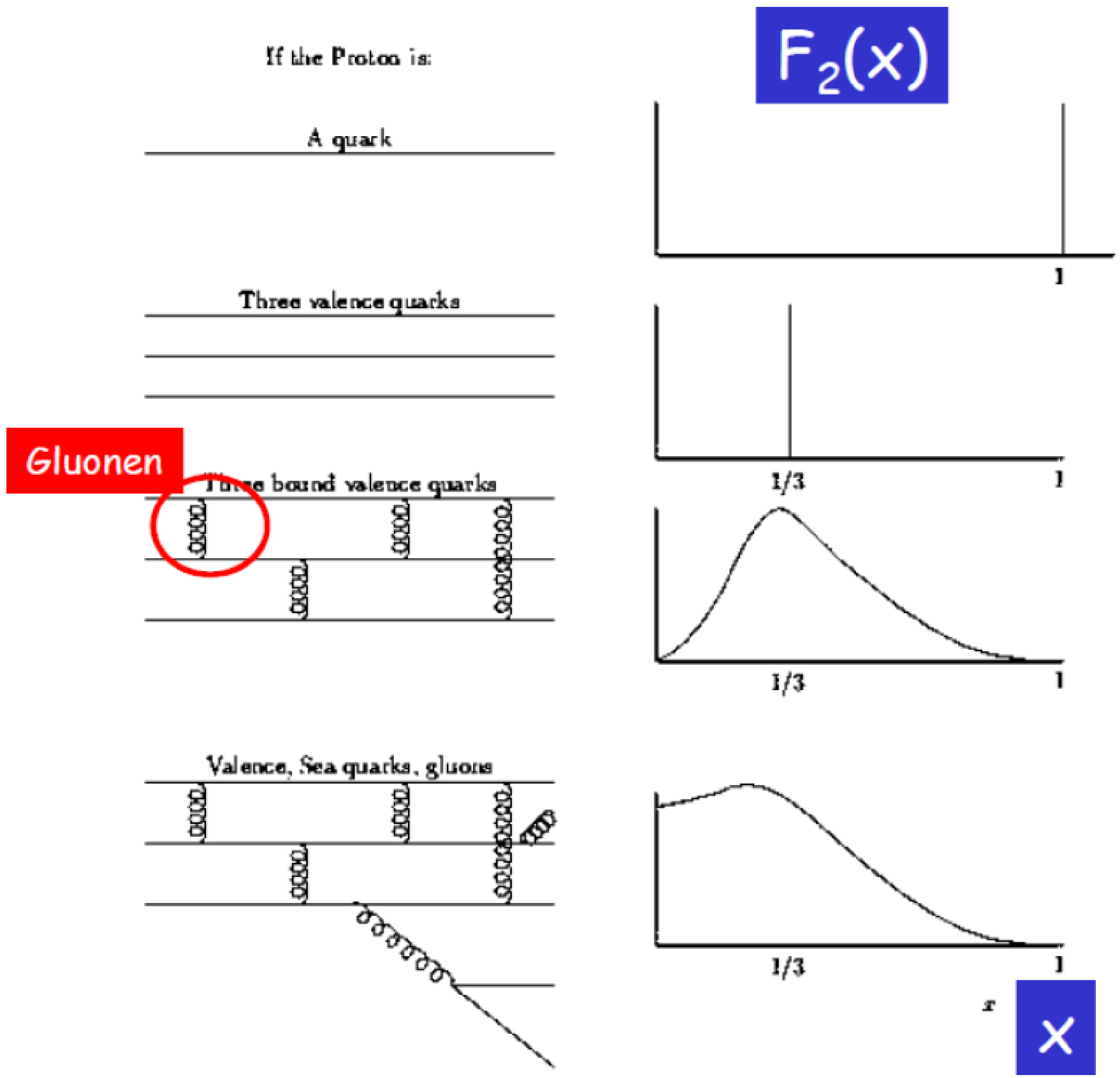
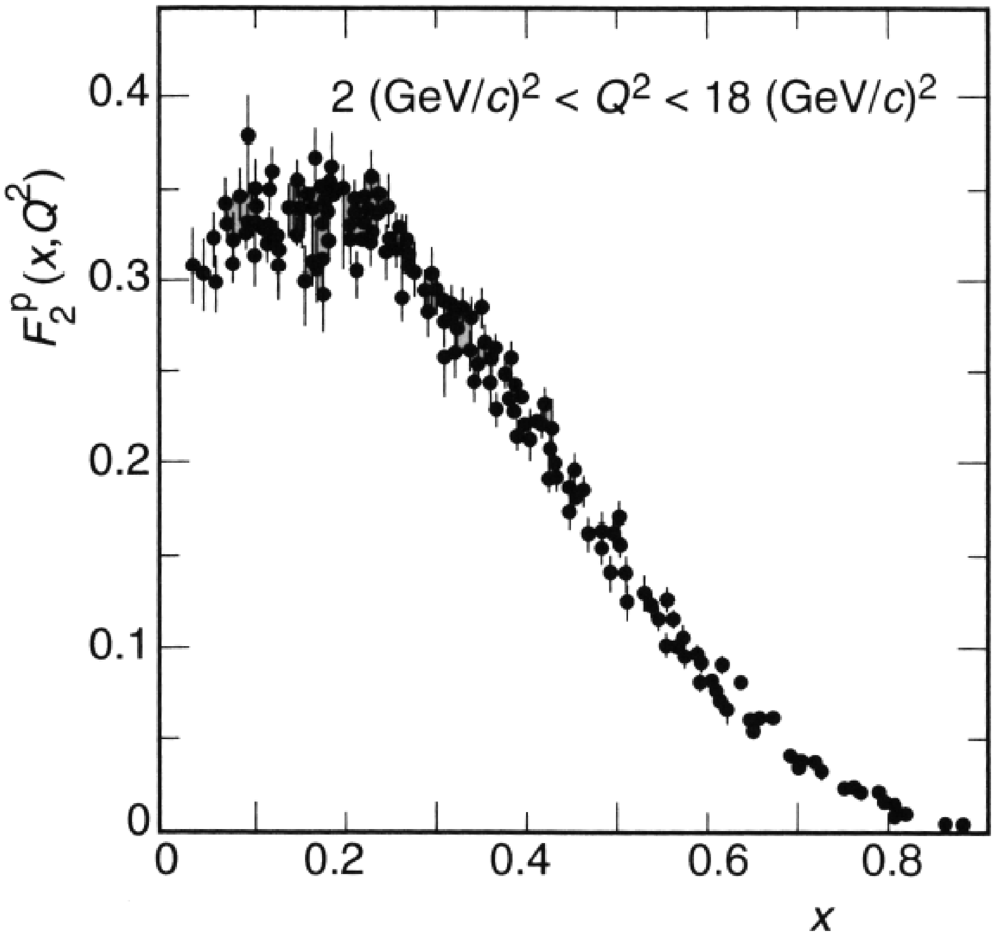


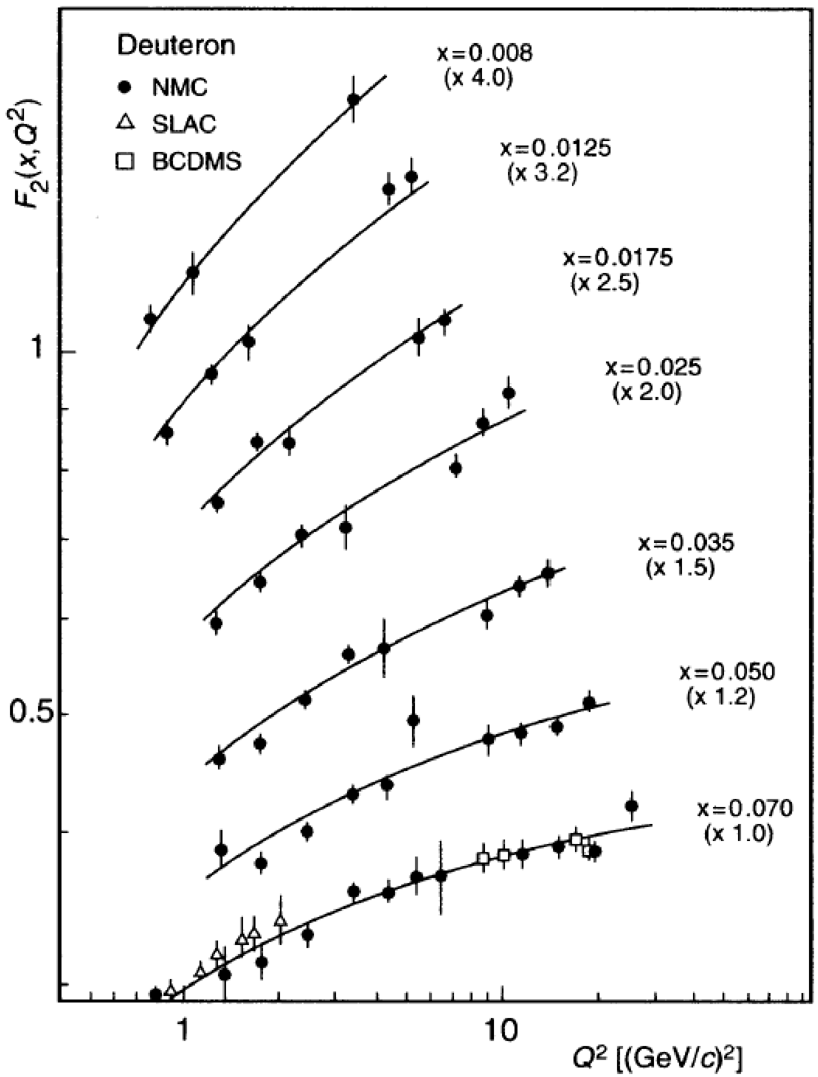
How does $F_2(x)$ look like?

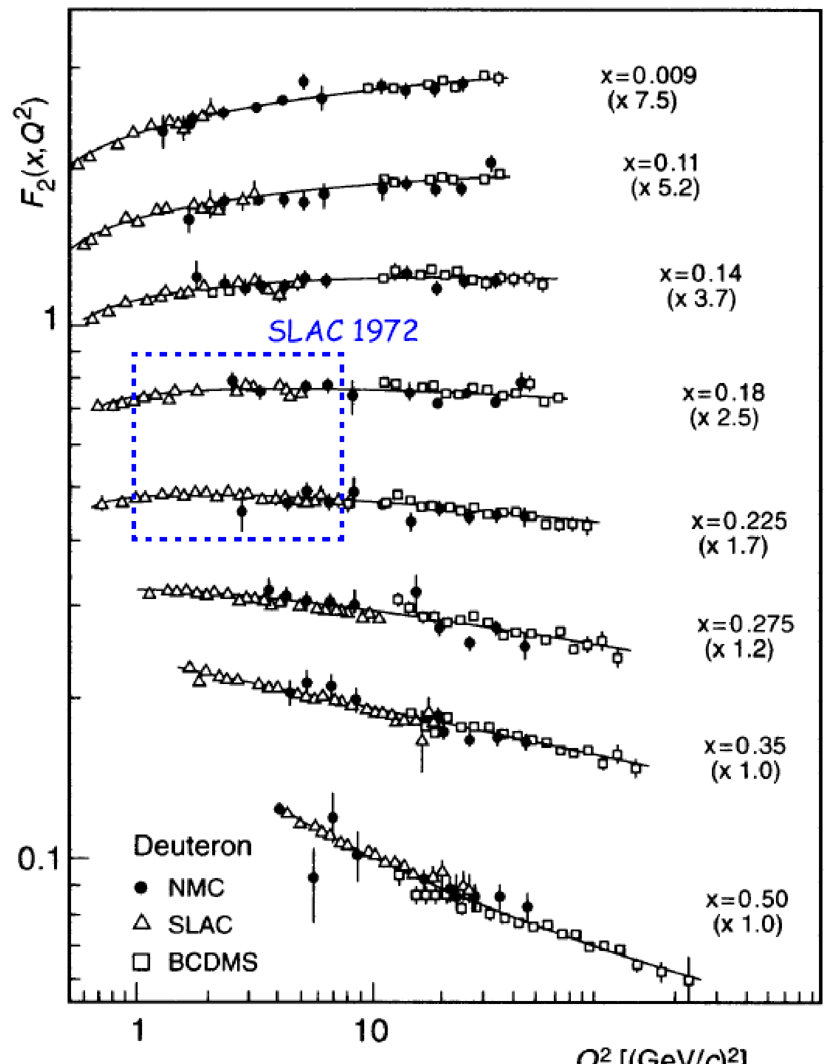
what happens at low x?



from Povh et al., „Teilchen und Kerne“

Scaling Violations

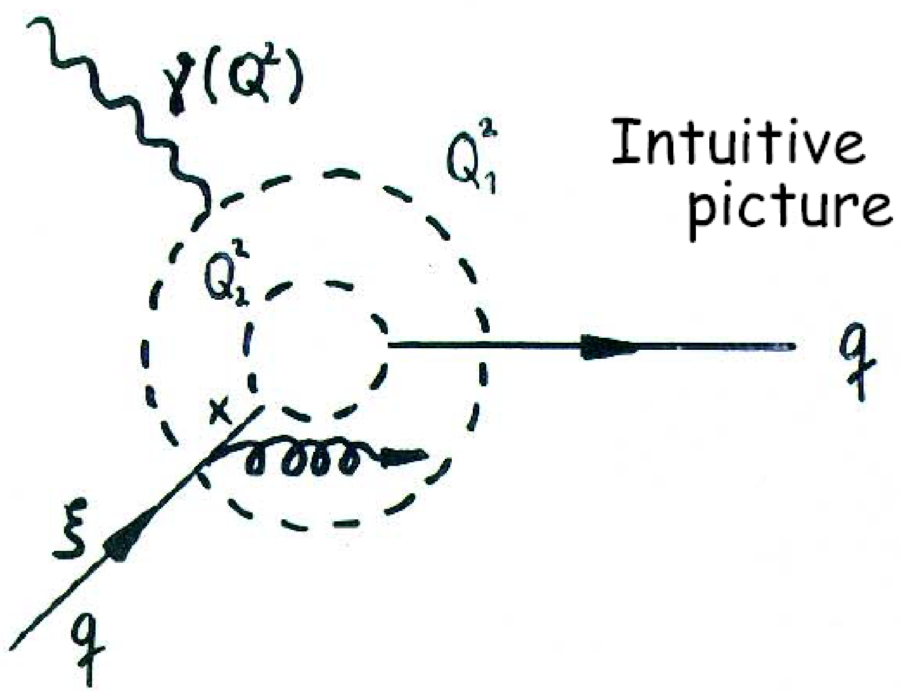




at smaller & larger x, the amount of quarks depends on Q^2!

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

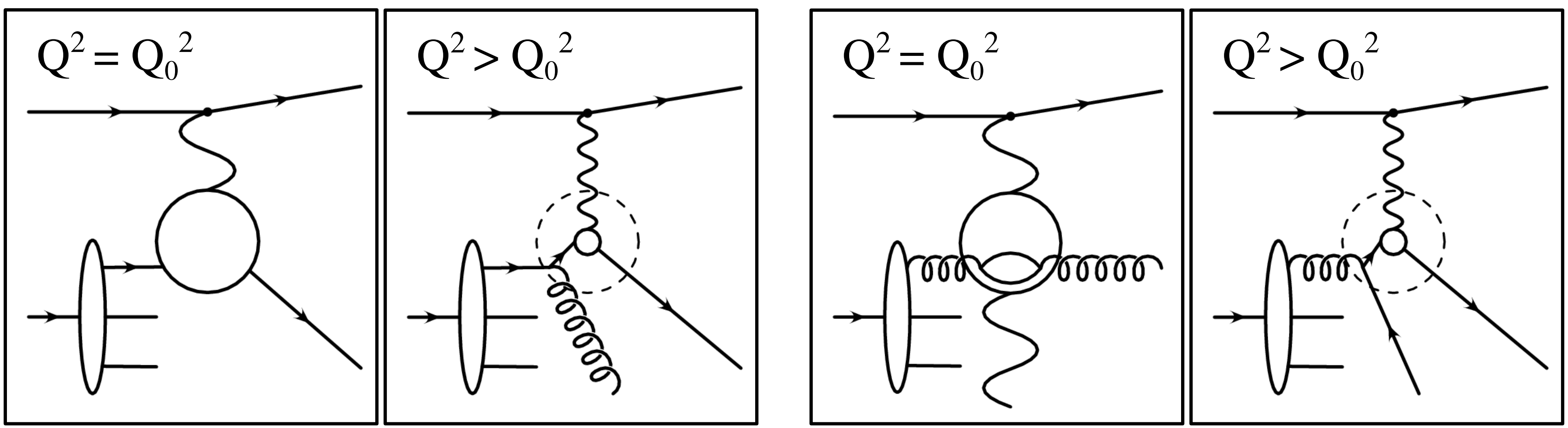
large Q^2:

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

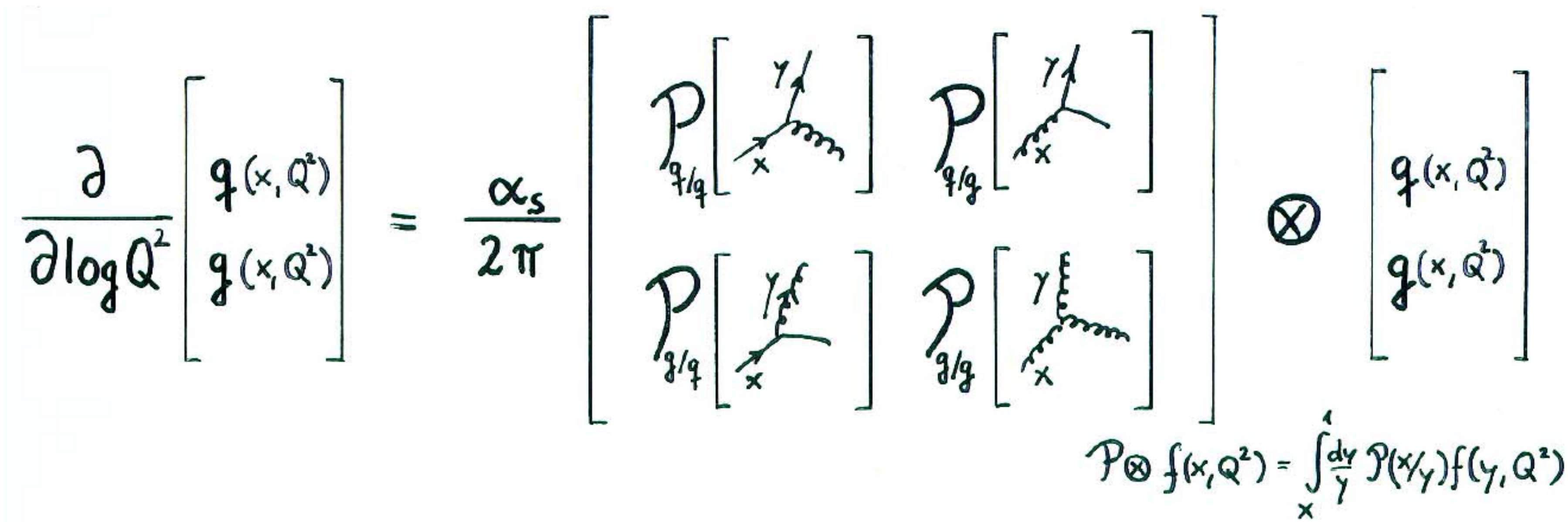
Skaling Violations

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

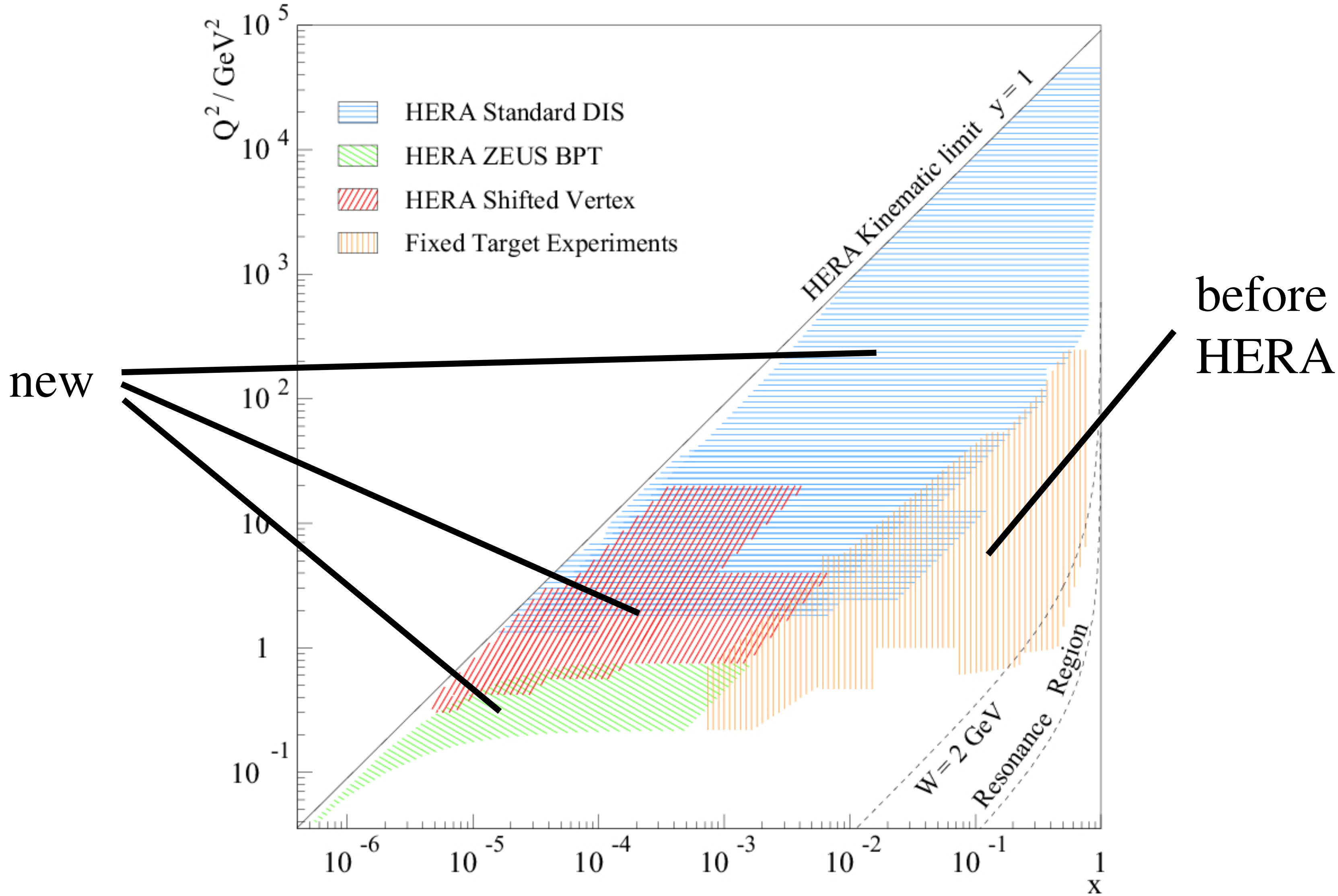


DGLAP Evolution Equations

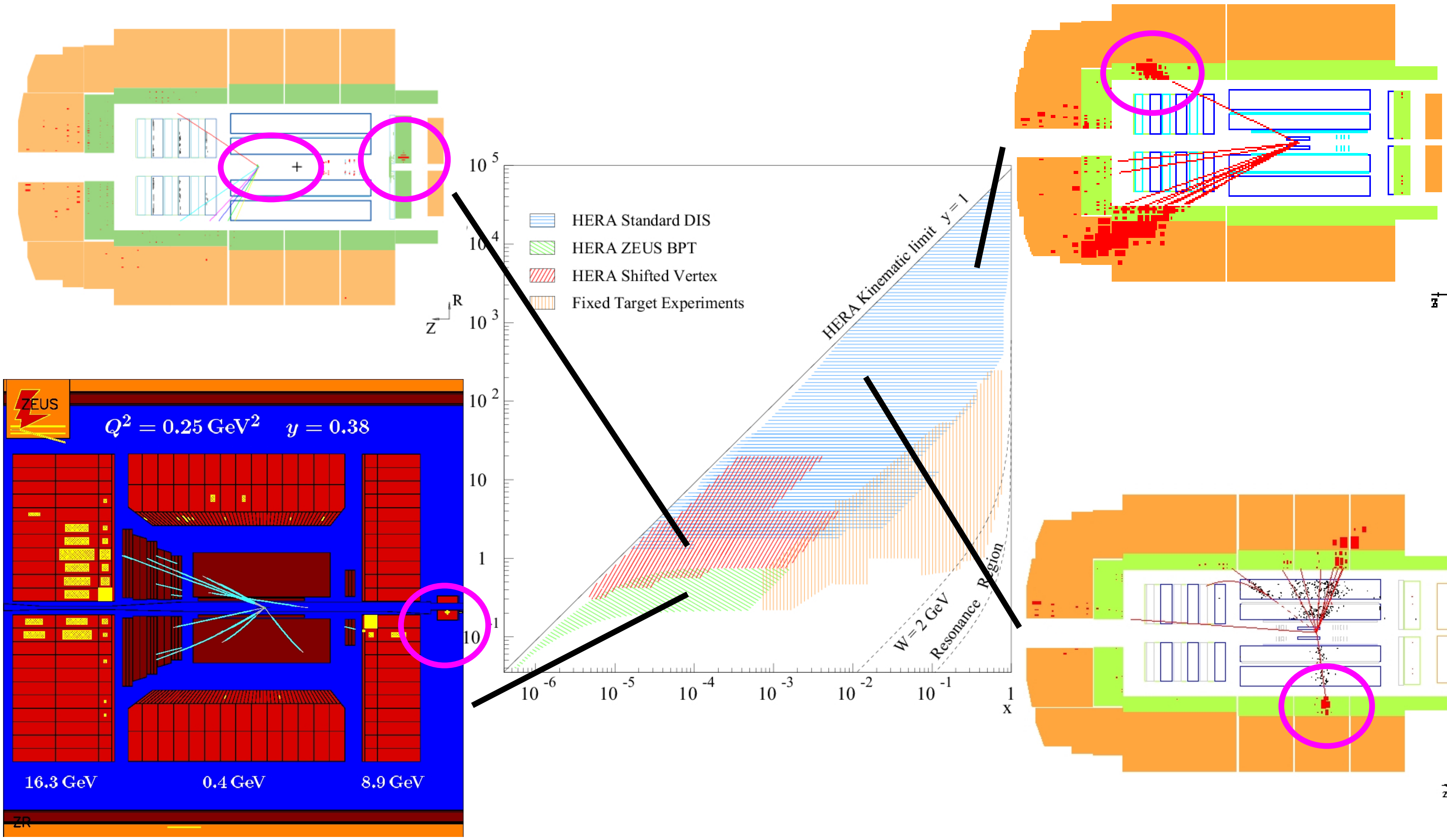


- Q^2 dependence of quark densities $q(x,Q^2)$ and gluon density $g(x,Q^2)$ is predicted
- no prediction for the x dependence → initial condition needed

HERA Kinematic Range

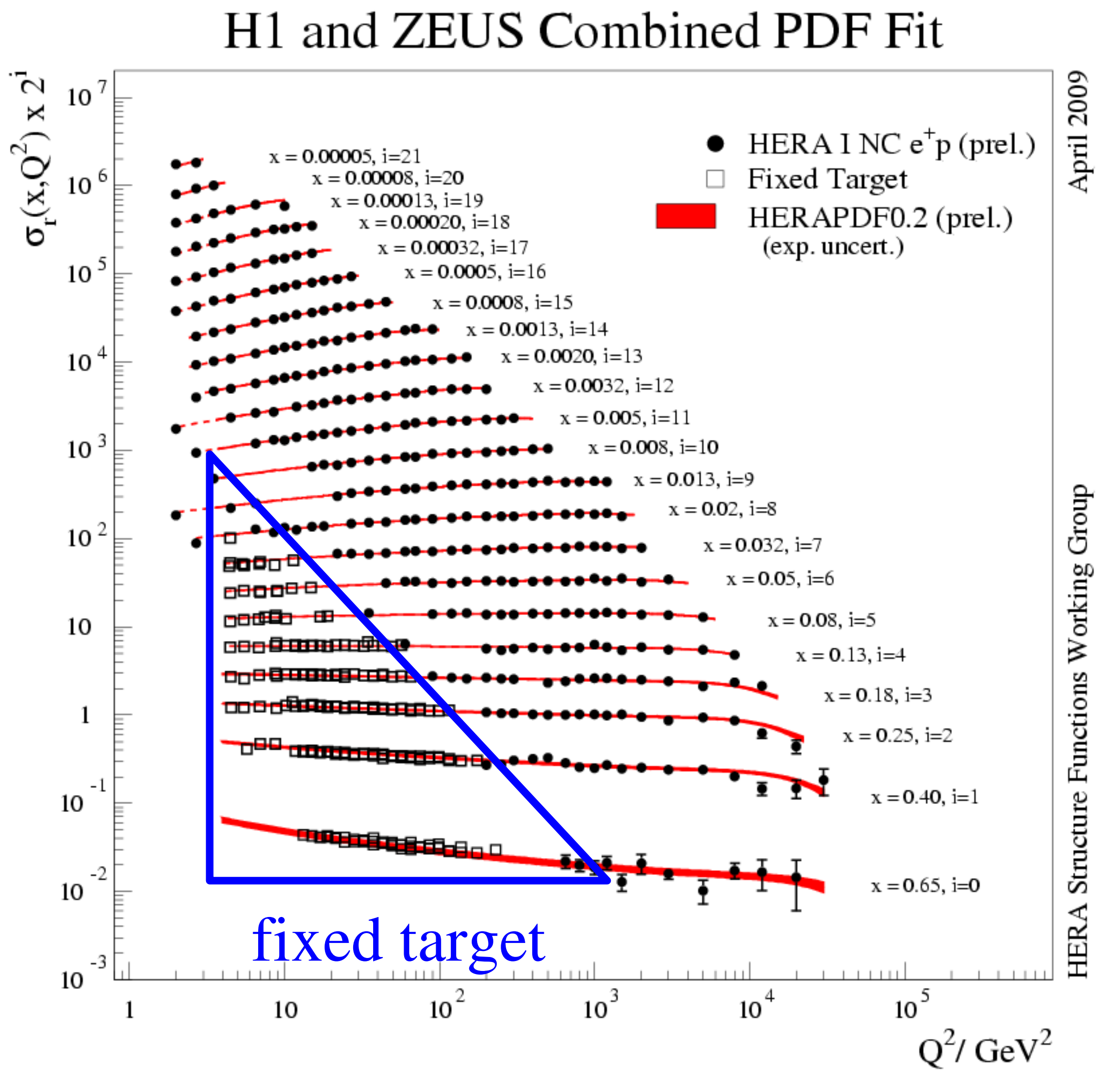


Events in Different Regions



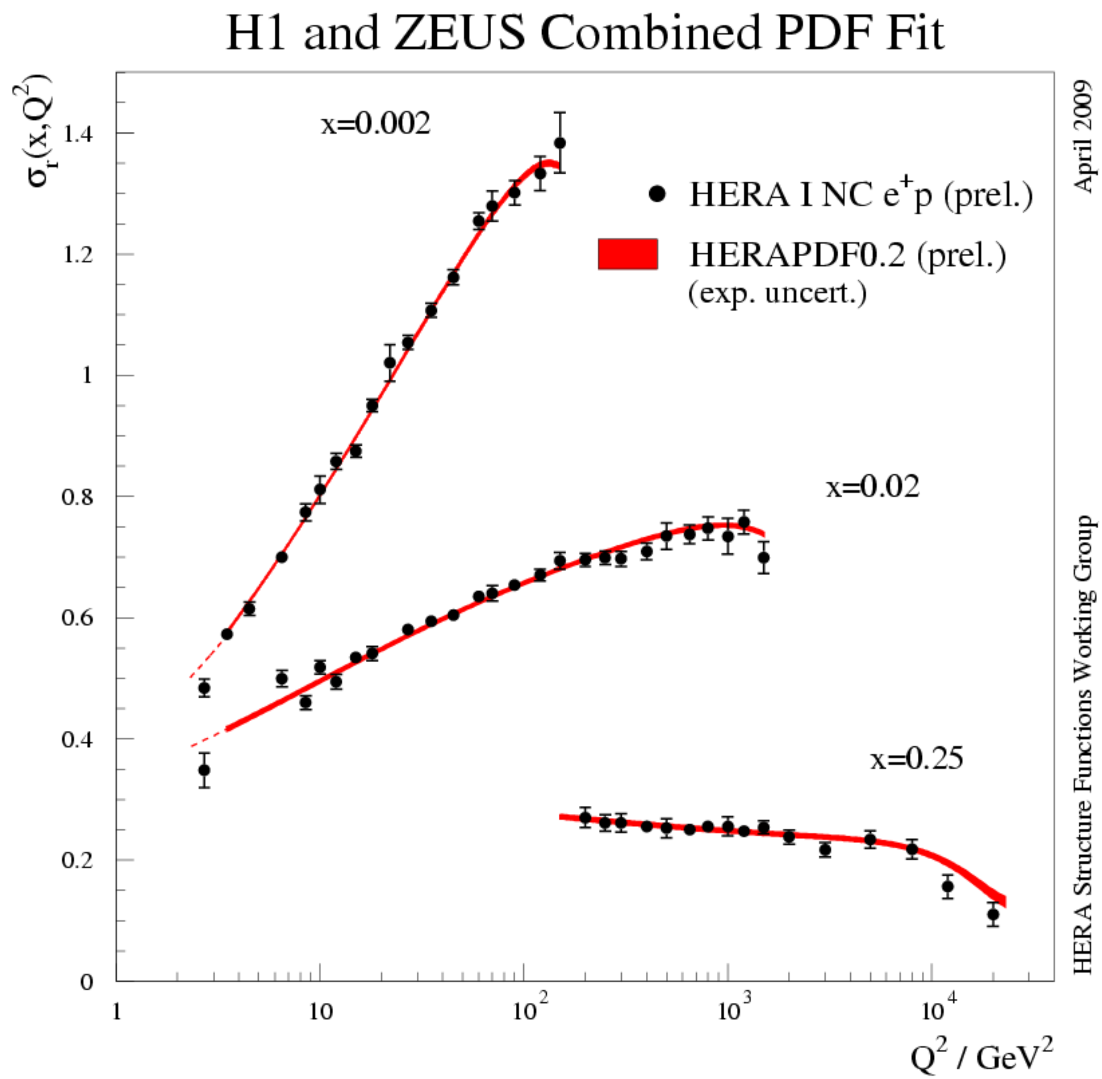
F_2 vs. Q^2

- 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

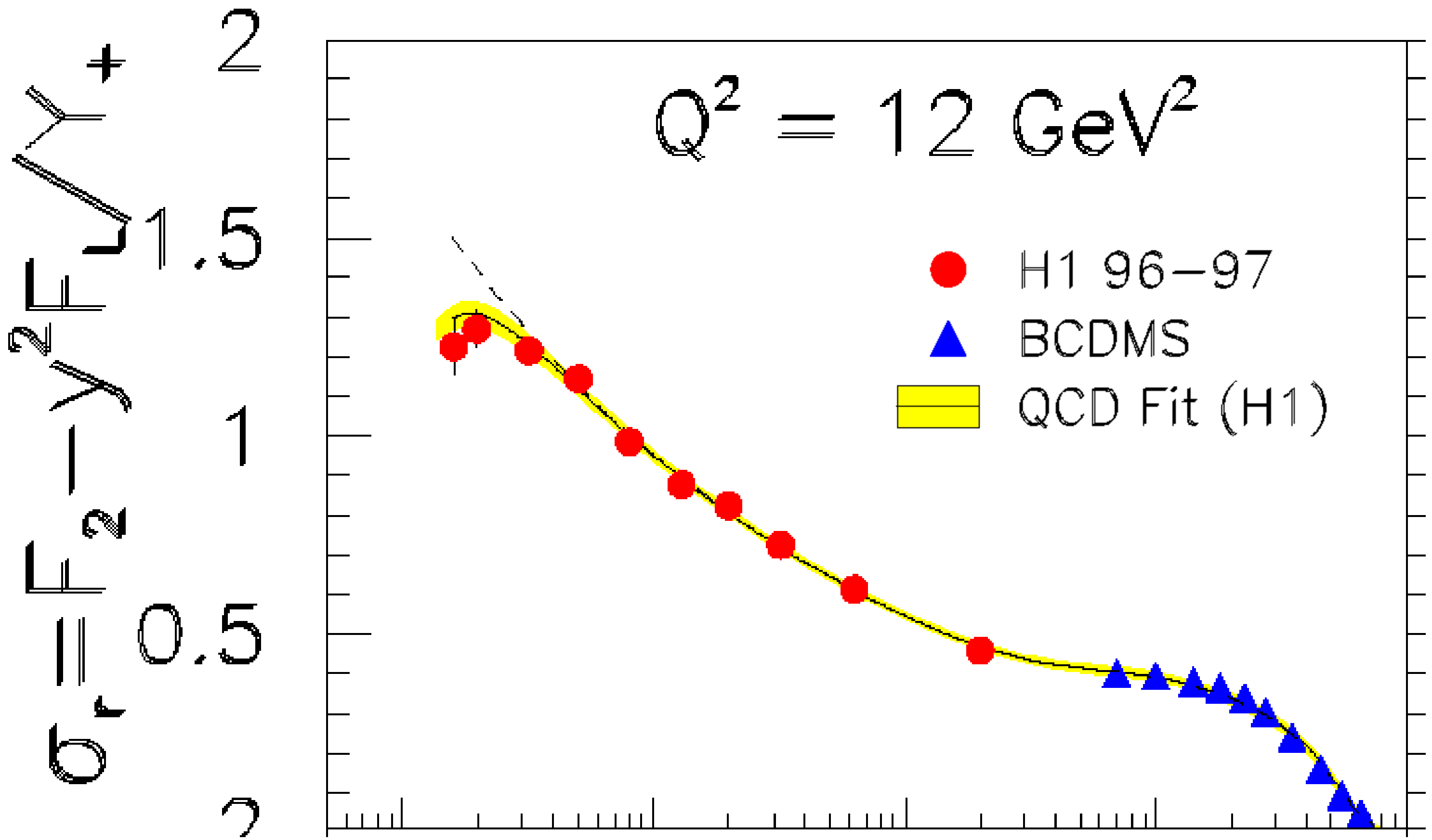


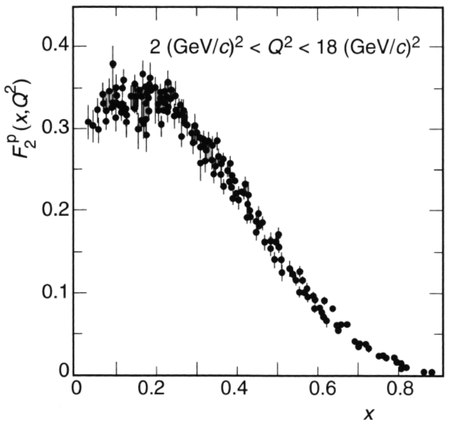
F_2 vs. Q^2: example bins

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

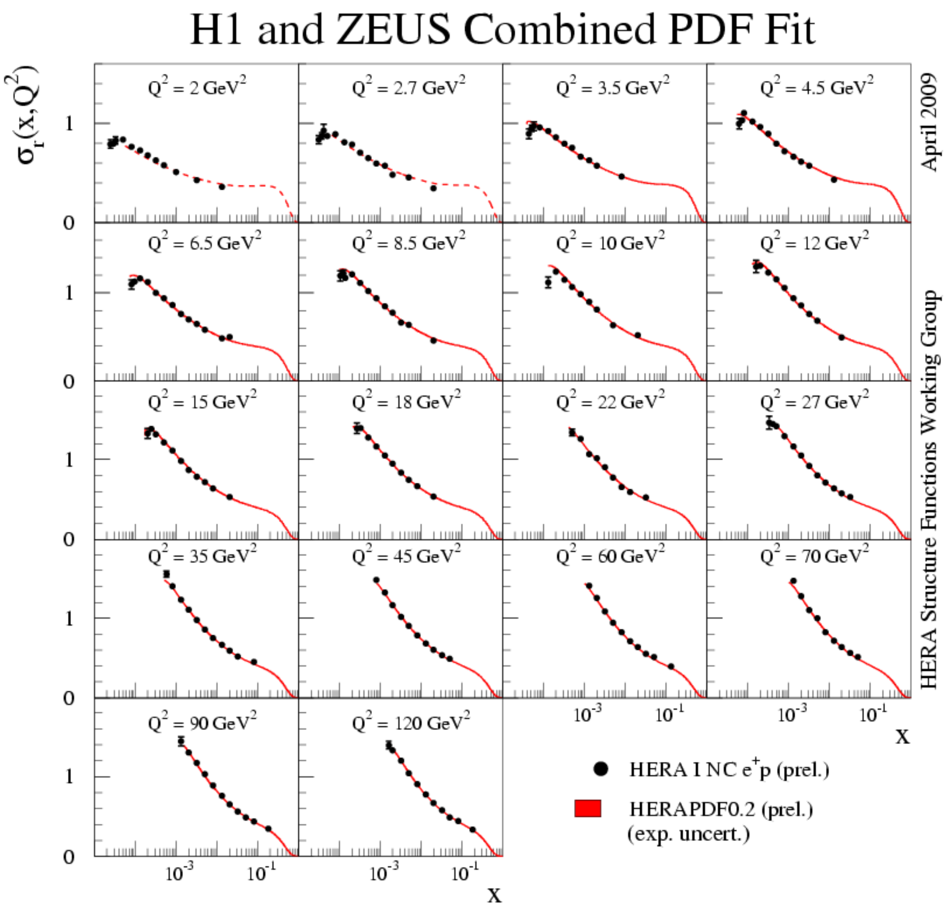


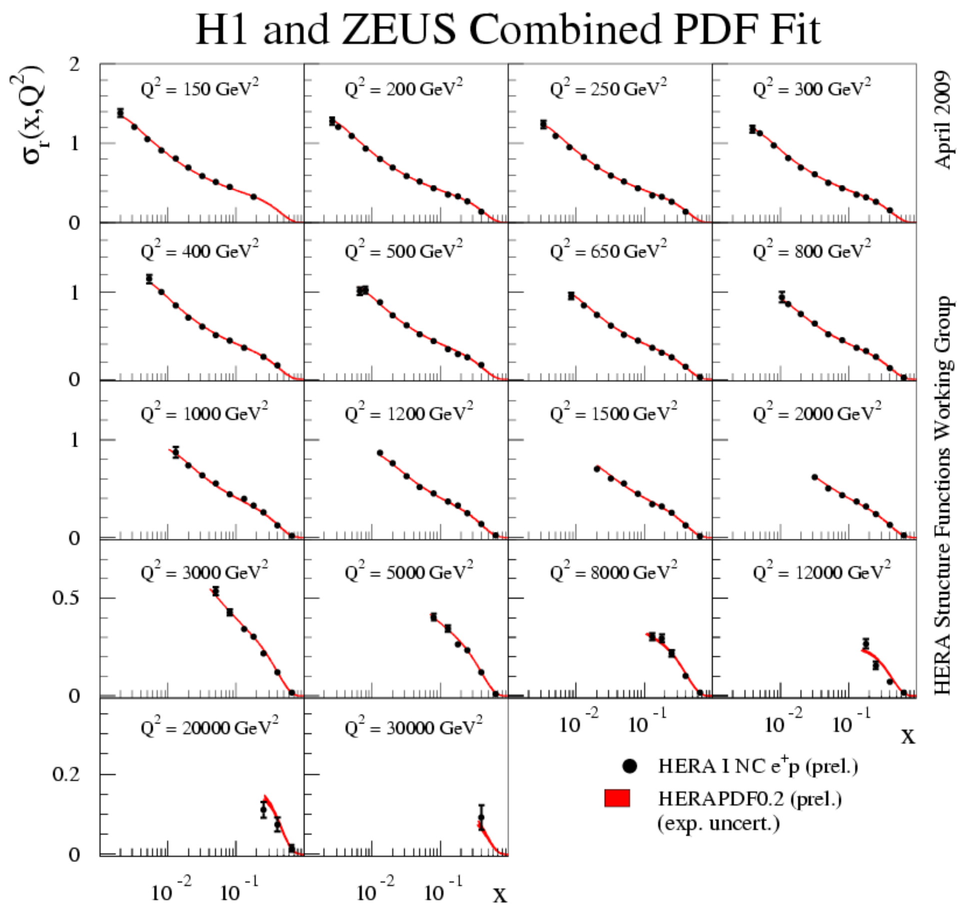
How does $F_2(x)$ look like?





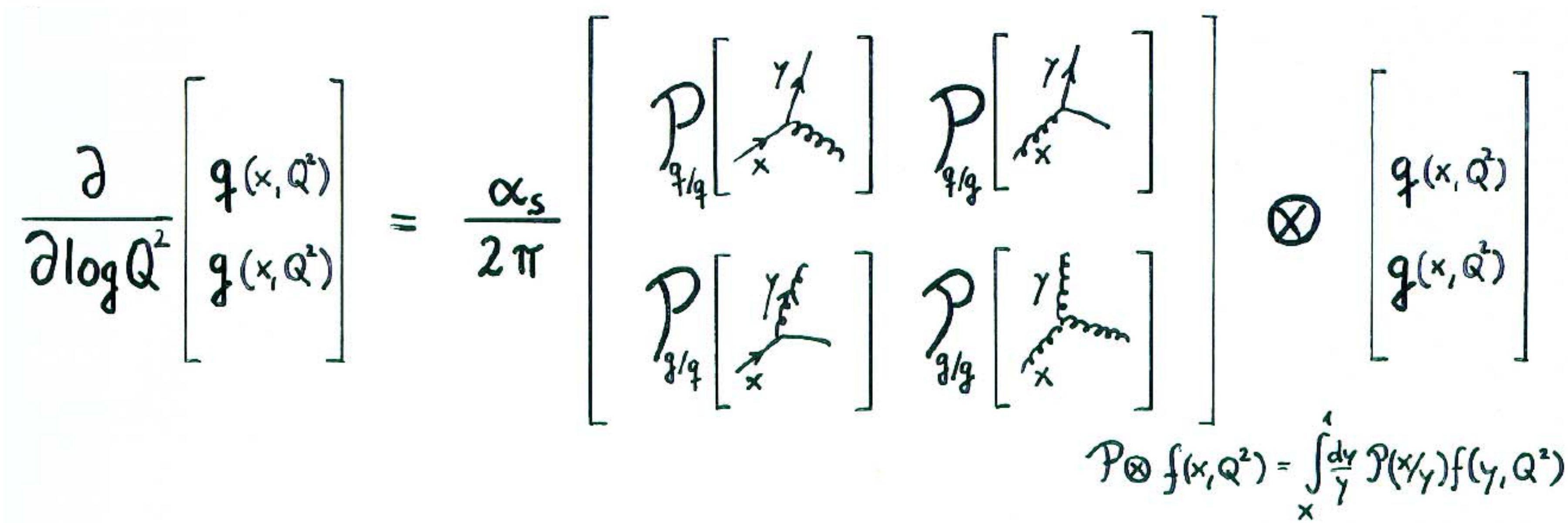
F_2 vs. x





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

DGLAP Evolution Equations



- 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

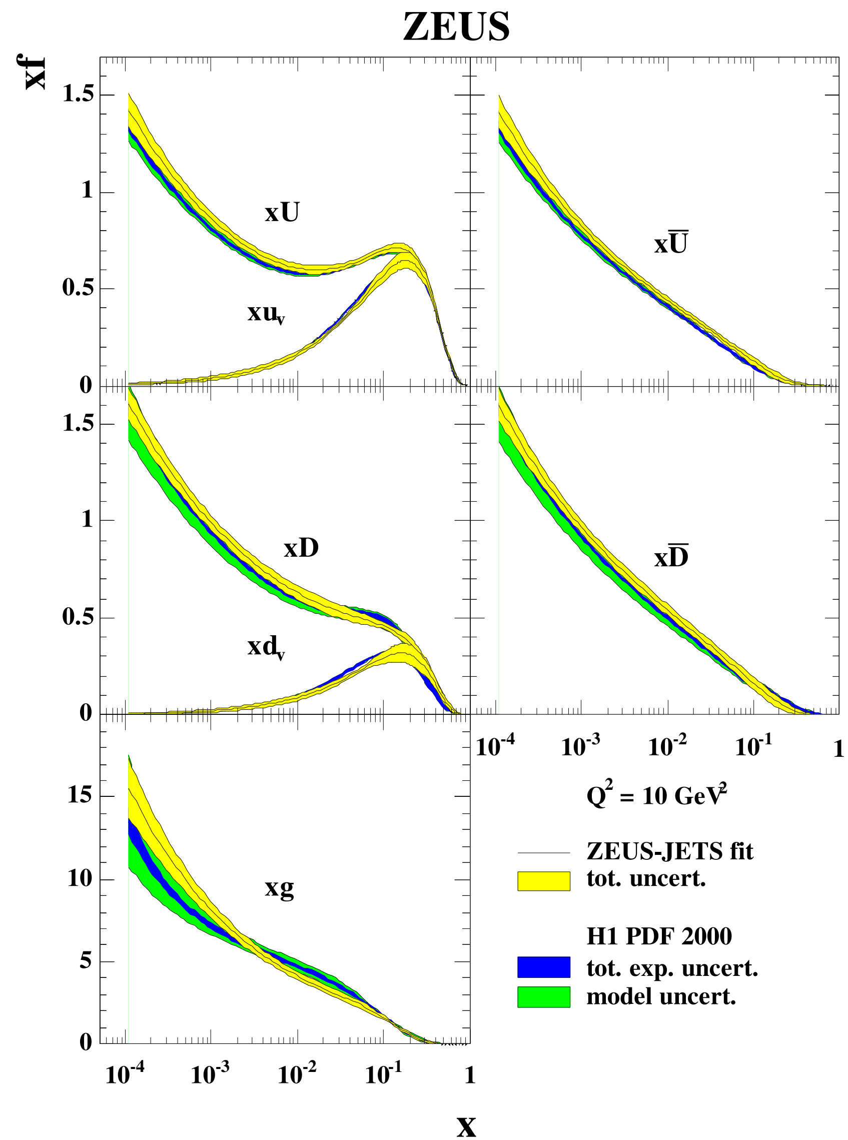
- ➔ assume parametrisation of the parton density functions (PDFs) as a function of x at a starting scale Q_0^2 (typically around 4 - 7 GeV^2):
  $$x\,q(x, Q_0^2) = A\,x^B (1-x)^C \left[1 + D\,x + E\,x^2 + F\,x^3\right]$$
- ➔ evolve the PDFs to all measured Q^2, calculate F_2, and fit the parameters to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

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

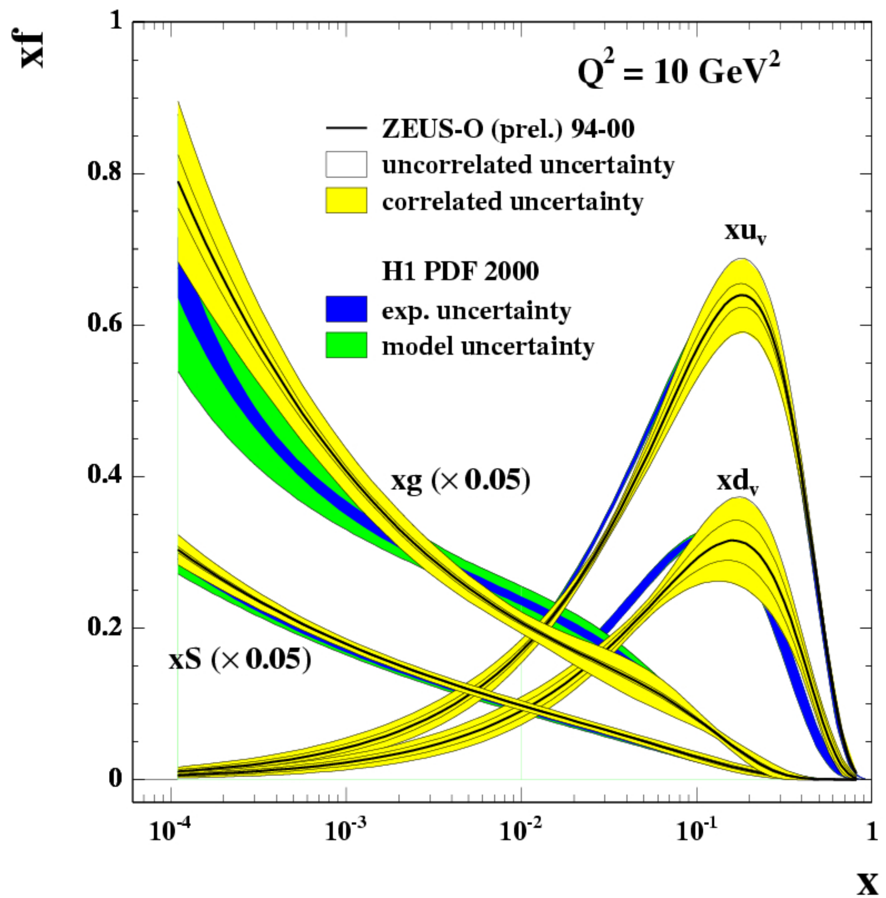
Parton Density Fits

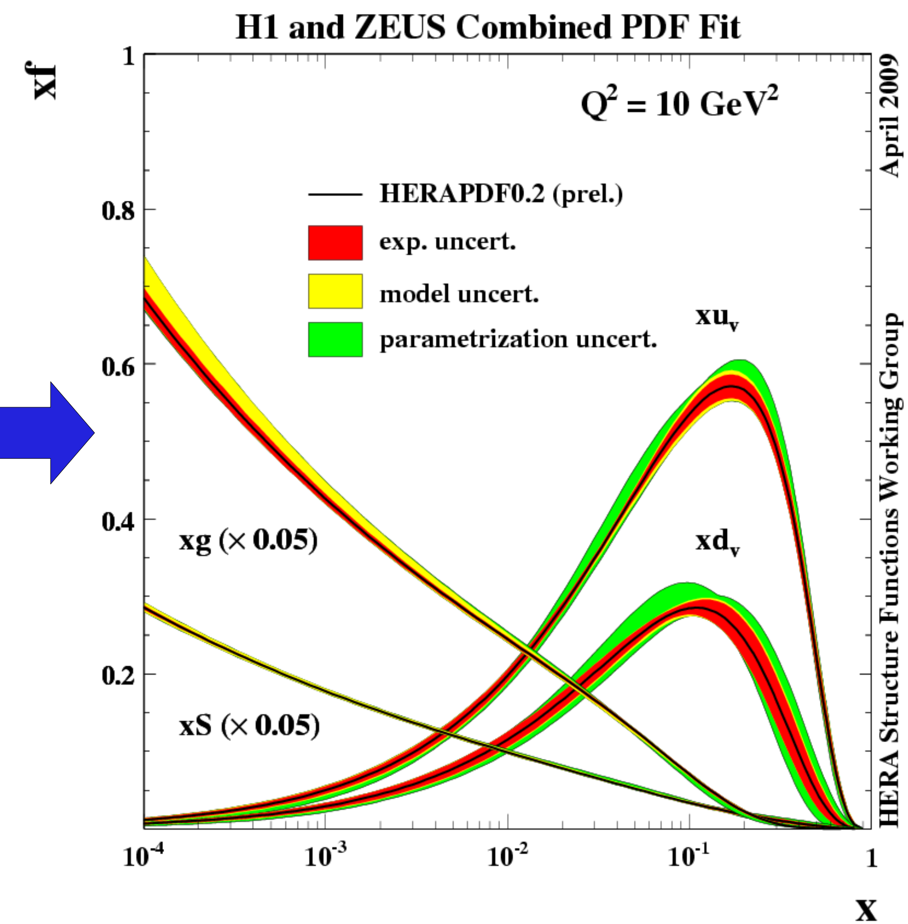
quark and antiquark densities:

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



Combined H1 & ZEUS Parton Density





combination of data from H1 and ZEUS
gives big improvements!

Longitudinal Structure Function F_L

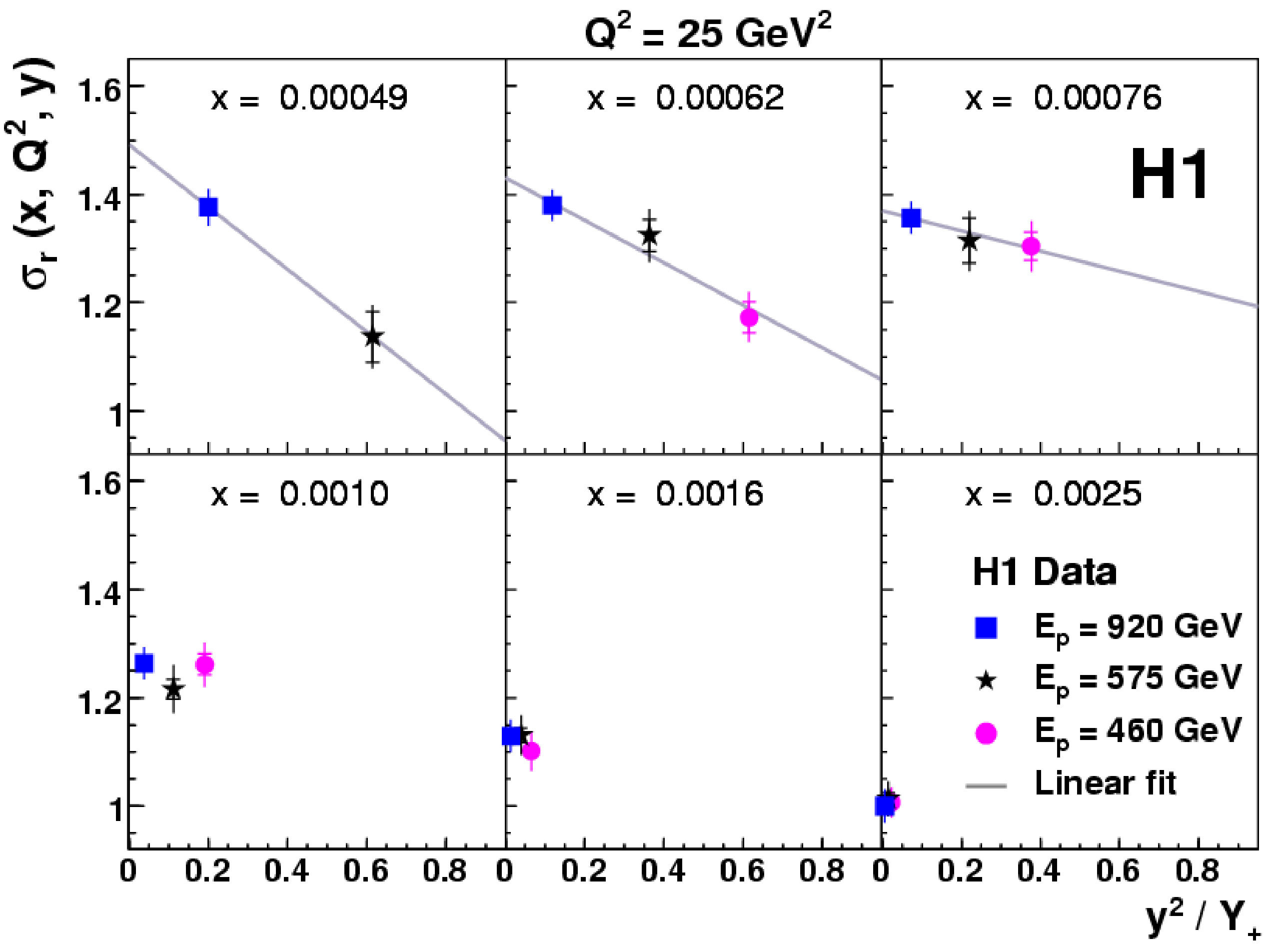
- Callan-Gross relation $2\,x\,F_1 = F_2$ only true in naive Quark-Parton-Model
- the longitudinal structure function F_L is defined as $F_L = F_2 - 2\,x\,F_1$
- F_L is directly proportional to the gluon density
- for a measurement of F_L one needs data at the same x and Q^2, but different y

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

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

➔ measure at different beam energies!

Longitudinal Structure Function F_L



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

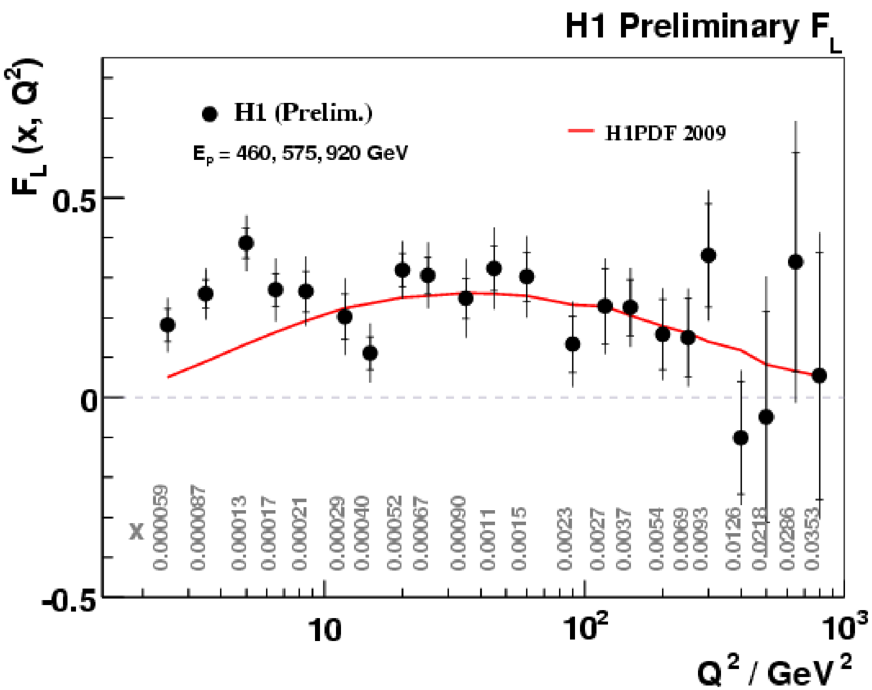
$$= F_2(x, Q^2) - \frac{y^2}{Y_+} F_L(x, Q^2)$$

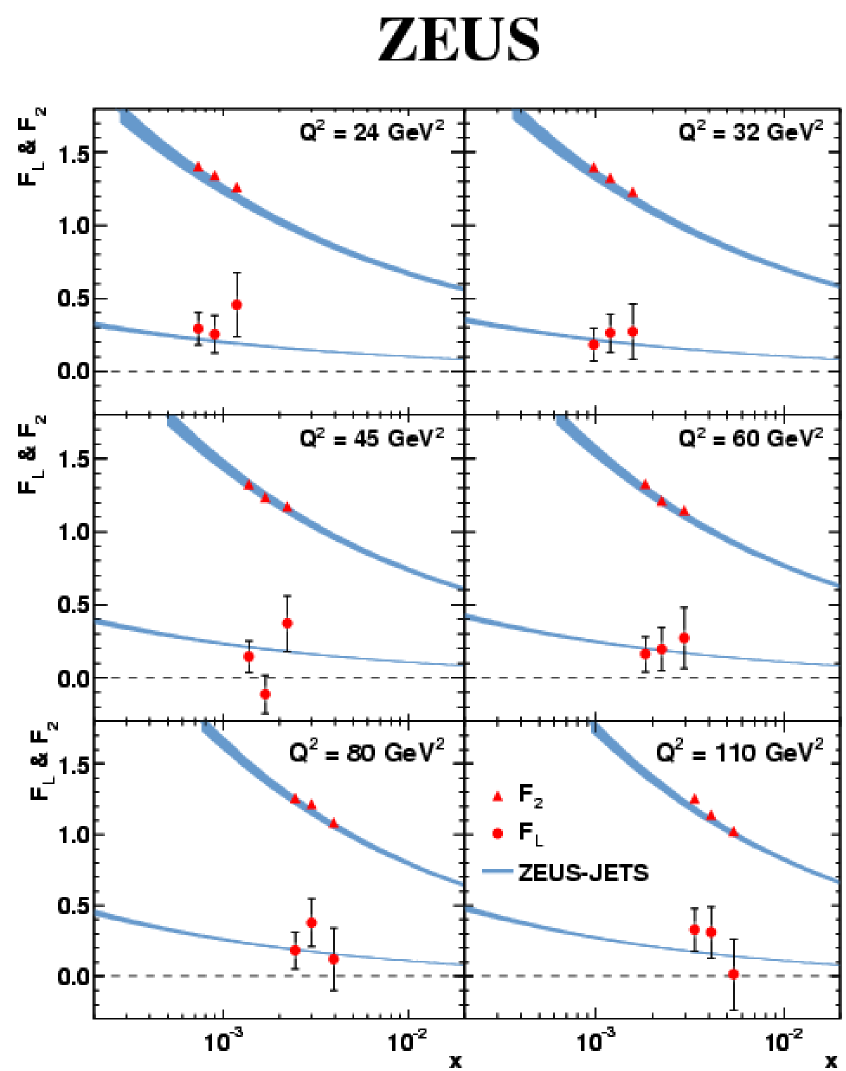
with $Y_+ = 1 + (1-y)^2$

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

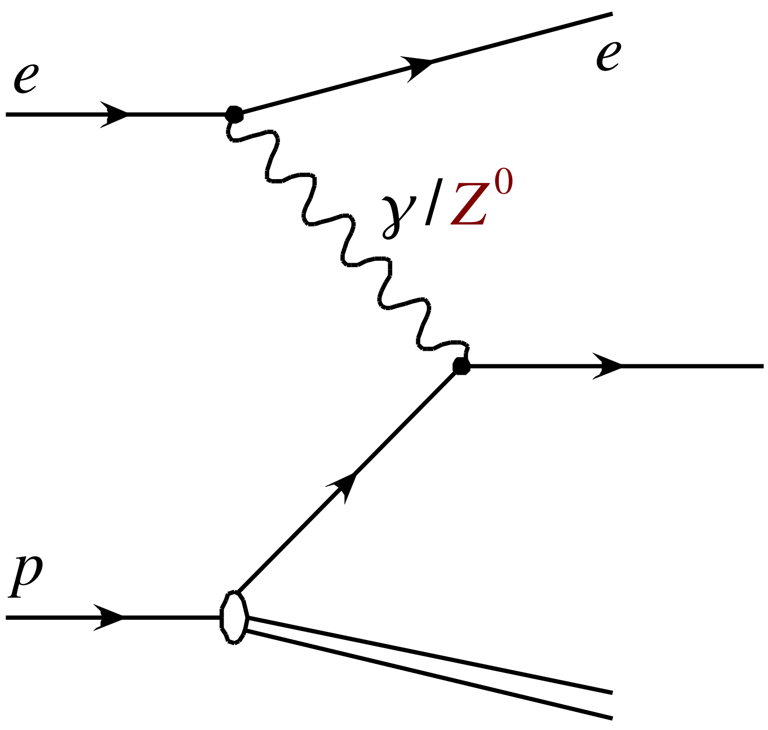
High Q^2 & Electroweak Physics

More Structure Functions

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

$$\frac{d^2\sigma^{\pm}_{NC}}{dx\,dQ^2} = \frac{2\pi\alpha^2}{Q^4}\frac{1}{x}Y_+\left[F_2(x,Q^2) - \frac{y^2}{Y_+}F_L(x,Q^2) \mp \frac{Y_-}{Y_+}xF_3(x,Q^2)\right]$$

$F_3 : \gamma - Z^0 - \text{interference}$



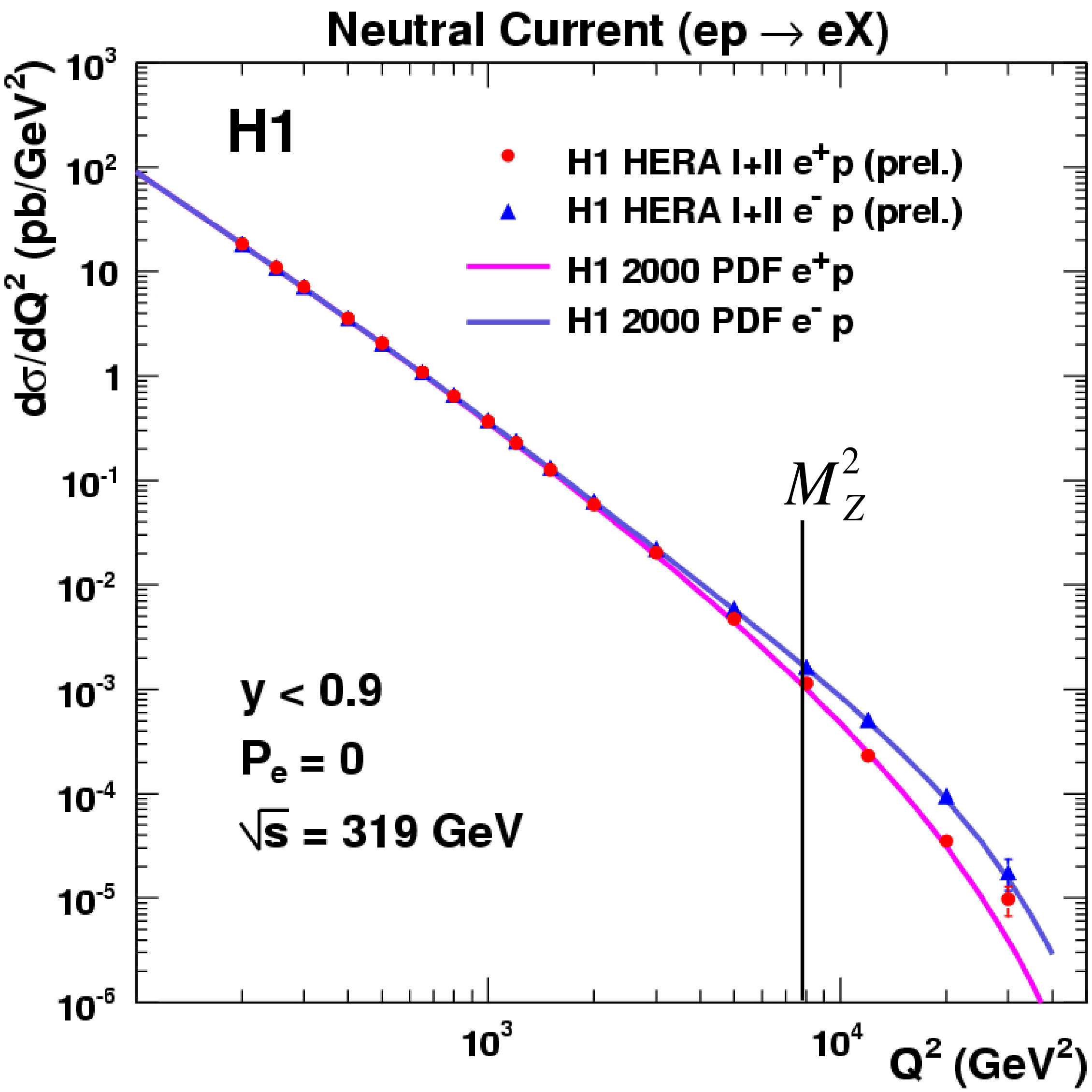
$$Y_{\pm} = 1 \pm (1-y)^2$$

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

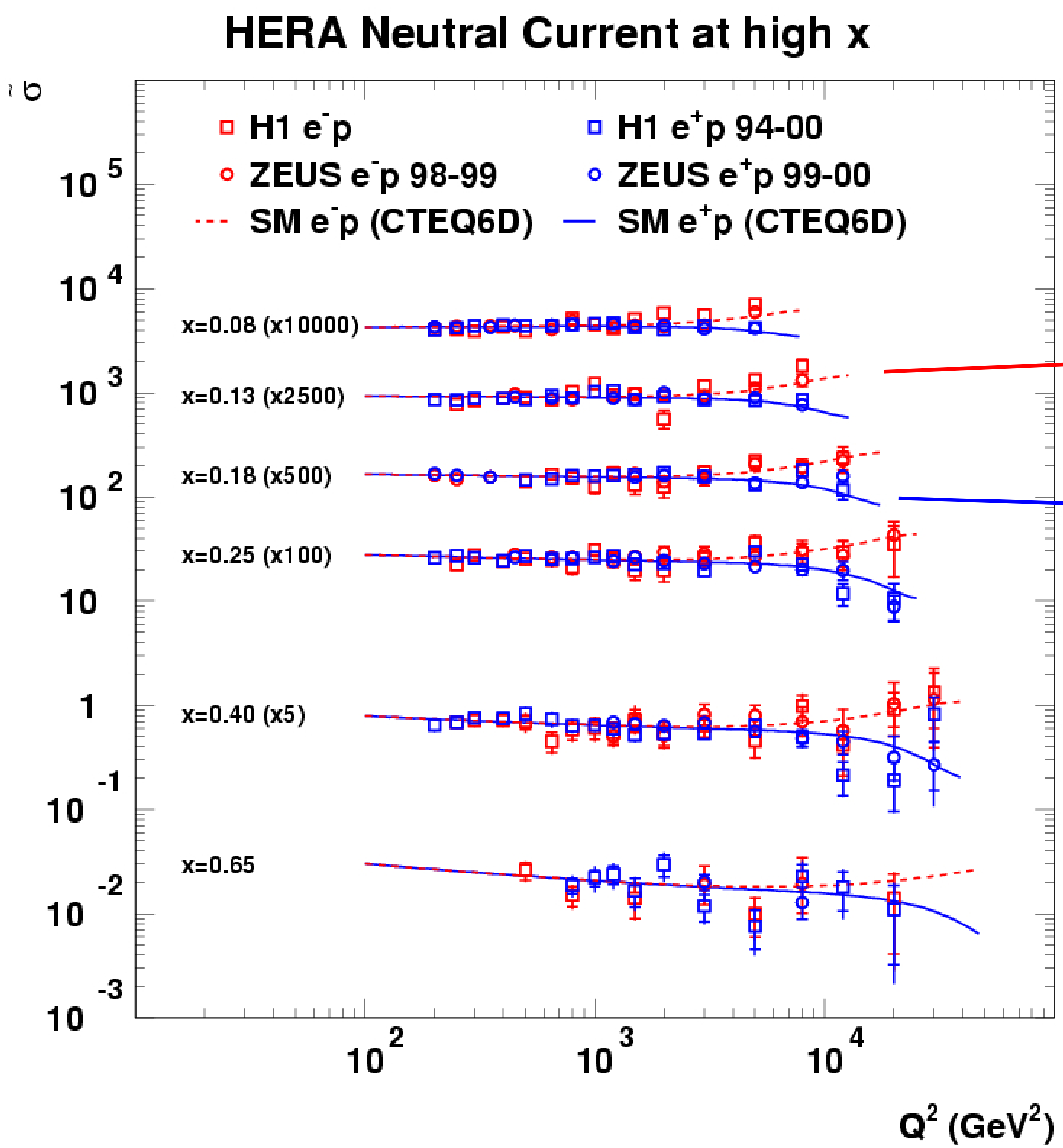
High Q^2 Neutral Current

- 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



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

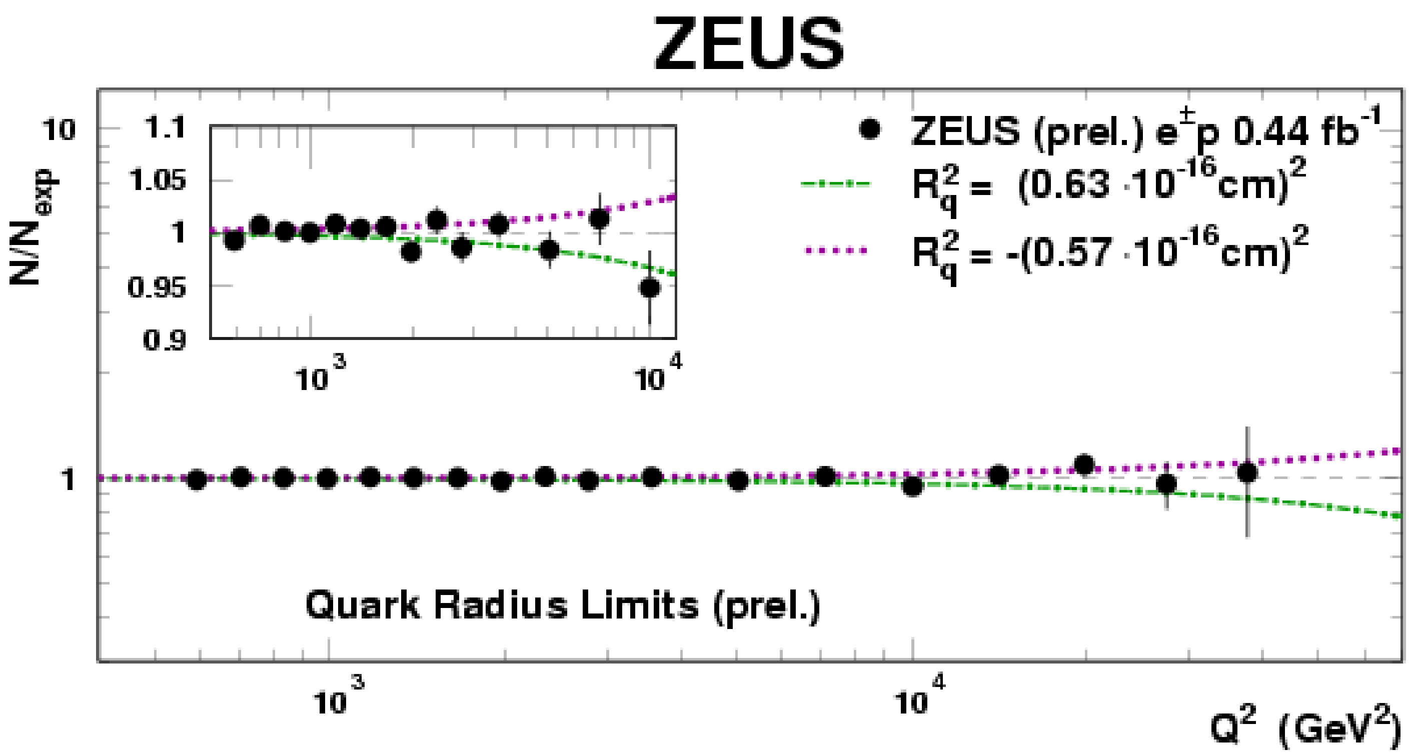
e⁻ positive interference

e⁺ negative interference

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

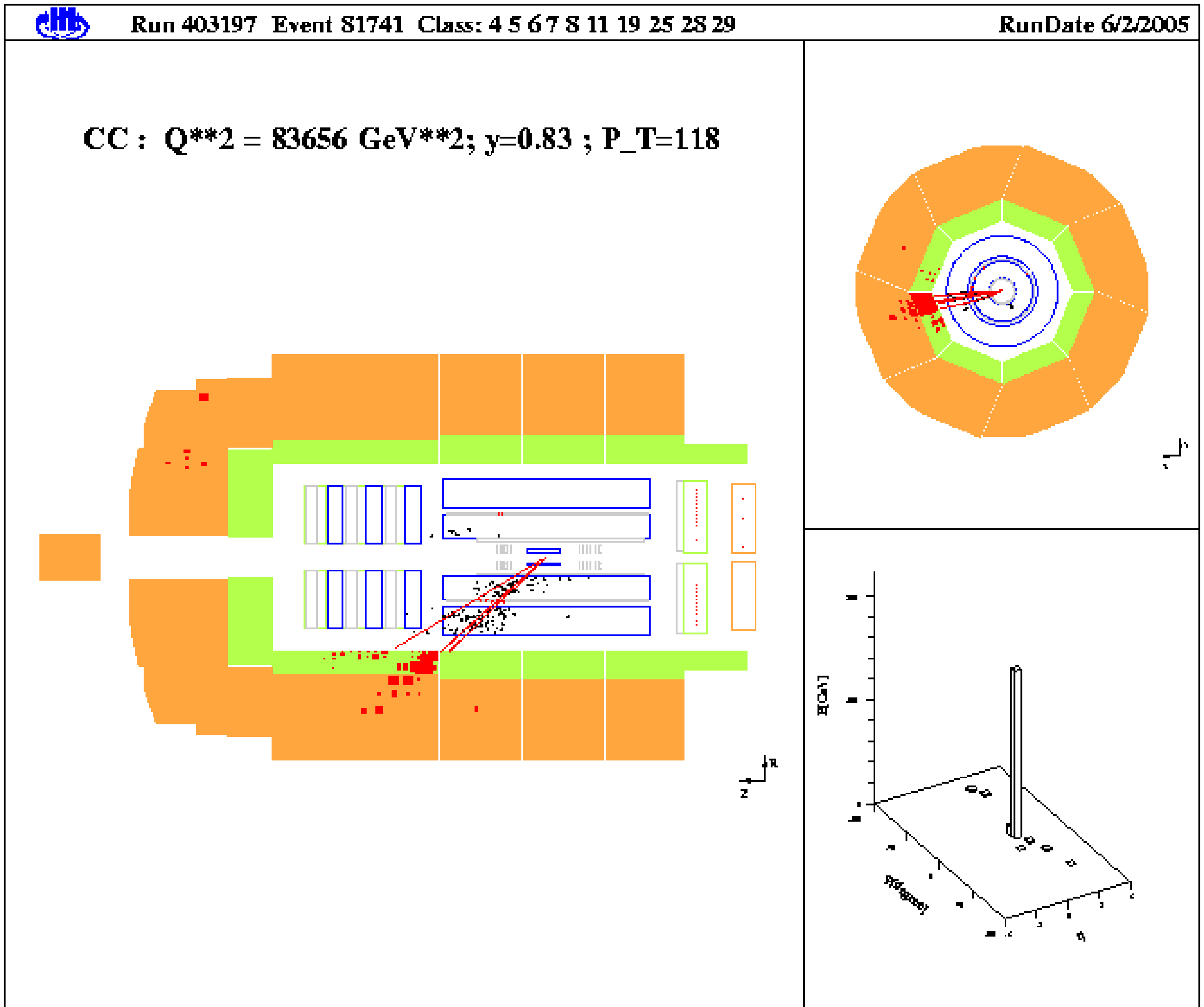
direct handle on valence quark distribution!

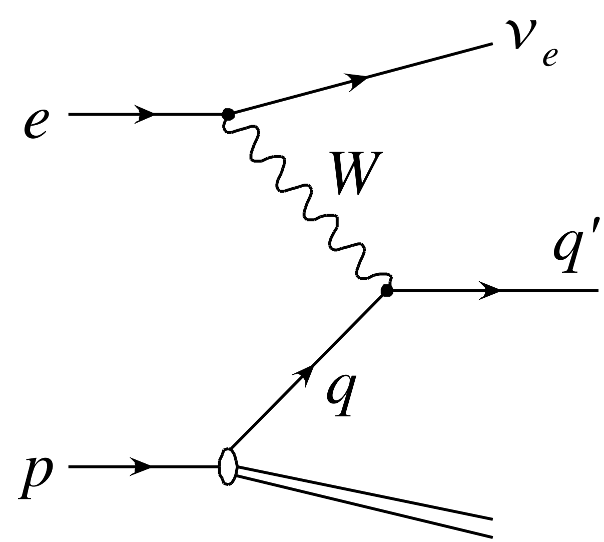
High Q^2 Neutral Current



- no significant deviation from Standard Model Fit at high Q^2
- can be interpreted as limit on quark size: $< 0.6 \cdot 10^{-18}$ m

Charged Current Interactions





neutrino not visible in detector

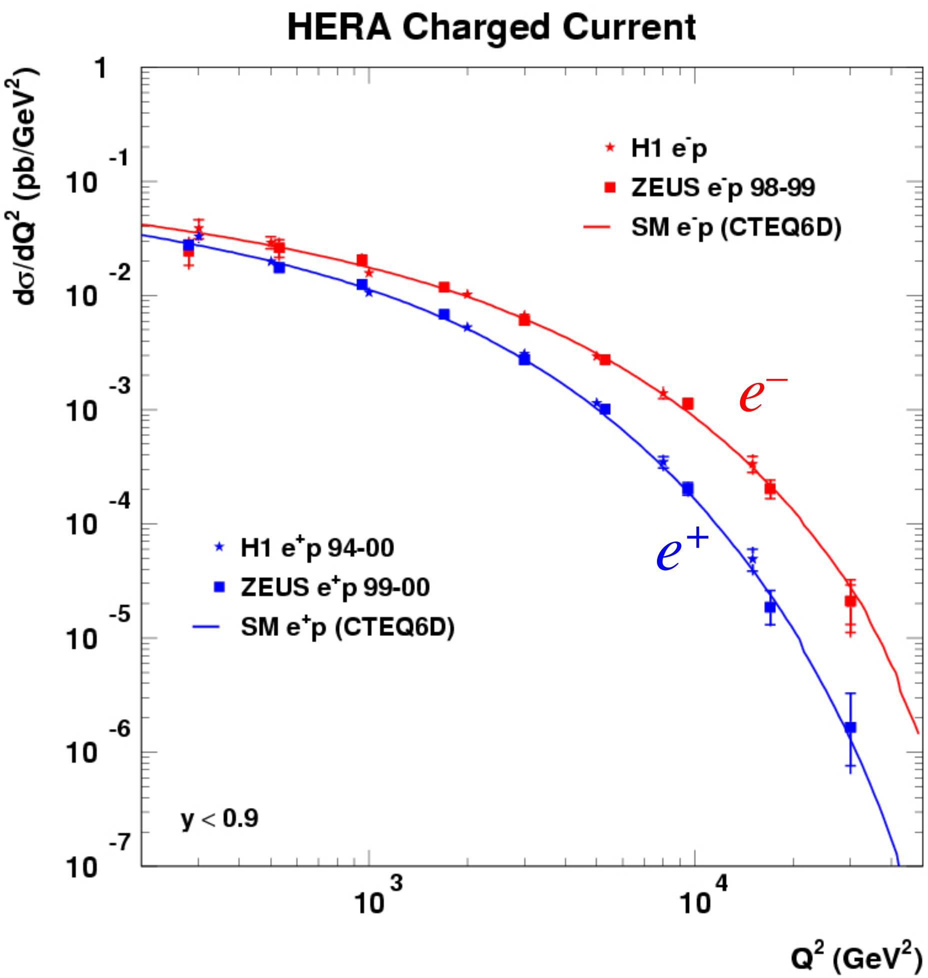
→ imbalance in transverse plane

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:
  $W_2^- = x(U+\overline{D}), \quad xW_3^- = x(U-\overline{D})$
  $W_2^+ = x(\overline{U}+D), \quad xW_3^+ = x(D-\overline{U})$
  $W_L^{\pm} = 0$

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



Comparison NC vs. CC

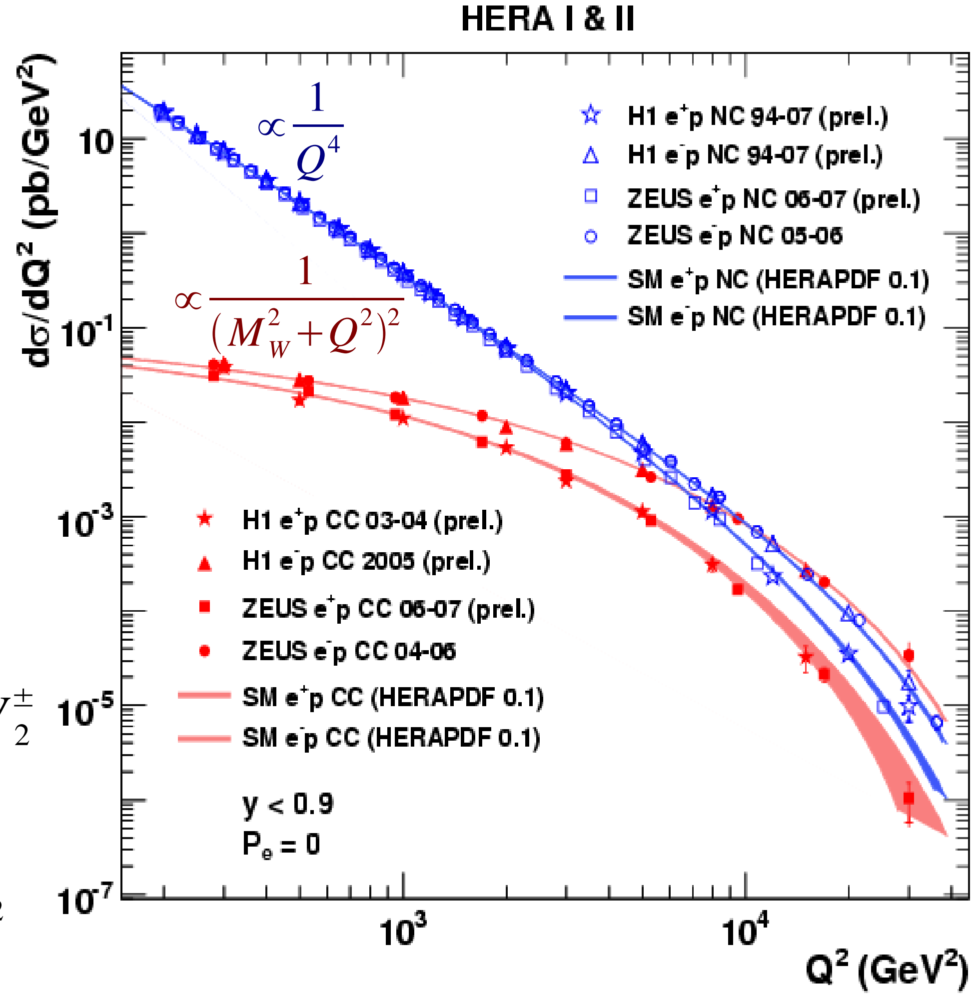
- at low Q^2: different dependences because of photon in NC
- at high Q^2: „electroweak unification“

but:

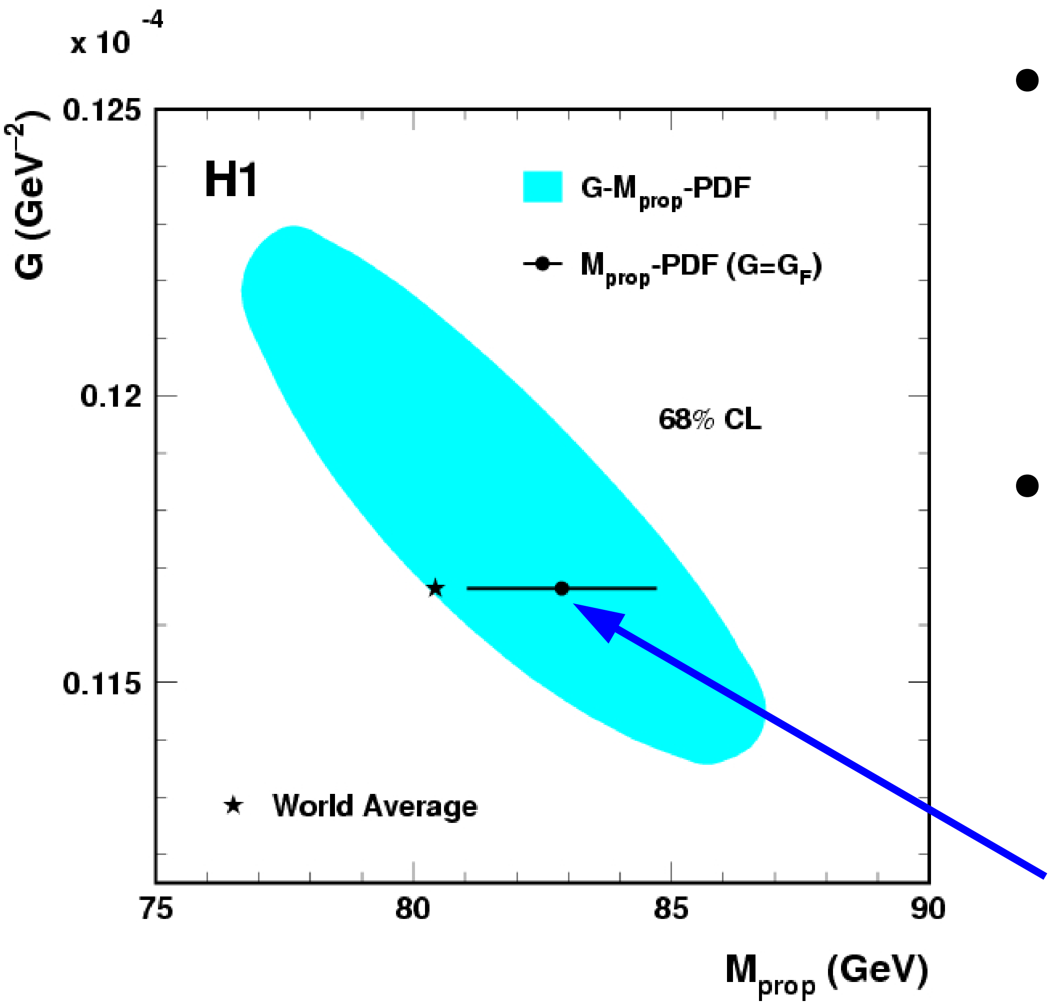
$$\frac{d^2\sigma_{CC}^{\pm}}{dx\,dQ^2} \approx \frac{G_F^2}{4\pi x}\cdot\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2 \cdot Y_+ W_2^{\pm}$$

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

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



Electroweak Parameters: *W* Mass

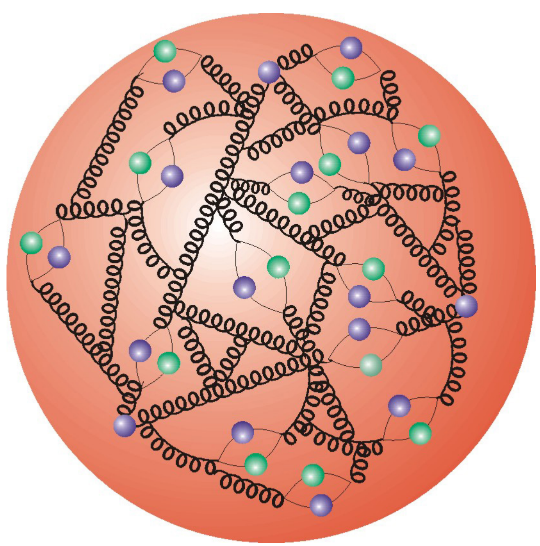


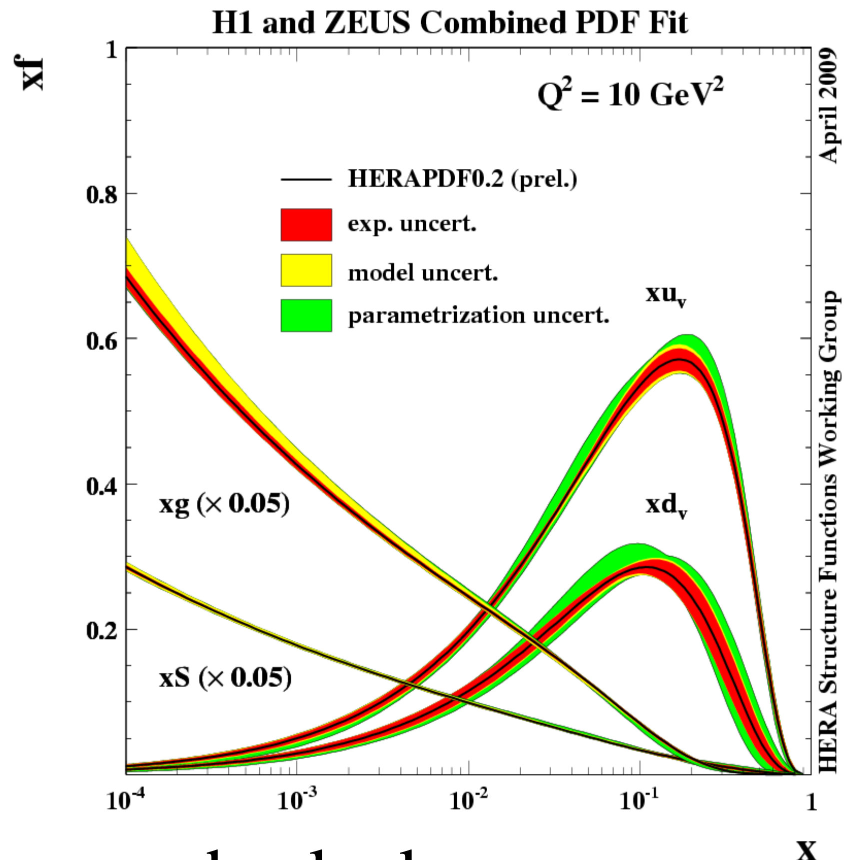
- $G = G_F$ determined by normalization of the CC cross section
- $M_{prop} = M_W$ determined by the Q^2 dependence of the CC cross section

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

Summary

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





- Standard Modell can be cross checked