Recent Results from HERA

I. Structure of Proton

$F_2(x, Q^2)$, $F_L(x, Q^2)$, $F_2^c(x, Q^2)$, $g(x, Q^2)$

II. Structure of Photon

$F_2^\gamma(x, Q^2)$ for real and virtual photons

III. Hard Diffraction

$\gamma p \to V p$, $\gamma^* p \to V p$

$F_2^{D(3)}(X_{I\!P}, \beta, Q^2)$

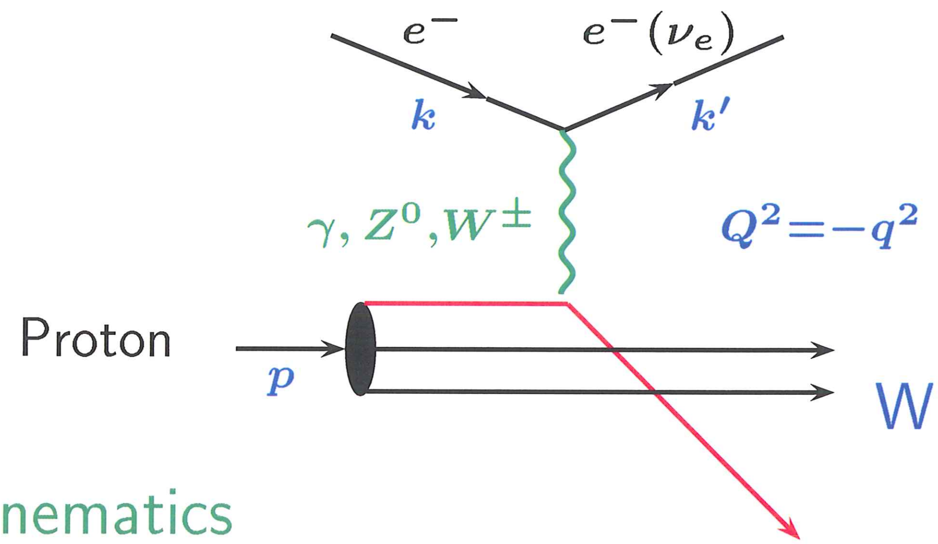
IV. Summary

International Conference on
Quark Nuclear Physics
Adelaide, 21–25.2.2000

D. Wegener
Dortmund University

I. Structure of Proton

Deep inelastic scattering



Kinematics

$$s = (p+k)^2$$

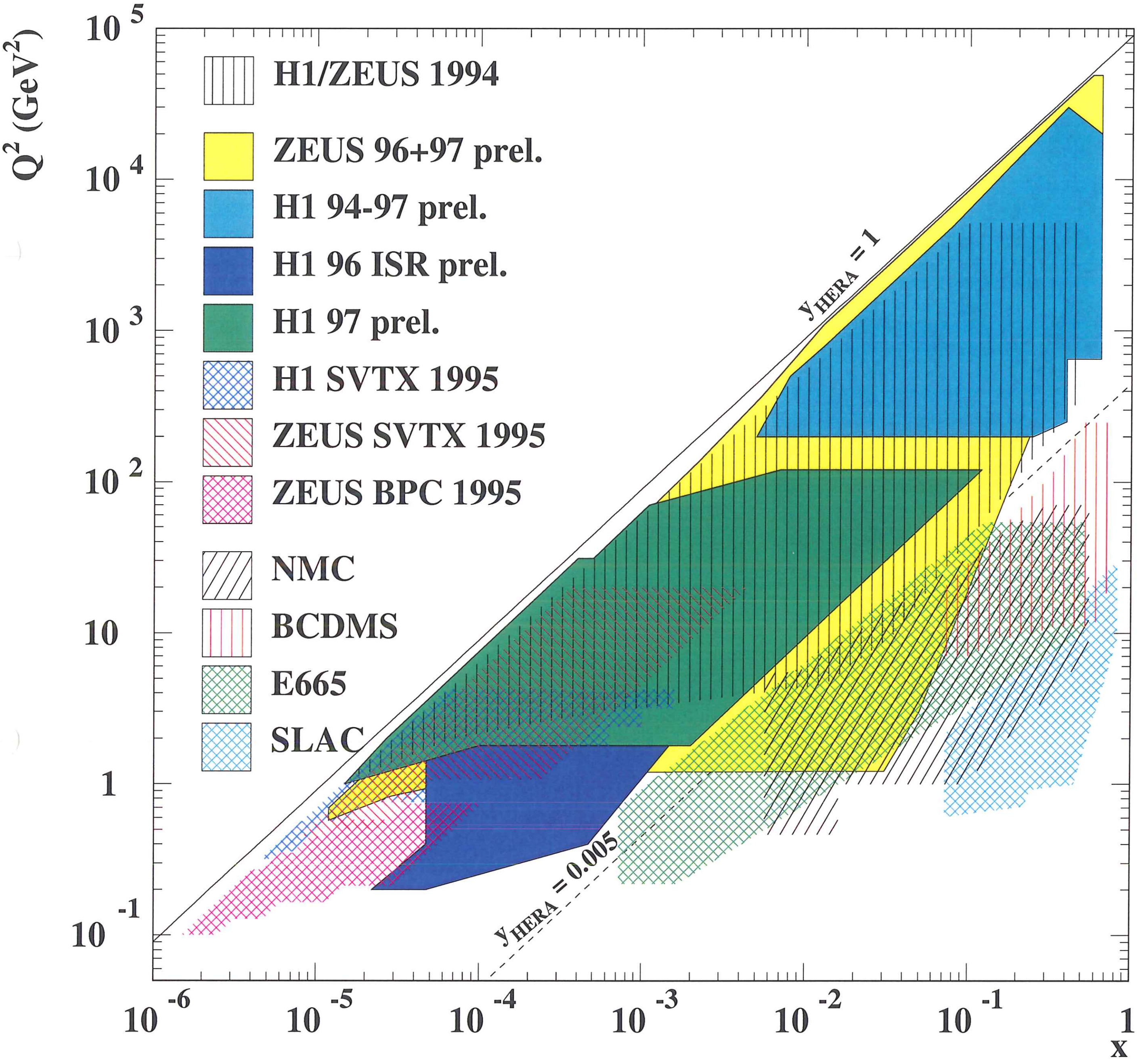
$$W^2 = (q+p)^2 \quad \text{hadronic final state mass}$$

$$Q^2 = -(k-k')^2 \quad \text{four momentum transfer}$$

$$y = \frac{q \cdot p}{k \cdot p} \quad \text{fractional energy transfer}$$

$$x = \frac{Q^2}{2\,p \cdot q} \quad \text{parton momentum fraction}$$

1. Structure Function F_2



$$\frac{d^2\sigma}{dx\,dQ^2} = \frac{4\pi\,\alpha^2}{x\,Q^2}\left\{\frac{y^2}{2}\,2x\,F_1(x,Q^2) + (1-y)F_2(x,Q^2)\right\}$$

QPM : $F_2(x) = \sum\ e_i^2\, x\, q_i(x) = 2x\,F_1(x)$

QCD :

$F_2(x,Q^2) - 2x\ F_1(x,Q^2) = F_L(x,Q^2) > 0$

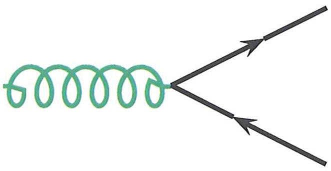
$F_L(x,Q^2)$ contributes at large y

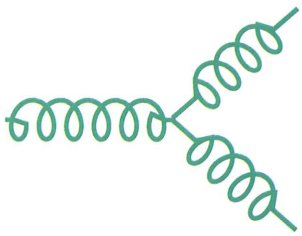
Why is $F_2(x,Q^2)$ measured ?

- Search for proton substructure
- Decompose proton into quarks and gluons
- Test perturbative QCD
- Input for future experiments at LHC (extrapolation over few orders of magnitude from present measurements !)

DGLAP – evolution :

$$\frac{\partial}{\partial \ln Q^2} \begin{pmatrix} q_i(x,Q^2) \\ g(x,Q^2) \end{pmatrix} = \frac{\alpha_s(Q^2)}{2\pi} \begin{pmatrix} P_{qq} & P_{qg} \\ P_{gq} & P_{gg} \end{pmatrix} \otimes \begin{pmatrix} q_i \\ g \end{pmatrix}$$

$P_{qg}^{(0)}$: 

$P_{gg}^{(0)}$: 

$e\,p \;\rightarrow\; e\,X$

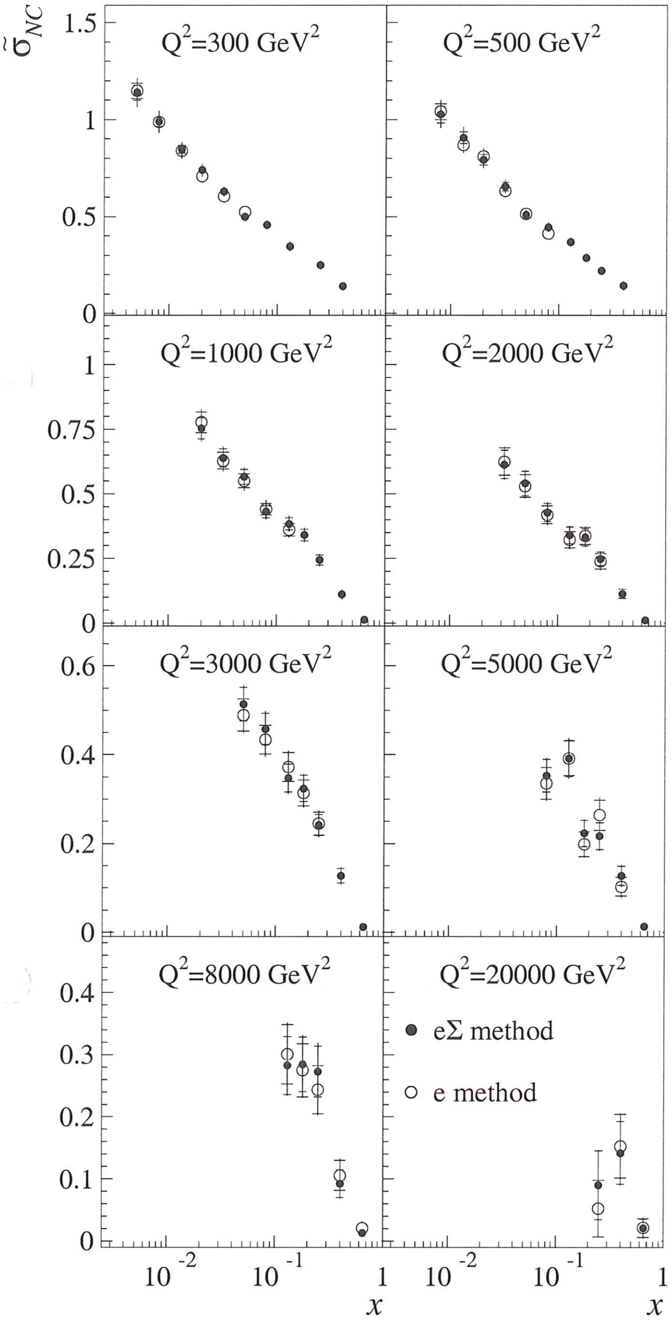
Kinematical variables :

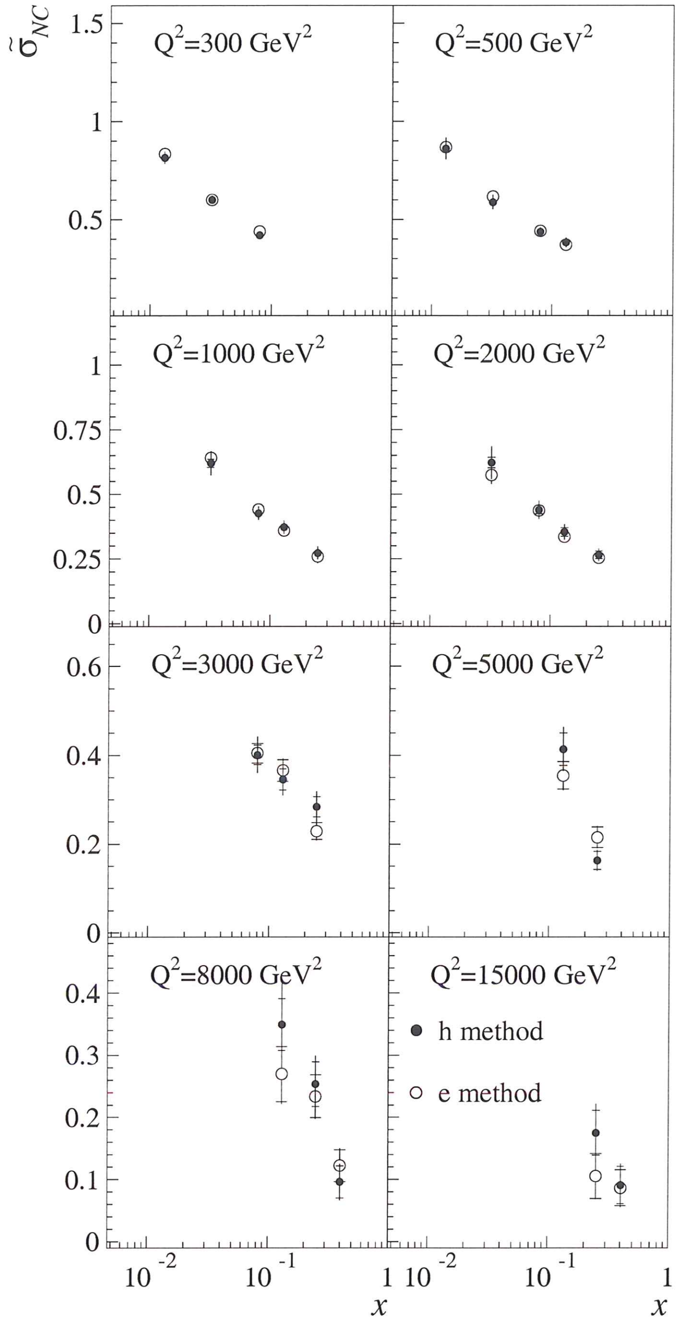
- Electron detection
- Hadron detection
- Mixed method

Advantage :

- Systematic checks possible
  Typical systematical uncertainty $< 4\,\%$
- Choose optimal method

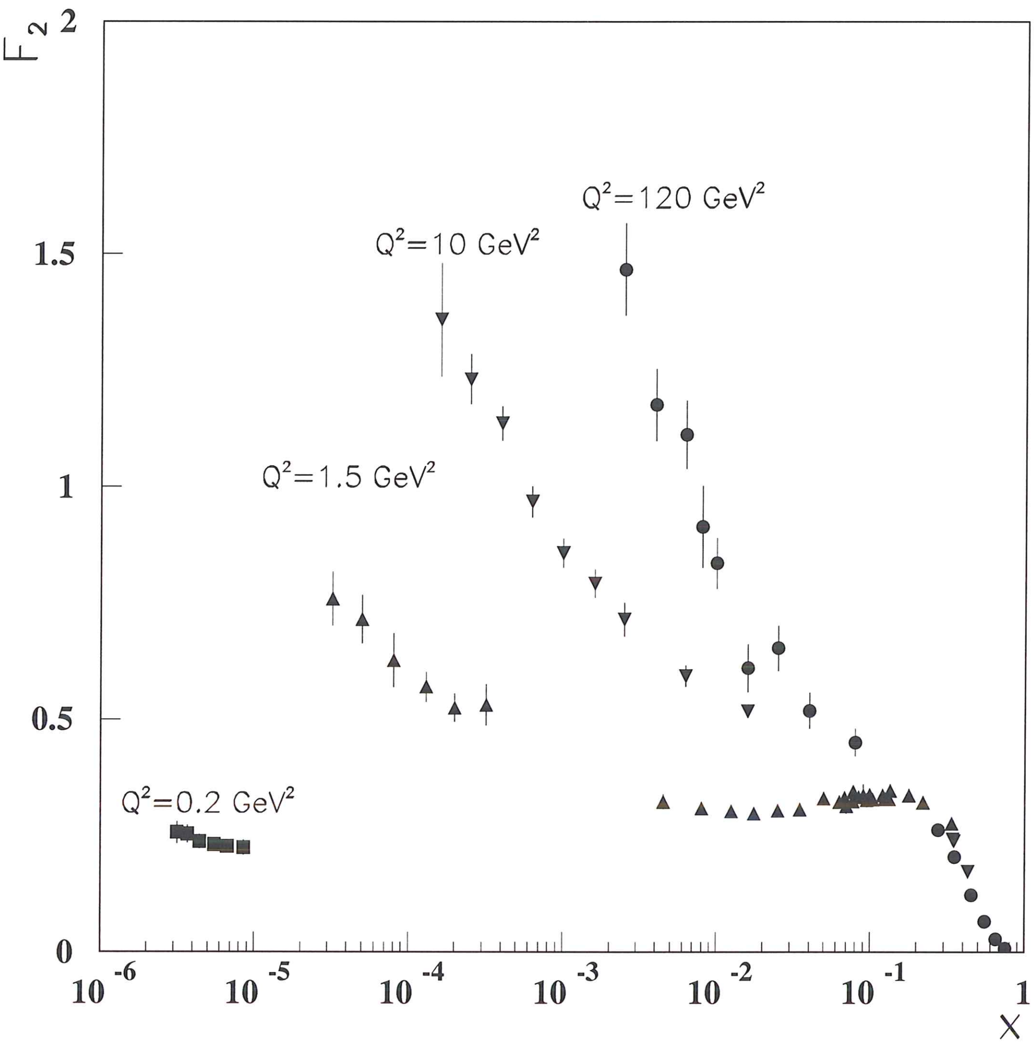
Good agreement for different methods :



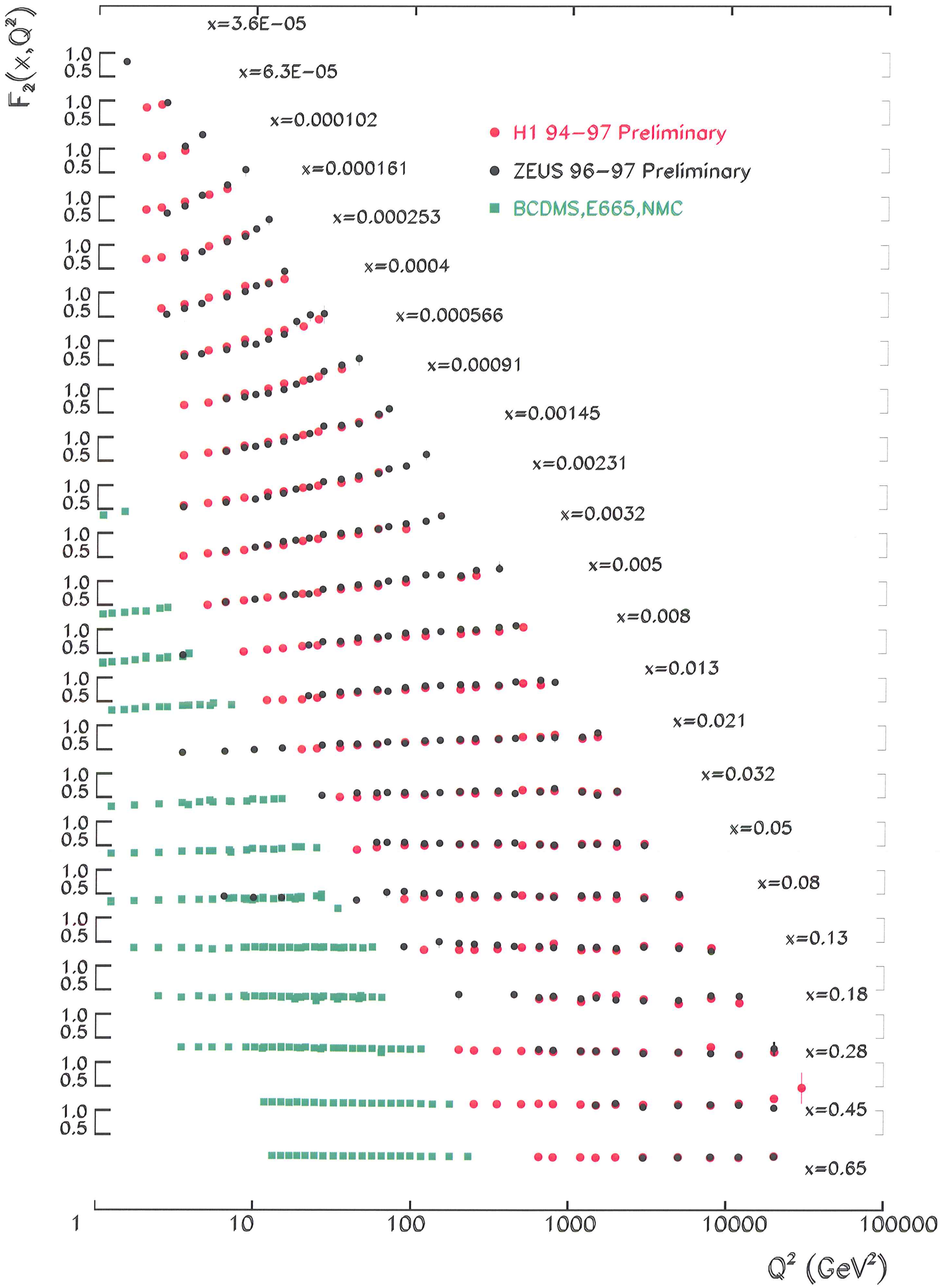


Structure Function $F_2(x, Q^2)$

Low x region

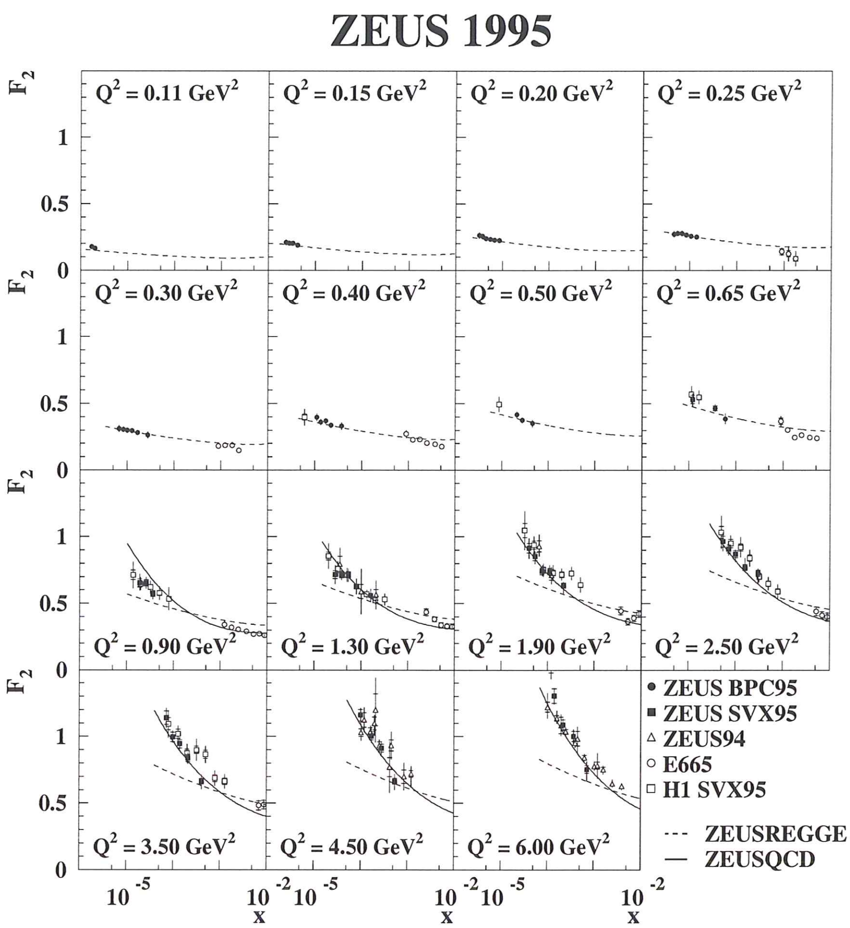


- Errors reduced by factor 2–3
  $R = 0$: 5 % ... 10 % change at lowest x-bin
- Good agreement with previous fixed target experiments
- Steep rise with decreasing x
  Steep rise with Q^2



$F_2(x,Q^2)$
x=3.6E-05
x=6.3E-05
x=0.000102
x=0.000161
x=0.000253
x=0.0004
x=0.000566
x=0.00091
x=0.00145
x=0.00231
x=0.0032
x=0.005
x=0.008
x=0.013
x=0.021
x=0.032
x=0.05
x=0.08
x=0.13
x=0.18
x=0.28
x=0.45
x=0.65
H1 94–97 Preliminary
ZEUS 96–97 Preliminary
BCDMS,E665,NMC
1.0
0.5
1
10
100
1000
10000
100000
Q^2 (GeV^2)

Small Q^2–region

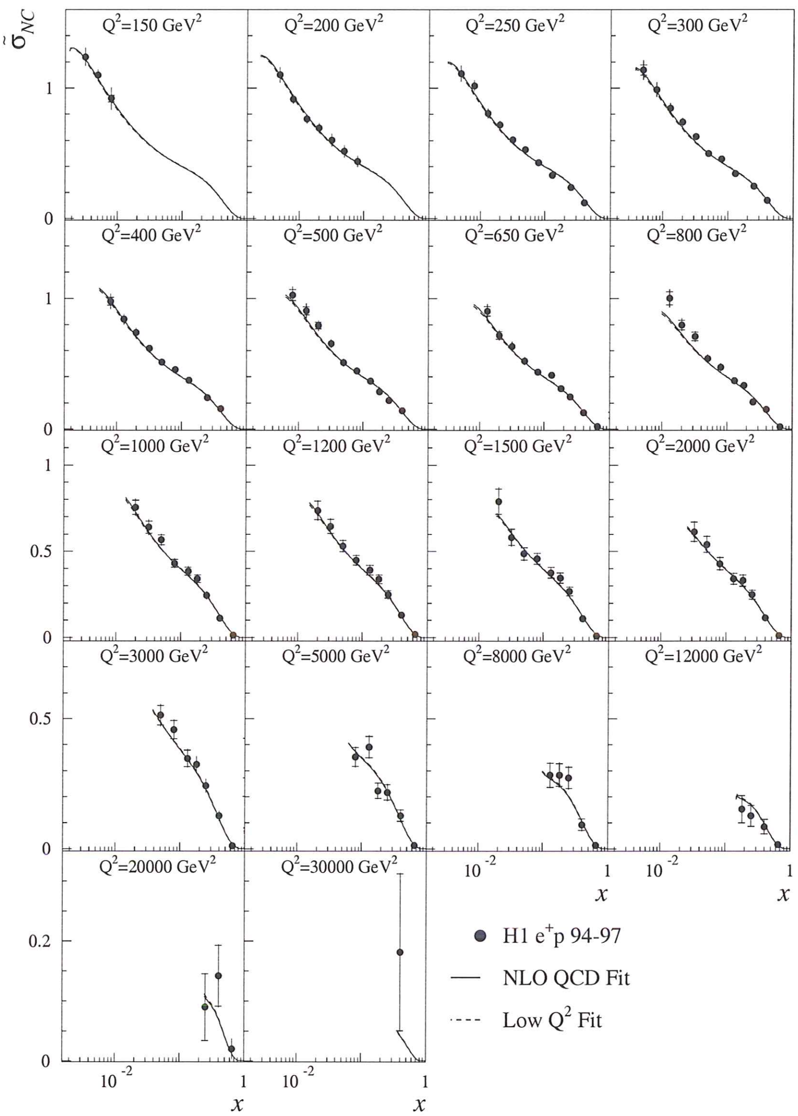


- Regge fit, successful for hadronic reactions, fails
- Pomeron ansatz with $\alpha(t = o, Q^2)$ good fit for $Q^2 < 0.5$ GeV^2
- GRV prediction : rise at low x due to radiation, for $Q^2 > 1$ GeV^2 successful
- No indication of saturation at low x
- For $Q^2{>}1$ GeV^2 pQCD processes become important
- For $Q^2{<}1$ GeV^2 nonperturbative processes start to dominate

Large Q^2–region

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

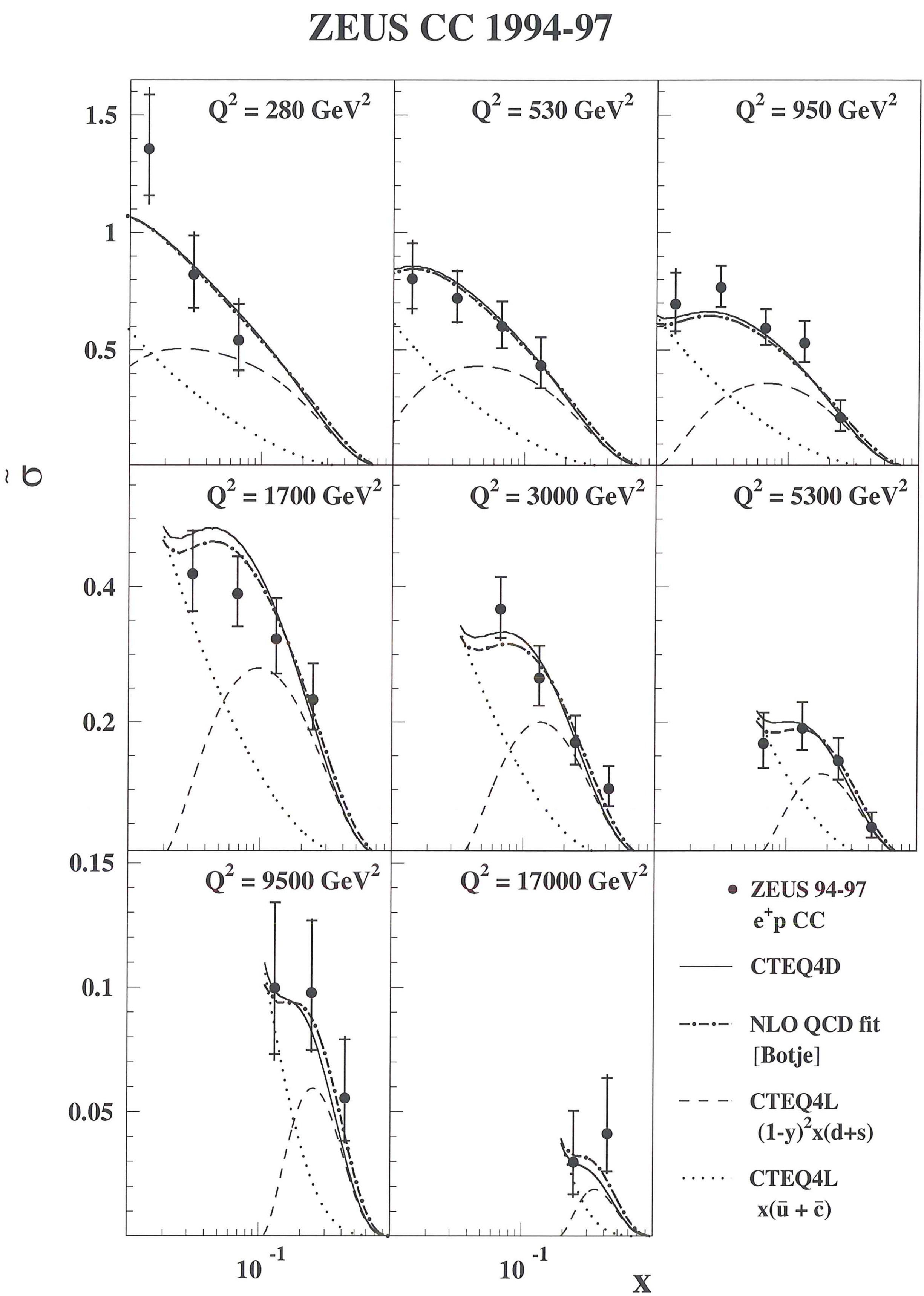
$$Y_+ = 1 + (1-y)^2$$

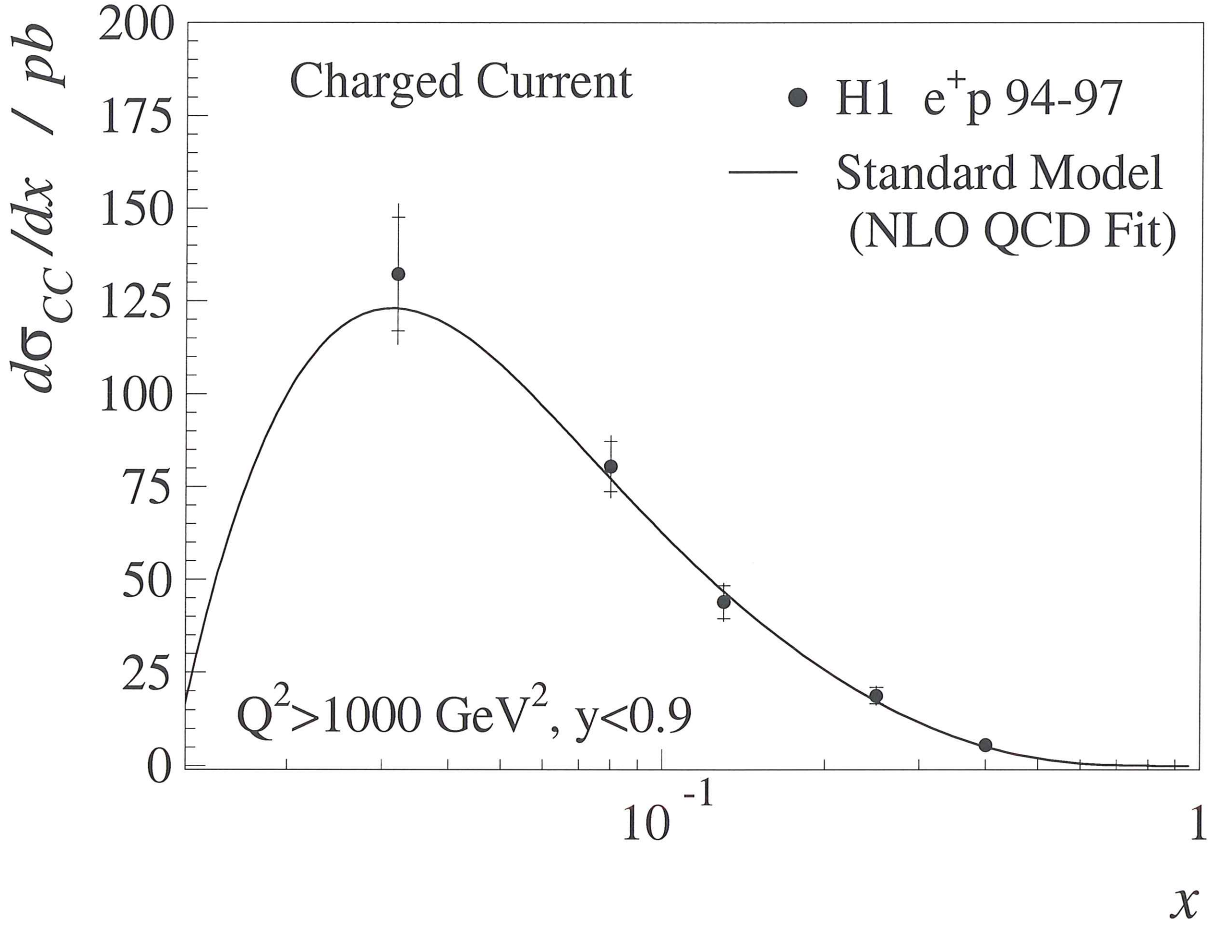


- Precision improved by factor 2
- NLO QCD fit to low Q^2 data extrapolated to high Q^2
  good agreement

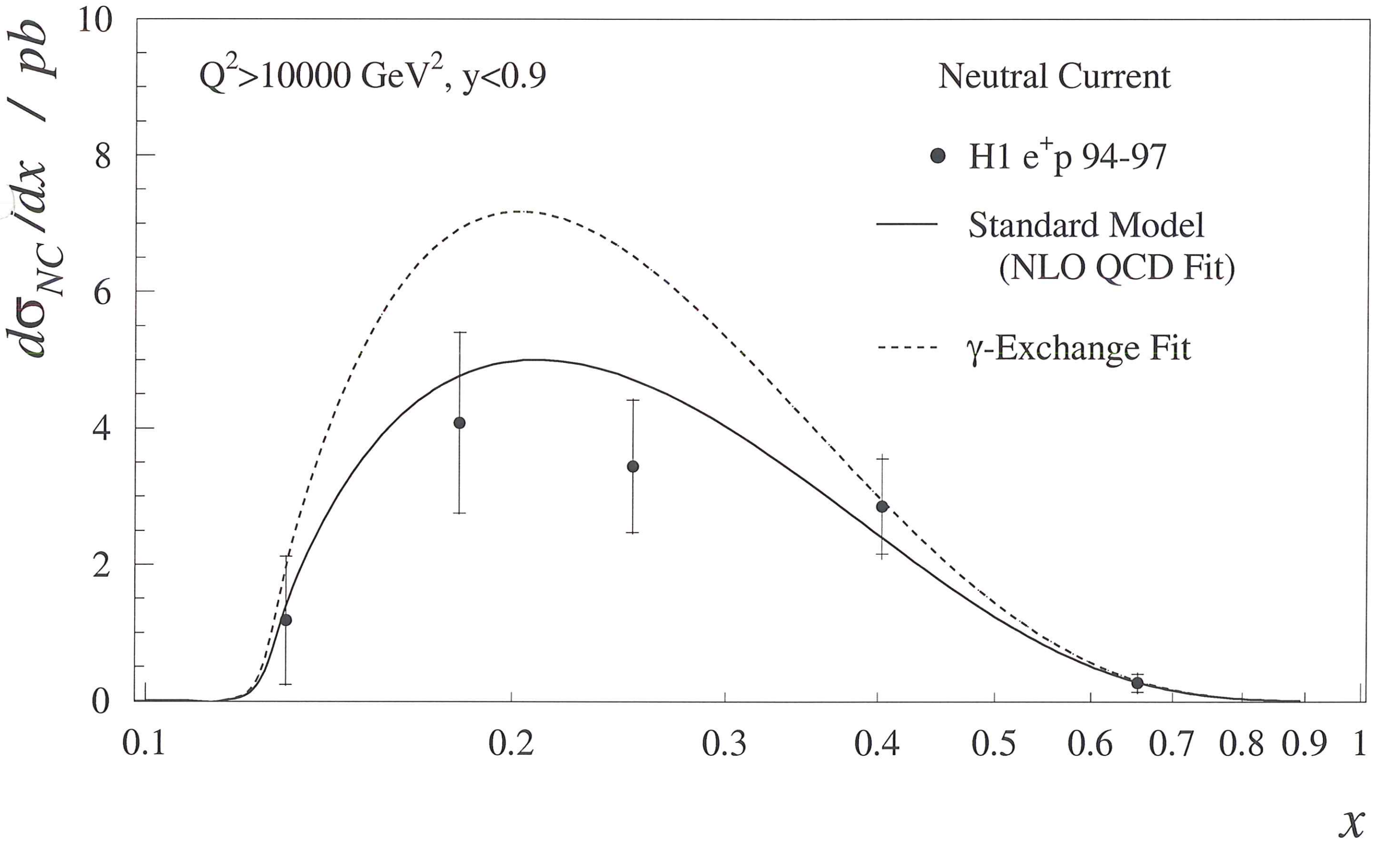
Separation of different quark flavors

Valence quarks dominate at large x and large Q^2:





Charged Current
H1 e+p 94-97
Standard Model
(NLO QCD Fit)
Q2>1000 GeV2, y<0.9
dσCC /dx / pb
x



Q2>10000 GeV2, y<0.9
Neutral Current
H1 e+p 94-97
Standard Model
(NLO QCD Fit)
γ-Exchange Fit
dσNC /dx / pb
x

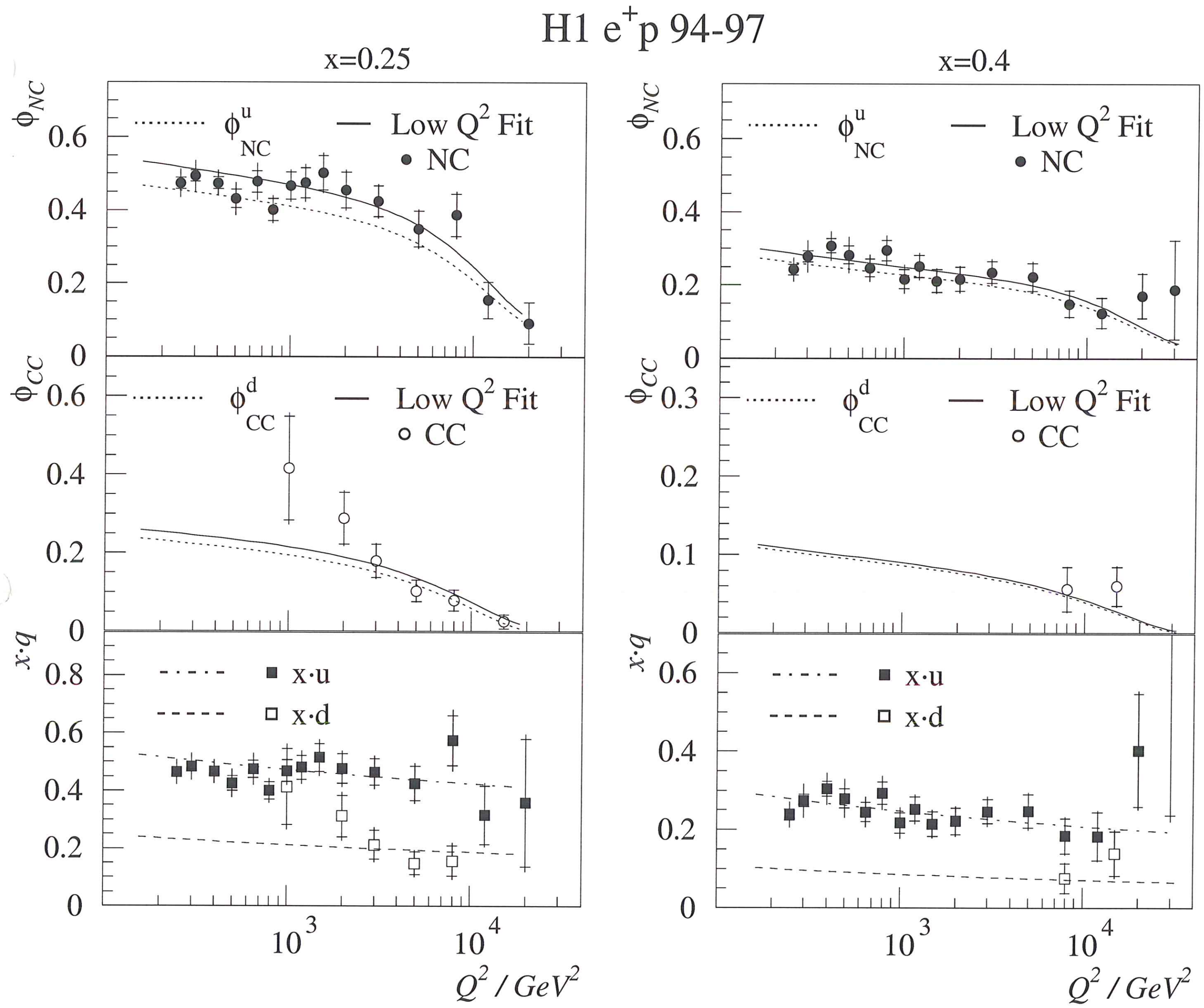
Separation of $u(x)$, $d(x)$:

$$\phi_{NC}(x,Q^2) = Y_+ \cdot x \left\{ \tfrac{4}{9}(u + c + \bar{u} + \bar{c}) + \tfrac{1}{9}(d + s + \bar{d} + \bar{s}) \right\}$$

$$\phi_{cc}(x,Q^2) = x \left\{ (\bar{u} + \bar{c}) + (1-y)^2 (d + s) \right\}$$

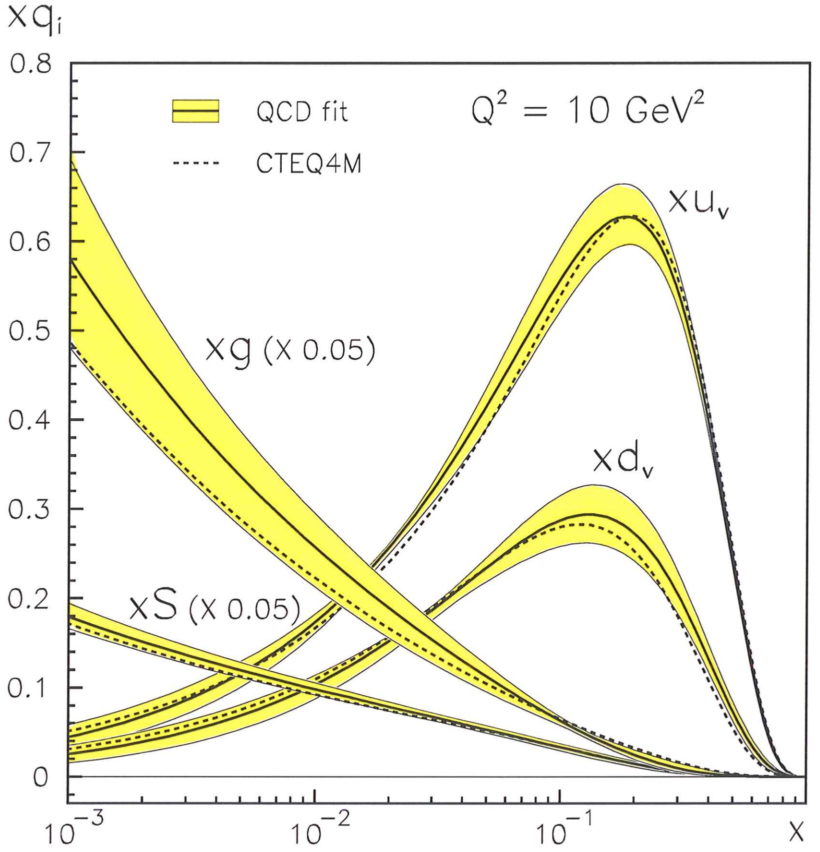
$$x\,u = \phi_{NC}^{meas} \left(\frac{x\,u}{\phi_{NC}} \right)_{low\,Q^2\,fit}$$

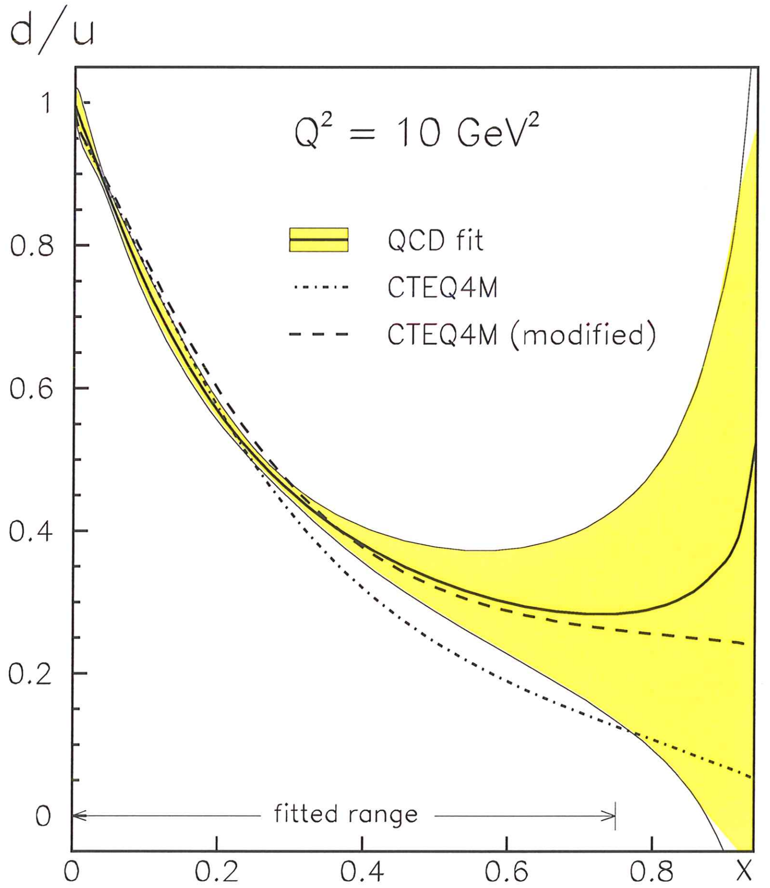
$$x\,d = \phi_{cc}^{meas} \left(\frac{x\,d}{\phi_{cc}} \right)_{low\,Q^2\,fit}$$



- No nuclear corrections necessary
- Upgrade of Hera : $L_{up} \approx 16 \cdot L_{today}$

QCD analysis of HERA and fixed target structure functions (Botje, DESY 99–038)





2. Structure Function F_L

$$\frac{d^2}{dx\,dQ^2} \cdot \left(\frac{2\pi\,\alpha^2}{x\,Q^4}\, Y_+(s) \right)^{-1} =$$

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

Methods to Extract $F_L(x, Q^2)$

- Running at different energies

  No priority presently

  ISR–events : analysis nearly finished

- Subtraction method

  Data insensitive to F_L at low y :

  determine $F_L(x,Q^2)$ by p QCD fit at low y

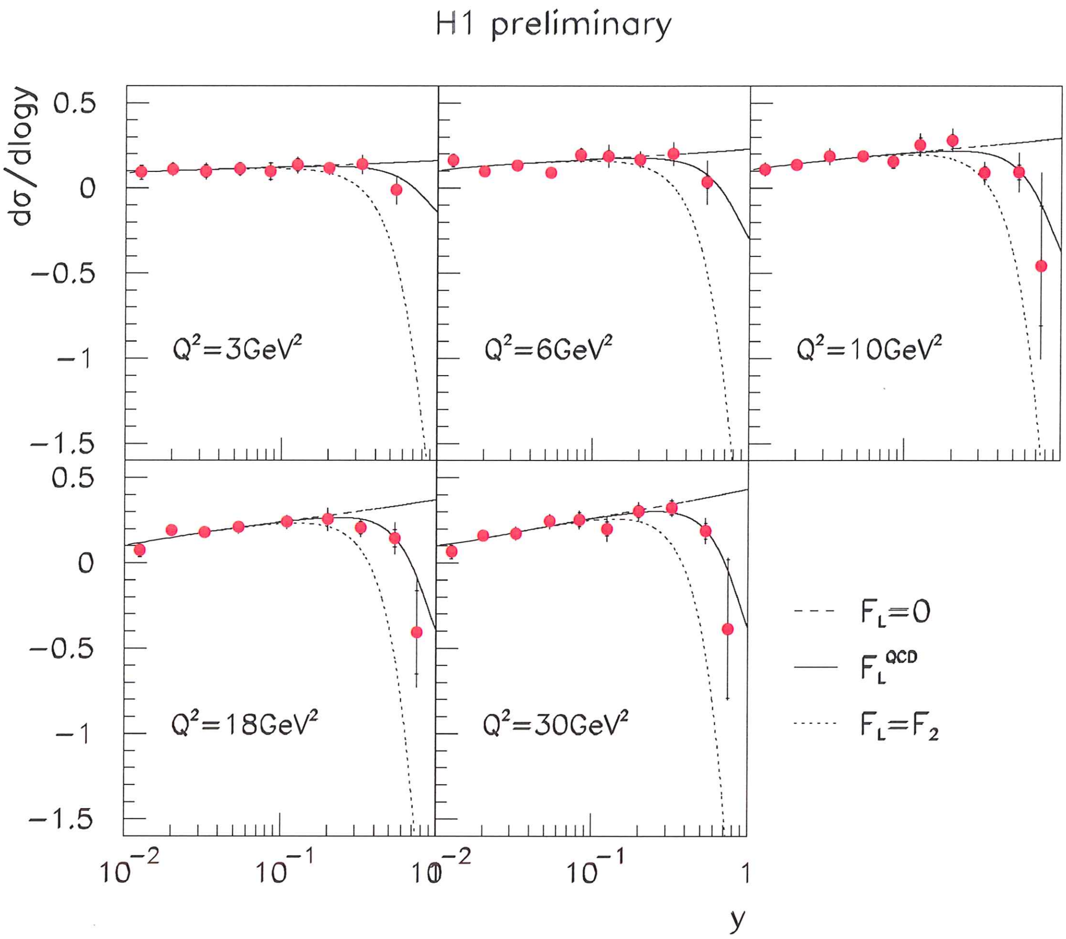
  extrapolate and subtract

- Slope method

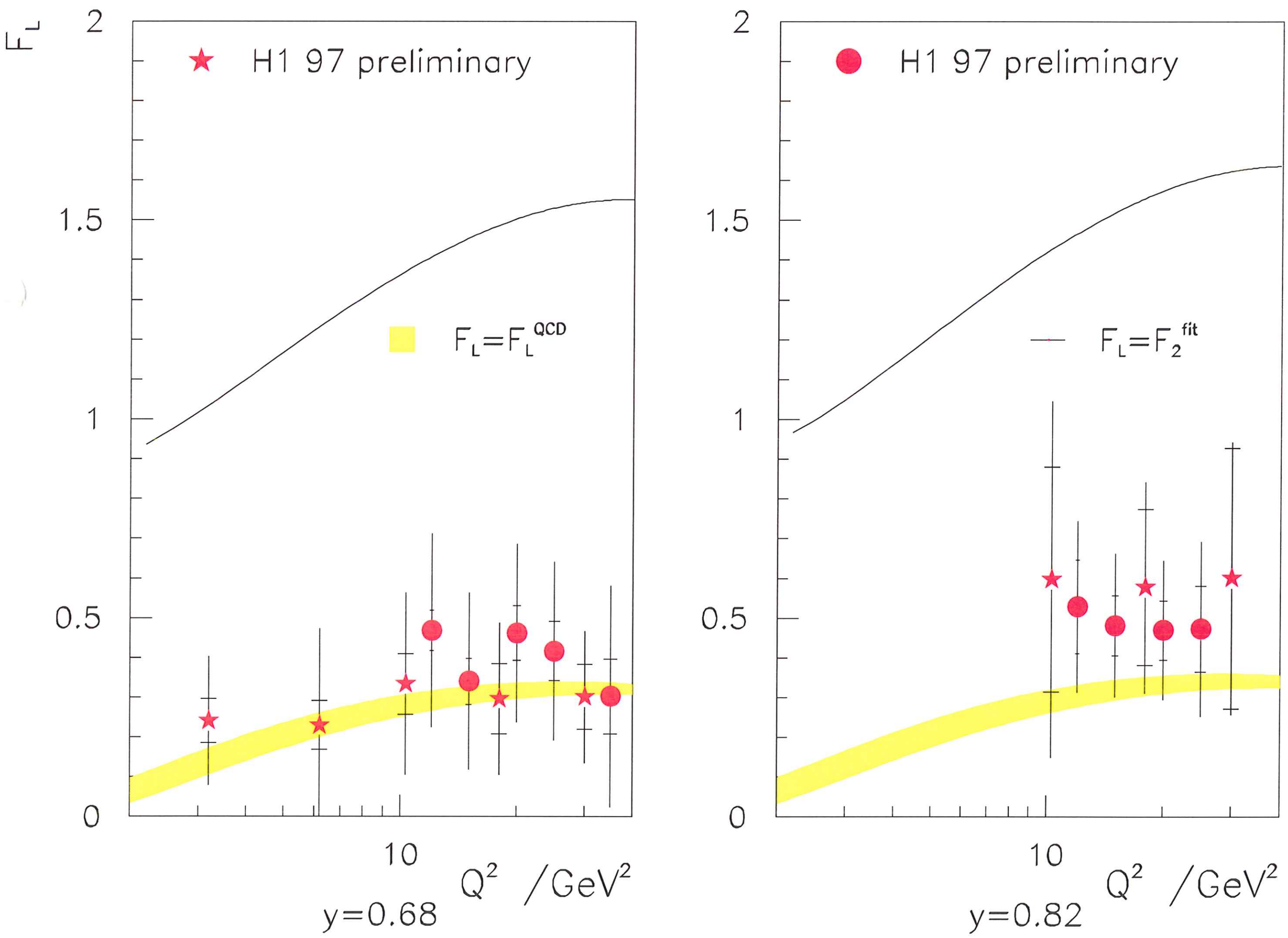
  $$\frac{d\sigma_r}{d\,ln\,y} = -\frac{\partial F_2}{\partial\,ln\,x} - F_L \cdot 2y^2 \frac{2-y}{Y_+^2} + \frac{\partial F_L}{\partial\,ln\,x} \frac{y^2}{Y_+}$$

  Ansatz

  $$\frac{\partial F_2}{\partial\,ln\,x} = a + b\,ln\,y$$

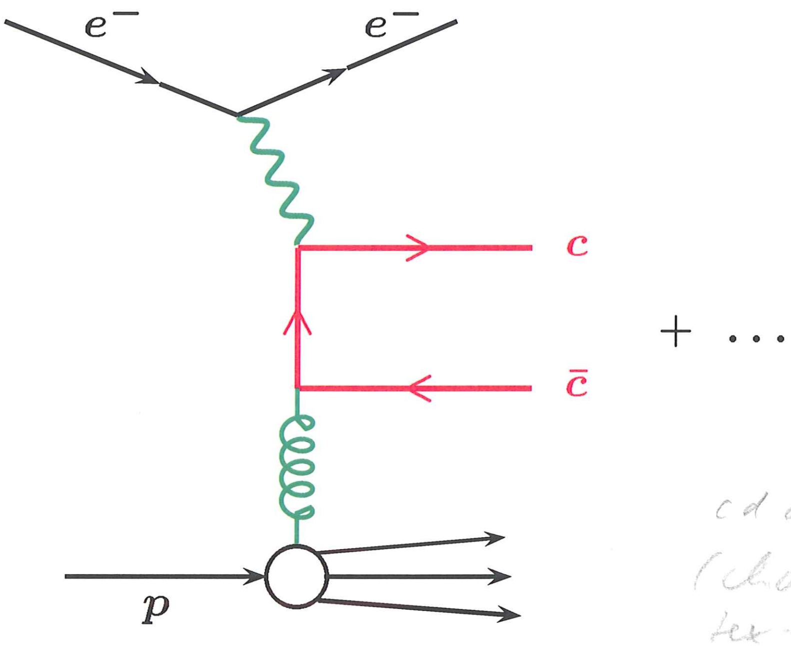


H1 preliminary
dσ/dlogy
0.5
0
−0.5
−1
−1.5
Q²=3GeV²
Q²=6GeV²
Q²=10GeV²
Q²=18GeV²
Q²=30GeV²
F_L=0
F_L^QCD
F_L=F_2
10^−2
10^−1
1
y



F_L
2
1.5
1
0.5
0
H1 97 preliminary
F_L=F_L^QCD
F_L=F_2^fit
10
Q² /GeV²
y=0.68
y=0.82

3. Charm Contribution $F_2^c(x, Q^2)$



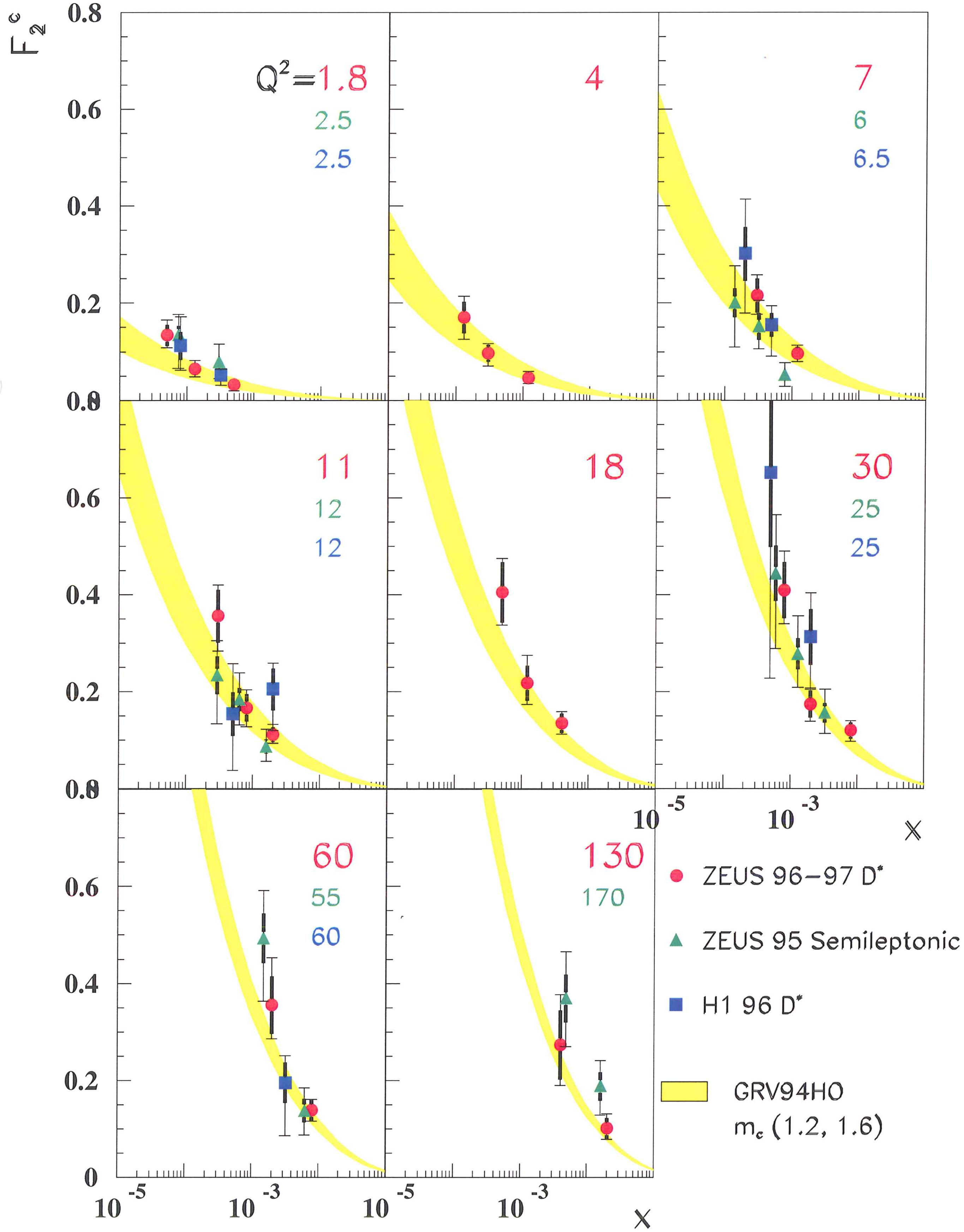
D^* tagging charm production

$$\frac{d^2\sigma}{dx\, dQ^2} = \frac{2\pi\, \alpha^2}{x\, Q^4}\, Y_+\, F_2^c(x, Q^2)$$

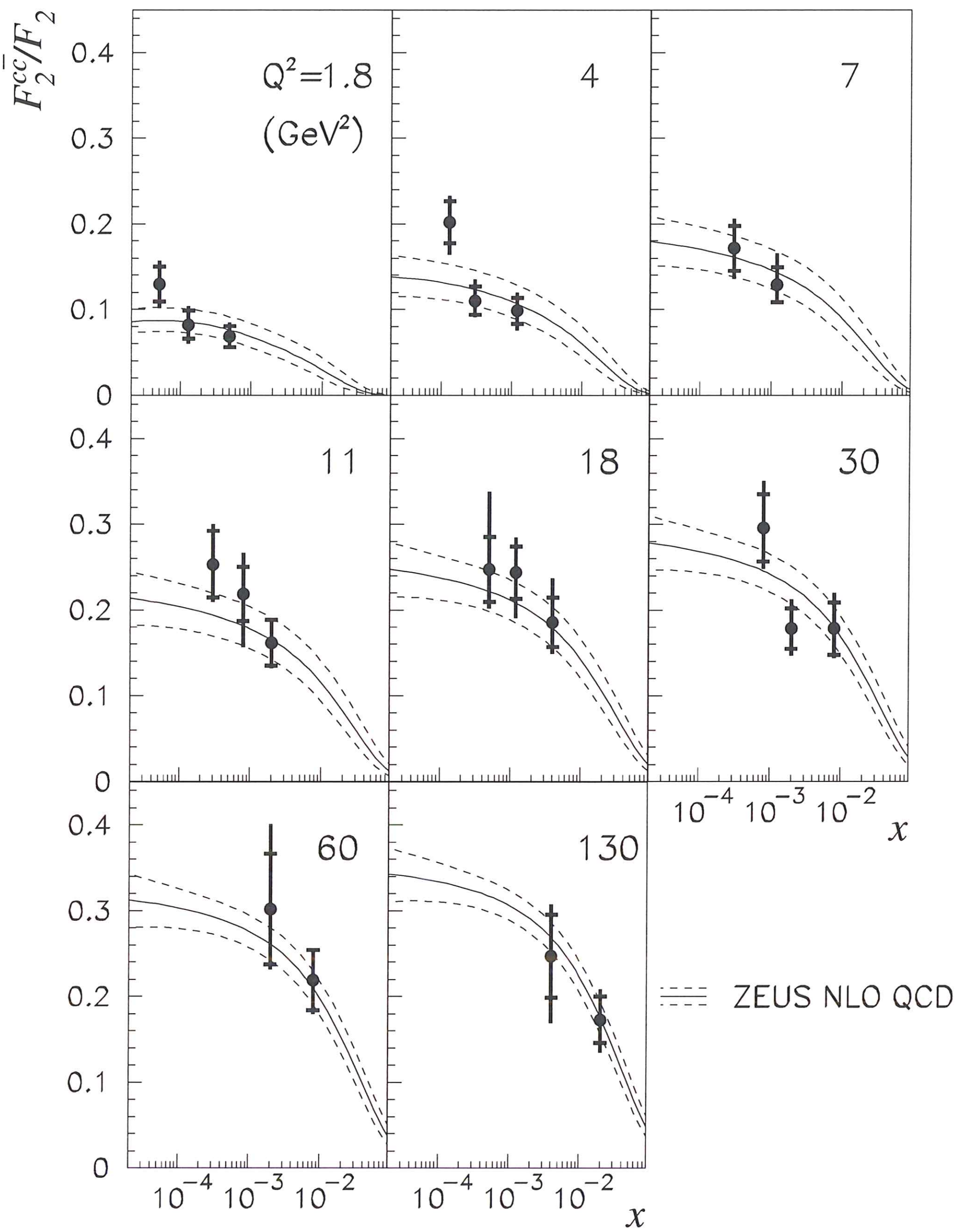
Experimental problems :

- Extrapolation to full η, p_t range
- $P(c \rightarrow D^*)$
- $F_{2L}^c(x, Q^2)$ neglected

HERA 95-97 PRELIMINARY



ZEUS 1996–97

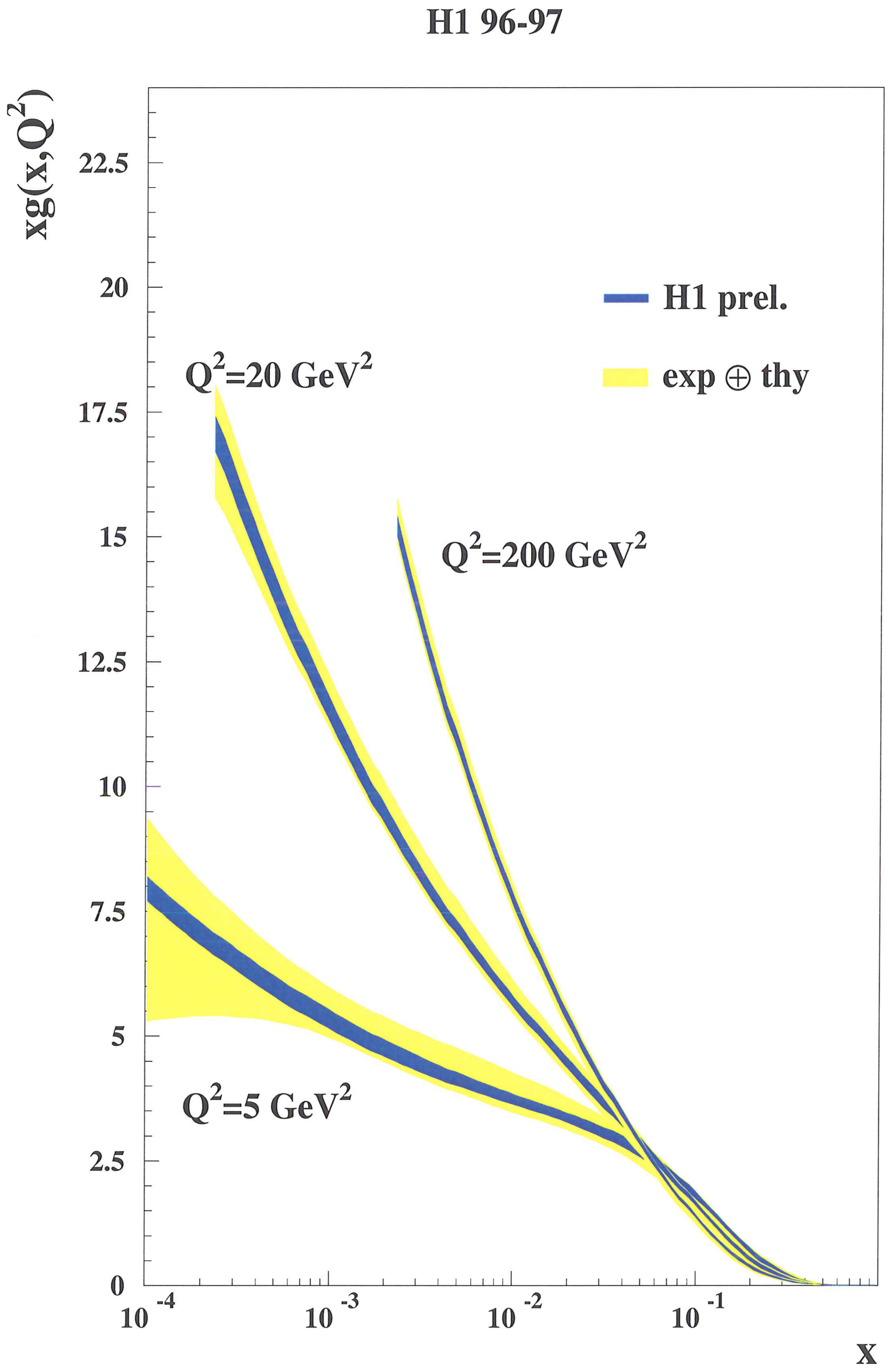


- Uncertainty 15 . . . 20 % : Statistics
  HERA upgrade
  Vertex detectors
- Steep rise at small x, increases with Q^2
- Good agreement with QCD

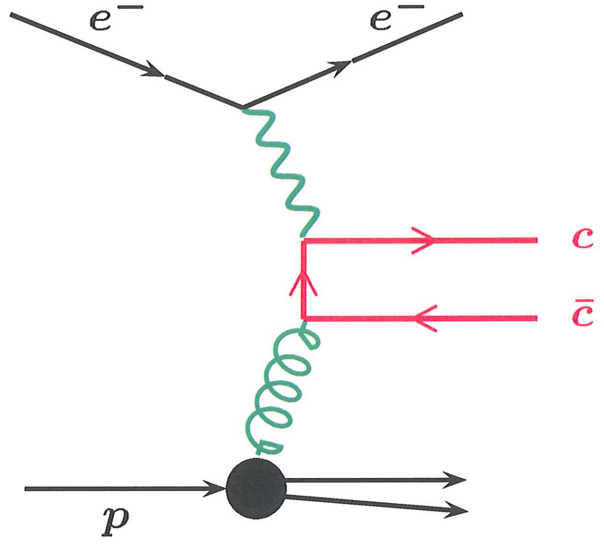
4. Gluon Structure of Proton

$$\frac{\partial F_2(x,Q^2)}{\partial \ln Q^2} \sim P_{qq} \otimes F_2(x,Q^2) + P_{qg} \otimes g(x,Q^2)$$

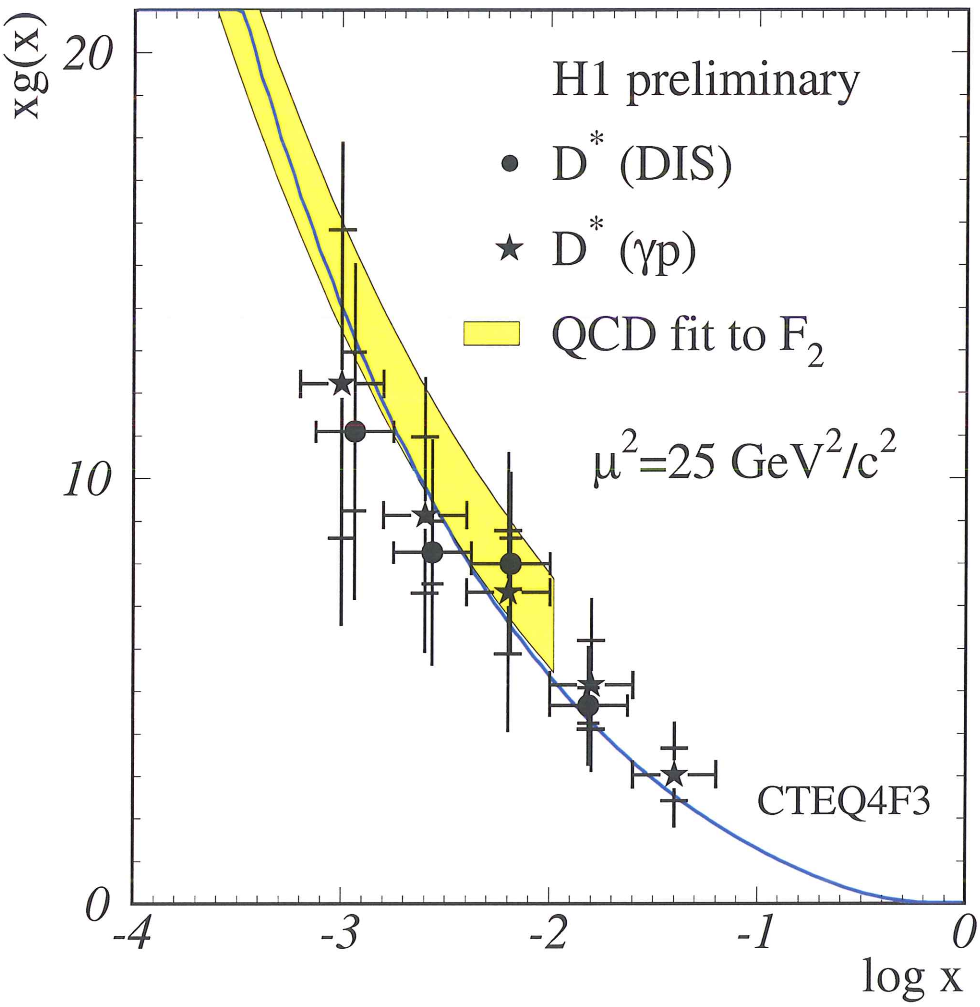
Global F_2 fits: $g(x,Q^2)$



D^* production dominantly via quark–gluon fusion



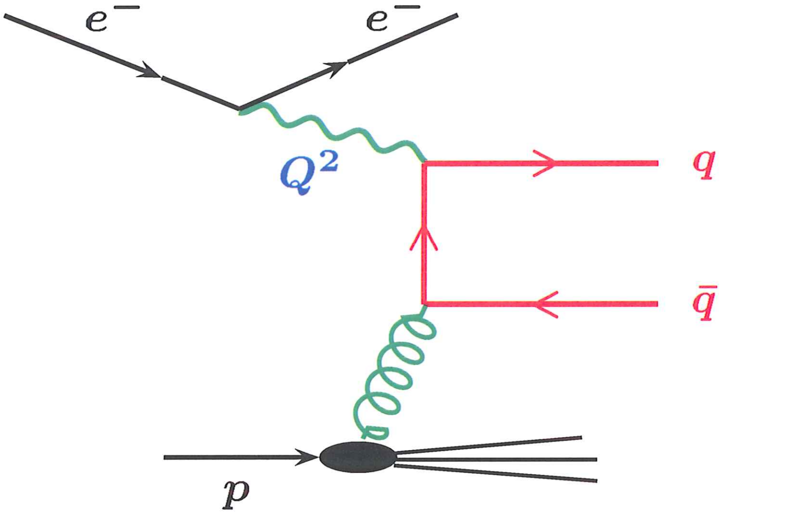
- Deep inelastic scattering D^*
  Photoproduction
- 2 jet production



II. Structure of Photon

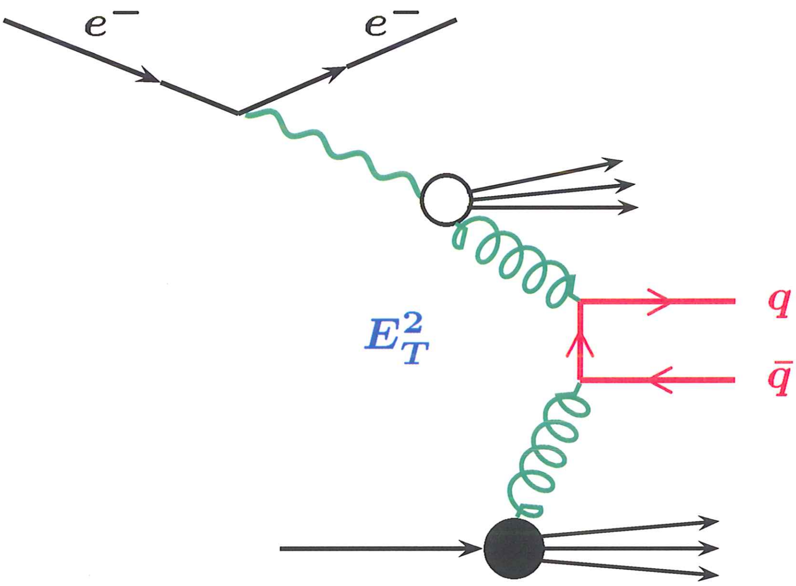
Photon structure : probe quantum fluctuations of field theory

HERA



direct process

$x_\gamma \to 1$



resolved process

$x_\gamma < 1$

- Hard scale Q^2, E_T^2 DIS

  E_T^2 photoproduction

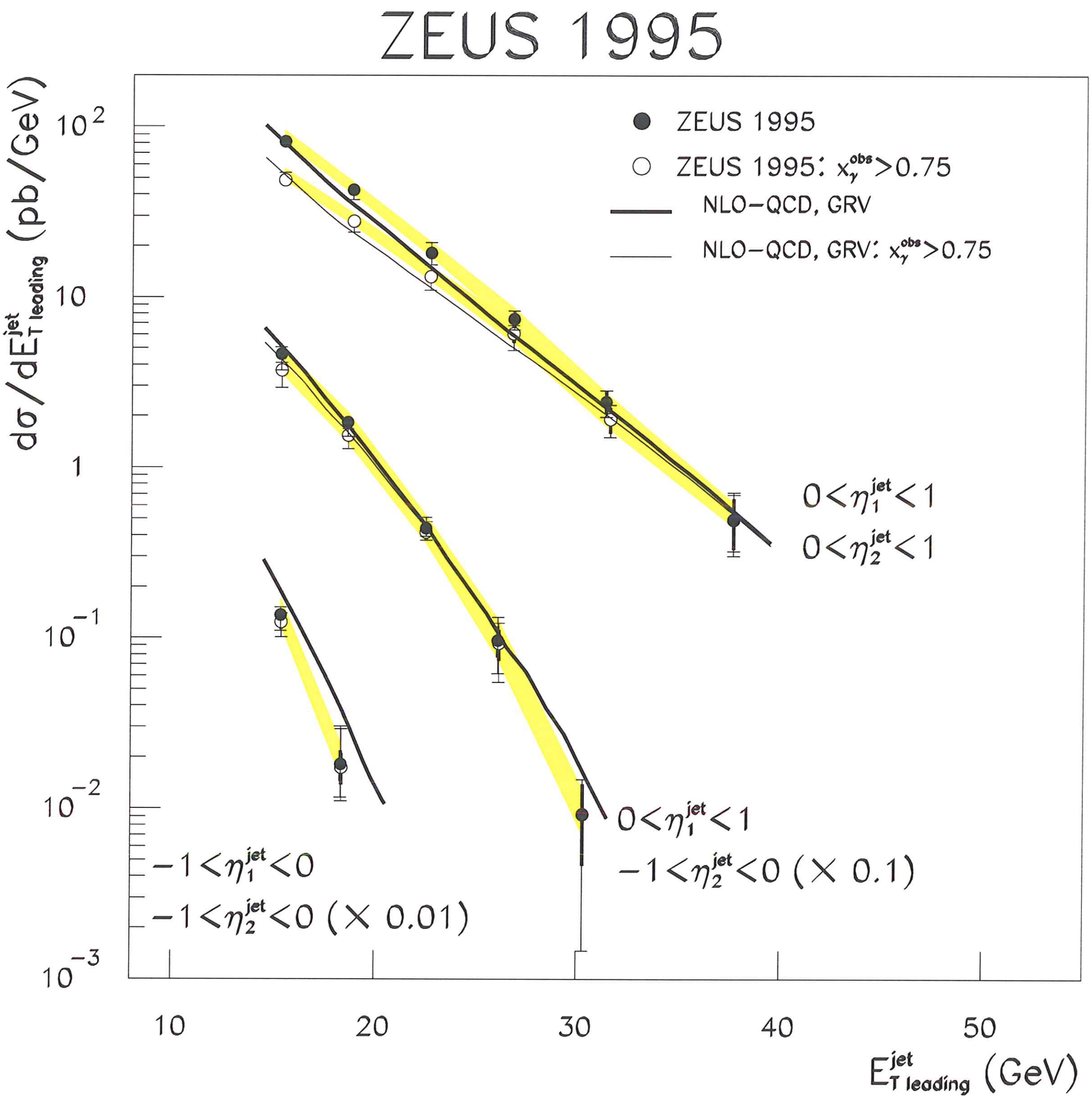
$$x_\gamma = \frac{\sum E_T^{jet} e^{-\eta_{jet}}}{2 \cdot y E_e}$$

Real photon :

HERA $q_{proton}(x,Q^2)$, $g_{proton}(x,Q^2)$ known

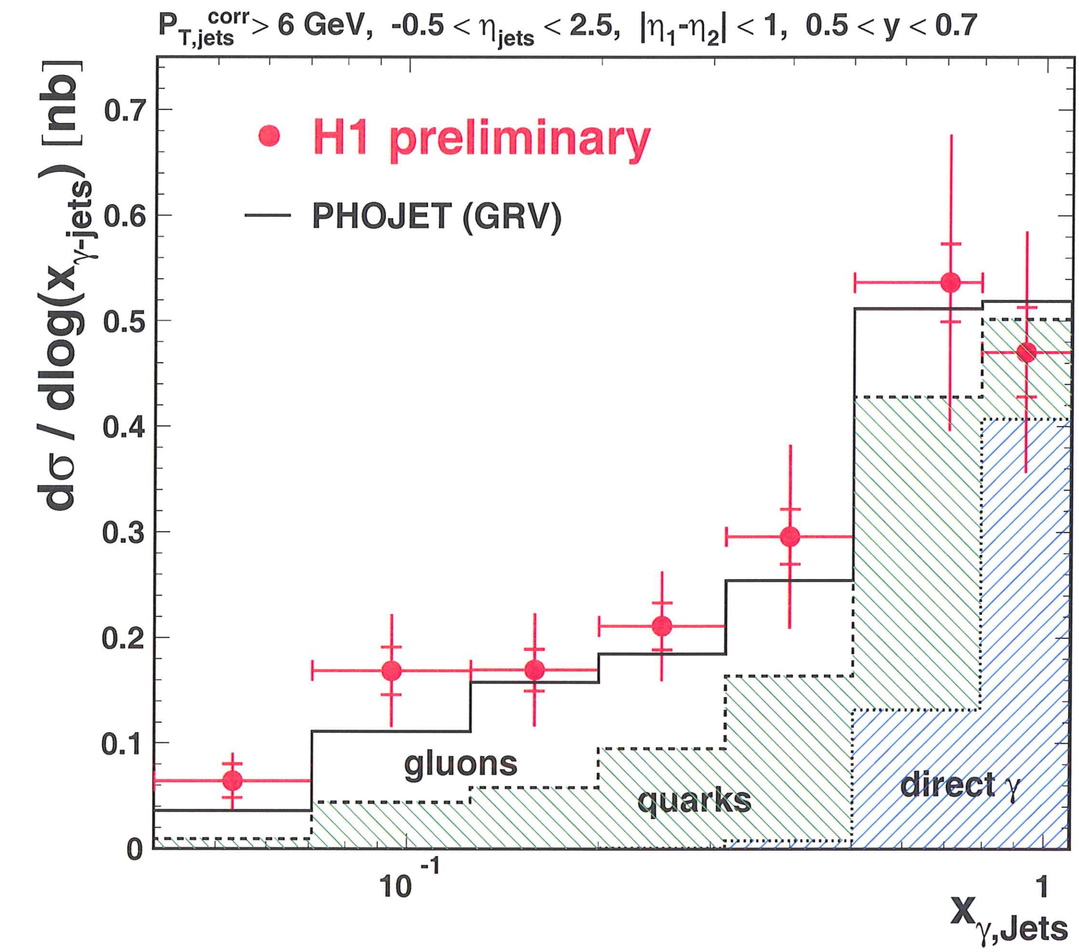
$\frac{d\sigma}{dt}$ known

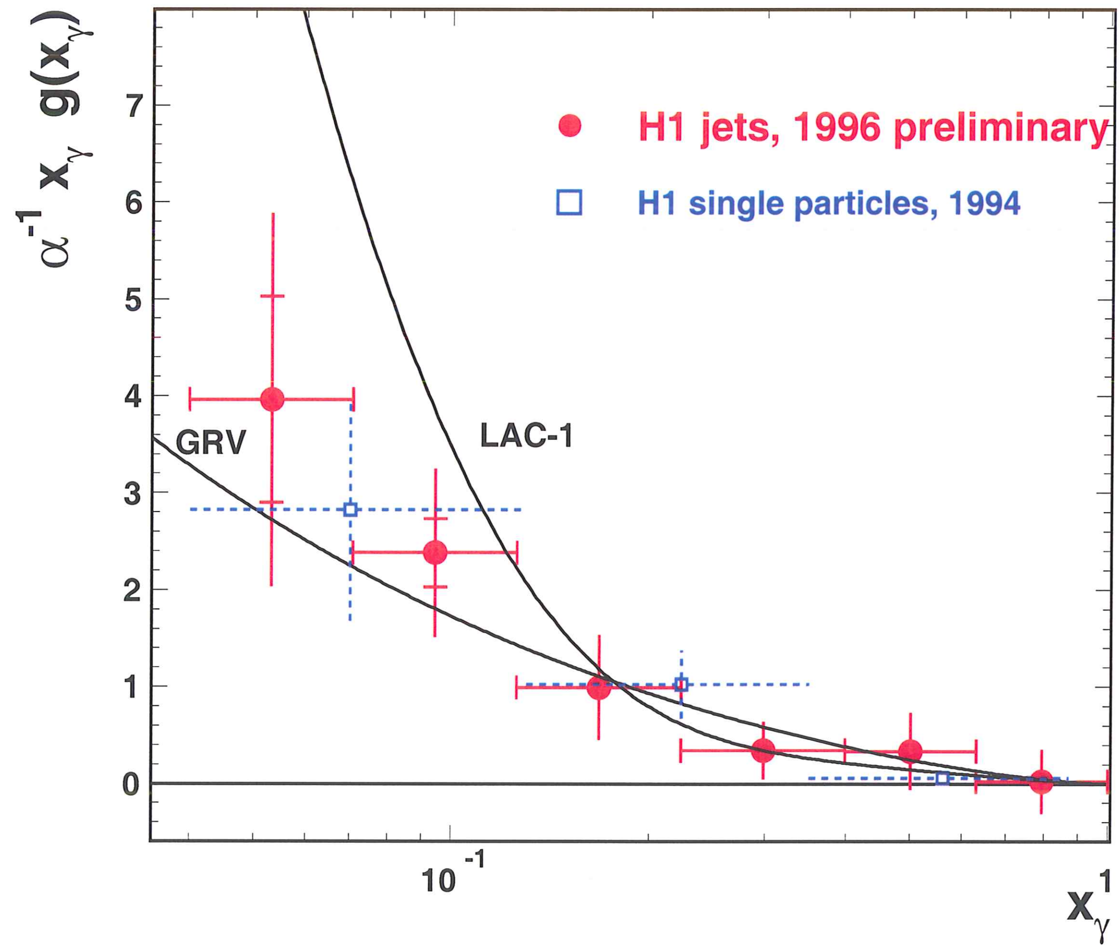
Measure $\frac{d\sigma}{d\,x_\gamma}$ ↗↘ unfold photon structure



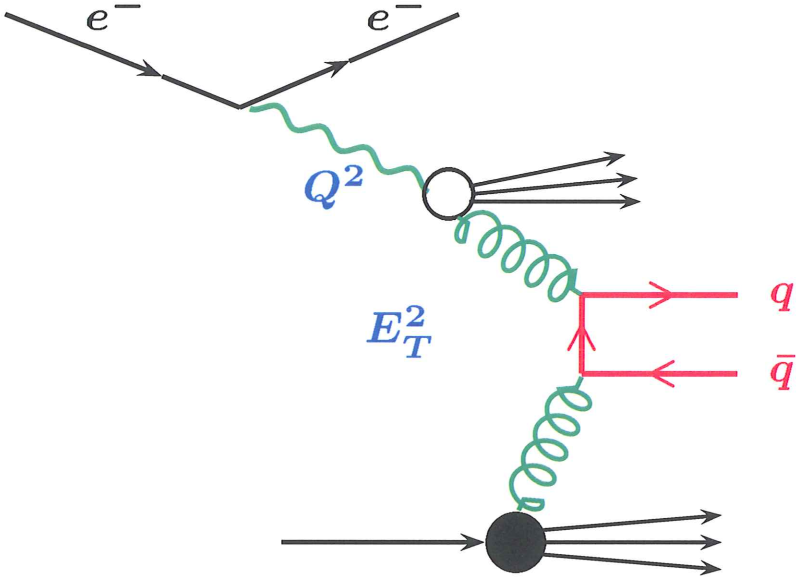
- Reasonable agreement of data and NLO–QCD
- Smaller discrepancies (ZEUS) fragmentation

- Photon structure of real photons



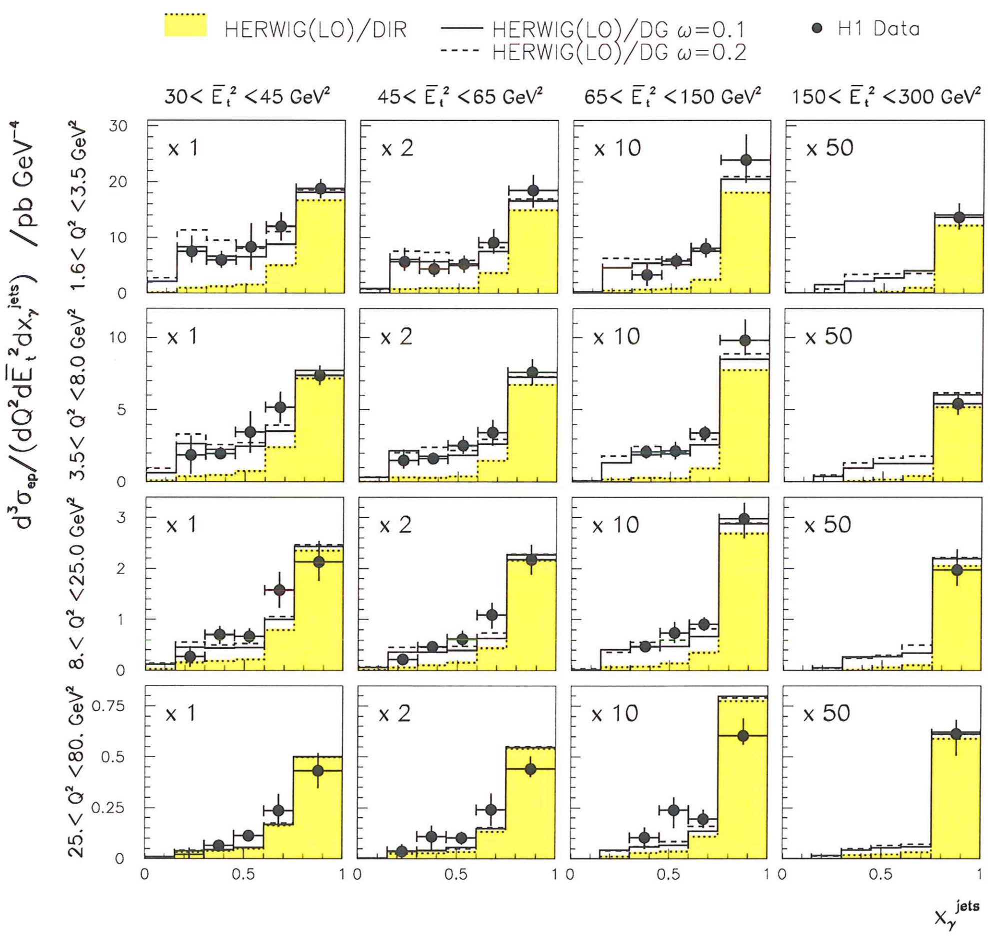


Virtual photons $Q^2 < E_T^2$



resolved process
$x_\gamma < 1$

$E_T^2 > Q^2 > 0$: Structure of virtual photon resolved



- Virtual photon has partonic structure
- $Q^2 \rightarrow E_t^2$ simple direct coupling $\gamma^* q\bar{q}$
- Comparison with LO + fragmentation + f_{γ^*}