STANDARD MODEL PHYSICS AT HERA

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QCD

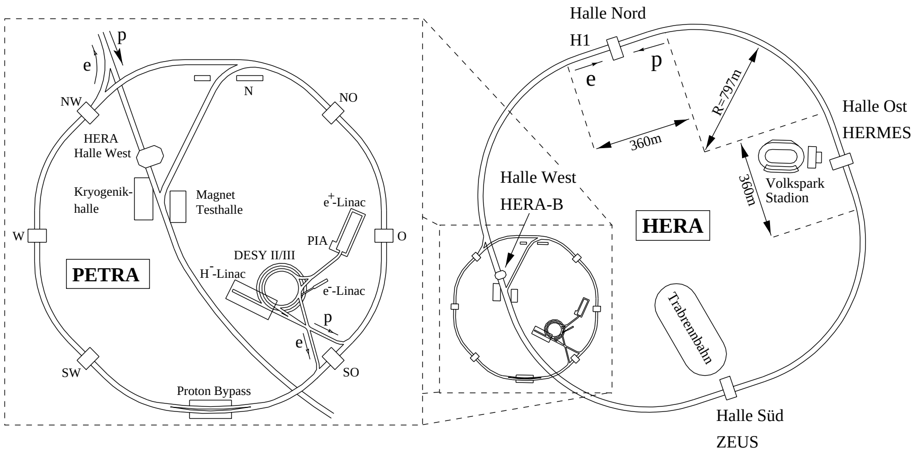
- proton sf $F_2(x, Q^2)$
- longitudinal sf $F_L(x, Q^2)$
- gluon $xg(x, Q^2)$
- strong coupling $\alpha_s(M_Z^2)$

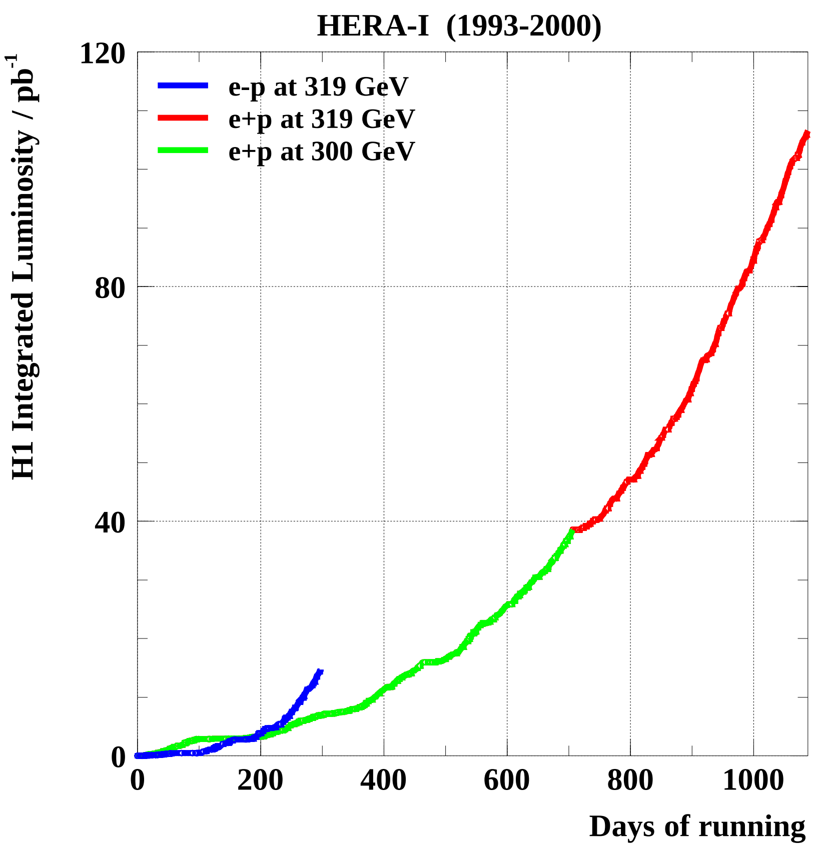
EW Sector

- NC and CC
- γZ interference
- sf $xF_3(x, Q^2)$
- W propagator mass

1994-97 e^+ 27.6 GeV $\longrightarrow$ $\longleftarrow$ p 820 GeV ($\sqrt{s} = 300$ GeV)

1998-00 e^-,e^+ p 920 GeV ($\sqrt{s} = 319$ GeV)

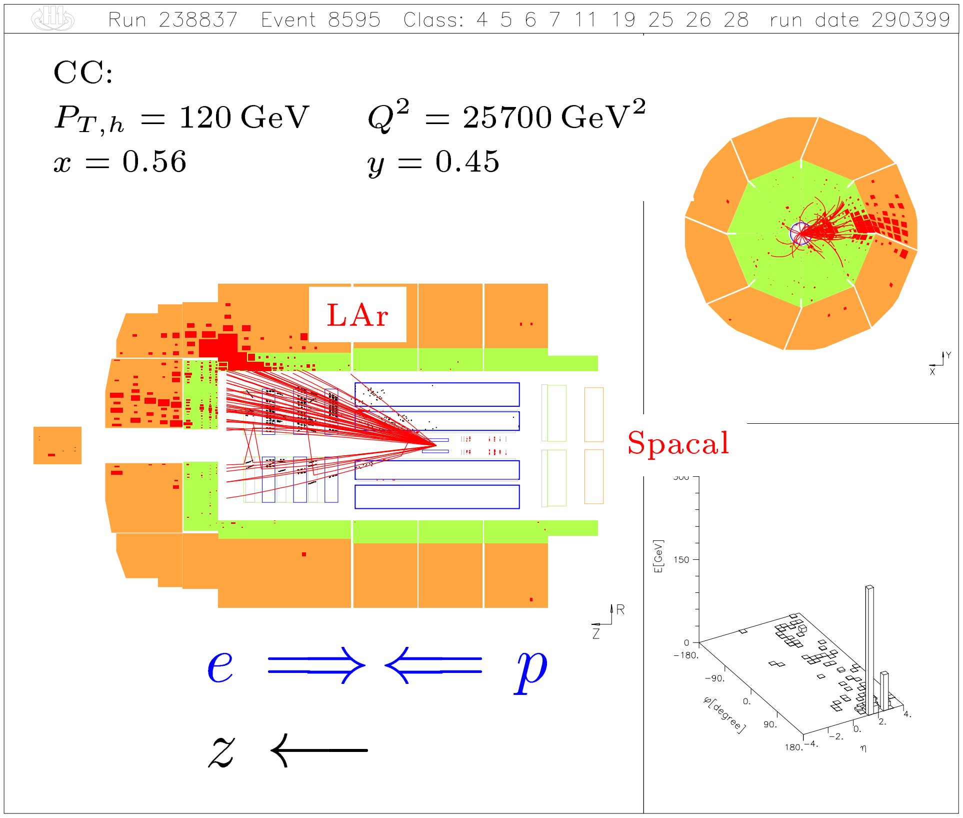




Luminosity H1(ZEUS)

e^+p ($\sqrt{s} = 300$ GeV):	36.6	(47.7)	pb^{-1}
e^+p ($\sqrt{s} = 319$ GeV):	65	(70)	pb^{-1}
e^-p ($\sqrt{s} = 319$ GeV):	16.4	(17)	pb^{-1}

H1 Spacal / Liquid Argon (LAr) Calorimeters



LAr: 45000 cells

$\sigma_{\theta_{e'}} : 0.3 - 3\,\mathrm{mrad}$

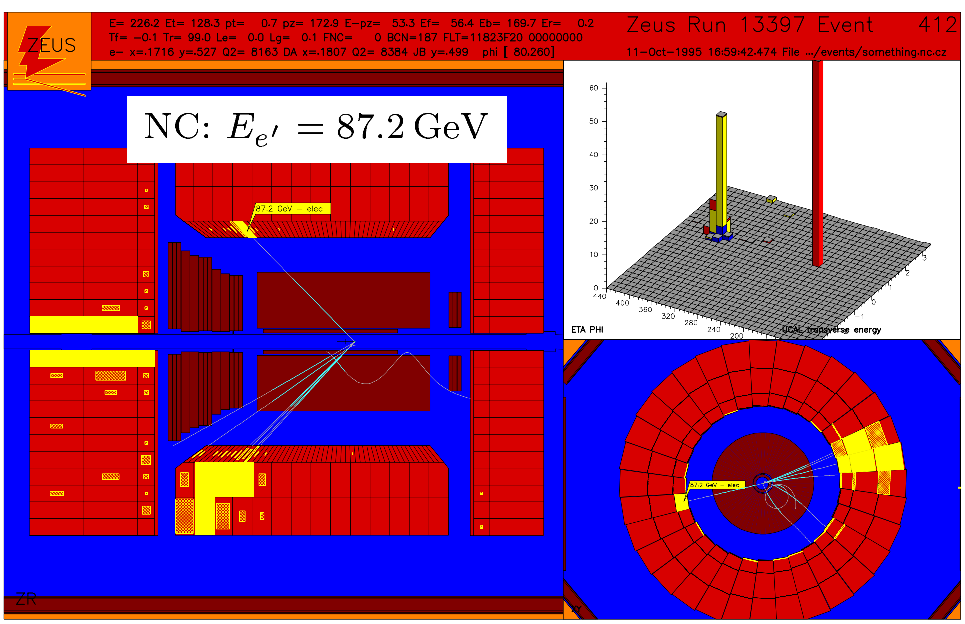
$\sigma(E)/E:$

$$\begin{cases} 7\%/\sqrt{E} & \text{Spacal} \\ 12\%/\sqrt{E} & \text{LAr em} \\ 50\%/\sqrt{E} & \text{LAr had} \end{cases}$$

$\Delta E/E(\mathrm{syst}):$

$$\begin{cases} 0.3 - 2\% & \text{em} \\ 2\% & \text{had} \end{cases}$$

ZEUS Uranium-Scintillator Calorimeter(UCAL)



UCAL: 6000 cells

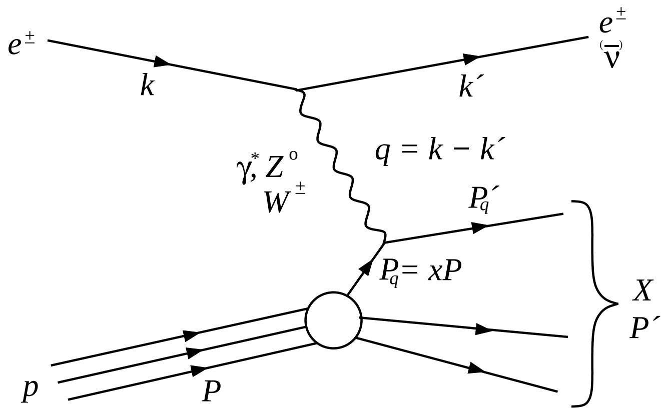
$\sigma_{\theta_{e'}} : 1\,\mathrm{mrad}$

$\sigma(E)/E:$

$$\begin{cases} 18\%/\sqrt{E} & \text{em} \\ 35\%/\sqrt{E} & \text{had} \end{cases}$$

$\Delta E/E(\mathrm{syst}):$

$$\begin{cases} 1 - 2\% & \text{em} \\ 2\% & \text{had} \end{cases}$$



$Q^2 = -q^2$ *virtuality of* $\gamma^*, Z^o, W^\pm$

$x = Q^2/2(pq)$ *Bjorken scaling variable*

$y = (Pq)/(pk)$ *inelasticity*

$Q^2 = xys$, $\sqrt{s}$ *is the centre-of-mass energy*

Neutral Current (NC) - γ^*, Z^o exchange

$$\frac{d^2\sigma_{NC}^{e^\pm p}}{dx\, dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+ \tilde{F}_2(x,Q^2) \mp Y_- x\tilde{F}_3(x,Q^2) - y^2 \tilde{F}_L(x,Q^2)\right]$$

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

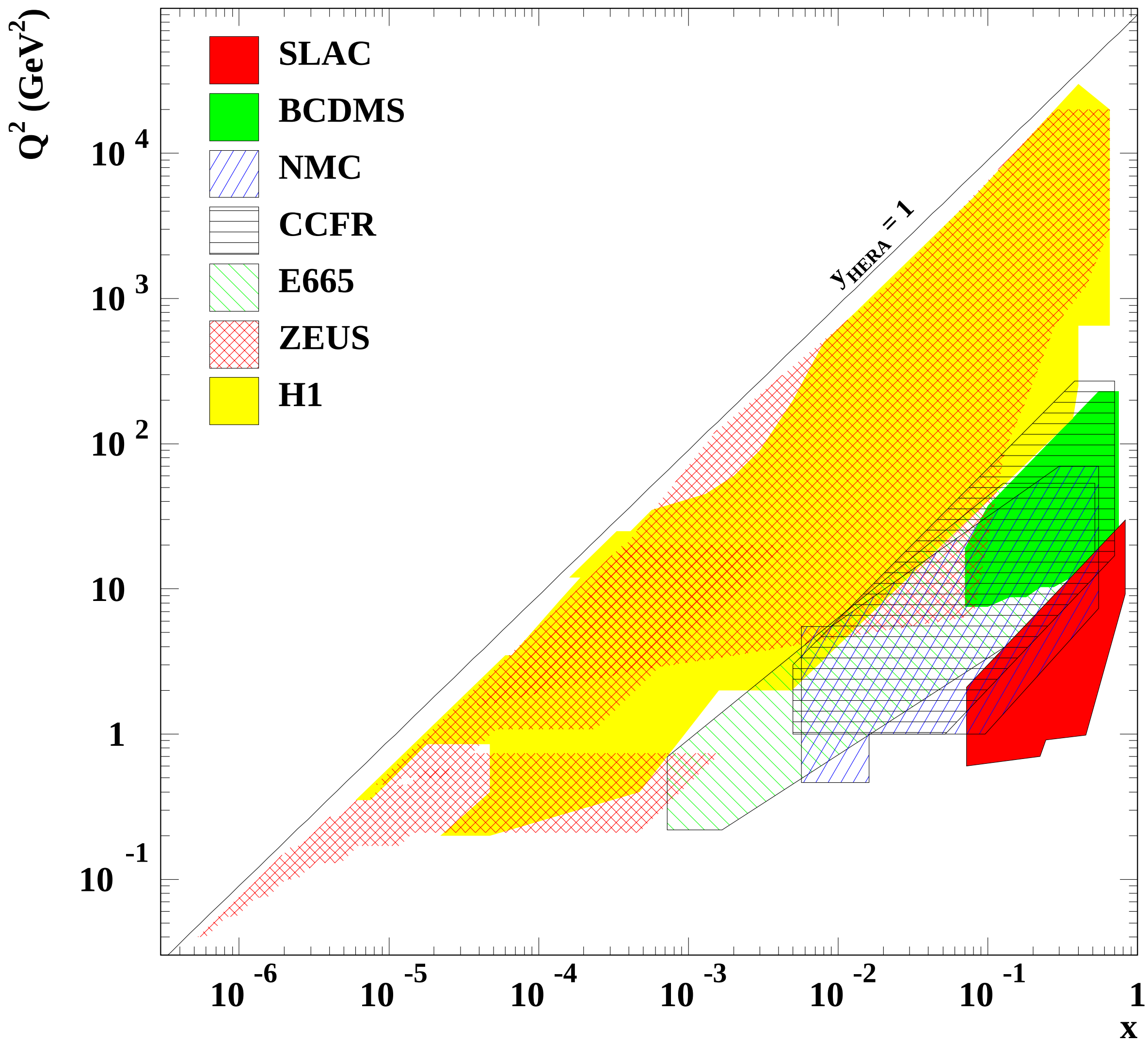
in LO: $\tilde{F}_2 = x\sum A_i(q_i + \bar{q}_i)$, $x\tilde{F}_3 = x\sum B_i(q_i - \bar{q}_i)$, $\tilde{F}_L = 0$

Charged Current (CC) - $W^\pm$ exchange

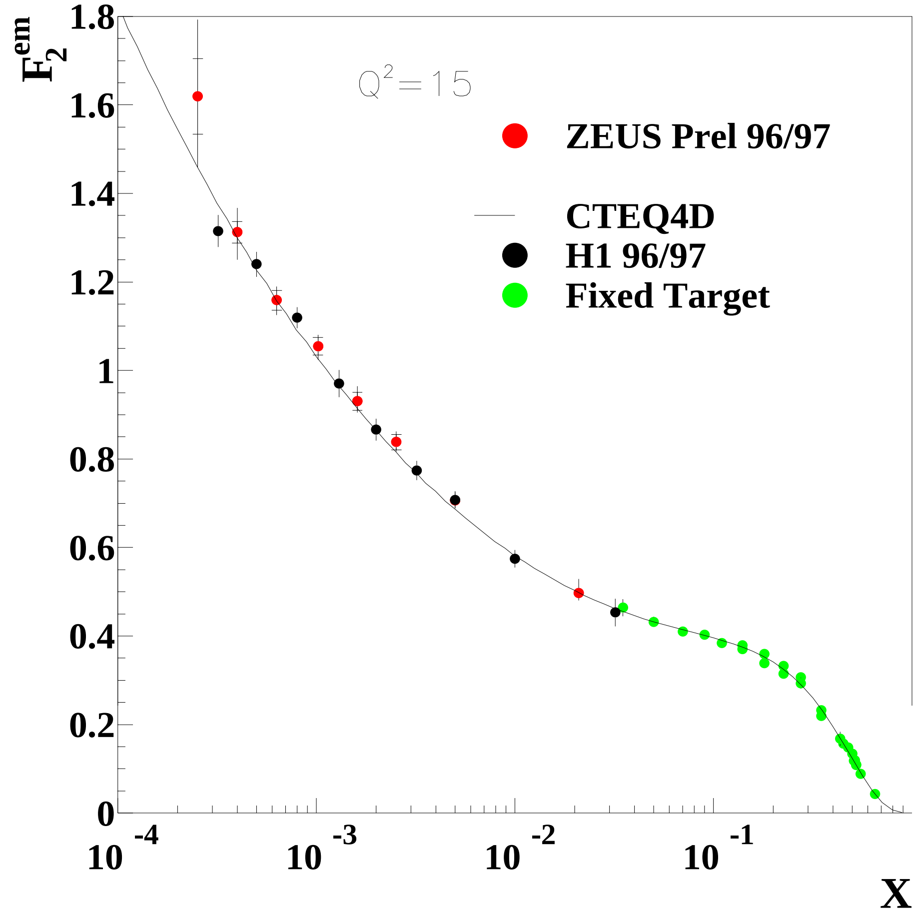
$$\frac{d^2\sigma_{CC}^{\pm}}{dx\, dQ^2} = \frac{G_F^2 M_W^4}{2\pi x}\frac{1}{(Q^2+M_W^2)^2}\, \tilde{\sigma}_{CC}^{\pm}(x,Q^2)$$

in LO: $\tilde{\sigma}_{CC}^{+} = x\left[(\bar{u}+\bar{c}) + (1-y)^2(d+s)\right]$

$\tilde{\sigma}_{CC}^{-} = x\left[(u+c) + (1-y)^2(\bar{d}+\bar{s})\right]$



$Q^2 \to 0$	transition to γp
$Q^2 \geq 1$ GeV^2	**QCD** evolution
$Q^2 \to s$	electroweak physics
$y \to 1$	sensitivity to F_L
$y \to 0.005$	overlap with fixed target exp.
$x \to 1$	probe valence quarks

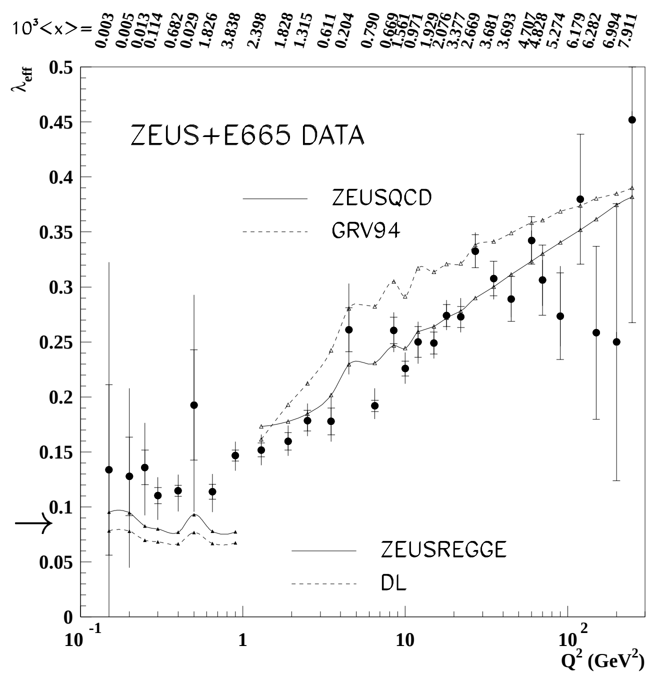


Rise of F_2 towards low x

(governed by gluons)

$$F_2 \propto x^{-\lambda} (or \propto W^{2\lambda})$$

$pp, \gamma p : \lambda = 0.08 \rightarrow$

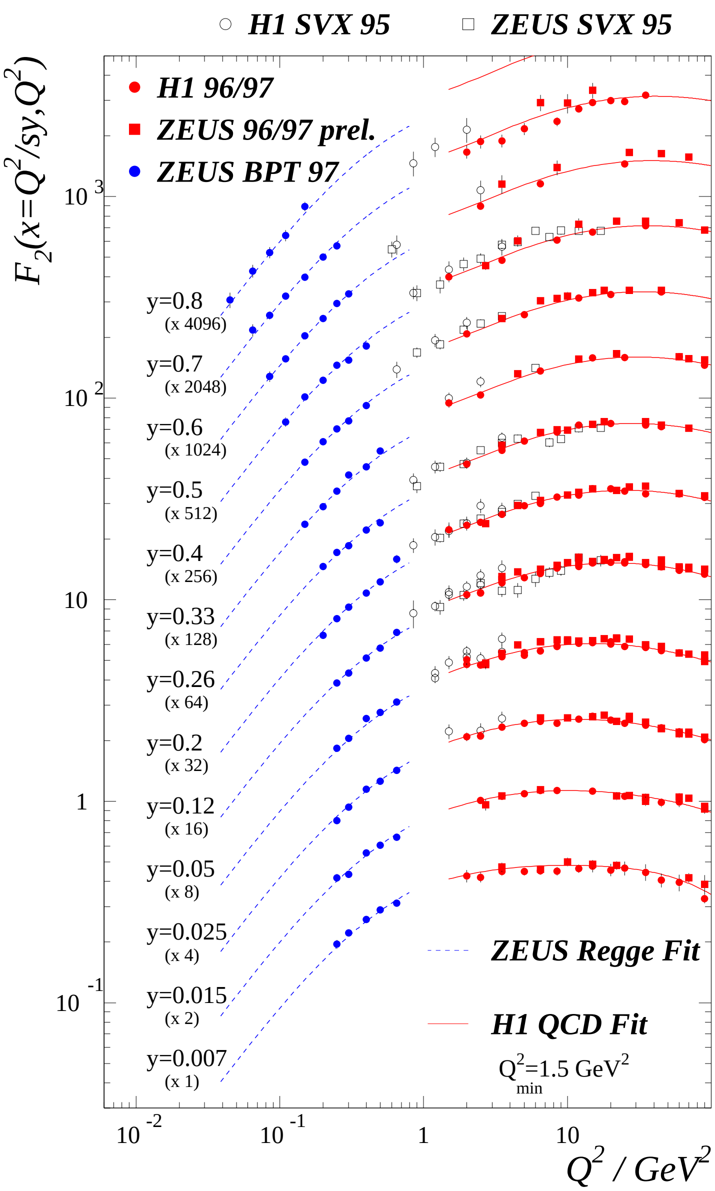


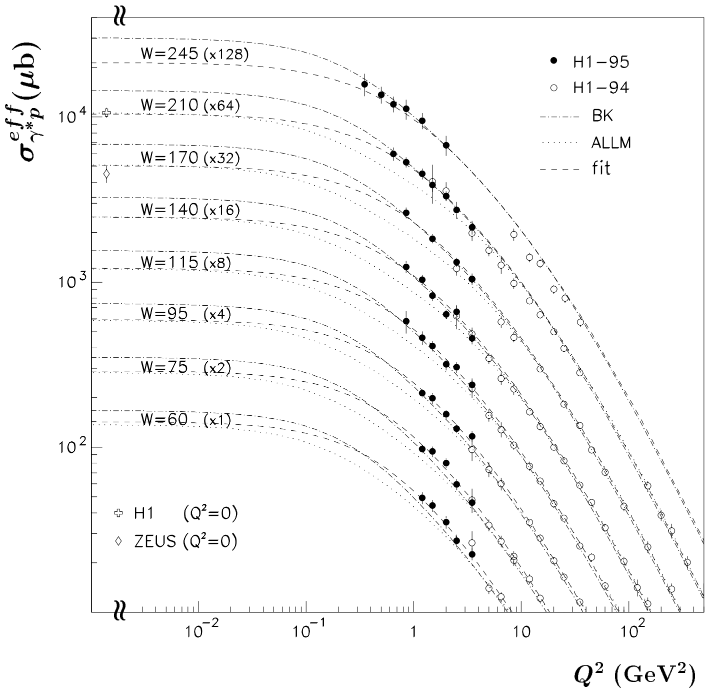
- good agreement between H1 and ZEUS
- overlap with fixed target experiments
- approaching soft pomeron ($\lambda = 0.08$) for $Q^2 \rightarrow 0$

$$\sigma_{tot}^{\gamma^* p}(W^2, Q^2) = \sigma_L^{\gamma^* p} + \sigma_T^{\gamma^* p} \approx \frac{4\pi\alpha^2}{Q^2} F_2(x = Q^2/W^2, Q^2)$$

$(W^2 \approx Q^2/x$ **at low** $x)$

direct comparison with ***real*** $\gamma\ p$ **data**





- *smooth transition to real photoproduction*
- *interplay of "soft" and "hard" physics:*
  - Regge *works up to* $Q^2 \approx 0.6\ \mathrm{GeV}^2$
  - pQCD *works down to* $Q^2 \approx 1\ \mathrm{GeV}^2$

1. *Asymptotic freedom* ($\alpha_s \to 0$ at short distances)

   pQCD (perturbative technique)

2. *Factorization*

$$P_1 \;=\!=\!=\!=\; f_i \quad x_1 P_1$$

$$\boxed{\hat{\sigma}_{ij}(Q^2)}$$

$$P_2 \;=\!=\!=\!=\; f_j \quad x_2 P_2$$

$$\sigma = f_i \overbrace{\otimes \hat{\sigma}_{ij} \otimes}^{\text{pQCD}} f_j$$

f_l is a non perturbative part

3. QCD *evolution* (DGLAP)

- NLO $\overline{\text{MS}}$:

$$\frac{1}{x} F_2(x, Q^2) = \sum_{i=1}^{n_f} e_i^2 C_i \otimes (q_i + \bar{q}_i) + C_g \otimes g$$

- evolution of parton densities:

$$g(x, Q^2)$$

$$q^S(x, Q^2) = \sum (q_i + \bar{q}_i)$$

$$q^{NS}(x, Q^2) = \sum (q_i - \bar{q}_i)$$

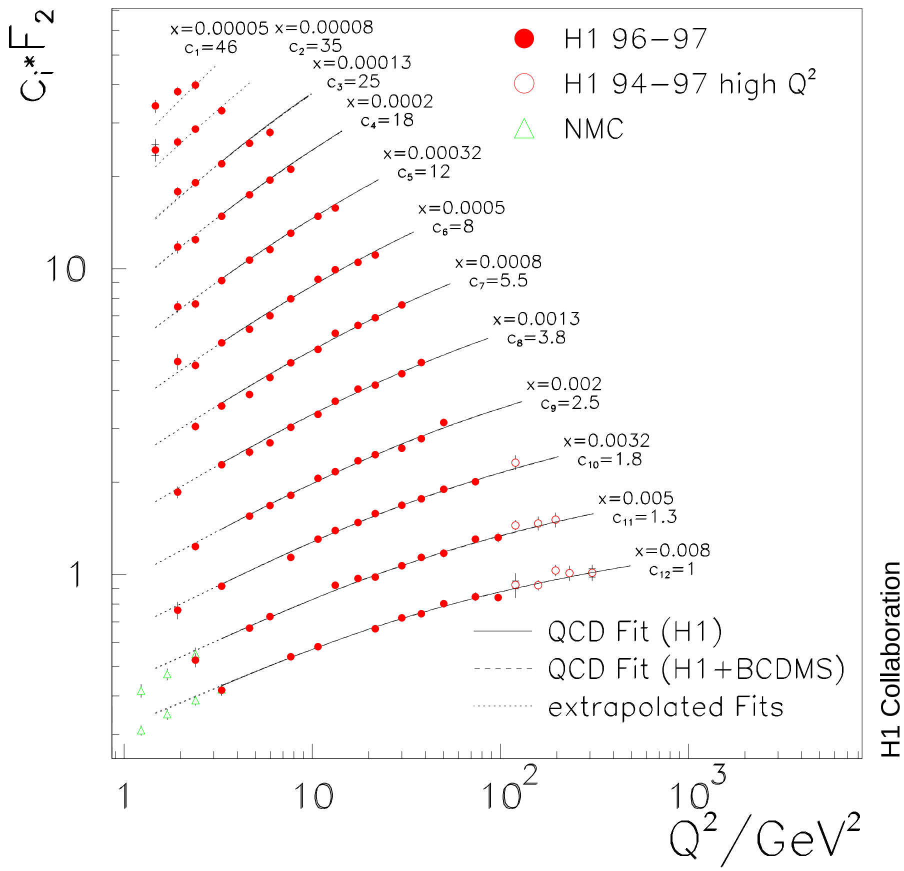
$$\frac{\partial}{\partial lnQ^2} \begin{pmatrix} q^S \\ g \end{pmatrix} = \frac{\alpha_s(Q^2)}{2\pi} \begin{bmatrix} P_{qq}^S P_{qg} \\ P_{gq} P_{gg} \end{bmatrix} \otimes \begin{pmatrix} q^S \\ g \end{pmatrix}$$

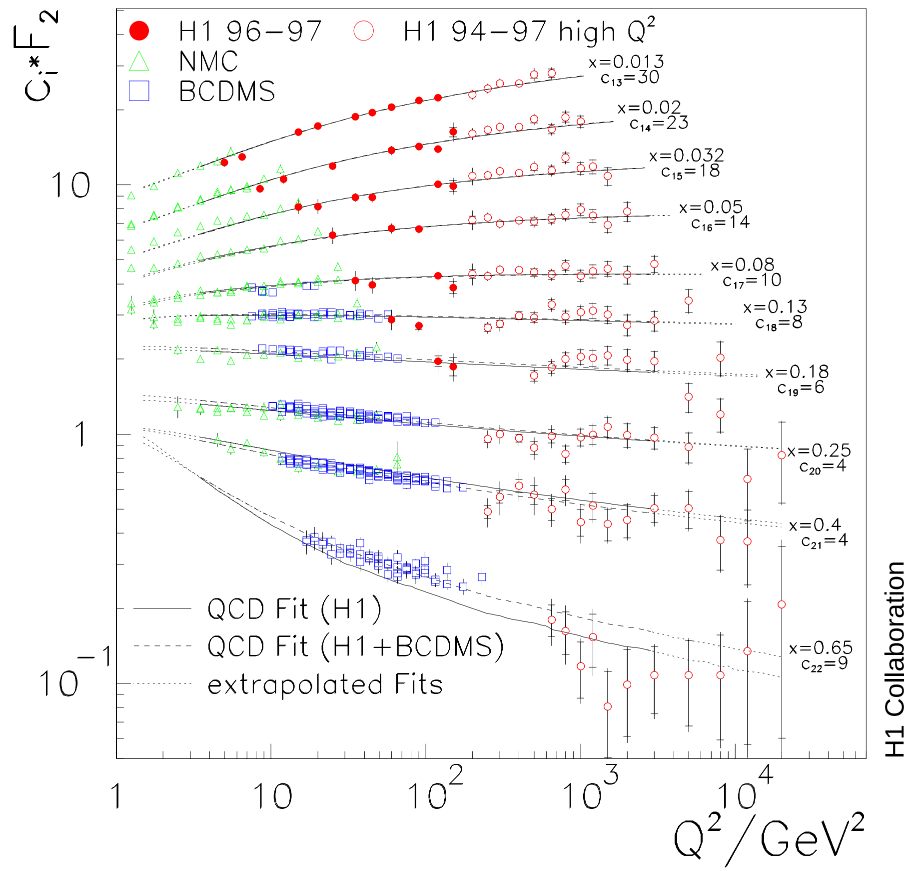
$$\frac{\partial}{\partial lnQ^2} q^{NS} = \frac{\alpha_s(Q^2)}{2\pi} P_{qq}^{NS} \otimes q^{NS}$$

Coefficient and Splitting Functions C_i and P_{ij} known to NLO

- Q^2 *dependence predicted by* pQCD
- x *dependence parameterised at* Q_o^2 (*from a* QCD *fit*)

Proton structure function $F_2(x, Q^2)$



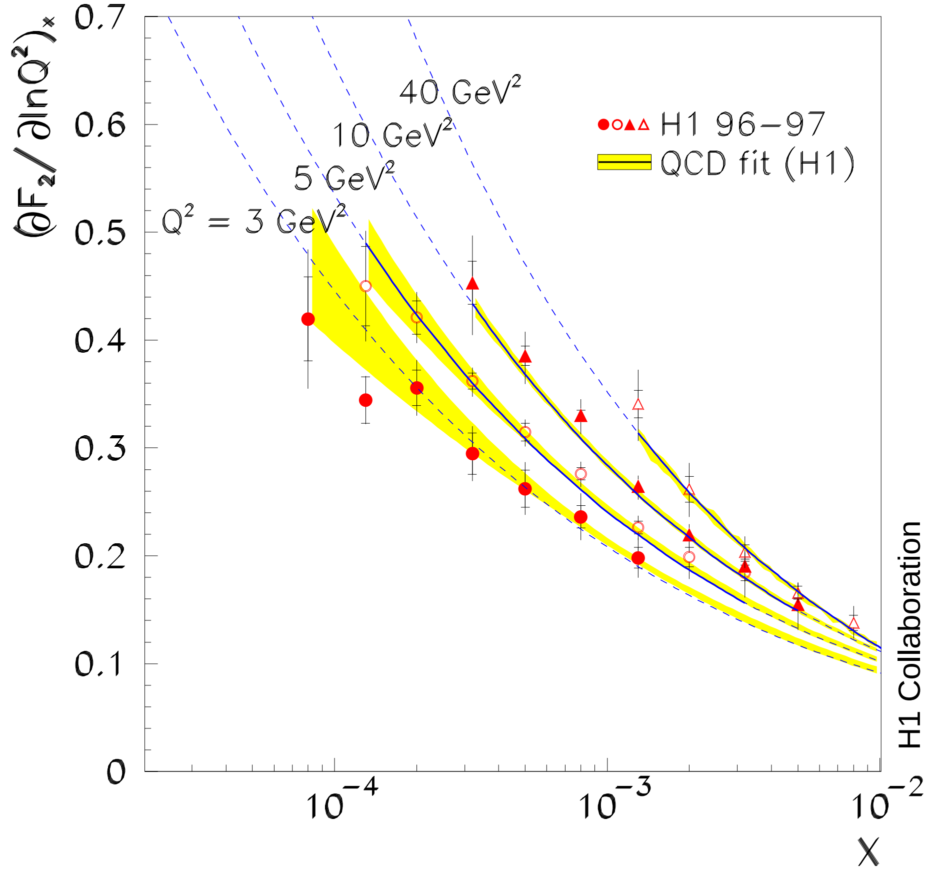


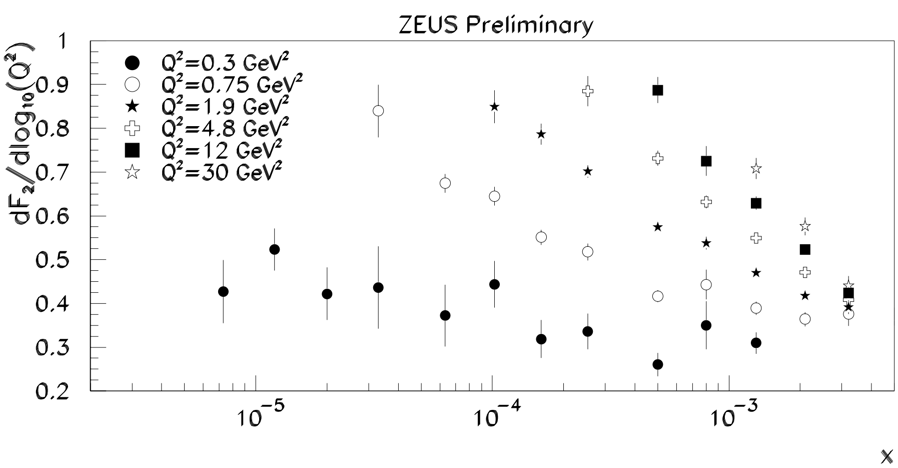
- *precision measurements (1% statistical and 2-3% systematical errors)*
- *overlapping and agree with fixed target experiment data*
- *Bjorken scaling at* $x \approx 0.1$
- *scaling violations: positive* at low x *and negative* at high x
- NLO DGLAP fits *describe the data well*

$(\partial F_2/\partial \ln Q^2)_x$ for different Q^2

scaling violations at low x are driven by gluon

$$\mathrm{d}F_2/\mathrm{d}\ln Q^2 \propto \alpha_s g \qquad \text{(LO)}$$



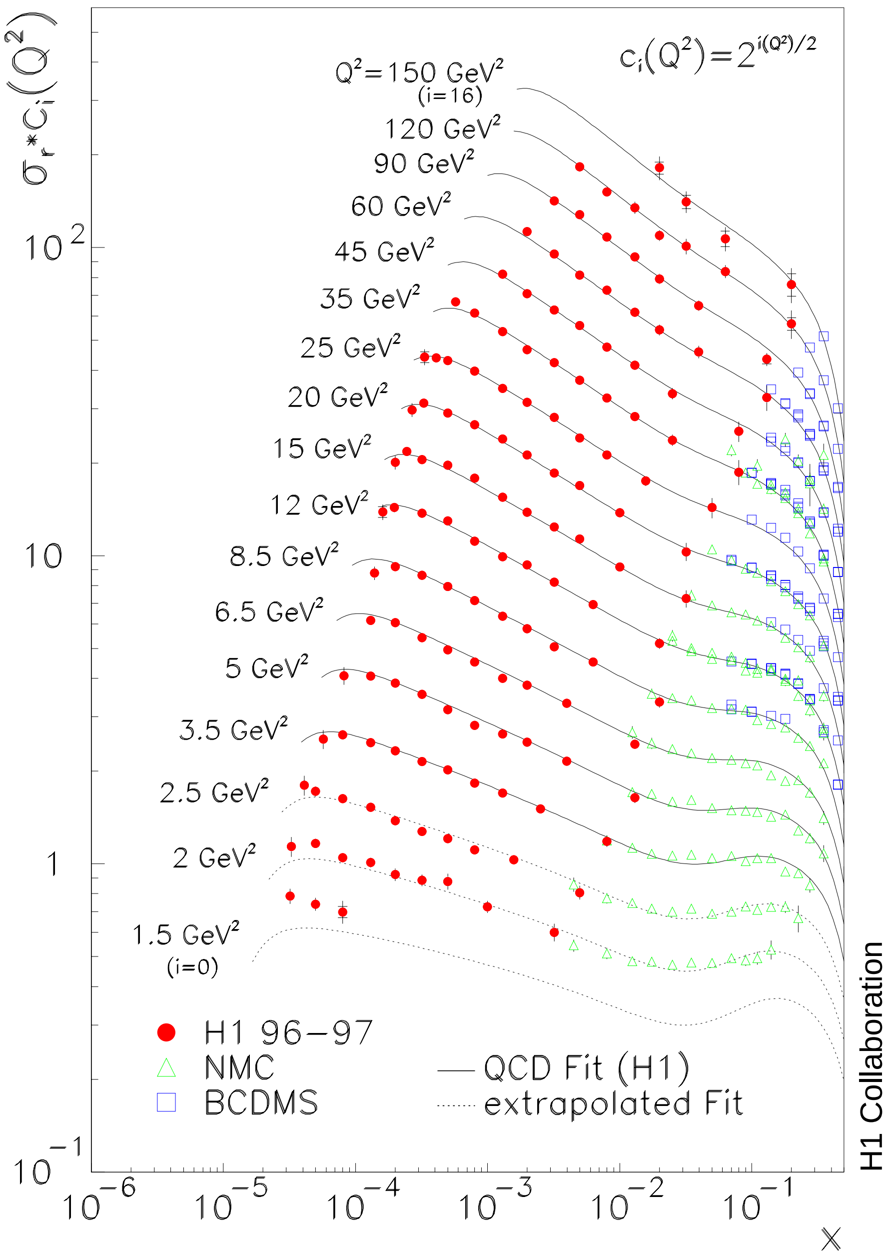


- a continuous rise towards low x for fixed Q^2
- consistent with NLO QCD fit for $Q^2 \geq 3$ GeV^2

Reduced NC cross section at medium Q^2

extention to high $y = 0.82$ sensitive to F_L

$$\tilde{\sigma}_{NC} \equiv \frac{1}{Y_+} \frac{Q^4 \; x}{2\pi\alpha^2} \frac{\mathrm{d}^2\sigma_{NC}}{\mathrm{d}x\mathrm{d}Q^2} = F_2 - \frac{y^2}{Y_+} F_L$$



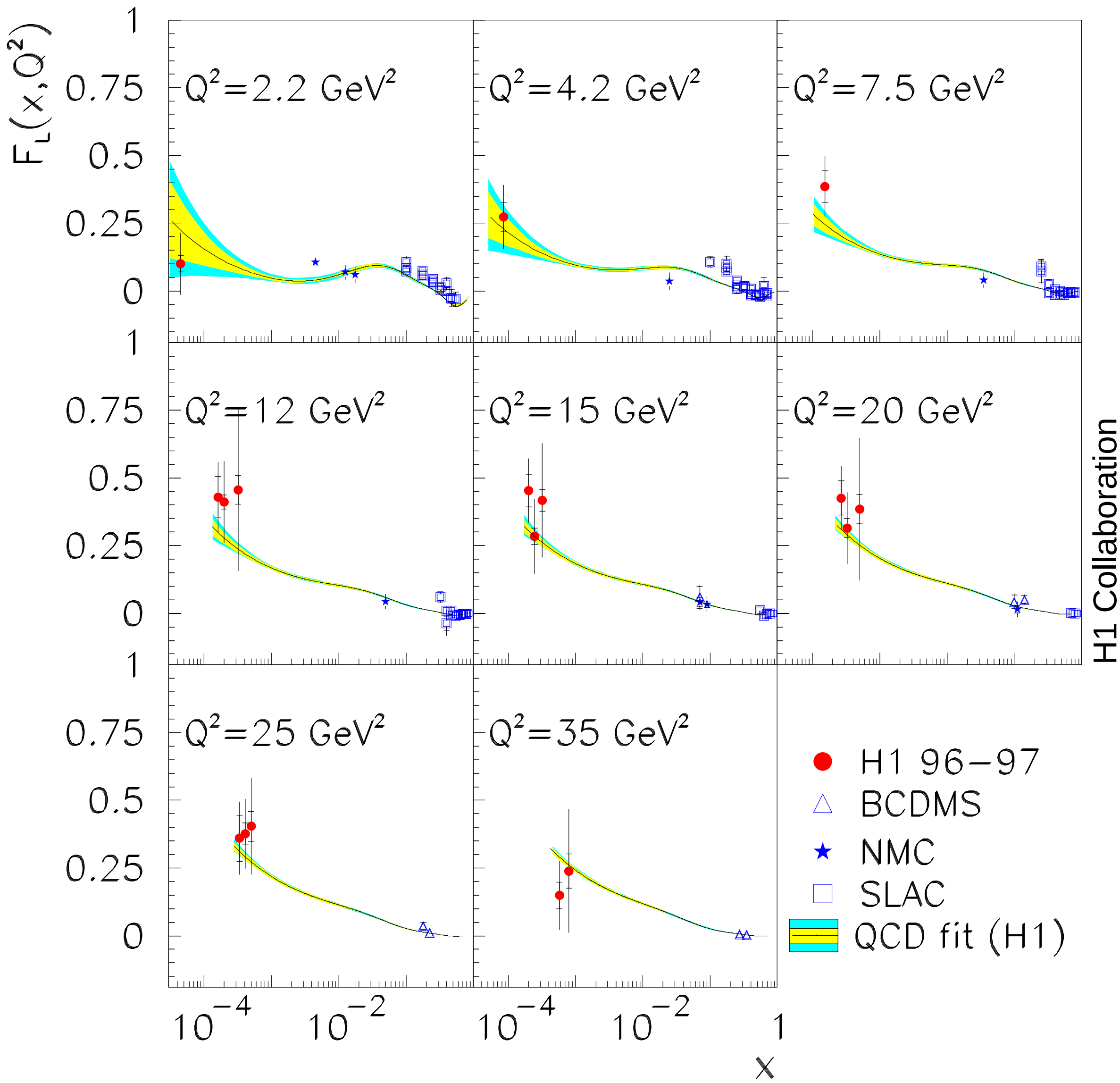
- *turn over* at highest y (smallest x) *due to* F_L

"subtraction" method

$$F_L = \frac{Y_+}{y^2}\left(F_2^{QCD\,fit} - \tilde{\sigma}_{NC}\right)$$

"derivative" method

$$\left(\frac{\partial \tilde{\sigma}_{NC}}{\partial \ln y}\right)_{Q^2} = \left(\frac{\partial F_2}{\partial \ln y}\right)_{Q^2} - F_L \cdot 2y^2 \cdot \frac{2-y}{Y_+^2} - \frac{\partial F_L}{\partial \ln y} \cdot \frac{y^2}{Y_+}$$



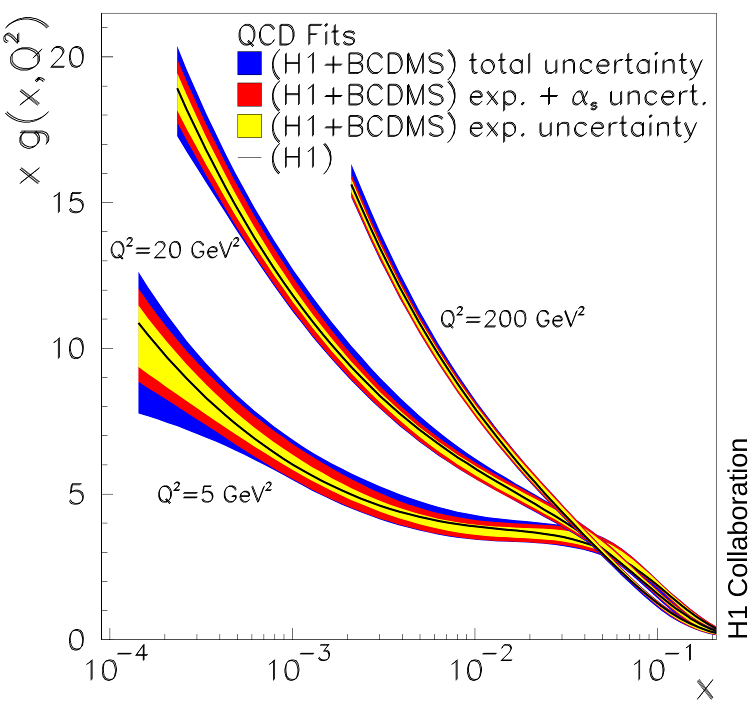
- extention of F_L to much lower x
- rise of F_L towards low x
- consistent with QCD
- *direct measurement in future by varying beam energies*

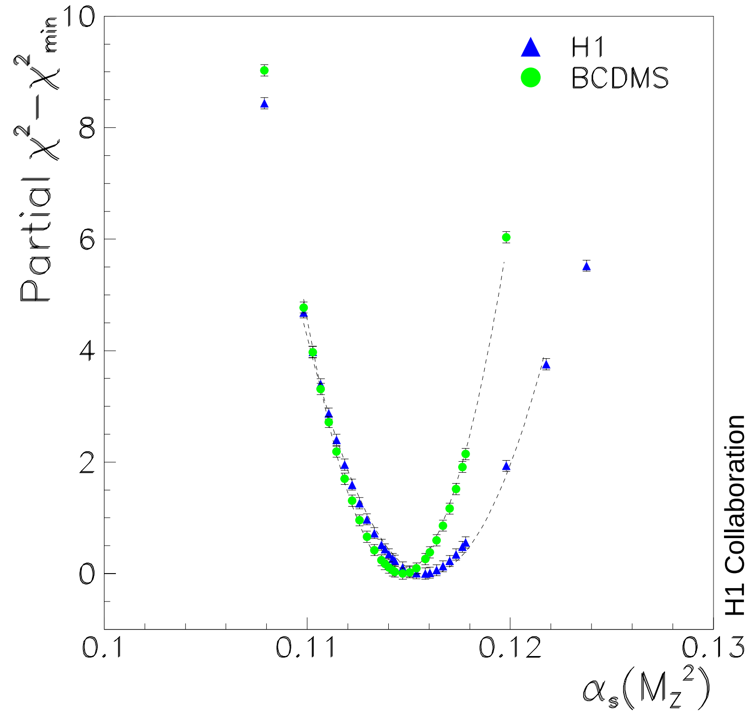
- *Simultaneous fit to gluon and α_s*
- *Only proton data sets* (*reduced inclusive NC cross sections*)

  low x : ep H1 $3.5 \leq Q^2 \leq 3000$ GeV^2

  high x: μp BCDMS with $y \geq 0.3$
- *NLO DGLAP evolution*

  with only two quark functions (A, V) *and gluon*
- $F_2 = F_2^{n_f=3} + F_2^c$; $Q_o^2 = 4$ GeV^2





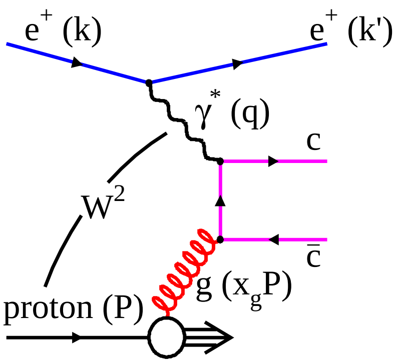
- $xg(x)$ rises towards low x – as F_2, $(\partial F_2/\partial \ln Q^2)_x$, F_L
- experim. accuracy of 3% for $xg(x)$ at $Q^2 = 20$ GeV^2

H1 and BCDMS give consistent contribution to errors on α_s

$$\alpha_s(M_Z^2) = 0.1150 \pm 0.0017\ (exp)\ {}^{+0.0009}_{-0.0005}\ (model)$$

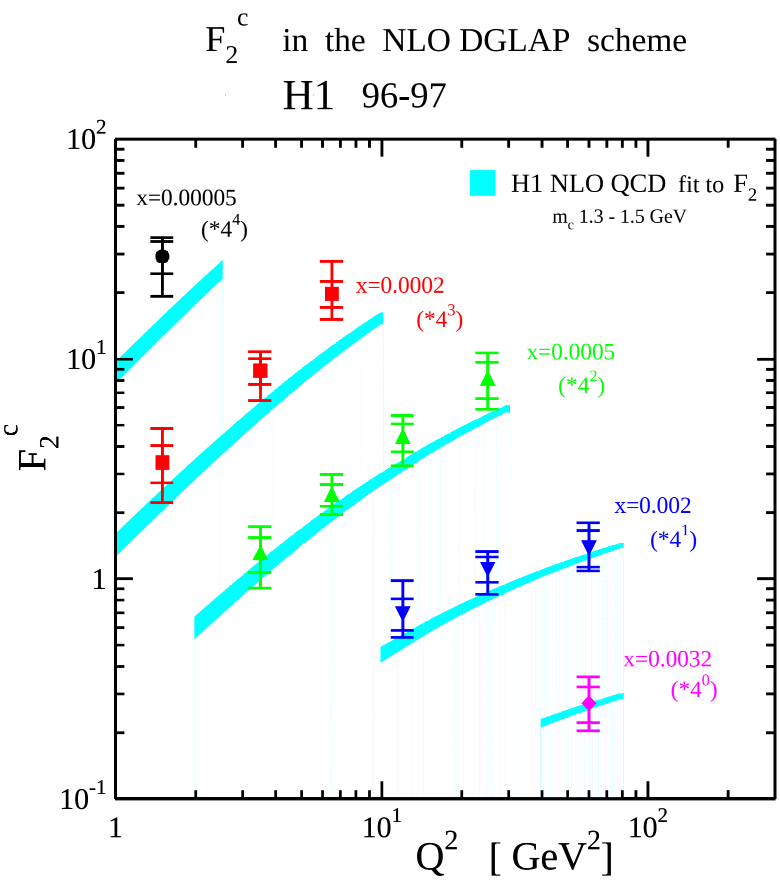
$\pm$ 0.005 *renormalisation and factorisation scales unc. in NLO*

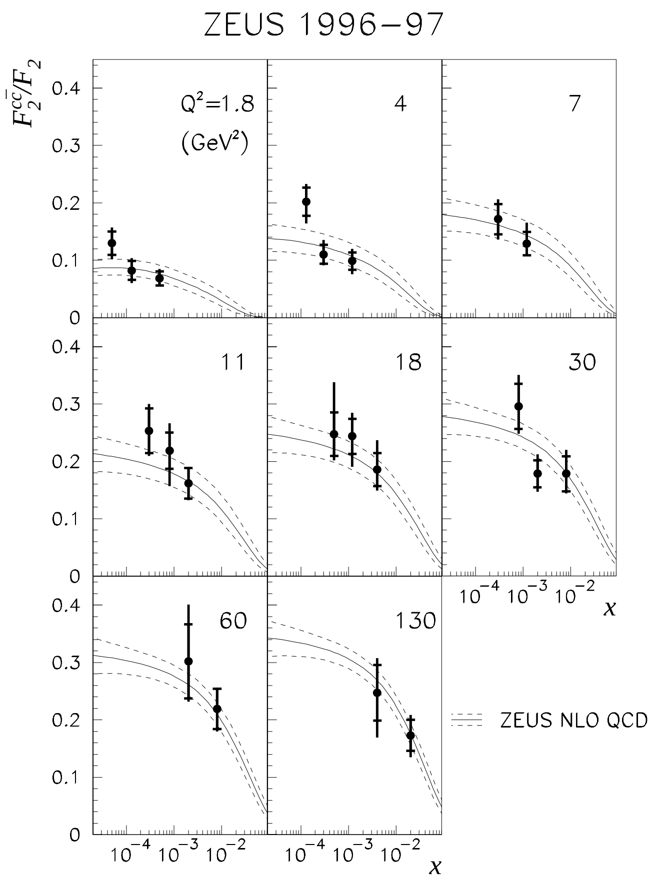
- expected uncertainty for NNLO is 0.002-0.003



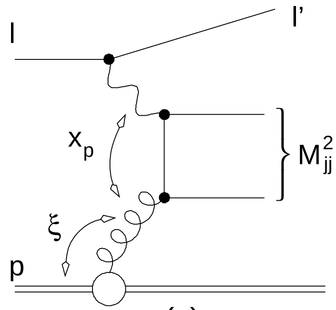
Boson Gluon Fusion (BGF)

$$D^* \rightarrow D^0 \pi_{slow} \rightarrow K\pi\pi_{slow}$$





- charm contribution is up to 25 – 30%
- in agreement with gluon from scaling violations

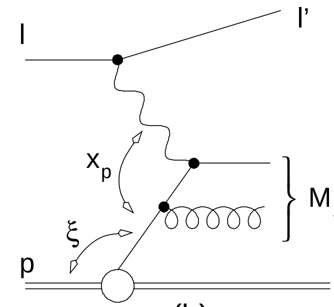


(c)

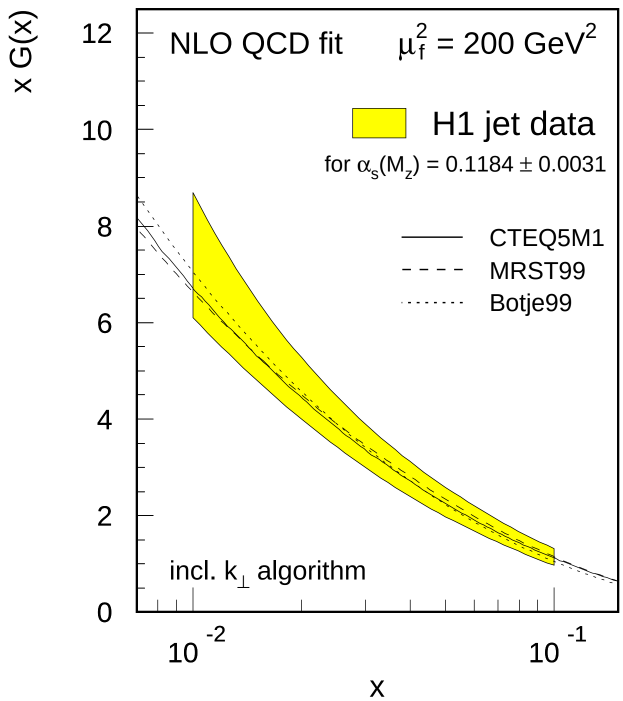
BGF: similar to $c\bar{c}$

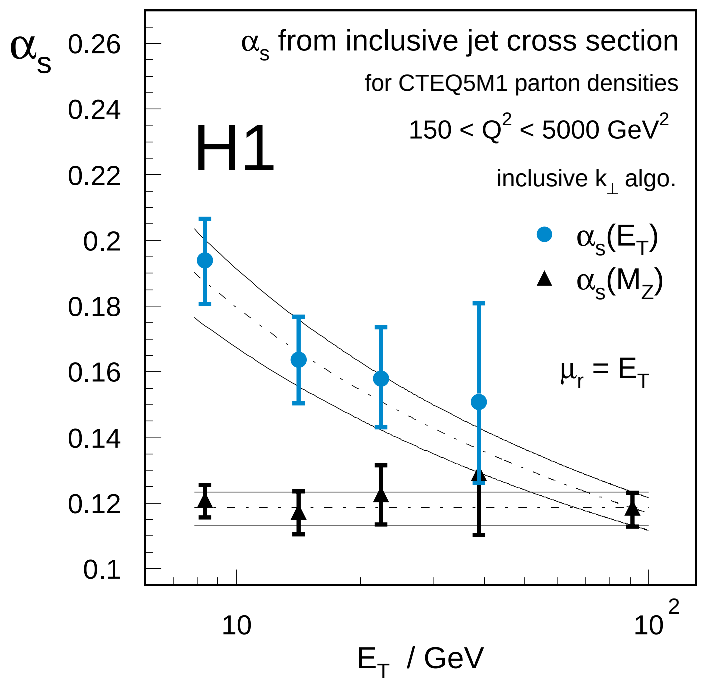
with $M_{jj} \gg M_{c\bar{c}}$ (i.e. higher x)

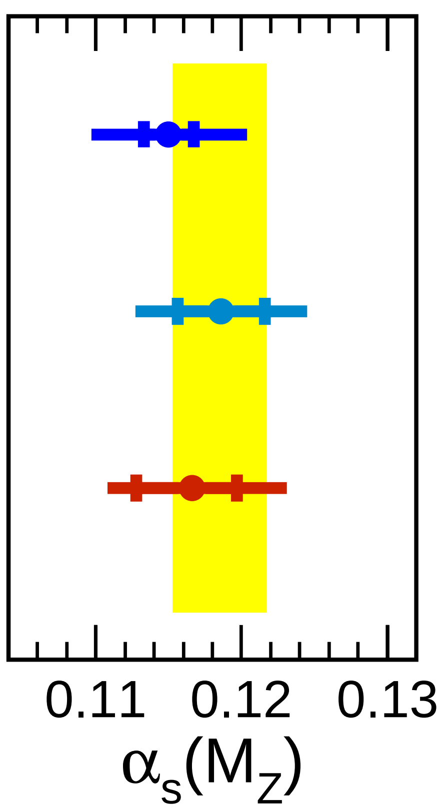
and more background →



(b)







(H1+BCDMS) Structure Functions

$3.5 < Q^2 < 3000$ GeV^2 / $\mu_r = Q$

H1 – Inclusive Jet Cross Section

$150 < Q^2 < 5000$ GeV^2 / $\mu_r = E_T$

ZEUS – Dijet Rate

$470 < Q^2 < 20000$ GeV^2 / $\mu_r = Q$

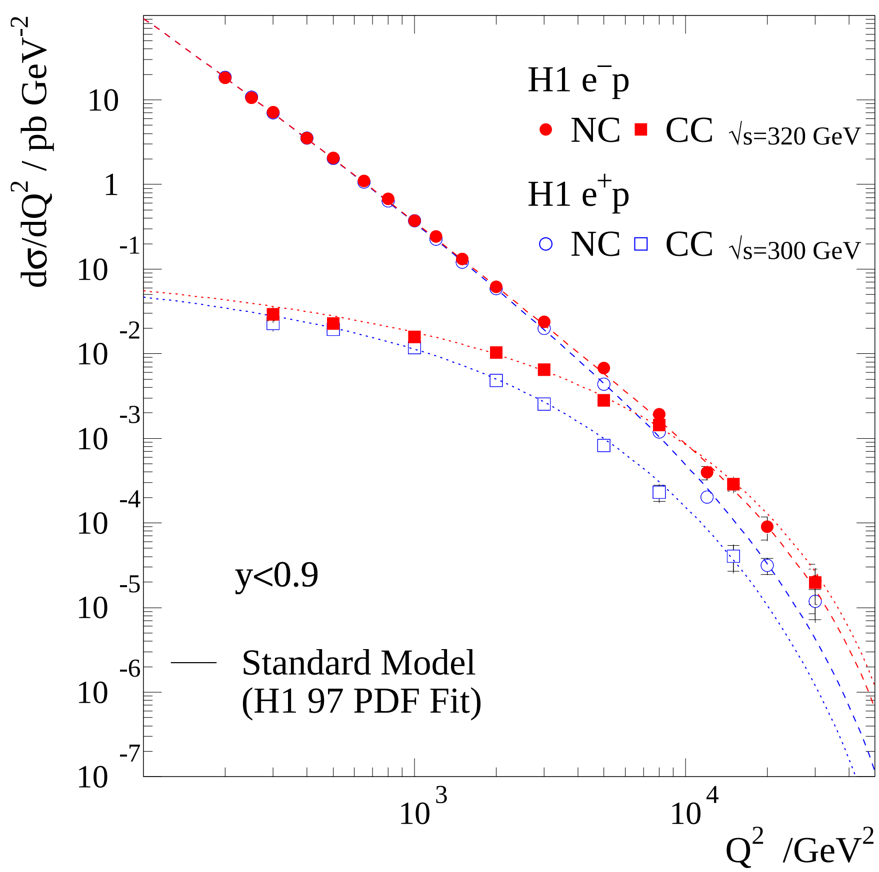
World average

(S. Bethke, J.Phys. G26 (2000) R27)

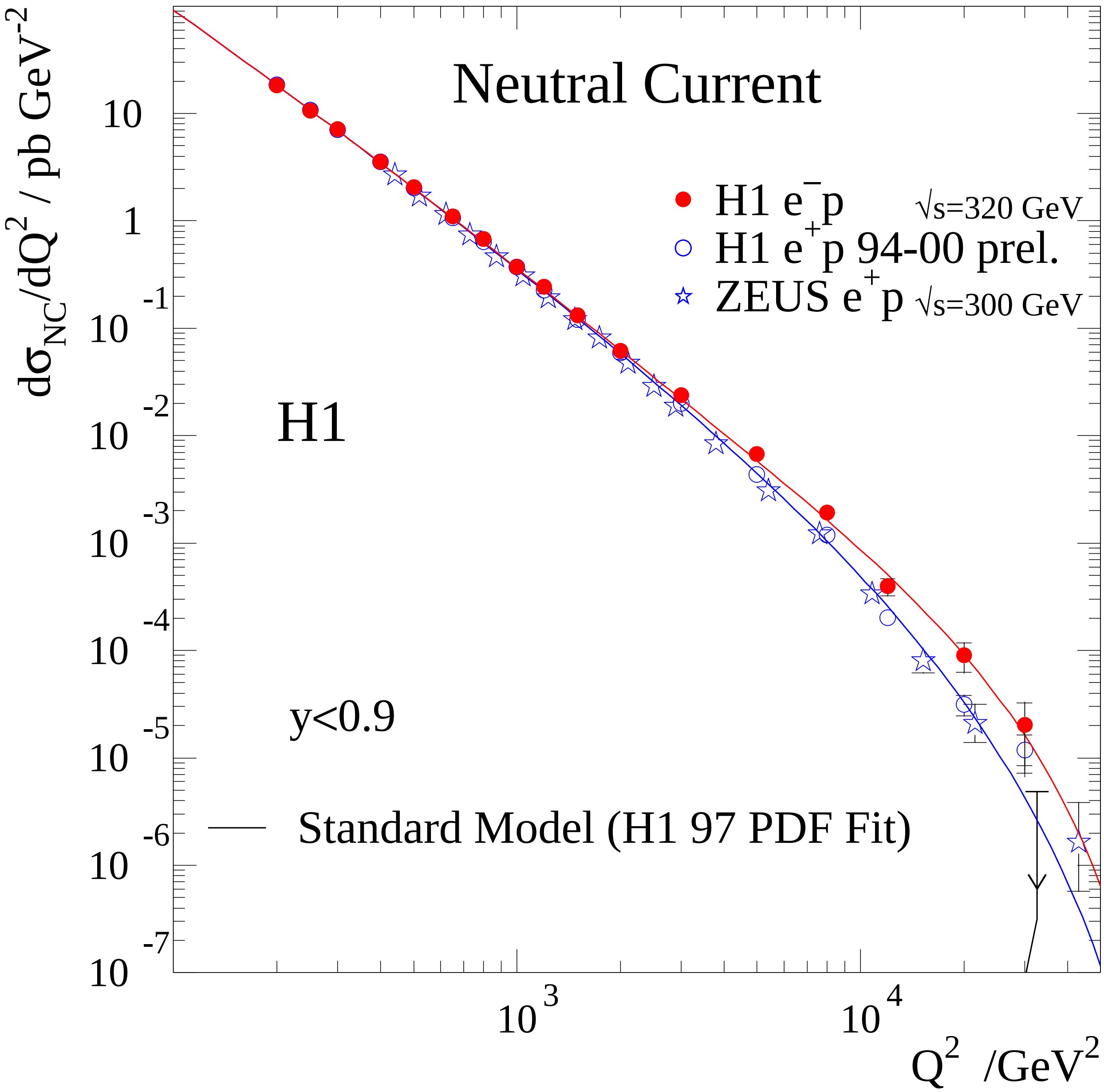
Electroweak Sector

(high $Q^2 \approx M_Z^2, M_W^2$)

unification of weak and electromagnetic forces



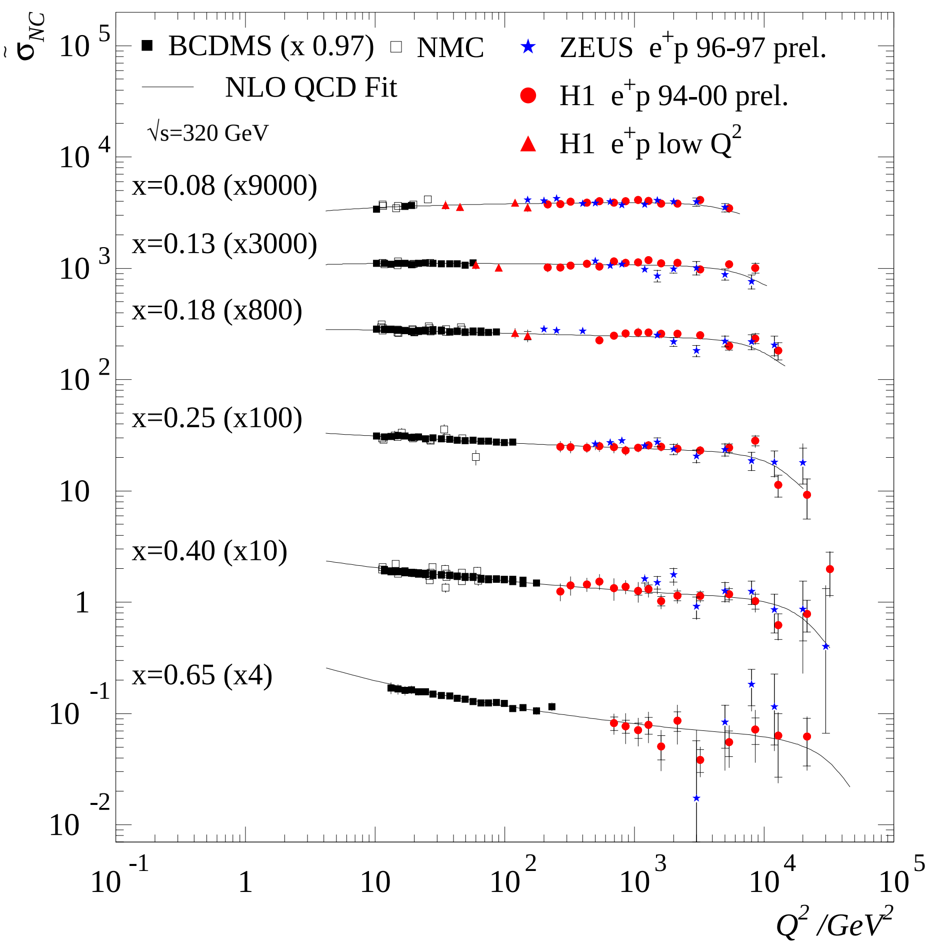
Q^2 dependence of the NC cross section

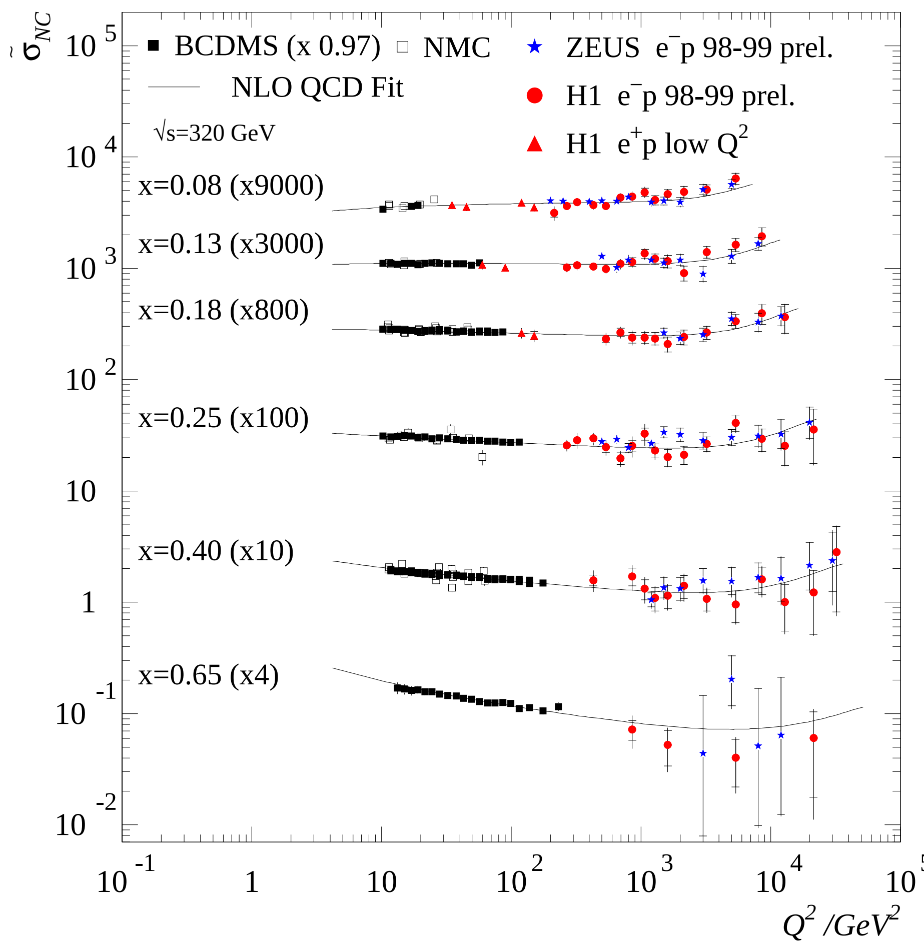


- $d\sigma/dQ^2$ falls by 7 orders of magnitude
- discovery potential at highest Q^2
- difference between e^+p and e^-p at high Q^2

Reduced NC cross section at high x

$$\tilde{\sigma}_{NC}^{e^{\pm}p}(x,Q^2) \equiv \frac{1}{Y_+}\,\frac{Q^4\ \ x}{2\pi\alpha^2}\,\frac{d^2\sigma_{NC}^{e^{\pm}p}}{dxdQ^2} = \tilde{F}_2(x,Q^2) \mp \frac{Y_-}{Y_+}x\tilde{F}_3(x,Q^2) - \frac{y^2}{Y_+}\tilde{F}_L(x,Q$$



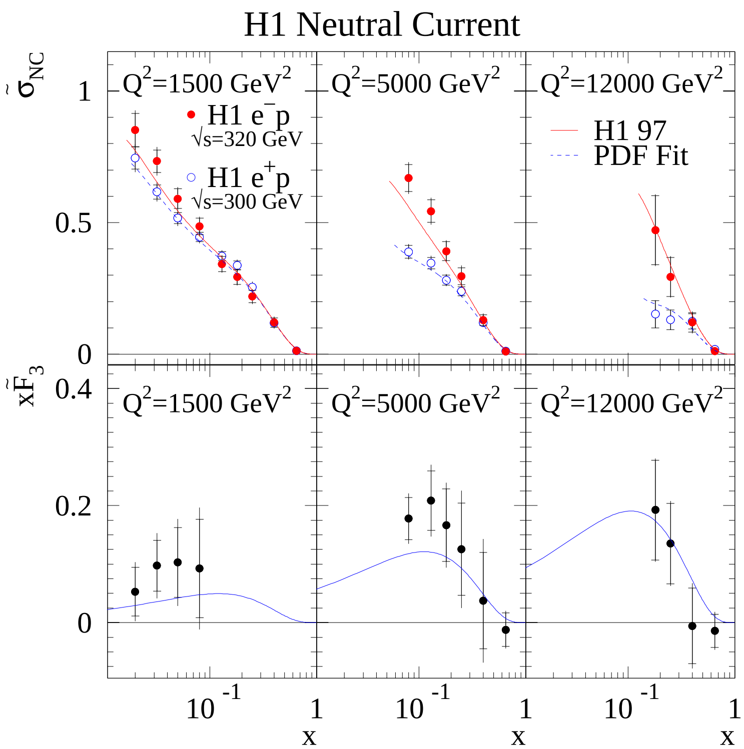


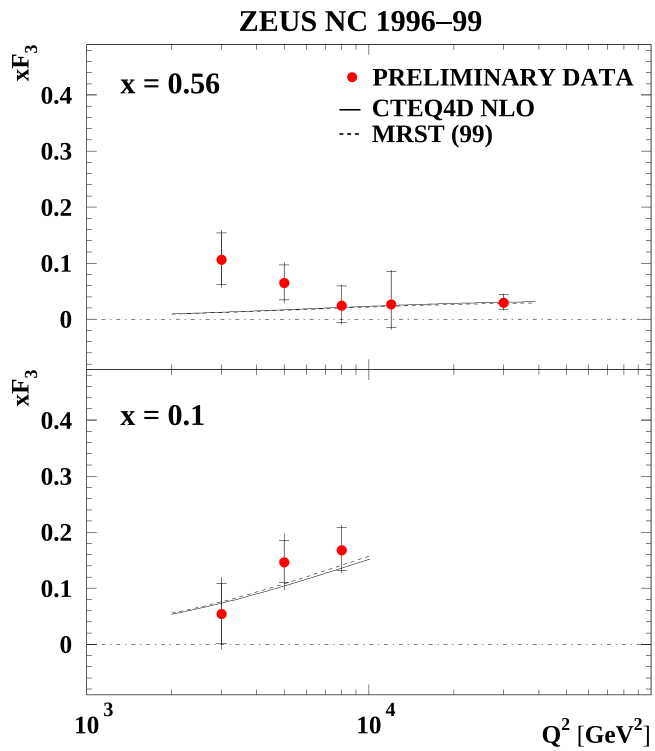
- negative(positive) contribution from γZ interference in $e^+(e^-)$ at high Q

Generalised structure function $x\tilde{F}_3(x,Q^2)$

$$\tilde{\sigma}_{NC}(e^{\pm}p) \simeq \tilde{F}_2 \mp \frac{Y_-}{Y_+} x\tilde{F}_3$$

difference between $e^{\pm}p$ is due to γZ interference

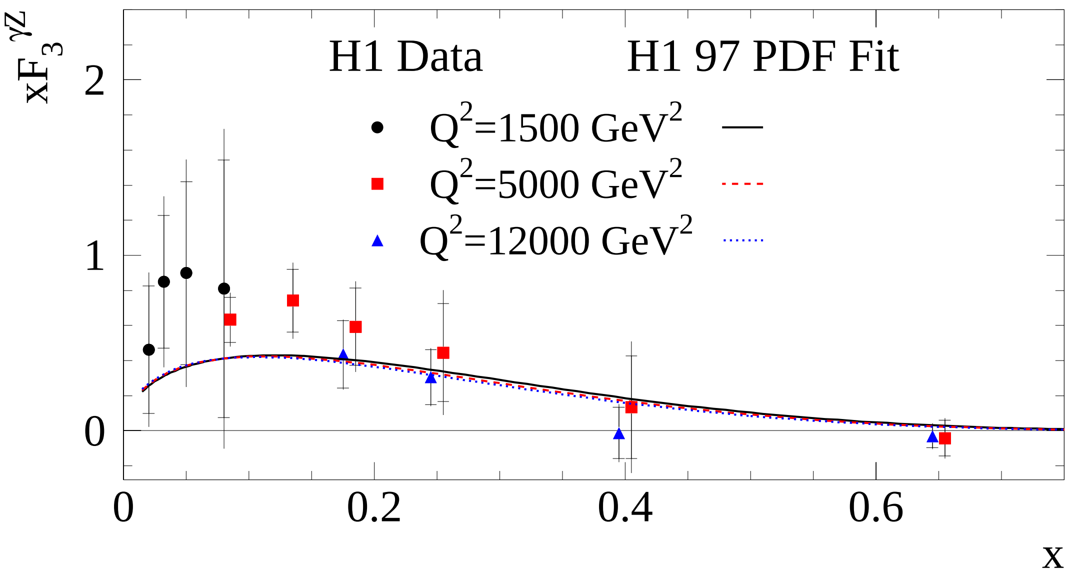




- *the first measurement of $x\tilde{F}_3$ at high Q^2*
- *errors limited by statistics*

Sum rule for $xF_3^{\gamma Z}(x)$

$$xF_3^{\gamma Z} \simeq x\tilde{F}_3 / \left[-a_e \kappa_w Q^2/(Q^2+M_Z^2)\right]$$



by analogy with Gross Llewellyn-Smith rule for neutrino:

$$\int_0^1 F_3^{\gamma Z} \mathrm{d}x = 2e_u a_u N_u + 2e_d a_d N_d = \frac{5}{3} \cdot \mathcal{O}(1-\alpha_s/\pi)$$

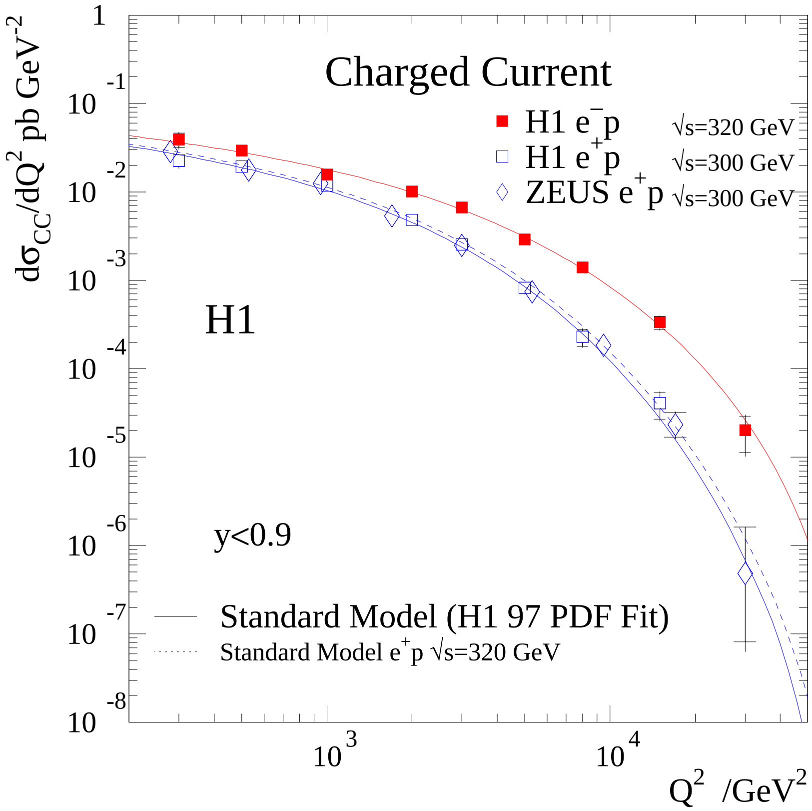
H1: $\int_{0.02}^{0.65} F_3^{\gamma Z} \mathrm{d}x = 1.88 \pm 0.35(\text{stat.}) \pm 0.27(\text{syst.})$

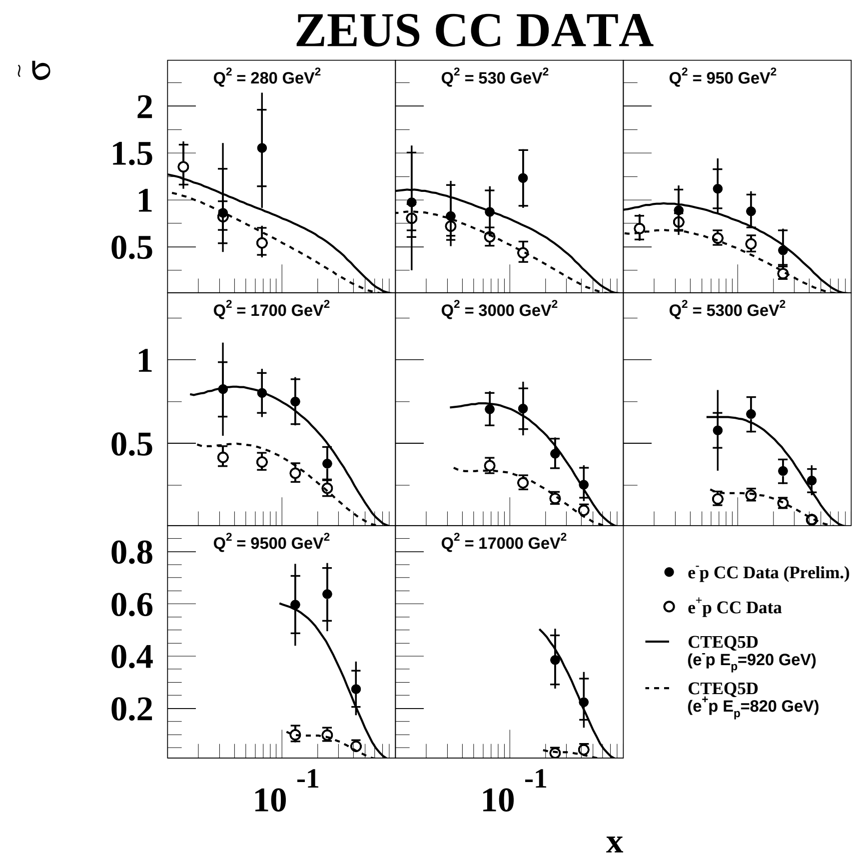
- *agrees with* $\int_{0.02}^{0.65} F_3^{\gamma Z}\, dx = 1.11$ (H1 97 PDF Fit)

CC cross section

in leading order (LO): $\tilde{\sigma}_{CC}(e^+p) = x\left[(\bar{u}+\bar{c}) + (1-y)^2(d+s)\right] \simeq (1-y)^2 x d_v$ **for** $x \to 1$

$\tilde{\sigma}_{CC}(e^-p) = x\left[(u+c) + (1-y)^2(\bar{d}+\bar{s})\right] \simeq x u_v$



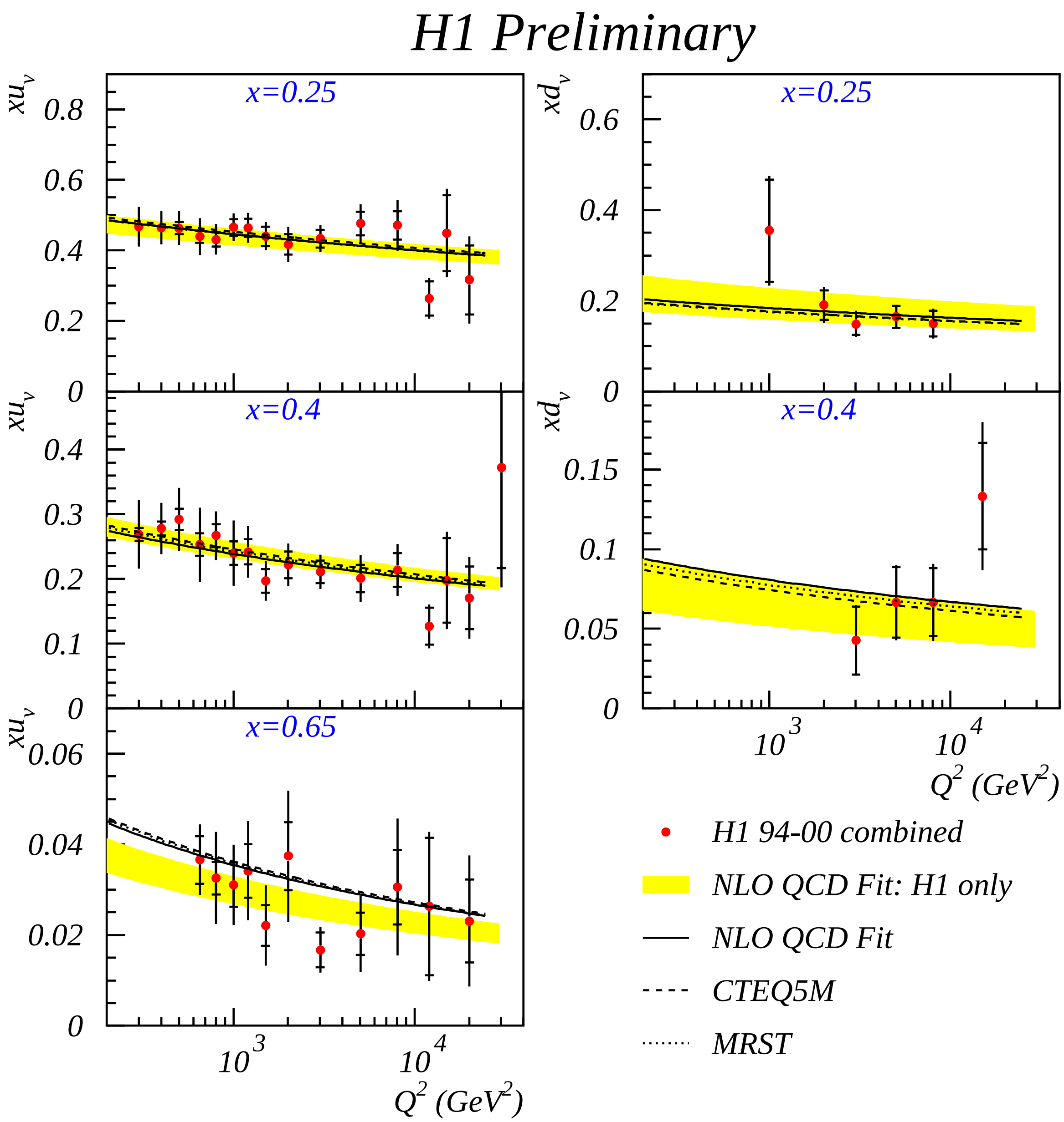


- *at low* x *(low* Q^2*)* $\rightarrow$ *sea dominance* $\rightarrow$ $\tilde{\sigma}_{CC}(e^+p) \approx \tilde{\sigma}_{CC}(e^-p)$
- *at high* x *(high* Q^2*)* $\rightarrow$ *valence quarks* $\rightarrow$ *order of magnitude difference*

Extraction of xu_v and xd_v from $\tilde{\sigma}^{e^\pm p}_{NC}$ and $\tilde{\sigma}^{e^\pm p}_{CC}$

almost model independent

$$xq_v(x,Q^2) = \sigma(x,Q^2)\left(\frac{xq_v}{\sigma}\right)_{fit} \quad \text{(only if } \left(\frac{xq_v}{\sigma}\right)_{fit} > 0.7\text{)}$$

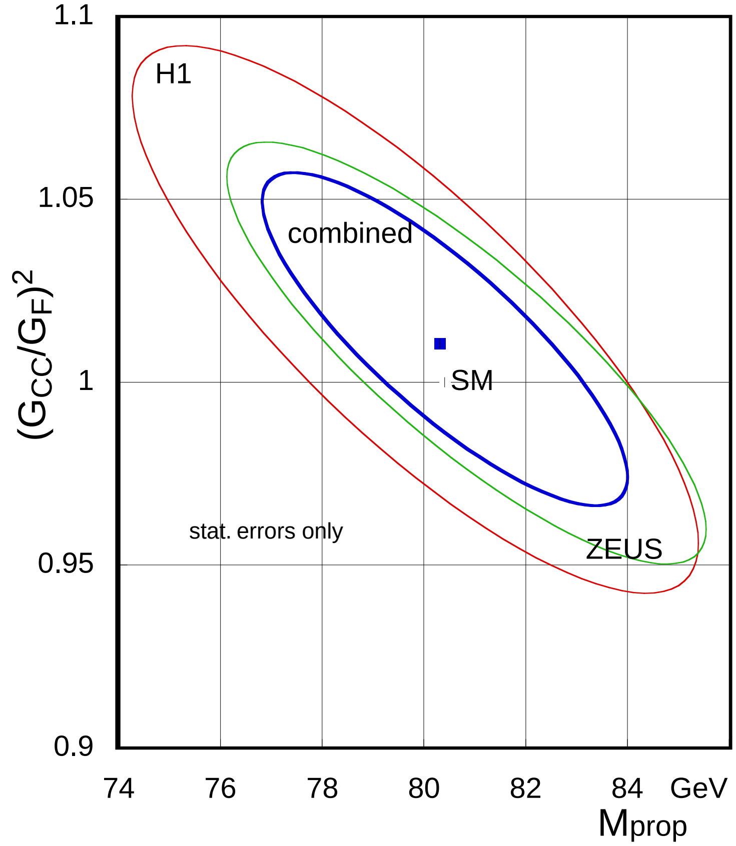


- xu_v, xd_v are consistent with NLO QCD Fit
- more statistics is needed (especially for $\tilde{\sigma}^{e^+p}_{CC}$)

$$\frac{d^2\sigma_{CC}}{dx\, dQ^2} \propto G_{CC}^2 \left(\frac{M_{prop}^2}{Q^2+M_{prop}^2}\right)^2$$

normalisation given by coupling G_{CC} (G_F)

shape given by propagator mass M_{prop} (M_W)



from constrained fit with $G_{CC} \equiv G_F$:

$$e^+p(ZEUS): M_W = 81.4^{+2.7}_{-2.6}(\text{stat.}) \pm 2.0(\text{syst.})^{+3.3}_{-3.0}(\text{pdf})\ \text{GeV}$$

$$e^+p(H1): M_W = 80.9 \pm 3.3(\text{stat.}) \pm 1.7(\text{syst.}) \pm 3.7(\text{pdf})\ \text{GeV}$$

$$e^-p(H1): M_W = 79.9 \pm 2.2(\text{stat.}) \pm 0.9(\text{syst.}) \pm 2.1(\text{pdf})\ \text{GeV}$$

- measured in the space-like regime
- in agreement with time-like measurements by LEP and TEVATRON

HERA I (1992-2000): $\approx 120\ pb^{-1}$ *for analysis per exp.*

Inclusive DIS cross section measurements:

from $Q^2 = 0.045\ GeV^2$ *to* $Q^2 = 30000\ GeV^2$,

from $x \approx 10^{-6}$ *to* $x \approx 1$.

High precision *(1% statistical and 2-3% systematical errors)*

approaching fixed target experiments

- *smooth transition to* γp $(Q^2 = 0)$
- *consistent picture of QCD* $(Q^2 \geq 1\ GeV^2)$

  F_2, $(\partial F_2/\partial \ln Q^2)_x$, $(\partial F_2/\partial \ln y)_{Q^2}$, F_L, F_2^c, *jets*

  gluon density $xg(x)$*:*

  experimental accuracy of 3% *at* $Q^2 = 20\ GeV^2$

  strong coupling constant:

  $$\alpha_s(M_Z^2) = 0.1150 \pm 0.0017\ (exp)^{+0.0009}_{-0.0005}\ (model)$$
  $$\pm 0.005\ (vary\ scales\ by\ 4)$$

- *electroweak physics* $(Q^2 \approx M_Z^2, M_W^2)$

  NC and CC, γZ *interference,* xF_3, *W propagator mass*

HERA II (2001-2006)

high luminosity: $\approx 150 pb^{-1}$ */ year / experiment*

longitudinal polarisation of the electron (positron) beam