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Proton Structure Functions

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- Introduction
- high Q^2, electro-weak effects
- QCD fits
- low x behaviour of F_2
- Conclusion

Introduction

proton (and n) best known hardronic particle

e.g. p charge agrees to $\sim 10^{-21}$ with that of electron,
mass is known better 10^{-7}

Internal properties less well known

e.g. charge radius on the % level

Internal hadronic structure

probed in hard interactions, described since the seventies by quark and gluon densities (pdfs)
explored in particular by lepton nucleon scattering

$\Longrightarrow$ One of the main activities at HERA

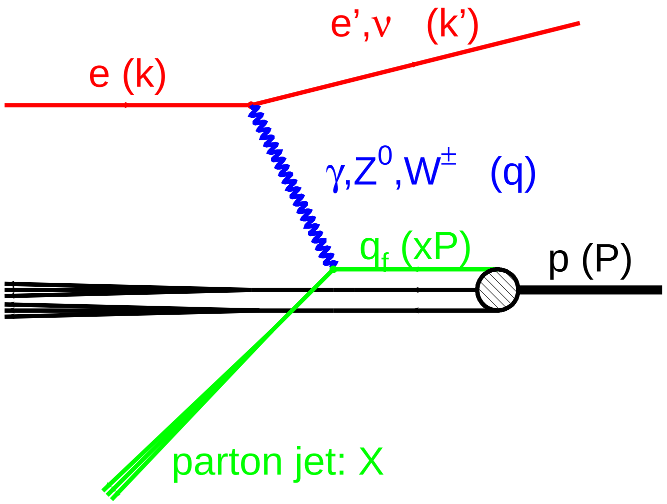
approaching few % level

Important as

- pdfs not yet predicted by QCD
- pdfs needed to predict other reactions, e.g. $\bar{p}p$
- Due to constraints by QCD, important testing ground for theory

GPDs, non-collinear pdfs, correlations, spin density not accessed in inclusive DIS, not discused here

Inclusive DIS $\quad ep \to eX$ (NC) $\quad ep \to \nu_e X$ (CC)



$Q^2 = -q^2$ — 4-momentum transfer

$x = Q^2/2(P \cdot q)$ — p momentum fraction of parton

$y = (P \cdot q)/(P \cdot k)$ — inelasticity

$NC \qquad d^2\sigma^{\pm}_{NC}/dxdQ^2 = \frac{2\pi\alpha^2}{xQ^4}[Y_+ \cdot \tilde{F}_2 \mp Y_- \cdot x\tilde{F}_3 - y^2 \cdot \tilde{F}_L] \equiv \frac{2\pi\alpha^2}{xQ^4}\tilde{\sigma}^{\pm}_{NC}$

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

$\tilde{F}_2$,	**dominating contribution,**	**in leading order QCD**	$\sim x\sum_q (q + \bar{q})$
$x\tilde{F}_3$,	**in particular γZ interference,**	**significant at large $Q^2 \gtrsim M_Z^2$**	$\sim x\sum_q (q - \bar{q})$
$\tilde{F}_L$,	**longitudinal contribution,**	**important only at large y,**	**zero in LO QCD**

$CC \qquad d^2\sigma^{\pm}_{CC}/dxdQ^2 = \frac{G_F^2}{2\pi x}(\frac{M_W^2}{Q^2+M_W^2})^2 \cdot \tilde{\sigma}^{\pm}_{CC}$

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

$\mathrm{d}\sigma/\mathrm{dQ}^2$ NC vs. CC and e^-p vs. e^+p

◊ H1 and ZEUS data consistent

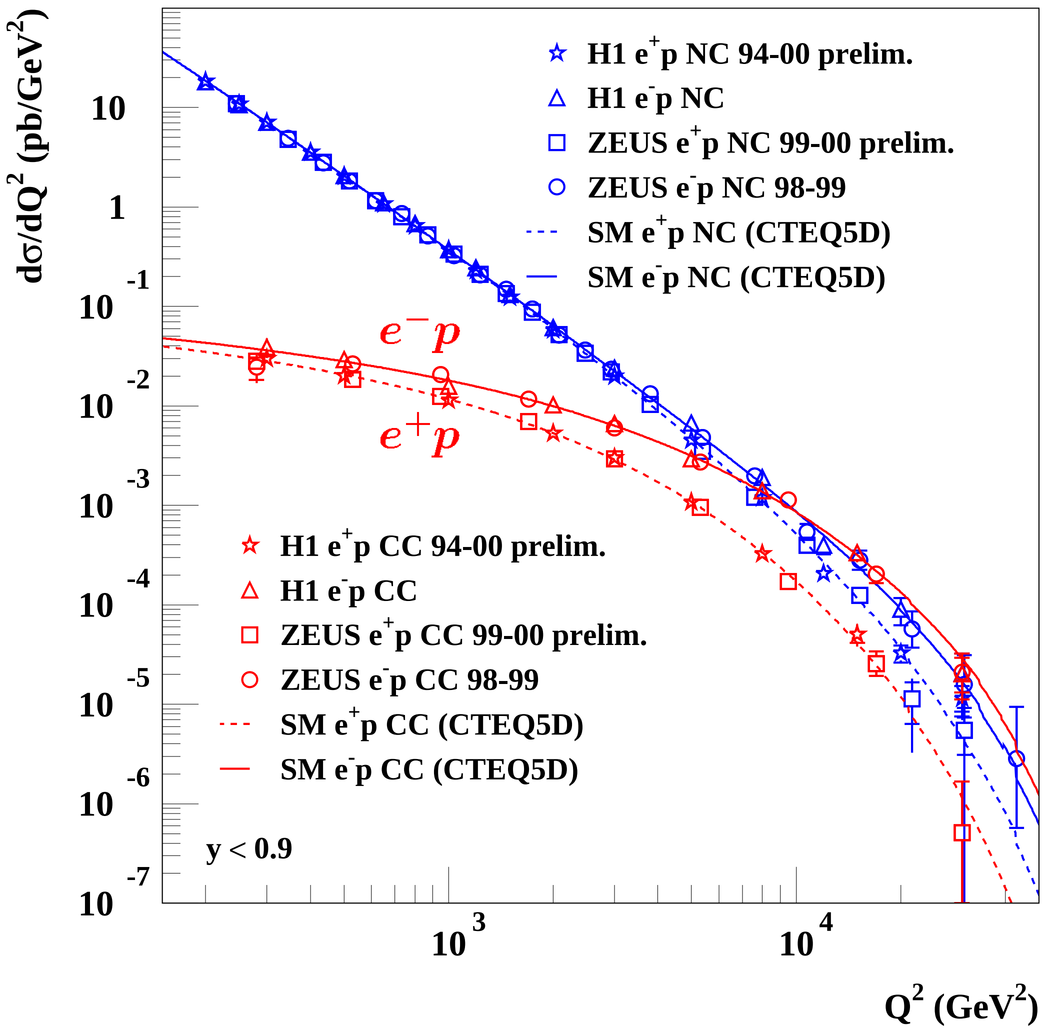
◊ NC $\sigma(e^-p) > \sigma(e^+p)$

γZ interference

◊ CC $\sigma(e^-p) > \sigma(e^+p)$

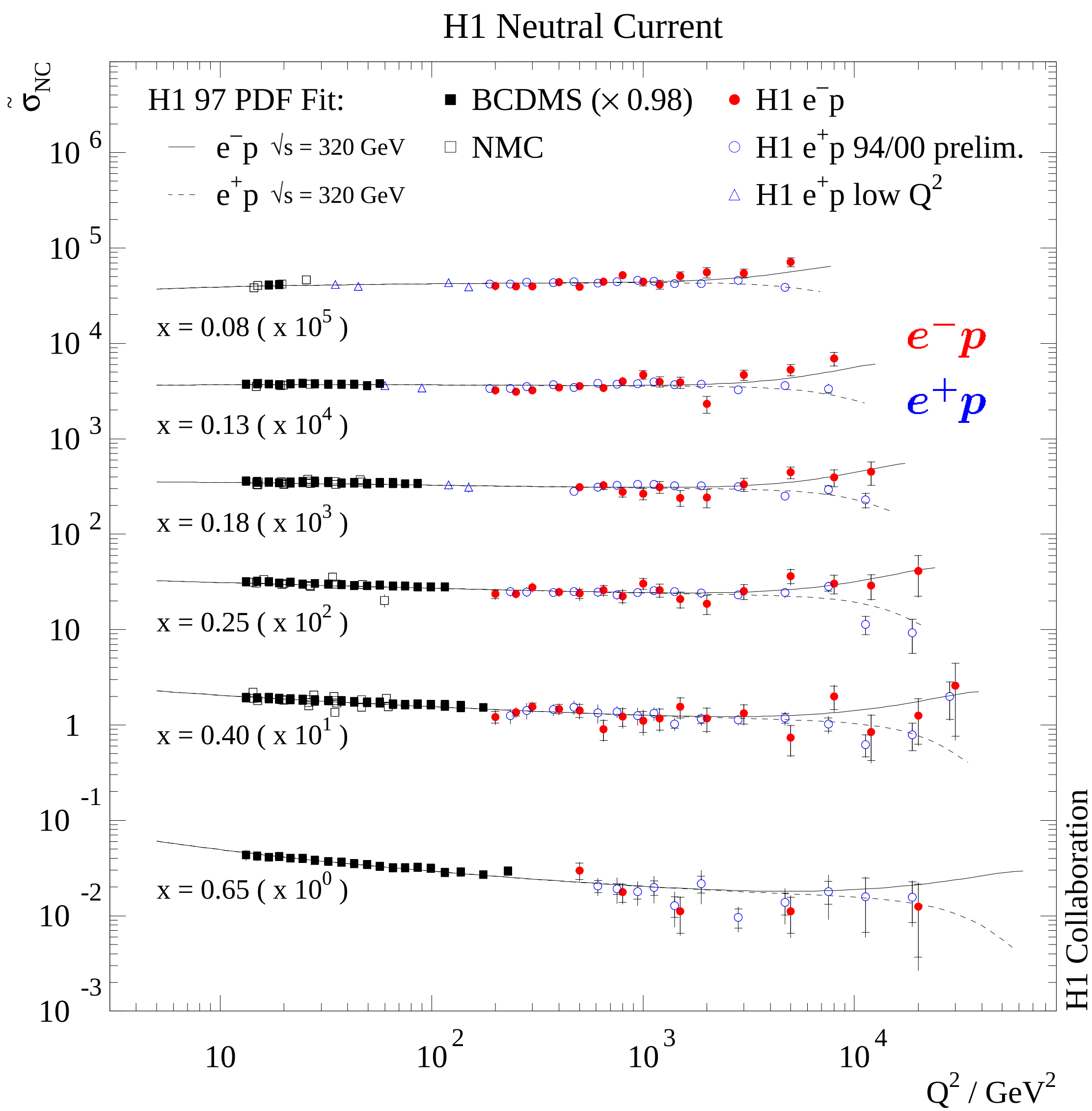
$\sim xu(x) \quad \sim (1-y)^2 d(x)$

◊ data well described by SM in range where NC $\mathrm{d}\sigma/\mathrm{dQ}^2$ varies by 7 orders



$Q^2 \gtrsim M_Z^2, M_W^2 \Rightarrow \sigma_{CC} \approx \sigma_{NC}$, illustration of electro-weak unification

NC reduced cross section $\tilde{\sigma}$ at high x



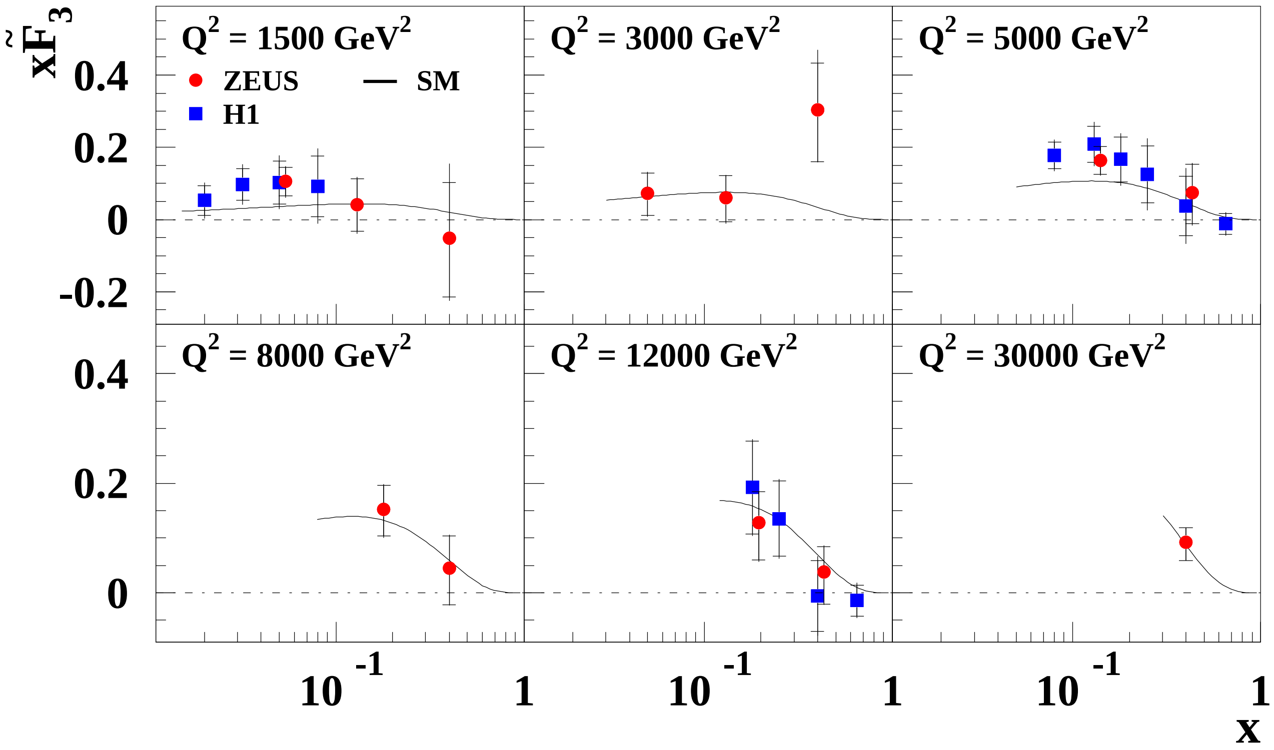
- **data consistent within errors with fixed target results**
- **electro-weak effects in NC visible at highest $Q2$**

⇒ evaluate xF_3

Results on xF_3

$$x\tilde{F}3 \approx x\tilde{F}3^{\gamma Z} \sim 2u_v + d_v$$

$x\tilde{F}3$ measured at large Q^2
consistently with SM



once precisly measured,

$xF3$ interesting consistency check for d_v density from NC ep only

($u(x)$ much better known)

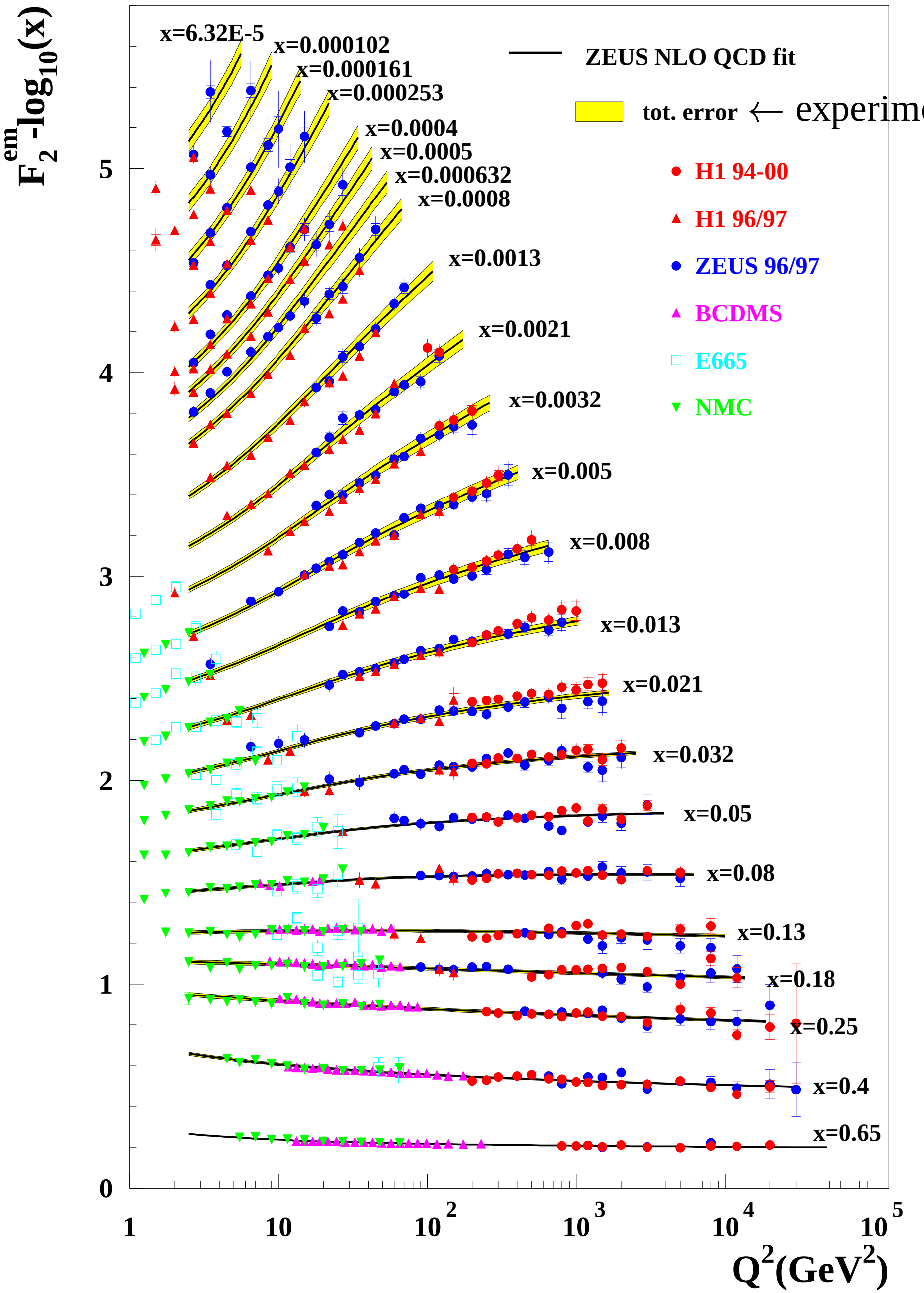
Recent QCD Analyses of F_2 data

Procedure :
- ∘ parametrisation of pdfs at starting scale Q_0^2
- ∘ Q^2 dependence by DGLAP pQCD evolution in NLO
- ∘ pdf parameters at Q_0^2 determined by fits to measured F_2 at $Q^2 > Q^2_{min}$

Approaches differ mainly in :
- ∘ amount of data used
- ∘ parametrisations at Q_0^2
- ∘ treatment of heavy quarks
- ∘ treatment of systematics

	H1 NC	H1 NC,CC	ZEUS NC
	Eur.Phys.J.C21(2001)3	ICHEP02, 978	DESY-02-105
other experiments used in main fi t			
	BCDMS (μp)	$(\mu p, \mu d)$	BCDMS, NMC $(\mu p, \mu d)$, E665$(\mu p, \mu d)$, CCFR(νFe)
fi tted distributions			
	ep valence and sea terms	$u+c,\ \bar{u}+\bar{c},\ d+s,\ \bar{d}+\bar{s},\ g$	$u_v(x),\ d_v(x),\ S(x),\ \bar{d}-\bar{u},\ g$
Q^2_{min}[GeV^2]	3.5	3.5	2.5
main aim	$\alpha_s,\ g(x)$	pdfs	pdfs, α_s

ZEUS NLO fit compared with HERA and fixed target NC data



▽ ZEUS and H1 NLO fits describe used data well

($\sim 10^{-4} < x < 0.65$)

▽ DGLAP QCD fit follows strong rise

at small x driven in the fits by g(x)

▽ Is this approach at small x really good enough?

(neglected $\ln 1/x$ terms important?)

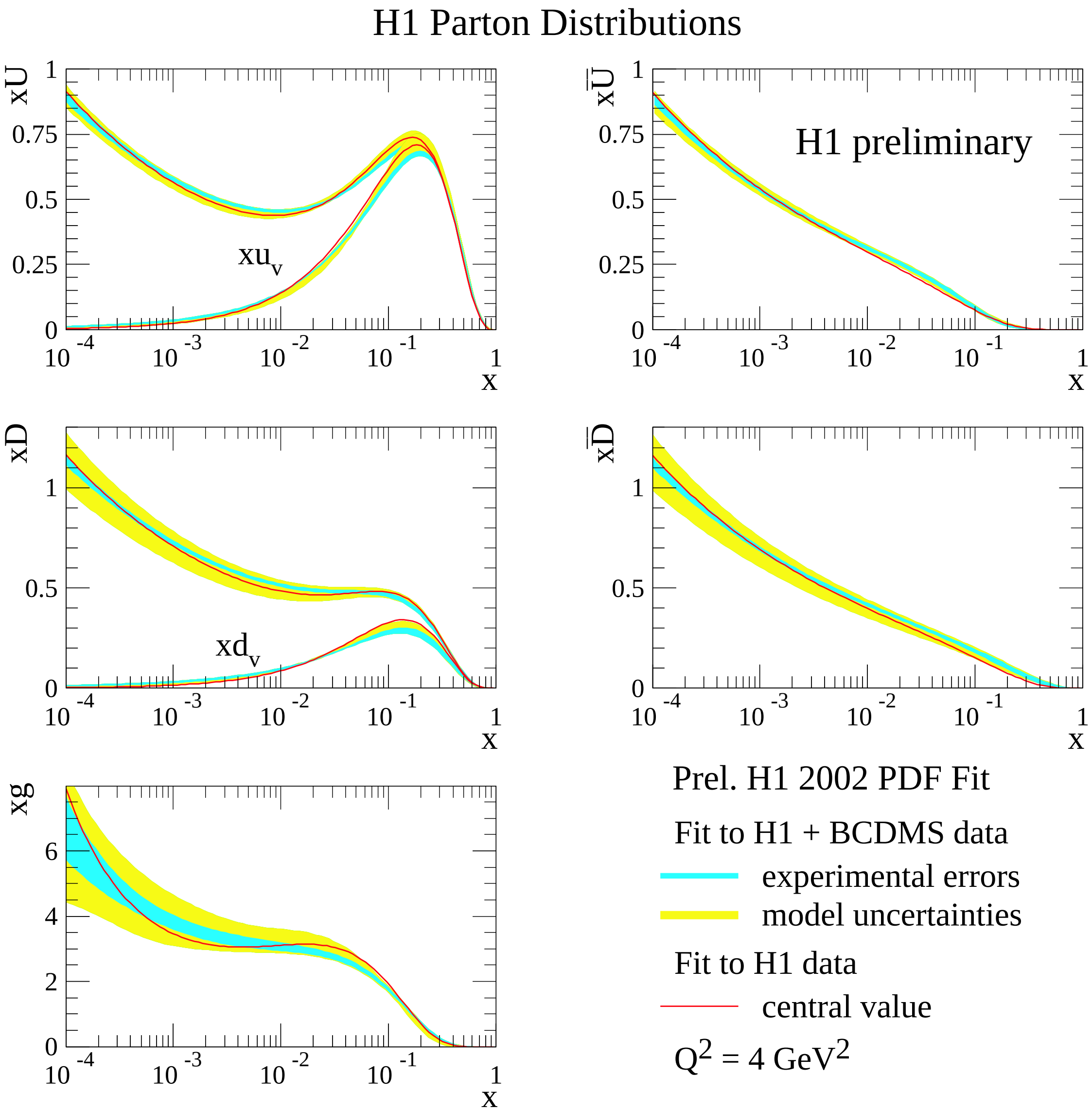
▽ or parametrisations too flexible ?

(e.g. ZEUS fit 11 parameters)?

In any case

data consistent with DGLAP evolution of pdfs

PDFs from H1 2002 Fit (prel.) fitting H1 (NC + CC) + BCDMS ($\mu p, \mu d$)



Determination of

$$U = u + c \qquad \bar{U} = \bar{u} + \bar{c}$$
$$D = d + s \qquad \bar{D} = \bar{d} + \bar{s}$$
$$u_v = U - \bar{U} \qquad d_v = D - \bar{D}$$
$$g$$

fitting in total 13 free parameters

$\alpha_s = 0.1185$ **fixed**

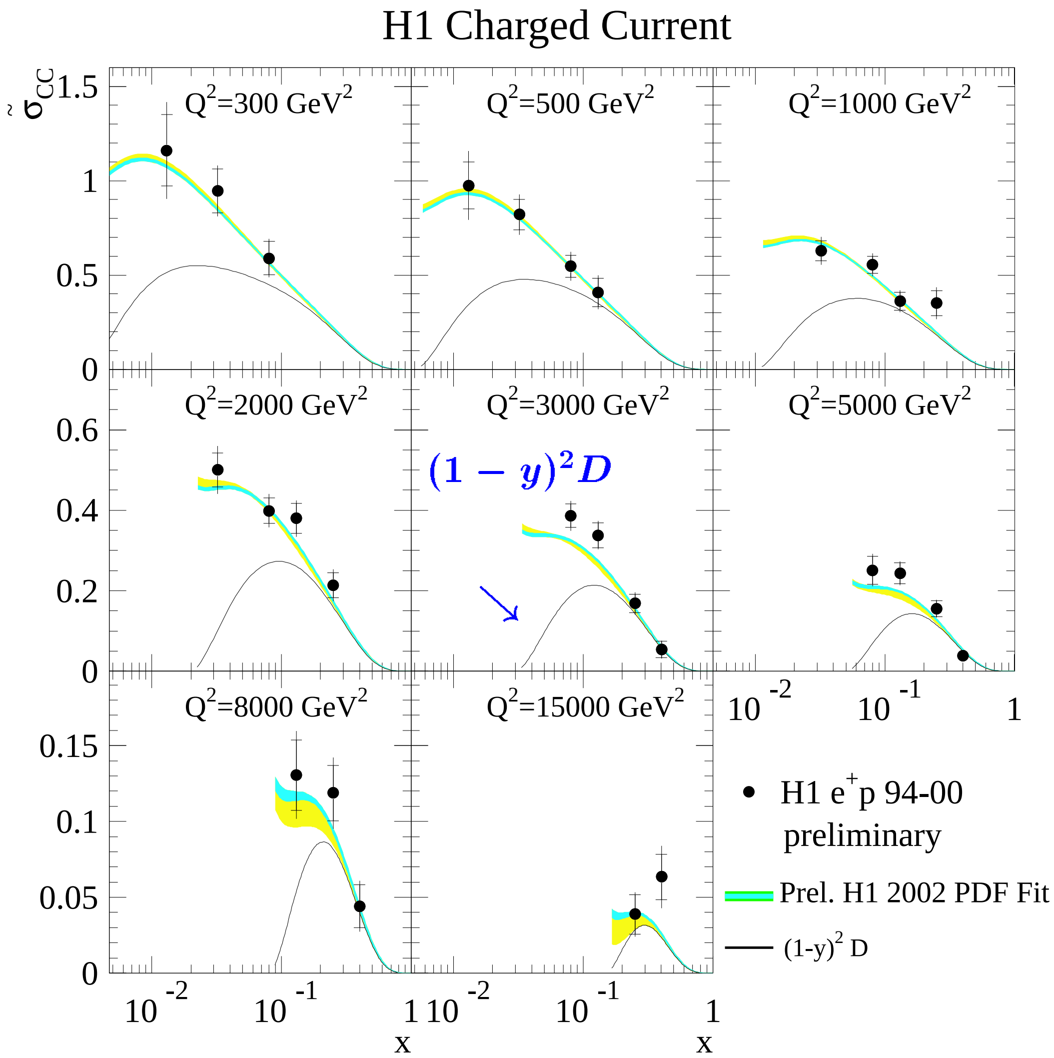
massless quarks

assuming $xb(x, Q^2)$ **for** $Q^2 < m_b^2$

H1-only fit is very consistent with fit including BCDMS for reduction of error bands at large x

Sensitivity to d quarks

distinguish u and d quarks at high x in CC



$e^+p \rightarrow \bar{\nu}_e X$

$$\sigma \sim x[(\bar{u}+\bar{c}) + (1-y)^2(d+s)]$$

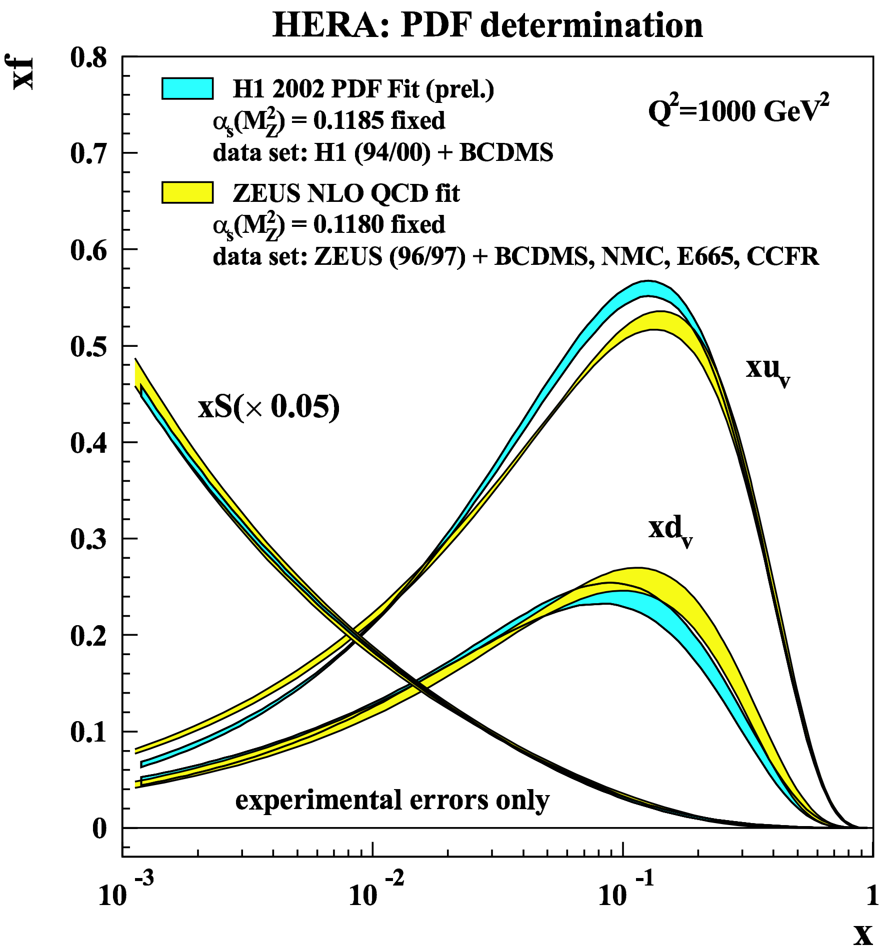
$e^-p \rightarrow \nu_e X$

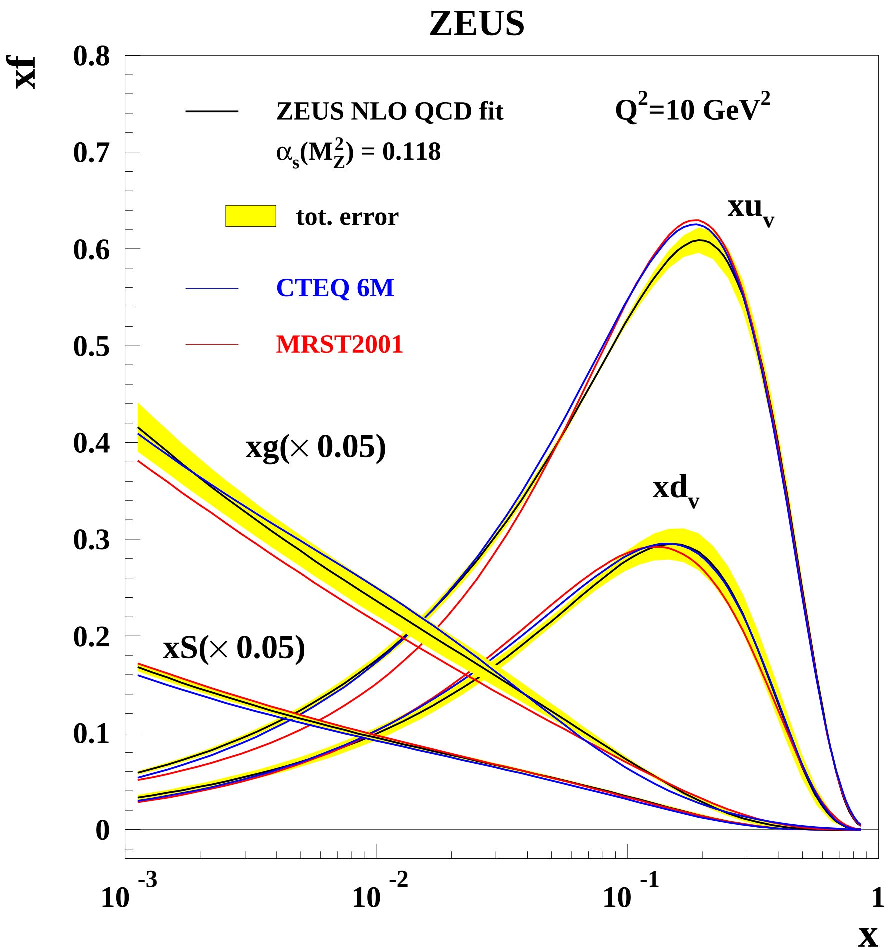
$$\sigma \sim x[(u+c) + (1-y)^2(\bar{d}+\bar{s})]$$

$(1-y)^2 D$ **dominates at $x \gtrsim 0.1$**

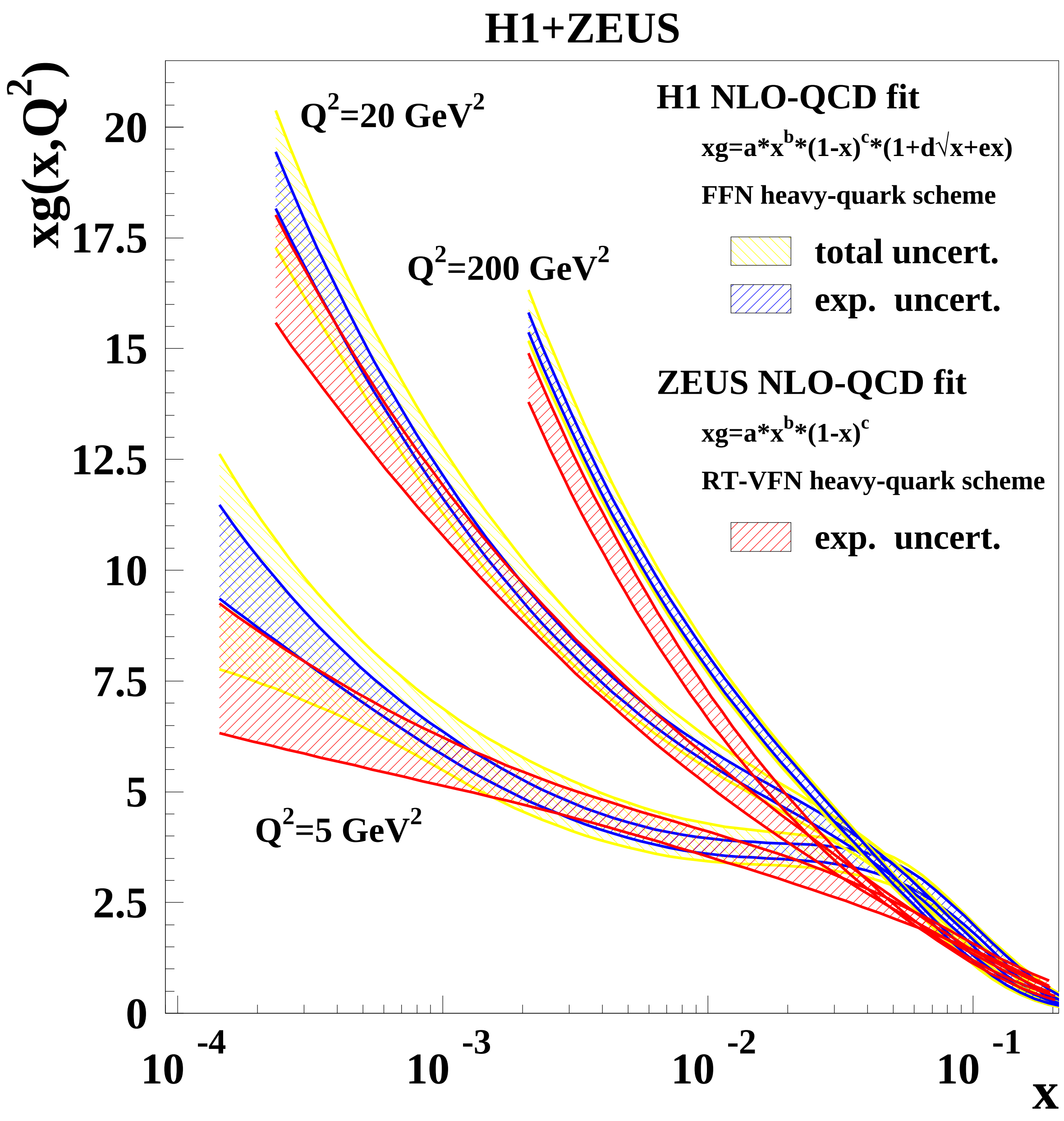
HERA data begin to constrain d quark without nuclear corrections

Comparison of different fits





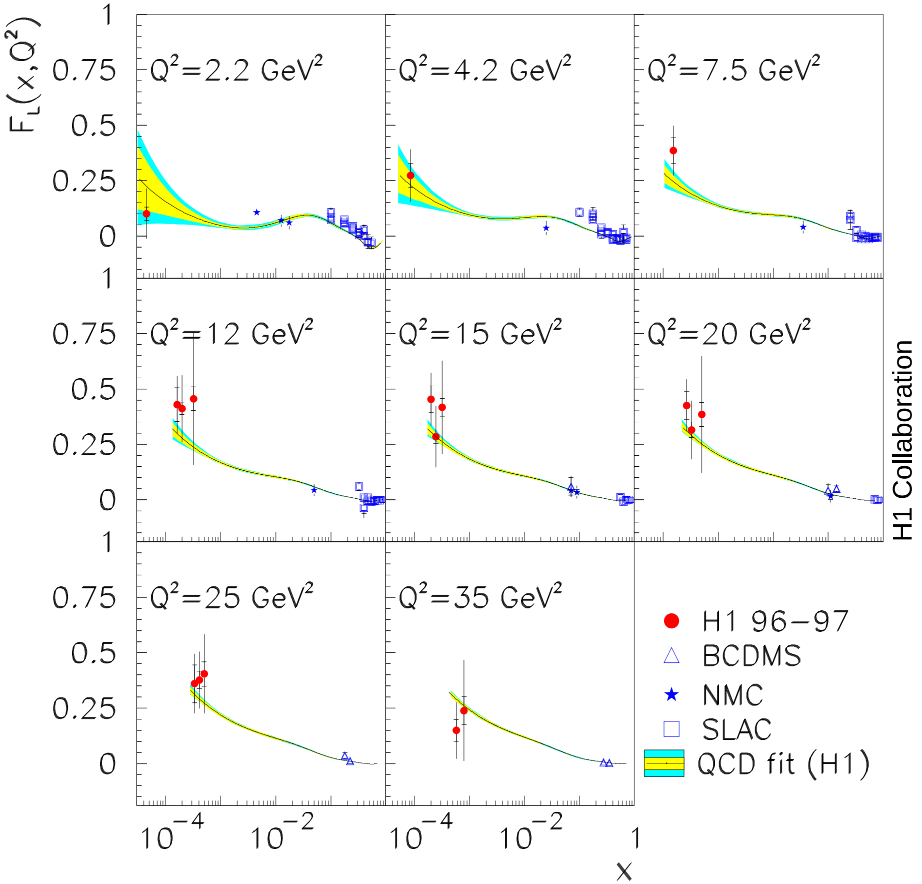
pdfs from inclusive DIS fits by ZEUS and H1 in reasonable agreement among themselves and with global fits



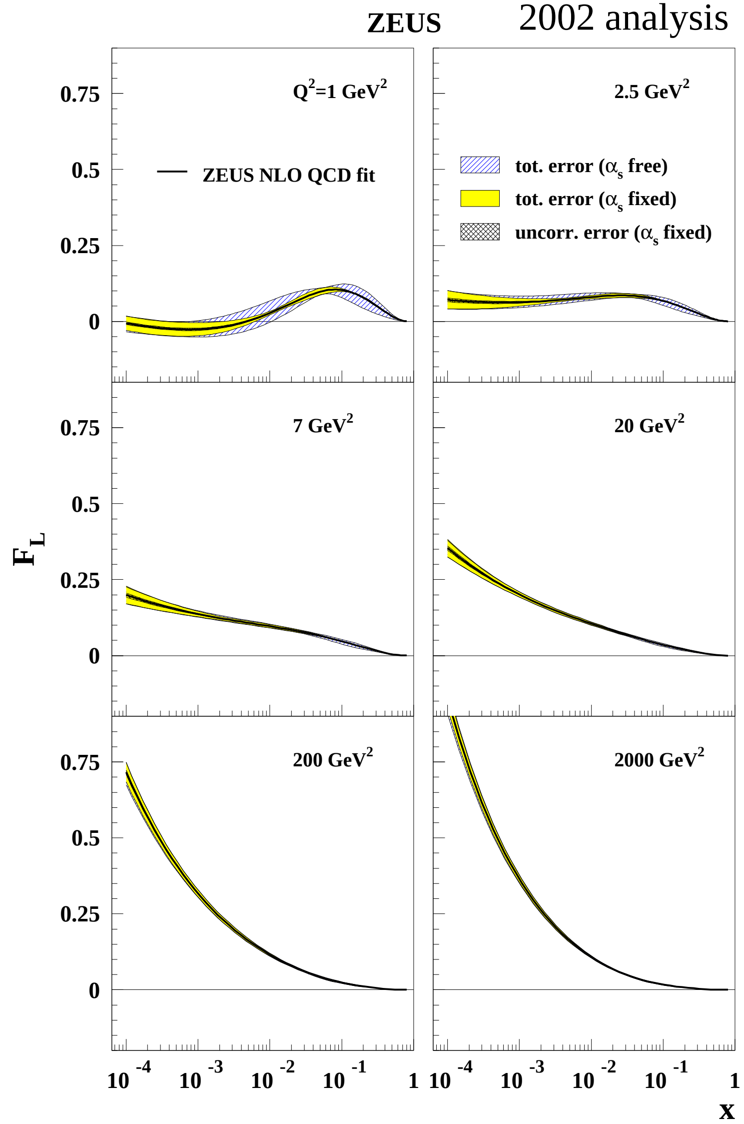
H1+ZEUS
xg(x,Q^2)
Q^2=20 GeV^2
Q^2=200 GeV^2
Q^2=5 GeV^2
H1 NLO-QCD fit
xg=a*x^b*(1-x)^c*(1+d√x+ex)
FFN heavy-quark scheme
total uncert.
exp. uncert.
ZEUS NLO-QCD fit
xg=a*x^b*(1-x)^c
RT-VFN heavy-quark scheme
exp. uncert.
0
2.5
5
7.5
10
12.5
15
17.5
20
10^-4
10^-3
10^-2
10^-1
x

F_L determinations and predictions

H1 2000 analysis



ZEUS 2002 analysis



at small x $F_L \sim \alpha_s x g(x)$ (approx.)

H1 determinations consistent with pQCD expectation

More data desirable, important consistency check

α_s

In central H1 and ZEUS fits $\alpha_s(M_Z^2)$ is fixed

Special fits with $\alpha_s(M_Z^2)$ as free parameter yield

H1 analysis 2000

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

ZEUS analysis

$$\alpha_s(M_Z^2) = 0.1166 \pm 0.0008(\text{uncorr.}) \pm 0.0032(\text{corr.}) \pm 0.0036(\text{norm.}) \pm 0.0018(\text{model})$$

uncorr. systematics **corr. systematics** **normalisation of exps.**

world average (PDG 2000) : $\alpha_s(M_Z^2) = 0.1185 \pm 0.0020$

theoretical error:

splitting terms not yet available in next to NLO for inclusive DIS

uncertainty of $\approx \pm 0.005$ estimated by change of renormalisation scale by factor 4

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results consistent and very competitive

will improve with NNLO

The Rise of F_2 towards low X

strong rise of F_2 since long discussed in QCD frame:

1974: (De Rujula, Glashow, Politzer, Treiman, Wilczek, Zee) **2000**

(1994: (Ball, Forte))

double asymptotic limit: rise faster

than any power of $\log(x)$, nearly like power in x.

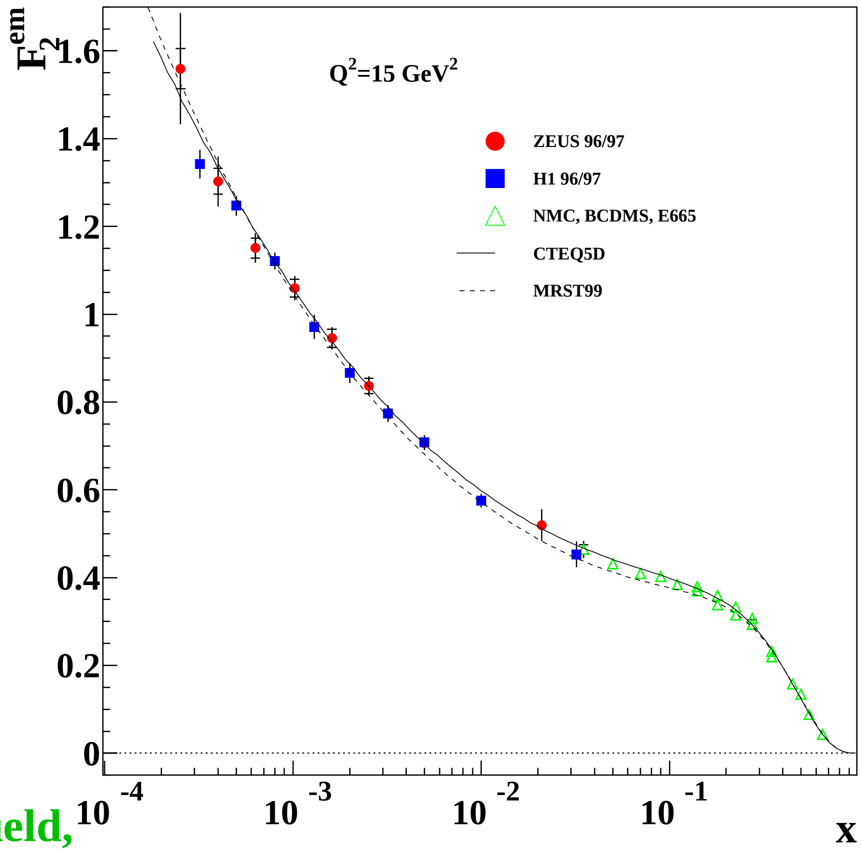
1976 - 1978 (Balitsky, Fadin, Kuraev, Lipatov)

BFKL theory expects power behaviour $F_2 \sim x^{-\lambda}$

1981, 1983 (Gribov, Levin, Ryskin)

1986 (Mueller, Qiu)

saturation effects due to increasing gluon densities



Recent years (Buchmüller, Gehrmann, Hebecker ;

Golec-Biernat, Wüsthoff ;......)

discussion of colour dipole models

$\gamma^* \rightarrow q\bar{q}, q\bar{q}g \quad \times$ **dipole-p cross section**

non-perturbative interaction with proton colour field,

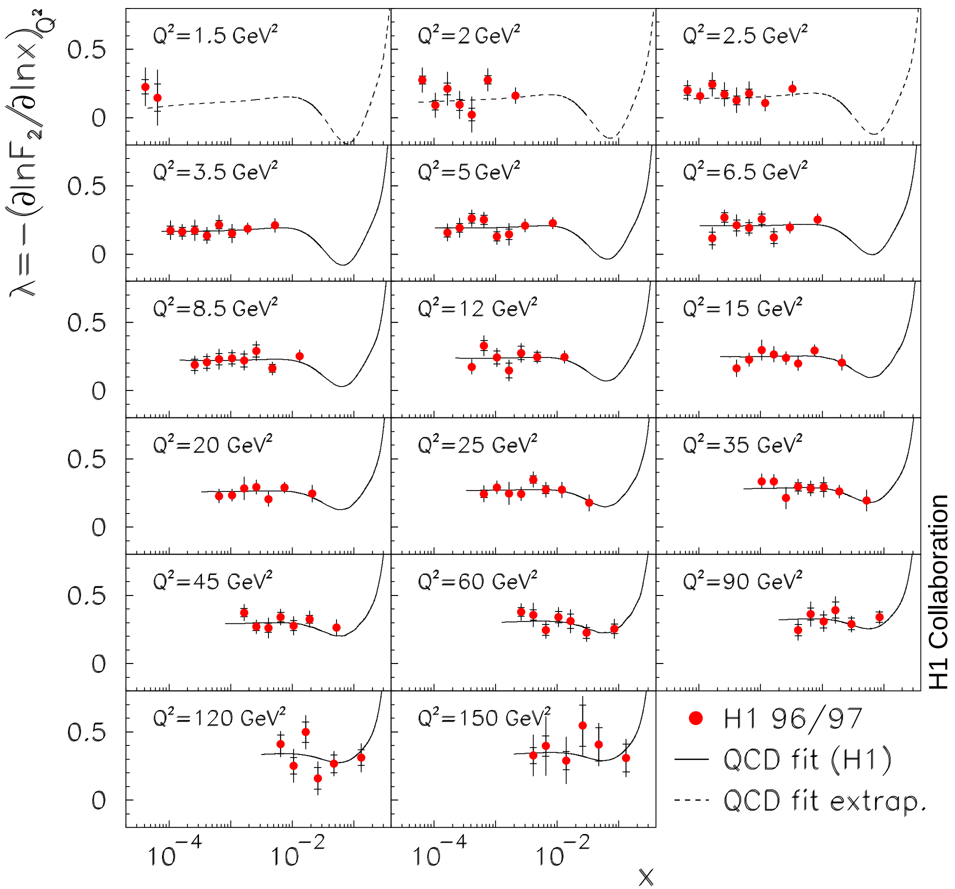
saturation at large radii, i.e. small Q^2, p_t^2 ,

reached at smaller x_{Bj} already at smaller radii, i.e. at larger Q^2, p_t^2.

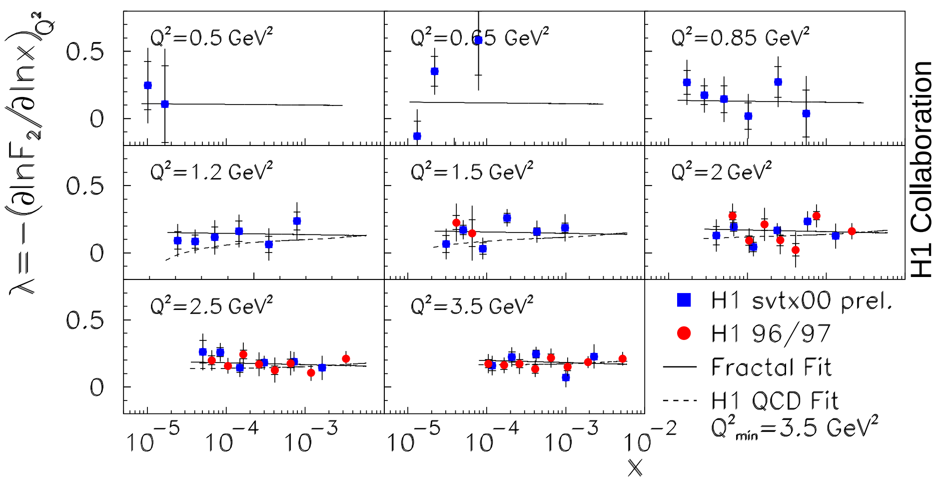
Precision of present data allows to study rise of F_2 locally

x dependence of $\lambda = -(\partial \ln F_2 / \partial \ln x)_{Q^2}$

nominal vertex data



shifted vertex data (+ nominal)

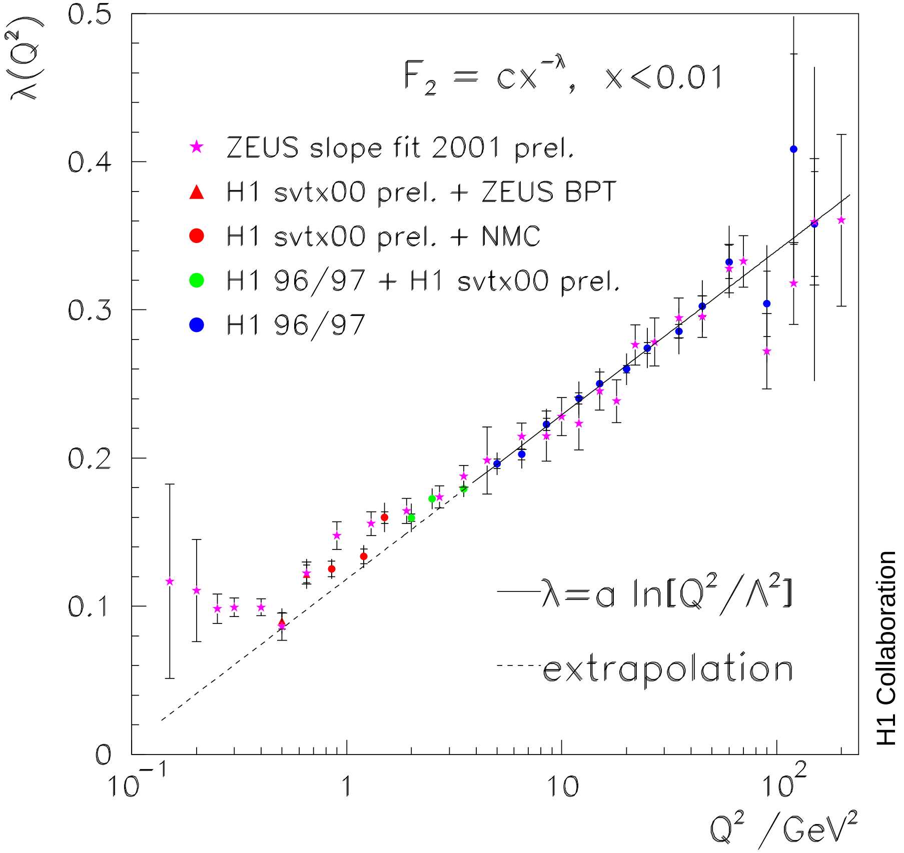


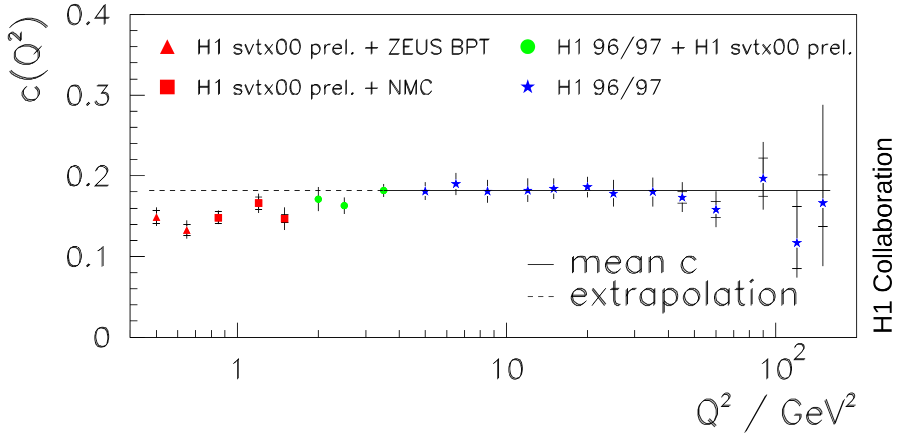
fixed Q^2, $x < 0.01$: $\lambda \approx$ const

$\Rightarrow F_2 = c(Q^2) \cdot x^{-\lambda(Q^2)}$

no taming of rise visible yet for $0.5 \lesssim Q^2 \lesssim 150$ GeV^2

Transition to small Q^2 H1 combined with NMC and ZEUS





for $Q^2 \lesssim 3$ GeV^2 :

deviation from log-dependence,

decrease of c

$$\sigma_{tot}^{\gamma^* p} = 4\pi\alpha^2/Q^2 \; F_2 \; \sim x^{-\lambda}/Q^2$$
$$s = W^2 \sim Q^2/x$$

Hadronic interactions at high energy:

Regge theory: $\sigma_{tot} \sim s^{\alpha_{I\!P}(0)-1}$

$\alpha_{I\!P}(0) - 1 \approx 0.08$ (Donnachie, Landshoff)

$\rightarrow$ expect

$F_2 \sim x^{-(\alpha_{I\!P}(0)-1)} \approx x^{-0.08}$, $\lambda \approx 0.08$

$Q^2 \lesssim 1$ GeV^2 :

rise compatible with soft hadronic interactions

Conclusions

- **Data on inclusive $e^{+-}p$ scattering much improved in recent years**
- **High Q^2 NC and CC interactions consistent with QCD and EW expectations**
- **pQCD fits, based on DGLAP evolution of pdfs describe data very well**
- **pdfs with uncertainties given and high precision α_s determined**
- **at $x \lesssim 0.01$ data consistent with $F_2 \sim x^{-\lambda}$, no damping of rise yet visible**
- **at low Q^2 ($Q^2 \lesssim 1$ GeV^2) rise similar as in soft hadronic interactions**