QCD at HERA

Günter Grindhammer, MPI Munich

on behalf of the **H1** and **ZEUS** collaborations

Inclusive DIS measurements: F_2

Gluon, valence, sea and $\alpha_s(M_Z)$

Gluon and charm

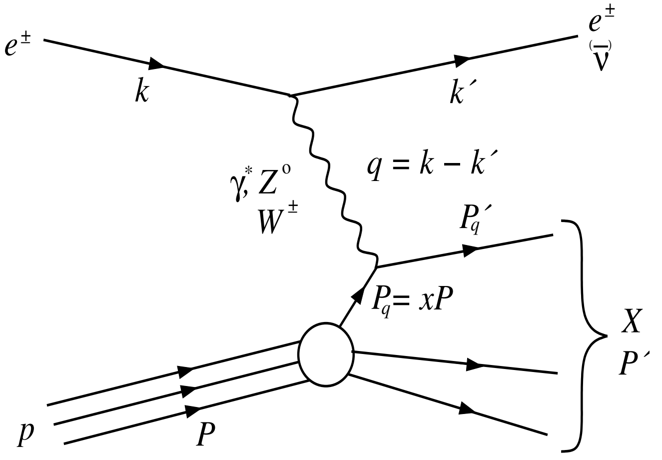
The low x region

$\alpha_s(M_Z)$ from jets

Low-x parton dynamics

Summary

Deep-Inelastic Scattering



$Q^2 = -(k-k')^2$	virtuality of γ^*, Z^0, $W^\pm$
$x = Q^2/2(pq)$	Bjorken scaling variable
$y = (Pq)/(pk)$	inelasticity

$Q^2 = xys$, $\sqrt{s} \approx 320$ GeV at HERA
$W^2 = (P+q)^2 = Q^2(1/x - 1)$ hadronic cms energy squared

Neutral Current: γ^*, Z° exchange

$$\frac{d^2\sigma_{NC}^{e^\pm p}}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}[Y_+\tilde{F}_2(x,Q^2) \mp Y_- x\tilde{F}_3(x,Q^2) - y^2\tilde{F}_L(x,Q^2)],\ Y_\pm = 1 \pm (1-y)^2$$

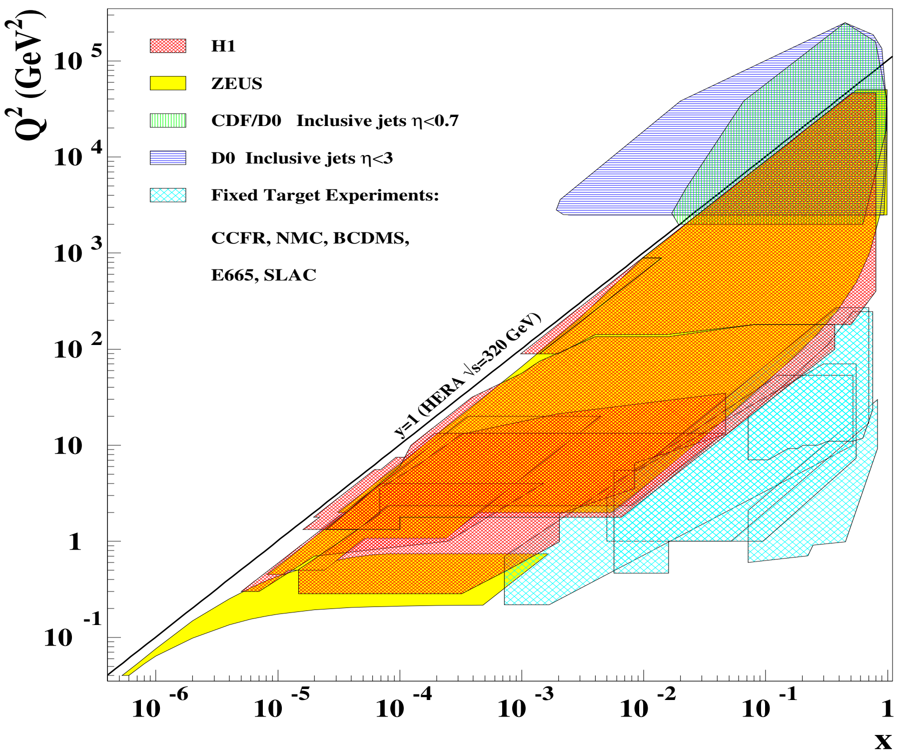
QPM: $F_2 = x\sum e_q^2(q+\bar{q}),\ xF_3 = 2x\sum e_q a_q(q-\bar{q}),\ F_L = 0$

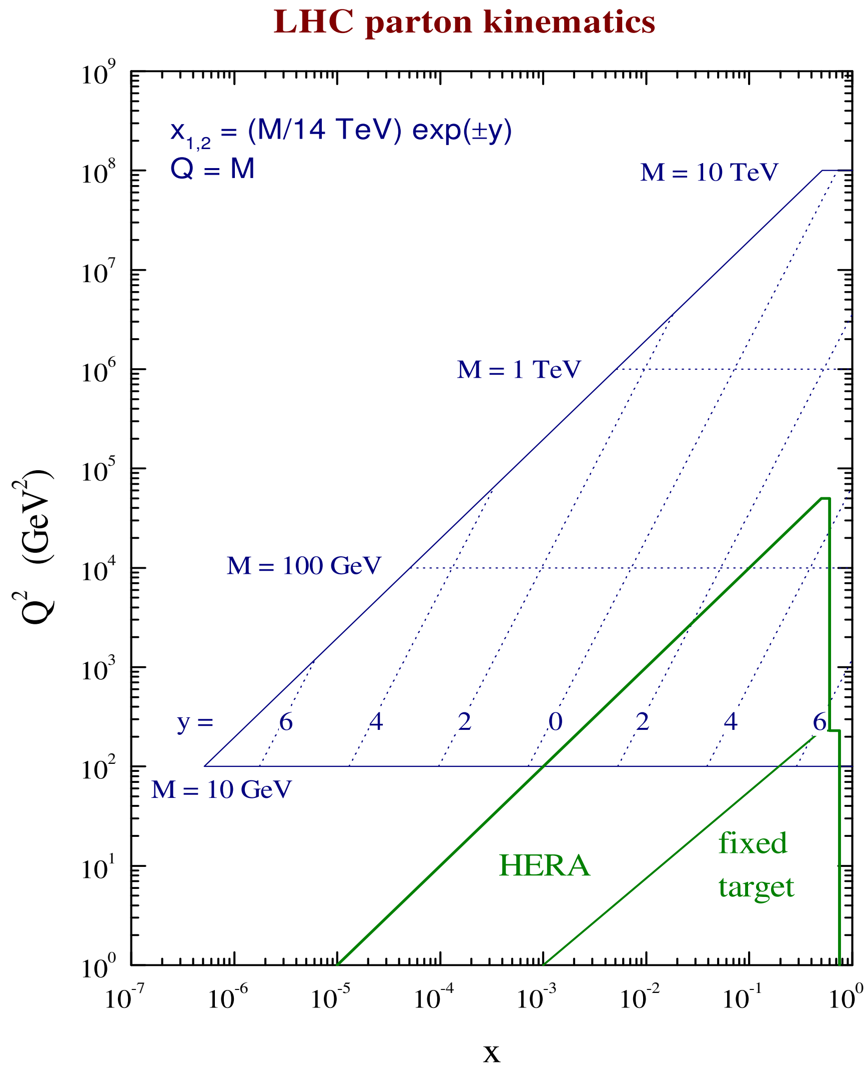
Charged Current: $W^\pm$ exchange

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

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

Kinematic Reach: Yesterday, Today and Tomorrow

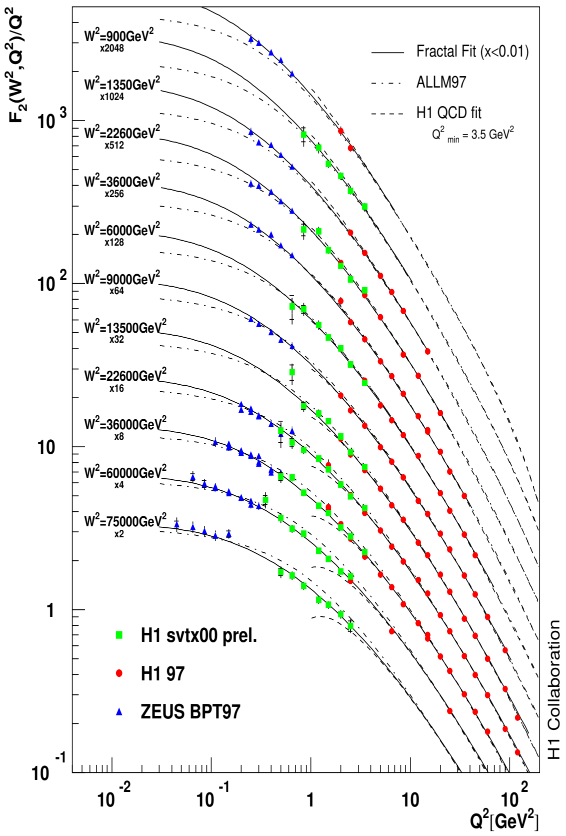


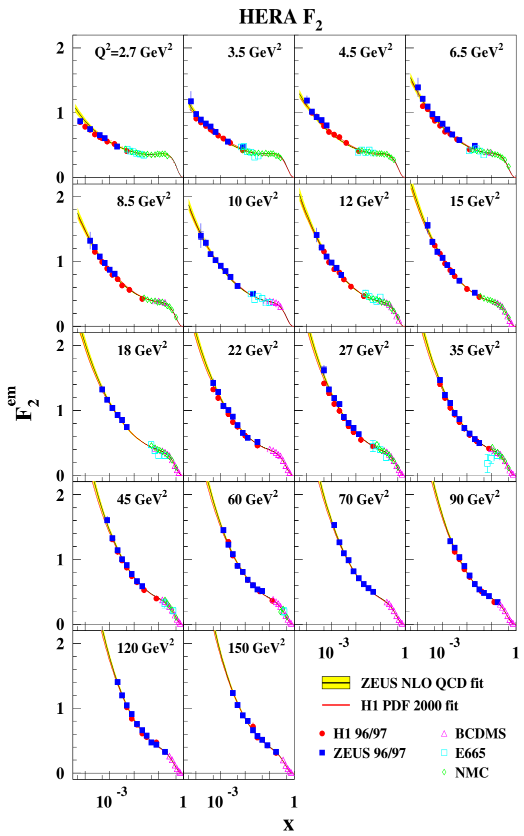


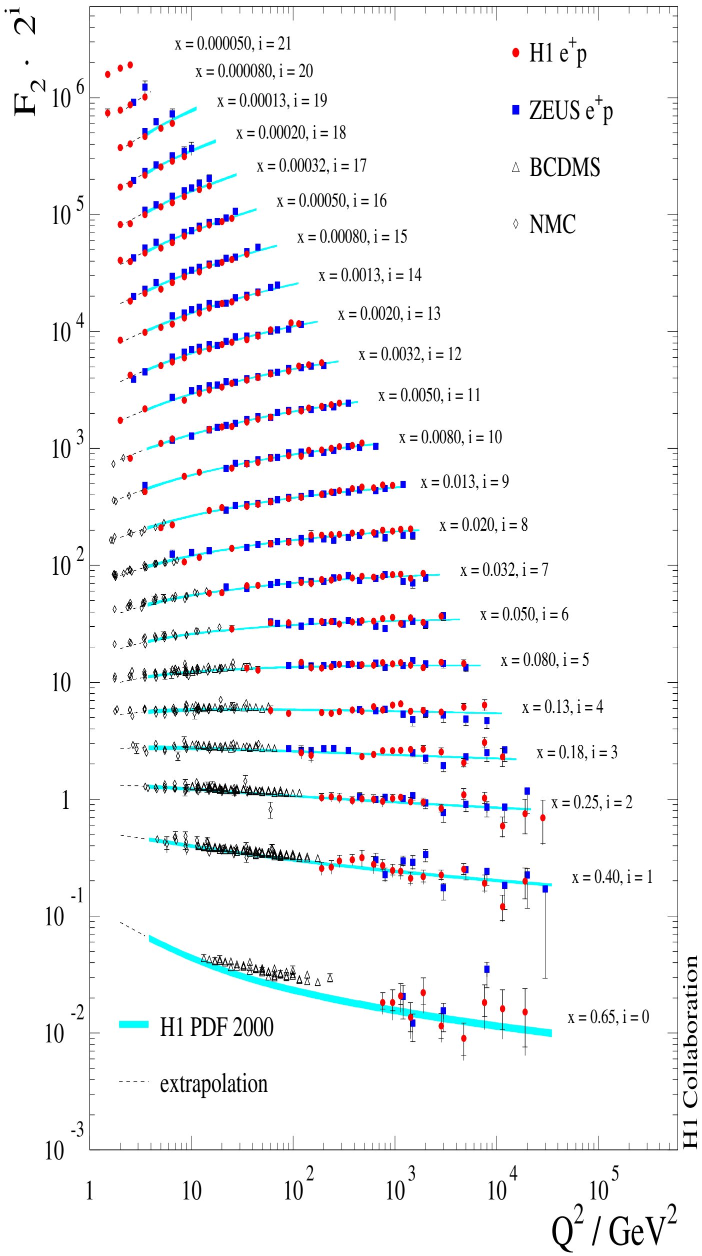
Q^2, $\ln\frac{1}{x}$ large	QCD evolution DGLAP, BFKL $xg(x, Q^2)$ and α_s
$x \rightarrow 0$	saturation ?
$Q^2 \rightarrow s$	electroweak physics
$x \rightarrow 1$	probe valence quarks

full x-range of HERA needed for the LHC

F_2 vs. x and Q^2



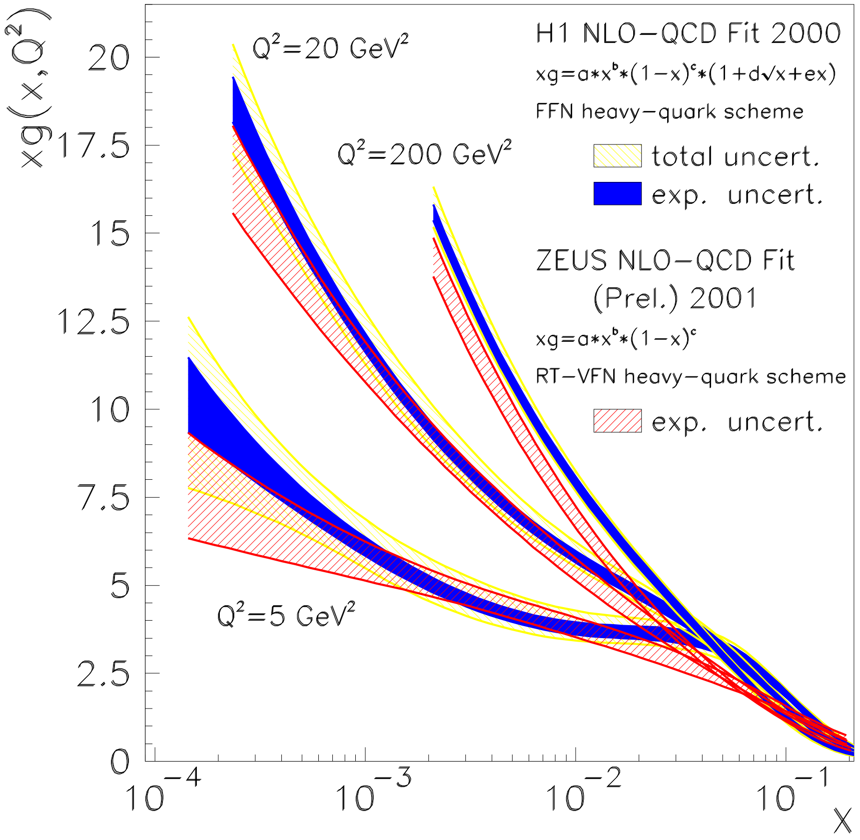


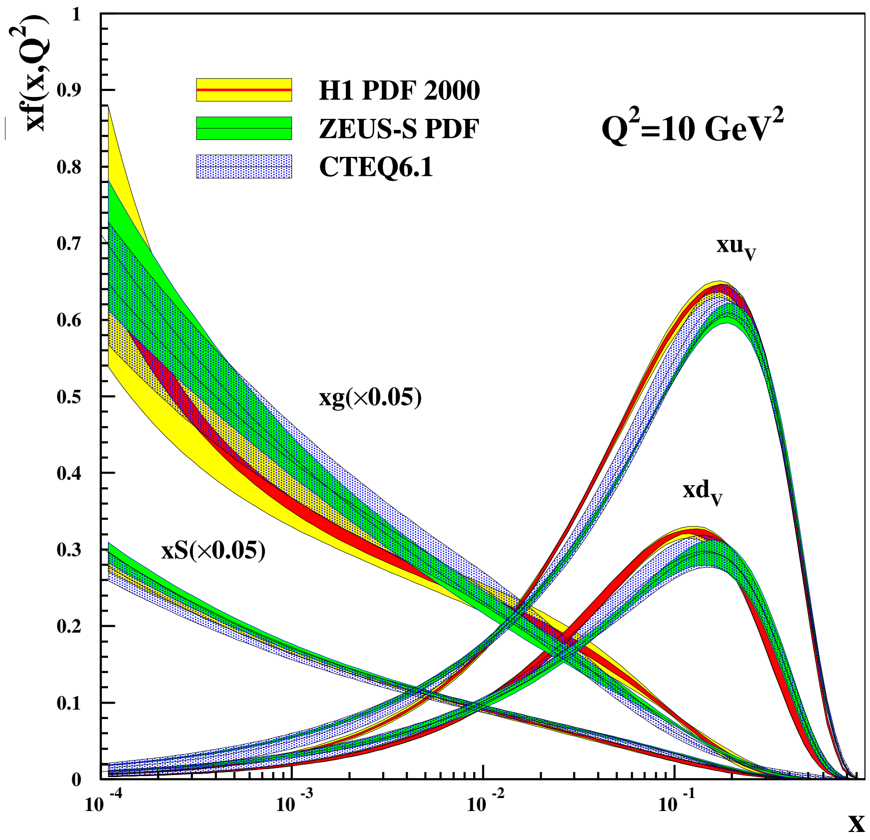


Rich and precise data for testing QCD:

- Transition from DIS to γp
- Rise of F_2 towards low x
- Scaling violations

Gluon, Valence and Sea Distributions

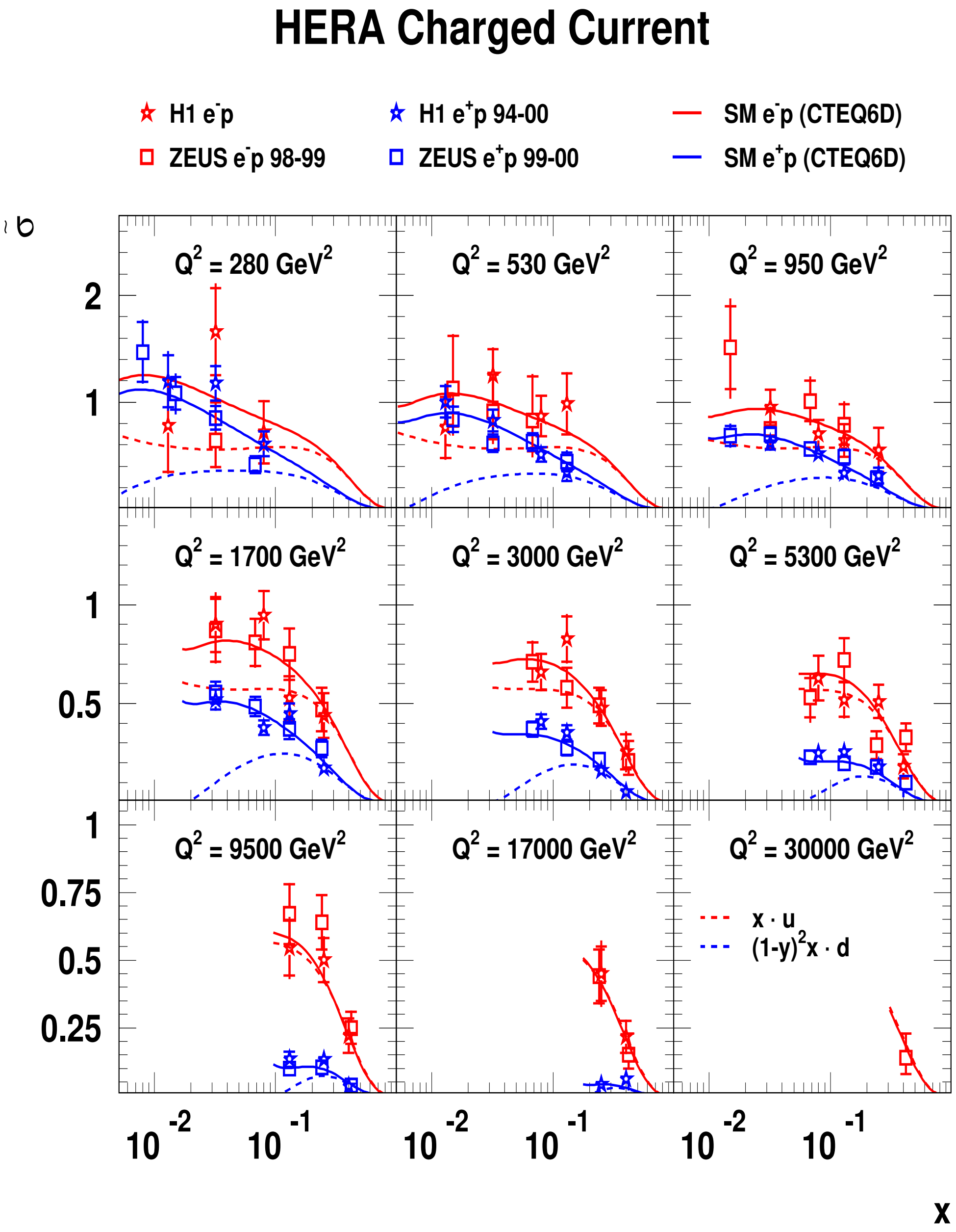




Differences and remaining uncertainties are due to:

- different assumptions
- parametric form of PDFs
- heavy flavor treatment
- consistency of data sets
- NNLO terms

CC at high Q^2: Valence Distributions



CC: e^+p and e^-p

- e^+p dominated by d at large x
- e^-p dominated by u at large x
- $e^{\pm}p$ CC and NC essential for flavor separation of PDFs

$\alpha_s(M_Z)$ from QCD fits

NLO

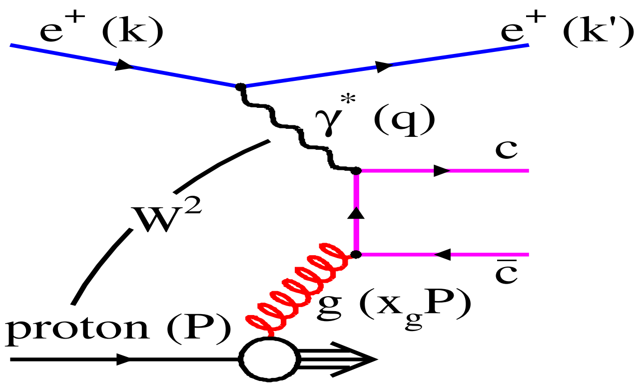
H1	$\alpha_s(M_Z) = 0.1150 \pm 0.0017\ (exp)$ $^{+\,0.0009}_{-\,0.0005}\ (model) \pm 0.005\ (theory)$
ZEUS	$\alpha_s(M_Z) = 0.1166 \pm 0.0008\ (uncor) \pm 0.0032\ (cor) \pm 0.0036\ (norm)$ $\pm 0.0018\ (model) \pm 0.004\ (theory)$
Alekhin	$\alpha_s(M_Z) = 0.1171 \pm 0.0015\ (exp) \pm 0.0033\ (theory)$

"NNLO"

Alekhin	$\alpha_s(M_Z) = 0.1143 \pm 0.0014\ (exp) \pm 0.0013\ (theory)$

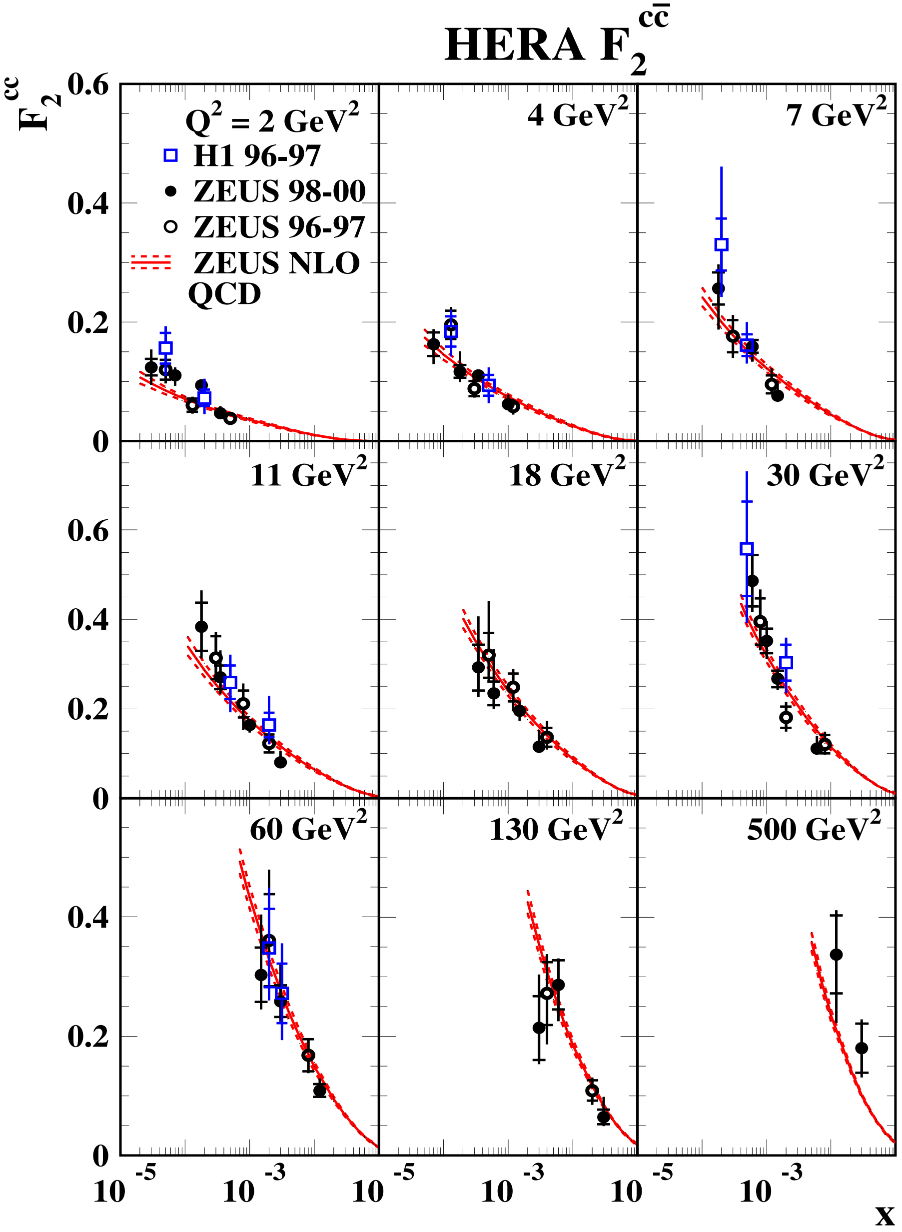
- H1 QCD fit includes BCDMS ($\mu p, y > 0.3$) data only
- ZEUS QCD fit includes BCDMS, NMC, E665, CCFR data
- consistent $\alpha_s(M_Z)$ values
- theory uncertainty (and value of $\alpha_s(M_Z)$) much reduced in "NNLO"

Gluon and Open Charm Production

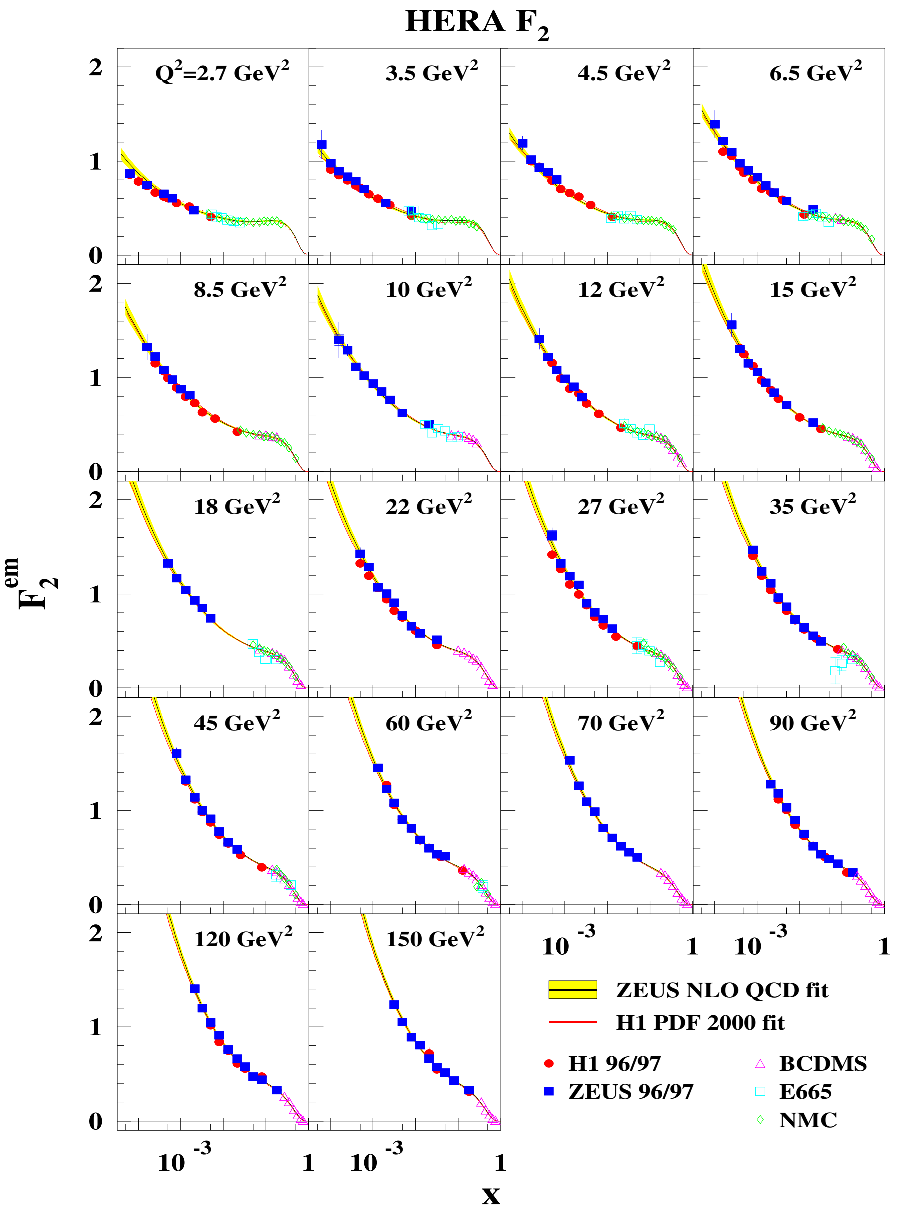


charm $\rightarrow D^* \rightarrow D^\circ\pi \rightarrow K\pi\pi$

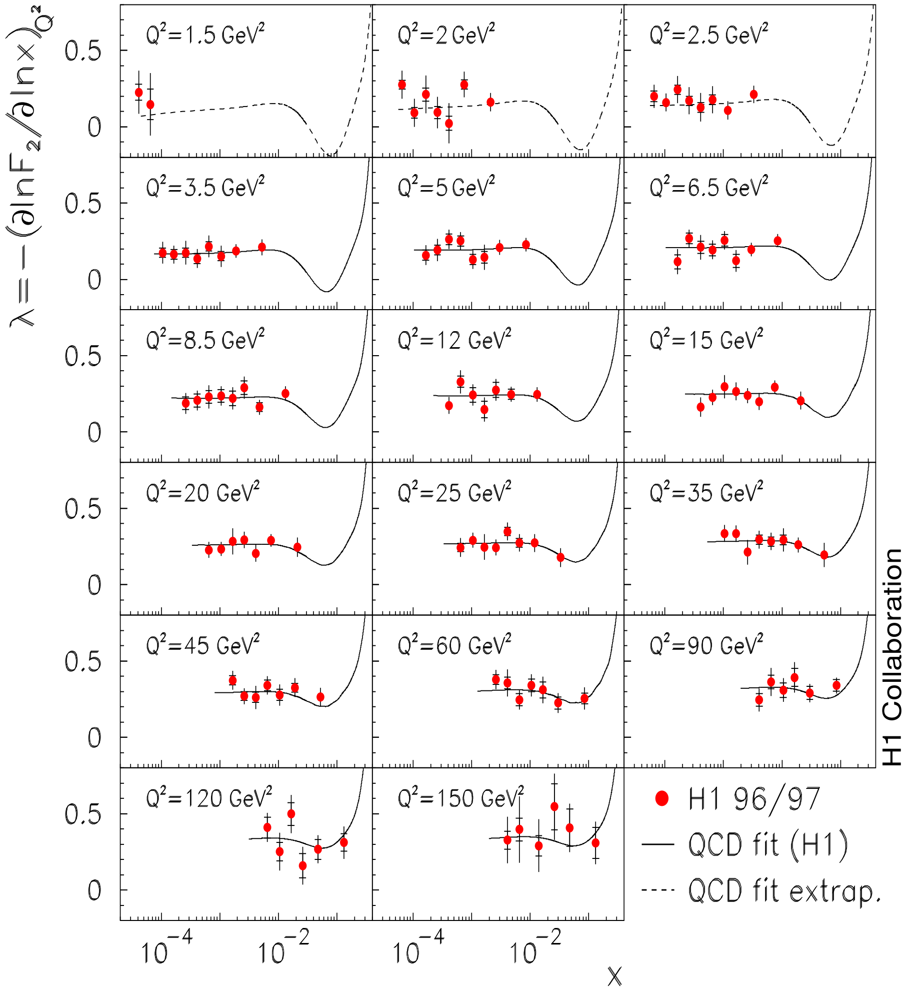
- scaling violations from F_2 and from charm agree
- $F_2^{c\bar{c}}/F_2 \approx 30\%$ at low x $\rightarrow$ treatment of charm in evolution important



Rise of F_2 at low x

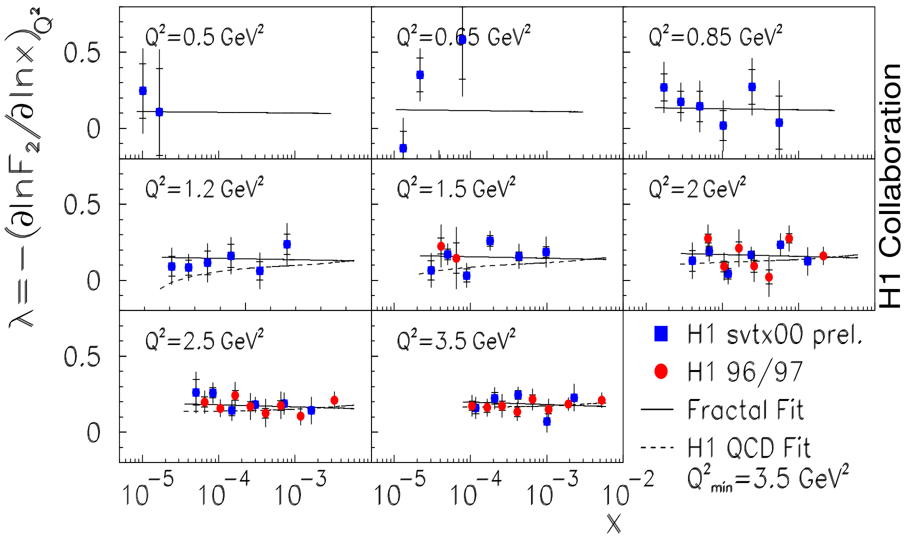


Rise of F_2 at low $x \longrightarrow (\partial F_2/\partial \ln x)_{Q^2}$



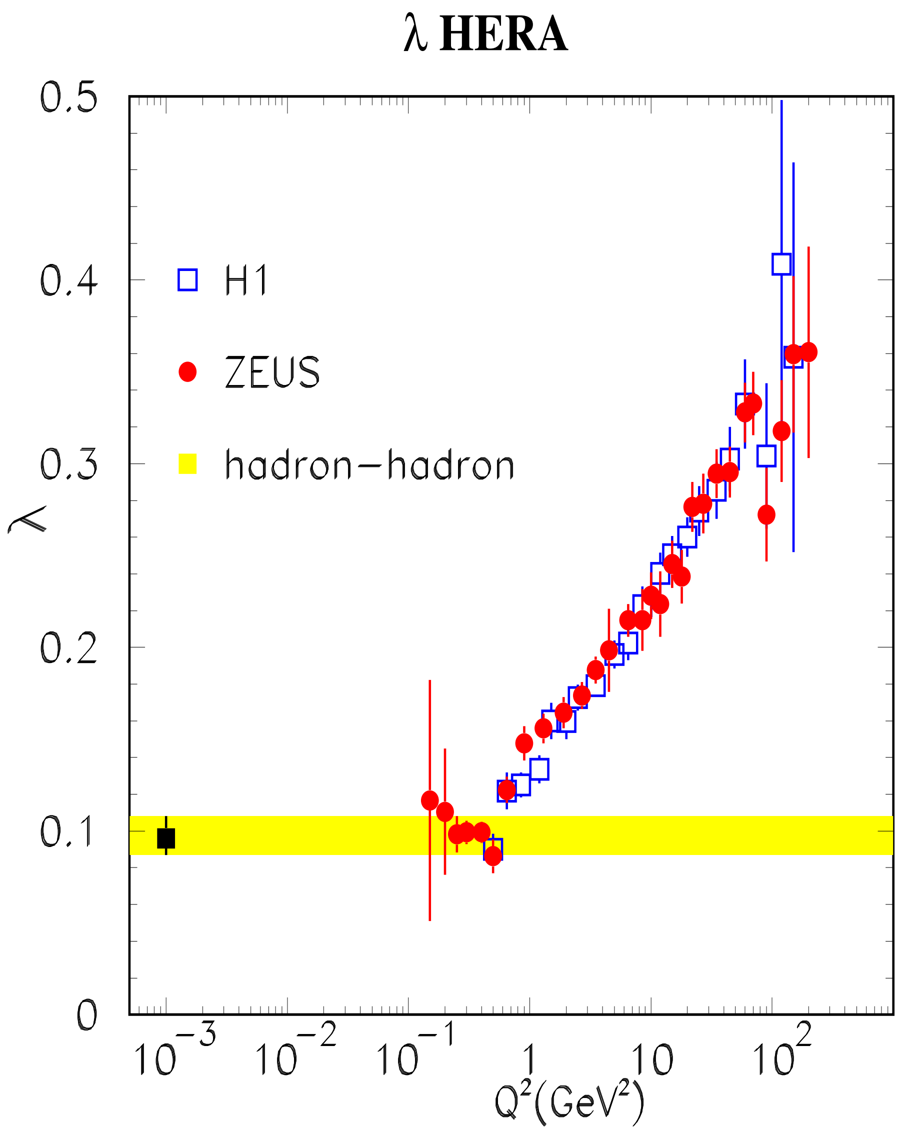
Study rise of F_2 locally

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



- $\lambda \approx$ const. at fixed Q^2 $(x < 0.01)$
- no change of dynamics observed at low x

Rise of F_2: $\lambda(Q^2)$

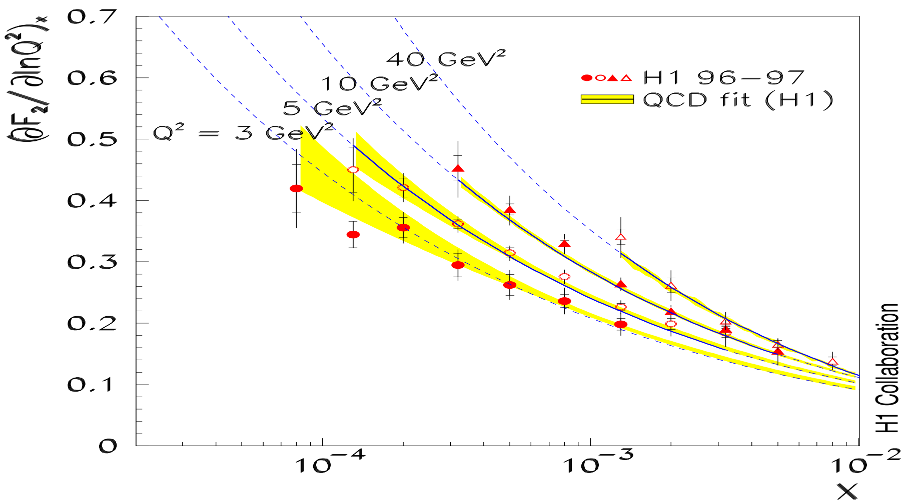


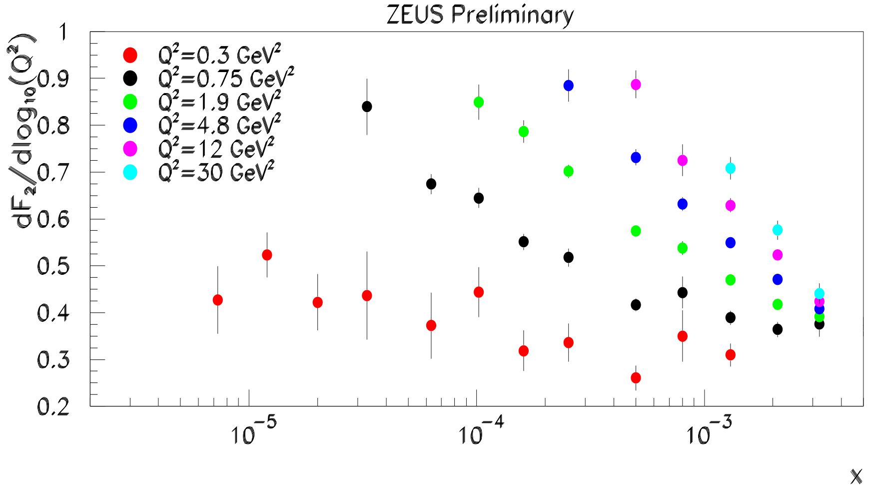
$\lambda(Q^2)$ from the fit to

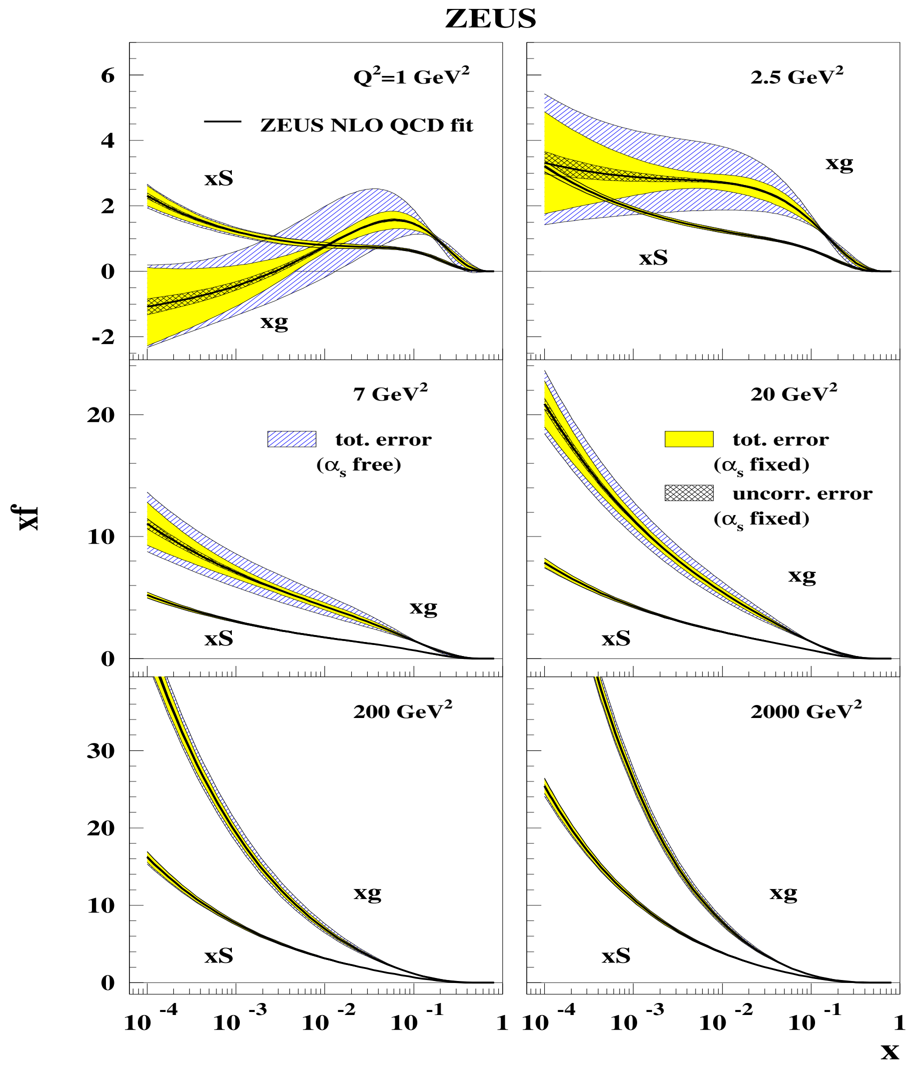
$$F_2(x, Q^2) = c(Q^2)\, x^{-\lambda(Q^2)}$$

- $\lambda(Q^2) \propto \ln Q^2$
- $\sigma_{NC} \propto W^{2\lambda}$
- change of behavior at $Q^2 \approx 0.5$ GeV^2
- soft Pomeron limit $\lambda \approx 0.09$ from energy dependence of hadron-hadron total cross sections

Gluon at low $x \longrightarrow (\partial F_2/\partial \ln Q^2)_x$



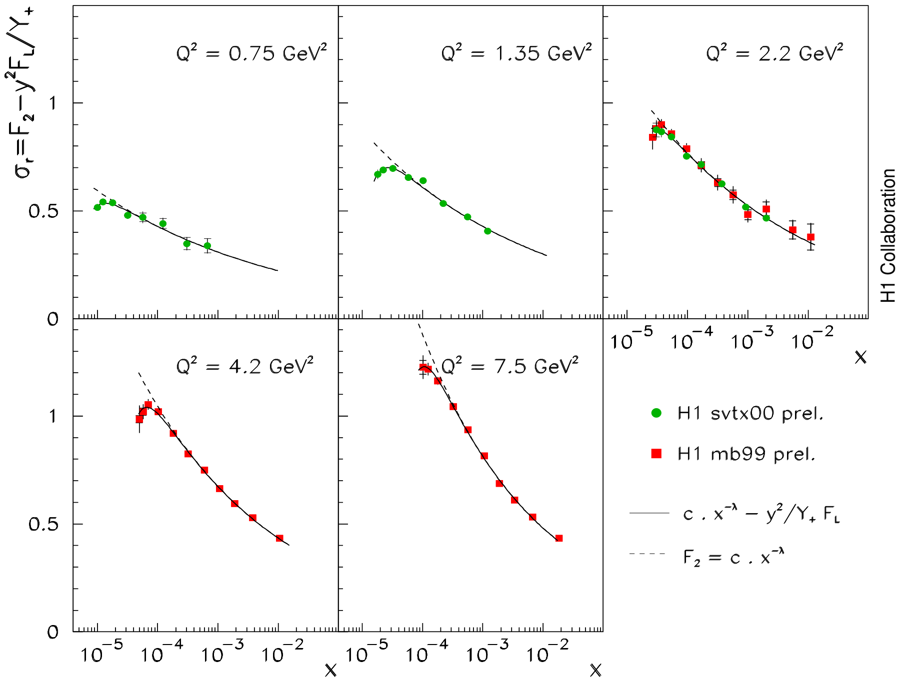




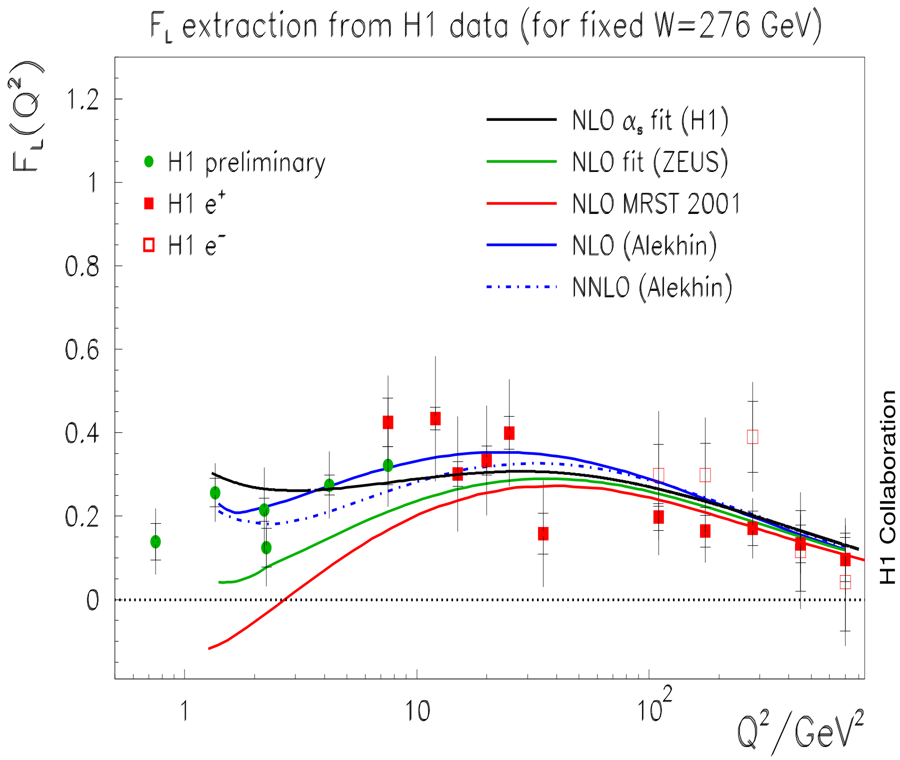
- data continues to rise towards low x
- consistent with QCD fit ($Q^2 \geq 3$ GeV^2)
- no obvious sign of saturation

however, negative gluon at low x , Q^2
$\longrightarrow F_L$

$F_L(x, Q^2)$

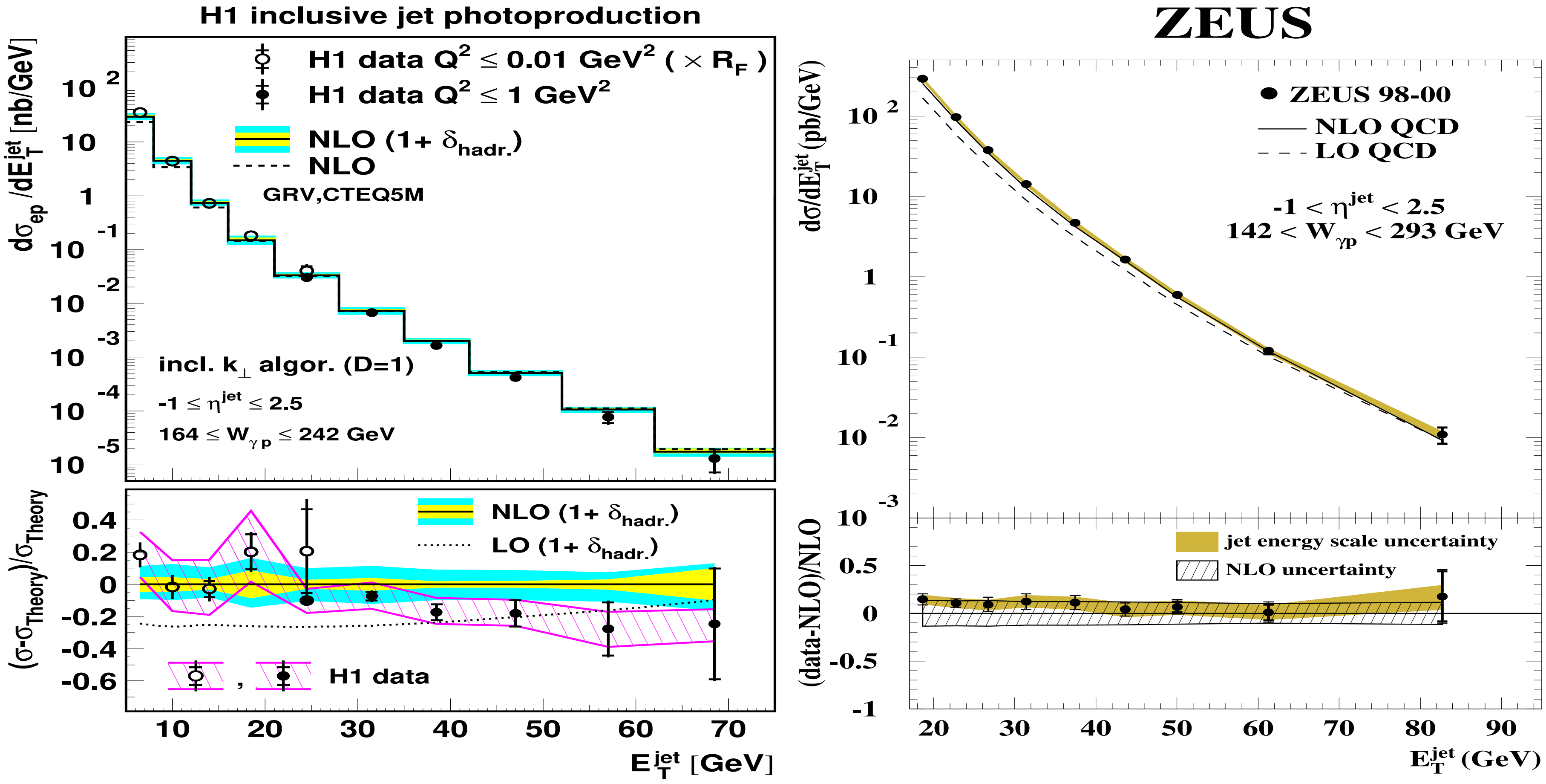


- $F_L \propto \sigma_L^{\gamma^* p} = 0$ in QPM
- $F_L \propto \sigma_L^{\gamma^* p} \neq 0$ in QCD
- $F_L = Y_+/y^2\,(F_2^{\mathrm{QCD-fit}} - \tilde{\sigma}_{NC})$



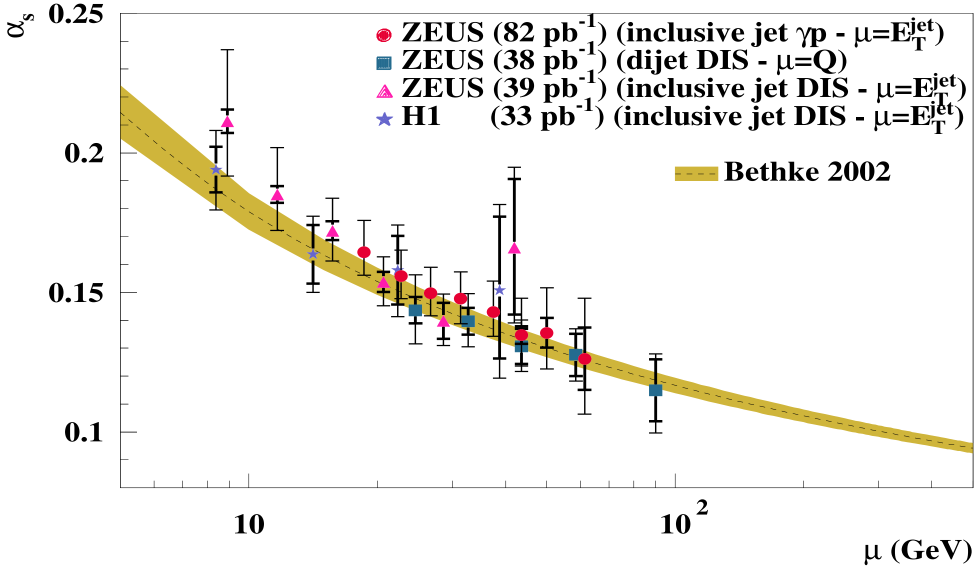
- $F_L \neq 0$
- F_L starts to discriminate predictions
- F_L measurement can be improved by varying s (proton energy)

Inclusive Jet Production in γp

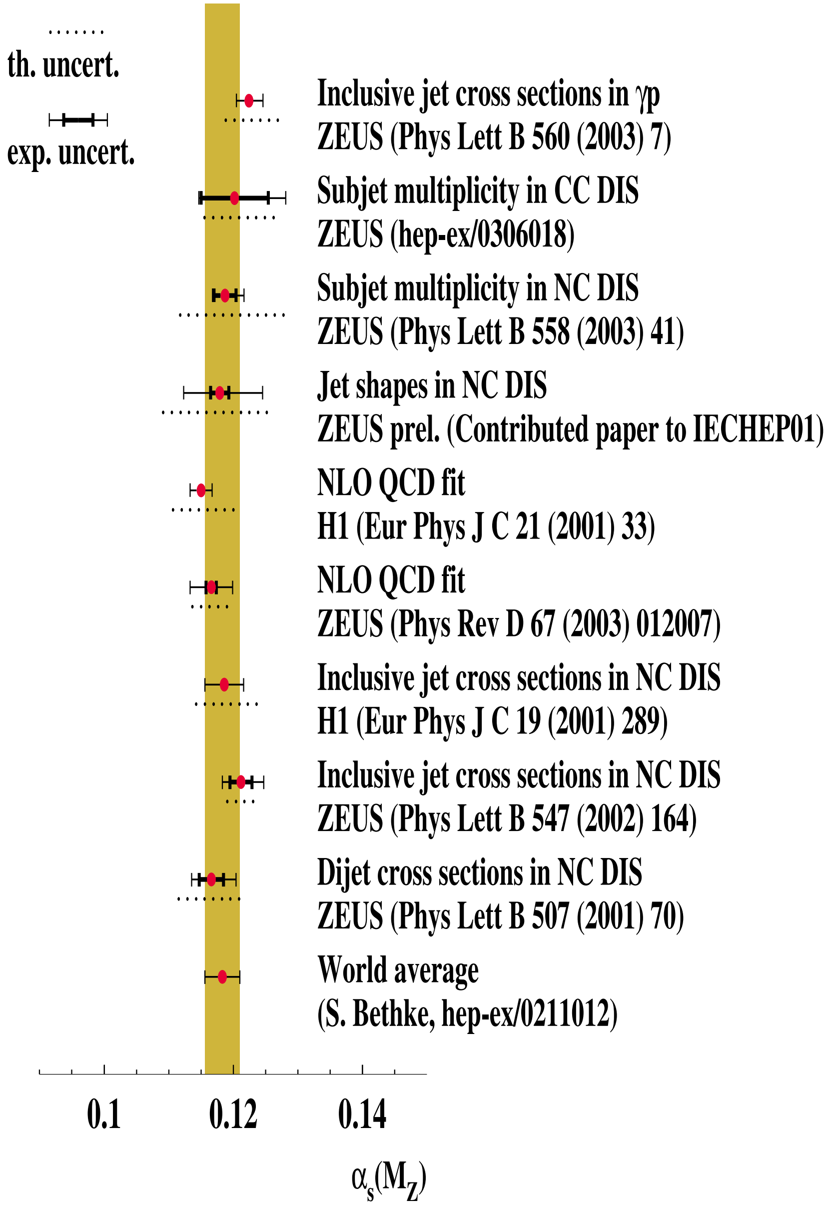


- Jets with $E_{\mathrm{T,jet}} > 5$ GeV (H1) and > 17 GeV (ZEUS)
- QCD in NLO describes data over 4 to 6 decades within exp. and theo. uncertainties $\Rightarrow$ extraction of α_s

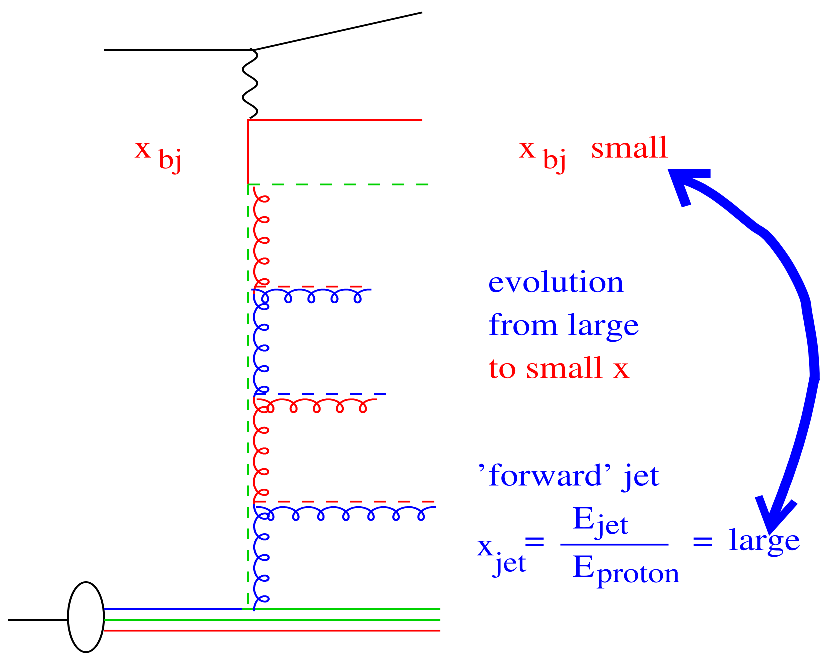
$\alpha_s(M_Z)$ at HERA from F_2 and Jets



- Bethke 2002: $\alpha_s(M_Z) = 0.1183 \pm 0.0027$
- good agreement between different measurements
- exp. uncertainties often smaller than theoretical ones
- NNLO calculations on the way



Forward Jets and Parton dynamics at low x

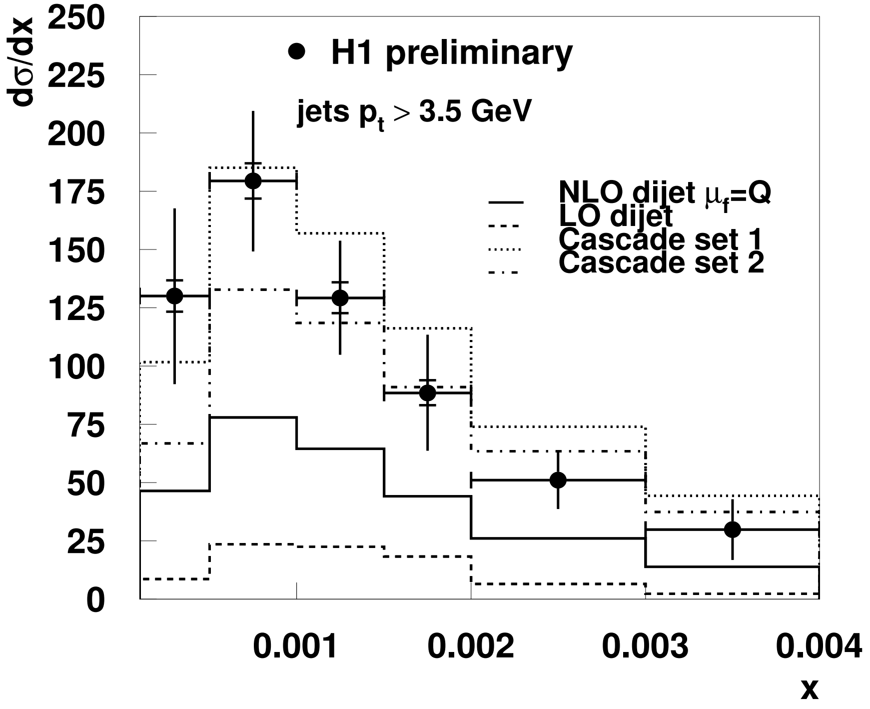


Different approximations for multi-parton emissions:

- DGLAP: ordered in p_t
- BFKL/CCFM: ordered in energy/angle

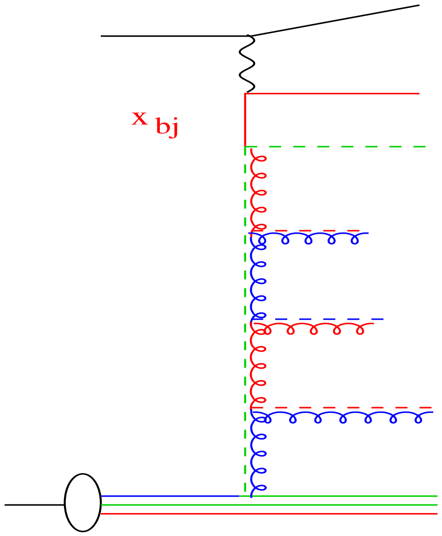
Mueller-Navelet: study forward jets $\Longrightarrow$
with $p_t^2 \approx Q^2$ and $x_{jet} >> x_{Bj}$
$\longrightarrow$ suppress DGLAP, enhance BFKL

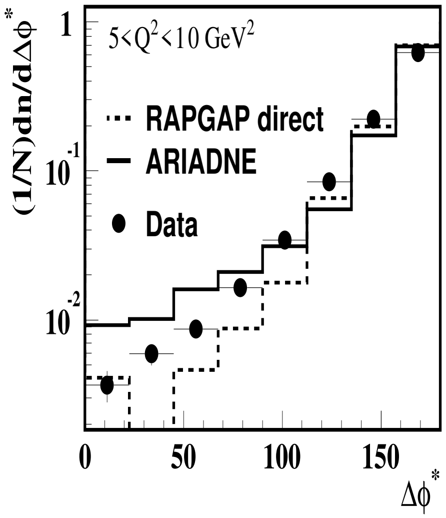
$5 < Q^2 < 75$ GeV^2
forward jet def. by incl. k_t algo.
$7^\circ < \theta_{jet} < 20^\circ$
$x_{jet} > 0.035$
$0.5 < p^2_{t,jet}/Q^2 < 2$



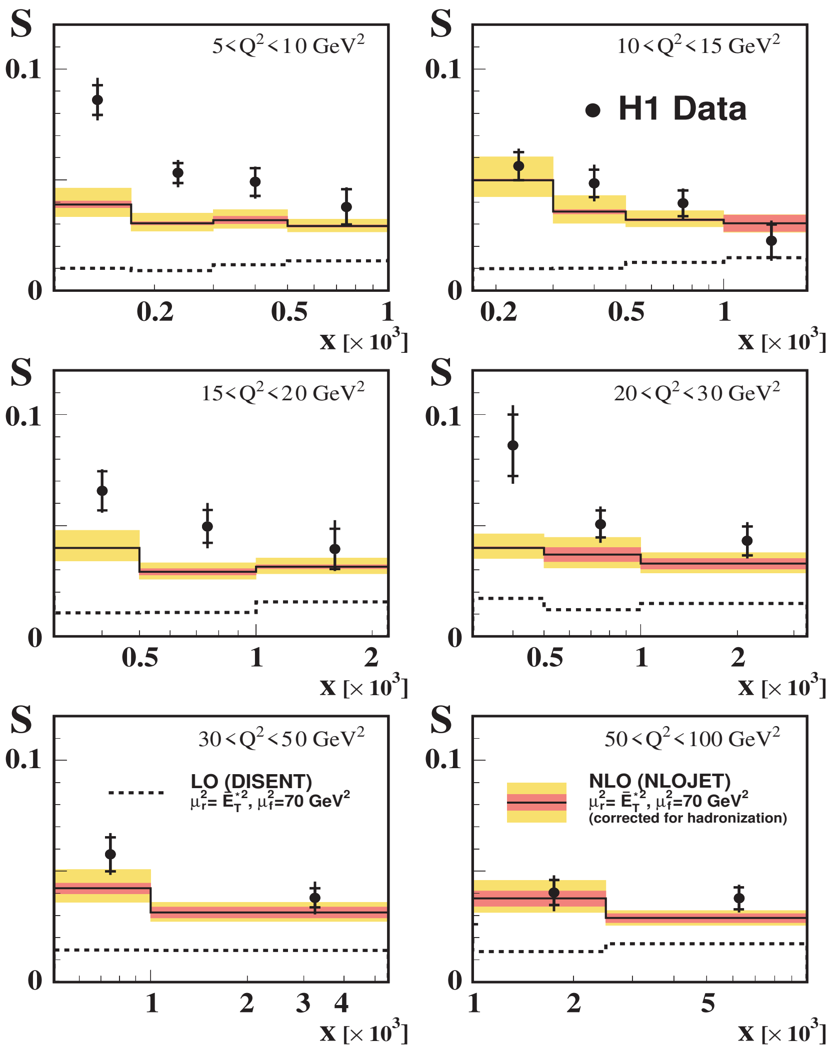
$\Rightarrow$ **DGLAP fails at low x**
$\Rightarrow$ **CCFM ok, sensitive to $xg(x, Q^2, k_t)$**

Parton Dynamics and Dijets at low x





$$S = N_{\rm dijet}^{\Delta\Phi^* \leq 120^\circ} / N_{\rm dijet}^{\rm tot}$$



$5 < Q^2 < 75$ GeV^2, $10^{-4} < x < 10^{-2}$

dijets in Breit frame

$E_{\mathrm{T},1} > 7$ GeV, $E_{\mathrm{T},2} > 5$ GeV

DGLAP+NLO MEs fail at low x , Q^2

CASCADE (not shown) can describe the data

Summary

- HERA provides rich inclusive data, covering 5 decades in Q^2 and x, with a precision reaching up to 2%
- pQCD (DGLAP evolution) very successful in describing it, allowing extraction of gluon & $\alpha_s(M_Z)$ and pdfs
- exploration of low x & Q^2 region with not yet understood results:
  - abrupt break in energy dependence ($\sigma \propto W^{2\lambda}$) from $\lambda \propto \ln Q^2$ to flat at $Q^2 \approx 0.5$ GeV^2
  - strange behavior of gluon (flat to even negative)
  - but no change in dynamics observed down to lowest x & Q^2 in $(\partial F_2/\partial \ln Q^2)_x$ and $(\partial \ln F_2/\partial \ln x)_{Q^2}$
  - F_L starts to discriminate between models, but exp. errors large
  - observed signs of parton dynamics different from DGLAP expectations in jet physics

HERA and detectors have been upgraded; background limitations appear to have been overcome recently, lumi is climbing, ZEUS and H1 are on the way to take lots of data !