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Session 4: Lepton-Hadron and Hadron-Hadron Scattering

Structure functions at low x and low Q^2 from HERA

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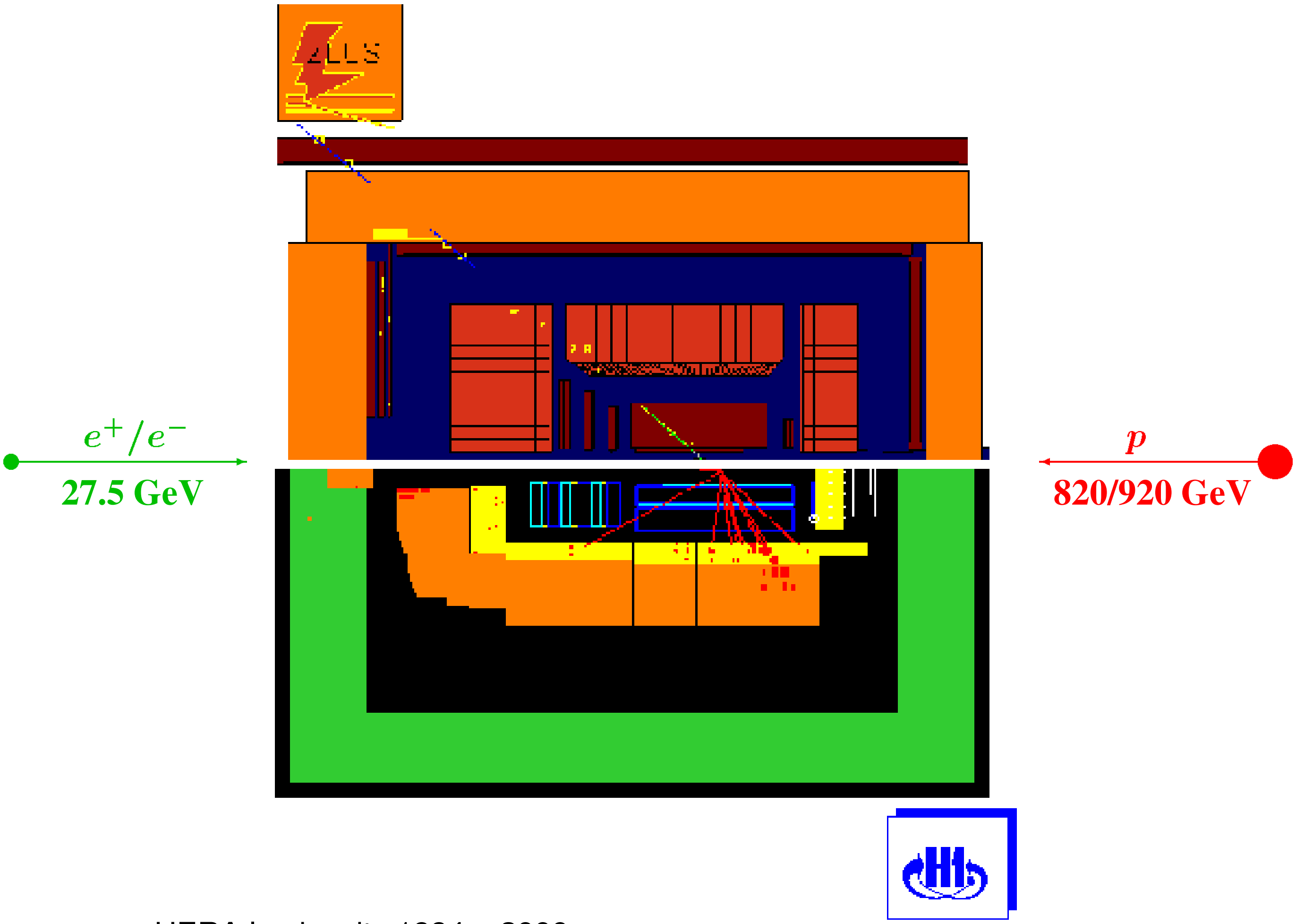
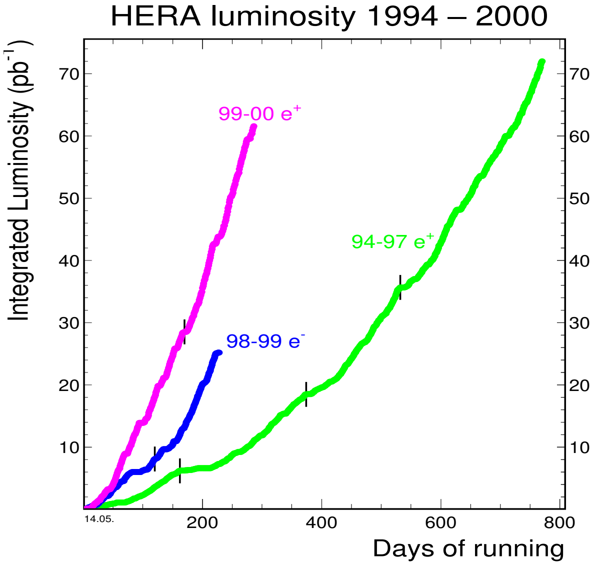
representing

Outline

- Introduction
- Proton Structure Functions
  - F_2 and F_L in pQCD domain
- Gluons in the Proton
  - F_2 scaling violation analysis
  - comparison with jets and charm
- Pushing the extremes
  - very low Q^2: transition to photoproduction
  - very low x: hunting for saturation
- Summary and Outlook

HERA collider

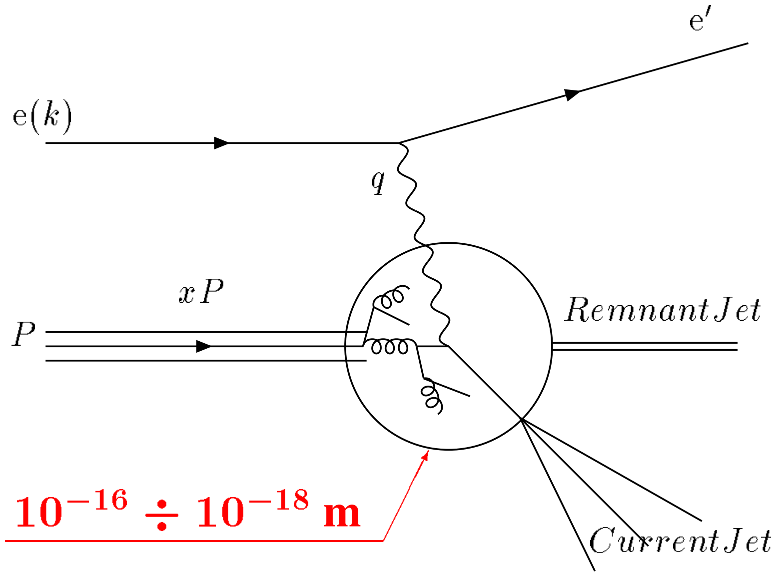




L/pb^{-1}	E_{cm} /GeV	H1	ZEUS
e-p	319	15	17
e+p	300	37	48
	319	44	45

★ Resolving hadronic structure at $10^{-16} \div 10^{-18}$ m

NC: Basic Definitions

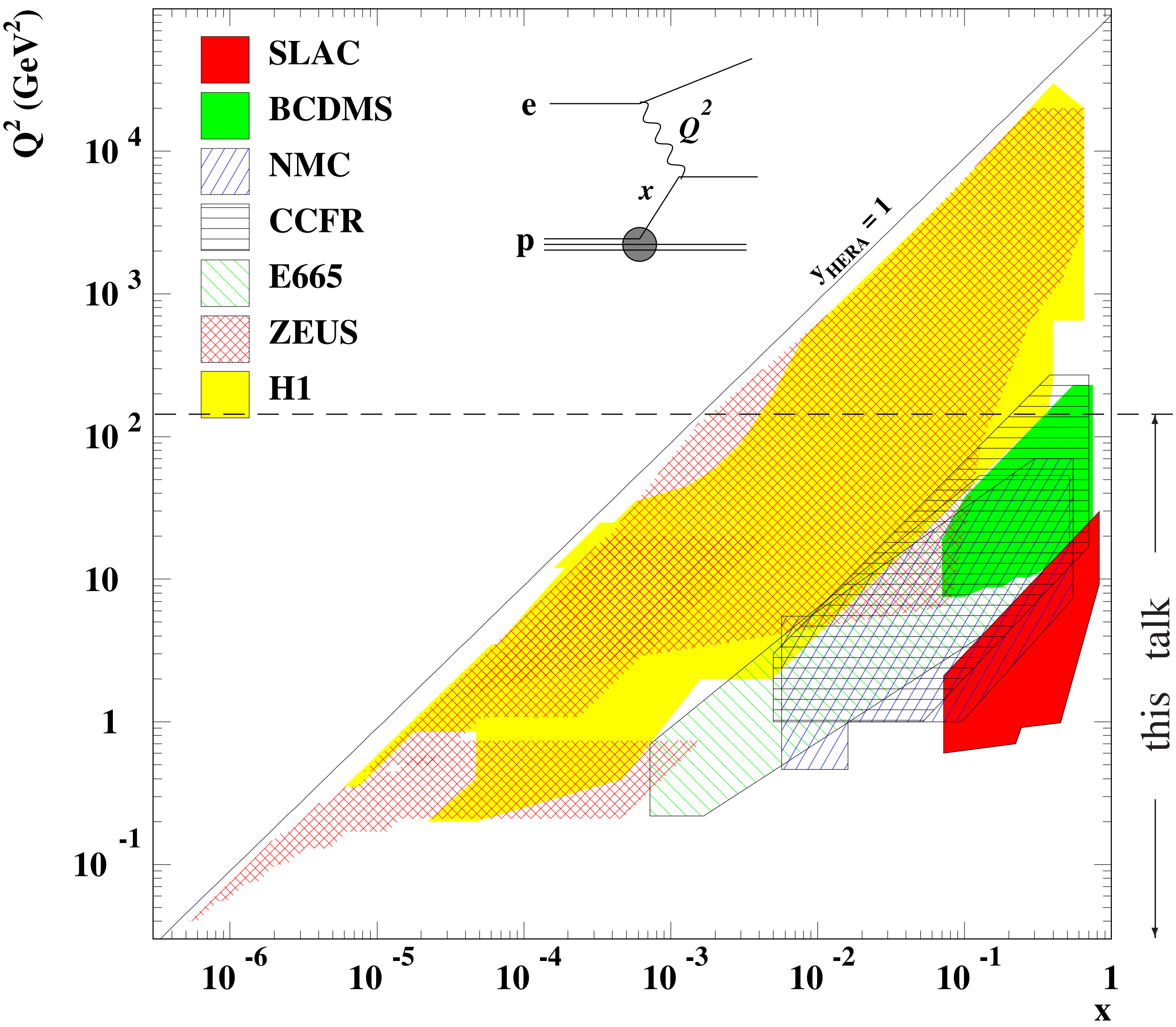


- $Q^2 \;=\; -q^2$ – 4-momentum transfer squared
- $x \;=\; \frac{-q^2}{2P\cdot q}$ – parton momentum fraction
- $y \;=\; \frac{P\cdot q}{P\cdot k}$ – inelasticity
- $W^2 \;=\; (q+P)^2$ – total hadronic energy squared
- $Q^2 \;=\; sxy$ $\quad W^2 = \frac{Q^2(1-x)}{x} + m_p^2 \rightarrow \frac{Q^2}{x}$ (at $x \rightarrow 0$)

$$\left.\frac{d^2\sigma^{NC}(ep)}{dxdQ^2}\right|_{Q^2 \ll M_Z^2}^{\text{Born}} = \frac{4\pi\alpha^2}{xQ^4}\left[y^2 x F_1 + (1-y)F_2\right]$$

- $F_2 = \sum_f A_f[xq_f(x,Q^2) + x\bar{q}_f(x,Q^2)]$ (LO QCD)
- $F_L = F_2 - 2xF_1$ – longitudinal structure function
  (important only at high $y > 0.4$)

HERA kinematic range

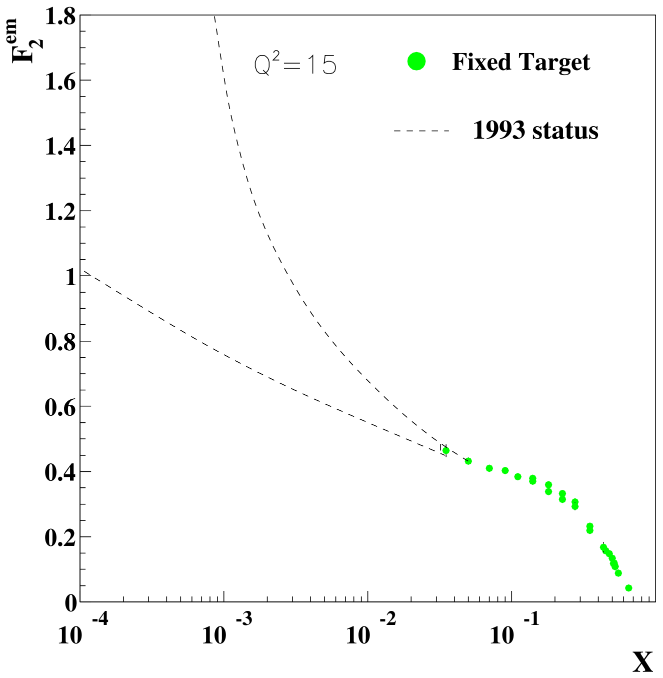


x/Q^2	$\rightarrow 10^{-5}$	$\Rightarrow$	low x limit of pQCD
y	$\rightarrow 0.005$	$\Rightarrow$	overlap with fixed target experiments
y	$\rightarrow 0.82$	$\Rightarrow$	sensitivity to F_L
Q^2	$\rightarrow 0.045\ \text{GeV}^2$	$\Rightarrow$	transition to γp
Q^2	$\rightarrow 50000\ \text{GeV}^2$	$\Rightarrow$	EW sector, (new physics?)
			Emphasized by the Upgrade-2000

Structure functions and QCD

Predictive power ?

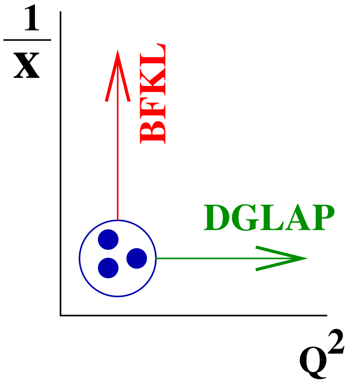
$$F_2(x,Q^2) = F_2(x,Q_0^2) \times (\text{QCD evolution})$$



different parton evolution schemes:

DGLAP resums $\log(\frac{Q^2}{Q_0^2})$ terms

BFKL resums $\log(\frac{1}{x})$ terms



$\Rightarrow$ Initial conditions are important. How to define them?

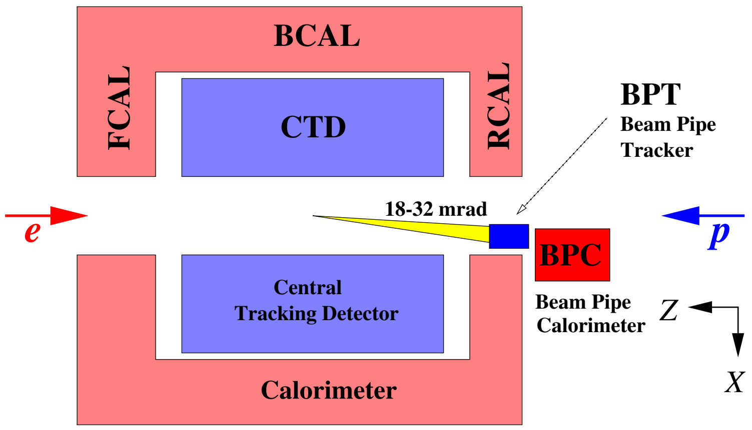
1. From first principles – best, but tough (lattice QCD?)
2. Educated guess – phenomenology (e.g. Regge model)
3. Measurement – experimental data (precision!)

Data Samples

Three data sets (ZEUS, H1) collected in 96/97:

- Very low Q^2:

$$\mathcal{L} = 3.9\ \mathrm{pb}^{-1}$$
$$Q^2 = 0.045 \div 0.65\ \mathrm{GeV}^2$$



(Similar H1 VLQ detector is installed only during 1998-2000 data taking)

- Low Q^2:

		ZEUS	H1
$\mathcal{L}$	=	$2.2\ \mathrm{pb}^{-1}$	$1.8\ \mathrm{pb}^{-1}$
Q^2	=	$2.2 \div 25\ \mathrm{GeV}^2$	$1.5 \div 10\ \mathrm{GeV}^2$

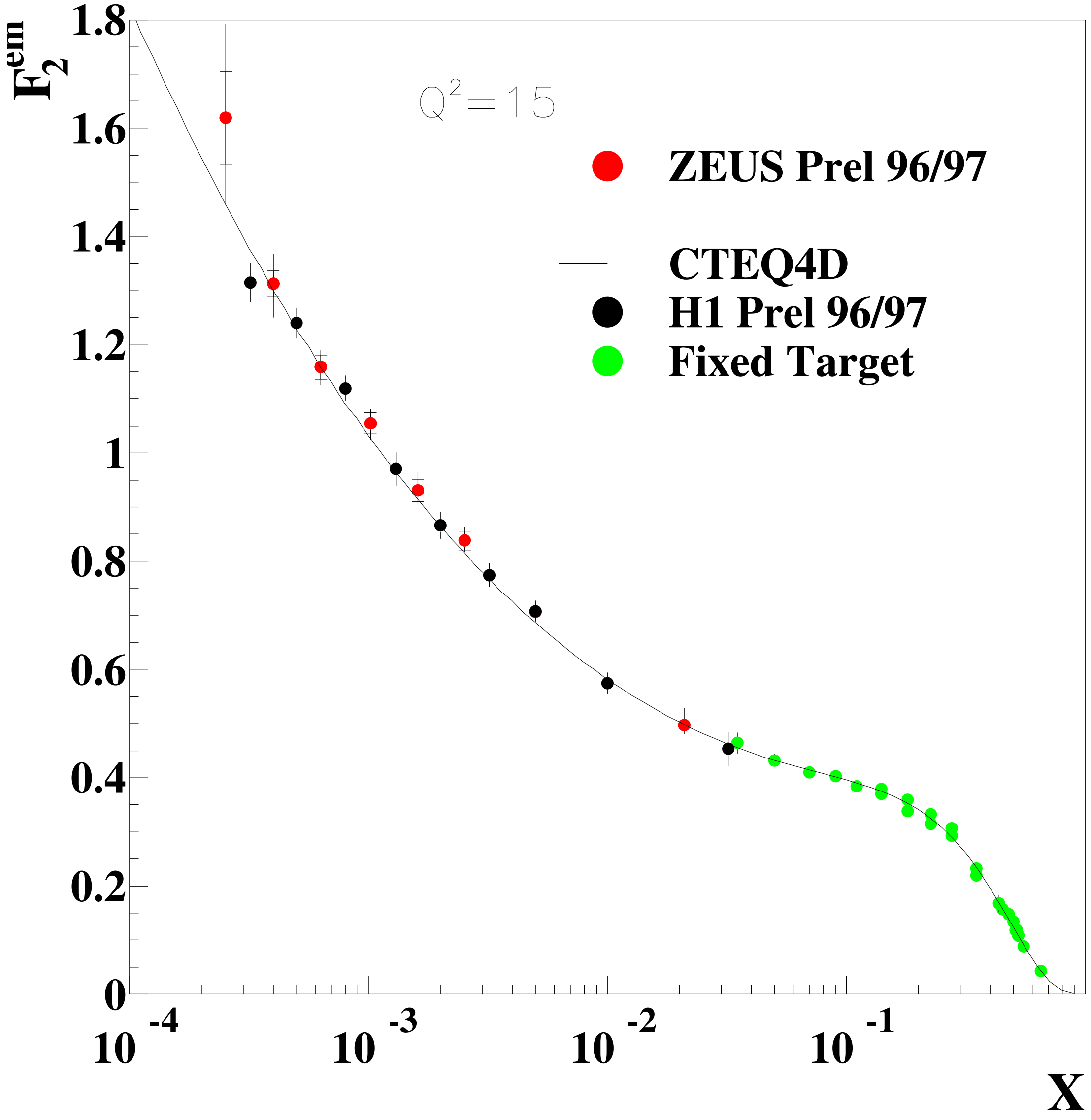
- Medium Q^2:

		ZEUS	H1
$\mathcal{L}$	=	$30.2\ \mathrm{pb}^{-1}$	$17.9\ \mathrm{pb}^{-1}$
Q^2	=	$25 \div 150\ \mathrm{GeV}^2$	$10 \div 150\ \mathrm{GeV}^2$

Typical precision (in the bulk region):

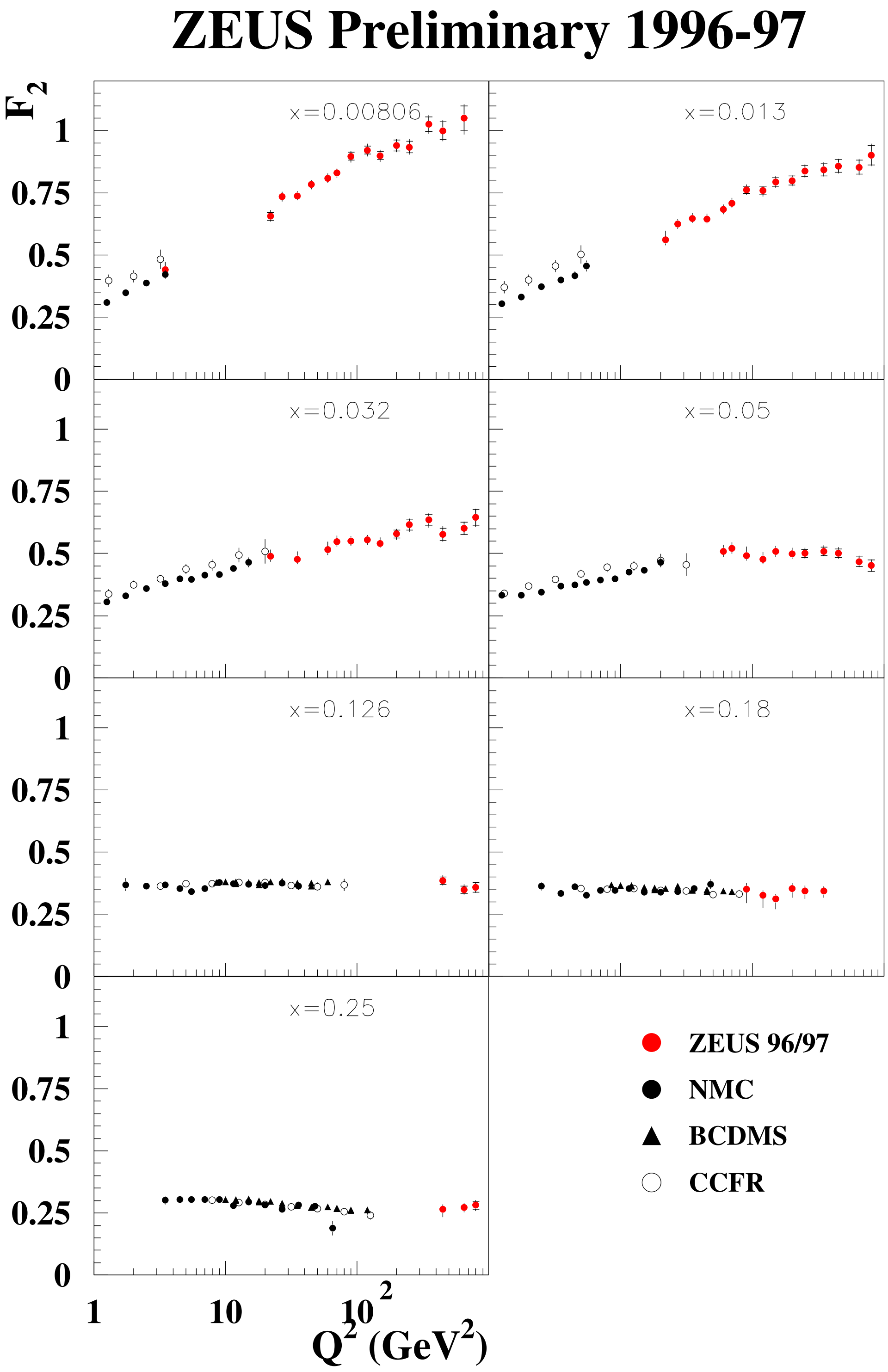
$$1\%(\mathrm{stat}) \oplus 2-3\%(\mathrm{syst}) \oplus 2\%(\mathrm{norm})$$

$F_2(x)$: HERA vs fixed target



- ★ High precision: 1%(stat) $\oplus$ 2-3$\%$(syst)
- ★ Good agreement between H1 and ZEUS
- ★ Overlap is achieved with fixed target experiments
- ★ **Strong rise at low x ($F_2 \sim x^{-\lambda}$)**

$F_2(Q^2)$: HERA vs fixed target



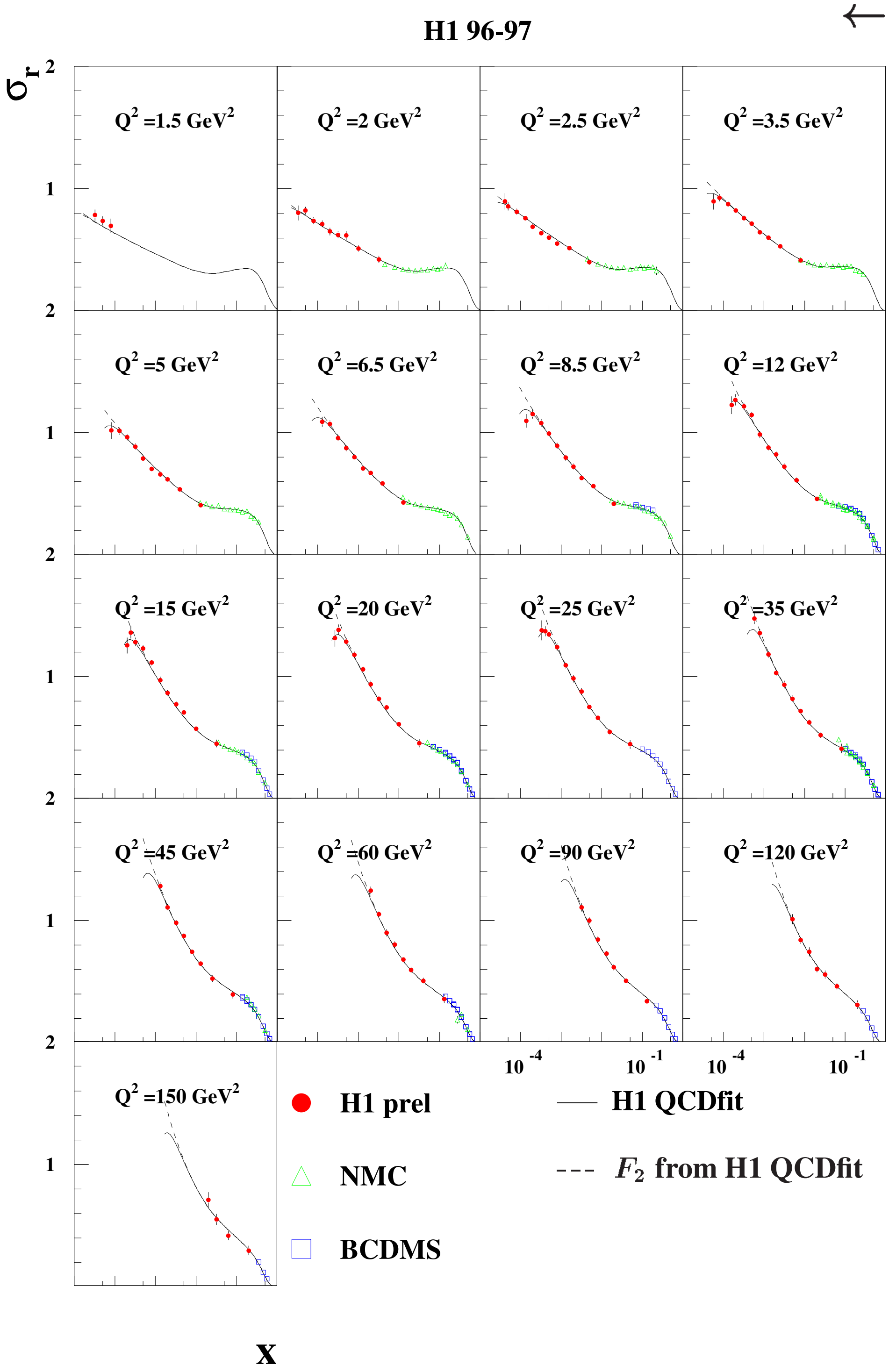
NC reduced cross section

$$\frac{d^2\sigma^{NC}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4} Y_+ \underbrace{\left(F_2 - \frac{y^2}{Y_+} F_L\right)}_{\sigma_r \equiv \tilde{\sigma}}$$

$Q^2 << M_Z^2; \quad Y_+ = 1 + (1-y)^2$

– 'reduced cross section'

$\leftarrow y = \frac{Q^2}{sx}$

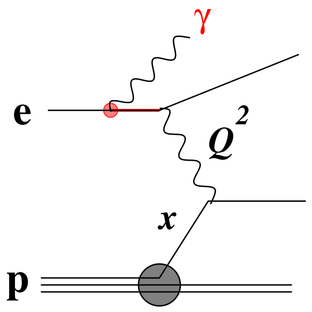


Extraction of F_L

$$\sigma_r = \left(F_2 - \frac{y^2}{Y_+}F_L\right) \quad \rightarrow \quad F_L \text{ gets important at high } y \quad \left(x = \frac{Q^2}{ys}\right)$$

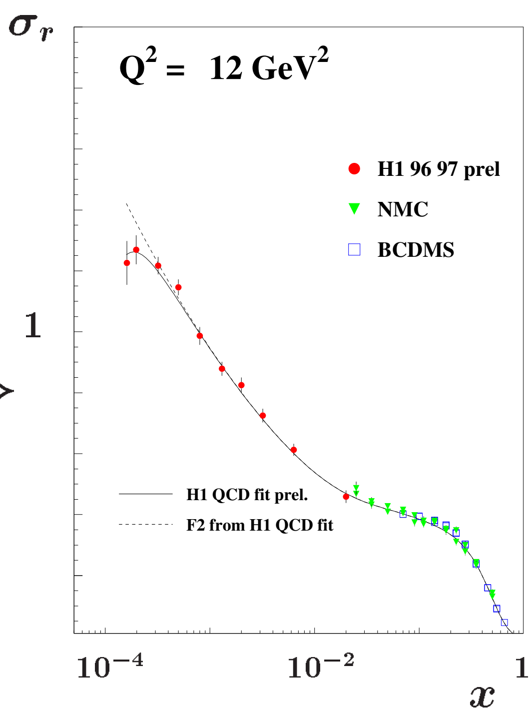
Methods

1. ISR events (all Q^2)



2. Subtraction ($Q^2 > 10$ GeV^2) $\Rightarrow$

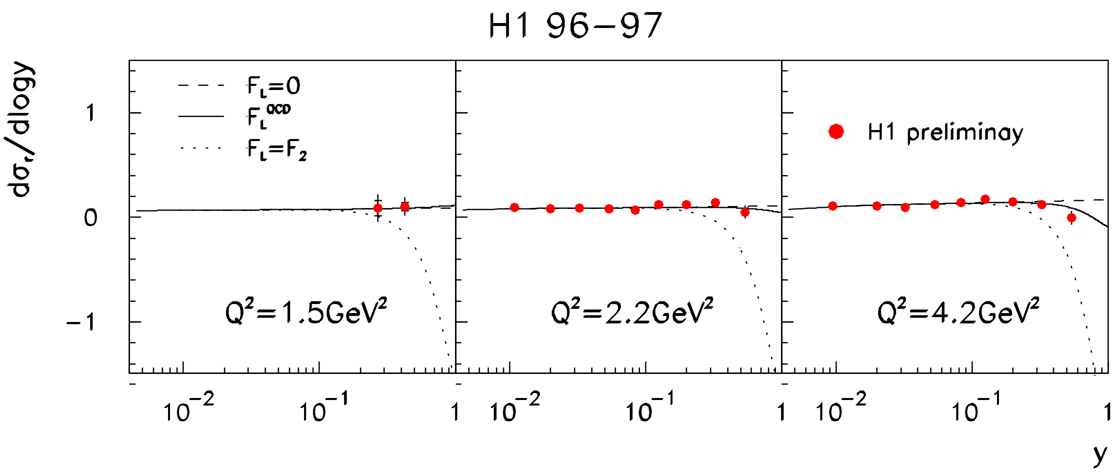
$$F_L = F_2^{QCD} - \frac{Y_+}{y^2}\sigma_r^{exp}$$



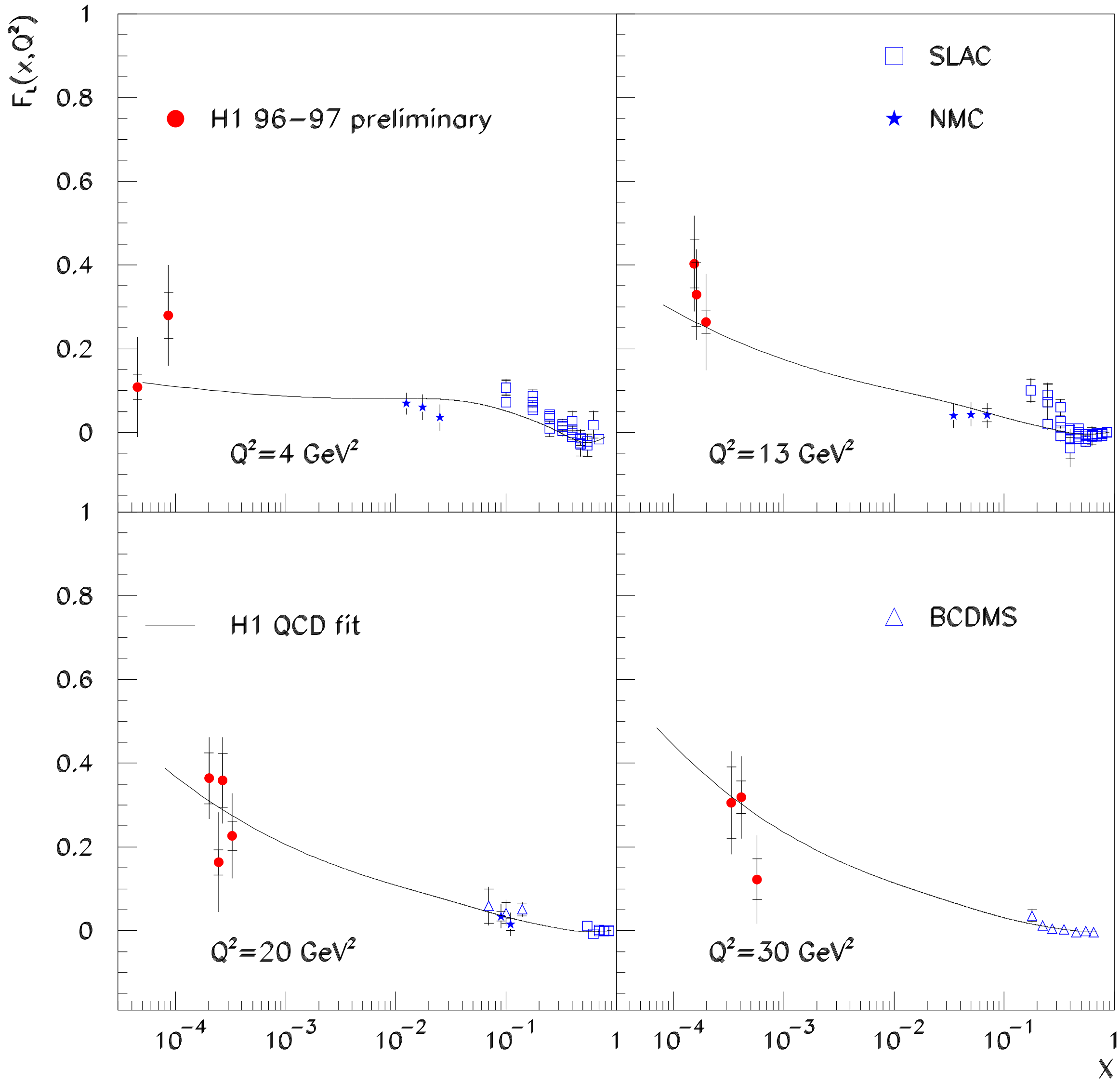
3. Derivative ($Q^2 < 10$ GeV^2)

$$\frac{\partial \sigma_r}{\partial \log y} = \frac{\partial F_2}{\partial \log y} - F_L 2y^2\frac{(2-y)}{Y_+^2} - \frac{\partial F_L}{\partial \log y}\cdot\frac{y^2}{Y_+^2}$$

$$F_2 \sim x^{-\lambda} \quad (x \sim 1/y) \quad \Rightarrow \quad \frac{\partial F_2}{\partial \log y} \sim \lambda + \lambda^2 \log y + \ldots$$



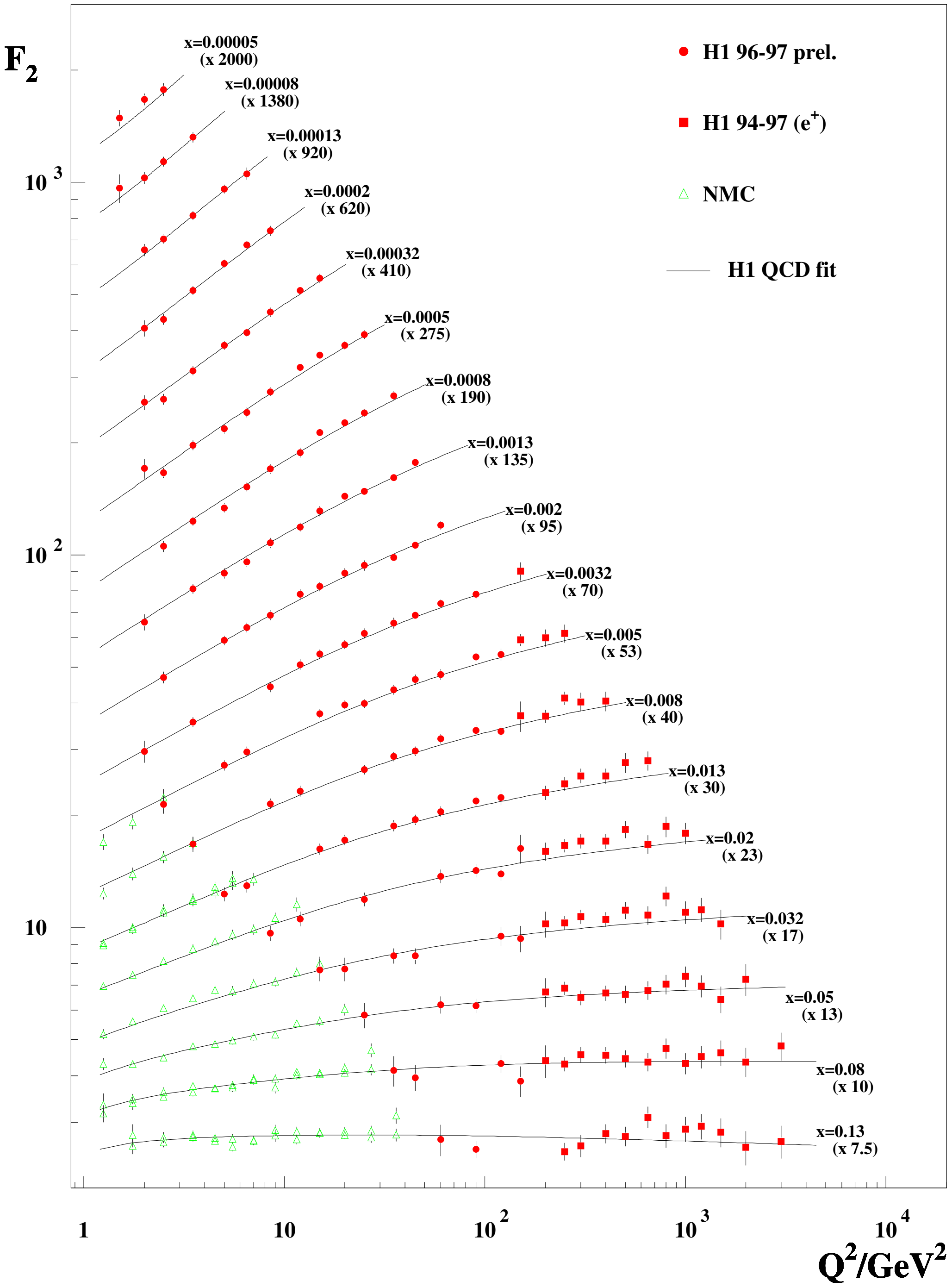
F_L: HERA vs Fixed target



★ **Rising at low x in accord with pQCD**

★ **For better precision have to use "classical" method (varying collision energy) $\Rightarrow$ After upgrade ...**

F_2 scaling violation

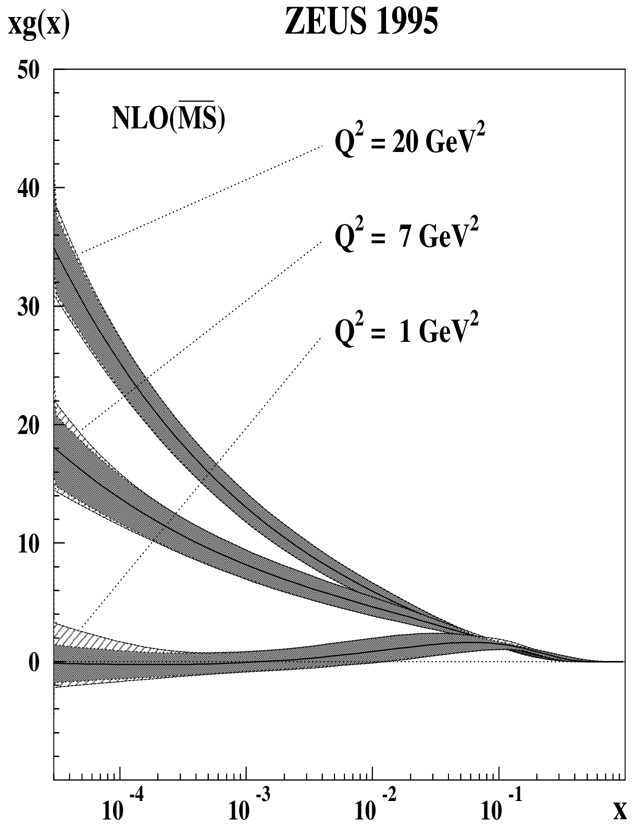


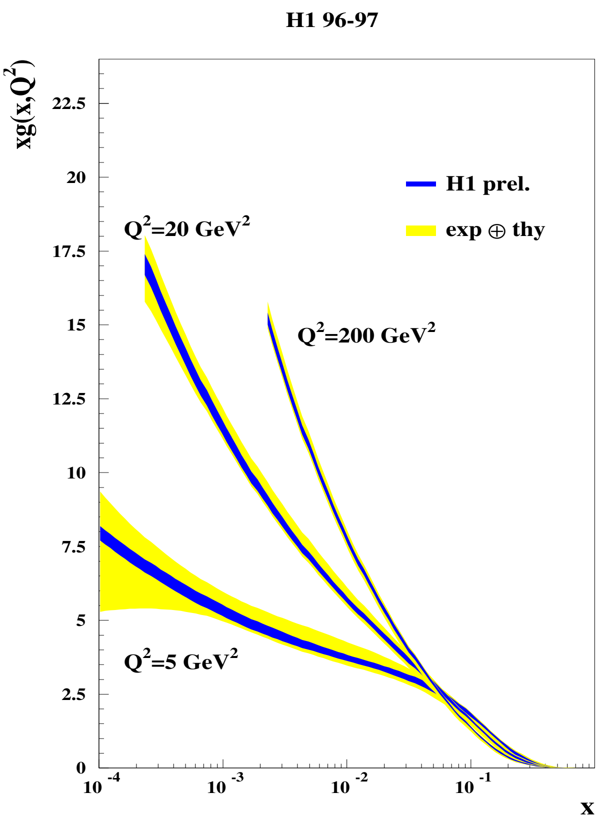
★ NLO QCD describes the data over 4 orders of magnitude, down to surprisingly low Q^2, $\mathcal{O}(1\mathrm{GeV}^2)$

Gluon Density in the Proton

The scaling violation of F_2 at low x is dominated by the gluon density:

$$\frac{\mathrm{d}F_2}{\mathrm{d}\log Q^2} \propto xg(x) \cdot \alpha_s$$





- Statistical errors are small. Systematics dominate (exp: Q^2_{min}, theor: α_s, charm mass, ...)

- Steep rise towards low x, non-singular behaviour at low Q^2

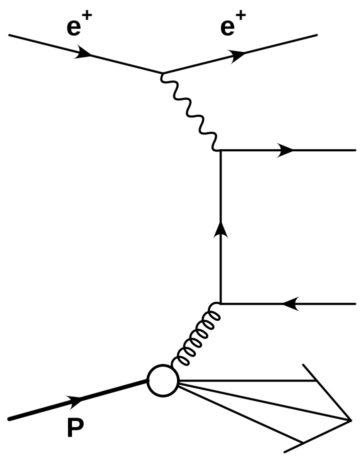
- Other methods? Select processes with large sensitivity to gluons

$F_2^{\rm charm}$ from HERA

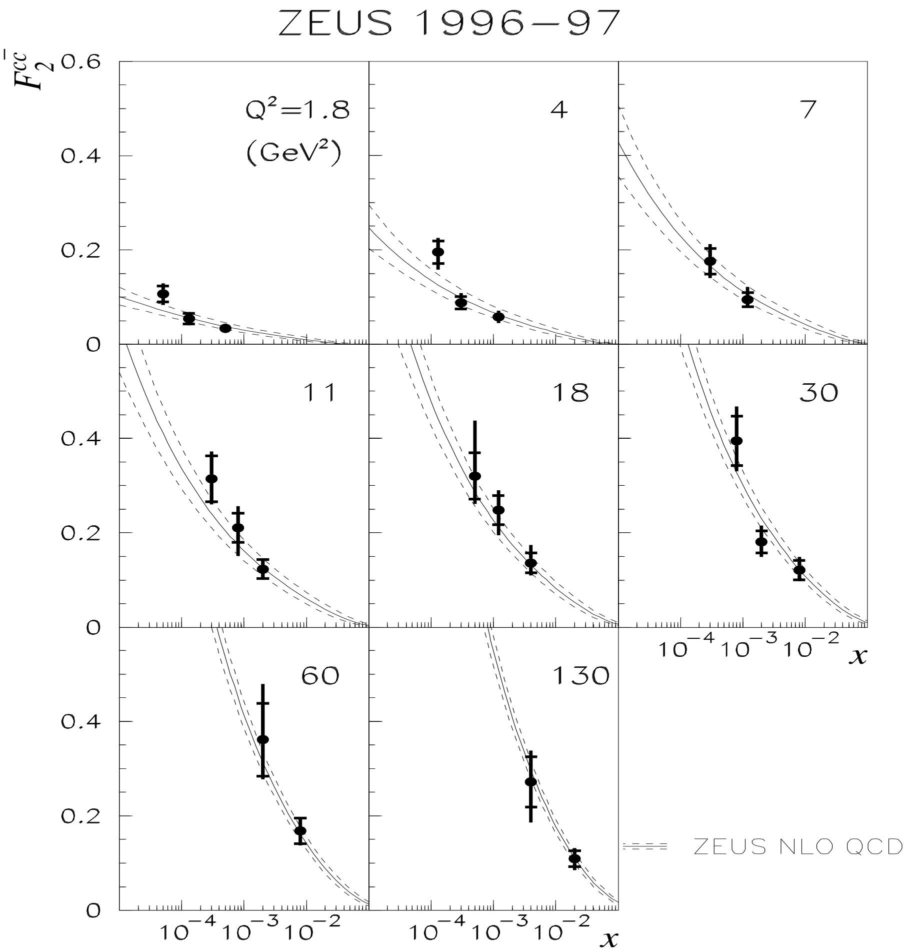
Boson-Gluon Fusion process (BGF)

as a direct handle of the gluon density $\Rightarrow$

tag by charm (or jets) in the final state

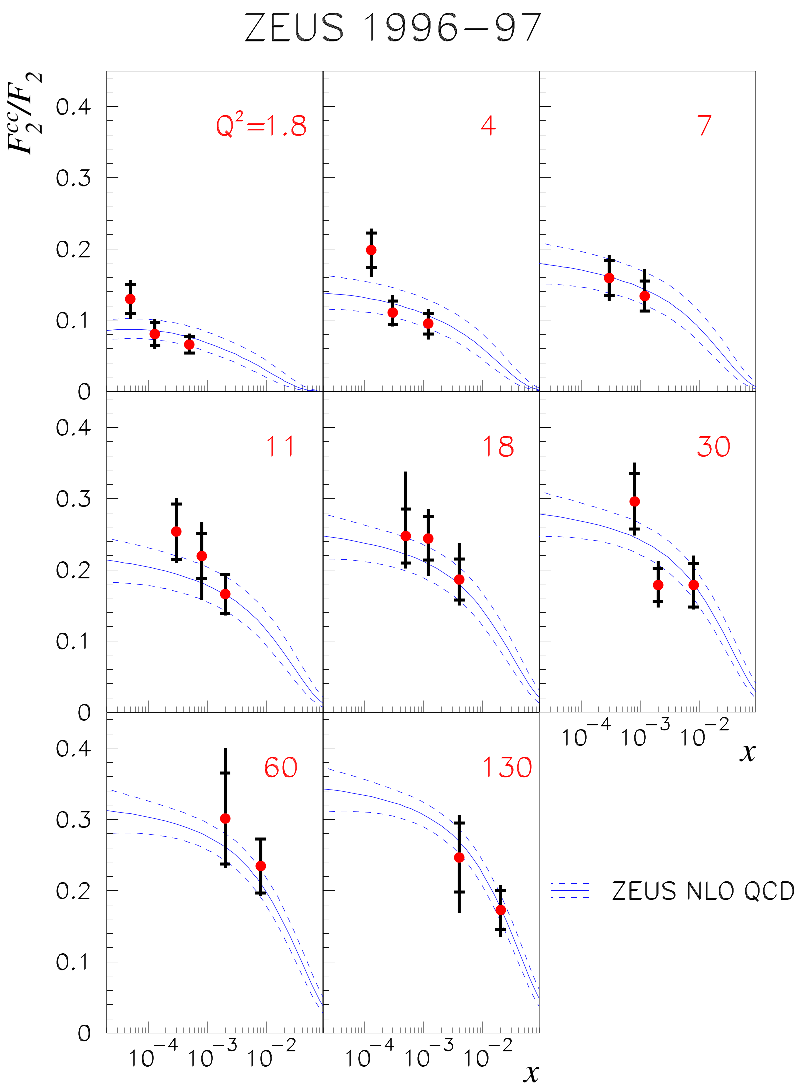


$$\frac{d^2\sigma(ep \to ec\bar{c}X)}{dx dQ^2} = \frac{2\pi^2\alpha}{xQ^4}(Y_+ F_2^{c\bar{c}} - y^2 F_L^{c\bar{c}})$$



Ratio of $F_2^{c\bar{c}}$ to F_2^p

(For the ratio F_2^p values are taken from NLO QCD fit)



★ $F_2^{c\bar{c}}$ rises faster than F_2^p

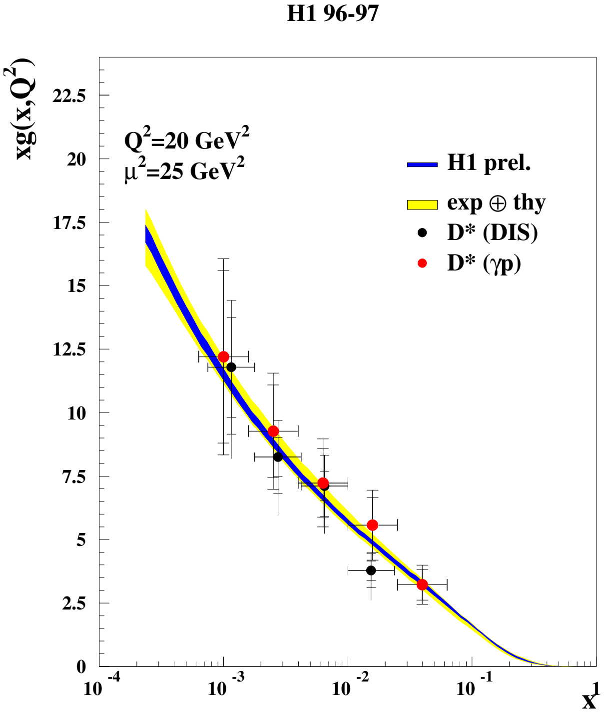
★ At low x $F_2^{c\bar{c}}$ accounts for:
$\simeq 10\%$ of F_2 at low Q^2
$\simeq 30\%$ of F_2 for $Q^2 > 11$ GeV^2

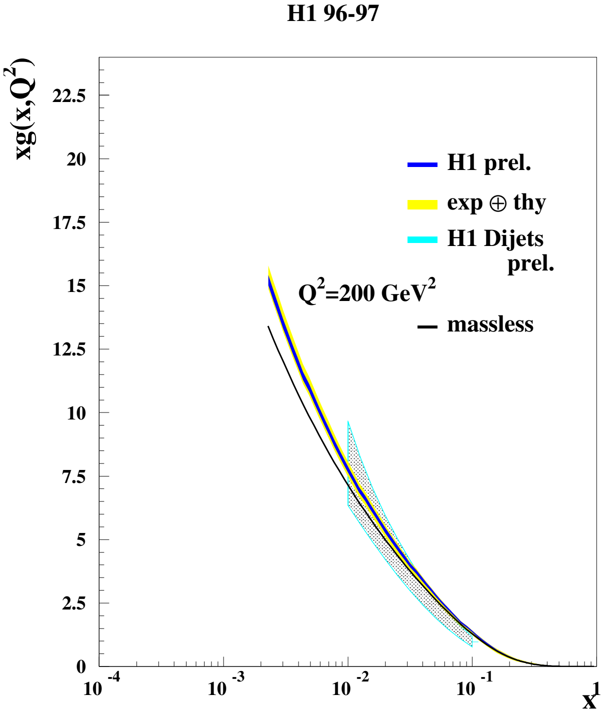
An important role of HQ at HERA !

Gluon Density from Charm and Jets

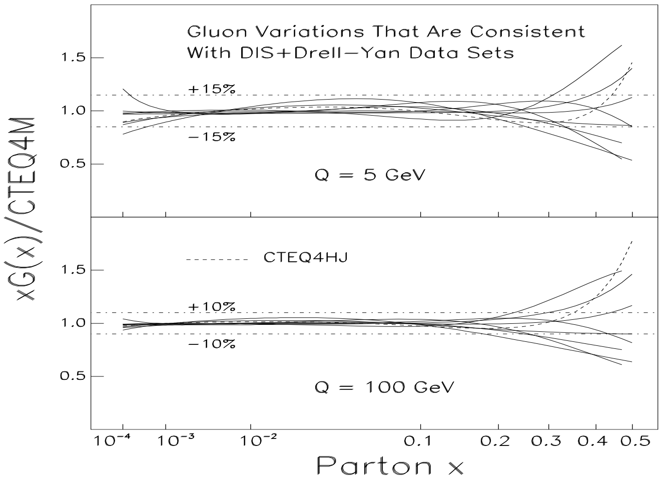
- Most precise extraction – from F_2 scaling violation
- BGF (charm, di-jets) – consistent (larger exp/theor uncertainties)

$\Rightarrow$ **universality**





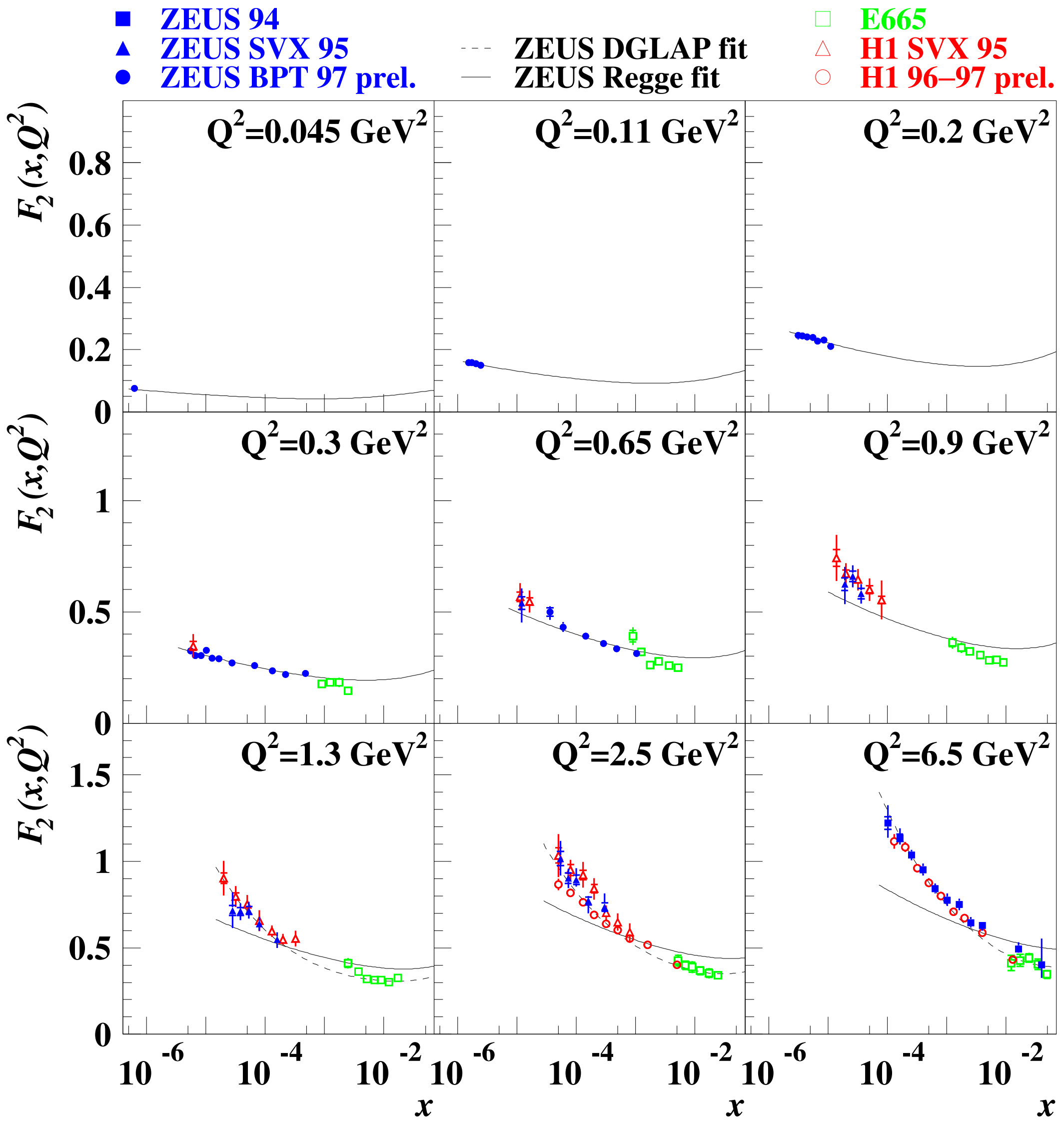
Impact on LHC physics (J.Huston et al.,1999)



★ **Gluon density at low $x < 0.1$ is constrained within 10%**
$\Rightarrow$ good control for Higgs production at LHC

Pushing QCD to low Q^2 extreme

$$F_2(x,Q^2) = \frac{Q^2}{4\pi^2\alpha} \underbrace{\left(\frac{M_0^2}{M_0^2+Q^2}\right)}_{\text{GVDM}} \cdot \underbrace{\left(A_{I\!R}\left(\frac{Q^2}{x}\right)^{\alpha_{I\!R}-1} + A_{I\!P}\left(\frac{Q^2}{x}\right)^{\alpha_{I\!P}-1}\right)}_{\text{Regge}}$$

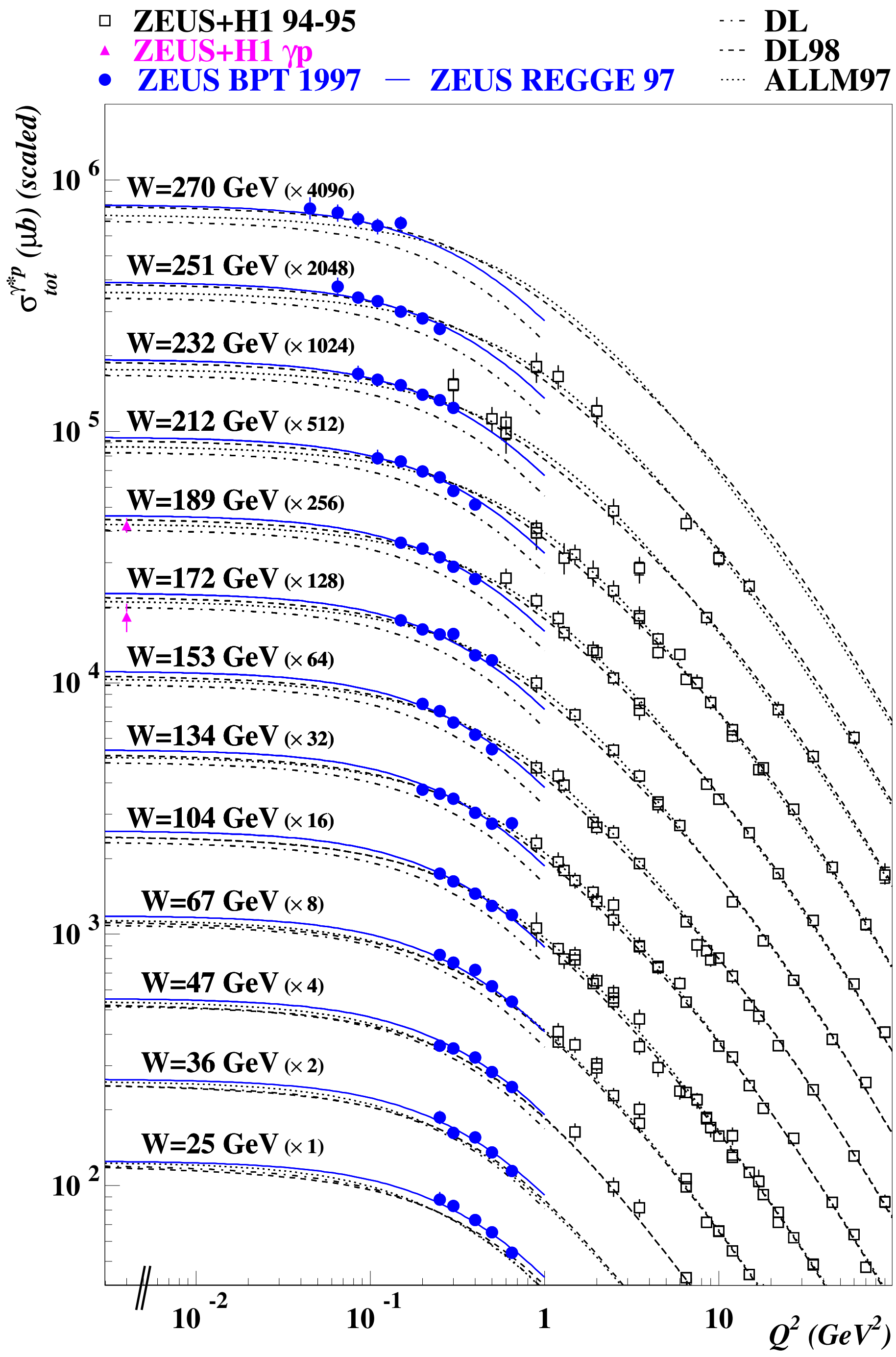


$$M_0^2 = 0.52 \pm 0.04\,\mathrm{GeV}^2 \qquad \alpha_{I\!P} = 1.102 \pm 0.007$$

★ **Transition to non-perturbative regime:**
pQCD $\longrightarrow$ Regge (GVDM) at $Q^2 \simeq 1$ GeV^2

Very low Q^2 domain: $\gamma^* p \to \gamma p$

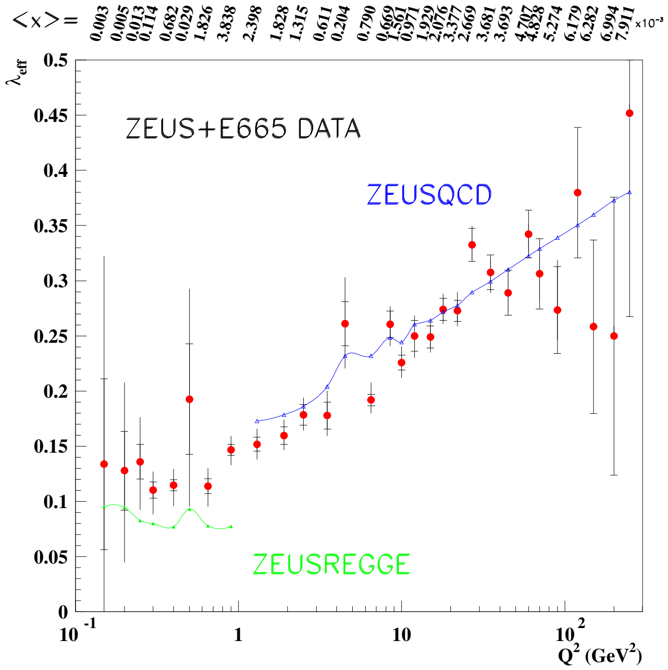
$$\sigma_{tot}^{\gamma^* p}(W, Q^2) = \sigma_T^{\gamma^* p} + \sigma_L^{\gamma^* p} \approx \frac{4\pi^2\alpha}{Q^2} F_2(x, Q^2)$$

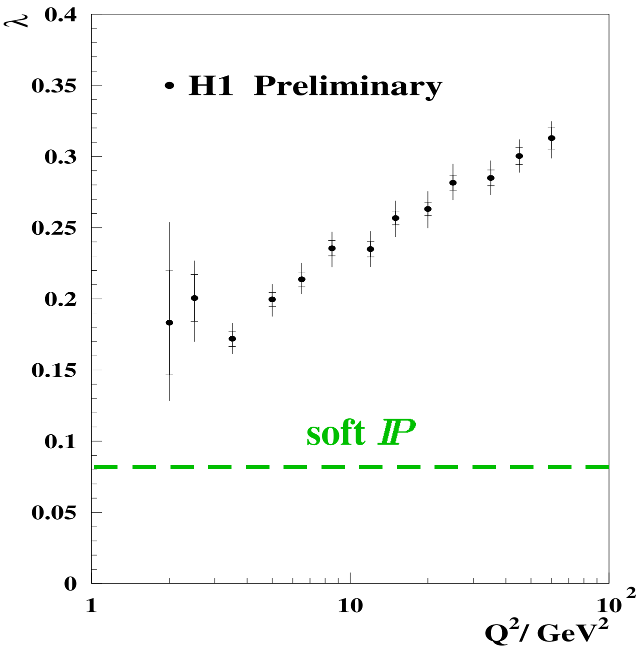


★ Smooth transition from partonic to hadronic degrees of freedom

Rise of F_2 at low x

$$F_2 \sim x^{-\lambda(Q^2)} \quad \rightarrow \quad \lambda_{\text{eff}}(Q^2) = \frac{d \ln F_2}{d \ln(1/x)}$$





★ Data: smooth transition. Theory – mismatch

How to bridge soft and hard regimes in a common picture?

$$\lambda = \alpha_{I\!P} - 1$$

Regge: Universal ("soft") $I\!P$ $\quad \alpha_{I\!P} \simeq 1.08$

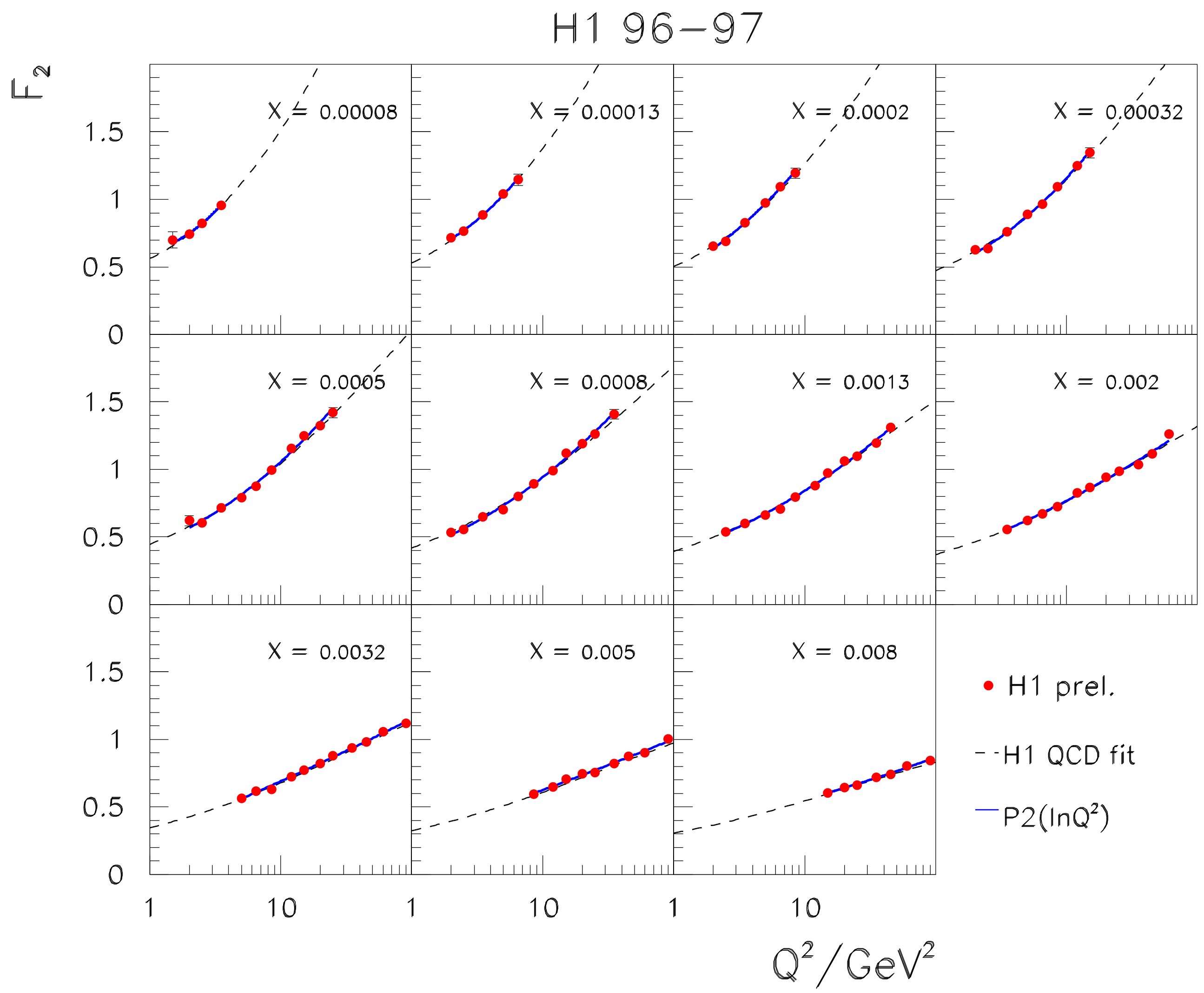
pQCD: Hard $I\!P$ (gluon ladder) $\quad \alpha_{I\!P} \simeq 1.17$ (NLO BFKL)

CKMT: Soft $I\!P$ $\leftarrow$ (SC) $\boxed{\text{"bare" } I\!P}$ (DGLAP evolution) $\longrightarrow \alpha_{I\!P}(Q^2)$

$\alpha_{I\!P} \approx 1.2$

$\hookrightarrow$ Nature of the Pomeron in QCD? $\Rightarrow$ Diffraction in DIS (another hot topic)

Pushing QCD to low x extreme: Saturation?



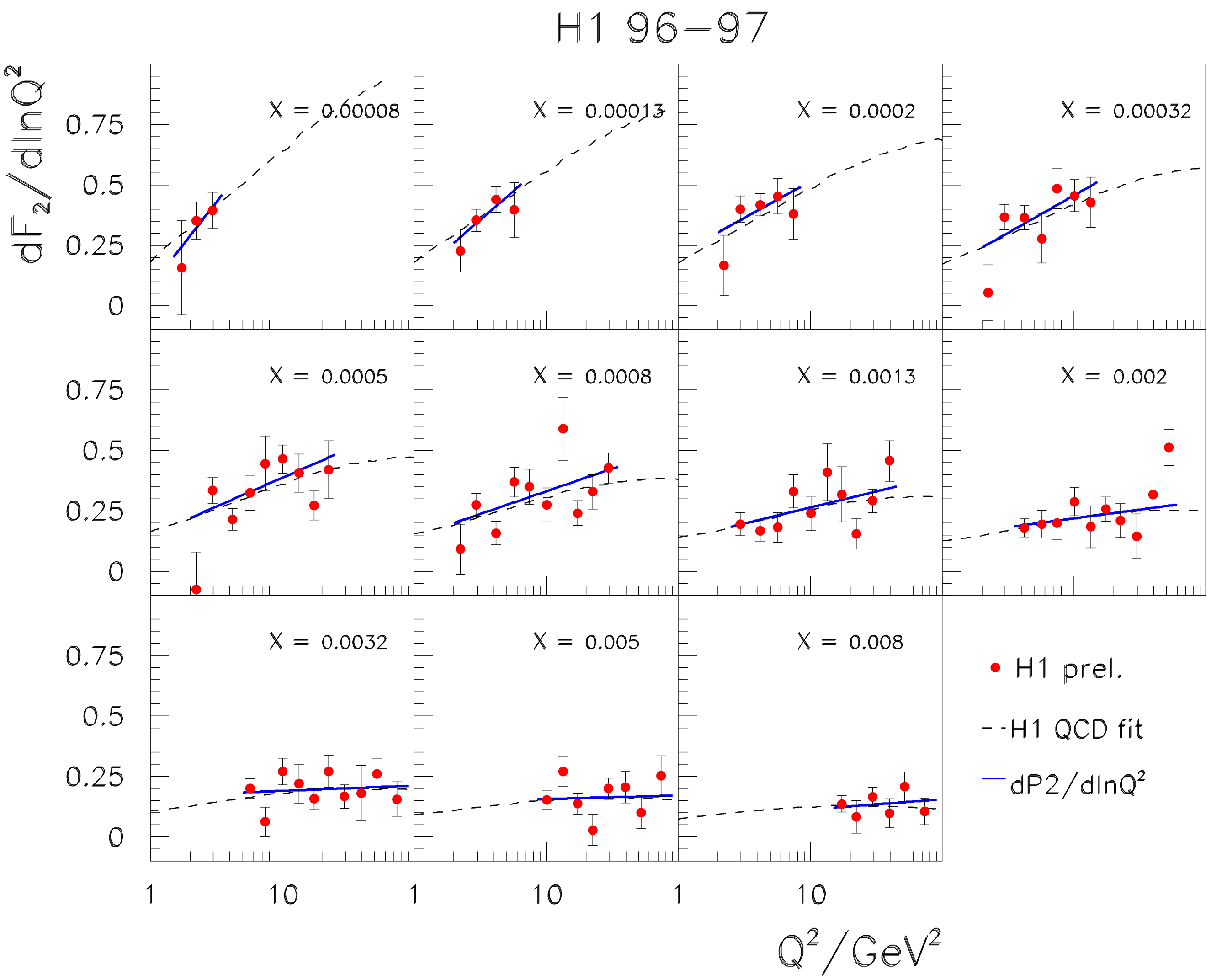
Unitarity: "That fast rise of F_2 cannot continue forever" $\Rightarrow$ at some $r_\perp^{sat} \approx 1/Q_s(x)$ gluon density becomes too high $\rightarrow$ rescatterings $\rightarrow$ non-linear QCD evolution equations $\rightarrow$ screening corrections $\rightarrow$ damping. Do we see this already at HERA?

$\Rightarrow$ Study an evolution of the Q^2 slope with x using local derivatives of F_2

Non-linear F_2 parametrization $\Rightarrow$ 2-dim derivatives

Local derivatives of F_2

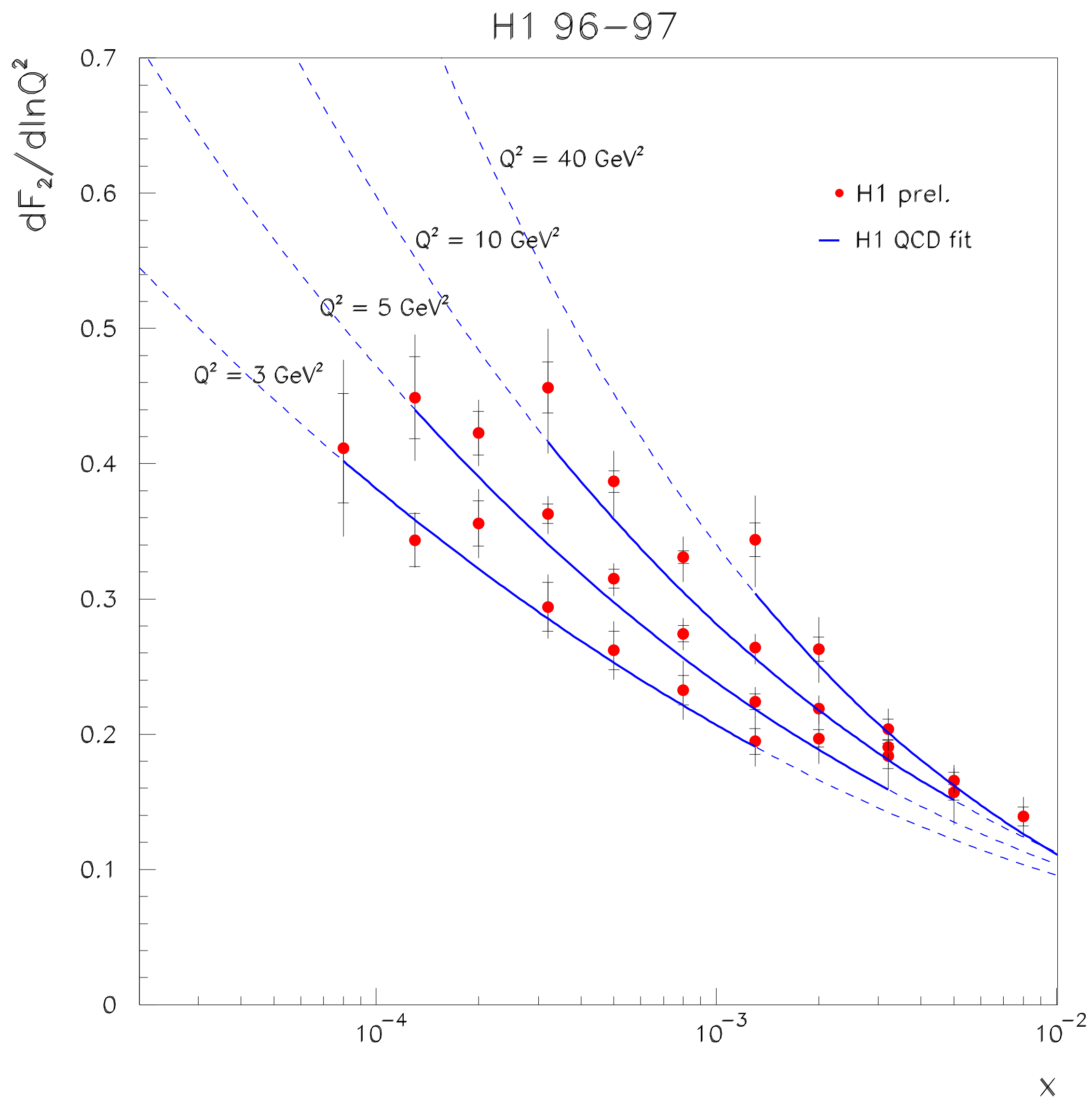
$$F_2 \simeq P2(\ln Q^2) \;\Rightarrow\; \frac{\partial F_2}{\partial \ln Q^2}(x, Q^2) = b + c \cdot \ln Q^2$$



- Local derivates of F_2 provide a model independent measurement of the scaling violation $\longrightarrow$ an important additional test of QCD

- NLO QCD (using DGLAP evolution equations) gives good description of the data (although exp. errors are still large)

Slope of F_2

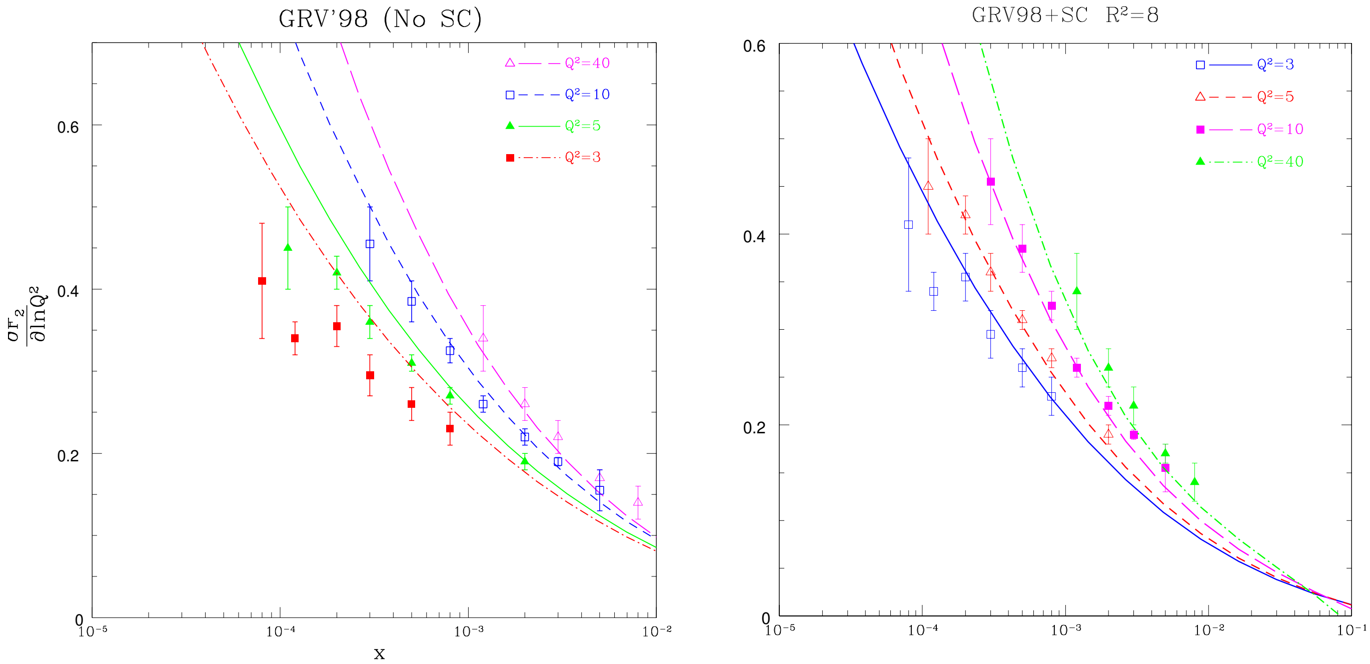


★ $\mathrm{d}F_2/\mathrm{d}\ln Q^2$ **is monotonically rising for all** Q^2
$\Rightarrow$ **no saturation?** **(but see E.Levin et.al)**

★ **Precision and the** (x, Q^2) **coverage are yet insufficient to go below** $Q^2 \simeq 3$ **GeV**^{2} **and** $x \simeq 10^{-4}$

Small exercise

(cf. E.Levin et al. "Physics at THERA", April 2000)



- Freedom in the choice of the initial conditions leads to the ambiguity: both GRV'98 with screening corrections (damped gluons at small x) and NLO QCD using DGLAP parton evolution scheme without saturation can describe H1 data on $\mathrm{d}F_2/\mathrm{d}\ln Q^2$
- Measurement of the derivatives $\mathrm{d}F_2/\mathrm{d}\ln Q^2$ at HERA (and THERA) provide a useful test of the gluon saturation
- Need yet more precise data at low x and still in perturbative regime. If not at HERA – then at THERA (TESLA $\times$ HERA) ?

Summary and Outlook

★ High level of precision is achieved at HERA:
Using $\mathbf{20 \div 30}$ pb^{-1} NC cross section is measured with $\mathbf{1\%}$ stat. and $\mathbf{2 \div 3\%}$ syst. error

★ New $\boldsymbol{F_2}$ measurements span over large kinematical range:
$\mathbf{0.045 < Q^2 < 150}$ GeV^2, $\mathbf{10^{-6} < x < 10^{-1}}$
$\boldsymbol{F_L}$ is determined for $\mathbf{2.2 < Q^2 < 35}$ GeV^2

★ NLO QCD is able to describe the data down to surprisingly low scales, $\mathbf{Q^2 \simeq 1}$ GeV^2 – accidentally?
Consistent picture of gluon at low x emerges.

★ Several interesting theoretical ideas, as well as many existing pdf parametrisations, can be further tested and constrained, provided yet more precise data in the transition region ($\mathbf{0.5 < Q^2 < 3}$ GeV^2) become available ($\boldsymbol{F_2, F_L, \partial F_2/\partial \ln Q^2}$)

★ Potential:

1994-2000 – $\boldsymbol{\mathcal{L} = 100}$ pb^{-1} per experiment
2000 – HERA upgrade
2001-2006 – $\boldsymbol{\mathcal{L} = 1000}$ pb^{-1} per experiment