DIS Results from HERA

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on behalf of the ZEUS and H1 Collaborations

Fifth Workshop on QCD
Villefranche-sur-mer
January 3-7, 2000

- Introduction to HERA $e^{\pm}p$ Physics
- Proton Structure
- NLO pQCD Tests
- NC and CC DIS at high momentum transfer
- Electroweak studies
- Conclusion and Outlook

DIS Results Overview

★ Introduction

- DIS Kinematics
- HERA luminosity
- Define cross sections and structure functions

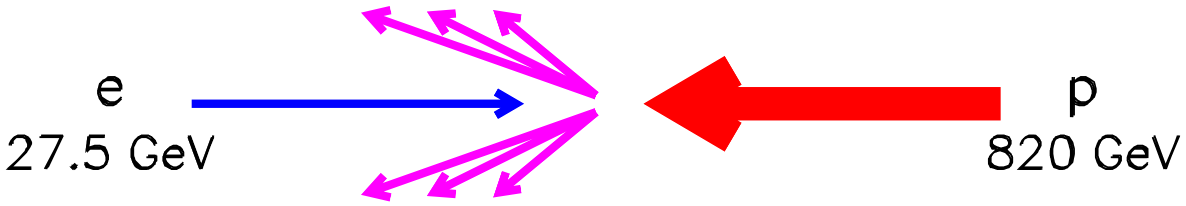
★ $e^{\pm}p$ Cross Sections and Structure Functions

- Overview of $F_2 \Rightarrow$ gluon
- low Q^2: extrapolation to $\sigma_{TOT}^{\gamma p}$
- high Q^2: study of electroweak effects

★ pQCD tests with charm and jets

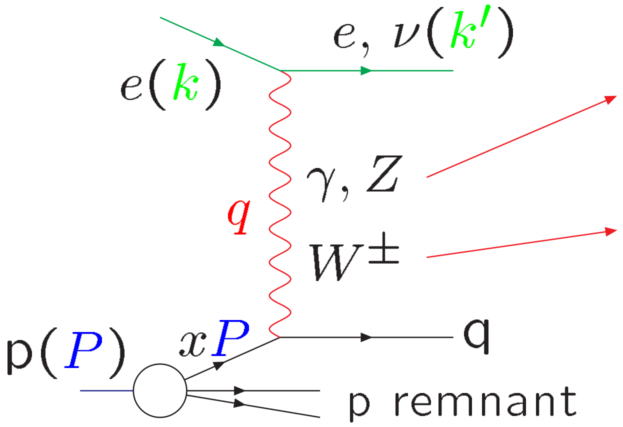
- F_2^c measurement $\Rightarrow$ gluon
- DIS dijet production $\Rightarrow$ gluon
- DIS jet production $\Rightarrow \alpha_s$

HERA Kinematic Variables



$\sqrt{s}$ = 300 GeV

$\rightarrow$ equivalent to 50 TeV fixed target energy



Neutral Current (NC)

Scattered e in main detector

e balances hadronic P_T

Charged Current (CC)

Scattered ν invisible

P_T imbalance

hadronic system only

negative four–momentum transfer squared:

$$Q^2 = -q^2 = -(k - k')^2$$

parton momentum fraction (Bjorken scaling variable):

$$x = Q^2/(2\, q \cdot P) = \frac{Q^2}{sy}$$

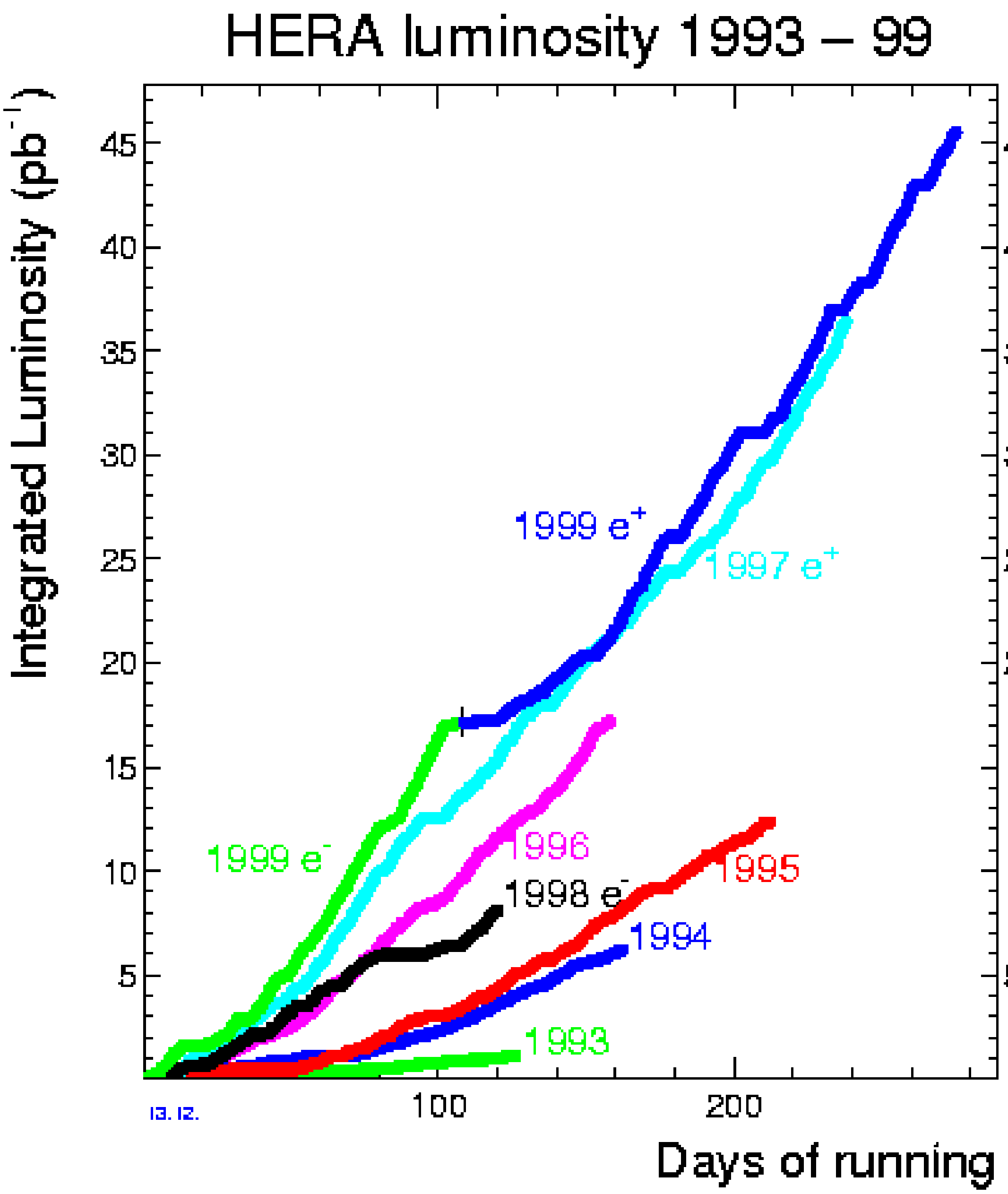
inelasticity (fractional energy transfer in p rest frame):

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

photon-proton center-of-mass energy squared:

$$W^2 = (P + q)^2 = \frac{Q^2(1-x)}{x}$$

Delivered HERA Luminosity



Integrated luminosity (pb^{-1}):

	E_p (GeV)	H1	ZEUS
e^+p	820	37	48
e^-p	920	14	16
e^+p	920	∼18	∼18

DIS in the Standard Model

Deep–inelastic ep scattering =
incoherent sum of elastic eq scatterings

$$\boxed{\sigma(ep) = \sum_{q,\bar{q}} f_{q|p} \cdot \sigma(eq)}$$

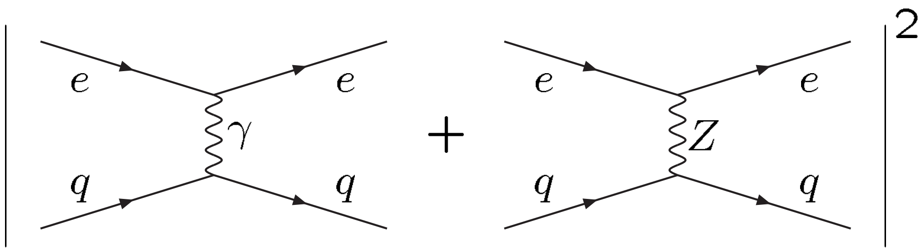
$f_{q|p} \equiv q$ = Parton distribution function (PDF)

Probability density to find quark q in the proton
carrying a fraction x of the proton momentum

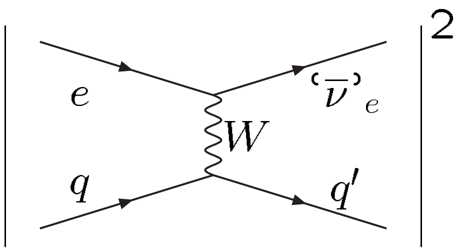
$\sigma(eq)$ = electron–quark cross–section

Leading Order:

$\sigma(eq \to eq) \propto$



$\sigma(eq \to \nu q') \propto$



Given by electroweak sector of Standard Model
as functions of α, G_F, $\sin^2\theta_W$, $(m_t,\ m_H)$

Structure Function Formalism

Neutral Current: $e^{\pm}p \to e^{\pm}X$

$$\frac{d^2\sigma^{\mathrm{BORN}}}{dx\,dQ^2}(e^{\pm}) = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+ F_2^{\mathrm{NC}} \mp Y_- xF_3^{\mathrm{NC}} - y^2 F_L^{\mathrm{NC}}\right]$$

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

naive Quark Parton Model:

$$F_2^{\mathrm{NC}} = \sum_{q=d,u,s,c,b} A_q \cdot [q + \bar{q}]$$

$$F_3^{\mathrm{NC}} = \sum_{q=d,u,s,c,b} B_q \cdot [q - \bar{q}]$$

$$F_L^{\mathrm{NC}} = 0$$

- A_q and B_q contain EW params including M_Z
- propagator term: $P_Z = \frac{M_Z^2}{Q^2 + M_Z^2}$
- xF_3 parity-violating structure function
- $F_L \neq 0 \Rightarrow$ NLO QCD depends on gluons
- Presence of gluon $\Rightarrow$ scaling violation $F_2(x, Q^2)$

$\boxed{Q^2 << M_Z^2}$

- Only γ exchange
- xF_3 contribution small
- Sensitive to F_L for $y \gtrsim 0.5$
- $\frac{d^2\sigma}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4} Y_+ F_2(x, Q^2)$

$\boxed{Q^2 \gtrsim M_Z^2}$

- γ and Z exchange
- Sensitive to xF_3
- F_L small

CC DIS Cross Section Formulae

Charged Current: $e^{\pm}p \to `\bar{\nu}' X$

$$\frac{d^2\sigma^{\text{BORN}}}{dx\,dQ^2}(e^+) = \frac{G_F^2}{2\pi} P_W^2 \left[(\bar{u} + \bar{c}) + (1-y)^2(d + s)\right]$$

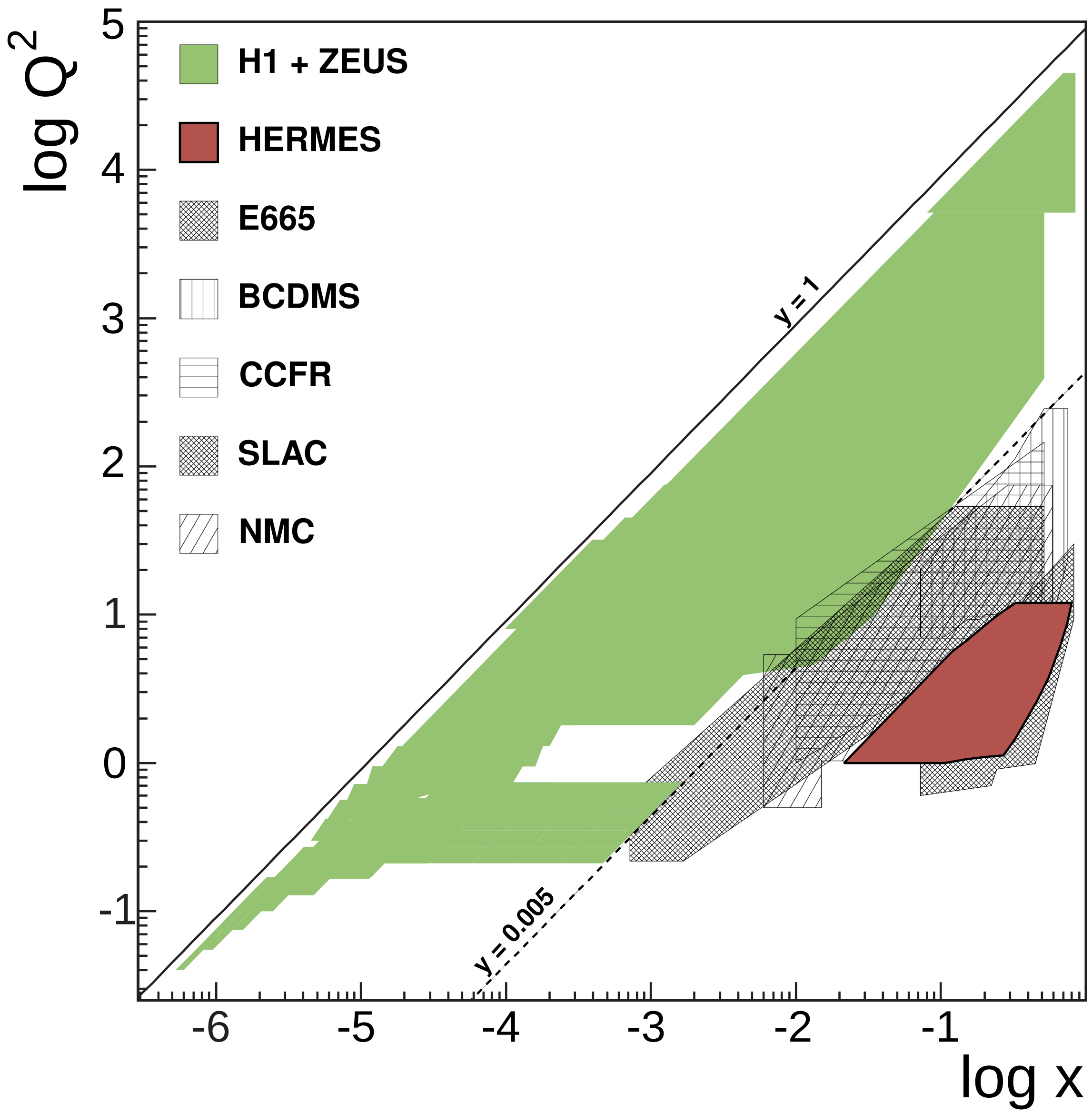
$$\frac{d^2\sigma^{\text{BORN}}}{dx\,dQ^2}(e^-) = \frac{G_F^2}{2\pi} P_W^2 \left[(u + c) + (1-y)^2(\bar{d} + \bar{s})\right]$$

$$P_W = \frac{M_W^2}{Q^2 + M_W^2}$$

- e^+ and e^- couple to different quark flavors
  $e^+p \Rightarrow d,\ \bar{u}$ sensitivity
  $e^-p \Rightarrow u,\ \bar{d}$ sensitivity

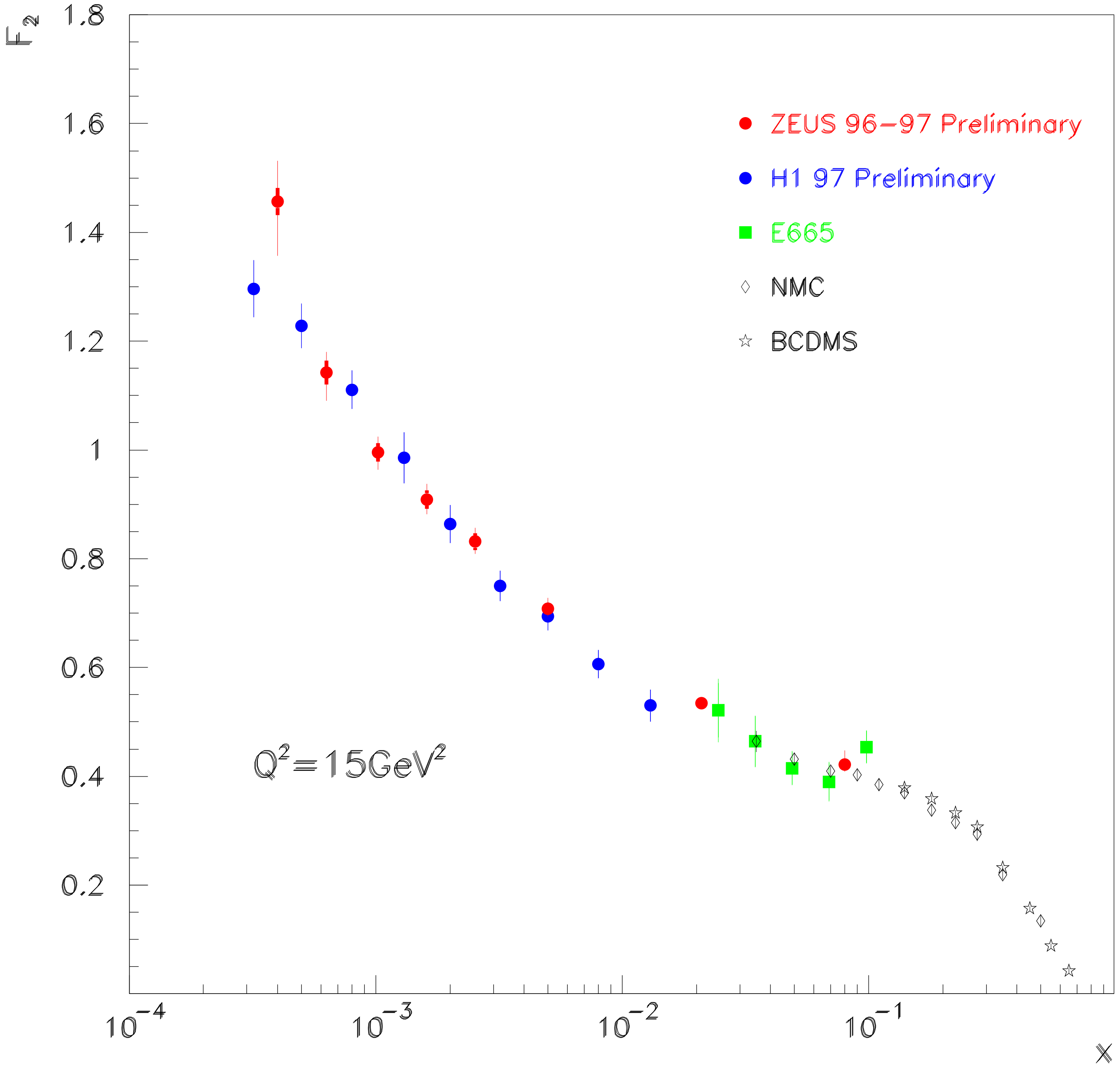
- $P_W \Rightarrow \begin{cases} \text{low } Q^2\text{:} & \text{weak } Q^2 \text{ dependence} \\ \text{high } Q^2\text{:} & \text{sensitivity to } W \text{ mass} \end{cases}$

HERA Kinematic Range



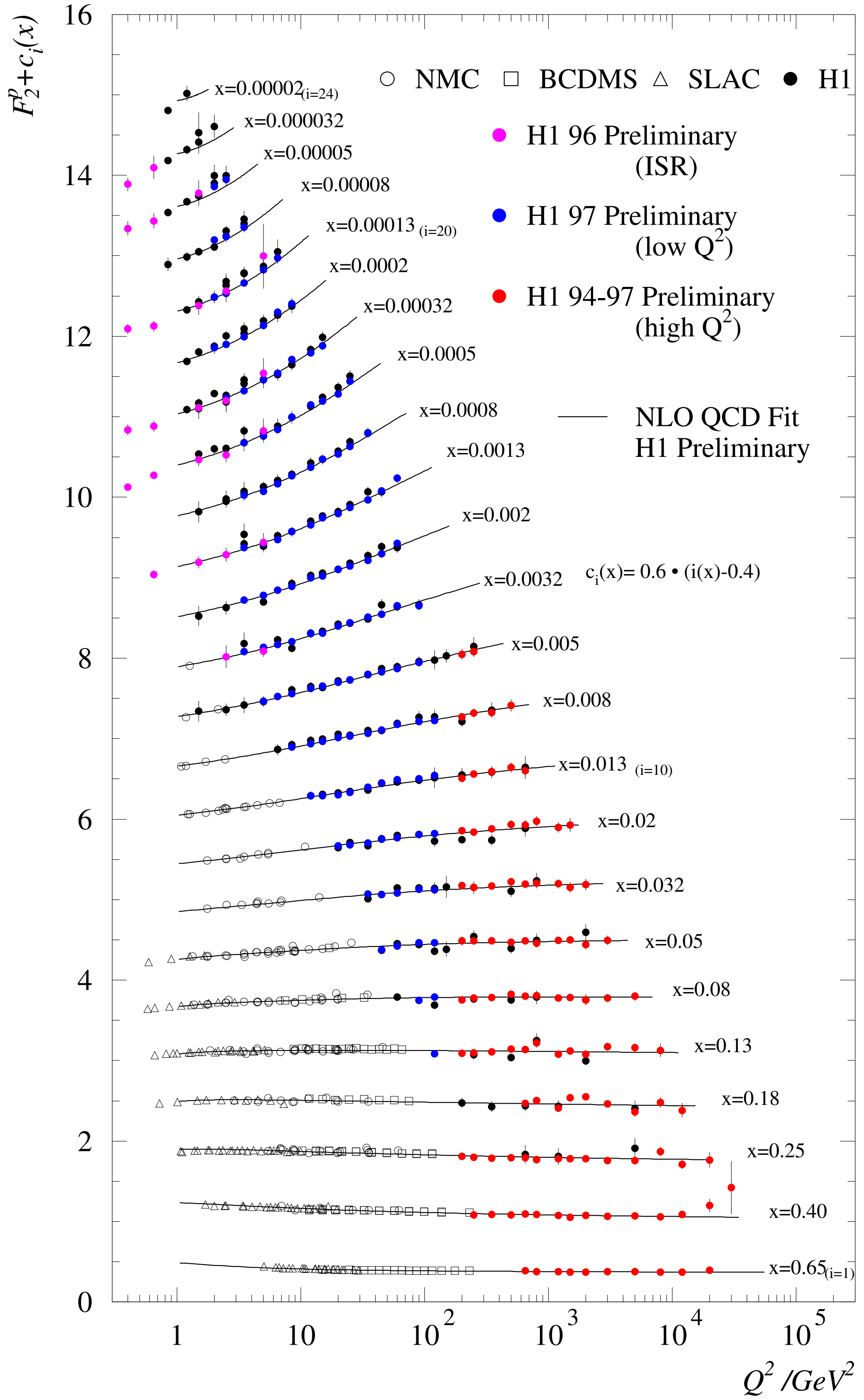
- low y: overlap with fixed-target experiments
- high y: sensitivity to F_L
- low Q^2: transition from $\gamma^* p$ to γp
- medium Q^2: tests of pQCD
- high Q^2: electroweak studies, exotics searches

Overview of F_2



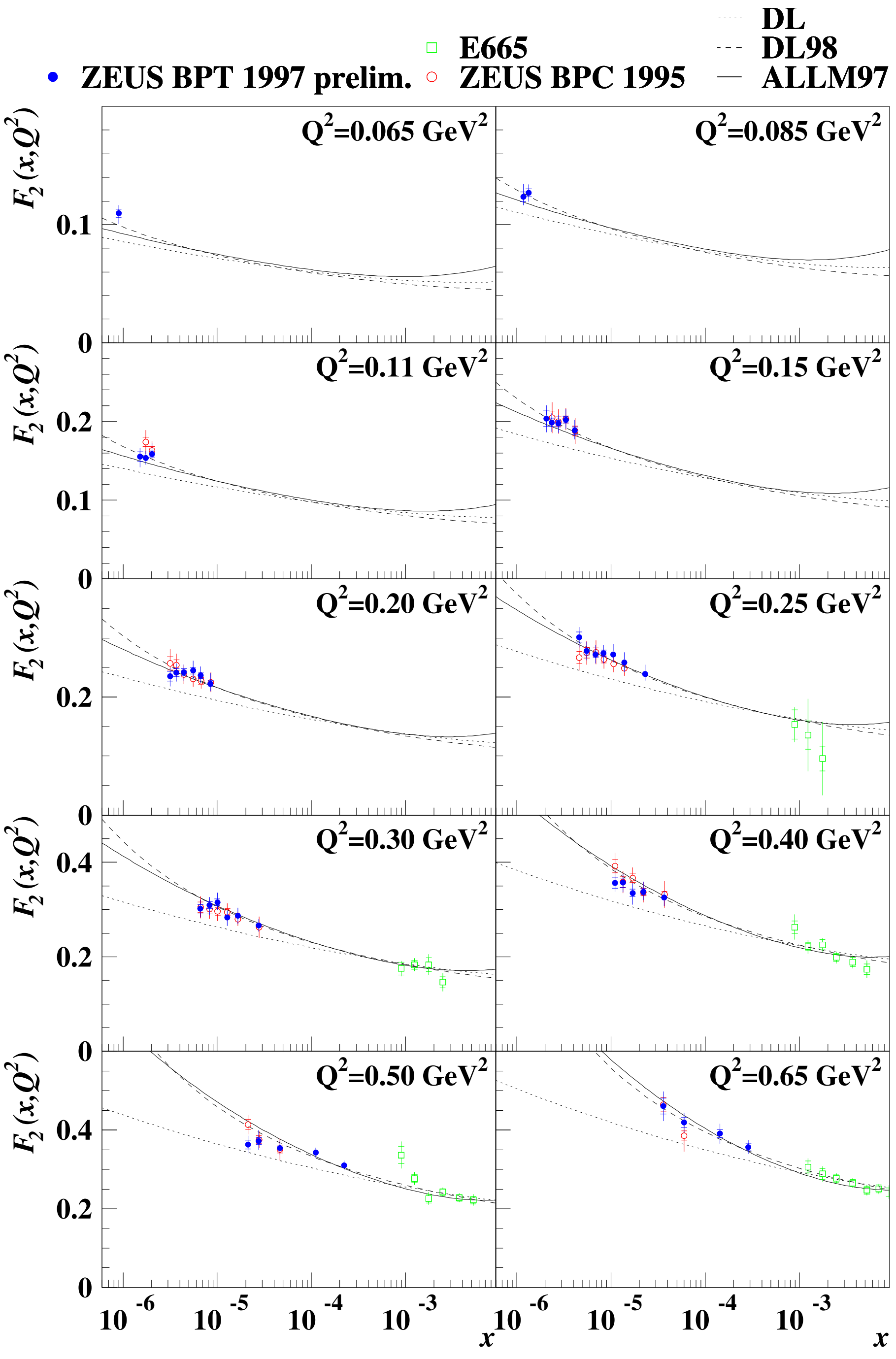
- fixed-target experiments measured high x
  $\Rightarrow$ valence quarks
- strong rise of F_2 with decreasing x
  low x $\Rightarrow$ sea quarks $\Rightarrow$ rising gluon
- good agreement among ZEUS/H1/fixed-target

H1 F_2 Scaling 1994-1997



- Scaling at $x \sim 0.1$ up to $Q^2 \sim 5000\,\text{GeV}^2$
- Scaling violations strongly increase at low x
  $\Rightarrow$ strong increase of gluon at low x

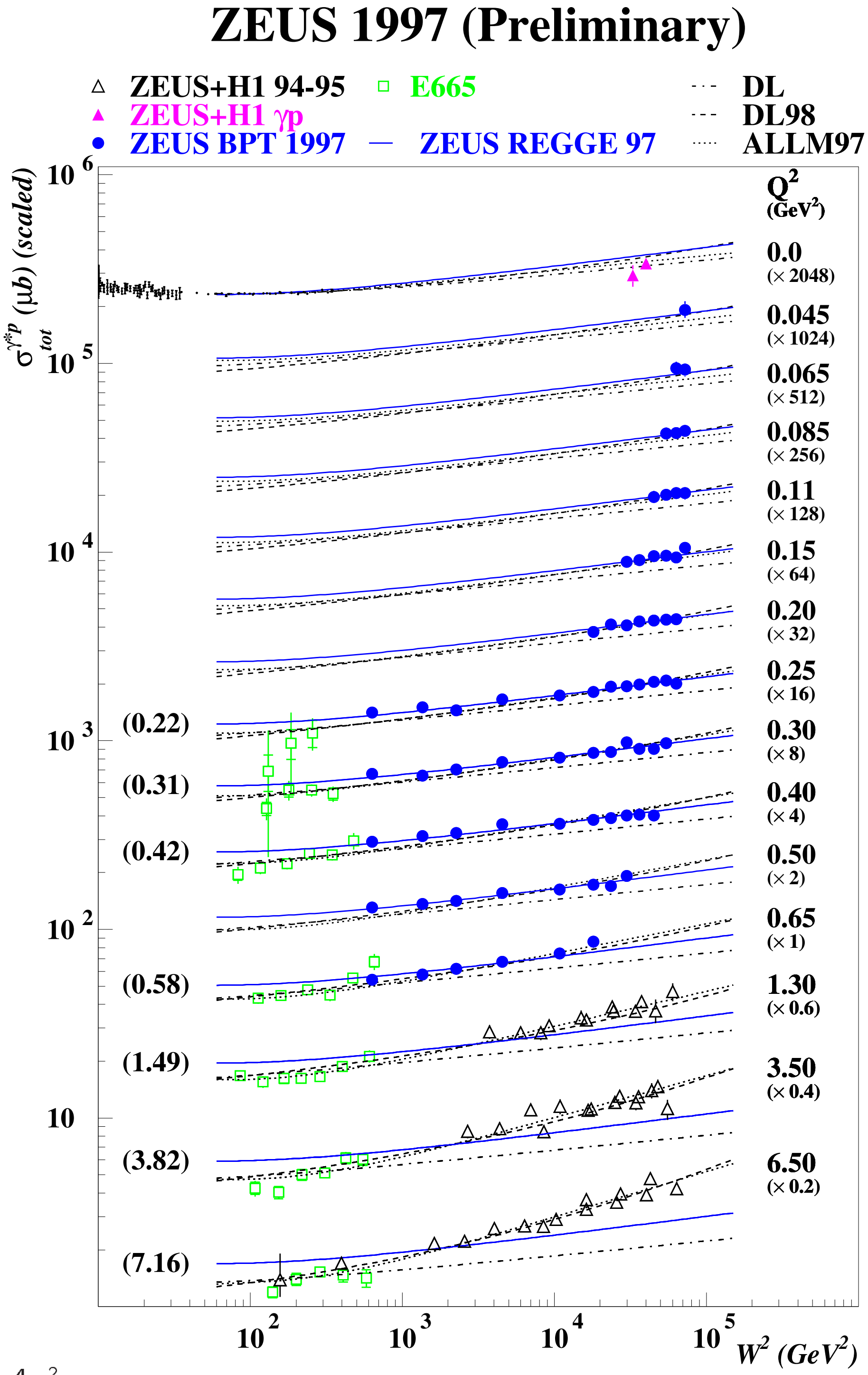
ZEUS BPC/BPT F_2 1997



- Beampipe detectors (BPC/BPT):
  Kinematic region $\rightarrow$ lower Q^2 and lower x

- F_2 rises even at lowest Q^2

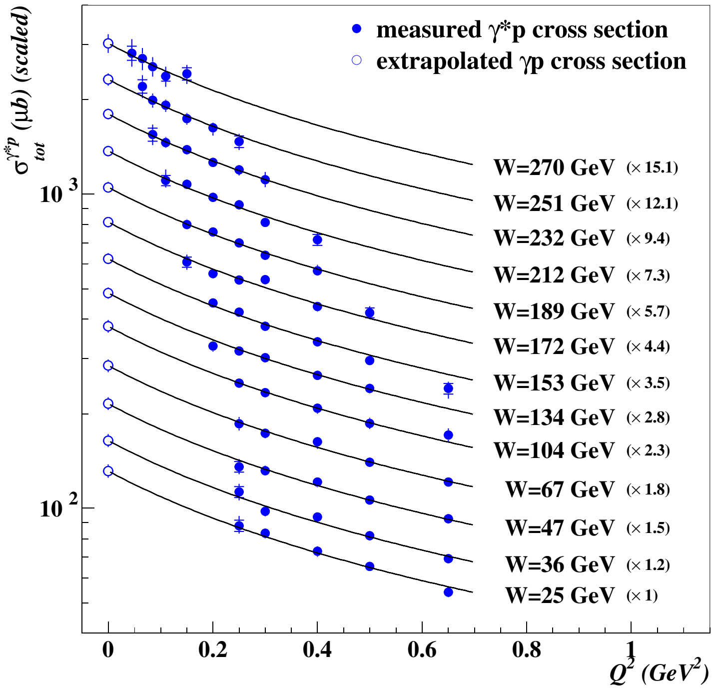
ZEUS BPC/BPT $\sigma_{tot}^{\gamma^* p}(W^2)$



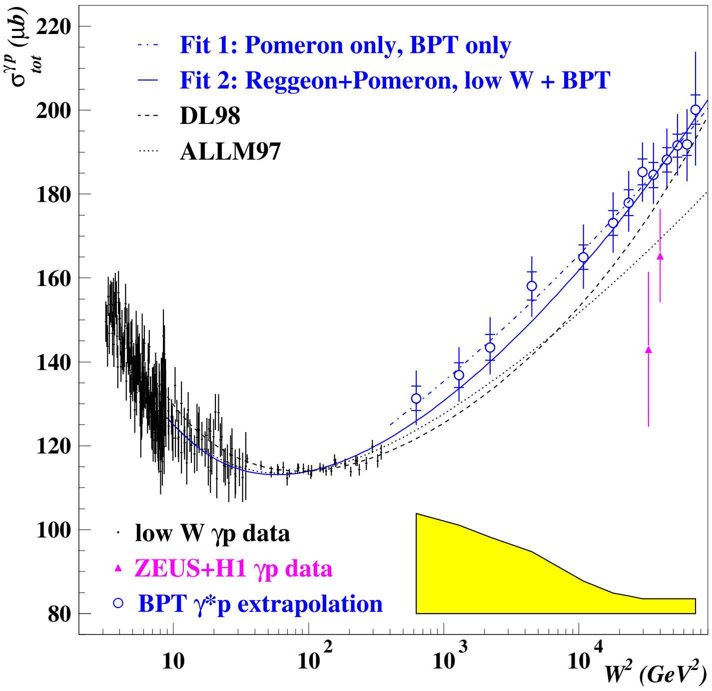
- $\sigma_{tot}^{\gamma^* p} = \frac{4\pi^2\alpha}{Q^2} F_2$
- rise of F_2 at low $x \Rightarrow \sigma_{tot}^{\gamma^* p} \sim Q^2/x$ at high W^2
- low Q^2: $\sigma_{tot}^{\gamma^* p} \propto (W^2)^{0.11}$
- high Q^2: $\sigma_{tot}^{\gamma^* p} \propto (W^2)^{0.2-0.4}$

ZEUS BPC/BPT extract $\sigma_{tot}^{\gamma p}$ 1997

ZEUS 1997 (Preliminary)



ZEUS 1997 (Preliminary)



- Improved range and statistics w.r.t. ZEUS 95
- GVDM fit $\Rightarrow$ extrapolate to $Q^2 \sim 0$

$$\sigma_{tot}^{\gamma^* p}(W^2, Q^2) = \left(\frac{m_0^2}{m_0^2 + Q^2}\right) \sigma_{tot}^{\gamma p}(W^2) \; ; \; m_0 \approx m_\rho$$

- Regge-type fits ($I\!\!P + I\!\!R$) $\Rightarrow W$ dependence

$$\sigma_{tot}^{\gamma^* p}(W^2, Q^2) = A_{I\!\!R} W^{2(\alpha_{I\!\!R}-1)} + A_{I\!\!P} W^{2(\alpha_{I\!\!P}-1)}$$

- Error band an estimate of model dependence

Extraction of F_L (H1)

- Method1: subtraction method

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

Measure σ_r for $y < 0.35$ (∼no F_L)

Fit F_2 at high y

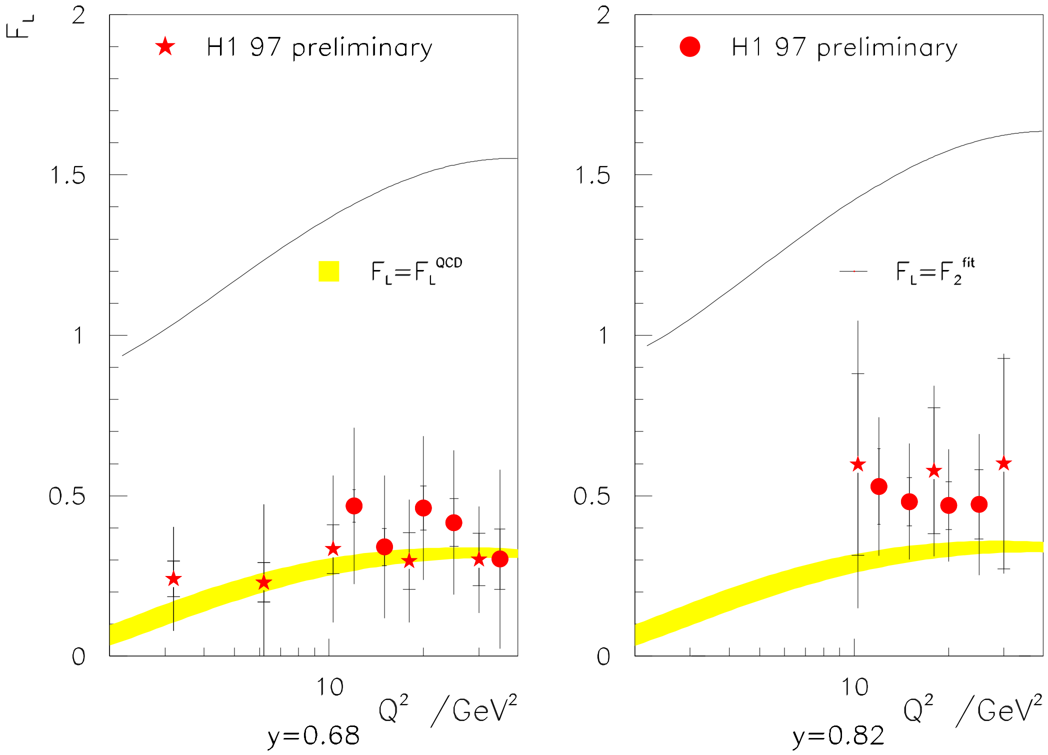
subtract out $F_L = \frac{Y_+}{y^2}\left(F_2^{fit} - \sigma_r\right)$

⋆ Method2: derivative method

$$\boxed{\frac{d\sigma}{d\ln y} = -\frac{dF_2}{d\ln y} - F_L \cdot 2y^2 \cdot \frac{2-y}{Y_+^2} + \frac{dF_L}{d\ln y}\cdot\frac{y^2}{Y_+}}$$

Assume $dF_2/d\ln y = A\ln y + B$

Straight-line fit to $d\sigma/d\ln y$ in Q^2 bins at $y < 0.2$



- Extracted F_L compatible with QCD prediction
- Same data, different data characteristics → agreement
- Slight tendency $F_L > F_L^{\rm QCD}$ at highest y (corr errors)
- Direct meas requires diff beam energies or ISR analysis

ZEUS and H1 NLO fits

Phenomenological Assumptions:

- DGLAP predicts Q^2 F_2 slope given PDF's at Q_0^2
  must input PDF x-dependence at Q_0^2
- $\overline{MS}$ renormalization
- Fixed-flavor-number scheme with u,d,s massless
- s=20% of sea at Q_0^2
- $S = 2(\bar{u} + \bar{d} + \bar{s})$
- Sea norm (mom sum rule): $\int_0^1 dx\, x\, (g + S + u_v + d_v) = 1$
- q counting rules $\int_0^1 dx\, u_v = 2$; $\int_0^1 dx\, d_v = 1$
- c from NLO γGF (Riemersma et al.), $m_c = 1.5 \pm 0.2$ GeV
- $\alpha_s(M_Z^2) = 0.118 \pm 0.005$
- $x\Sigma = \sum_i (xq_i + x\bar{q}_i) \simeq xS$ at low x

Input PDF's at starting scale Q_0^2:

$$xq(x, Q_0^2) = A_q x^{B_q} (1 - x)^{C_q} (1 + D_q x + E_q \sqrt{x})$$

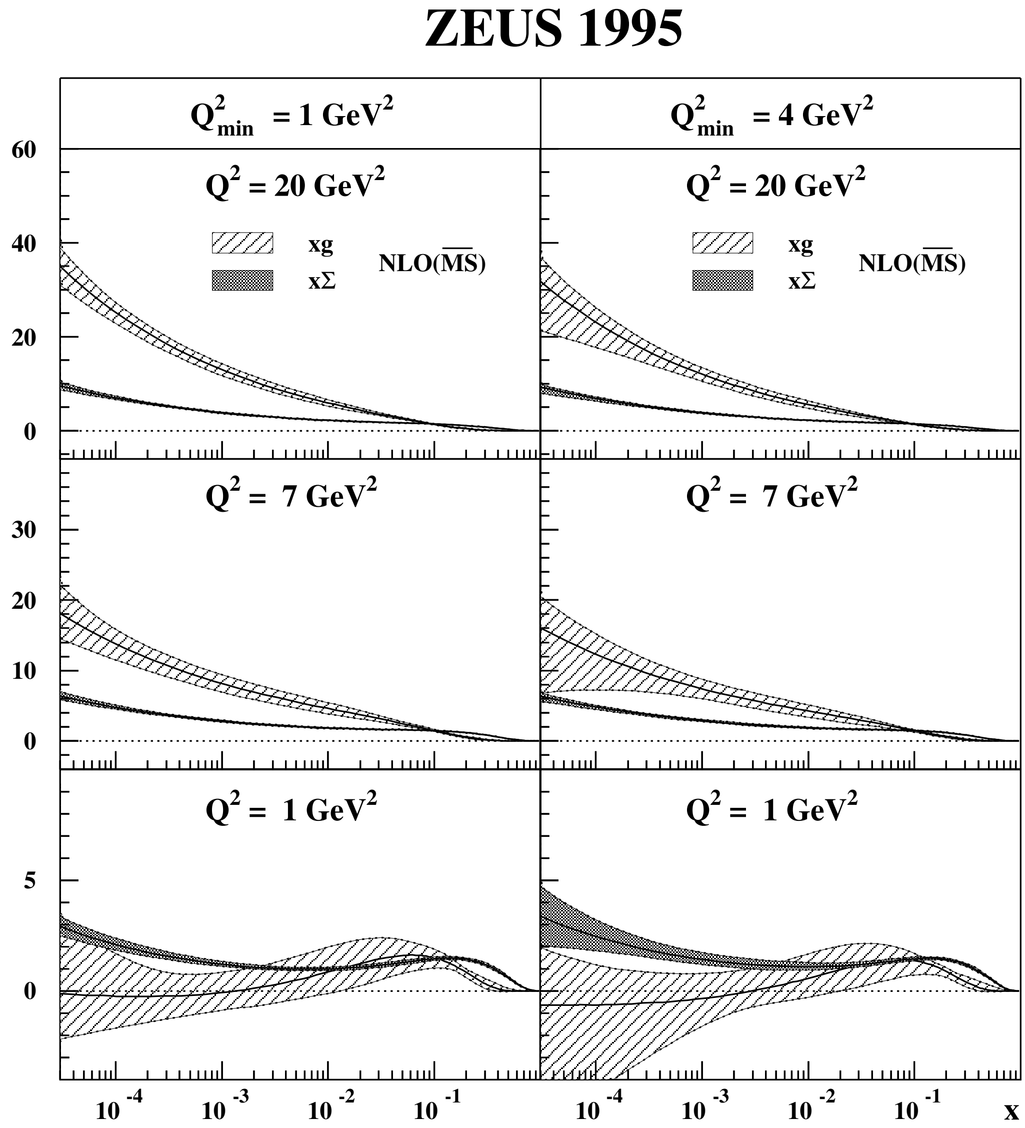
where q = gluon, valence u and d, sea quarks
fit parameters A_q, B_q, C_q, D_q, E_q

Data sets used:

ZEUS: 94+95 data $3 \cdot 10^{-5} < x < 0.7$ and $1 < Q^2 < 5000\text{GeV}^2$
NMC and BCDMS p+d data (correl. syst. errors)
$Q_0^2 = 7\text{GeV}^2$

H1: 94–97 data $Q^2 > 5\text{GeV}^2, Q^2 > 15\text{GeV}^2$ for $x > 0.5$
NMC and BCDMS p+d data (correl. syst. errors)
$Q_0^2 = 2\text{GeV}^2$
$D_g = 0$

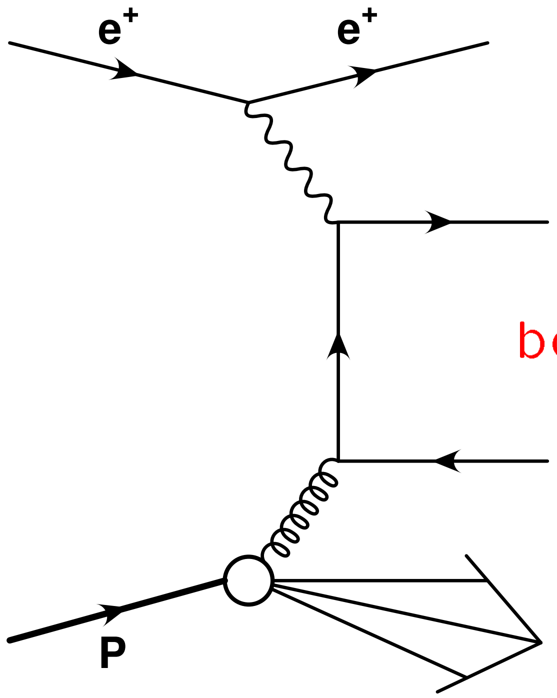
Gluon in NLO QCD F_2 fit (ZEUS)



- large gluon density at low x in DIS
- gluons decrease at low Q^2 as $\Rightarrow \gamma p$ limit

$\Rightarrow$ rapid rise in F_2 not driven by rapid increase in gluon density at small x from parton splitting only

BGF sensitive to gluons in proton



boson-gluon fusion (BGF)

Inclusive D^* production

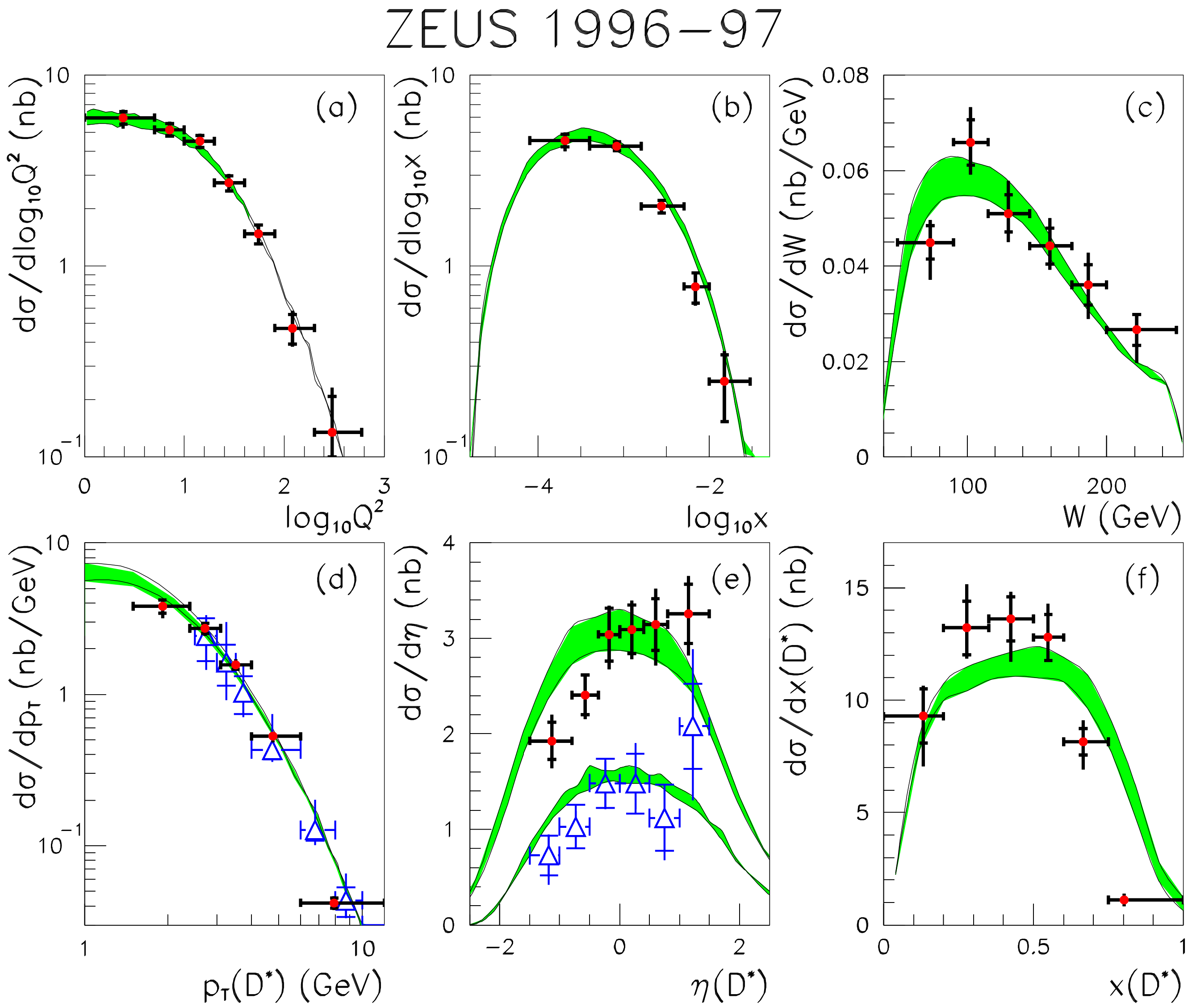
$$\boxed{\begin{aligned} e^+ p \to e^+ \, & D^{*\pm} X \\ & \to D^0 \pi^\pm \\ & \qquad \to K\pi \text{ or } K\pi\pi\pi \end{aligned}}$$

Dijet production

Sensitivity to gluon for these processes

F_2^c: Charm in the Proton (ZEUS)

Inclusive D^* production



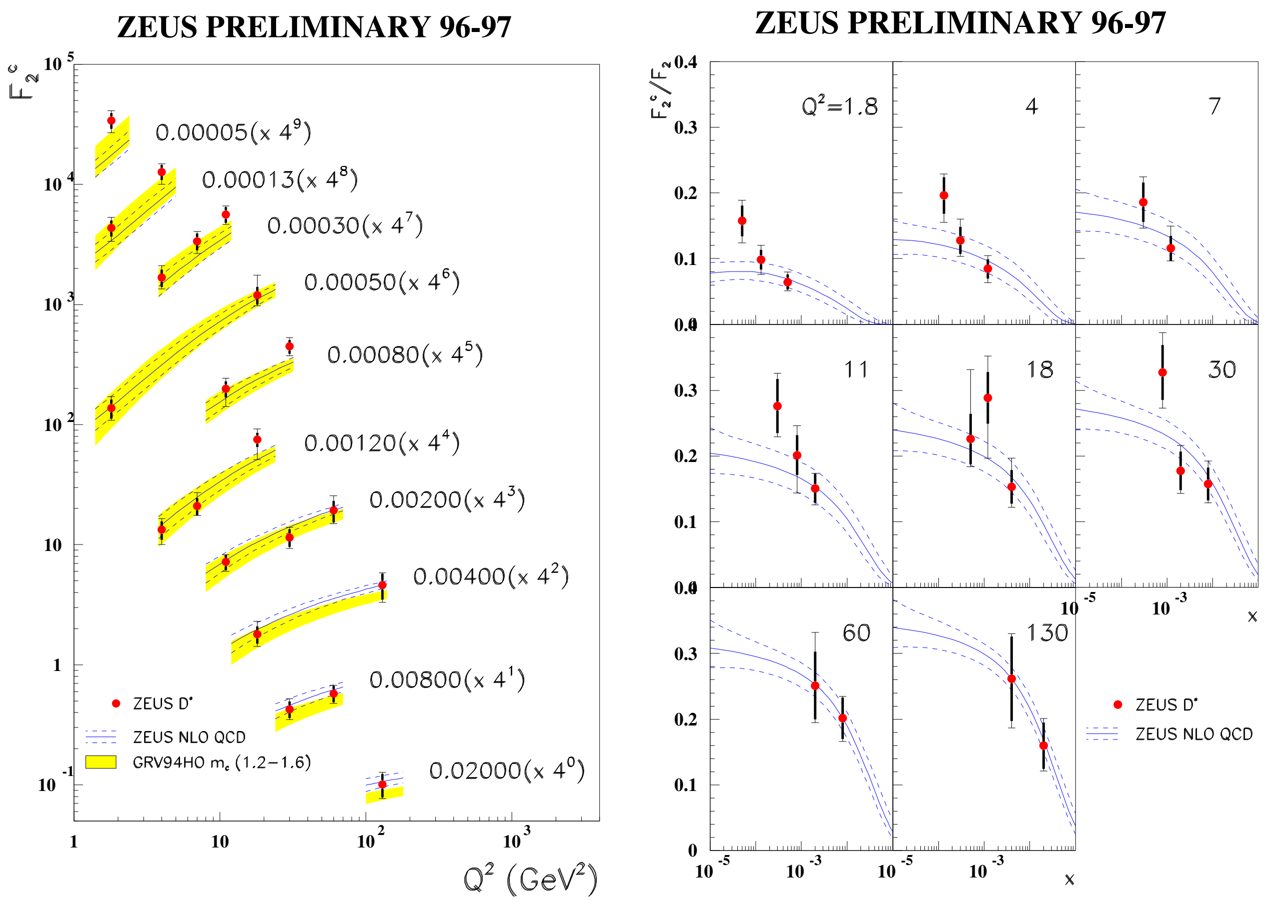
● $D \to K\pi$ △ $D \to K\pi\pi\pi$

- NLO Calculation (Harris and Smith)
- Modified Peterson fragmentation function $c \to D^*$
- Branching ratio $D^{*\pm} \to D^0 \pi_s^\pm$ (PDG)
- F_L^c small ($\sim 1\%$), neglected

Extrapolate to full phase space

Charm Contribution to F_2 (ZEUS)

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

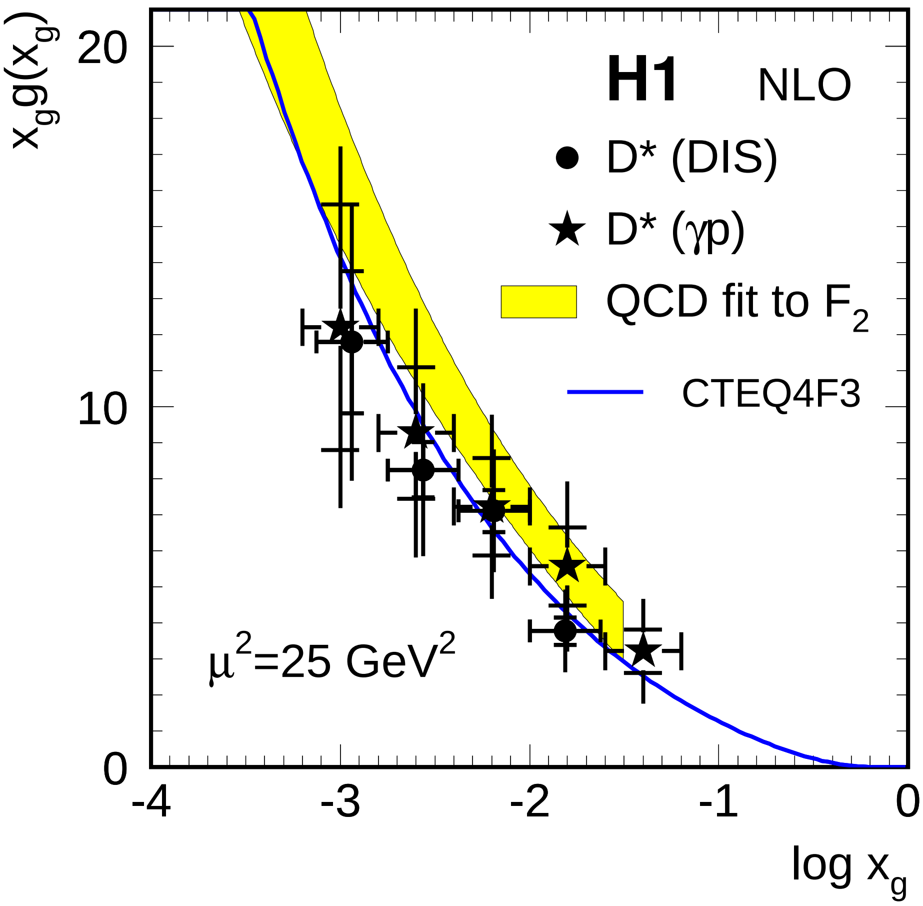


- $1.2 < m_c < 1.6$ GeV shown as band
- good agreement with NLO QCD fit

  Consistent gluon picture
- strong scaling violations $\Rightarrow$ rising gluon
- rise of F_2^c stronger than F_2
- increase of proton charm content with Q^2

Gluon Density from Charm (H1)

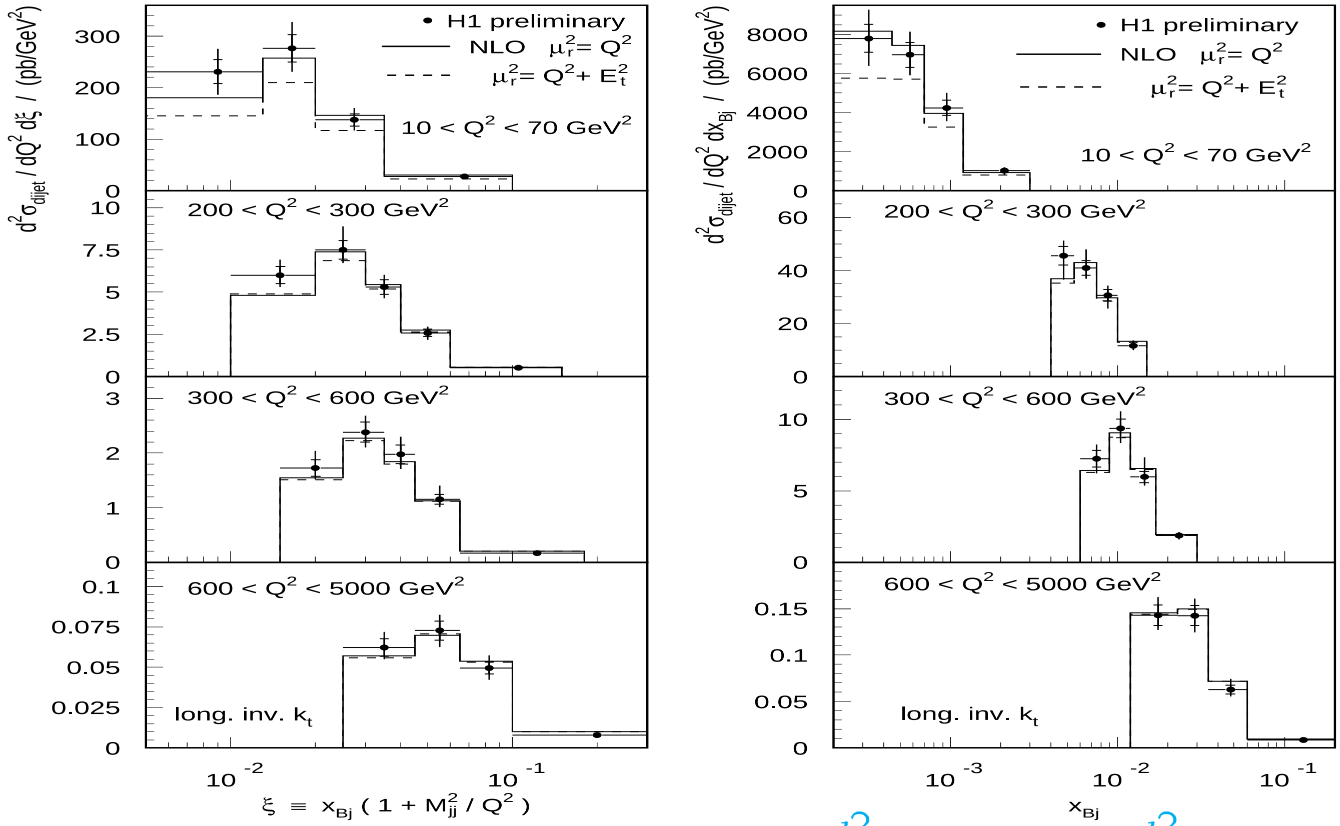
Extract gluon density from D^* in DIS/γp



- Steep rise of gluon for decreasing x
- DIS and γp results agree very well

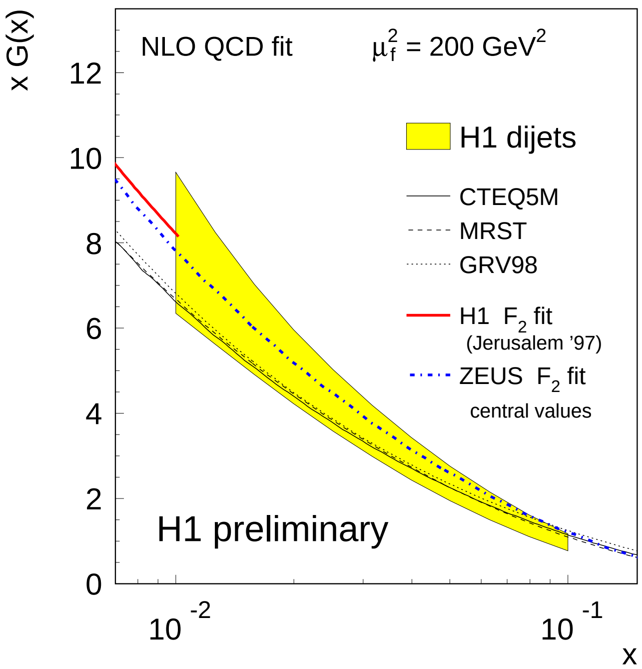
Gluon distribution from dijets (H1)

Mainly boson-gluon fusion



From an NLO QCD fit to $\frac{d^2\sigma}{dQ^2 d\xi}$ and $\frac{d^2\sigma}{dQ^2 dx_{Bj}}$

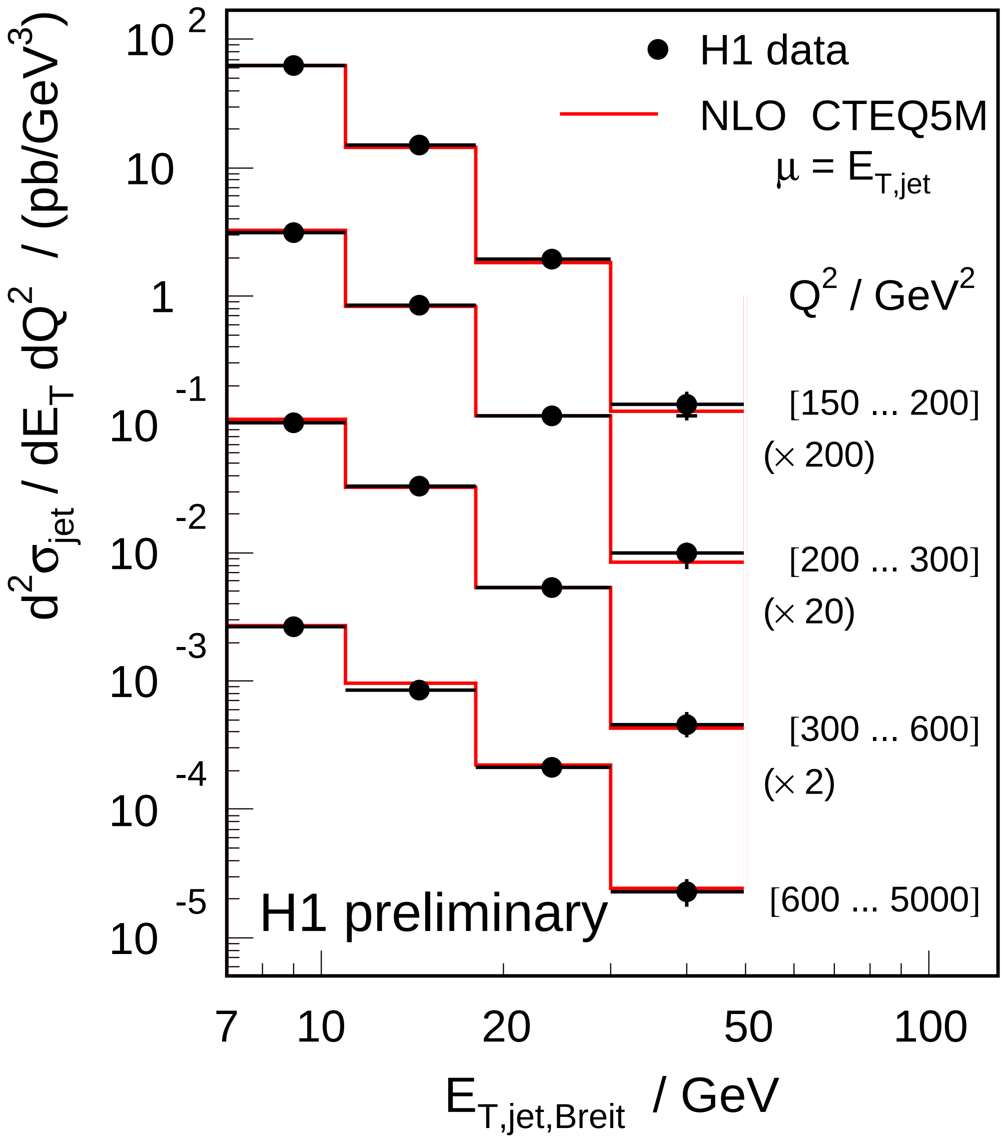
(quark densities from F_2, α_s fixed)



Get the same
GLUON
as in F_2 and F_2^c
using H1 data only

Measuring α_s with jets (H1)

Inclusive jet cross section with $E_T^{\text{jet}} > 7$ GeV

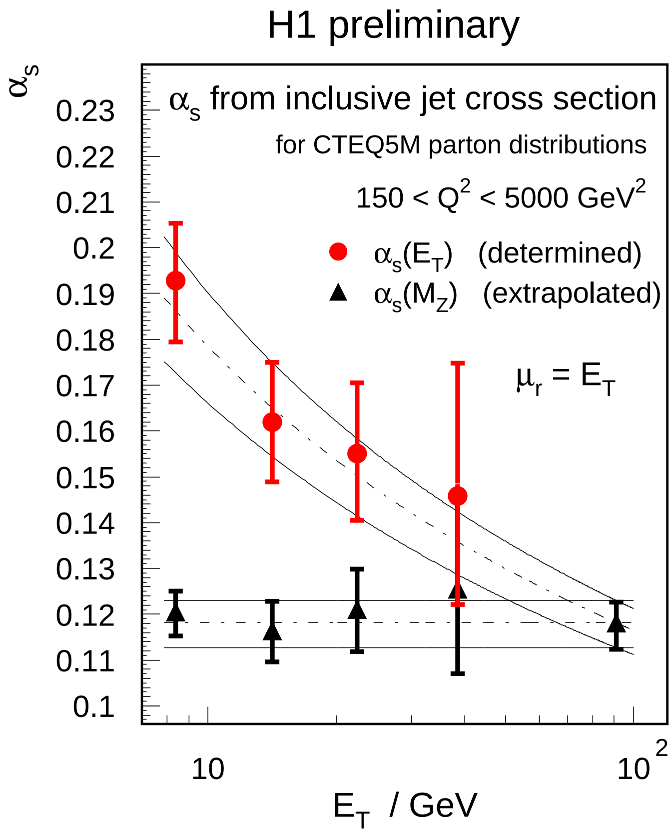


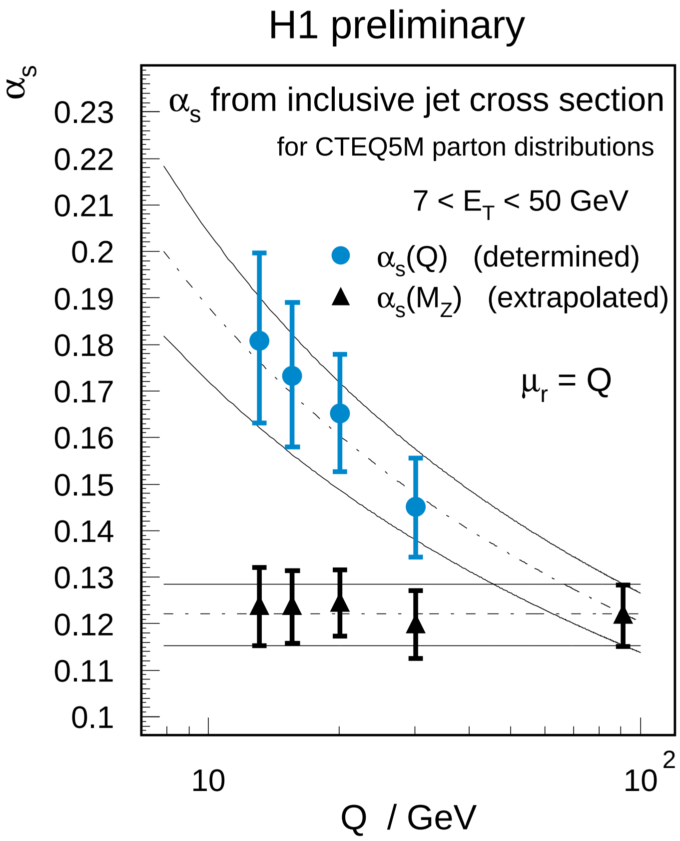
α_s determined from combined NLO QCD fit to above data points including correlations

$\alpha_s(M_Z)$
$$= 0.1181 \pm 0.0030(\text{exp})^{+0.0039}_{-0.0046}(\text{th})^{+0.0036}_{-0.0015}(\text{PDF})$$

world average (S. Bethke '98): $\alpha_s(M_Z) = 0.119 \pm 0.004$

Measuring α_s with jets (H1)

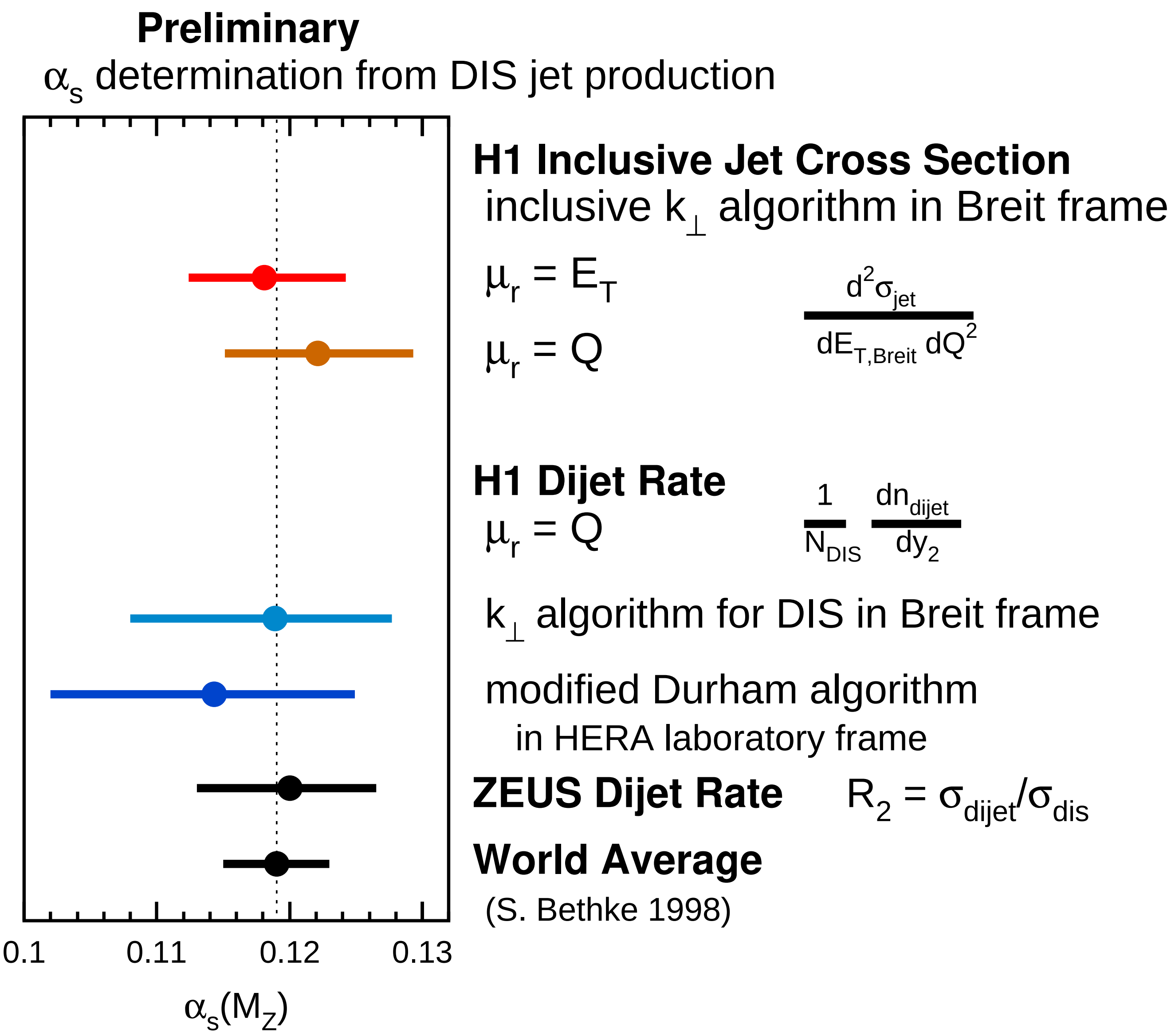




Note: right-most triangle result of combined fit

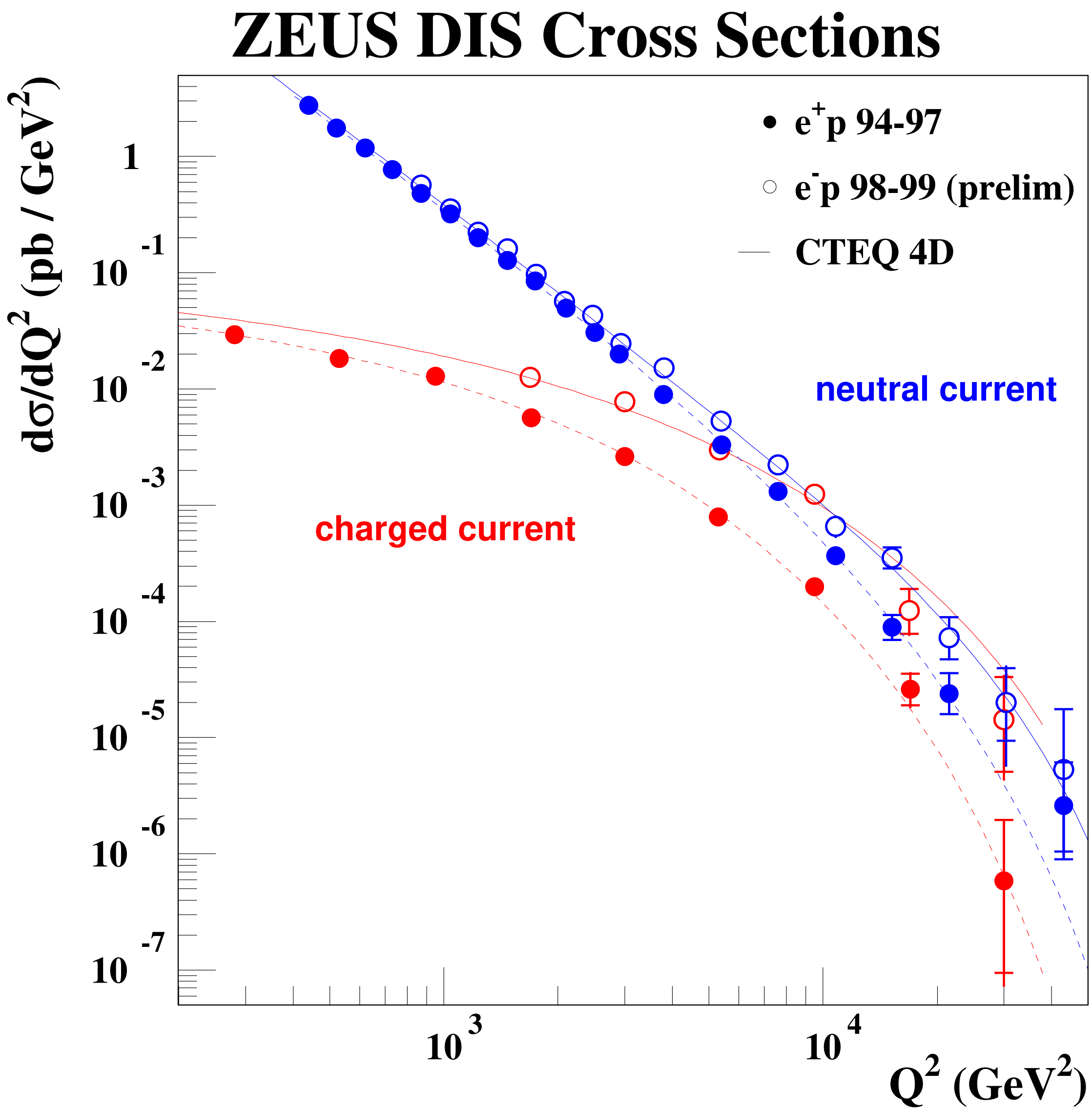
- α_s determined from separated NLO QCD fit to data points on previous slide
- Running of α_s consistent with expectation

Summary: measuring α_s with jets



- ★ Similar α_s obtained from dijet event rate (H1) and dijet event rate (ZEUS) (not described)
- ★ Competitive measurements by ZEUS and H1
- ★ Results agree with world average

High-Q^2 NC/CC cross sections (ZEUS)

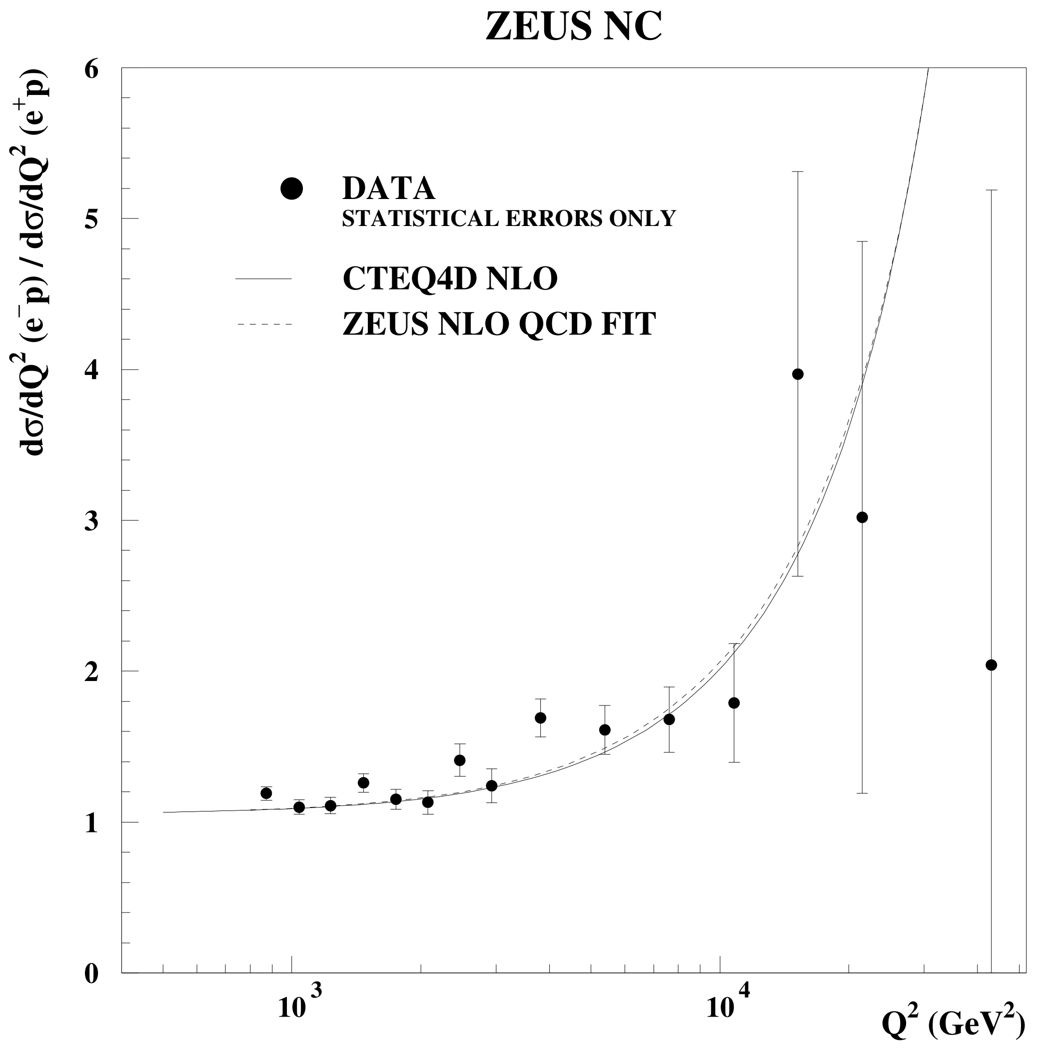


- Electroweak unification scale $\sim 10^4$
  At $Q^2 \gtrsim 10^4$ NC $\approx$ CC
- Statistical precision limited at high x/high Q^2
- Cross sections sensitive to valence quark densities and electroweak parameters

Electron-proton collisions at ZEUS

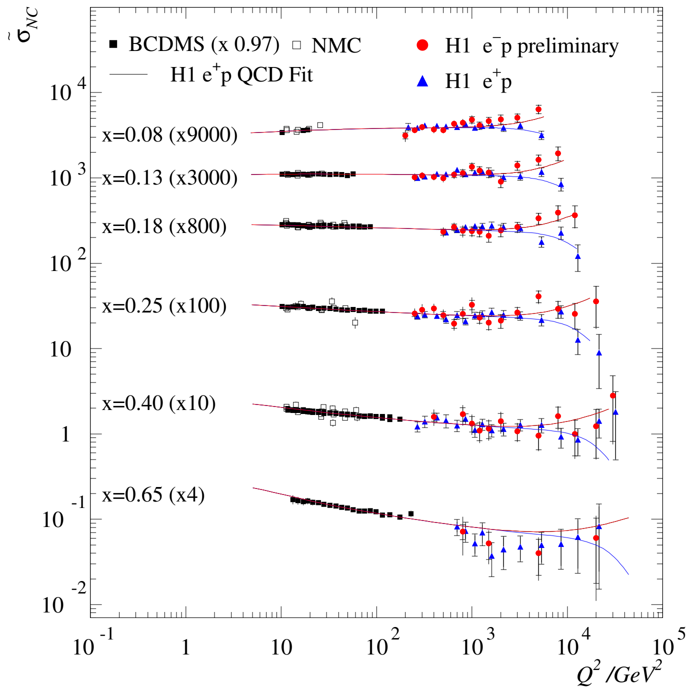
$$\frac{d^2\sigma}{dx\,dQ^2}(e^{\pm}p) = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+ F_2^{NC} \mp Y_- \, xF_3^{NC} - y^2 F_L\right]$$

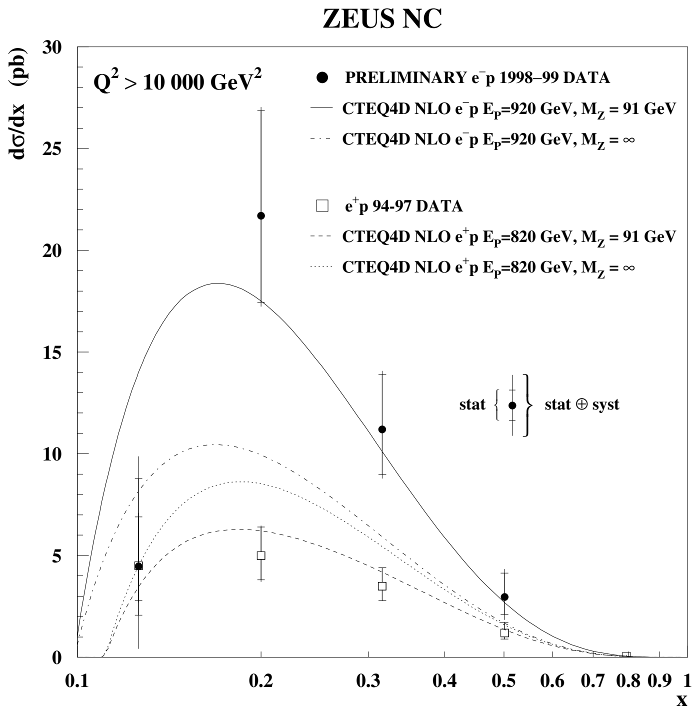
$$xF_3 = \frac{Q^4}{4\pi\alpha^2}\left[\frac{d^2\sigma}{dx\,dQ^2}(e^- p) - \frac{d^2\sigma}{dx\,dQ^2}(e^+ p)\right]$$



Electroweak effects in high-Q^2 NC

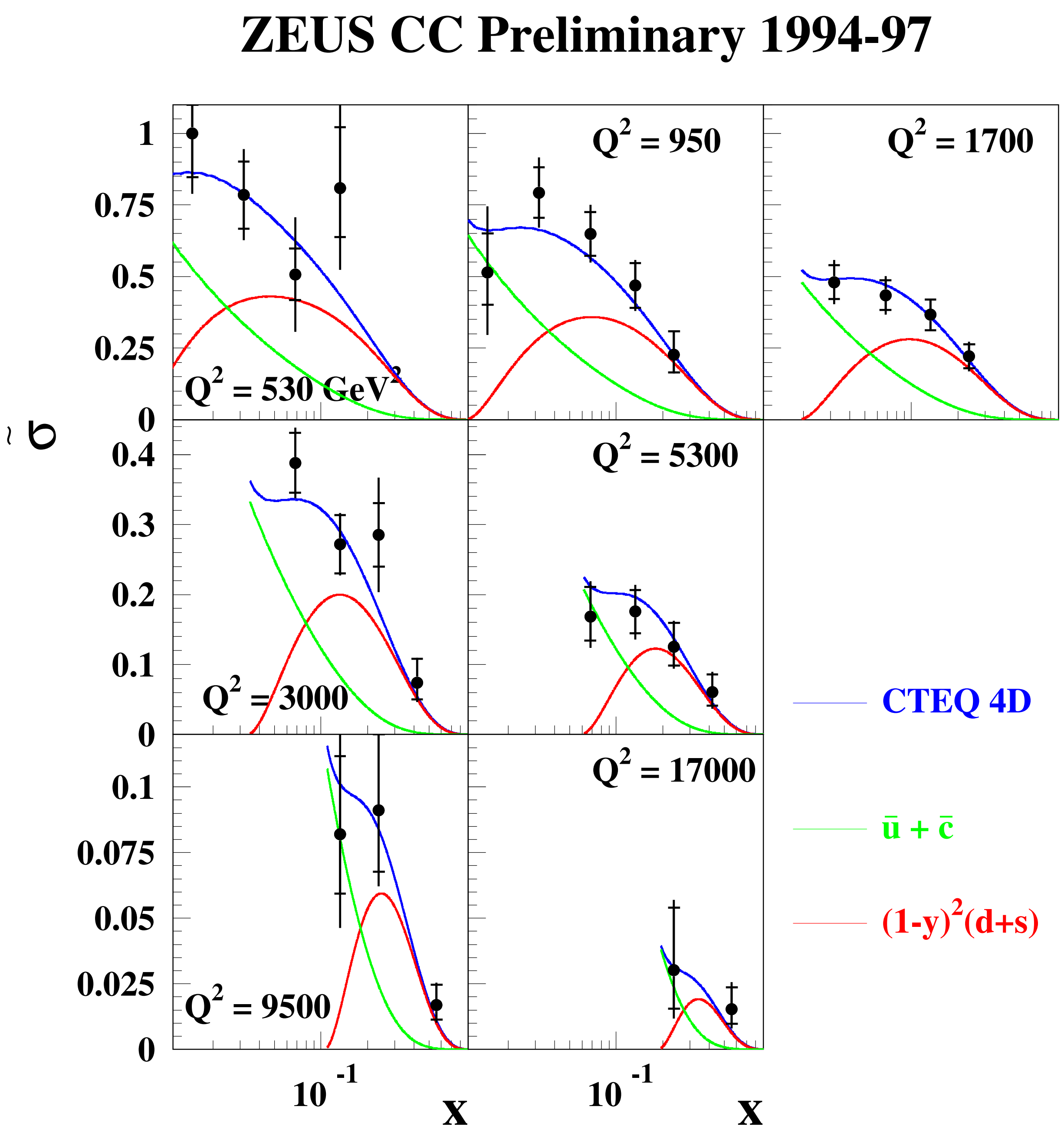
$$\sigma_r = \left(\frac{Q^4 x}{2\pi\alpha^2 Y_+} \right) \frac{d^2\sigma}{dx\, dQ^2}$$





- Evidence for $\gamma - Z$ interference
- Evidence for Z exchange in spacelike DIS

CC Weighted Cross Section $\tilde{\sigma}$

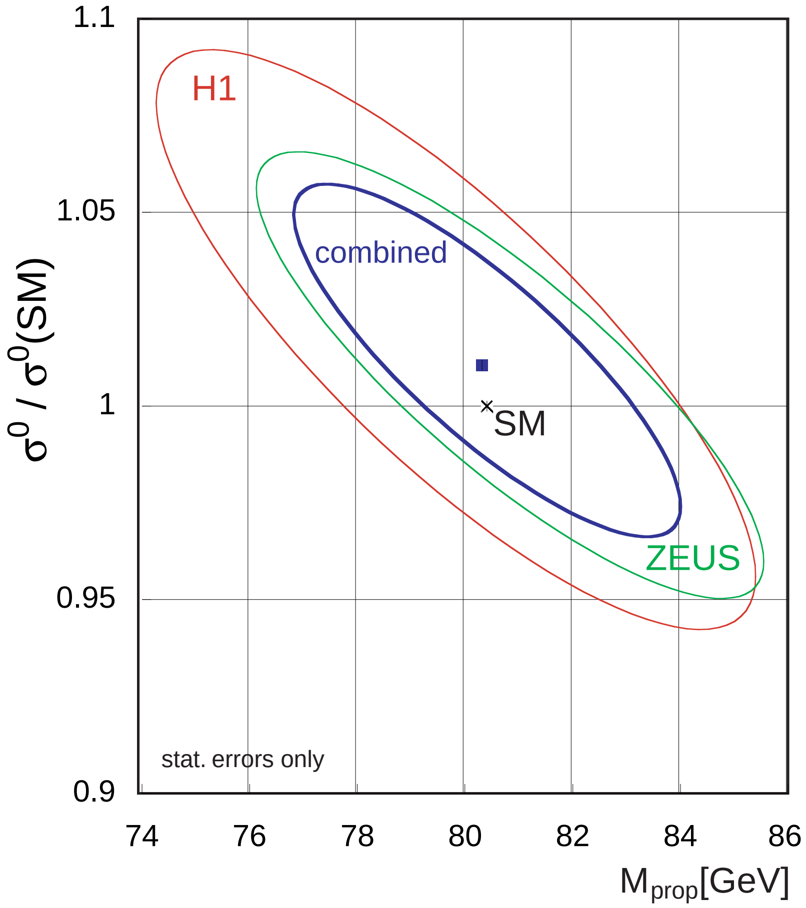


- Sensitivity to PDF's:

$$\tilde{\sigma} = \frac{d^2\sigma}{dx dQ^2} \cdot \frac{2\pi x}{G_F^2} \cdot \left(\frac{M_W^2}{Q^2 + M_W^2}\right)^{-2}$$
$$= x(\bar{u} + \bar{c}) + x(1-y)^2(d+s)$$

CC sensitivity to sea and d quarks !

Propagator mass M_W



- Sensitivity to M_W from CC propagator terms

ep	spacelike measurement of M_W
e^+e^-, $p\bar{p}$	timelike measurement of M_W

- χ^2–fit SM to data (other EW params fixed):

$$\boxed{\begin{array}{l}\text{ZEUS: } M_W = 78.6^{+2.5}_{-2.4}\,{}^{+3.3}_{-3.0}\text{ GeV} \\ \text{H1: } M_W = 81.2 \pm 3.3 \pm 4.3\text{ GeV}\end{array}}$$

$$M_W = 80.41 \pm 0.10 \text{ (PDB 98)}$$

- Confirm EW prediction in spacelike regime

Conclusions and Outlook

- H1 and ZEUS testing QCD and measuring proton structure in new kinematic regions
  $4 \times 10^{-2} \lesssim Q^2 \lesssim 2 \times 10^4$ and $2 \times 10^{-5} \lesssim x \lesssim 7 \times 10^{-1}$

  - low Q^2 DIS probes transition between soft physics and pQCD

  - NLO pQCD fits give good description of the data
    DGLAP evolution still works even at very low Q^2

  - Consistent picture of gluon from several measurements

  - Electroweak measurements in good agreement with Standard Model

- Luminosity

  2000: HERA lumi upgrade
  2001–2005: $1000\,\mathrm{pb}^{-1}$

- Future:

  - Higher precision at medium and high-Q^2
  - Greater discovery potential
  - Valence quark distributions in the proton
  - Precision electroweak physics