New Results from HERA

Camille M. Ginsburg
The Ohio State University / ZEUS

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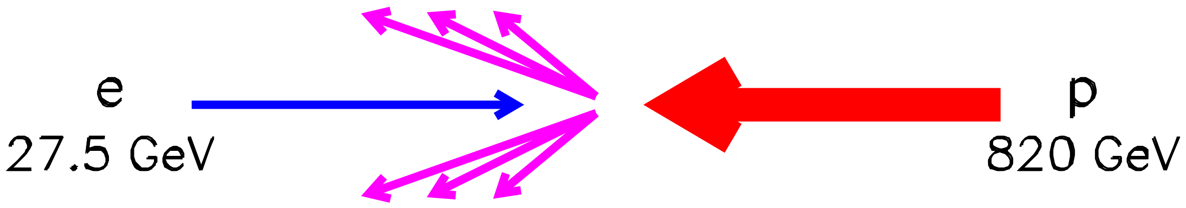
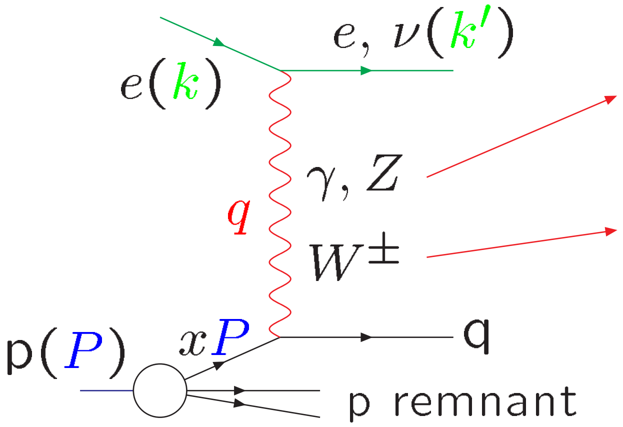
- Introduction to HERA $e^{\pm}p$ Physics
- Proton Structure
  - Proton structure functions
  - Gluon in the proton
  - Charm and Beauty production
- NC and CC DIS at high momentum transfer
- New electroweak physics at HERA
- Conclusion and Outlook

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

four–momentum transfer squared:

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

parton momentum fraction (Bjorken scaling variable):

$$x = Q^2/(2\, q \cdot P)$$

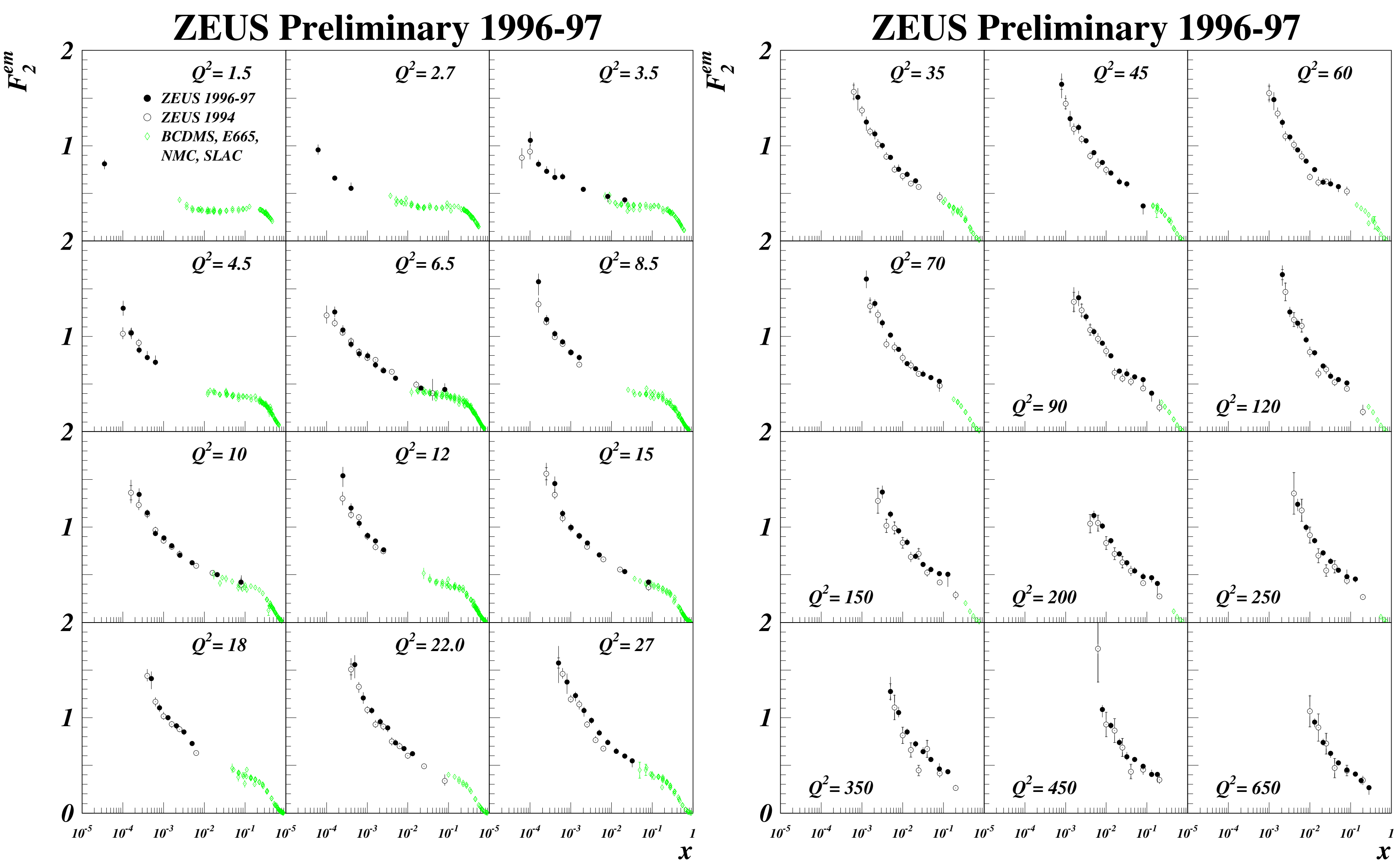
inelasticity (fractional energy transfer in p rest frame):

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

where: $Q^2 = sxy$

HERA: Q^2 up to 90,000 GeV^2 possible

The HERA $ep \to eX$ kinematic range



- HERA $ep \to eX$ data
- Extends fixed target kinematic range significantly

DIS in the Standard Model

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

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

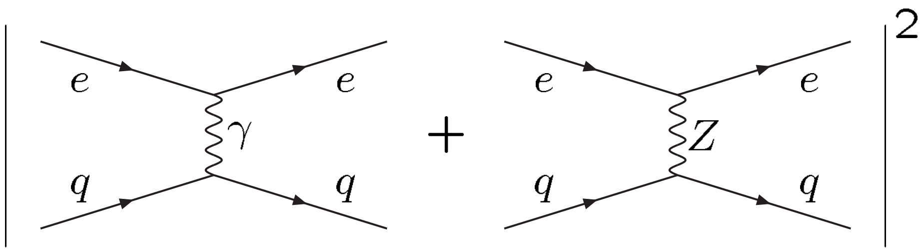
$f_{q|p} \equiv q =$ Parton distribution function (PDF)

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

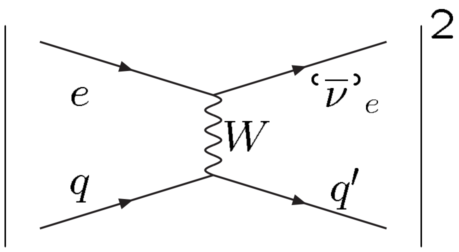
$\sigma(eq)$ = electron–quark cross–section

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

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

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

naive Quark Parton Model:

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

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

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

- A_q and B_q contain EW params including M_Z
- propagator term: $P_Z = \frac{M_Z^2}{Q^2 + M_Z^2}$
- F_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
- F_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 F_3
- F_L small

CC DIS Cross Section Formulae

Charged Current: $e^{\pm}p \rightarrow$ '$\overline{\nu}$'X

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

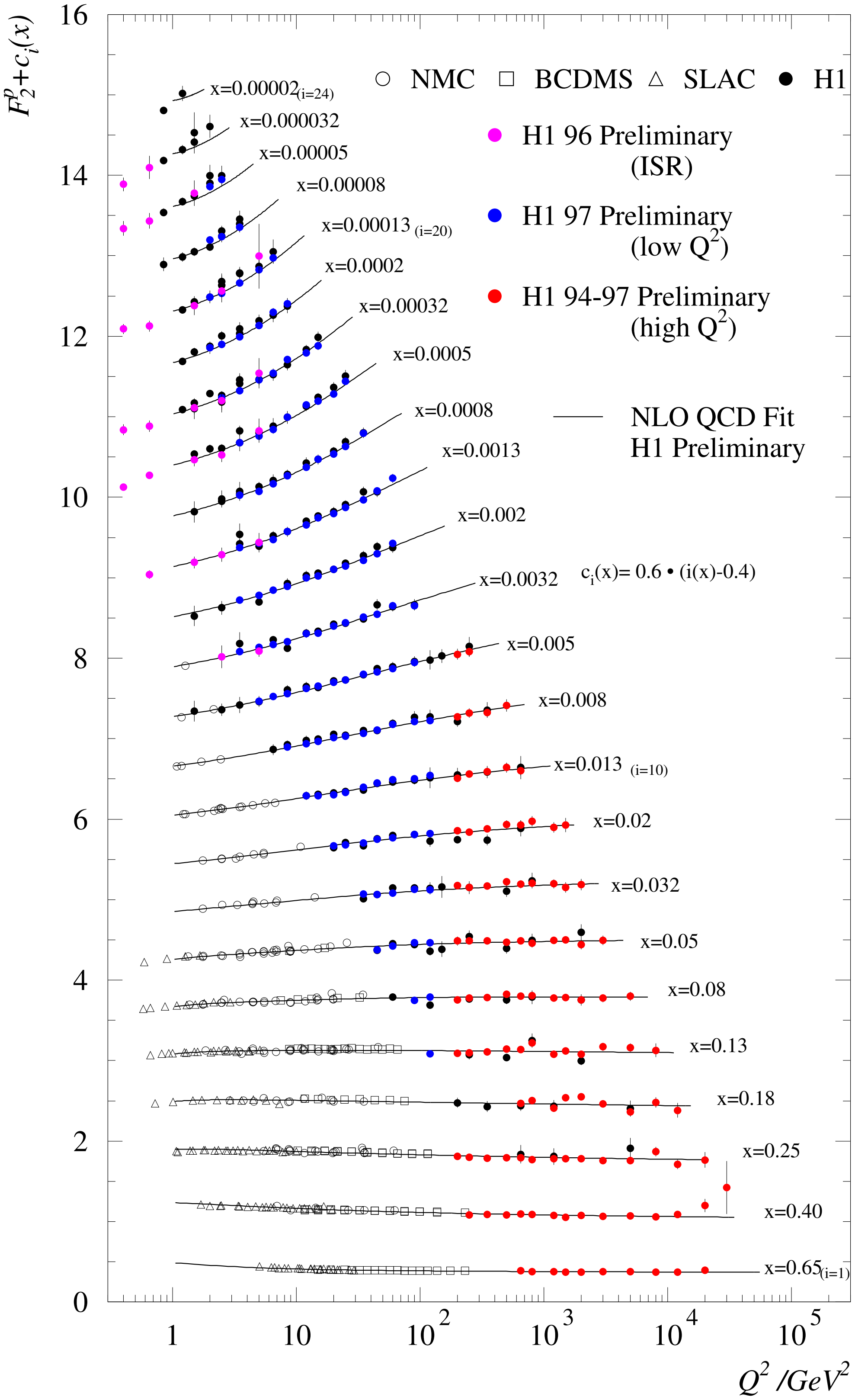
$$\frac{d^2\sigma^{\mathrm{BORN}}}{dx\,dQ^2}(e^-) = \frac{G_F^2}{2\pi} P_W^2 \left[(u+c) + (1-y)^2(\bar{d}+\bar{s})\right]$$

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

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

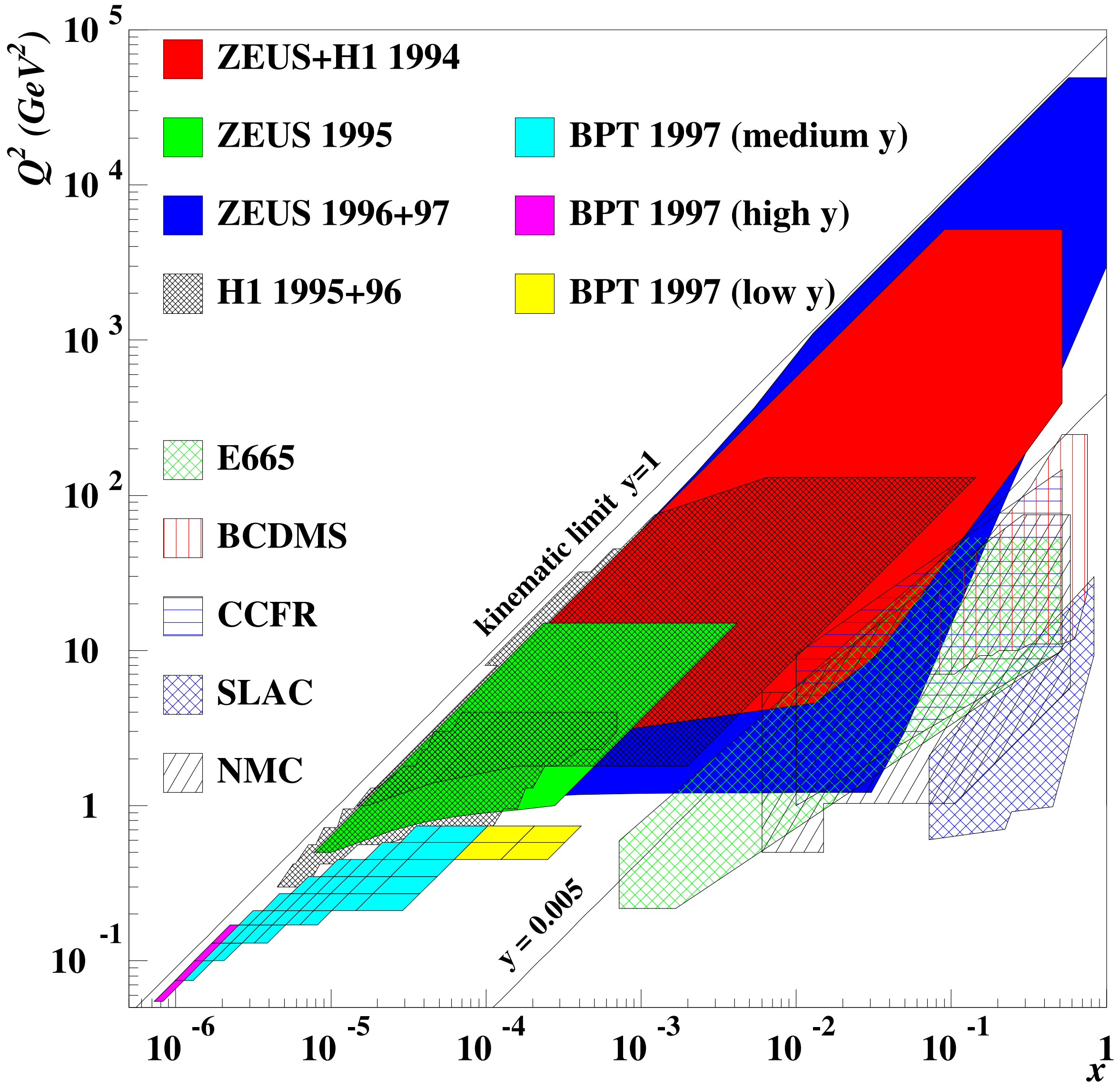
- $P_W \Rightarrow \begin{cases} \text{low } Q^2\text{: weak } Q^2 \text{ dependence} \\ \text{high } Q^2\text{: sensitivity to } W \text{ mass} \end{cases}$

H1 F_2 Scaling 1994-1997



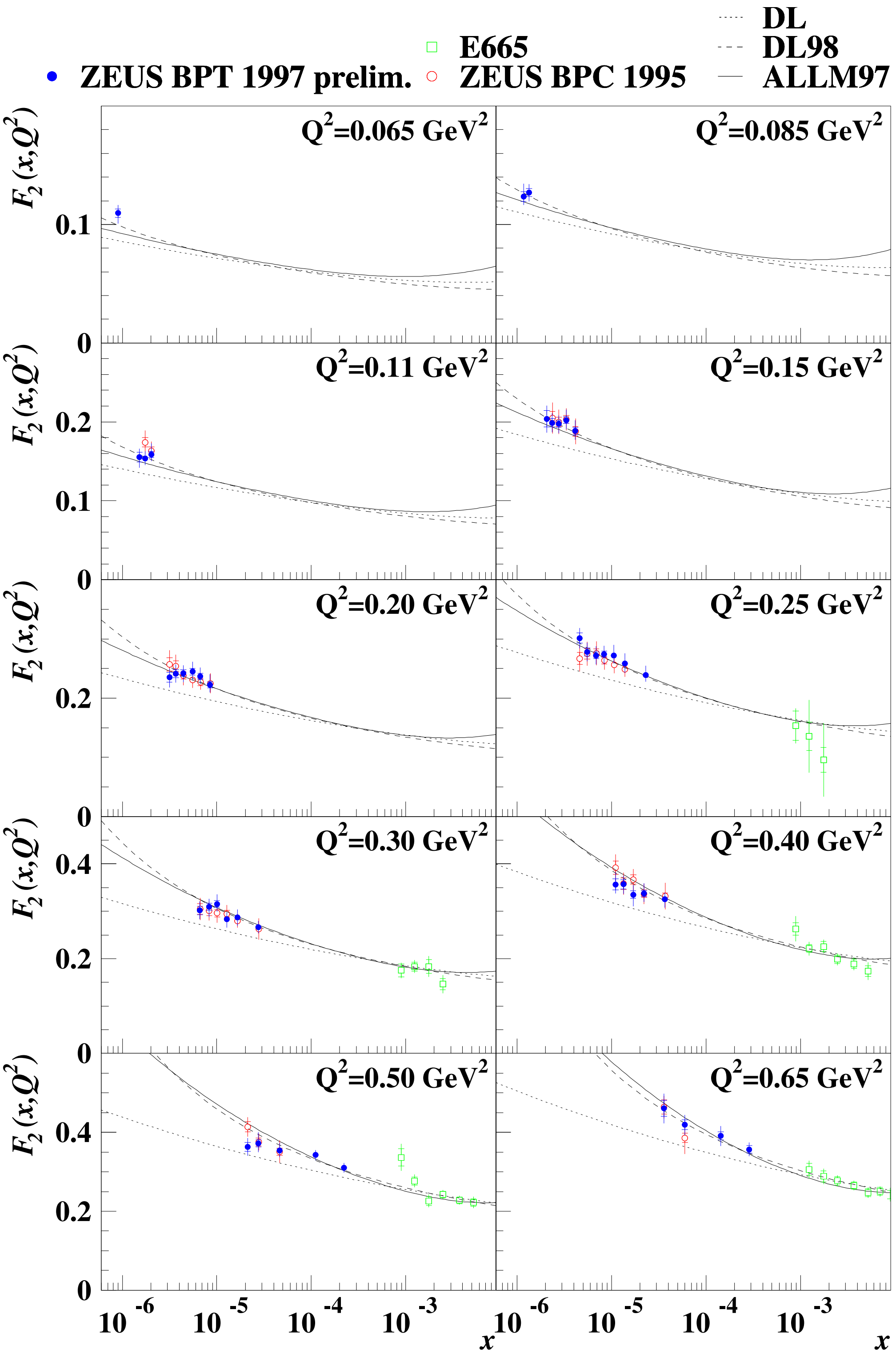
- Scaling at $x \sim 0.1$ up to $Q^2 \sim 5000$ GeV^2
- Scaling violations strongly increase at low x
  $\Rightarrow$ strong increase of gluon at low x

ZEUS BPC/BPT F_2 1997



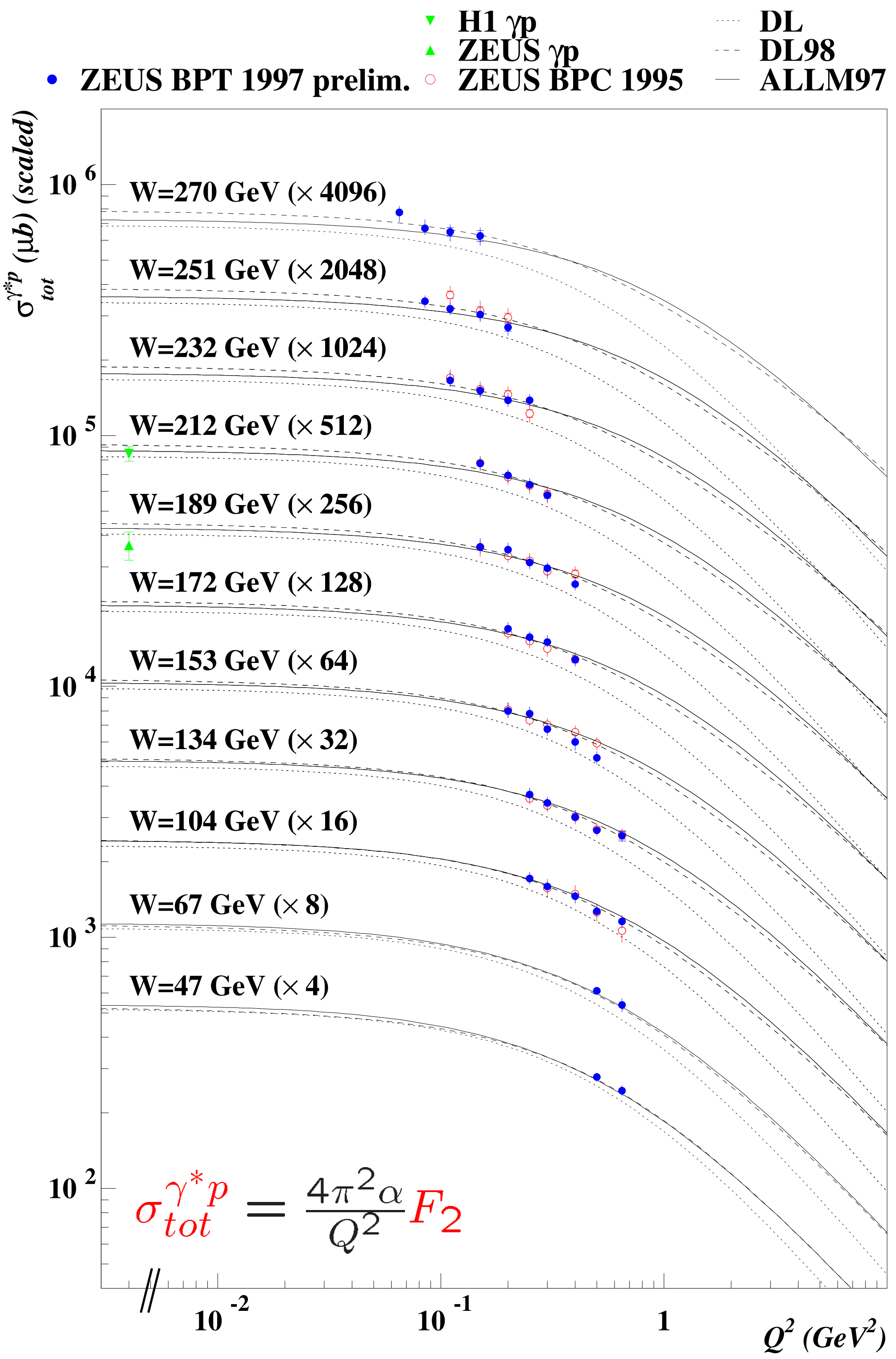
- New ZEUS detector close to beamline detects small-angle scattered positrons
- Kinematic region $\Rightarrow$ lower Q^2 and lower x

ZEUS BPC/BPT F_2 1997



- Kinematic region $\Rightarrow$ lower Q^2 and lower x

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



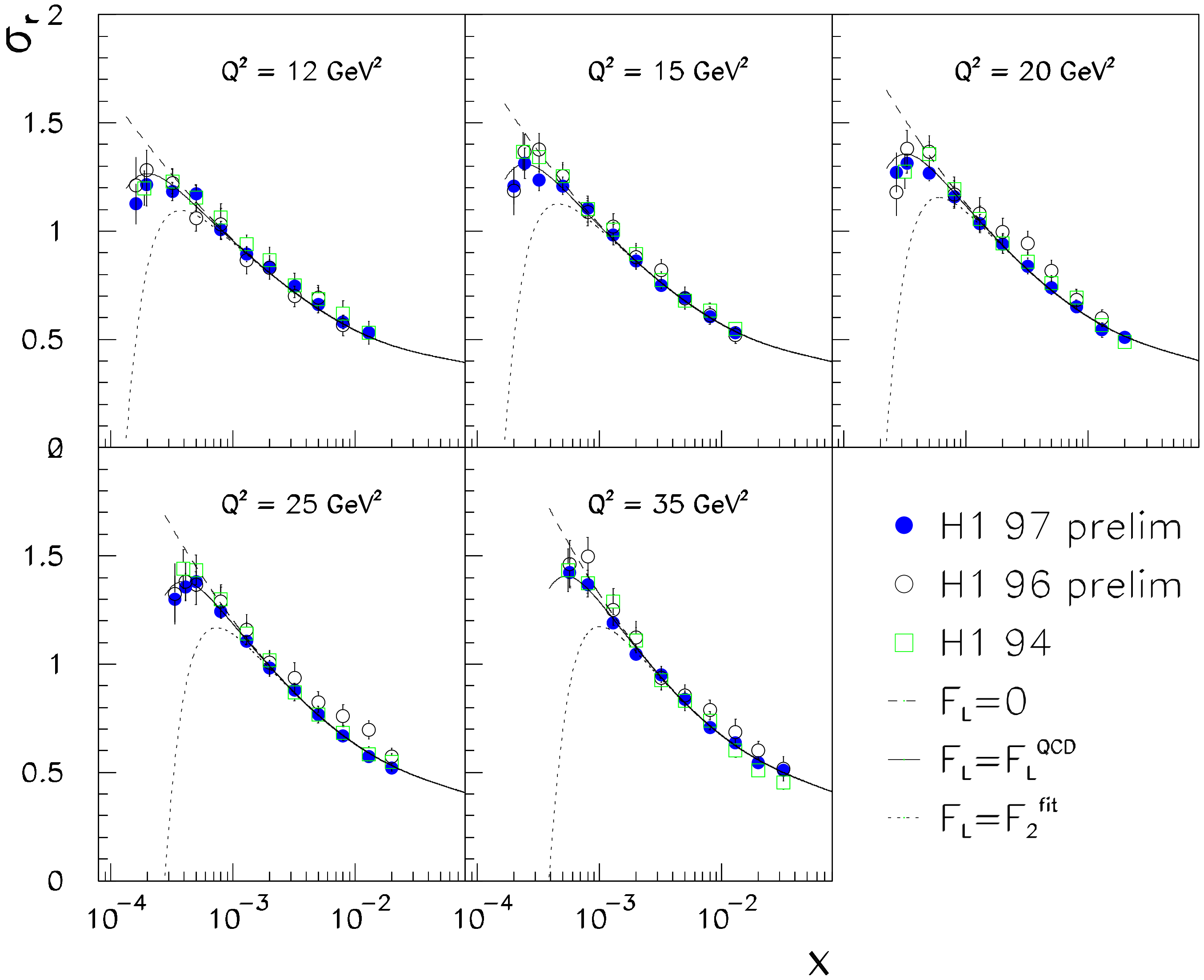
- Improve range and statistics w.r.t. ZEUS 95
- GVDM fit $\Rightarrow Q^2 \sim 0$
- Regge-type fits $(IR + IP) \Rightarrow W$ dependence

F_L from NC cross section (H1)

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 $y < 0.35$ ($\sim$no F_L)
- Fit F_2 at high y
- subtract out $F_L = \frac{Y_+}{y^2}\left(F_2^{fit} - \sigma_r\right)$



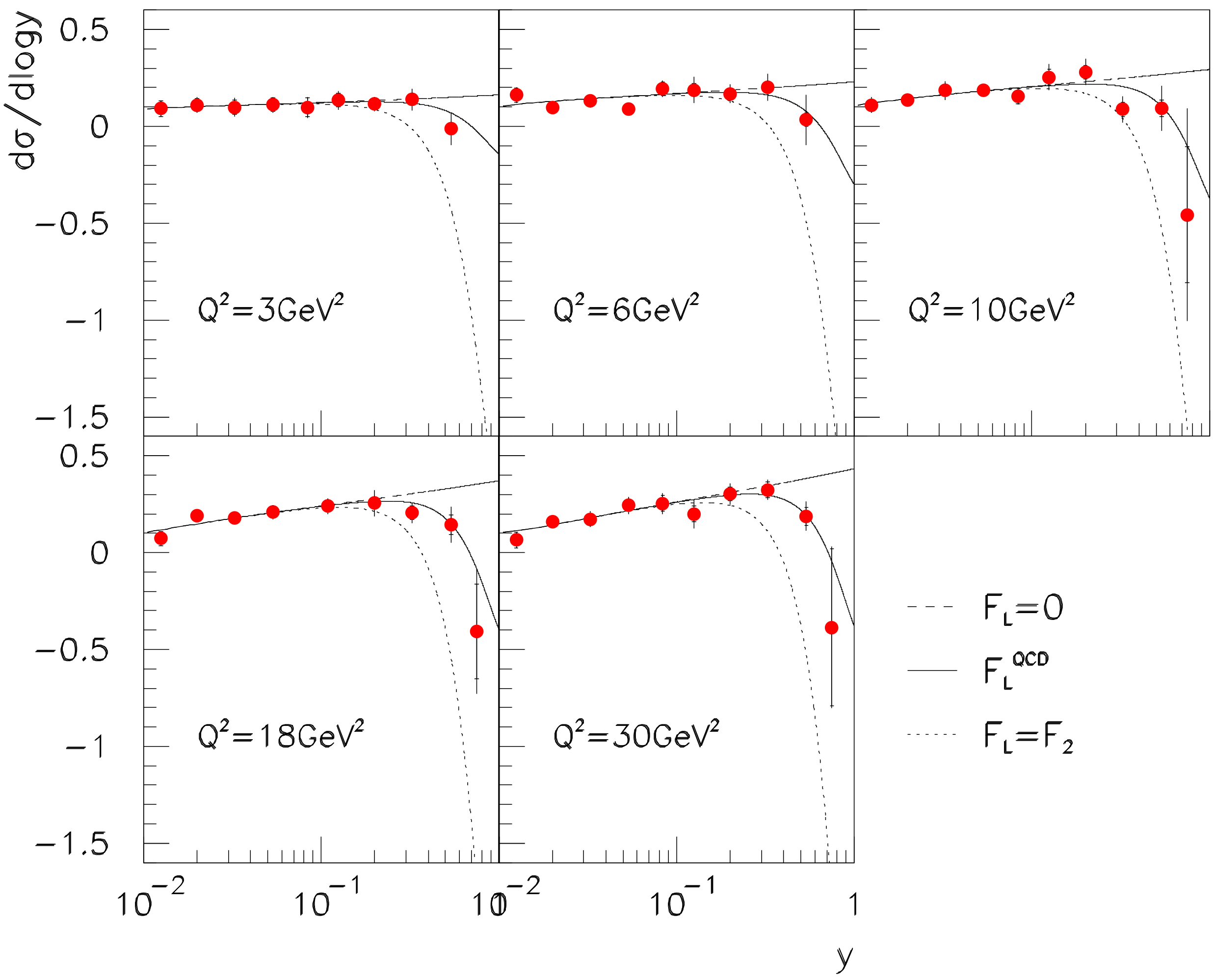
F_L from $d\sigma/d\ln y$ (H1)

Derivative method

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

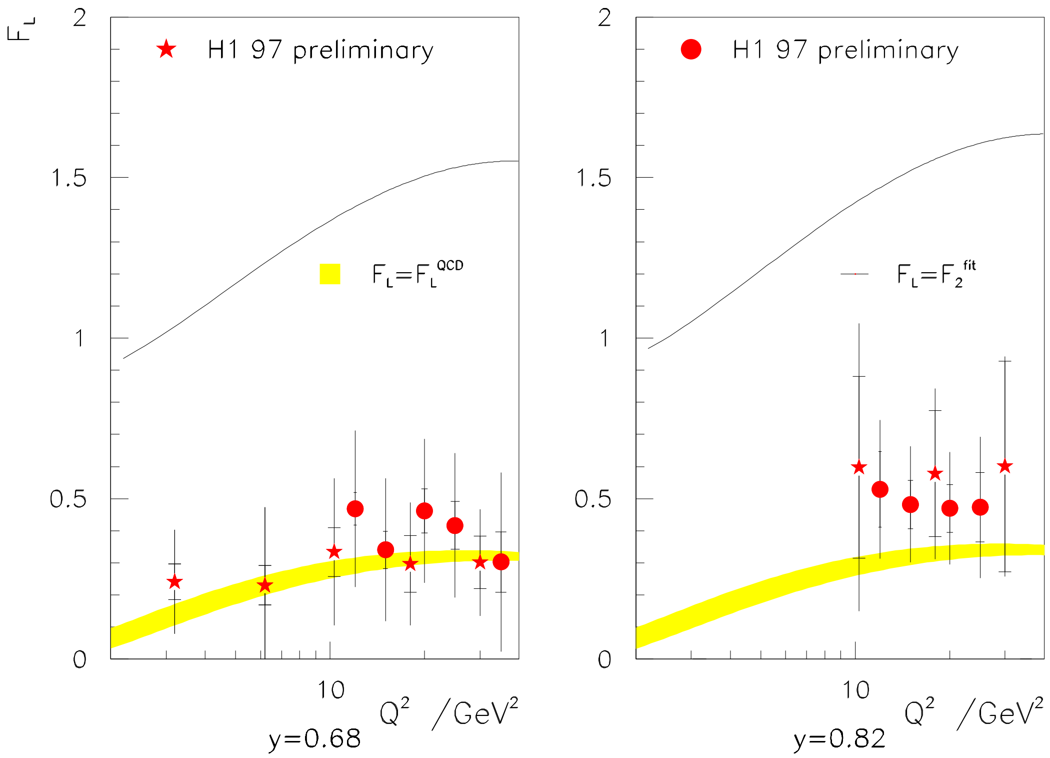
- Assume $dF_2/d\ln y = A\ln y + B$
- Straight-line fit to $d\sigma/d\ln y$ in Q^2 bins at $y < 0.2$
- Access to lower Q^2 than with subtraction method

H1 preliminary



F_L extraction summary (H1)

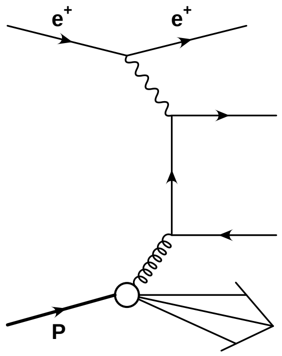
- Method1: subtraction method ●
- Method2: derivative method ⋆



- Extracted F_L compatible with QCD prediction
- Agreement between methods;
  same data, different data characteristics
- Slight tendency $F_L > F_L^{QCD}$ at highest y
- Direct measurement requires changing beam energies

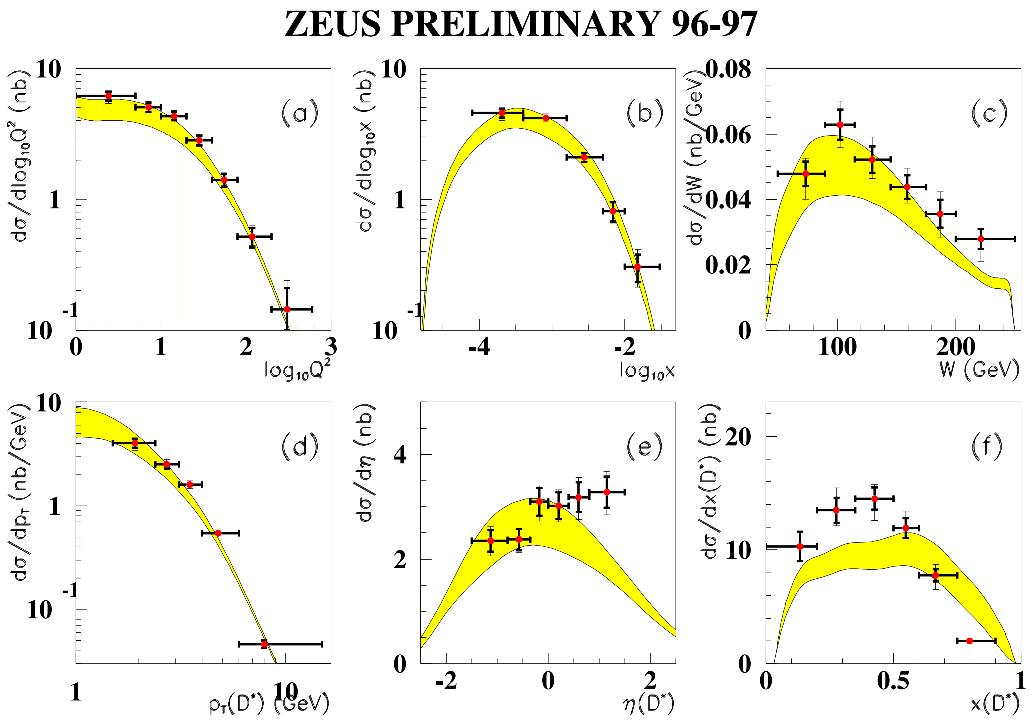
Charm in the Proton

Inclusive D^* production



$$e^+p \to e^+ D^{*\pm} X$$
$$\to D^0\pi^\pm$$
$$\to K^-\pi^+$$

BGF dominant process $\Rightarrow$ sensitivity to gluon

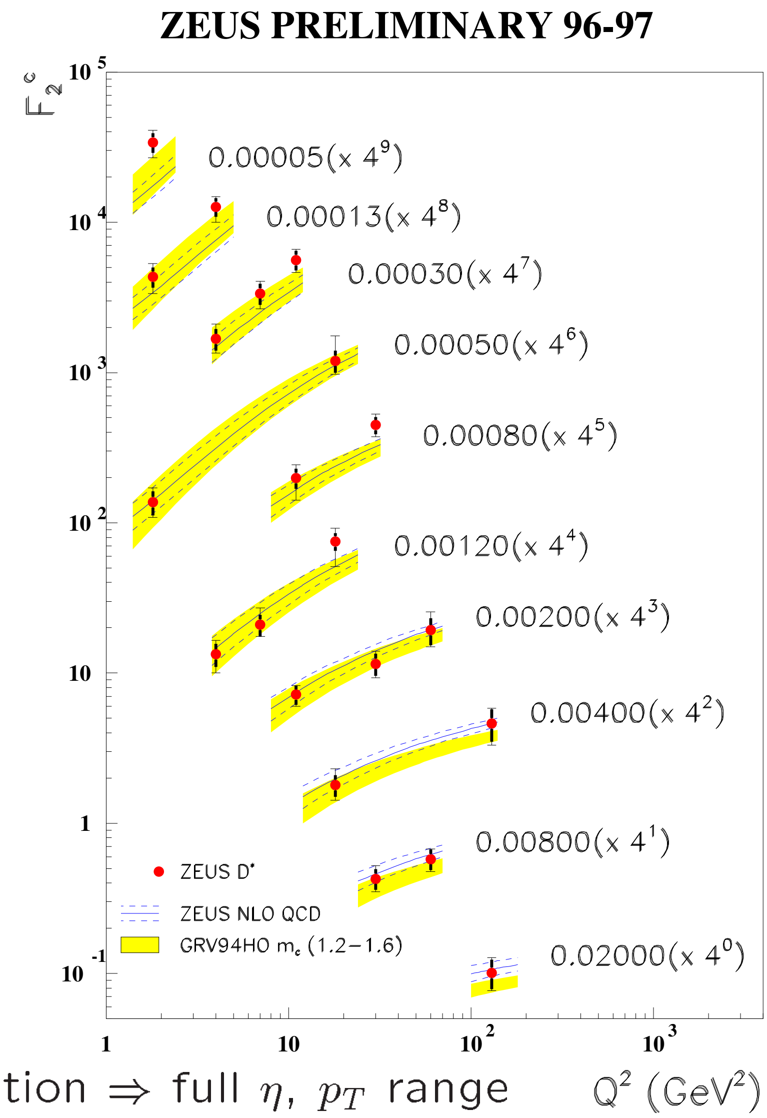


- Agreement with massive NLO pQCD ok [Harris & Smith]
- Deviation in η and $x(D^*)$

  Fragmentation Effect?
- Small effect on data extrapolation outside measured region

Charm Contribution to F_2

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

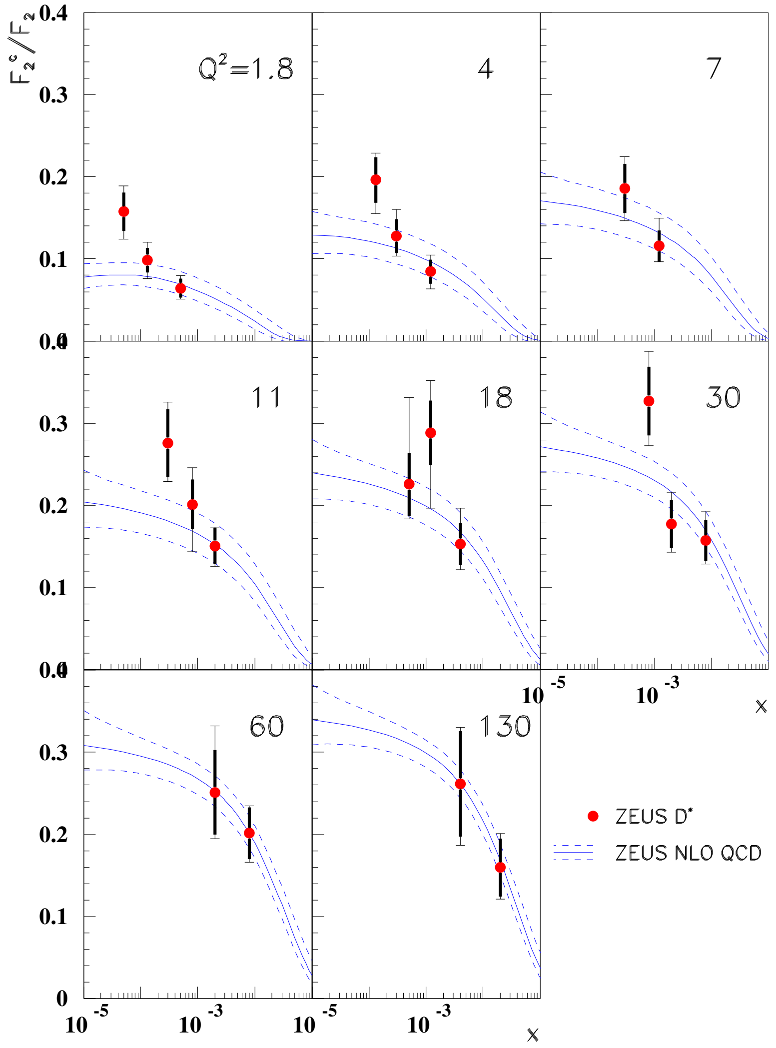


- extrapolation $\Rightarrow$ full η, p_T range
- fragmentation function $c \to D^*$
- F_L^c small and neglected
- $1.2 < m_c < 1.6$ GeV shown as band
- good agreement with NLO QCD fit

F_2^c: strong rise with decreasing x

Charm Contribution to F_2 (ZEUS)

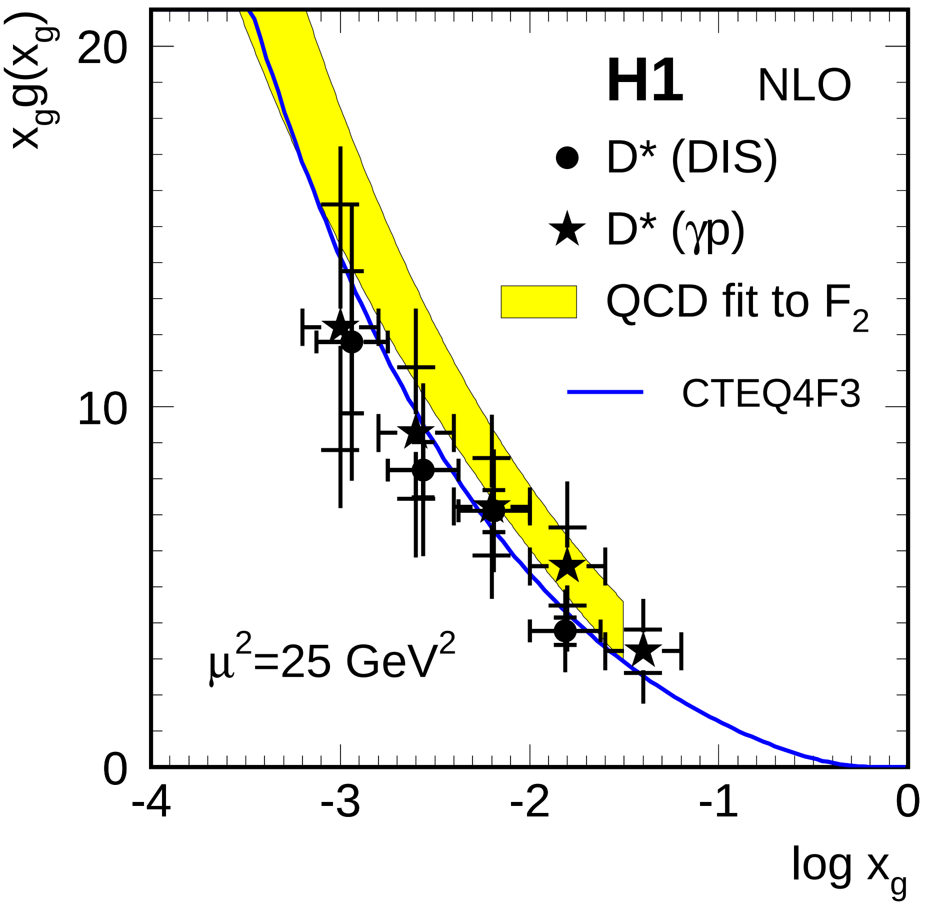
ZEUS PRELIMINARY 96-97



- Charm fraction of F_2 rises steeply with decreasing x

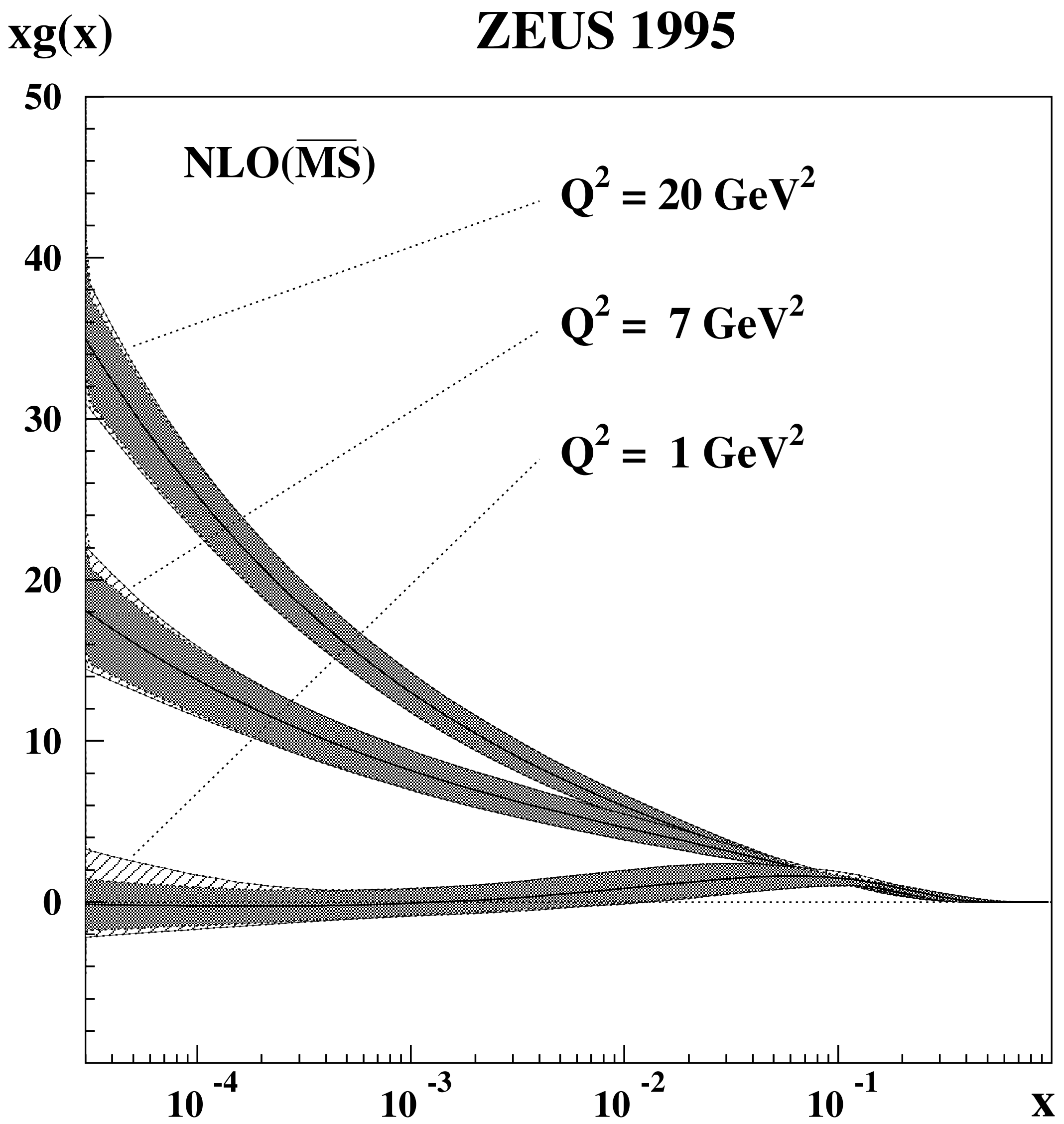
Gluon Density from Charm (H1)

Extract gluon density from D^* in DIS/γp



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

Gluon in NLO QCD F_2 fit

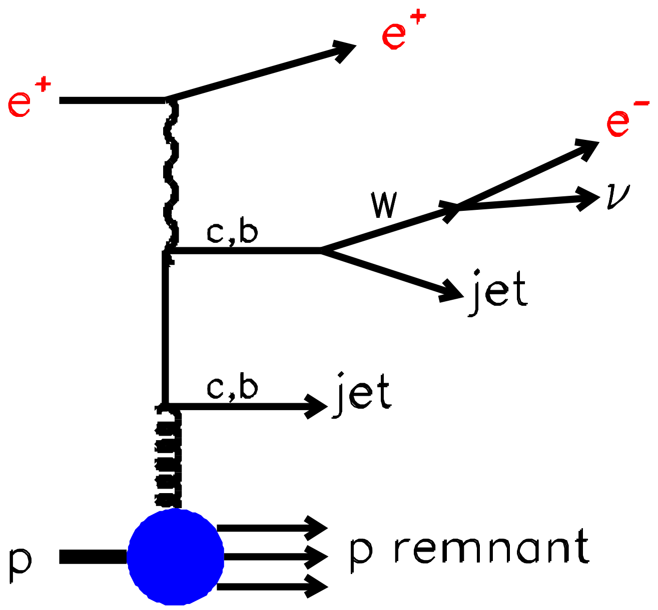


- large gluon density at low x in DIS
- no gluons at low Q^2 as $\Rightarrow \gamma p$ limit

Beauty Production

Or: How to observe beauty without a vertex detector

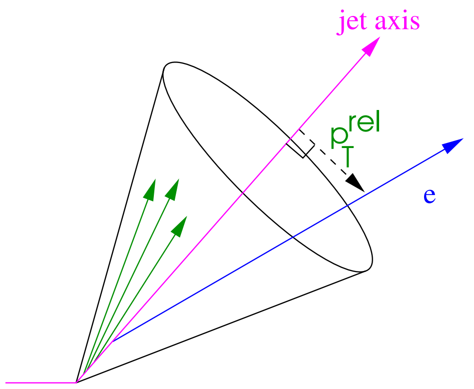
$$e^{+}p \rightarrow jj + e^{-} + X$$

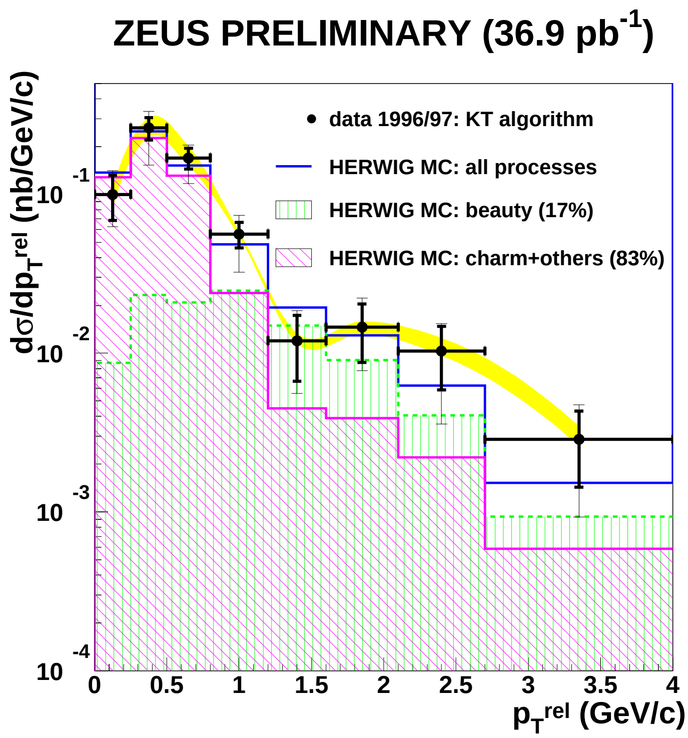


- Scattered positron not observed $\Rightarrow Q^2 \sim 0$
- Two jets $E_t > 7, 6$ GeV, central region $|\eta| < 2.4$
- Final state electron using dE/dx
- Result inclusive: beauty, charm+light quarks

Beauty production

heavier quark $\Rightarrow e^-$ has larger p_T relative to jet





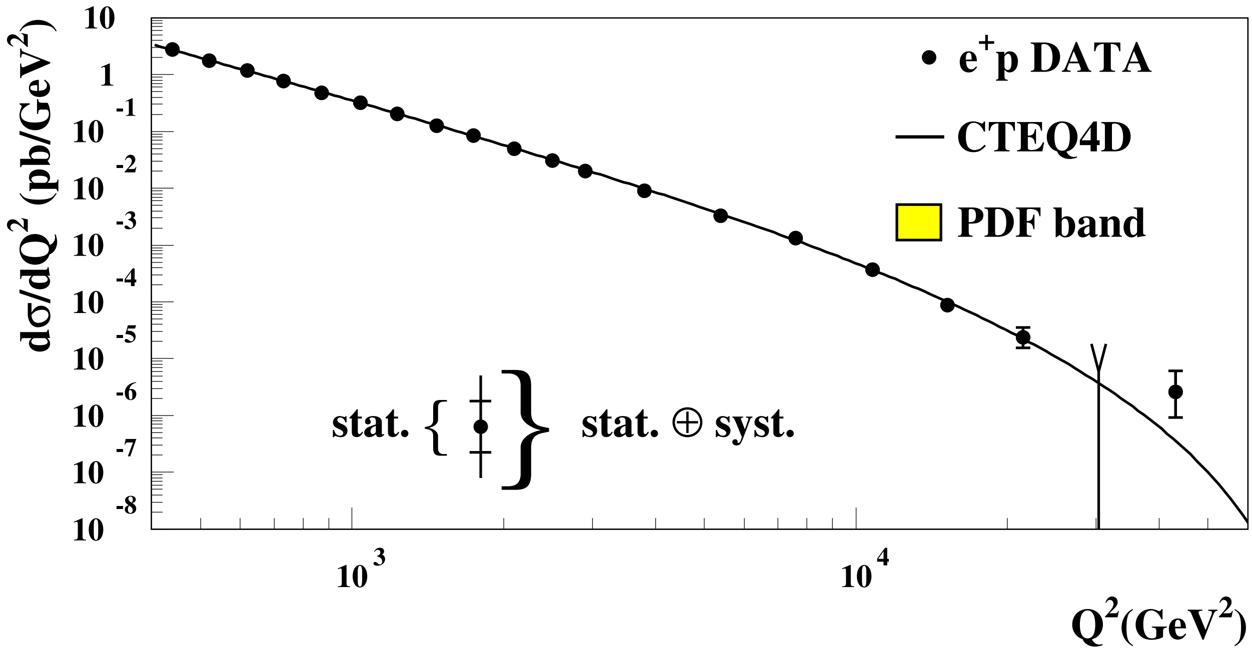
- Fit $p_T^{rel} \Rightarrow$ determine beauty fraction needed
- Shape well described by MC
- Beauty fraction: Good agreement data/MC

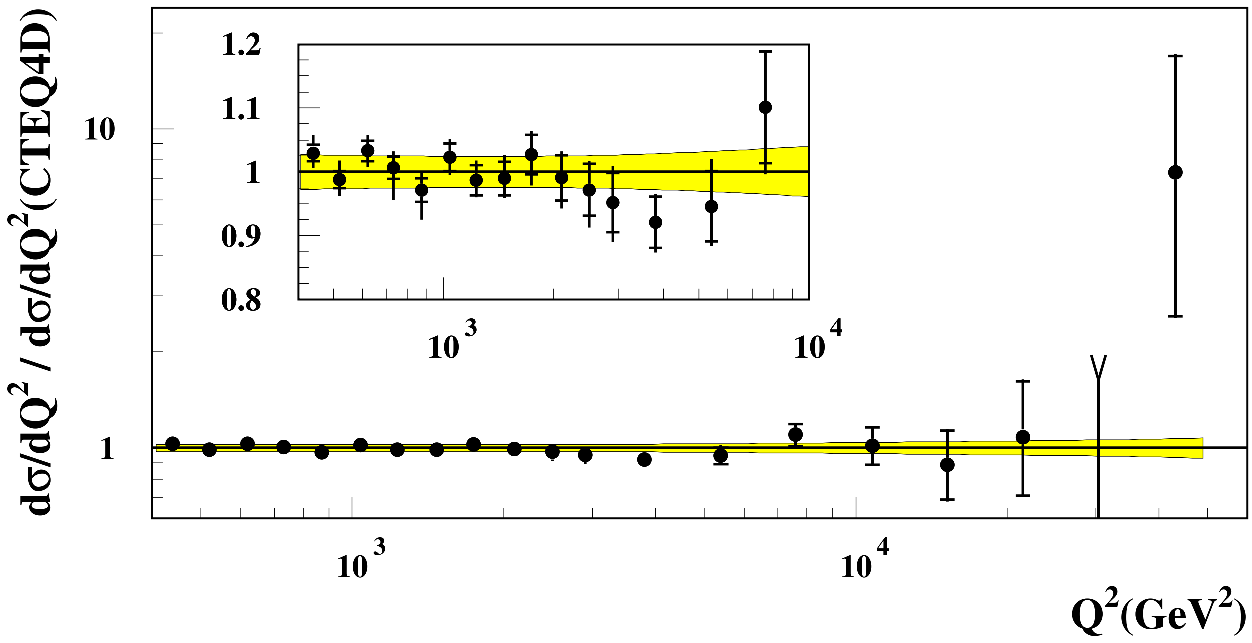
$20 \pm 6^{+12}_{-7}\%$ (fit)
17% (LO MC prediction)

- Measured absolute beauty cross section lies above LO MC

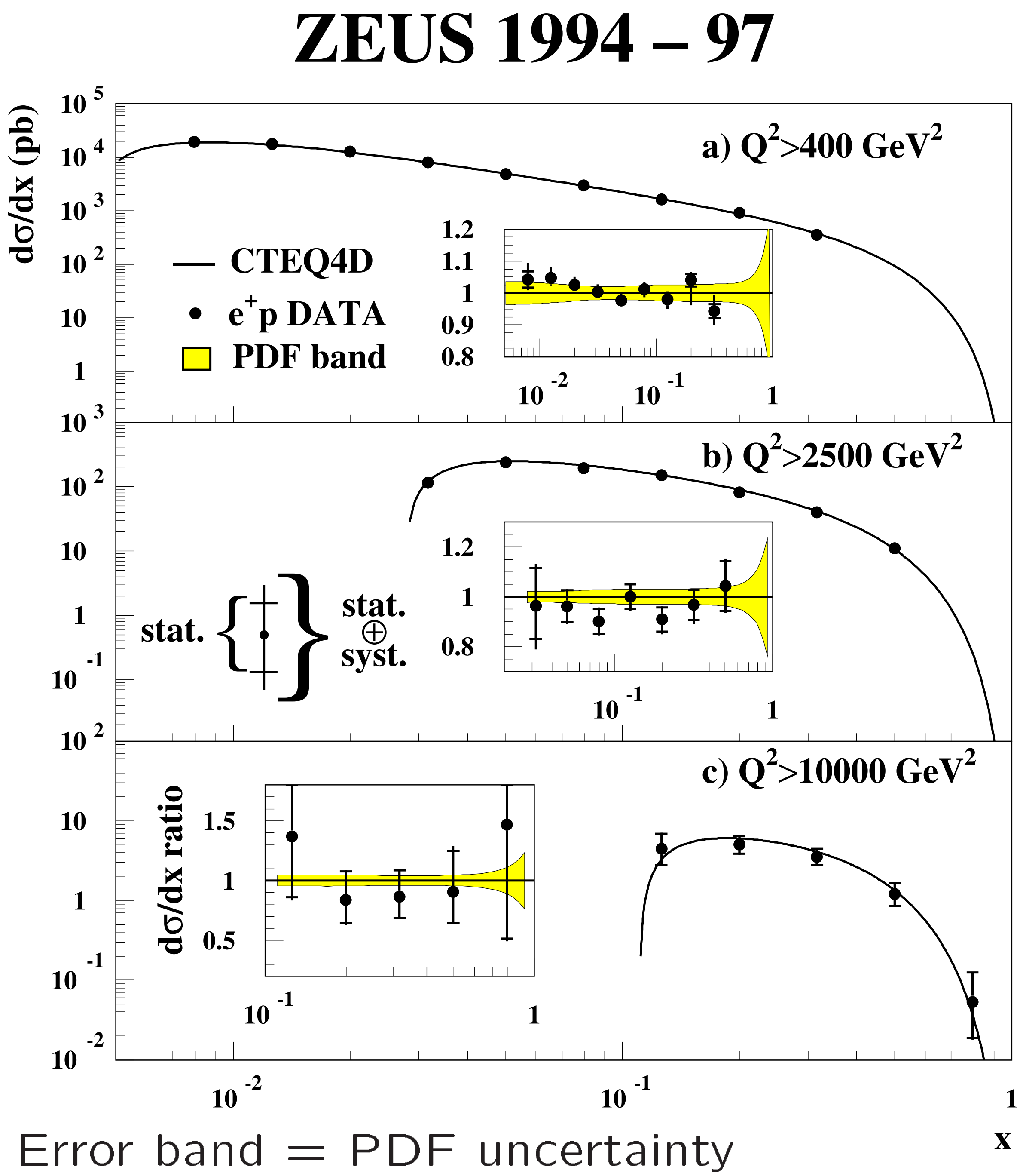
NC Cross Section $d\sigma/dQ^2$

ZEUS 1994 – 97





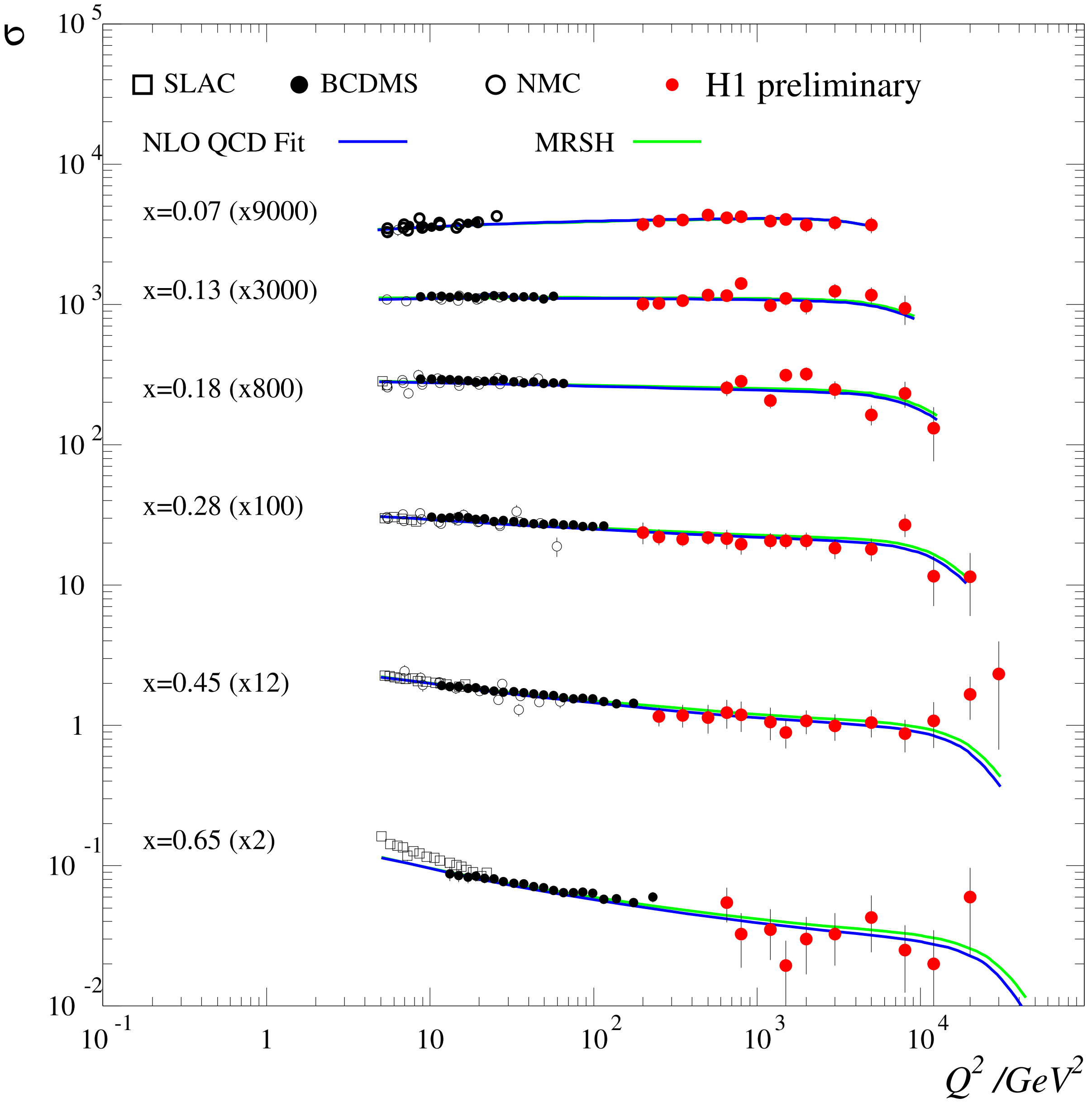
- Error band = PDF uncertainty
- Very good agreement with SM prediction
- Slight excess at highest Q^2



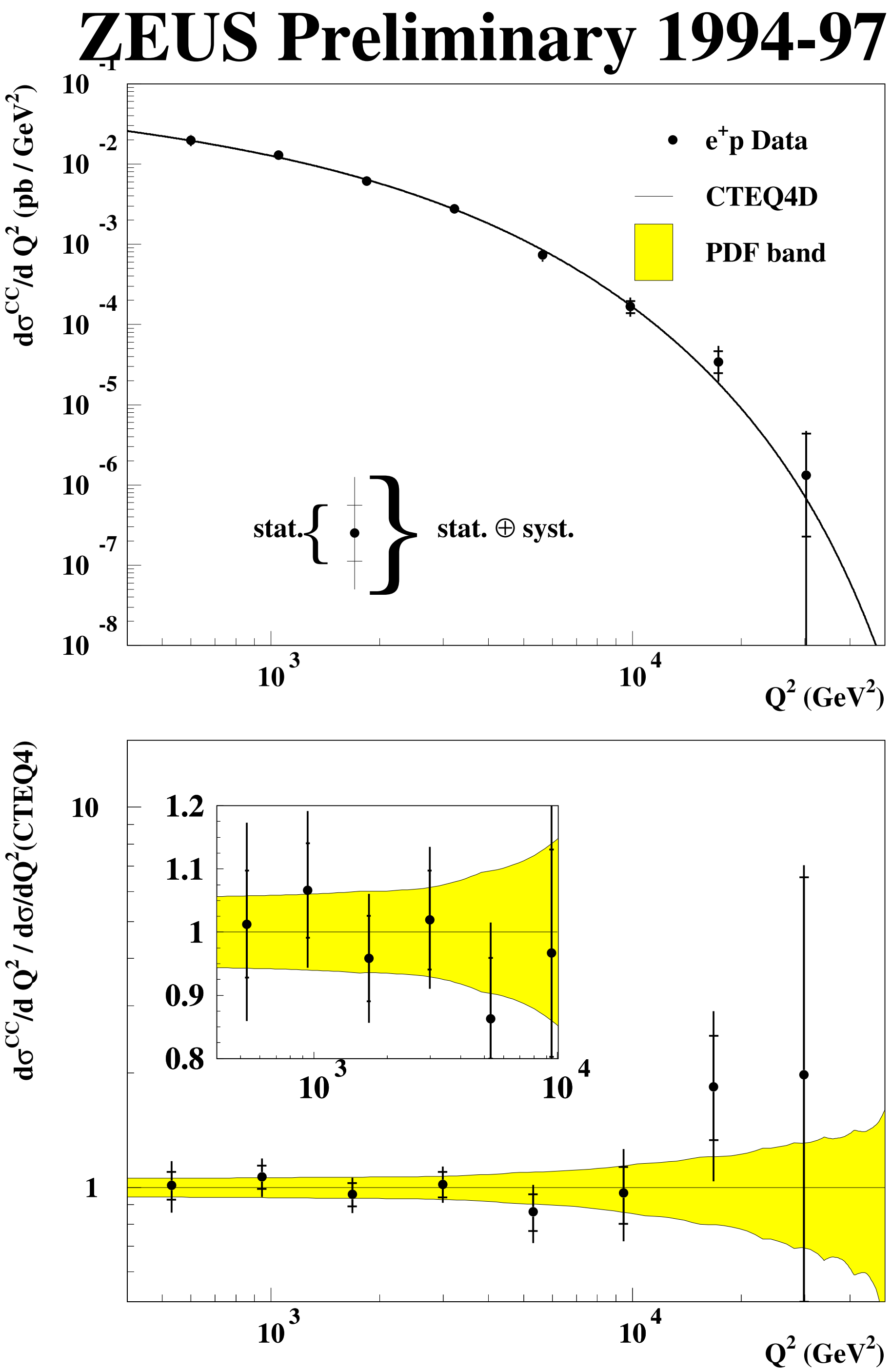
- Error band = PDF uncertainty
- Very good agreement with SM prediction
- No significant deviations at high x

NC reduced cross section (H1)

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

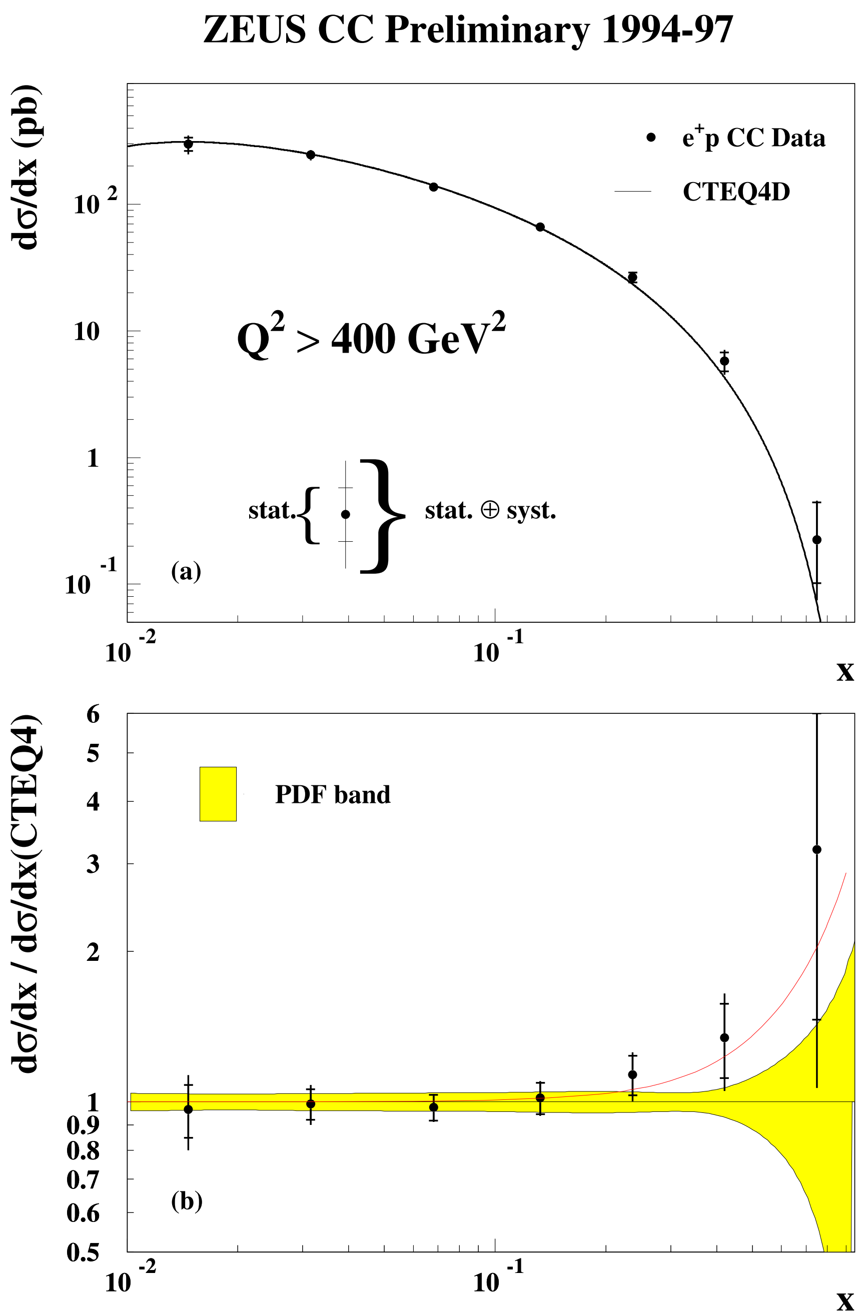


- No obvious discrepancies HERA/fixed-target
- Statistical precision limited at high x/high Q^2
- Excess at $x \sim 0.45$



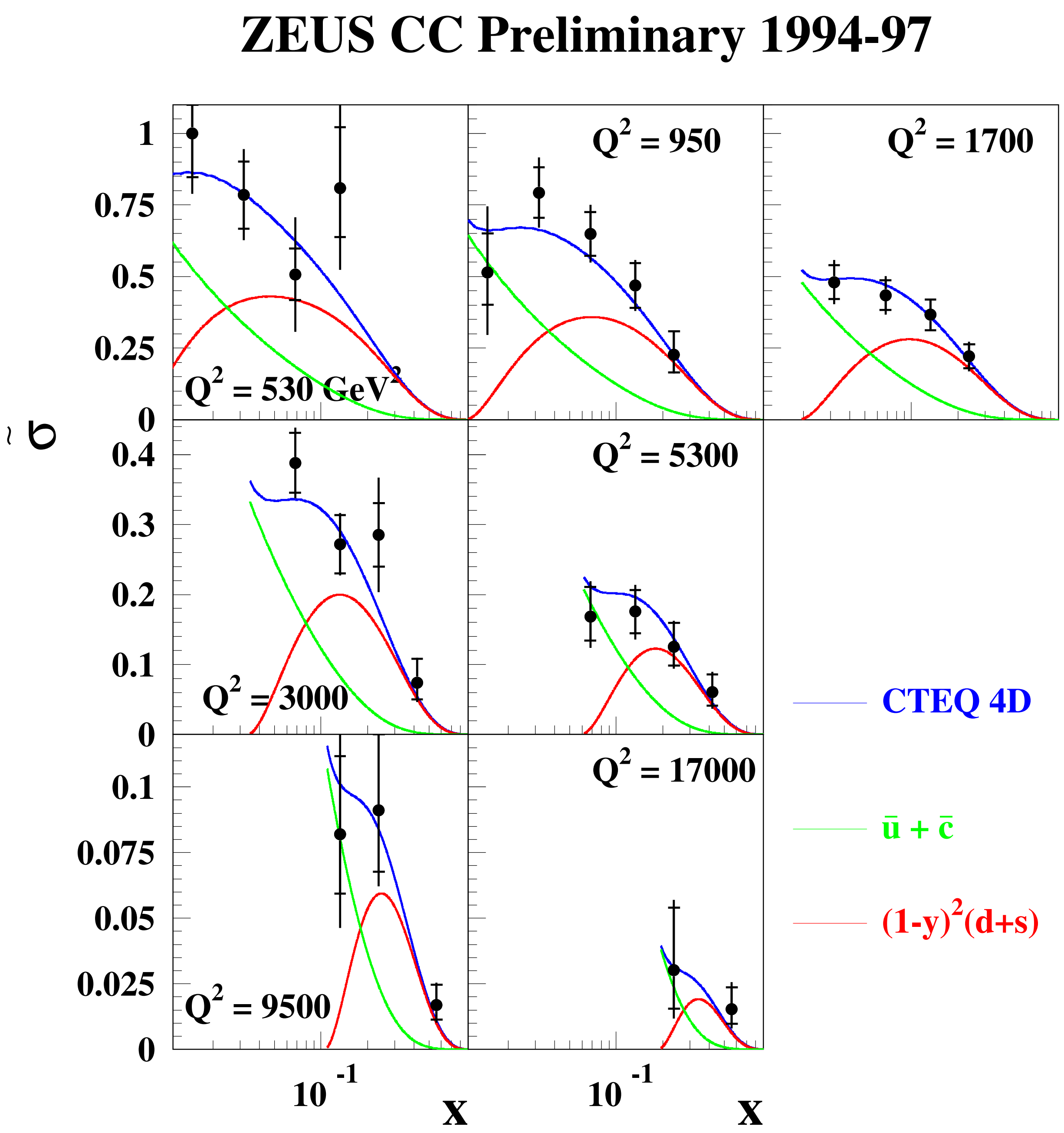
- Error band = PDF uncertainty
- Good agreement with SM prediction

CC Cross Section $d\sigma/dx$



- Error band = PDF uncertainty
- Good agreement with SM prediction
- Slight excess at highest x
- red line: $d/u(x=1) \sim 0.2$ [Yang & Bodek]

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

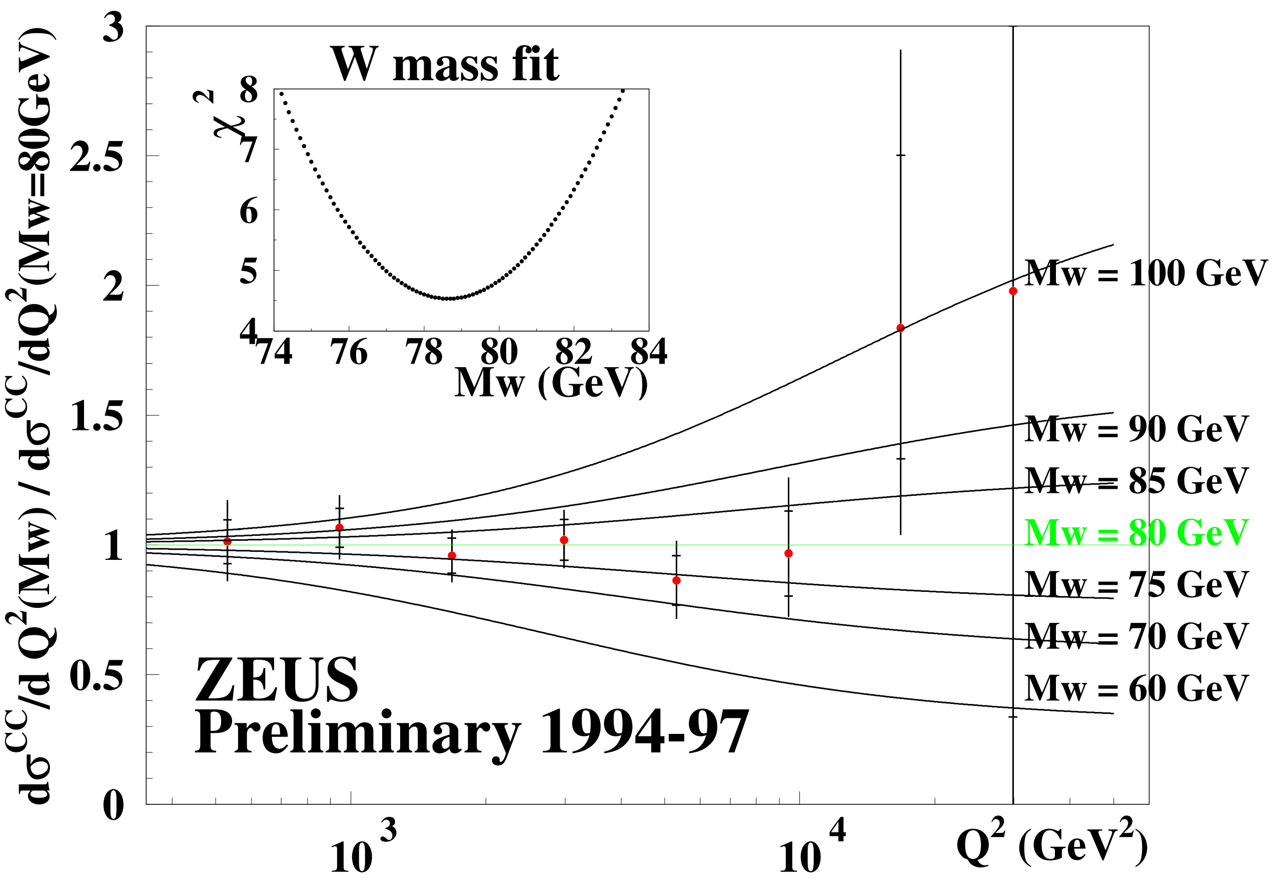


- Sensitivity to PDF's:

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

$\boxed{\text{CC sensitivity to sea and } d \text{ quarks !}}$

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

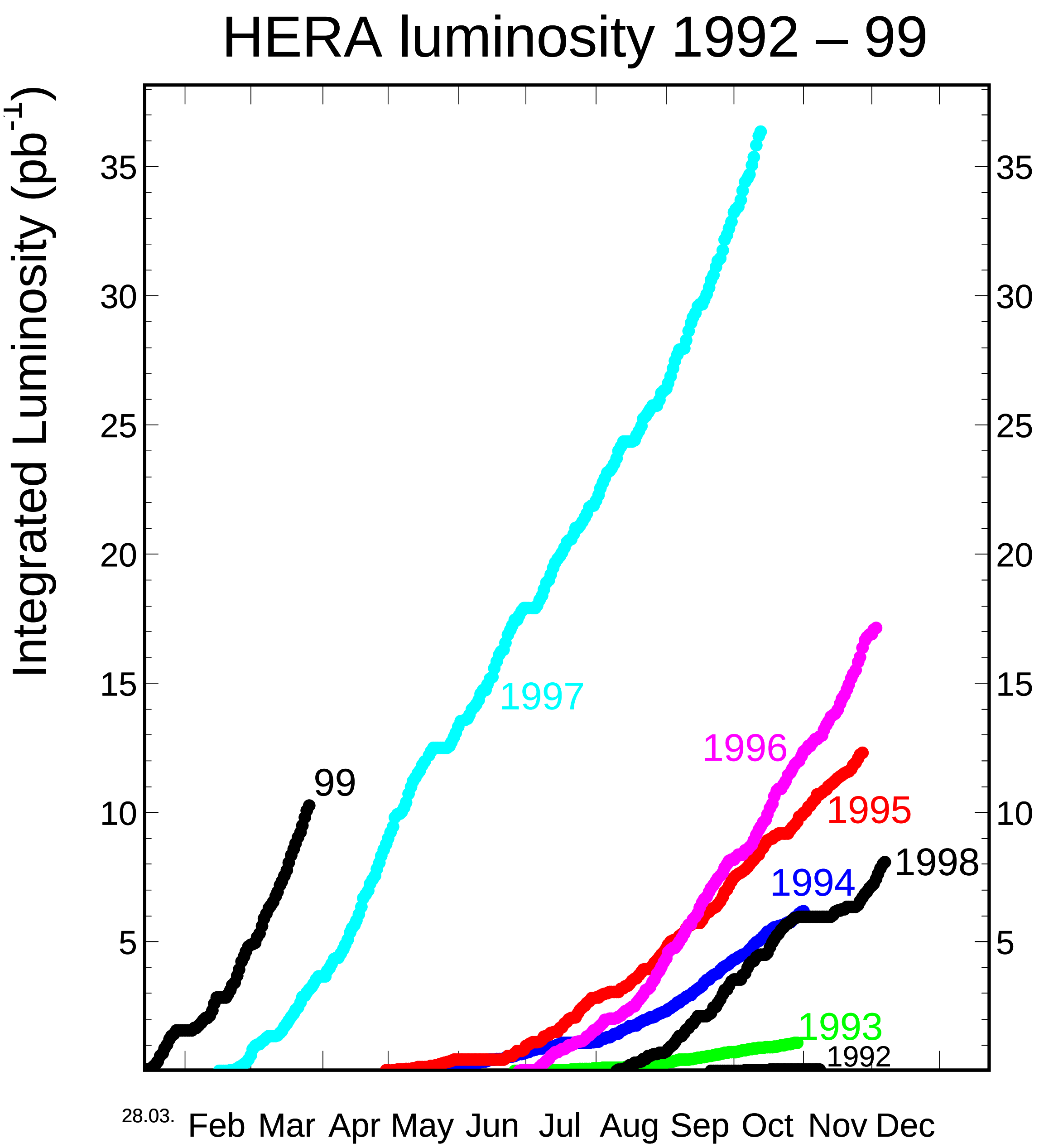
- χ^2–fit SM to data (other EW params fixed):

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

$M_W = 80.41 \pm 0.10$ (PDB 98)

- Confirm EW prediction in spacelike regime

Delivered HERA Luminosity



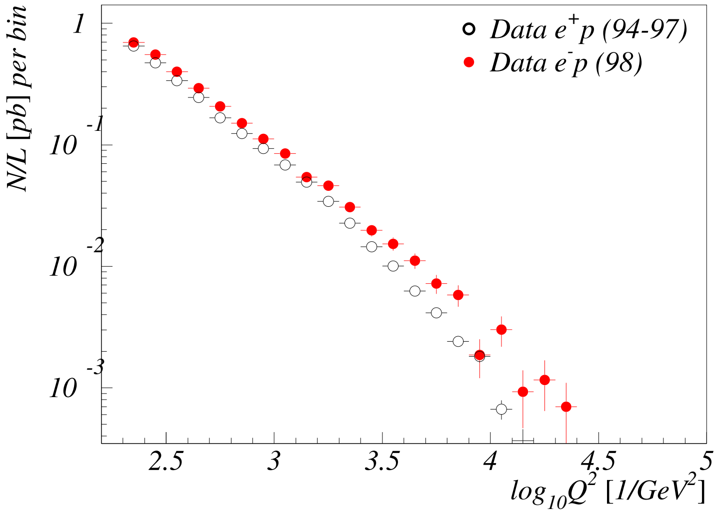
- positrons $\int \mathcal{L}dt = 71\ \mathrm{pb}^{-1}$ (delivered)
- electrons $\int \mathcal{L}dt = 17\ \mathrm{pb}^{-1}$ (delivered)

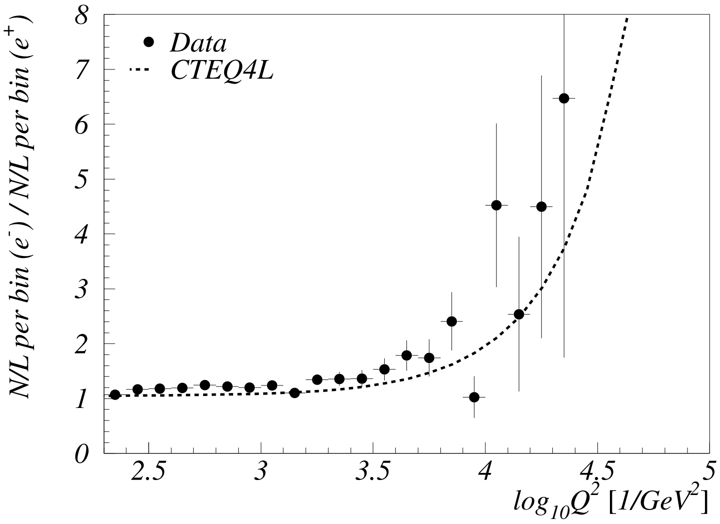
Electron running at ZEUS

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

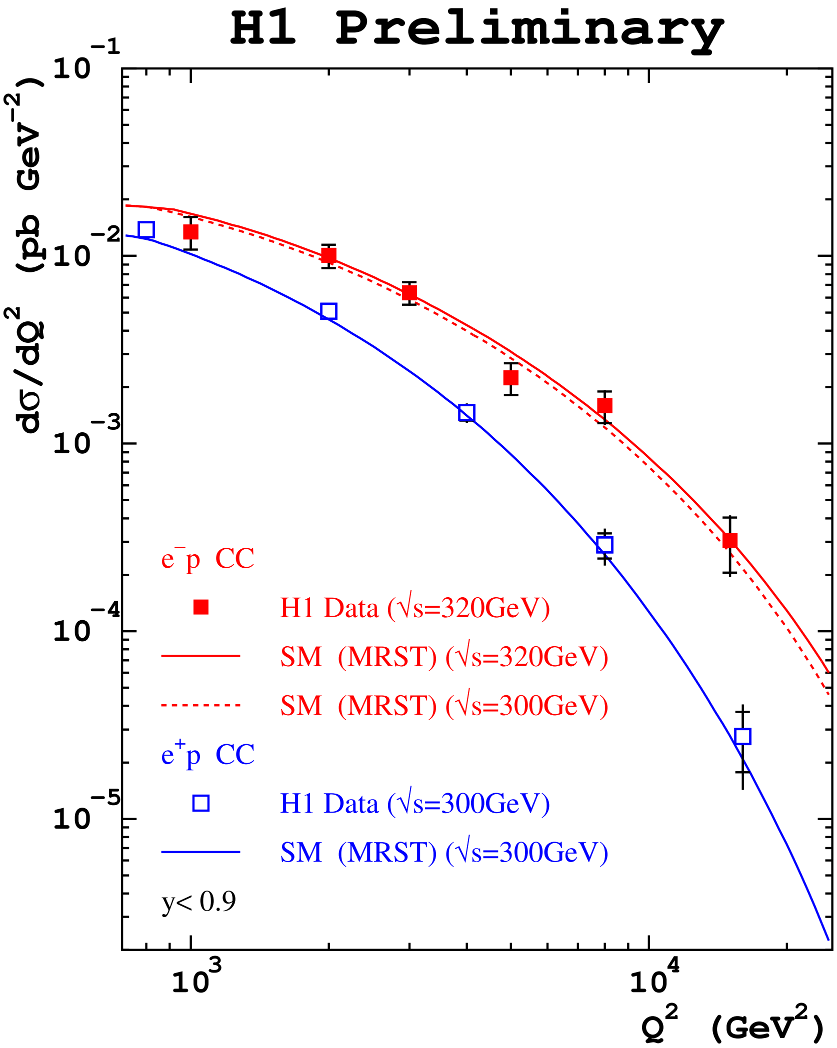
$$xF_3 = \frac{Q^4}{4\pi\alpha^2}\left[\frac{d^2\sigma}{dx\,dQ^2}(e^- p) - \frac{d^2\sigma}{dx\,dQ^2}(e^+ p)\right]$$

ZEUS preliminary





Electron running at H1



- $e^{-}p$ CC sensitive to u in proton
- $e^{+}p$ CC sensitive to d in proton
- $\sigma(e^{-}p) > \sigma(e^{+}p)$

  $\Rightarrow$ statistics already comparable

Conclusions and Outlook

- H1 and ZEUS testing QCD and measuring proton structure in new kinematic regions

- ZEUS NC and CC cross sections for Q^2 over 4 orders of magnitude in good agreement with Standard Model
  Excess remains in high Q^2, significance reduced

Phenomenology $\Leftrightarrow$ experiment Mainly good agreement, some questions remain!

- Luminosity

  1998–now: e^-p data at $E_p = 920$ GeV
  $\rightarrow$ already $\times \gtrsim 10$ e^- statistics: $\sim 12\,\mathrm{pb}^{-1}$
  1999–2000 Expect $\sim 50\,\mathrm{pb}^{-1}$
  2000: HERA lumi upgrade
  2001–2005: $500 - 1000\,\mathrm{pb}^{-1}$

- Future:

  - Higher precision at medium and high-Q^2
  - Greater discovery potential
  - Electroweak physics