# Structure Function Results from ZEUS

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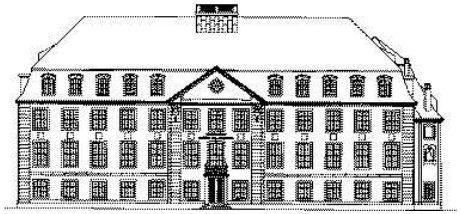

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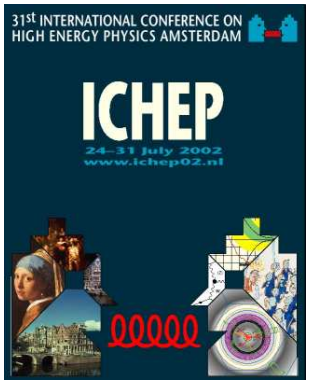
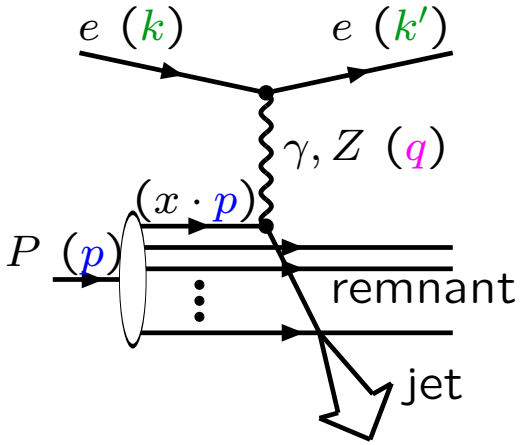


# Deep inelastic $ep$ scattering at HERA

**Neutral Current (NC)**



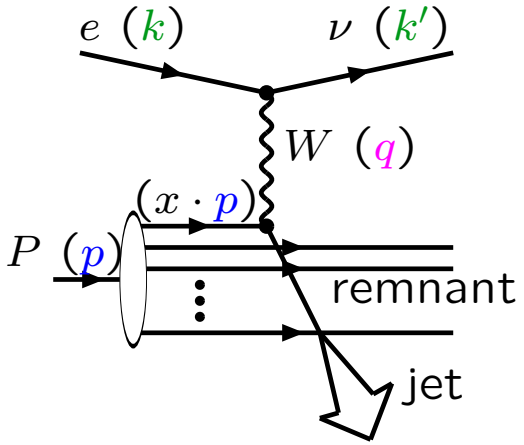

$$Q^2 = -q^2 = -(k - k')^2$$

$$x = \frac{Q^2}{2\, p \cdot q}$$

$$y = \frac{p \cdot q}{p \cdot k}$$

$$s = (k + p)^2$$

**Charged Current (CC)**




$$\frac{d^2\sigma(e^{\pm}p)}{dx\, dQ^2} = \frac{2\pi\alpha^2}{x\, Q^4} \times \left[\, Y_+ F_2^{\mathrm{NC}} \mp Y_- x F_3^{\mathrm{NC}} - y^2 F_L^{\mathrm{NC}} \,\right]$$

$$F_2^{\mathrm{NC}} = x \sum_{q=u\ldots b} A_f \left[\, q + \bar{q} \,\right]$$

$$x F_3^{\mathrm{NC}} = x \sum_{q=u\ldots b} B_f \left[\, q - \bar{q} \,\right]$$

$$\frac{d^2\sigma(e^{-}p)}{dx\, dQ^2} = \frac{G_F^2}{4\pi x} \frac{M_W^4}{(Q^2 + M_W^2)^2} \times \left[Y_+ F_2^{\mathrm{CC}} + Y_- x F_3^{\mathrm{CC}} - y^2 F_L^{\mathrm{CC}}\right]$$

$$F_2^{\mathrm{CC}} = x\left[u + c + \bar{d} + \bar{s}\right]$$

$$x F_3^{\mathrm{CC}} = x\left[u + c - \bar{d} - \bar{s}\right]$$

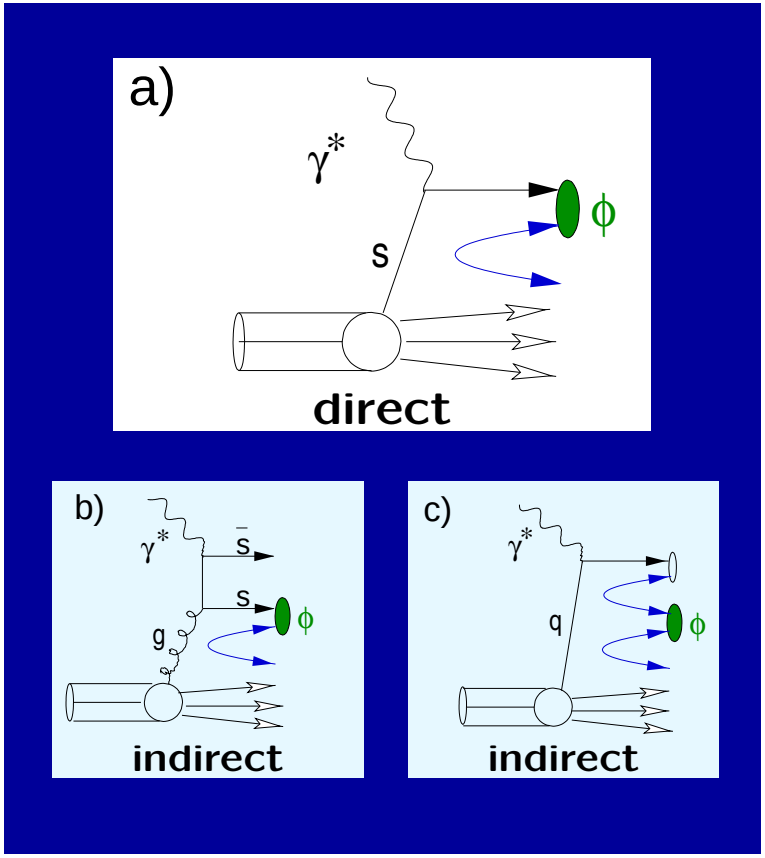
# Inclusive $\phi(1020)$-meson production in DIS

- $\phi$ is produced
  - directly from $s$ quarks in the proton (a)
  - indirectly from $s$ quarks produced via BGF (b), hadronization (c) ...
- Generally, the direct process is swamped by indirect processes

- Define $x_p(\phi) = 2p(\phi)/Q$ with $p(\phi) = \phi$ momentum in Breit frame

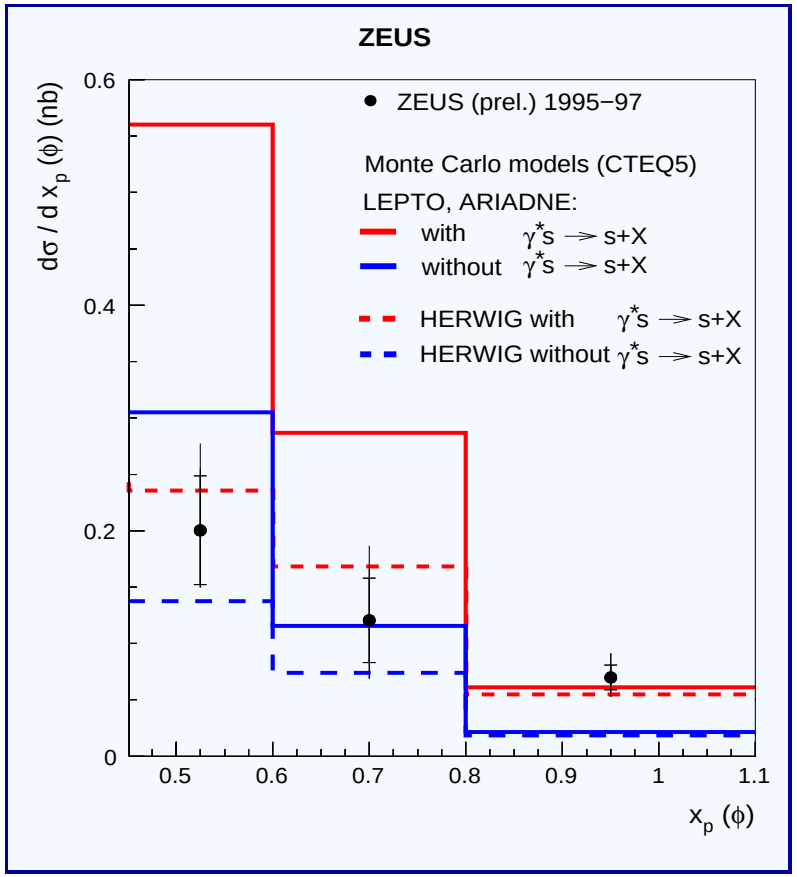
  for direct $\phi$ production $x_p \sim 1$

  $\Rightarrow$ at high $x_p$, $\phi$ cross section sensitive to $s$-quark content of proton



# Inclusive $\phi(1020)$-meson production in DIS

- **Data set:** $45.0\,\mathrm{pb}^{-1}$ $e^+p$ (1995–1997)
- **Kinematic range:** $10 < Q^2 < 100\,\mathrm{GeV}^2$, $2 \cdot 10^{-4} < x < 10^{-2}$
- **Measured cross section (ZEUS prel.):**
  $\sigma(e^+p \to e^+\phi p) = 0.506 \pm 0.022\,\mathrm{nb}$



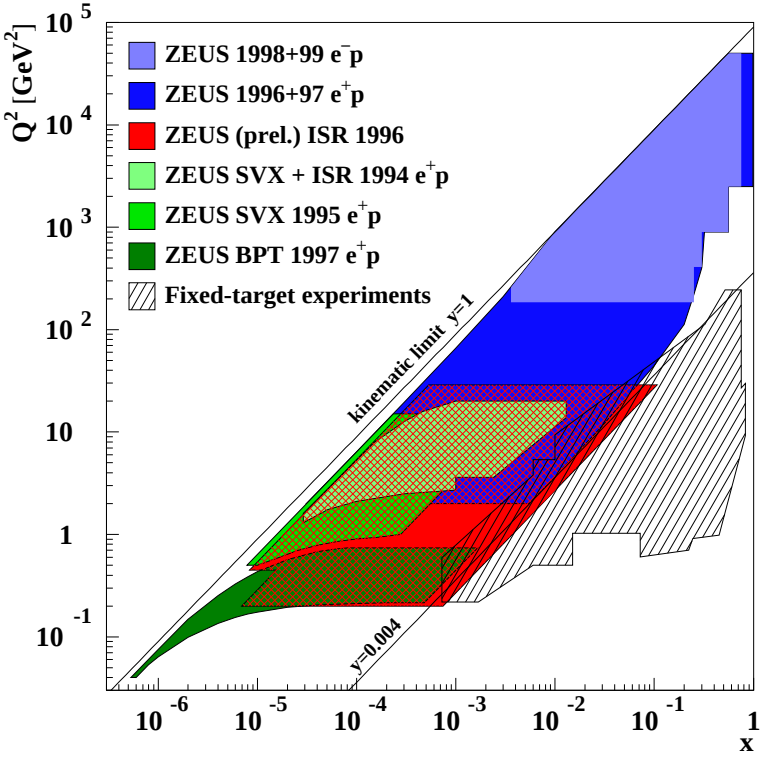

- $x_p$ **distribution of** $d\sigma/dx_p$

  **medium** $x_p$**:** Data favor HERWIG

  **high** $x_p$**:** Data prefer models with strange-sea contribution

# $F_2$ from initial-state radiative events

- Acceptance of main detector for scattered electron limited to $\theta^\star \gtrsim 4^\circ \Rightarrow Q^2 \gtrsim 2\,\mathrm{GeV}^2$
- $F_2$ at lower $Q^2$ measured by
  - shifting the IP up the lepton beam (SVX)
  - using dedicated small-angle detector (BPC)
  - lowering CMS energy (ISR analysis)




## ISR analysis:

- Select events where a $\gamma$ was radiated from the incoming electron (ISR $\gamma$)

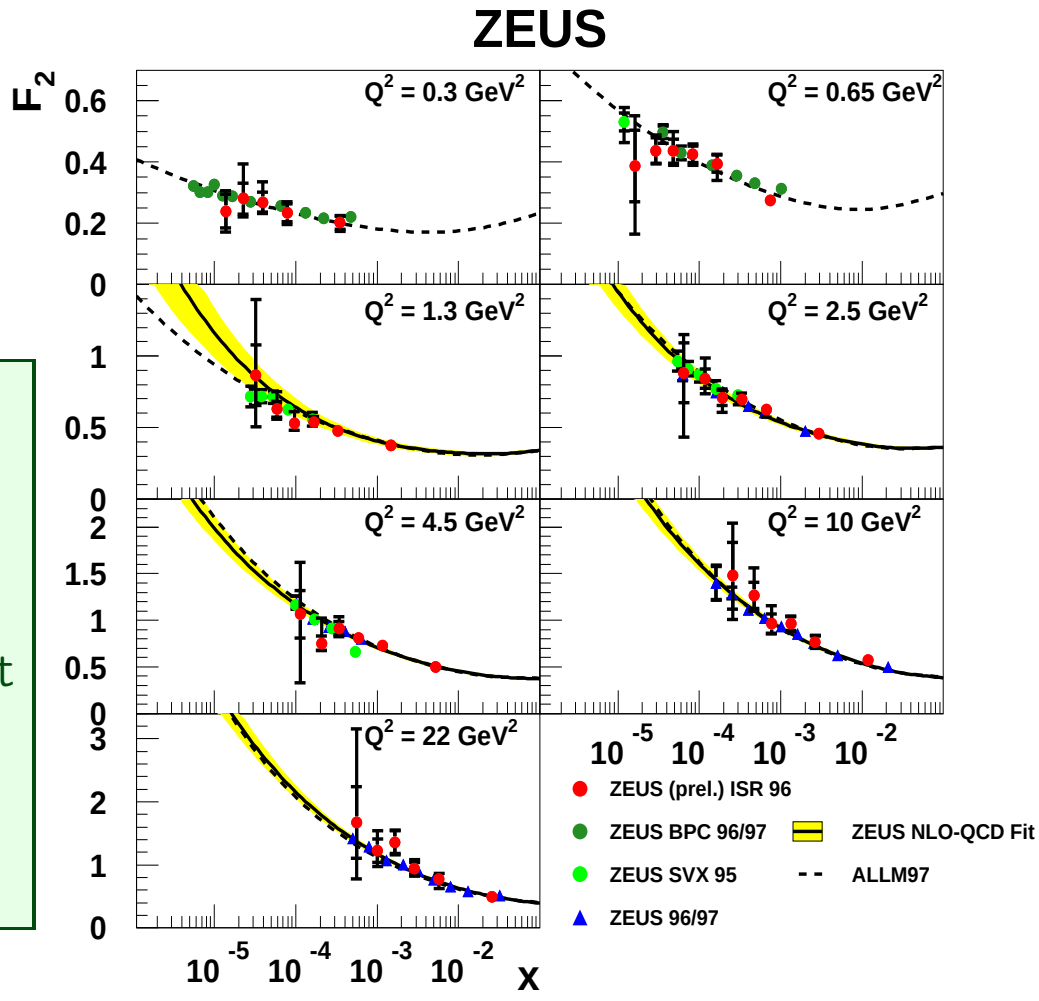
  $\Rightarrow \sqrt{s}$ lowered by factor $(E_e - E_\gamma)/E_e$

  $\Rightarrow e^\pm$ with low $Q^2$ scatter into main detector
- Fills gap in $F_2$ coverage around $Q^2 = 1\,\mathrm{GeV}^2$

# $F_2$ from initial-state radiative events

- **Data set:** $3.8\,\mathrm{pb}^{-1}$ $e^+p$ (1996)
- **Kin. Range:** $0.3 < Q^2 < 22\,\mathrm{GeV}^2$
  $1 \cdot 10^{-5} < x < 3 \cdot 10^{-2}$

- ISR analysis extends covered region around $Q^2 = 1.3\,\mathrm{GeV}^2$ to higher $x$
- Good agreement between ISR and other analyses in overlap region
- Data well described by theory and fit
- ISR events well understood
  $\Rightarrow$ Direct measurement of $F_L$ possible in the future



# High-$Q^2$ NC cross sections from $e^-p$ DIS

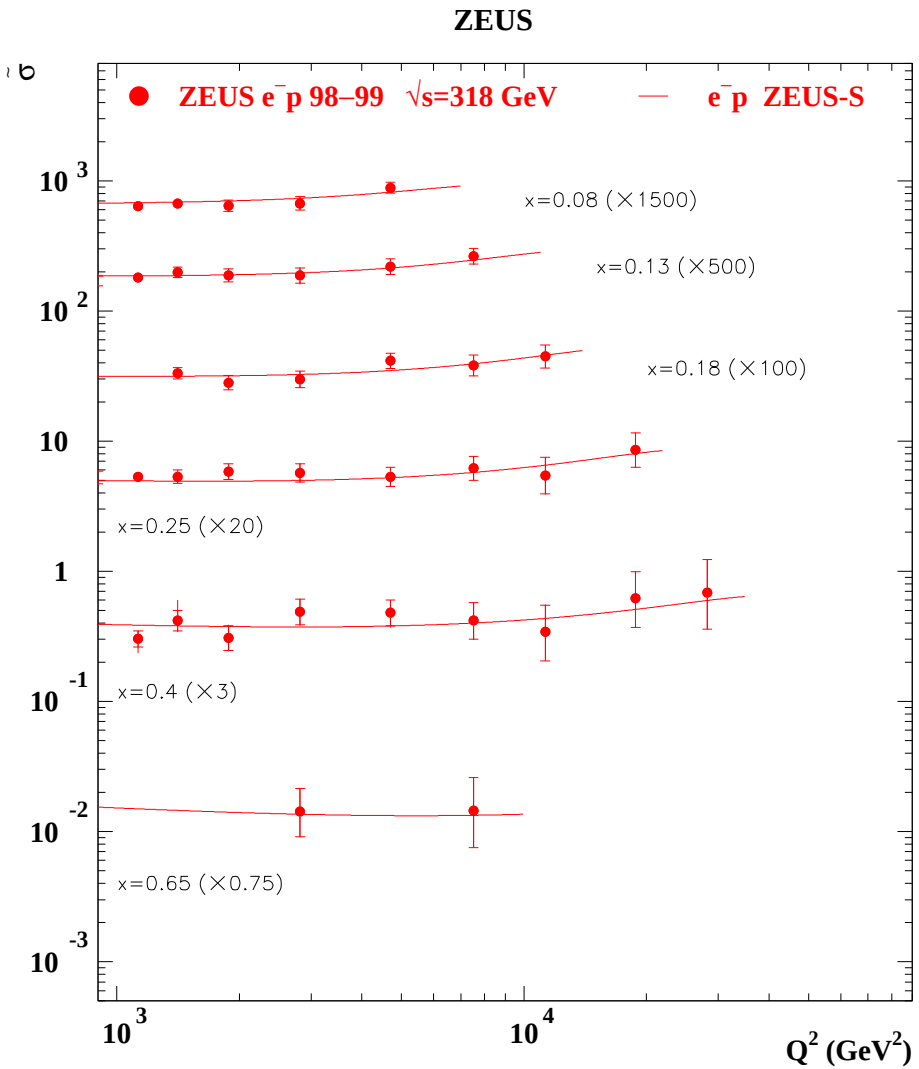
- Electromagnetic interactions are invariant under $P$ and $C$
  $\Rightarrow \sigma^{\mathrm{NC}}(e^-p) \approx \sigma^{\mathrm{NC}}(e^+p)$ for $Q^2 \ll M_Z^2$ ($\gamma$-only exchange)
- Weak interactions do not preserve $P$ and $C$ but $\sim CP$
  $\Rightarrow \sigma^{\mathrm{NC}}(e^-p) > \sigma^{\mathrm{NC}}(e^+p)$ for $Q^2 \gtrsim M_Z^2$ ($|\gamma + Z|$ exchange)
- Parity violating terms of $\sigma^{\mathrm{NC}}(e^{\pm}p)$ are combined in structure function $xF_3$, whereas $F_2$ is invariant under $P$

**Comparison of $e^-p$ and $e^+p$ cross sections provides direct test of the electroweak sector of the SM**

# High-$Q^2$ NC cross sections from $e^-p$ DIS

- **Data set:** 15.9 pb$^{-1}$ $e^-p$ (1998–99)
  (the only $e^-p$ data set at HERA)
- **Kin. Range:** $185 < Q^2 < 50000\,\text{GeV}^2$
  $0.0037 < x < 0.75$

- Good agreement between $e^-p$ data and theory (ZEUS fit 96/97)
  (lower $Q^2$ data points not shown)



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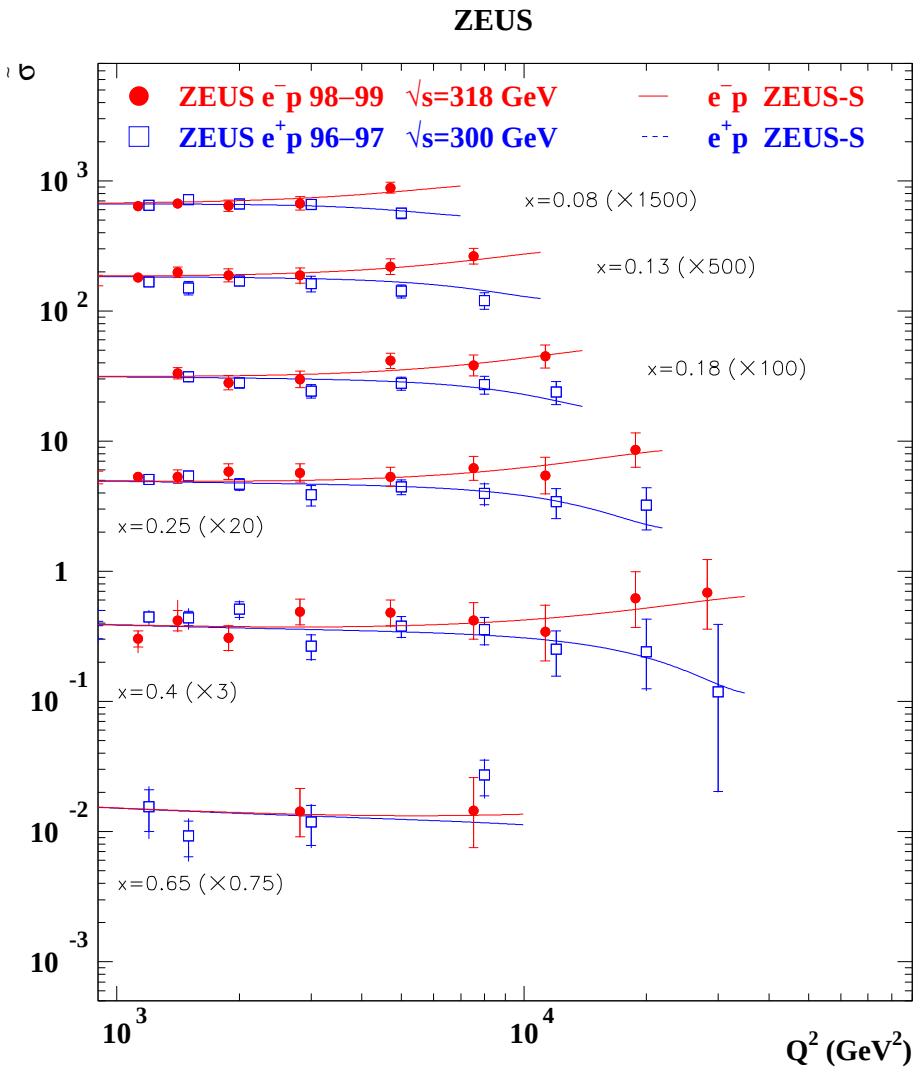
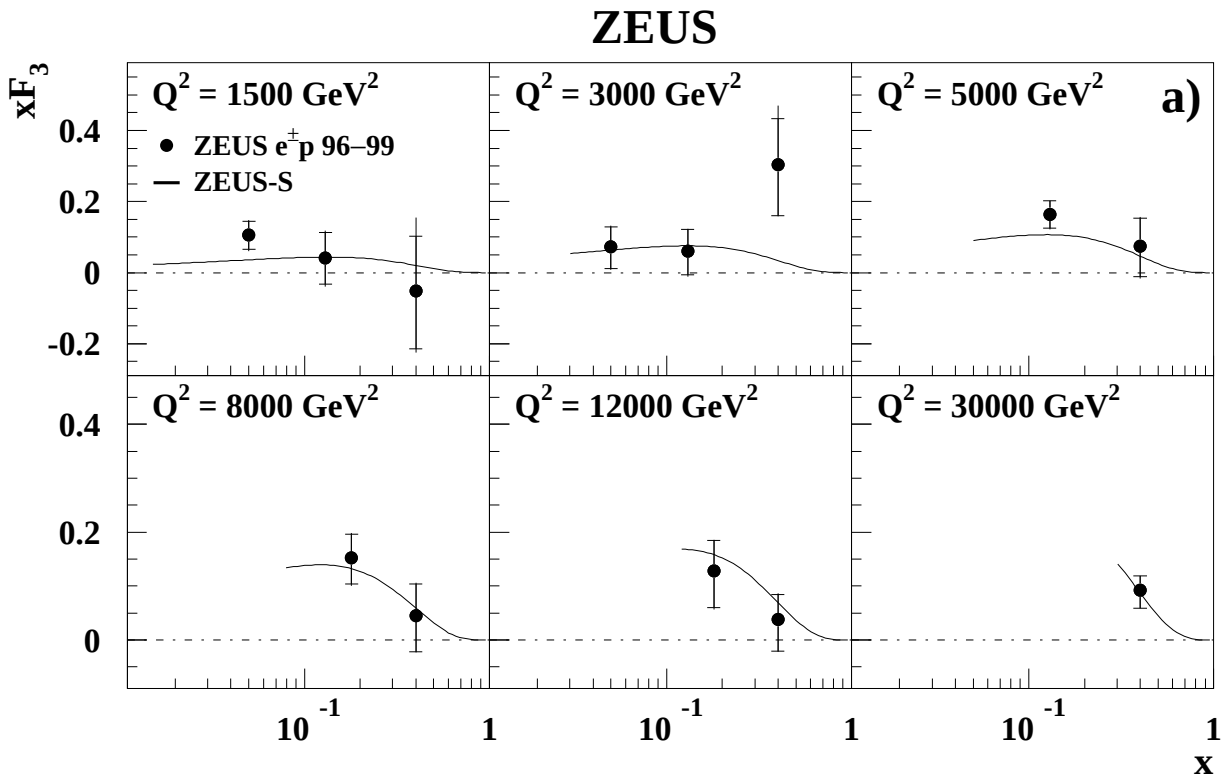
- Good agreement between $e^-p$ data and theory (ZEUS fit 96/97)
  (lower $Q^2$ data points not shown)

- Comparison to $e^+p$ (30 pb$^{-1}$, 1996–97) confirms opposite effect of $Z$ exchange for $Q^2 \gtrsim 5000\,\text{GeV}^2$
- This effect is used to extract the parity-violating structure function $xF_3$



# High-$Q^2$ NC — Extraction of $xF_3$




- $xF_3$ is measured $\neq 0$
- Data well described by theory
- Precision limited by low $e^-p$ statistics

# High-$Q^2$ CC cross sections from $e^-p$ DIS

- Charged current reactions only sensitive to specific quark flavors:

  $\boldsymbol{e^-p}$: $u$, $c$, $\bar{d}$, $\bar{s}$ $\qquad$ ($\boldsymbol{e^+p}$: $\bar{u}$, $\bar{c}$, $d$, $s$)

- $W$ only couples to left-handed fermions and right-handed antifermions

  $\Rightarrow$ $\boldsymbol{e^-q}$ angular distributions flat

  $\boldsymbol{e^-\bar{q}}$ angular distributions show $(1-y)^2$ behavior

- pure weak interaction $\Rightarrow$ CC cross section directly depending on $M_W$

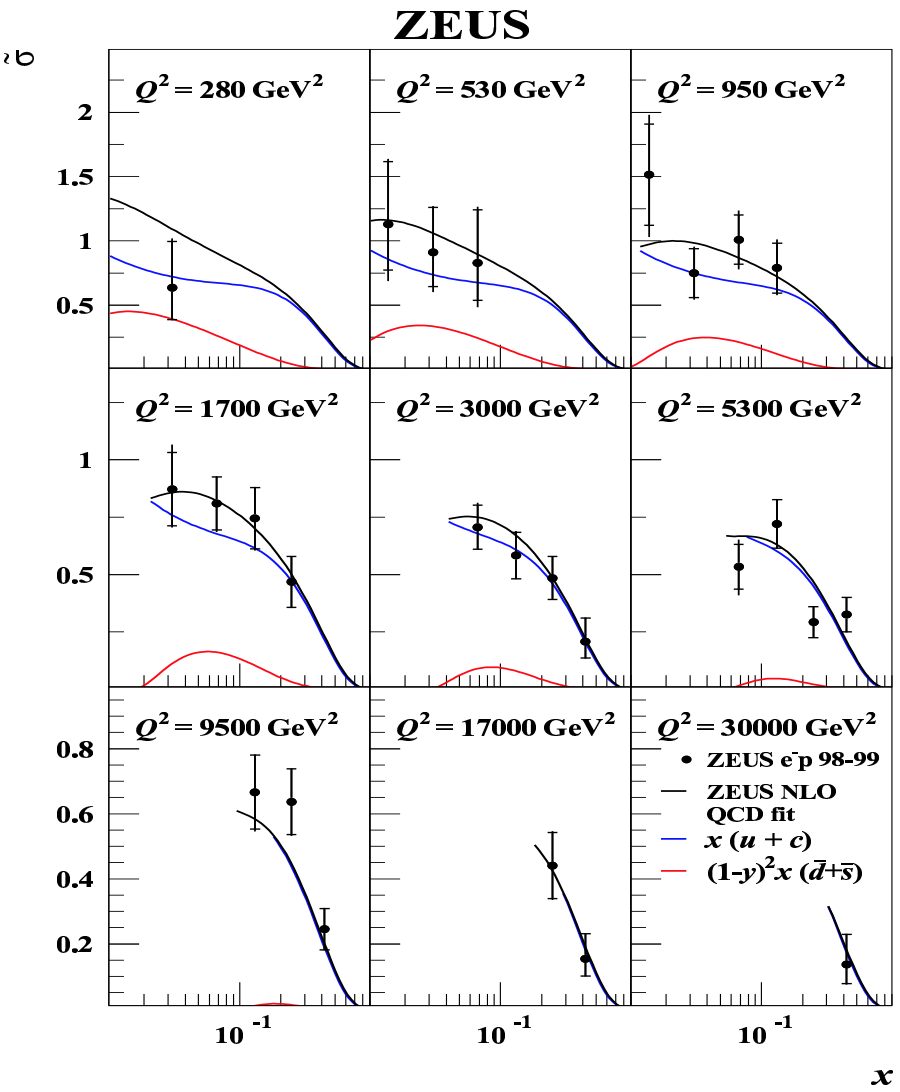
$$\frac{d\sigma}{dQ^2} \propto \frac{M_W^4}{\left(Q^2 + M_W^2\right)^2}$$

**Measuring CC cross sections**

- **yields information about flavor-content of proton**
- **can be used to determine $M_W$ in space-like region**

# High-$Q^2$ CC cross sections from $e^-p$ DIS

- **Data set:** 16.4 pb$^{-1}$ $e^-p$ (1998–99)
- **Kin. Range:** $280 < Q^2 < 30000\,\text{GeV}^2$
  $0.015 < x < 0.42$



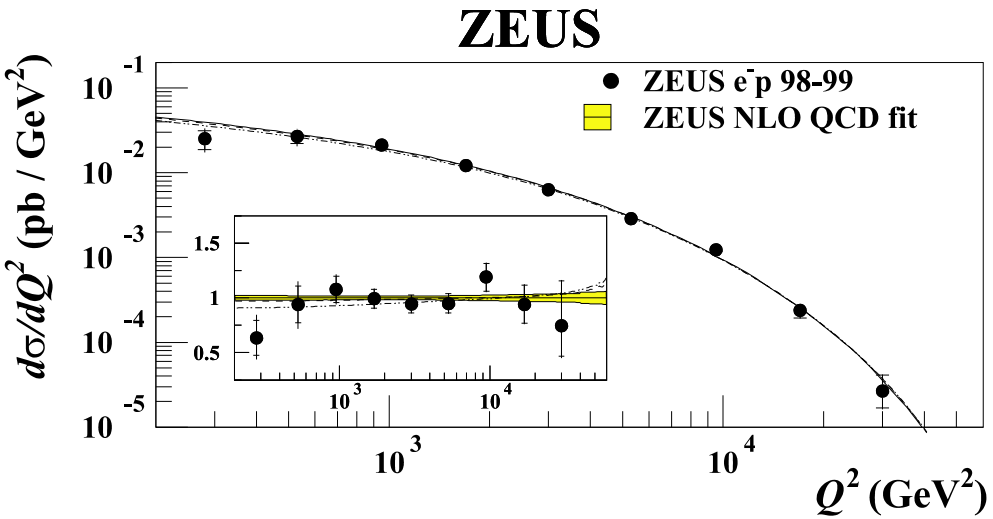

- Good agreement between data and prediction (ZEUS fit 96/97)
- At high $x$ cross section is dominated by $u$ (valence) quarks
  $\Rightarrow$ direct measurement of $u$ quark PDF
- $(\bar{d} + \bar{s})$ sea is suppressed towards low x due to helicity structure of reaction

# High-$Q^2$ CC cross sections from $e^-p$ — $M_W$ fit

- LO fit to $d\sigma/dQ^2$ distribution:

$$\frac{d\sigma}{dQ^2} \propto \frac{M_W^4}{\left(Q^2 + M_W^2\right)^2}$$

- $G_F = 1.166 \cdot 10^{-5}\,\text{GeV}^{-2}$



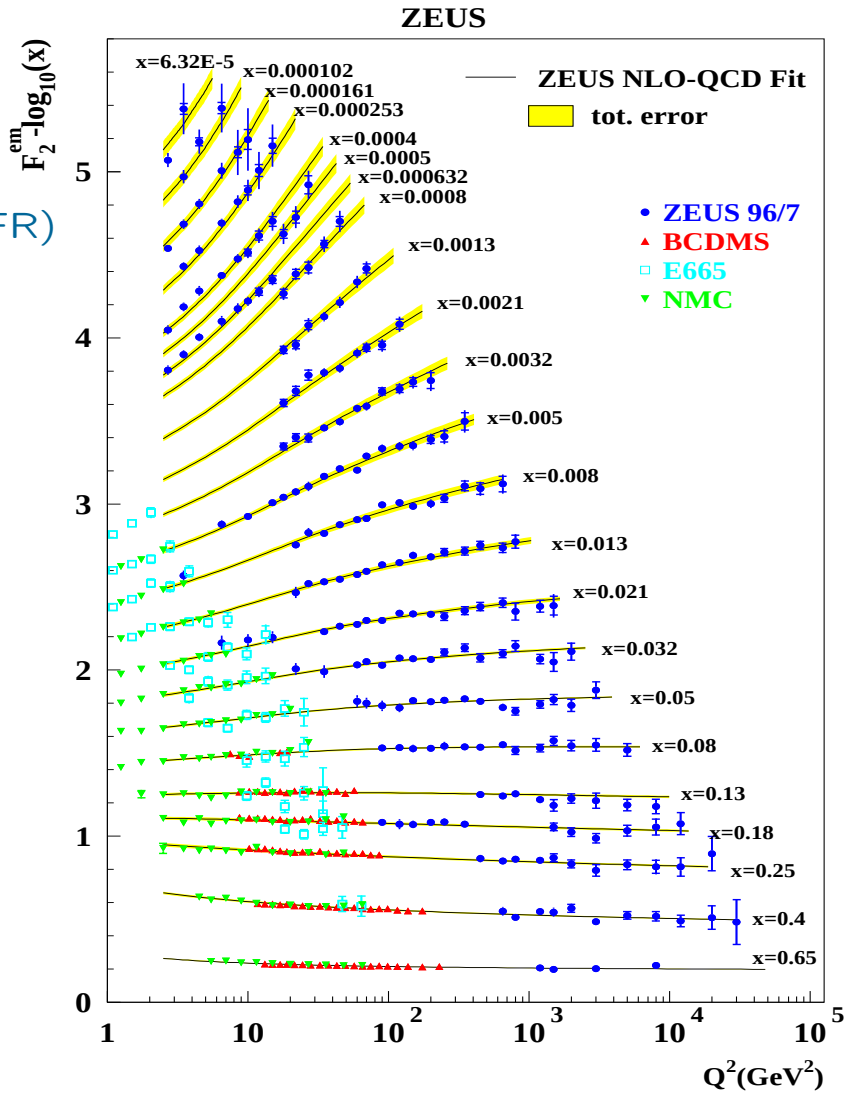

**Fit results:**

- $M_W = 80.3 \pm 2.1\,(\text{stat}) \pm 1.2\,(\text{sys}) \pm 1\,(\text{PDF})\,\text{GeV}$
  $(M_W = 81.4\ ^{+2.7}_{-2.6}\ ^{+2.0}_{-2.0}\ ^{+3.3}_{-3.0}\,\text{GeV}$ from $e^+p)$
- In agreement with world average value
  $M_W = (80.419 \pm 0.056)\,\text{GeV}$
- Measurement in space-like region at HERA complementary to those in the time-like region at LEP and Tevatron

# NLO QCD analysis of data on DIS

**Description of fit:**

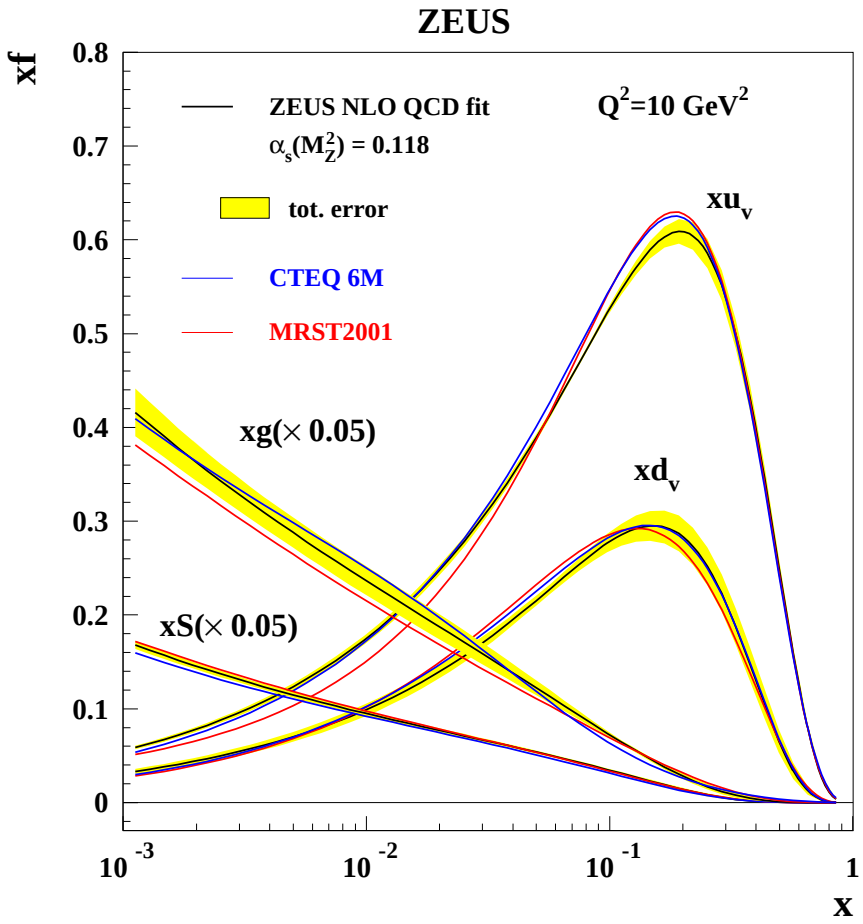
- Global NLO QCD fit to ZEUS (until 1997) and fixed-target data (BCDMS, NMC, E665, CCFR)
- Full information on point-to-point correlation of systematic uncertainties used
- Kinematic range covered by data points: $2.5 < Q^2 < 30000\,\mathrm{GeV}^2$, $6.3 \cdot 10^{-5} < x < 0.65$
- Fit yields excellent description of data down to $Q^2 \approx 0.8\,\mathrm{GeV}^2$



# NLO QCD analysis of data on DIS

- Fixed-target data constrain
  - valence distribution,
  - flavor composition of sea
  - quark distribution at high $x$
- New precise ZEUS data yields information on
  - gluon distribution
  - quark densities at low $x$
  - $\alpha_s(M_Z)$ (fit yields $\alpha_s = 0.1166 \pm 0.0053$)

- Size of error band dominated by correlated systematics
- ZEUS fit compatible with MRST2001 and CTEQ6M



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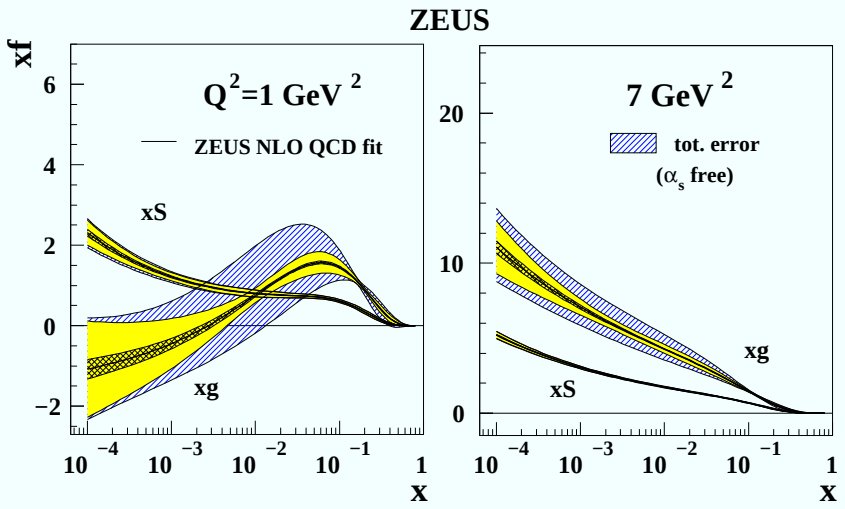
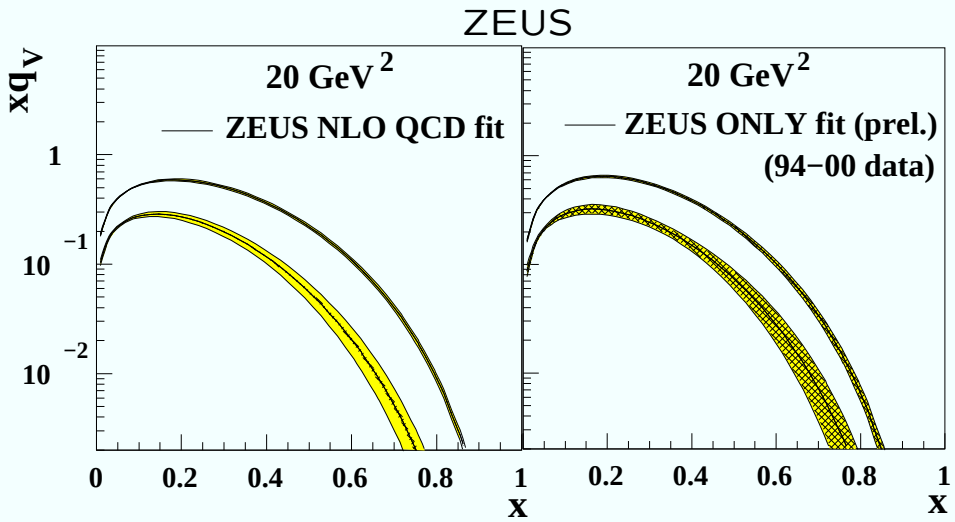



- rise of $F_2$ in low-$x$, low-$Q^2$ region not completely caused by gluons




- using only ZEUS data (1994–00) yields similar uncertainties on valence PDFs as the standard fit with fixed-target data

# Summary (I)

- Cross section measurements of **inclusive $\phi$ production in DIS** **(ICHEP 850)** yield $\sigma(e^+p \to e^+\phi p) = 0.506 \pm 0.021(\text{stat})^{+0.006}_{-0.003}(\text{sys})\,\text{nb}$
- ZEUS data prefer models with strange proton content

- Measurement of **$F_2$ from initial-state radiative events** **(ICHEP 771)** fills gap in coverage of kinematic plane around $Q^2 = 1\,\text{GeV}^2$ to higher $x$
- ISR data in good agreement with "standard" analyses in overlap region
- ISR data allow a first direct measurement of $F_L$ in the future

- Comparing **high-$Q^2$ NC cross sections from $e^-p$ DIS** **(ICHEP 766)** with those from $e^+p$ shows effects of weak interaction via $Z$ exchange
- $e^-p$ data in good agreement with predictions from EW theory and pQCD
- First ZEUS measurement of $xF_3 \neq 0$

# Summary (II)

- Measurement of **high-$Q^2$ CC cross sections from $e^-p$ DIS** **(ICHEP 763)**
  in good agreement with predictions from electroweak theory and QCD
- $M_W$ fit to $d\sigma/dQ^2$ in the space-like region yields $M_W = 80.3 \pm 2.1 \pm 1.2 \pm 1\,\text{GeV}$

- The **NLO QCD analysis of data on DIS** **(ICHEP 765)**
  uses both ZEUS and fixed-target results
  and takes full point-to-point systematic error correlations into account
- ZEUS fit compatible with MRST2001 and CTEQ6M
- Rapid rise of $F_2$ in low-$x$, low-$Q^2$ region not completely caused by gluons
- ZEUS data (1994–2000) alone precise enough to yield
  similar uncertainties on valence PDFs as the standard fit with fixed-target data

**Recent precision data from ZEUS complete coverage of a large kinematic-plane area (6 orders of magnitude in $x$ and $Q^2$) and yield $xF_3$.**

**All ZEUS results are fitted consistently by NLO QCD and yield precise PDFs.**