

Measurements of the proton structure in the electroweak regime at HERA

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on behalf of  and  collaborations

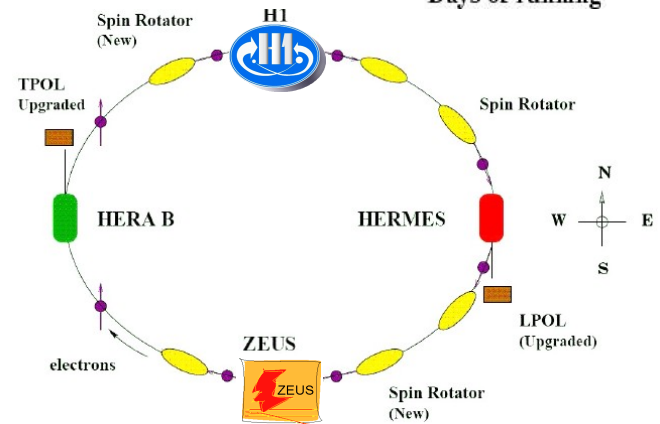
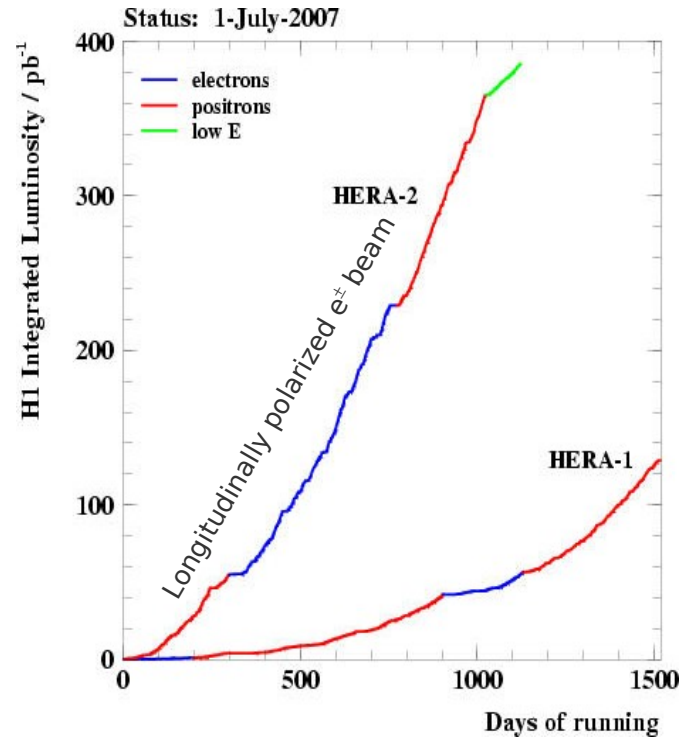
- DIS at HERA
- High Q^2 cross sections and electroweak physics
- Combined electroweak and QCD fit
- Summary

HERA

- $e^\pm(27.5 \text{ GeV})$, $p(820/920 \text{ GeV})$,
 $\sqrt{s} = 300/318 \text{ GeV}$
- Two large multipurpose detectors:
H1 and **ZEUS** (asymmetric design)
- 1994-2000: HERA I data
 2003-07 HERA II data with
 longitudinal e^\pm polarisation:

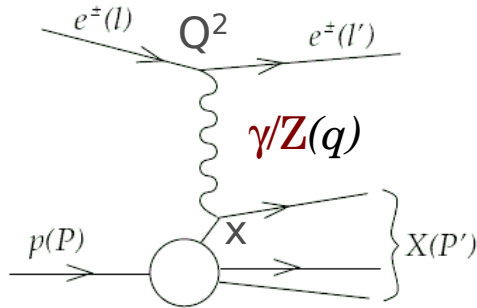
$$P_e = \frac{N_R - N_L}{N_R + N_L} \sim 30\text{-}40\% \text{ at HERA}$$

- $\sim 0.5 \text{ fb}^{-1}$ of luminosity recorded by
 the each experiment

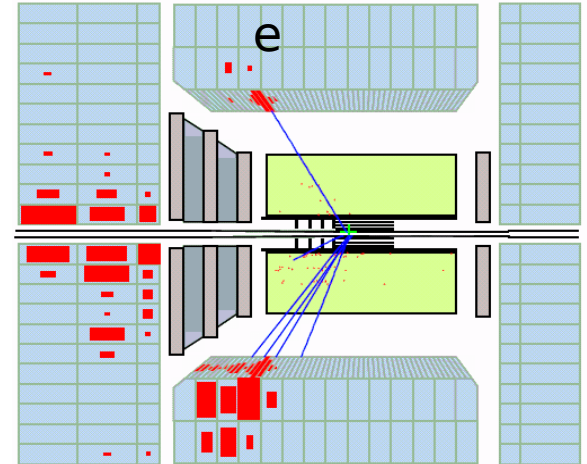


Neutral current DIS cross section

neutral current DIS cross section:



Q^2 - virtuality of exchange boson
 x - Bjorken scaling variable
 y - inelasticity



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

dominant contribution \uparrow
 important at high Q^2 \uparrow
 sizable at high y \uparrow

$$Y_\pm = 1 \pm (1 - y)^2$$

$$k = \frac{1}{4 \sin^2 \theta_w \cos^2 \theta_w} \frac{Q^2}{Q^2 + M_Z^2}$$

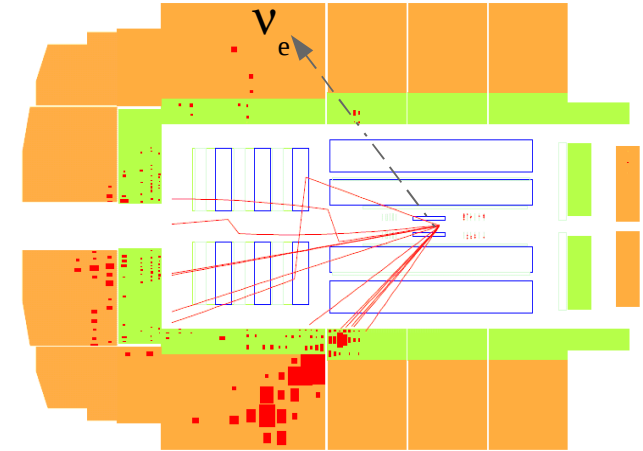
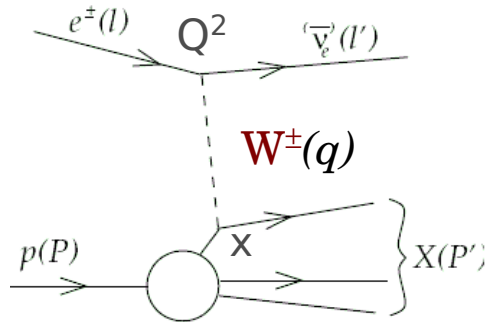
→ polarisation dependence due to γZ interference and Z terms:

$$\tilde{F}_2^\pm = F_2 + k(-v_e \mp P_e a_e) F_2^{\gamma Z} + k^2(v_e^2 + a_e^2 \pm 2P_e v_e a_e) F_2^Z$$

$$x \tilde{F}_3^\pm = k(-a_e \mp P_e v_e) x F_3^{\gamma Z} + k^2(2v_e a_e \pm P_e(v_e^2 + a_e^2)) x F_3^Z$$

Charged current DIS cross section

charged current DIS cross section:



$$\frac{d^2\sigma_{CC}^{e^\pm p}}{dx dQ^2} = (1 \pm P_e) \frac{G_F^2}{2\pi x} \left(\frac{M_W^2}{Q^2 + M_W^2} \right)^2 \tilde{\sigma}_{CC}^{e^\pm p}$$

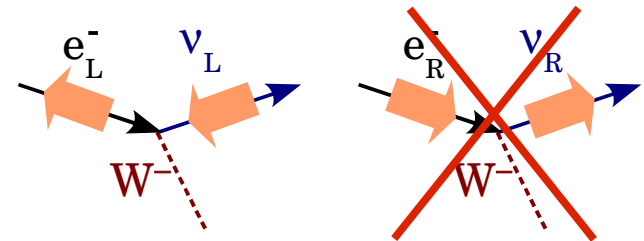
→ linear polarisation dependence

In SM weak interaction acts only on left-handed particles (right-handed anti-particles)

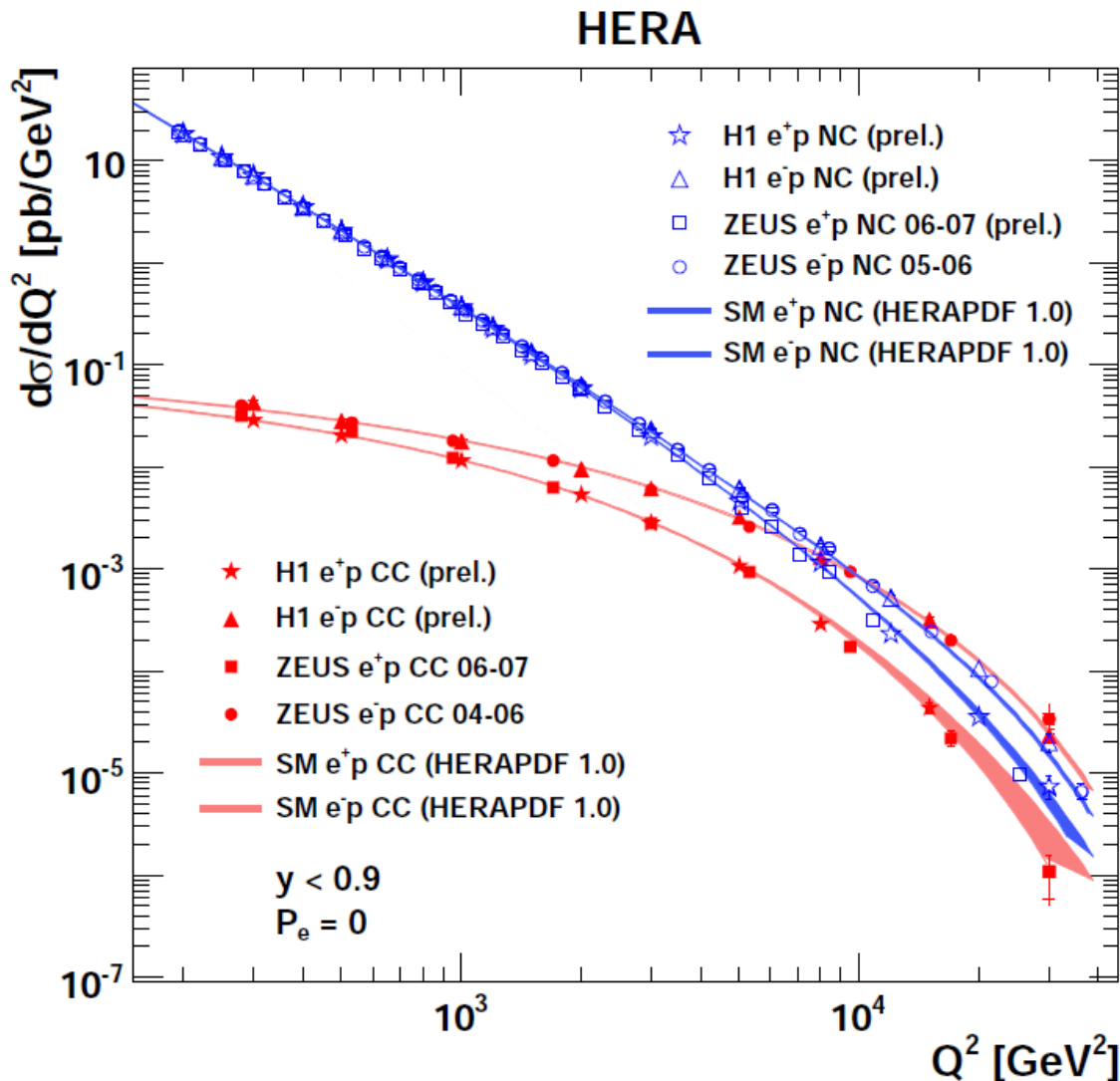
at LO e^+/e^- sensitive to different quark densities:

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

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



Charged and neutral currents at HERA



neutral (γ/Z)
charged (W^\pm)
currents cross sections
at $Q^2 \gtrsim M_{Z/W}^2$ scale
get similar:
EW unification

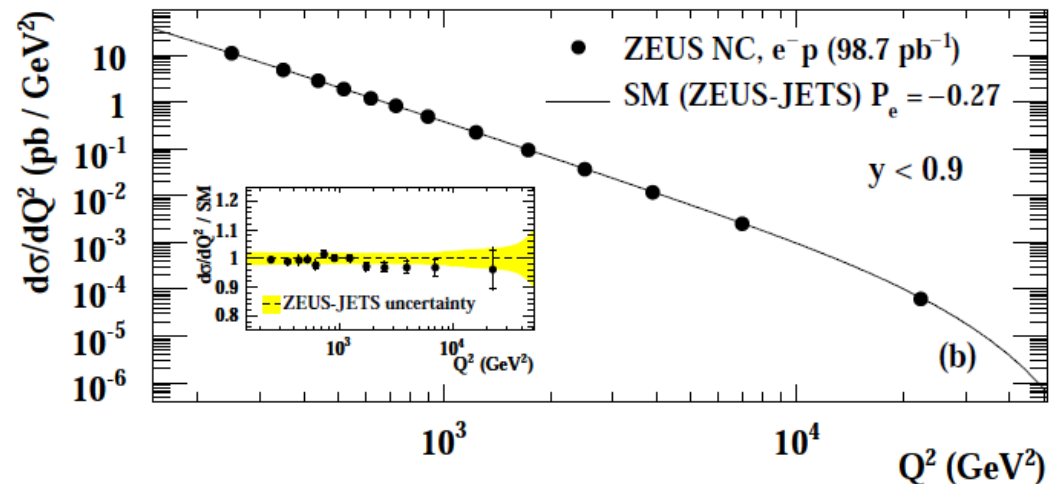
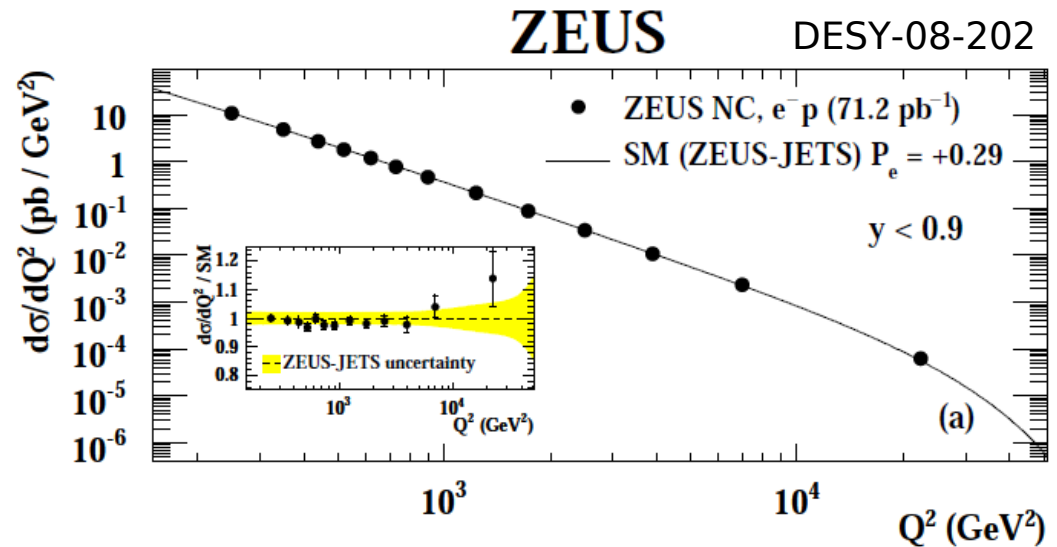
good agreement with
SM (HERAPDF 1.0)

Polarised neutral current measurements

- single differential cross sections with longitudinally polarised lepton beams (HERA II)

$d\sigma/dQ^2$ (e^-p) NC
measurement in ZEUS

sensitivity to polarisation
→ polarisation asymmetries



Polarisation asymmetry in neutral currents

- the charge dependent polarisation asymmetries in neutral currents
 - direct measure of EW effects

neglecting Z term generalised structure function F_2 is expressed:

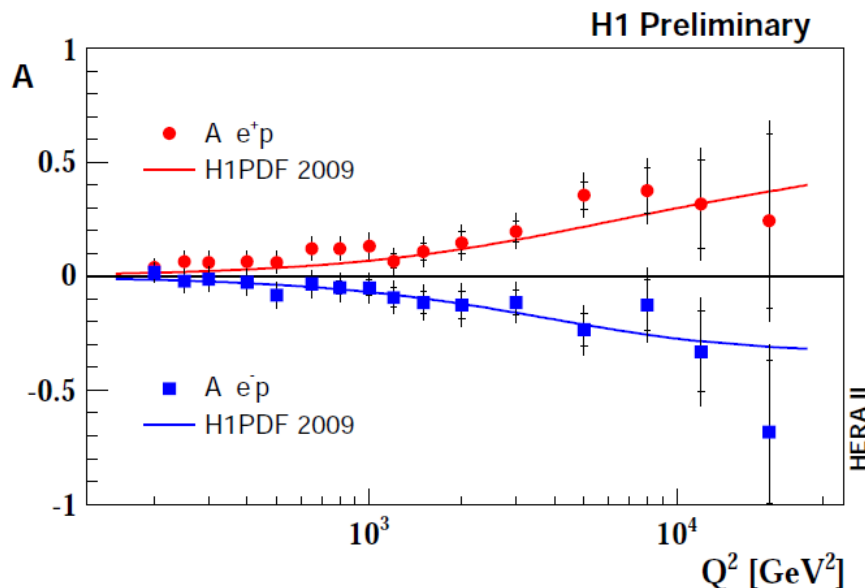
$$\tilde{F}_2^\pm \approx F_2 + k(-v_e \mp P e a_e) F_2^{\gamma Z}$$

at LO: $F_2^{\gamma Z} = x \sum 2e_q v_q (q + \bar{q})$

polarisation asymmetry A is proportional to a $v_e v_q$ combination:

$$A^\pm = \frac{2}{P_R - P_L} \frac{\sigma^\pm(P_R) - \sigma^\pm(P_L)}{\sigma^\pm(P_R) + \sigma^\pm(P_L)} \simeq \mp k a_e \frac{F_2^{\gamma Z}}{F_2}$$

- direct measurement of the parity violation



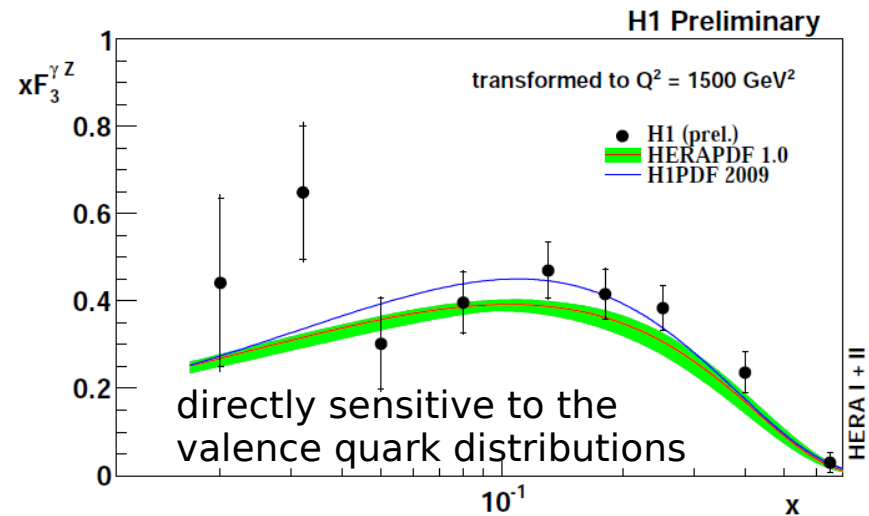
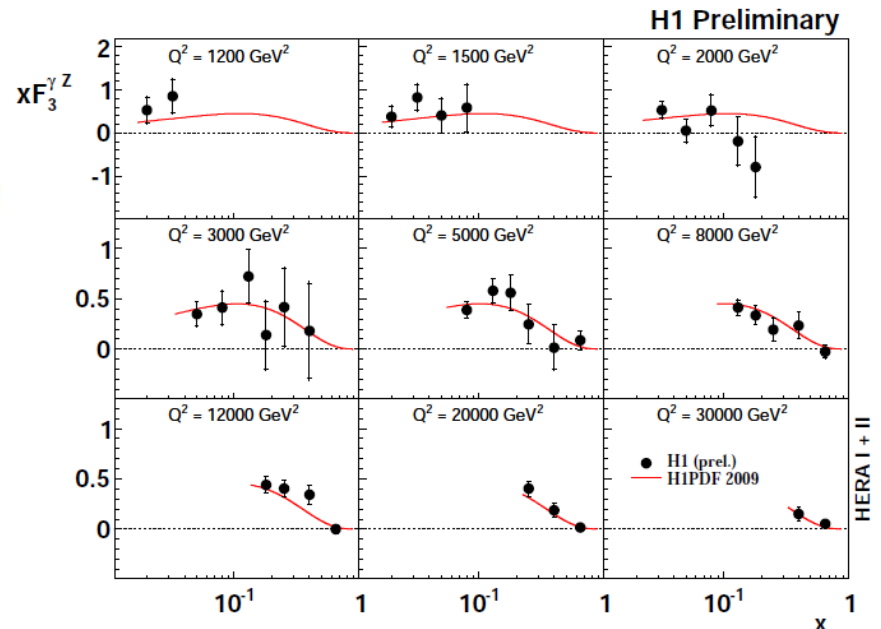
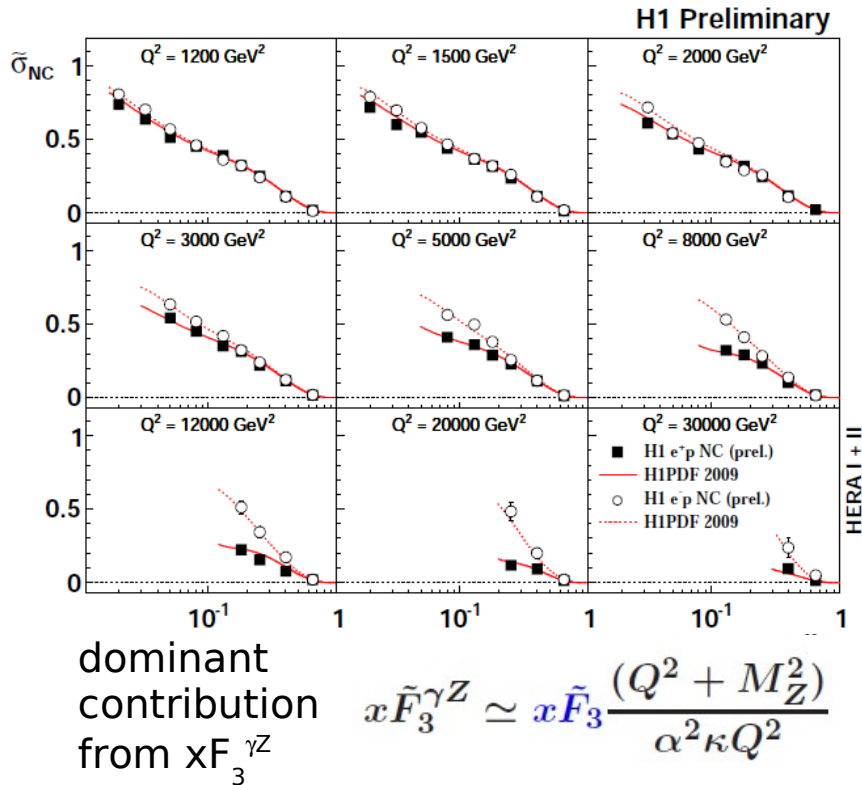
full HERA II statistics

Structure function xF_3

Structure function $x\tilde{F}_3$

$$\tilde{\sigma}^{\pm} = \frac{d^2\sigma_{NC}^{e^{\pm}p}}{dx dQ^2} \frac{xQ^4}{2\pi\alpha^2 Y_+} = \tilde{F}_2 \mp \frac{Y_-}{Y_+} x\tilde{F}_3 - \frac{y^2}{Y_+} \tilde{F}_L$$

$$x\tilde{F}_3 = \frac{Y_+}{2Y_-} [\tilde{\sigma}^- - \tilde{\sigma}^+]$$

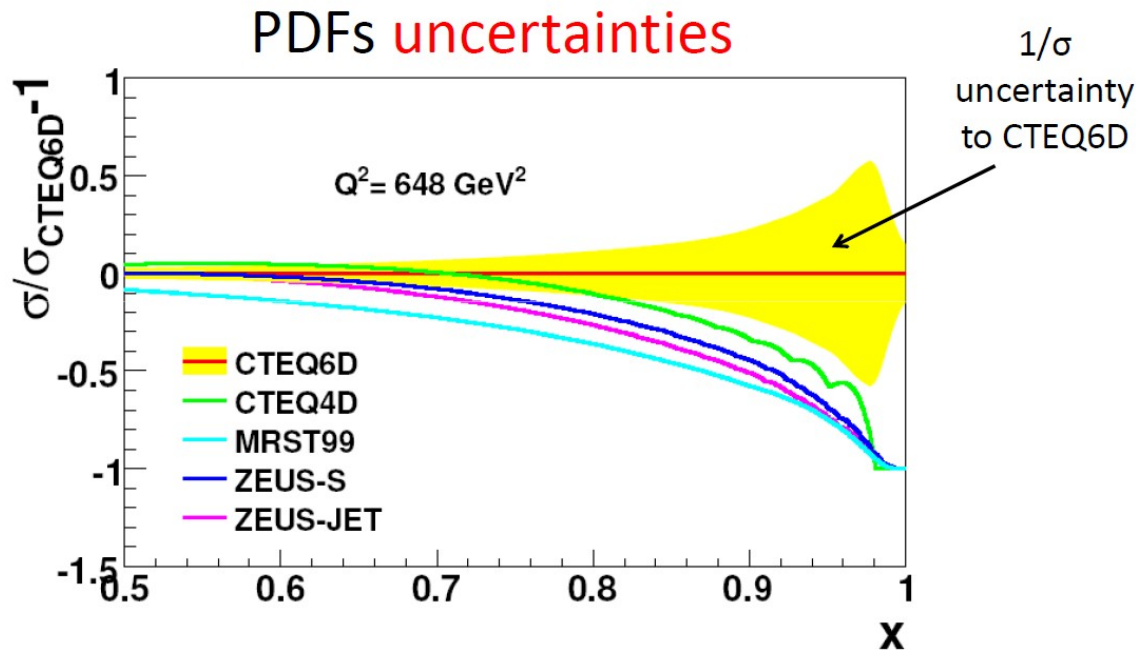


New NC measurement in ZEUS

- new method to measure neutral current cross sections at large Bjorken x (e^-p , $Q^2 \geq 575 \text{ GeV}^2$)

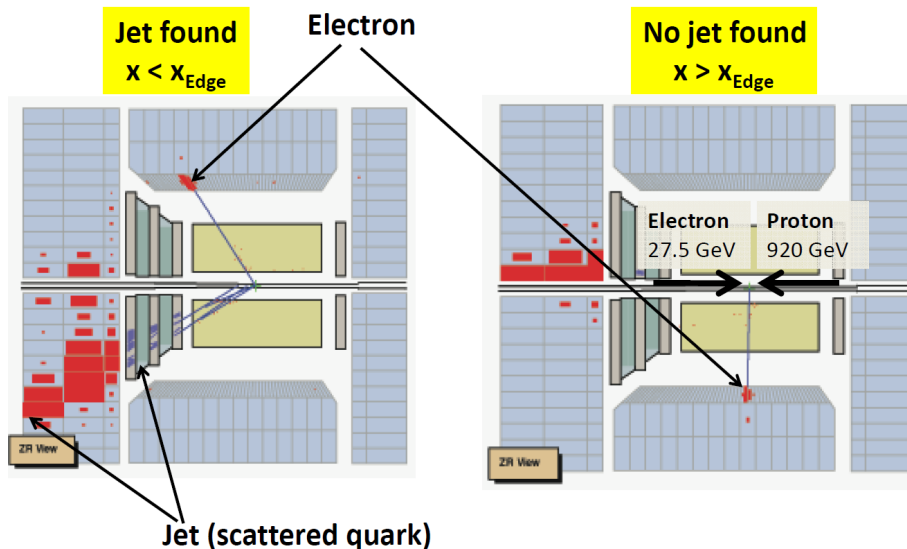
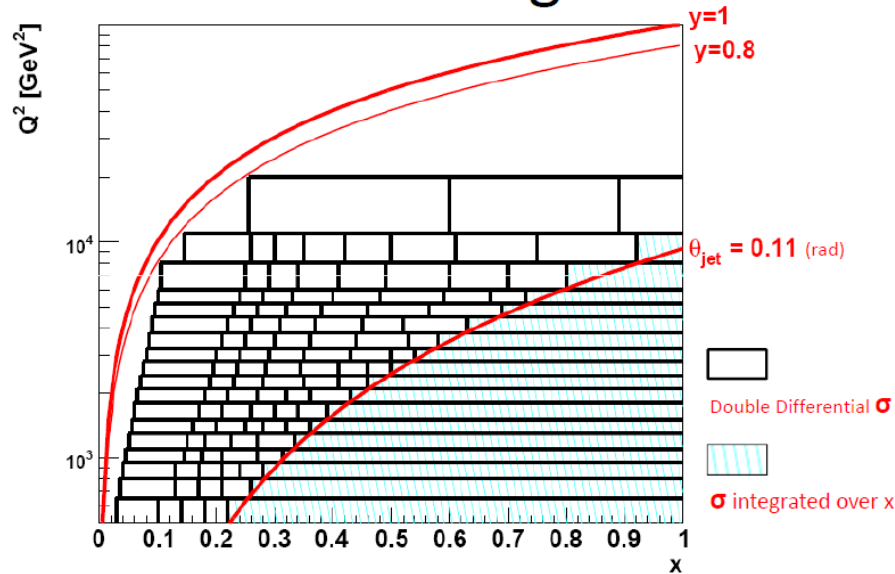


Motivation: reduced PDF uncertainty at high x



New NC measurement in ZEUS

Binning



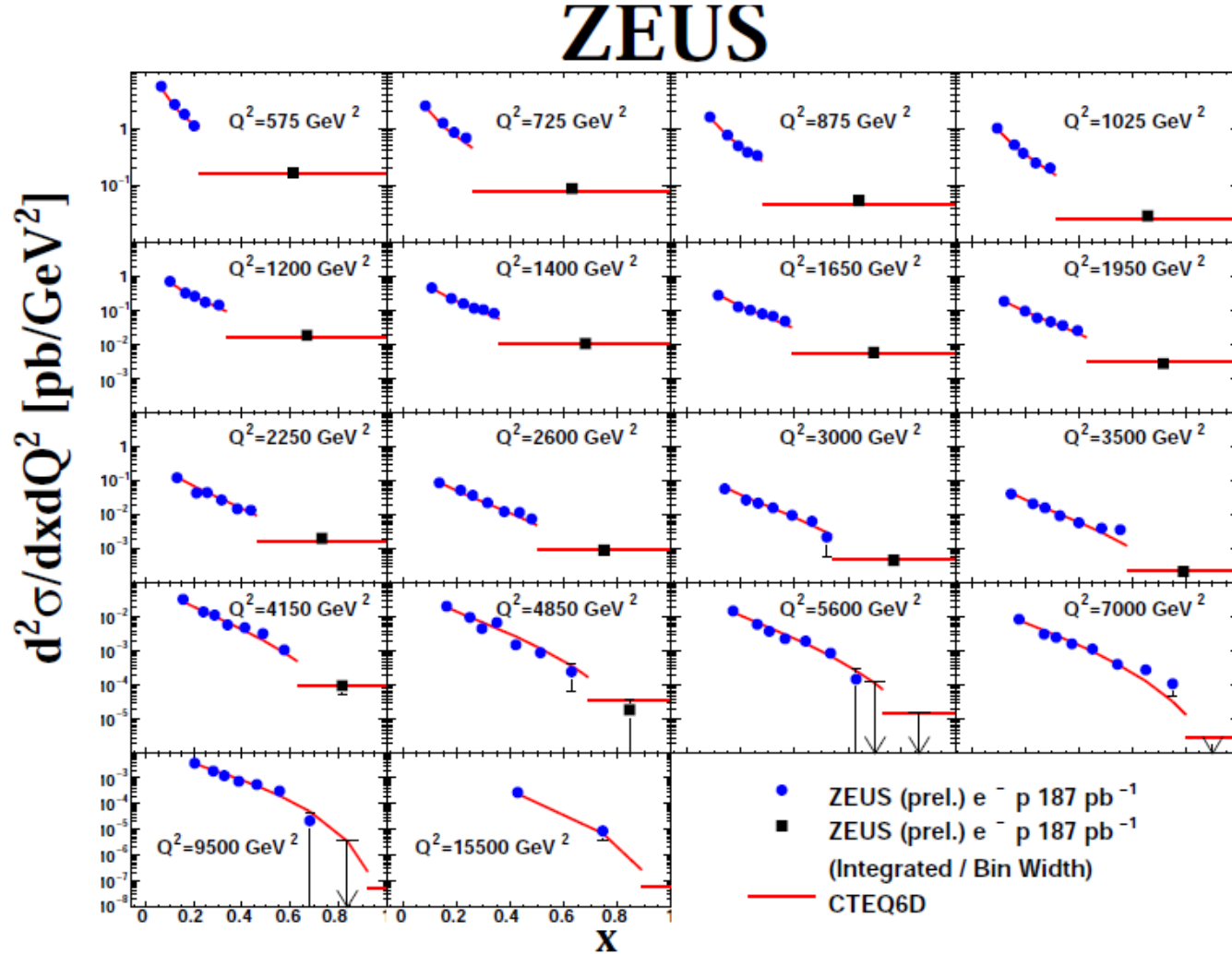
Full HERA II e⁻p data sample
- new x reconstruction method

Idea:
use hadronic system information
(jet energy and angle) to
determine x

- events sorted in Q^2 bins from e and in x bins from the jet
- events reconstructed with 0 jets use to calculate integrated x-os section for:

$$x_{\text{Edge}}(\theta_{\text{jet}} = 0.11) < x < 1$$

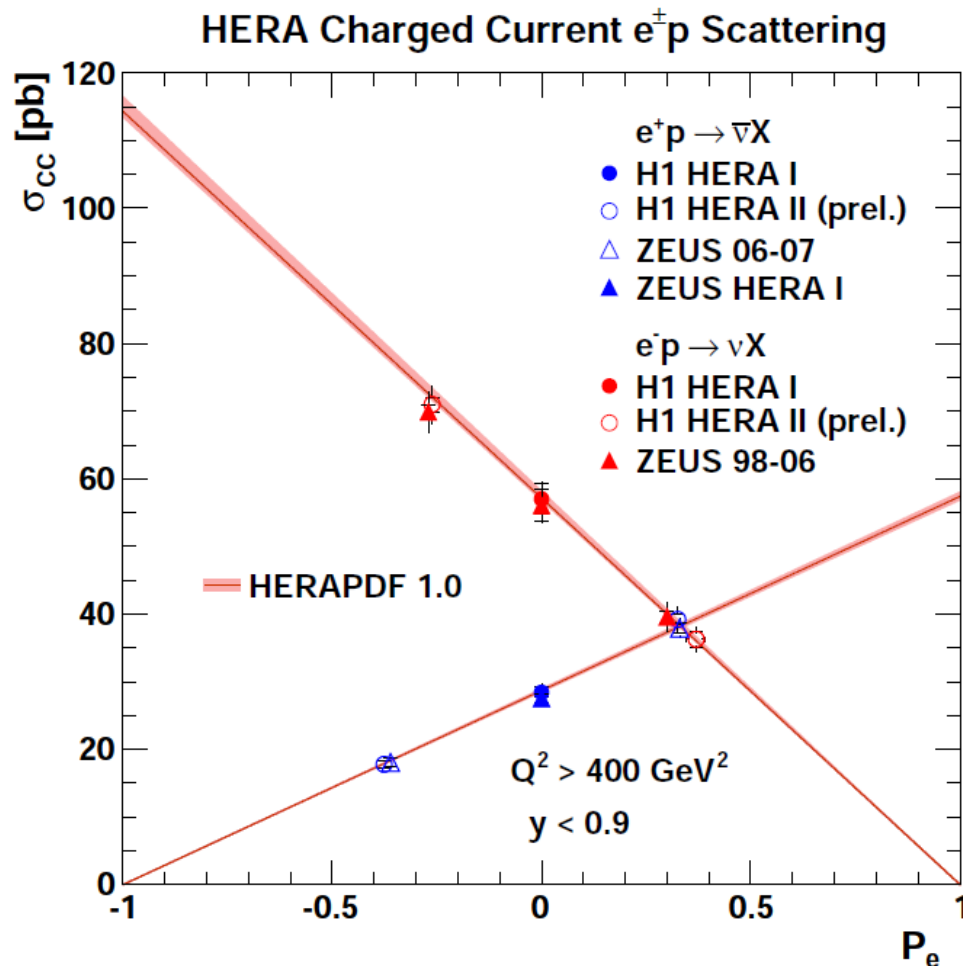
New NC measurement in ZEUS



- extended kinematic coverage for DIS
- significantly improved precision to previous ZEUS measurement

Charged currents at HERA

SM weak interactions: only left-handed particles interact (right-handed currents forbidden)



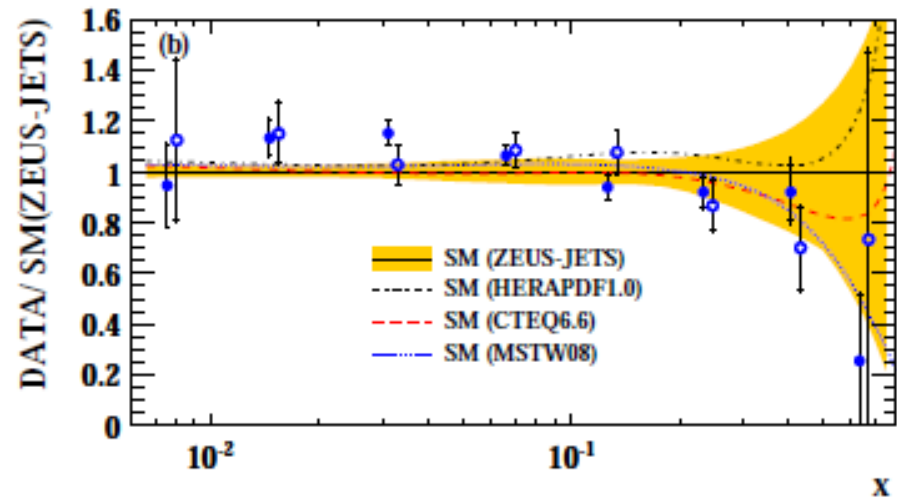
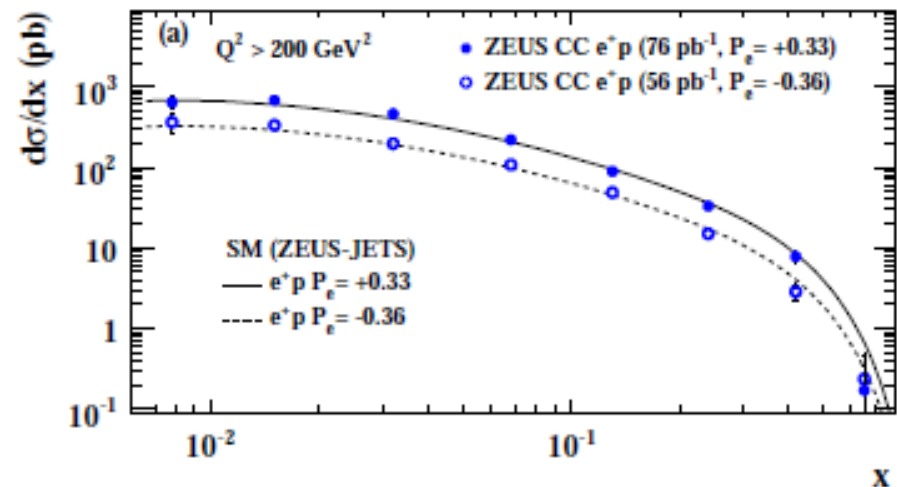
$$\frac{d^2\sigma_{CC}^{e^\pm p}}{dx dQ^2} = (1 \pm P_e) \frac{G_F^2}{2\pi x} \left(\frac{M_W^2}{Q^2 + M_W^2} \right)^2 \tilde{\sigma}_{CC}^{e^\pm p}$$

HERA results are consistent with SM

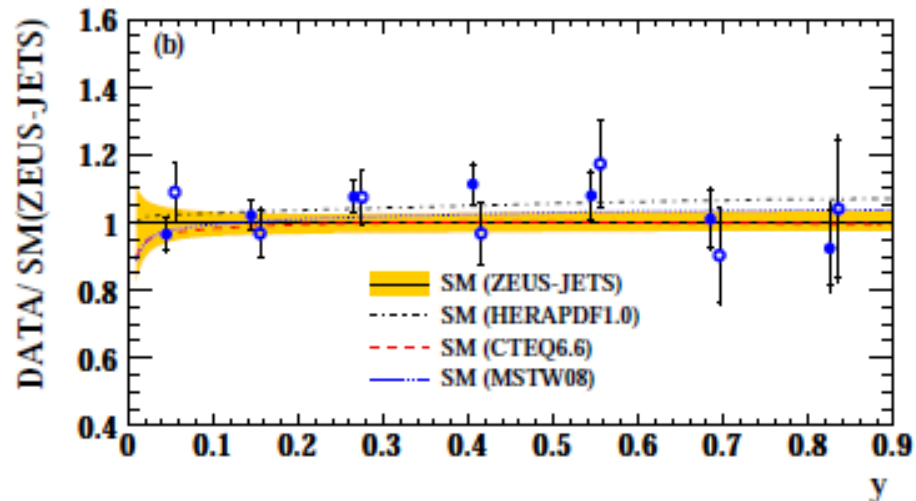
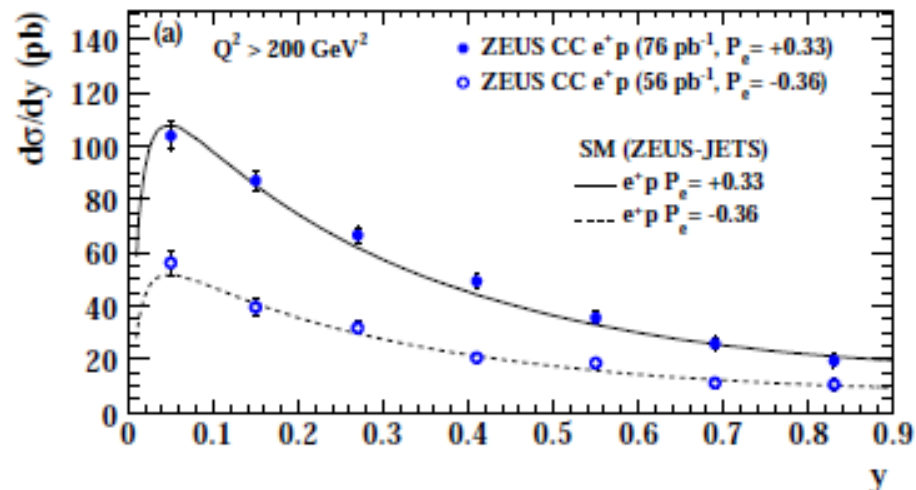
(polarised) single differential CC x-os sections

- single differential cross sections with longitudinally polarised lepton beams (e^+p)

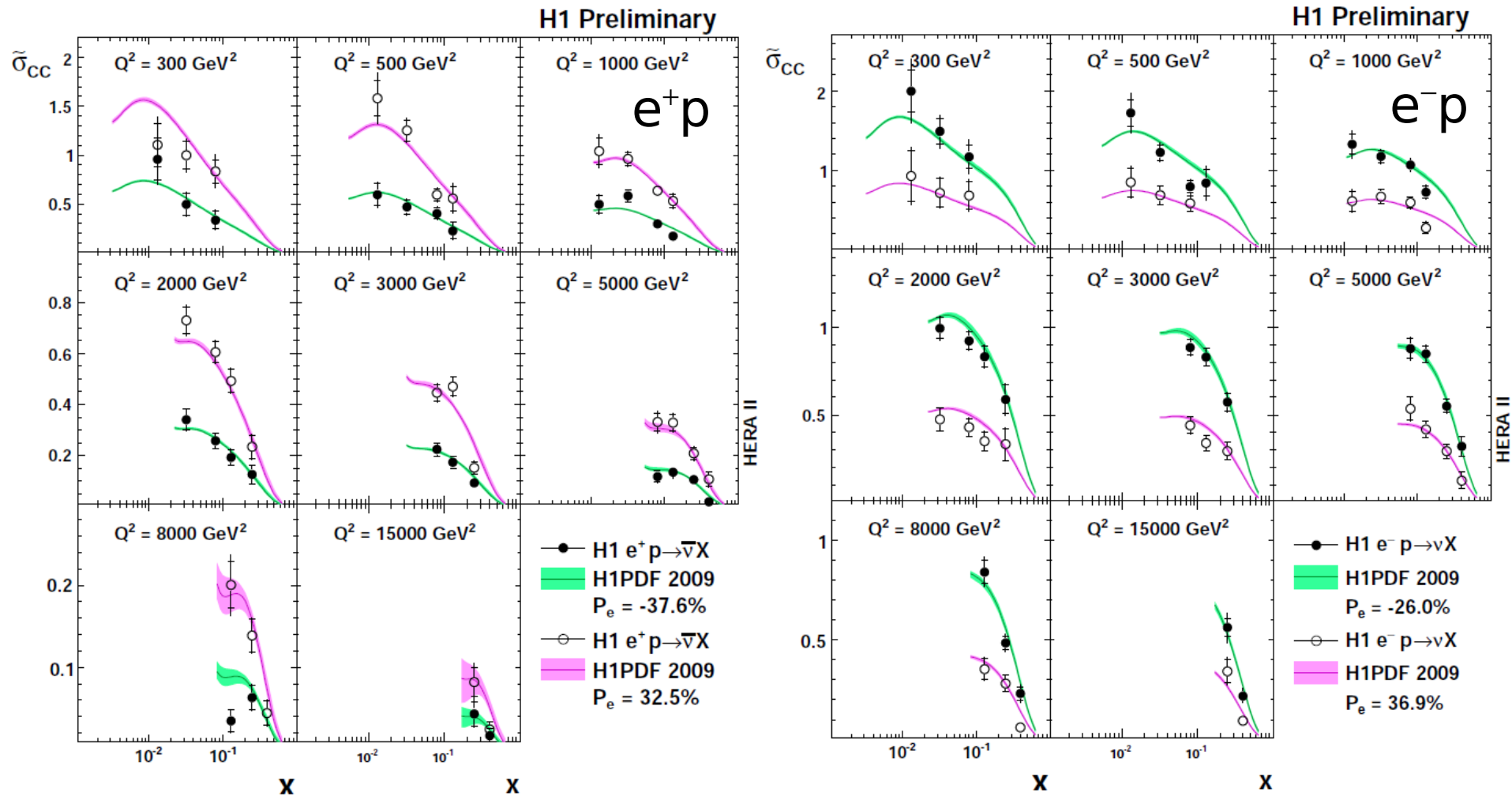
ZEUS



ZEUS



(polarised) double differential CC x-os sections



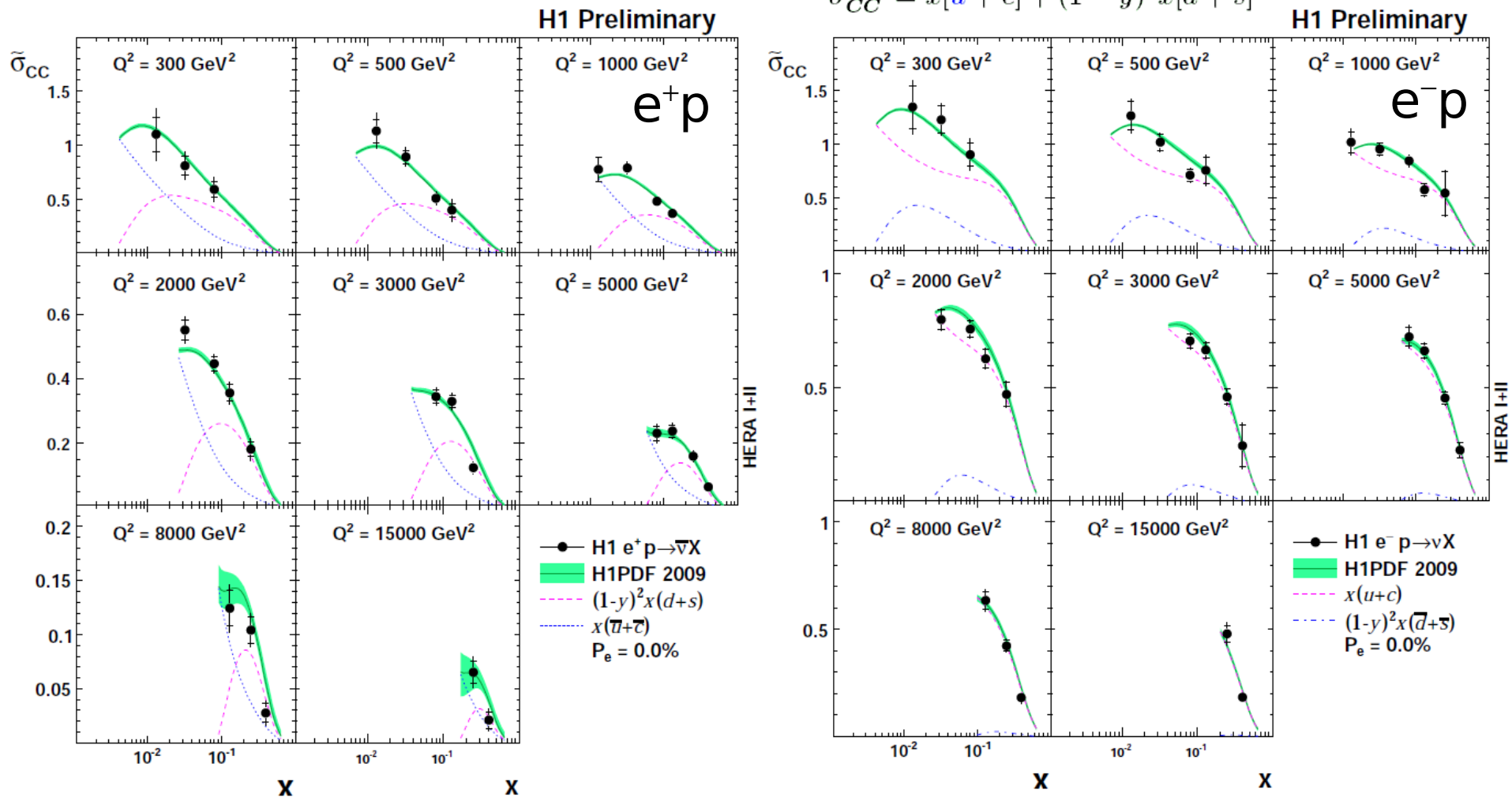
→ full HERA II data sample

Double differential CC x-os sections

CC e⁺/e⁻: flavour sensitivity

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

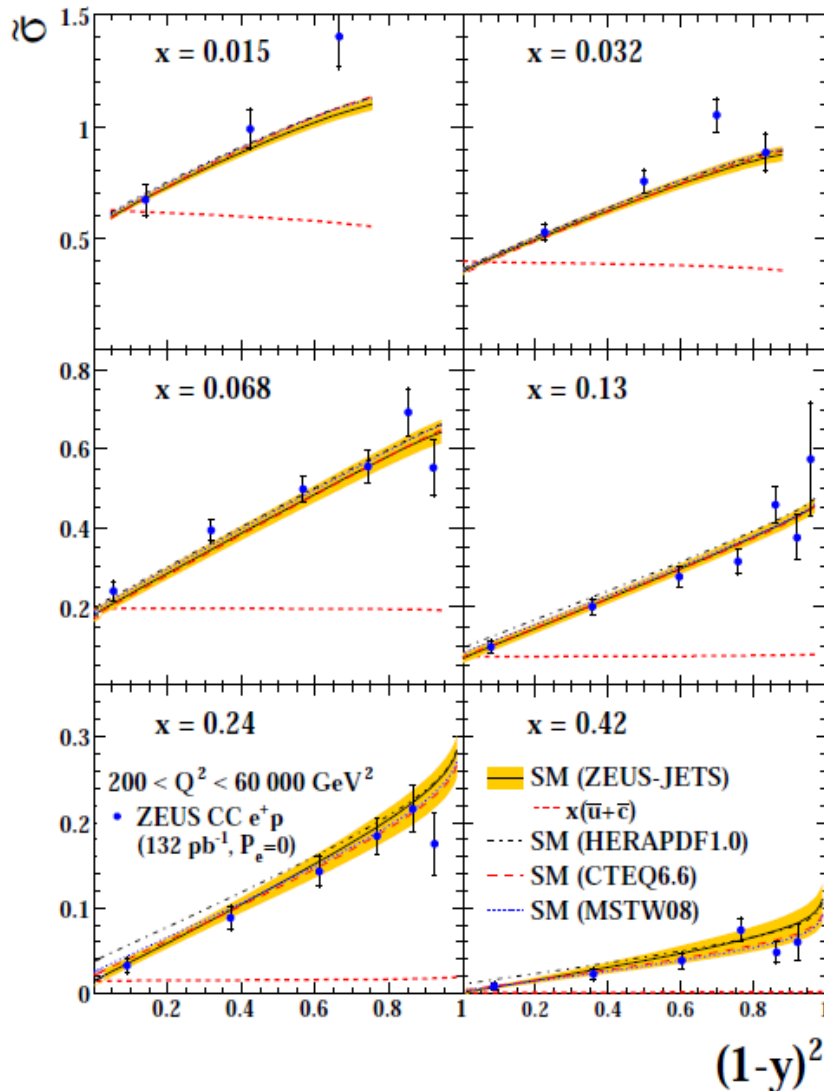
$$\tilde{\sigma}_{CC}^{e^-p} = x[u + c] + (1-y)^2 x[\bar{d} + \bar{s}]$$



→ combined H1 (HERA I + II) data (~450 pb⁻¹)

Helicity structure in CC interactions

ZEUS



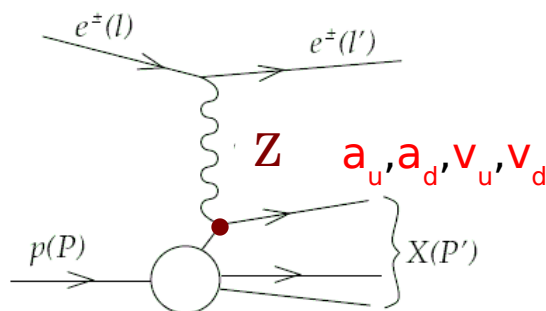
- Unpolarised reduced cross section in bins of x as a function of $(1 - y)^2$ → helicity structure of CC interactions
- At leading order in QCD:
 - Intercept gives $(\bar{u} + \bar{c})$ contribution
 - Slope gives the $(d + s)$ contribution.

$$(1 - y)^2 \propto (1 + \cos \theta^*)^2$$

Combined QCD & EW fit

→ neutral and charged current cross sections are used to constrain Parton Distribution Functions (PDFs)

- weak couplings a_u, a_d, v_u, v_d of light quarks to Z boson can be extracted from DIS data with combined QCD-EW fit



- γZ interference and Z exchange in neutral currents
- NC at high Q^2 of polarised HERA II data bring additional sensitivity on v_q
- charged currents for u-, d-quark separation

Combined QCD & EW fit: coupling sensitivity

General NC cross section:

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

In unpolarised case:

terms with v_e (~ 0)
can be neglected

$$\begin{aligned} \tilde{F}_2^\pm &= F_2 - v_e \left(\frac{\kappa_W Q^2}{Q^2 + M_Z^2} \right) F_2^{\gamma Z} + (v_e^2 + a_e^2) \left(\frac{\kappa_W Q^2}{Q^2 + M_Z^2} \right)^2 F_2^Z \\ x \tilde{F}_3^\pm &= \pm a_e \left(\frac{\kappa_W Q^2}{Q^2 + M_Z^2} \right) x F_3^{\gamma Z} \mp 2a_e v_e \left(\frac{\kappa_W Q^2}{Q^2 + M_Z^2} \right)^2 x F_3^Z \end{aligned}$$

$$\left. \begin{aligned} [F_2, F_2^{\gamma Z}, F_2^Z] &= x \sum_q [e_q^2, 2e_q v_q, v_q^2 + a_q^2] \{q + \bar{q}\} \\ [x F_3^{\gamma Z}, x F_3^Z] &= x \sum_q [e_q^2 a_q, 2v_q a_q] \{q - \bar{q}\} \end{aligned} \right\} \begin{aligned} v_q &- \text{constrained from } F_2^Z \\ a_q &- \text{mainly constrained by } x F_3^{\gamma Z} \end{aligned}$$

Combined QCD & EW fit: coupling sensitivity

In polarised case ($P_e \neq 0$):

terms with v_e (~ 0)
can be neglected

$$\tilde{F}_2^\pm = F_2 + k(-v_e \mp P_e a_e) F_2^{\gamma Z} + k^2(v_e^2 + a_e^2 \pm 2P_e v_e a_e) F_2^Z$$

$$xF_3^\pm = k(-a_e \mp P_e v_e) xF_3^{\gamma Z} + k^2(2v_e a_e \pm P_e(v_e^2 + a_e^2)) xF_3^Z$$

additional constraints
(v_q from $F_2^{\gamma Z}$)

$$[F_2, F_2^{\gamma Z}, F_2^Z] = x \sum_q [e_q^2, 2e_q v_q, v_q^2 + a_q^2] \{q + \bar{q}\}$$

$$[xF_3^{\gamma Z}, xF_3^Z] = x \sum_q [e_q^2 a_q, 2v_q a_q] \{q - \bar{q}\}$$

Combined QCD & EW fit: data



Full HERA low and high Q^2 data used in the simultaneous QCD-EW fit (best available precision):

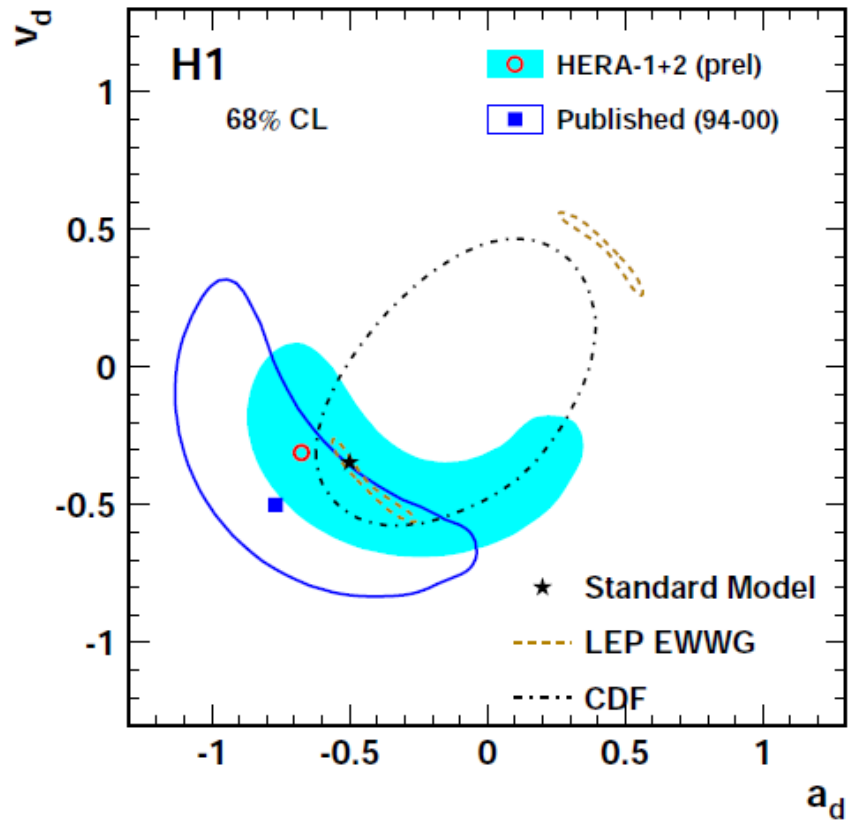
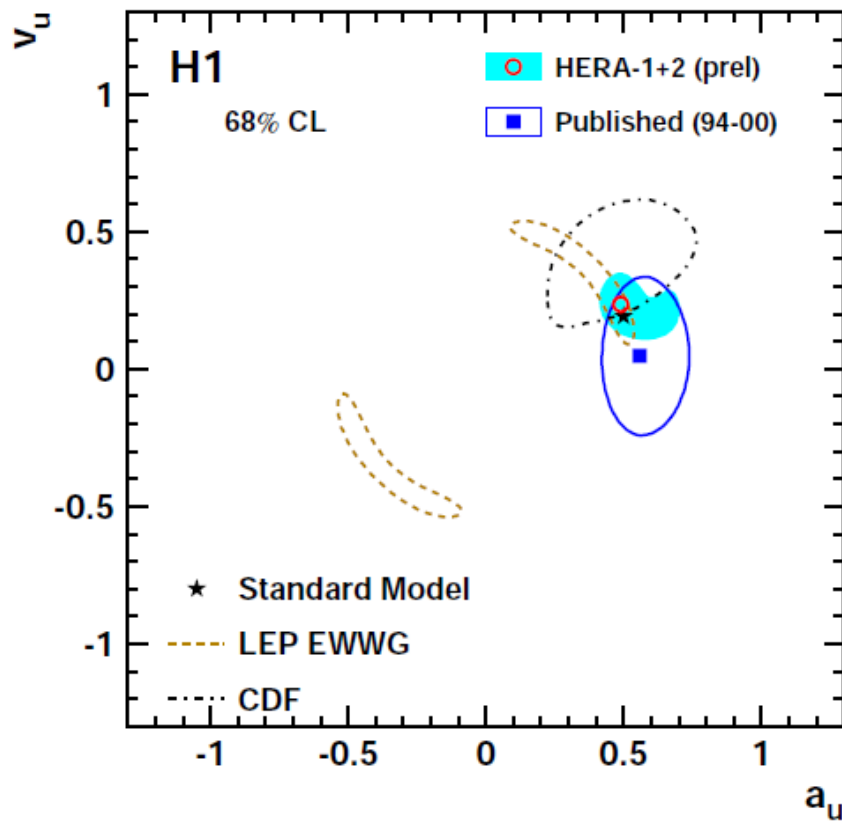
- combined measurement of e^+p scattering at low Q^2 ($\sim 2\%$ overall accuracy) [Eur. Phys. J. C63, 625 \(2009\) \[ArXiv 0904.0929\]](#)
- medium Q^2 (e^+p) precision measurement (1.3-2% accuracy) [Eur. Phys. J. C64, 561 \(2009\) \[ArXiv 0904.3513\]](#)
- preliminary high Q^2 $e^\pm p$ NC and CC data [H1prelim-09-043](#) & [H1prelim-09-042](#)

HERAPDF 1.0 parametrisation strategy used in the fit

[JHEP 1001:109,2010, arXiv:0911.0884 \[hep-ex\]](#)

Combined QCD & EW fit: results

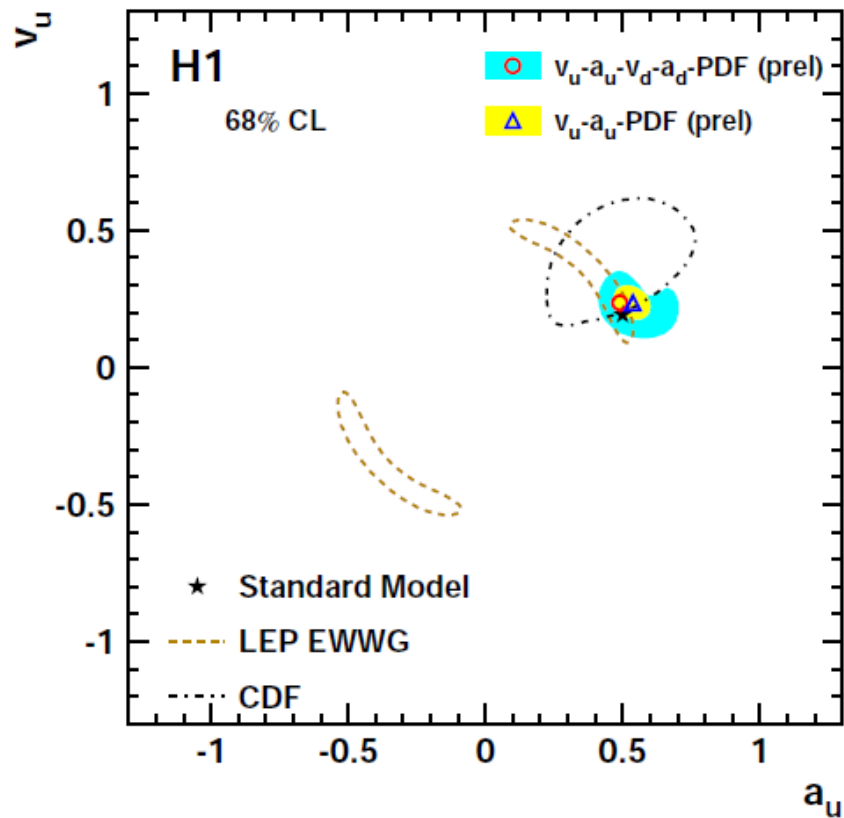
$$\chi^2/\text{dof} = 1183.8 / (1244 - 14) = 0.96$$



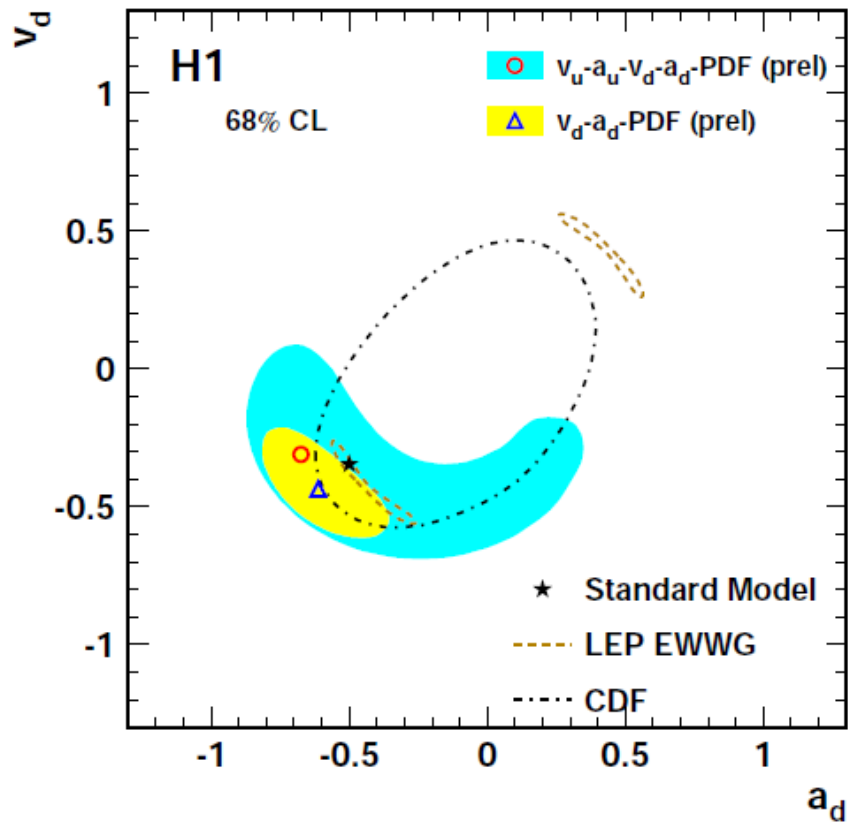
→ improved precision on V_q
→ HERA results are competitive to LEP and Tevatron

Combined QCD & EW fit: results

Fix d quark couplings & fit v_u - a_u -PDF



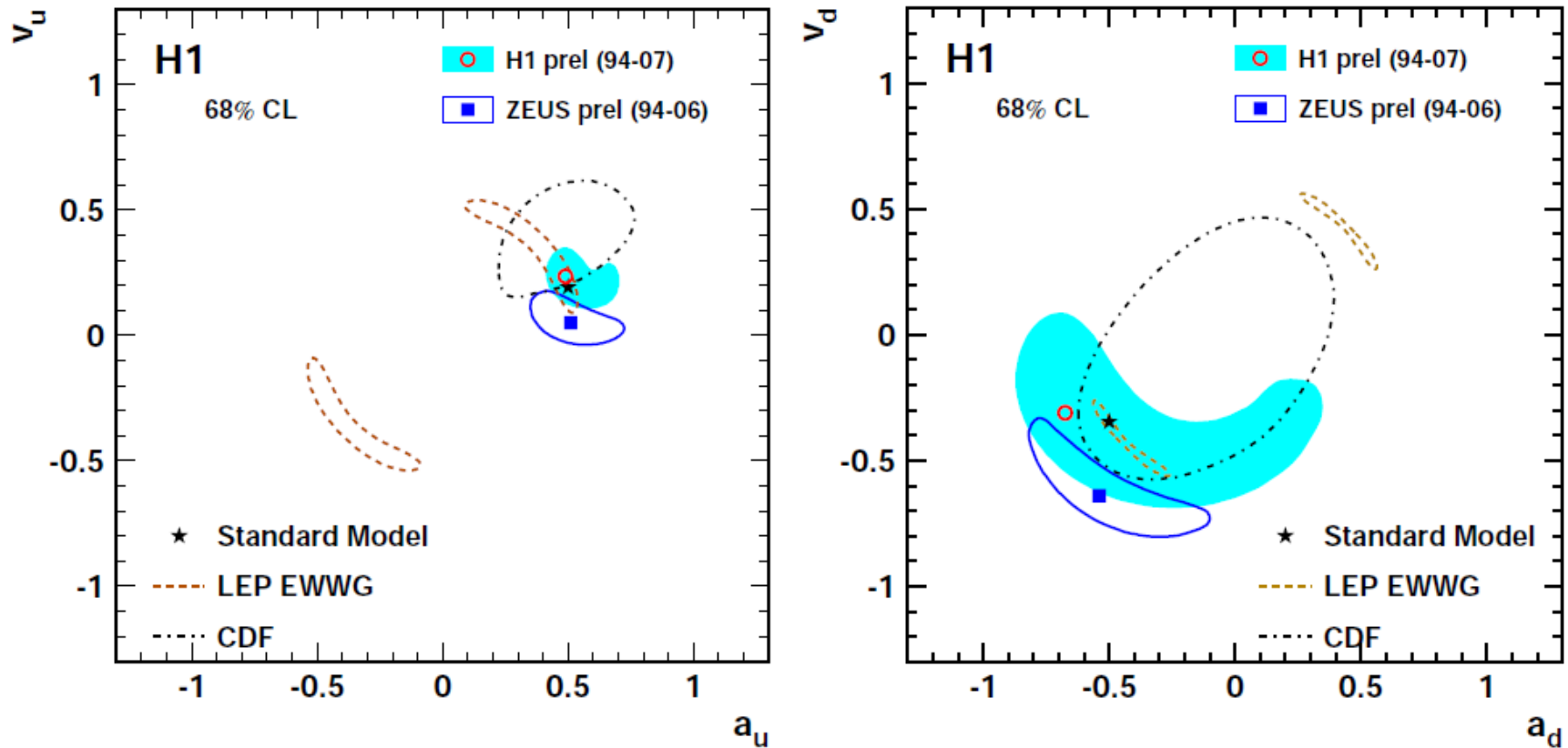
Fix u quark couplings & fit v_d - a_d -PDF



→ Reduced correlation and thus much improved precision

Combined QCD & EW fit: results

- comparison with **ZEUS**



→ For final precision, need the combined H1+ZEUS data

Summary

→ the latest results from HERA on proton structure measurements were presented:

- high Q^2 NC/CC cross sections:

- full HERA statistics, measurements of EW effects via longitudinal lepton polarisation

- QCD+EW fits:

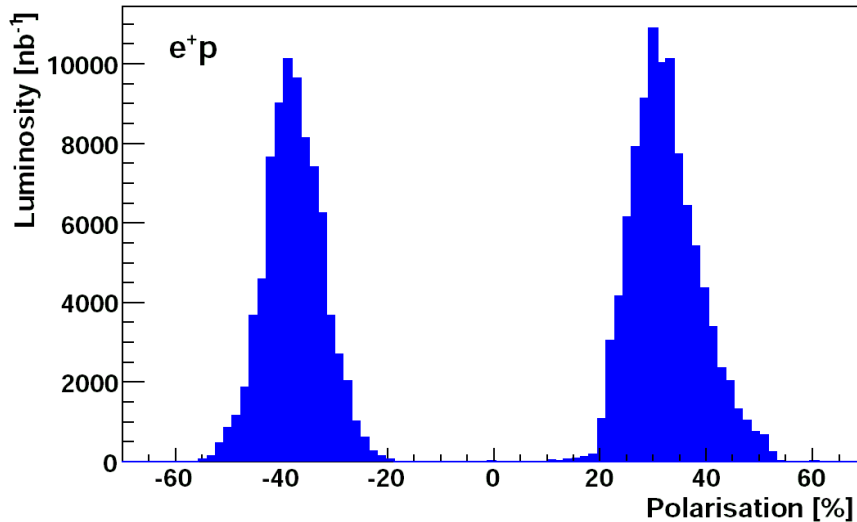
- determination of EW parameters (light quark couplings)
 - improved sensitivity due to polarisation effects

→ for the combination of H1 and ZEUS measurements and HERAPDF1.0 see talks by Jolanta Sztuk-Dambietz and Voica Radescu

Backup slides

HERA2 CC Data

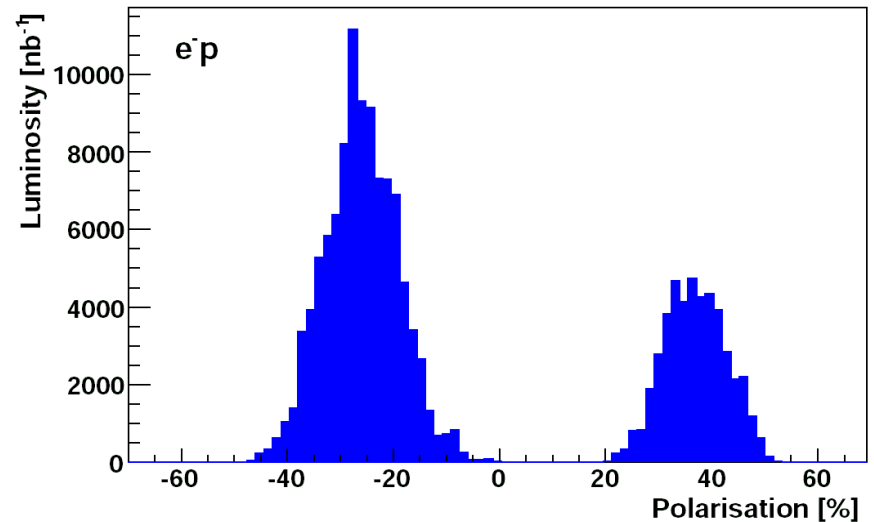
e^+p



LH: $L = 81.9 \text{ [pb}^{-1}\text{]} \pm 1.6_{\text{stat}} \pm 2.1_{\text{sys}}$
 $\langle P \rangle = -37.6 \pm 0.01_{\text{stat}} \pm 1.39_{\text{sys}} \text{ [%]}$

RH: $L = 98.1 \text{ [pb}^{-1}\text{]} \pm 1.3_{\text{stat}} \pm 2.1_{\text{sys}}$
 $\langle P \rangle = 32.5 \pm 0.00_{\text{stat}} \pm 1.15_{\text{sys}} \text{ [%]}$

e^-p



LH: $L = 103.2 \text{ [pb}^{-1}\text{]} \pm 1.3_{\text{stat}} \pm 2.1_{\text{sys}}$
 $\langle P \rangle = -26.1 \pm 0.01_{\text{stat}} \pm 0.97_{\text{sys}} \text{ [%]}$

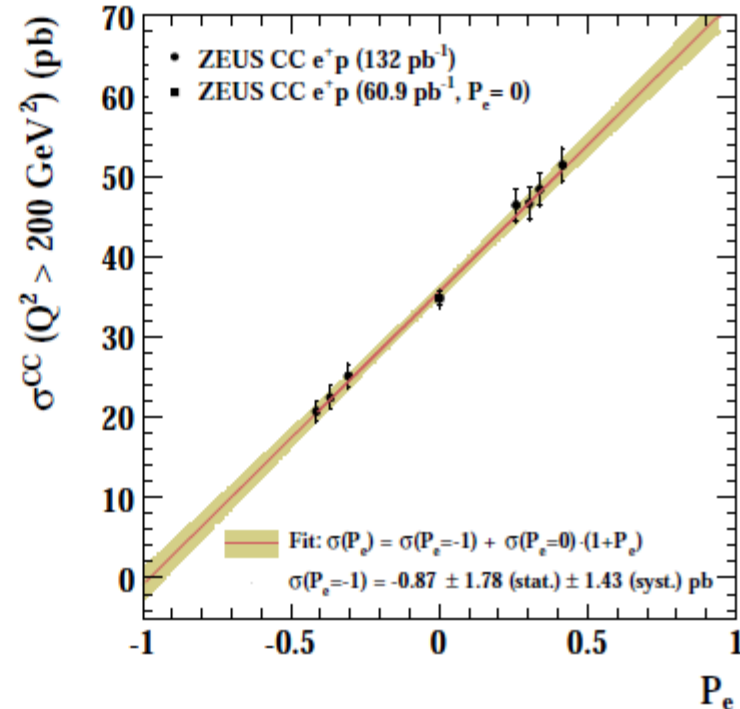
RH: $L = 45.9 \text{ [pb}^{-1}\text{]} \pm 1.3_{\text{stat}} \pm 2.1_{\text{sys}}$
 $\langle P \rangle = 36.9 \pm 0.01_{\text{stat}} \pm 2.3_{\text{sys}} \text{ [%]}$

low polarisation runs excluded from analyses

Total CC cross section

Total Cross Sections II

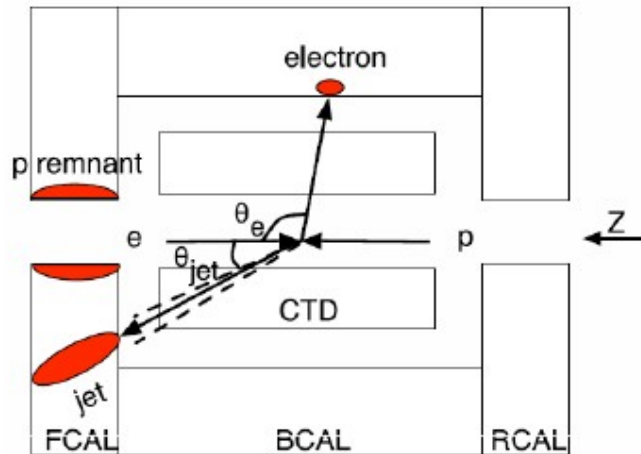
- Measure cross section in 8 bins of polarisation
- Do not constrain linear fit to zero at $P_e = -1$
- Derive upper limit on $\sigma_{CC}^{e^+p}(P_e = -1) \Rightarrow$ lower limit on mass of W_R assuming:
 - $g_L = g_R$
 - Light ν_R



$$\sigma_{CC}^{e^+p}(P_e = -1) = -0.87 \pm 1.78 \text{ (stat.)} \pm 1.43 \text{ (syst.) pb}$$
$$M_{W_R} > 198 \text{ GeV (95\%CL)}$$

New NC measurement: kinematic reconstruction

Q^2 and x reconstruction



$$Q^2 = 2E_e E'_e (1 + \cos\theta_e)$$

$$x = \frac{Q^2}{s y}$$

$$Q^2 = \frac{p_{Tjet}^2}{1 - y}$$

$$y = \frac{(E - P_z)_{jet}}{2E_0}$$

$$p_{Te} = p_{Tjet}$$



$$x = \frac{E_{jet}(1 + \cos\theta_{jet})}{2E_p \left(1 - \frac{E_{jet}(1 - \cos\theta_{jet})}{2E_e}\right)}$$



$$x = \frac{(p_{Te}/\sin\theta_{jet})(1 + \cos\theta_{jet})}{2E_p \left(1 - \frac{(p_{Te}/\sin\theta_{jet})(1 - \cos\theta_{jet})}{2E_e}\right)}$$

Reconstruction of x

Best resolution achieved

One jet events

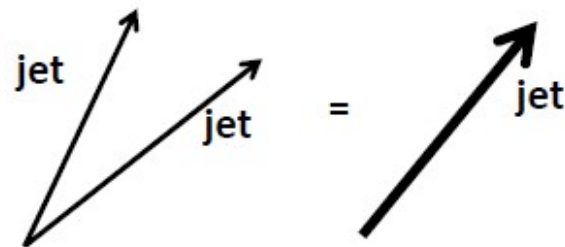
$$x = \frac{(p_{t_e}/\sin\theta_{jet})(1 + \cos\theta_{jet})}{2E_p(1 - \frac{(p_{t_e}/\sin\theta_{jet})(1 - \cos\theta_{jet})}{2E_e})}$$

multi jets events

$$x = \frac{p_{t_{jets}}^2}{s y_{jb}(1 - y_{jb})}$$

$$p_{t_{jets}}^2 = \left(\sum_i \bar{p}_{x_{jet}}\right)^2 + \left(\sum_i \bar{p}_{y_{jet}}\right)^2$$

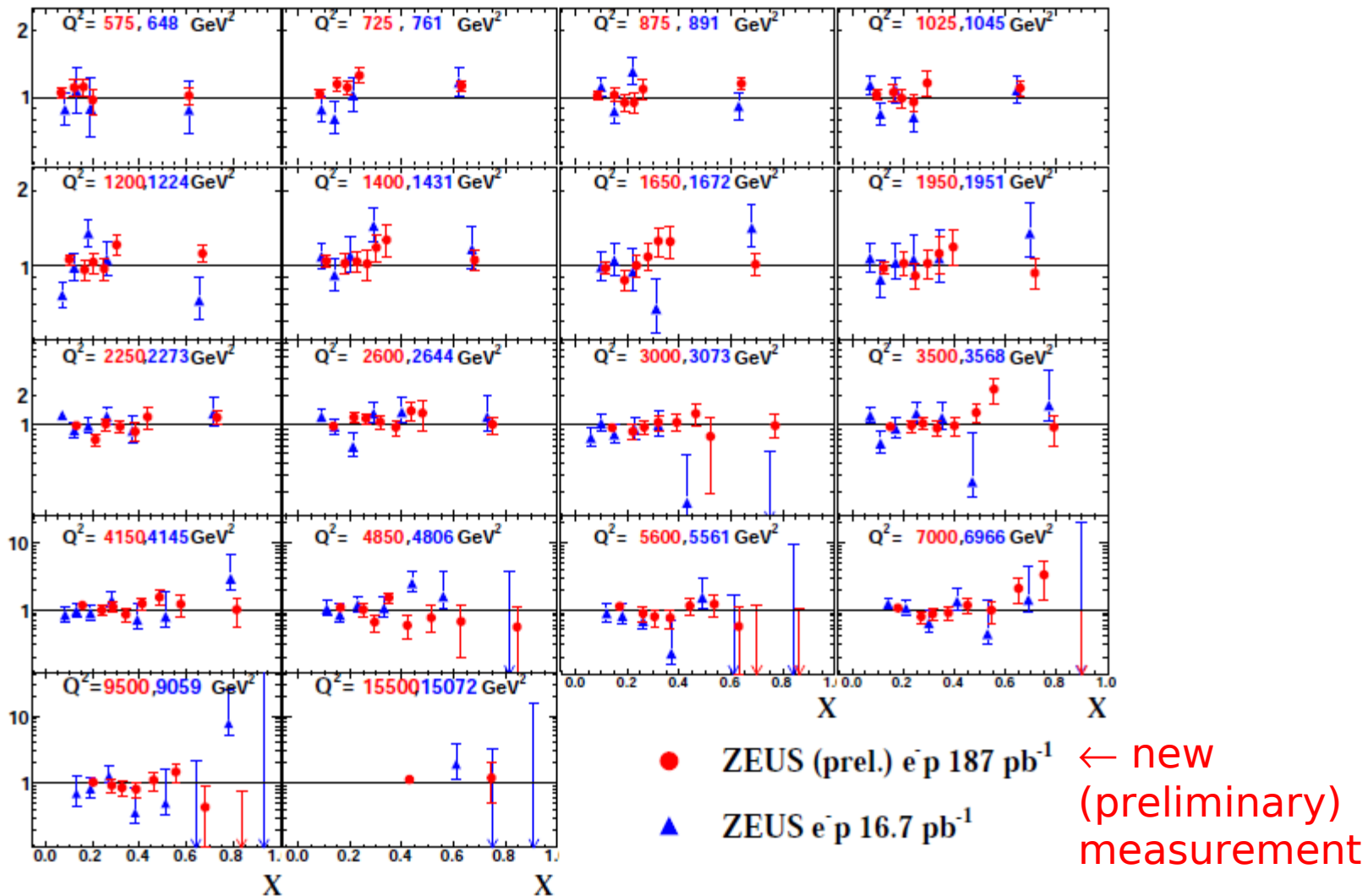
$$y_{jb} = \frac{\sum_i [E_{jet_i} (1 - \cos\theta_{jet_i})]}{2E_e}$$



New NC measurement in ZEUS

ZEUS

DATA/THEORY(CTEQ6D)



Combined QCD & EW fit: results

- comparison to data (high Q^2 polarised e^+p NC)

