Measurements of the proton structure in the electroweak regime at HERA

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DESY

on behalf of H1 and ZEUS collaborations

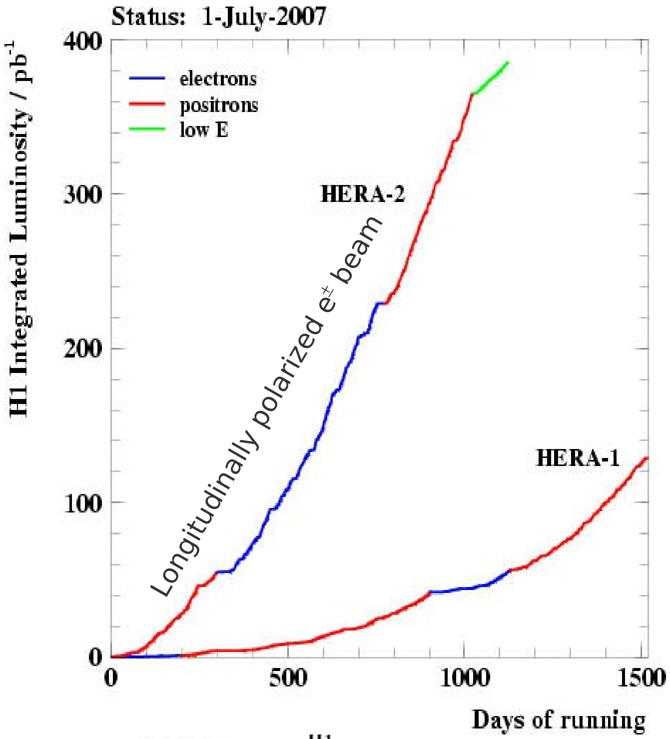
- → DIS at HERA
- → High Q^2 cross sections and electroweak physics
- → Combined electroweak and QCD fit
- → Summary

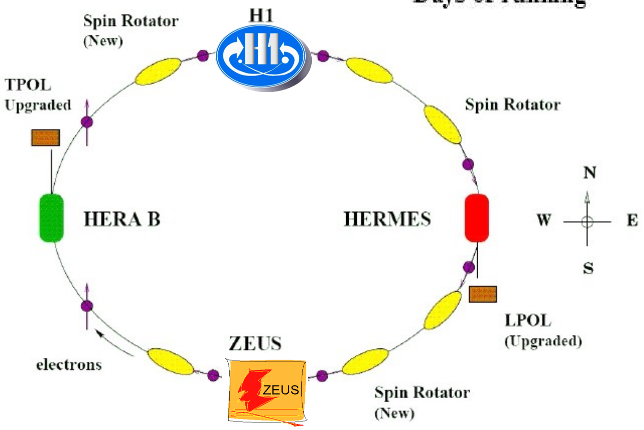
HERA

- $e^{\pm}$(27.5 GeV), p(820/920 GeV), $\sqrt{s}$ = 300/318 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:

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

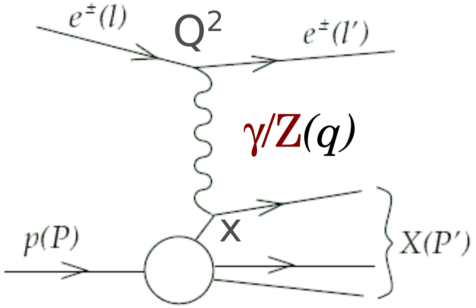
- ~0.5 fb^{-1} of luminosity recorded by the each experiment


Longitudinally polarized e± beam



Neutral current DIS cross section

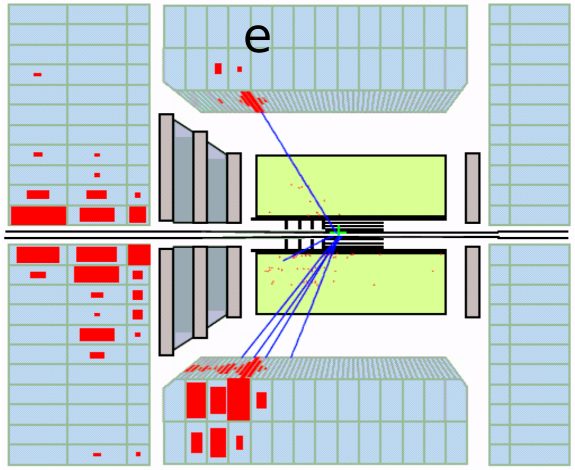
neutral current DIS cross section:



Q^2 - virtuality of exchange boson

x – Bjorken scaling variable

y - inleasticity



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

dominant contribution

important at high Q^2

sizable at high y

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

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

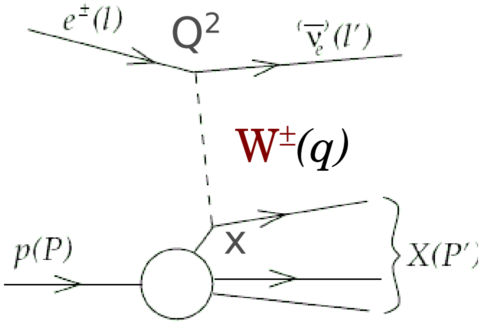
→ polarisation dependence due to γZ interference and Z terms:

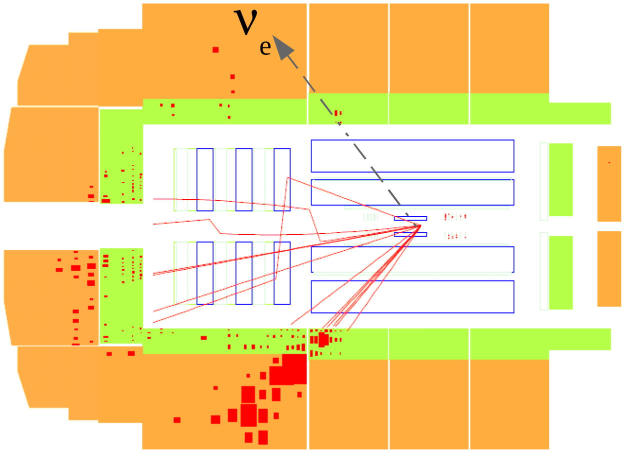
$$\tilde{F}_2^\pm = F_2 + k(-v_e \mp P_e a_e)F_2^{\gamma Z} + k^2\left(v_e^2 + a_e^2 \pm 2P_e v_e a_e\right)F_2^Z$$

$$x\tilde{F}_3^\pm = k(-a_e \mp P_e v_e)xF_3^{\gamma Z} + k^2(2v_e a_e \pm P_e(v_e^2 + a_e^2))xF_3^Z$$

Charged current DIS cross section

charged current DIS cross section:





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

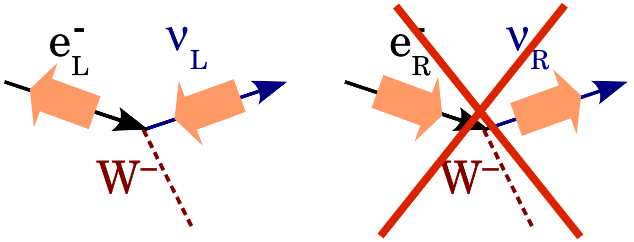
→ linear polarisation dependence

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

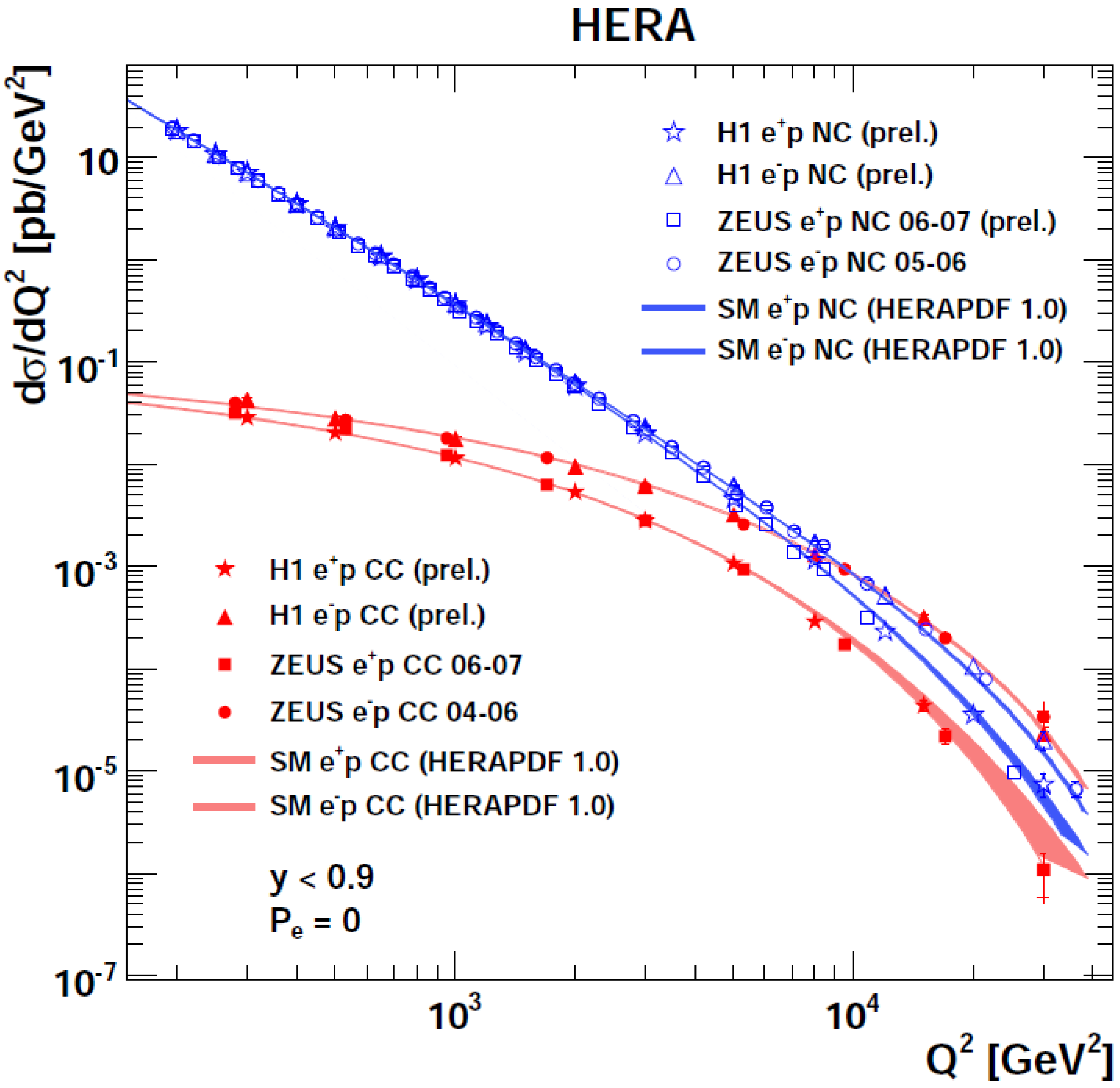
at LO e^+/e^- sensitive to different quark densities:

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

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



Charged and neutral currents at HERA



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

EW unification

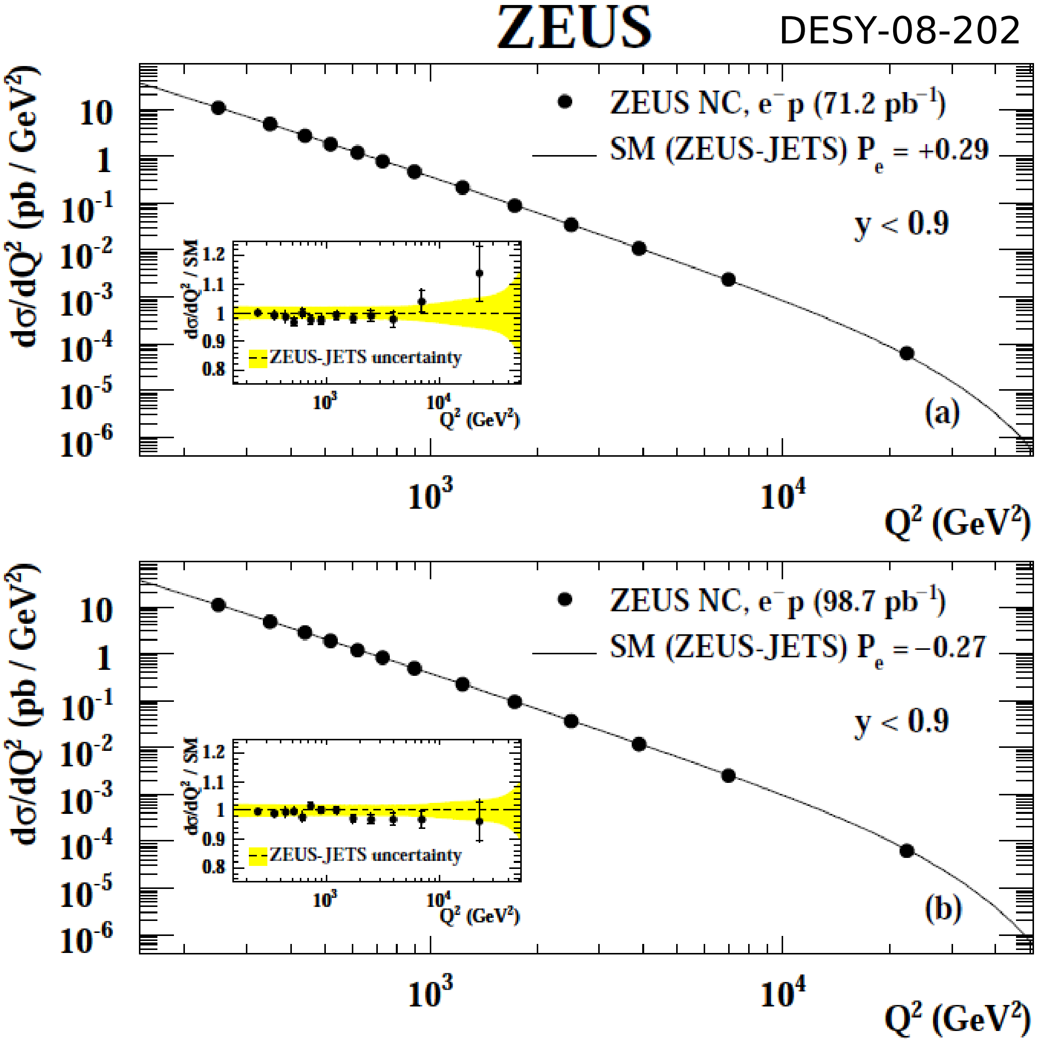
good agreement with
SM (HERAPDF 1.0)

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



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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:

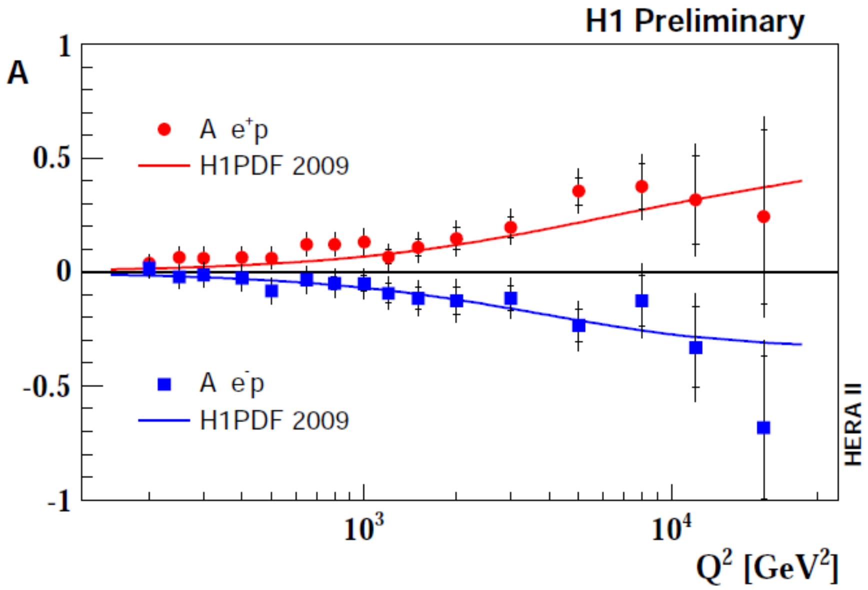
$$\tilde{F}_2^{\pm} \approx F_2 + k(-v_e \mp P_e a_e) F_2^{\gamma Z}$$

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

polarisation asymmetry A is proportional to $a_e v_q$ 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



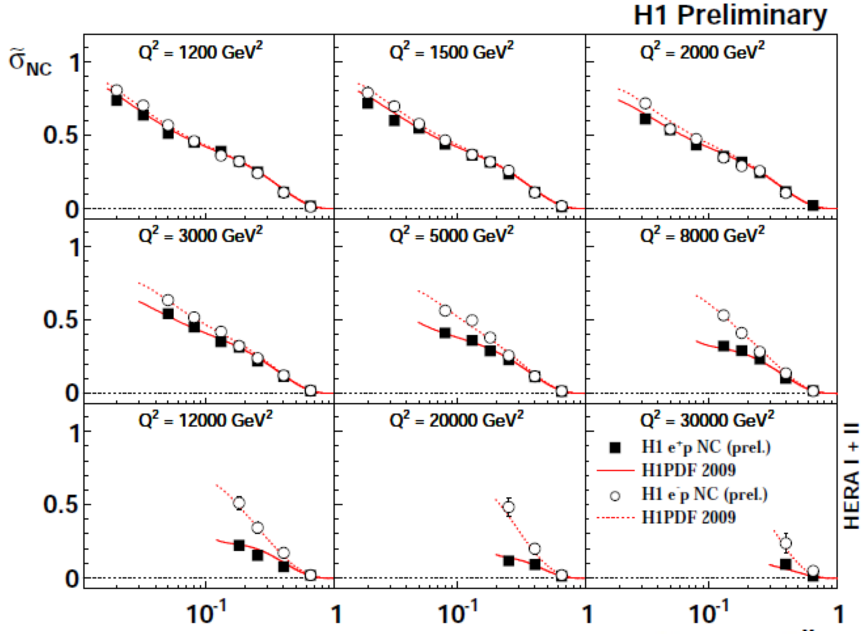
full HERA II statistics

Structure function xF_3

Structure function xF_3

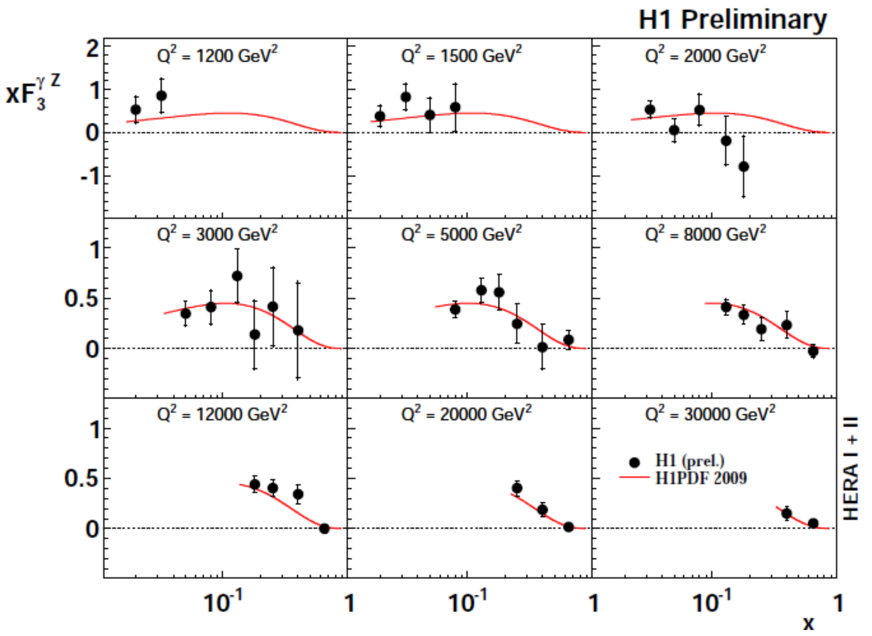
$$\tilde{\sigma}^{\pm} = \frac{d^2\sigma_{NC}^{e^{\pm}p}}{dx\,dQ^2}\frac{xQ^4}{2\pi\alpha^2}\frac{1}{Y_+} = \tilde{F}_2 \mp \frac{Y_-}{Y_+}x\tilde{F}_3 - \frac{y^2}{Y_+}\tilde{F}_L$$

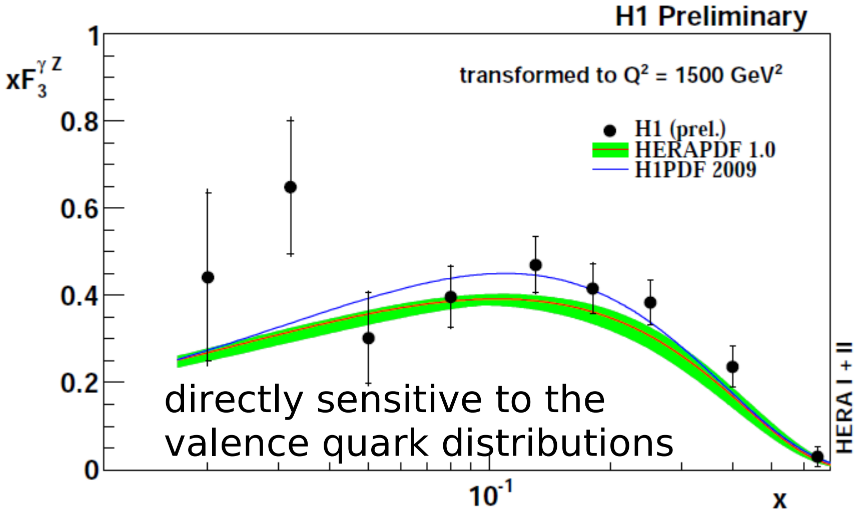
$$\boxed{x\tilde{F}_3 = \frac{Y_+}{2Y_-}[\tilde{\sigma}^- - \tilde{\sigma}^+]}$$



dominant contribution from $xF_3^{\gamma Z}$

$$x\tilde{F}_3^{\gamma Z} \simeq x\tilde{F}_3\frac{(Q^2+M_Z^2)}{\alpha^2\kappa Q^2}$$



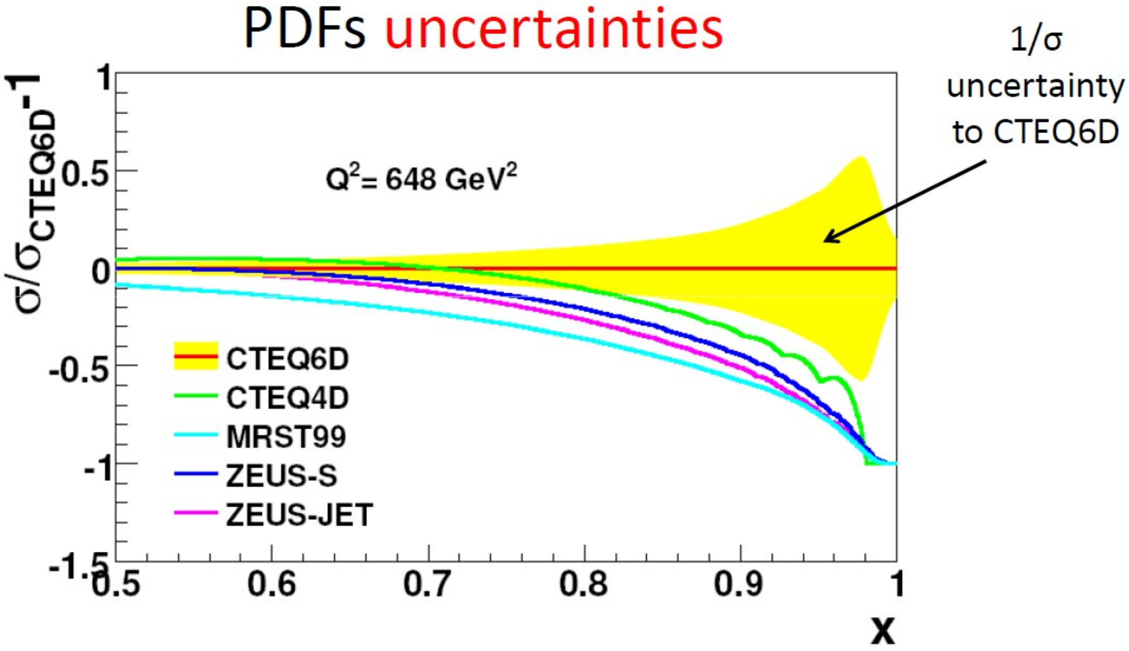


directly sensitive to the valence quark distributions

New NC measurement in ZEUS

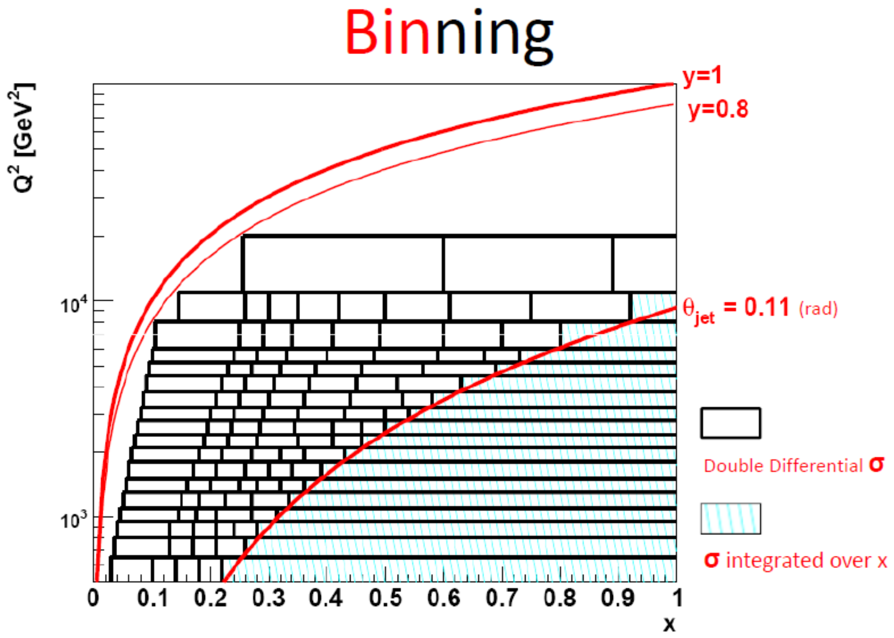
- new method to measure neutral current cross sections at large Bjorken x (e^-p, $Q^2 \geq 575$ GeV^2)

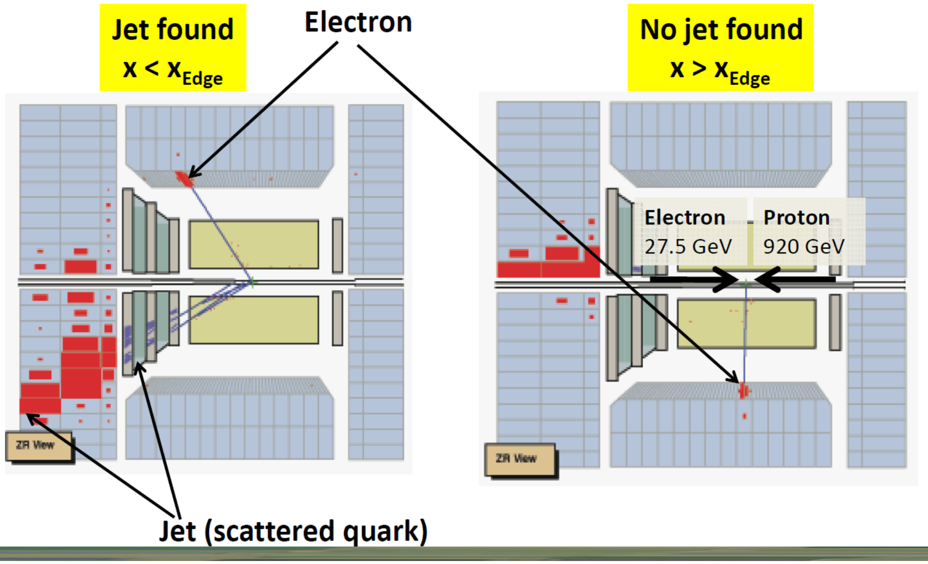
Motivation: reduced PDF uncertainty at high x


PDFs uncertainties

1/σ uncertainty to CTEQ6D

New NC measurement in ZEUS





Full HERA II e^-p data sample

- new x reconstruction method

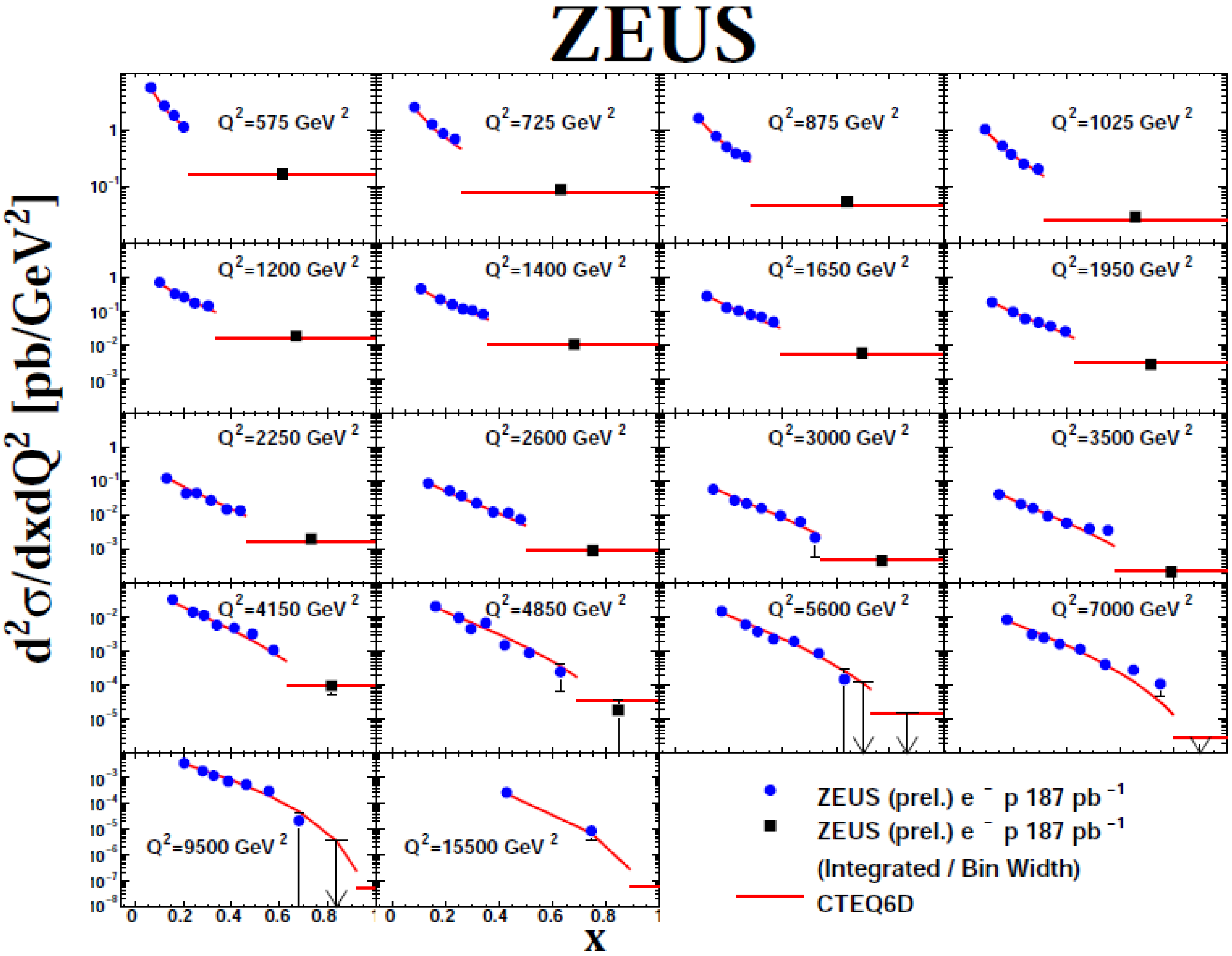
<u>Idea:</u>

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:

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

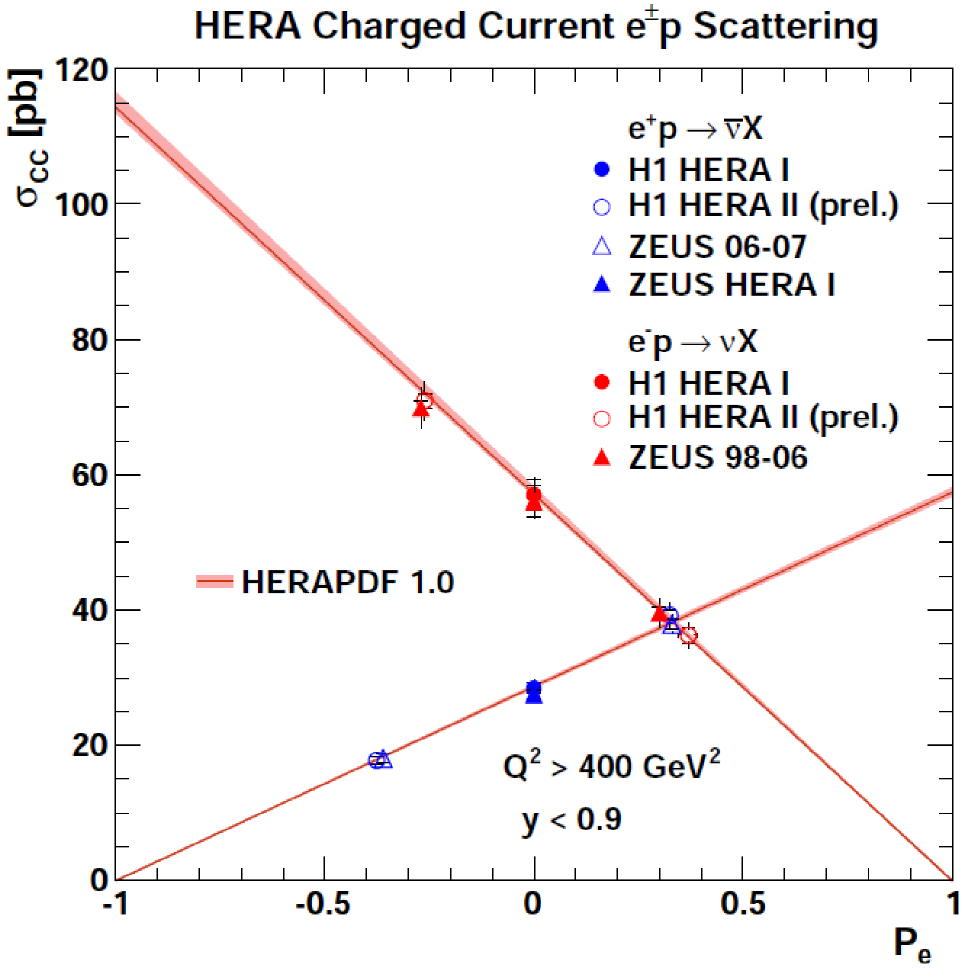
New NC measurement in ZEUS



- 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)

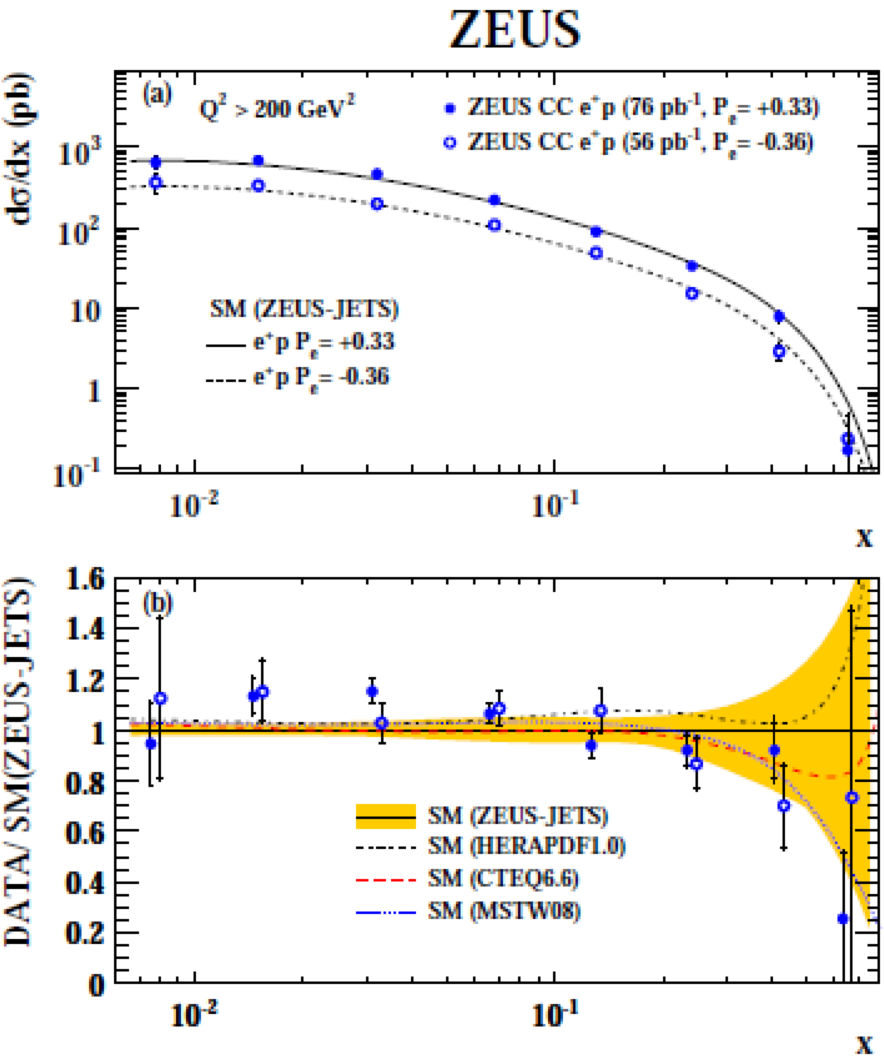


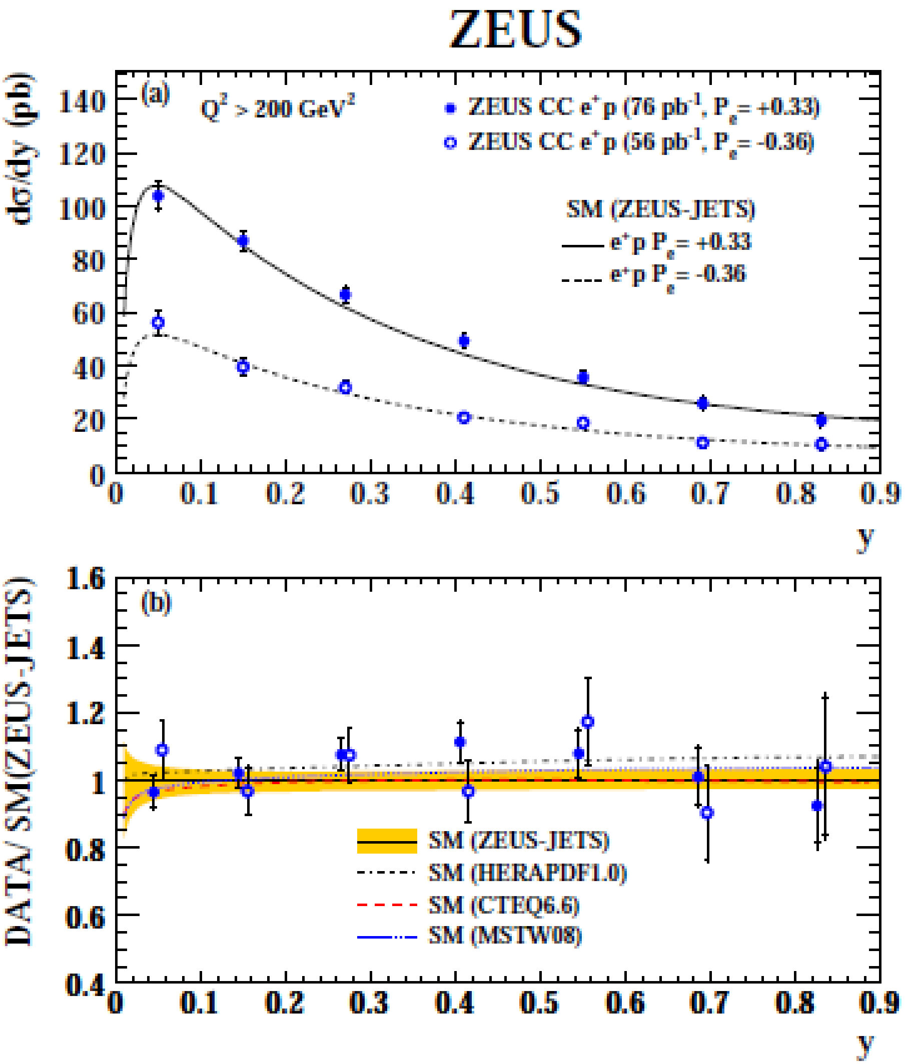
$$\frac{d^2\sigma_{CC}^{e^\pm p}}{dx\,dQ^2} = (1 \pm P_e)\frac{G_F^2}{2\pi x}\left(\frac{M_W^2}{Q^2+M_W^2}\right)^2 \tilde{\sigma}_{CC}^{e^\pm p}$$

HERA results are consistent with SM

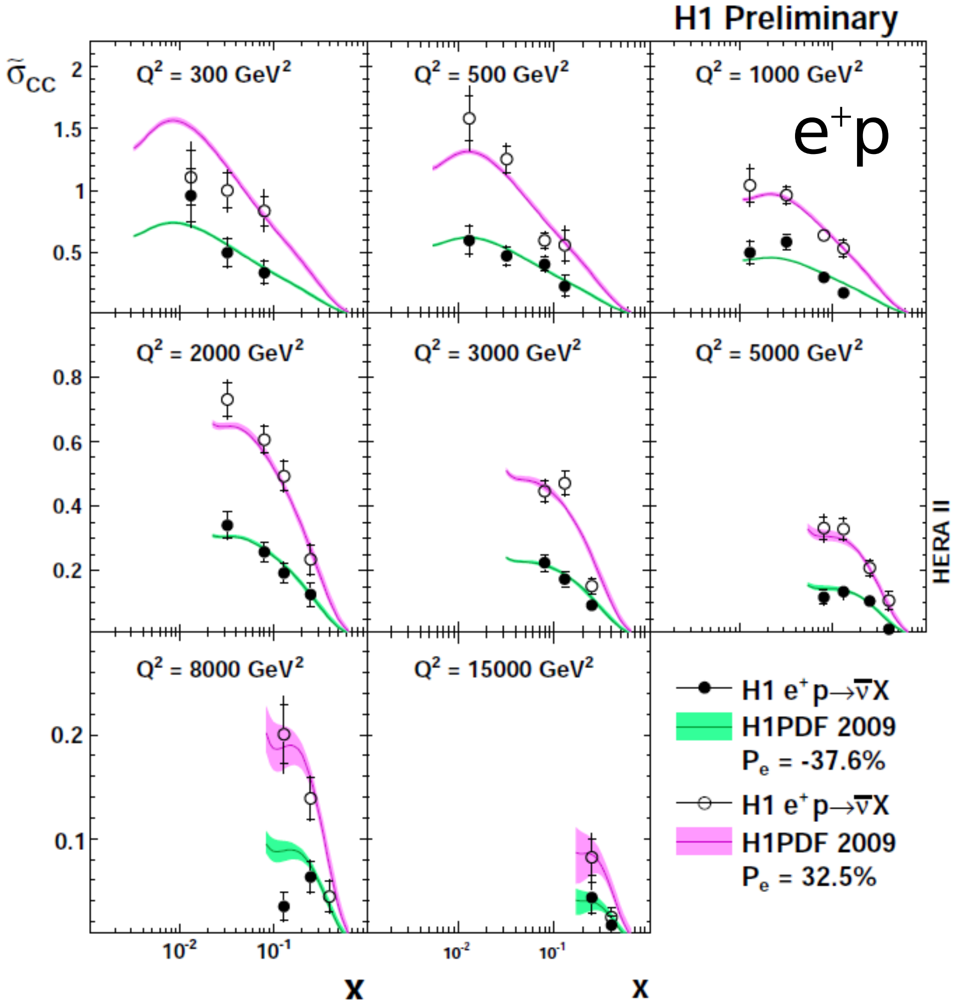
(polarised) single differential CC x-os sections

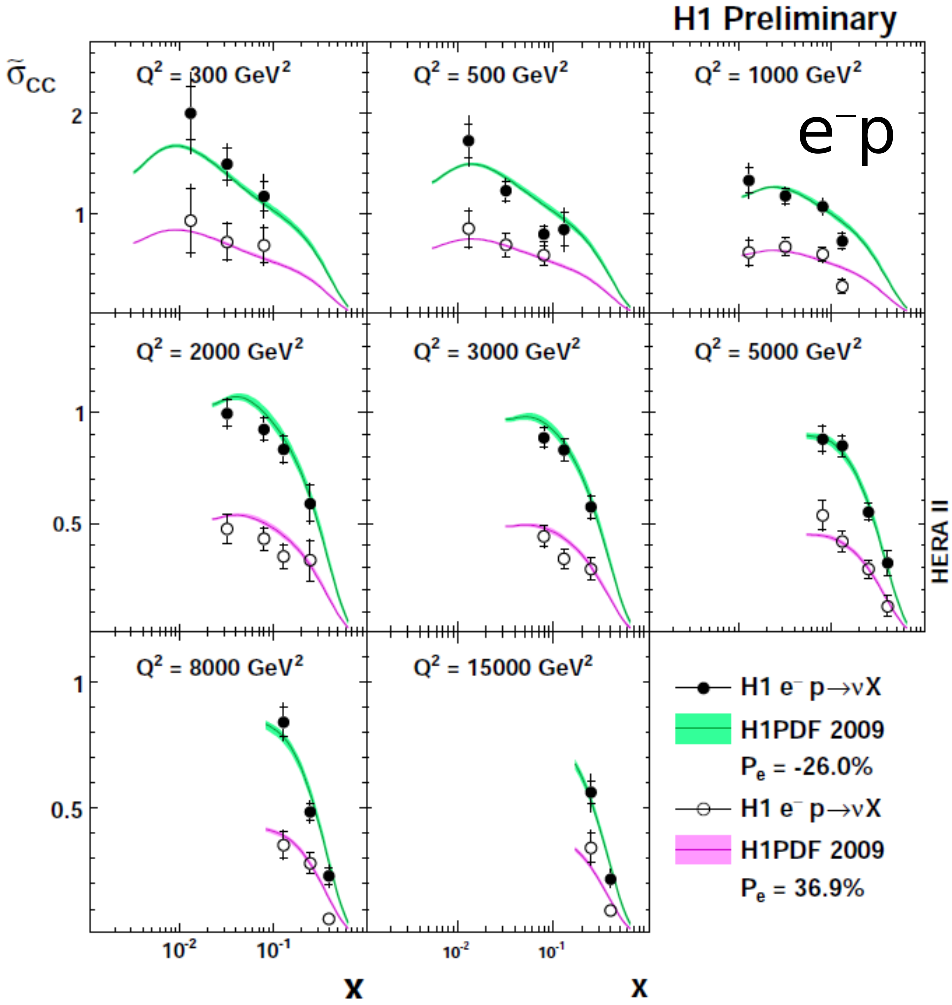
- single differential cross sections with longitudinally polarised lepton beams (e^+p)





(polarised) double differential CC x-os sections





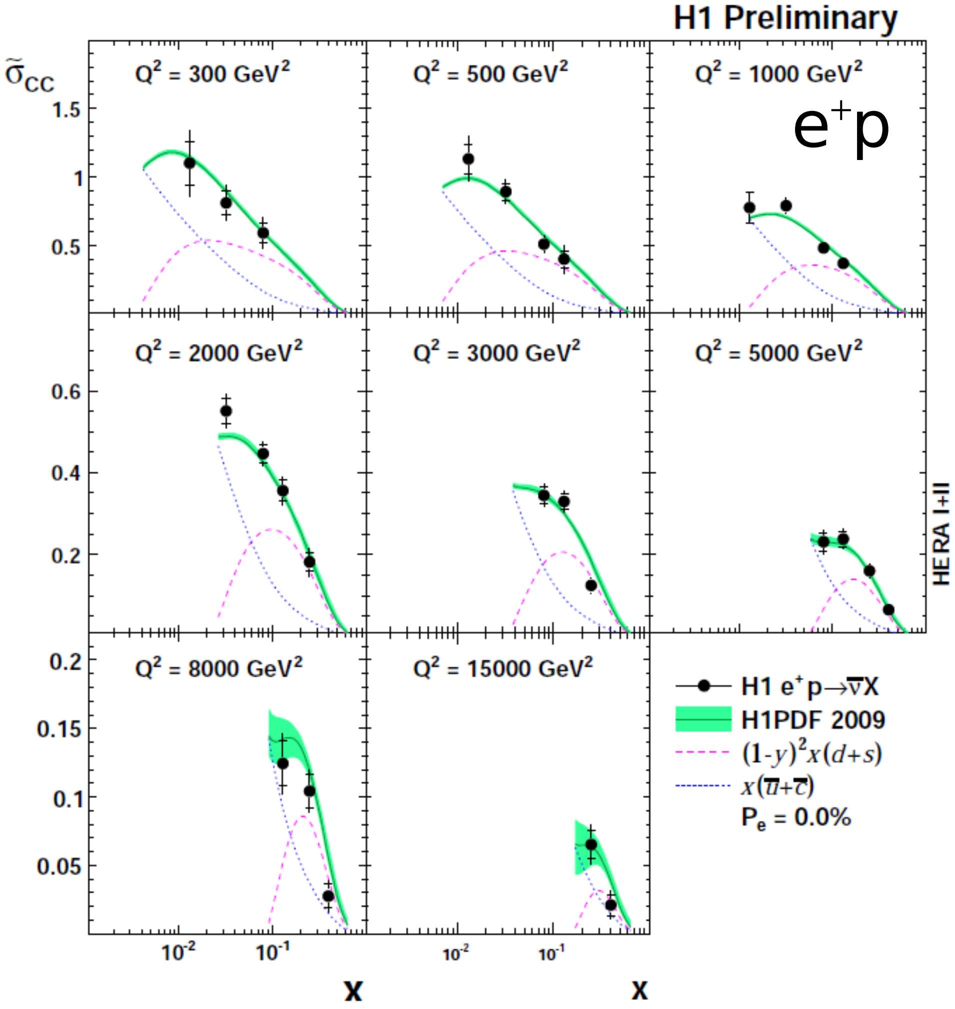
→ full HERA II data sample

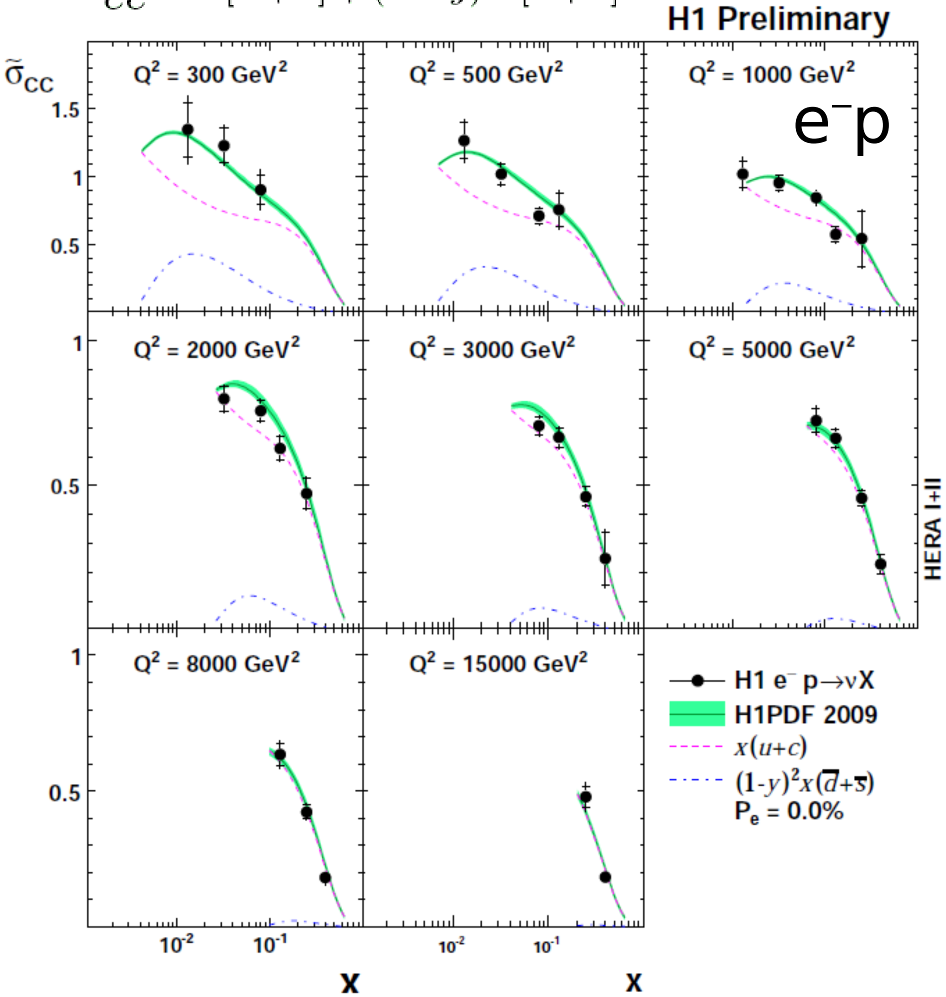
Double differential CC x-os sections

CC e^+/e^-: flavour sensitivity

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

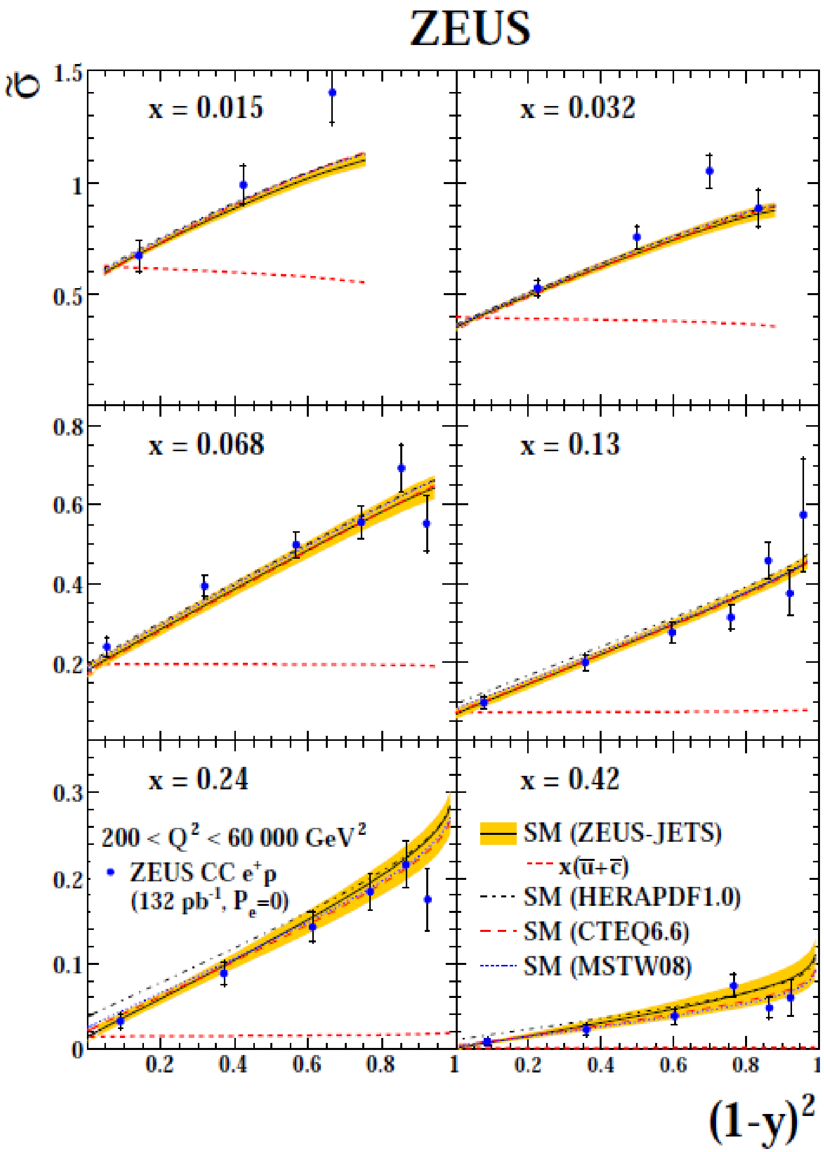
$$\tilde{\sigma}_{CC}^{e^-p} = x[u + c] + (1-y)^2 x[\overline{d}+\overline{s}]$$





→ combined H1 (HERA I + II) data (~450 pb^{-1})

Helicity structure in CC interactions



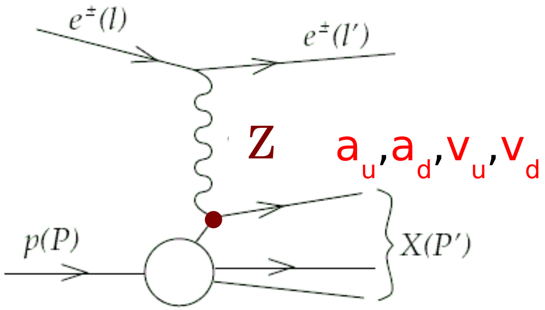
- Unpolarised reduced cross section in bins of *x* as a function of $(1-y)^2$ $\rightarrow$ helicity structure of CC interactions
- At leading order in QCD:
  - Intercept gives $(\bar{u}+\bar{c})$ contribution
  - Slope gives the $(d+s)$ contribution.

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

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:

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

In unpolarised case:

terms with v_e (~0)
can be neglected

$$\tilde{F}_2^\pm = F_2 - \cancel{v_e}\left(\frac{\kappa_w Q^2}{Q^2+M_Z^2}\right)F_2^{\gamma Z} + (\cancel{v_e^2} + a_e^2)\left(\frac{\kappa_w Q^2}{Q^2+M_Z^2}\right)^2 F_2^Z$$

$$x\tilde{F}_3^\pm = \pm a_e\left(\frac{\kappa_w Q^2}{Q^2+M_Z^2}\right)xF_3^{\gamma Z} \mp 2a_e\cancel{v_e}\left(\frac{\kappa_w Q^2}{Q^2+M_Z^2}\right)^2 xF_3^Z$$

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

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

v_q - constrained from F_2^Z

a_q – mainly constrained by $xF_3^{\gamma Z}$

Combined QCD & EW fit: coupling sensitivity

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

terms with v_e(~0) can be neglected

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

$$x\tilde{F}_3^{\pm} = \qquad k(-a_e \mp P_e \cancel{v_e}) xF_3^{\gamma Z} + k^2 (2\cancel{v_e} a_e \pm P_e(\cancel{v_e}^2 + a_e^2)) xF_3^Z$$

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

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

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

Combined QCD & EW fit: data

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

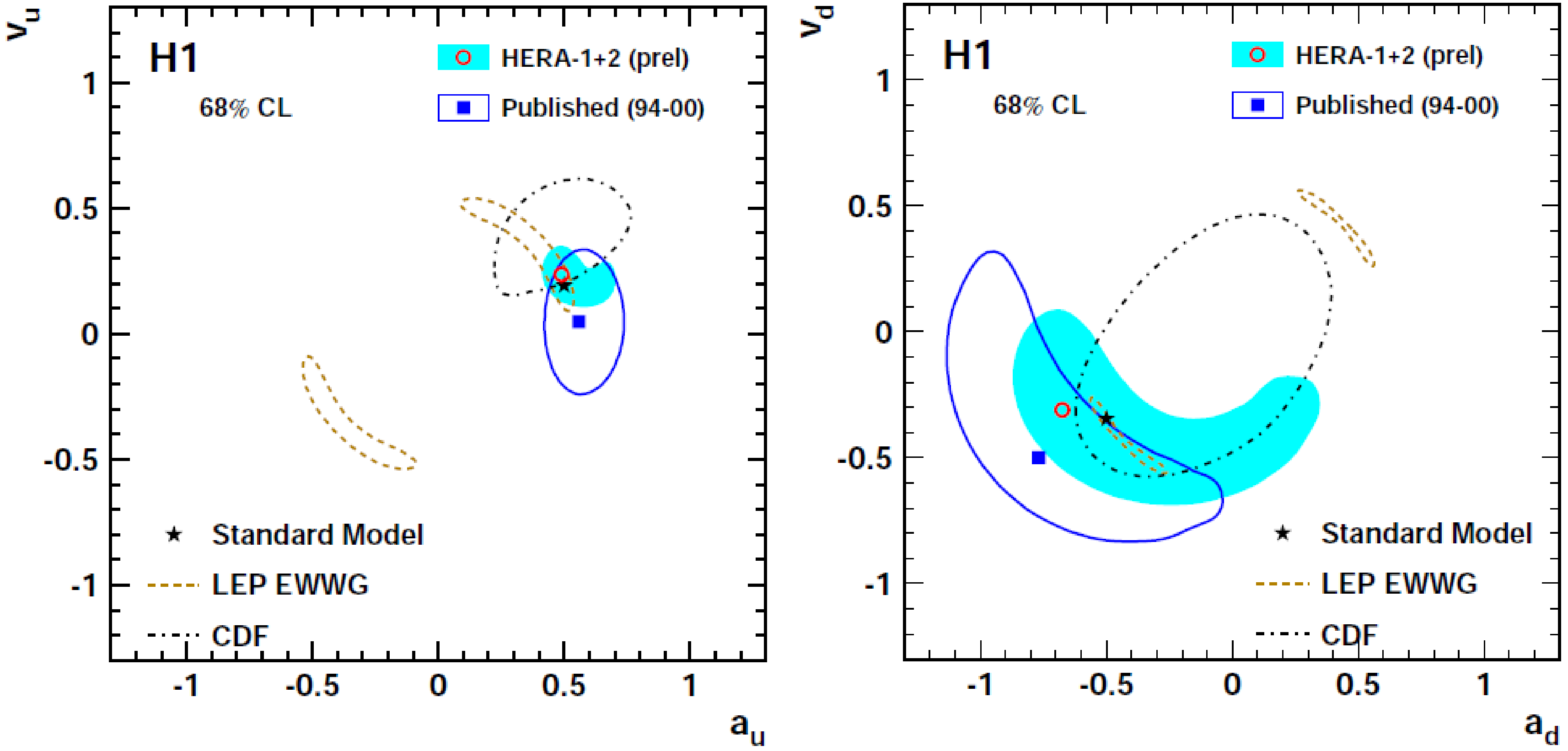
- combined measurement of e^+p scattering at low Q^2 (~2% overall accuracy) Eur. Phys. J. C63, 625 (2009) [ArXiv 0904.0929]
- medium Q^2 (e^+p) precision measurement (1.3-2% accuracy) Eur. Phys. J. C64, 561 (2009) [ArXiv 0904.3513]
- preliminary high Q^2 $e^{\pm}p$ NC and CC data H1prelim-09-043 & H1prelim-09-042

HERAPDF 1.0 parametrisation strategy used in the fit

JHEP 1001:109,2010, arXiv:0911.0884 [hep-ex]

Combined QCD & EW fit: results

χ2/dof=1183.8/(1244-14)=0.96

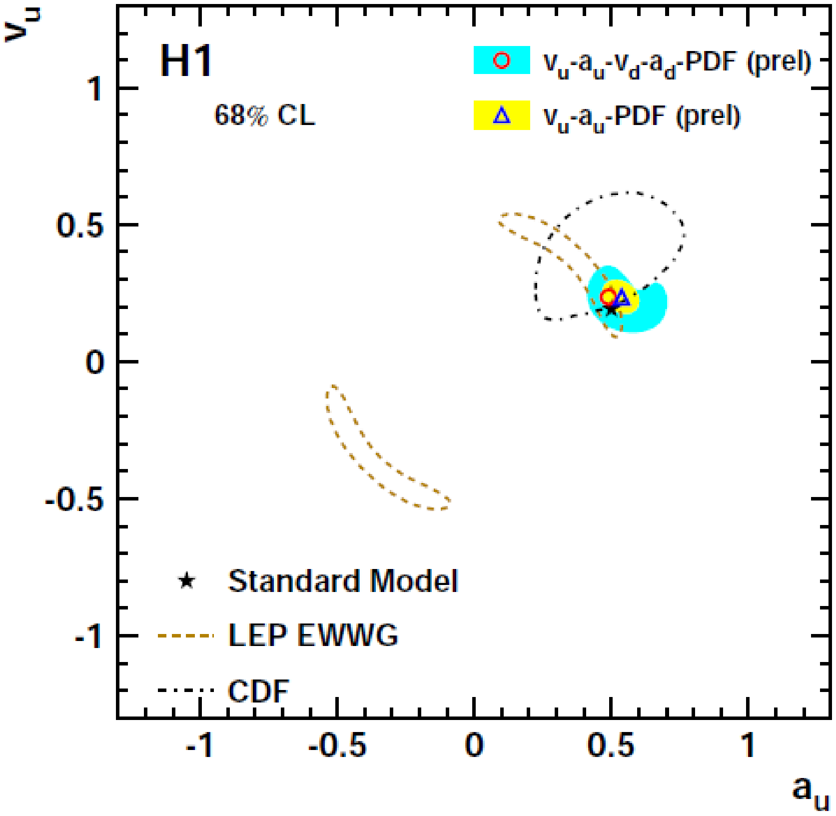


→ improved precision on v_q

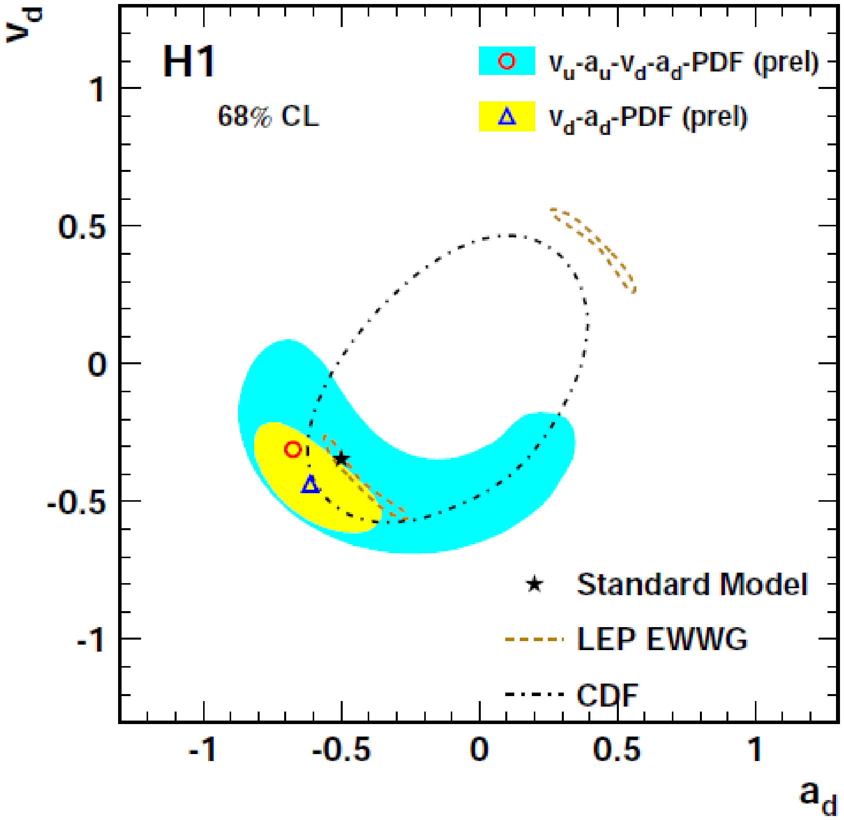
→ HERA results are competitive to LEP and Tevatron

Combined QCD & EW fit: results

Fix d quark couplings & fit v_u-a_u-PDF



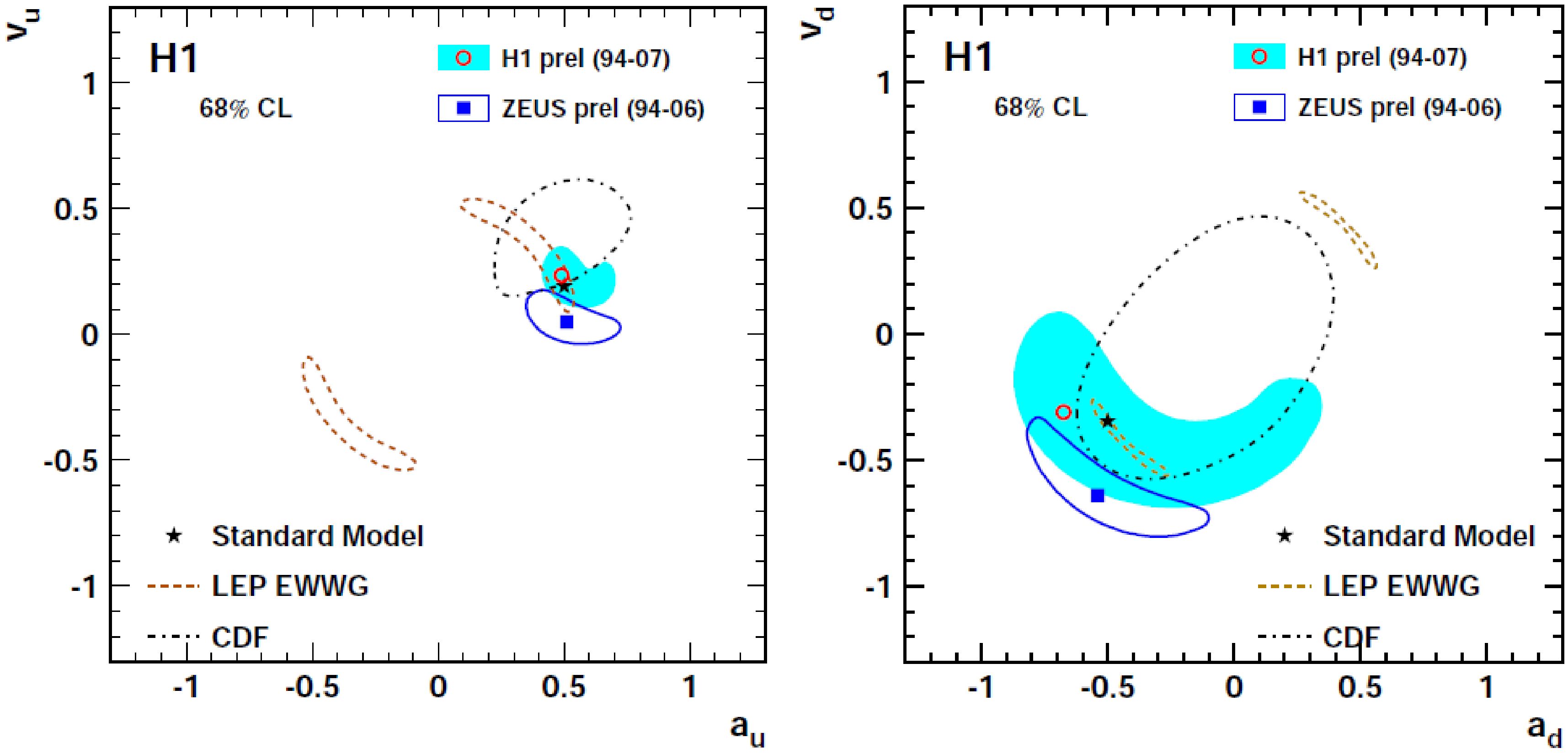
Fix u quark couplings & fit v_d-a_d-PDF



→ 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:

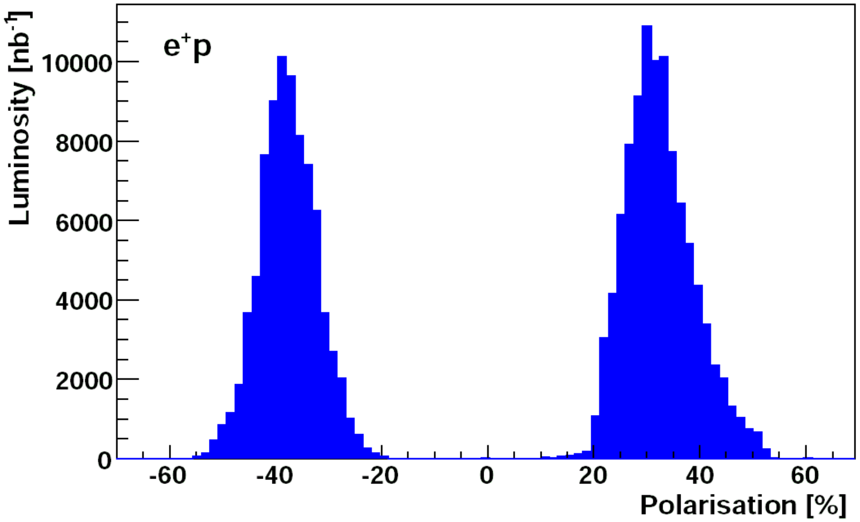
- high Q^2 NC/CC cross sections:
    - full HERA statistics, measurements of EW effects via longitudinal lepton polarisation
- QCD+EW fits:
    - determination of EW parameters (light quark couplings)
    - improved sensitivity due to polarisation effects

→ 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



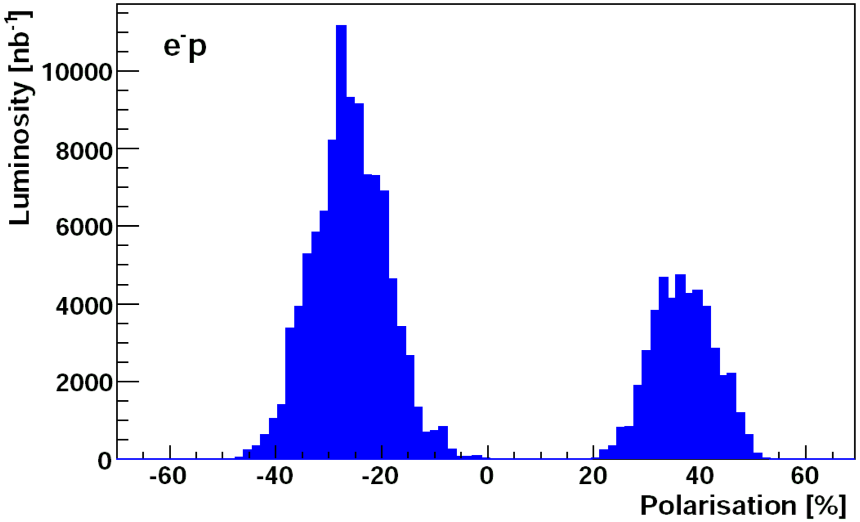
LH: L = 81.9 [pb^{-1}] $\pm 1.6_{stat}$ $\pm 2.1_{sys}$

<P>= -37.6 $\pm 0.01_{stat}$ $\pm 1.39_{sys}$ [%]

RH: L = 98.1 [pb^{-1}] $\pm 1.3_{stat}$ $\pm 2.1_{sys}$

<P>= 32.5 $\pm 0.00_{stat}$ $\pm 1.15_{sys}$ [%]

e^-p



LH: L = 103.2 [pb^{-1}] $\pm 1.3_{stat}$ $\pm 2.1_{sys}$

<P>= -26.1 $\pm 0.01_{stat}$ $\pm 0.97_{sys}$ [%]

RH: L = 45.9 [pb^{-1}] $\pm 1.3_{stat}$ $\pm 2.1_{sys}$

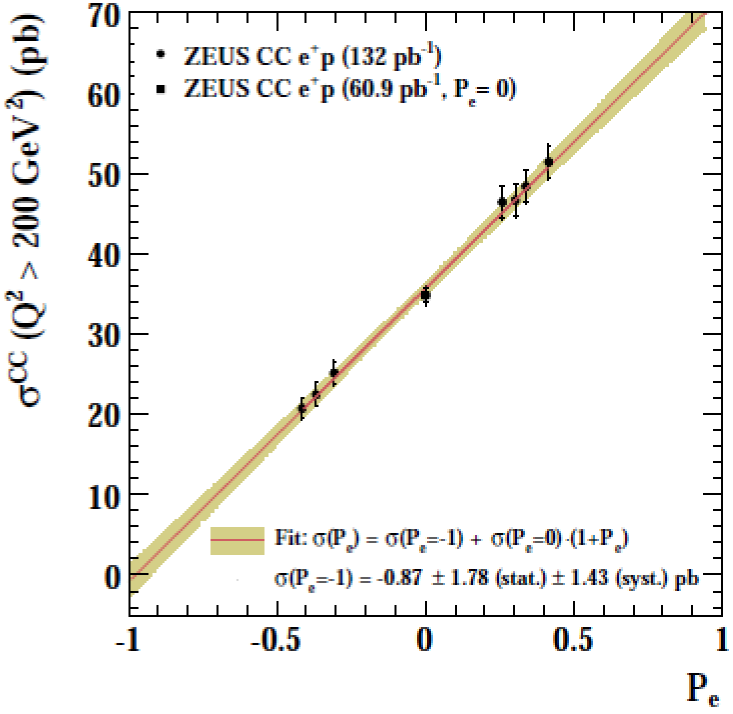
<P>= 36.9 $\pm 0.01_{stat}$ $\pm 2.3_{sys}$ [%]

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

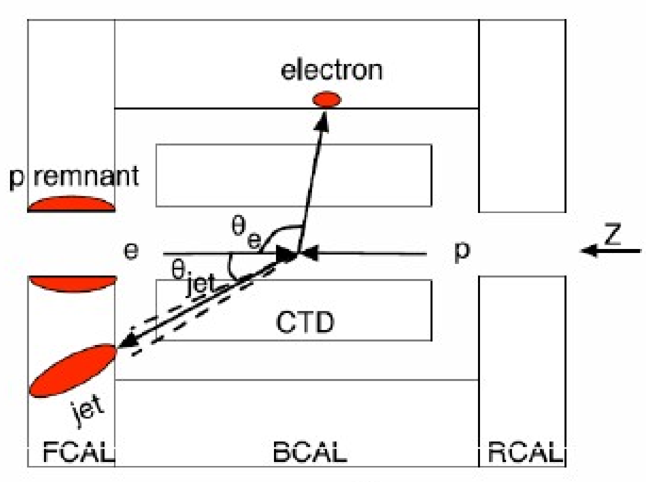


$$\sigma_{CC}^{e^+p}(P_e = -1) = -0.87 \pm 1.78\ \text{(stat.)} \pm 1.43\ \text{(syst.) pb}$$

$$M_{W_R} > 198\ \text{GeV}\ \ (95\%\text{CL})$$

New NC measurement: kinematic reconstruction

Q^2 and x reconstruction



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

$$x = \frac{Q^2}{sy}$$

$$Q^2 = \frac{p^2_{T_{\mathrm{jet}}}}{1-y}$$

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

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

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

New NC measurement: kinematic reconstruction

Reconstruction of x

Best resolution achieved

One jet events

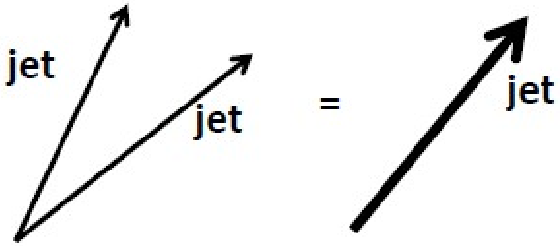
$$x = \frac{(p_{t_e}/sin\theta_{jet})(1 + cos\theta_{jet})}{2E_p(1 - \frac{(p_{t_e}/sin\theta_{jet})(1 - cos\theta_{jet})}{2E_e})}$$

multi jets events

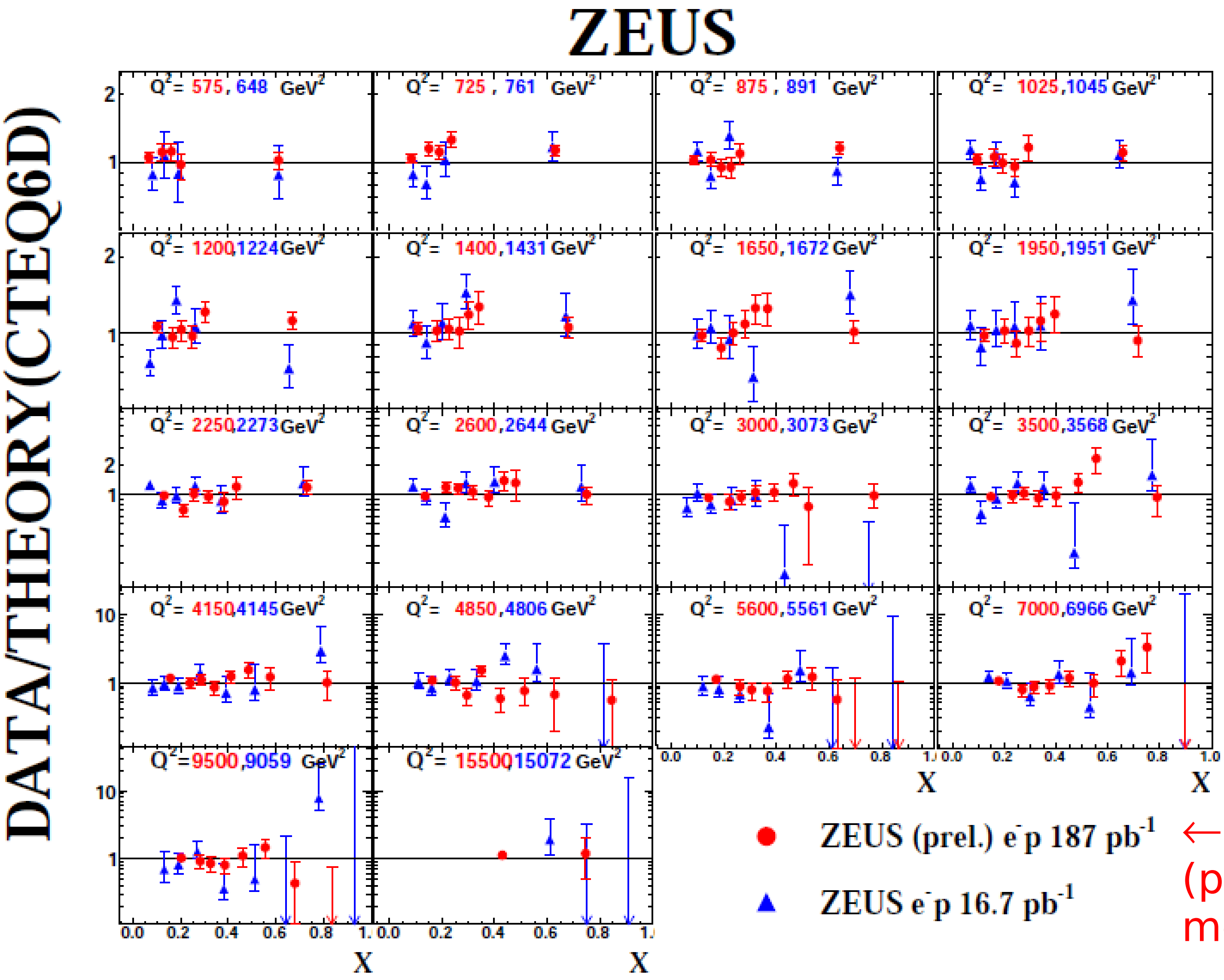
$$x = \frac{p^2_{t_{jets}}}{s\, y_{jb}(1 - y_{jb})}$$

$$p^2_{t_{jets}} - (\sum_i p_{x_{jet}})^2 + (\sum_i p_{y_{jet}})^2$$

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



New NC measurement in ZEUS



← new (preliminary) measurement

Combined QCD & EW fit: results

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