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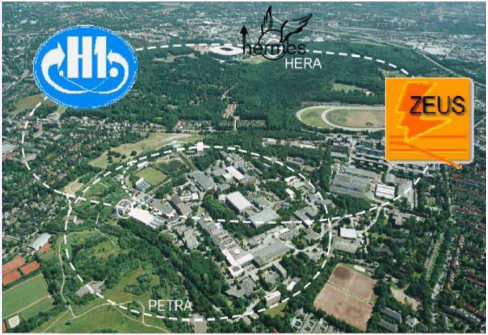
Electroweak Physics and Proton Structure Measurements at HERA

WIN'09 Workshop, Perugia

On behalf of the H1 and ZEUS Collaborations

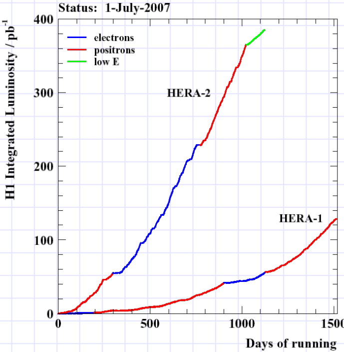
DESY - HU Berlin
September 15, 2009

HERA, H1 and ZEUS. 1992-2007



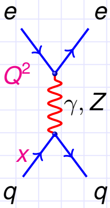
- $E_e \times E_p = 27.5 \times 920$ GeV^2
- $\sqrt{s} = 318$ GeV
- ~ 0.5 fb^{-1} / experiment
- Balanced e^+p and e^-p samples
- Low E_p runs for F_L

- Longitudinaly polarised lepton beam at HERA II
- Average $P_e \sim 35\%$
- Polarisation build-up time ~ 30 min



Deep Inelastic Scattering:
a Proton Structure Probe

Measured cross sections → Structure Functions



$$\tilde{\sigma}_{NC}(e^{\pm}p) = \frac{xQ^4}{2\pi\alpha^2 Y_+}\frac{d^2\sigma_{NC}(e^{\pm}p)}{dxdQ^2} =$$

$$= \tilde{F}_2 \mp \frac{Y_-}{Y_+} x\tilde{F}_3 - \frac{y^2}{Y_+}\tilde{F}_L$$

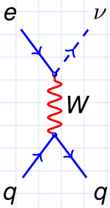
$$Y_{\pm} = 1 \pm (1-y^2)$$
$$y = \frac{Q^2}{sx}$$

- Virtuality Q^2: spacial resolution probe $\lambda \sim 1/\sqrt{Q^2}$
- x: momentum fraction of struck parton

$\tilde{F}_2$:
- Dominant
- Valence + sea quarks

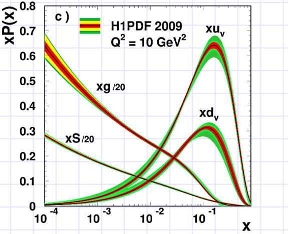
$x\tilde{F}_3$:
- High Q^2
- Valence quarks

$\tilde{F}_L$:
- High y
- Gluon



$$\frac{d^2\sigma^{e^{\pm}p}_{CC}}{dxdQ^2} = (1 \pm P_e)\frac{G_F^2}{4\pi x Y_+}\left[\frac{M_W^2}{Q^2+M_W^2}\right]^2 \tilde{\sigma}^{(e^{\pm}p)}_{CC}$$

- Quark flavor sensitive
- Linear polarisation dependence



Polarised Neutral Current Cross Section

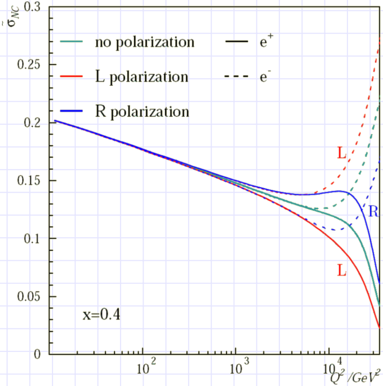
NC structure functions, $\tilde{F}_2$ and $x\tilde{F}_3$, can be decomposed as:

$$\begin{array}{lcccc} & \gamma \text{ exchange} & \gamma Z \text{ interference} & & Z \text{ exchange} \\ \tilde{F}_2 = & F_2 & - (v_e \pm P_e a_e)\chi_Z F_2^{\gamma Z} & + & (v_e^2 + a_e^2 \pm 2P_e v_e a_e)\chi_Z^2 F_2^Z \\ x\tilde{F}_3 = & & - (a_e \pm P_e v_e)\chi_Z xF_3^{\gamma Z} & + & (2v_e a_e \pm P_e(v_e^2 + a_e^2))\chi_Z^2 xF_3^Z, \end{array}$$

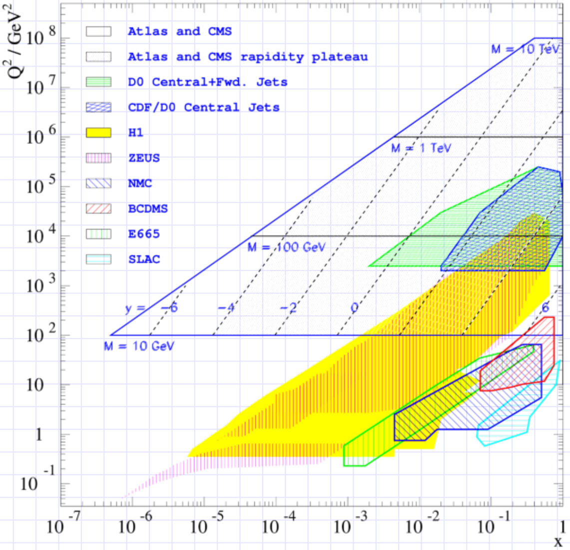
where: "+" for e^+p, "-" for e^-p

Polarisation dependence:

- Dominating e/m contribution is independent of P_e
- Polarised contribution appears at high Q^2, mainly due to γZ interference

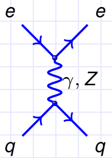


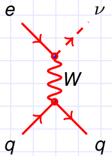
Experimental Data on the Proton Structure



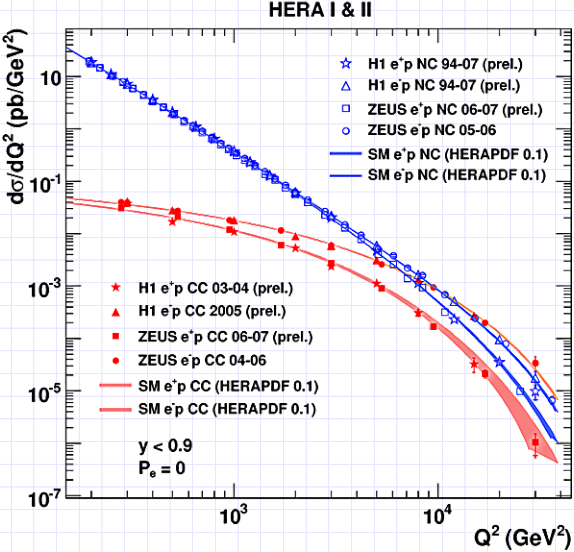
- Large extension of the explored space in x, Q^2.
- Huge extentsion of the knowledge due to the HERA collider.
- Low x region is accesable by HERA only.

Inclusive NC and CC Measurements





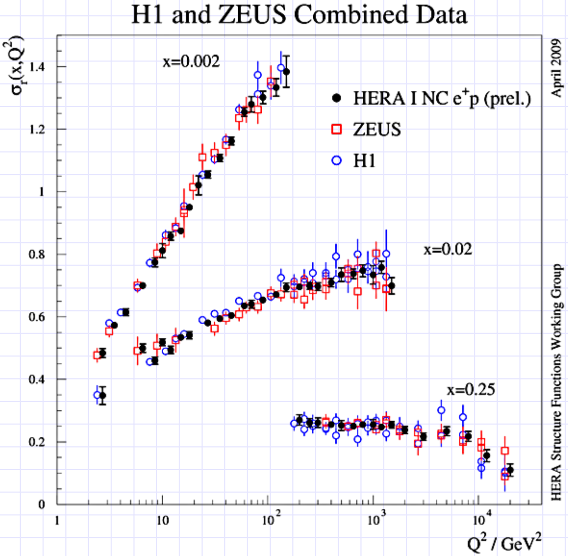
EW unification at the $M_{W,Z}$ scale



Good agreement with SM (HERAPDF0.1) over large kinematic range

Combination of HERA Data

Combination of HERA I Data



Precision improvement is obtained by combining H1 and ZEUS measurement.

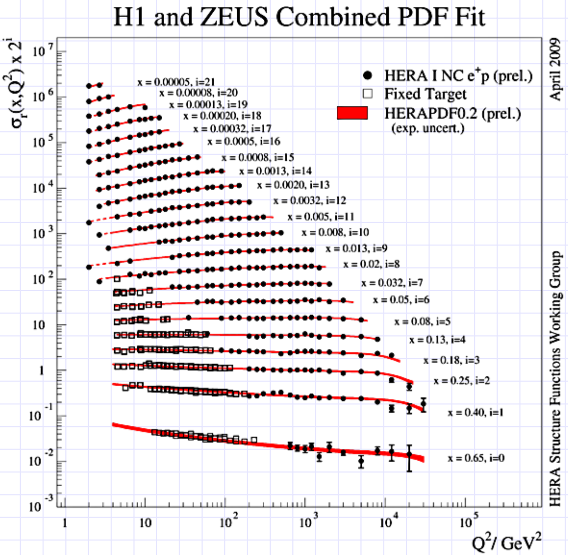
Average H1 and ZEUS data before applying QCD analysis.

Achieved by fitting σ_r values, global normalisations and the correlated systematic uncertainties.

$$\sigma_r^{\pm} = F_2 - \frac{y^2}{Y_+} F_L \mp \frac{Y_-}{Y_+} xF_3$$

Experiments cross calibrate each other: systematic uncertaintes reduced together with statistical errors.

Combined HERA Data



Combination of the published H1/ZEUS data collected at HERA I for CC, NC, $e^{\pm}p$ mode.

For NC e^+p:

- 5 decades in x
- 5 decades in Q^2
- 1.5 - 3 % precision data

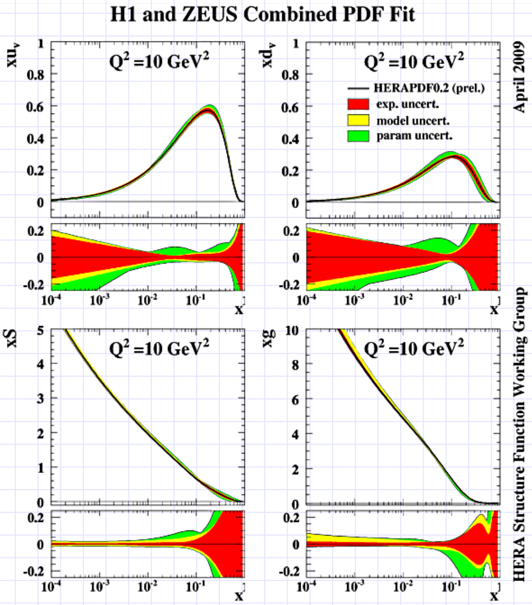
$$F_2 = x \sum e_q^2 (q + \bar{q})$$

- Sensitive to $4u + d$
- Gluon: from scaling violations of F_2

$$\frac{\partial F_2}{\partial lnQ^2} \propto xg$$

HERA data precision is similar to fixed target experiments. Good consistency between H1 and ZEUS. Stringent test of DGLAP evolution.

QCD Analysis of the HERA Combined Data



HERAPDF0.2 – NLO QCD analysis of the combined HERA data.

Parametrisation: at $Q_0^2 = 1.9$ GeV^2 as $Ax^B(1-x)^C(1+Dx+\cdots)$, Throne-Roberts treatement of heavy flavours

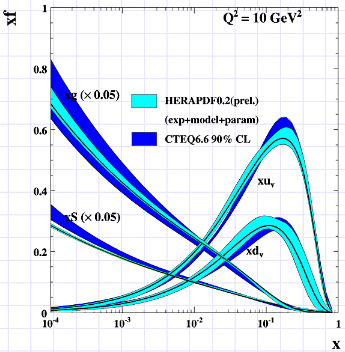
Experimental errors

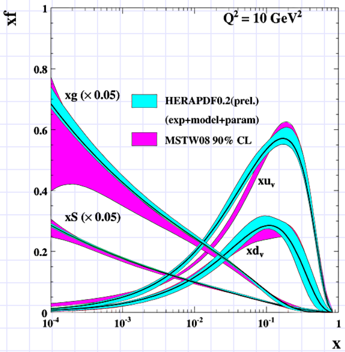
Model errors from variation of theory parameters like Q_0^2, m_c, m_b

Parameterisation errors from extra $D, E, \cdots$ terms in the parameterisation

Accurate xS and xg at low x due to precise measurement of F_2.

HERAPDF0.2 Compared to Global QCD Fits





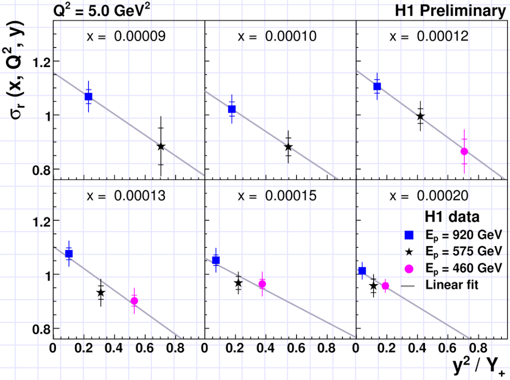
At low x HERAPDF0.2 is more precise for $xS(x), xg(x)$ vs global fits of CTEQ and MSTW:

- Global fits don't include the combined HERA/recent H1 data.
- Different error treatment – ongoing discussion in PDF4LHC workshop meetings.

Structure Function F_L

Measurement of the Structure Function F_L

- In quark-parton model $F_L = 0$ for spin 1/2 quarks.
- In QCD $F_L > 0$ due to gluon emission. Large $xg(x)$ at low x implies sizable $F_L \rightarrow F_L$ is crucial test of QCD.
- Reduced proton beam energy runs at the end of HERA operation dedicated to measure F_L.



$$\sigma_r(y) = F_2 - \frac{y^2}{Y_+} F_L$$

- Linear fit to the data at different centre-of-mass energies to obtain F_2 and F_L.
- Relative normalisation from low y data.

Structure Function F_L

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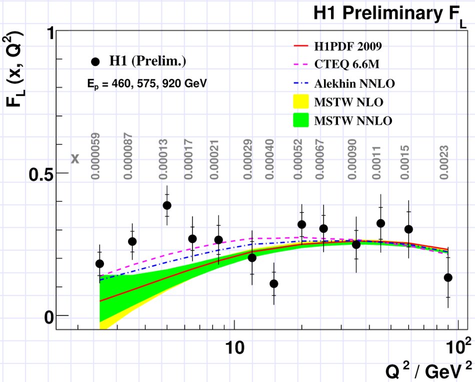
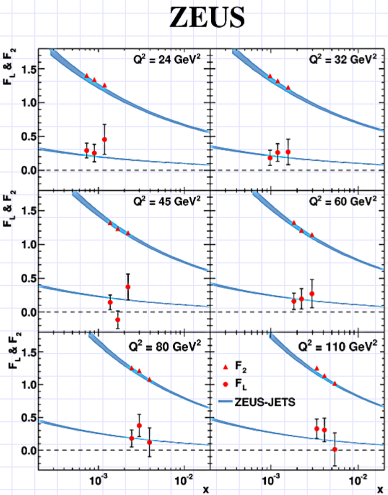


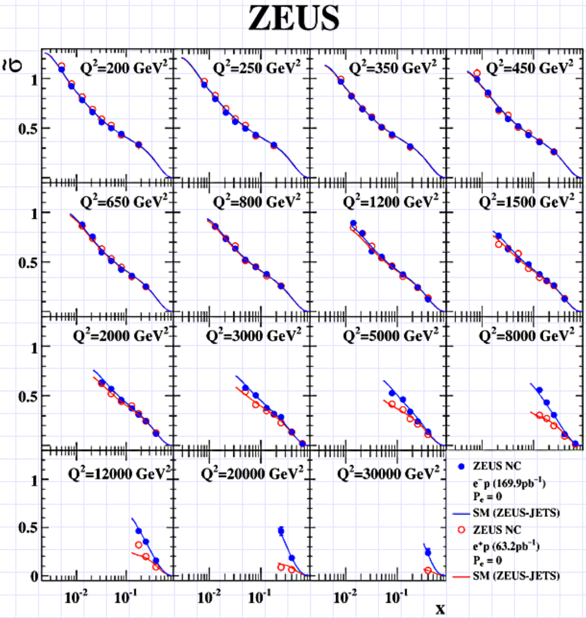
H1prelim-09-044



- For $Q^2 < 10$ GeV^2 F_L acquires sizable higher order corrections.
- MSTW and H1PDF2009 predictions use the same scheme to calculate F_L.
- Data agree better with calculation of CTEQ and Alekhin.

NC and CC at High Q^2

Unpolarised NC Cross Section at High Q^2



High Q^2 NC: e^-p and e^+p

- Good agreement with SM (ZEUS-JETS) over large kinematic range
- NC x-section charge asymmetry is due to xF_3

$$\tilde{\sigma}^{e^\pm p}_{NC} = \tilde{F}_2 - \frac{y^2}{Y_+}\tilde{F}_L \mp \frac{Y_-}{Y_+} x\tilde{F}_3$$

- Visible at large Q^2

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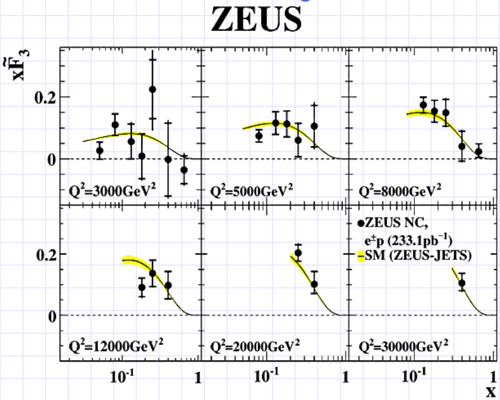
xF_3 Structure Function

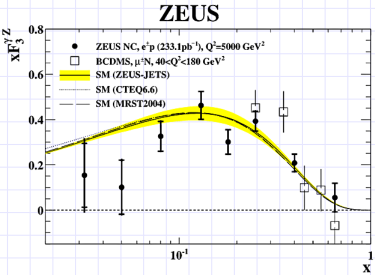


Unpolarised NC cross-sections:

$$\tilde{\sigma}_{NC}^{e^{\pm}p} = \tilde{F}_2 - \frac{y^2}{Y_+}\tilde{F}_L \mp \frac{Y_-}{Y_+} x\tilde{F}_3$$

$$x\tilde{F}_3 = \frac{Y_+}{2Y_-}\left(\tilde{\sigma}^{e^-p} - \tilde{\sigma}^{e^+p}\right)$$

$xF_3^{\gamma Z}$: adjust all xF_3 measurements to $Q^2 = 5000$ GeV^2. Neglect pure Z exchange.



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

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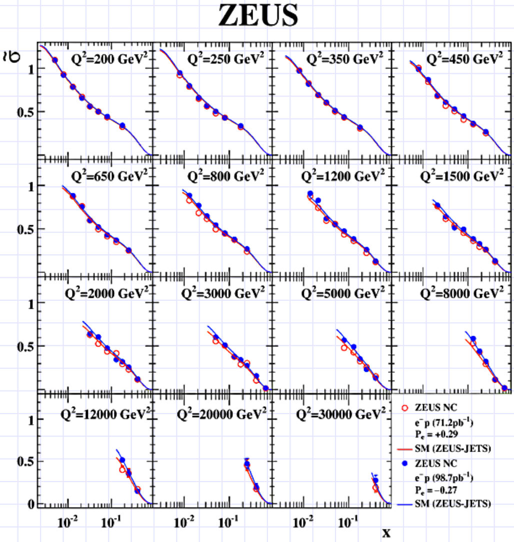
Polarised NC Cross Section at High Q^2



Neglecting pure Z exchange term, generalised $\tilde{F}_2$:

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

where

$$\chi = \frac{1}{4 \sin^2 \theta_W \cos^2 \theta_W} \frac{Q^2}{Q^2 + M_Z^2}$$

At leading order

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

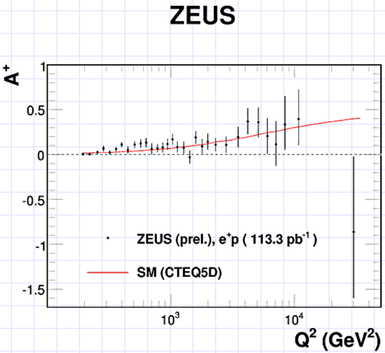
Polarisation asymmetry is parity violating.

NC e^-p: $P_e = +29\%$ and $P_e = -27\%$

DESY-08-202

Polarisation Asymmetry in NC

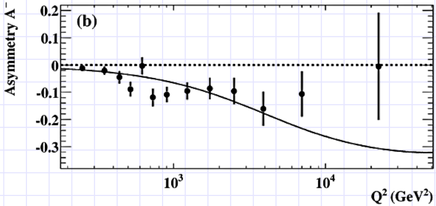
$$A^{\pm} = \frac{2}{P_R - P_L} \cdot \frac{\sigma^{\pm}(P_R) - \sigma^{\pm}(P_L)}{\sigma^{\pm}(P_R) + \sigma^{\pm}(P_L)}$$



Parity violation:

$$A^{\pm} \simeq \mp k a_e \frac{F_2^{\gamma Z}}{F_2} \sim a_e v_q$$

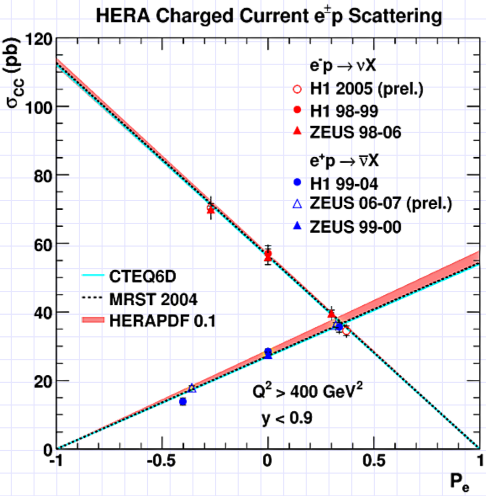
$$A^{\pm} \simeq \pm k \frac{1 + d_v/u_v}{4 + d_v/u_v}$$



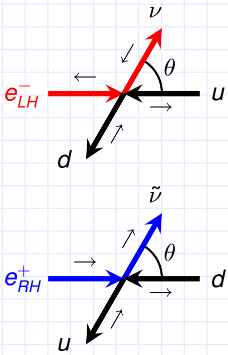
- To be performed using all HERA II data
- Combine H1 and ZEUS measurements

ZEUS-prel-08-005, DESY-08-202

Charged Current Cross Section

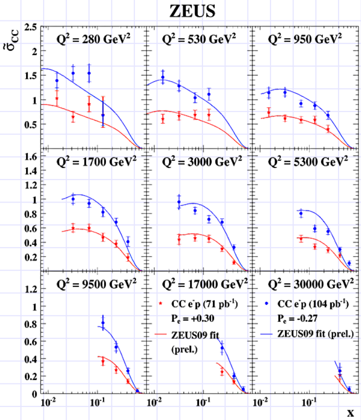


$$\sigma_{CC}^{e^{\pm}p}(P_e) = (1 \pm P_e)\sigma_{CC}^{e^{\pm}p}(P_e = 0)$$

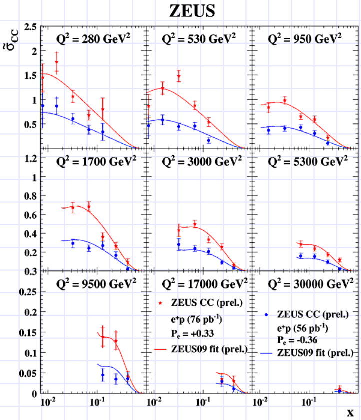


CC cross section is linearly proportional to the degree of the longitudinal $e^{\pm}$ beam polarisation. Consistent with no right-handed weak currents.

Double Differential CC Cross Section



$e^- p$



$e^+ p$

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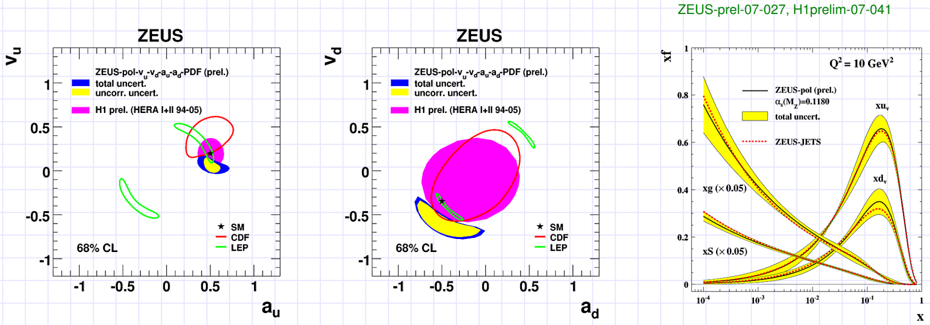
Complete HERA II $e^- p$ sample

Flavor selecting nature of CC:

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

Combined EW-QCD Fits



- Extract 5 PDFs ($g, u, \bar{u}, d, \bar{d}$) and weak couplings to Z (a_u, a_d, v_u, v_d) simultaneously
  - NC: γZ interference / Z exchange sensitive to a_u, a_d and can resolve signs of couplings
  - CC: flavor sensitivity helps to disentangle u and d quarks
- Precision competitive with LEP and Tevatron results
- Most precise value for u-coupling to Z comes from HERA

Summary

- HERA ended its run at Jun 2007: $\sim 1\ \text{fb}^{-1}$ collected by H1 and ZEUS
- HERA provides most precise inclusive structure function measurements, which brought significant improvements to our knowledge on proton structure
  - Combination of H1 and ZEUS published HERA-I data gives ultimate precision at low x.
- First direct measurements of F_L at low x.
- Observation and measurement of electroweak effects.
- Combined QCD+EW fit performed.
- New high precison results based on complete HERA sample expected in future will further improve our understanding on proton structure and provide a stringent test of the QCD and EW theories at high x and Q^2.