Electroweak Physics at HERA

Trong Hieu Tran, on behalf of the H1 Collaboration

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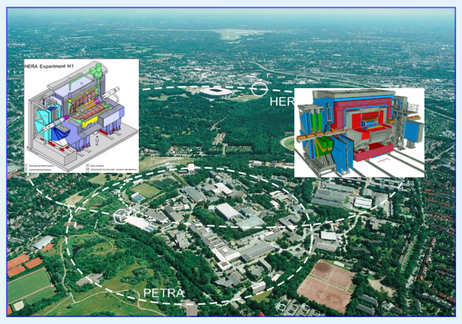
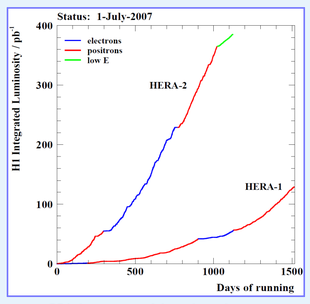
HERA collider

The unique *ep* collider, HERA, located at Hamburg, Germany, running 1994-2007, allowed the measurement of the Standard Model parameters and the neutral current couplings of quarks using DIS (Deep Inelastic Scattering) data at a center-of-mass energy of 319 GeV.
Two colliding experiments: H1 and ZEUS.



HERA-I: 1994-2000
integrated luminosity e^-p ~ 15 pb^{-1}
e^+p ~ 100 pb^{-1}
HERA-II: 2003-2007
integrated luminosity: e^-p ~ 200 pb^{-1}
e^+p ~ 200 pb^{-1}
use of longitudinally polarized electron beam



H1 integrated luminosity until the end of July 2007

Coupling of light quarks to Z^0 boson

The generalized neutral current structure functions can be written using the polarization

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

$$x\tilde{F}_3 = -(a_e - P_e v_e)\kappa_Z x F_3^{\gamma Z} + \left[2v_e a_e - P_e(v_e^2 + a_e^2)\kappa_Z^2 x F_3^Z\right]$$

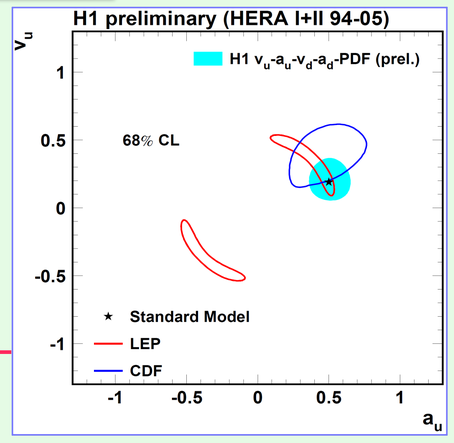
where $F_2^{\gamma Z}$ and F_2^Z, $xF_3^{\gamma Z}$ and xF_3^Z are related to the sum of quarks and anti-quarks densities:

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

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

- ► a_u constraint mainly by unpolarized data
- ► v_u constraint mainly by polarized data

Complementary to measurements previously made by CDF (*) and LEP (**) experiments



Weak neutral current coupling of the *u* quark in comparison with similar results from CDF and combined LEP experiments

(*) D. Acosta *et al.* [CDF Collaboration], Phys. Rev. **D71** (2005), 052002.
(**) [LEP and SLD Electroweak working groups], hep-ex/0412015 http://lepewwg.web.cern.ch/LEPEWWG/plots/summer2004/.

Parity violation in charged current interaction

Weak interaction affects only left-handed particles
► charged current cross sections vary linearly as a function of polarization.

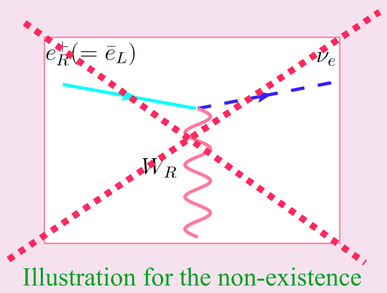
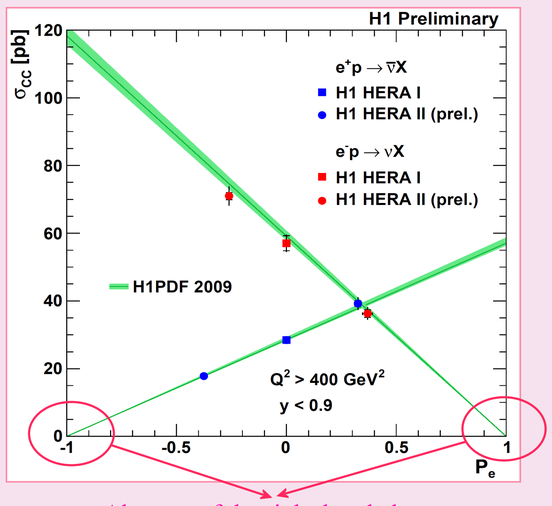


Illustration for the non-existence of the right-handed current

(*) C. Adloff *et al.* [H1 Collaboration], Eur. Phys. J. **C30** (2003), 1–2.
C. Adloff *et al.* [H1 Collaboration], Eur. Phys. J. **C13** (2000), 609–39.
C. Adloff *et al.* [H1 Collaboration], Eur. Phys. J. **C19** (2001), 269–88.

Charged current total cross section for polarized and published unpolarized data samples (*)



Absence of the right-handed current

Polarization asymmetry

Polarization asymmetry is defined from e^-p and e^+p, left-handed and right-handed neutral current cross sections as

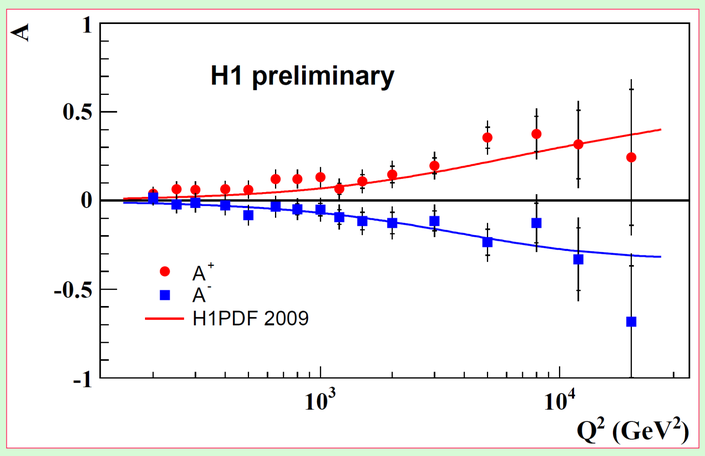
$$A = \frac{2}{P_R - P_L} \cdot \frac{\sigma^{\pm}(P_R) - \sigma^{\pm}(P_L)}{\sigma^{\pm}(P_R) + \sigma^{\pm}(P_L)}.$$

Approximately, A can be expressed in terms of structure functions:

$$A^{\pm} \simeq \mp P_Z a_e \frac{F^{\gamma Z}}{F_2}$$

At high Q^2, the difference between A values for e^+p and e^-p interaction becomes important due to the Z-boson exchange.

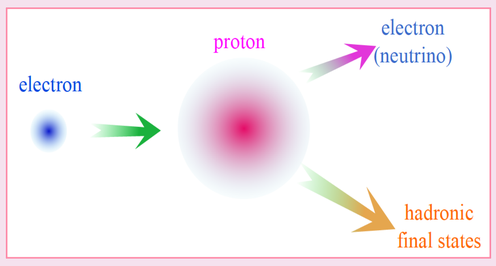
The results are found to be in good agreement with the Standard Model expectation determined from H1PDF 2009 fit (*)



Q^2 dependence of polarization asymmetry for e^-p and e^+p data compared to the prediction of the Standard Model

(*) F. D. Aaron *et al.* [H1 Collaboration], Eur. Phys. J **C64** (2009), 561.

Deep inelastic scattering



DIS charged current and neutral current cross sections are expressed using proton structure functions

$$\frac{d^2\sigma_{CC}}{dxdQ^2} = (1 + P_e)\frac{G_F^2}{4\pi x}\left[\frac{M_W^2}{M_W^2 + Q^2}\right]^2 \left(Y_+ W_2 - Y_- x W_3 - y^2 W_L\right)$$

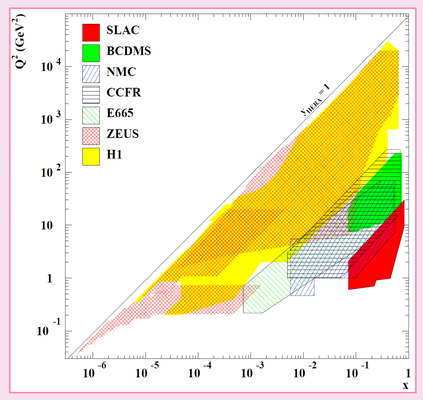
$$\frac{d^2\sigma_{e^\pm}^{NC}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+ F_2^{\pm}(x,Q^2) - y^2 F_L^{\pm}(x,Q^2) \mp Y_- x F_3^{\pm}(x,Q^2)\right]$$

$$Q^2 = -q^2 = (k - k')^2, \quad Q^2 \in [0, s]$$
$$x = \frac{Q^2}{2P \cdot q}, \quad x \in [0, 1]$$
$$y = \frac{q \cdot P}{k \cdot P}, \quad y \in [0, 1]$$
$$W^2 = (q + P)^2, \quad W^2 \in [M_p^2, s],$$
$$\nu = \frac{p \cdot P}{M}$$

DIS kinematics

where
- k and k' are the four-momentum vectors of the incident and of the scattered lepton, correspondingly
- P the four-momentum vector of the incident proton.

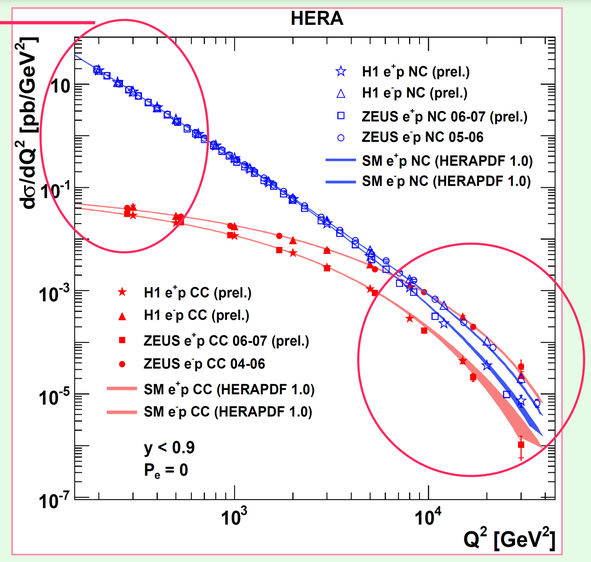
HERA covers a wide kinematic range, up to five orders in magnitude in log-scale of Q^2



HERA kinematic plane compared to other experiments

Electroweak unification

Difference at low Q^2 due to photon exchange. The charged current events are suppressed by massive W-boson.



Unpolarized neutral and charged currents single differential cross section for combined HERA-I & HERA-II, e^-p and e^+p data measured by H1 and ZEUS

(*) F.D. Aaron *et al.* [H1 Collaboration and ZEUS Collaboration] JHEP **1001** (2010) 109.

HERA data allow a visualization of the "unification" of the electromagnetic and weak interactions at highest values of Q^2.

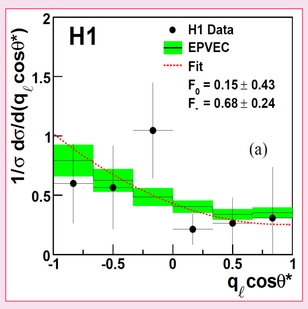
The results are compared with the corresponding Standard Model expectation determined from the HERAPDF 1.0 fit (*).

W-boson polarization fraction

Measurement based on isolated lepton sample in which a W-boson is produced. The $\cos\theta^*$ in decay $W \to e/\mu + \nu$ is exploited, where θ^* is the angle between W-boson momentum in the lab frame and that of the charged decay lepton in the W rest frame.

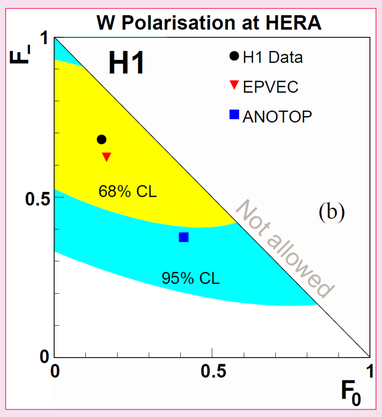
$$\frac{1}{\sigma_{W\to\ell+\nu}}\frac{d\sigma_{W\to\ell+\nu}}{d\cos\theta^*} = \frac{3}{4}F_0\left(1 - \cos^2\theta^*\right) + \frac{3}{8}F_-\left(1 - \cos\theta^*\right)^2 + \frac{3}{8}F_+\left(1 + \cos\theta^*\right)^2$$

F_- : left-handed polarization fraction
F_0 : longitudinal fraction
F_+ : right-handed fraction, $F_+ \equiv 1 - F_- - F_0$



Single differential cross section as a function of $q_l \cos\theta^*$ for on-shell W-boson

The left-handed and longitudinal fractions (F_- and F_0) are extracted simultaneously by a fit to the single W-boson production single differential cross section.



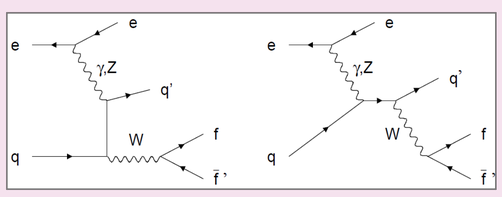
Plane showing the fit result for the simultaneously extracted left handed (F_-) and longitudinal (F_0) W-boson polarization fraction (point) with the corresponding 68% and 95% CL contours

F.D. Aaron *et al.* [H1 Collaboration], Eur. Phys. J. C **64** (2009) 251

Single W-boson production

Single W-boson production can occur at HERA through either neutral or charged current like interactions:
$ep \to eWX$ or $ep \to \nu WX$

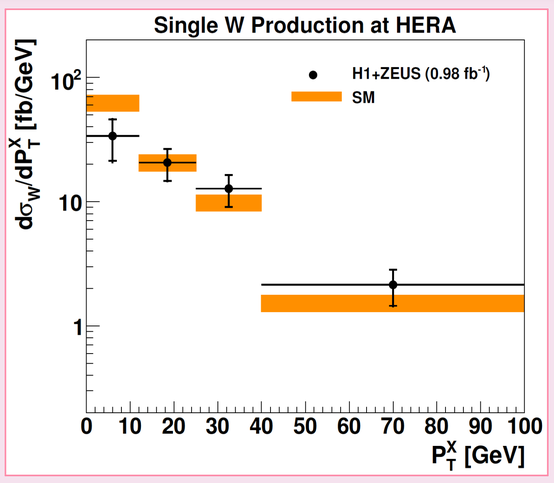
Two dominant processes are:



The total single W-boson production cross section at HERA is measured as:

$\sigma_W^{data} = 1.06 \pm 0.16$ (stat.) ± 0.07 (sys.) pb

The measured cross section is in good agreement with the Standard Model expectation of 1.26 ± 0.19 pb.



The single W-boson production cross section as a function of the hadronic transverse momentum measured using the combined H1 and ZEUS data at a center-of-mass energy of 319 GeV.

F.D. Aaron *et al.* [H1 Collaboration and ZEUS Collaboration], JHEP **1003** (2010) 035.