

Electroweak Physics at HERA

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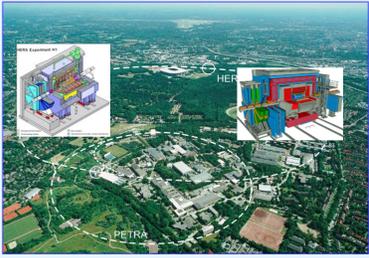


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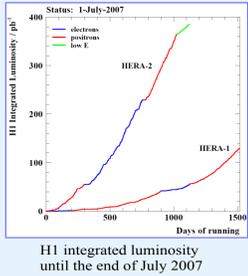
HERA collider

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 $e^+p \sim 15 \text{ pb}^{-1}$
 $e^-p \sim 100 \text{ pb}^{-1}$

HERA-II: 2003-2007
integrated luminosity: $e^+p \sim 200 \text{ pb}^{-1}$
 $e^-p \sim 200 \text{ pb}^{-1}$
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

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

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

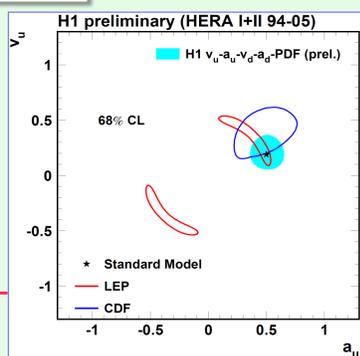
where $F_2^{\gamma Z}$ and F_2^Z , $x F_3^{\gamma Z}$ and $x F_3^Z$ are related to the sum of quarks and anti-quarks densities:

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

$$[x F_3^{\gamma Z}, x F_3^Z] = 2x \sum_q [e_q a_q, v_q a_q] \{q - \bar{q}\}$$

- 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.

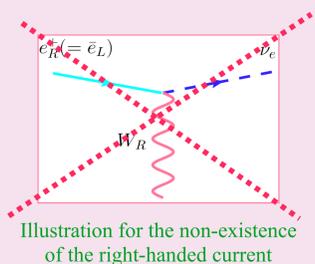
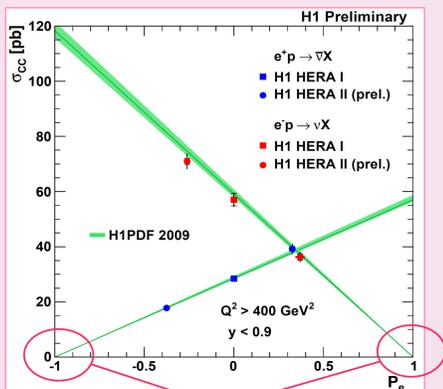


Illustration for the non-existence of the right-handed current

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



Absence 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.

Polarization asymmetry

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

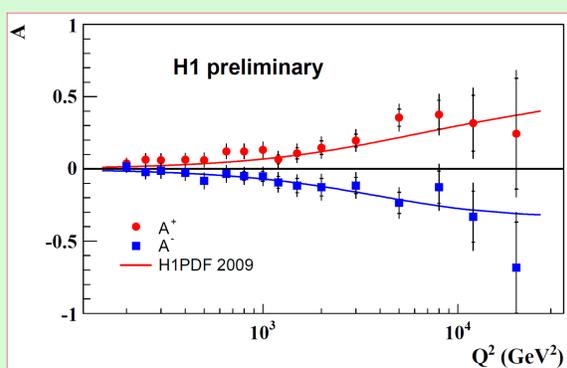
$$A = \frac{2}{P_R - P_L} \cdot \frac{\sigma^\pm(P_R) - \sigma^\pm(P_L)}{\sigma^\pm(P_R) + \sigma^\pm(P_L)}$$

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.

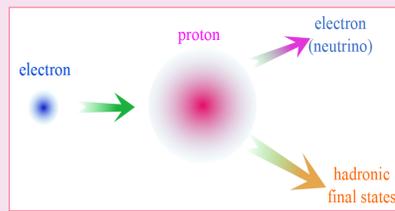
The results are found to be in good agreement with the Standard Model expectation determined from H1PDF 2009 fit (*)



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

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

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

$$Q^2 = -q^2 = (k - k')^2, \quad Q^2 \in [0, s]$$

$$x = \frac{Q^2}{2P \cdot q}, \quad x \in [0, 1]$$

$$y = \frac{q \cdot P}{k \cdot P}, \quad y \in [0, 1]$$

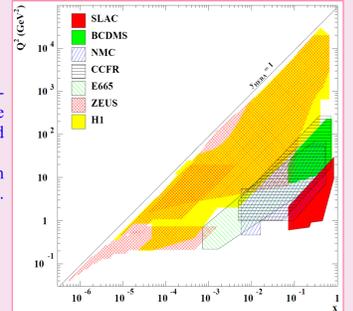
$$W^2 = (q + P)^2, \quad W^2 \in [M_p^2, s]$$

$$\nu = \frac{p \cdot P}{M}$$

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.

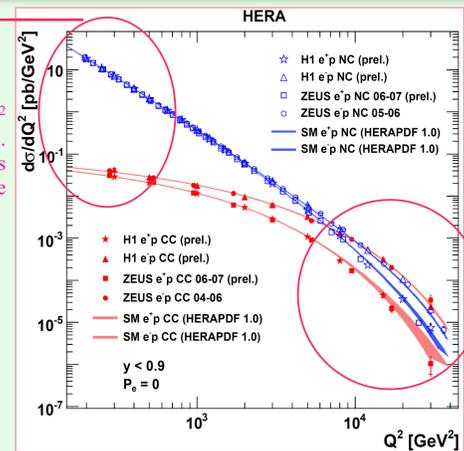
HERA covers a wide kinematic range, up to five orders in magnitude in log-scale of Q^2



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

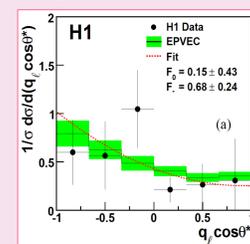
Measurement based on isolated lepton sample in which a W -boson is produced. The $\cos \theta^*$ in decay $W \rightarrow e\mu + \nu$ is exploited, where θ^* is the angle between W -boson momentum in the lab frame and that of the charged decay lepton in the W rest frame.

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

F_- : left-handed polarization fraction

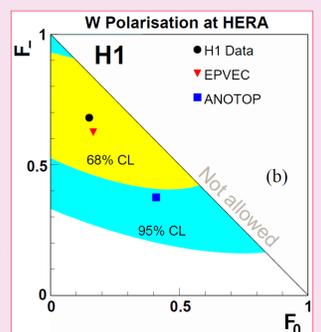
F_0 : longitudinal fraction

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



Single differential cross section as a function of $q_e \cos \theta^*$ 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.



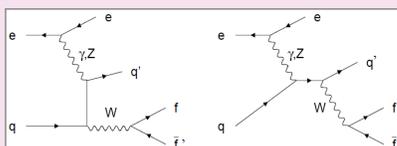
Plane showing the fit result for the simultaneously extracted left handed (F_-) and longitudinal (F_0) W -boson polarization fraction (point) with the corresponding 68% and 95% CL contours

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:
 $ep \rightarrow eW^+X$ or $ep \rightarrow \nu W^+X$

Two dominant processes are:

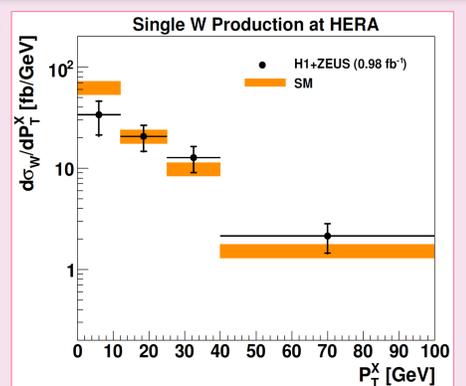


The total single W -boson production cross section at HERA is measured as:

$$\sigma_{W, \text{data}} = 1.06 \pm 0.16 \text{ (stat.)} \pm 0.07 \text{ (sys.) pb}$$

The measured cross section is in good agreement with the Standard Model expectation of $1.26 \pm 0.19 \text{ pb}$.

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



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.