Electroweak results from $e^{\pm}p$ collisions at HERA

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On behalf of
the H1 and ZEUS collaborations

PHOTON 2007, July 10, Paris

Outline:

-HERA I, HERA II collider and the experiments ZEUS and H1

-Inclusive $e^{\pm}p$ NC, CC cross sections at high Q^2

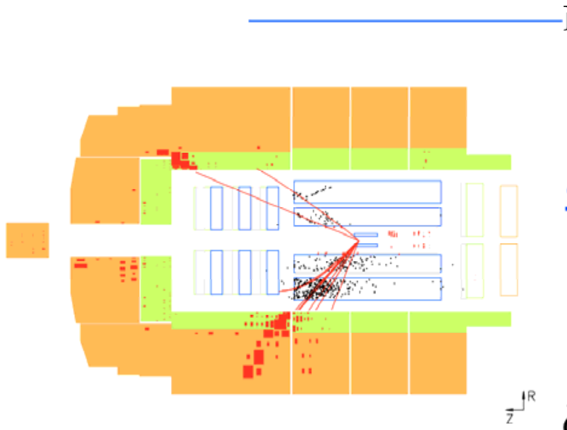
-Polarized inclusive $e^{\pm}p$ cross sections

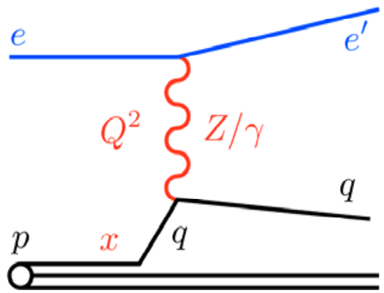
-Electroweak studies at EW unification scale

-Combined QCD-EW fits: weak couplings of quarks

-Conclusions and future results.

Neutral current cross sections





Event topology:

- Scattered electron in the detector

Kinematic variables:

- Momentum transfer squared Q^2
- Fraction of proton momentum x carried by struck quark
- Inelasticity $y = \frac{1-cos\theta^\star}{2} = \frac{Q^2}{sx}$

Cross-section:

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

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

Structure functions:

$$\tilde{F}_2^\pm = F_2 \quad -(v_e \pm P_e a_e)\kappa\frac{Q^2}{Q^2+M_Z^2}\quad F_2^{\gamma Z} \quad +\dots$$

$$x\tilde{F}_3^\pm = \quad -(a_e \pm P_e v_e)\kappa\frac{Q^2}{Q^2+M_Z^2}\quad xF_3^{\gamma Z} \quad +\dots$$

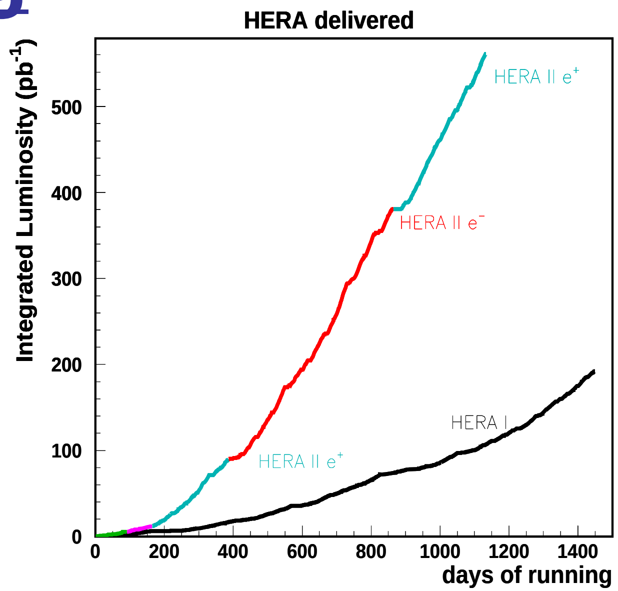
γ exchange — $Z\gamma$ interference — Z exchange

P_e: e beam polarisation
$\kappa^{-1} = \sin^2 2\theta_W$
v, a: electroweak couplings

$\tilde{F}_2$ is sensitive to sea and valence quarks: $F_2 \sim \sum_q (q+\bar{q})$
$x\tilde{F}_3$ is sensitive to valence quarks alone: $xF_3 \sim \sum_q (q-\bar{q})$

HERA Running

- HERA-I : 1992-2000 unique ep collider
  - Unpolarized e^+ and e^- beams
  - 26 GeV e , 820 GeV p
- HERA-II : years 2003-Mar/2007
  - High luminosity to allow more statistical sensitivity for large Q^2
  - 27.6 GeV e , 920 GeV p, $s^2=320^2 GeV^2$
  - Longitudinally polarized e+ and e- beams to allow direct sensitivity to EW effects
  - Upgraded detectors



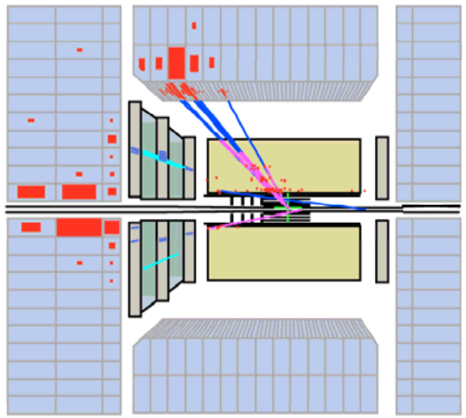
	HERA-I	HERA-II
e^-	~20 pb^{-1}	~290 pb^{-1}
e^+	~100 pb^{-1}	~270 pb^{-1}

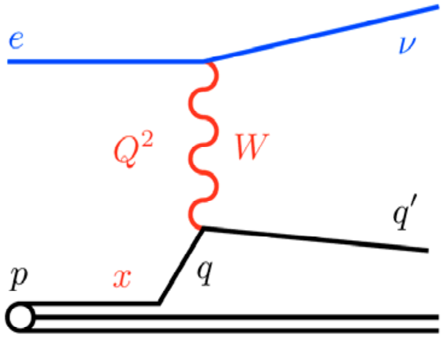
1 fb^{-1} collected by H1+ZEUS

- April-June 2007: a special run with three low proton beam energies (460.-575. GeV) to measure F_L structure function.

Charged current

Charged current





Event topology:

- Neutrino escapes detection

Kinematic variables:

- Momentum transfer squared Q^2
- Fraction of proton momentum x carried by struck quark
- Inelasticity $y = \frac{1-cos\theta^\star}{2} = \frac{Q^2}{sx}$

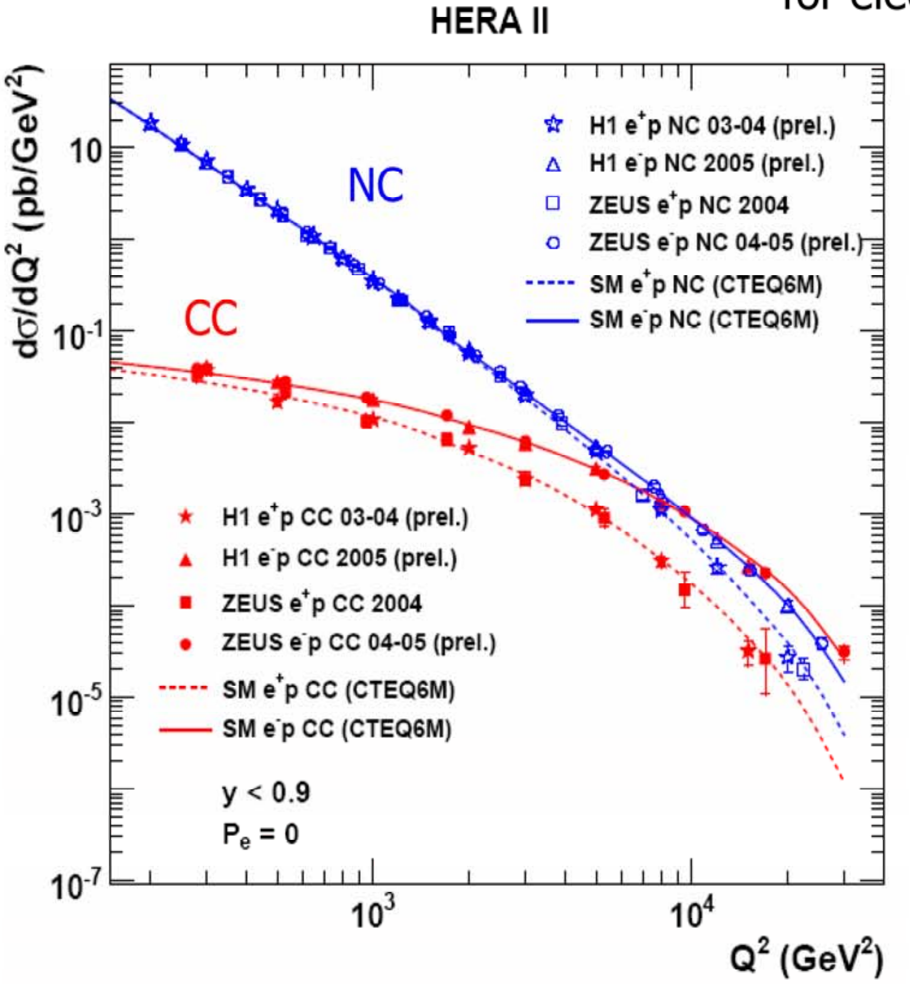
$$\frac{d^2\sigma^{CC}}{dx\,dQ^2}(e^+p) = (1+P_e)\quad \frac{1}{x}\quad \frac{G_F^2 M_W^4}{4\pi(Q^2+M_W^2)^2}\quad [(1-y)^2(xd+xs)+(x\bar{u}+x\bar{c})]$$

$$\frac{d^2\sigma^{CC}}{dx\,dQ^2}(e^-p) = (1-P_e)\quad \frac{1}{x}\quad \frac{G_F^2 M_W^4}{4\pi(Q^2+M_W^2)^2}\quad [(xu+xc)+(1-y^2)(x\bar{d}+x\bar{s})]$$

Polarisation — W exchange — Parton densities

Measurement of NC & CC cross sections

for electron & positron scattering



Unpolarised cross sections

Cross sections measured over 6 orders of magnitude

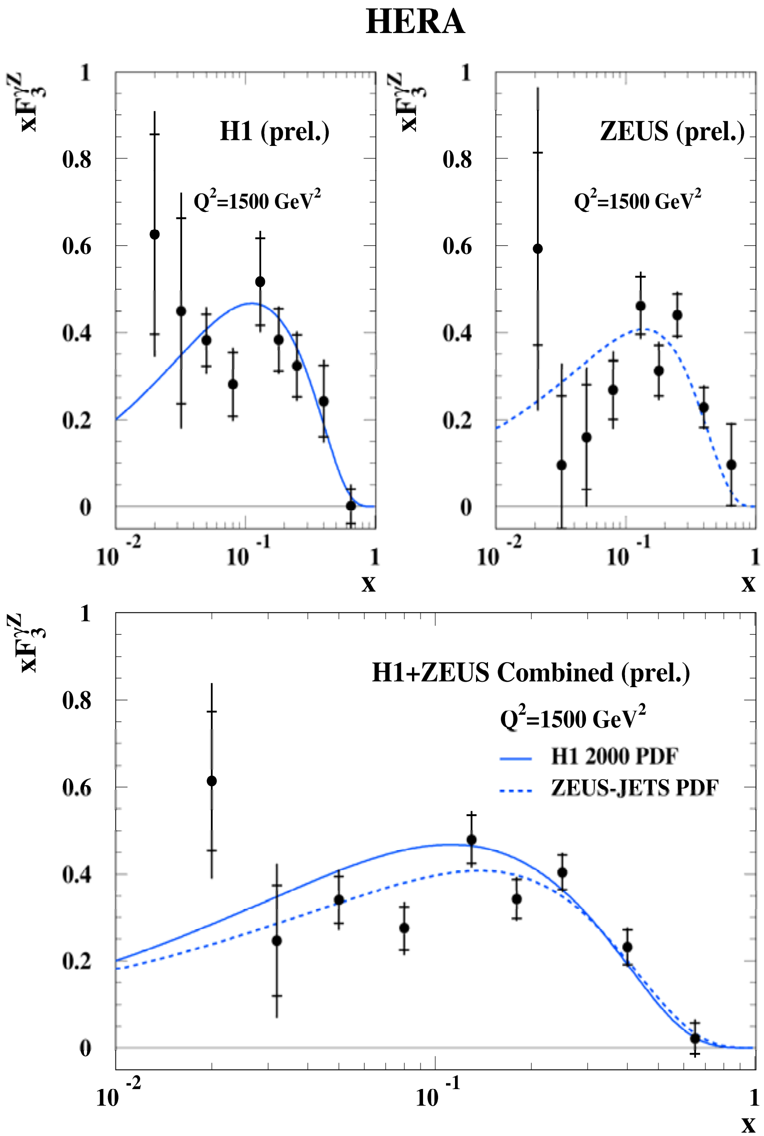
NC cross section dominated by photon exchange

NC e^+/e^- difference due to Z^0 exchange

CC cross section similar to NC cross section at high Q^2 → EW unification

Remaining difference due to PDFs

Extraction of $xF_3^{\gamma Z}$ by $\sigma_{NC}(e^-) - \sigma_{NC}(e^+)$



$xF_3^{\gamma Z}$: $\tilde{F}_3$ with kinematical factors removed

$$xF_3^{\gamma Z} = \sum_q 2e_q a_q(xq - x\bar{q}) = \frac{2}{3}xu_v + \frac{1}{3}xd_v$$

$\rightarrow$ Valence quark content of p

$\rightarrow$ Sensitivity to a_q

Weak Q^2 dependence $\rightarrow$ transform all points to $Q^2 = 1500\,\mathrm{GeV}^2$

Sum rule:

$$\int_0^1 \frac{xF_3^{\gamma Z}}{x} dx = \int_0^1 (\frac{2}{3}u_v + \frac{1}{3}d_v)dx = \frac{5}{3}$$

Combined result from ZEUS, H1:

$$\int_{0.02}^{0.65} \frac{xF_3^{\gamma Z}}{x} dx = 1.21 \pm 0.09\ (\mathrm{stat}) \pm 0.08\ (\mathrm{sys})$$

Compatible with Sum rule if integral is extrapolated to $[0, 1]$

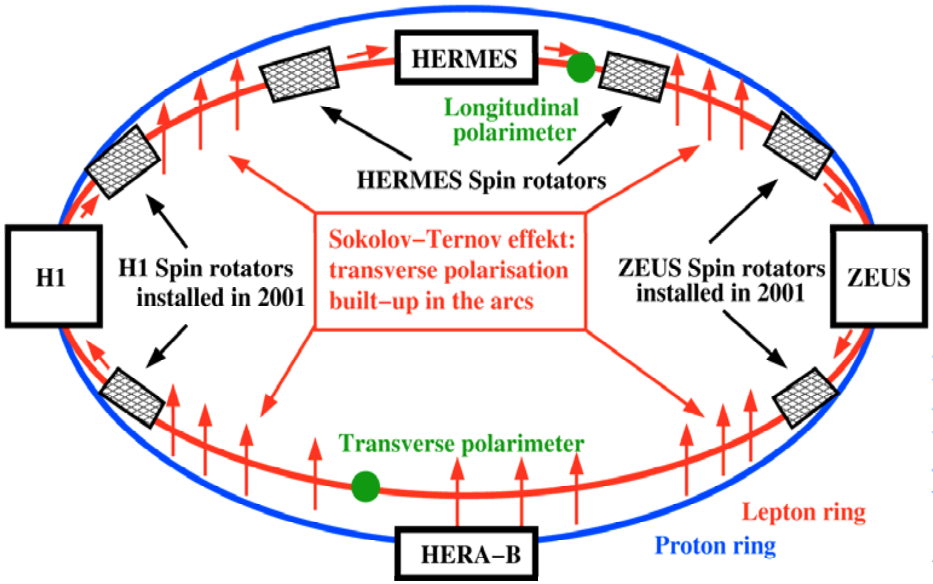
DIS at EW scale with polarization

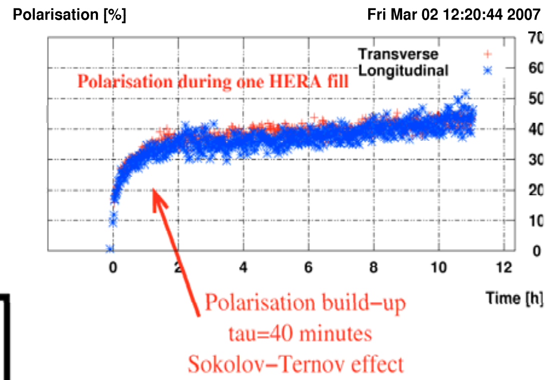
First polarized DIS at EW scale

-- Right-handed CC ?

-- Parity violation in weak NC

Lepton polarisation at HERA II





Polarisation is changing during the fill

Monitored by two independent Compton polarimeters

$P_e = 30 \ldots 45\%$ achieved regularly

HERA I+II:

Transverse polarisation for H1+ZEUS

Not useful for physics

HERA II:

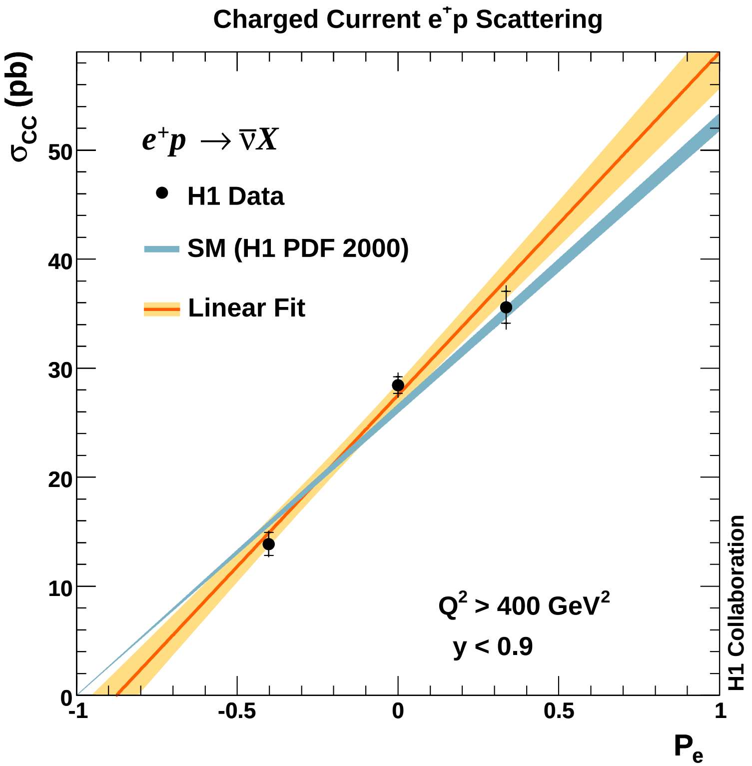
Luminosity upgrade for H1+ZEUS

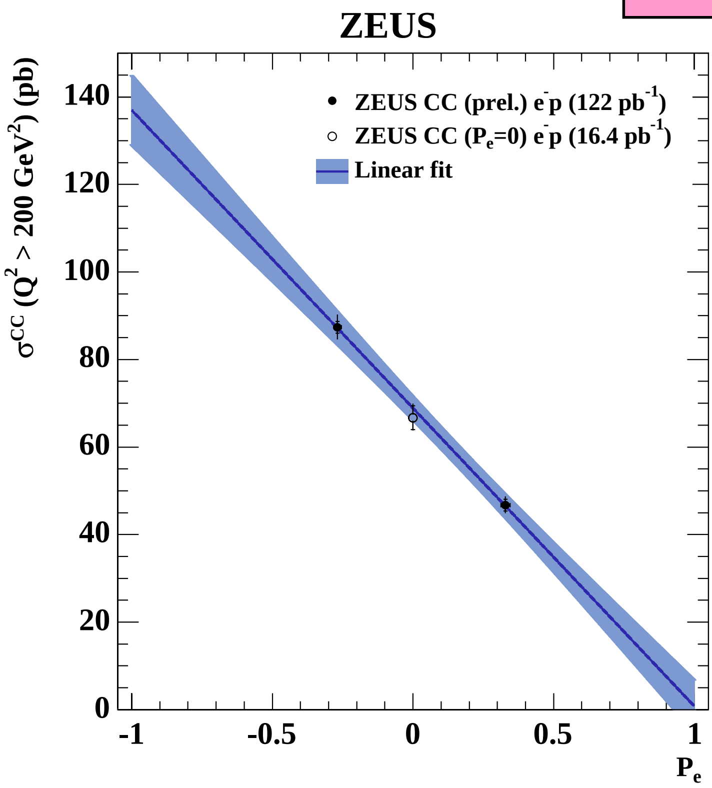
Longitudinal polarisation for H1+ZEUS

→ new electroweak results

W_R mass limit

HERA-II Data





▶ Assuming $g_L = g_R$ and ν_R is light:

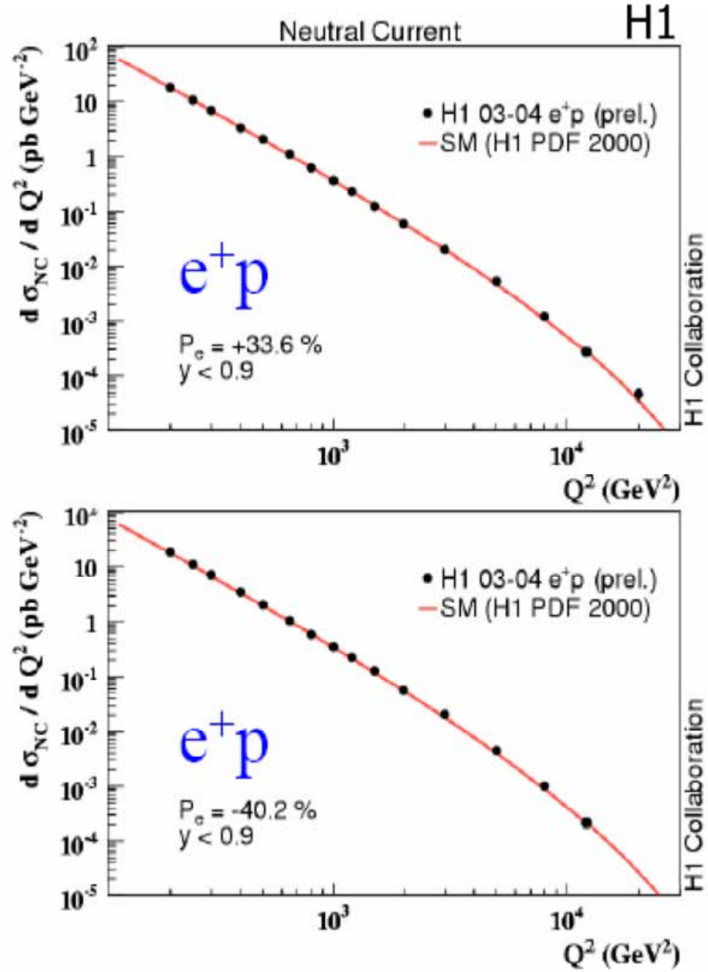
$M(W_R) > 208$ GeV (from H1 e^+ data)

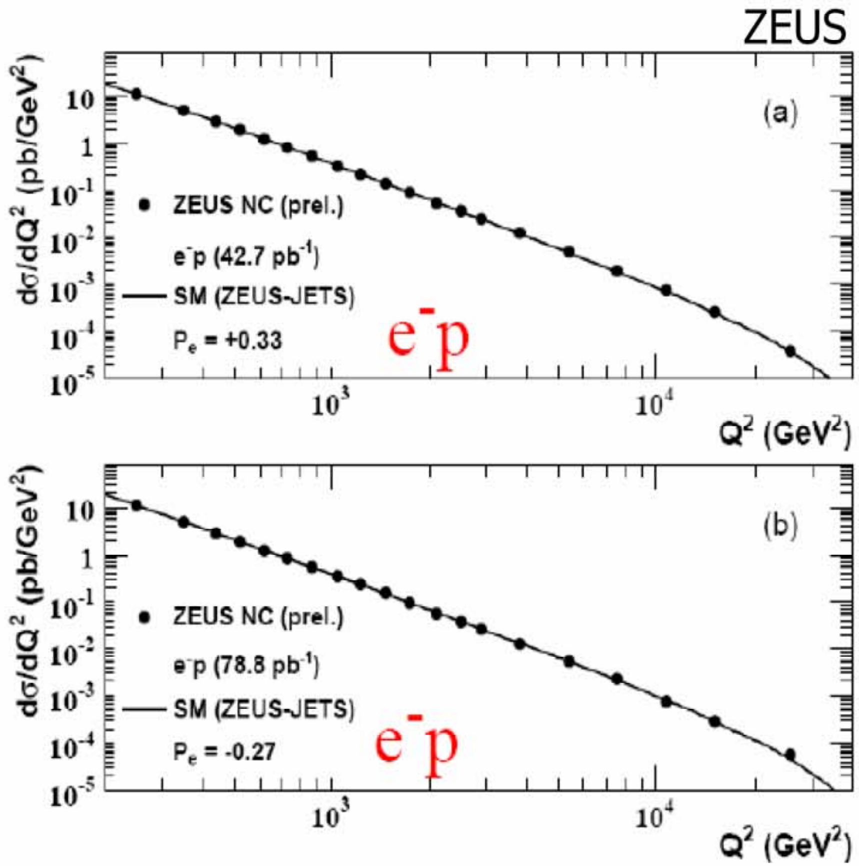
(Error dominated by polarization uncertainty)

H1 e^-: 186 GeV
ZEUS e^-: 180 GeV

- β^+ decay: > 310 GeV (polarized ^{12}N decay)
- cf. W' : > 786 GeV by CDF (W'→eν,μν)

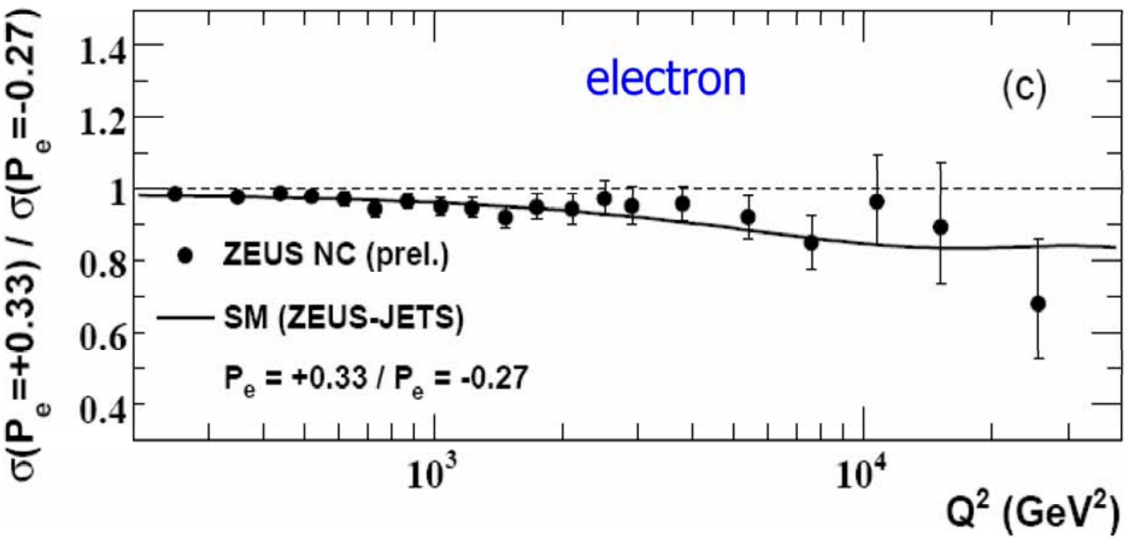
Polarized e^+,e^- NC cross sections

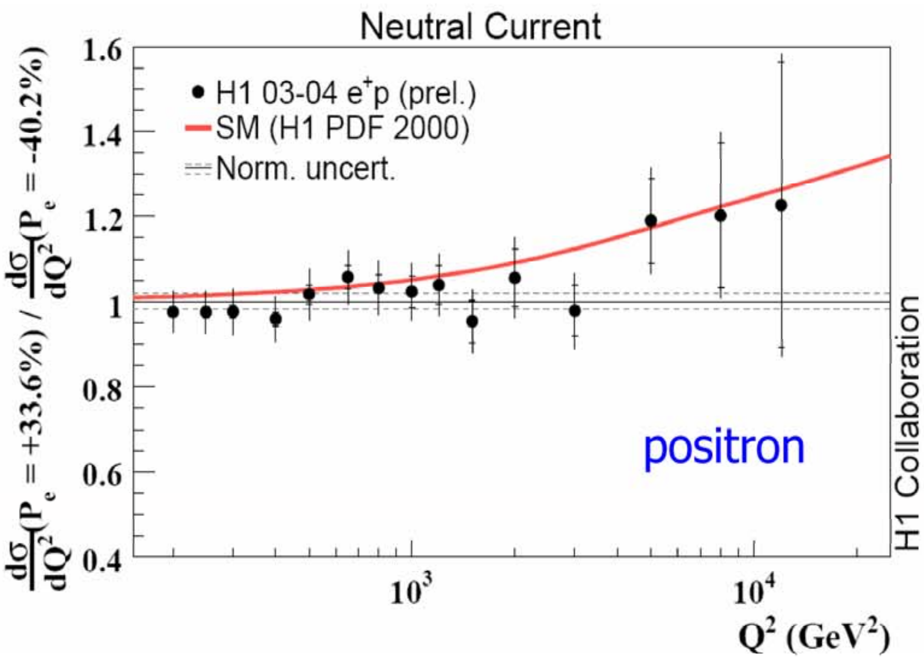




Both experiments measured positron/electron, left/right cross sections

NC R/L polarization ratio





Measure ratio of NC cross section

$$\frac{d\sigma}{dQ^2} \quad \text{R/L}$$

Effect increases with Q^2
As do the statistical uncertainties!

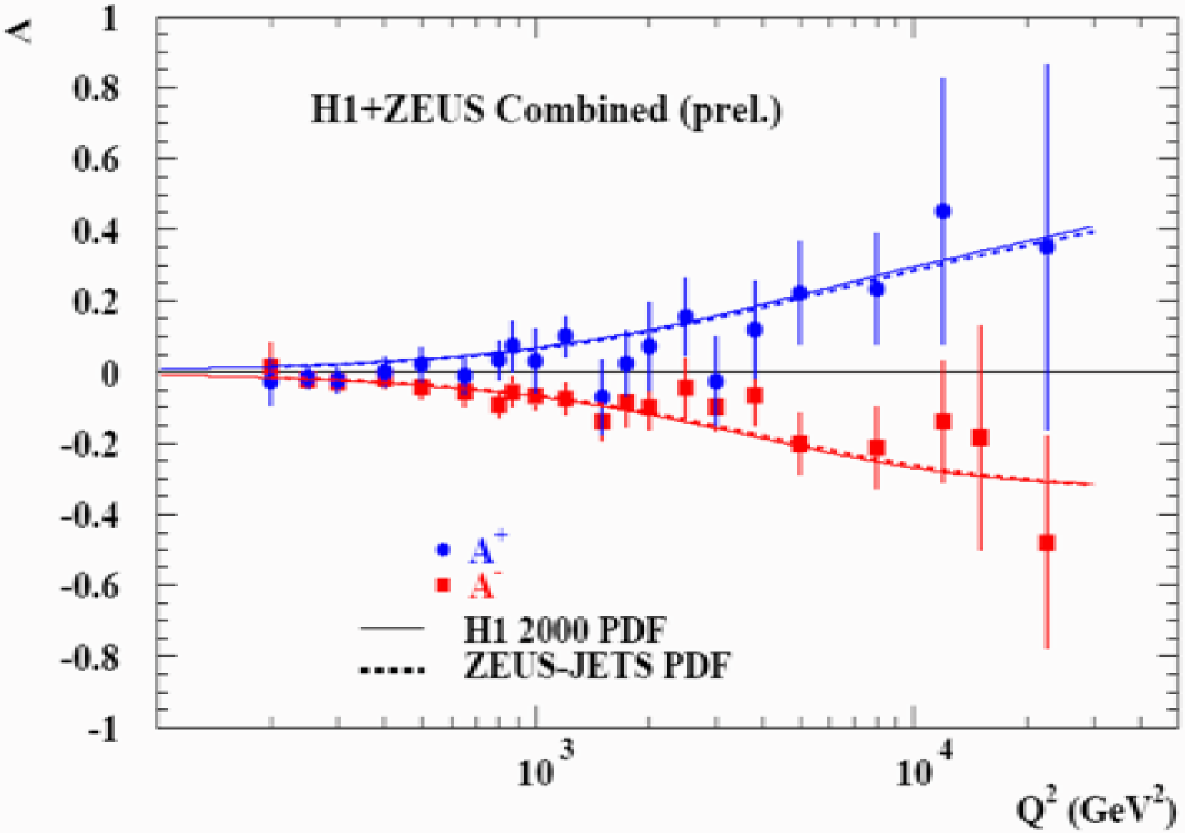
Data consistent with SM

suppression of electron R
enhancement of positron R

NC polarization asymmetry

$$A^{\pm} = \frac{2}{P_R - P_L} \cdot \frac{\sigma^{\pm}(P_R) - \sigma^{\pm}(P_L)}{\sigma^{\pm}(P_R) - \sigma^{\pm}(P_L)} \approx \chi_Z a_e \frac{F_2^{\gamma Z}}{F_2}$$

Direct measure of parity violation



define the difference of positron and electron polarisation asymmetries

$$\delta A = A^{+} - A^{-}$$

χ^2 of δA being different from zero = 4.0 (3.1 x 10^{-3} probability)

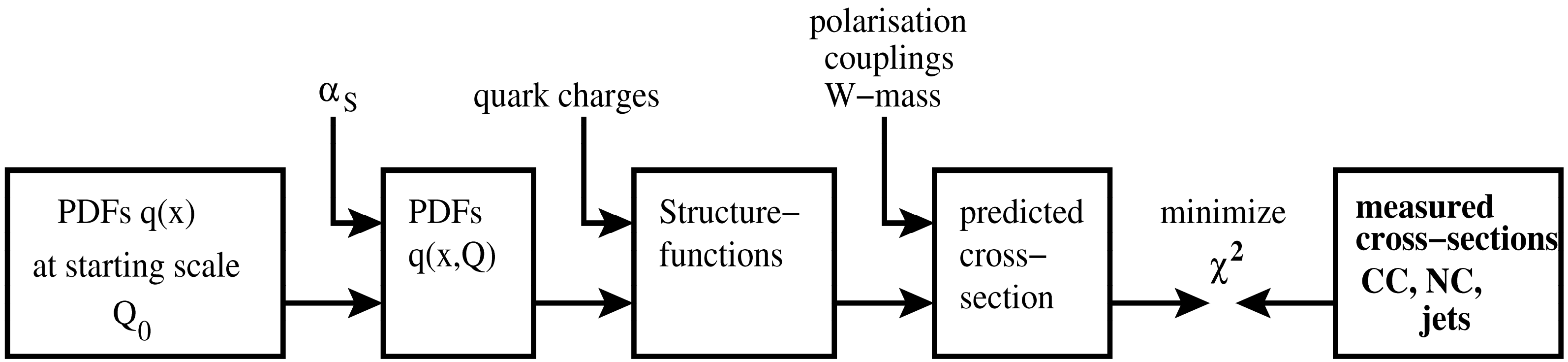
QCD + EW combined analysis

- Mw
- Light quark couplings to Z

Electroweak fits at HERA

Charged current: sensitivity to G_F, M_W

Neutral current: sensitivity to light quark axial and vector couplings $v_{u,d}$, $a_{u,d}$



HERA fits: mainly about precise determination of α_S and PDFs

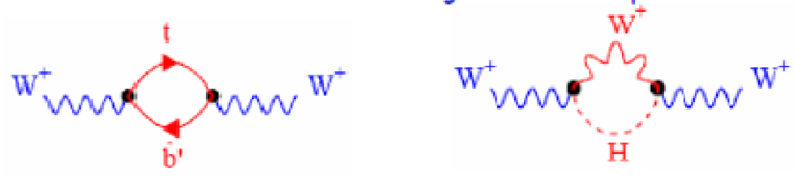
Results presented here: recent papers about HERA fits of electroweak parameters.

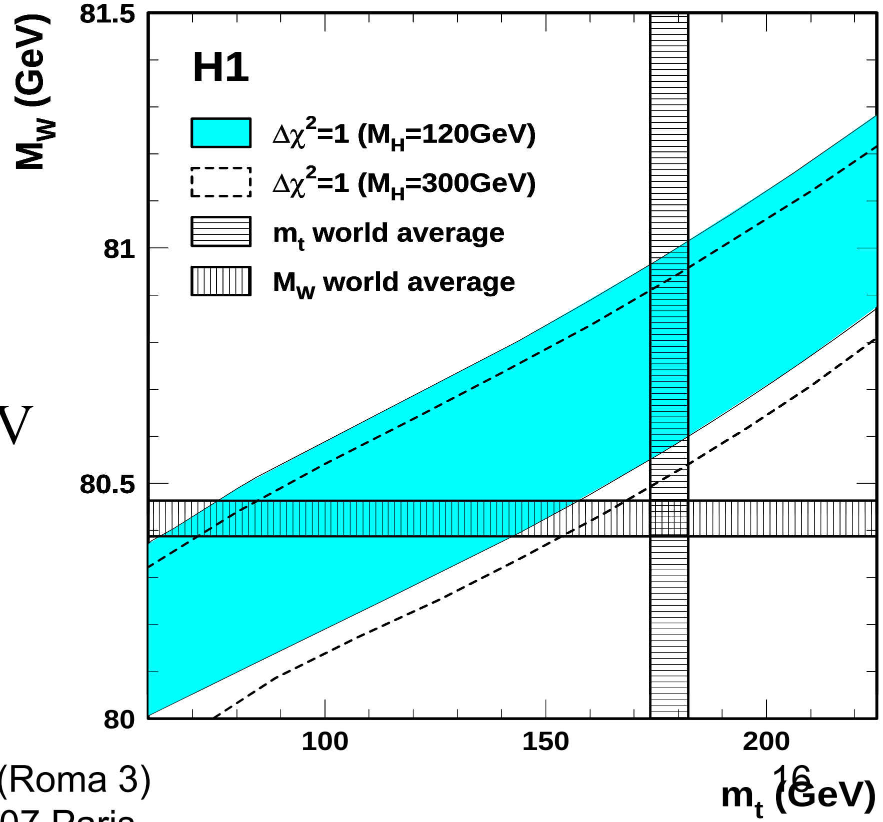
M_W in the framework of SM

- In the SM G_F and M_W are related ➔ Fits fully assuming SM
  - -- On-Mass-Shell (OMS) scheme

$$\frac{d^2\sigma}{dxdQ^2} = \frac{\pi\alpha^2}{4M_w^2(1-\frac{M_W^2}{M_Z^2})^2}\frac{1}{(1-\Delta r)^2}(\frac{M_W^2}{Q^2+M_W^2})^2\Phi(pdfs)$$

Quadratic dependence on m_t Logarithmic dependence on M_H





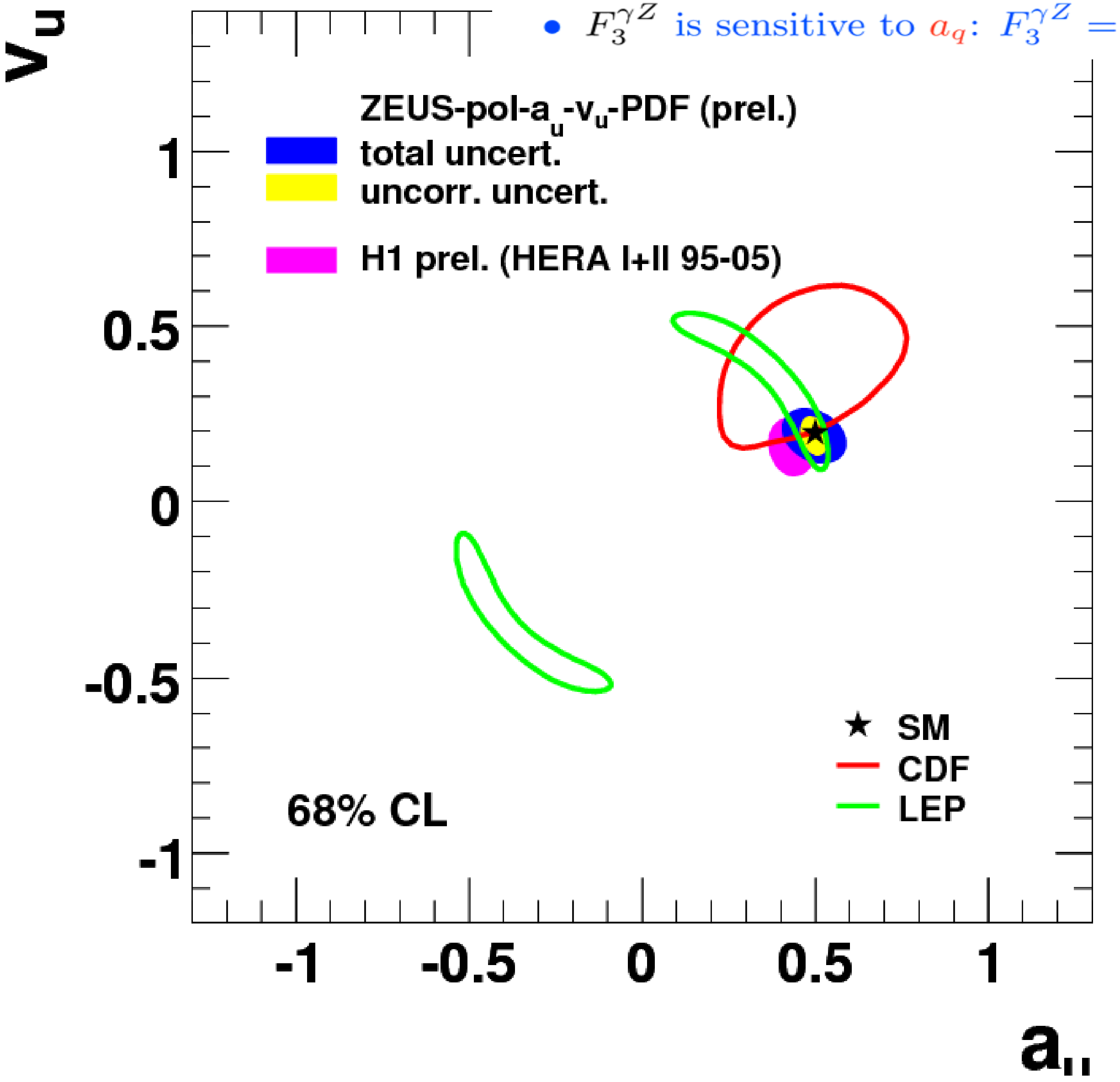
▶ A fit to M_W with M_Z fixed
-- $M_W = 80.786 \pm 0.205(\exp)$ GeV

▶ A fit to m_t with M_Z ,M_w fixed
-- $m_t = 104 \pm 44(\exp)$ GeV
-- Determination of m_{Top} in DIS
(via loop corr)

Electroweak u and d coupling to Z0

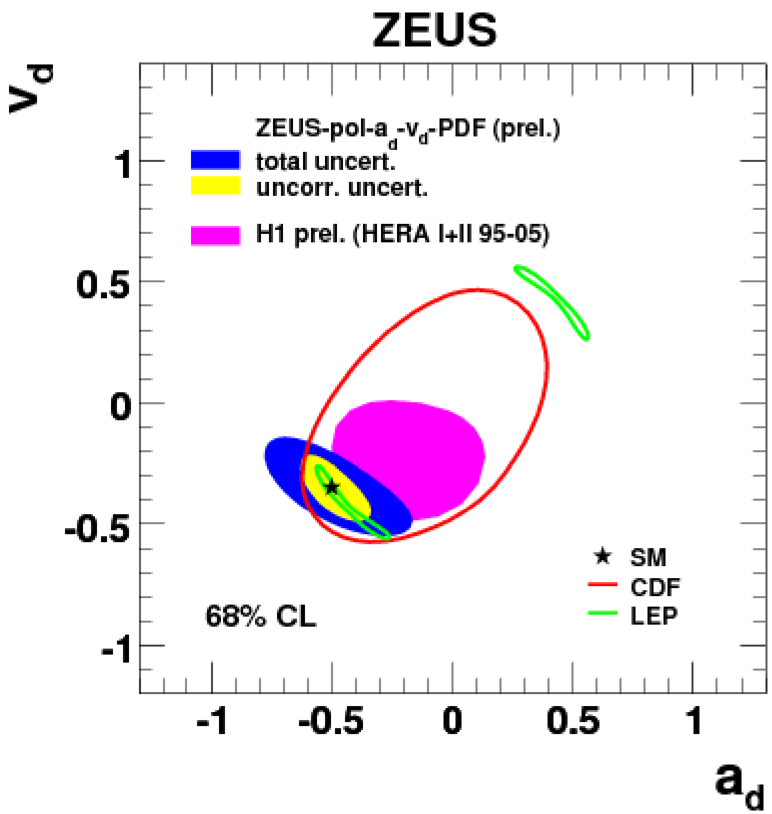
NC cross-section: measure u, d quark axial and vector couplings:

- $F_2^{\gamma Z}$ is sensitive to v_q: $F_2^{\gamma Z} = 2\sum_q e_q v_q (xq + x\bar{q})$
- $F_3^{\gamma Z}$ is sensitive to a_q: $F_3^{\gamma Z} = 2\sum_q e_q a_q (xq + x\bar{q})$



Half constrained fit: v_d ,a_d couplings fixed at SM val.

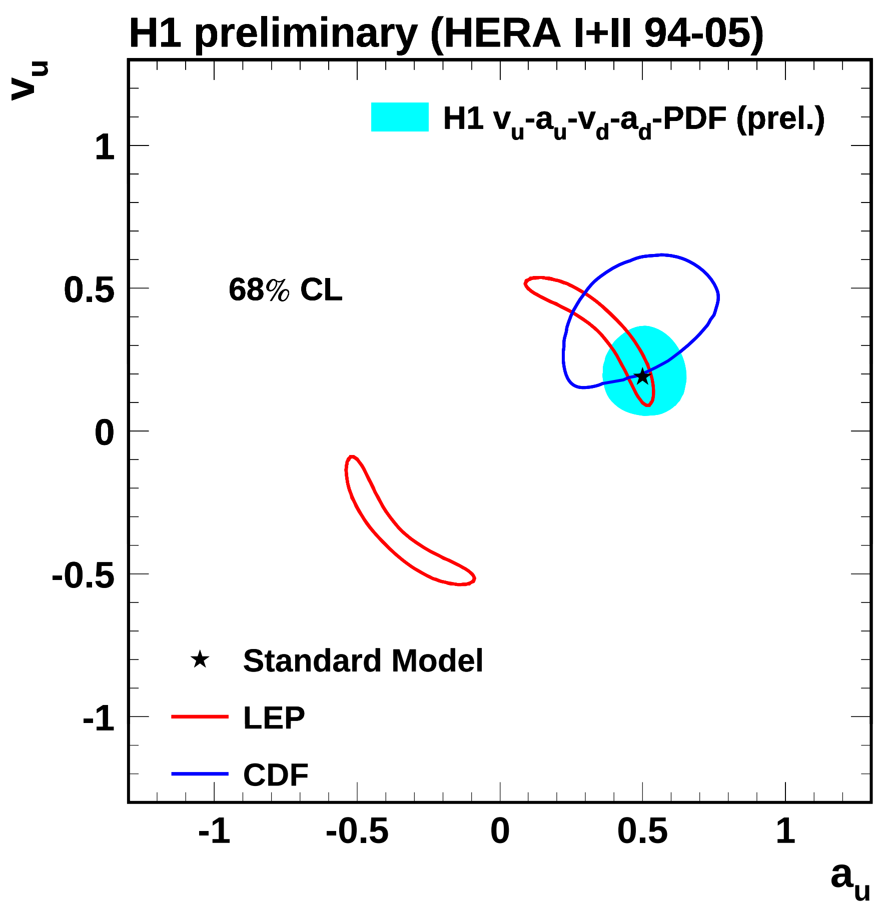
Constrained fit to d quark couplings



Half constrained fit: v_u,a_u couplings fixed at SM values.

Un-(minimum) constrained fit

► **All four (V_u,A_u,V_d,A_d) free fit**



► **A EW+QCD fit to determine: T^3_u, T^3_d, $\sin^2\theta_W$**

In the SM

$$v_f = T^3{}_f - 2e_f \sin^2\theta_W$$

$$a_f = T^3{}_f$$

$$T^3{}_u = 0.47 \pm 0.05 \pm 0.13$$

$$T^3{}_d = -0.55 \pm 0.18 \pm 0.35$$

$$\sin^2\theta_w = 0.231 \pm 0.024 \pm 0.070$$

Nb: In this fit, $\sin^2\theta_W$ also contributes to the propagator term

Electroweak results from $e^{\pm}p$ collisions at HERA

Summary

●HERA is now able to investigate elementary interactions with high luminosity and longitudinal polarization:

--- NC & CC measured at **EW unification** scale with e^+ and e^-.

--- **First polarized** DIS at EW scale.

--- V-A structure of CC tested at high energy.

--- First measurement of parity violation in weak NC at EW scale.

---- Simultaneous QCD & EW fits made;

---- **Best** determination of light quarks **a,v** couplings to Z^0.

●HERA till now confirms the glory of the **SM**.

Future

● HERA ended its high energy run on 21/Mar/2007: **1 fb^{-1}** by H1 and ZEUS

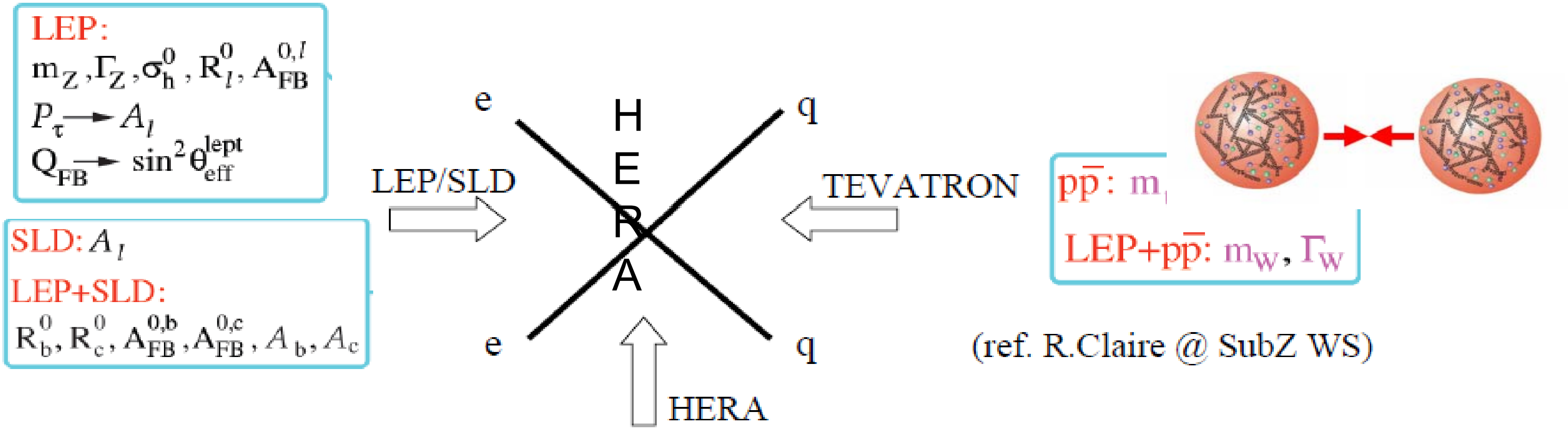
--- **~Half analyzed**. HERA legacy in EW sector will come soon.

--- Low energy run has followed to determine F_L .

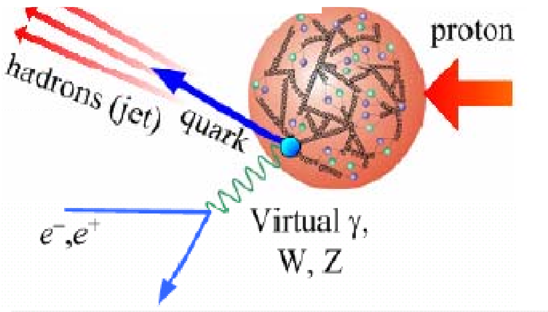
--- HERA switched off June 30 2007 at 23:26. ***Many years of analysis***.-

Backup slides

Colliders at EW scale



► HERA



● Search for new symmetries and particles.

● Use own proton Parton Density Functions (PDF)

● Probe proton structure by t-channel exchange of gauge bosons

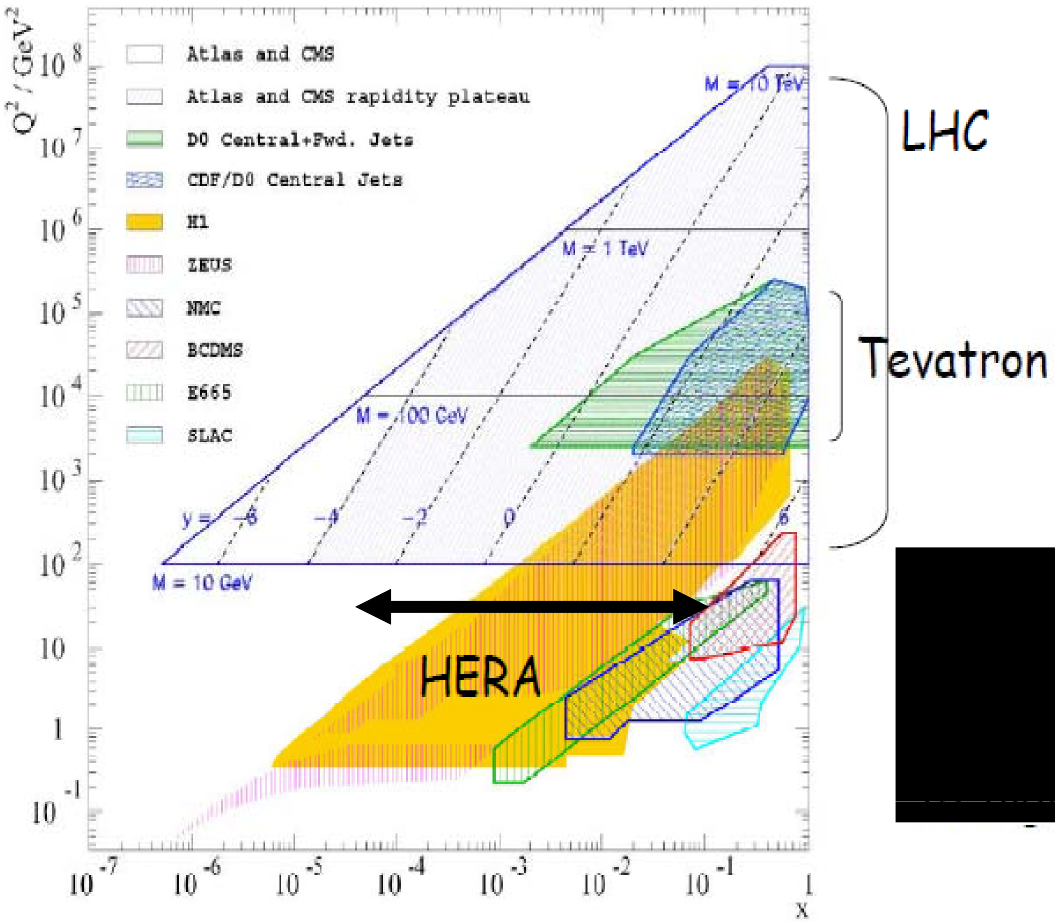
- At low Q^2: mainly by γ

-- At high Q^2: γ/Z (NC) and W (CC)

$$\sigma(ep) \propto \sum \sigma(eq)_{EW} \otimes (pdf)_{QCD}$$

● Investigate electron-quark elementary processes based on knowledge of proton structure (at lower Q^2 + DGLAP evolution)

High Q^2 at HERA and LHC



High Q^2 region :

-- DGLAP evolution of proton structure.

-- Based on these knowledge, study elementary processes (EW) at large energy scale

Low Q^2 region :

-- Precise measurement c proton structure

(Remind: gluons/sea at $x=10^{-4}\sim10^{-2}$ are determined by HERA)

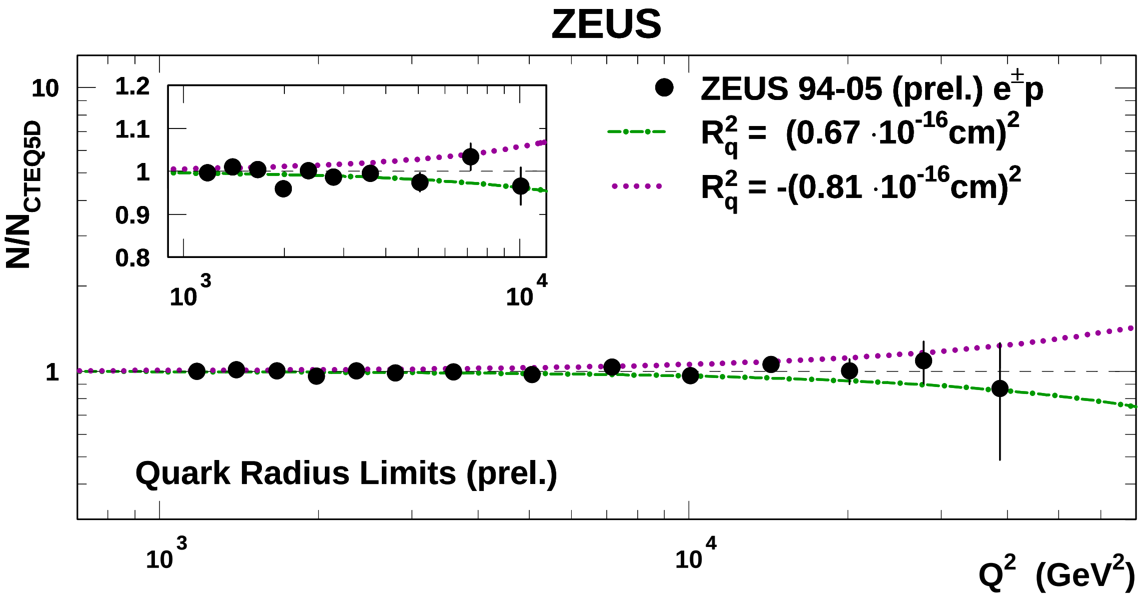
Quark radius

► Probing proton with highest spatial resolution

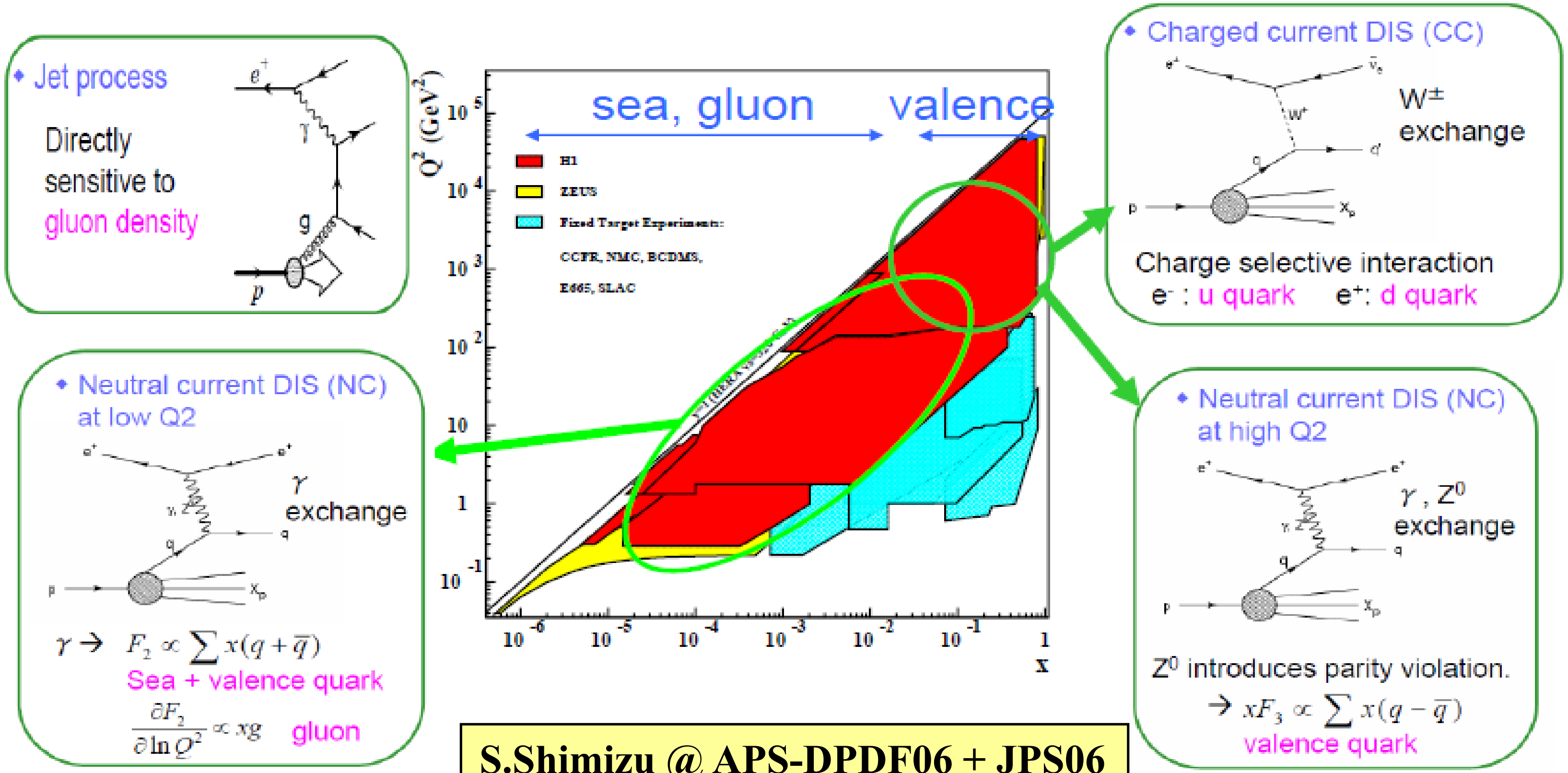
– Quark radius : if there is structure in the quark, DIS cross section at high Q^2 will be modified due to spatial distribution of quark charge :

$$\frac{d\sigma}{dQ^2} = \frac{d\sigma^{SM}}{dQ^2}\left(1 - \frac{R_q^{\ 2}}{6} Q^2\right)^2$$

(like "form factor" with Rq corresponding to the average radius of quark charge)



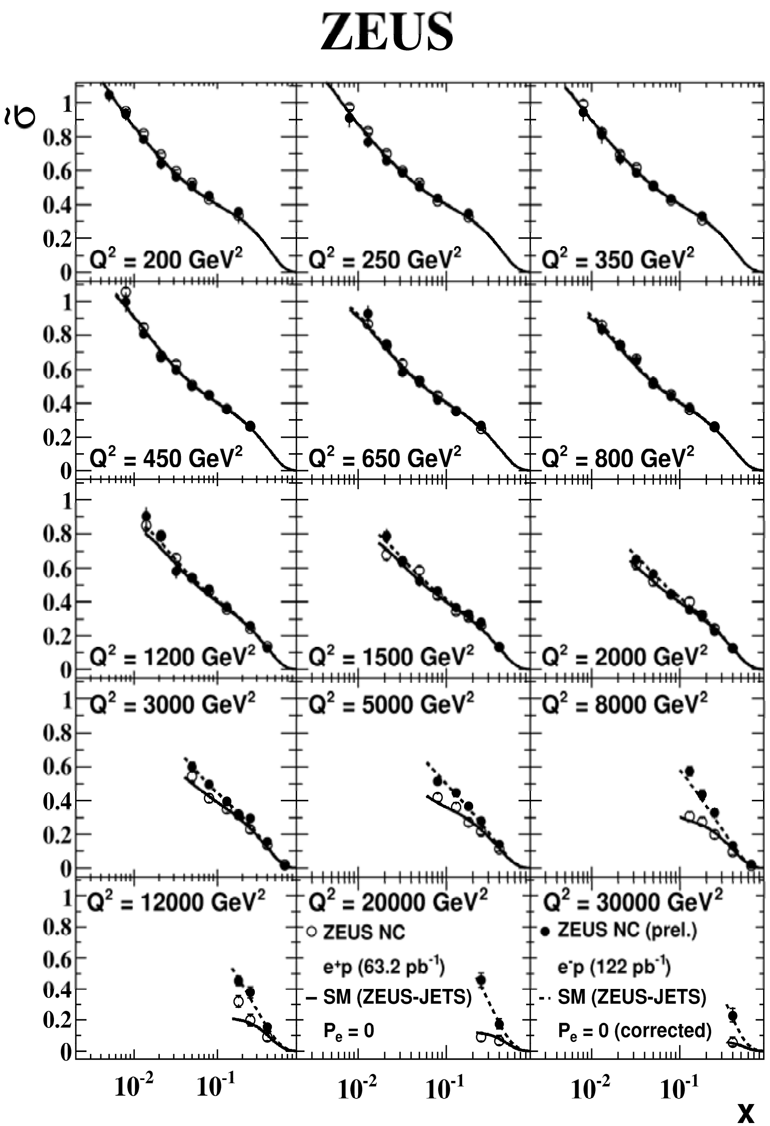
EW+QCD fit



S.Shimizu @ APS-DPDF06 + JPS06

- A fit to single experimental data
  - -- H1 fit to H1 data only, ZEUS fit to ZEUS data only
  - -- Advantage: Handling of systematic errors is straightforward
    Free from target-mass correction in fixed-target data
- A fit to determine both PDF and EW parameters
  - -- Advantage: correlation automatically taken into account

Double-differential NC cross-section, xF_3



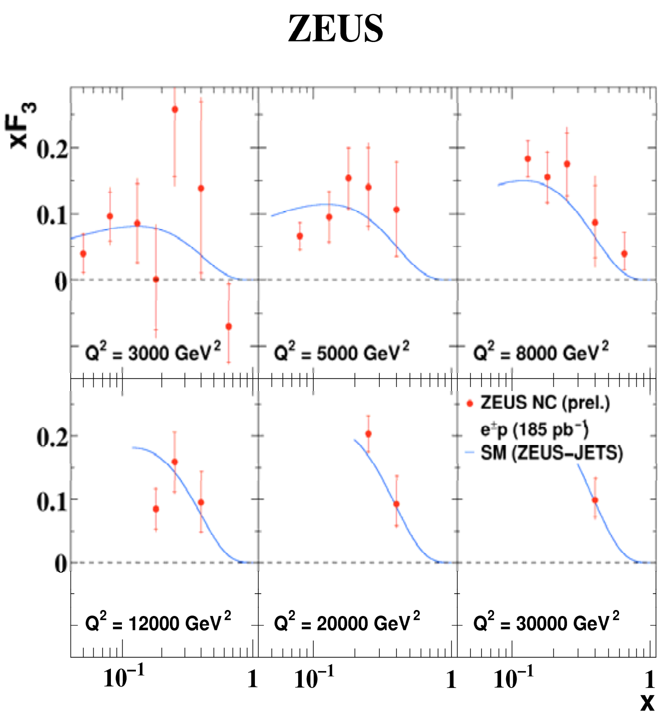
Reduced cross-section

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

Plot: ZEUS high Q^2 data for HERA I (e^+p) and HERA II (e^-p)

Difference between e^+ and e^-: electroweak effects

$\rightarrow$ extract structure function $x\tilde{F}_3$

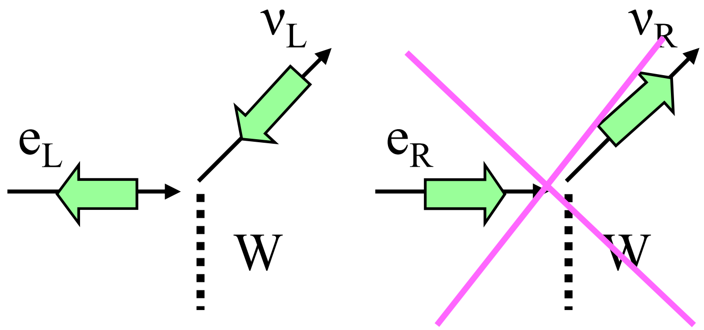


EW with polarized lepton beams

● Polarization = Asymmetry of Helicity states:
$P = (N_R - N_L) / (N_R + N_L)$
● Helicity = Chirality (if mass is neglected)
➔ By means of Pol, chiral structure can be tested.

► **Charged-current DIS**

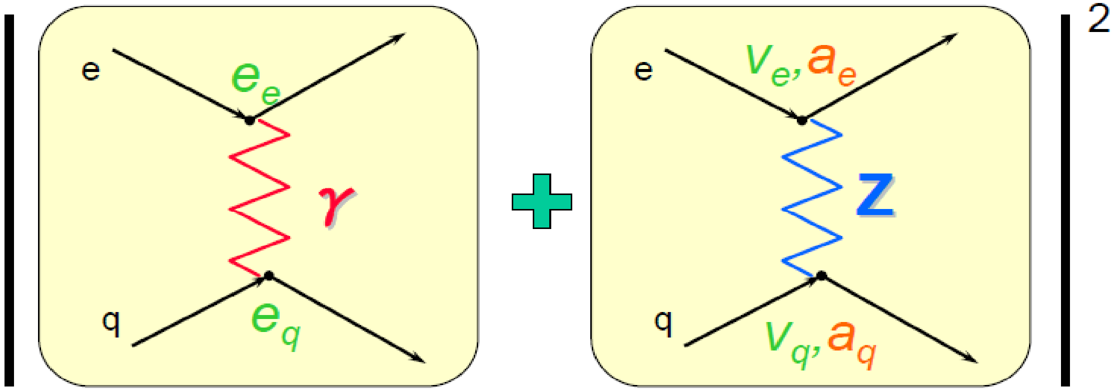
● "Pure" Weak
→ Chiral structure of weak int. is directly visible as a function of Polarization
● Weak = "100% parity violated" (no RH)
→ Zero cross section @ Pol=1 (-1 for e^+)
➔ $\sigma(Pol) = (1 \pm Pol)\,\sigma(Unpol)$



► **Neutral-current DIS**

● Weak's parity violating effect through γ-Z interference and pure Z
→ visible only at large Q^2
● Such γ-Z and Z terms contain EW parameters, i.e. quark couplings to Z, $\sin\theta_W$, M_Z

Light quark couplings to Z



$$\frac{d^2\sigma_{e^\pm p}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[\left\{1+(1-y)^2\right\}\tilde{F}_2 \mp \left\{1-(1-y)^2\right\}x\tilde{F}_3\right]$$

$$\begin{aligned}\tilde{F}_2 &= F_2^{\gamma} - (v_e \pm P_e a_e)\chi_Z F_2^{\gamma Z} + ((v_e^2 + a_e^2) \pm P_e 2 v_e a_e))\chi_Z^2 F_2^Z \\ \tilde{F}_3 &= - (a_e \pm P_e v_e)\chi_Z F_3^{\gamma Z} + ((2 v_e a_e \pm P_e(v_e^2 + a_e^2))\chi_Z^2 F_3^Z\end{aligned}$$

Unpol: $\sigma(e^+) - \sigma(e^-) \rightarrow F_3^{\gamma Z}$
Pol : $\sigma(P_e \rightarrow) - \sigma(P_e \leftarrow) \rightarrow F_2^{\gamma Z}$
$\Downarrow$
Unpol: $\sigma(e^+) - \sigma(e^-) \rightarrow a_f$
Pol : $\sigma(P_e \rightarrow) - \sigma(P_e \leftarrow) \rightarrow v_f$

- **EW structure functions in QPM**

$$\begin{aligned}F_2^{\gamma Z} &= 2 e_f v_f \Sigma_i x[q_f + \overline{q_f}] \\ F_2^{Z} &= (v_f^2 + a_f^2)\Sigma_i x[q_f + \overline{q_f}] \\ F_3^{\gamma Z} &= 2 e_f a_f \Sigma_i x[q_f - \overline{q_f}] \\ F_3^{Z} &= 2 v_f a_f \Sigma_i x[q_f - \overline{q_f}]\end{aligned}$$