Electroweak results from ep collisions at HERA

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On behalf of
the H1 and ZEUS collaborations

Hadron Collider Physics Symposium 2007 (HCP07)
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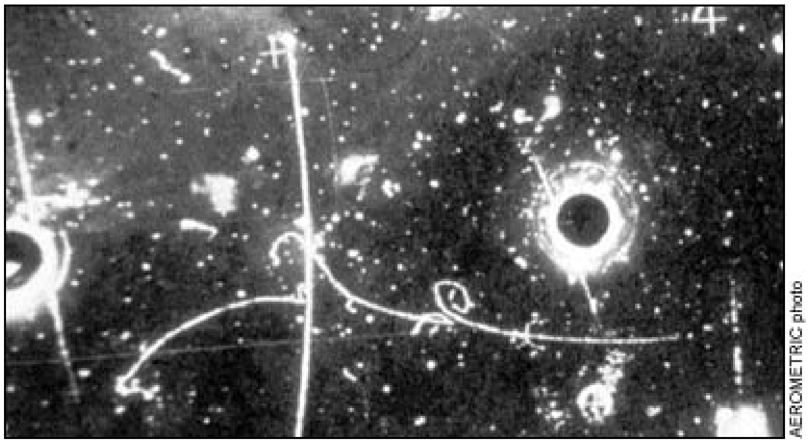
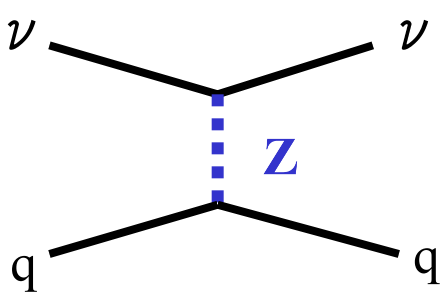
EW @ DIS ?

- Remember: Weak neutral current was "DIScovered" by the Gargamelle

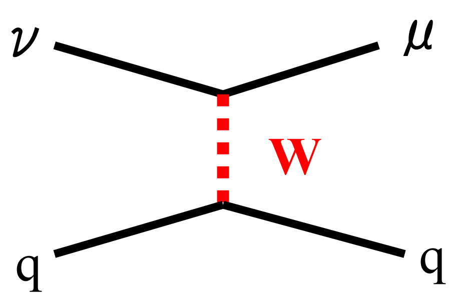


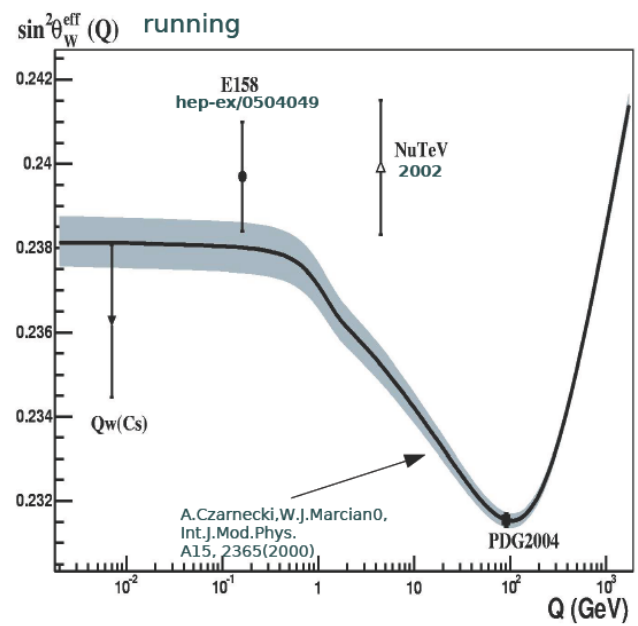
- ν -DIS has been a good test bench for the weak mixing angle, $\sin\theta_W$: nowadays as well "NuTeV anomaly"

Neutral current (NC)



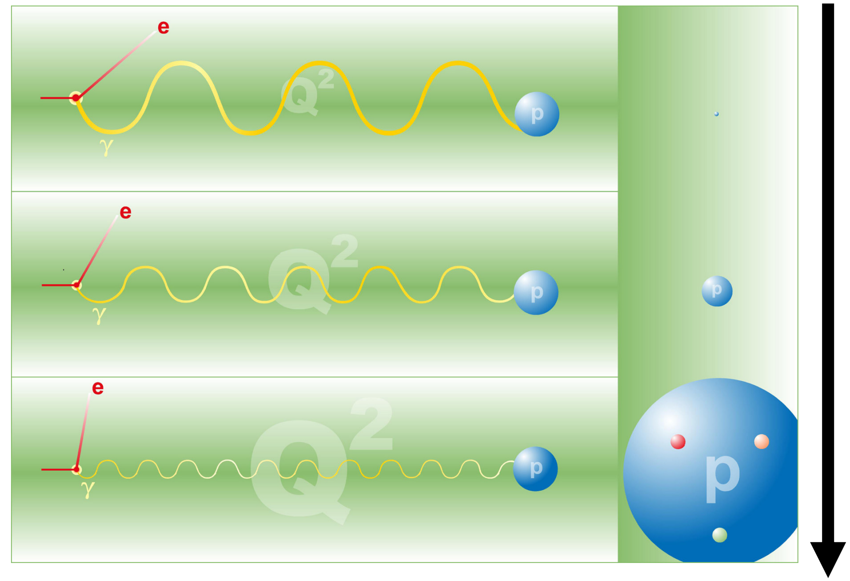
Charged current (CC)





"Pure" weak int. @ $Q^2 \lesssim O(100)$ GeV^2
(Q^2 is momentum transfer squared)

HERA : world only ep collider



Q^2 large

Q^2 corresponds to:

the scale (wavelength) to probe the proton $\lambda \sim 1/\sqrt{Q^2}$

the scale of the elementary interaction between e and quark

$$Q^2{}_{MAX} = s$$

At HERA: Ee=27.5 GeV, Ep=920 GeV

$$\sqrt{s} = 320\,\text{GeV}$$

$$Q^2{}_{MAX} \sim 10^5\,GeV^2$$

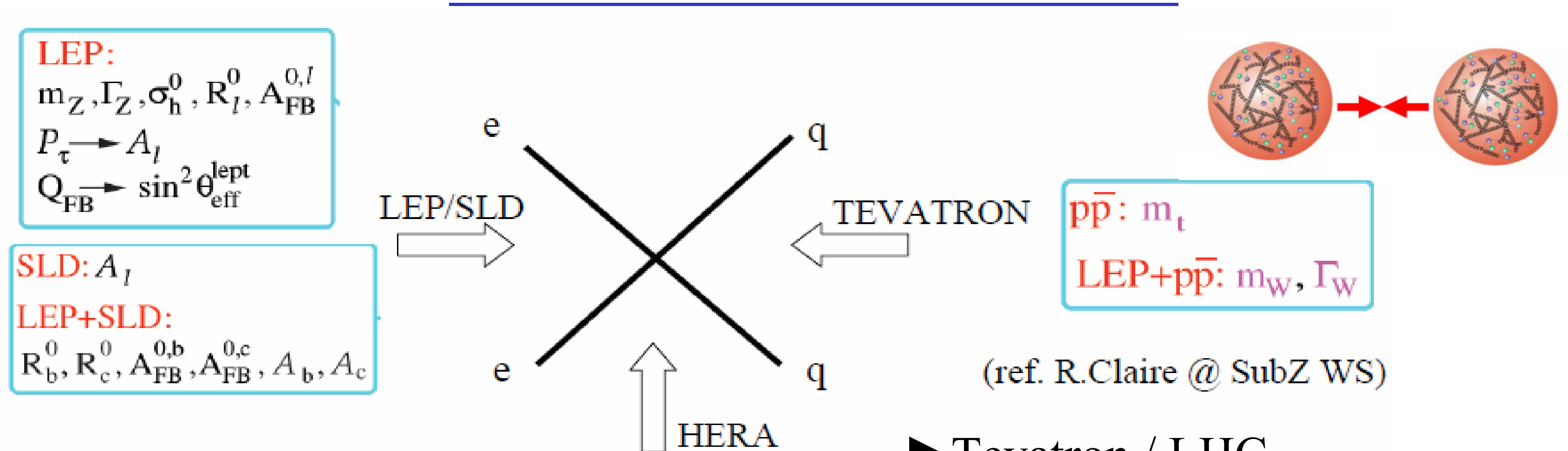
$$\lambda_{MAX} \sim 1/1000\,r_{proton}$$

(corresponds to ~50 TeV incident beam on fixed target)

ν -DIS: Weak @ $Q^2 \lesssim O(100)\ GeV^2$

HERA: Electro-Weak @ $Q^2 \approx$ EW scale

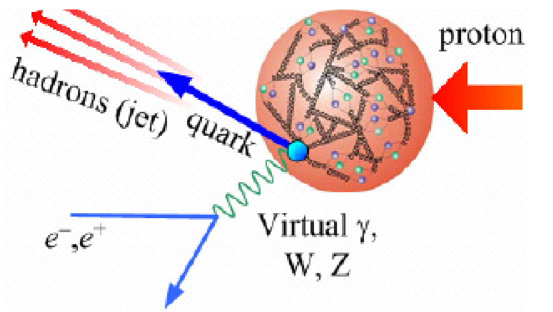
Colliders at EW scale



▶ Tevatron / LHC

- Search for new symmetries and particles.
- Proton structures are "necessary inputs"

▶ HERA

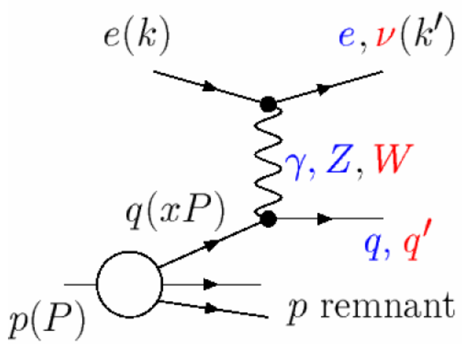


- Probe proton structure by t-channel exchange of gauge bosons
  - -- At low Q^2: mainly by γ
  - -- At high Q^2: γ/Z (NC) and W (CC)
- Investigate electron-quark elementary processes based on knowledge of proton structure (at low Q^2)

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

A "SM" study!

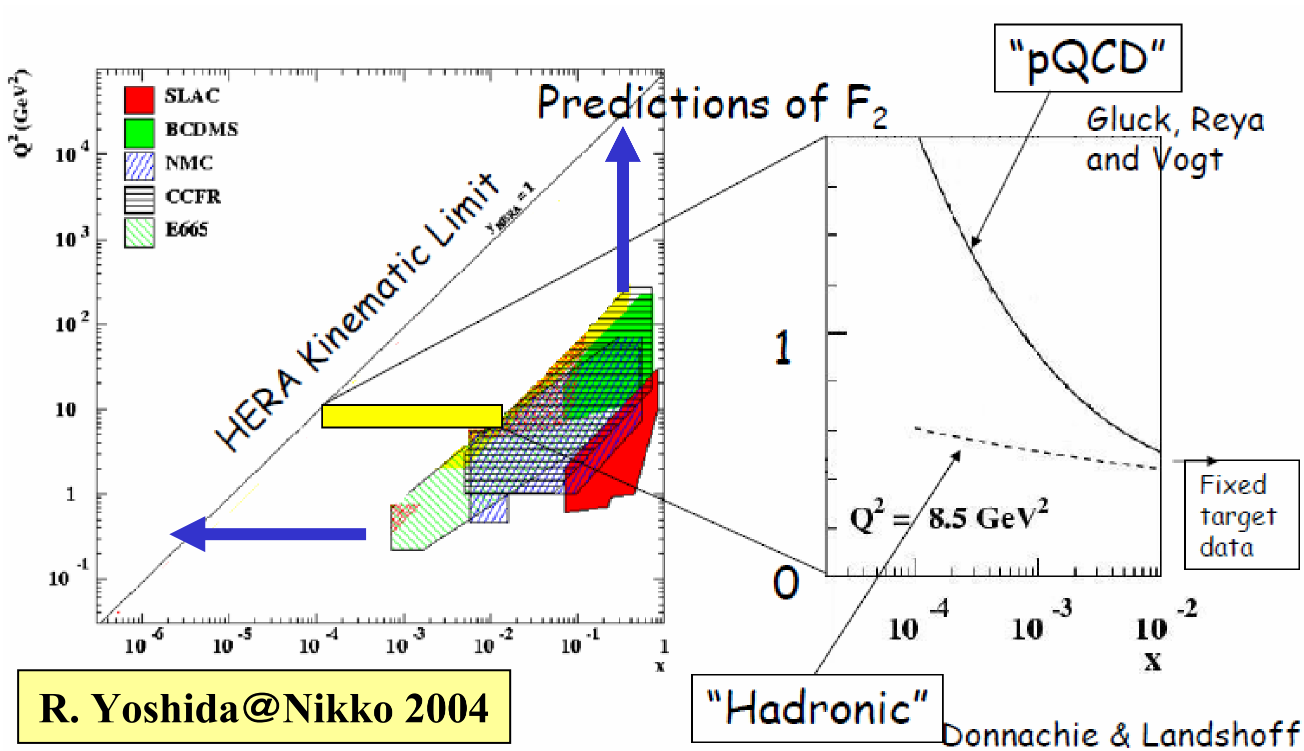
HERA Kinematics



① Q^2 two orders higher. Look for quark structure.

② Bjorken scaling variable x, two orders smaller.

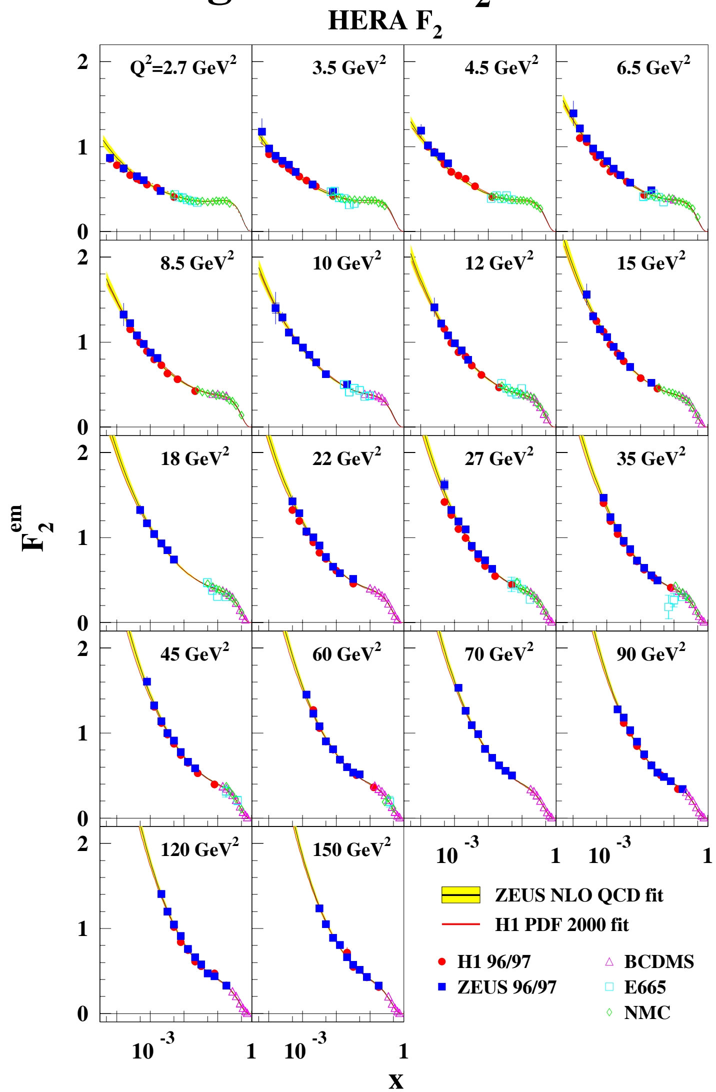
$$x = Q^2 / 2pq$$: Mom. Fraction of the struck quark

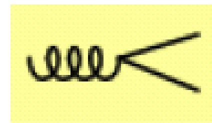


R. Yoshida@Nikko 2004

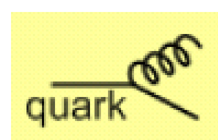
HERA legacy on proton structure

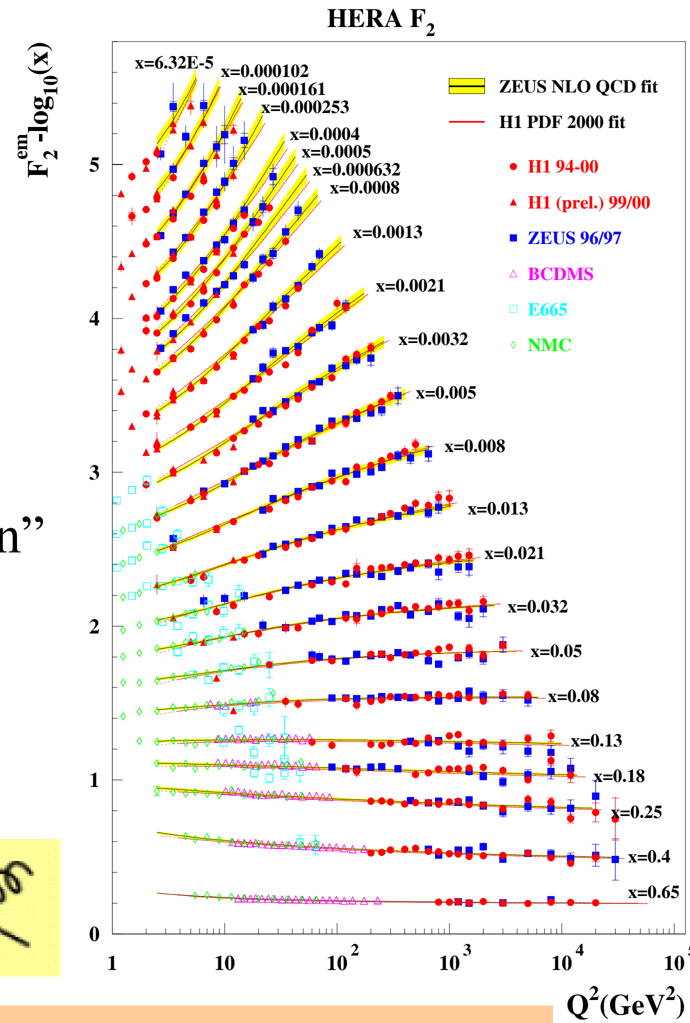
- "Strong Rise" of F_2 ➔ Proof of pQCD view !





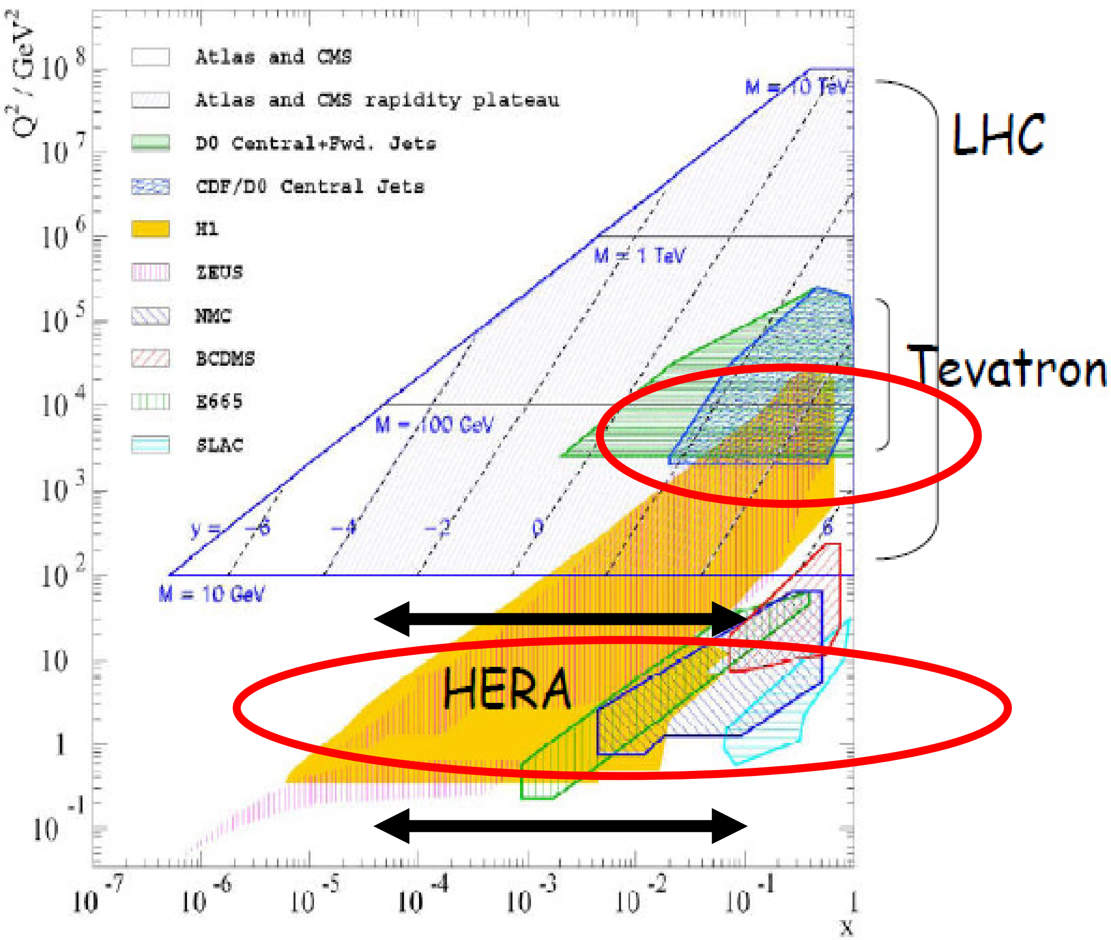
"Scaling violation" (Q^2 dependence) is also well described!





HERA showed the pQCD is valid down to $x>10^{-4}$ and Q^2 > a few GeV^2
➔ Ready to look at large Q^2 region

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

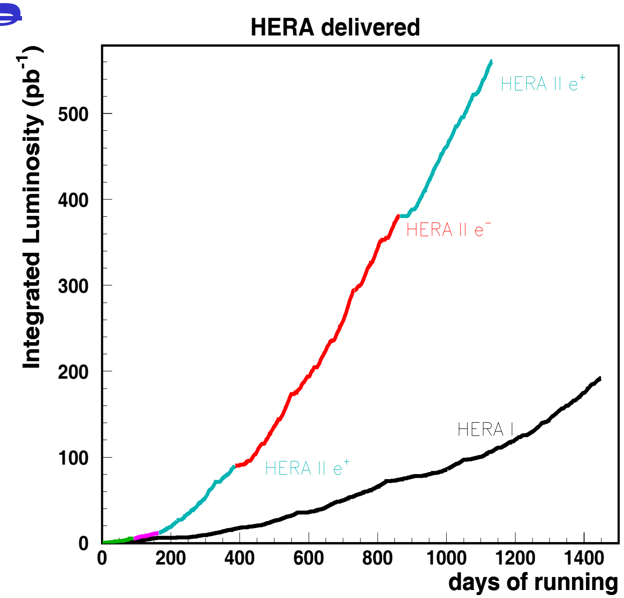
↑

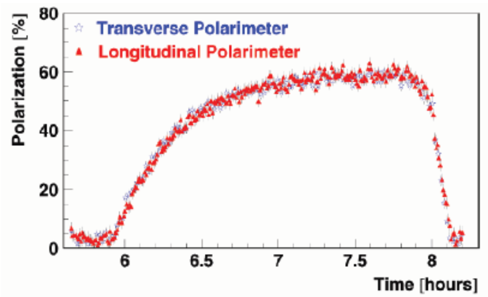
Low Q^2 region:
-- Precise measurement of proton structure

This is exactly what we're about to do: HERA→LHC
(Remind: gluons/sea at $x=10^{-4} \sim 10^{-2}$ are determined by HERA)

HERA Running

- ▶ HERA-I : Until year 2000
  - ● Unpolarized e^+ and e^- beams
- ▶ HERA-II : since year 2002 until Mar/2007
  - ● High luminosity to allow more statistical sensitivity for large Q^2
  - ● Longitudinally polarized e+ and e- beams to allow direct sensitivity to EW





– Transverse Pol due to Sokolov-Termnov effects
– Change transverse pol. to longitudinal pol.

	HERA-I	HERA-II
e^-	~20 pb^{-1}	~200 pb^{-1}
e^+	~100 pb^{-1}	~200 pb^{-1}

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

- ▶ Low Energy Run : Mar – **2/July/2007**
  - ● A special run with low proton beam energy (460 GeV) to measure "F_L" structure function

End of ~15 years of HERA project

The years 2007-2008 will be a turning point; HERA final results will be brought while LHC will be starting up

I. DIS @ EW scale

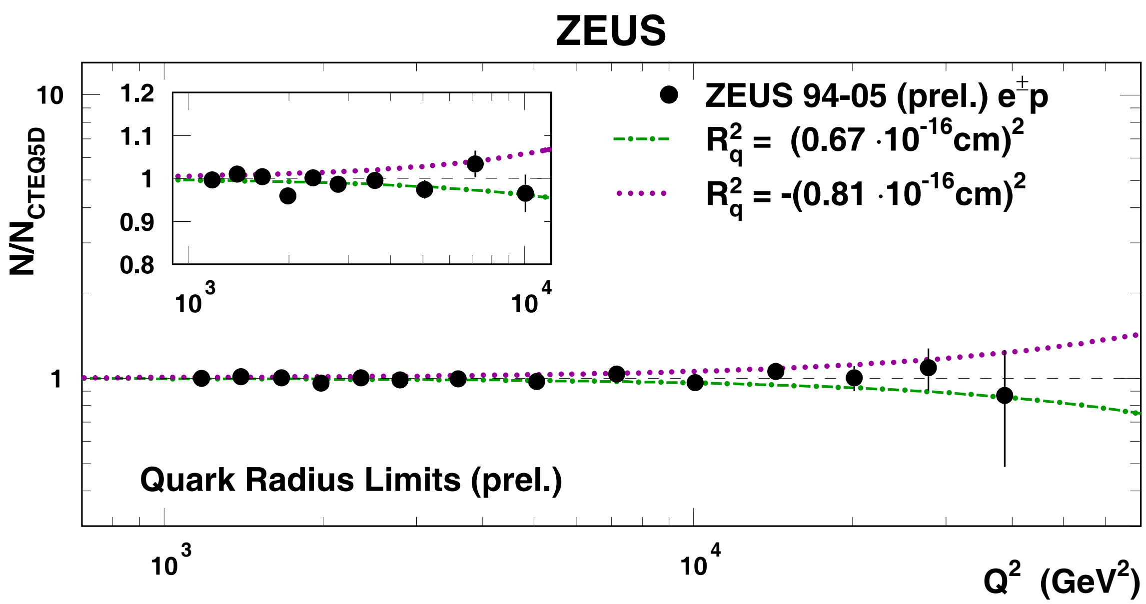
- Quark radius
- EW unification

Quark radius

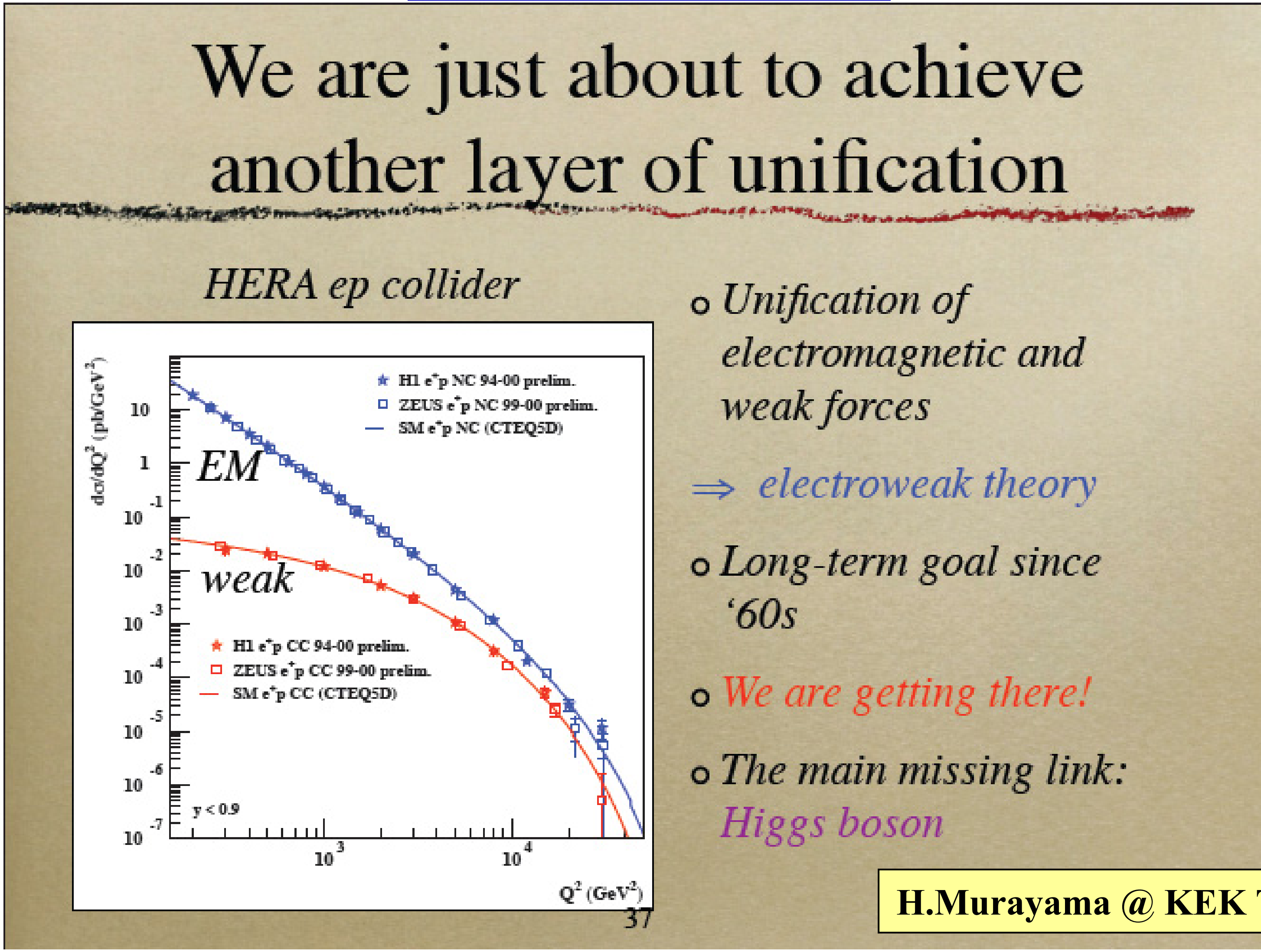
- Probing proton with highest spatial resolution
  - Quark radius： if there is structure in the quark, DIS cross section at high Q^2 will be modified due to spatial distribution of quark charge：

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

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



EW unification



H.Murayama @ KEK TC 2007

- NC and CC cross sections become similar at EW scale
  ➔ "EW unification" (Differences remained are mainly due to PDFs)

II. DIS @ EW scale with polarization

- First polarized DIS @ EW scale

  -- Right-handed CC

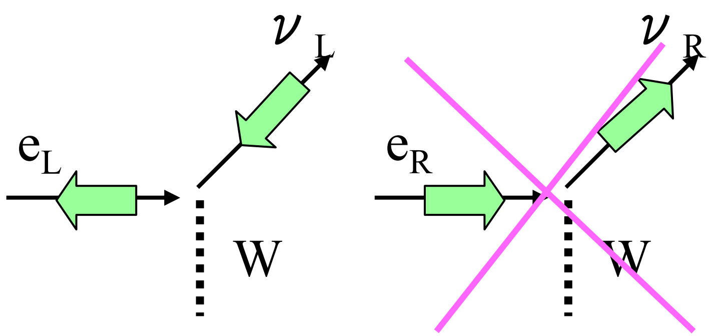
  -- Parity violation in weak NC

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^+)
  ➔ $\sigma(\text{Pol}) = (1 \pm \text{Pol})\ \sigma(\text{Unpol})$

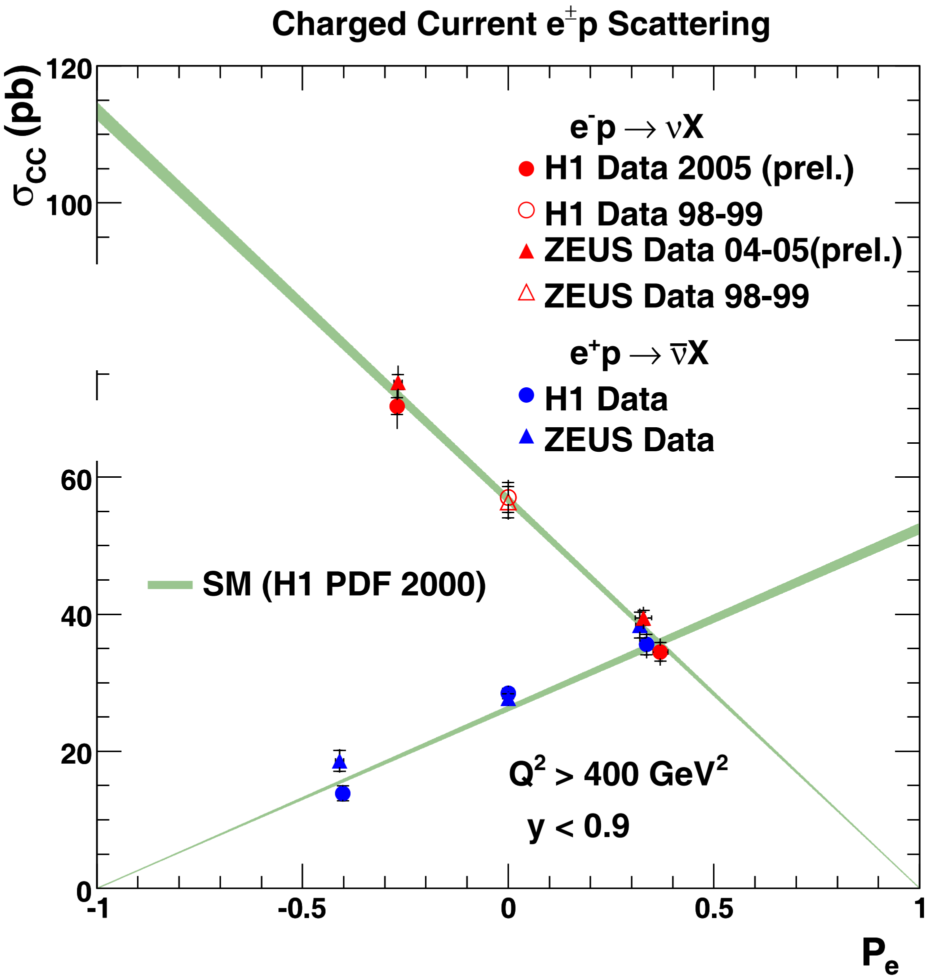


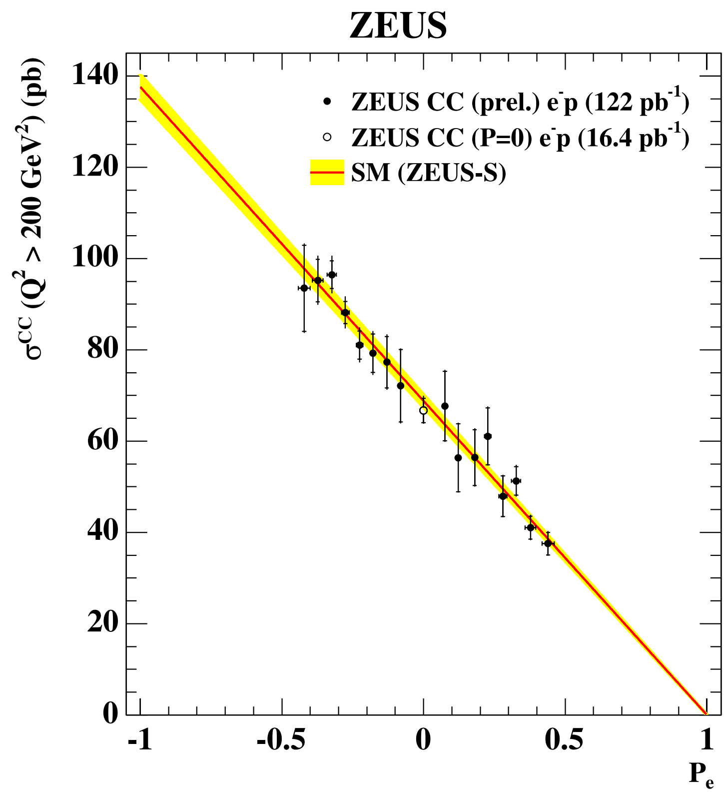
► Neutral-current DIS

- 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

CC cross section vs. polarization

HERA-II Data

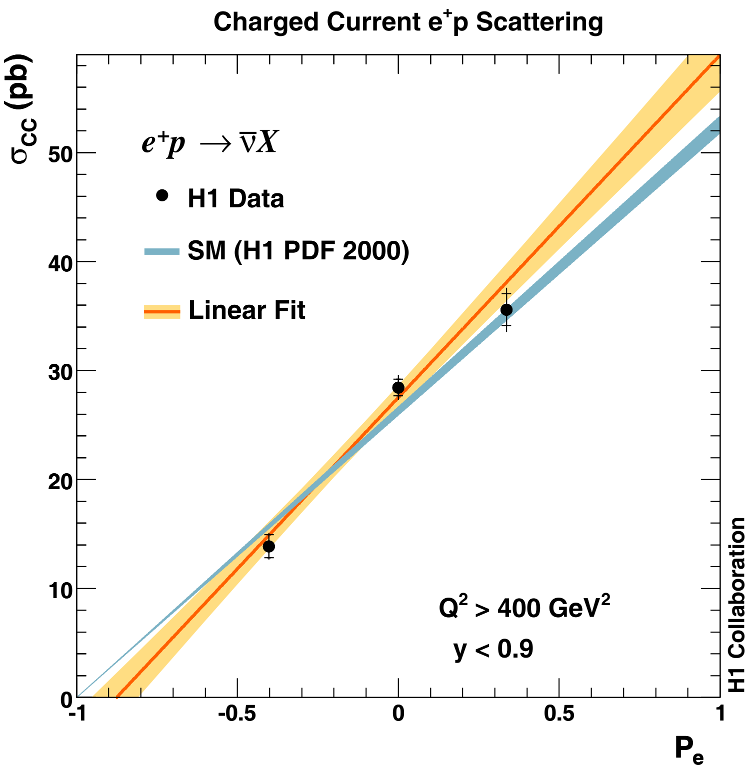


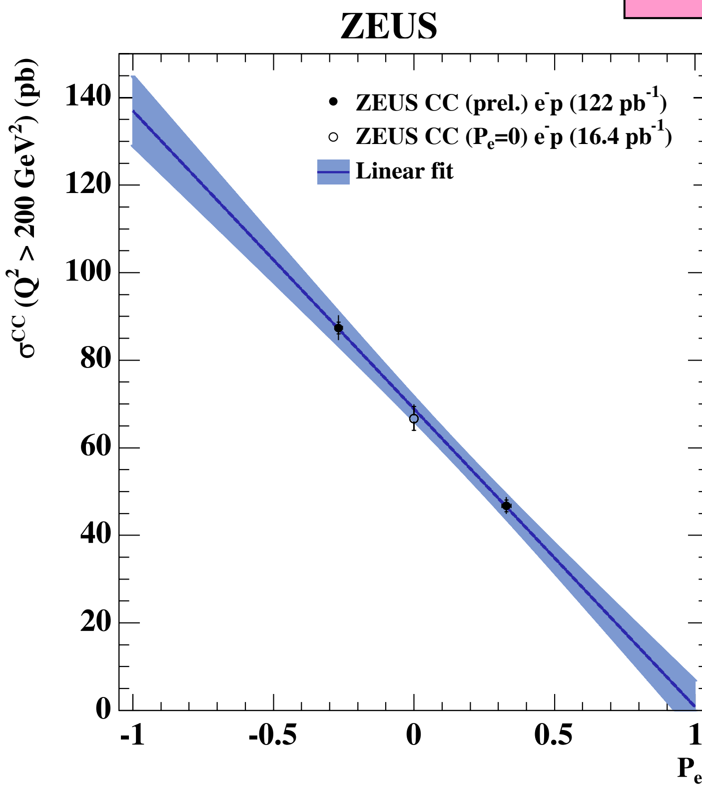


- Clear demonstration of linear dependence on pol. ((1-Pe)/2)
- Consistent with SM prediction of: σ (RH CC)=0
  (Error band from PDF uncertainty)
- Direct sensitivity to W_R → Next Slide

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)

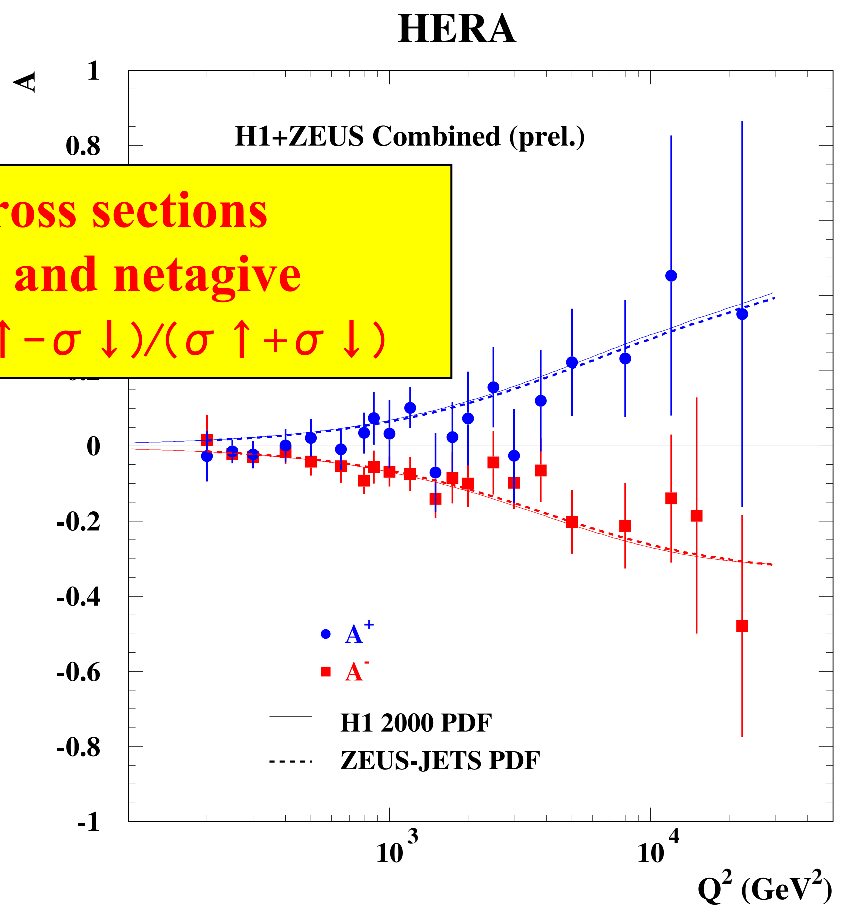
H1 e^-: 186 GeV
ZEUS e^-: 180 GeV

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

NC cross section vs. polarization

HERA-II Data

- $d\sigma / dQ^2$: Polarization effects as a function of Q^2



Asymmetry of cross sections between positive and netagive polarized: $A=(\sigma\uparrow - \sigma\downarrow)/(\sigma\uparrow + \sigma\downarrow)$

Positron

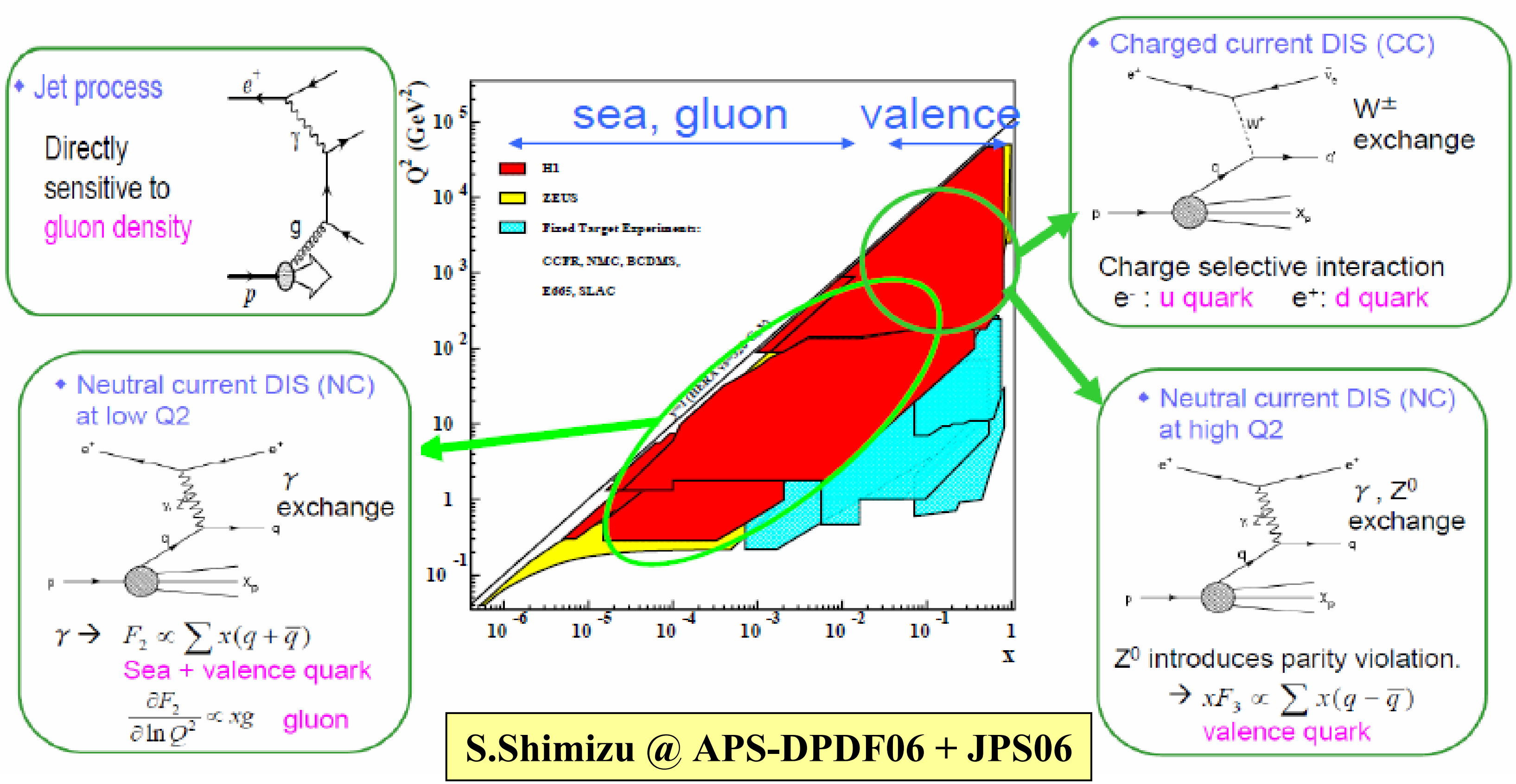
Electron

Parity violation of weak NC observed for the first time at EW scale

III. QCD+EW combined analysis

- Mw
- Light quark couplings to Z

EW+QCD fit



- 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

Determination of M_W

- **Determination in t-channel (propagator mass)**

► If we assume: G_F is $M_W=\infty$ at low energy

$$\sigma(\mathrm{CC\ @\ HERA}) \propto G_F^{\ 2} \left(\frac{M_W^{\ 2}}{M_W^{\ 2}+Q^2}\right)^2$$

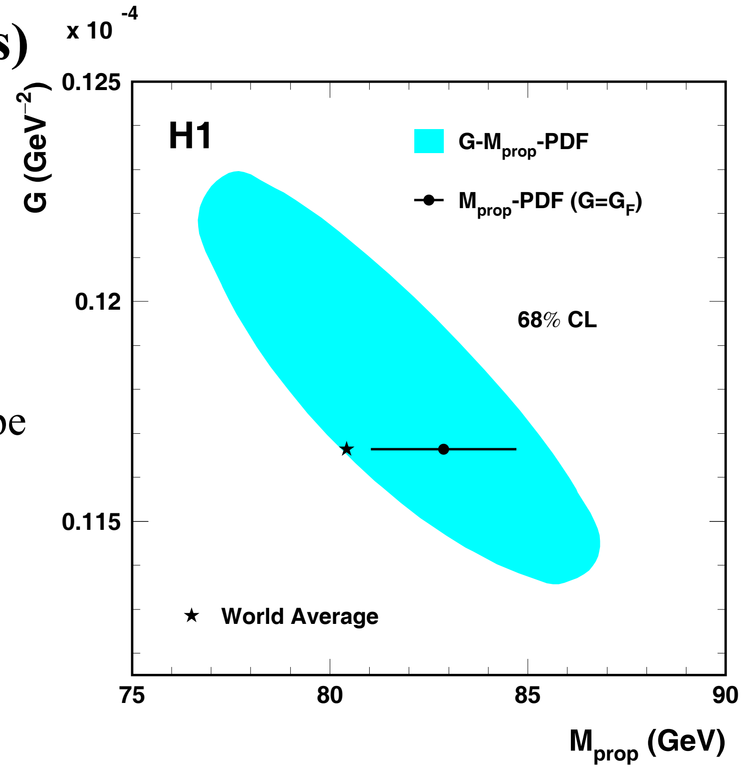
Nb. M_W contributes both normalization and shape

➔ G_F obtained agree with muon decay "CC universality"

➔ With fixed G_F @ muon decay:

$$\mathrm{H1}: M_W = 82.9 \pm 1.8(\mathrm{exp})^{+0.32}_{-0.18}(\mathrm{model})\ \mathrm{GeV}$$

$$\mathrm{ZEUS}: M_W = 79.1 \pm 0.8(stat+uncor.syst) \pm 1.0(cor.syst)\ \mathrm{GeV}$$



► Without assuming G_F: genuine propagator mass

$$\sigma(\mathrm{CC\ @\ HERA}) \propto g^2 \frac{1}{(M_W^{\ 2}+Q^2)^2}$$

$$\mathrm{ZEUS}: M_W = 82.8 \pm 1.5\,(stat+uncor.syst) \pm 1.3\,(cor.syst)\ \mathrm{GeV}$$

Complementary and consistent results to the M_W determined at s-channel LEP/TEV

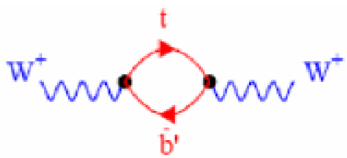
M_W in the framework of SM

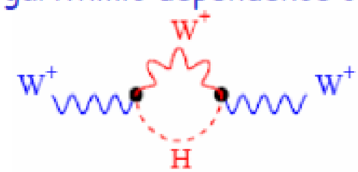
- In the SM G_F and M_W are related ➔ Fits fully assuming SM

  -- On-Mass-Shell (OMS) scheme

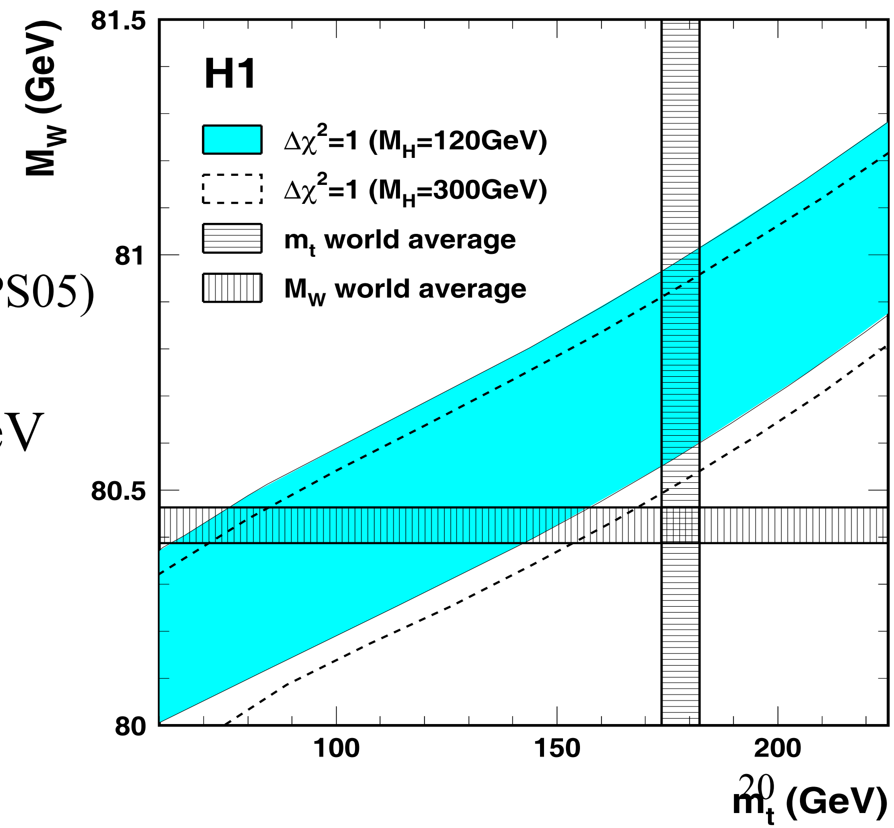
$$\frac{d^2\sigma}{dxdQ^2} = \frac{\pi\alpha^2}{4M_w^{\ 2}(1-\frac{M_W^{\ 2}}{M_Z^{\ 2}})^2}\frac{1}{(1-\Delta r)^2}(\frac{M_W^{\ 2}}{Q^2+M_W^{\ 2}})^2\Phi(pdfs)$$

Quadratic dependence on m_t Logarithmic dependence on M_H





(ref. Z.Zhang @ EPS05)



► A fit to M_W with M_Z fixed

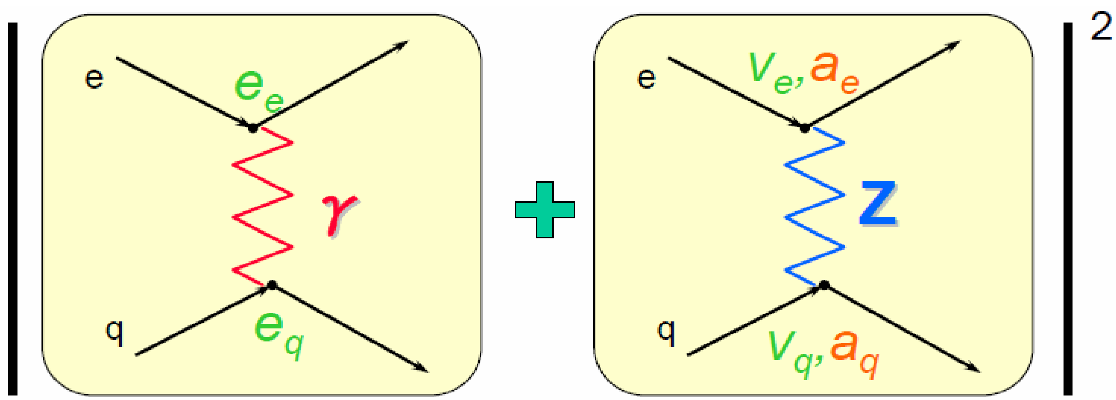
-- $M_W = 80.786 \pm 0.205(\mathrm{exp})$ GeV

► A fit to m_t with M_Z ,M_w fixed

-- $m_t = 104 \pm 44(\mathrm{exp})$ GeV

-- Determination of m_{Top} in DIS (via loop corr)

Light quark couplings to Z



$$\frac{d^2\sigma_{e^\pm p}}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[\{1+(1-y)^2\}F_2 \mp \{1-(1-y)^2\}xF_3\right]$$

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

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 : $\sigma(P_e \rightarrow) - \sigma(P_e \leftarrow) \rightarrow v_f$

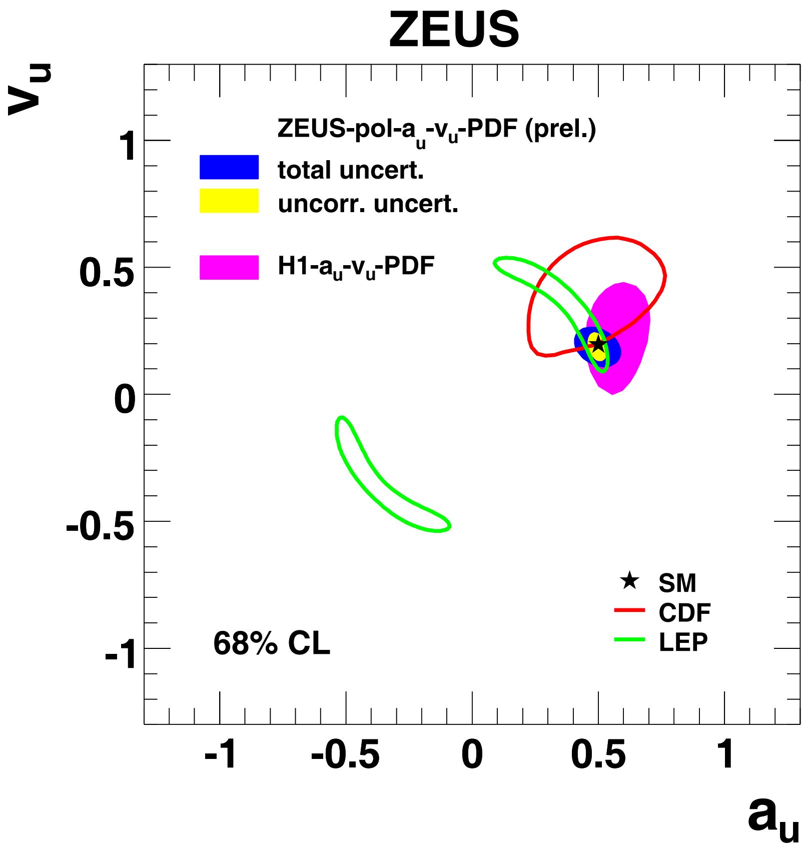
- **EW structure functions in QPM**

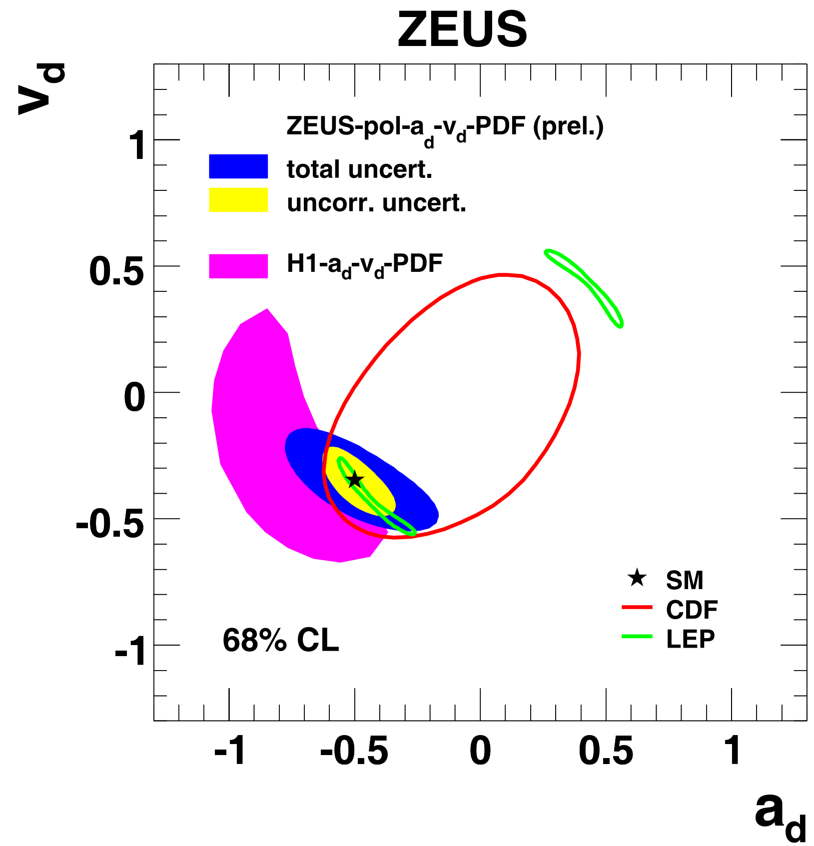
$$F_2^{\gamma Z} = 2 e_f v_f \Sigma_i x[q_f + \overline{q_f}]$$
$$F_2^{Z} = (v_f^2 + a_f^2)\Sigma_i x[q_f + \overline{q_f}]$$
$$F_3^{\gamma Z} = 2 e_f a_f \Sigma_i x[q_f - \overline{q_f}]$$
$$F_3^{Z} = 2 v_f a_f \Sigma_i x[q_f - \overline{q_f}]$$

V/A couplings extraction [constrained]

► A fit with V_u, A_u free to be determined in addition to PDFs

► A fit with V_d, A_d free to be determined in addition to PDFs

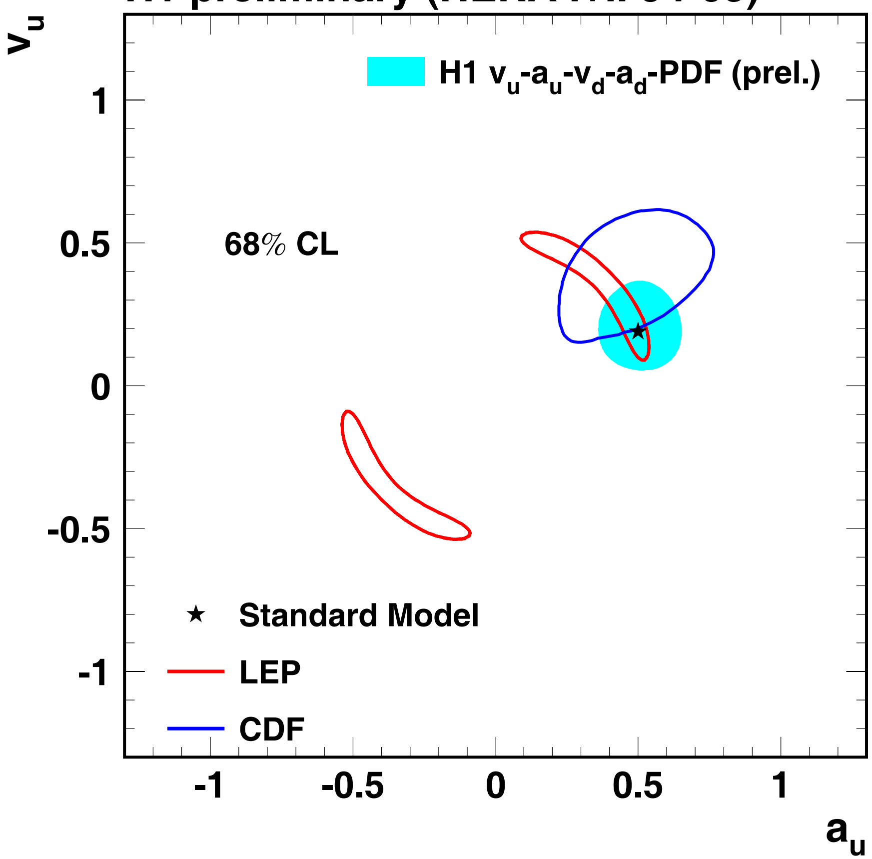




- High precision, competitive to other experiments
- Note: Pink contour is a fit using HERA-I → Cleary shows HERA-II sensitivity to vector couplings

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

Summary

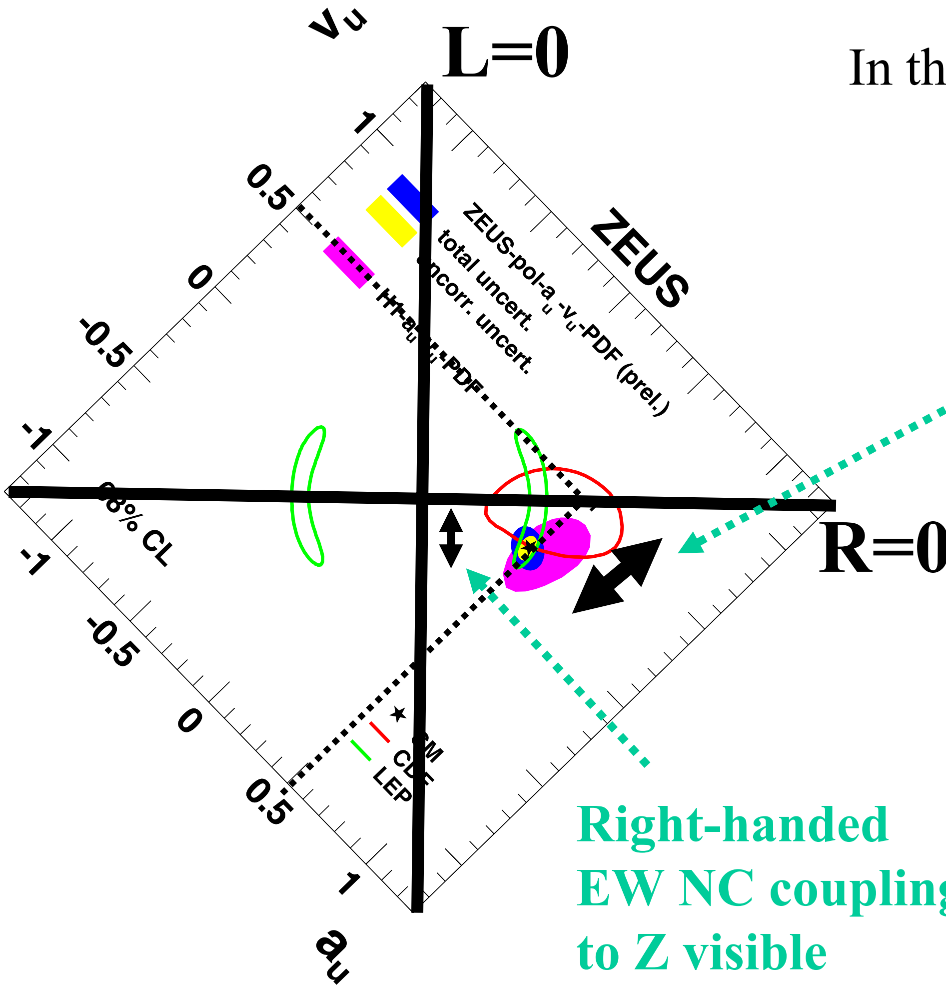
- HERA has provided most precise inclusive structure function measurements, which brought significant improvements to our knowledge on proton structure

- Based on this precise understanding of the proton structure, HERA is now able to investigate elementary interactions with high luminosity and longitudinal polarization provided since 2003
    - --- First polarized DIS @ EW scale
    - --- Direct sensitivity to right-handed CC
    - --- First observation of parity violation in weak NC @ EW scale
    - --- Best determination of light quarks NC couplings

- HERA ended its high energy run on 21/Mar/2007: 1 fb-1 by H1 and ZEUS
    - --- HERA legacy in EW sector will come soon.

Determination of SM EW parameters

- V_u, V_d, A_u, A_d : parameterization as less model dependence as possible



In the SM

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

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

$\sin^2\theta_W$ is visible

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

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

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

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

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

Right-handed EW NC coupling to Z visible (R=(V-A)/2)