Electroweak physics in ep scattering with polarised leptons

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On behalf of
the H1 and ZEUS collaborations

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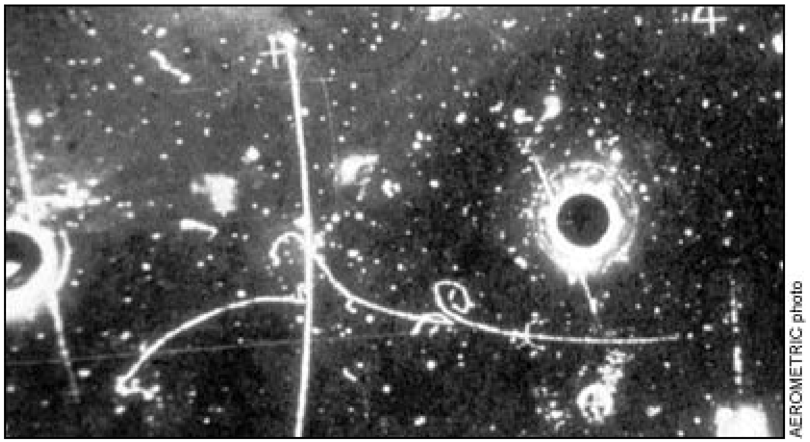
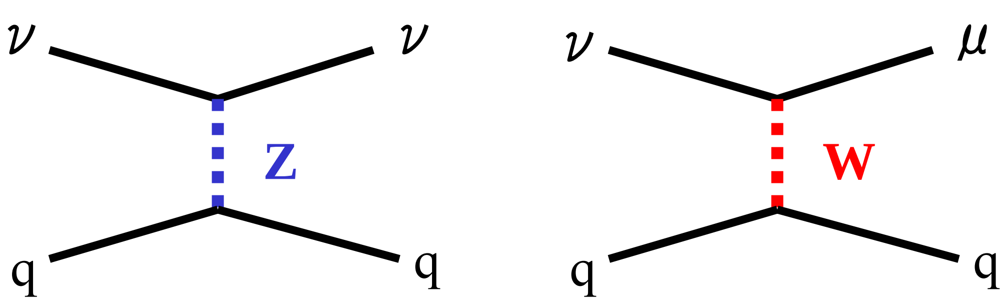
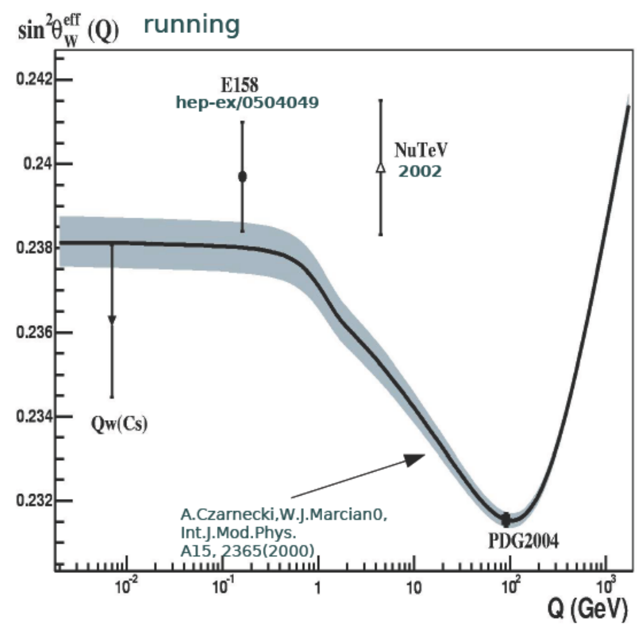
EW @ DIS ?

- Remember: Weak neutral current was “DIScovered” by the Gargamelle



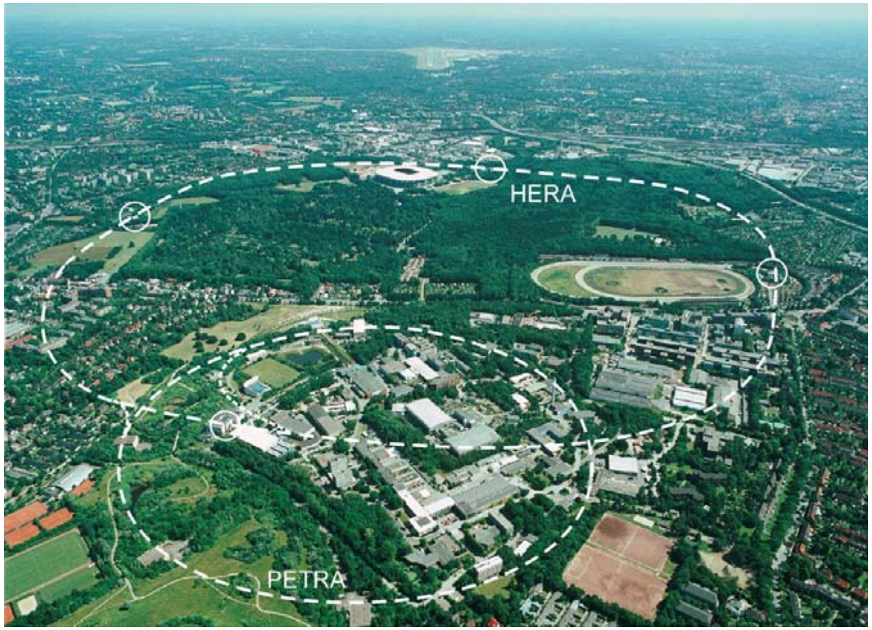
- ν -DIS has been a good test bench for the weak mixing angle, $\sin\theta_W$: nowadays as well “NuTeV anomaly”

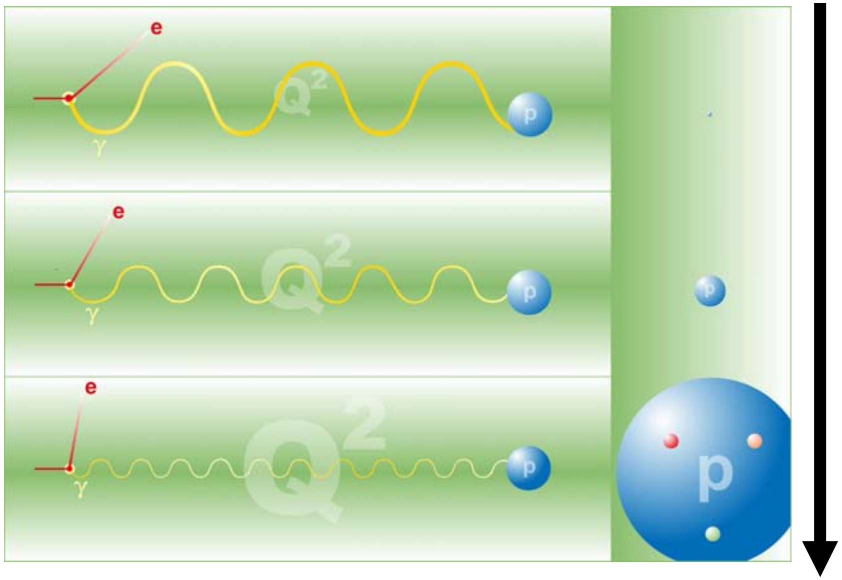




“Pure” weak int. @ $Q^2 \approx 0$
(Q^2 is momentum transfer squared)

HERA : world's the only ep collider





Q² large

Q² 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)

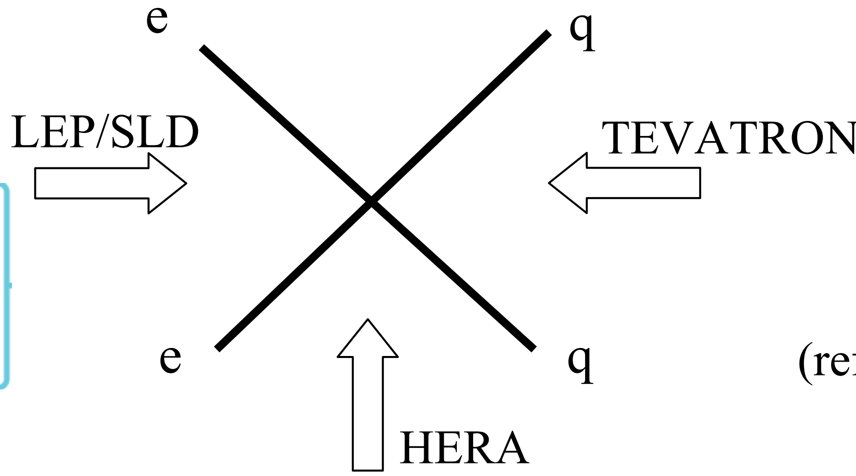
ν -DIS: Weak @ $Q^2 \approx 0$

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

Colliders at EW scale

LEP:
$m_Z, \Gamma_Z, \sigma_h^0, R_l^0, A_{FB}^{0,l}$
$P_\tau \longrightarrow A_l$
$Q_{FB} \longrightarrow \sin^2\theta_{eff}^{lept}$

SLD: A_l
LEP+SLD:
$R_b^0, R_c^0, A_{FB}^{0,b}, A_{FB}^{0,c}, A_b, A_c$



$p\bar{p}$: m_t
LEP+$p\bar{p}$: m_W, Γ_W

(ref. R.Claire @ SubZ WS)

▶ HERA

- t-channel exchange of gauge bosons
  - -- γ/Z interference in propagator
  - -- propagator masses
- Parton Distribution Functions (PDFs) are needed

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

A "SM test":
-- Test & measure proton structure (i.e. PDFs) at lower Q^2
-- Examine EW between e and q at EW scale, based on own knowledge of PDFs
-- Examination can be done for both NC and CC

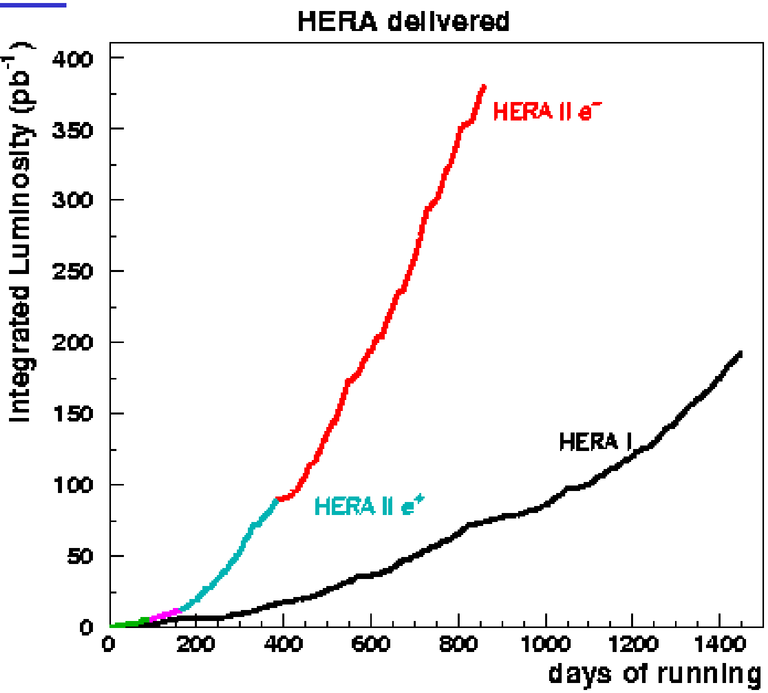
HERA Data

▶ HERA-I : ➔ Year 2000

- Unpolarized e+ and e- beams
- Structure function measurement at:
  $1.5 \le Q^2 \le 30000$ GeV^2, i.e.
  -- Starting from low Q^2
  -- Covering wide Q^2 range
- Initial EW result: "EW unification"

▶ HERA-II : Year 2002 ➔

- High luminosity to allow more statistical sensitivity for large Q^2
- Longitudinally polarized e+ and e- beams to allow direct sensitivity to EW



Contents of this talk are:

I. Proton structure

II. DIS @ EW scale (unpolarized)

III. DIS @ EW scale with polarization

IV. QCD+EW combined fit

giving both legacy and hot results of HERA !

	HERA-I	HERA-II
e-	~20 pb^{-1}	~120 pb^{-1}
e+	~100 pb^{-1}	~40 pb^{-1}

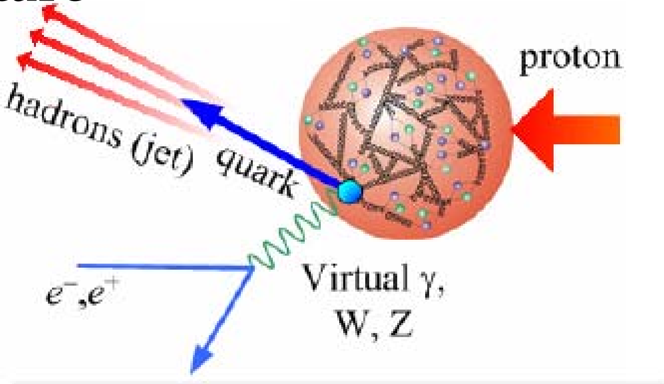
(Luminosity for data analyzed)

I. Proton structure

- SF measurement and PDF determination

Structure Functions (SFs)

- **DIS is a straightforward tool to probe p structure**



  - Virtuality: $Q^2 = -(k-k')^2$
    ➔ Spatial resolution of probe $\lambda \sim 1/\sqrt{Q^2}$
  - Bjorken scaling variable: $x = Q^2 / 2pq$
    ➔ Momentum fraction of struck parton
  - Inelasticity: $y = pk / pq$
    ➔ Energy transfer to proton (at p rest frame)

$$Q^2 = xys$$

- **Experiment measures Cross-sections: ➔ Structure Functions (SFs)**

$$\frac{d^2\sigma}{dxdQ^2} = \frac{2\pi\alpha^2}{Q^4} Y_+ F_2$$

If proton is point like → $\frac{d^2\sigma}{dxdQ^2} = \frac{2\pi\alpha^2}{Q^4} Y_+$

$$Y_+ = 1 + (1-y)^2$$

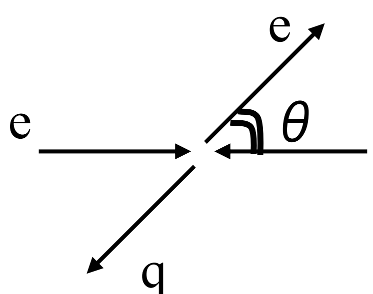
(The longitudinal SF, F_L, is neglected)

Measure in terms of:
- **Mom.frac. of q**
- **Spatial resolution**

SFs parameterize target structure, i.e how far from point-like

Quark-Parton Model (QPM)

- Kinematic is in y: y corresponds to scattering angle between e and quark



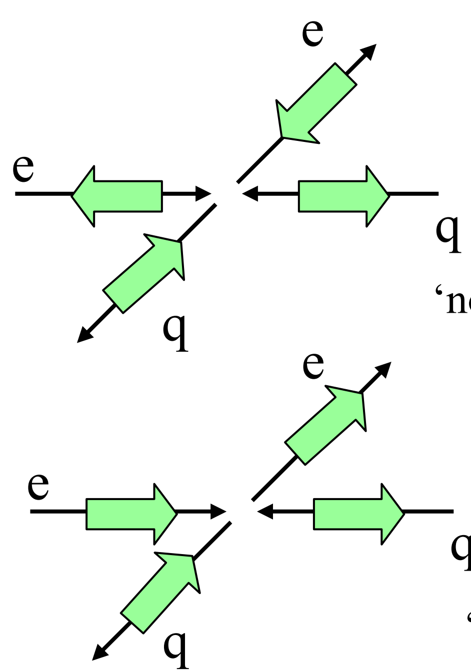
$$y = (1-\cos\theta)/2$$

$$\frac{d^2\sigma}{dxdQ^2} = \frac{2\pi\alpha^2}{Q^4} Y_+ F_2$$

V: $Y_+ = 1 + (1-y)^2$

A: $Y_- = 1 - (1-y)^2$

(at e-q c.m.s)



LL(RR)

$\sigma \propto 1$

'no helicity suppression'

LR

$\sigma \propto (1-y)^2$

'helicity suppressed'

► At low Q^2 where electro-magnetic dominates:

-- F_2 =Vector component only

-- All quarks contribute to F_2 according to their charges: $F_2 = x\Sigma e_q{}^2(q+\bar{q})$

SFs = (Charges)^2 × Parton Distribution Functions (PDFs)
Xsecs = Coupling × Propagator × Kinematic Factor × SFs

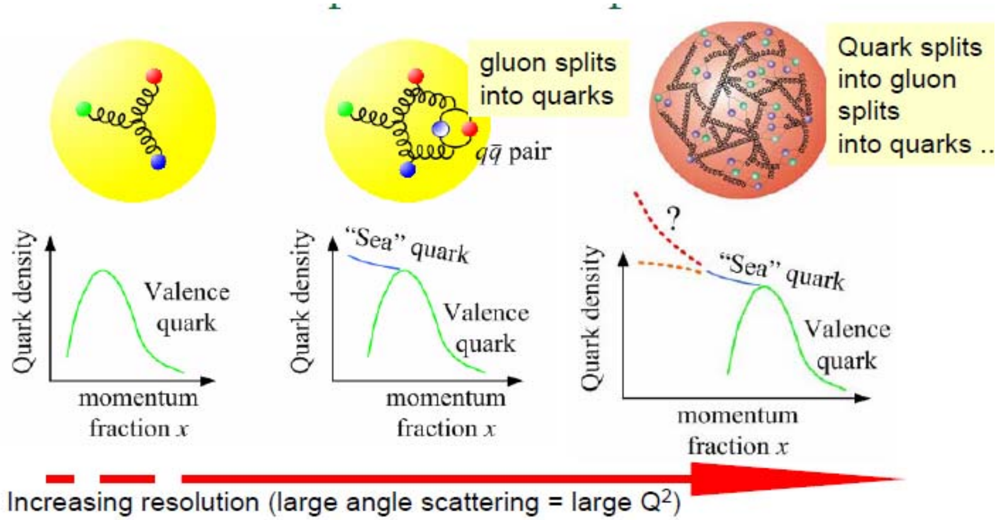
QCD evolution: gluon

► Beyond QPM

-- PDF is not that static
→ "evolution" as Q^2 grows.

-- Structure depends on the resolution to see it.

-- pQCD can describe this evolution: "DGLAP eq."



$$\frac{\partial}{\partial \ln Q^2}\begin{pmatrix}\Sigma \\ xg\end{pmatrix} = \alpha_s \begin{pmatrix} P_{qq} & P_{gq} \\ P_{gq} & P_{gg}\end{pmatrix} \otimes \begin{pmatrix}\Sigma \\ xg\end{pmatrix}$$

At low-x: $\frac{\partial F_2}{\partial \ln Q^2} \propto \alpha_s xg$

$$\frac{\partial}{\partial \ln Q^2} q_{NS} = \sigma_s P_{qq} \otimes q_{NS}$$

- F_2 is sum of q / qbar PDFs
  → Gluon not directly in F_2 (in LO)
- Gluon owes "slope" of F_2 in log Q^2 evolution

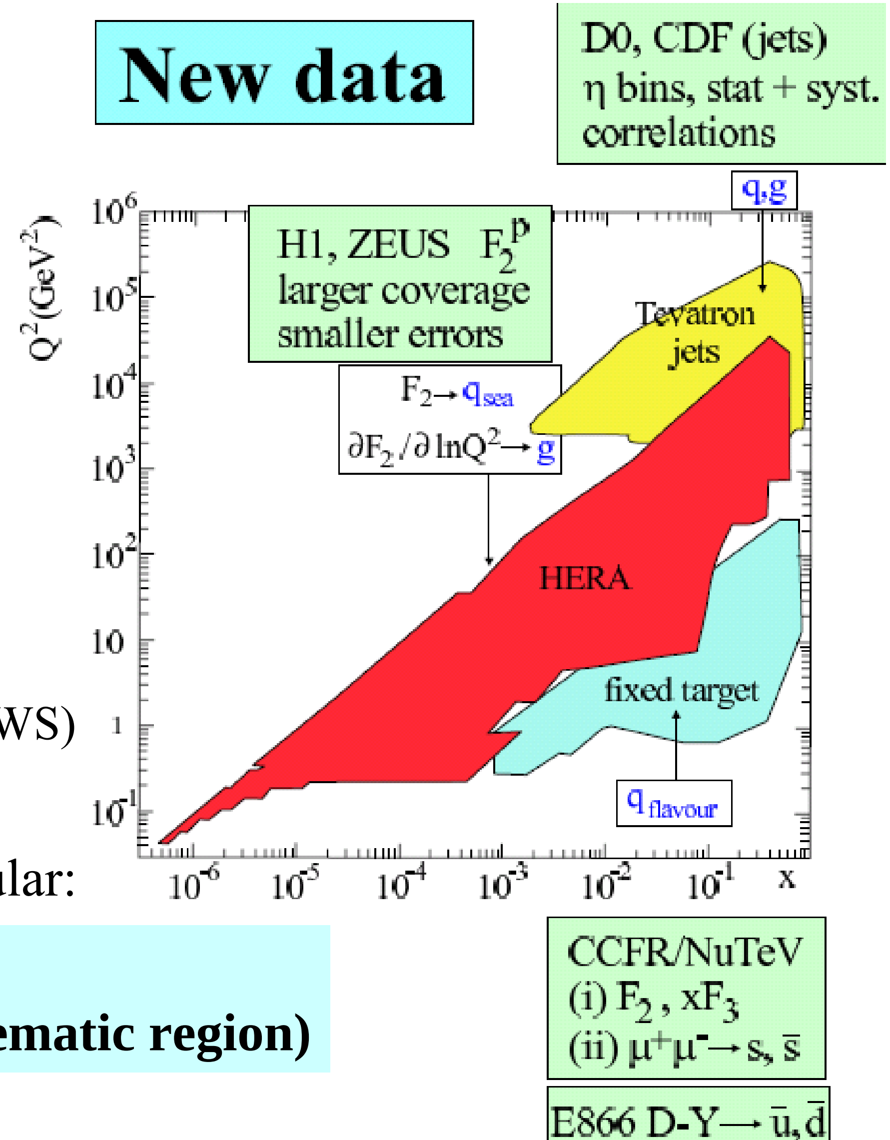
● However, pQCD cannot predict x-dependence of PDFs a priori
➔ PDFs are determined by a global fitting to experimental data (next slide)

Determination of PDFs

● Initial PDFs (x-dependence) at Q^2_0 are determined by a global fit to various experimental data.

※ PDF are not observable (but F_2 are)
→ Universality should be checked in various processes

(ref. A.Martin @ DIS WS)

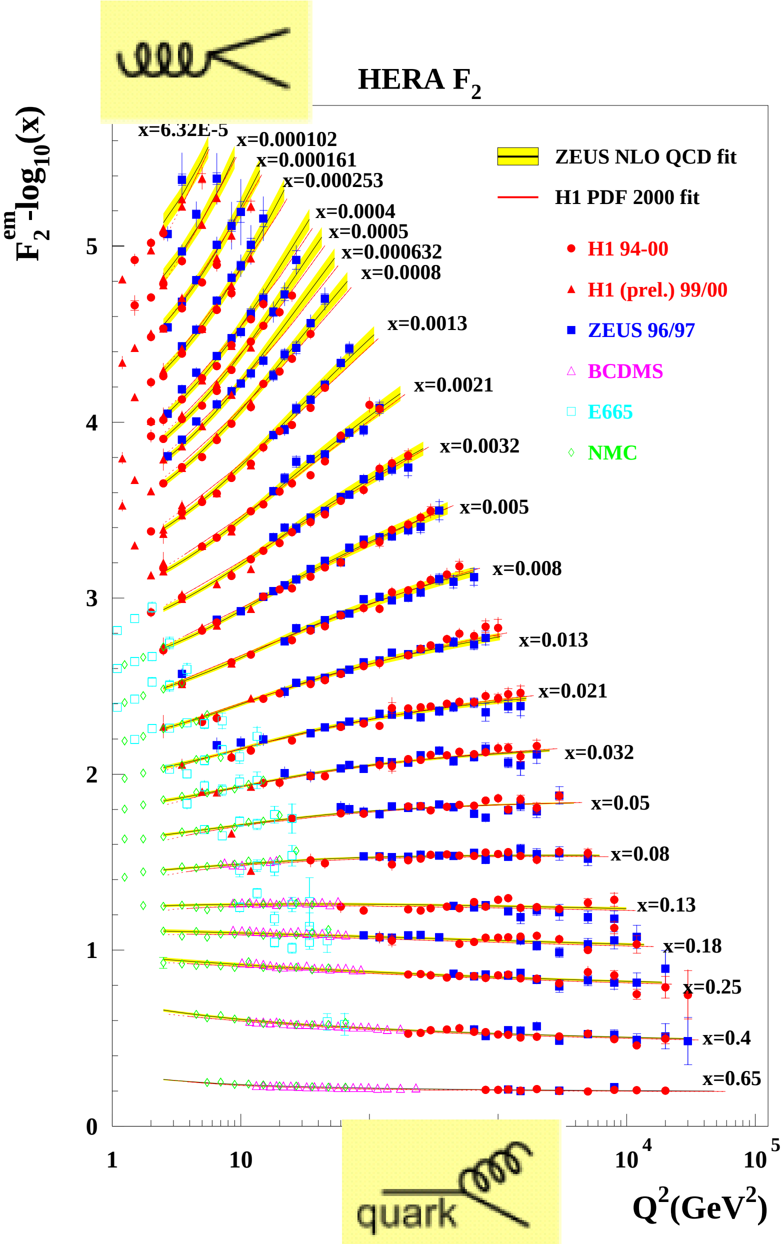


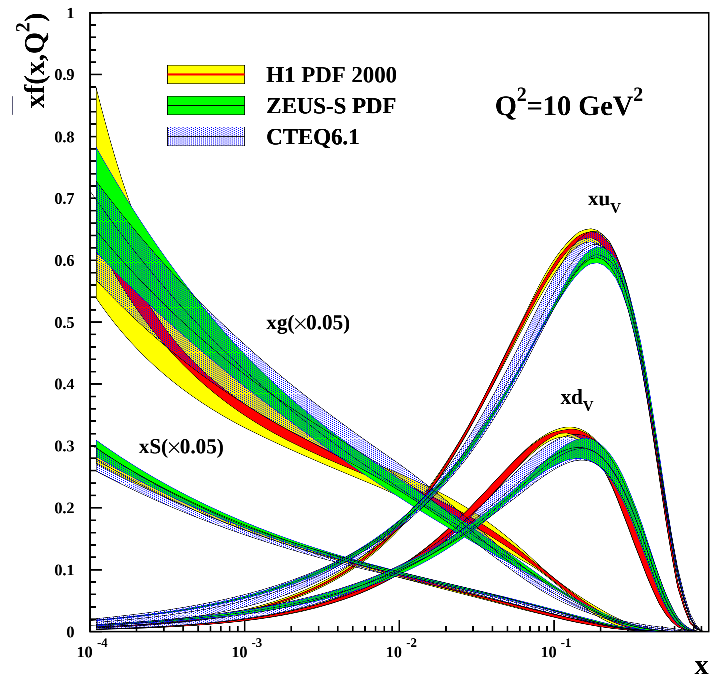
► HERA plays significant role, in particular:
-- Gluon
-- Sea quarks

At $x=10^{-4}$ to 10^{-1}
(LHC main kinematic region)

HERA Legacy

HERA-I Data





- NLO pQCD describes F_2 over:
  - -- 4 orders in Q^2
  - -- 3 orders in x
- Scaling violation excellently described
  ➔ DIS-invisible gluon could be determined so precisely from this scaling violations:

PDF has been determined precisely. ➔ Ready to look EW @ high Q^2

II. DIS @ EW scale

- NC and CC cross sections at high Q^2
- EW unification

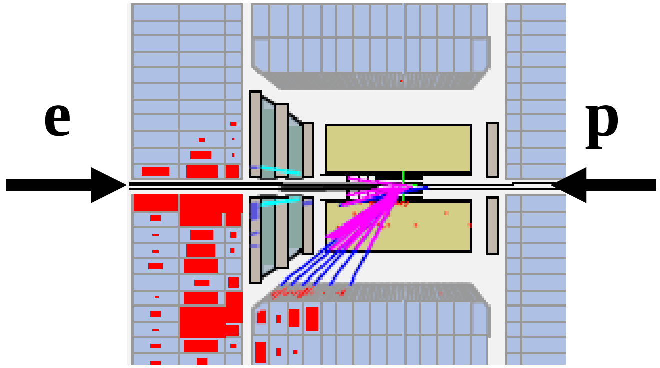
DIS at high Q^2 [CC]

- CC ep → ν X: Pure Weak (only L) also happens

$$\frac{d^2\sigma(e^+p)}{dxdQ^2} = \frac{G_F^{\,2}}{2\pi}\left(\frac{M_W^{\,2}}{M_W^{\,2}+Q^2}\right)^2 \{(\bar{u}+\bar{c})+(1-y)^2(d+s)\}$$

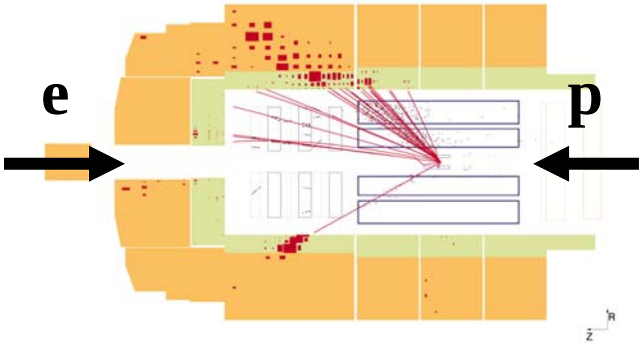
$$\frac{d^2\sigma(e^-p)}{dxdQ^2} = \frac{G_F^{\,2}}{2\pi}\left(\frac{M_W^{\,2}}{M_W^{\,2}+Q^2}\right)^2 \{(u+c)+(1-y)^2(\bar{d}+\bar{s})\}$$

e-p:
-- charge selecting nature: only up-type q (downtype anti-q)
-- anti-q receives $(1\text{-}y)^2$ helicity suppression



- Selection: presence of large missing transverse energy: Pt,miss
- Kinematics reconstructed using hadrons (only possibility)

… while NC event looks like:



- Selection: presence of high p_T scattered electron, scattered at large angle
- Kinematics well reconstructed using either electrons or hadrons (or both)

DIS at high Q^2 [NC]

- NC ep → eX: Z effects at high Q^2
  - -- F_2 receives additional terms
  - -- "Axial" SF, F_3, comes into

$$\frac{d^2\sigma(e^\pm P)}{dxdQ^2} = \frac{2\pi\alpha^2}{Q^4}\{Y_+\tilde{F}_2 \mp Y_- x\tilde{F}_3\}$$

For axial: sign flips between particles and anti-particles

-- Sign flips between e+/e-

-- q/qbar contributes to xF_3 with different sign

→ xF_3 is proportional to valence q

Nb.: xF_3 is written as F_3 in the equations below for simplicity

$$\tilde{F}_2 = \Sigma A_q x(q+\overline{q}) = F_2^\gamma - v_e\chi_Z F_2^{\gamma Z} + (v_e^2+a_e^2)\chi_Z^2 F_2^Z$$
$$\tilde{F}_3 = \Sigma B_q x(q-\overline{q}) = - a_e\chi_Z F_3^{\gamma Z} + 2v_e a_e\chi_Z^2 F_3^Z$$

1st-order V, 1st-order A: γ-Z interference

2nd-order V, 2nd-order A: Pure Z

$$\chi_Z = \frac{1}{\sin^2 2\theta_w}\frac{Q^2}{M_Z{}^2+Q^2}$$

: Propagator term

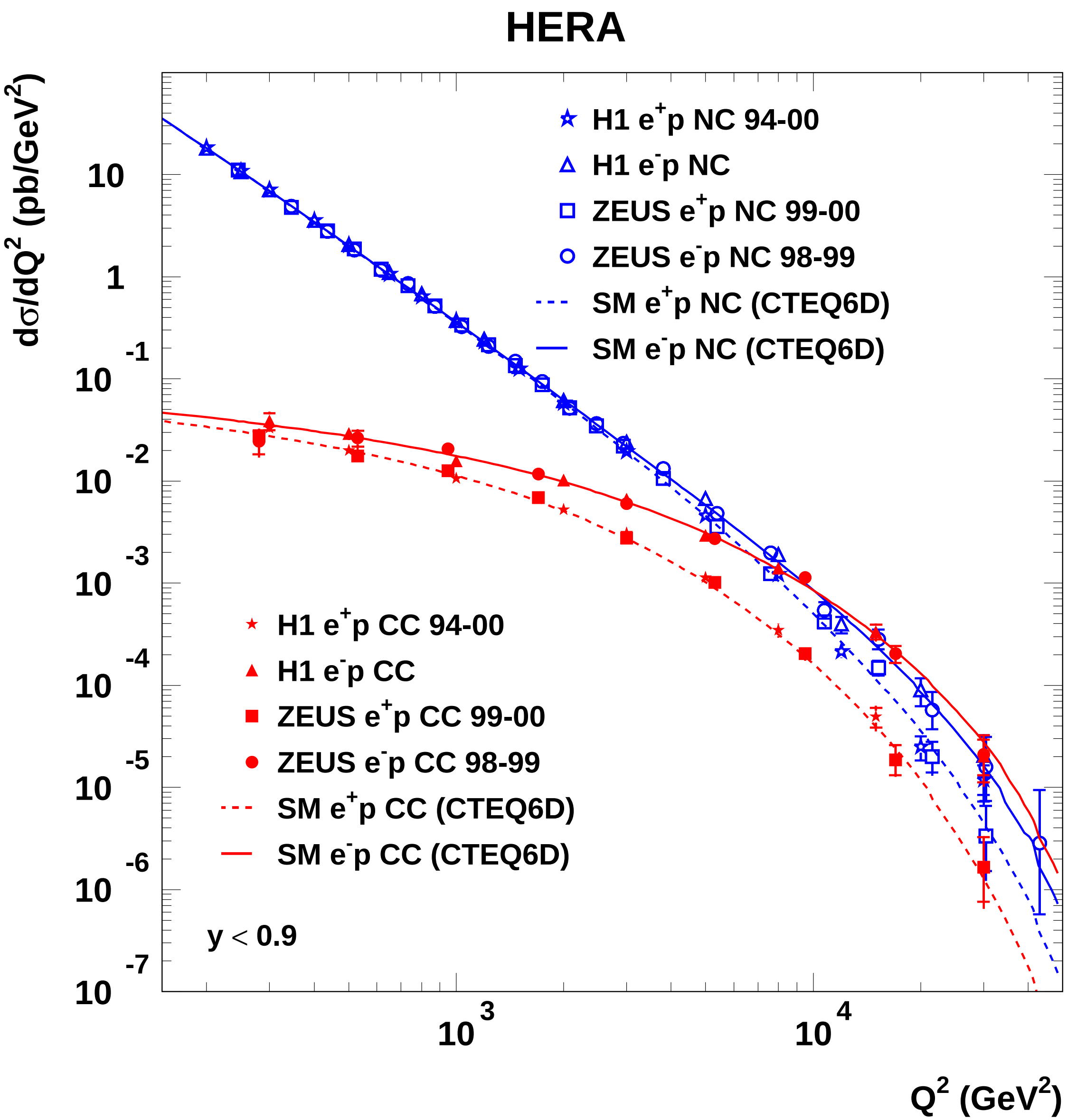
▶ $v_e \approx 0$

-- F_2 : 2nd order only, ~ $a_e{}^2\chi_z{}^2 F_2{}^Z$

-- F_3 : 1st order (= γ/Z i/f) ~ $a_e\chi_Z F_3{}^{\gamma Z}$

EW unification

HERA-I Data



- Axial component (xF_3) can be seen as a difference between e+ and e- NC

- NC and CC cross sections become similar at EW scale

➔ "EW unification"

(Differences remained are mainly due to PDFs)

III. DIS @ EW scale with polarization

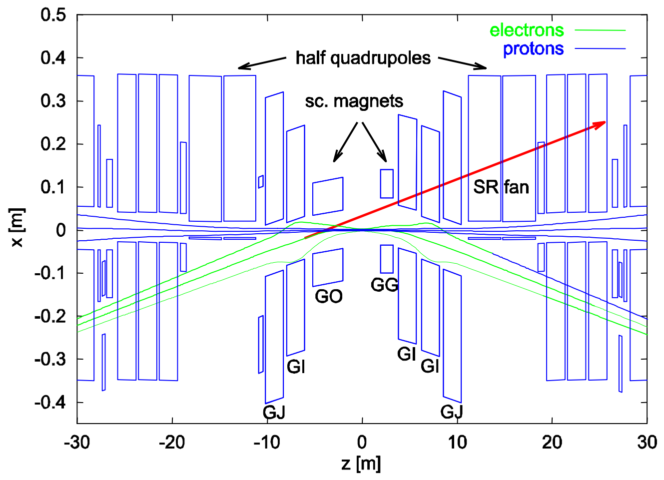
- Polarization at HERA
- First polarized DIS @ EW scale

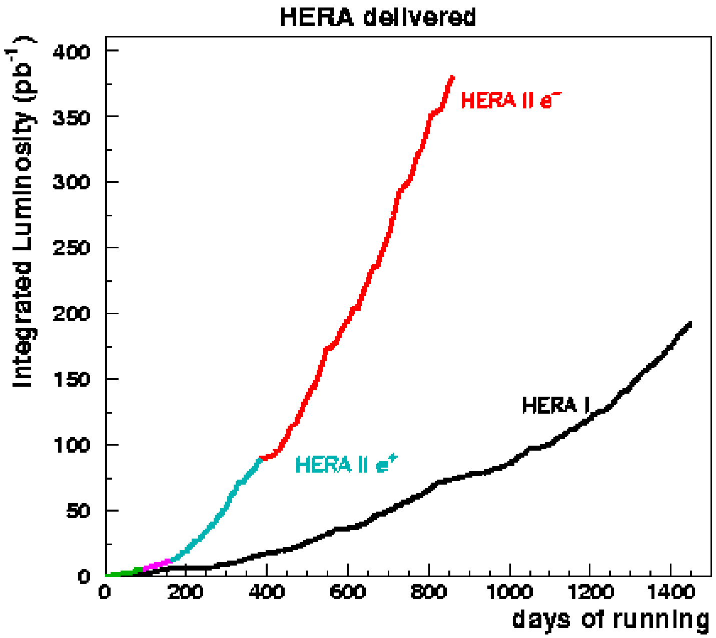
  -- Right-handed CC

  -- Parity violation in weak NC

HERA-II upgrade

- **Luminosity Upgrade : → Large luminosity is needed to look high Q^2**





-- Final focusing magnets ("mini-beta") closer to the detector to achieve high luminosity

-- Synchrotron backgrounds initially suffered at begin. of HERA-II has solved

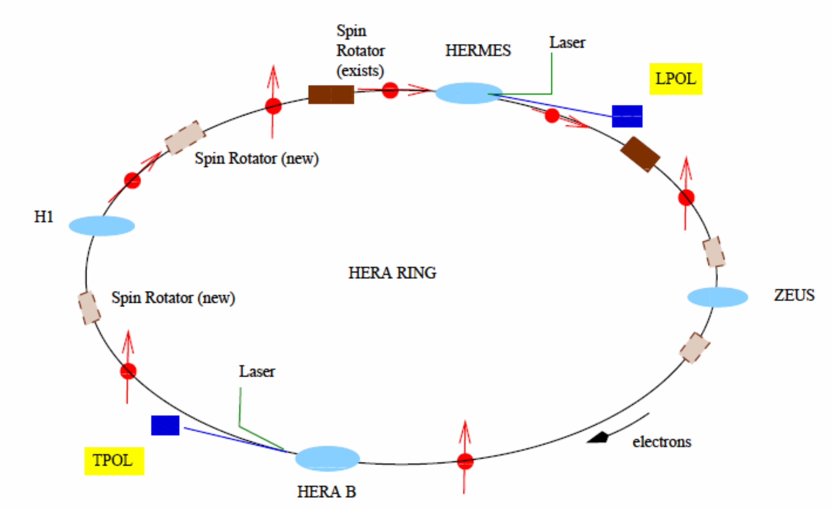
-- N.b Vacuum improvement in year 1998 enables efficient e- running

(Very short e- lifetime was the reason of small luminosity in HERA-I e- data)

- A clear improvement of performance ("slope" improves)
- HERA-II luminosity already exceeds HERA-I's

Polarization at HERA-II

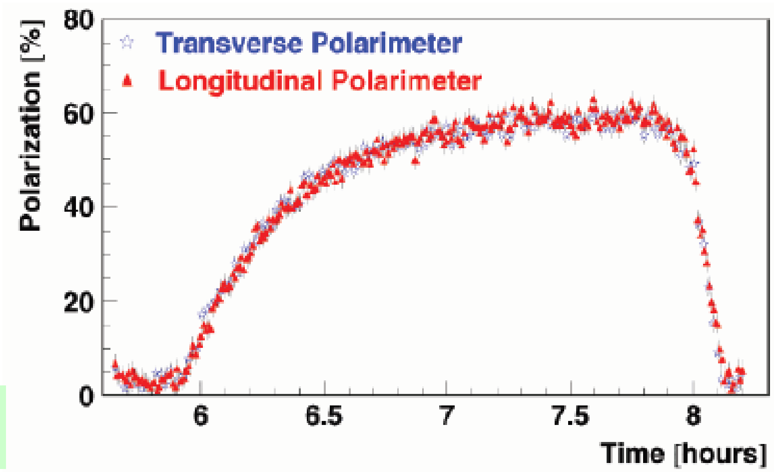
- **Longitudinal polarization of lepton beam : → Direct EW sensitivity**



Pe varies run by run.(30-50 %)

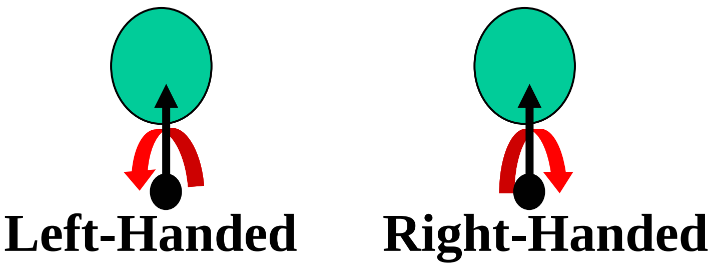
- ☐ Sokolov-Ternov effect
  - → Lepton beam has transverse polarization
  - → Rise Time @ HERA ~ 40 min.
- ☐ Spin rotator before/after the H1/ZEUS to flip T → L polarization (and vice-versa back)
- ☐ Two + one (new) independent Laser Compton Polarimeters

	HERA-I	HERA-II
e-	~20 pb^{-1}	e^- R : ~ 40 pb^{-1} @ Pe=~ +37% e^- L : ~ 80 pb^{-1} @ Pe=~ -27%
e+	~100 pb^{-1}	e^+ R: ~ 20 pb^{-1} @ Pe=~ +34 % e^+ L: ~ 20 pb^{-1} @ Pe=~ -40 %



The first time of polarized DIS @ EW scale

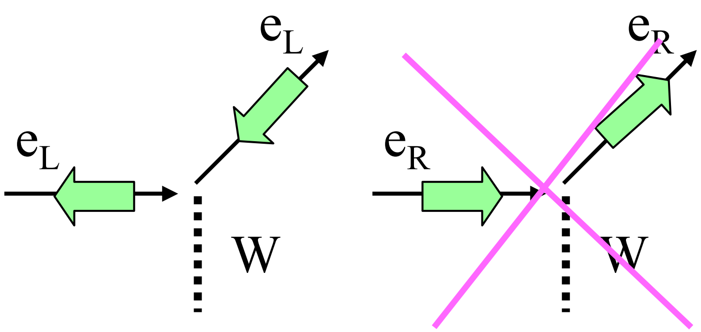
EW physics with polarized lepton beams



- 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.
- RH != LH is: parity violation

▶ 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+)
  ➔ σ(Pol) = (1+Pol) σ(Unpol)



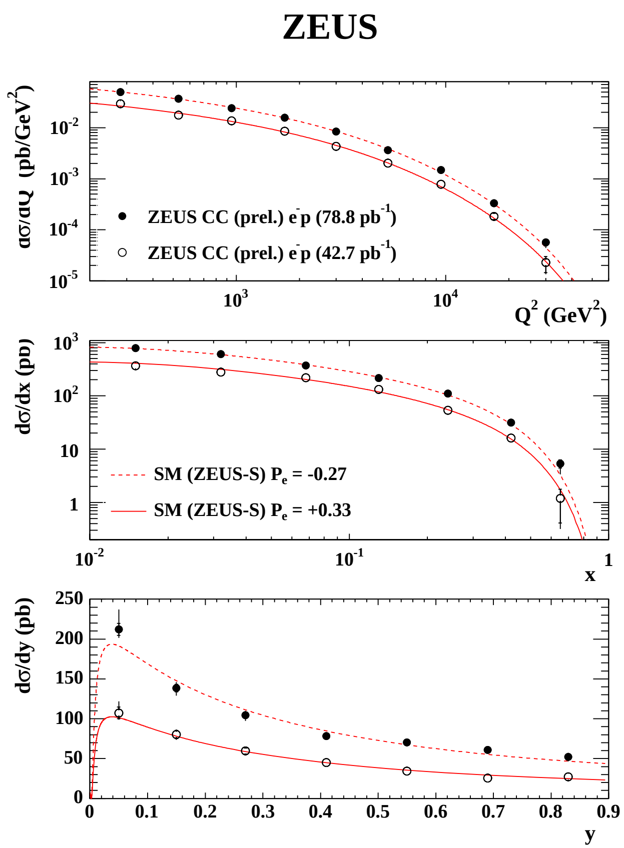
▶ Neutral-current DIS

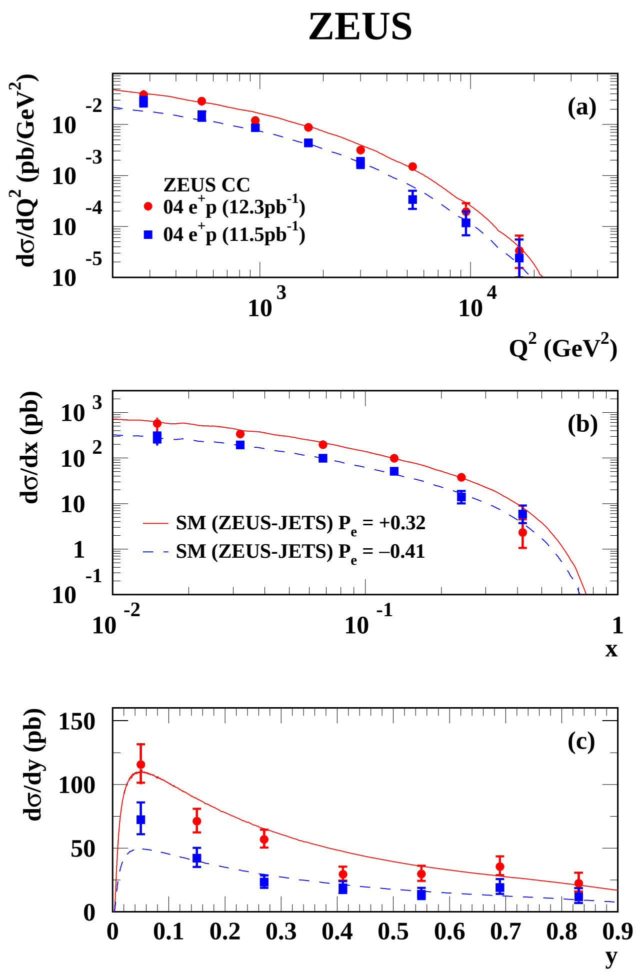
- Weak's parity violating effect through γ-Z interference and pure Z
  → visible only at large Q^2
- Such γ-Z and Z terms contain EW parameters,
  i.e. quark couplings to Z, $\sin\theta_W$, M_Z

CC single-differential cross-sections

HERA-II Data

► dσ/dx, dσ/dy

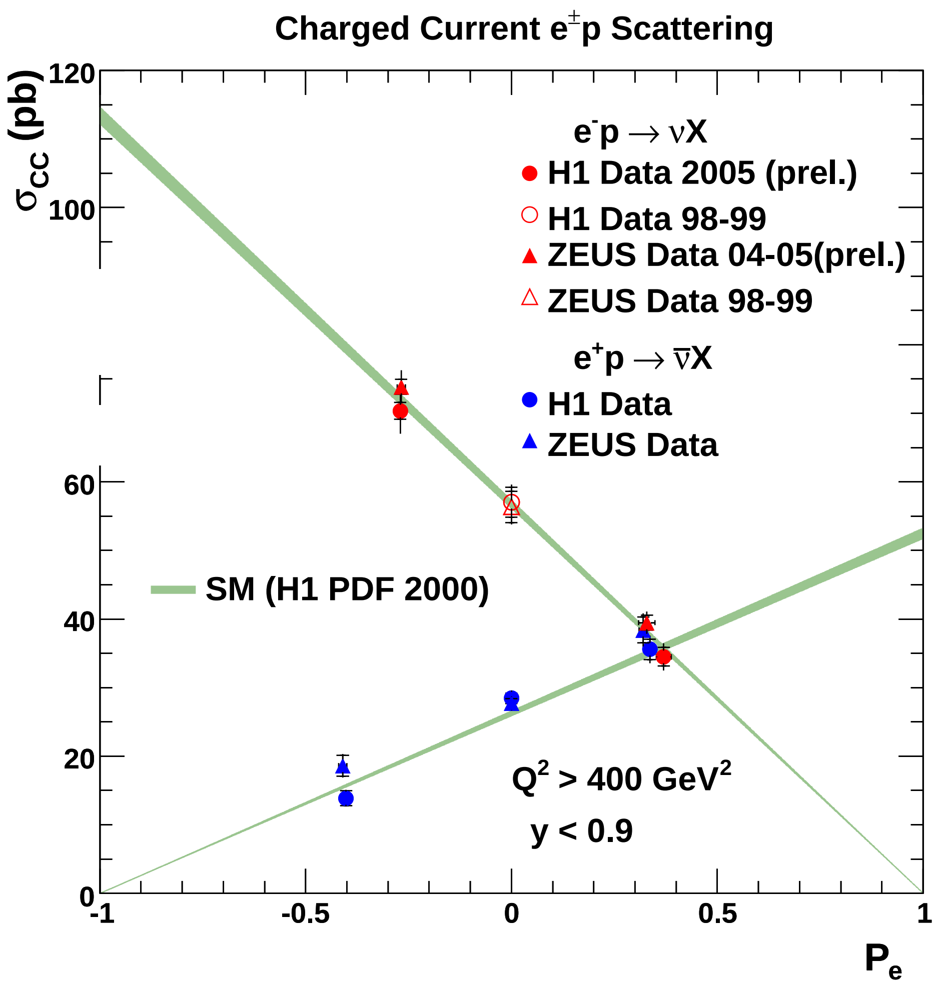


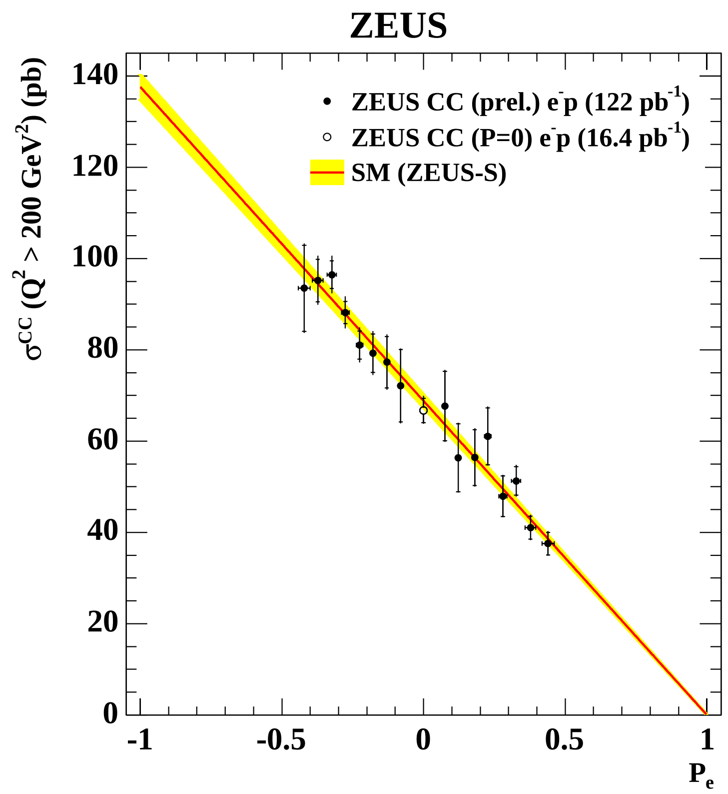


- Clear normalization difference observed between +ve/-ve polarizations for all kinematic phase space
- To see polarization dependence clearer: total cross section ➔ Next page

CC cross section vs. polarization

HERA-II Data

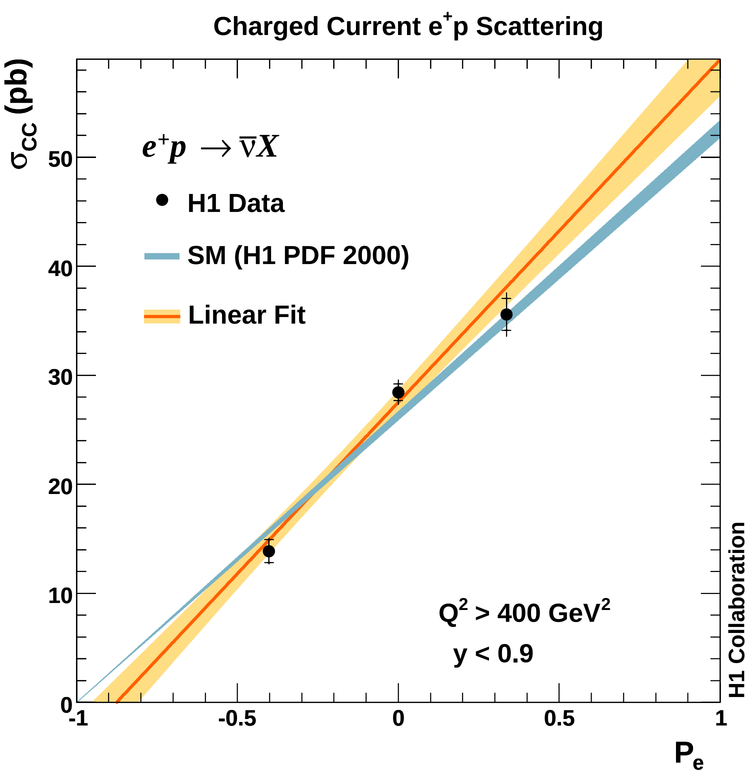


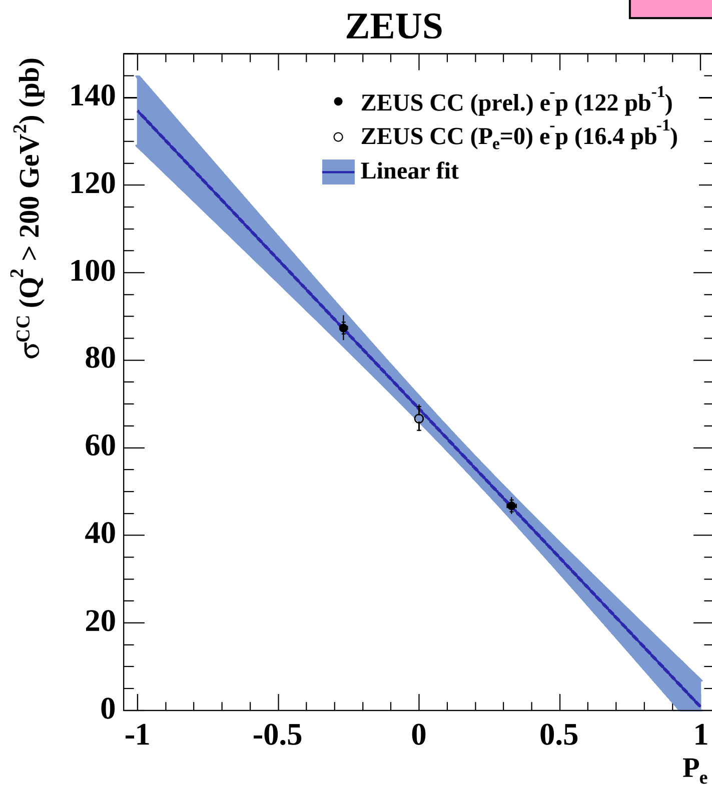


- Clear demonstration of linear dependence on pol. ((1-Pe)/2)
- Consistent with SM prediction of: σ (RH CC)=0
  (Error band from PDF uncertainty)
- Direct sensitivity to W_R → Next Slide

W_R mass limit

HERA-II Data





- ▶ Assuming $g_L = g_R$ and ν_R is light:
  - -- W_R mass limit was derived as 208 GeV (← H1 e+)
  - (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, μ ν)

Polarization effects in NC

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

Nb.: xF_3 is written as F_3 for simplicity

- Polarization modifies γZ and Z terms as:
  - -- Axial to F_2, vector to F_3
  - -- Modification degree by P_e

▶ $v_e \approx 0$

-- F_2 : 1st order, ~ $\pm P_e a_e \chi_Z F_2^{\gamma Z}$

-- F_3 : 2nd order only, ~ $\pm P_e a_e^2 \chi_Z^2 F_3^Z$

Unpol:

$\sigma(e^+) - \sigma(e^-) \rightarrow F_3^{\gamma Z}$

Pol :

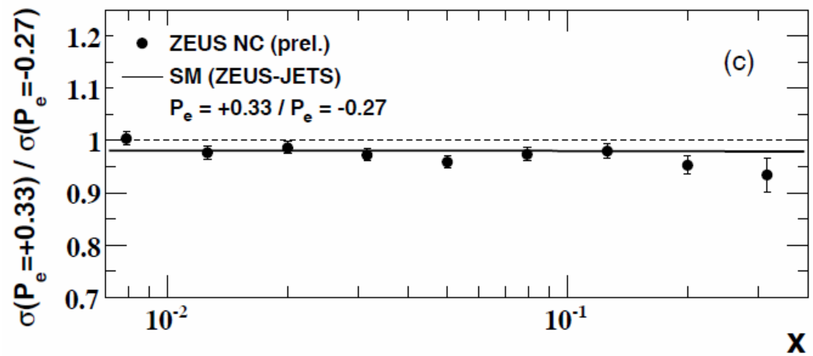
$\sigma(P_e \rightarrow) - \sigma(P_e \leftarrow) \rightarrow F_2^{\gamma Z}$

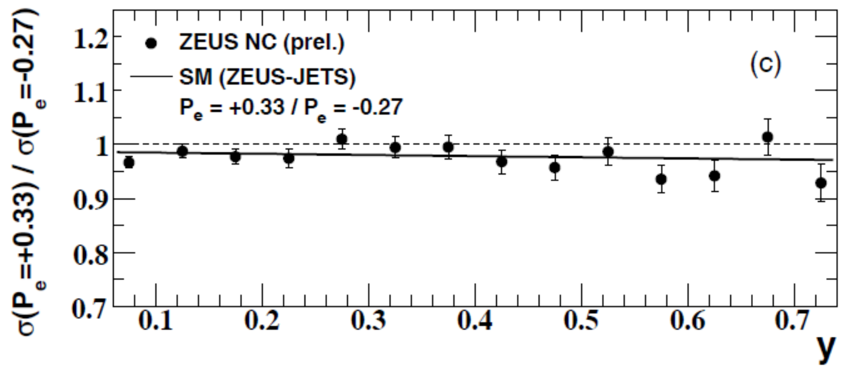
- Polarization effects expected only at EW scale, i.e large Q^2

NC cross section vs. polarization

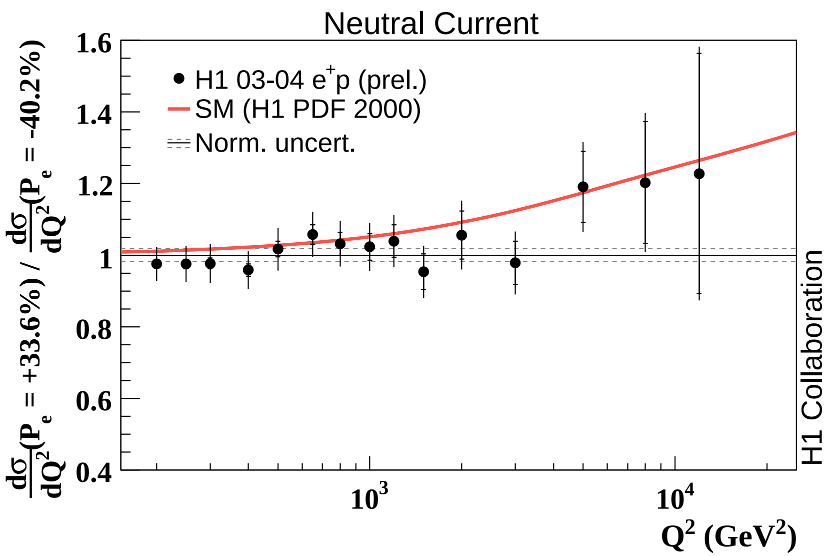
HERA-II Data

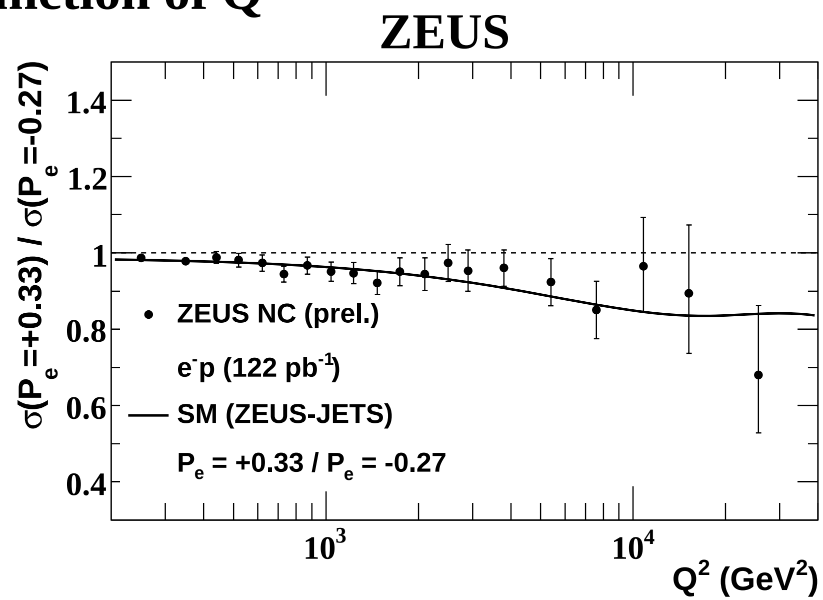
- **d σ / dx, d σ / dy : Polarization effects no strong dependence on x/y**





- **d σ / dQ² : Polarization effects as a function of Q²**



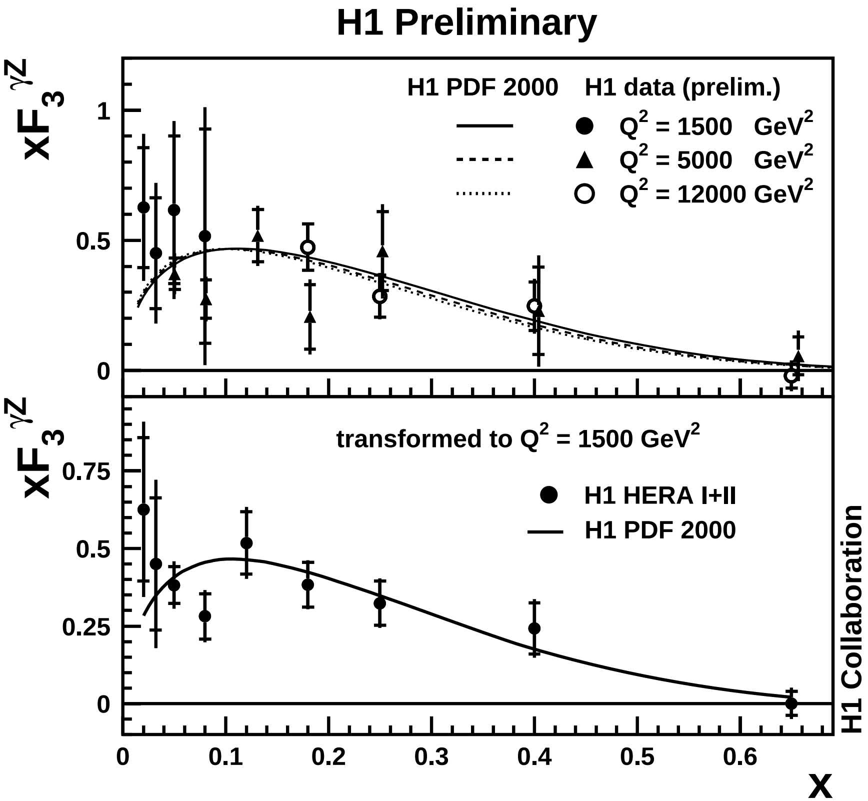


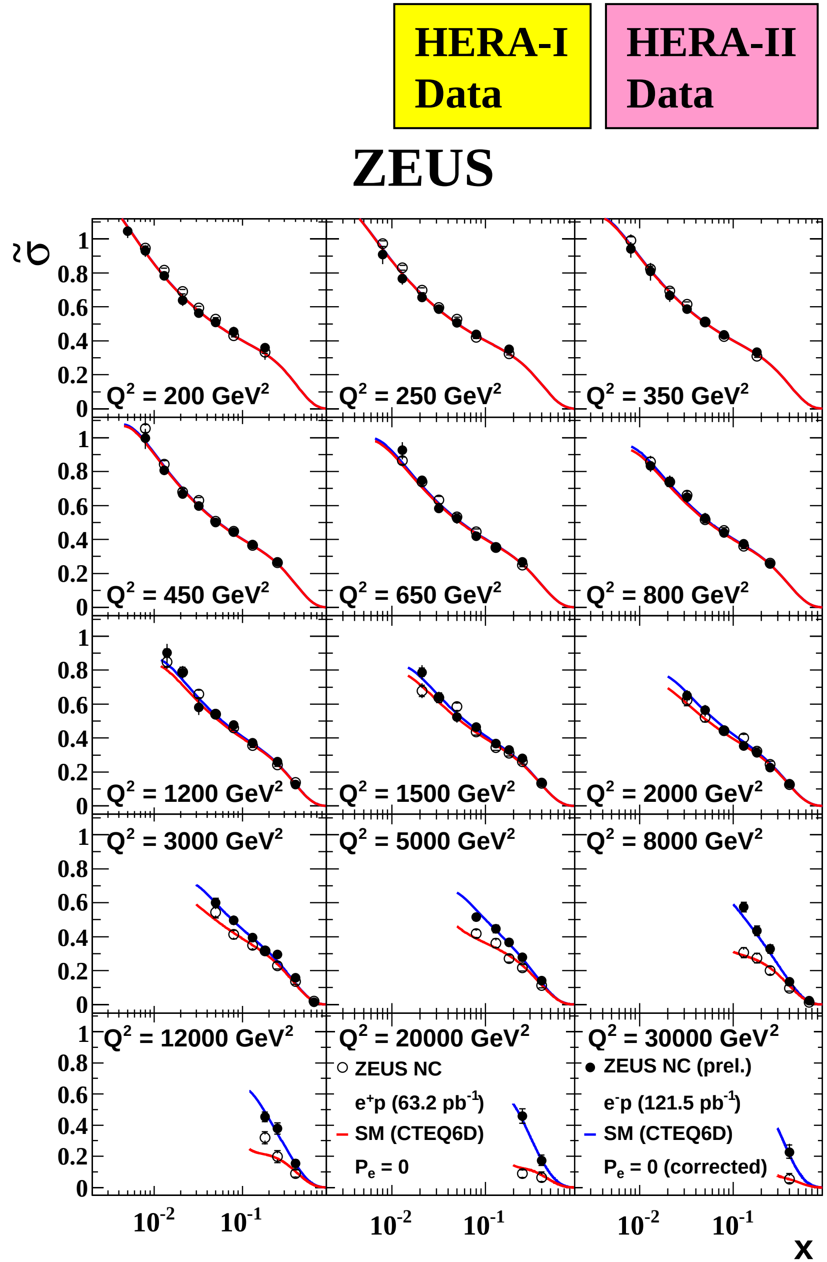
Parity violation of weak NC observed for the first time at EW scale

xF_3

- HERA-II e- = Big luminosity (7 times of HERA-I e-)
  → Combine RH and LH samples to obtain 'pseudo-unpolarized'

▶ xF3 = HERA-I e+ - HERA-II e-





- Axial SF xF_3 is determined with good precision @ EW scale

IV. QCD+EW combined analysis

- Mw
- Light quark couplings to Z

EW+QCD fit

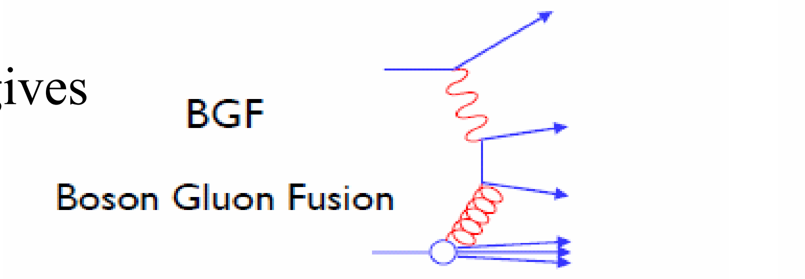
- A fit to determine both PDF and EW parameters
  -- Advantage: correlation automatically taken into account

- A fit to single experimental data
  -- H1 fit to H1 data only, ZEUS fit to ZEUS data only
  -- Advantage: handling on systematic errors is straightforward

□ H1 [published]
HERA-I : F_2 + Unpol. highQ^2 NC+CC

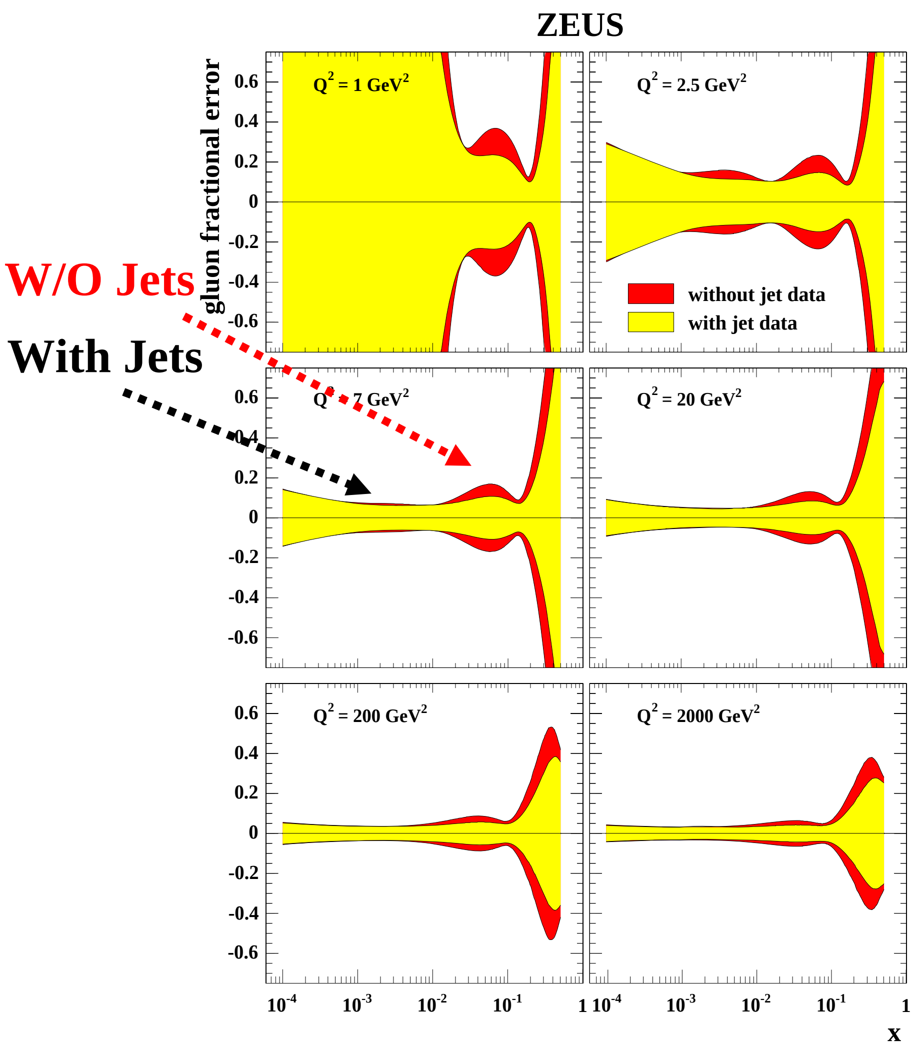
□ ZEUS [prel.]
HERA-I : F_2 + Unpol. highQ^2 NC+CC
+ HERA-I : DIS incl.Jet + PhP di-Jets. ← **"ZEUS-JETS" [published]**
+ HERA-II : Polarized e- NC and CC ← **"ZEUS-POL" [prel.]**

※ Photoproduction (Q^2=0) dijets gives direct access to gluon and α_s →



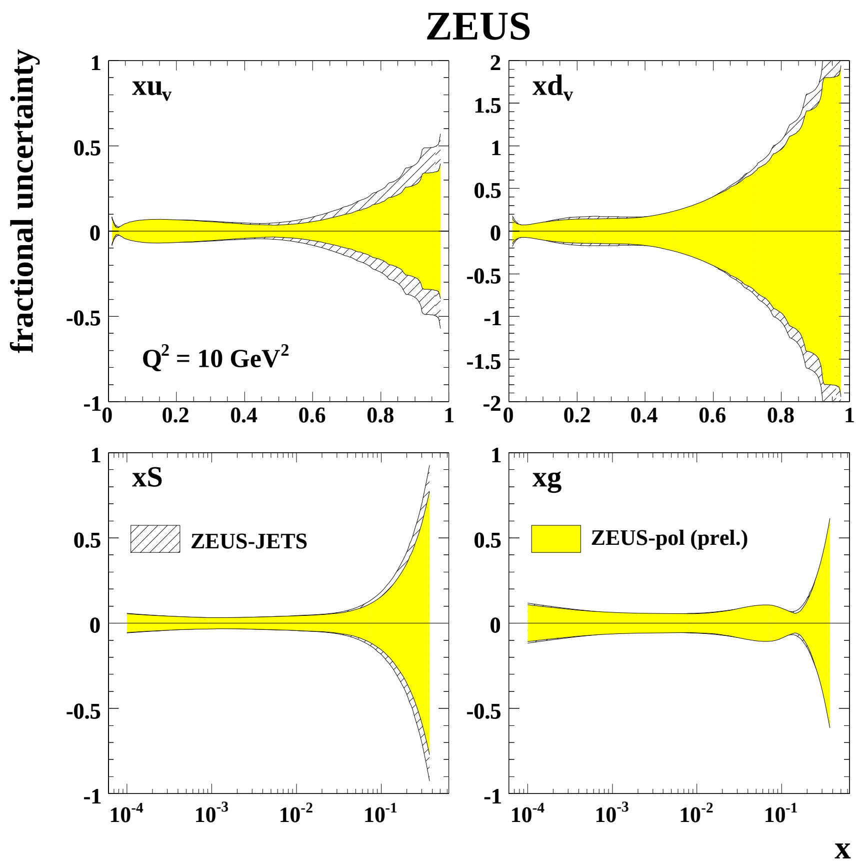
PDFs

- **Precision of gluon PDF**
  -- Improved by adding Jets



- **Precision of u-quark PDF**
  -- Improved in particular at large x as expected, i.e. $\sigma(NC) \propto 4u + d$

$$\sigma(CC) \propto u$$



Determination of M_W

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

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

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

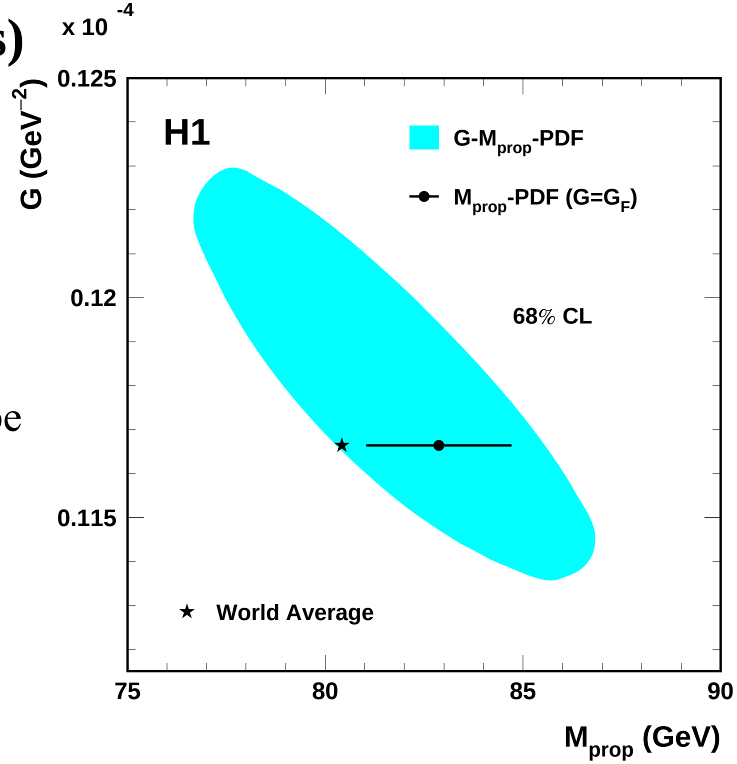
Nb. M_W contributes both normalization and shape

➔ 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 MW determined at s-channel LEP/TEV

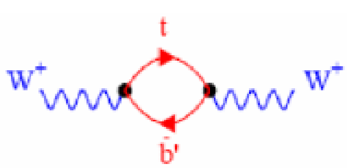
M_W in the framework of SM

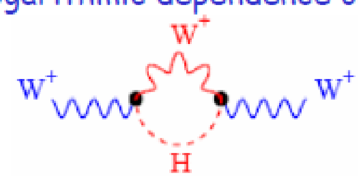
- In the SM G_F and M_W are related ➔ Fits fully assuming SM

  -- On-Mass-Shell (OMS) scheme

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

Quadratic dependence on m_t Logarithmic dependence on M_H





(ref. Z.Zhang @ EPS05)

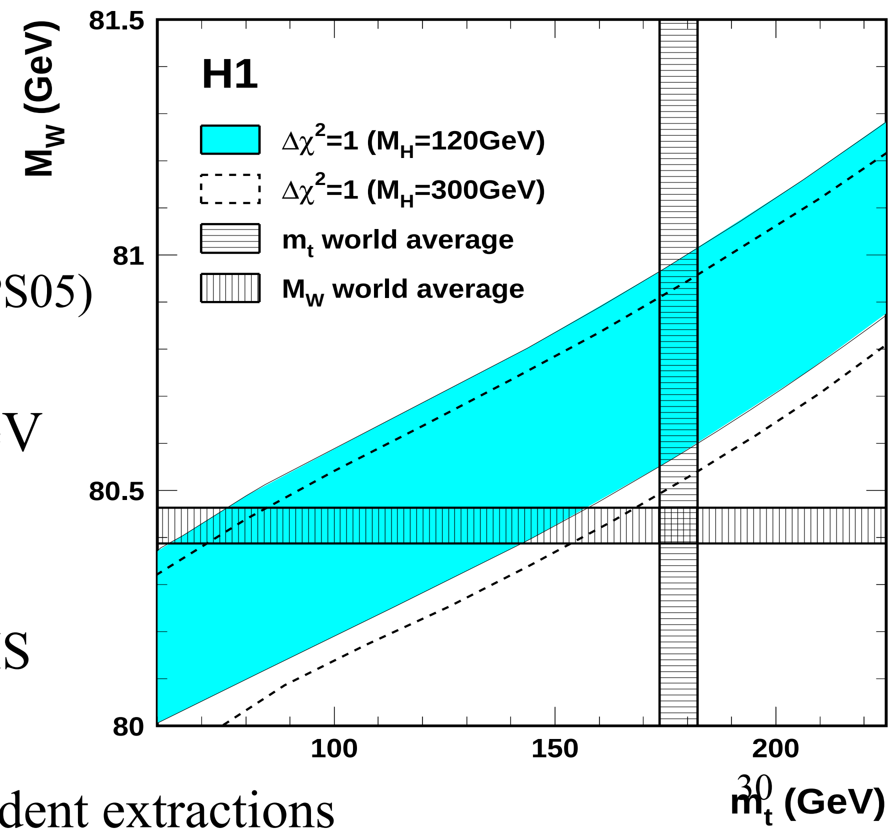
▶ A fit to M_W with M_Z fixed

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

▶ A fit to m_t with M_Z ,M_w fixed

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

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



※ Nb. These are model-dependent extractions

Light quark couplings to Z

- **EW structure functions in QPM**

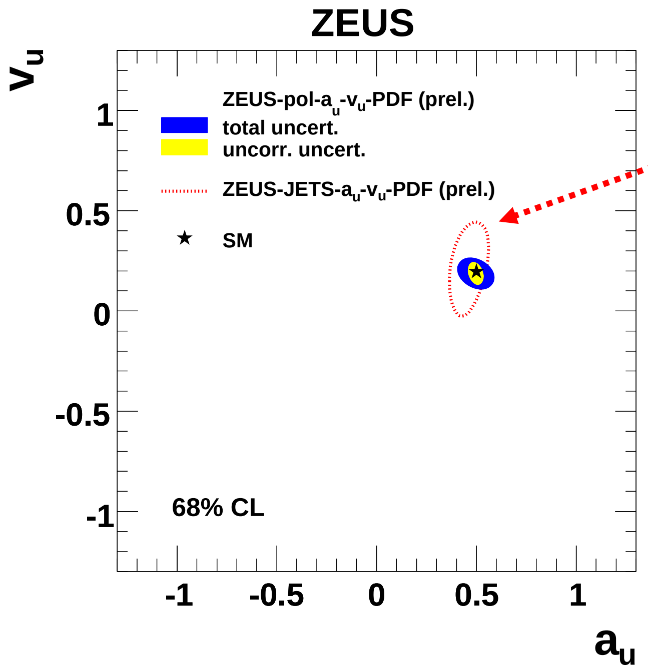
$$
\begin{aligned}
F_2^{\gamma Z} &= 2e_f v_f \Sigma_i x[q_f + \overline{q_f}] \\
F_2^{Z} &= (v_f^2 + a_f^2)\Sigma_i x[q_f + \overline{q_f}] \\
F_3^{\gamma Z} &= 2e_f a_f \Sigma_i x[q_f - \overline{q_f}] \\
F_3^{Z} &= 2v_f a_f \Sigma_i x[q_f - \overline{q_f}]
\end{aligned}
$$

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

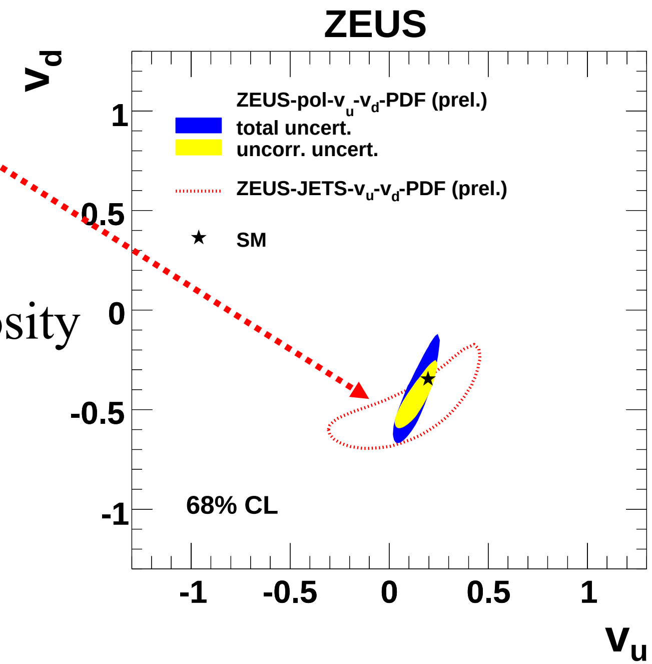
Nb.: xF_3 is written as F_3 for simplicity

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

► **A fit with V_u, V_d are free to be determined in addition to PDFs**



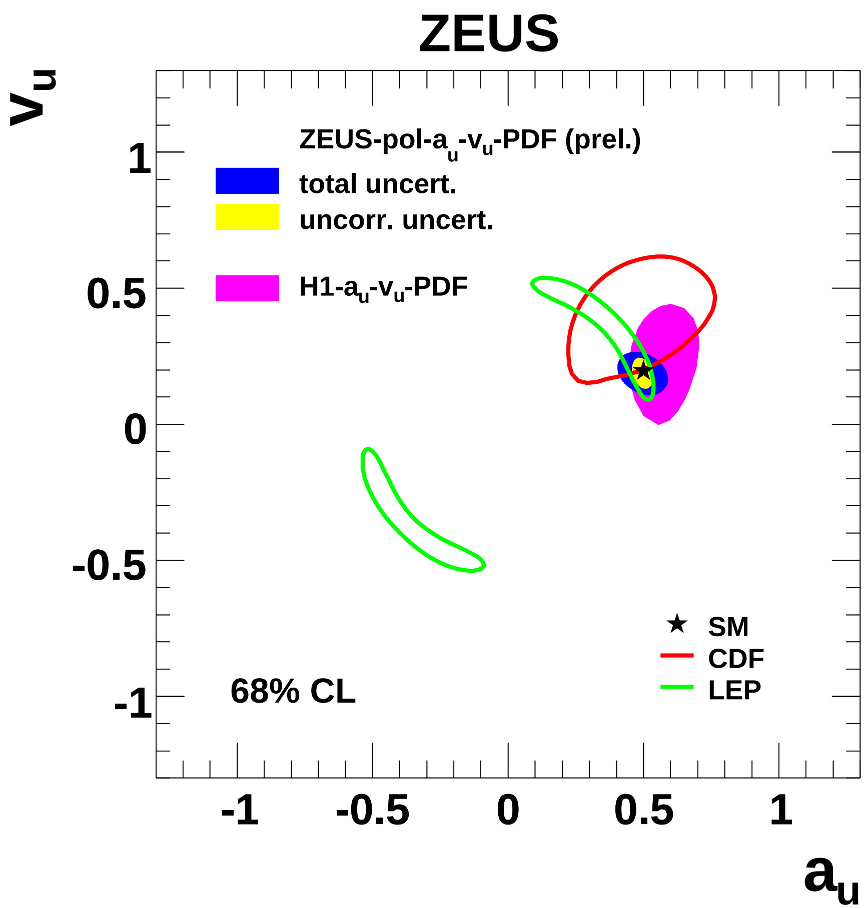
w/o HERA-II



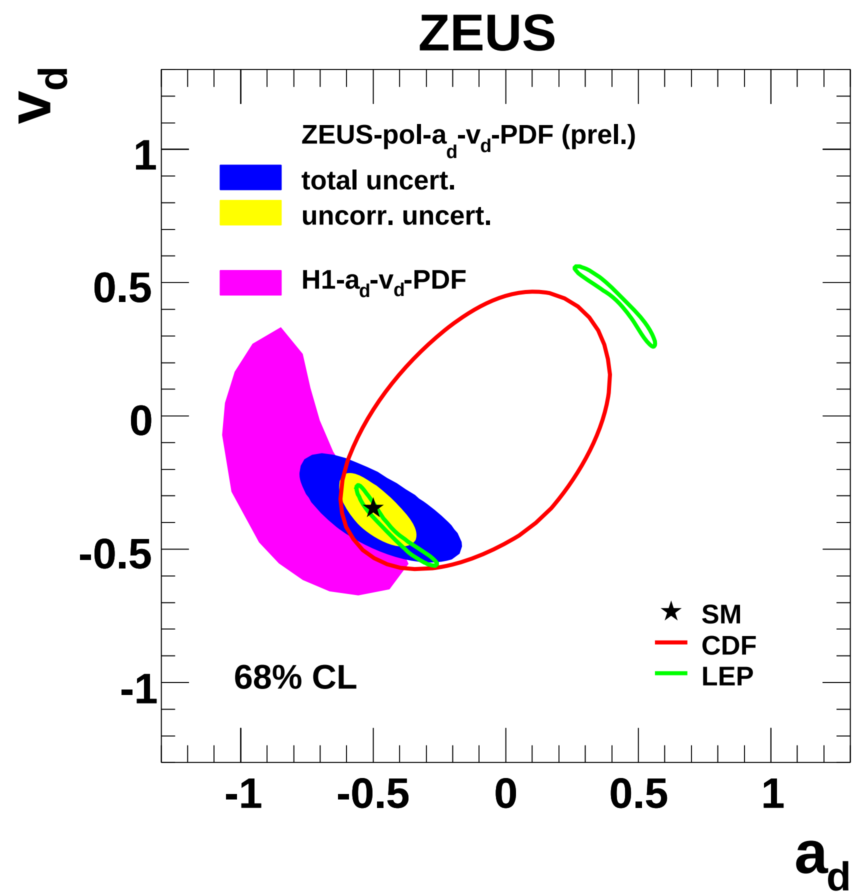
- Large luminosity
→ improves a
- Polarization
→ improves v

Quark couplings compared to other exp

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



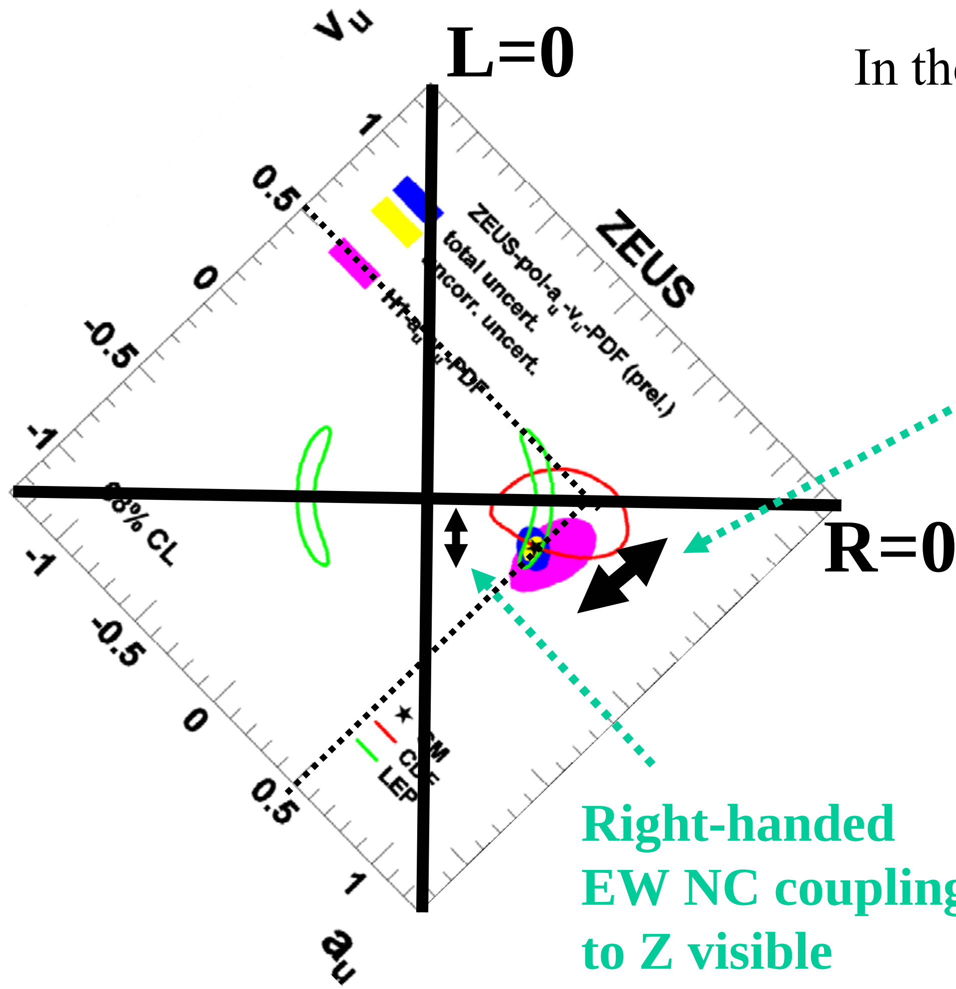
► A fit with V_d, A_d are free to be determined in addition to PDFs



- High precision, competitive to other experiments

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

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

► **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

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 interaction with large 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 will run until 30/June/2007 to collect large sample of e+ with longitudinal polarization.

--- HERA's legacy results on EW will come soon.

Backup Slides

Weak Isospin

- **Sensitivity to right-handed weak isospin**

$$v_f = T^3{}_{f,L} - T^3{}_{f,R} - 2e_f \sin^2\theta_W$$

$$a_f = T^3{}_{f,L} + T^3{}_{f,R}$$

► **A EW+QCD fit to determine: $T^3{}_{u,R}$, $T^3{}_{d,R}$, $\sin^2\theta_W$ ($T^3{}_{u,L}$ and $T^3{}_{d,L}$ fixed @ SM values)**

$$T^3{}_{u,R} = -0.07 \pm 0.07 \pm 0.07$$

$$T^3{}_{d,R} = -0.26 \pm 0.19 \pm 0.19$$

$$\sin^2\theta_W = 0.238 \pm 0.011 \pm 0.023$$