Electroweak physics in ep scattering with polarised leptons

Kunihiro Nagano (KEK, Japan)

On behalf of
the H1 and ZEUS collaborations

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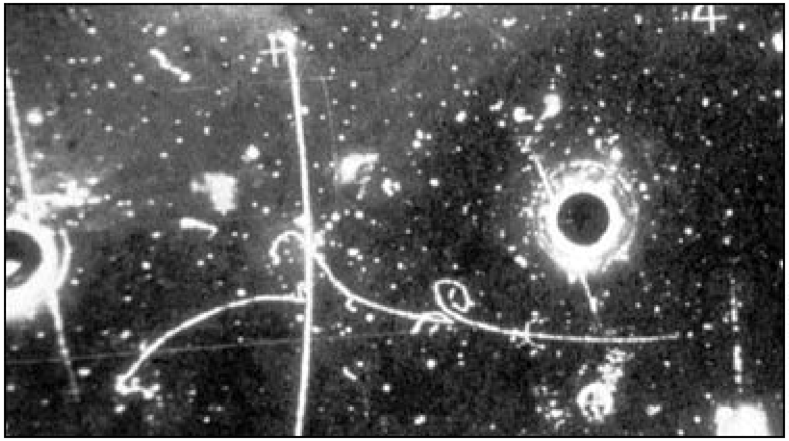
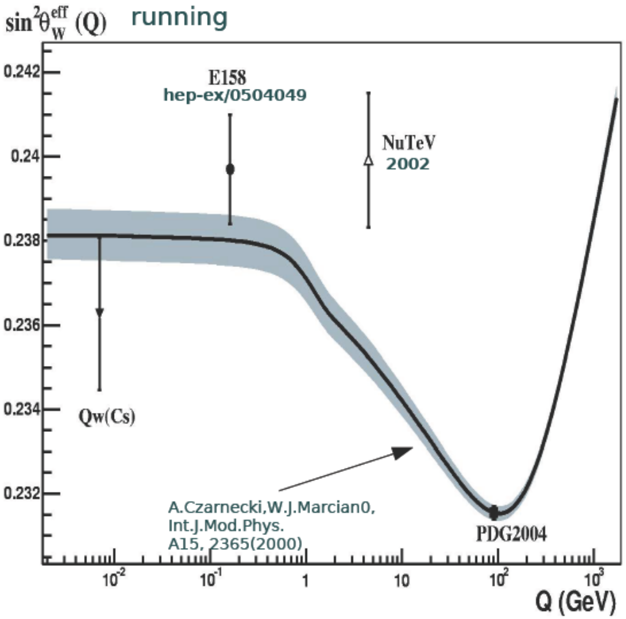
EW @ DIS ?

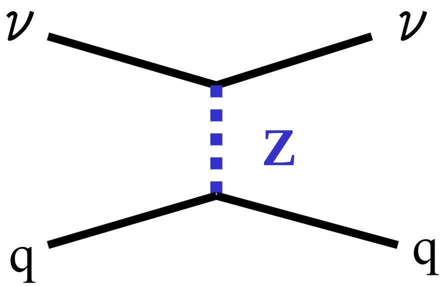
- Remember: Weak neutral current was "DIScovered" by the Gargamelle

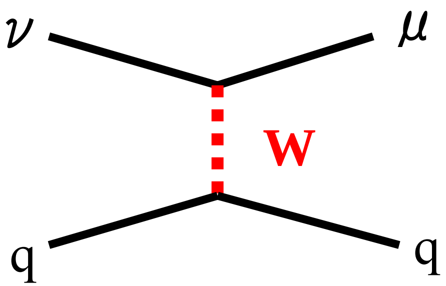


AEROMETRIC photo

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

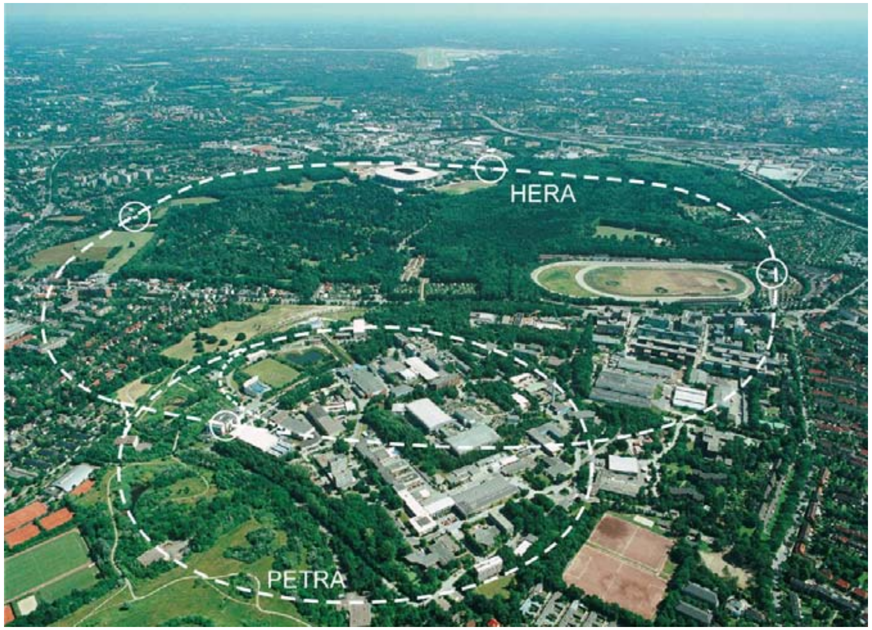


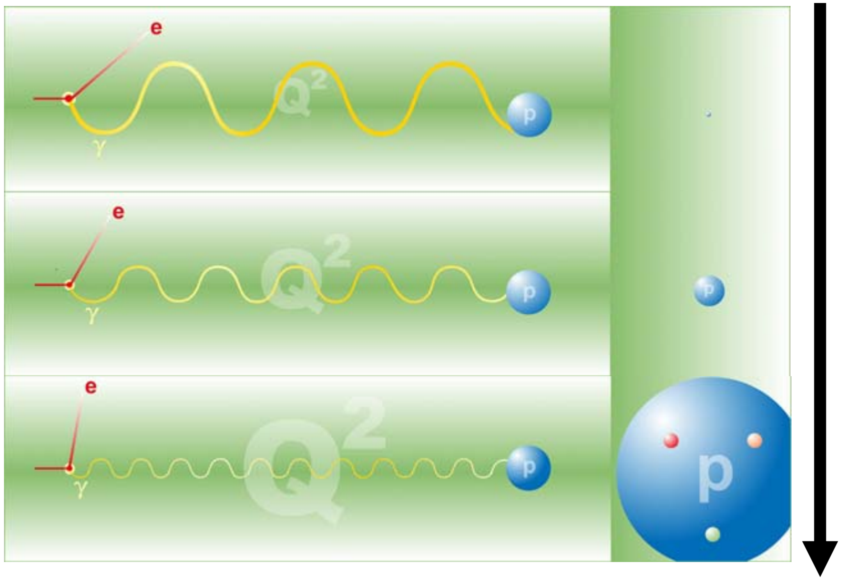




"Pure" weak int. @ $Q^2 \approx 0$
(Q^2 is momentum transfer squared)

HERA : world's the only ep collider





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

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

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

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

(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:

$m_Z, \Gamma_Z, \sigma_h^0, R_l^0, A_{FB}^{0,l}$

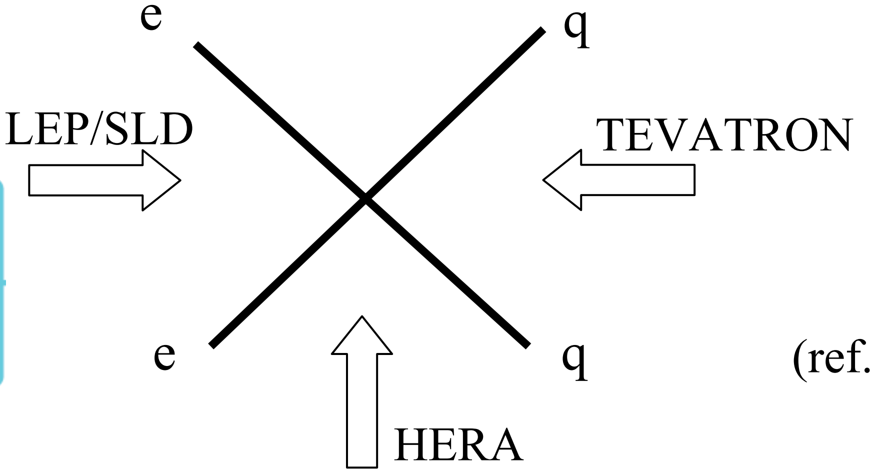
$P_\tau \rightarrow A_l$

$Q_{FB} \rightarrow \sin^2\theta_{eff}^{lept}$

SLD: A_l

LEP+SLD:

$R_b^0, R_c^0, A_{FB}^{0,b}, A_{FB}^{0,c}, A_b, A_c$



e

q

LEP/SLD

TEVATRON

e

q

HERA

$p\bar{p}$: 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":

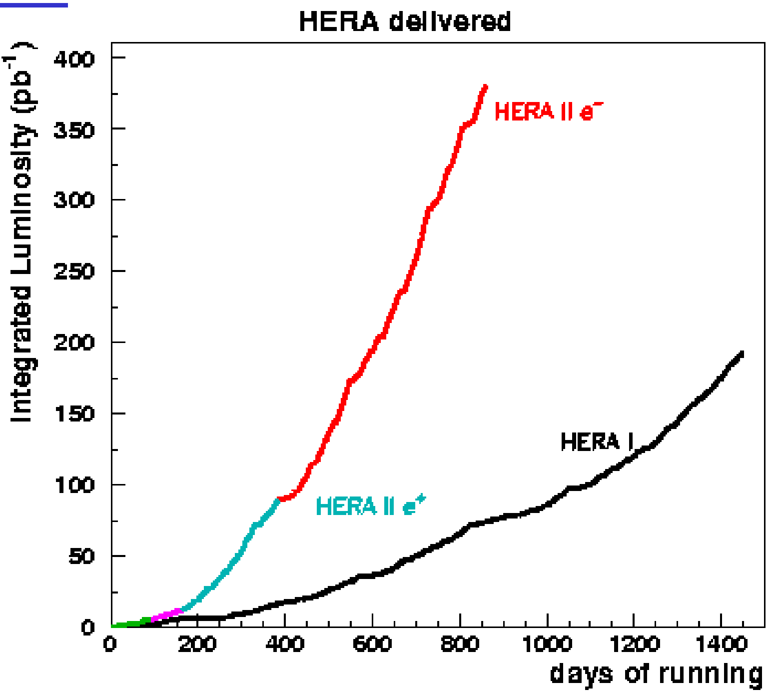
-- Test & measure proton structure (i.e. PDFs) at lower Q^2

-- 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:
    $1.5 \leq Q^2 \leq 30000$ 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



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

(Luminosity for data analyzed)

Contents of this talk are:

I. Proton structure
II. DIS @ EW scale (unpolarized)
III. DIS @ EW scale with polarization
IV. QCD+EW combined fit

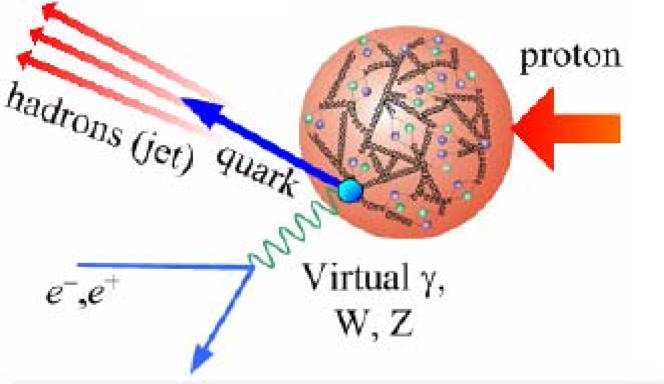
giving both legacy and hot results of HERA !

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)

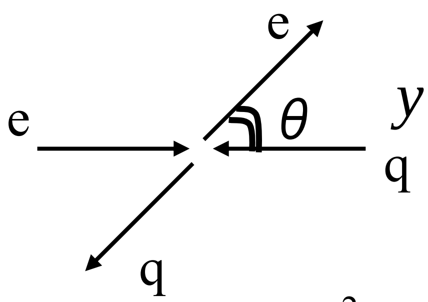
Measure in terms of:
- ➢ **Mom.frac. of q**
- ➢ **Spatial resolution**

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

(at e-q c.m.s)

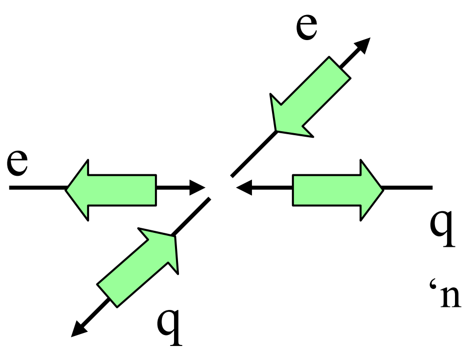


$$y = (1 - \cos\theta)/2$$

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

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

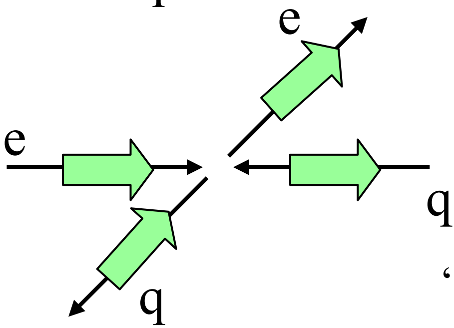
A: $Y_- = 1 - (1-y)^2$



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: $F_2 = x\Sigma e_q{}^2 (q + \bar{q})$

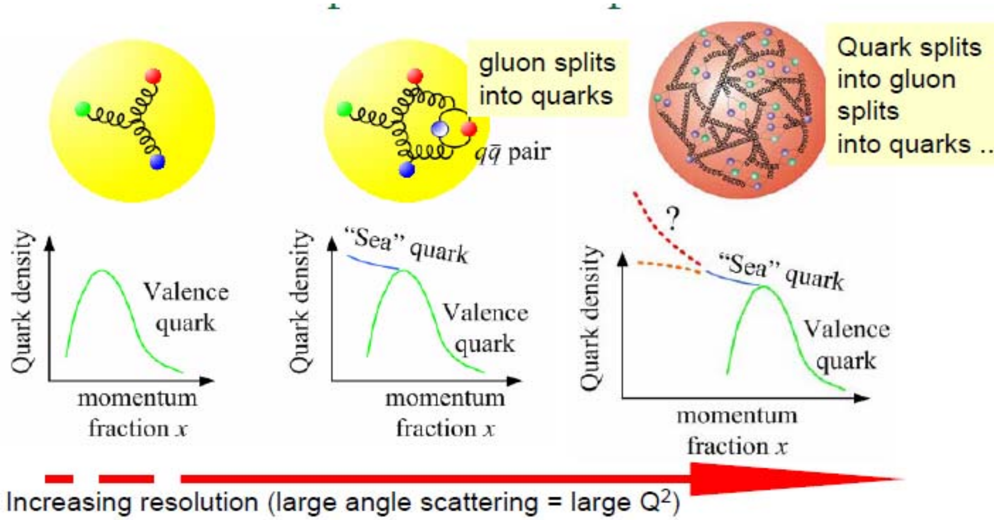
SFs = (Charges)^2 × Parton Distribution Functions (PDFs)

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."



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

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

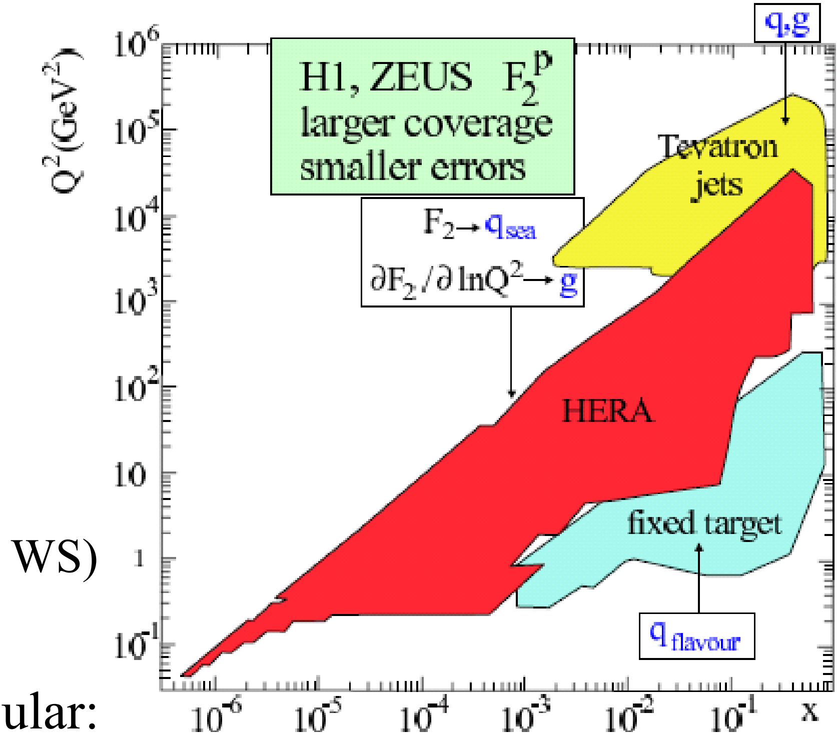
● However, pQCD cannot predict x-dependence of PDFs a priori
➔ PDFs are determined by a global fitting to experimental data (next slide)

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

New data



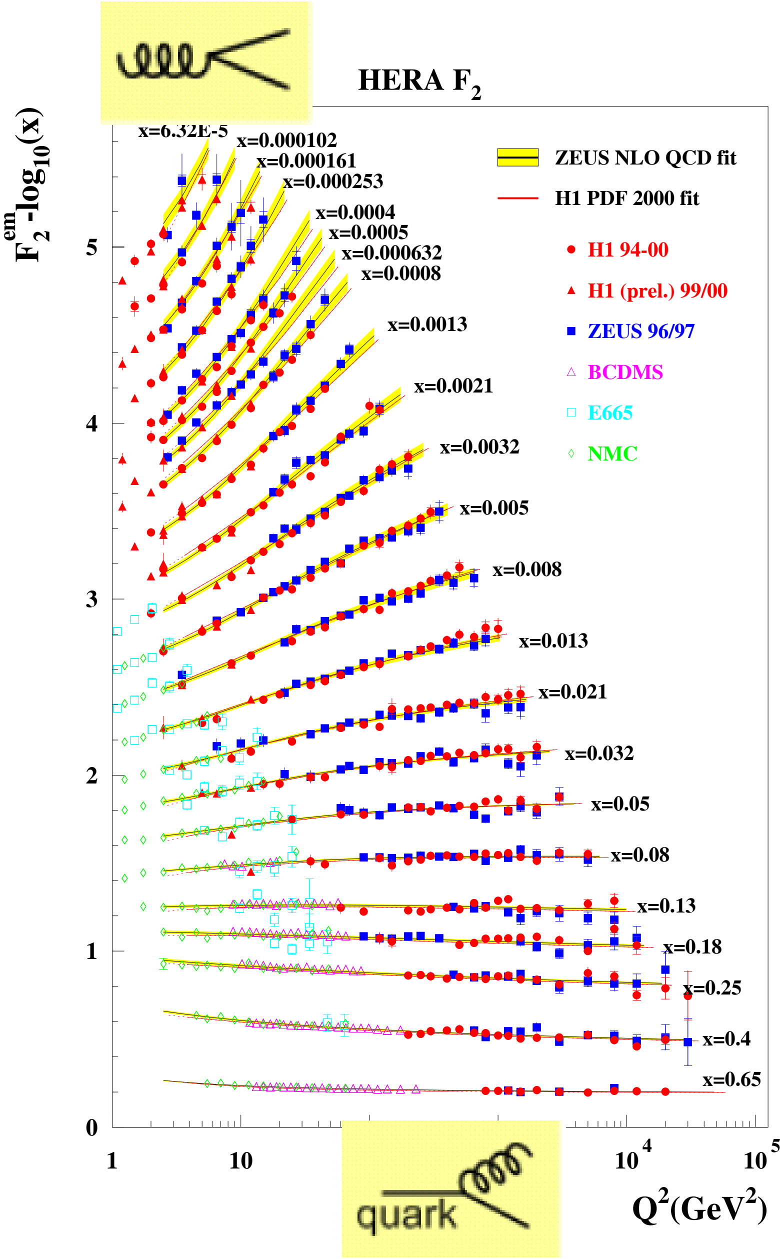
(ref. A.Martin @ DIS WS)

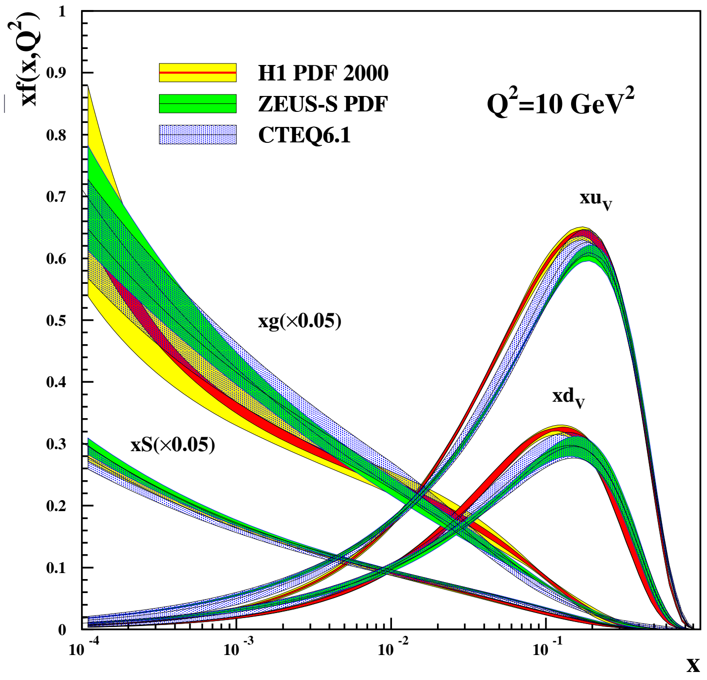
► HERA plays significant role, in particular:
  - -- Gluon
  - -- Sea quarks

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

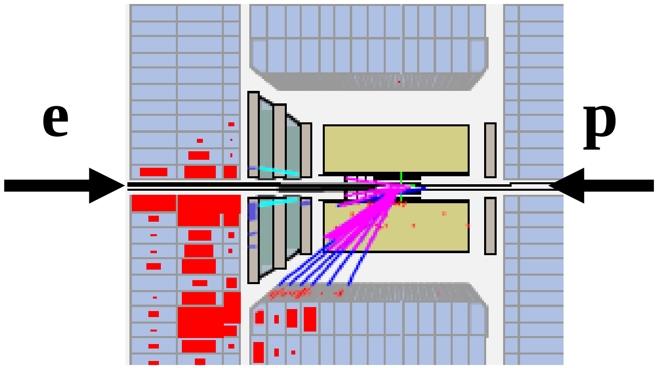
DIS at high Q^2 [CC]

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

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

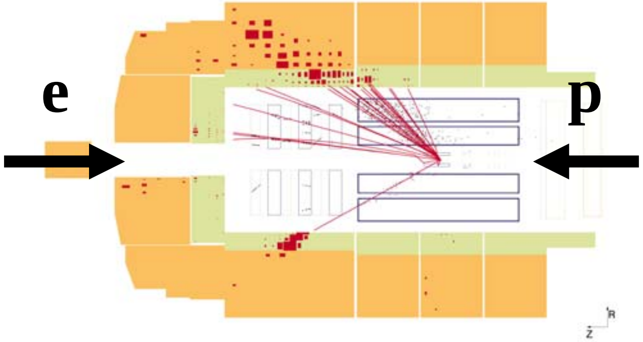
$$\frac{d^2\sigma(e^-p)}{dxdQ^2}=\frac{G_F{}^2}{2\pi}\left(\frac{M_W{}^2}{M_W{}^2+Q^2}\right)^2\{(u+c)+(1-y)^2(\bar{d}+\bar{s})\}$$

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

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

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

1st-order V   2nd-order V

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

1st-order A   2nd-order A

γ-Z interference   Pure Z

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

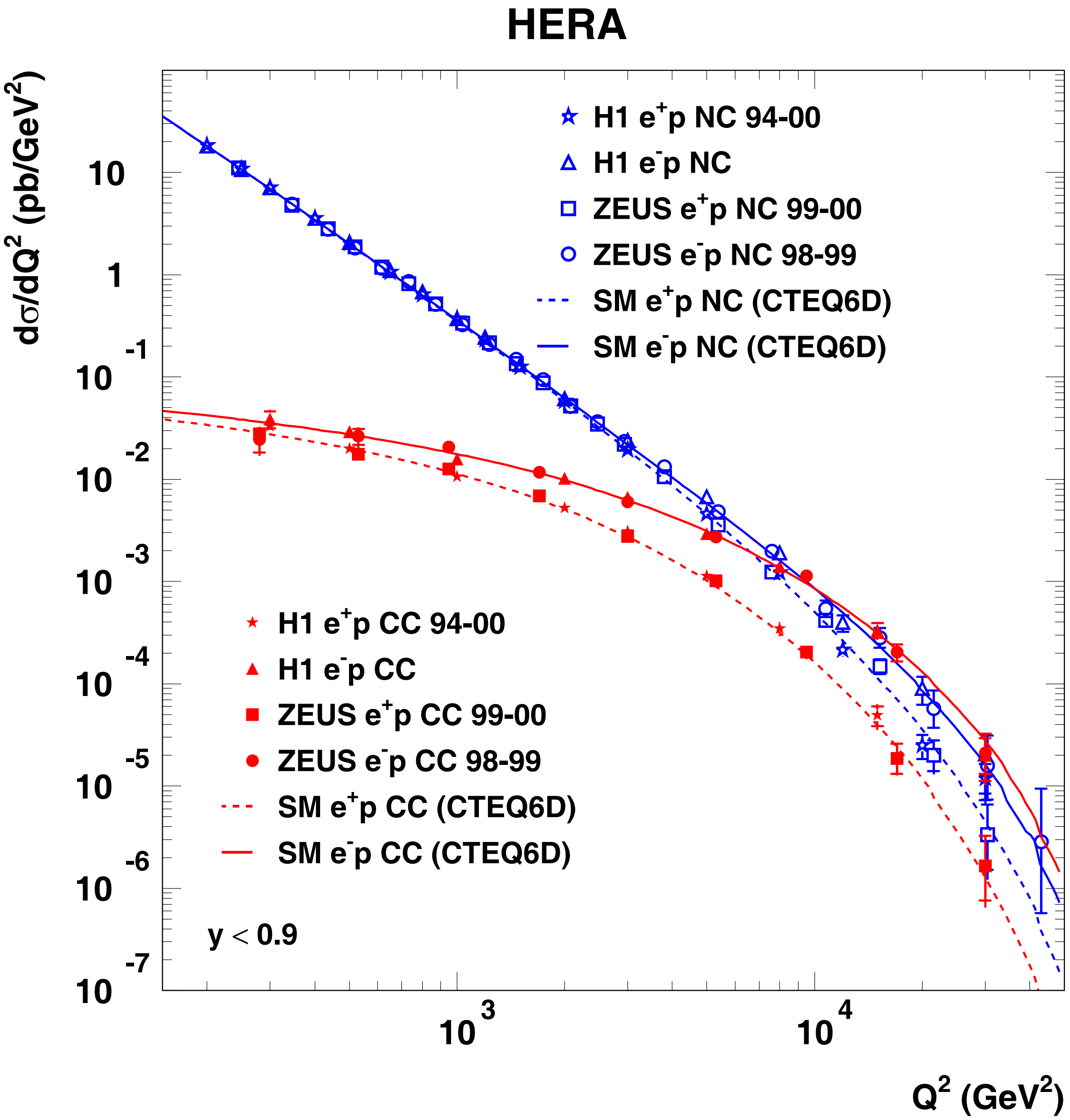
: Propagator term   ▶ $v_e \approx 0$

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

-- 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”

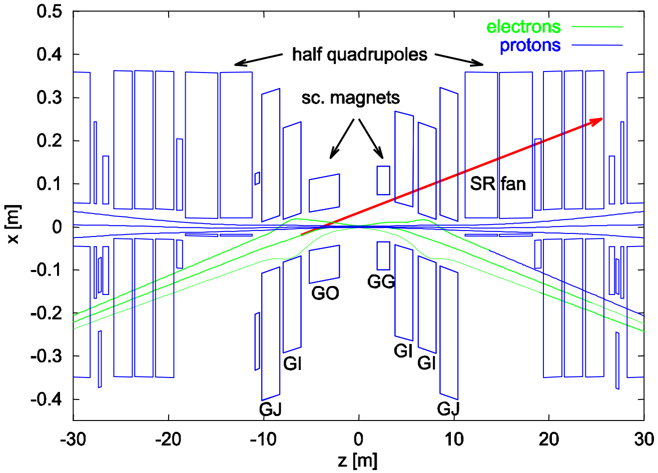
(Differences remained are mainly due to PDFs)

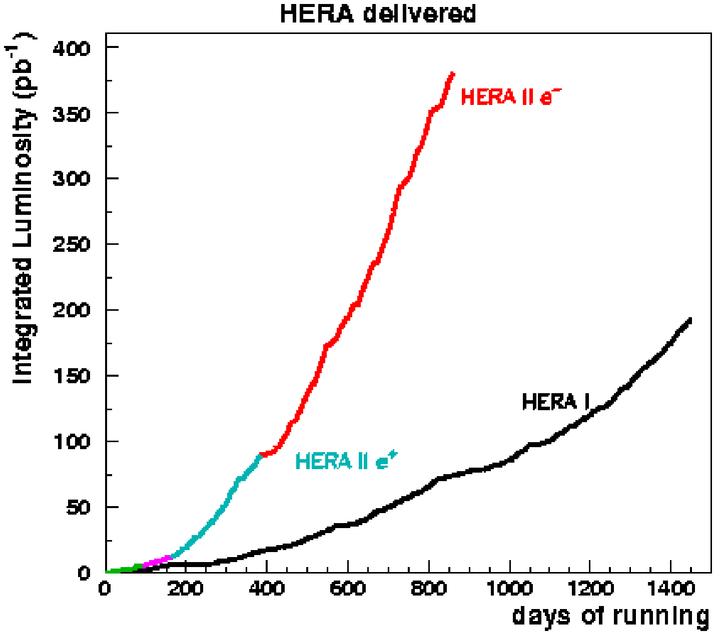
III. DIS @ EW scale with polarization

- 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

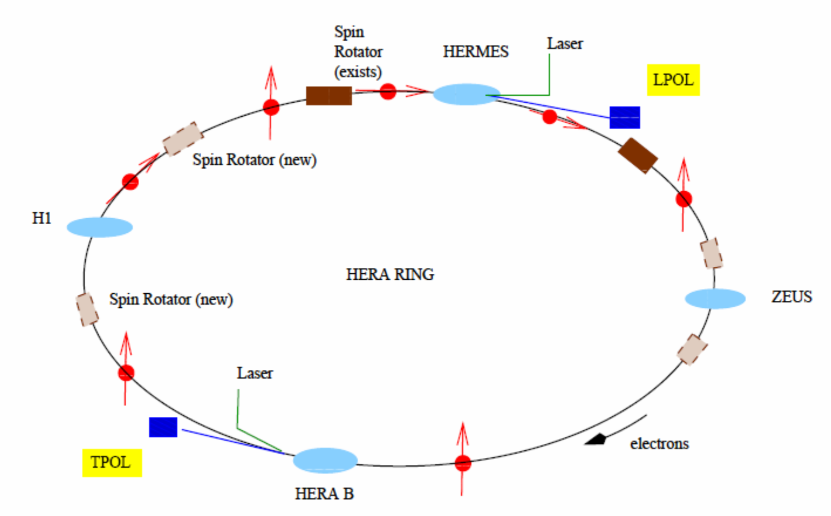
-- N.b Vacuum improvement in year 1998 enables efficient e- running

(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

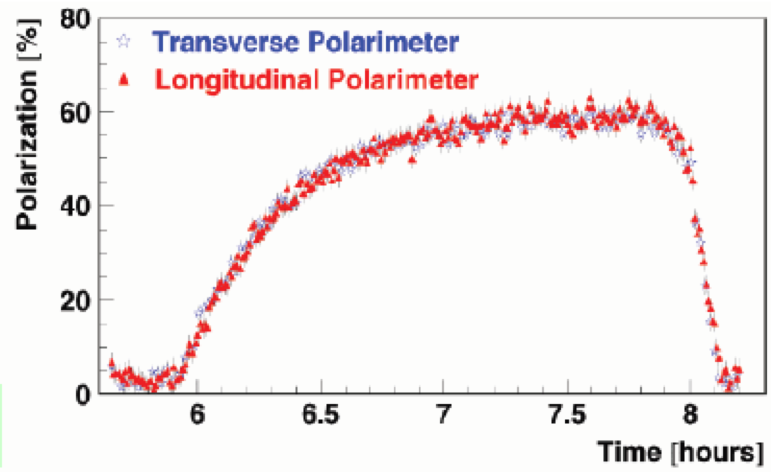
→ Lepton beam has transverse polarization

→ Rise Time @ HERA ~ 40 min.

☐ Spin rotator before/after the H1/ZEUS to flip T → L polarization (and vice-versa back)

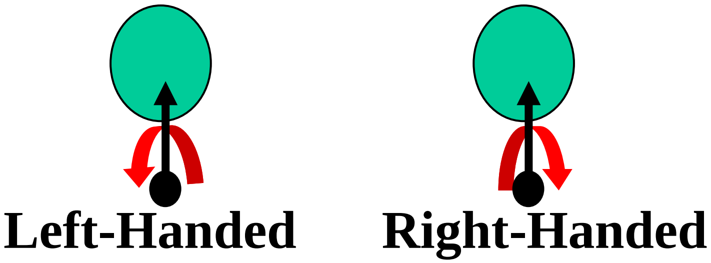
☐ Two + one (new) independent Laser Compton Polarimeters

	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

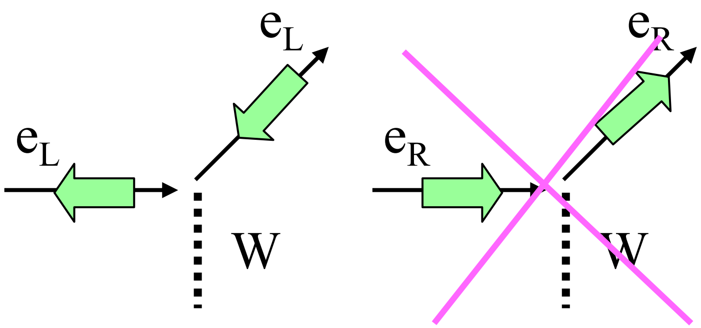
EW physics with polarized lepton beams



- 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+)
  ➔ $\sigma(\mathrm{Pol}) = (1+\mathrm{Pol})\ \sigma(\mathrm{Unpol})$



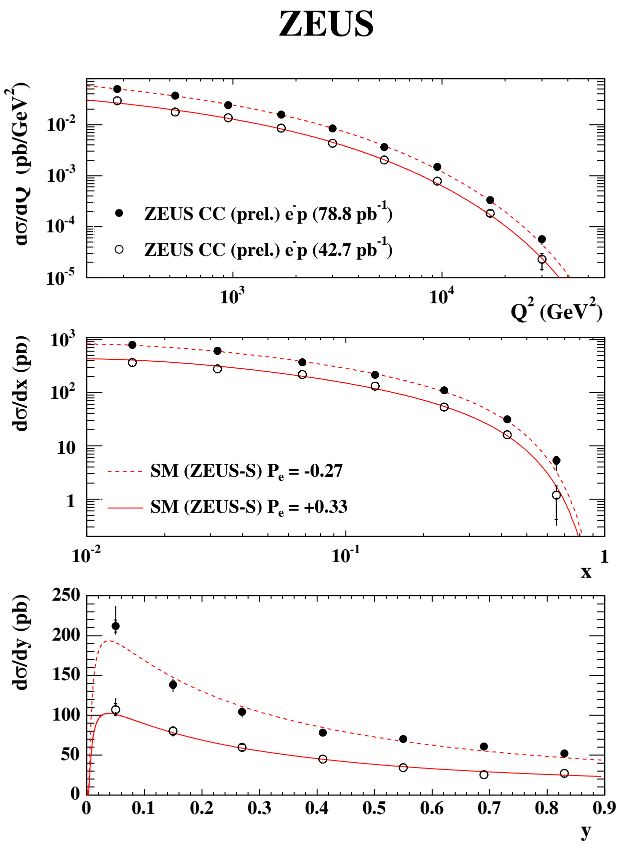
▶ Neutral-current DIS

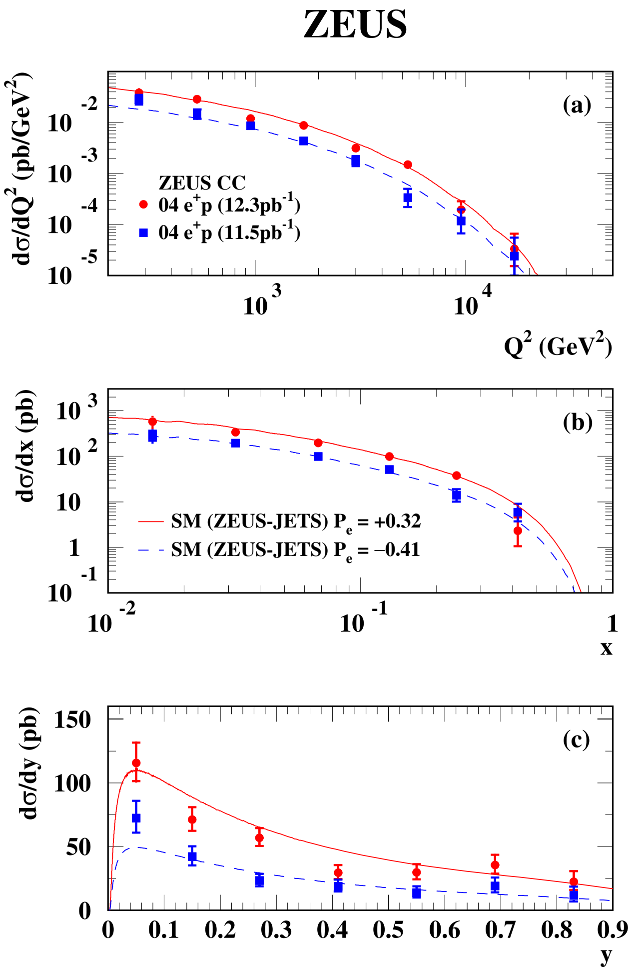
- Weak's parity violating effect through γ-Z interference and pure Z
  → visible only at large Q^2
- Such γ-Z and Z terms contain EW parameters, i.e. quark couplings to Z, $\sin\theta_W$, M_Z

CC single-differential cross-sections

HERA-II Data

- ► dσ/dx, dσ/dy

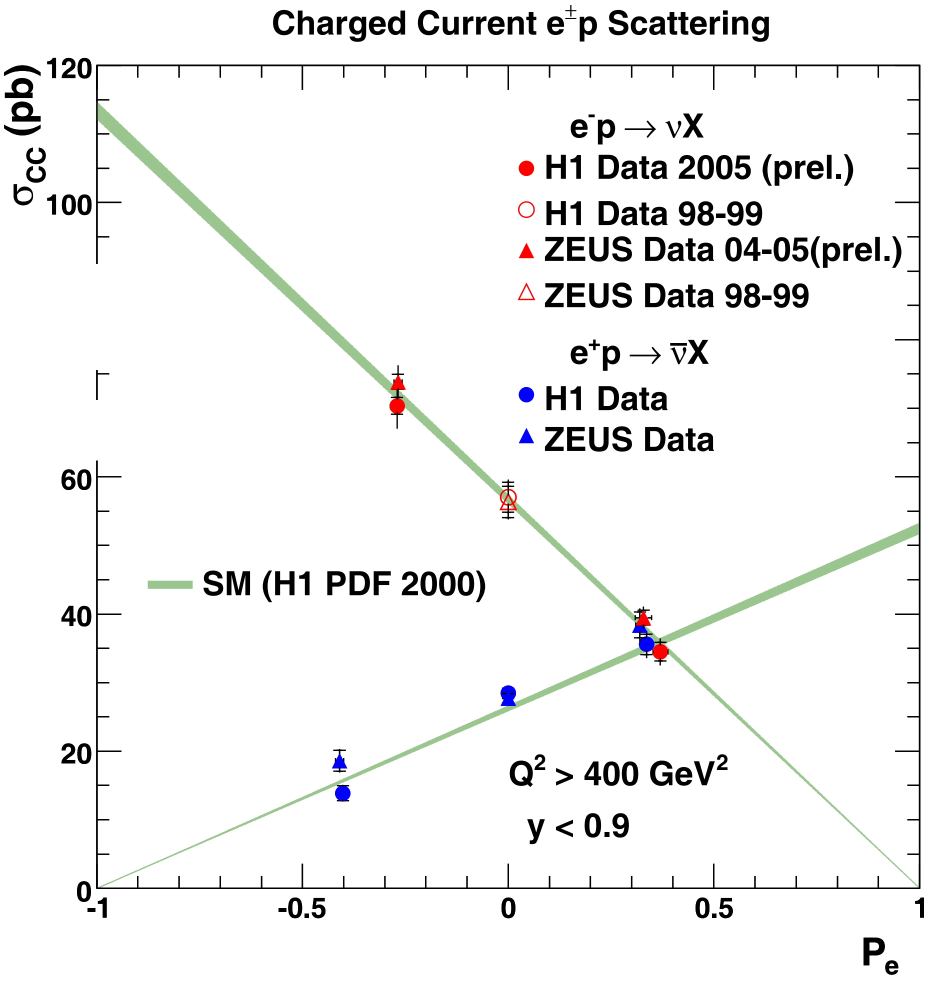


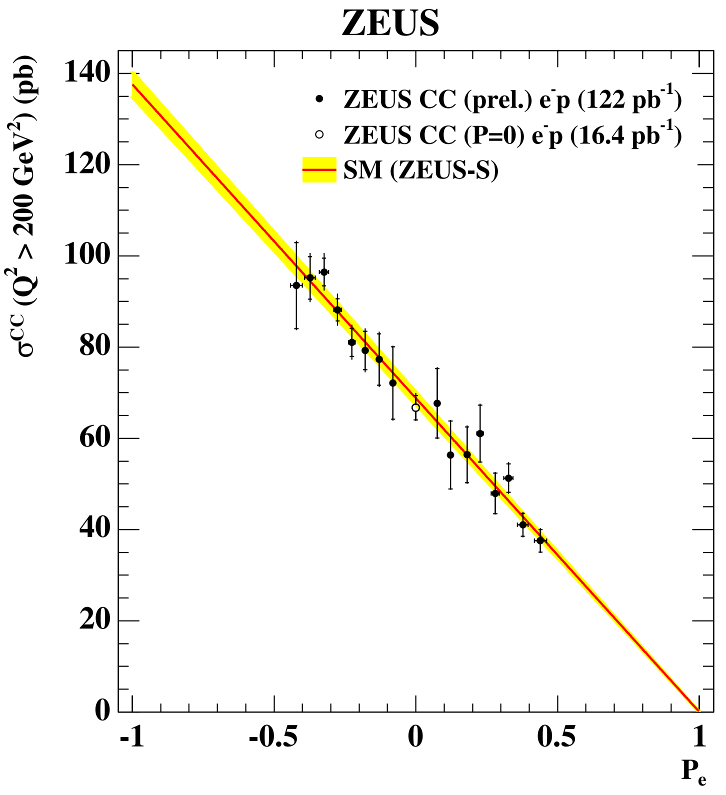


- ● Clear normalization difference observed between +ve/-ve polarizations for all kinematic phase space
- ● To see polarization dependence clearer: total cross section ➔ Next page

CC cross section vs. polarization

HERA-II Data



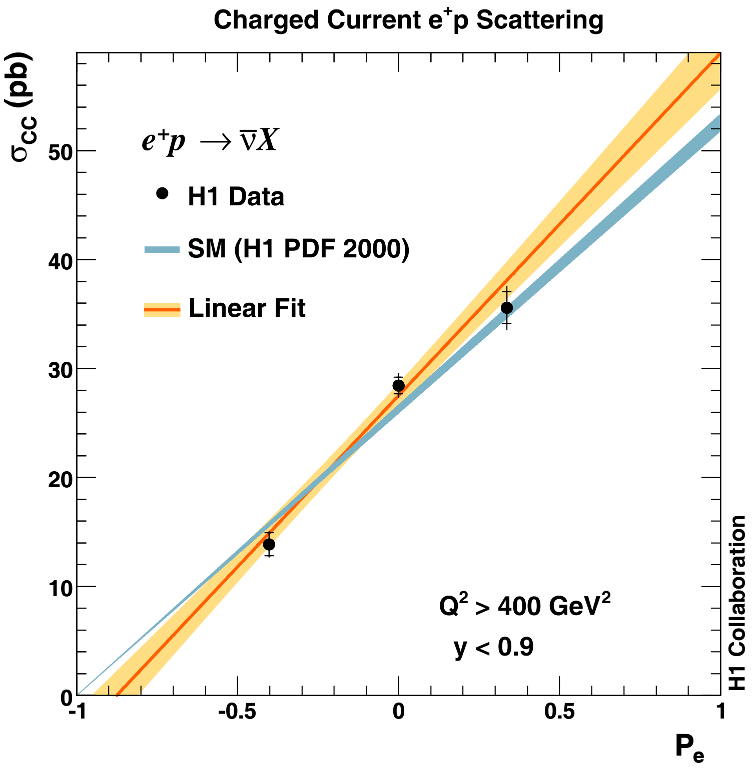


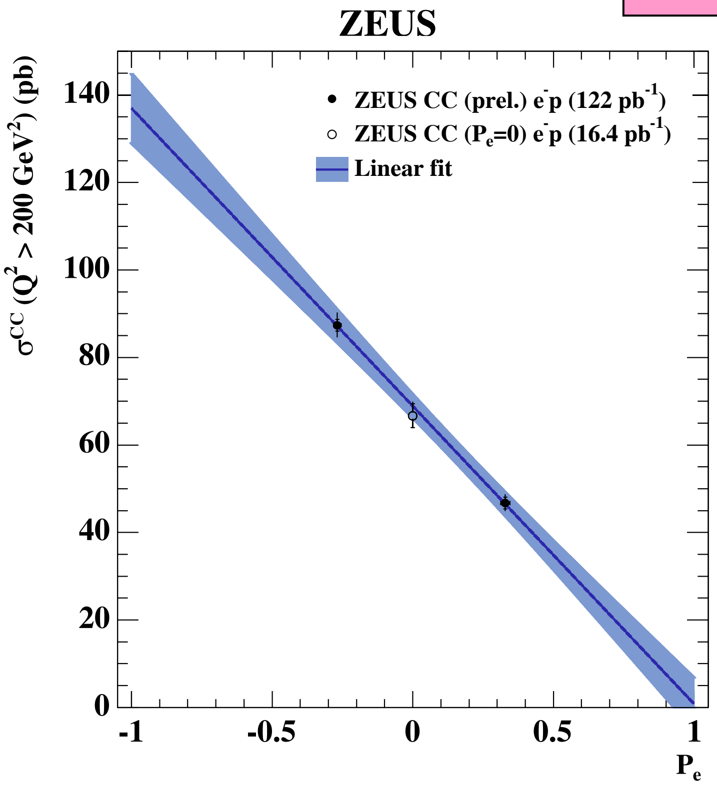
- Clear demonstration of linear dependence on pol. ((1-Pe)/2)

- 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, $\mu\nu$)

Polarization effects in NC

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

Nb.: xF_3 is written as F_3 for simplicity

- Polarization modifies γ Z 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 :

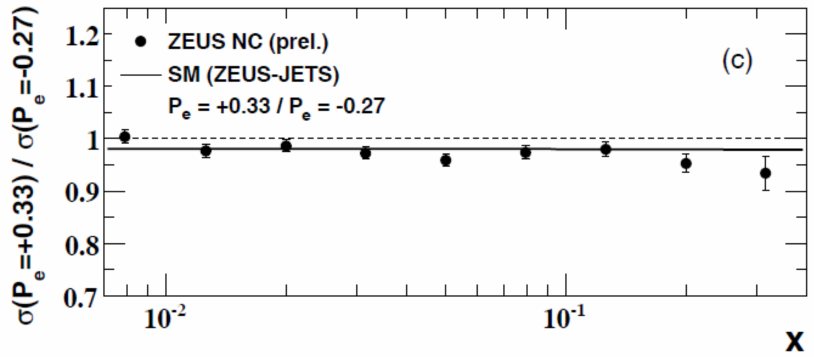
$\sigma(P_e \rightarrow) - \sigma(P_e \leftarrow) \rightarrow F_2^{\gamma Z}$

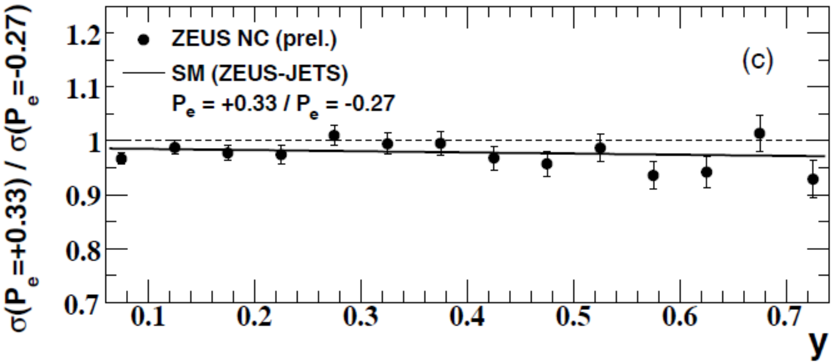
- Polarization effects expected only at EW scale, i.e large Q^2

NC cross section vs. polarization

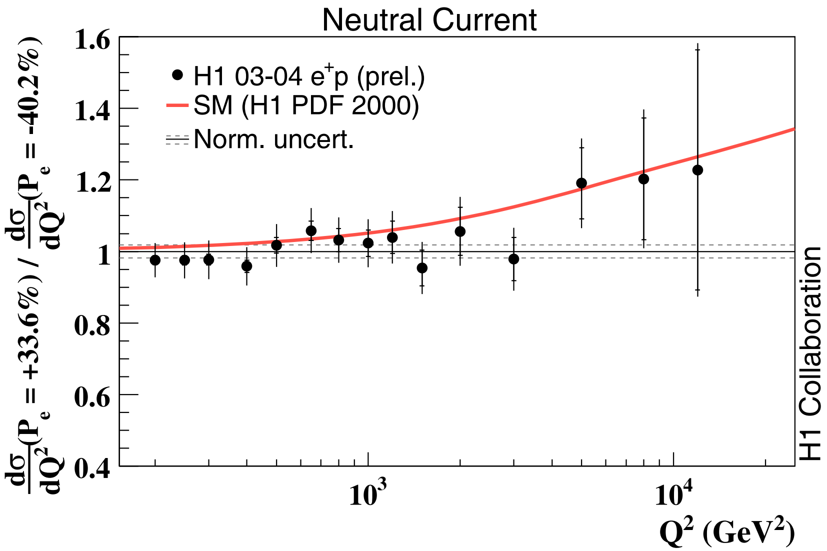
HERA-II Data

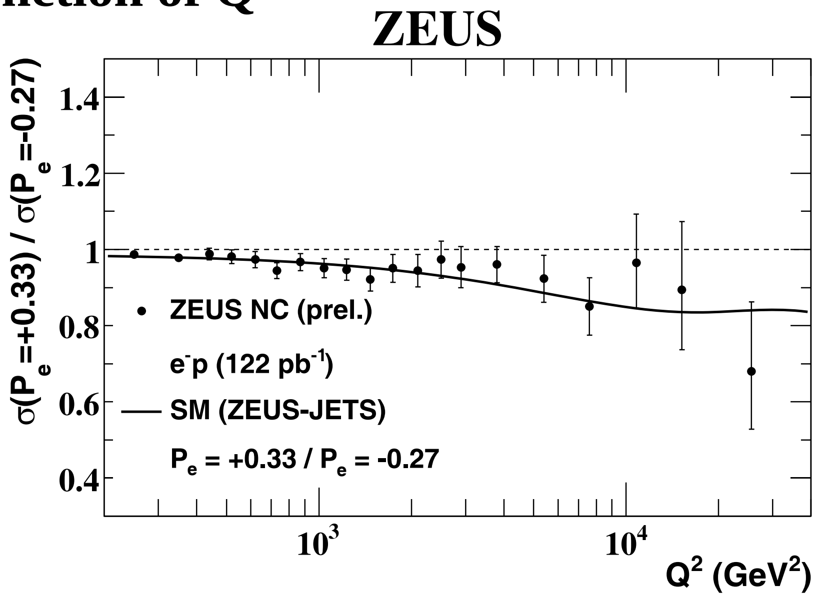
- $d\sigma/dx$, $d\sigma/dy$: Polarization effects no strong dependence on x/y





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





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

xF_3

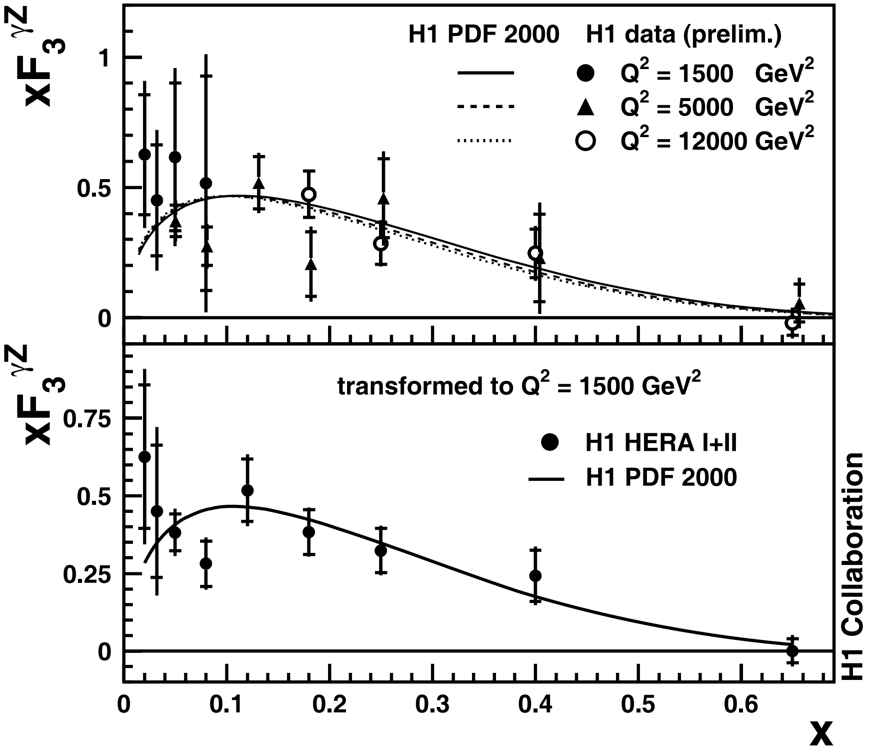
HERA-I Data

HERA-II Data

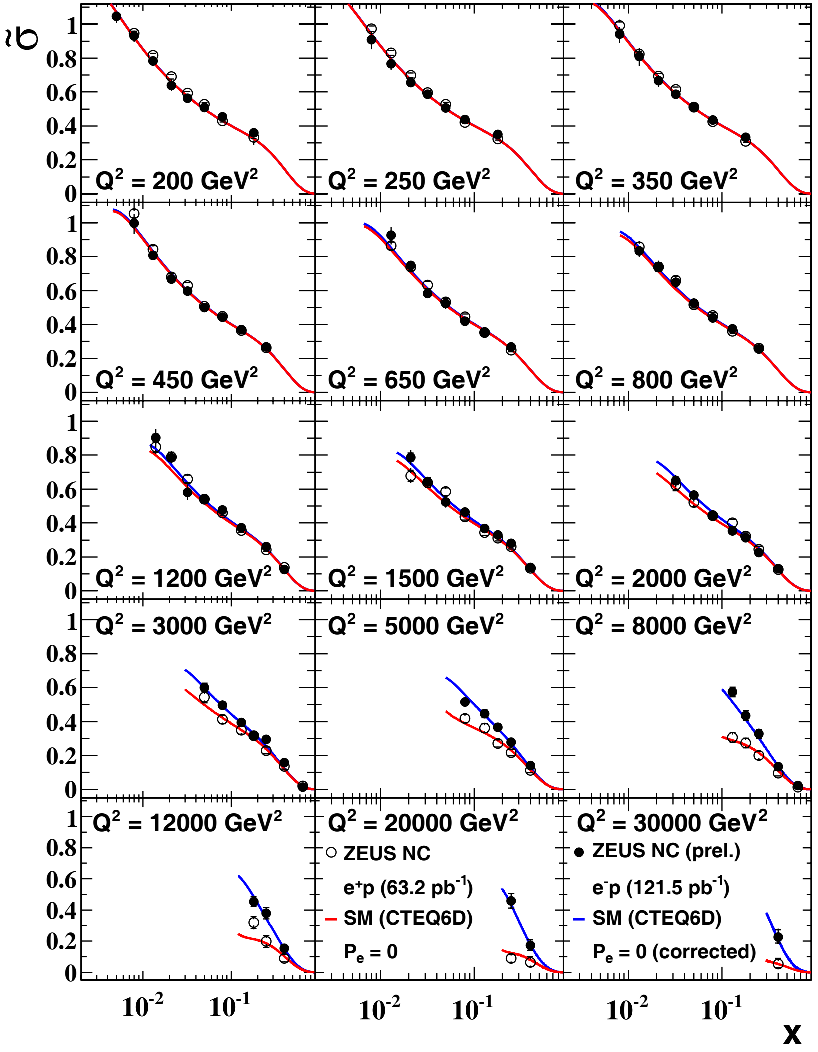
- HERA-II e- = Big luminosity (7 times of HERA-I e-)
  → Combine RH and LH samples to obtain 'pseudo-unpolarized'

▶ xF3 = HERA-I e+ - HERA-II e-

H1 Preliminary



ZEUS



- 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

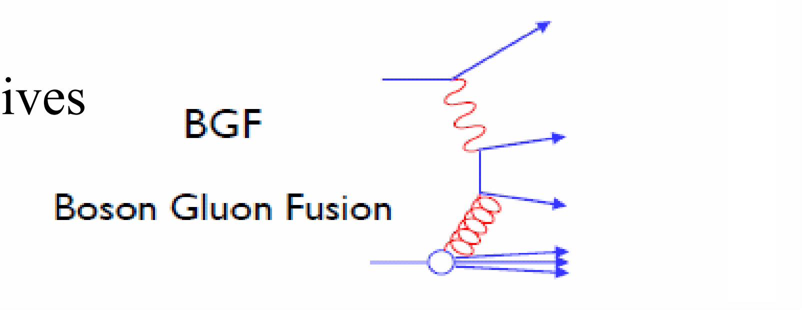
- A fit to determine both PDF and EW parameters
  -- Advantage: correlation automatically taken into account

- 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**

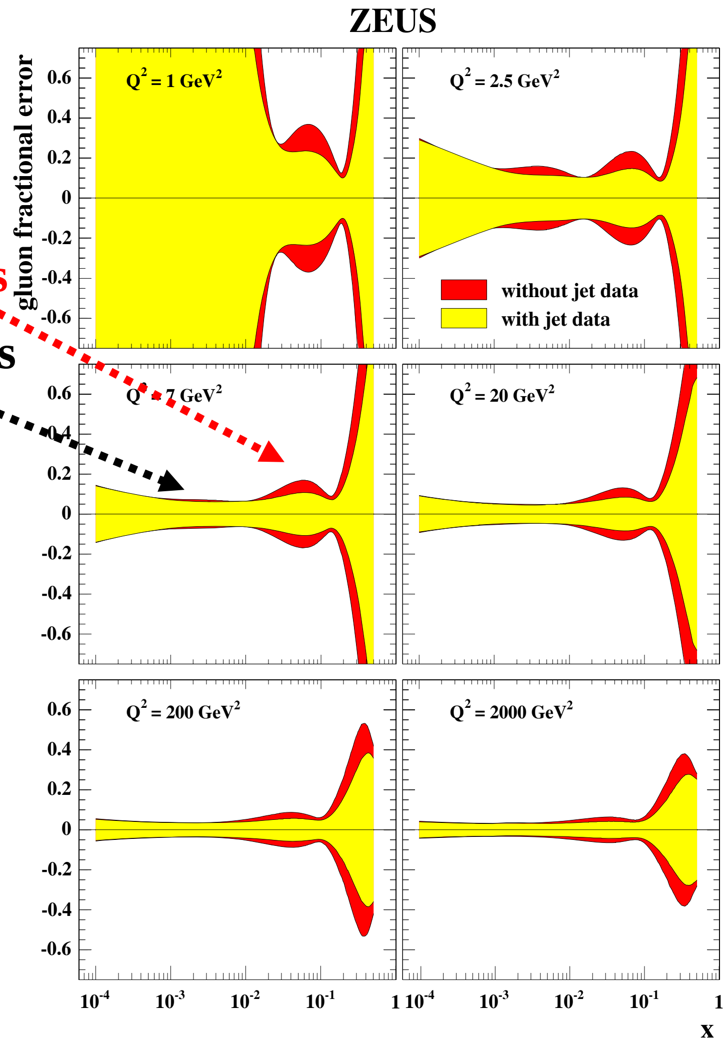
  -- Improved in particular at large x as expected, i.e.

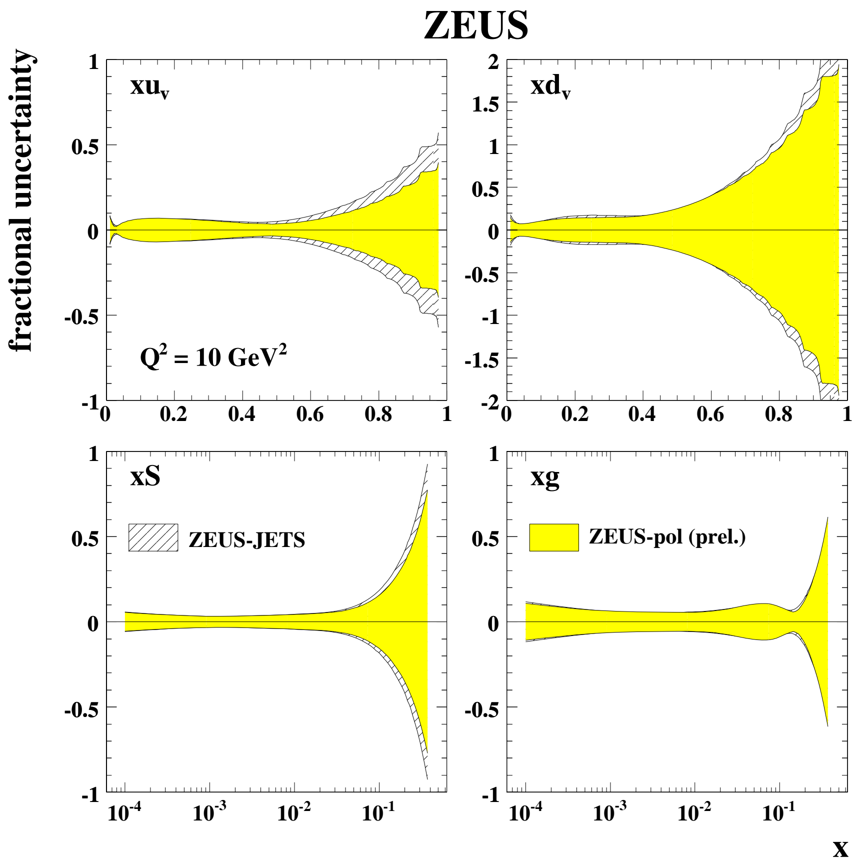
$$\sigma(NC) \propto 4u + d$$

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

W/O Jets

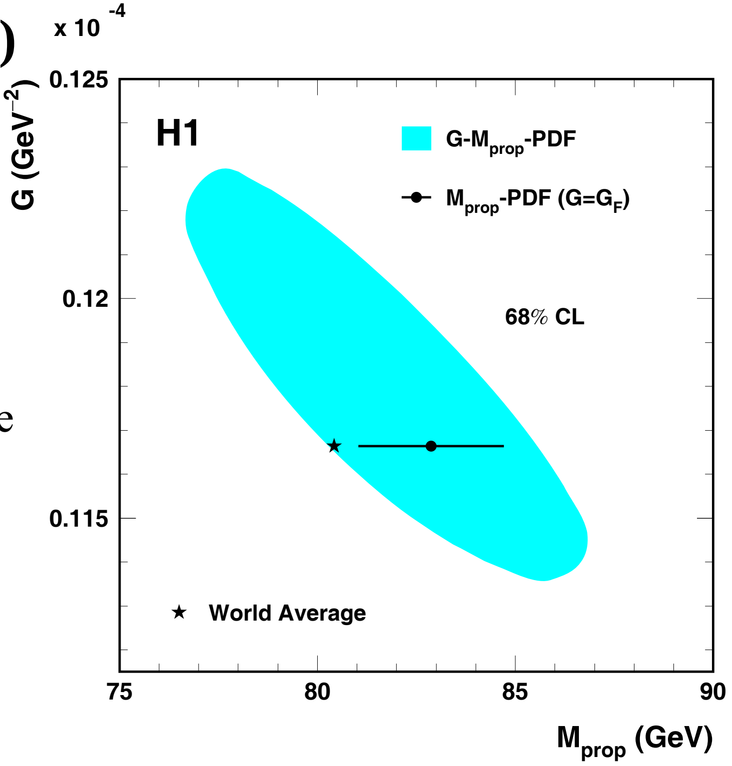
With Jets





Determination of M_W

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



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

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

Nb. M_W contributes both normalization and shape

➔ G_F obtained agree with muon decay "CC universality"

➔ With fixed G_F @ muon decay:

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

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

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

▶ Without assuming G_F: genuine propagator mass

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

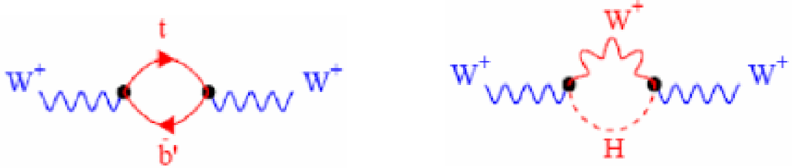
$$\mathrm{ZEUS}: M_W = 82.8 \pm 1.5\,(stat + uncor.syst) \pm 1.3\,(cor.syst)\ \mathrm{GeV}$$

M_W in the framework of SM

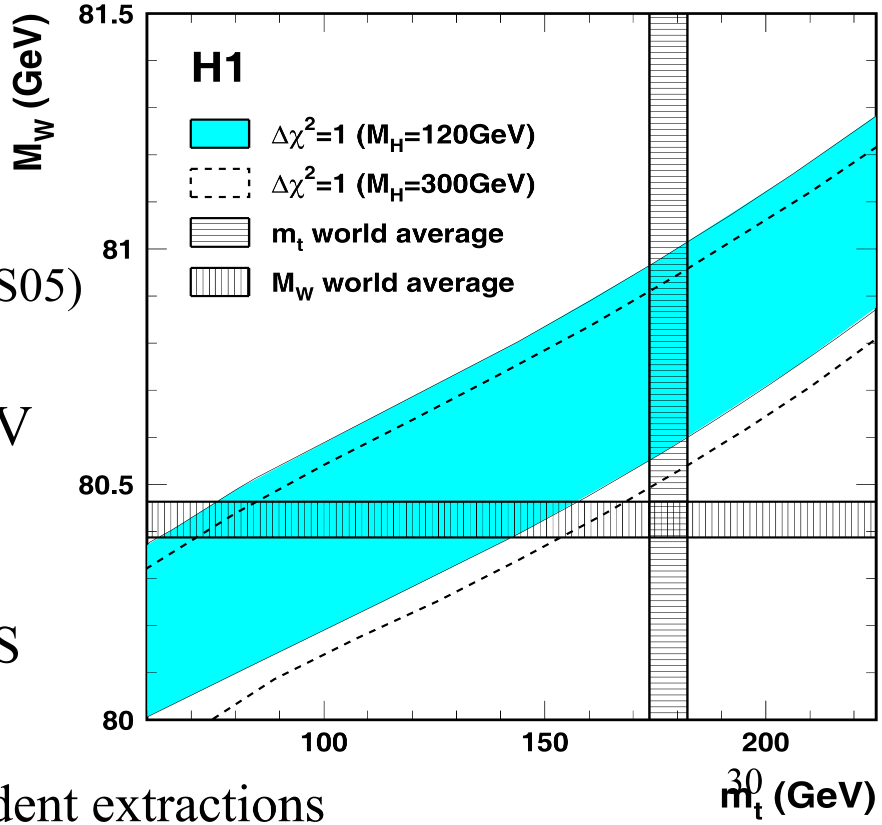
- In the SM G_F and M_W are related ➔ Fits fully assuming SM
  - -- On-Mass-Shell (OMS) scheme

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

Quadratic dependence on m_t Logarithmic dependence on M_H



(ref. Z.Zhang @ EPS05)



▶ A fit to M_W with M_Z fixed

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

▶ A fit to m_t with M_Z, M_w fixed

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

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

※ Nb. These are model-dependent extractions

Light quark couplings to Z

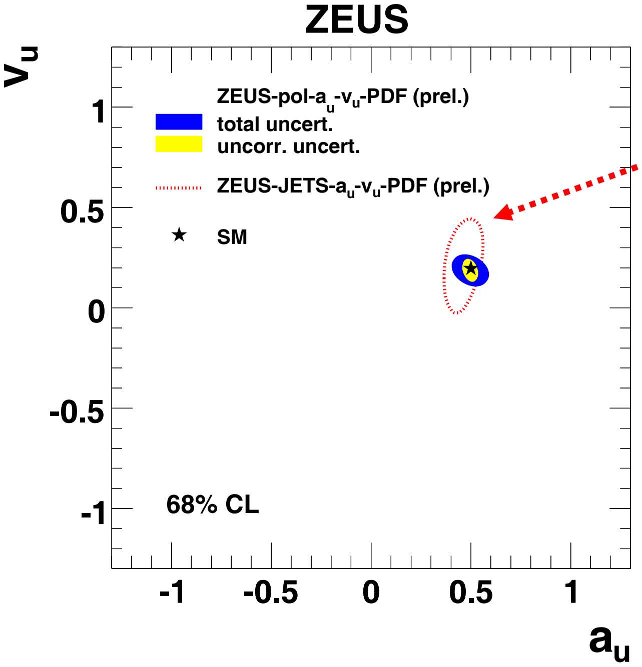
- EW structure functions in QPM

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

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

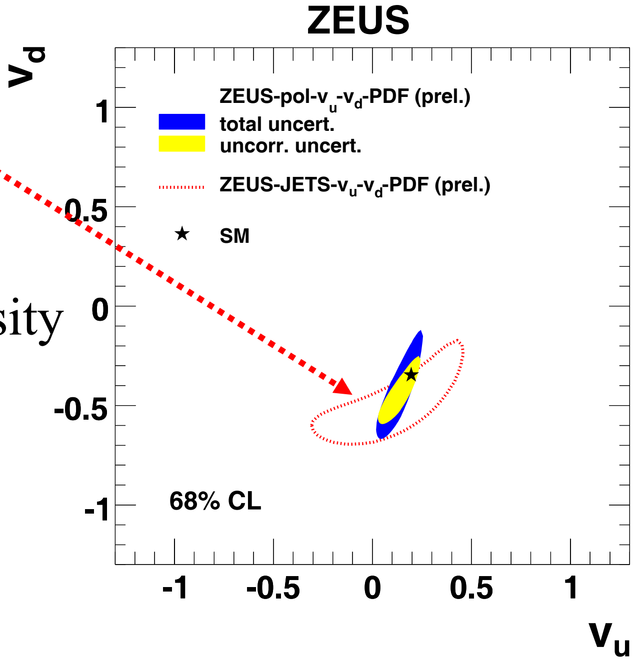
► A fit with V_u, A_u are free to be determined in addition to PDFs



w/o HERA-II

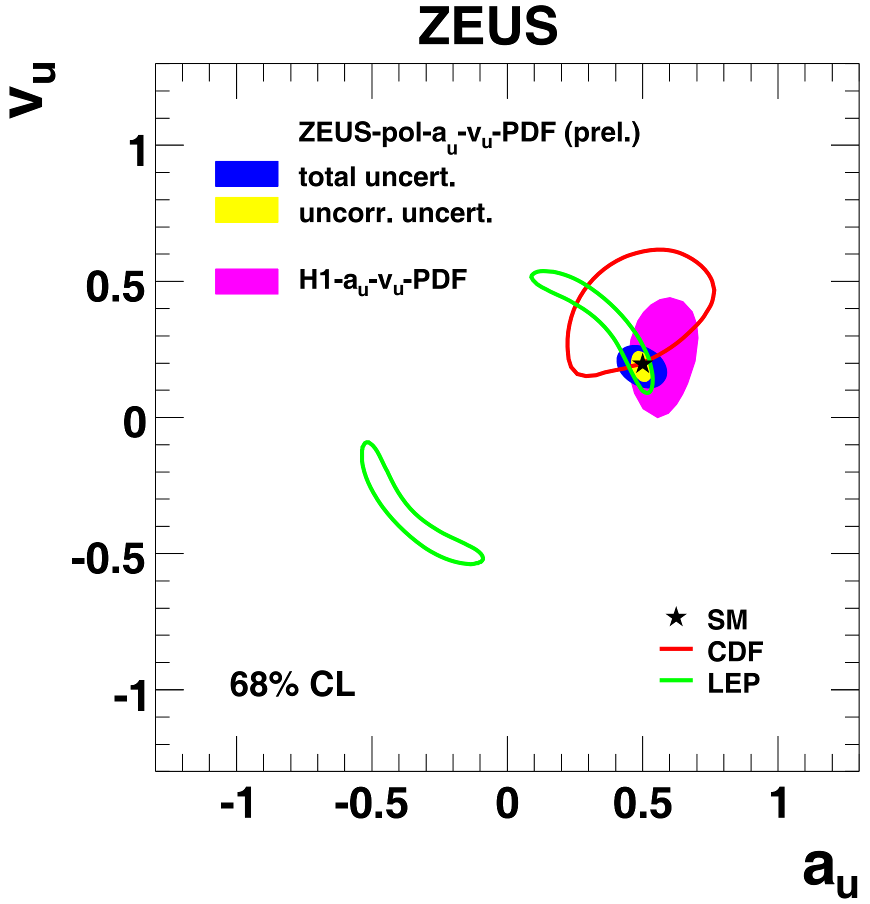
- Large luminosity
→ improves a
- Polarization
→ improves v

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

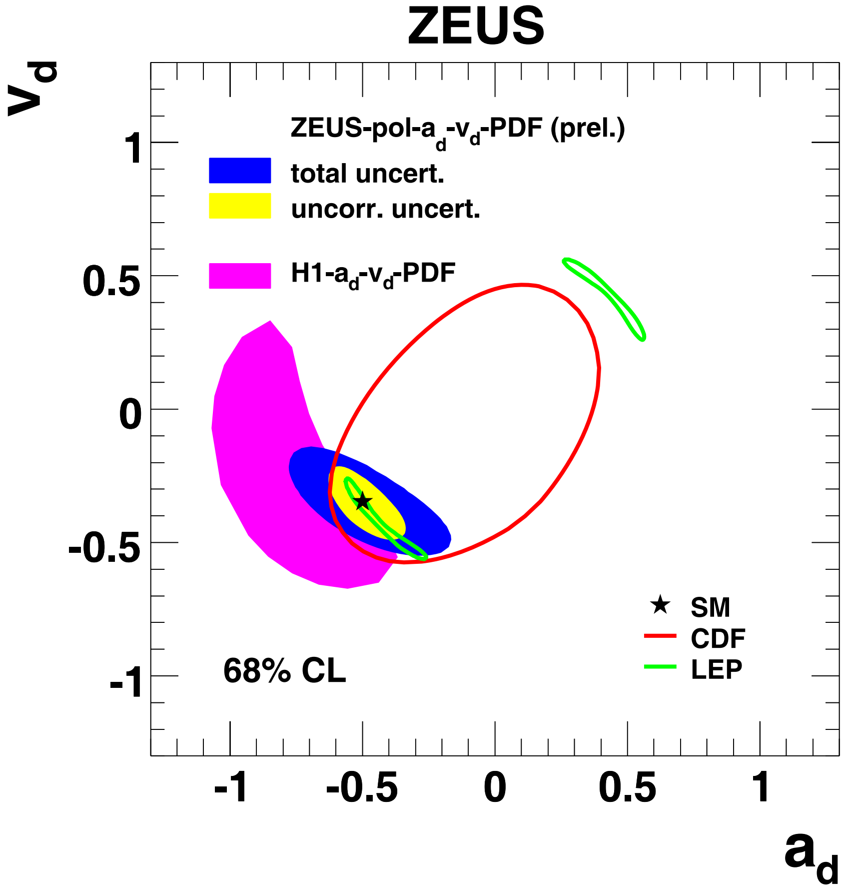


Quark couplings compared to other exp

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



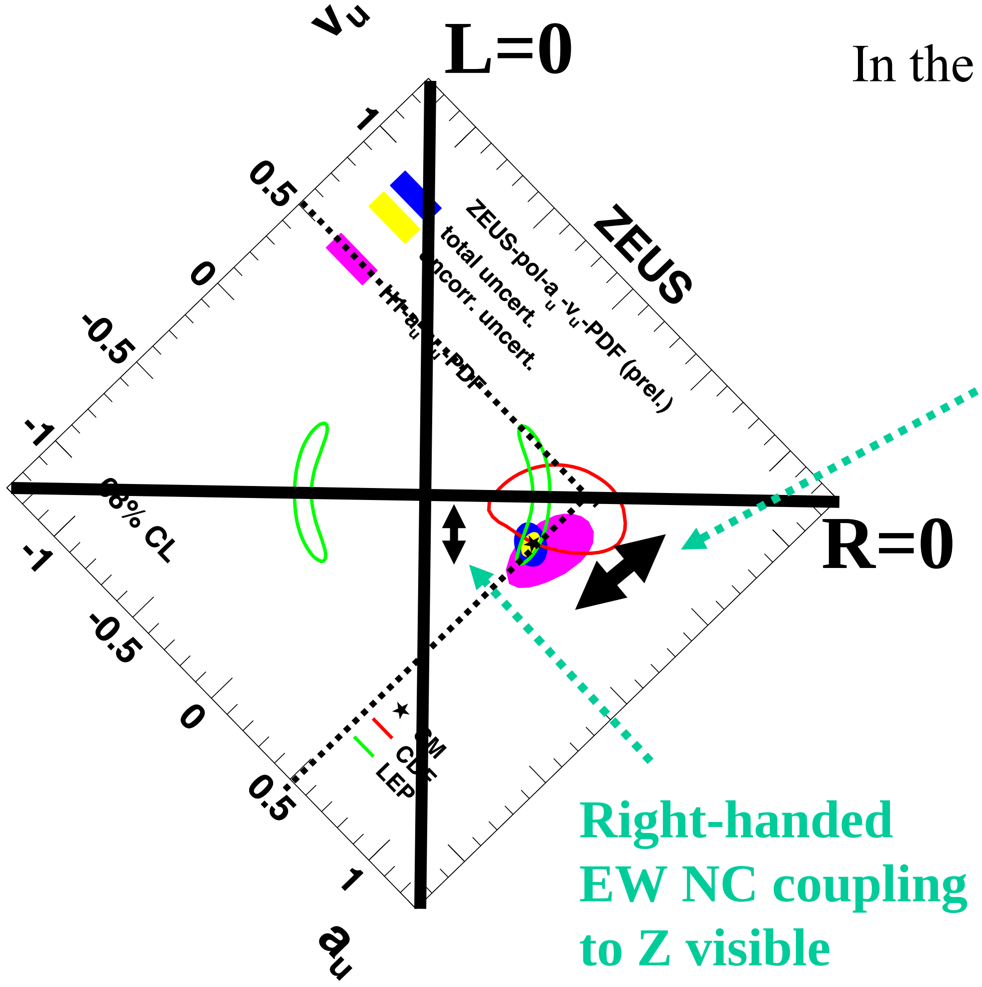
► A fit with V_d, A_d are free to be determined in addition to PDFs



- 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

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

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

$\sin^2\theta_W$ 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)

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**

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

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

► **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)**

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

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

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