Electroweak Analysis on Spin-Dependent DIS Cross Sections at HERA

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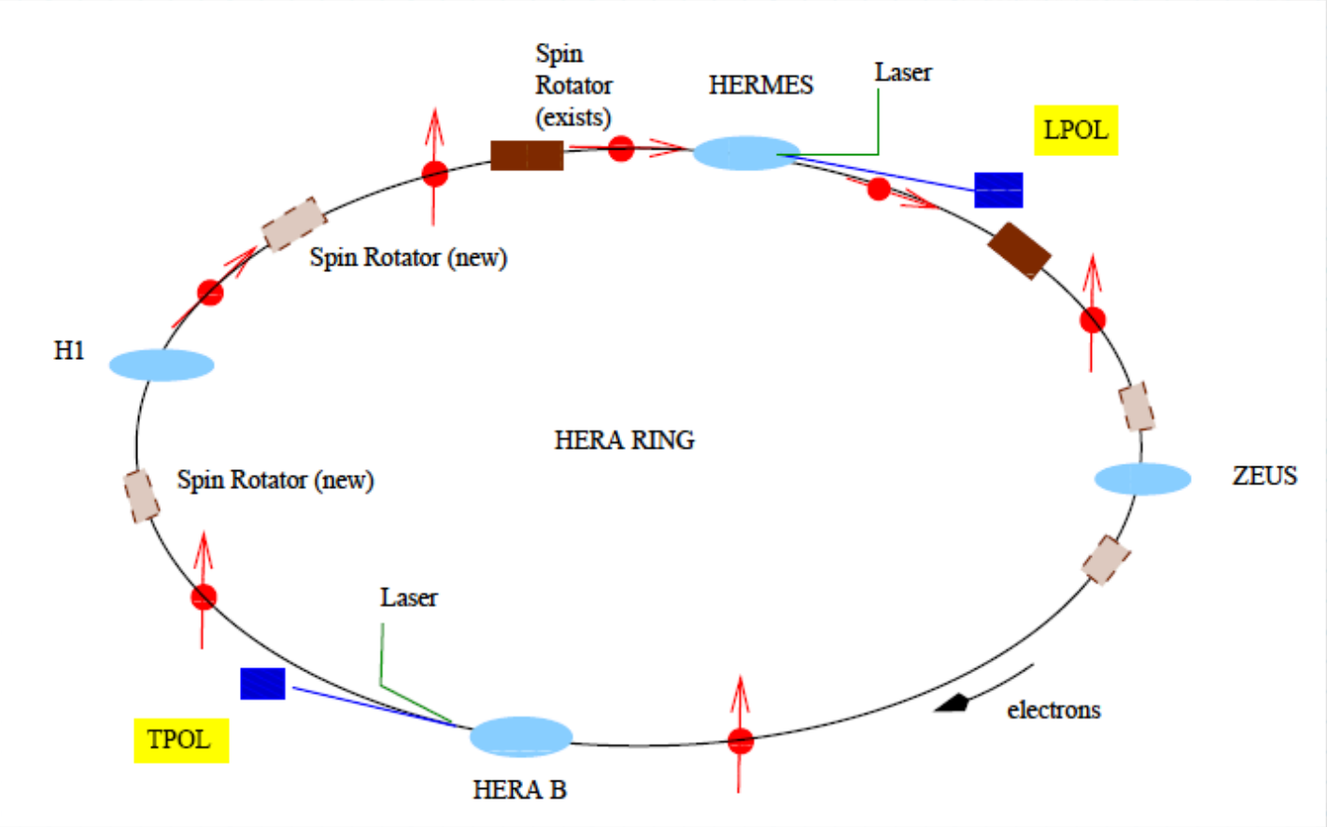
The HERA collider

* The only e-p collider in the world.
* 920 GeV p × 27.5 GeV $e^{\pm}$ → $\sqrt{s}$=320 GeV
* Highest $Q^2 \approx 40{,}000$ GeV^2 → probe the proton structure down to **0.001 fm**
* Running since 1991.
  Till 2000: HERA-I data
  (unpolarized $e^{\pm}p$ collision)

DESY, Hamburg

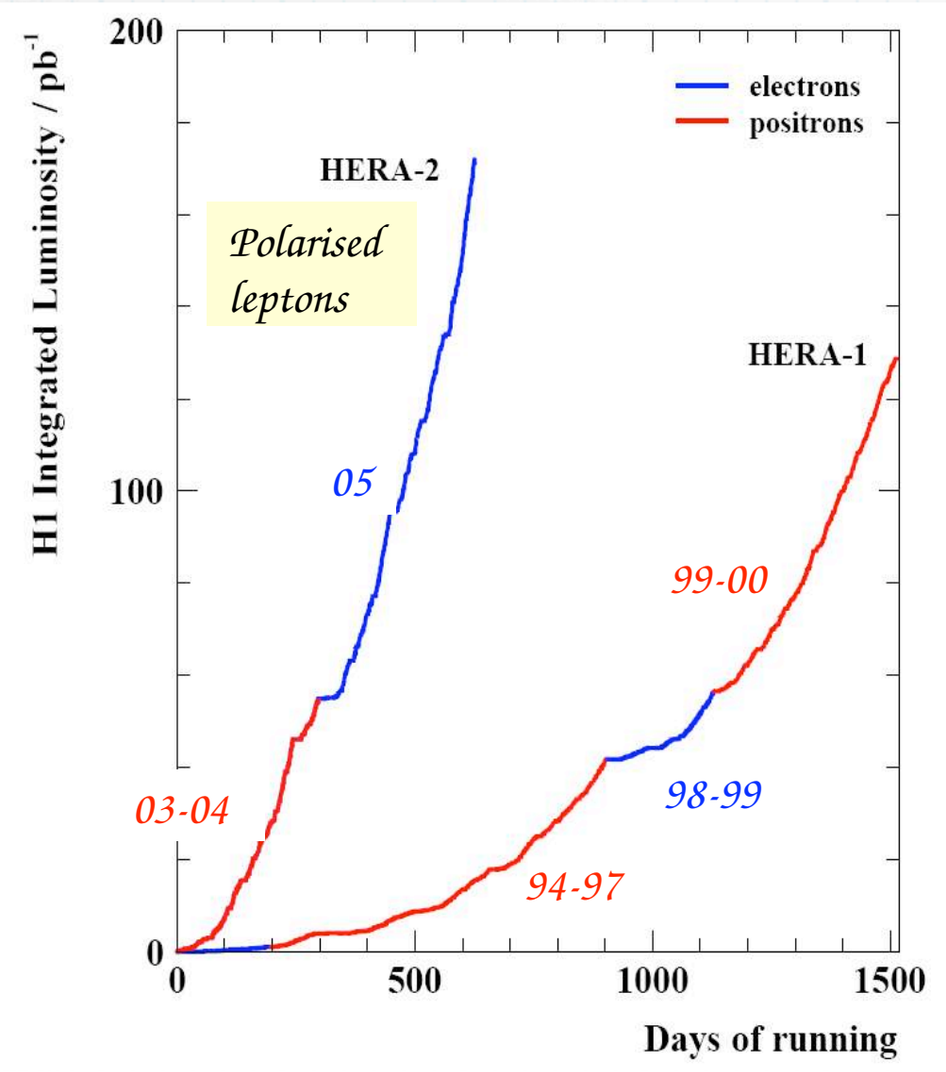
HERA upgrade: HERA-II

* 2001-2002: upgrade machine and exp'ts.
* (1) Higher luminosity: **5X**HERA-I
* (2) Longitudinally polarized $e^{\pm}$ beam for H1/ZEUS
  - Spin rotators
  - Available only to HERMES (fixed target) in HERA-I
* Elecroweak physics in DIS at high Q^2
  (Nb: no proton polarization
  →No proton-spin physics)



HERA-II performances

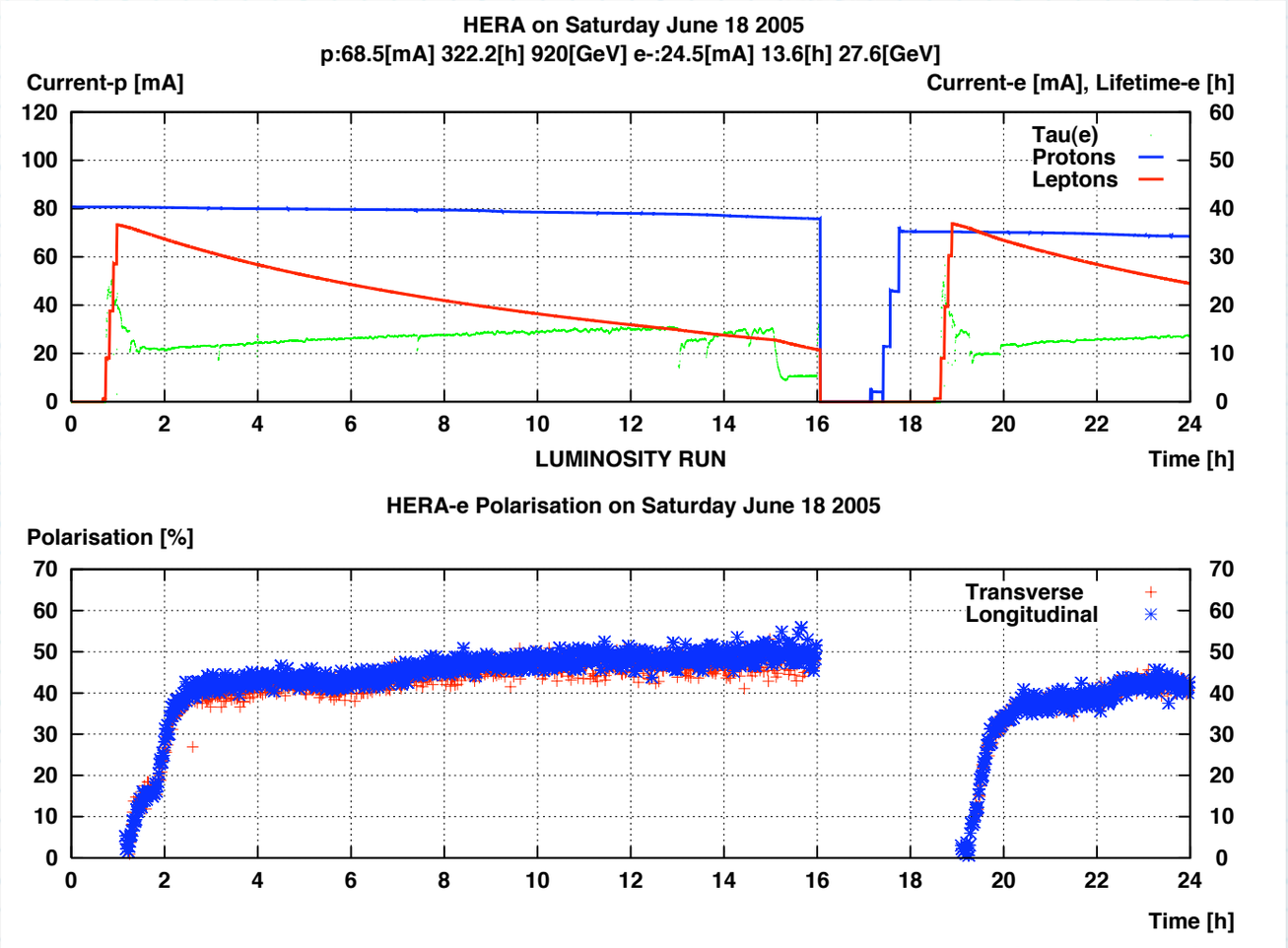
* Luminosity



	HERA-I	HERA-II
e-	~15 pb^{-1}	~110 pb^{-1}
e+	~110 pb^{-1}	~30 pb^{-1}

/exp't

* Polarization

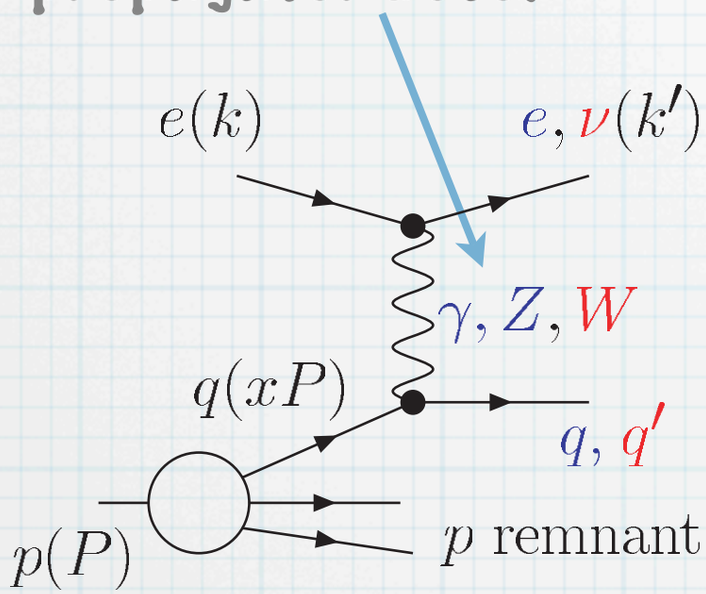


Average polarization ≈30-40%

Balanced amount for left- and right-handed

Lepton-hadron scattering (DIS)

t-channel (space-like) propagator boson



$$Q^2 = -(k-k')^2$$

$$x = \frac{Q^2}{2P\cdot(k-k')}$$

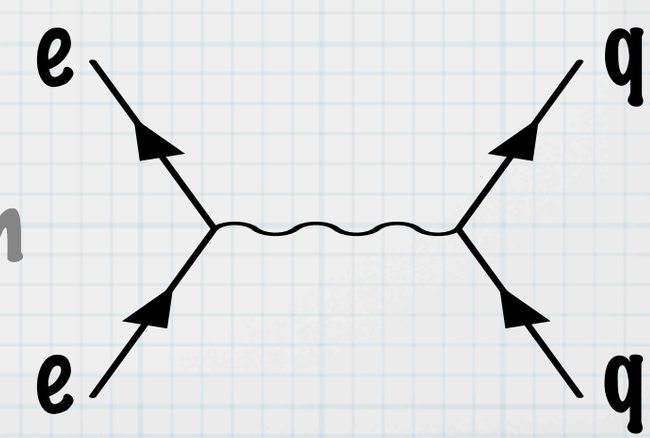
$$y = \frac{P\cdot(k-k')}{P\cdot k}$$

* Virtuality Q^2: resolving power
* Bjorken x: parton distribution (PDF)

$\sigma \approx$ (coupling)$^2 \times$ propagator $\times$ PDF(x,Q^2)

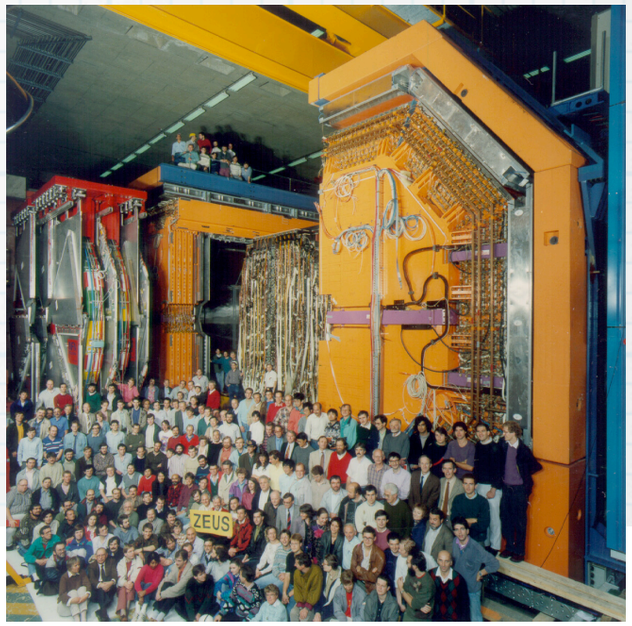
Electroweak QCD

cf. LEP, TeVatron: s-channel (time-like) boson

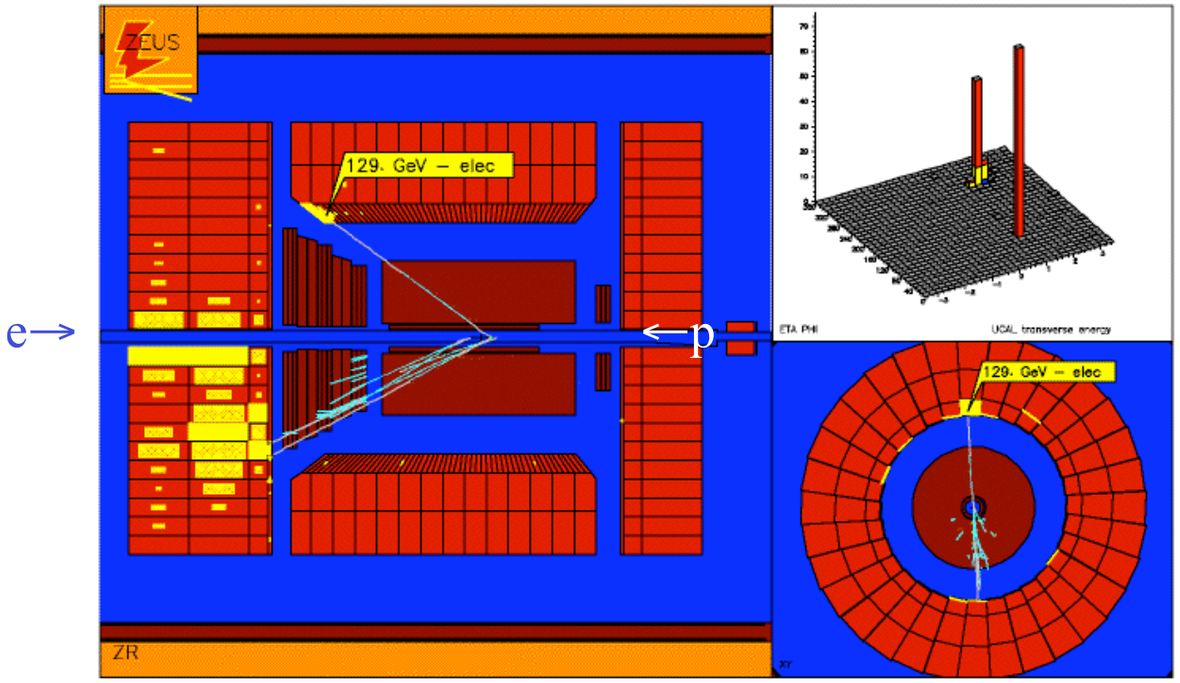


Collider detectors @ HERA

- ZEUS Detector
  - Uranium-Scintillator calorimeter
    - $\sigma(E)/E = 18\%/\sqrt{E}$ for electrons
    - $\sigma(E)/E = 35\%/\sqrt{E}$ for hadrons
  - Central tracking detector
    - $\sigma(p_T)/p_T =$
      $0.0058\,p_T \oplus 0.0065 \oplus 0.0014/p_T$



- H1 Detector
  - Liquid-Ar calorimeter
    - $\sigma(E)/E = 12\%/\sqrt{E}$ for electrons
    - $\sigma(E)/E = 50\%/\sqrt{E}$ for hadrons
  - Central tracking detector



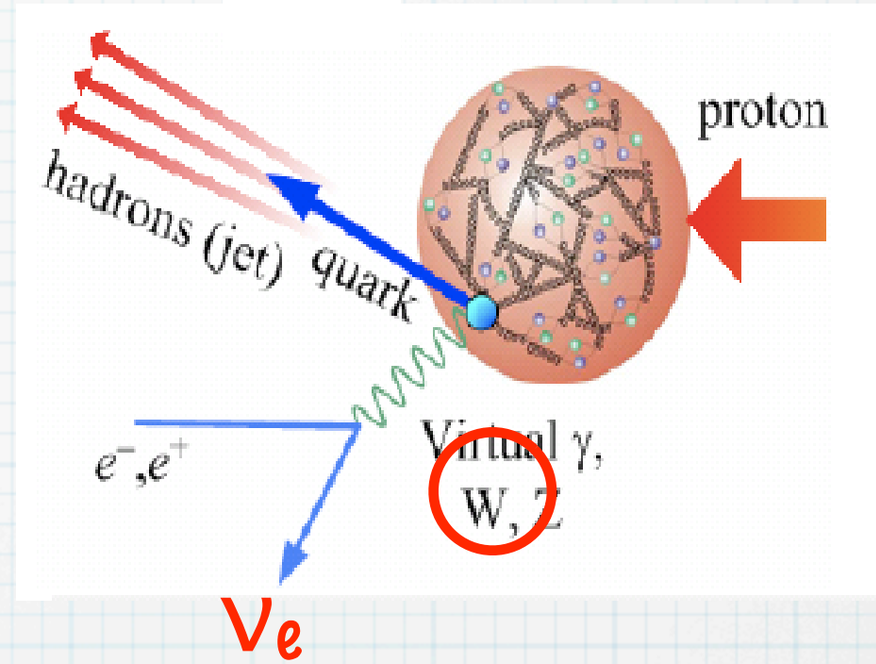
2 out of $(E_e, \theta_e, E_h, \theta_h)$
→ Reconstruction of (x, Q^2)

Polarized DIS cross sections

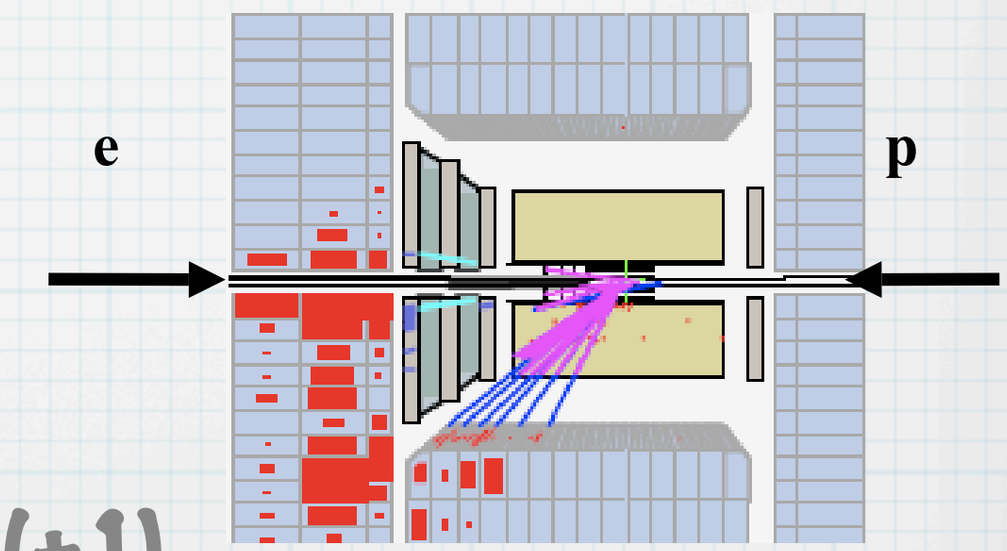
* **Charged Current (CC)**
  e^+ and e^- interact with different quarks

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

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



* **W is pure left-handed: Cross section is linear to Pol.**
  $\sigma^{\pm}(\mathrm{Pol}) = (1\pm\mathrm{Pol})\ \sigma(\mathrm{Unpol})$

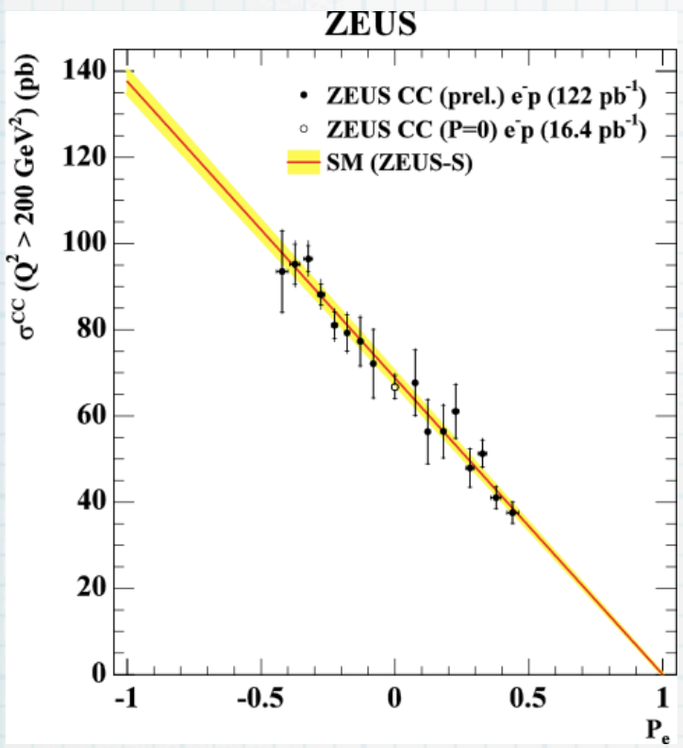


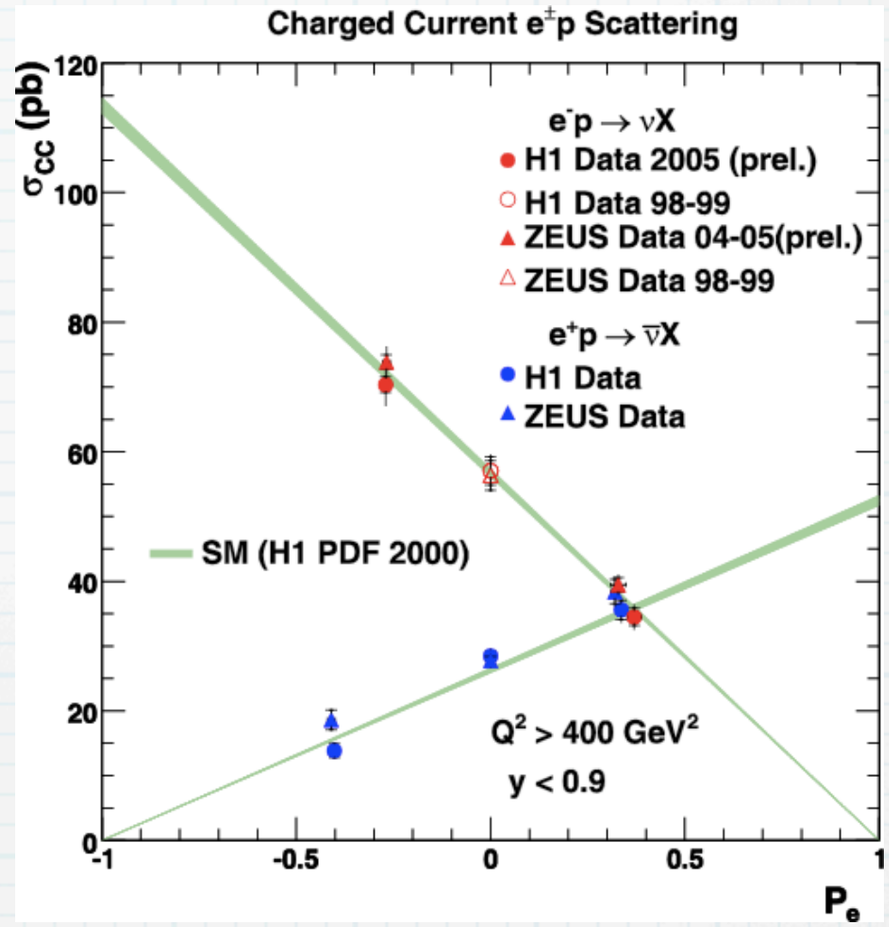
$e^+p(e^-p)$ xsec vanishes for P=-1(+1)

$y=Q^2/sx$=inelasticity=$(1-\cos\vartheta^*)/2$ in e-q CMS

Polarized CC: results

* Total cross section





* Clear left-handed nature of weak currents
* Extrapolation to P=±1 → limits on W_R (assuming $g_L=g_R$ and light ν_R)

  $m(W_R) > 208$ GeV @ 95% C.L. (H1 e^+ data)

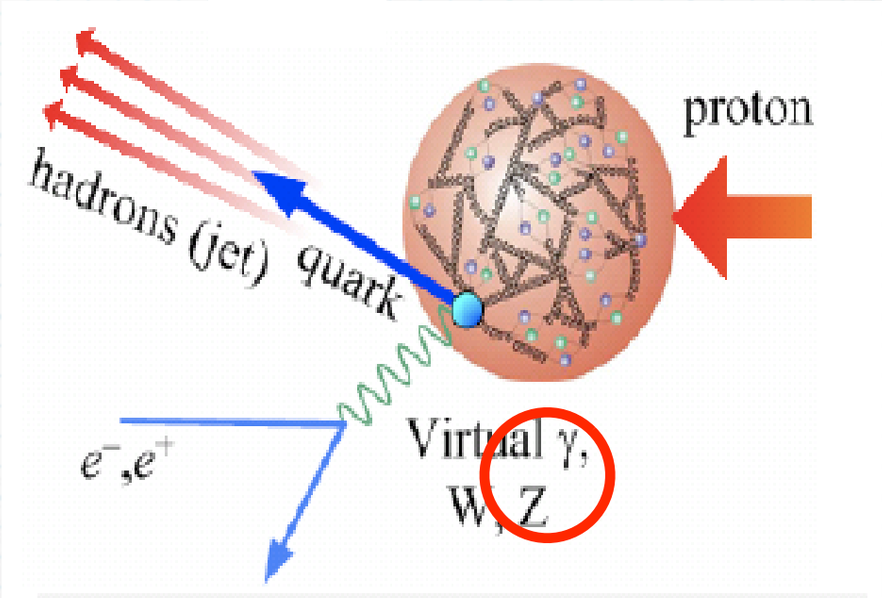
Neutral current DIS

* Cross section

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

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

For simplicity, xF_3 is written as F_3 in the following.



* Structure functions (unpol.)

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

pure γ (EM) γ-Z interference (1st order EW) pure Z (2nd order EW)

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

→ only visible at high Q^2 ($Q^2 >\sim M_Z^2$)

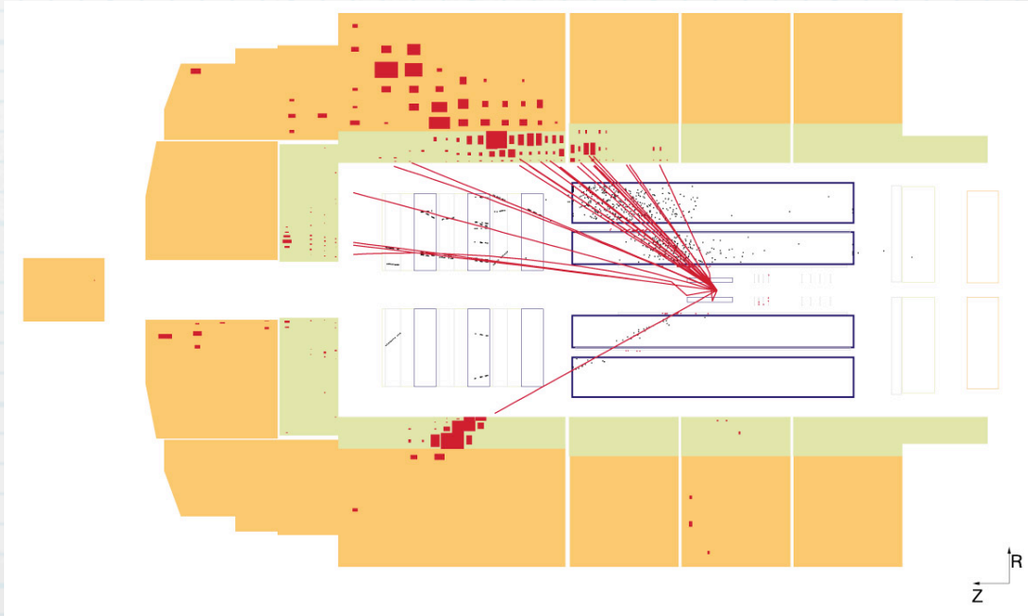
* Electroweak couplings

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

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

$2\sin^2\theta_w \sim 1/2 \rightarrow v_e \sim 0$

EW effects in unpol. DIS → only visible is $F_3^{\gamma Z}$: $\sigma(e^-) - \sigma(e^+)$



Polarized NC DIS

* Structure functions (pol.)

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

pure γ (EM) γ-Z interference (1st order EW) pure Z (2nd order EW)

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

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

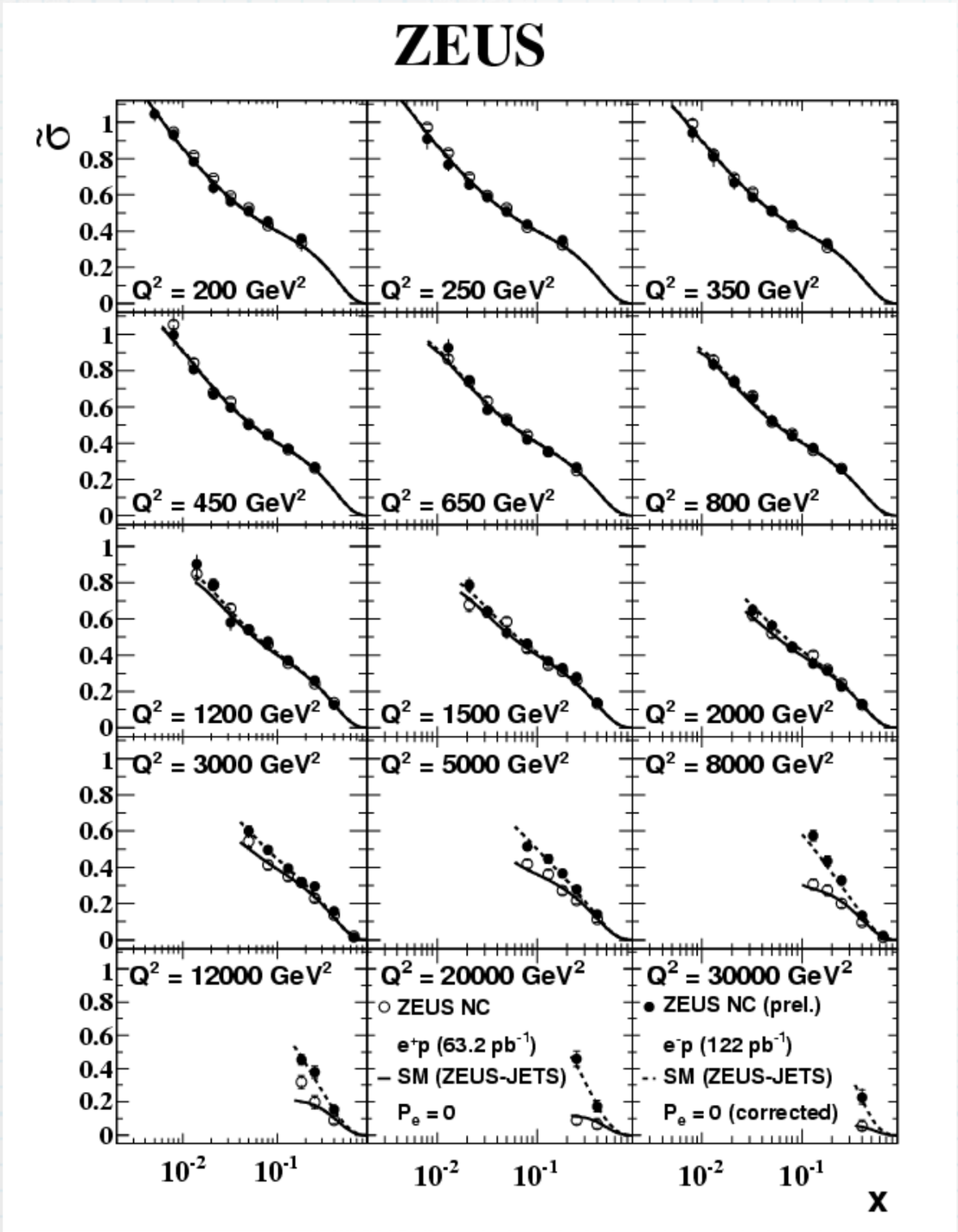
$v_e \sim 0 \Rightarrow$ Lepton polarization gives access to $F_2^{\gamma Z}$: $\sigma(e_R) - \sigma(e_L) \Rightarrow v_f$ of quarks

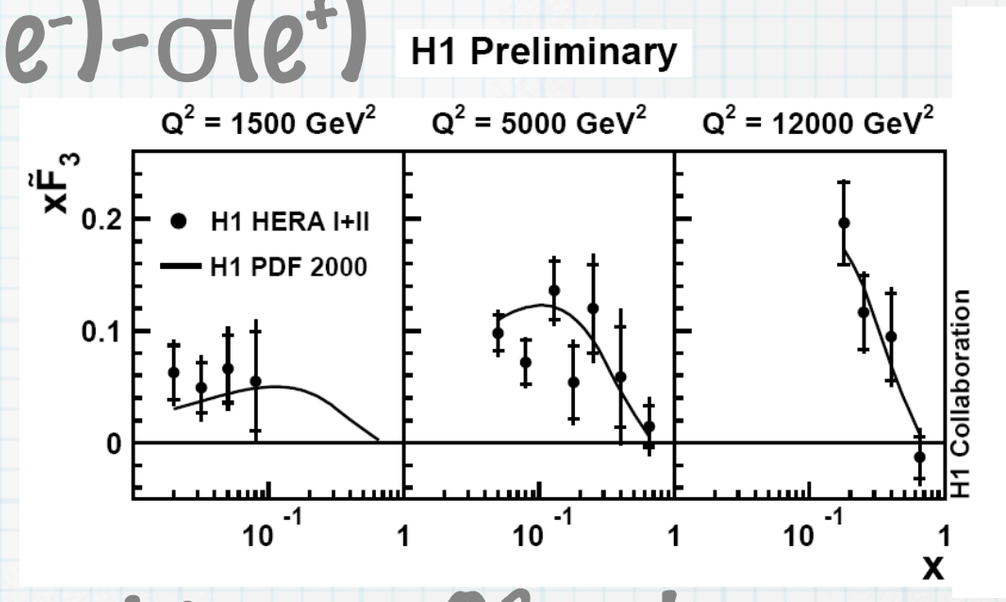
As shown before, $\sigma(e^-) - \sigma(e^+)$ gives $F_3^{\gamma Z} \Rightarrow a_f$ of quarks (and valence-quark PDF)

* Four lepton beams (+ and -, L and R) give vector- and axial-vector coupling of quarks (mainly u and d quarks)

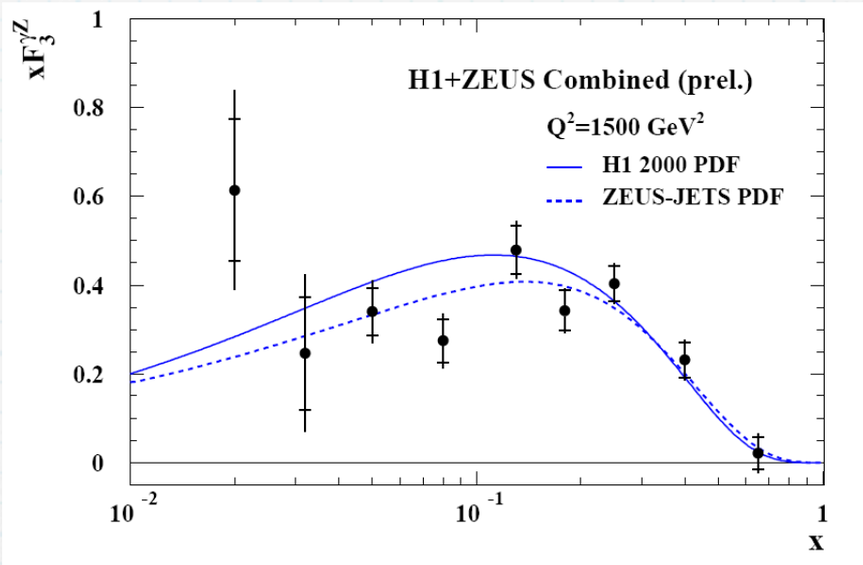
NC DIS results (1)

* xF_3 determination from $\sigma(e^-)-\sigma(e^+)$





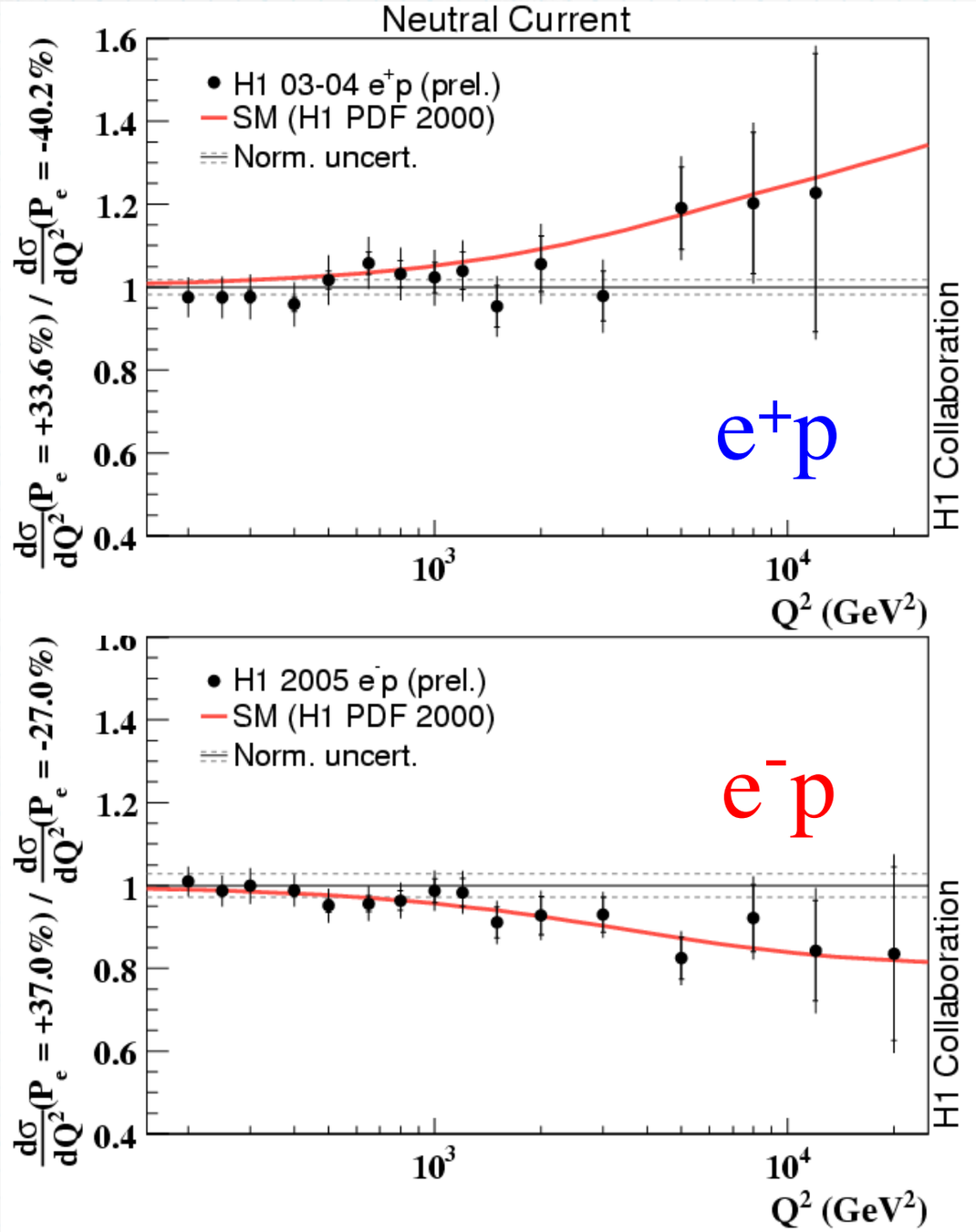
Combined to one Q^2 value:



Valence PDF determination at large Q^2: complementary to neutrino DIS data at low Q^2.

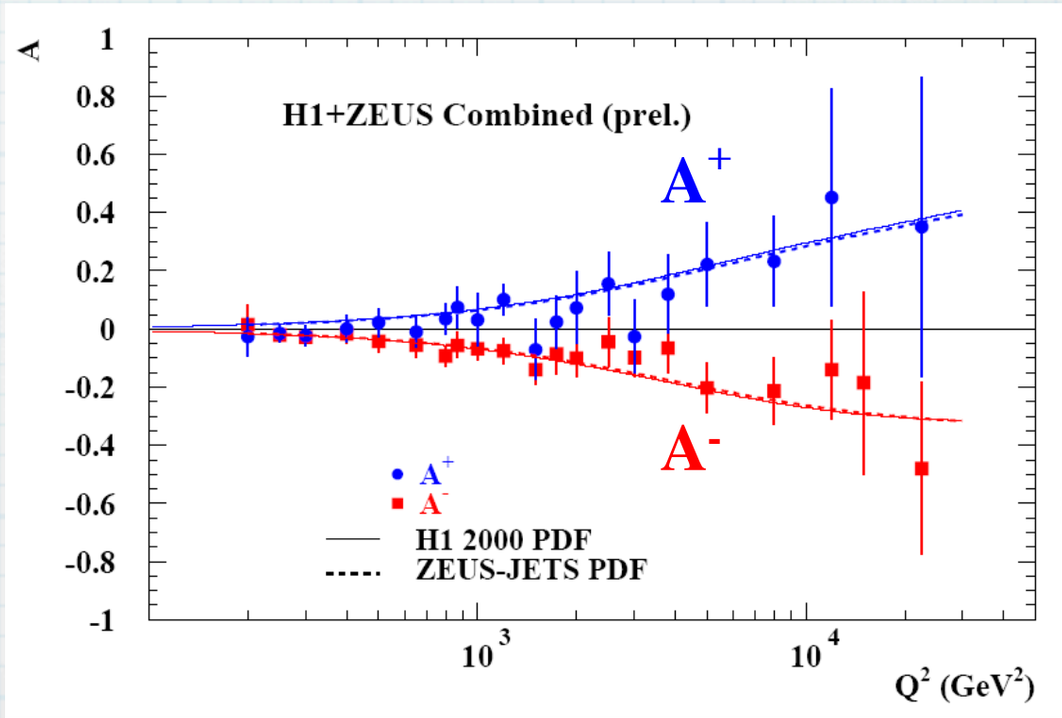
NC DIS results (2)

* Polarization asymmetry at high Q^2



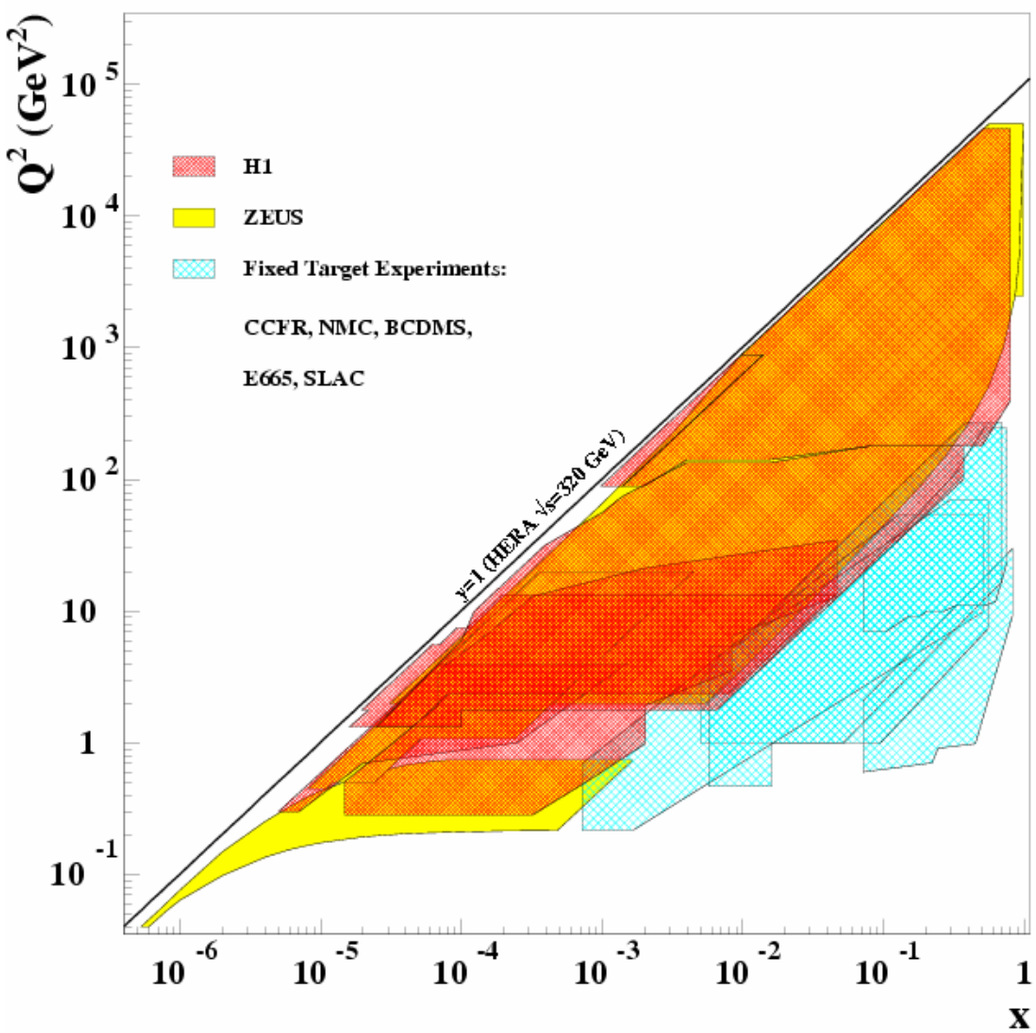
* Parity violation in weak neutral current at EW scale: observed for the first time in DIS

$$A^{\pm} = \frac{2}{P_R - P_L} \cdot \frac{\sigma^{\pm}_{NC}(P_R) - \sigma^{\pm}_{NC}(P_L)}{\sigma^{\pm}_{NC}(P_R) + \sigma^{\pm}_{NC}(P_L)} \qquad \begin{matrix} P_R > 0 \\ P_L < 0 \end{matrix}$$



Combined QCD & EW fits

HERA kinematic plane



③ Based on own knowledge of PDFs, EW parameters can be extracted at high-Q^2

② Perturbative QCD can predict the Q^2 evolution of PDFs, DGLAP equation

① x-dependence of PDFs at initial scale, Q^2_0 are determined from fits to the measured cross sections at low Q^2

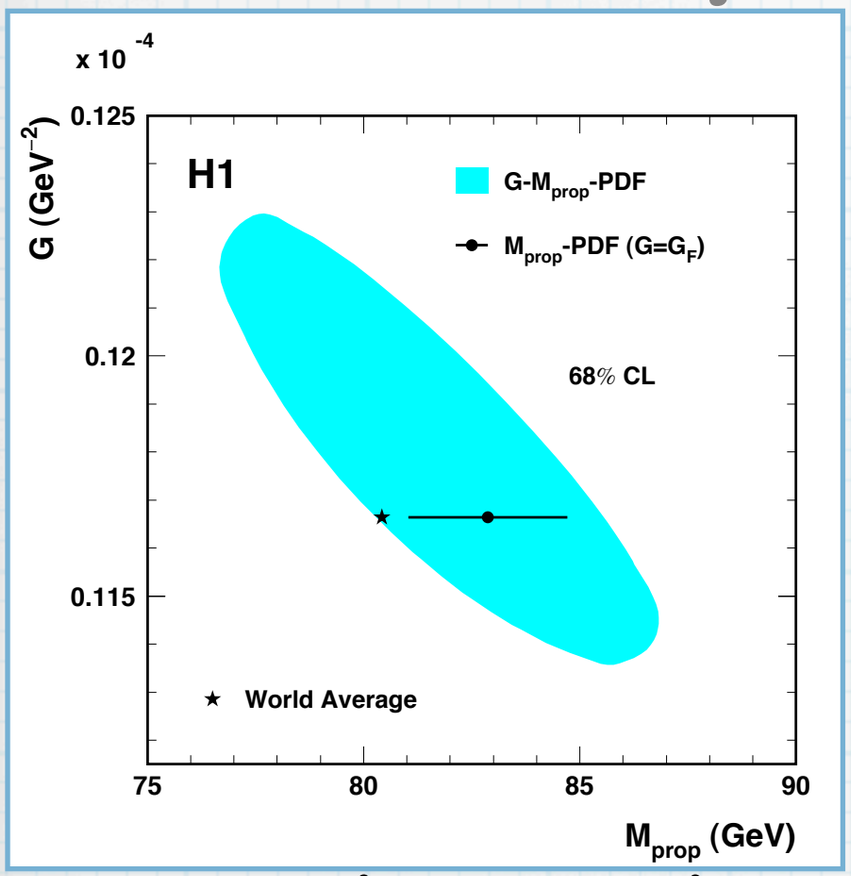
Such a unique study, the simultaneous determination on PDFs and EW parameters, is only possible at HERA!

5

* Y. Ri, ICHEP06

M_W determination from CC

* Model-independent M_W-G_F fit (H1, unpol.)



$$\sigma(\mathrm{CC}\,@\,\mathrm{HERA}) \propto G_F^{\,2}\left(\frac{M_W^{\,2}}{M_W^{\,2}+Q^2}\right)^2$$ **t-channel propagator**

Latest ZEUS M_W fit on HERA-I+II data (G_F fixed)

$$M_W = 79.1 \pm 0.77(stat+uncorr) \pm 0.99(corr.sys.)\,[\mathrm{GeV}]$$ (prel.)

* Model-dependent EW analysis: use full SM correlation

Loop correction (m_{top}, m_{Higgs})

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

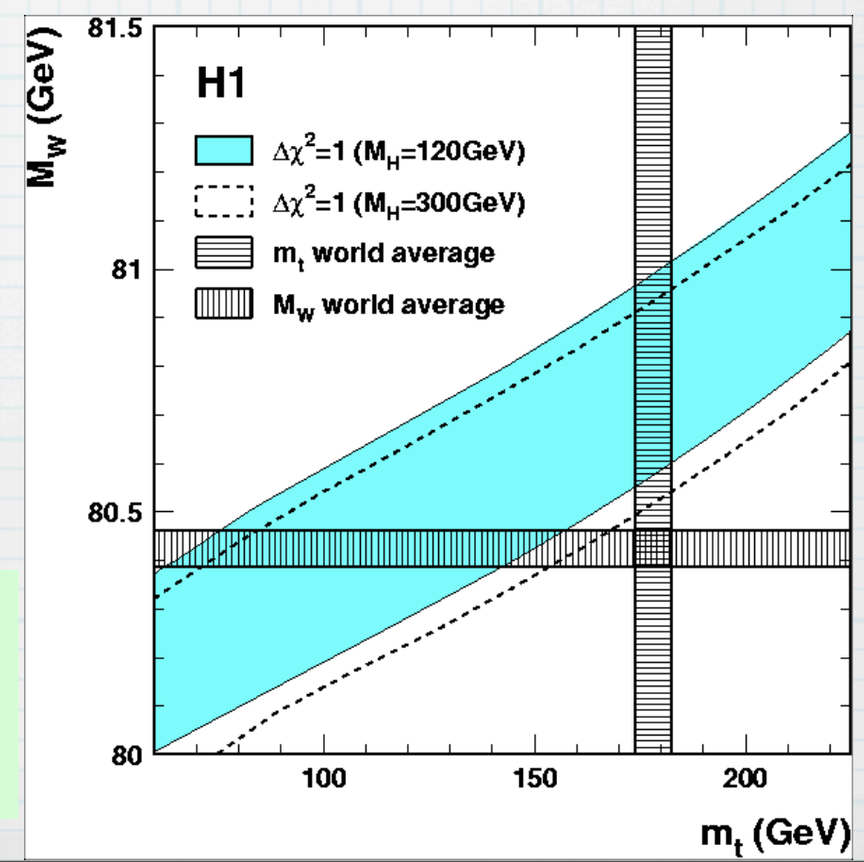
- ▶ A fit to M_W with M_Z, m_t fixed:

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

- ▶ A fit to m_t with M_Z, M_W fixed:

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

Complementary and consistent results to M_W determined at s-channel in LEP/TeVatron

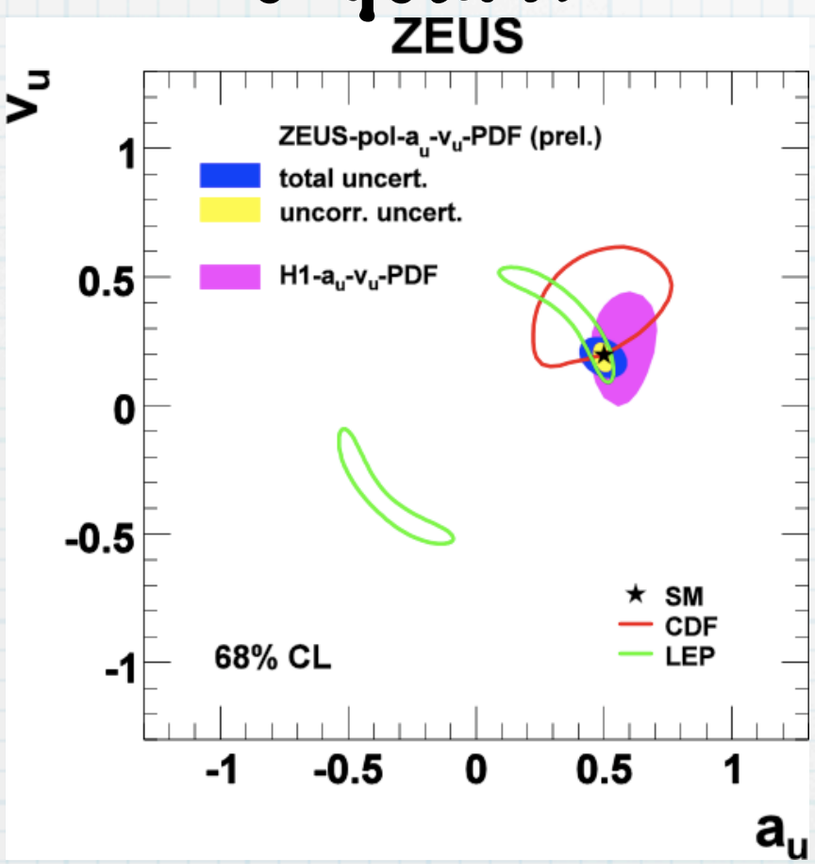


Light-quark NC couplings

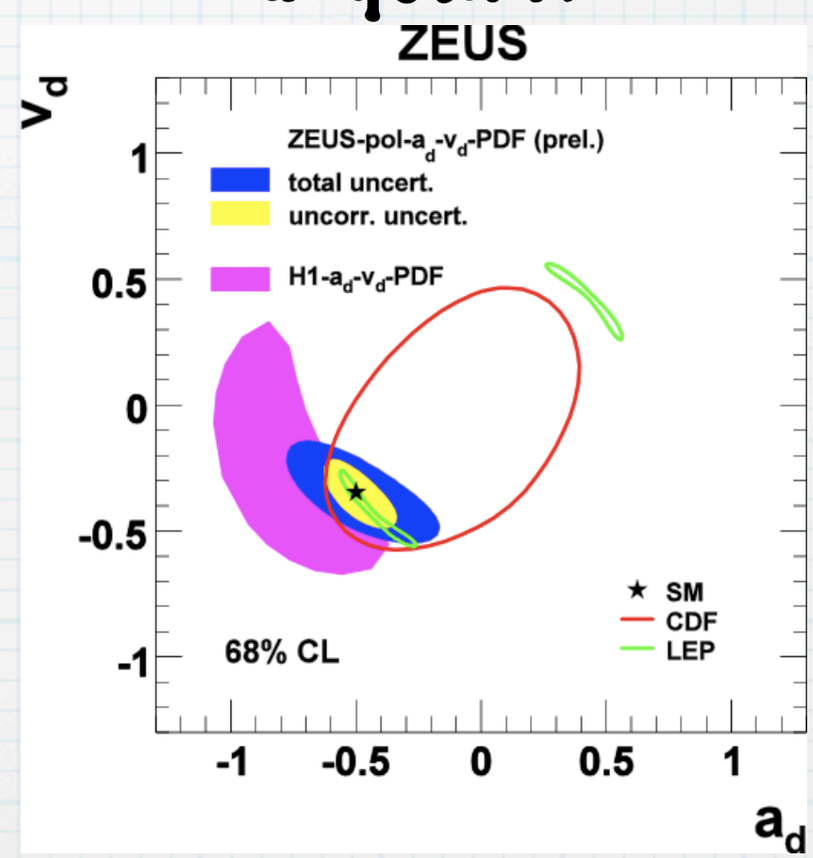
* ZEUS-POL fit on HERA-I low-Q^2, high-Q^2 $e^{\pm}$, Jets data + HERA-II pol NC/CC (e^-)

H1 (unpol.)

u-quark



d-quark



* Clear improvement using pol. data.
* Better precision than TeVatron, LEP.

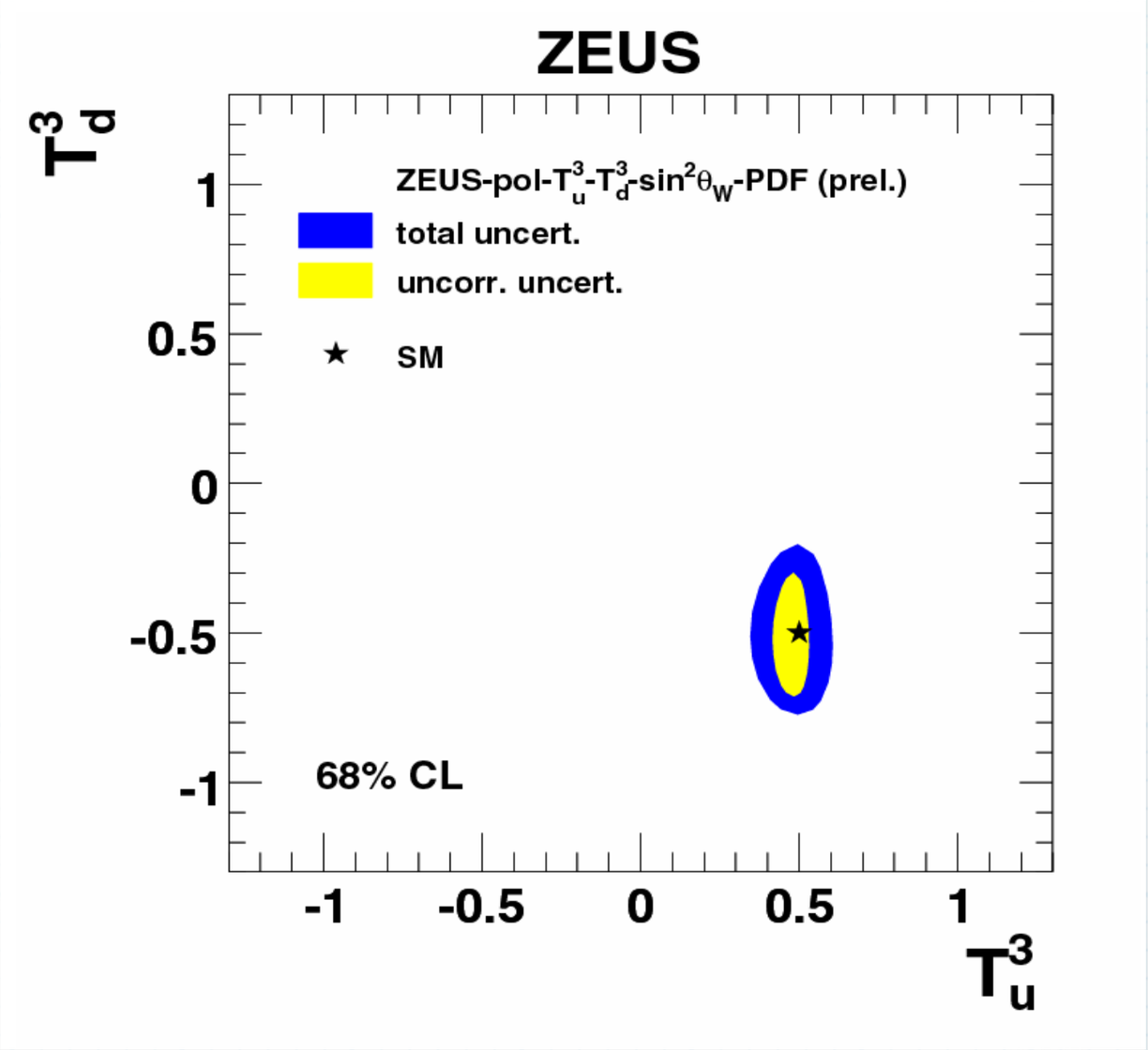
Testing SM

* Determine weak isospin of quarks & $\sin^2\theta_W$

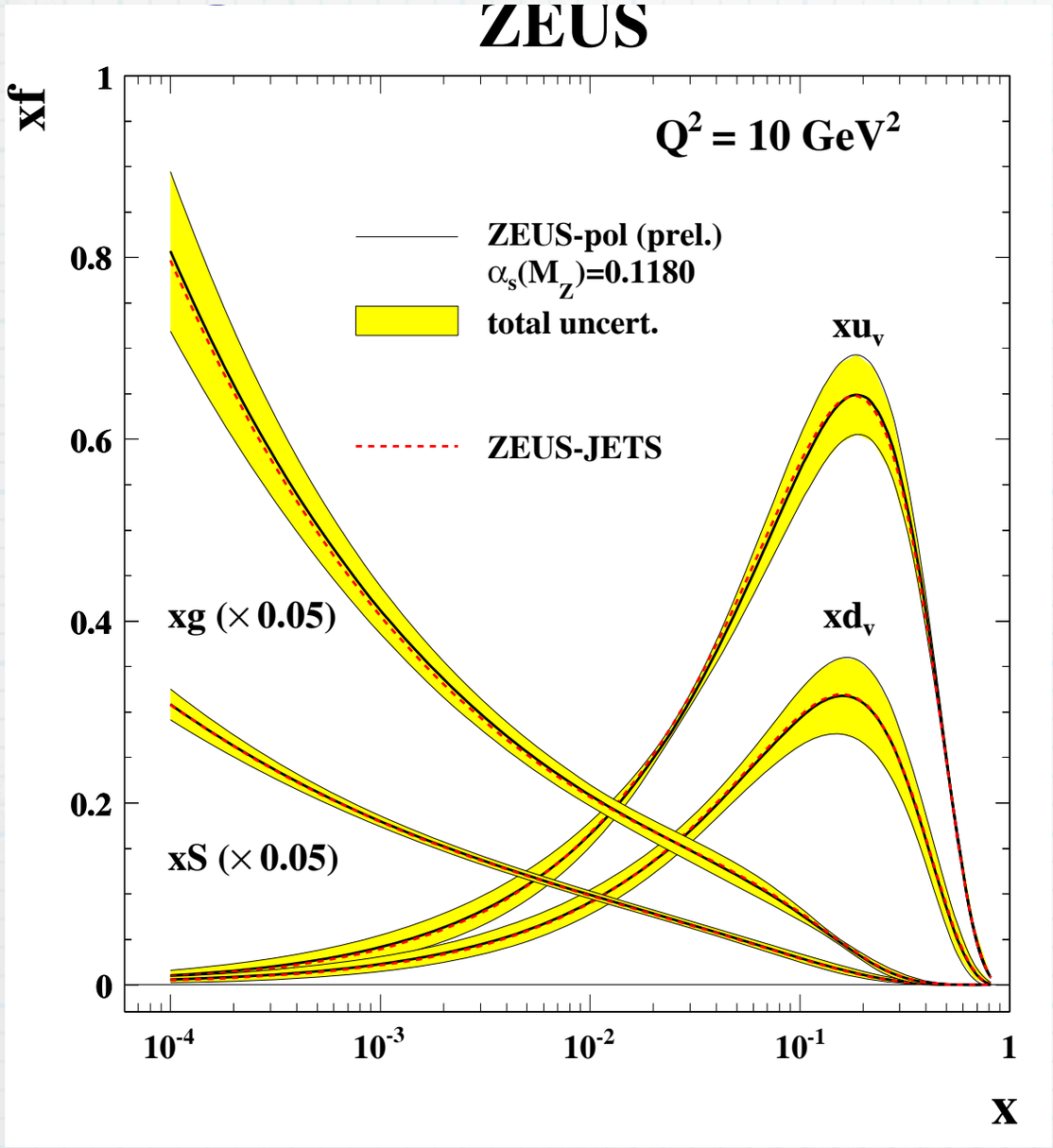
$$v_f = T^3{}_f - 2e_f \sin^2\theta_W$$

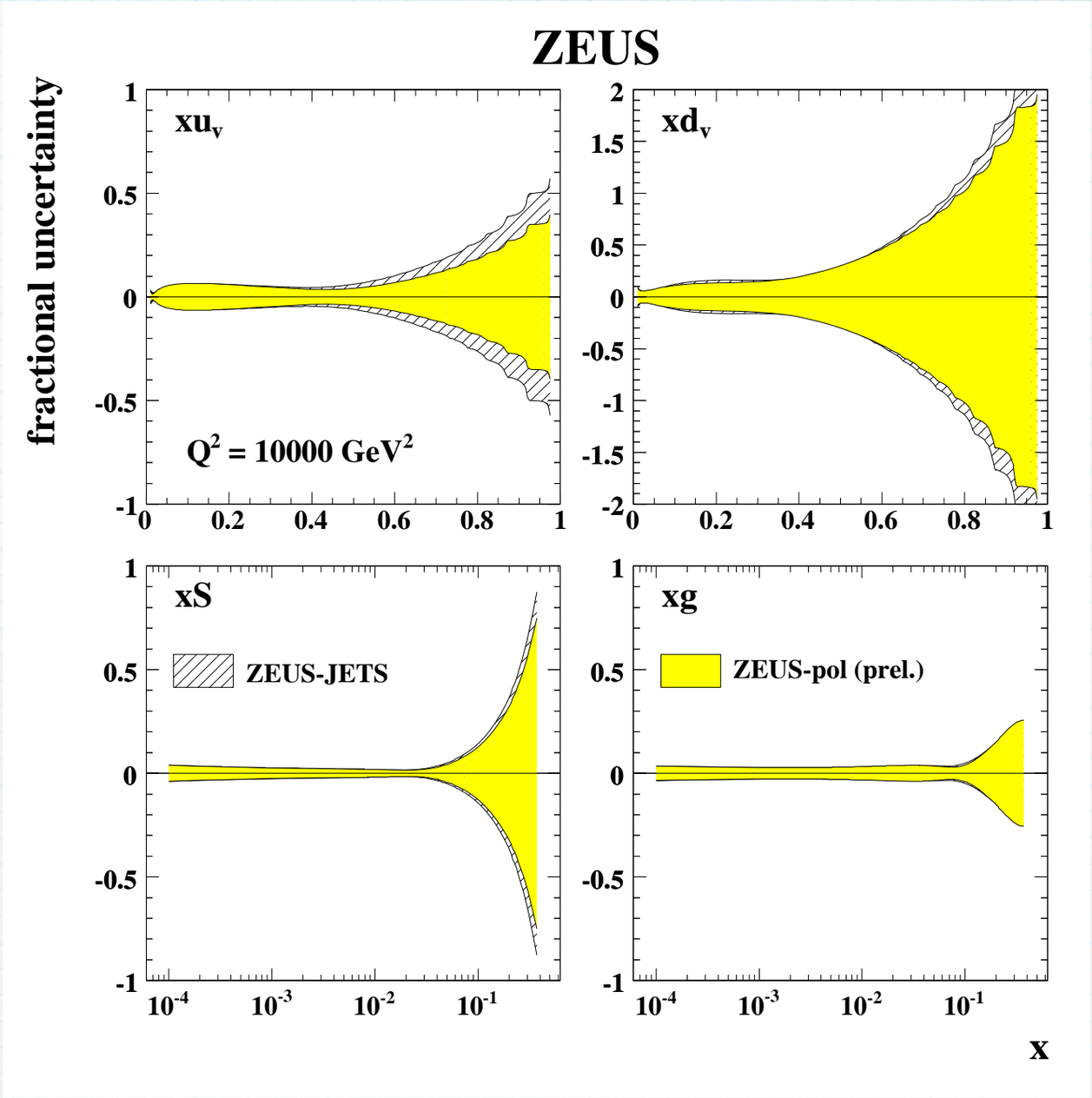
$$a_f = T^3{}_f$$

	ZEUS-POL-T_u^3-T_d^3-$\sin^2\theta_W$
T_u^3	0.47±0.05±0.13
T_d^3	-0.55±0.18±0.35
$\sin^2\theta_W$	0.231±0.024±0.070



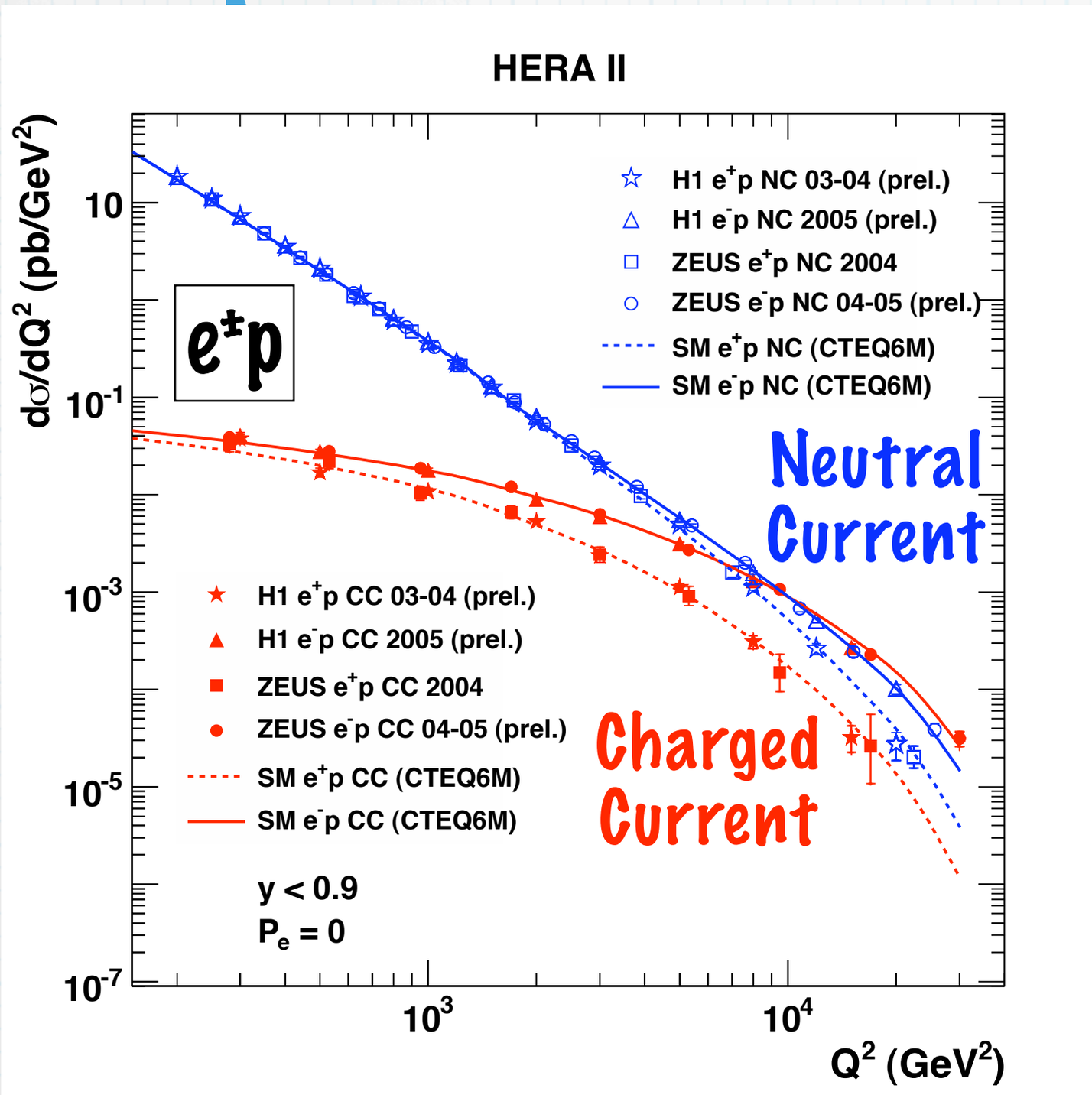
Obtained PDFs





* Improved precision at large Q^2
  → good news for LHC physics

Updated "unification plot"



* At low Q^2: **EM** and **weak** forces are much different. (large W mass)
* At EW scale: Two forces unify to **Electroweak** interaction.

Now ← Big Bang

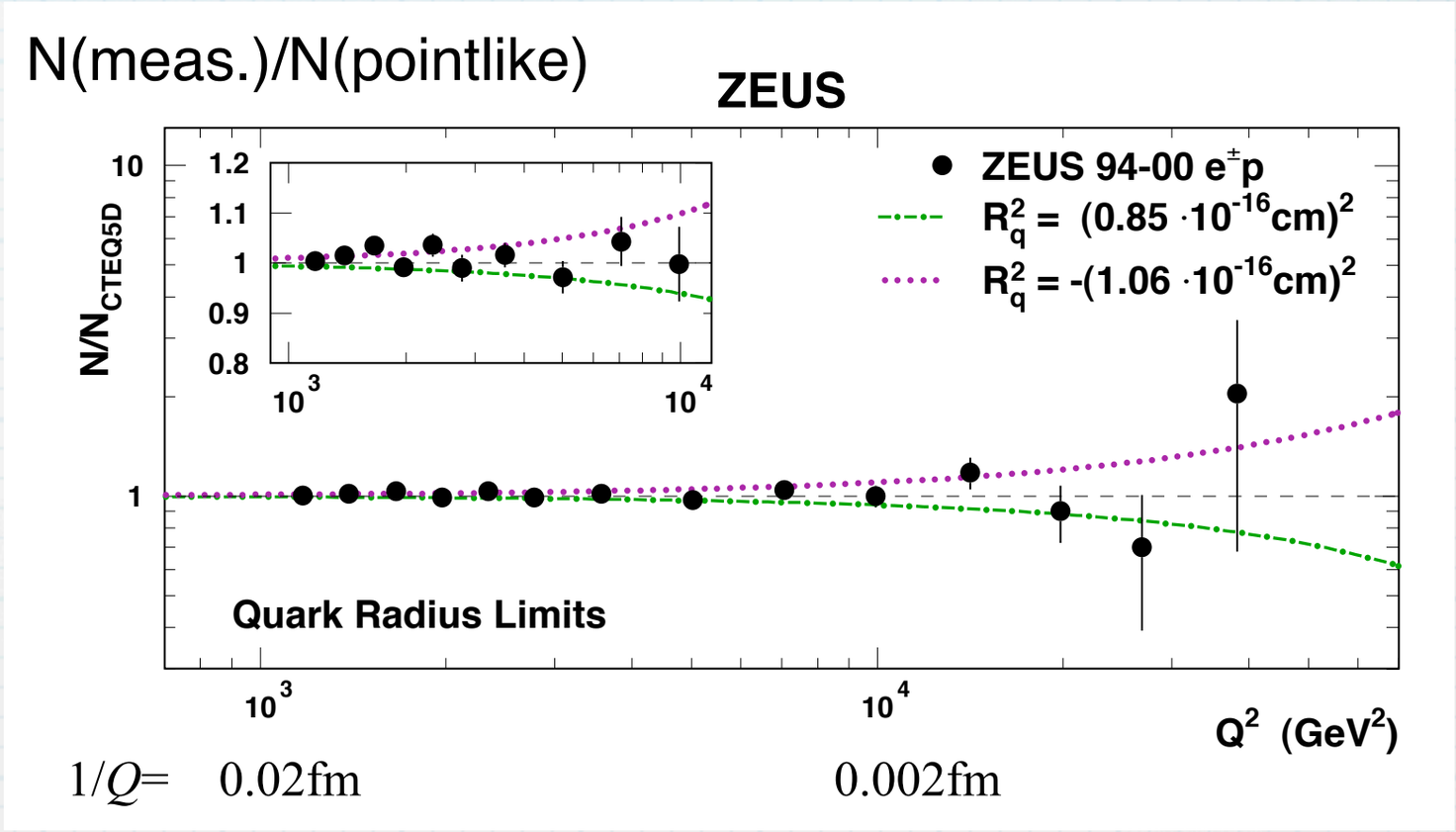
Beyond SM (example)

* Is quark pointlike?
  If composite, cross section will dump once the resolution reaches its size.

* Repeat Hofstadter's proton form-factor meas. for quarks.

- $\sigma(Q^2) = \sigma_{SM}(1 - \langle R_q^2 \rangle Q^2/6)^2$

$R_q < 0.85 \times 10^{-16}$ cm



smaller distance

Summary

* HERA-II is delivering large luminosity with lepton polarization.
* Using its unique data, determination of PDF and EW parameters are possible, taking full correlations between them.
* Competitive/complementary results are obtained in fundamental EW physics.
* Continue to take (e+) data till Jun. 2007: valuable data set before LHC start-up.