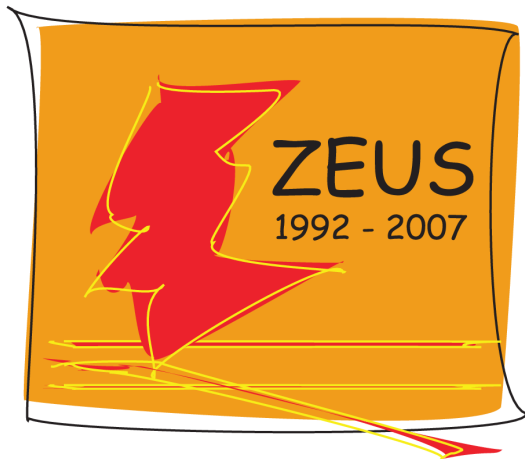


Measurement of the Structure of the Proton at HERA

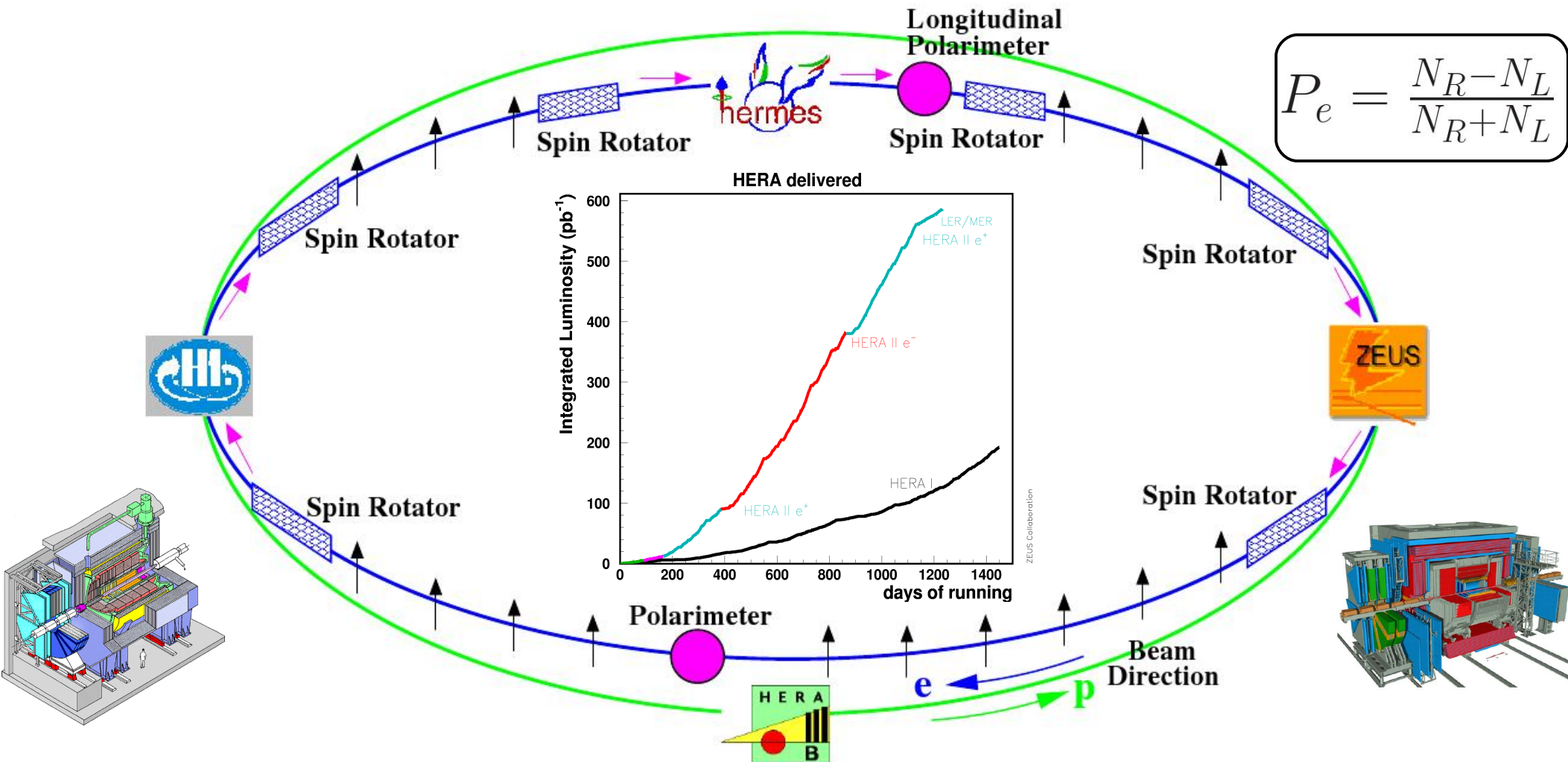
Michał Własenko
University of Bonn



OUTLINE:

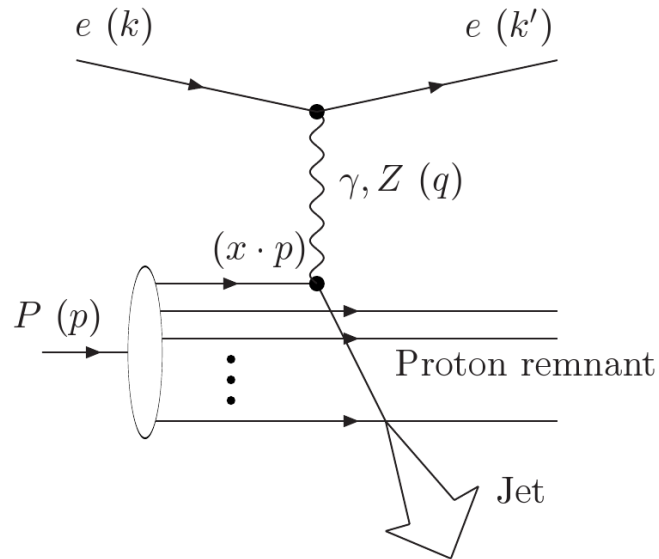
- NC and CC cross sections
- HERA combined PDF fits
- First direct measurements of F_L

The HERA collider



- $E_p = 920 \text{ GeV}$, $E_e = 27.5 \text{ GeV}$, $\sqrt{s} \approx 320 \text{ GeV}$ (high-energy runs)
- Polarized lepton beams at HERA2, average $P = 30 - 40\%$
- Total recorded luminosity: **0.5 fb⁻¹** by both collaborations

NC Deep Inelastic Scattering

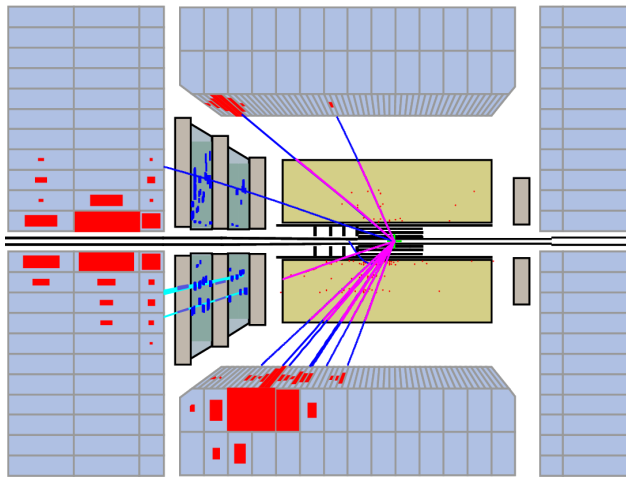


DIS KINEMATICS

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

$$x = \frac{Q^2}{2p \cdot q} \quad y = \frac{p \cdot q}{p \cdot k}$$

$$s = (k + p)^2 \quad Q^2 = sxy$$



Q^2 is the probing power of the lepton
 x is the Bjorken scaling variable
 y is the inelasticity

$$Y_{\pm} = 1 \pm (1 - y)^2$$

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

NC Structure Functions

dominant
contribution

e^\pm
polarization

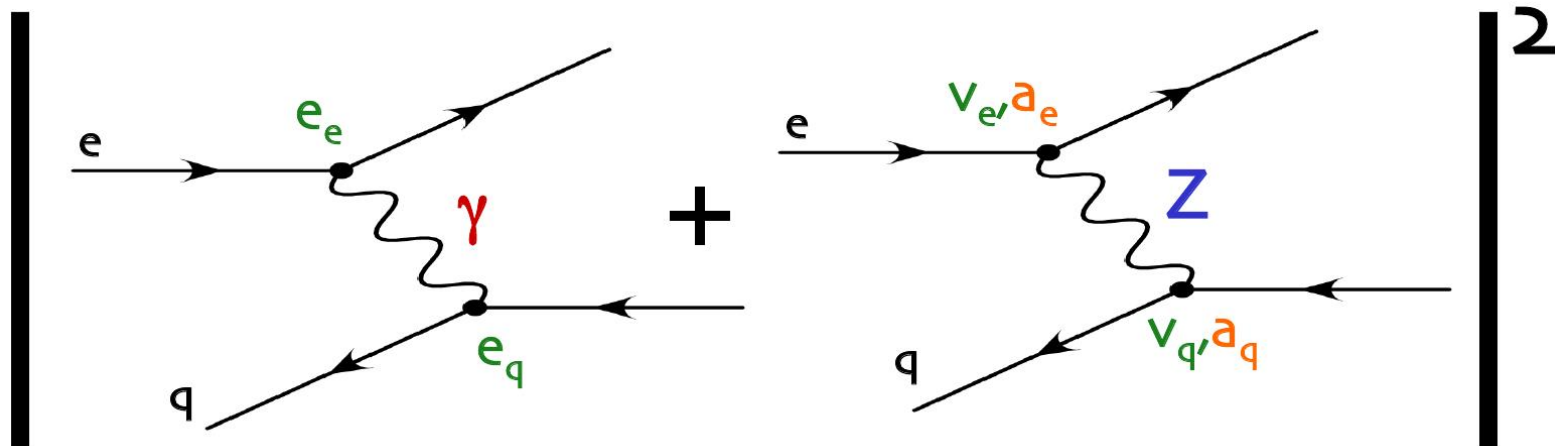
$$\chi_Z = \frac{1}{\sin^2 2\theta_W} \frac{Q^2}{M_Z^2 + Q^2}$$

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

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

axial-vector & vector
couplings of e^\pm to Z_0

sensitivity only at high Q^2



NC Structure Functions

**dominant
contribution**

**e^\pm
polarization**

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

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**axial-vector & vector
couplings of e^\pm to Z_0**

sensitivity only at high Q^2

$$[F_2^\gamma, F_2^{\gamma Z}, F_2^Z] = \sum [e_q^2, 2e_q v_q, v_q^2 + a_q^2] x (q + \bar{q}) \quad \text{sea \& valence quarks}$$

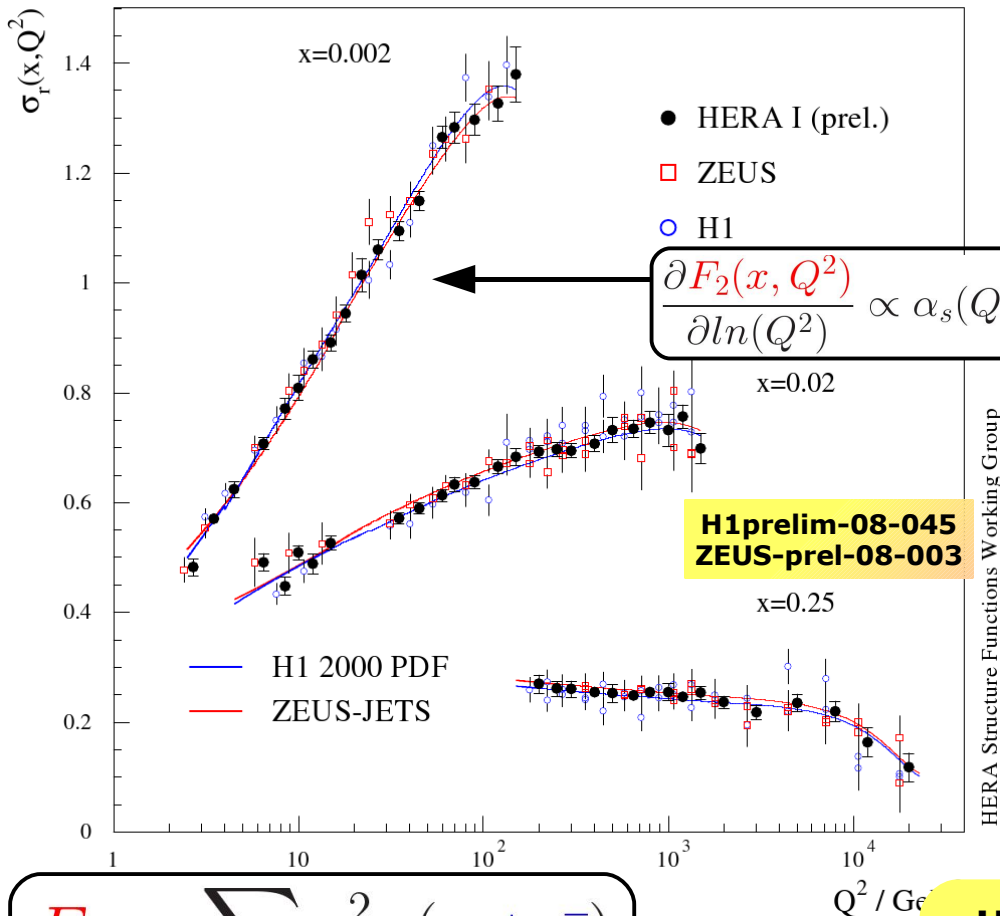
$$[x F_3^{\gamma Z}, x F_3^Z] = \sum_q [e_q a_q, v_q a_q] 2x (q - \bar{q}) \quad \text{valence quarks}$$

$$xg(x) = 1.8 \left(\frac{3\pi}{2\alpha_s} F_L(0.4x) - F_2(0.8x) \right) \simeq \frac{8.3}{\alpha_s} F_L \quad \text{gluons via } F_L \text{ at high } y$$

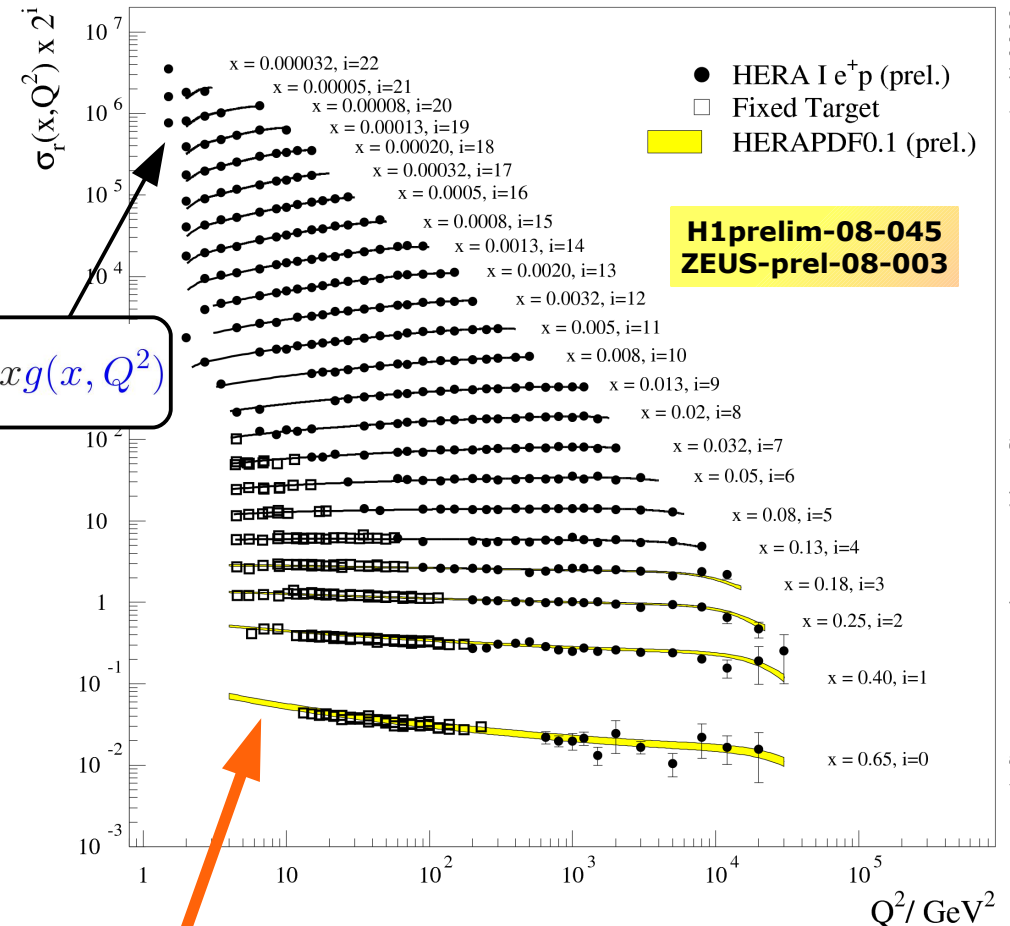
HERA combined NC cross sections (F_2)

$$\sigma_r^{e^\pm p \rightarrow e^\pm X} = F_2 - \frac{y^2}{Y_+} F_L \mp \frac{Y_-}{Y_+} x F_3$$

HERA I e^+p Neutral Current Scattering - H1 and ZEUS



H1 and ZEUS Combined PDF Fit

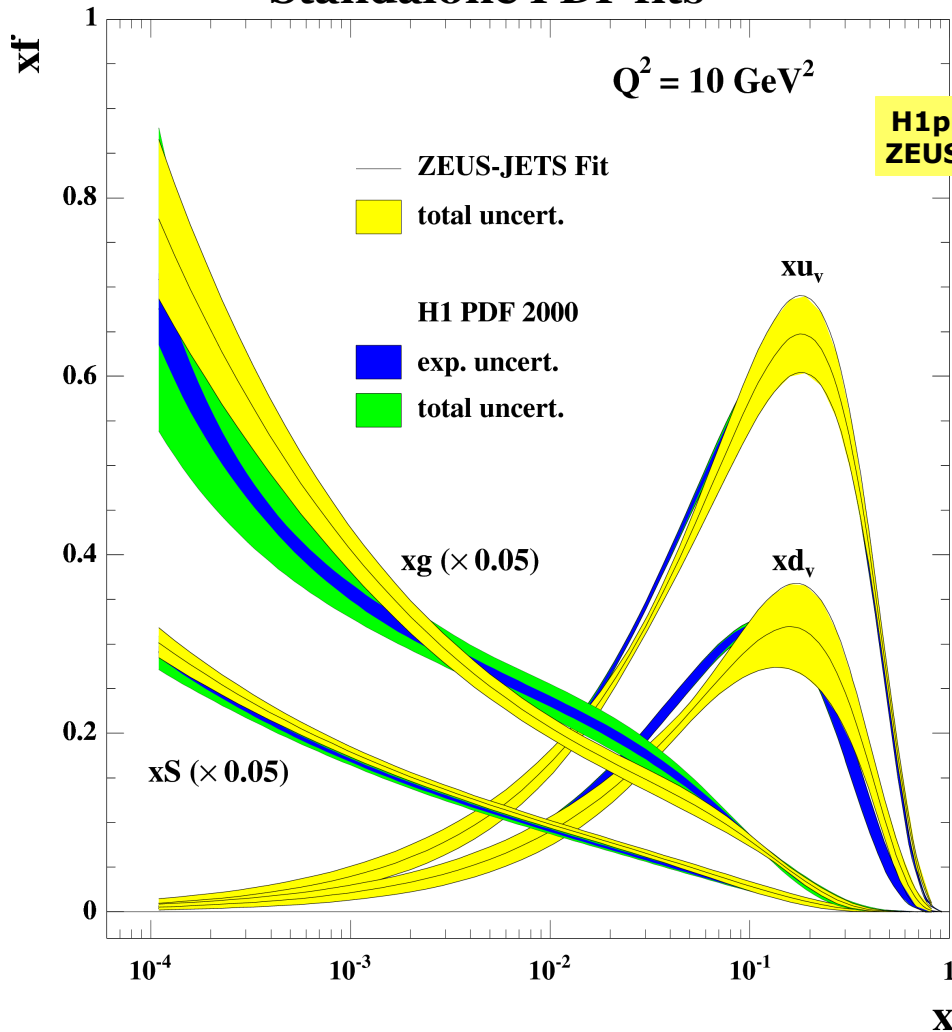


$$F_2 \approx \sum_q e_q^2 x (q + \bar{q})$$

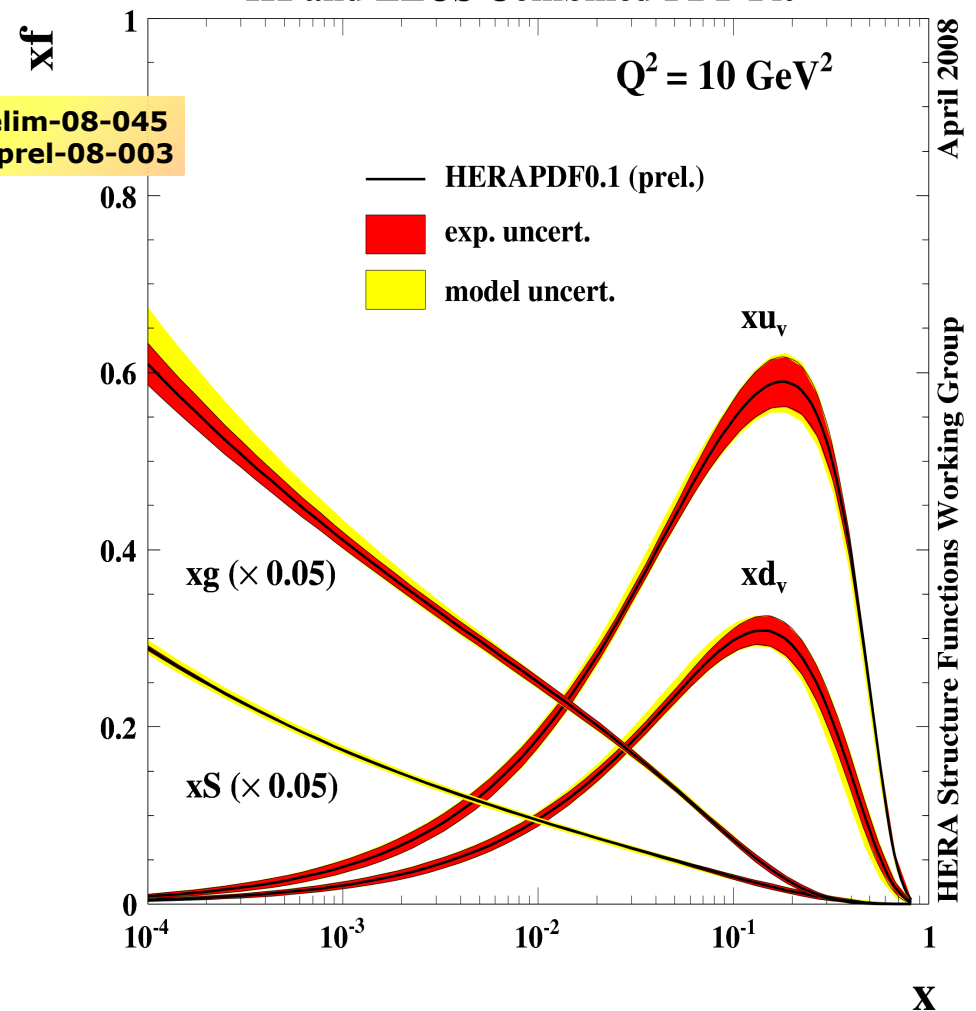
- HERAI precision: 2-3% (syst. limited)
- NLO QCD precisely describes F_2 over 4 orders of magnitude in (x, Q^2) including scaling violation

PDF fits on HERAI data

Standalone PDF fits

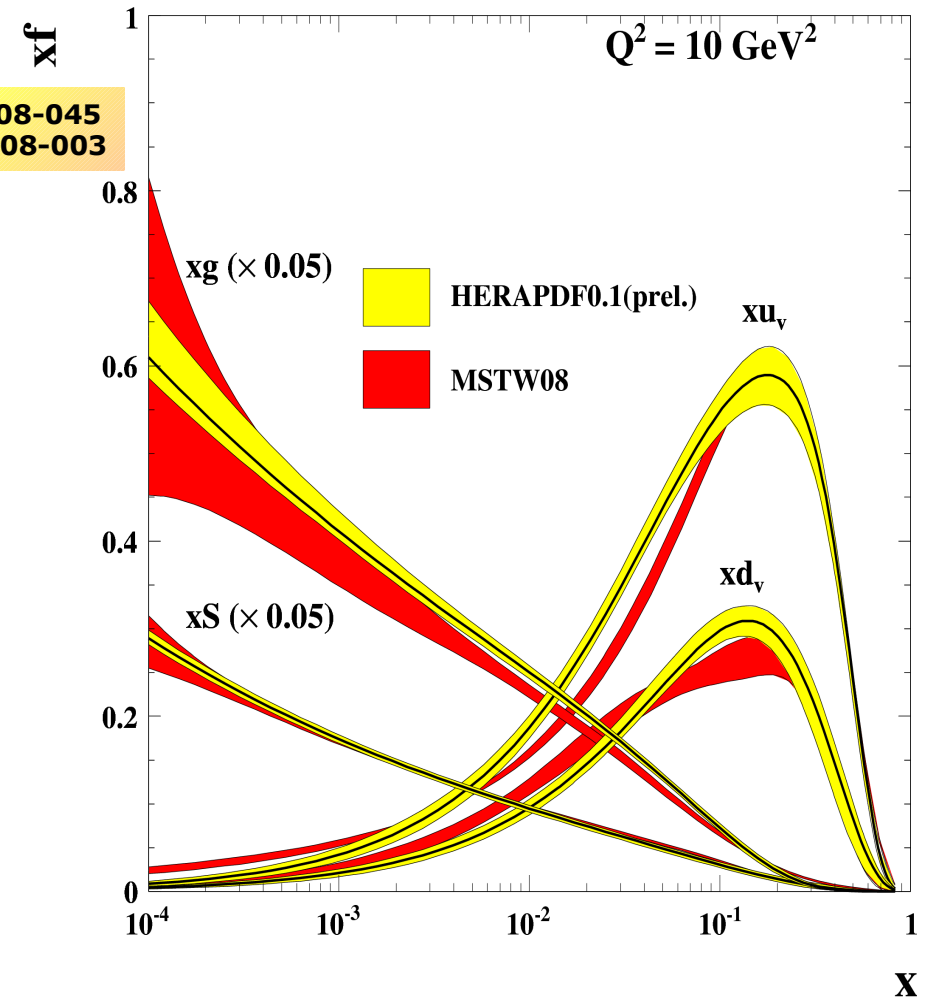
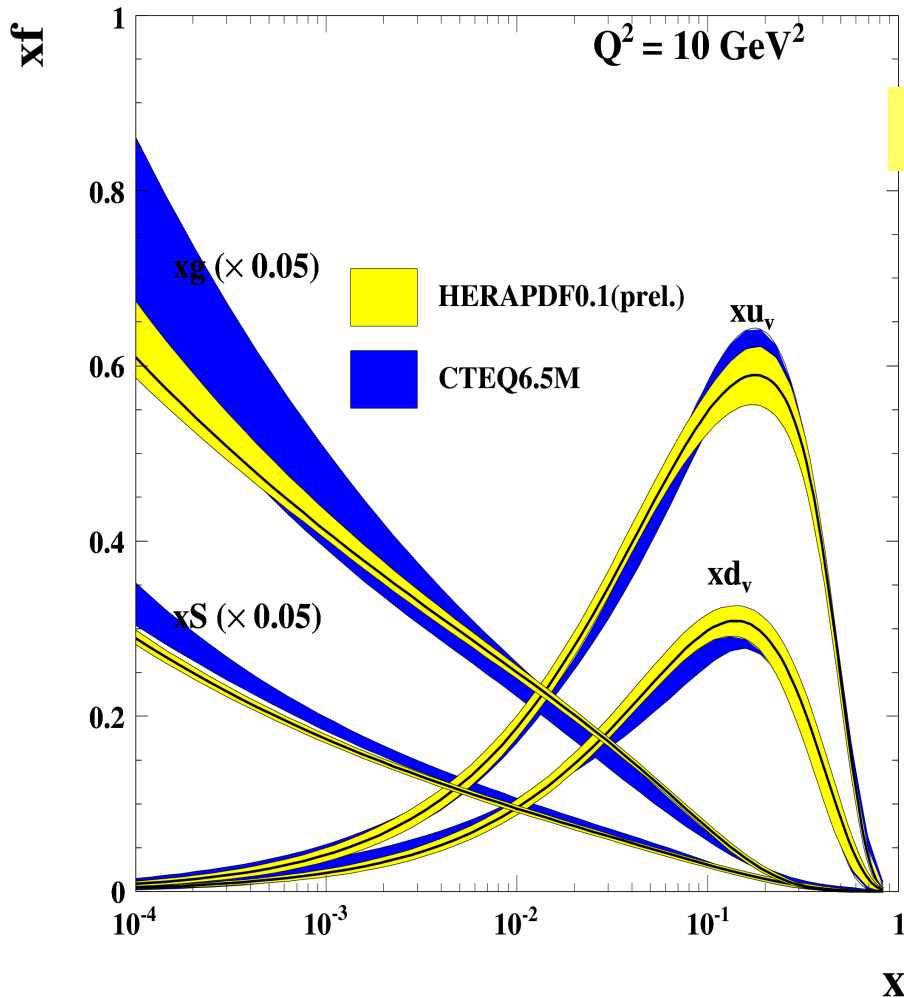


H1 and ZEUS Combined PDF Fit



- Standalone fits compatible over the whole HERA kinematic plane, with $g(x)$ a bit different
- After $\sigma(x, Q^2)$ averaging (model-independent way), $\chi^2/\text{NDF} = 477/562$ for the PDF fit

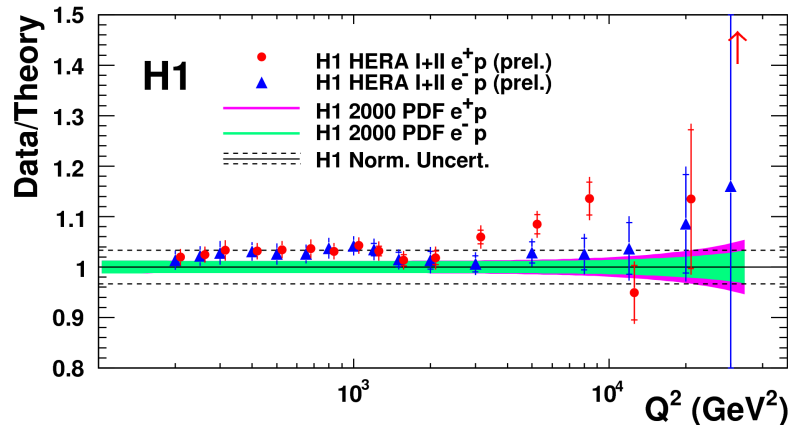
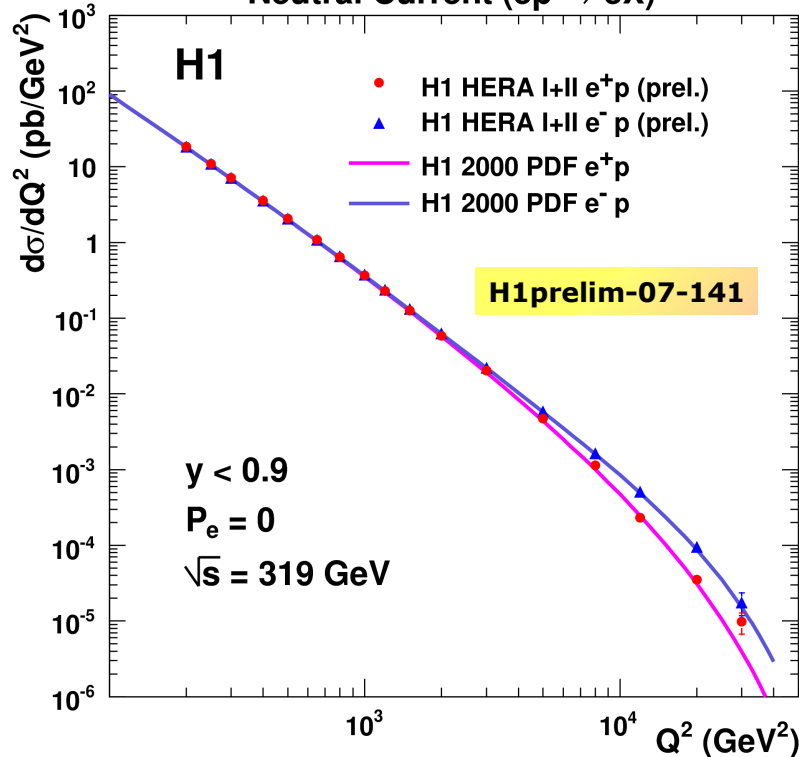
Comparison to Global Fits



- Compared to the recent Global fits, HERA PDFs offer tighter uncertainties
- Global fits, however involve a much larger variety of input experiments
- HERAPDF fits library available (via LHAPDF), providing valuable input for Tevatron and LHC

Unpolarized high Q^2 NC cross sections

Neutral Current ($ep \rightarrow eX$)

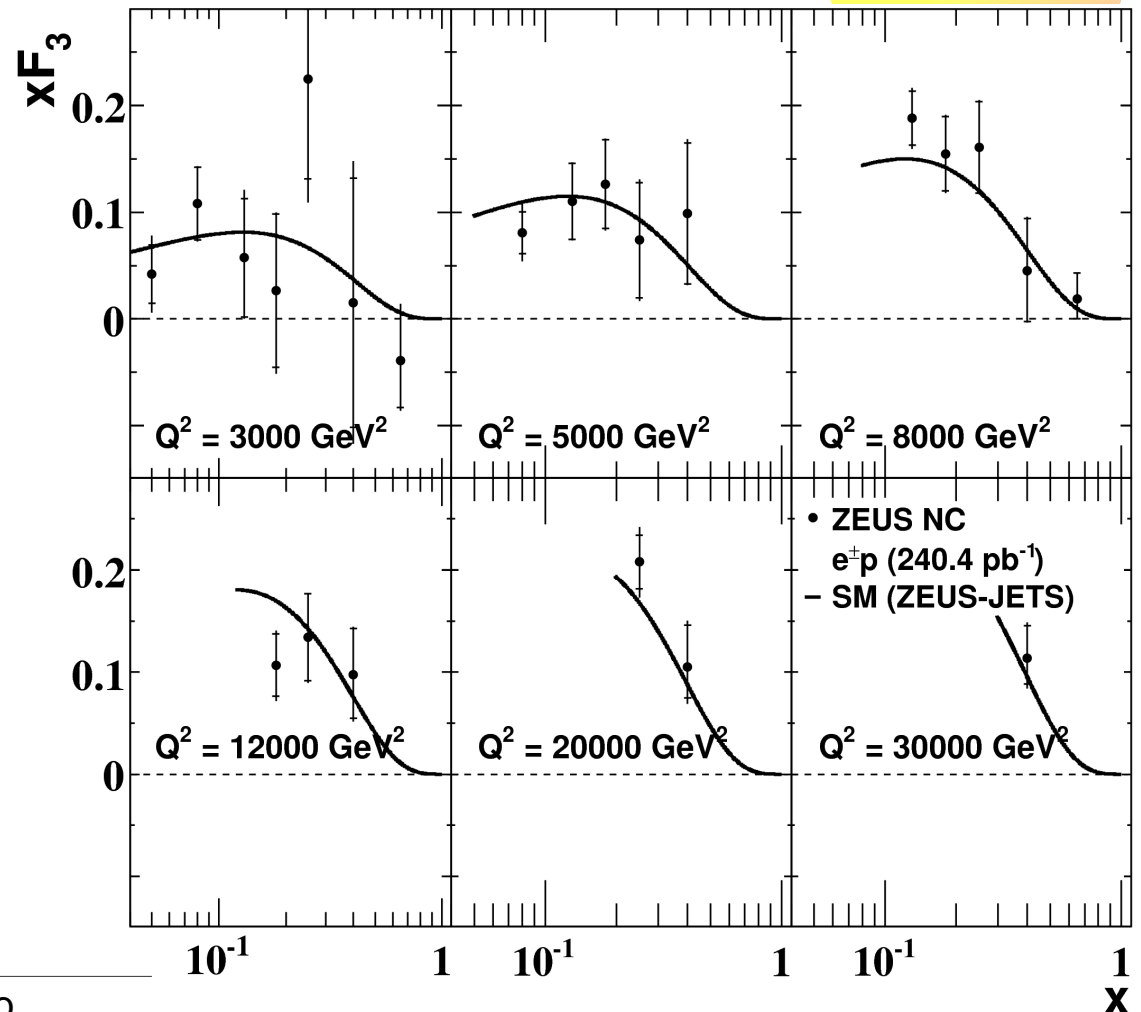


$$x\tilde{F}_3 = \frac{Y_+}{2Y_-}(\tilde{\sigma}^{e^-p} - \tilde{\sigma}^{e^+p}) \approx \frac{x}{3}(2u_v + d_v)$$

$$\sigma_r^{e^\pm p \rightarrow e^\pm X} = F_2 - \frac{y^2}{Y_+}F_L \mp \frac{Y_-}{Y_+}xF_3$$

ZEUS

ZEUS-prel-07-012



High Q^2 NC with polarized e^\pm

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

- Polarization asymmetry provides direct measure for the EW effects

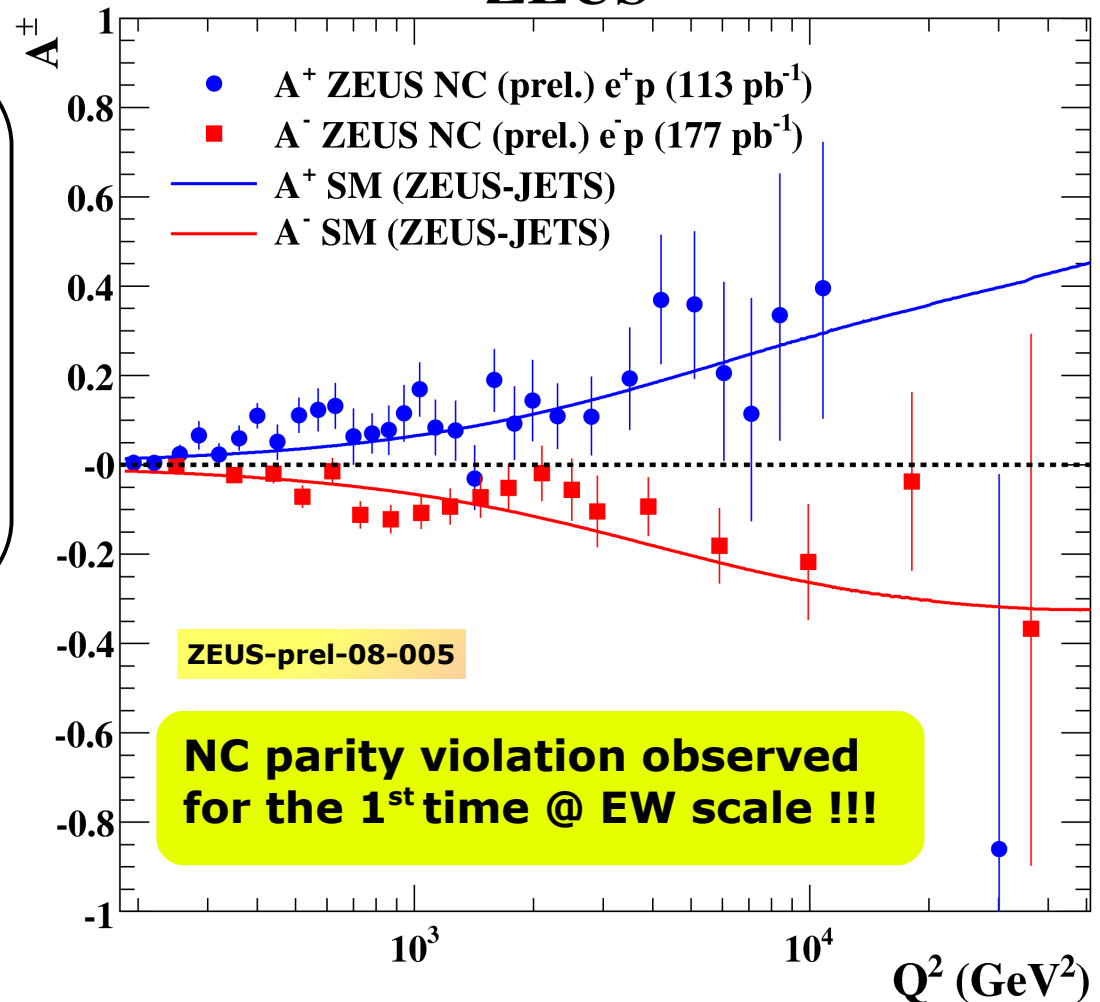
$$A^\pm = \frac{2}{P_e^+ - P_e^-} \frac{\sigma^\pm(P_e^+) - \sigma^\pm(P_e^-)}{\sigma^\pm(P_e^+) + \sigma^\pm(P_e^-)}$$

$$A^\pm \simeq \mp \chi_Z a_e \frac{F_2^{\gamma Z}}{F_2^\gamma} \propto a_e v_q$$

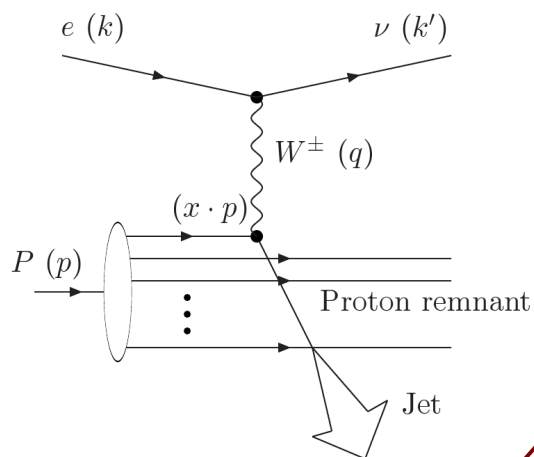
- A^\pm at large x also measures d_v/u_v

$$A^\pm \simeq \pm \chi_Z \frac{1 + d_v/u_v}{4 + d_v/u_v}$$

ZEUS



CC cross sections

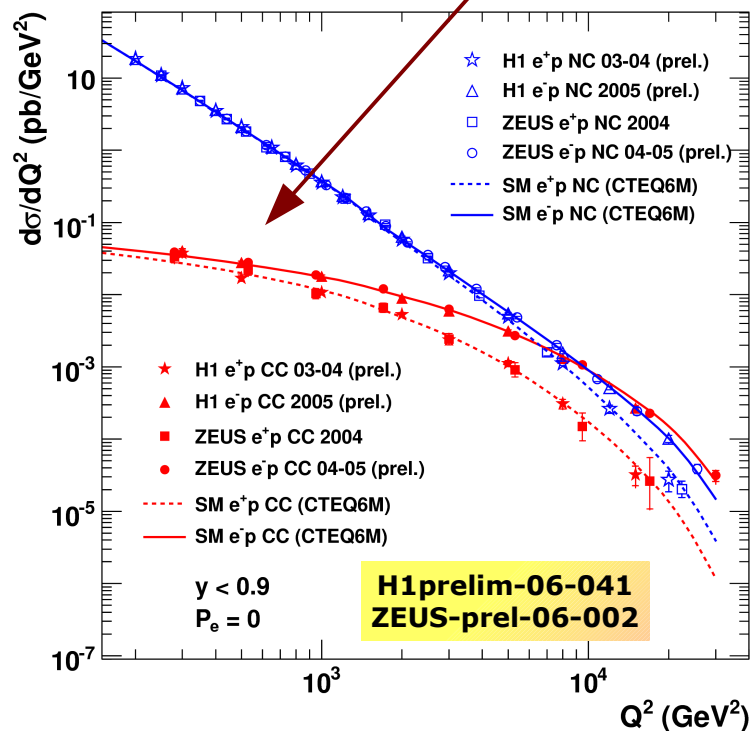


$$\frac{d\sigma^{e^-p}}{dx dQ^2} = \frac{G_F^2}{2\pi} \frac{M_W^4}{(Q^2 + M_W^2)^2} \left((u + c) + (1 - y)^2 (\bar{d} + \bar{s}) \right)$$

$$\frac{d\sigma^{e^+p}}{dx dQ^2} = \frac{G_F^2}{2\pi} \frac{M_W^4}{(Q^2 + M_W^2)^2} \left((\bar{u} + \bar{c}) + (1 - y)^2 (d + s) \right)$$

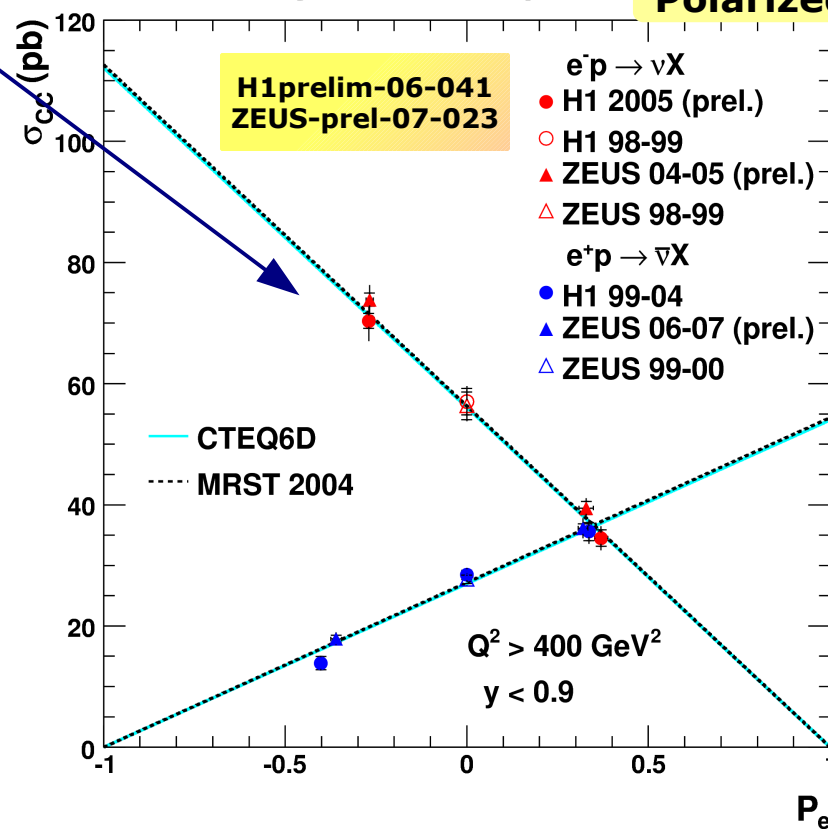
$$\sigma_{CC}^{e^\pm p}(P_e) = (1 \pm P_e) \sigma_{CC}^{e^\pm p}(P_e = 0)$$

Unpolarized CC



Charged Current $e^\pm p$ Scat

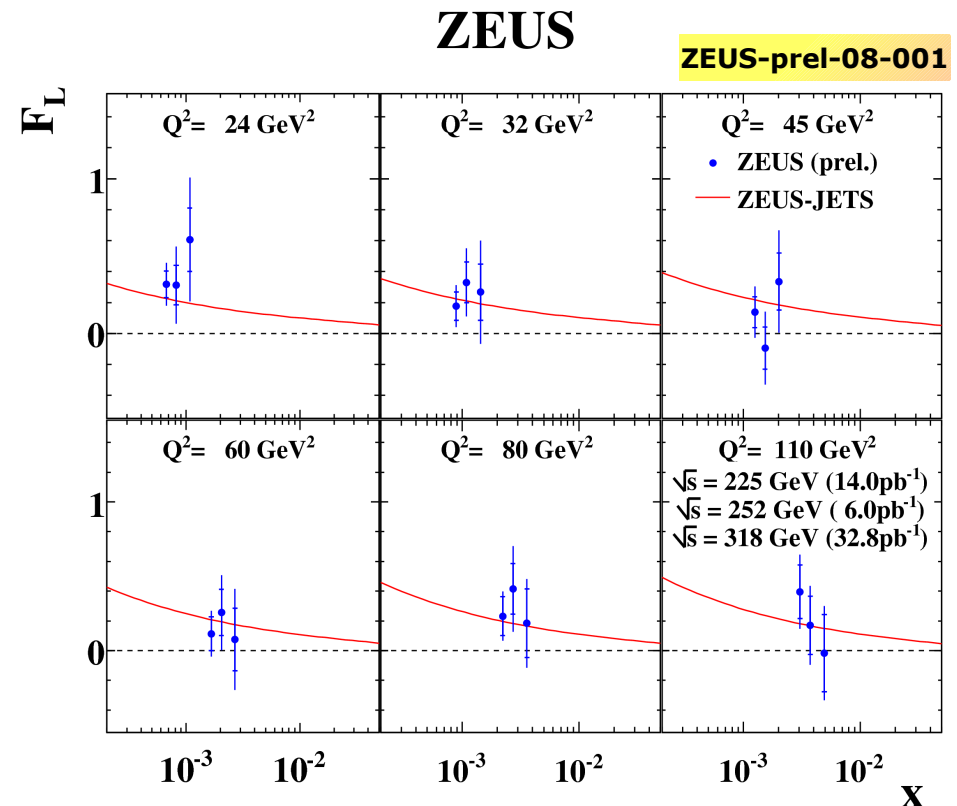
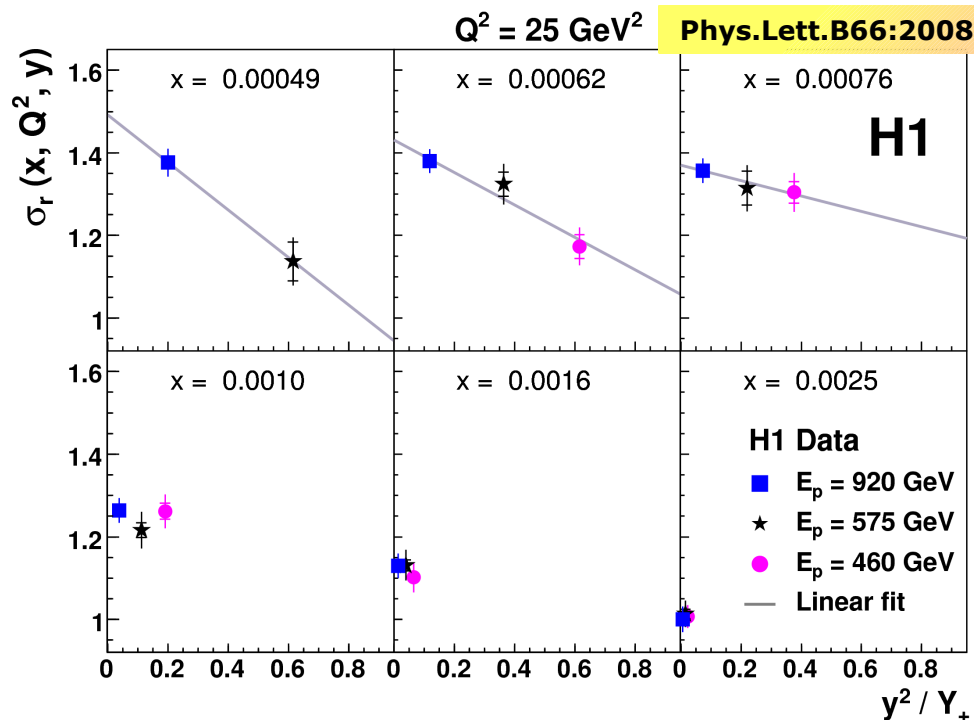
Polarized CC



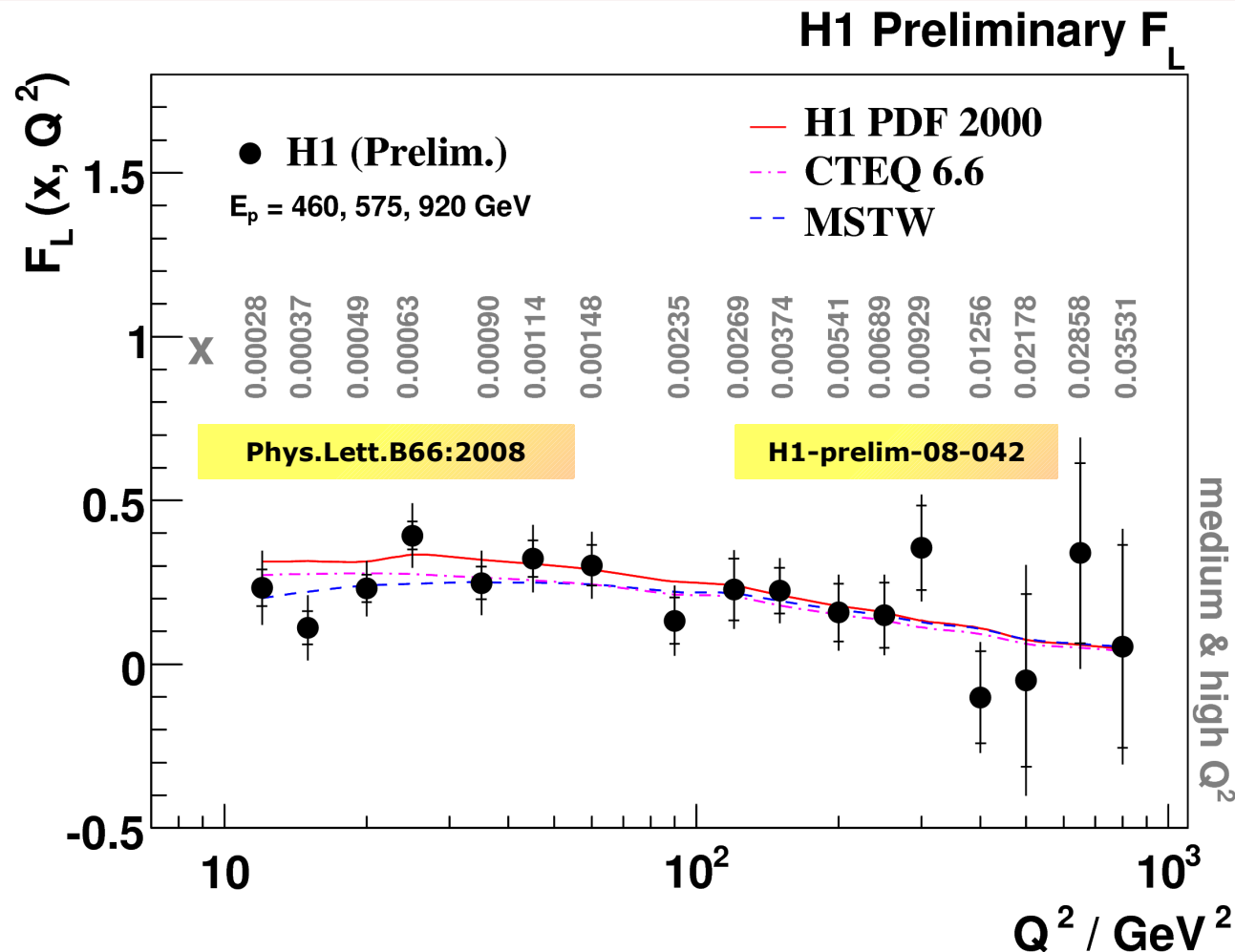
Measurements of F_L

$$\sigma_r(x, Q^2, y) = F_2(x, Q^2) - \frac{y^2}{Y_+} \cdot F_L(x, Q^2) \Rightarrow F_L(x, Q^2) = \frac{\partial \sigma_r(x, Q^2, y)}{\partial (y^2/Y_+)} \quad y = \frac{Q^2}{xs}$$

- Indirect measurements of F_L performed on previous HERA data by H1 (model-dependent)
- First ever direct F_L measurements performed by varying \sqrt{s} : 318, 251, 225 GeV
- Acceptances: ZEUS ($y < 0.8, Q^2 > 24 \text{ GeV}^2$), H1 ($y < 0.9, Q^2 > 12 \text{ GeV}^2$)



Measurements of F_L



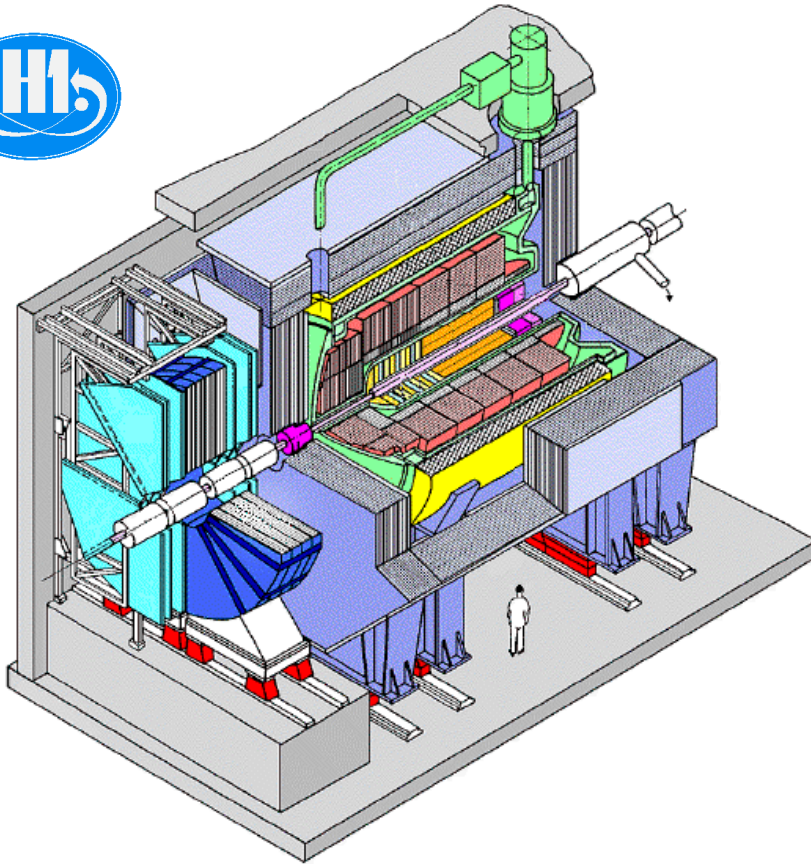
- Both results consistent with each other, and $F_L \neq 0$
- H1's averaged over x results consistent with predictions from pQCD
- F_L confirms expectations on the behavior of $g(x, Q^2)$ (coming from F_2)

Summary and outlook

- H1 and ZEUS combined the inclusive NC results from HERAI data
- HERA combined PDF fits (available as **HERAPDF** library via LHAPDF) achieved unprecedented precision
- Middle and high Q^2 NC and CC HERAII data are still being analyzed and published
- First direct F_L measurement published this Summer (can be expected to further constrain the low- x pQCD description)
- All inclusive results in excellent agreement with SM
- HERA approaching its 'final word' (1 fb^{-1}), producing priceless input for Tevatron and the LHC

backup

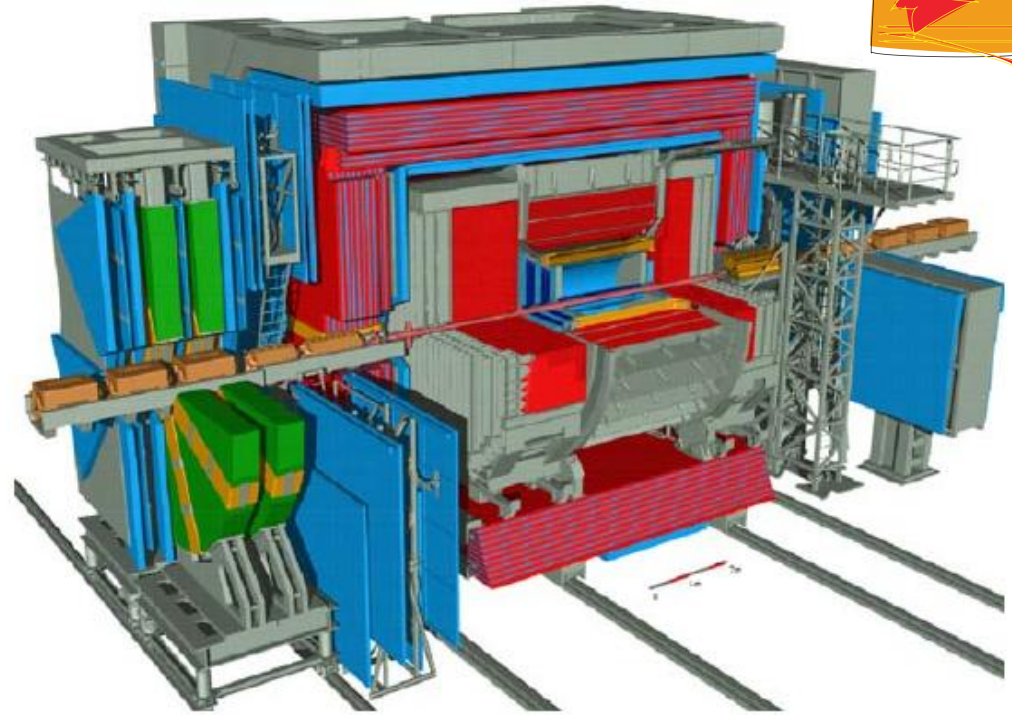
The H1 & ZEUS detectors



H1 calorimeters (45000 cells)

- $\sigma(E)/E = 0.07/\sqrt{E}$ (EM, small θ)
- $\sigma(E)/E = 0.12/\sqrt{E}$ (EM, central θ)
- $\sigma(E)/E = 0.5/\sqrt{E}$ (HAD)

Central + forward + backward **trackers**

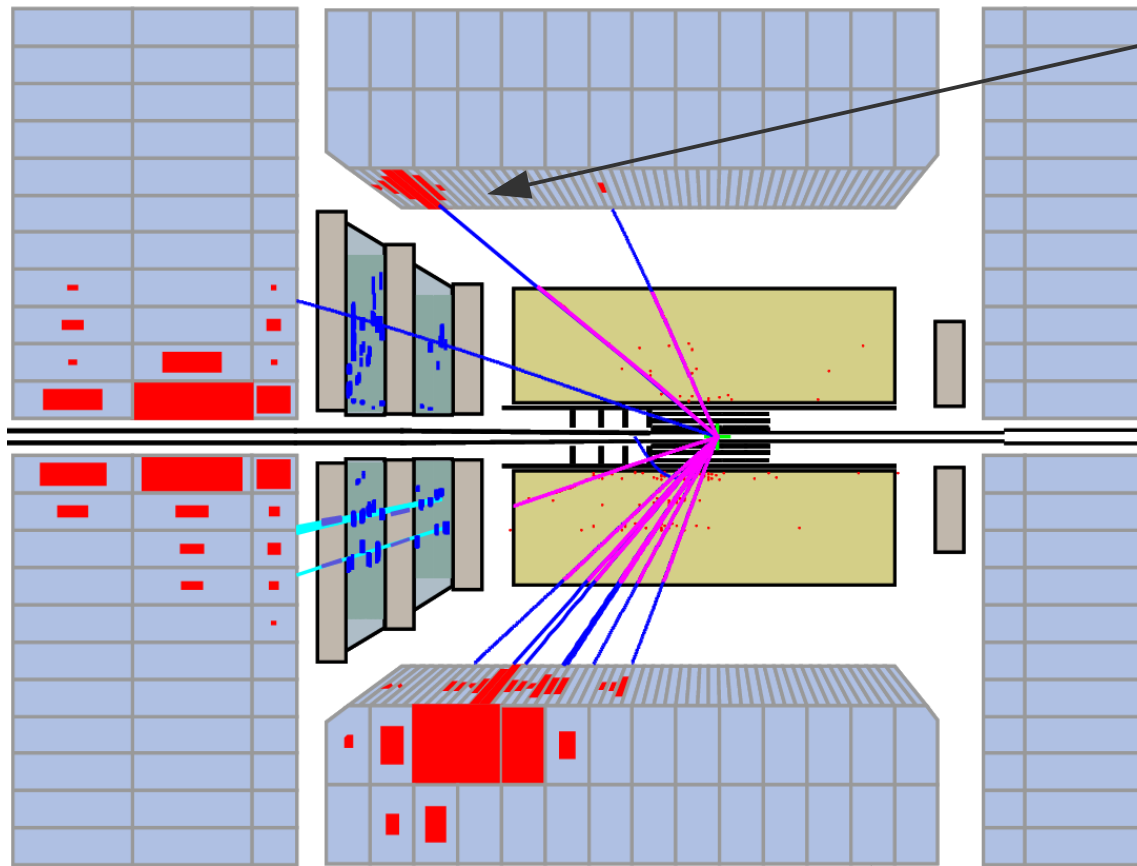


ZEUS calorimeter (12000 cells)

- $\sigma(E)/E = 0.18/\sqrt{E}$ (EM)
- $\sigma(E)/E = 0.35/\sqrt{E}$ (HAD)

Central + forward **trackers**

NC DIS event reconstruction



Scattered, isolated e^\pm
(high E_e)

Balanced total $\mathbf{P}_T \approx 0$ GeV

$$\mathbf{E} - \mathbf{P}_z = E_p + E_e - E_p + E_e \approx 2E_e$$

**Kinematics can be reconstructed
using the scattered e^\pm (or the H.F.S)**

$$Q_{EL}^2 = 2E_e E'_e (1 + \cos \theta_e)$$

$$x_{EL} = \frac{E_e}{E_p} \cdot \frac{E'_e (1 + \cos \theta_e)}{2E_e - E'_e (1 - \cos \theta_e)}$$

$$y_{EL} = 1 - \frac{E'_e}{2E_e} (1 - \cos \theta_e)$$

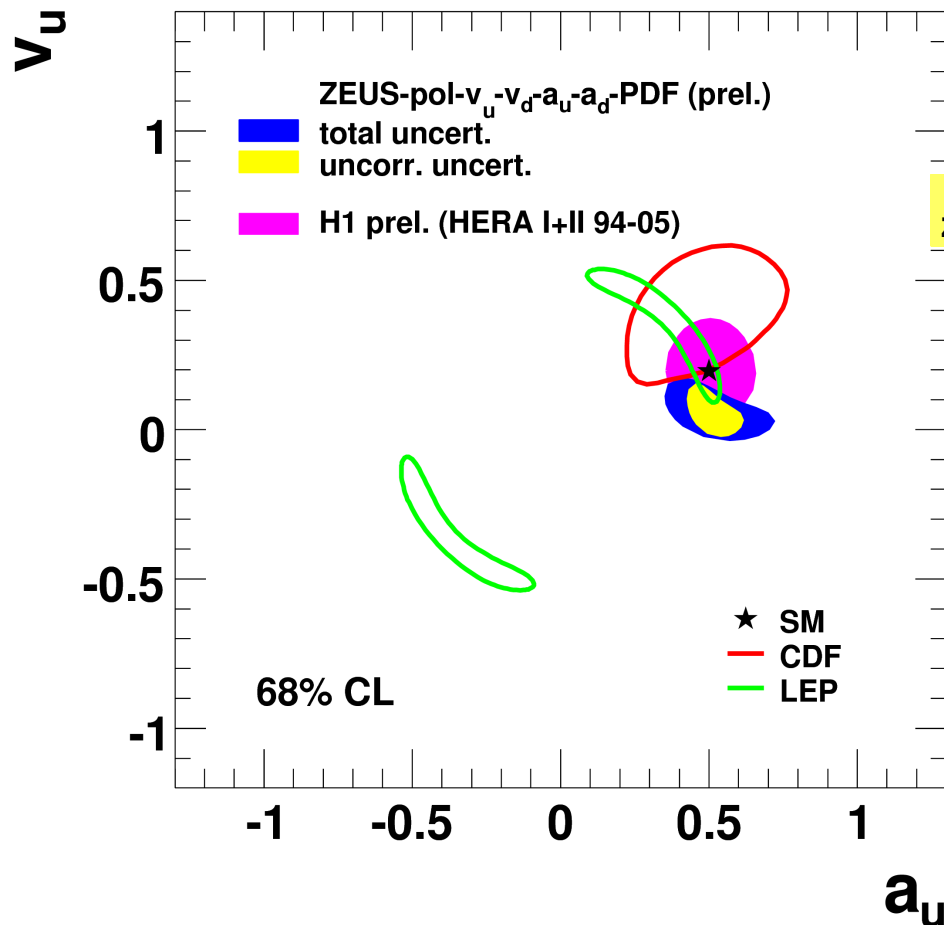
(Some more) Electroweak Physics @ HERA

$$[F_2^\gamma, F_2^{\gamma Z}, F_2^Z] = \sum_q [e_q^2, 2e_q v_q, v_q^2 + a_q^2] x(q + \bar{q})$$

$$[xF_3^{\gamma Z}, xF_3^Z] = \sum_q [e_q a_q, v_q a_q] 2x(q - \bar{q})$$

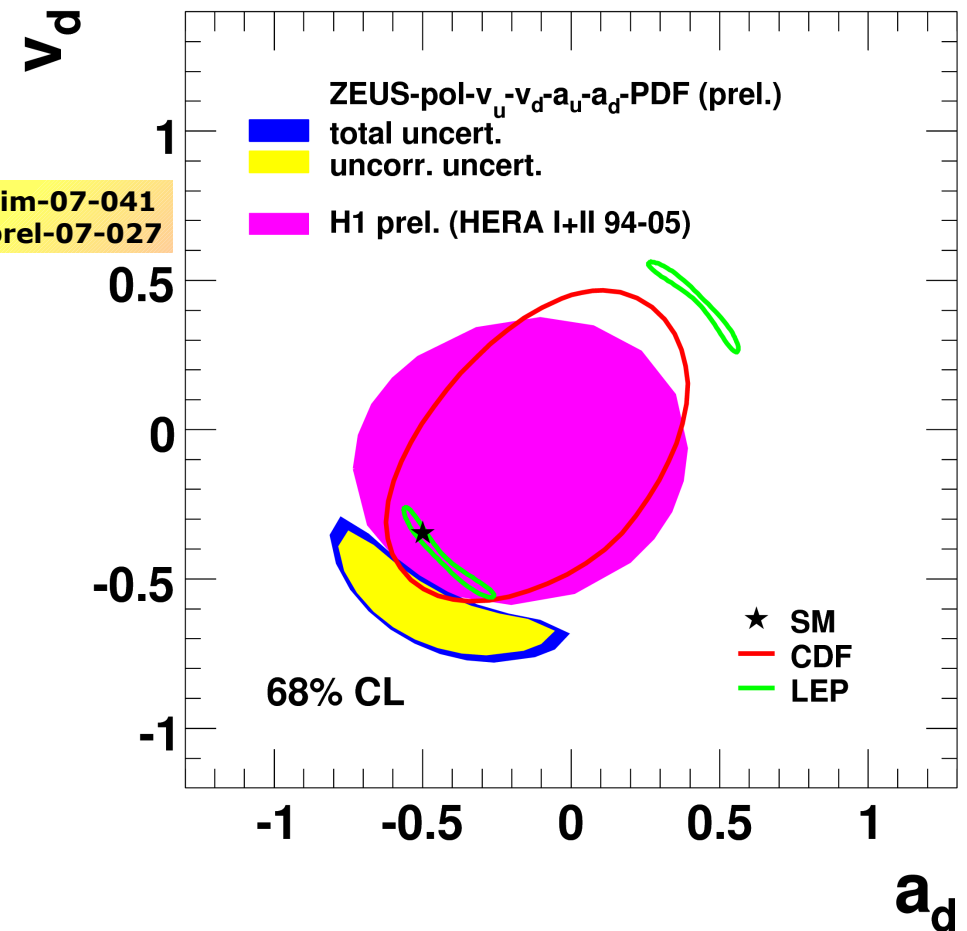
- **QCD + EW fit:** to determine **PDFs** and **u, d** quark couplings to **Z_0**
- HERA competitive with LEP and Tevatron

ZEUS

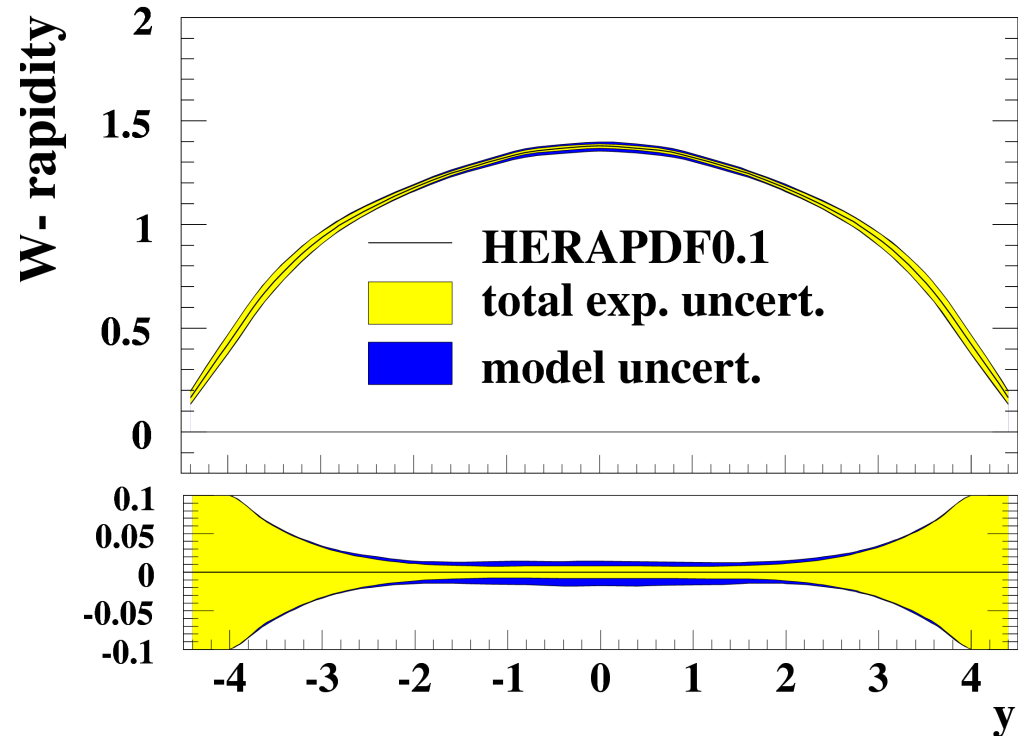
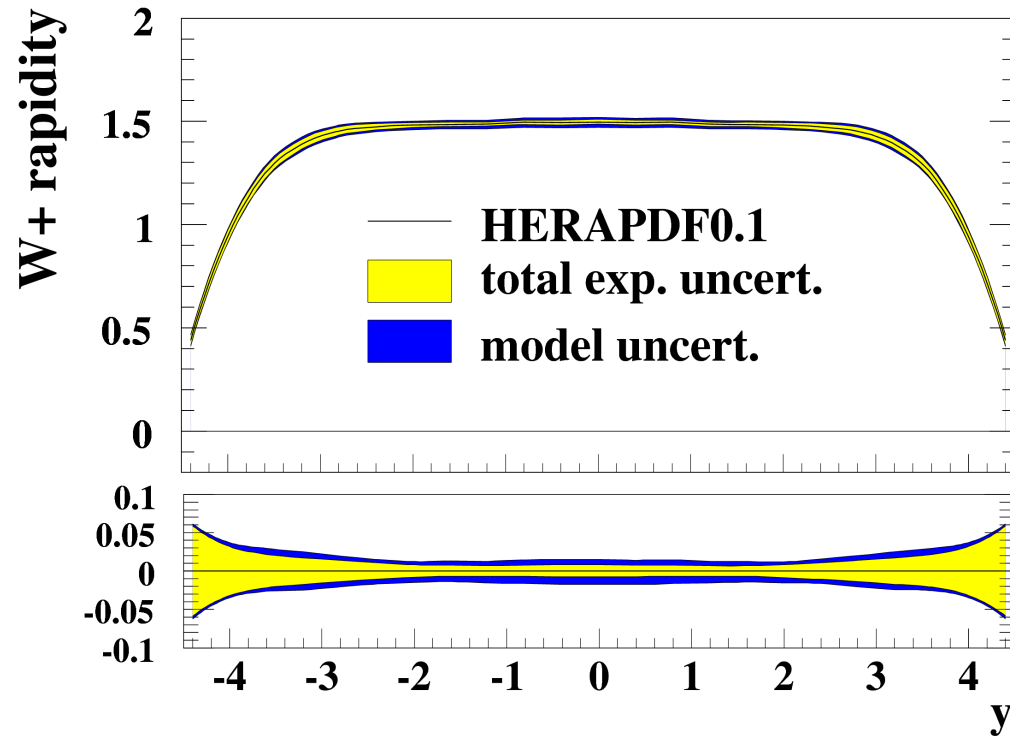


H1prelim-07-041
ZEUS-prel-07-027

ZEUS



(Example) predictions using HERAPDF0.1



- Predicted rapidity distribution of $W^+(W^-)$ bosons in inclusive W production at the LHC as predicted using only the HERA PDFs
- Small fractional error on the production