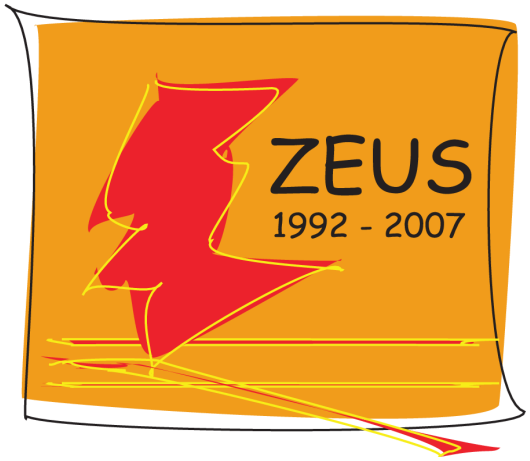
Measurement of the Structure of the Proton at HERA



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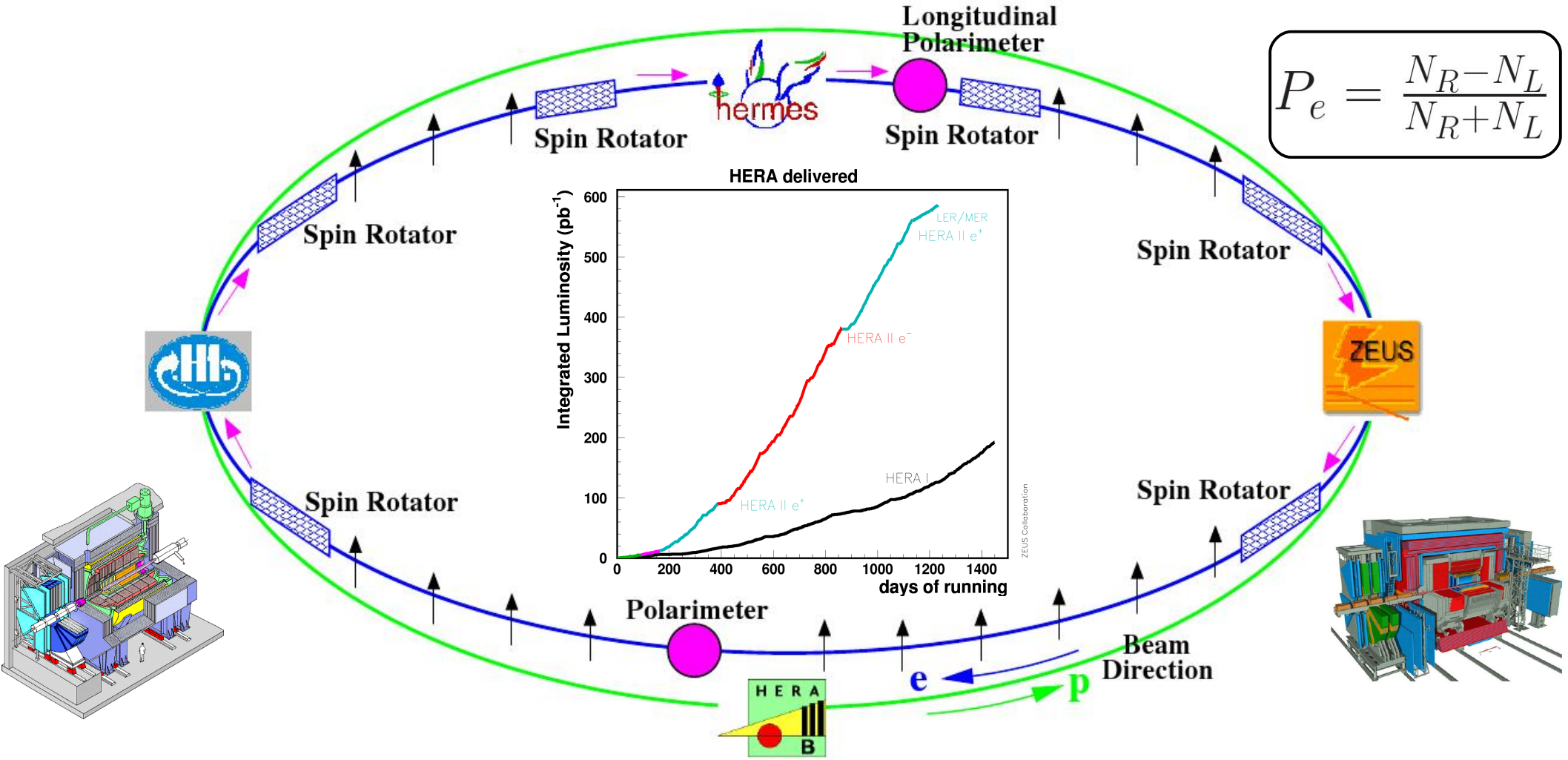
OUTLINE:

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

bmb+f
Bundesministerium für Bildung und Forschung

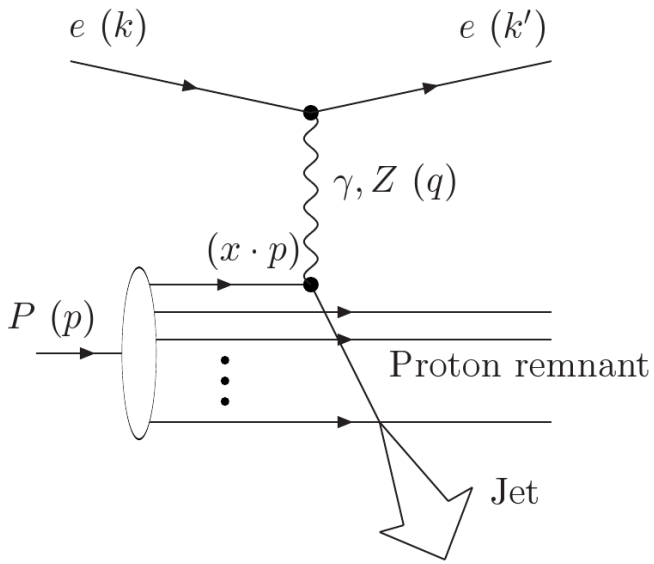
The HERA collider

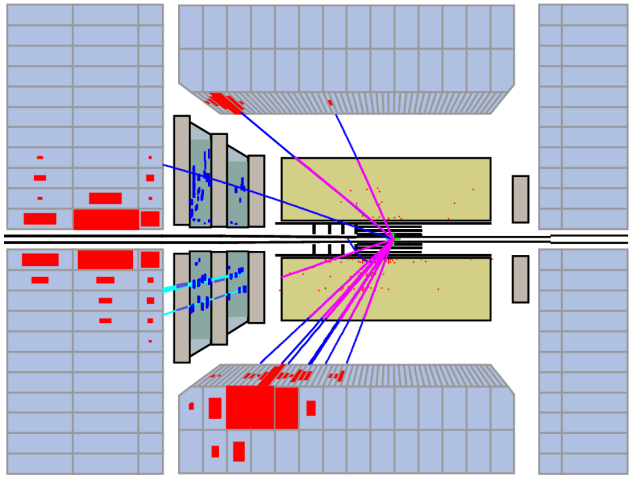


$$P_e = \frac{N_R - N_L}{N_R + N_L}$$

- E_p = **920 GeV**, E_e = **27.5 GeV**, $\sqrt{s} \approx$ **320 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

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

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

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

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

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

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

NC Structure Functions

dominant contribution

$e^{\pm}$ polarization

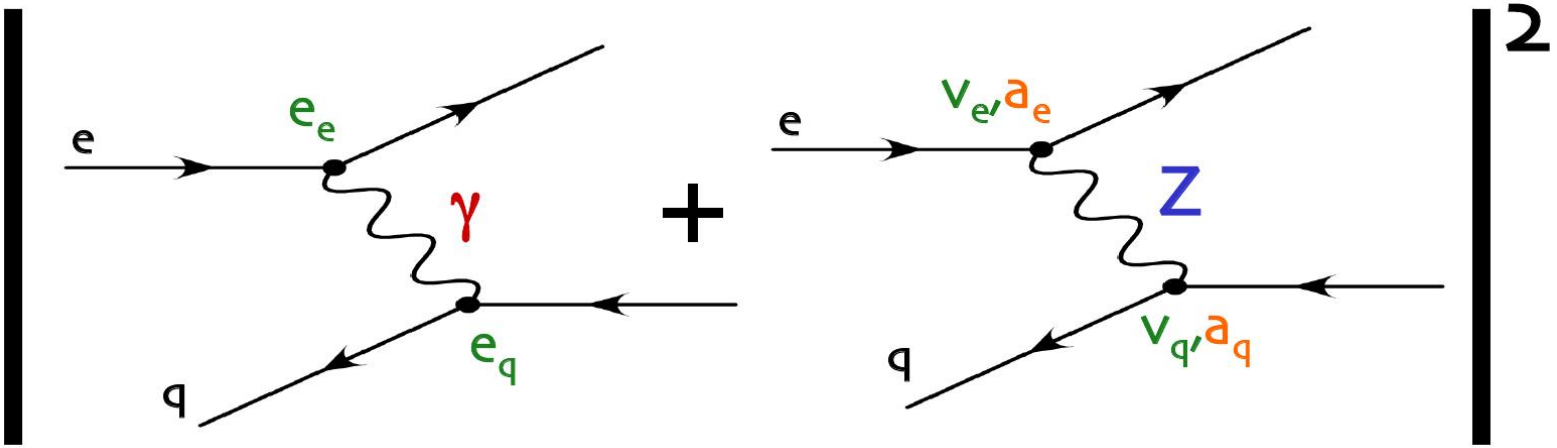
$$\chi_Z = \frac{1}{\sin^2 2\theta_W} \frac{Q^2}{M_Z^2 + Q^2}$$

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

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

sensitivity only at high Q^2

axial-vector & vector couplings of $e^{\pm}$ to Z_o



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sensitivity only at high Q^2

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

sea & valence quarks

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

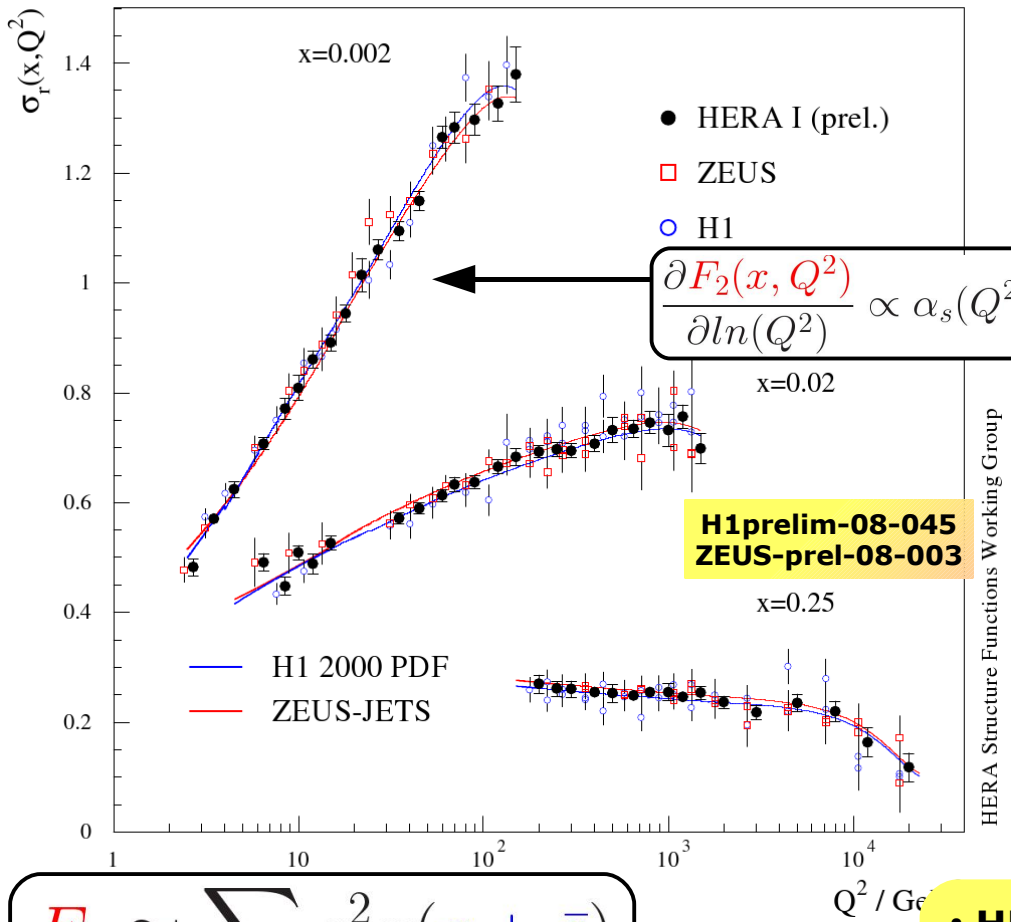
valence quarks

$$xg(x) = 1.8\left(\frac{3\pi}{2\alpha_s} F_L(0.4x) - F_2(0.8x)\right) \backsimeq \frac{8.3}{\alpha_s} F_L$$

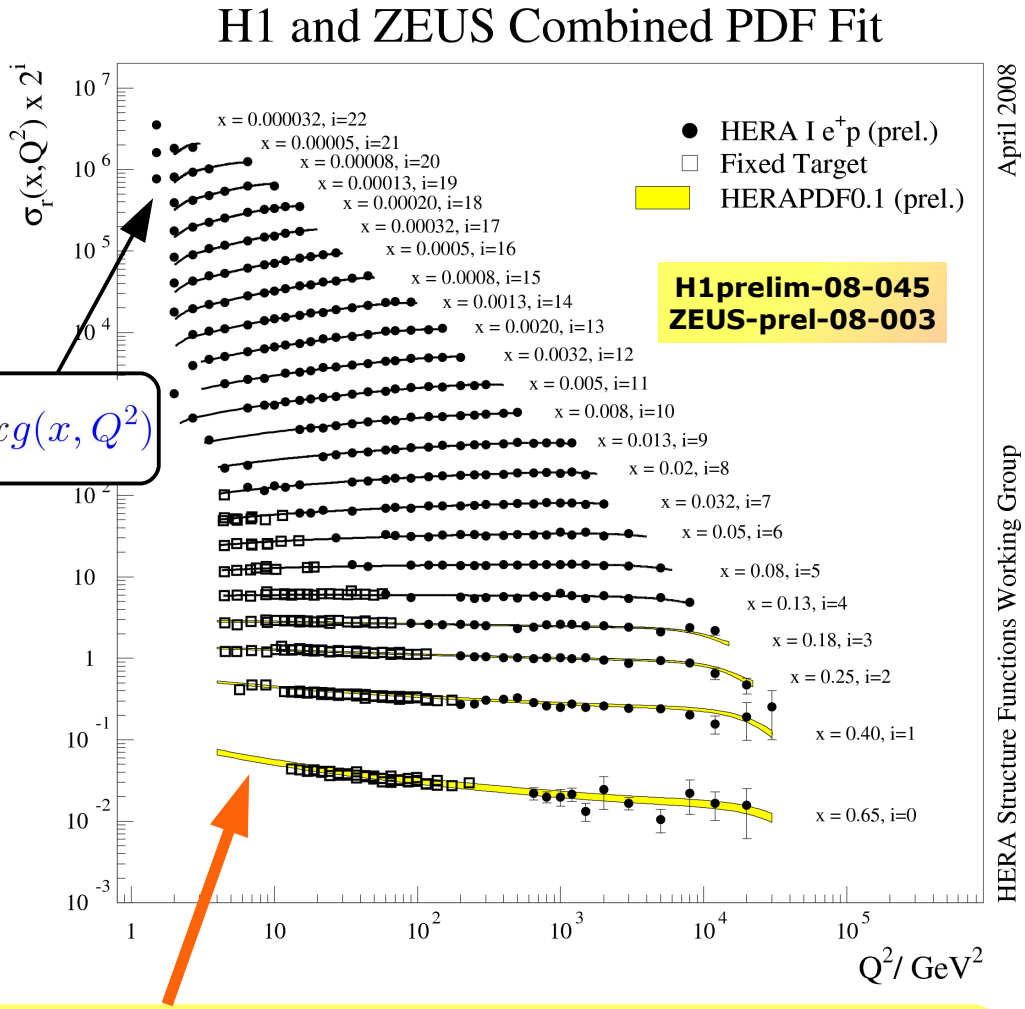
gluons via F_L at high y

HERA combined NC cross sections (F_2)

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



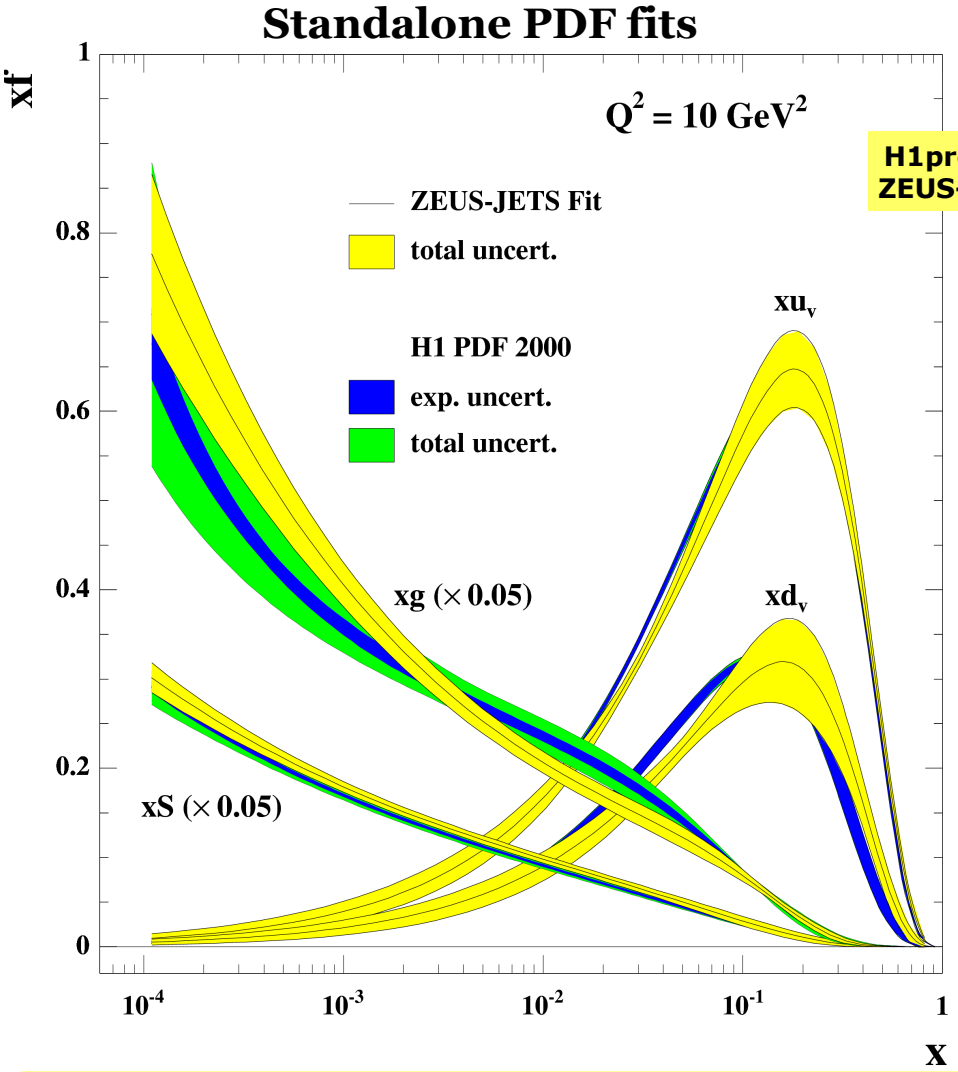
$$\frac{\partial F_2(x,Q^2)}{\partial ln(Q^2)} \propto \alpha_s(Q^2) x g(x,Q^2)$$

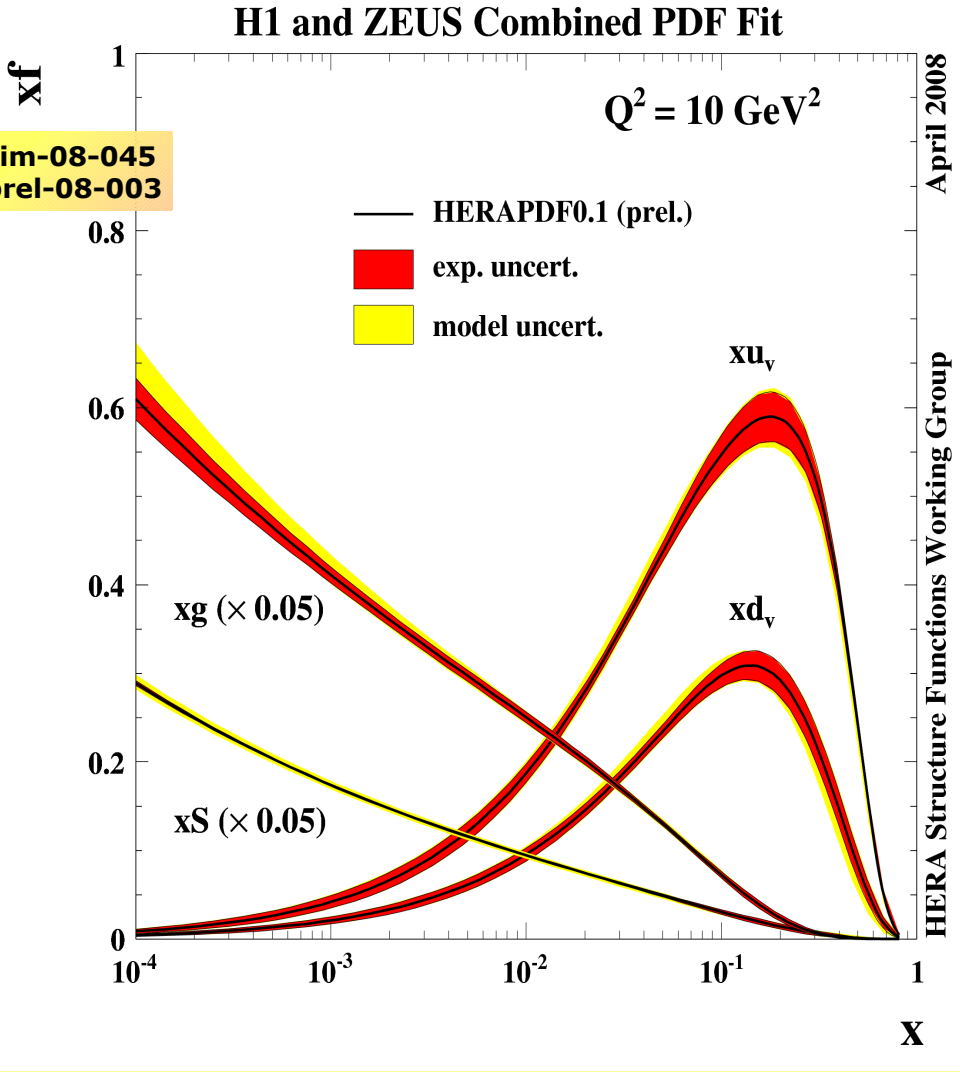


$$F_2 \approx \sum_q e_q^2 x(q + \bar{q})$$

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

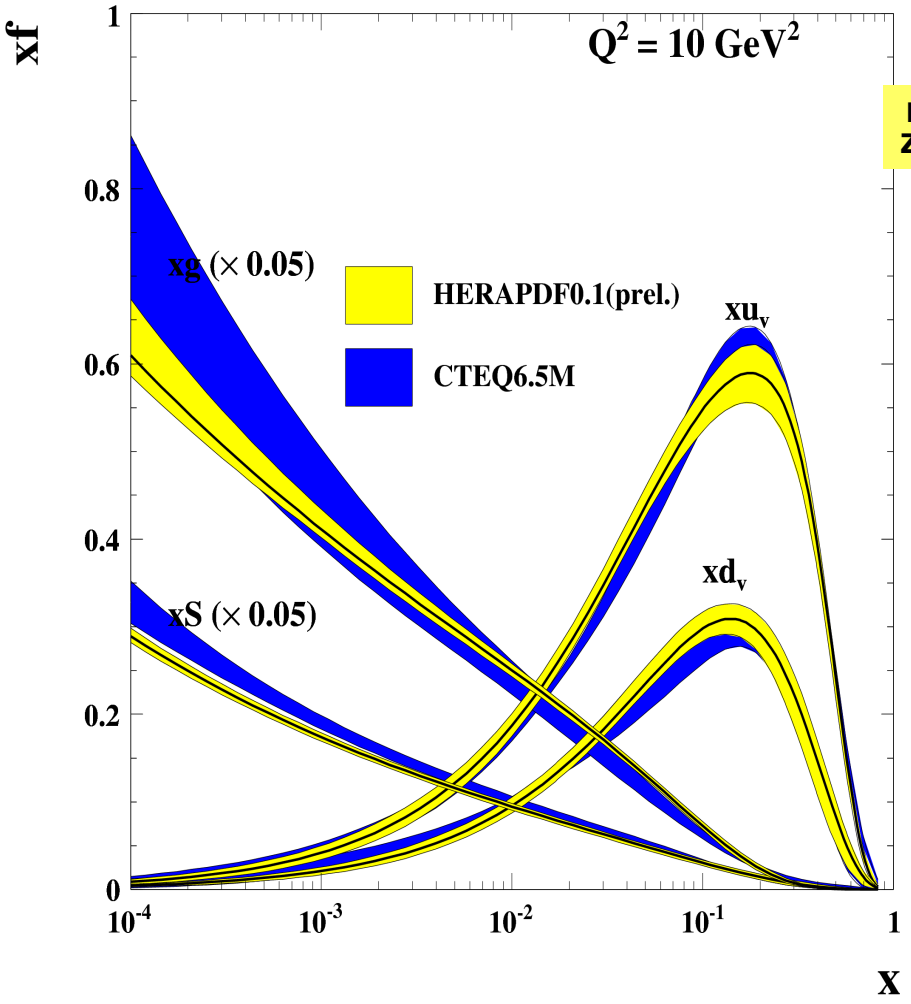
PDF fits on HERAI data



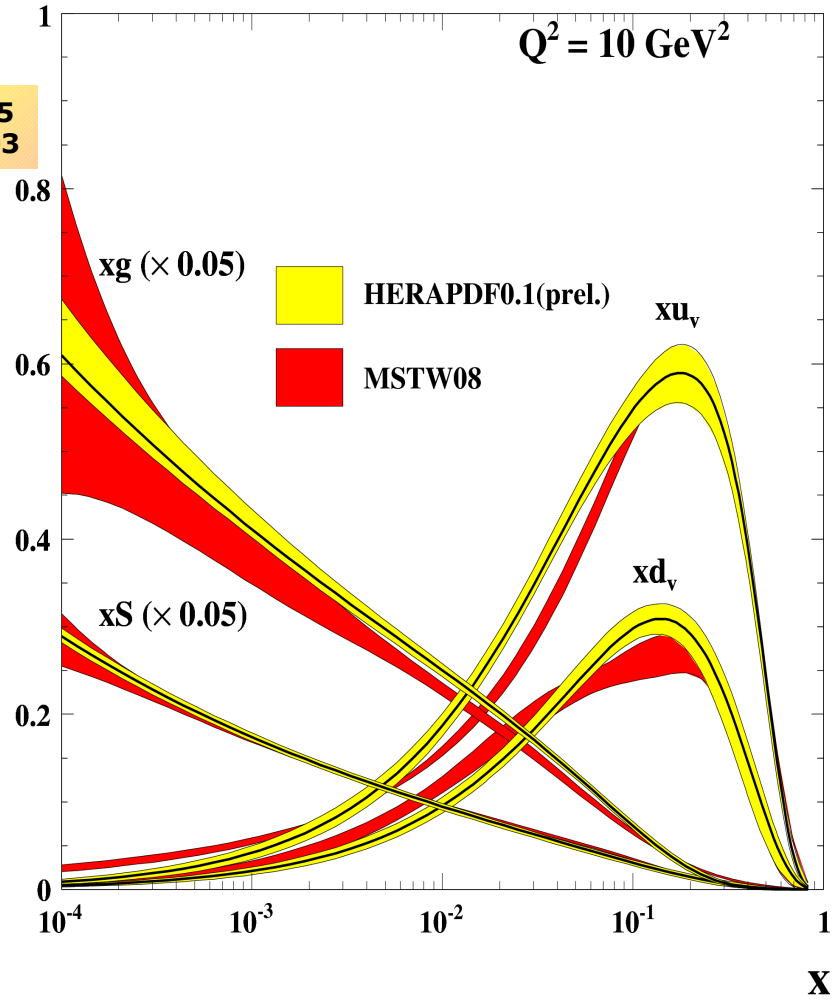


- Standalone fits compatible over the whole HERA kinematic plane, with ***g(x)*** a bit different
- After ***σ(x,Q²)*** averaging (model-independent way), **χ^2/NDF = 477/562** for the PDF fit

Comparison to Global Fits

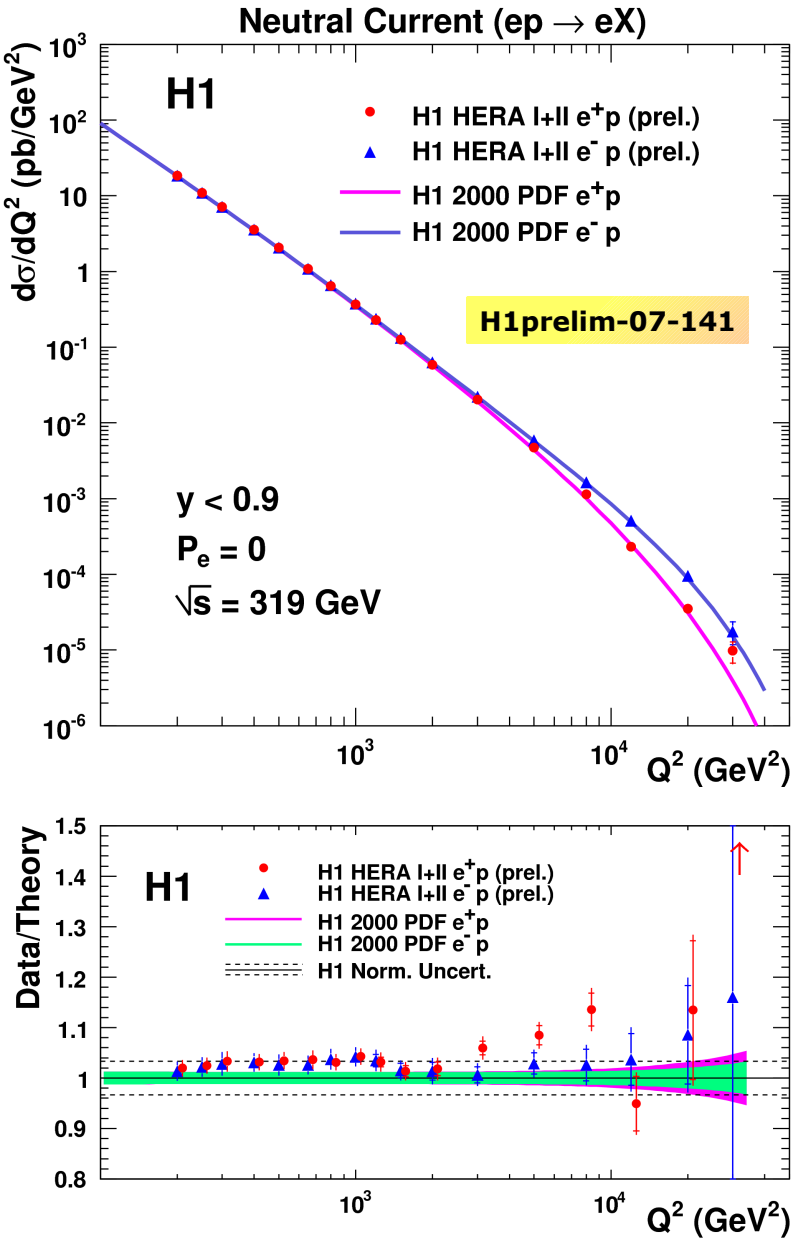


H1prelim-08-045
ZEUS-prel-08-003



- 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

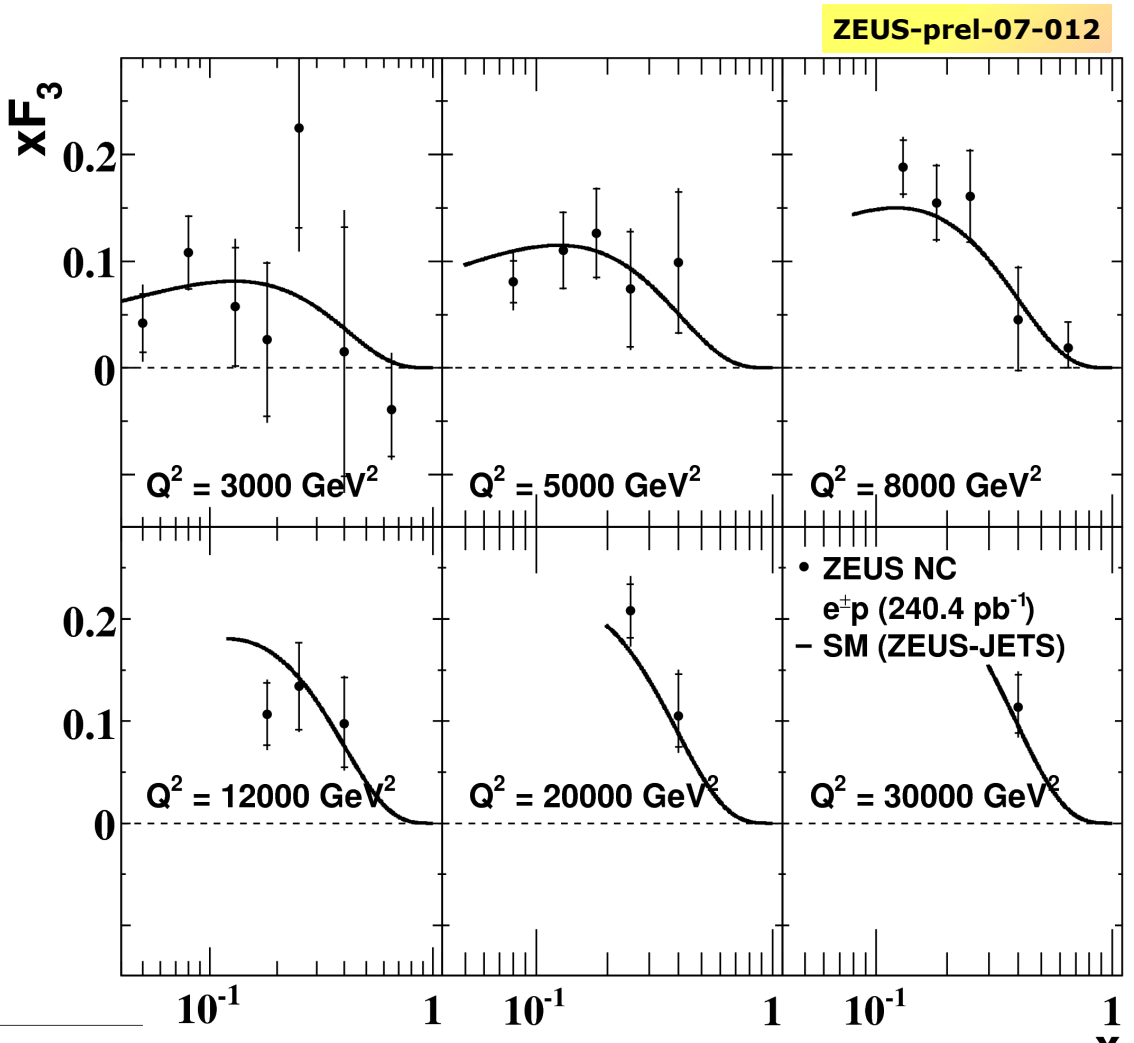
Unpolarized high Q^2 NC cross sections



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

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

ZEUS



High Q^2 NC with polarized $e^{\pm}$

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

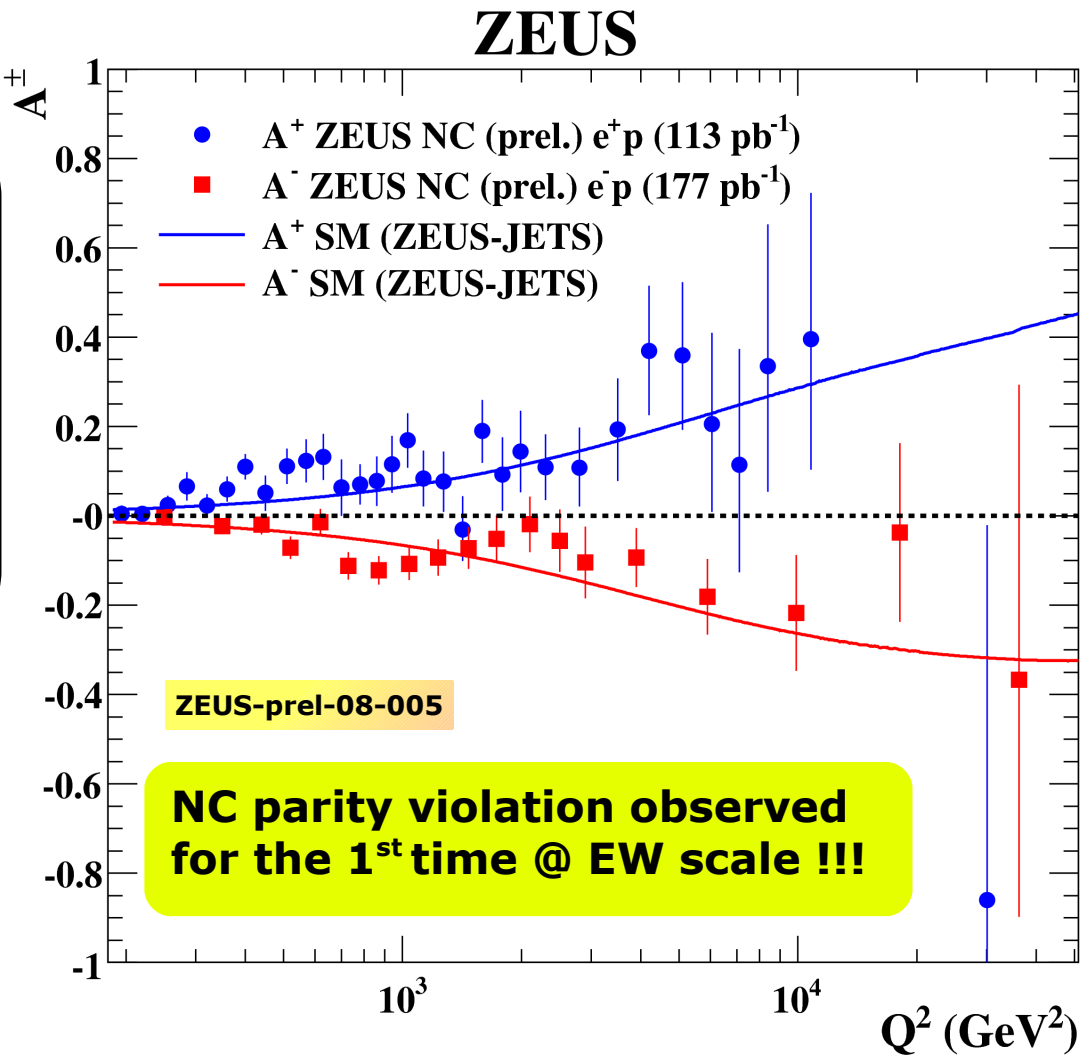
- Polarization asymmetry provides direct measure for the EW effects

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

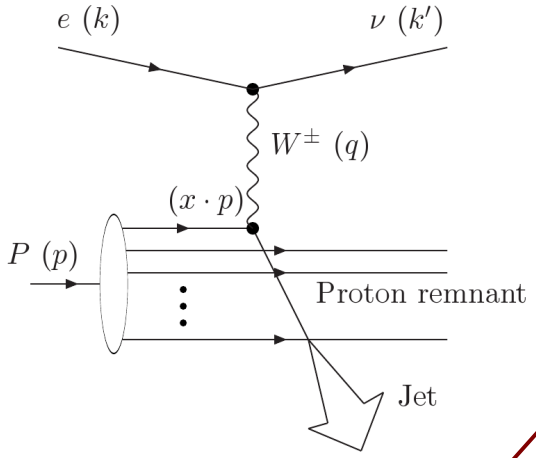
$$A^{\pm} \simeq \mp\chi_Z a_e \frac{F_2^{\gamma Z}}{F_2^{\gamma}} \propto a_e v_q$$

- $A^{\pm}$ at large x *also* measures d_v/u_v

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



CC cross sections

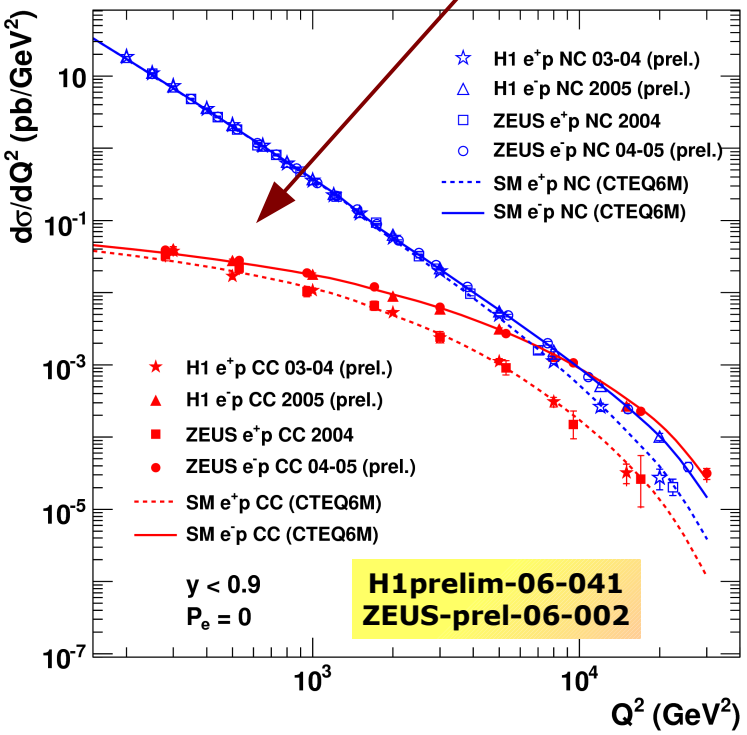


$$\frac{d\sigma^{e^-p}}{dxdQ^2} = \frac{G_F^2}{2\pi}\frac{M_W^4}{(Q^2+M_W^2)^2}\Big((u+c)+(1-y)^2(\bar{d}+\bar{s})\Big)$$

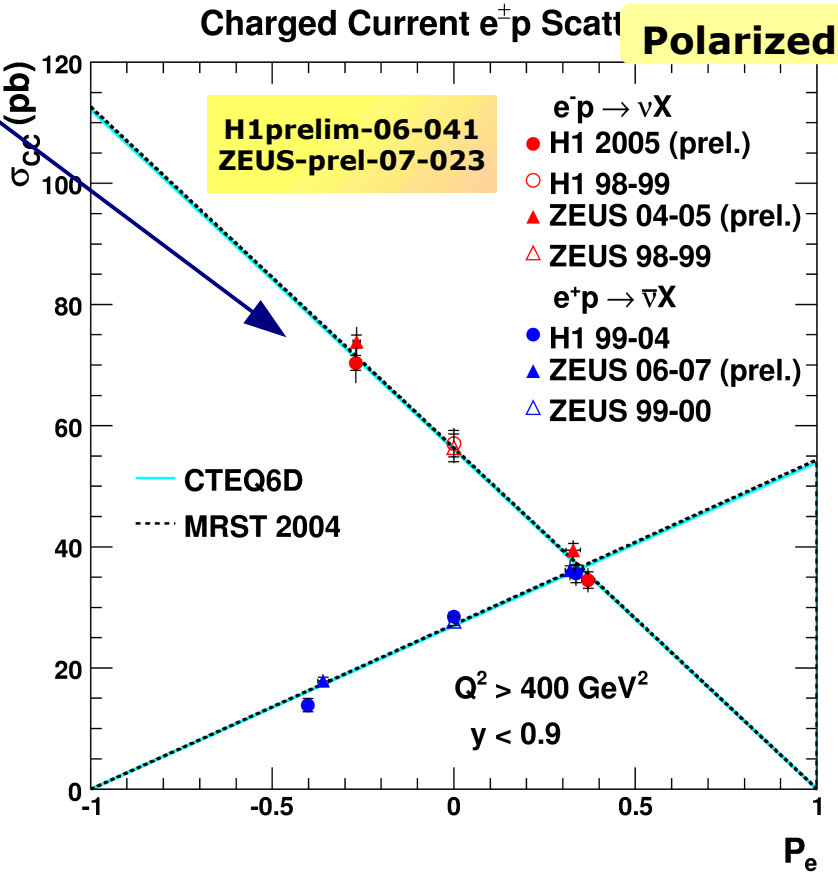
$$\frac{d\sigma^{e^+p}}{dxdQ^2} = \frac{G_F^2}{2\pi}\frac{M_W^4}{(Q^2+M_W^2)^2}\Big((\bar{u}+\bar{c})+(1-y)^2(d+s)\Big)$$

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

Unpolarized CC



Polarized CC

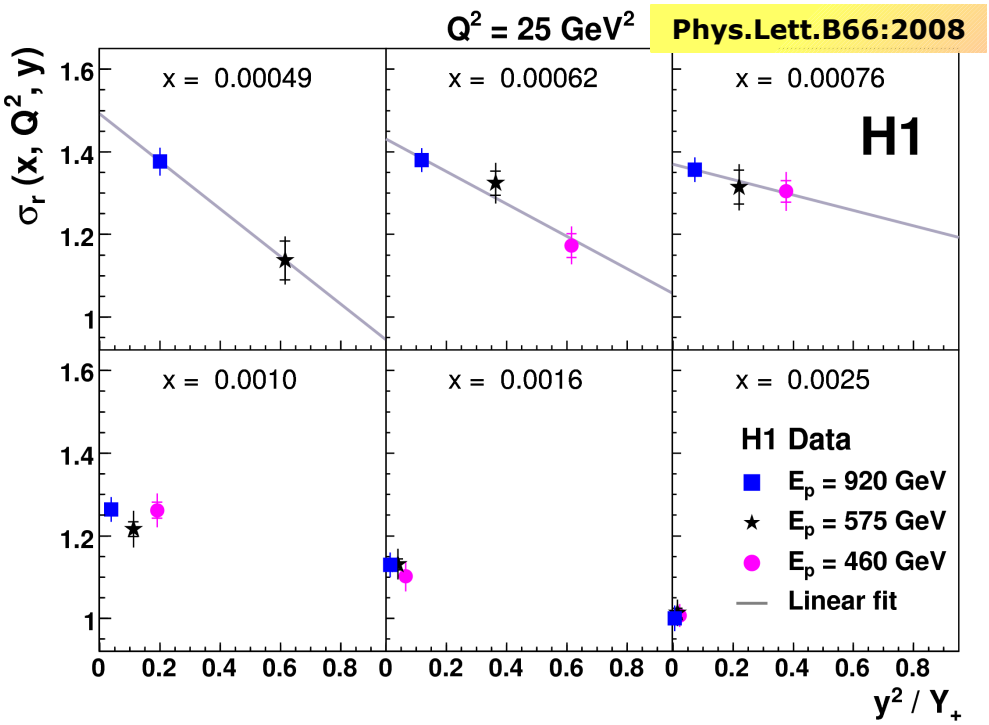


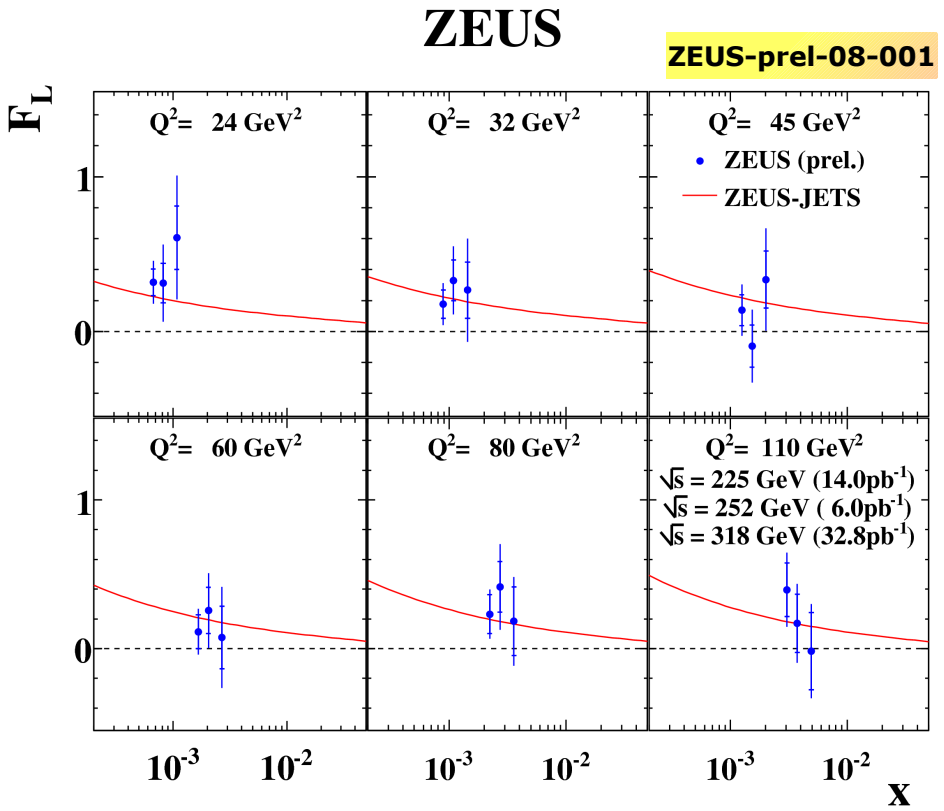
Measurements of F_L

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

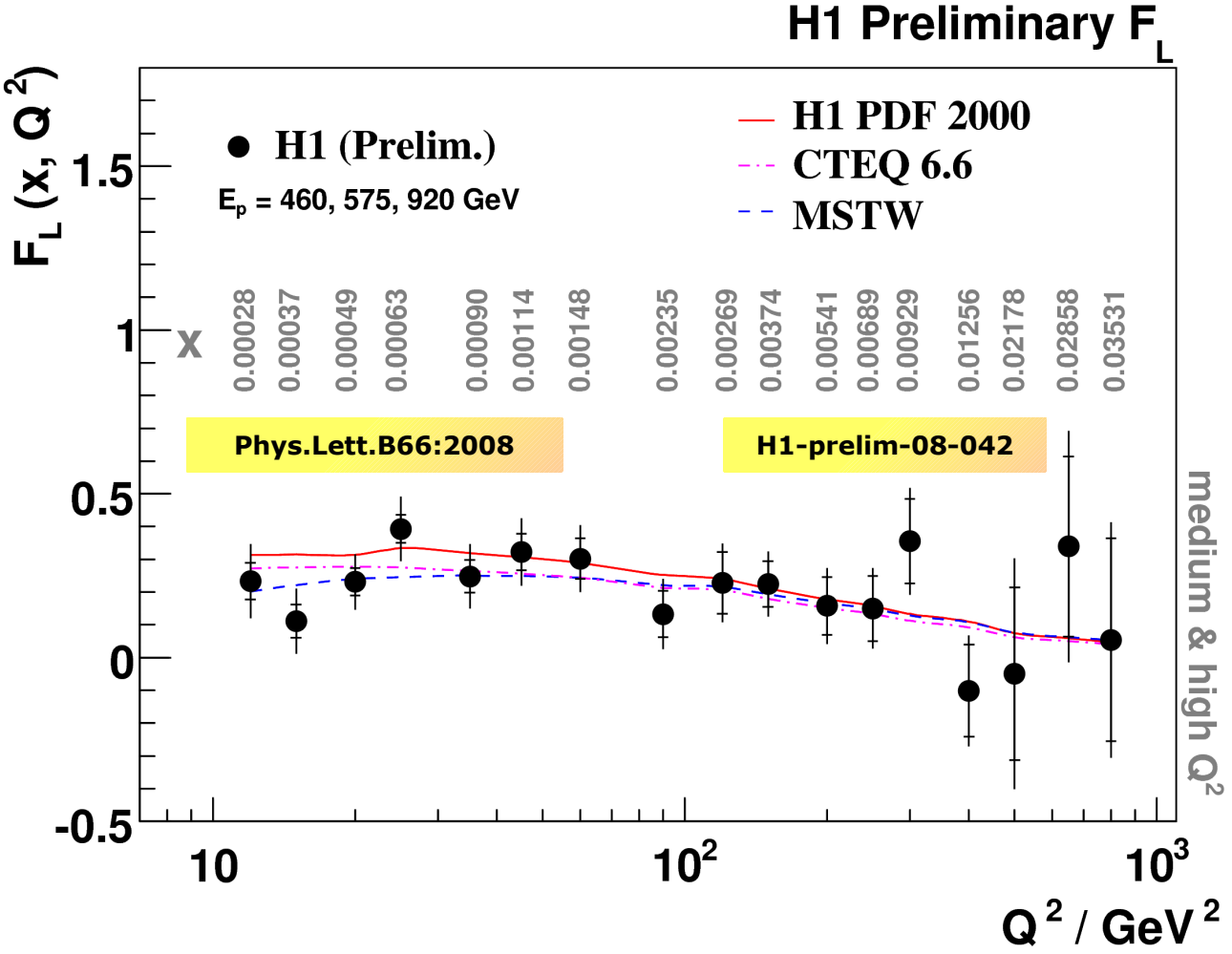
$$y = \frac{Q^2}{xs}$$

- 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 ($y < 0.8$, $Q^2 > 24$ GeV^2), H1 ($y < 0.9$, $Q^2 > 12$ GeV^2)





Measurements of F_L



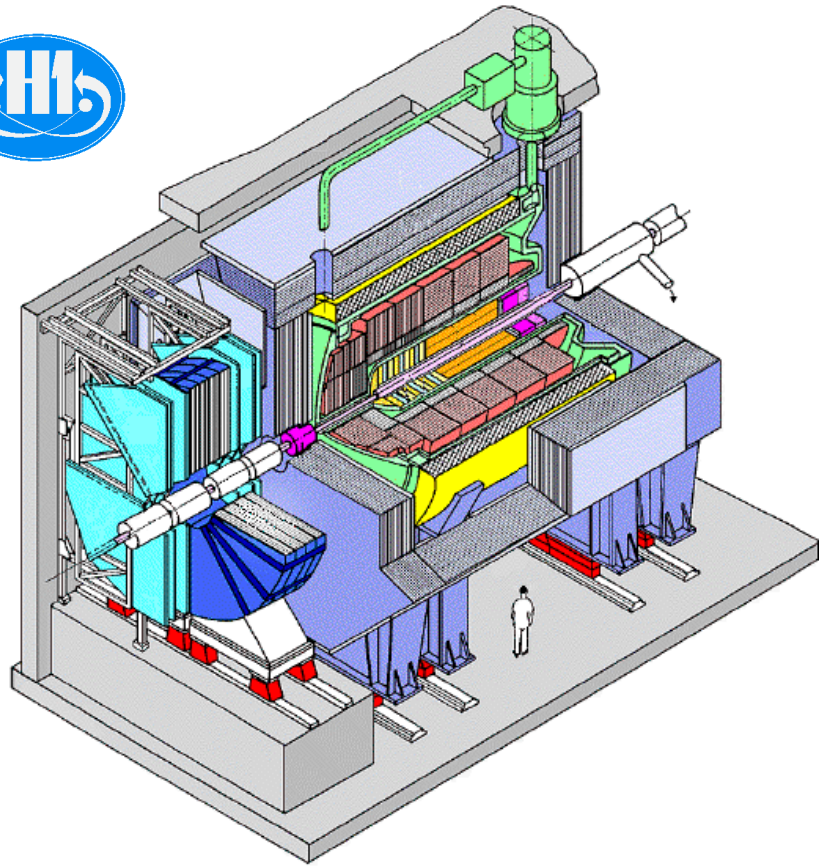
- Both results consistent with each other, and $F_L \neq 0$
- H1's averaged over *x* results consistent with predictions from pQCD
- F_L confirms expectations on the behavior of $g(x,Q^2)$ (coming from F_2)

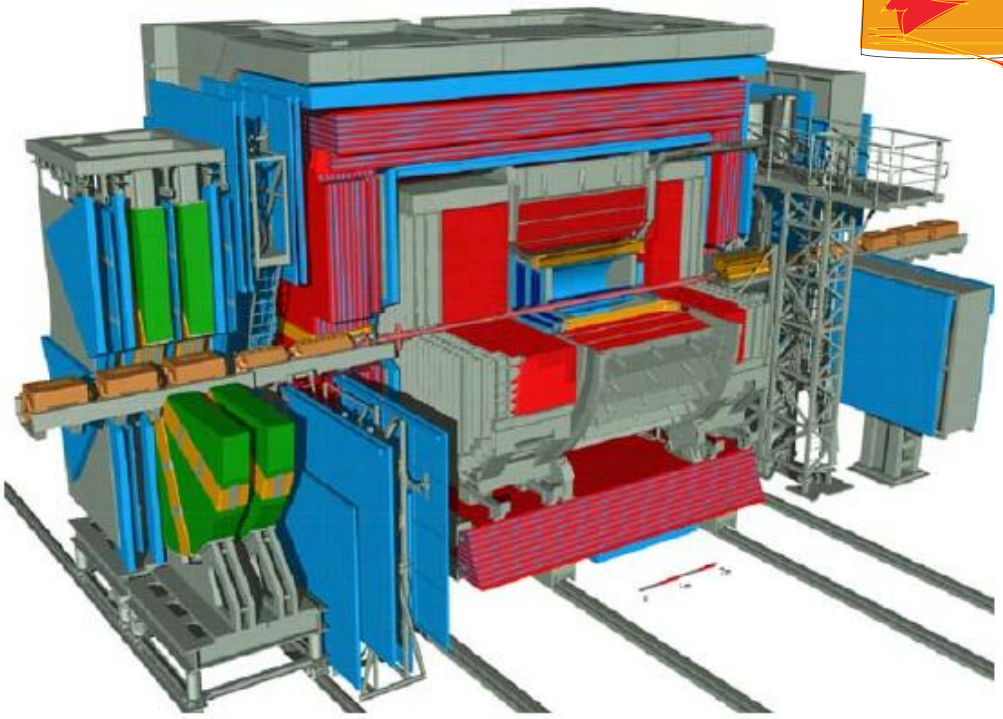
Summary and outlook

- 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 $\boldsymbol{F_L}$ 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





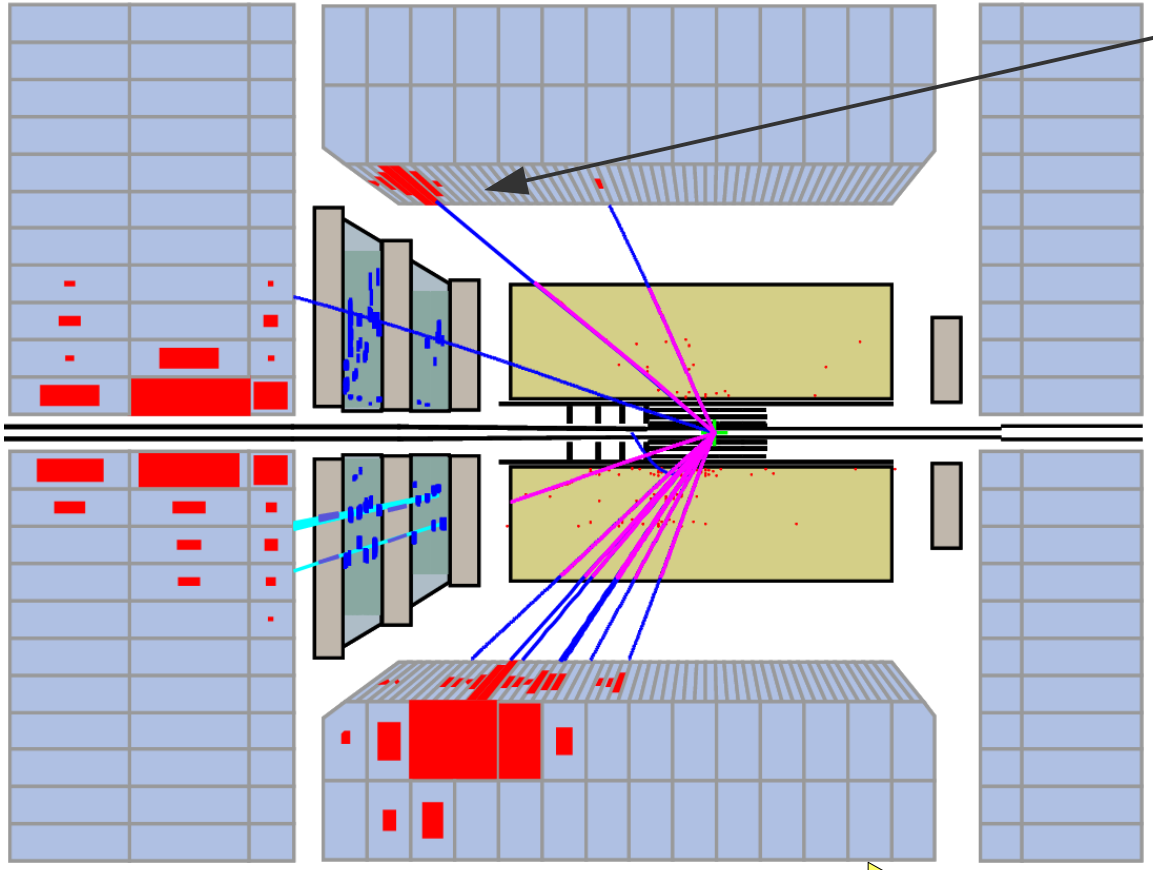
H1 calorimeters (45000 cells)
- $\sigma(E)/E = 0.07/\sqrt{E}$ (EM, small θ)
- $\sigma(E)/E = 0.12/\sqrt{E}$ (EM, central θ)
- $\sigma(E)/E = 0.5/\sqrt{E}$ (HAD)

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 $P_T \approx 0$ GeV

$E - P_z = E_P + E_e - E_P + E_e \approx 2E_e$

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

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

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

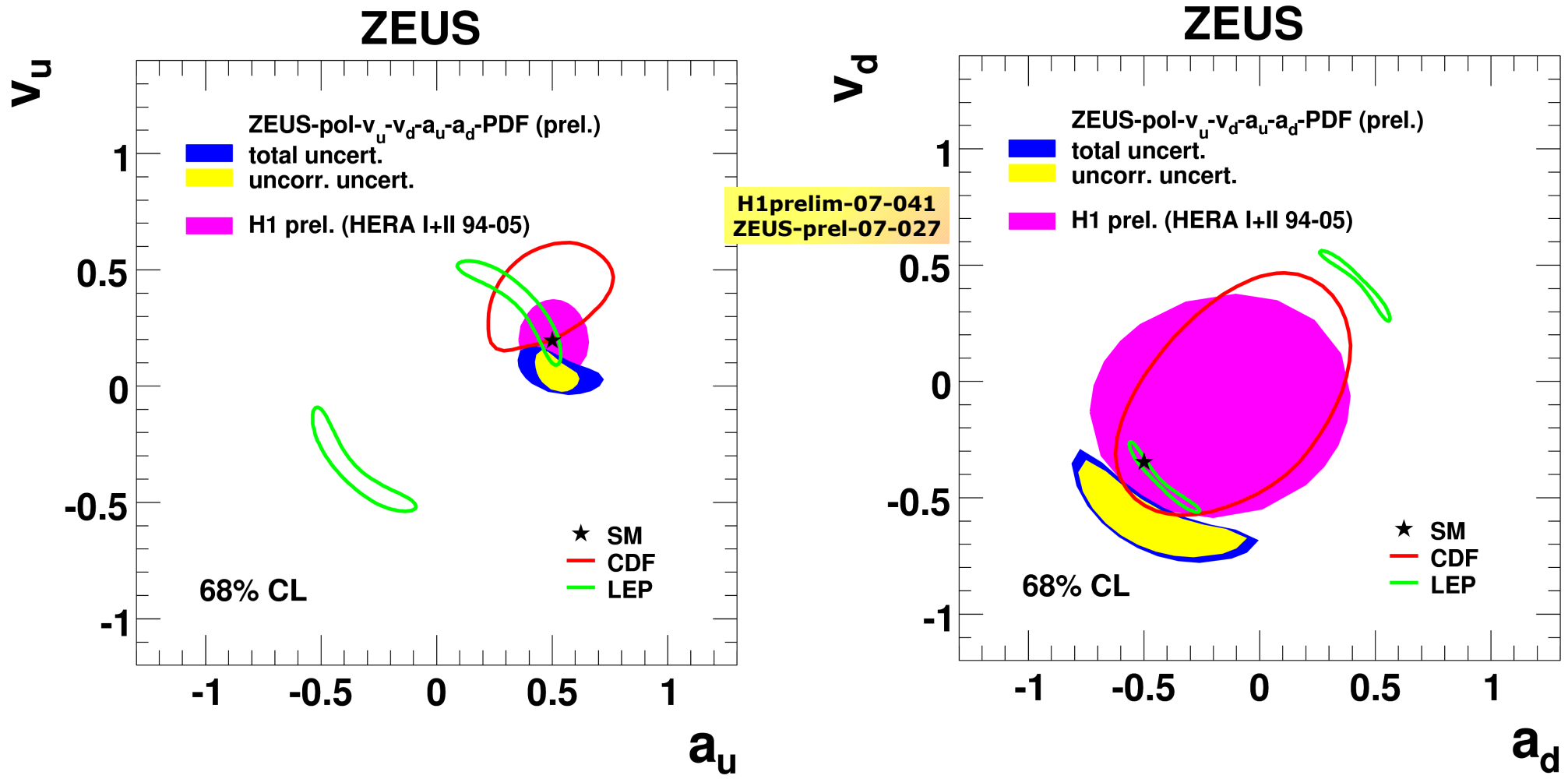
$$y_{EL} = 1 - \frac{E'_e}{2E_e}(1-\cos\theta_e)$$

(Some more) Electroweak Physics @ HERA

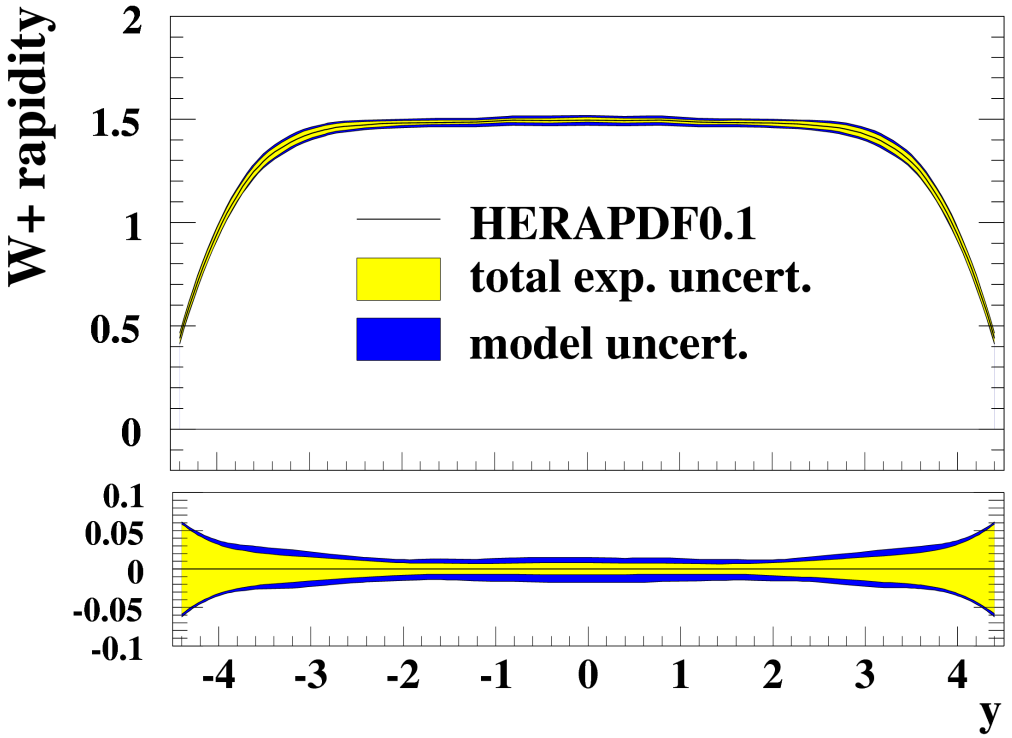
$$[F_2^{\gamma}, F_2^{\gamma Z}, F_2^{Z}] = \sum_q [e_q^2, 2e_q v_q, v_q^2 + a_q^2] x(q + \bar{q})$$

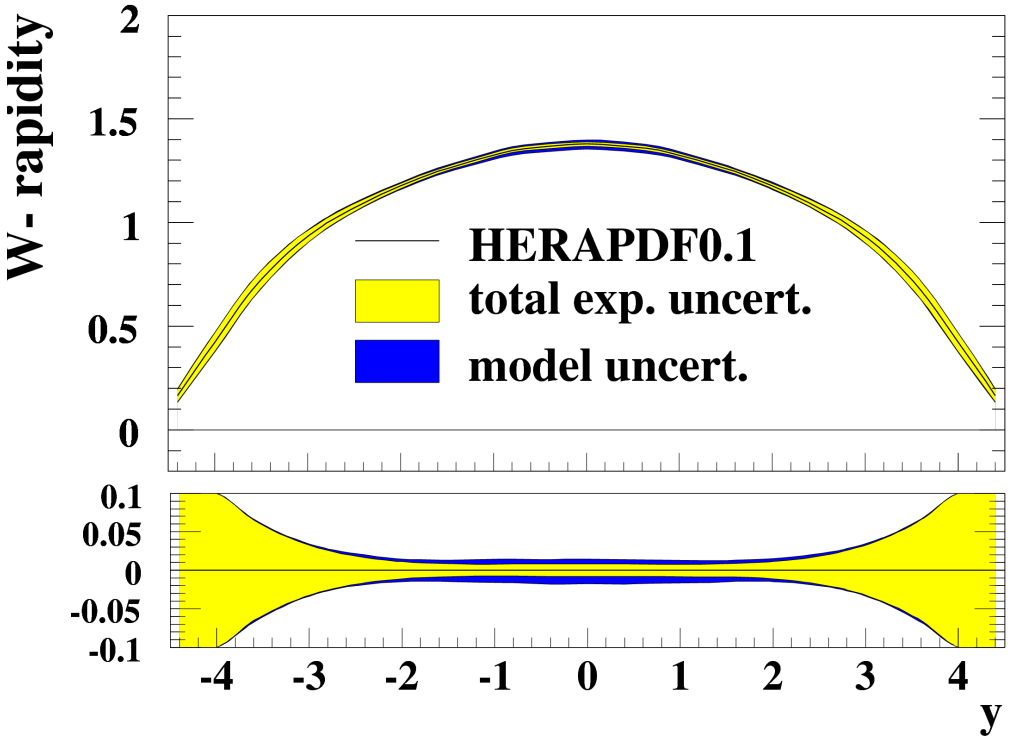
$$[xF_3^{\gamma Z}, xF_3^{Z}] = \sum_q [e_q a_q, v_q a_q] 2x(q - \bar{q})$$

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



(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