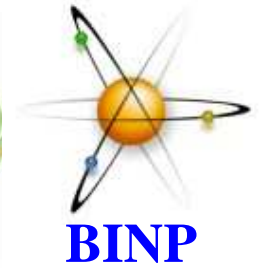




NEW TRENDS IN HIGH-ENERGY PHYSICS

(experiment, phenomenology, theory)

Alushta, Crimea, Ukraine, September 23 - 29, 2013



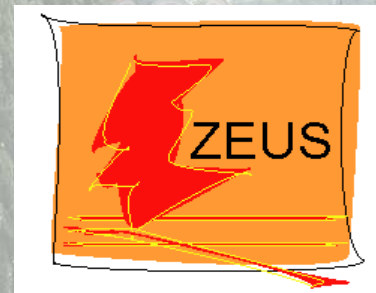
Inclusive DIS at high Q^2 at HERA

S. Levonian (DESY)

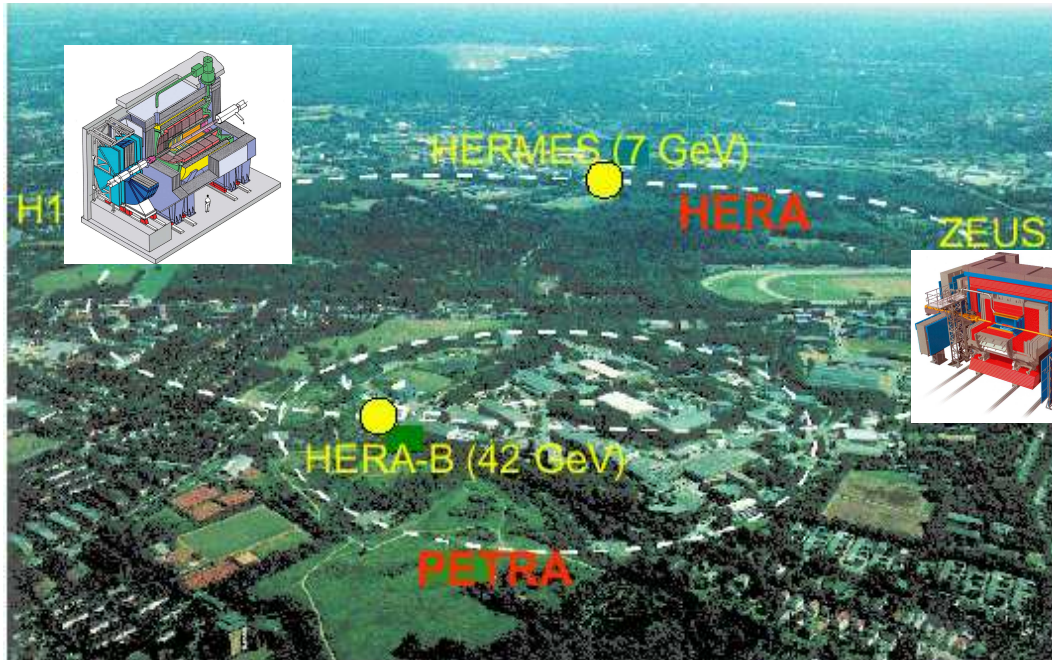
representing



and



HERA: The World's Only ep Collider

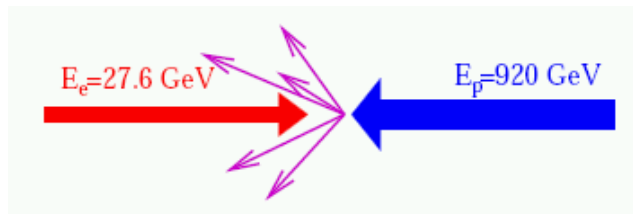


HERA-1 (1993-2000) $\simeq 120 \text{ pb}^{-1}$

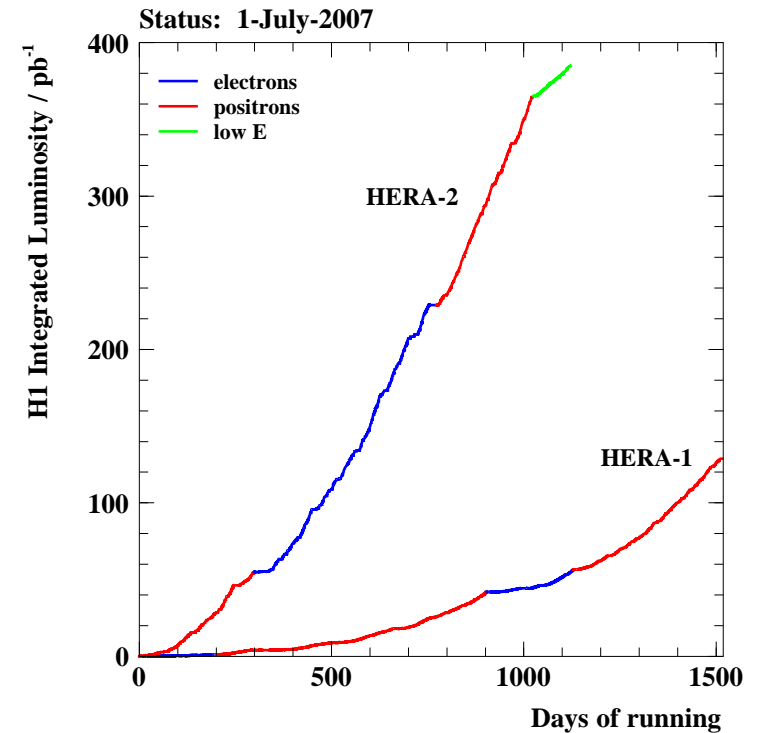
HERA-2 (2003-2007) $\simeq 380 \text{ pb}^{-1}$

Final Data samples

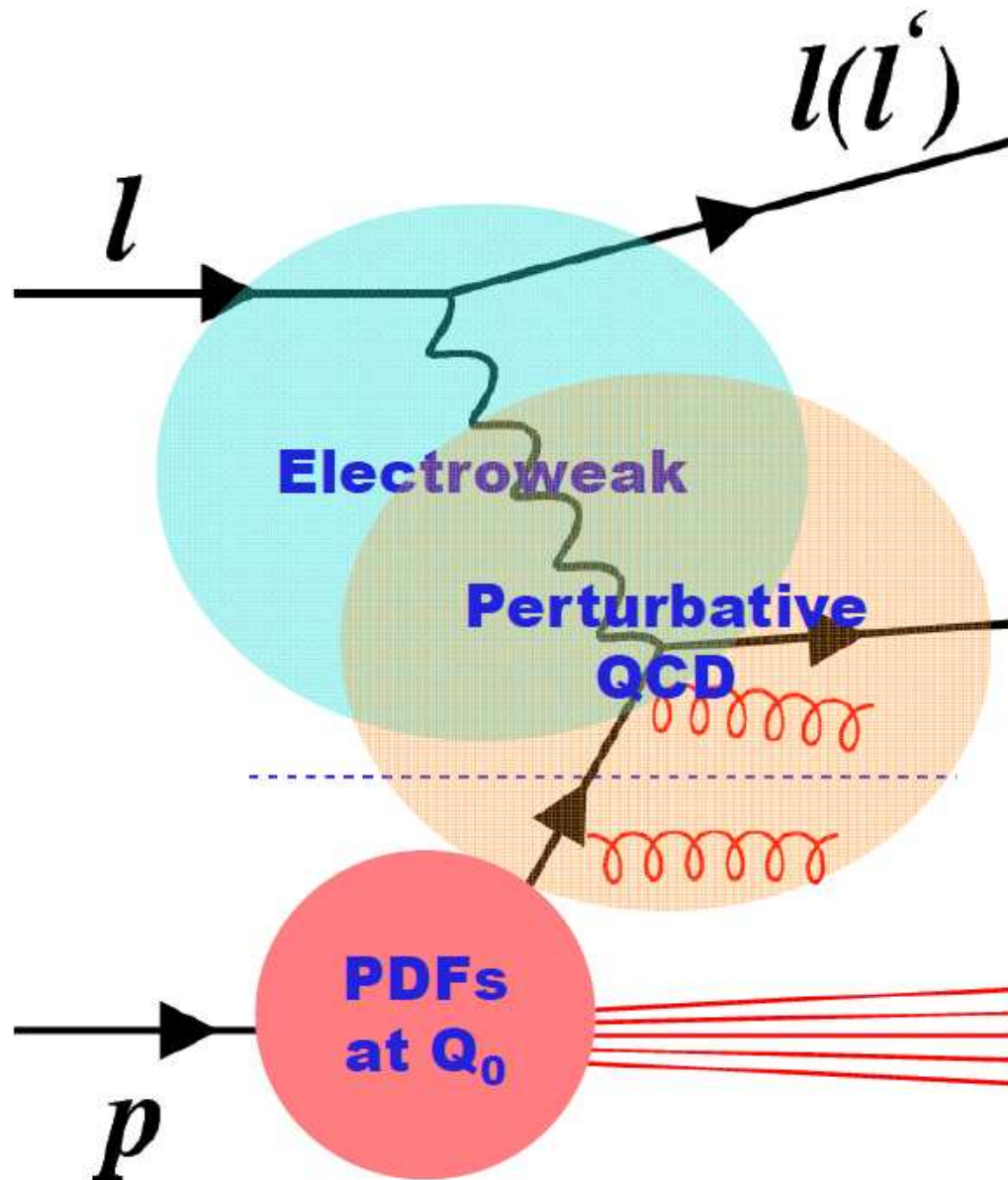
H1+ZEUS: $2 \times 0.5 \text{ fb}^{-1}$



- 1998 E_p upgrade: $820 \Rightarrow 920 \text{ GeV}$
(\sqrt{s} : $301 \Rightarrow 319 \text{ GeV}$)
- 2001 HERA-2 upgrade: $\mathcal{L} \times 3$, Polarised e^+/e^-
($\langle P \rangle = 40\%$)



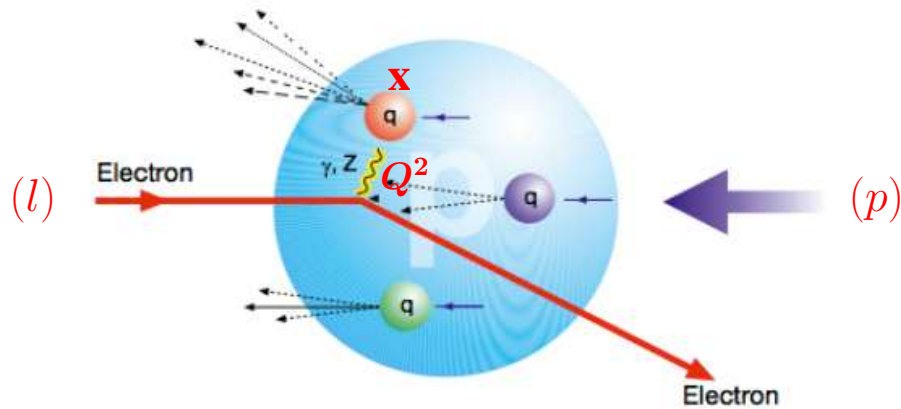
Deep-Inelastic Scattering at HERA



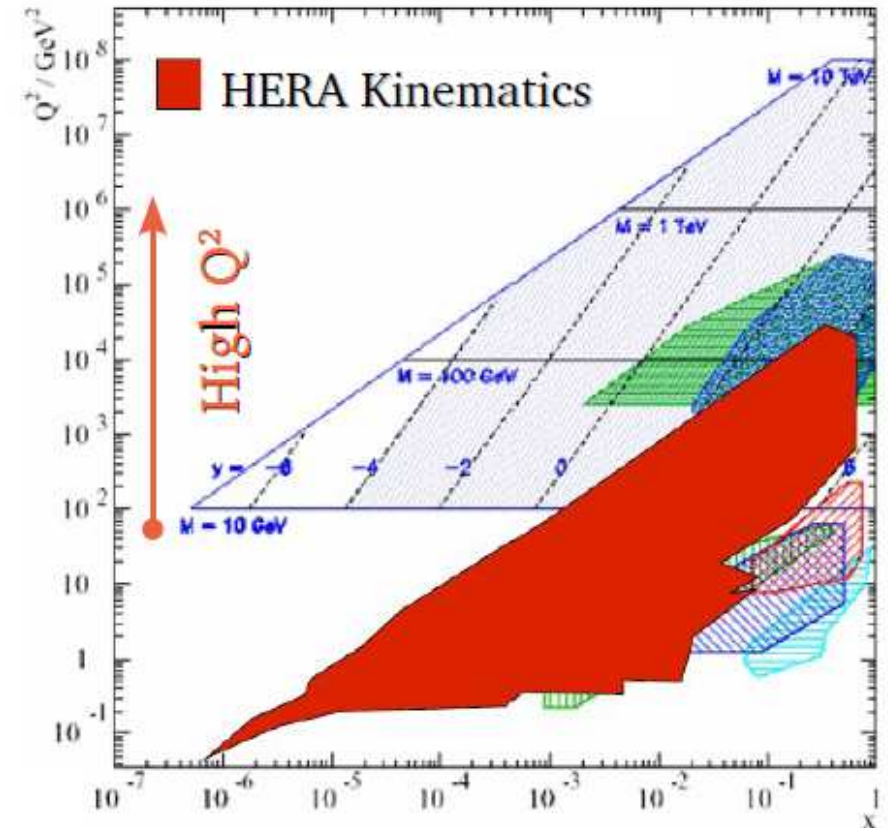
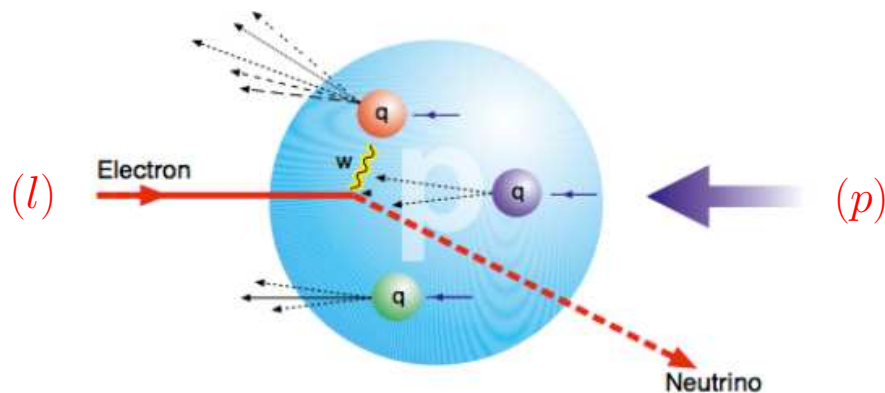
- Testing all basic ingredients of the Standard Model
- Probing structure of a proton down to 10^{-18} m

Deep-Inelastic Scattering at HERA

Neutral Current DIS: $ep \rightarrow e'X$



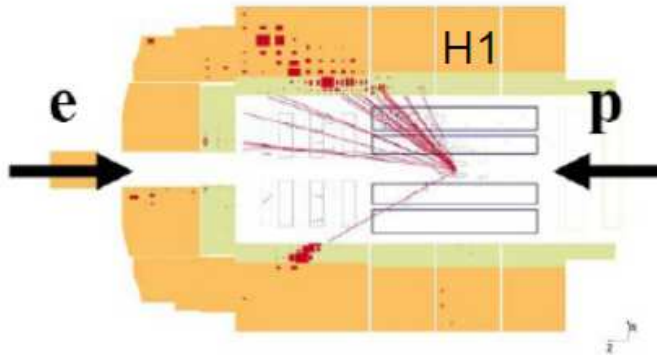
Charged Current DIS: $ep \rightarrow \nu X$



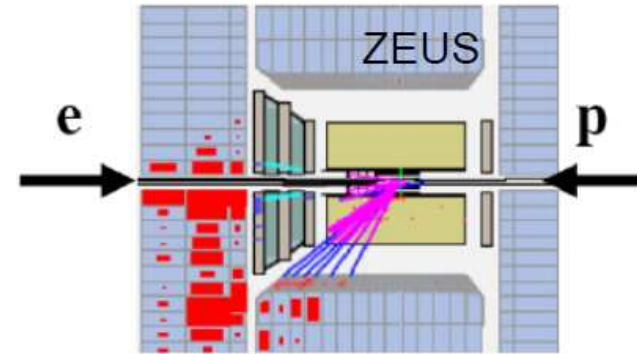
Kinematics: (Momentum transfer)²: $Q^2 = -q^2$
 Bjorken x : $x = Q^2 / (2p \cdot q)$
 Inelasticity: $y = (p \cdot q) / (p \cdot l)$
 (Total hadronic energy)²: $W^2 = (p + q)^2$
 $W^2 \simeq Q^2 / x$

DIS: Cross sections and Structure Functions

Neutral Current (NC): $e^\pm p \rightarrow e^\pm X$



Charged Current (CC): $e^\pm p \rightarrow \nu X$



$$\frac{d\sigma_{NC}^\pm}{dx dQ^2} = \frac{2\pi\alpha^2}{x} \left[\frac{1}{Q^2} \right]^2 [Y_+ \tilde{F}_2 \mp Y_- x \tilde{F}_3 - y^2 \tilde{F}_L]$$

$$\frac{d\sigma_{CC}^\pm}{dx dQ^2} = \frac{G_F^2}{4\pi x} \left[\frac{M_W^2}{M_W^2 + Q^2} \right]^2 [Y_+ \tilde{W}_2^\pm \mp Y_- x \tilde{W}_3^\pm - y^2 \tilde{W}_L^\pm]$$

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

$$\tilde{F}_2 \propto \sum (xq_i + x\bar{q}_i)$$

Dominant contribution
($F_2 + F_2^{\gamma Z} + F_2^Z$)

$$W_2^- = x(U + \bar{D}) \quad W_2^+ = x(D + \bar{U})$$

$$x\tilde{F}_3 \propto \sum (xq_i - x\bar{q}_i)$$

Only sensitive at high Q^2
($x F_3^{\gamma Z} + x F_3^Z$)

$$xW_3^- = x(U - \bar{D}) \quad xW_3^+ = x(D - \bar{U})$$

$$\tilde{F}_L \propto \alpha_s \cdot xg(x, Q^2)$$

Only sensitive at high y

$$U = u + c, \quad \bar{U} = \bar{u} + \bar{c}, \quad D = d + s, \quad \bar{D} = \bar{d} + \bar{s}$$

HERA-2 vs HERA-1

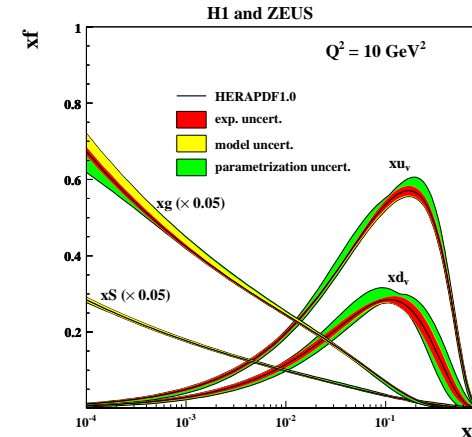
HERA-1



Combined Measurement and QCD Analysis
of the Inclusive DIS at HERA



JHEP 01 (2010) 109 \Rightarrow HERAPDF 1.0



dominated by
low x /low Q^2
(statistics)

HERA-2



CC e^-p – *EPJ C61 (2009) 223*

NC e^-p – *EPJ C62 (2009) 625*

CC e^+p – *EPJ C70 (2010) 945*

NC e^+p – *PRD 87 (2013) 052014*

Longitudinally polarized leptons

$$\mathcal{L}(e^+) = 3 \times \text{HERA-1} \quad \mathcal{L}(e^-) = 10 \times \text{HERA-1}$$



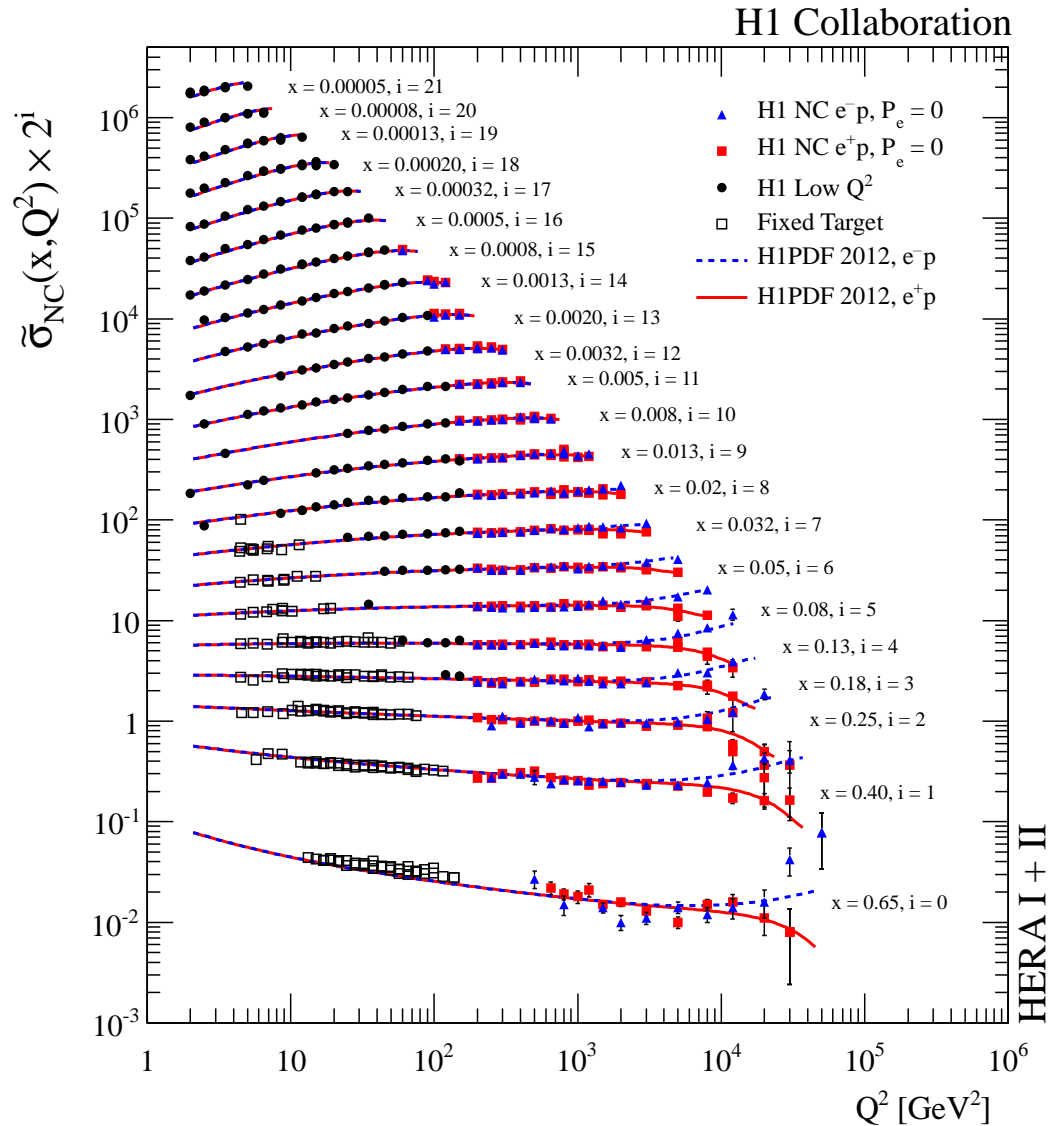
NC+CC $e^\pm p$ – *JHEP 09 (2012) 061*

(also combination with H1 HERA-1 data
is performed \Rightarrow H1PDF 2012)

breakdown of HERA-II data samples

	R	L
e^-p	$\mathcal{L} = 47.3 \text{ pb}^{-1}$ $P_e = (+36.0 \pm 1.0)\%$	$\mathcal{L} = 104.4 \text{ pb}^{-1}$ $P_e = (-25.8 \pm 0.7)\%$
e^+p	$\mathcal{L} = 101.3 \text{ pb}^{-1}$ $P_e = (+32.5 \pm 0.7)\%$	$\mathcal{L} = 80.7 \text{ pb}^{-1}$ $P_e = (-37.0 \pm 0.7)\%$

Unpolarized Reduced NC Cross Sections - H1



Final H1 (HERA I+II) NC data

(854 points \rightarrow 413 σ_{NC} values; $\chi^2/NDF = 412/441$)

Precision 1.5% for $Q^2 < 500$ GeV 2

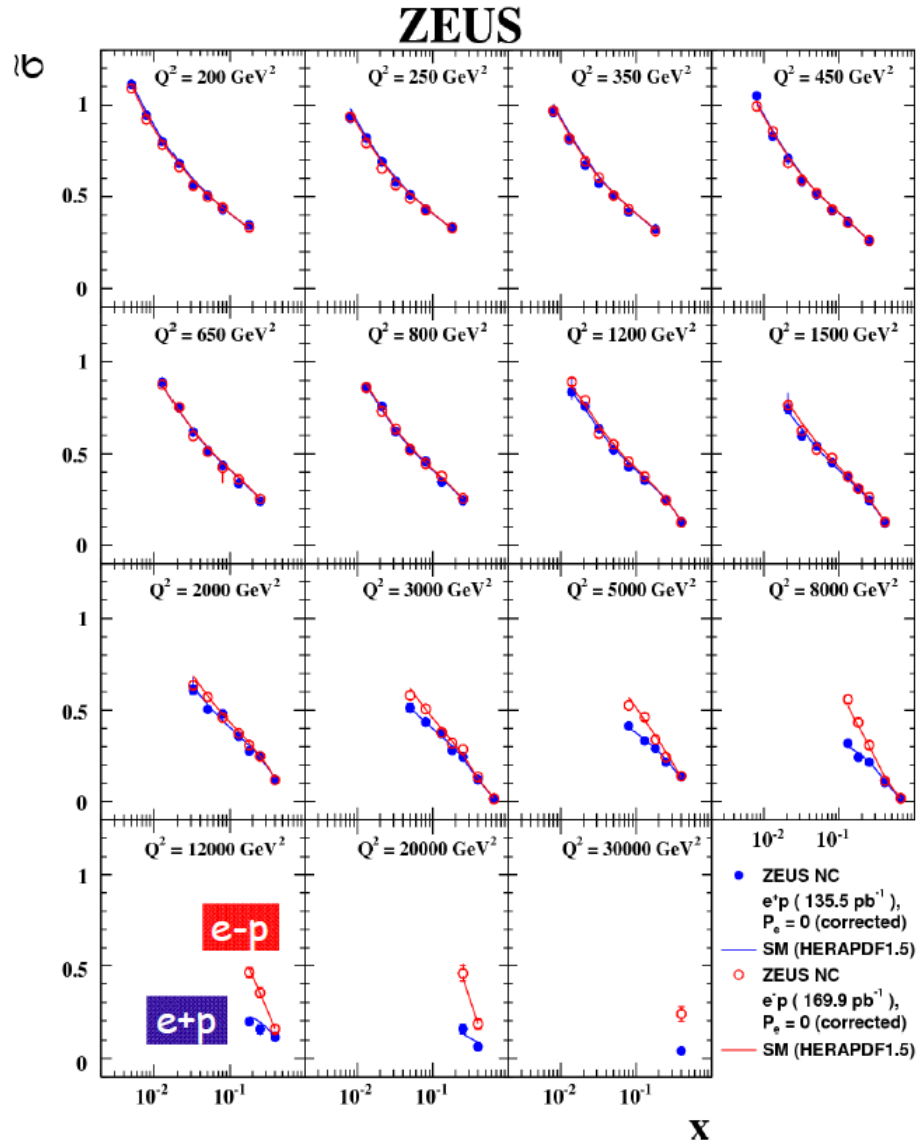
(factor 2 reduction in error wrt HERA-I)

Extended reach at high x

At high Q^2 difference between e^+ and e^-
due to Z -exchange term $x F_3$

H1PDF2012 (NLO DGLAP)
describes data well

Unpolarized Reduced NC Cross Sections - ZEUS



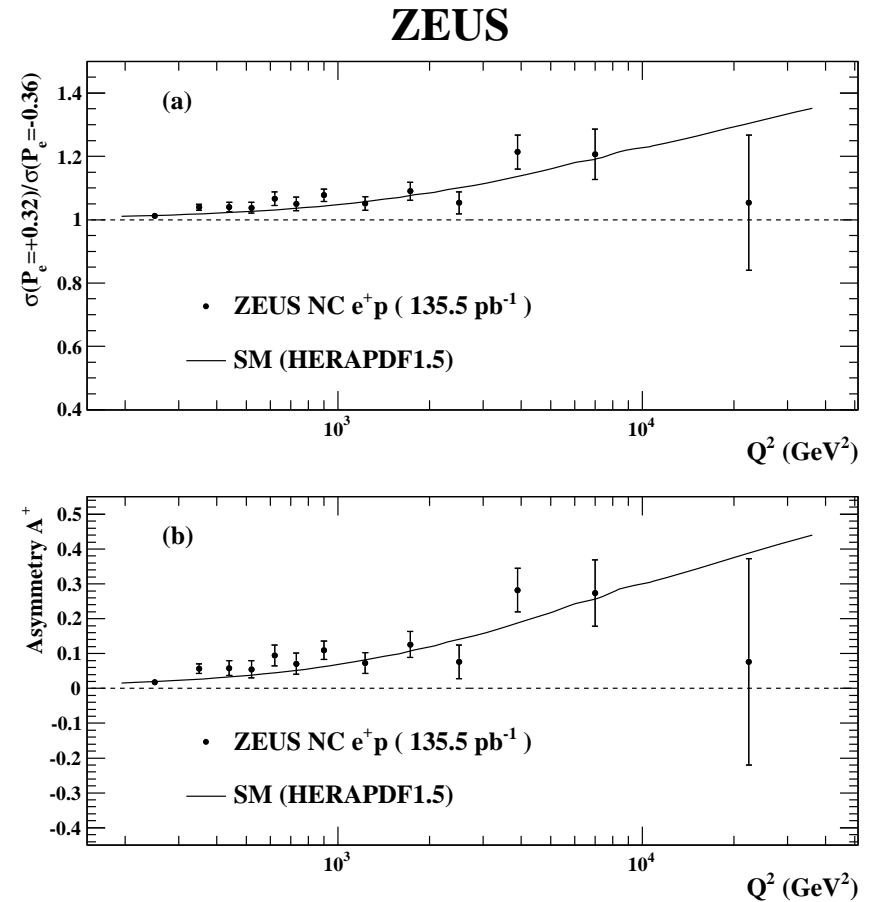
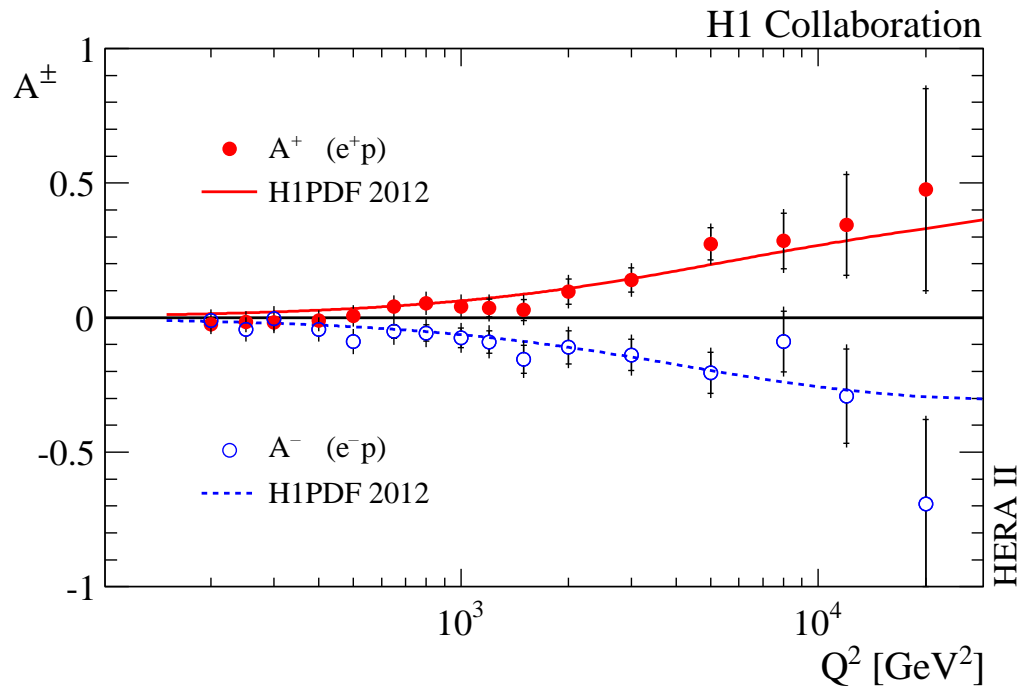
Final ZEUS (HERA II) high Q^2 NC results

x –dependence: strong scaling violation
due to high density of sea quarks at low x

Data well described by DGLAP NLO QCD

NC Polarization Asymmetry

$$A^{\pm} = \frac{2}{P_L - P_R} \cdot \frac{\sigma^{\pm}(P_L) - \sigma^{\pm}(P_R)}{\sigma^{\pm}(P_L) + \sigma^{\pm}(P_R)}$$

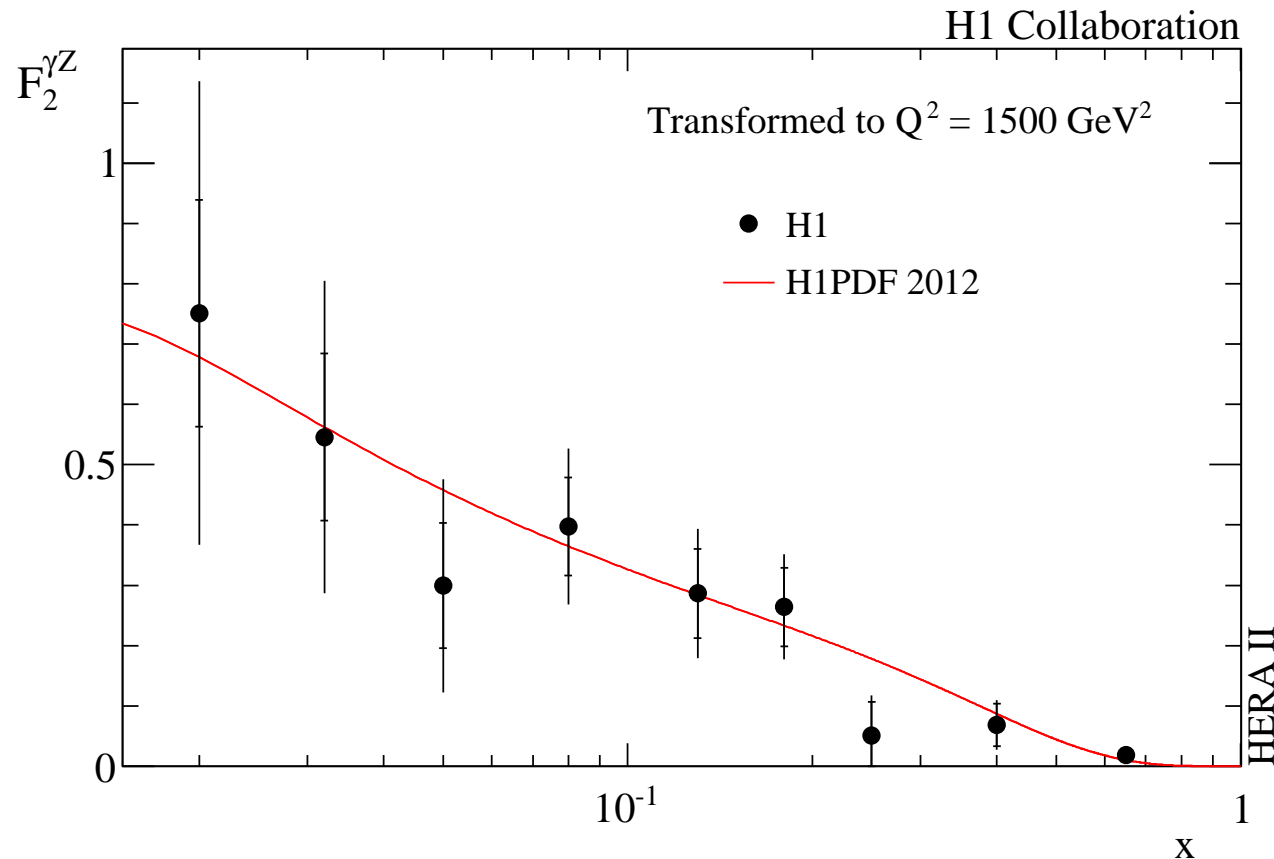


★ A direct measure of parity violation in NC DIS (at low Q^2 $A^{\pm} \approx 0$, at high Q^2 $A^+ \approx -A^-$)

★ Access to u_v/d_v ratio: at large x $A^{\pm} \propto \frac{1+d_v/u_v}{4+d_v/u_v}$

NC - $F_2^{\gamma Z}$ Structure Function

$$\Delta\sigma^\pm = \frac{\sigma^\pm(P_L^\pm) - \sigma^\pm(P_R^\pm)}{P_L^\pm - P_R^\pm} \sim \mp F_2^{\gamma Z} + xF_3^{\gamma Z} - xF_3^Z \Rightarrow F_2^{\gamma Z} = \Delta\sigma^- - \Delta\sigma^+$$



First ever direct measurement of $F_2^{\gamma Z}$ (all 4 NC cross sections are needed: LH/RH, e^-/e^+)

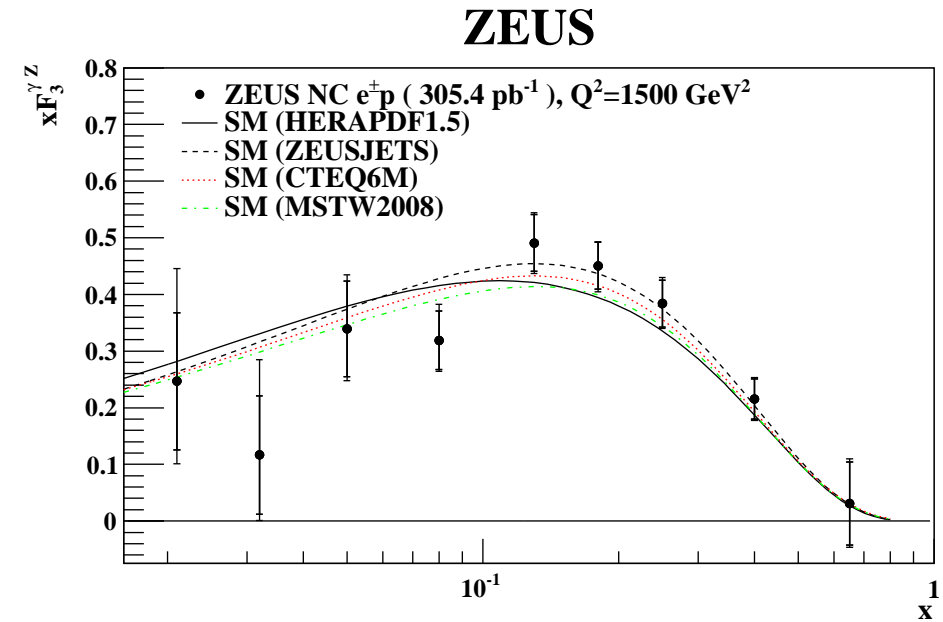
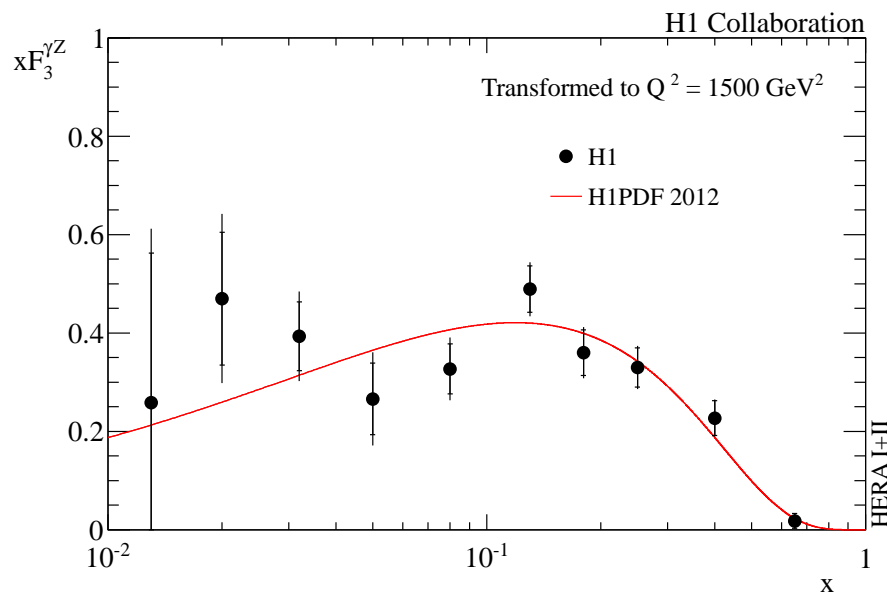
x -behavior reflects parton composition: $F_2^{\gamma Z} \sim q + \bar{q}$

NC - $x F_3^{\gamma Z}$ Structure Function

$$x F_3 \propto (\sigma_{\text{NC}}^- - \sigma_{\text{NC}}^+) \approx x F_3^{\gamma Z} \quad (\text{pure } Z\text{-term negligible for unpolarized cross sections})$$

From combined HERA I+II H1 data

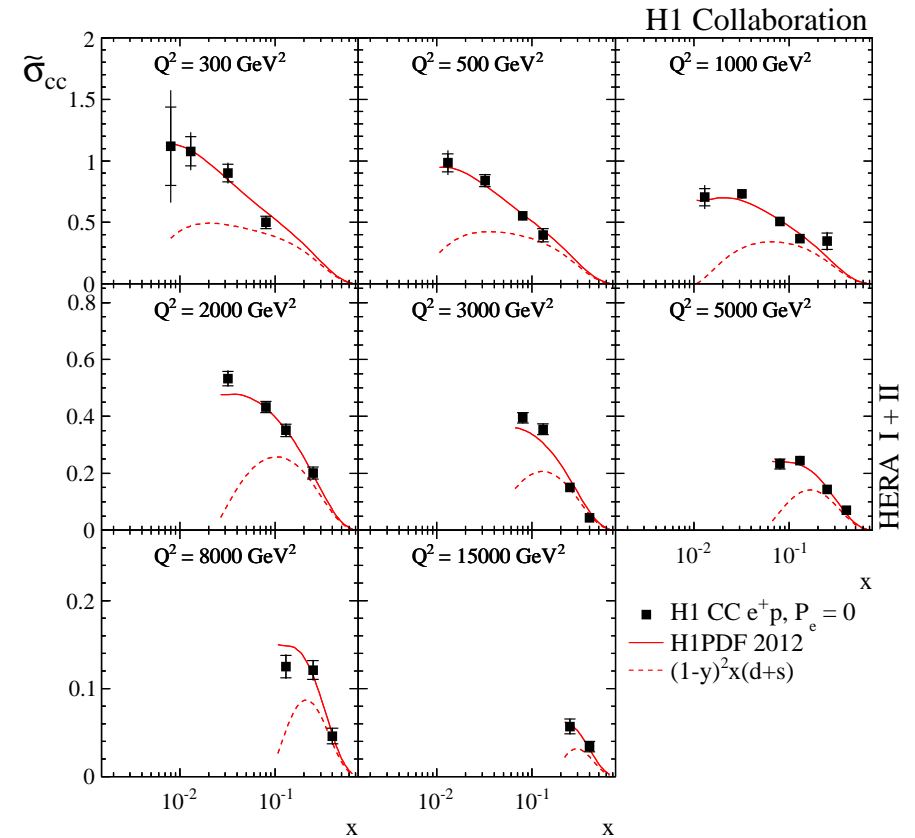
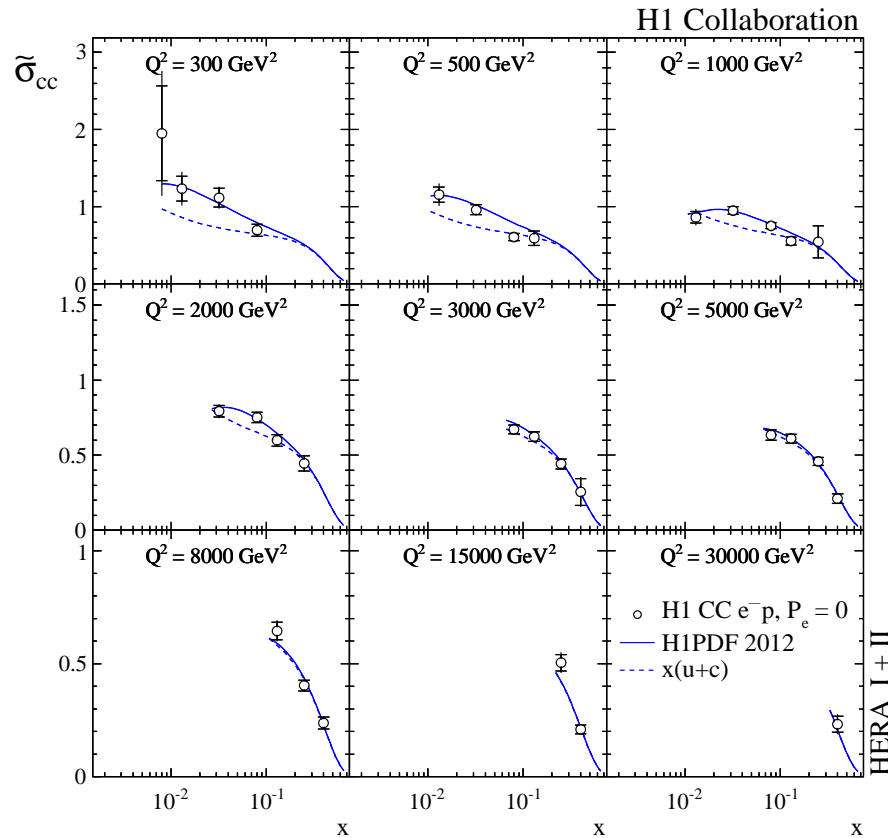
HERA II only



$$x F_3 \sim x q - x \bar{q} = x q_v \Rightarrow \text{Constrain valence quarks } (2u_v + d_v)$$

CC Double Differential Cross Sections

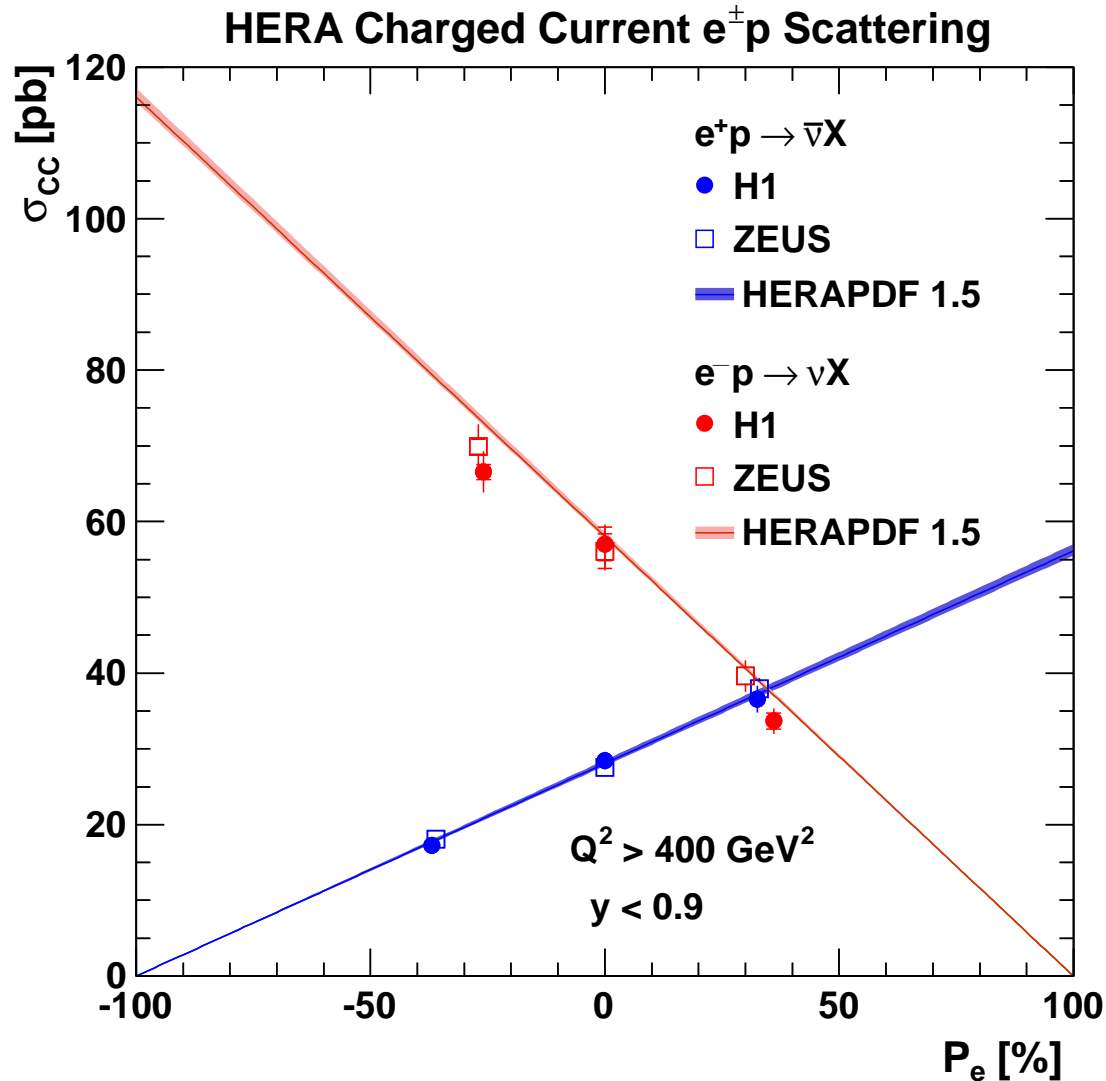
$$\tilde{\sigma}_{\text{CC}}^{\pm} = (1 \pm P_e)(Y_+ W_2^{\pm} \mp Y_- x W_3^{\pm} - y^2 W_L^{\pm})(1 + \Delta_{\text{CC}}^{\text{weak}})$$



- ★ Strong polarization dependence (parity violation)
- ★ Provides unique flavour decomposition of the proton structure
 strong (5 – 10%) constraint on d_v at high x (further gain after final H1+ZEUS combination)

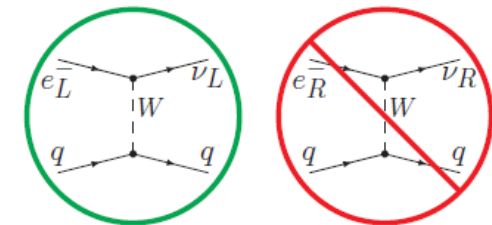
Total CC Cross Sections

$$\sigma_{\text{pol}}^{CC}(e^\pm p) = (1 \pm P_e) \cdot \sigma_{\text{unpol}}^{CC}(e^\pm p)$$



Full HERA measurement

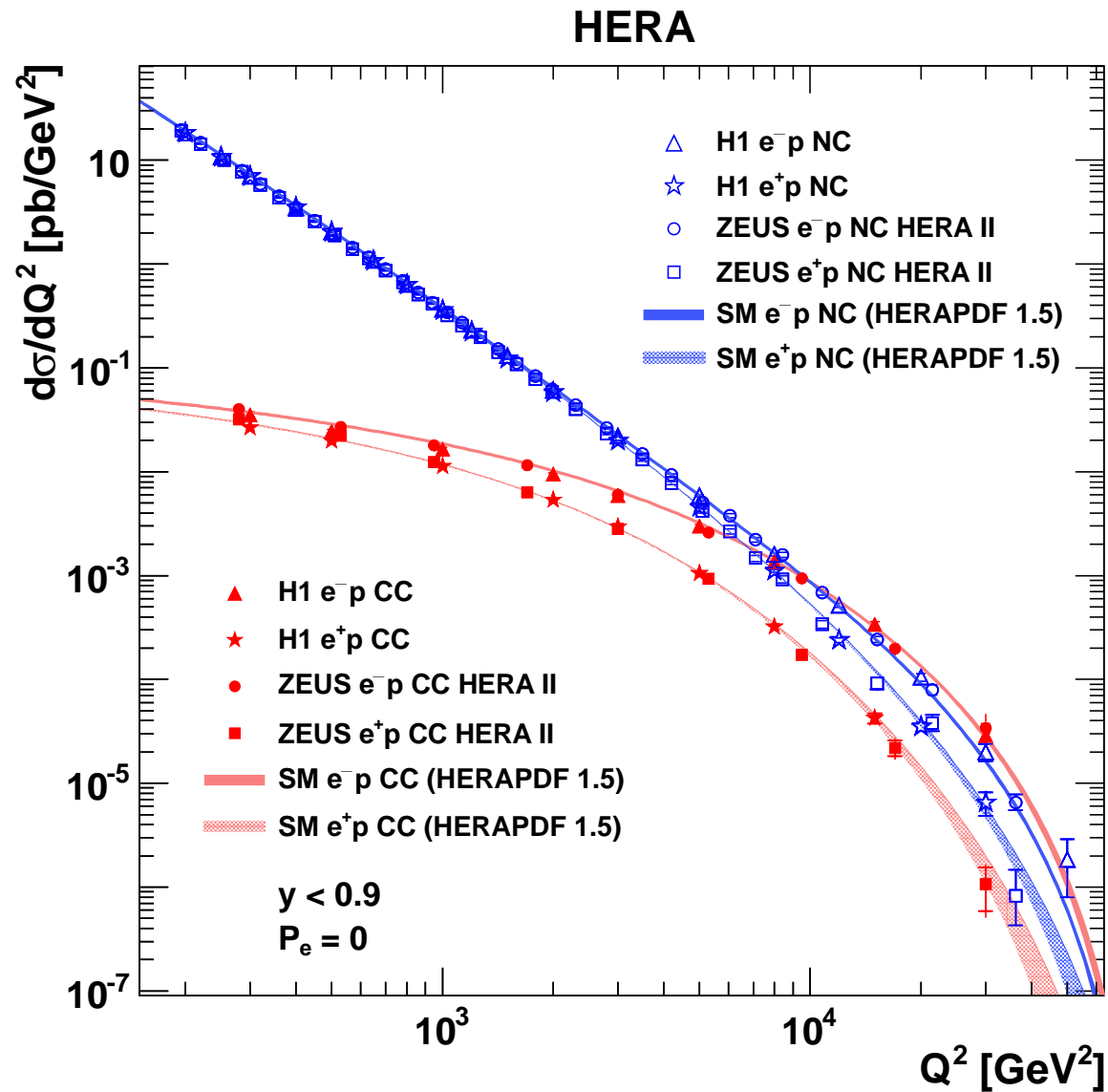
SM: zero cross section
for RH e^- and LH e^+



Experimentally, at 95% CL

$$M(W_R) > 200 \text{ GeV}$$

Electroweak Unification



H1: Combined HERA I+II result
 ZEUS: HERA II measurement

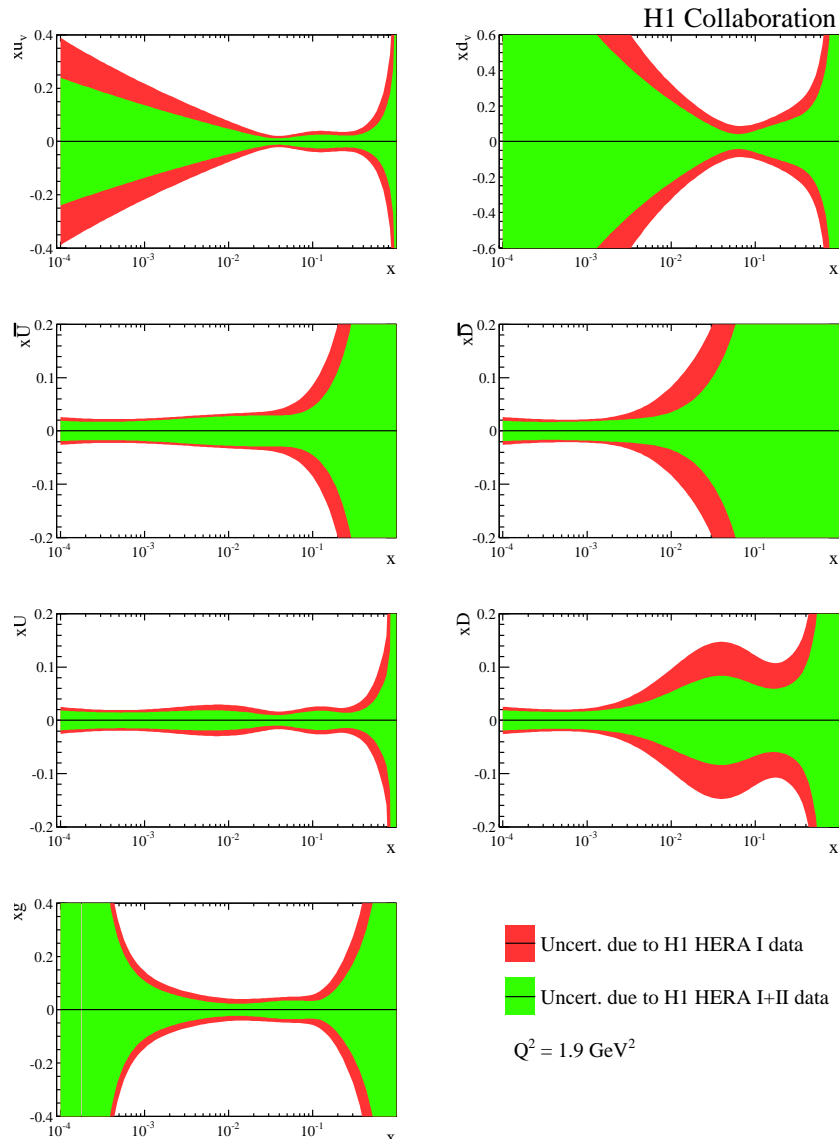
Typical precision:

NC $\sim 1.5\%$

CC $\sim 4\%$

\Rightarrow textbook plot

Impact of New HERA-2 Data on Proton PDFs



Comparison of PDF uncertainties for H1 fits with and without final HERA-II data

H1PDFs obtained with HERAFitter based on QCDNUM (v17.04), NLO (MSbar scheme, RT HF-mass scheme)

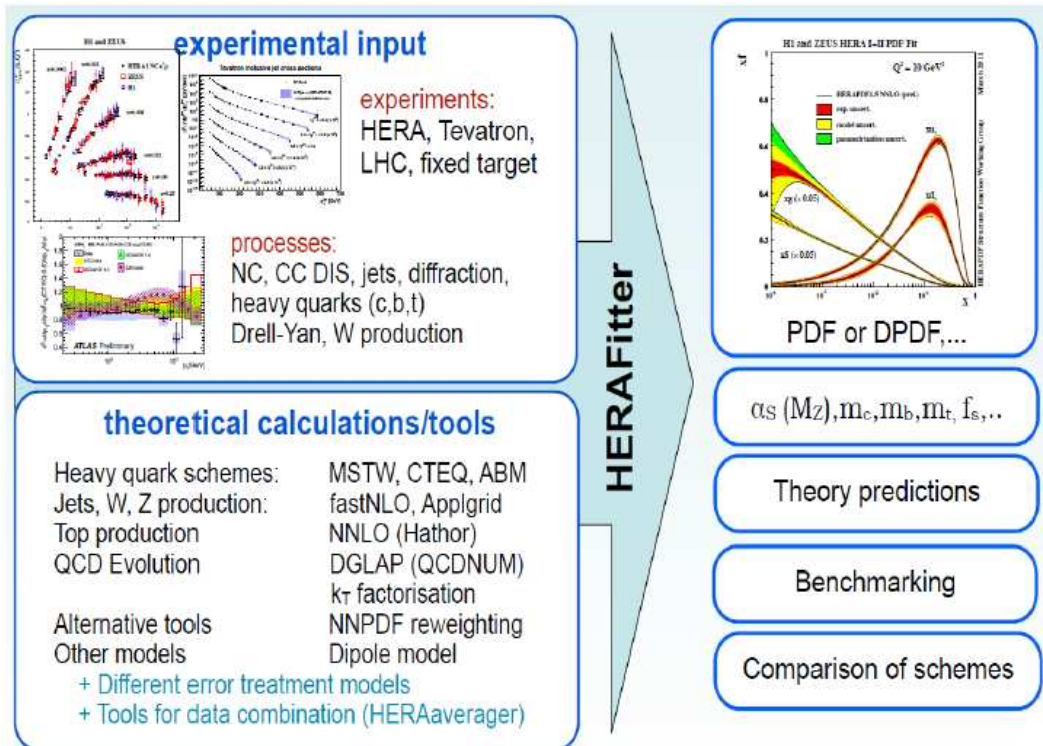
Large improvement in $x d_v$ and $x D$
 \Rightarrow driven by more precise CC data
 Improvement in $x u_v$ from NC at high x
 High- x gluon also improved from scaling violation

Further improvements – after final H1+ZEUS combination

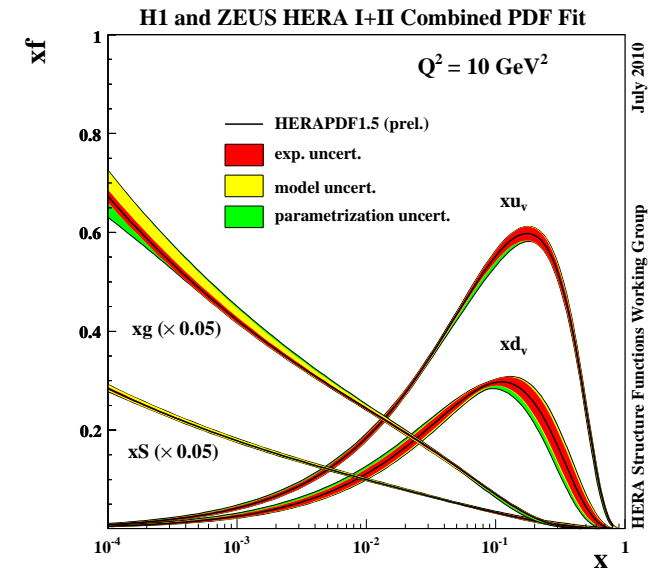
HERAPDF versions

HERAFitter

an open source QCD fit framework



HERAPDF Version	Included data	Order
HERAPDF 1.0	HERA-I NC,CC data	NLO, NNLO
HERAPDF 1.5	HERA-I NC,CC data partial HERA-II data	LO, NLO, NNLO recommended
HERAPDF 1.6	HERA-I NC,CC data partial HERA-II data, jets	NLO
HERAPDF 1.0 + charm	HERA-I NC,CC data charm	NLO
HERAPDF 1.7	HERA-I NC,CC data partial HERA-II data, jets, charm	NLO
HERAPDF 2.0	HERA-I NC,CC data HERA-II data	LO, NLO, NNLO planned



Summary

■ H1 and ZEUS completed their final Inclusive DIS measurements

- ▷ polarized lepton beams at HERA-2 allowed measurement of parity violation effects with improved accuracy
- ▷ right handed W boson with mass below 200 GeV ruled out
- ▷ structure function $F_2^{\gamma Z}$ measured for the first time
- ▷ improved constraints on the partonic content of the proton especially at high x

■ Standard Model provides an excellent description of the data

- ▷ in electroweak sector
- ▷ for QCD phenomena

■ New combination of final HERA DIS data is underway

- ▷ ultimate precision ($\sim 1\%$ in bulk region for 1 fb^{-1} H1+ZEUS combined data)
- ▷ QCD fit \Rightarrow HERAPDF 2.0 (LO, NLO, NNLO)
- ▷ stringent pQCD tests:
is DGLAP sufficient to describe high precision HERA data over 5 orders in x and Q^2 ?