Inclusive DIS at High Q^2 with Longitudinally Polarized Beams at HERA

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On behalf of
the H1 Collaboraton

HERA ep collider: largest electron microscope

HERA-1: 1992-2000, unpolarized beams
HERA-2: 2004-2007, longitudinally polarized $e^{\pm}$ beams

Inclusive neutral current (NC) and charged current (CC) cross sections:

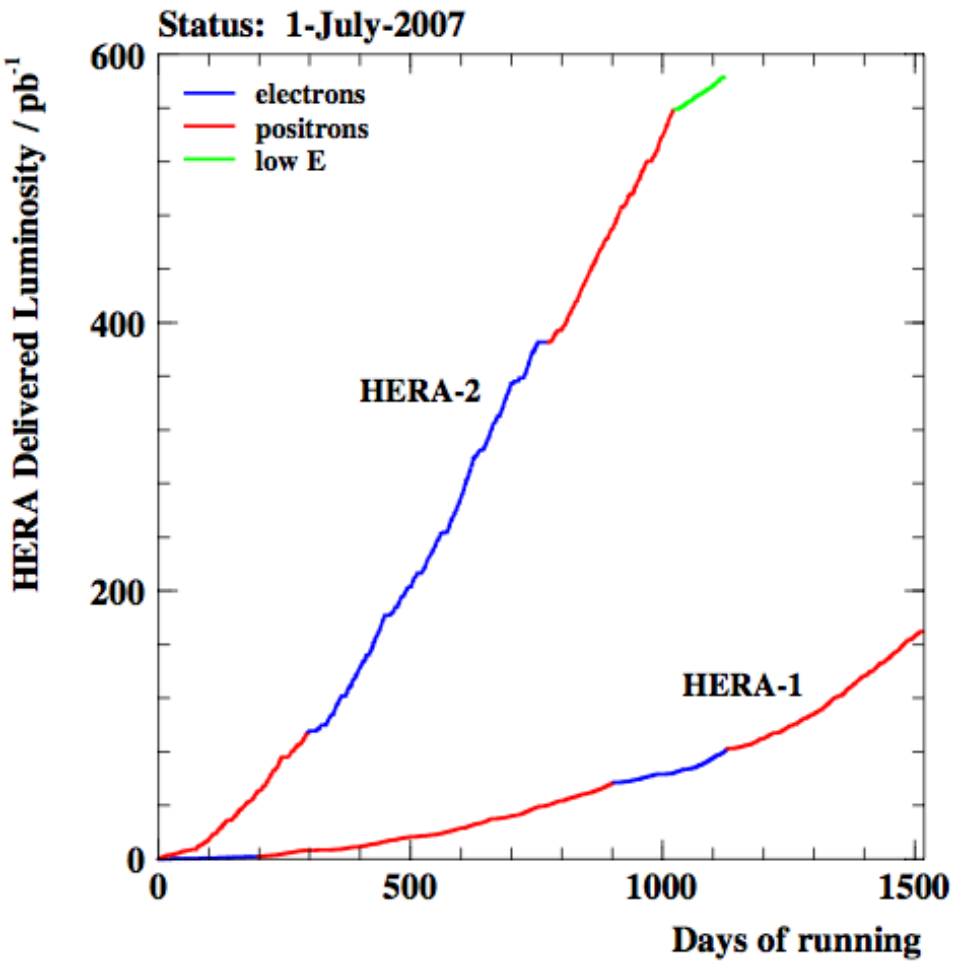
- Primary source for constraining Parton Distribution Functions (PDFs)
- Essential ingredients for making theoretical predictions at LHC

HERA-2 vs. HERA-1

4 distinct data sets at HERA-2:

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

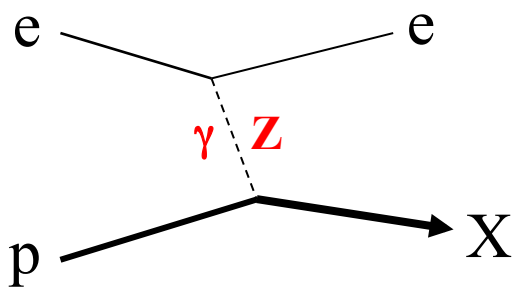
Longitudinally polarized $e^{\pm}$ beams at interaction point obtained from transversely polarized beams with spin rotators



Lumi e- ↗ ~10
Lumi e+ ↗ ~3

Neutral and Charged Current DIS

NC $e^{\pm}p$ event



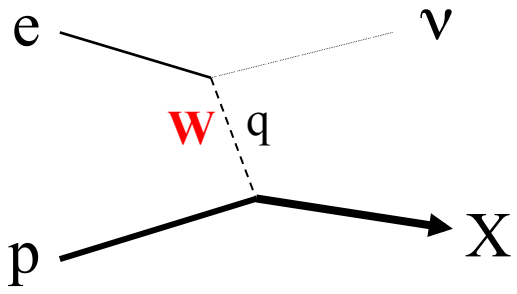
Event kinematics:

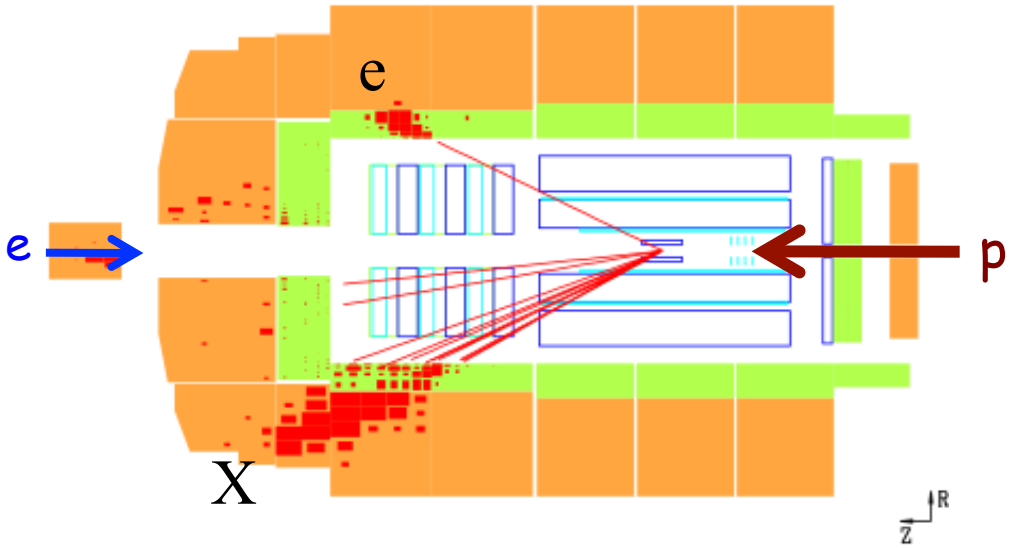
$Q^2=-q^2$

x: momentum fraction of struck parton

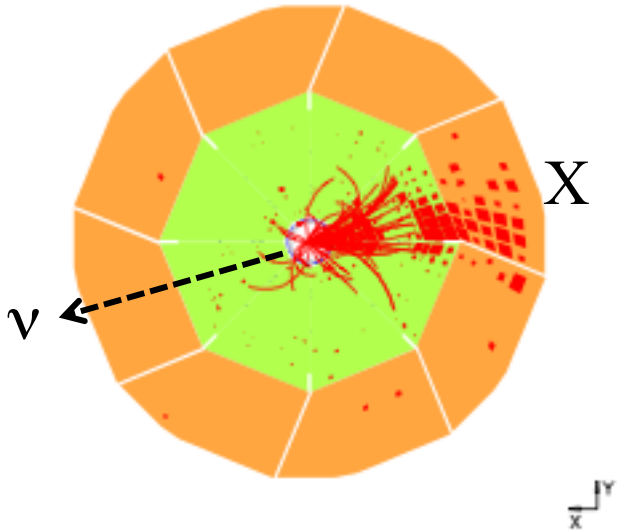
$y=Q^2/sx$: inelasticity

CC $e^{\pm}p$ event





Final states e & X balanced in transverse plane



Unbalanced due to missing ν

Cross Sections, Structure Functions, PDFs

$$\frac{d^2\sigma^{\pm}_{\rm NC}}{dxdQ^2} \sim Y_+\tilde{F}_2 \mp Y_- x\tilde{F}_3 \;^{*} \qquad \text{with} \quad Y_\pm = 1 \pm (1-y)^2$$

γ exchange — γZ interference — Z exchange

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

v_e~0, ➔ some of the terms are negligible

$$x\tilde{F}_3 = -(a_e - \cancel{P_e v_e})\kappa_Z x F_3^{\gamma Z} + \left[\cancel{2v_e a_e} - P_e(\cancel{v_e^2} + a_e^2)\right]\kappa_Z^2 x F_3^Z$$

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

$$\kappa_Z^{-1} = \frac{2\sqrt{2}\pi\alpha}{G_F M_Z^2}\frac{Q^2 + M_Z^2}{Q^2}$$

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

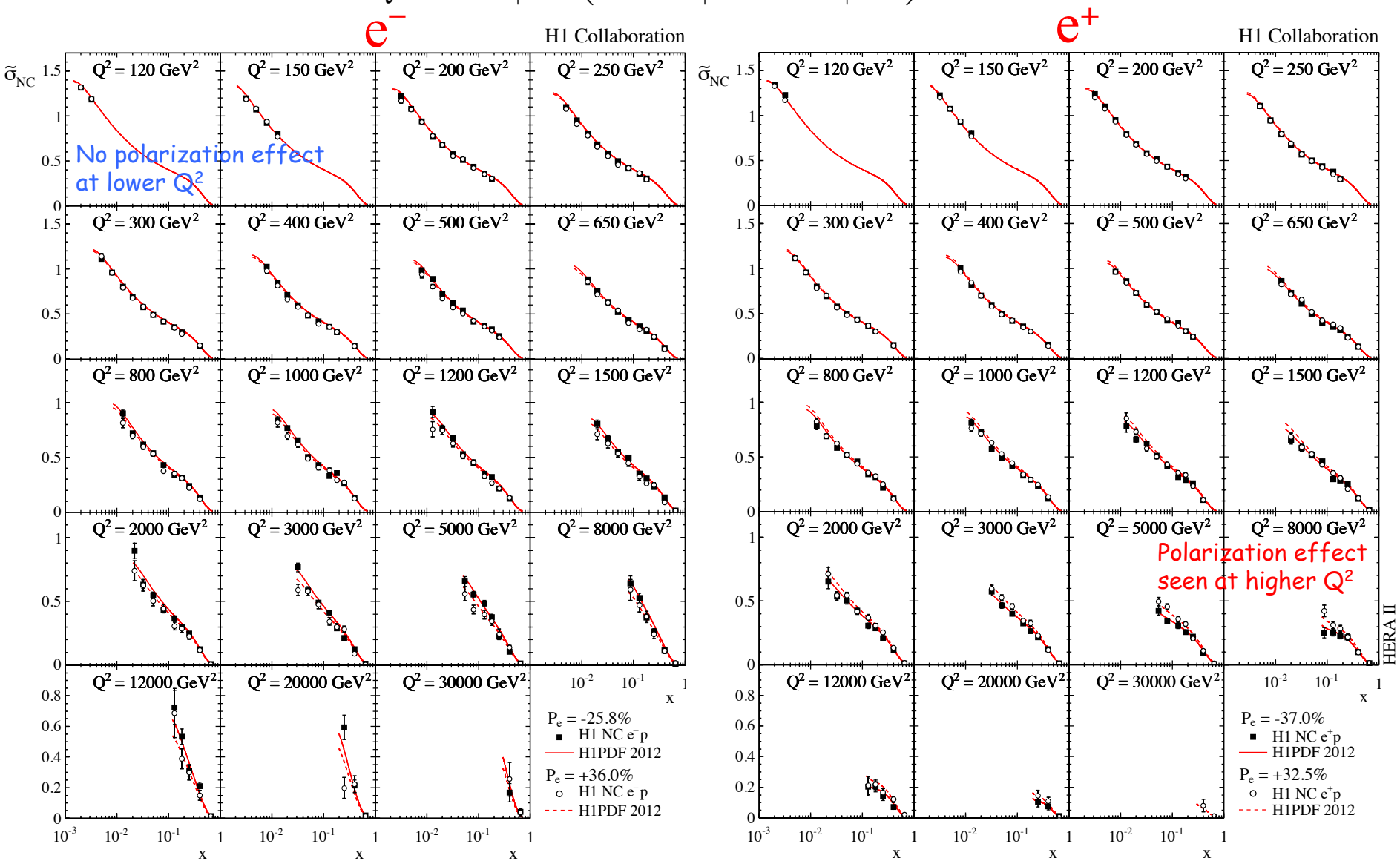
Structure function formulae given for e^-p scattering, for e^+p, $P_e \rightarrow -P_e$

CC cross sections have similar but different structure functions and PDF combinations

* F_L=0 in LO parton model,
F_L~g at NLO,
Scaling violation $F_2 \rightarrow g$

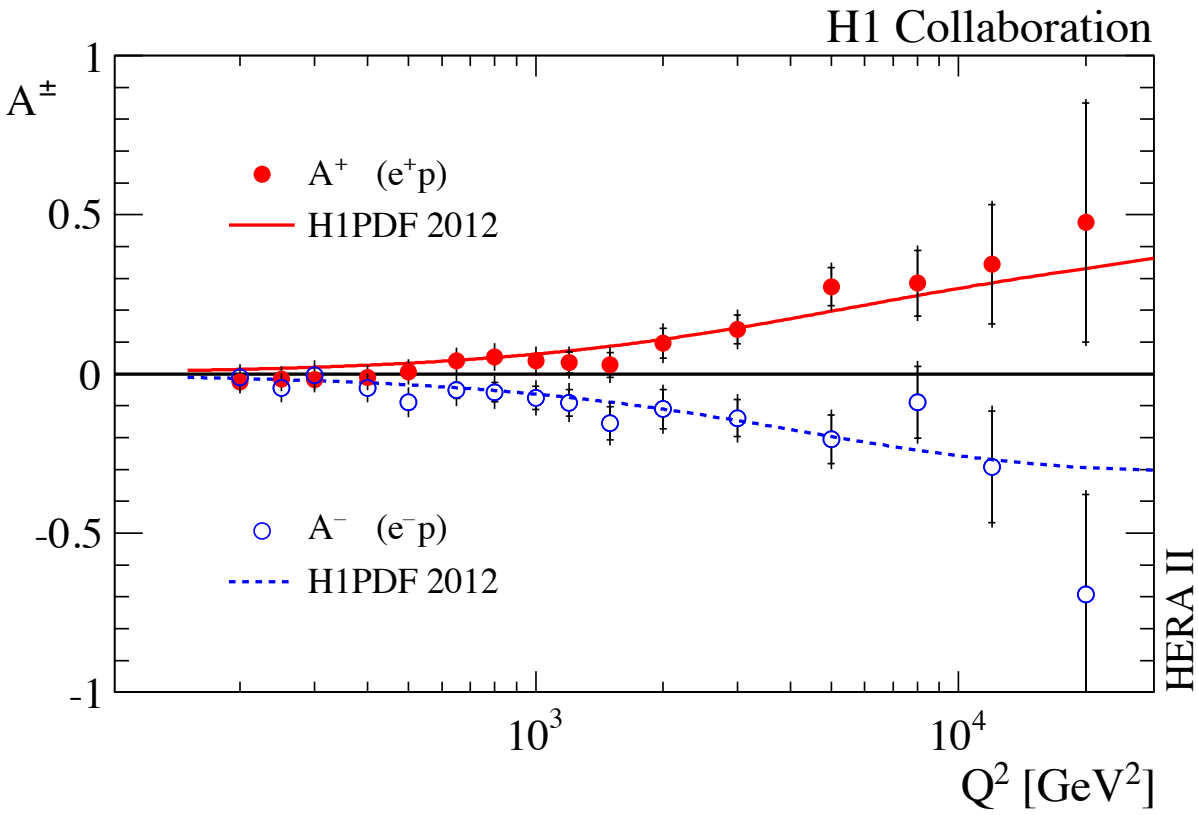
NC Double Differential Cross Sections

$$\tilde{\sigma}^{\pm}_{\rm NC}(x,Q^2) \equiv \frac{{\rm d}^2\sigma^{\pm}_{\rm NC}}{{\rm d}x{\rm d}Q^2}\frac{xQ^4}{2\pi\alpha^2}\frac{1}{Y_+} = \left(\tilde{F}_2^{\pm} \mp \frac{Y_-}{Y_+}x\tilde{F}_3^{\pm} - \frac{y^2}{Y_+}\tilde{F}_L^{\pm}\right)(1+\Delta^{\rm weak}_{\rm NC}) \qquad Y_{\pm} = 1 \pm (1-y)^2$$



NC Polarization Asymmetry

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

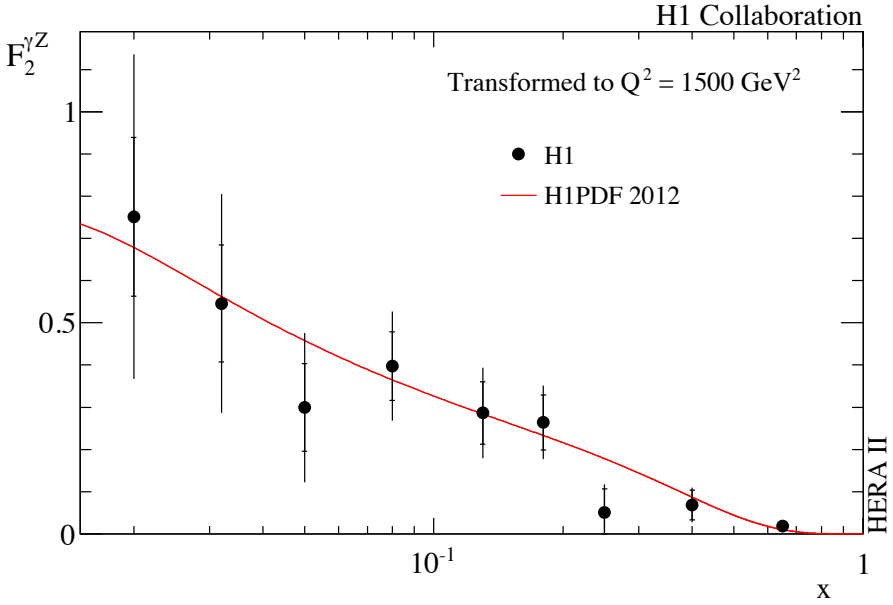


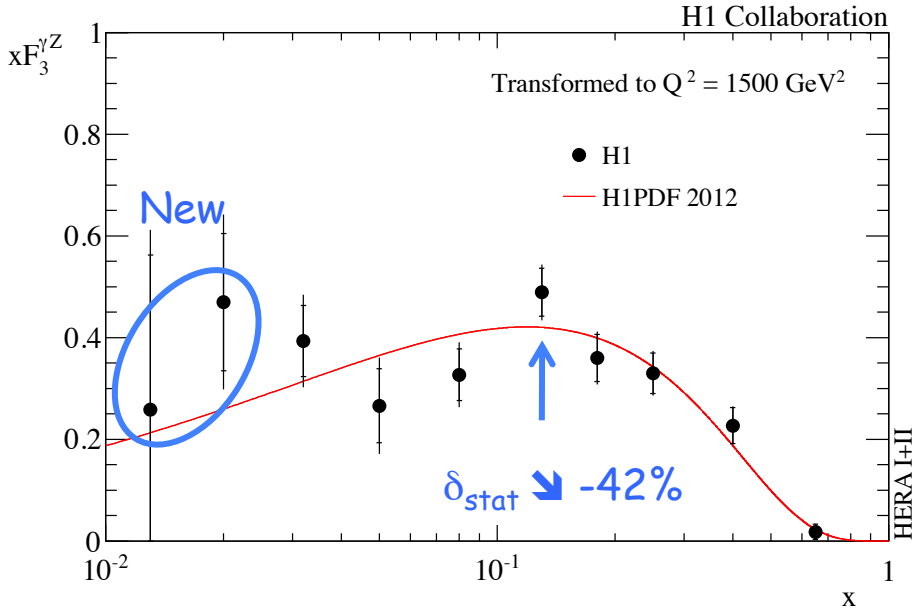
A direct measure of parity violation effect in NC DIS

Structure Functions $F_2^{\gamma Z}$, $xF_3^{\gamma Z}$

First measurement $F_2^{\gamma Z}$ extracted from polarized NC cross sections

Improved $xF_3^{\gamma Z}$ using combined HERA-1+2 data



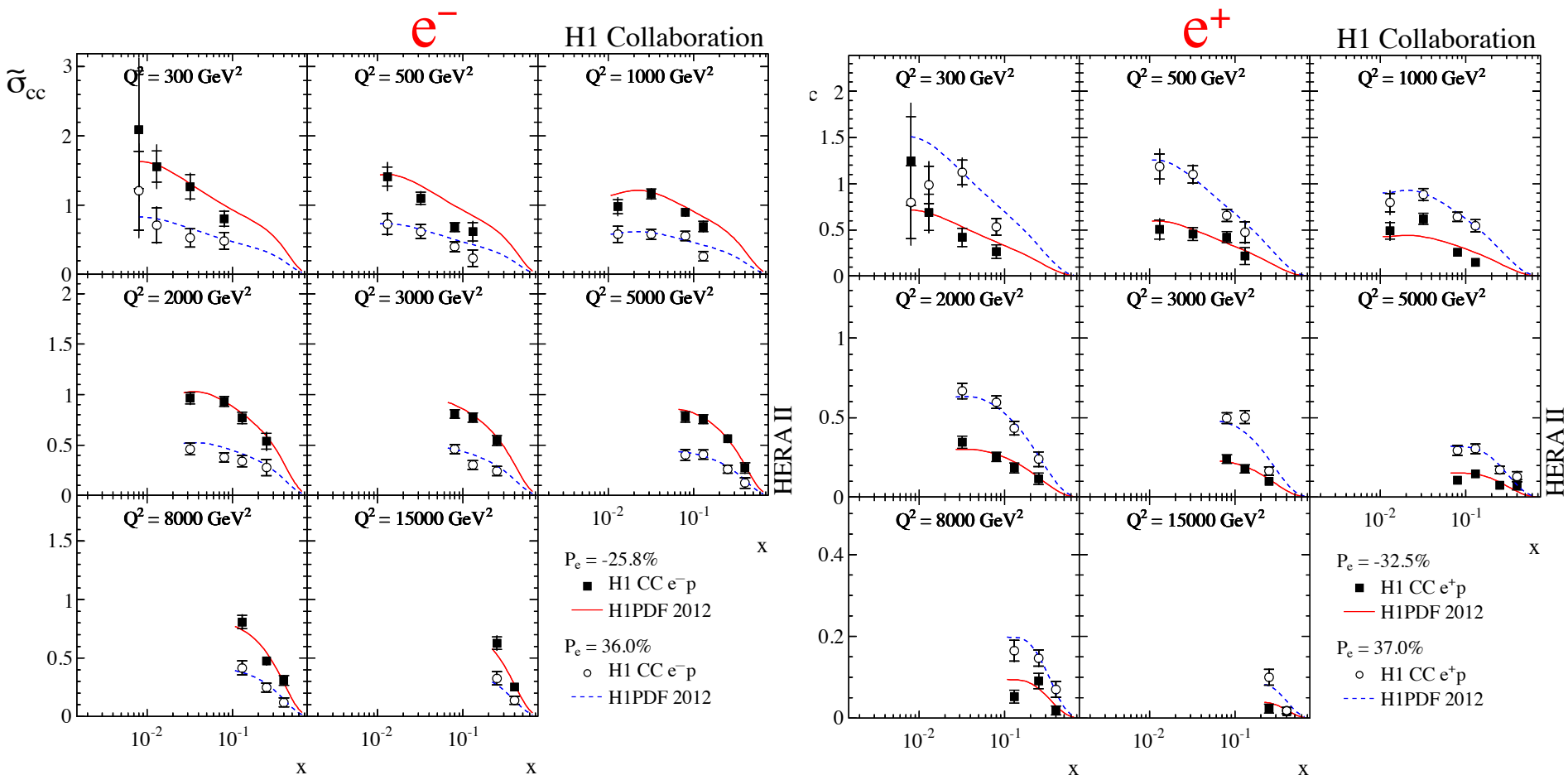


x dependence of $F_2^{\gamma Z}$ and $xF_3^{\gamma Z}$ reflects their parton compositions

$F_2^{\gamma Z} \sim q + qbar$ $\qquad$ $xF_3^{\gamma Z} \sim xq_v$

CC Double Differential Cross Sections

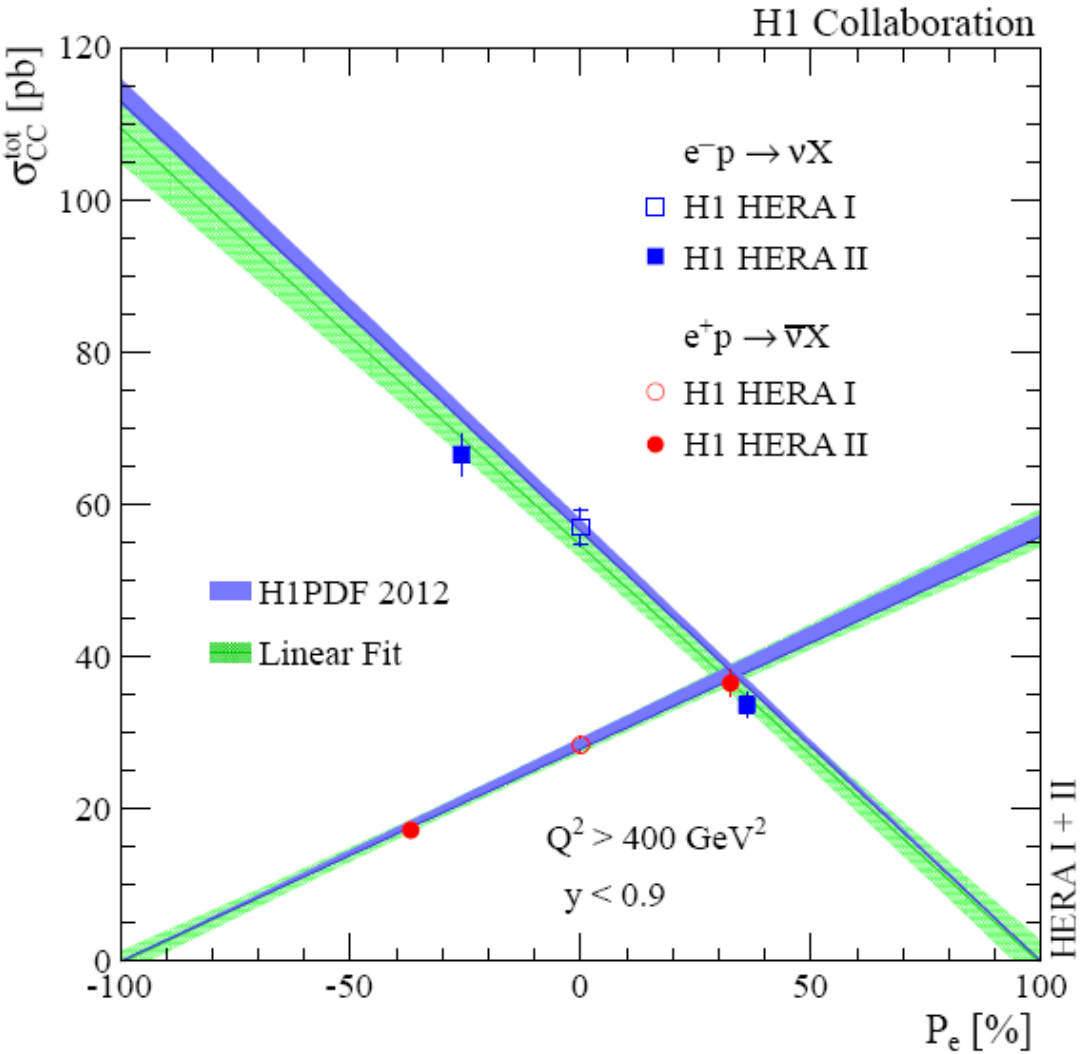
$$\tilde{\sigma}^{\pm}_{\mathrm{CC}} \equiv \frac{4\pi x}{G_F^2}\left[\frac{M_W^2+Q^2}{M_W^2}\right]^2 \frac{\mathrm{d}^2\sigma^{\pm}_{\mathrm{CC}}}{\mathrm{d}x\mathrm{d}Q^2} = (1\pm P_e)\left(Y_+W_2^{\pm} \mp Y_-xW_3^{\pm} - y^2W_L^{\pm}\right)(1+\Delta^{\mathrm{weak}}_{\mathrm{CC}})$$



CC cross sections have strong polarization dependence (P violation), provide unique flavor decomposition of proton

Total CC Cross Sections

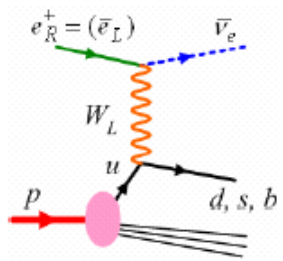
SM CC: $\sigma^{\pm}_{CC}(P_e) = (1 \pm P_e)\sigma^{\pm}_{CC}(0)$



Right Handed CC: $\sigma^{\pm}_{RHCC}(P_e) = (1 \mp P_e)\sigma^{\pm}_{RHCC}(0)$

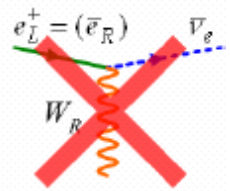
Extrapolated cross sections~0
- at P_e=+1 for e^-
- at P_e=−1 for e^+

➔ Only left-hand W in SM

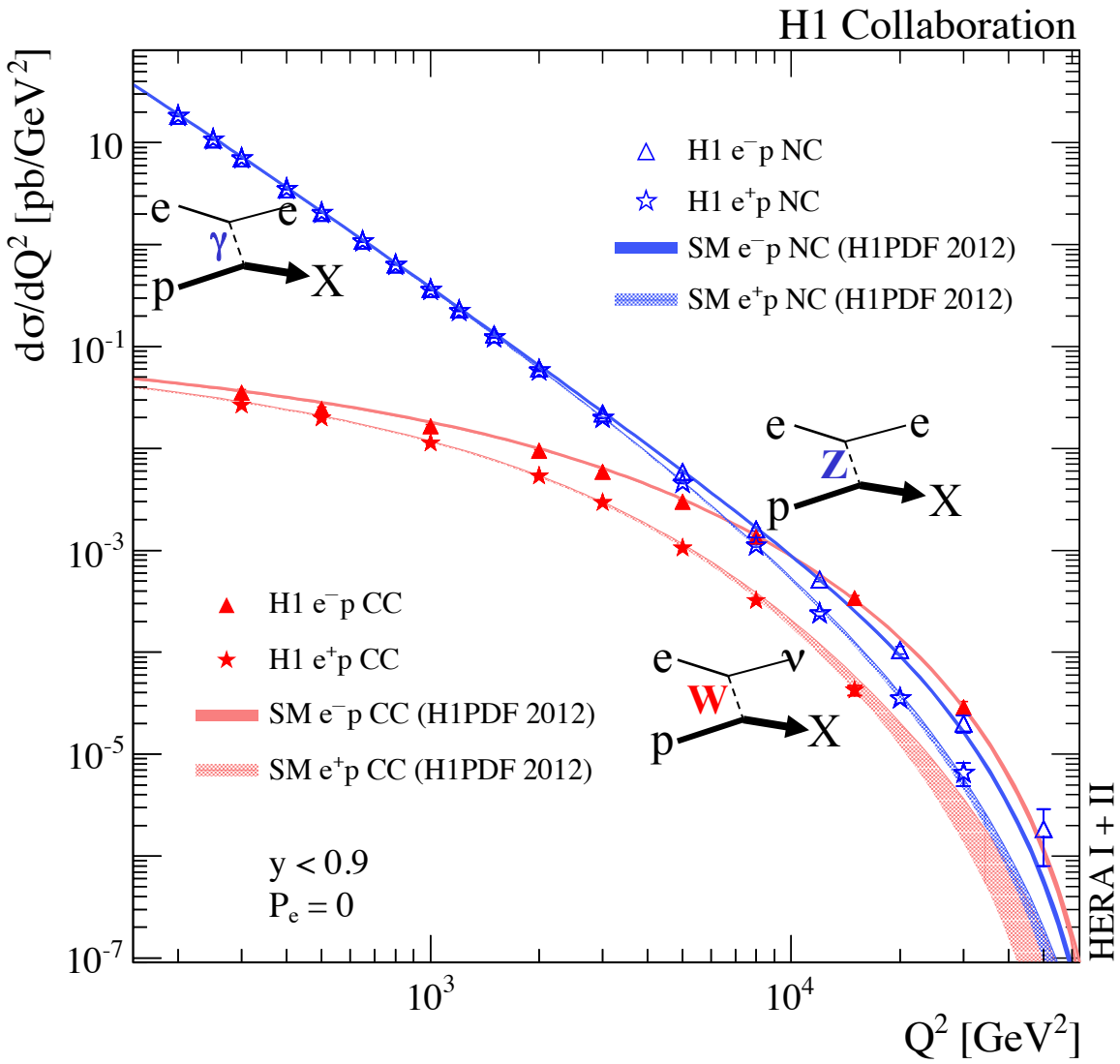


If $g_L = g_R$ & ν_R light

➔ e^-: M_{WR}>214 GeV (95%CL)
➔ e^+: M_{WR}>194 GeV (95%CL)



HERA-1+2 Combined NC & CC $d\sigma/dQ^2$



Combined HERA-1+2 data

→Typical total precision:

NC e^+: ~1.5%

NC e^-: ~2.0%

CC $e^\pm$: ~4%

➔ Beautiful illustration of unification of electromagnetic and weak interaction strength

New QCD Analysis: H1PDF 2012

In order to see the impact of the new HERA-2 NC+CC high Q^2 data on PDFs, a NLO QCD fit performed including all published H1 data

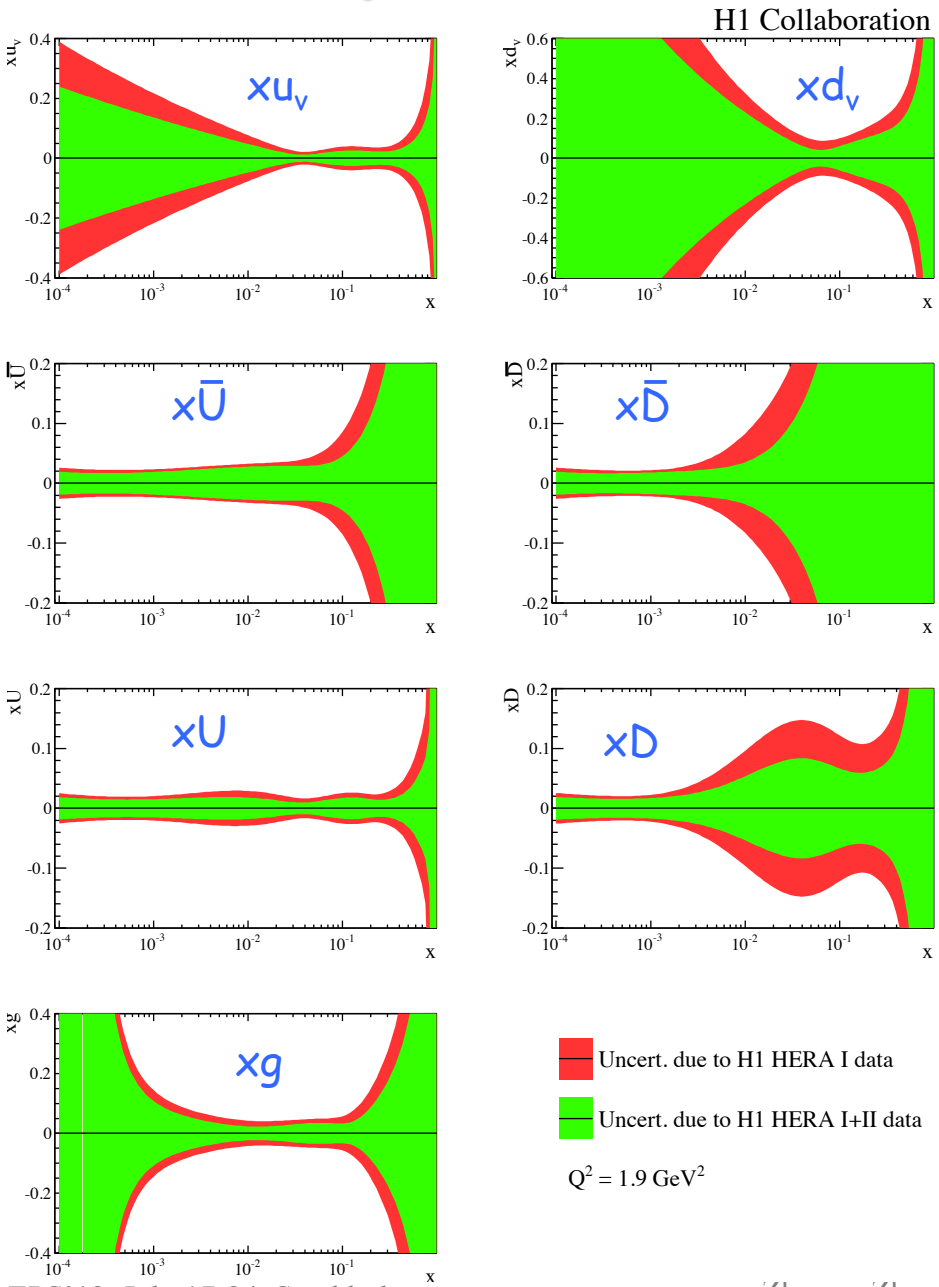
Published earlier HERA data have been the main inputs to all global PDFs fits

New

Data set	$x_{\min}$	$x_{\max}$	$Q^2_{\min}$ (GeV^2)	$Q^2_{\max}$ (GeV^2)	$\delta\mathcal{L}$ (%)	Ref.	Comment
e^+ Combined low Q^2	0.00004	0.20	0.5	150	0.5	[72]	$\sqrt{s} = 301, 319$ GeV
e^+ Combined low E_p	0.00003	0.003	1.5	90	0.5	[72]	$\sqrt{s} = 225, 252$ GeV
e^+ NC 94-97	0.0032	0.65	150	30 000	$0.5 \oplus 1.4$	[1]	$\sqrt{s} = 301$ GeV
e^+ CC 94-97	0.013	0.40	300	15 000			
e^- NC 98-99	0.0032	0.65	150	30 000	$0.5 \oplus 1.7$	[2]	$\sqrt{s} = 319$ GeV
e^- CC 98-99	0.013	0.40	300	15 000			
e^- NC 98-99 *high* y	0.00131	0.0105	100	800			$\sqrt{s} = 319$ GeV
e^- NC 99-00	0.0032	0.65	150	30 000	$0.5 \oplus 1.4$	[3]	$\sqrt{s} = 319$ GeV; incl. *high* y
e^+ CC 99-00	0.013	0.40	300	15 000			$\sqrt{s} = 319$ GeV
e^+ NC *high* y	0.0008	0.0105	60	800	$2.3 \oplus 1.0 \oplus 1.1$		$\sqrt{s} = 319$ GeV
e^- NC *high* y	0.0008	0.0105	60	800	$2.3 \oplus 1.2 \oplus 0.8$		$\sqrt{s} = 319$ GeV
e^+ NC L	0.002	0.65	120	30 000	$2.3 \oplus 1.5$		$\sqrt{s} = 319$ GeV
e^+ CC L	0.008	0.40	300	15 000			
e^+ NC R	0.002	0.65	120	30 000	$2.3 \oplus 1.5$		
e^+ CC R	0.008	0.40	300	15 000			
e^- NC L	0.002	0.65	120	50 000	$2.3 \oplus 1.5$		$\sqrt{s} = 319$ GeV
e^- CC L	0.008	0.40	300	30 000			
e^- NC R	0.002	0.65	120	30 000	$2.3 \oplus 1.5$		
e^- CC R	0.008	0.40	300	15 000			

The data cover ~5 orders of magnitude in Q^2 and x

Impact of the New HERA-2 Data



HERAFitter based on QCDNUM (v17.04)
NLO, MSbar scheme
RT heavy flavor mass scheme

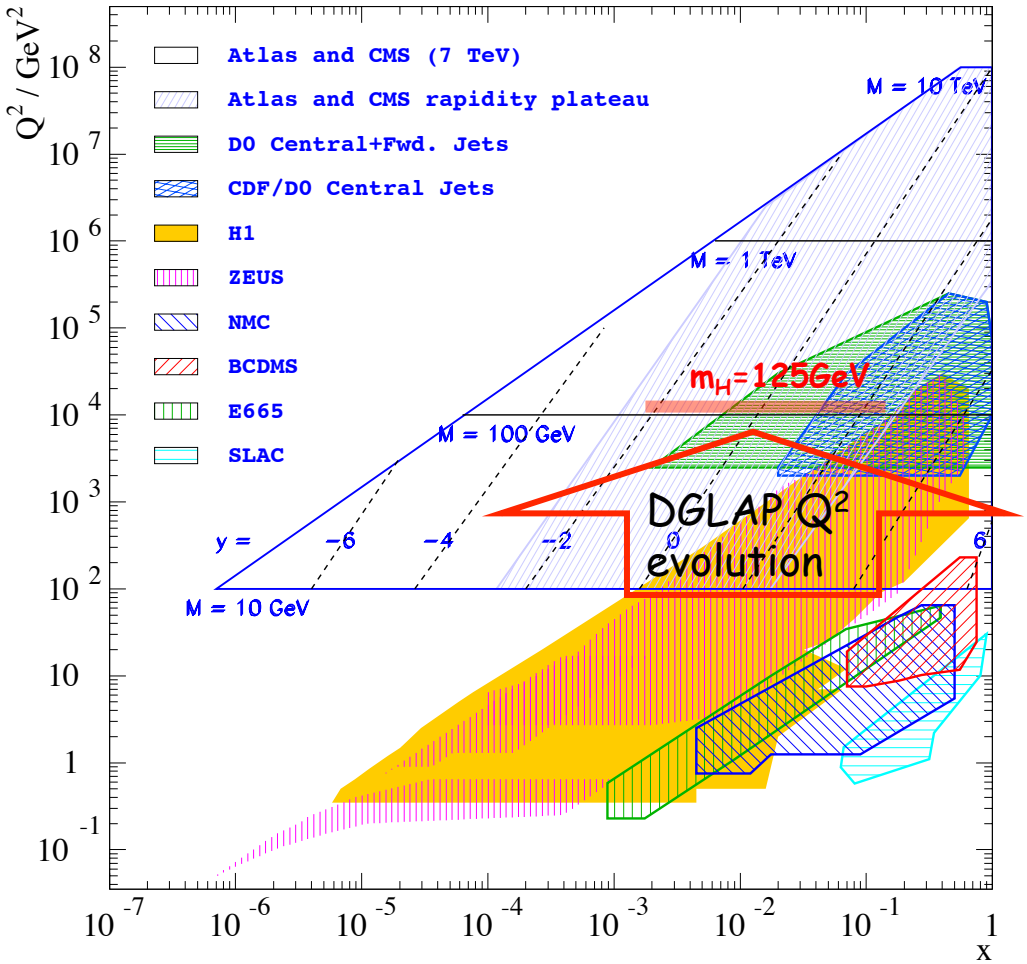
5 sets of PDFs with 13 free parameters with quark number and momentum sum rules:

$$
\begin{aligned}
xg(x) &= A_g x^{B_g}(1-x)^{C_g} - A'_g x^{B'_g}(1-x)^{25}\,, \\
xu_v(x) &= A_{u_v} x^{B_{uv}}(1-x)^{C_{uv}}\left(1+E_{u_v}x^2\right)\,, \\
xd_v(x) &= A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}\,, \\
x\overline{U}(x) &= A_{\overline{U}} x^{B_{\overline{U}}}(1-x)^{C_{\overline{U}}}\,, \\
x\overline{D}(x) &= A_{\overline{D}} x^{B_{\overline{D}}}(1-x)^{C_{\overline{D}}}\,.
\end{aligned}
$$

➔ Improvement in precision for all PDFs in full x range in particular for down-type quarks xD

Summary

- With the polarized lepton beams at HERA-2, parity violation effects observed/confirmed with improved precision
- Absence of right-handed CC W boson
- First $F_2^{\gamma Z}$ and improved $xF_3^{\gamma Z}$ determinations
- NC & CC cross section data valuable for further constraining PDFs
- H1+ZEUS HERA-2 combination will come soon



The universal PDFs extracted from HERA can be directly applied to LHC in the relevant kinematic region through DGLAP Q^2 evolution