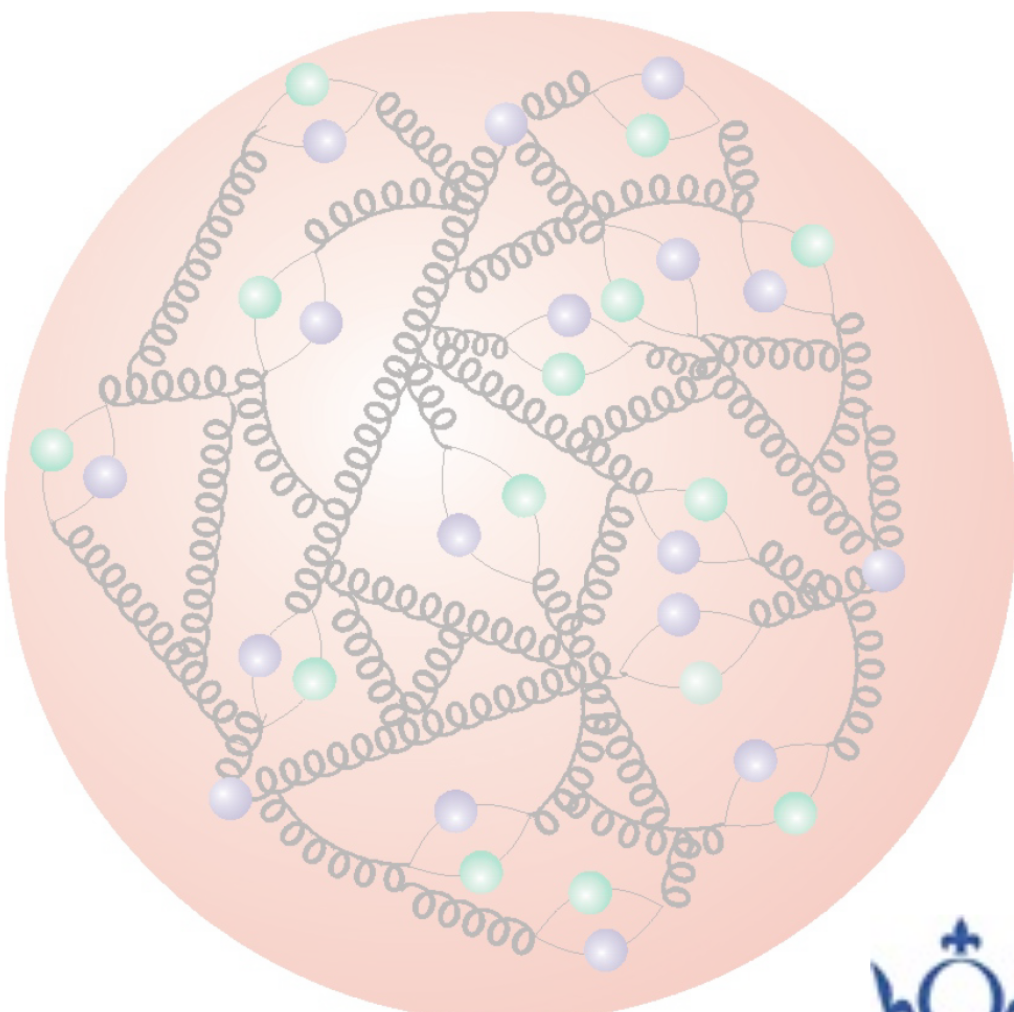
Electroweak/QCD Fit to NC & CC HERA Data



- Introduction
- Structure Functions
- H1 Measurements at High Q^2
- Combined QCD / EW Fit
- Results

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International Europhysics Conference on High Energy Physics

Grenoble, France

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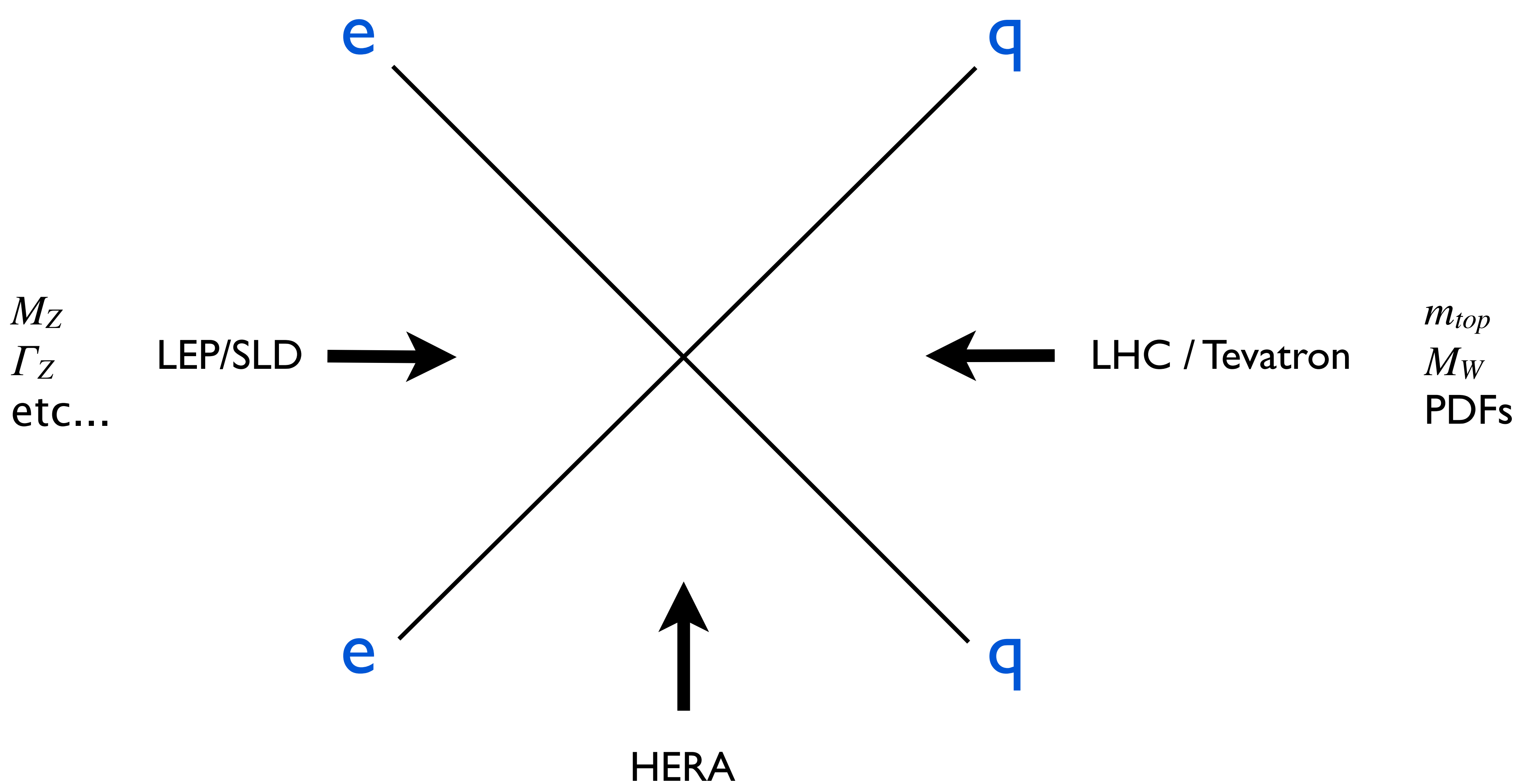
Colliders At The Electroweak Scale



HERA data probes t-channel boson exchange
Sensitive to
- boson masses
- EW couplings
- PDFs

$\sigma(ep) = \sigma(eq) \otimes$ PDFs

EW $\otimes$ QCD

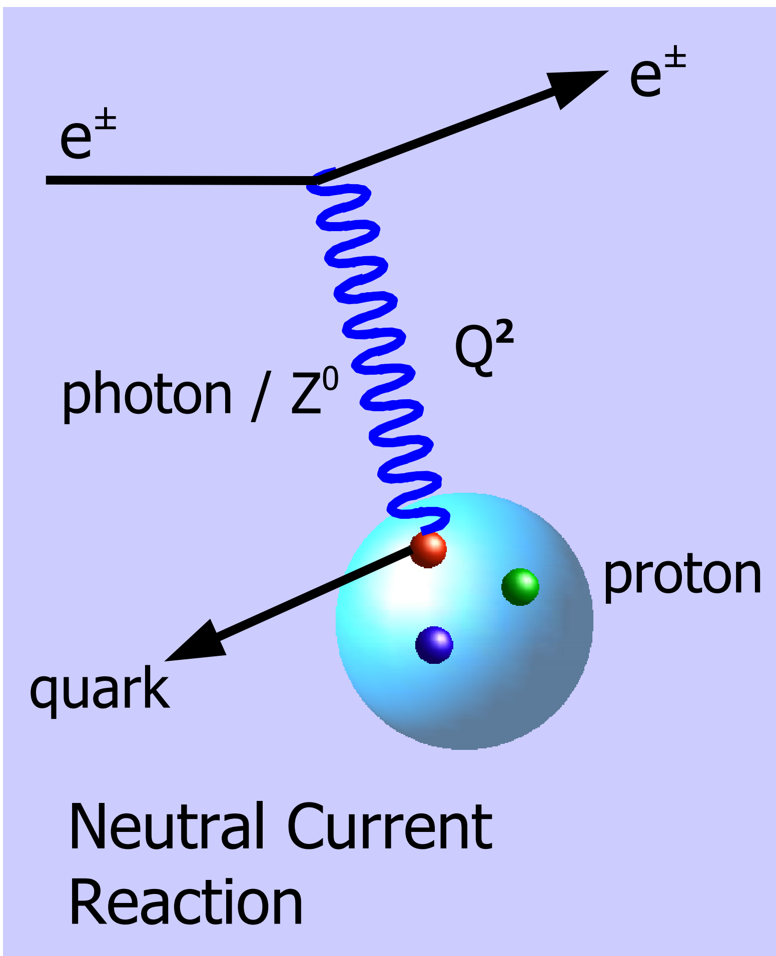
Extraction of EW parameters requires simultaneous QCD & EW fit

Neutral and Charged Current DIS

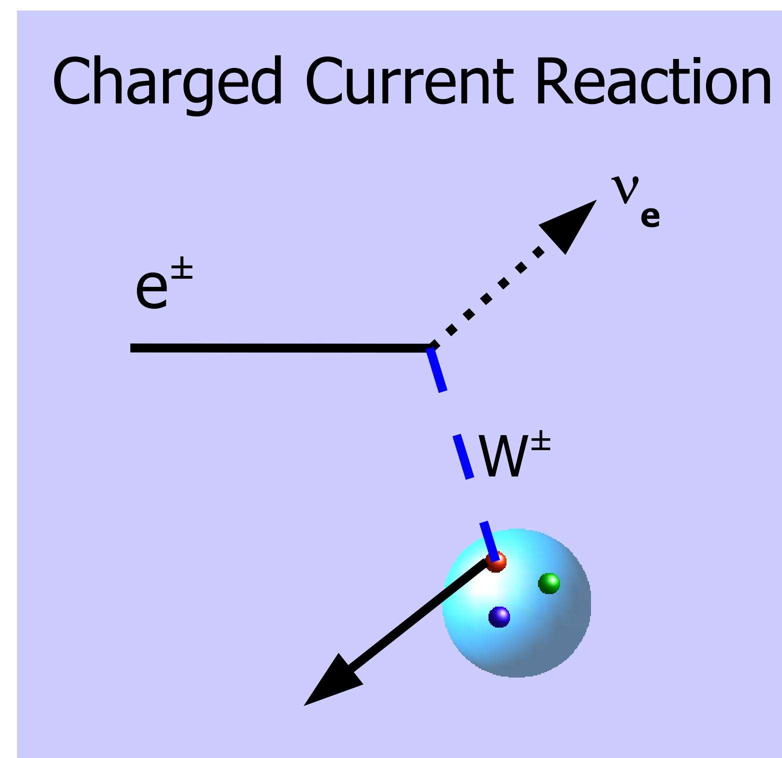
HERA NC and CC cross sections test Standard Model in region of large space-like momentum transfer, Q^2

At fixed $\sqrt{s}$ only two kinematic variables: x & Q^2

$Q^2 = s.x.y$



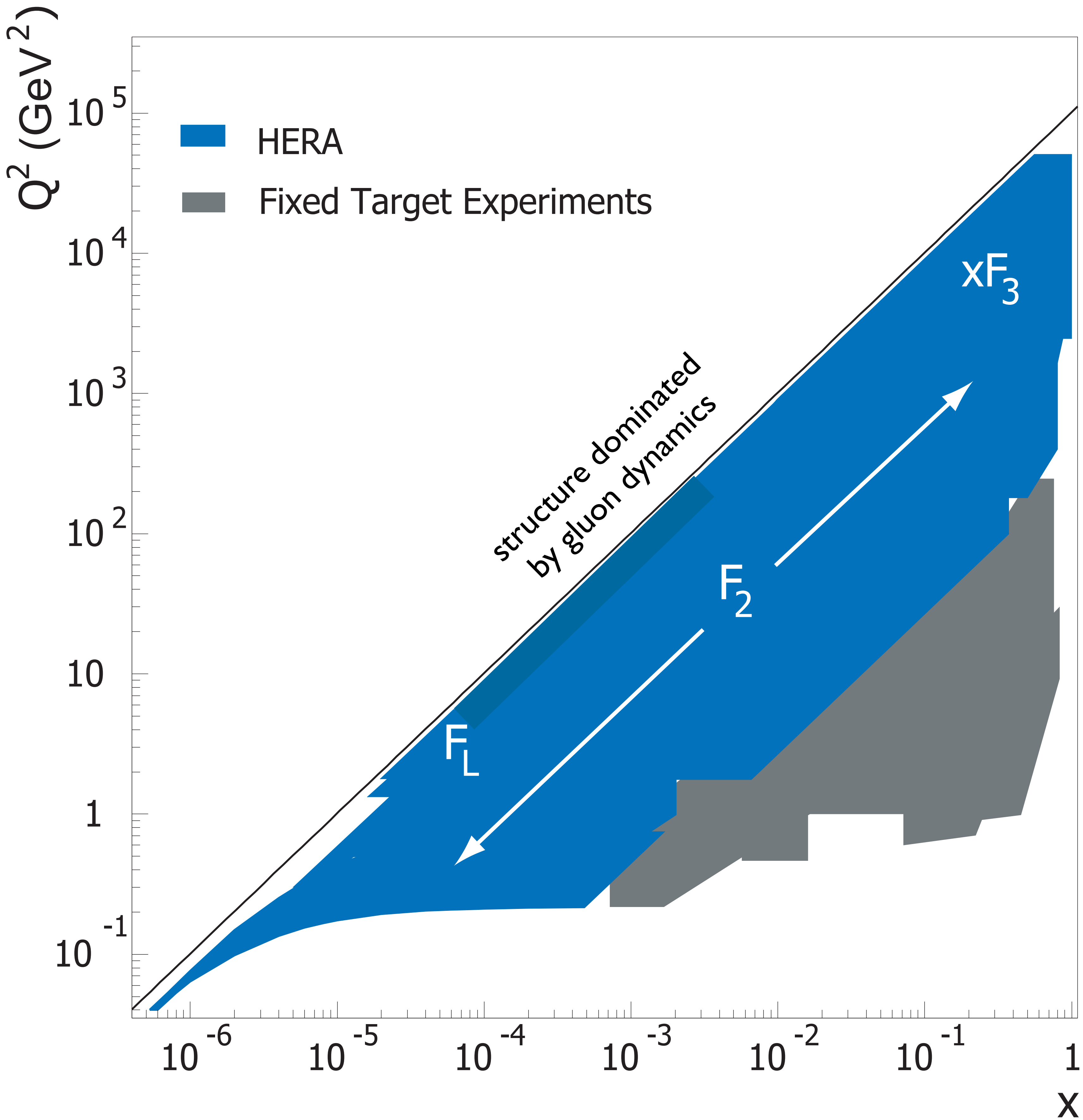
Q^2 = resolving scale of the probe



x = momentum fraction of proton carried by struck quark

At HERA: $10^{-6} - 1$

HERA Phase-space



HERA data cover wide region of x,Q^2

<u>NC Measurements</u>

F_2 dominates most of Q^2 reach

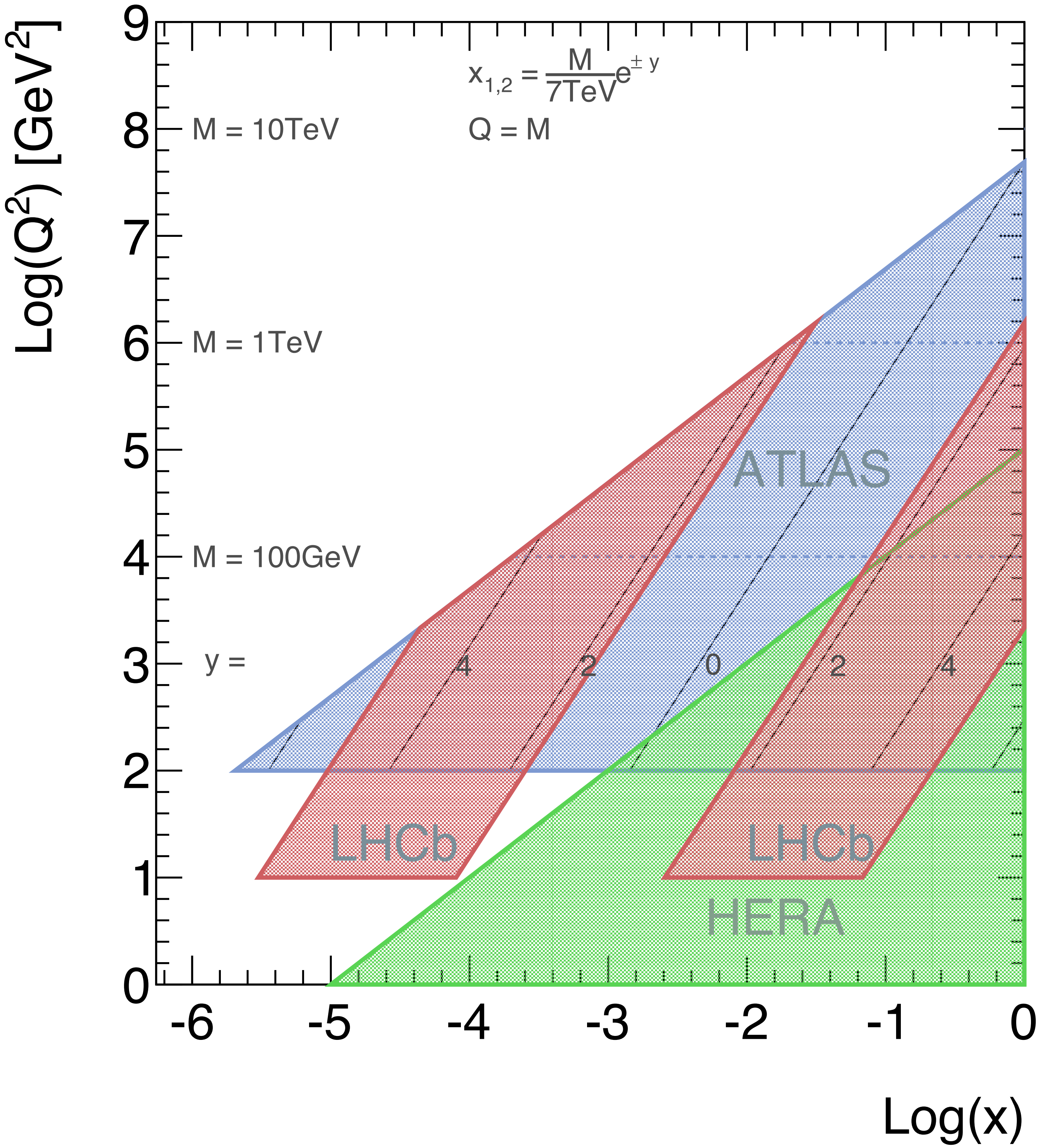
xF_3 contributes in EW regime

F_L contributes only at highest y

<u>CC Measurements</u>

W_2 and xW_3 contribute equally

W_L only at high y



LHC: largest mass states at large x

For central production $x=x_1=x_2$

$$M=x\sqrt{s}$$

i.e. M > 1 TeV probes x>0.1

Searches for high mass states require precision knowledge at high x

Z′ / quantum gravity / susy searches...

DGLAP evolution allows predictions to be made

High x predictions rely on

- data (DIS / fixed target)
- sum rules
- behaviour of PDFs as $x\rightarrow 1$

Structure Functions

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

$$\frac{d\sigma^{\pm}_{CC}}{dxdQ^2} = (1-P_e)\,\frac{G_F^2}{4\pi x}\left[\frac{M_W^2}{M_W^2+Q^2}\right]^2\left[Y_+\tilde{W}_2^{\pm} \mp Y_- x\tilde{W}_3^{\pm} - y^2\tilde{W}_L^{\pm}\right]$$

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

P_e is the degree of lepton polarisation

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

$x\tilde{F}_3 \propto \sum (xq_i - x\bar{q}_i)$ Only sensitive at high $Q^2 \sim M_Z^2$

$\tilde{F}_L \propto \alpha_s \cdot xg(x,Q^2)$ Only sensitive at low Q^2 and high y

similarly for pure weak CC analogues:

$W_2^{\pm}$, $xW_3^{\pm}$ and $W_L^{\pm}$

The NC reduced cross section defined as:

$$\tilde{\sigma}^{\pm}_{NC} = \frac{Q^2 x}{2\alpha\pi^2}\frac{1}{Y_+}\frac{d^2\sigma^{\pm}}{dxdQ^2}$$

$$\tilde{\sigma}^{\pm}_{NC} \sim \tilde{F}_2 \mp \frac{Y_-}{Y_+}x\tilde{F}_3$$

The CC reduced cross section defined as:

$$\sigma^{\pm}_{CC} = \frac{2\pi x}{G_F^2}\left[\frac{M_W^2+Q^2}{M_W^2}\right]^2\frac{d\sigma^{\pm}_{CC}}{dxdQ^2}$$

$$\frac{d\sigma^{\pm}_{CC}}{dxdQ^2} = \frac{1}{2}\left[Y_+ W_2^{\pm} \mp Y_- xW_3^{\pm} - y^2 W_L^{\pm}\right]$$

Structure Functions

pure photon piece — interference piece — pure weak piece

$$\tilde{F}_2^{\pm} = F_2 - (\cancel{v_e} \pm P_e a_e)\kappa \frac{Q^2}{Q^2 + M_Z^2} F_2^{\gamma Z} + (\cancel{v_e^2} + a_e^2 \pm P_e \cancel{2 v_e a_e})\kappa^2 \left[\frac{Q^2}{Q^2 + M_Z^2}\right]^2 F_2^Z$$

$$x\tilde{F}_3^{\pm} = -(a_e \pm P_e \cancel{v_e})\kappa \frac{Q^2}{Q^2 + M_Z^2} xF_3^{\gamma Z} + (\cancel{2 a_e v_e} \pm P_e [\cancel{v_e^2} + a_e^2])\kappa^2 \left[\frac{Q^2}{Q^2 + M_Z^2}\right]^2 xF_3^Z$$

interference piece — pure weak piece

v_e is small ~0.05

⇒ terms contribute little

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

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

$F_2^{\gamma Z}$	→ main v_q constraint
F_2^Z	→ main constraint on a_q / v_q correlation
xF_3^Z	→ main a_q constraint

Structure Functions

NC data constrain:
- singlet quarks / gluon PDFs
- non-singlet valence quark PDFs at high Q^2

But, flavour sensitivity is weak

CC data enable flavour decomposition of proton:

$$
\begin{aligned}
W_2^- &= x(u + c + \overline{d} + \overline{s})\,, W_2^+ = x(\overline{u} + \overline{c} + d + s)\,, \\
xW_3^- &= x(u + c - \overline{d} - \overline{s})\,, xW_3^+ = x(d + s - \overline{u} - \overline{c})
\end{aligned}
$$

Requires e^+ and e^- scattering data

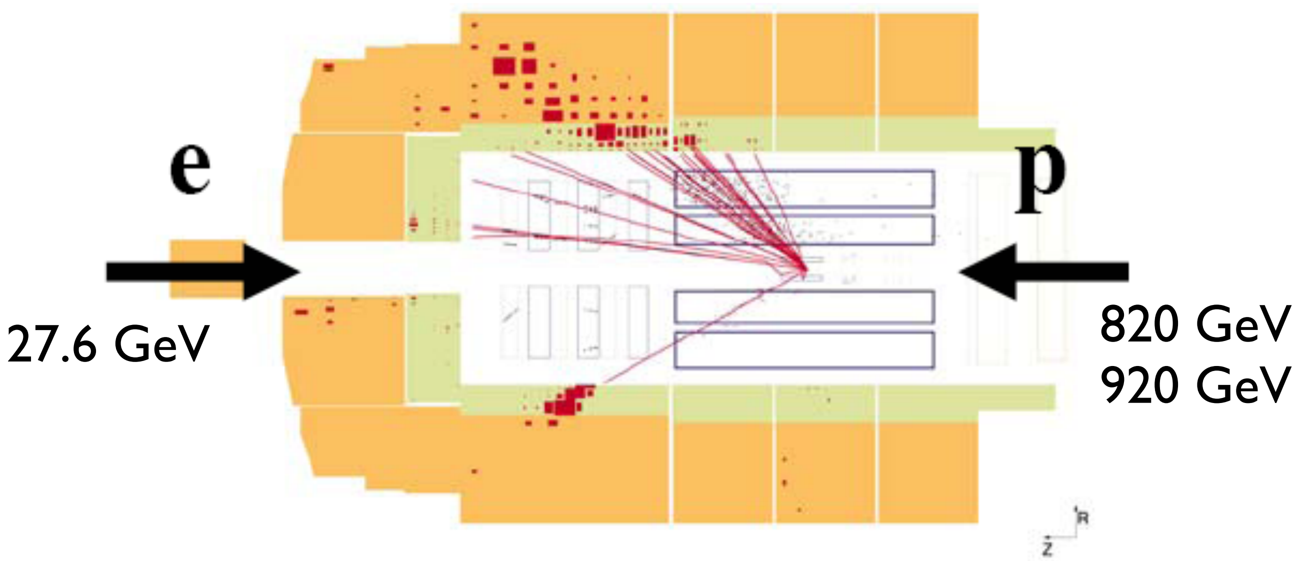
$$\frac{d^2\sigma_{CC}^-}{dxdQ^2} = \frac{G_F^2}{2\pi}\left(\frac{M_W^2}{M_W^2 + Q^2}\right)^2 \left[(u + c) + (1-y)^2(\overline{d} + \overline{s})\right]$$

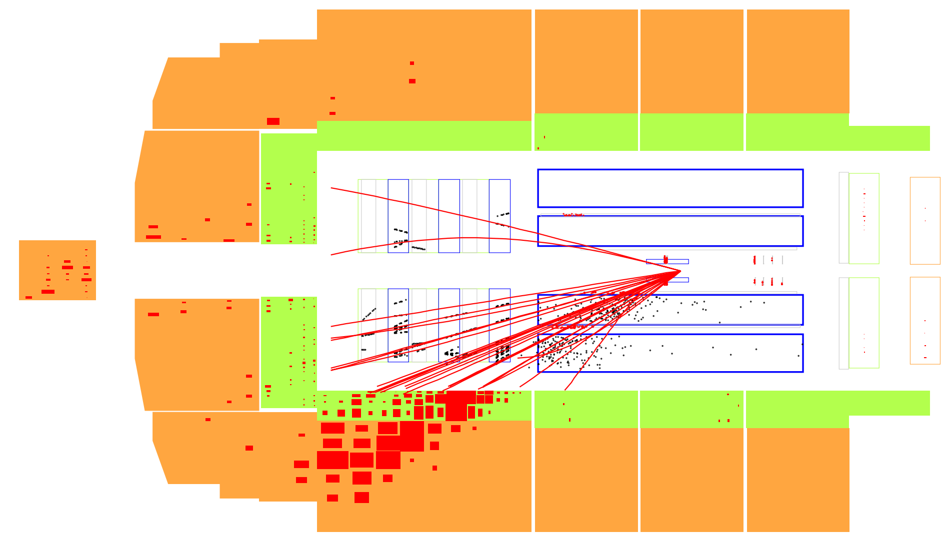
$$\frac{d^2\sigma_{CC}^+}{dxdQ^2} = \frac{G_F^2}{2\pi}\left(\frac{M_W^2}{M_W^2 + Q^2}\right)^2 \left[(\overline{u} + \overline{c}) + (1-y)^2(d + s)\right]$$

CC e+ data provide strong d_v constraint at high x (y ~ 0)

For polarised lepton beams CC cross section scales linearly with P

H1 - Neutral and Charged Current Selections





Neutral current event selection:

High P_T isolated scattered lepton
Suppress huge photo-production background by imposing longitudinal energy-momentum conservation

Kinematics may be reconstructed in many ways: energy/angle of hadrons & scattered lepton provides excellent tools for sys cross checks

Removal of scattered lepton provides a high stats "pseudo-charged current sample"
Excellent tool to cross check CC analysis

Final selection: $\sim 10^5$ events per sample at high Q^2
$\sim 10^7$ events for $10 < Q^2 < 100$ GeV^2

Charged current event selection:

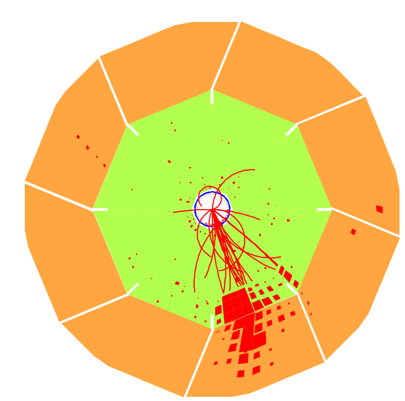
Large missing transverse momentum (neutrino)

Suppress huge photo-production background

Topological finders to remove cosmic muons

Kinematics reconstructed from hadrons

Final selection: $\sim 10^3$ events per sample

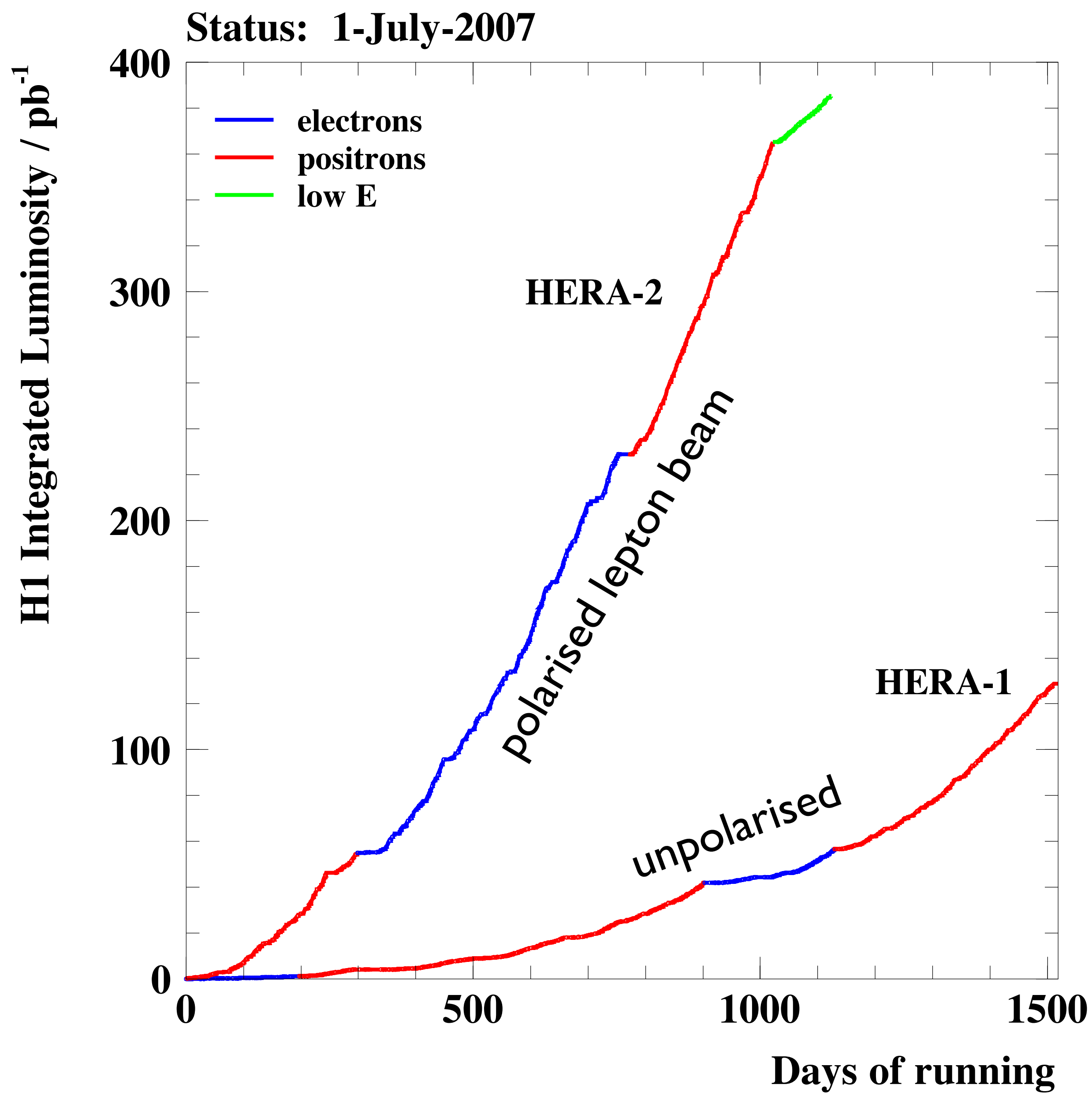


HERA Operation

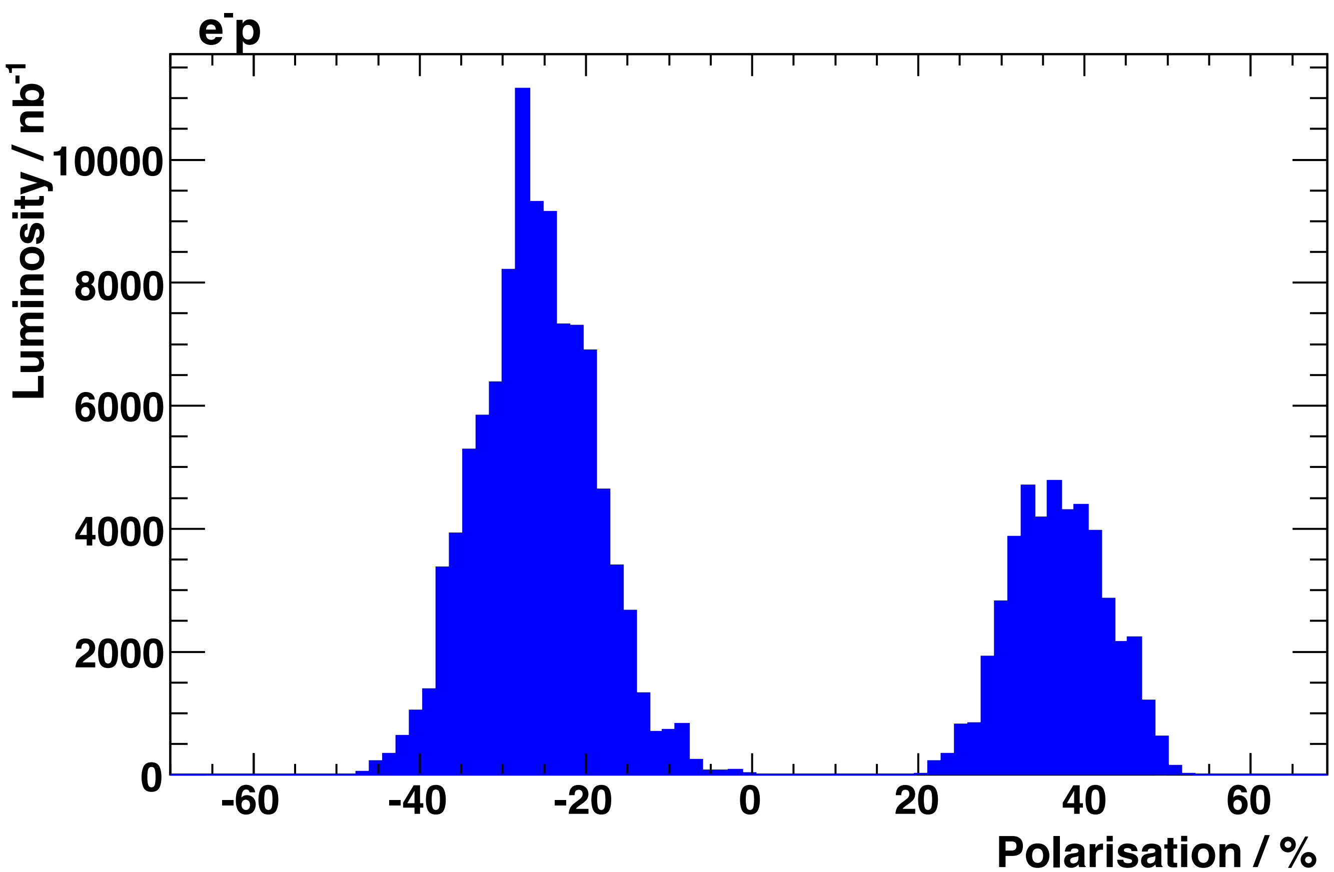
<u>HERA-I operation 1993-2000</u>
Ee = 27.6 GeV
Ep = 820 / 920 GeV
$\int\mathcal{L}$ ~ 110 pb^{-1} per experiment

<u>HERA-II operation 2003-2007</u>
Ee = 27.6 GeV
Ep = 920 GeV
$\int\mathcal{L}$ ~ 330 pb^{-1} per experiment
Longitudinally polarised leptons

<u>Low Energy Run 2007</u>
Ee = 27.6 GeV
Ep = 575 & 460 GeV
Dedicated F_L measurement

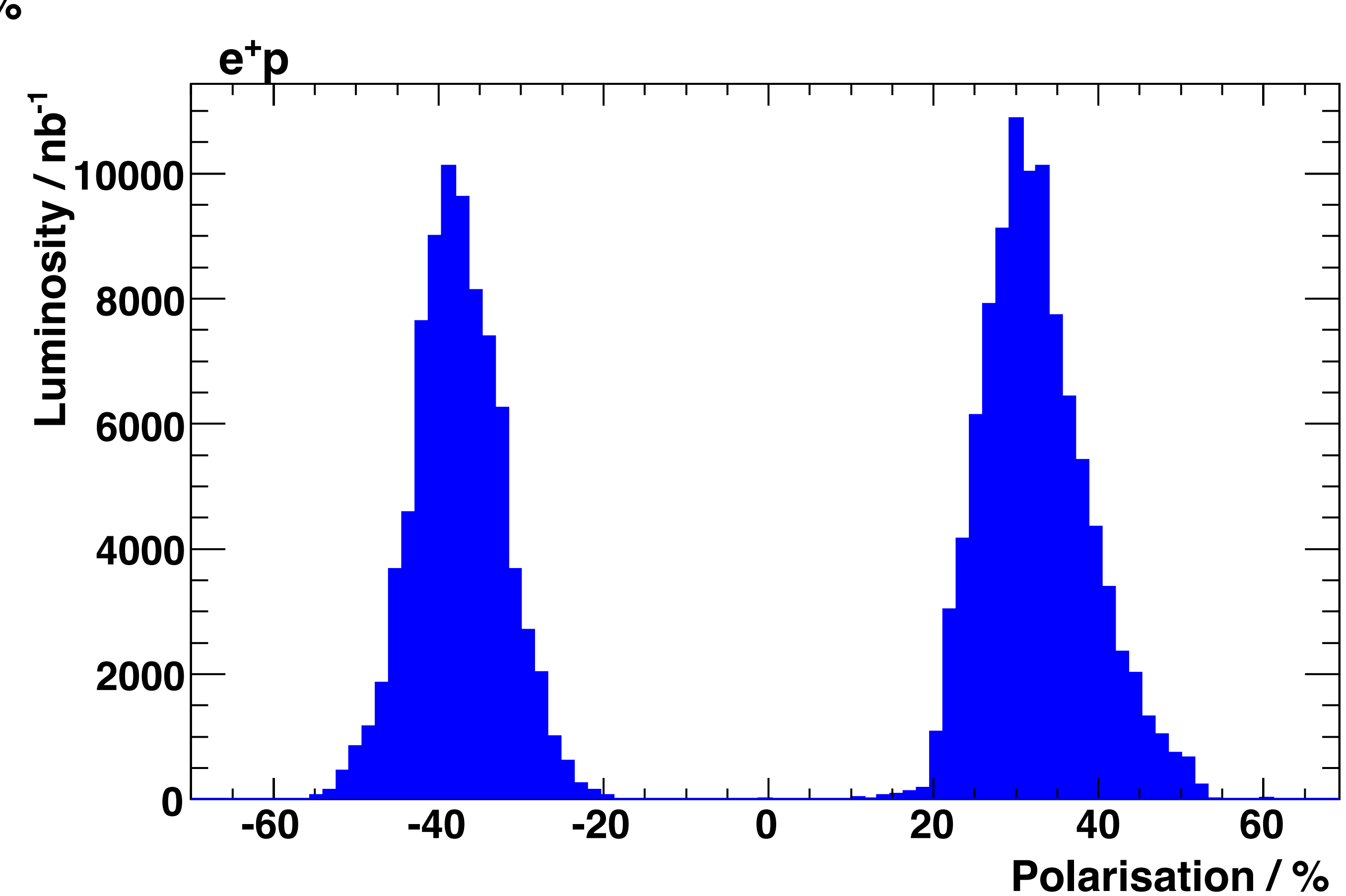


Luminosity & Polarisation



HERA-II Luminosity

	R	L
e^-p	$\mathcal{L} = 45.9\ \text{pb}^{-1}$ $P_e = (+36.9 \pm 2.3)\%$	$\mathcal{L} = 103.2\ \text{pb}^{-1}$ $P_e = (-26.1 \pm 1.0)\%$
e^+p	$\mathcal{L} = 98.1\ \text{pb}^{-1}$ $P_e = (+32.5 \pm 1.2)\%$	$\mathcal{L} = 81.9\ \text{pb}^{-1}$ $P_e = (-37.6 \pm 1.4)\%$



H1 Structure Function Data

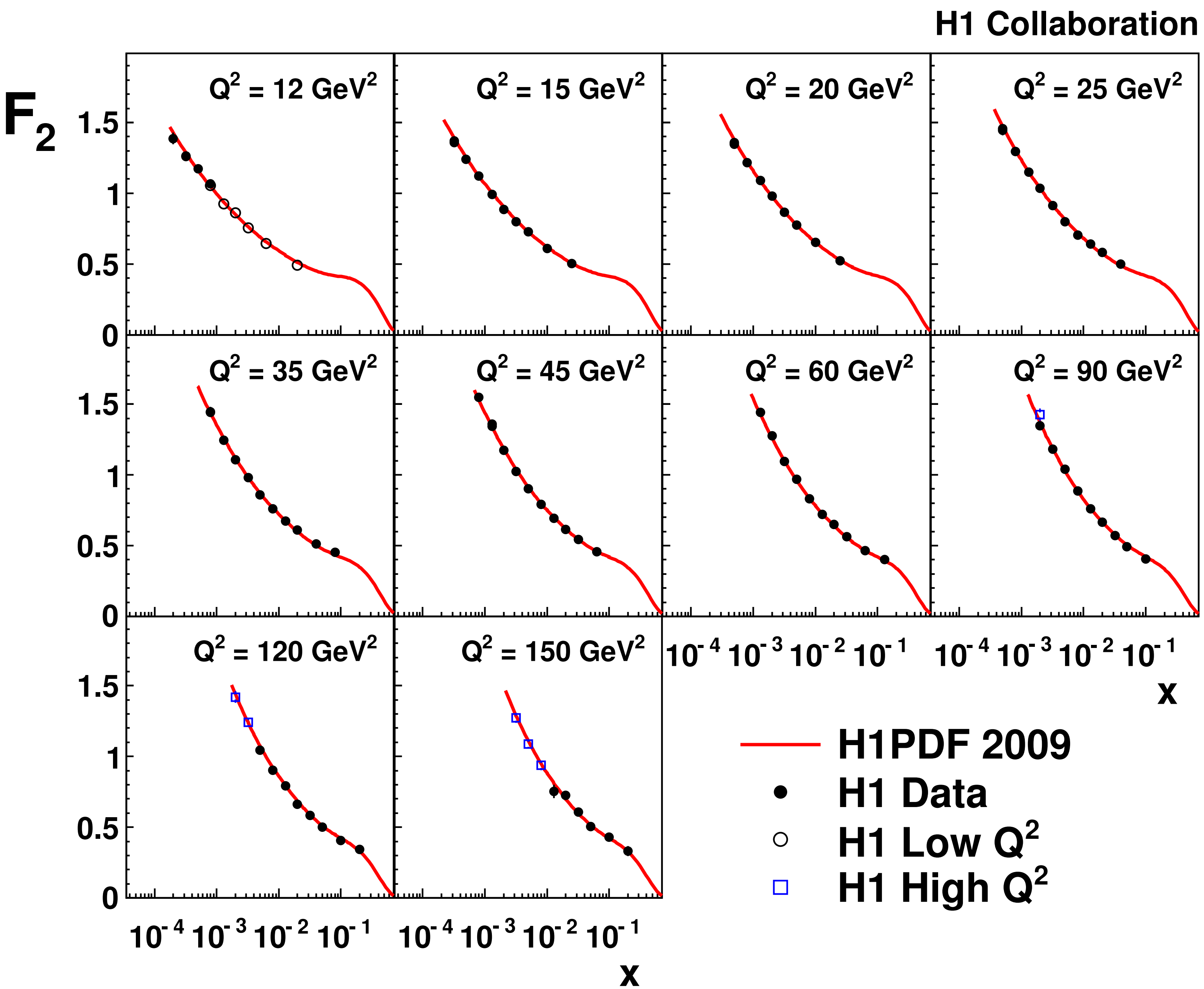
Summary of HERA-I datasets

Data Set		x Range		Q^2 Range GeV^2		$\mathcal{L}$ pb^{-1}	e^+/e^-	$\sqrt{s}$ GeV
H1 svx-mb	95-00	5×10^{-6}	0.02	0.2	12	2.1	e^+p	301-319
H1 low Q^2	96-00	2×10^{-4}	0.1	12	150	22	e^+p	301-319
H1 NC	94-97	0.0032	0.65	150	30000	35.6	e^+p	301
H1 CC	94-97	0.013	0.40	300	15000	35.6	e^+p	301
H1 NC	98-99	0.0032	0.65	150	30000	16.4	e^-p	319
H1 CC	98-99	0.013	0.40	300	15000	16.4	e^-p	319
H1 NC HY	98-99	0.0013	0.01	100	800	16.4	e^-p	319
H1 NC	99-00	0.0013	0.65	100	30000	65.2	e^+p	319
H1 CC	99-00	0.013	0.40	300	15000	65.2	e^+p	319

Summary of HERA-II datasets

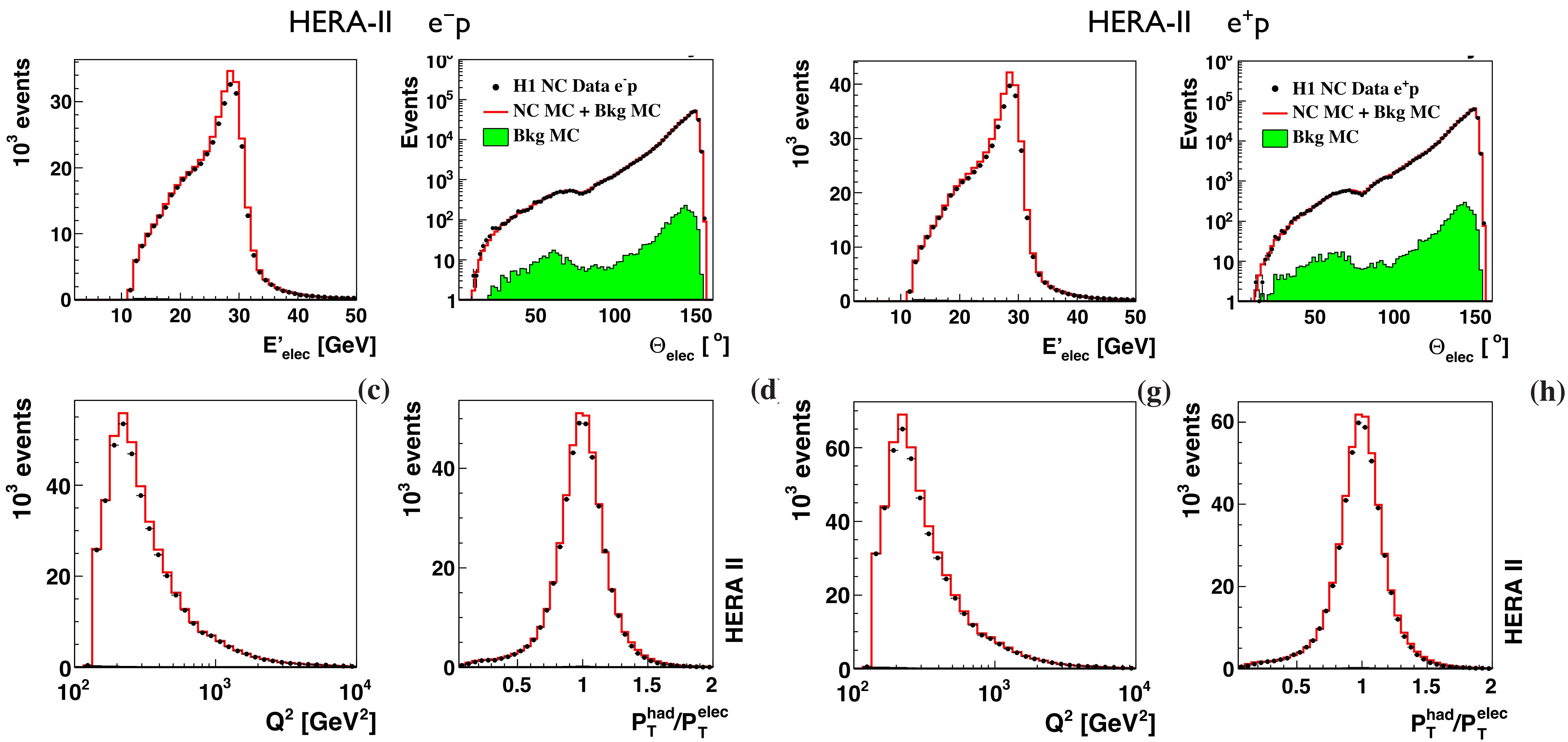
H1 CC e^-p	149 pb^{-1}	H1prelim-09-043
H1 CC e^+p	180 pb^{-1}	H1prelim-09-043
H1 NC e^-p	149 pb^{-1}	H1prelim-09-042
H1 NC e^+p	180 pb^{-1}	H1prelim-09-042

Precision F_2 at Medium Q^2



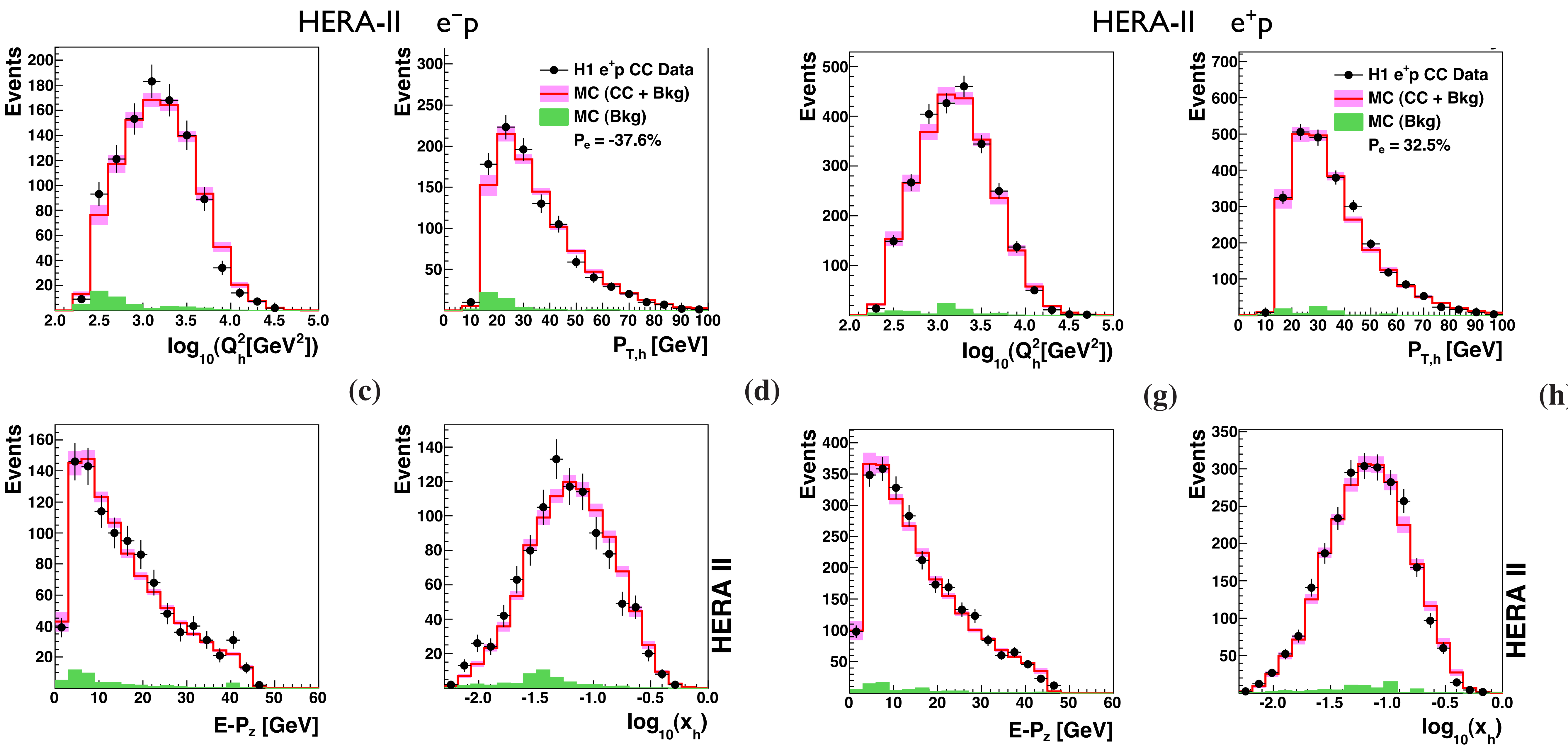
Precision data from H1 for $Q^2 < 150\ GeV^2$
Typical uncertainty of 1.3 - 2 %
Provides strong constraints on PDFs
 - gluon and singlet quarks

DESY-09-005
H1 Collab, Eur.Phys.J.C64 (2009) 561



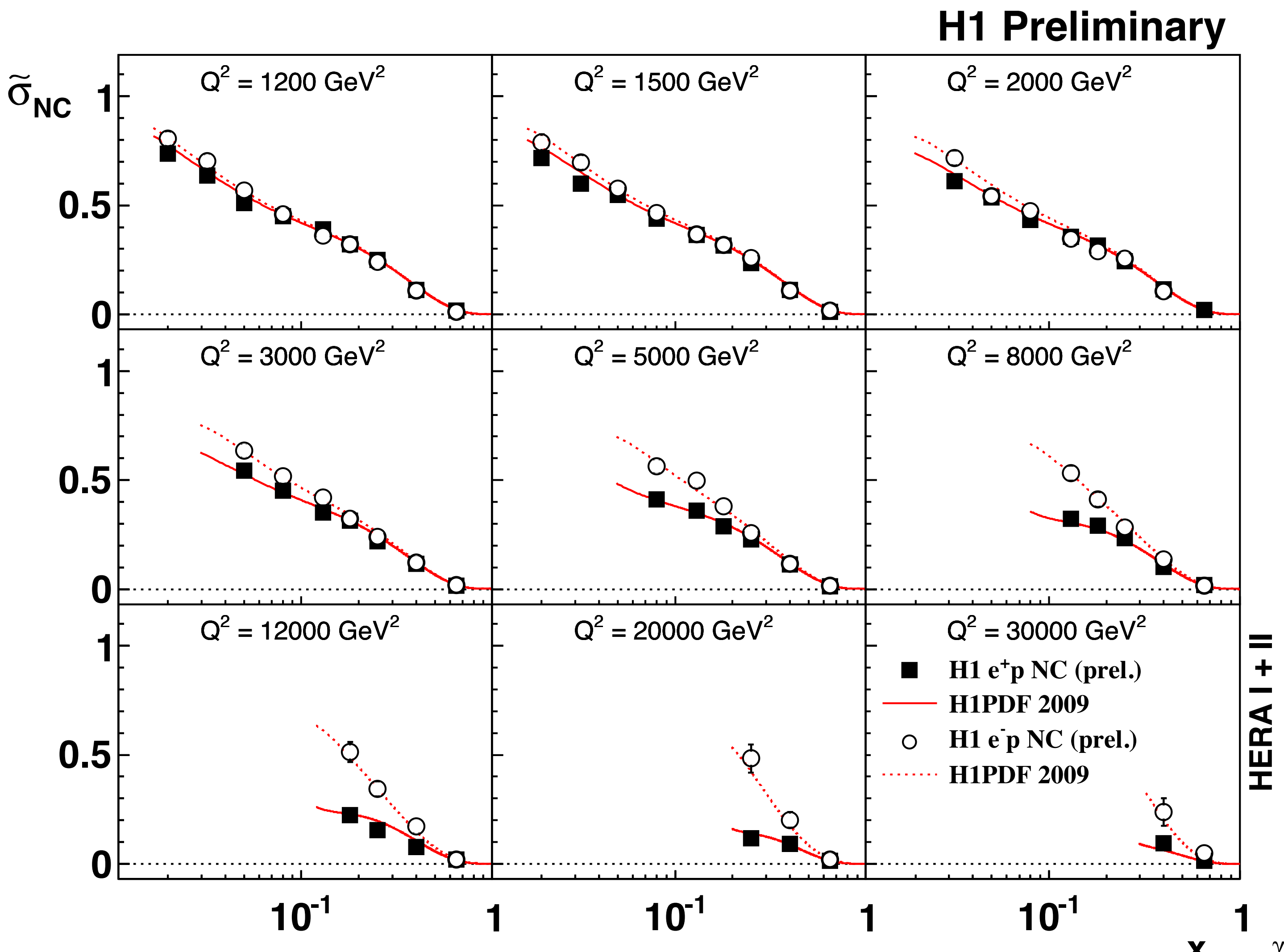
Kinematic distributions are well described by MC
~3% normalisation shift
within preliminary luminosity uncertainty ±2.1%

Charged Current Control Distributions



Kinematic distributions are well described by MC
Within errors normalisation is fine

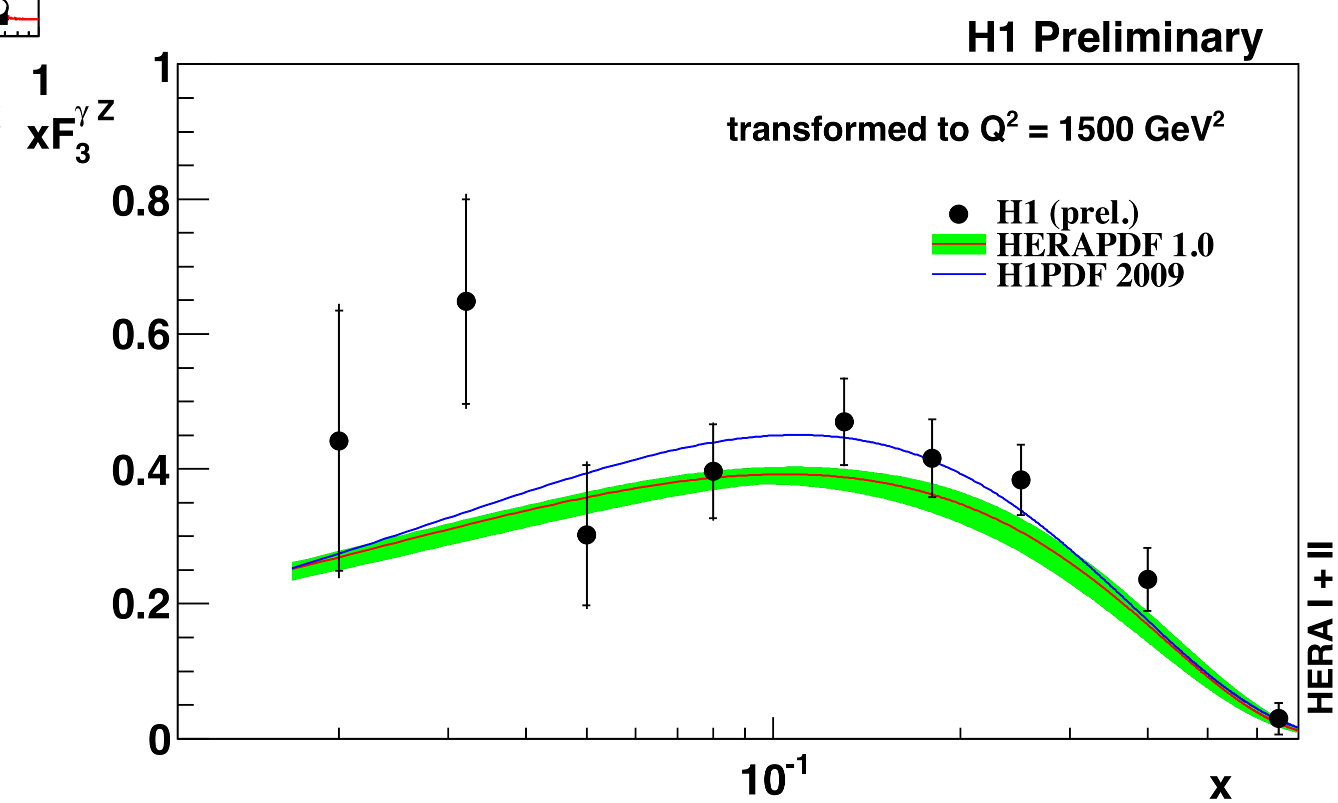
xF_3



At high Q^2 xF_3 arises due to Z^0 effects
enhanced e^- cross section wrt e^+
Difference is xF_3
Sensitive to valence PDFs

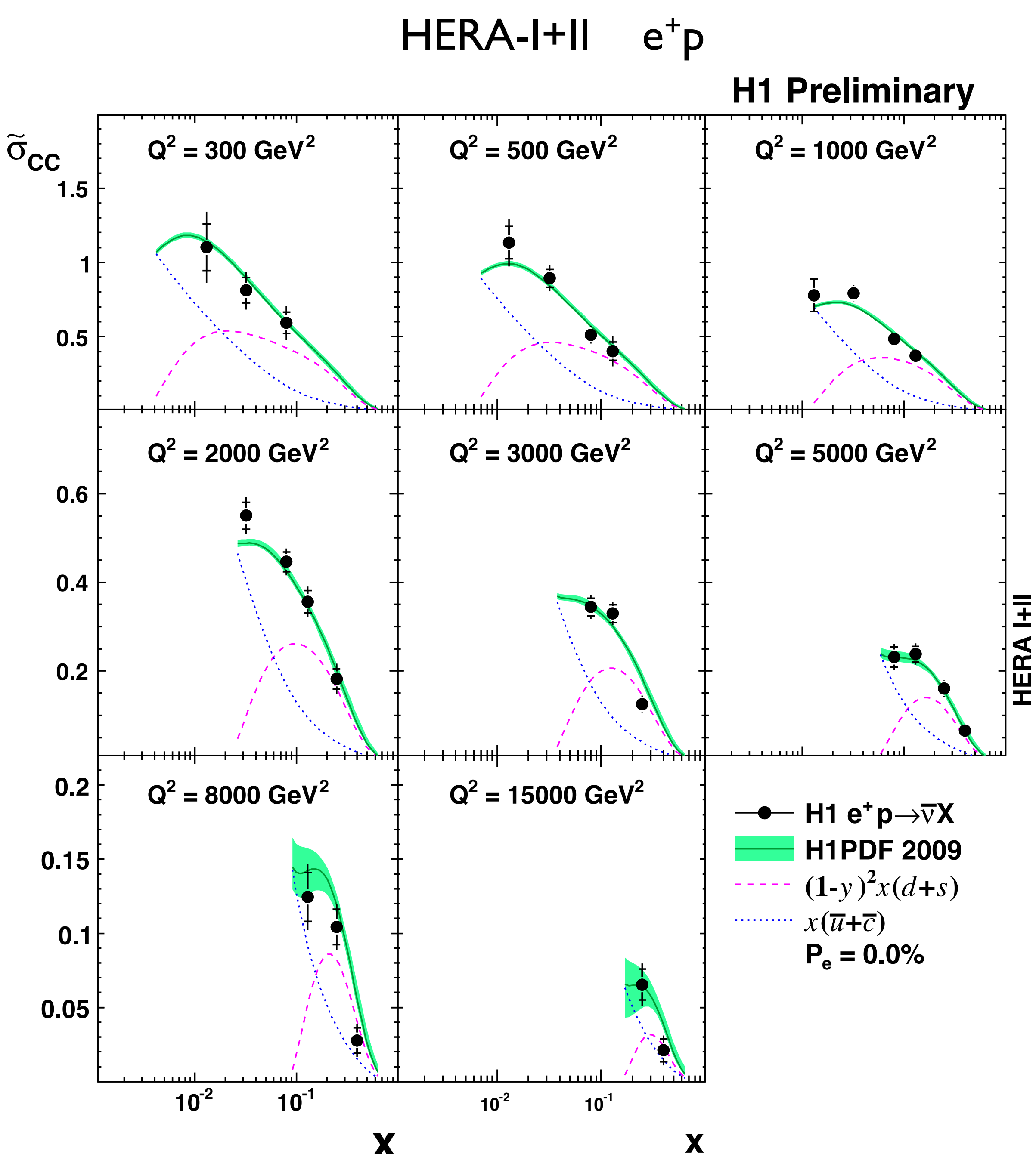
$$x\tilde{F}_3 = \frac{Y_+}{2Y_-}(\tilde{\sigma}^-_{NC} - \tilde{\sigma}^+_{NC}) \approx a_e \chi_Z x F_3^{\gamma Z}$$

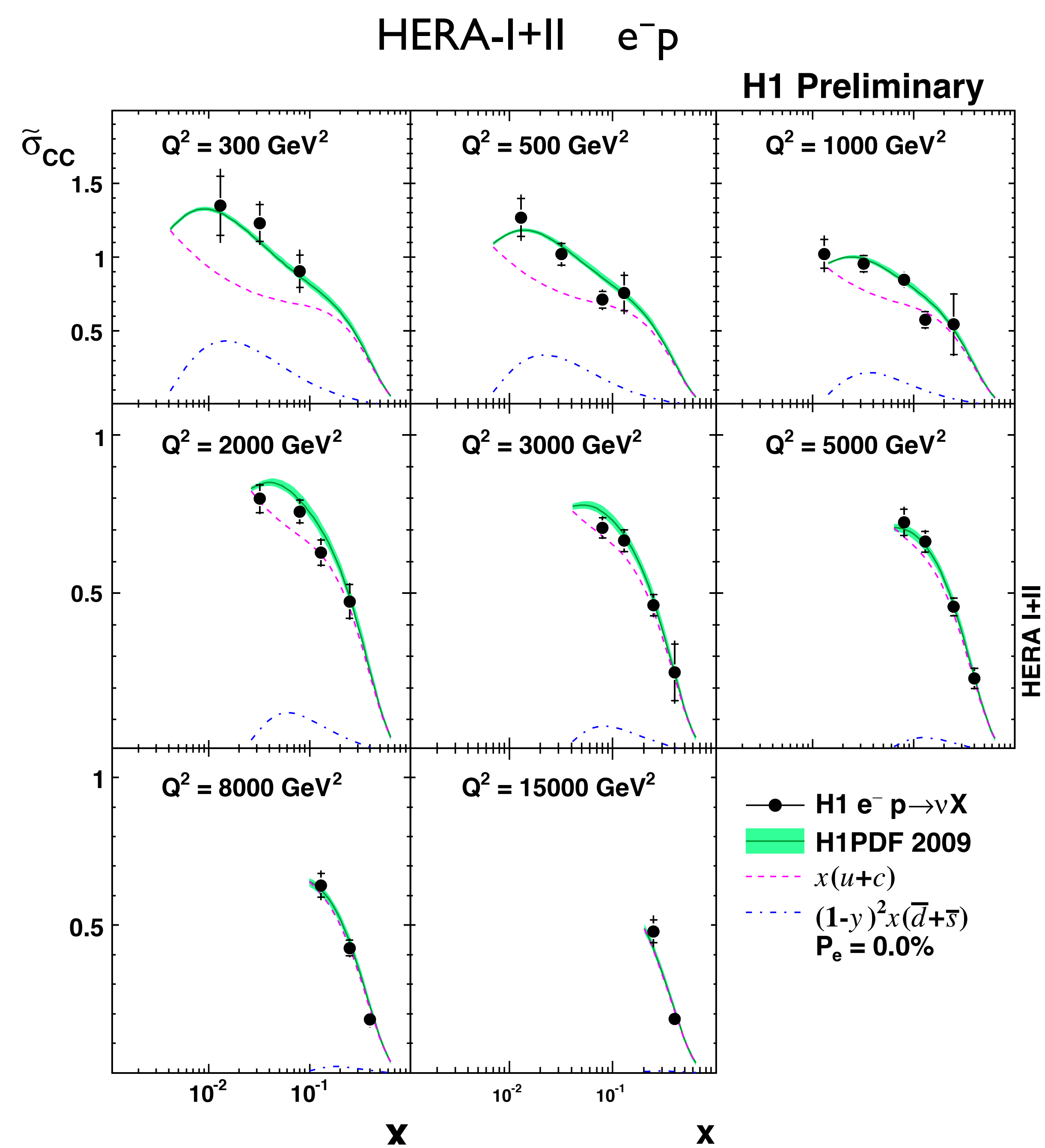
$$x\tilde{F}_3 \propto \sum (xq_i - x\bar{q}_i)$$



desy-10-228

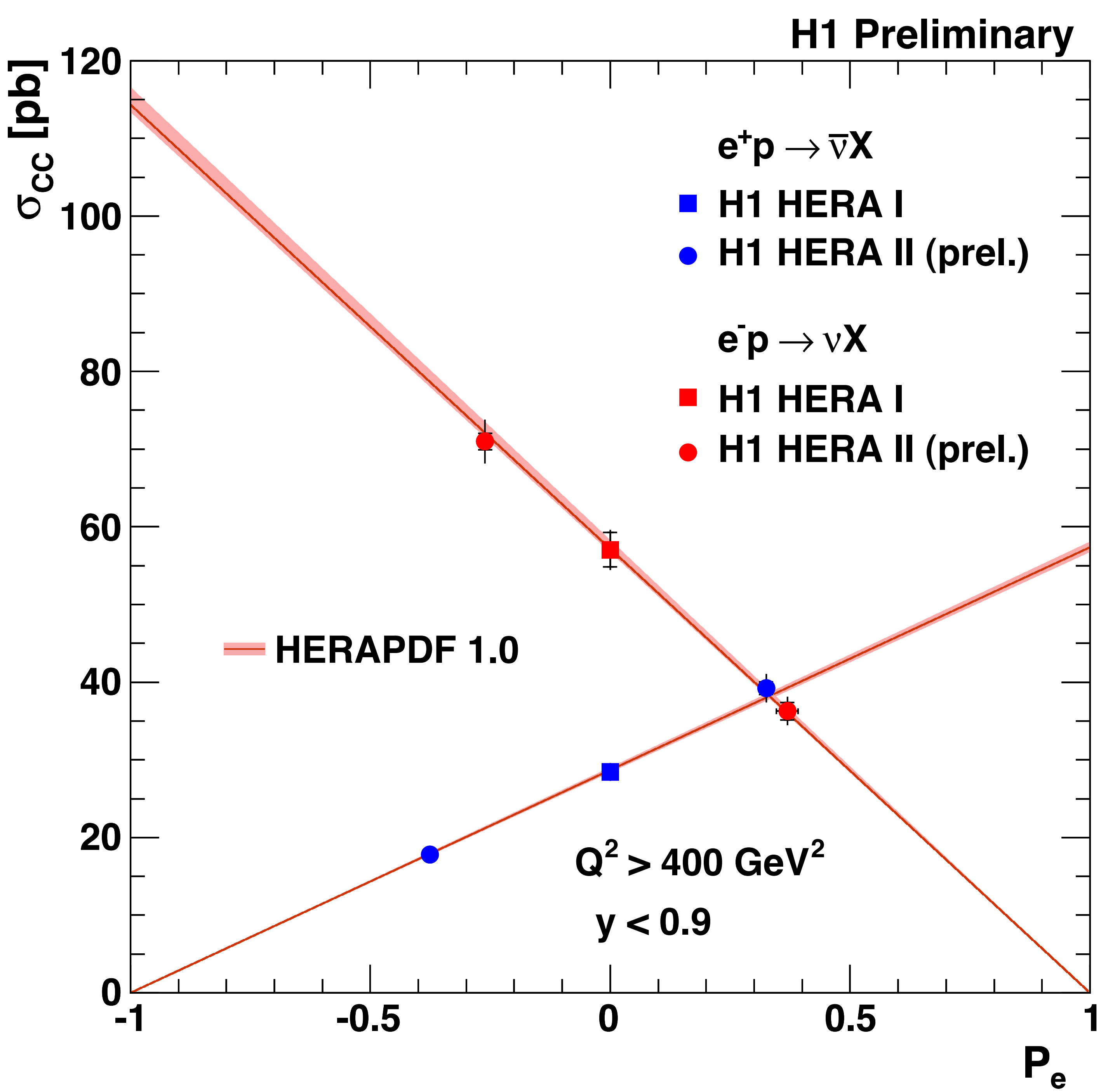
CC Flavour Sensitivity



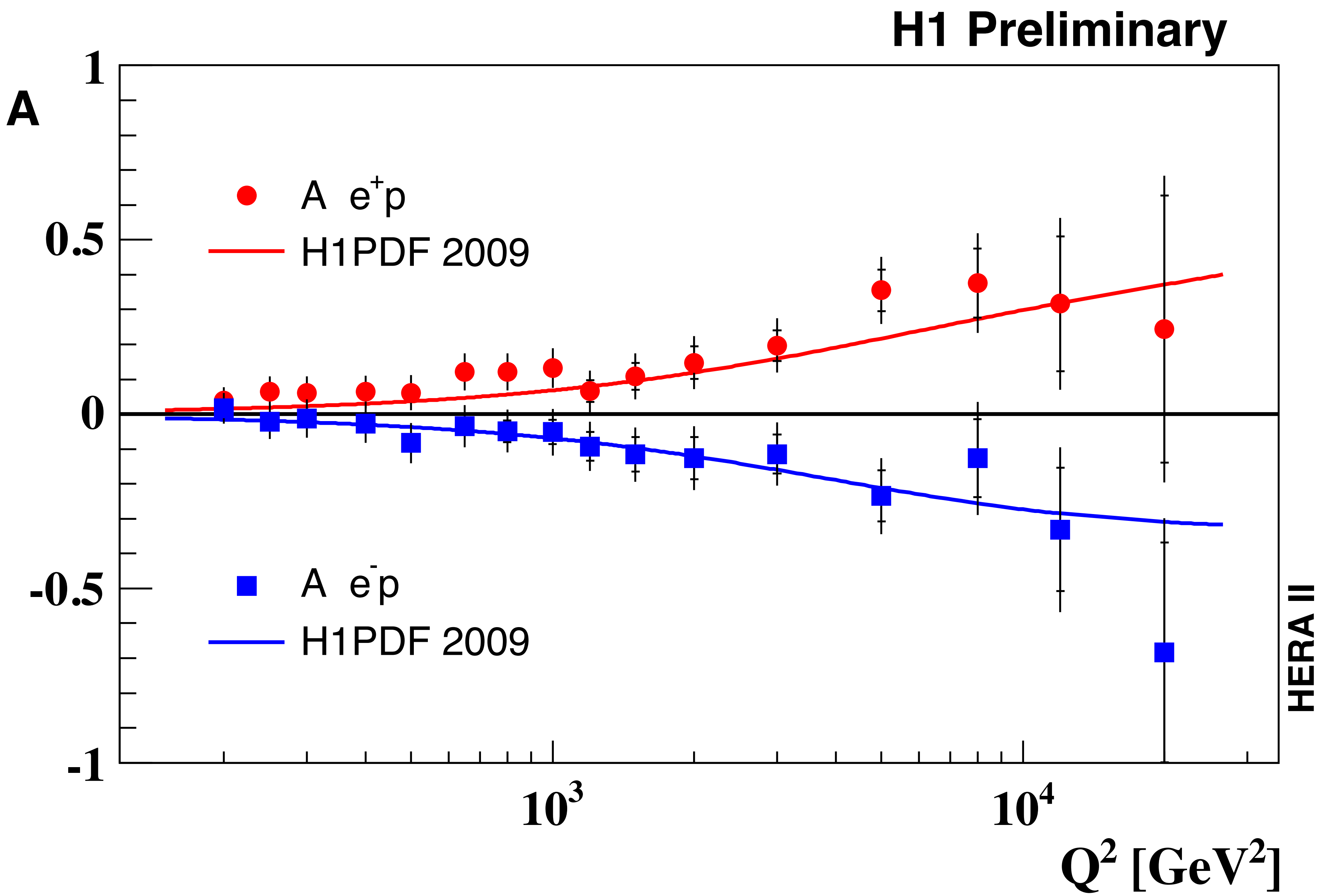


Dashed lines show quark flavour composition
High x d_v is not well constrained by NC data
Good constraints from CC e^+ data

CC Polarisation Dependence



Clear linear scaling of CC cross section
Verifies absence of weak right-handed currents



NC parity violating effects are more subtle
Measure NC polarisation asymmetry

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

QCD & EW Fit

<u>Combined QCD & EW Fit</u>

Combined NC and CC HERA-I data from H1

No usage of other experimental data (e.g. non-DIS)

Complete MSbar NLO fit

NLO: standard parameterisation with14 parameters

Fit PDFs and light quark axial/vector couplings

EW parameters from PDF2009:

M_{top} = 171.3 GeV

M_W = 80.398 GeV

α_S = 0.1176

PDFs parameterised at starting scale Q_0^2

$$xf(x,Q_0^2) = A \cdot x^B \cdot (1-x)^C \cdot (1 + Dx + Ex^2 + Fx^3)$$

xg, xu_v, xd_v, $x\bar{U}$, $x\bar{D}$ → xg, $xU = xu + xc$, $xD = xd + xs$, $x\bar{U} = x\bar{u} + x\bar{c}$, $x\bar{D} = x\bar{d} + x\bar{s}$ →

$$\begin{aligned} xg(x) &= A_g x^{B_g}(1-x)^{C_g} \cdot [1 + D_g x] \\ xU(x) &= A_U x^{B_U}(1-x)^{C_U} \cdot [1 + D_U x + F_U x^3] \\ xD(x) &= A_D x^{B_D}(1-x)^{C_D} \cdot [1 + D_D x] \\ x\overline{U}(x) &= A_{\overline{U}} x^{B_{\overline{U}}}(1-x)^{C_{\overline{U}}} \\ x\overline{D}(x) &= A_{\overline{D}} x^{B_{\overline{D}}}(1-x)^{C_{\overline{D}}} , \end{aligned}$$

$x\bar{s} = f_s x\bar{D}$ strange sea is a fixed fraction f_s of $\bar{D}$ at Q_0^2

Apply momentum/counting sum rules:

$$\int_0^1 dx \cdot (xu_v + xd_v + x\bar{U} + x\bar{D} + xg) = 1$$

$$\int_0^1 dx \cdot u_v = 2 \qquad \int_0^1 dx \cdot d_v = 1$$

Parameter constraints:

$B_{uv} = B_{dv}$

$B_{Ubar} = B_{Dbar}$

sea = 2 x (Ubar +Dbar)

Ubar = Dbar at x=0

$Q_0^2 = 4$ GeV^2

$Q^2 > 3.5$ GeV^2

$2 \times 10^{-4} < x < 0.65$

Fits performed in massless HQ scheme

Alternative parametric form included as uncertainty
Taken from HERAPDF1.0 QCD fit

HERAPDF1.0
Combine NC and CC HERA-I data from H1 & ZEUS
Complete MSbar NLO fit
NLO: standard parameterisation with10 parameters
α_s = 0.1176 (fixed in fit)

$$xf(x,Q_0^2) = A \cdot x^B \cdot (1-x)^C \cdot (1 + Dx + Ex^2 + Fx^3)$$

xg	xg	$xg(x) = A_g x^{B_g}(1-x)^{C_g},$
xu_v	$xU = xu + xc$	$xu_v(x) = A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}\left(1 + E_{u_v}x^2\right),$
xd_v →	$xD = xd + xs$ →	$xd_v(x) = A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}},$
$x\bar{U}$	$x\bar{U} = x\bar{u} + x\bar{c}$	$x\bar{U}(x) = A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}},$
$x\bar{D}$	$x\bar{D} = x\bar{d} + x\bar{s}$	$x\bar{D}(x) = A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}.$

Experimental systematic sources of uncertainty allowed to float in fit
Include model assumptions into uncertainty:
f_s , m_c , m_b , $Q^2{}_0$, $Q^2{}_{min}$

Variation	Standard Value	Lower Limit	Upper Limit
f_s	0.31	0.23	0.38
m_c [GeV]	1.4	1.35$^{(a)}$	1.65
m_b [GeV]	4.75	4.3	5.0
Q^2_{min} [GeV^2]	3.5	2.5	5.0
Q^2_0 [GeV^2]	1.9	1.5$^{(b)}$	2.5$^{(c,d)}$

$^{(a)}Q^2_0 = 1.8$ $^{(c)}m_c = 1.6$
$^{(b)}f_s = 0.29$ $^{(d)}f_s = 0.34$

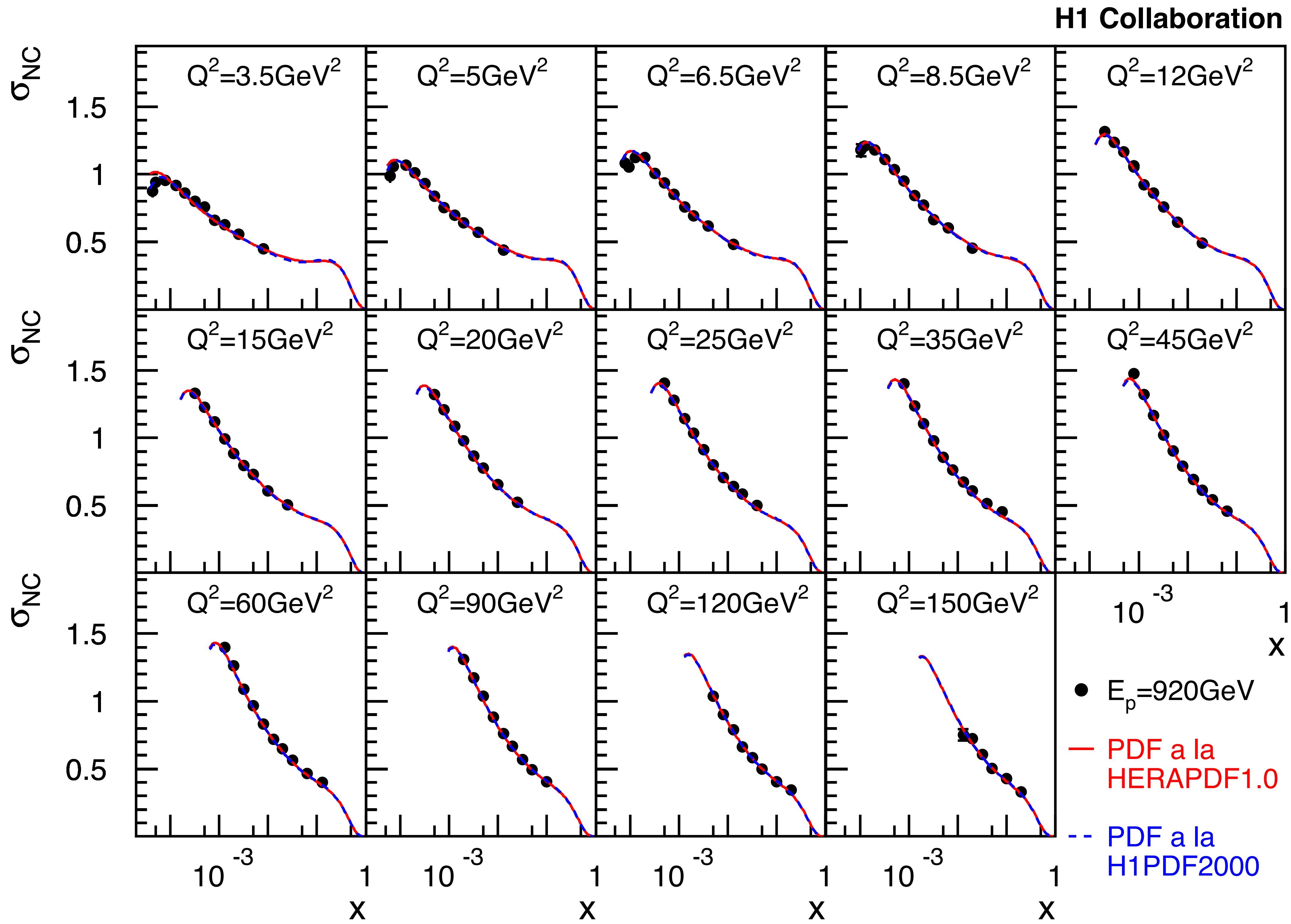
Excellent consistency of input data allow standard statistical error definition:
$\Delta\chi^2 = 1$

Uncertainties

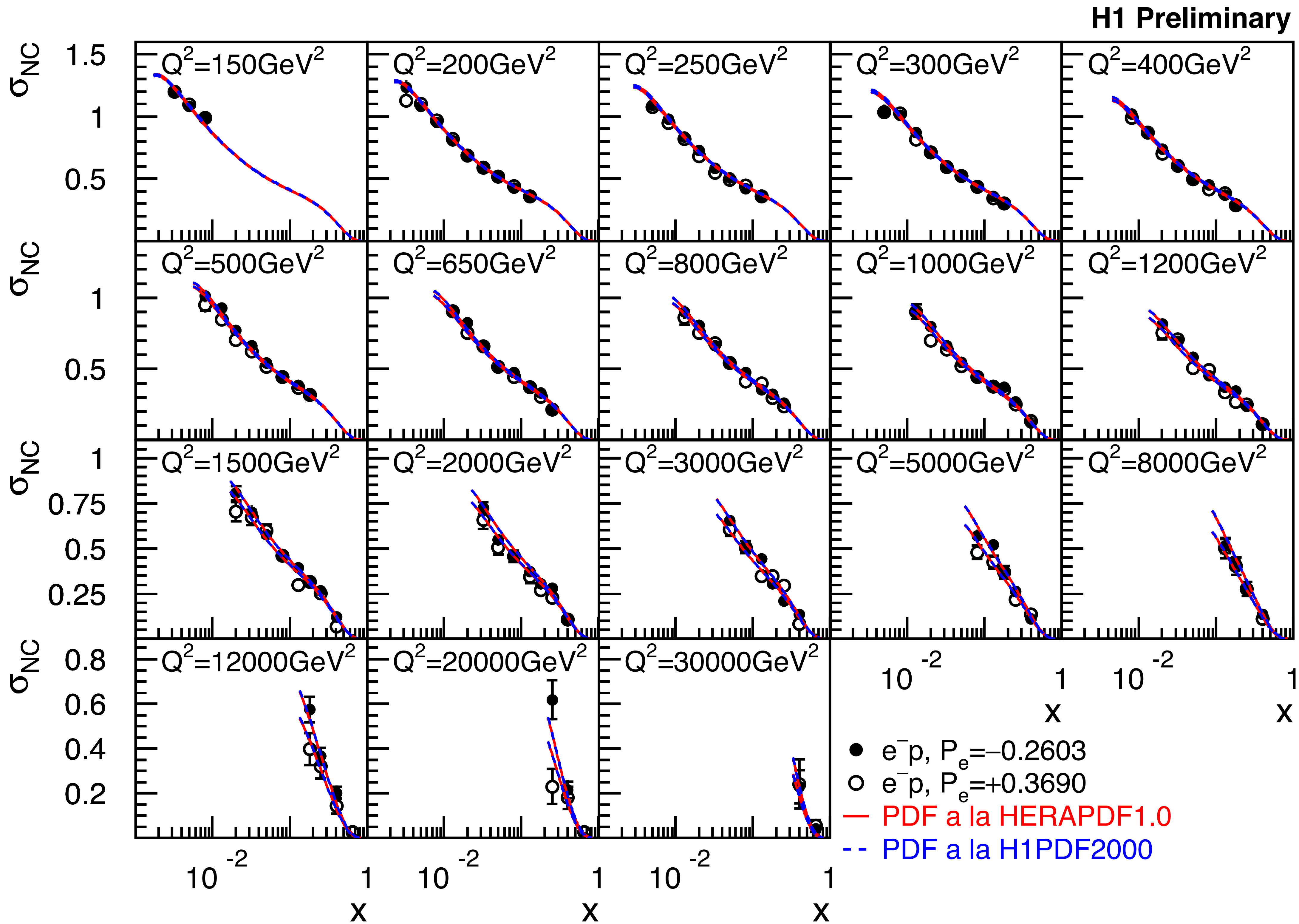
	a_u	v_u	a_d	v_d
Model	±0.02	±0.01	±0.03	±0.01
SM	±0.02	±0.01	±0.03	±0.02
Param.	±0.03	±0.02	±0.06	±0.06
Total Sys.	±0.04	±0.02	±0.07	±0.06
Exp.	±0.06	±0.08	±0.19	±0.27

New combined QCD & EW fit performed
Takes into account full correlation of uncertainties
χ^2/ndf = 1184 / 1230 = 0.96

Results

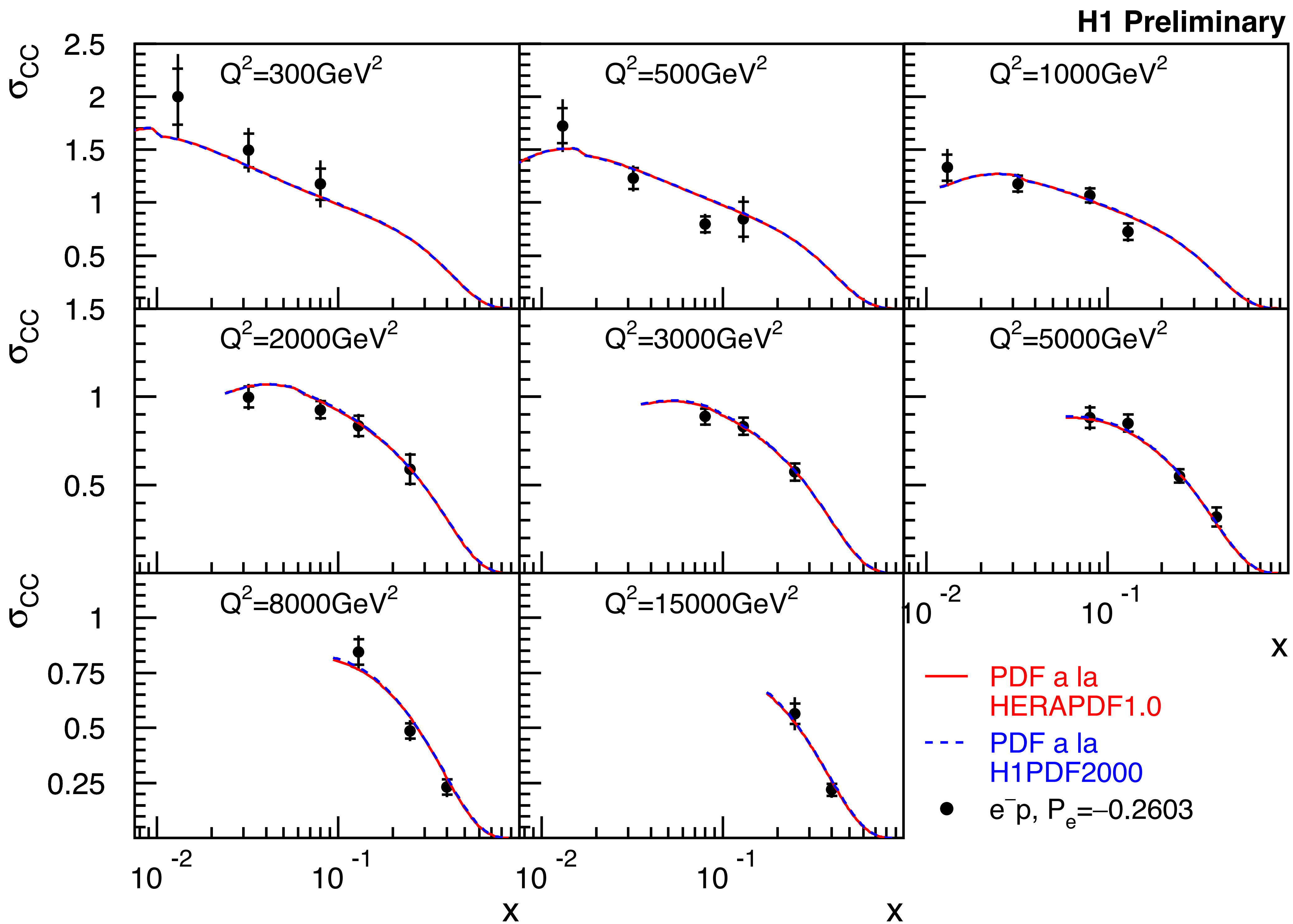


QCD/EW Fit gives good description of precision F_2 data



Polarised LH / RH neutral current cross sections in e^-p scattering

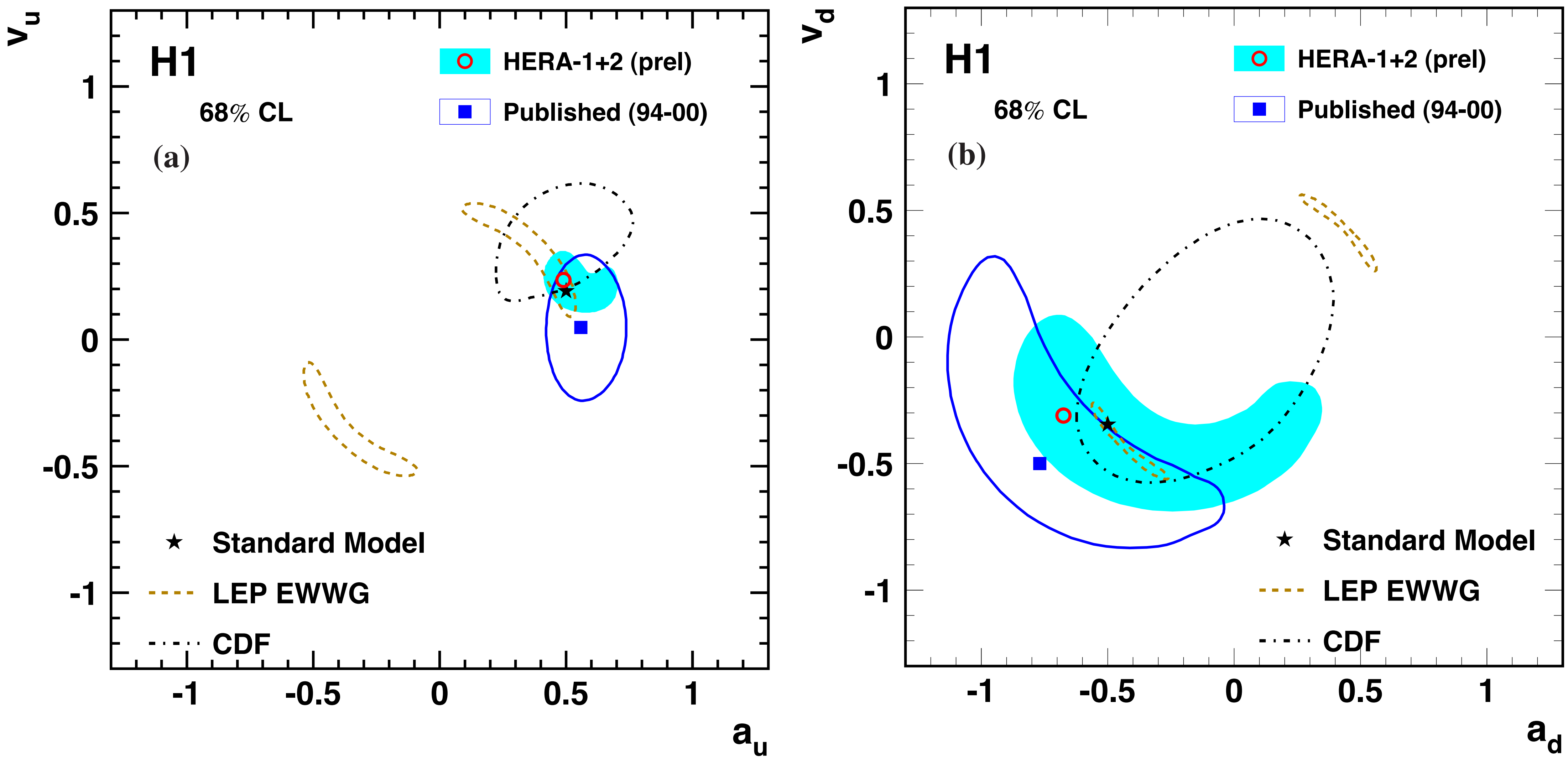
Results



Polarised LH charged current cross sections in e^-p scattering

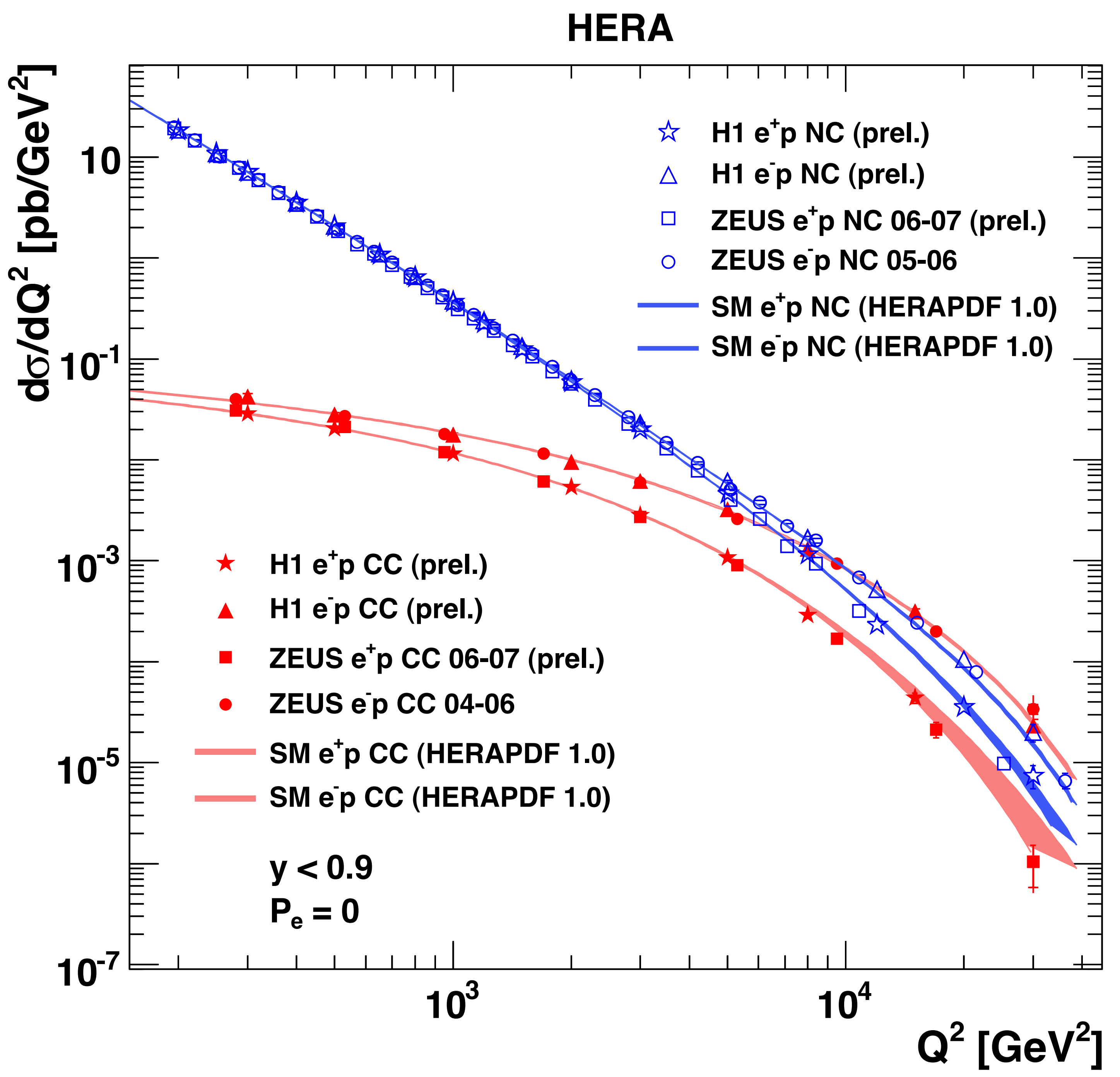
Results

Fit	v_u-a_u-v_d-a_d-PDF	v_u-a_u-PDF	v_d-a_d-PDF	SM
a_u	$0.49 \pm 0.06 \pm 0.04$	0.53 ± 0.04	–	0.5
v_u	$0.23 \pm 0.08 \pm 0.02$	0.23 ± 0.04	–	0.191
a_d	$-0.67 \pm 0.19 \pm 0.07$	–	-0.61 ± 0.15	-0.5
v_d	$-0.31 \pm 0.27 \pm 0.06$	–	-0.44 ± 0.13	-0.346
χ^2/dof	1183.8/1230	1184.5/1232	1184.2/1232	–



Fits with new polarised HERA-I data shown in 68% CL blue contour
Improved sensitivity to vector couplings compared to HERA-I unpolarised data (blue shaded area)
Competitive determinations to CDF and LEP
HERA data resolves LEP sign ambiguity

Conclusions



- HERA data provide some of the most stringent constraints on PDFs
- Stress-test of QCD over 4 orders of mag. in Q^2
- HERA data provide a self-consistent data set for complete flavour decomposition of the proton
- Combined QCD & EW analysis performed gives improved precision on axial & vector couplings

Soon to publish final HERA-II data