Electroweak Physics at FCC-eh

Electroweak Physics in ep

Data Simulation

Observables and Role of PDFs

Masses (W,Z,H,t)

Weinberg angle and its scale dependence

Light Quark Weak Neutral Current Couplings

Note:
All FCC-eh results are work in progress and some of LHeC too

Daniel Britzger (DESY) and Max Klein (U Liverpool)
for the LHeC/FCC-eh Study Group

Contribution to the FCC Physics Week, CERN, 17. January, 2017

Electroweak Effects in NC DIS Cross Section

$$\begin{aligned} \mathbf{F_2^\pm} &= F_2 + \kappa_Z(-v_e \mp P a_e)\cdot F_2^{\gamma Z} + \kappa_Z^2(v_e^2 + a_e^2 \pm 2P v_e a_e)\cdot F_2^Z \\ \mathbf{xF_3^\pm} &= \kappa_Z(\pm a_e + P v_e)\cdot xF_3^{\gamma Z} + \kappa_Z^2(\mp 2 v_e a_e - P(v_e^2 + a_e^2))\cdot xF_3^Z . \end{aligned}$$

$$\kappa_Z(Q^2) = \frac{Q^2}{Q^2 + M_Z^2}\cdot\frac{1}{4\sin^2\Theta\cos^2\Theta} \qquad v_f = i_f - e_f 2\sin^2\Theta \qquad a_f = i_f$$

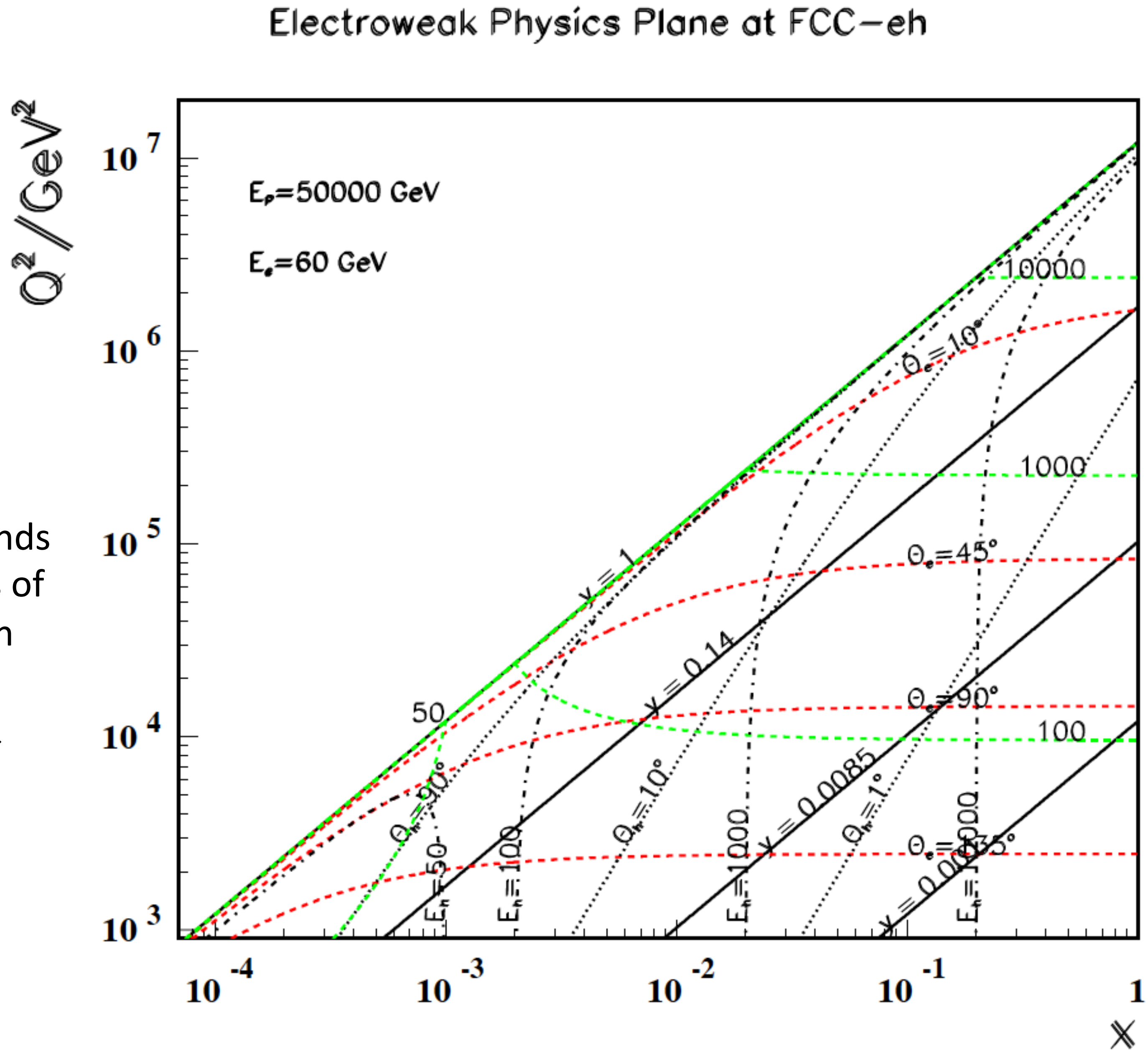
$$\begin{aligned} (F_2, F_2^{\gamma Z}, F_2^Z) &= x\sum(e_q^2, 2e_q v_q, v_q^2 + a_q^2)(q + \bar{q}) \\ (xF_3^{\gamma Z}, xF_3^Z) &= 2x\sum(e_q a_q, v_q a_q)(q - \bar{q}), \end{aligned}$$

	e^2	2ev
u	4/9	2/9
d	1/9	2/9

NC: yy, yZ, ZZ. Lepton beam helicity P, M_Z, v and a couplings, PV through va
CC: pure weak cross section (G_F, M_W) → 3 independent variables, DIS: OMS

M. Klein and T. Riemann[1]
Institut für Hochenergiephysik der AdW der DDR, DDR-1615 Berlin-Zeuthen
Received 19 October 1983 Z. Phys. C – Particles and Fields 24, 151–155 (1984)

Can we measure at high Q^2 ? Yes, we could!

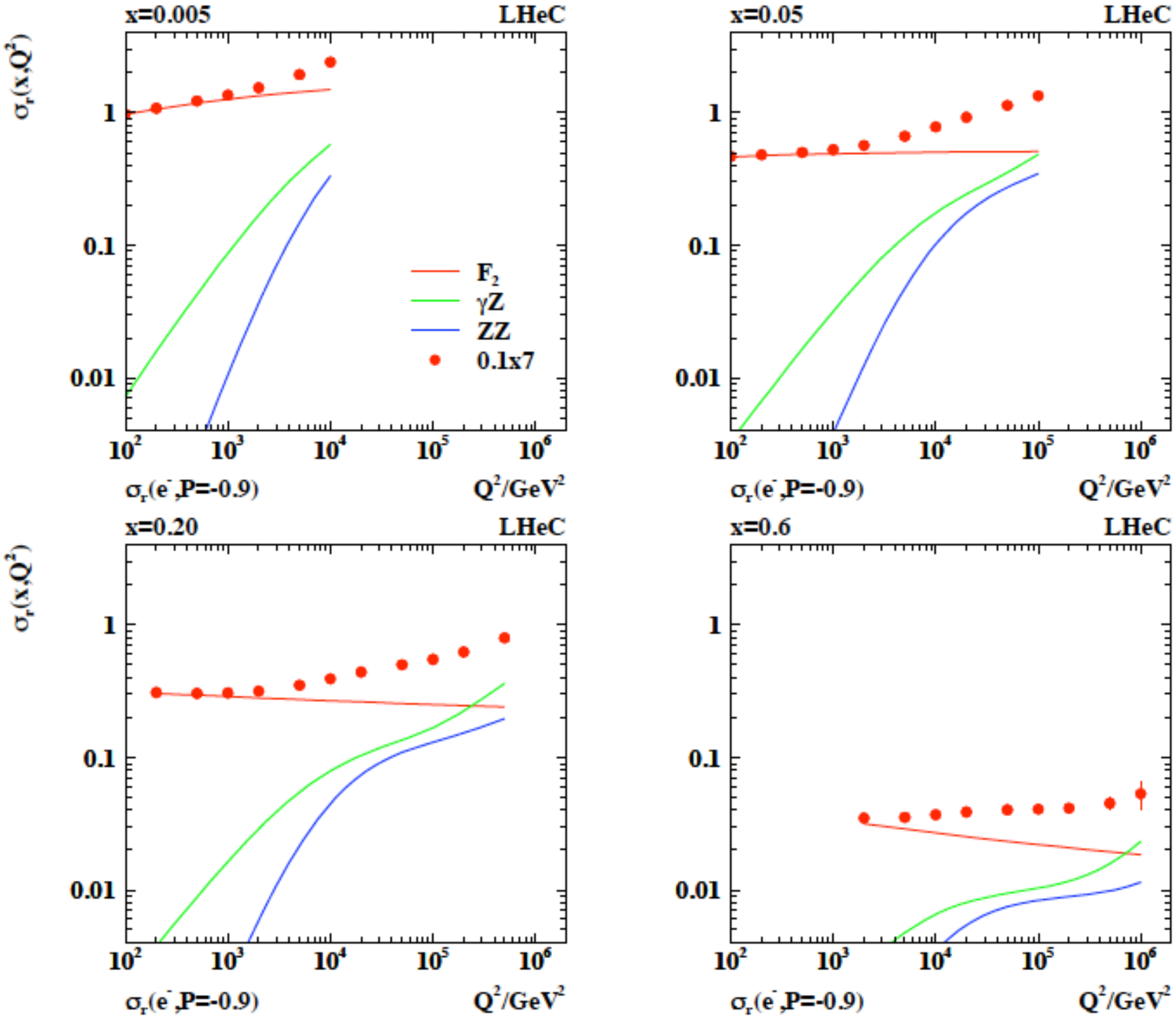


FCC-eh extends three orders of magnitude in Q^2 beyond

$Q^2 = M_Z^2$ →

← 90^o

Reduced NC e^-p Scattering Cross Section [P=-0.9, 10fb^{-1}]



Huge Z exchange effects →

At small Q^2 , $\sigma_r=F_2$

Both at x=0.2 (the point of Bj scaling) and at larger x (the region of gluon bremsstrahlung which makes F_2 decrease with Q^2), the reduced NC cross section rises

Polarisation Asymmetry and R=NC/CC

$$\frac{2}{P_L - P_R} \cdot A^{\pm} \simeq \mp \kappa_Z a_e \frac{F_2^{\gamma Z}}{(F_2 + \kappa_Z a_e Y_- x F_3^{\gamma Z}/Y_+)} \simeq \mp \kappa_Z a_e \frac{F_2^{\gamma Z}}{F_2}$$

$$\frac{2}{P_L - P_R} \cdot A^{\pm} \simeq \pm \kappa \frac{1 + d_v/u_v}{4 + d_v/u_v}.$$

Classic asymmetry (Prescott et al, 1978) accesses weak interaction, $F_2^{\gamma Z}$ is a new, direct measure of valence quarks at high x

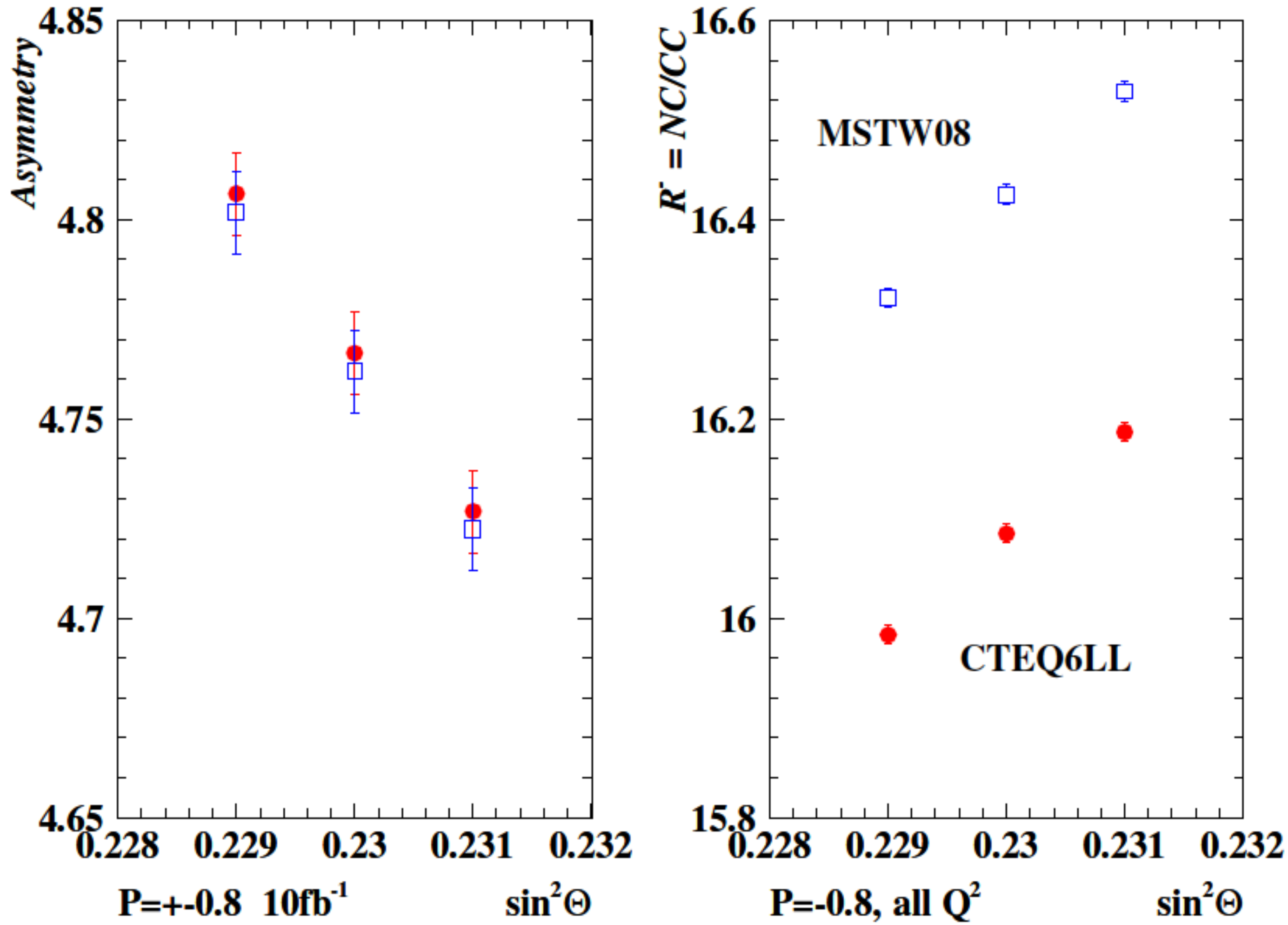
$$R^{\pm} = \frac{\sigma^{\pm}_{NC}}{\sigma^{\pm}_{CC}} = \frac{2}{(1 \pm P)\kappa_W^2} \cdot \frac{\sigma^{\pm}_{r,NC}}{\sigma^{\pm}_{r,CC}}$$

$$R^{\pm} \simeq \frac{2a_e^2}{(1 \pm P)\cos^2\Theta} \cdot \frac{Y_+ F_2^Z - Y_- P x F_3^Z}{Y_+ W_2^{\pm} + Y_- x W_3^{\pm}}$$

R accesses weak interaction and the pure weak structure functions which are best measured at the FCC-eh

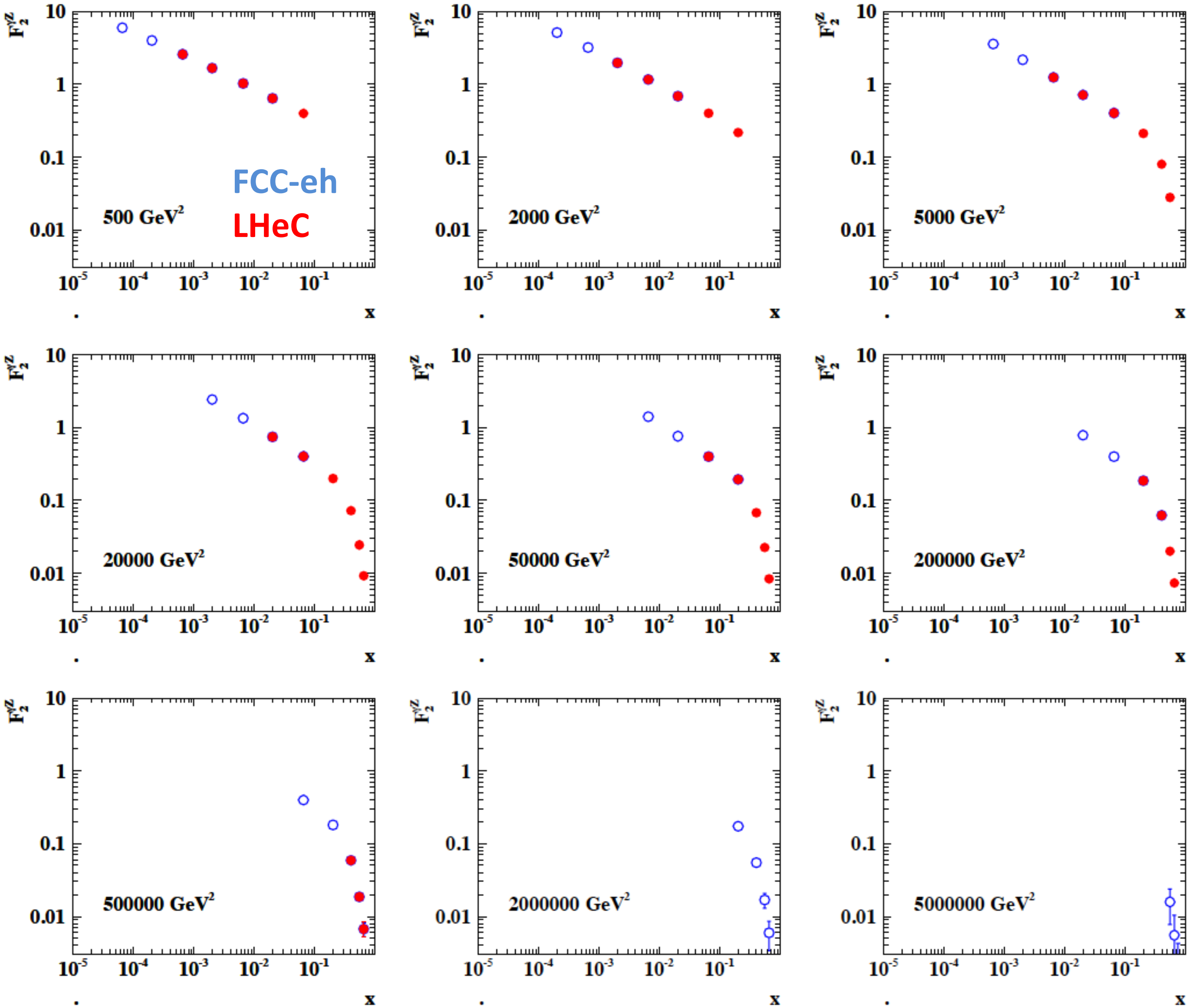
Note that in experiment you would measure the cross sections and determine all correlations which is still more informative than A or R but contains their physics.

Polarisation Asymmetry and R=NC/CC

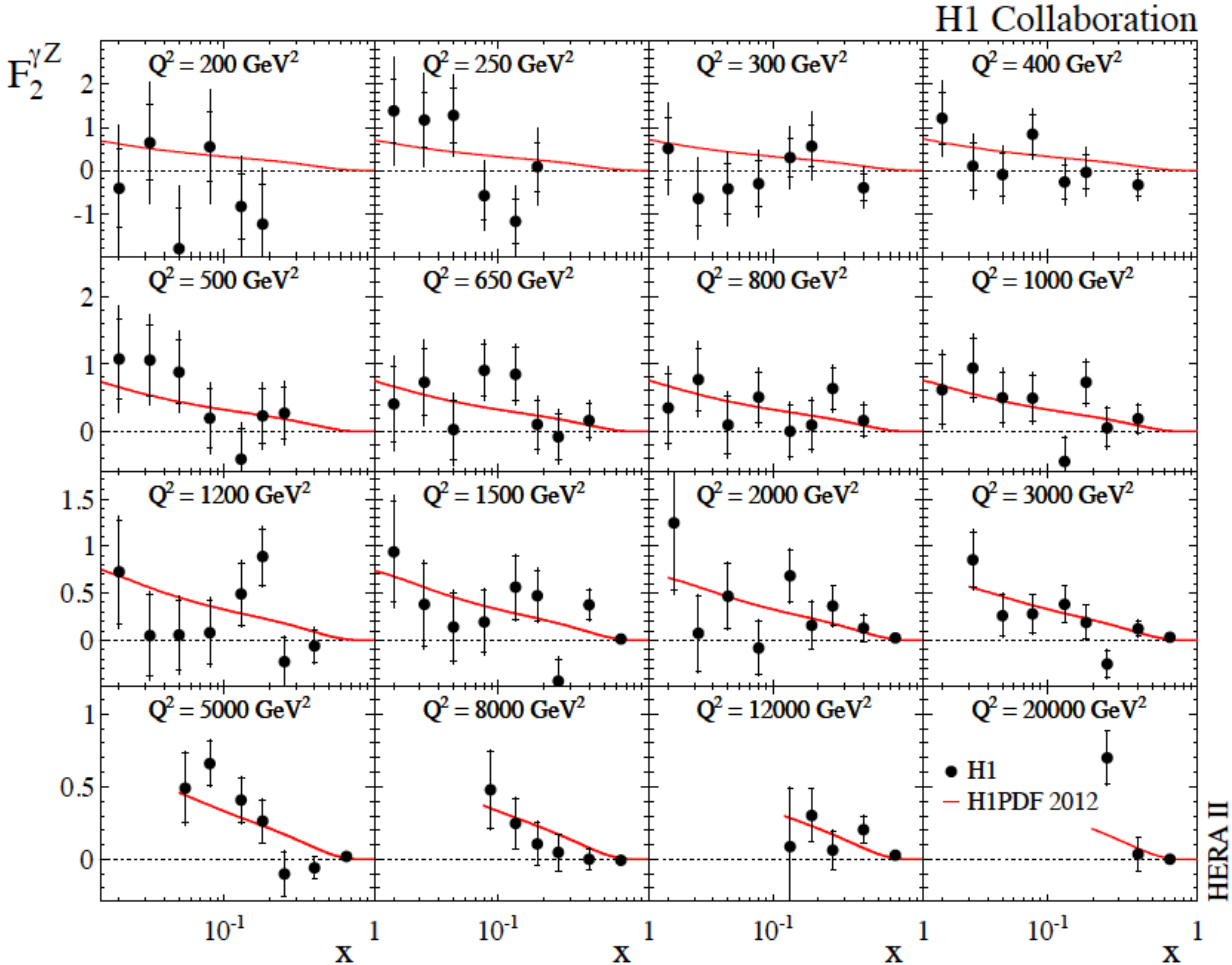


Strong sensitivity to Glashow's Weinberg angle. PDF effects to R largely an artefact

Parity Violation Structure Function $F_2^{\gamma Z} = x \sum 2 e_q v_q (q \mp \bar{q})$



LHeC: 7 TeV, FCC-eh: 50 TeV, E_e=60 GeV, integrated L of 100 fb^{-1} for P= +- 0.8



H1: arXiv:1207.7007: much smaller x and Q^2 range, imprecise, but first measurement ever

Data (NC,CC) Simulation for QCD + el.weak Evaluation

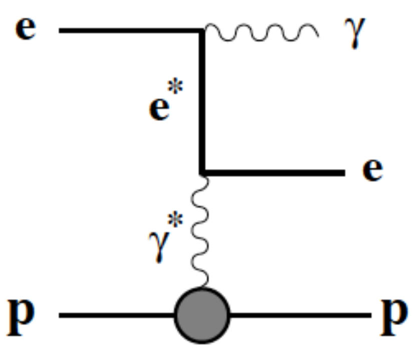
Numerical treatment of correlated and uncorrelated systematic and statistical errors
[based on PHE-1990-02 (J.Blümlein, M.Klein), cross checked with H1 Monte Carlo]

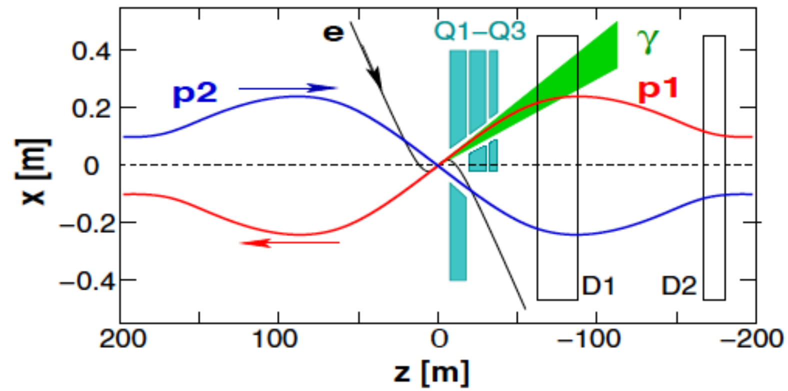
source of uncertainty	error on the source or cross section
scattered electron energy scale $\Delta E'_e/E'_e$	0.1 %
scattered electron polar angle	0.1 mrad
hadronic energy scale $\Delta E_h/E_h$	0.5 %
calorimeter noise (only $y < 0.01$)	1-3 %
radiative corrections	0.5%
photoproduction background (only $y > 0.5$)	1 %
global efficiency error	0.7 %

- Assumptions gauged with H1, probably conservative.
- This approach determines full set of uncorrelated and correlated uncertainties
- ALL PDFs and electroweak fit results presented to this workshop have full systematic error
- This also holds for the LHeC CDR alphas analysis leading to 0.1-0.2% total uncertainty

Luminosity measurement at the LHeC

CDR
JPhysG39
075001(12)
p561-566





Method	Stat. error	Syst.error	Systematic error components		Application
BH (γ)	0.05%/sec	1 – 5%	$\sigma(E \gtrsim 10\text{GeV})$	0.5%	Monitoring, tuning,
			acceptance, A	$10\%(1-A)$	short term variations
			E-scale, pileup	0.5 – 4%	
BH (e)	0.2%/sec	3 – 6%	$\sigma(E \gtrsim 10\text{GeV})$	0.5%	Monitoring, tuning,
			acceptance	2.5 – 5%	short term variations
			background	1%	
			E-scale	1%	
QEDC	0.5%/week	1.5%	σ (el/inel)	1%	Absolute $\mathcal{L}$,
			acceptance	1%	global normalisation
			vertex eff.	0.5%	
			E-scale	0.3%	
NC DIS	0.5%/h	2.5%	σ ($y < 0.6$)	2%	Relative $\mathcal{L}$,
			acceptance	1%	mid-term variations
			vertex eff.	1%	
			E-scale	0.3%	

Table 13.1: Dominant systematics for various methods of luminosity measurement.

LR: photon detector
← acceptance 95%

→ Luminosity from BH photons to 1%

BH to another order

… BH(e), QCDC, F_2
as cross checks

NC Cross Section Correlated Uncertainties (Q^2=20000 GeV^2)

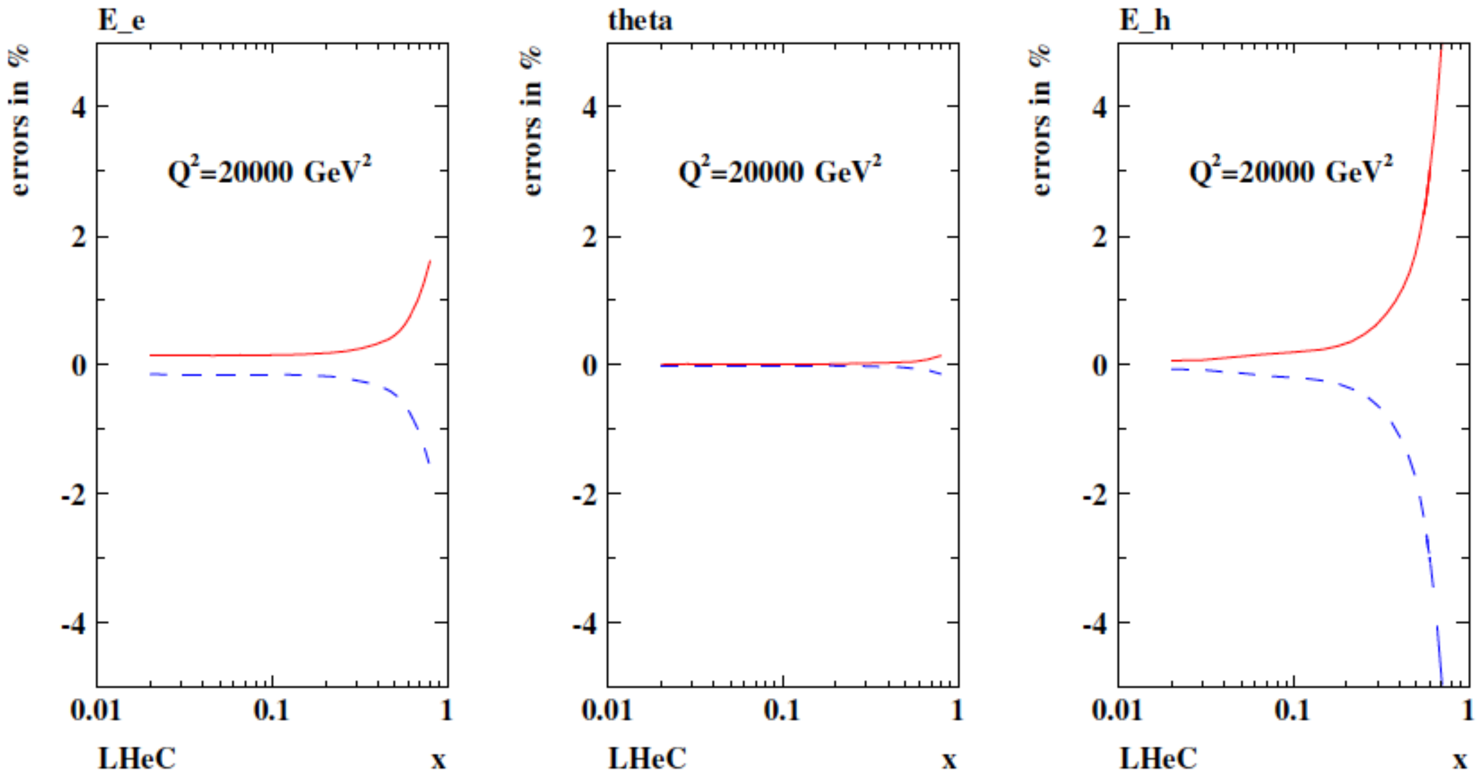


Figure 3.3: Neutral current cross section errors, calculated for $60 \times 7000\,\mathrm{GeV}^2$ unpolarised e^-p scattering, resulting from scale uncertainties of the scattered electron energy $\delta E'_e/E'_e = 0.1\,\%$, of its polar angle $\delta\theta_e = 0.1\,\mathrm{mrad}$ and the hadronic final state energy $\delta E_h/E_h = 0.5\,\%$, at large $Q^2 = 20000\,\mathrm{GeV}^2$ and correspondingly large x. Note that the characteristic behaviour of the relative uncertainty at large x, i.e. to diverge $\propto 1/(1-x)$, is independent of Q^2, i.e. persistently observed at $Q^2 = 200000\,\mathrm{GeV}^2$ for example too.

From LHeC CDR

NC Cross Section Correlated Uncertainties (Q^2=2 GeV^2)

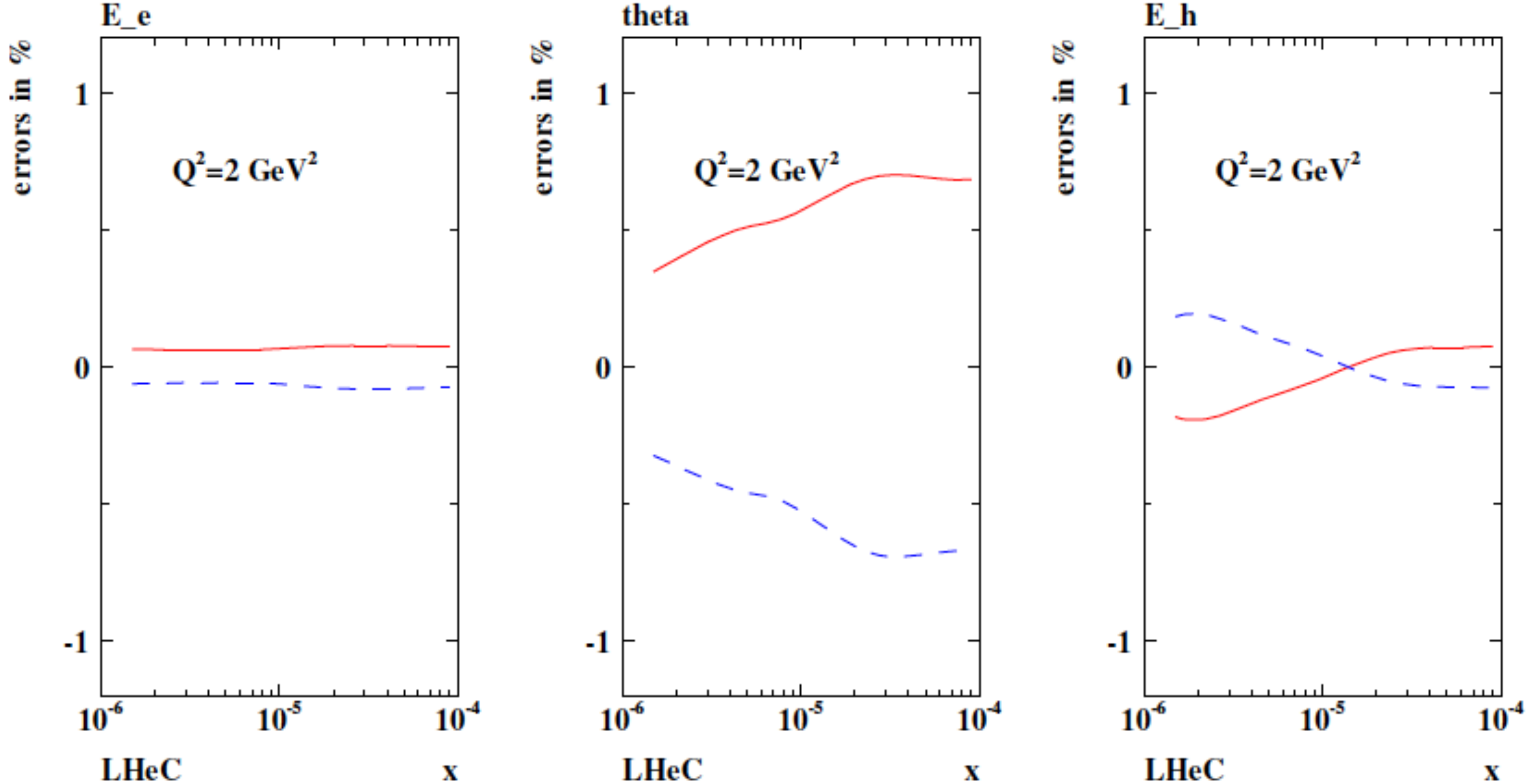


Figure 3.2: Neutral current cross section errors, calculated for $60 \times 7000\,\mathrm{GeV}^2$, resulting from scale uncertainties of the scattered electron energy $\delta E'_e/E'_e = 0.1\,\%$, of its polar angle $\delta\theta_e = 0.1\,\mathrm{mrad}$ and the hadronic final state energy $\delta E_h/E_h = 0.5\,\%$, at low $Q^2 = 2\,\mathrm{GeV}^2$ and correspondingly low x.

From LHeC CDR

PDFs and their effect on electroweak physics

FCC-eh and LHeC:Input: high precision (stat+syst) data on

Neutral Current (x: 10^{-6}-1; Q^2:1-10^6) Charged Current (10^{-4}-1; 100-10^6)

Tagging of Charm and Beauty with high precision and coverage. ep (eD)

Completely new PDF Programme

Determine ALL pdfs in a coherent way + the strong coupling to 0.1% accuracy

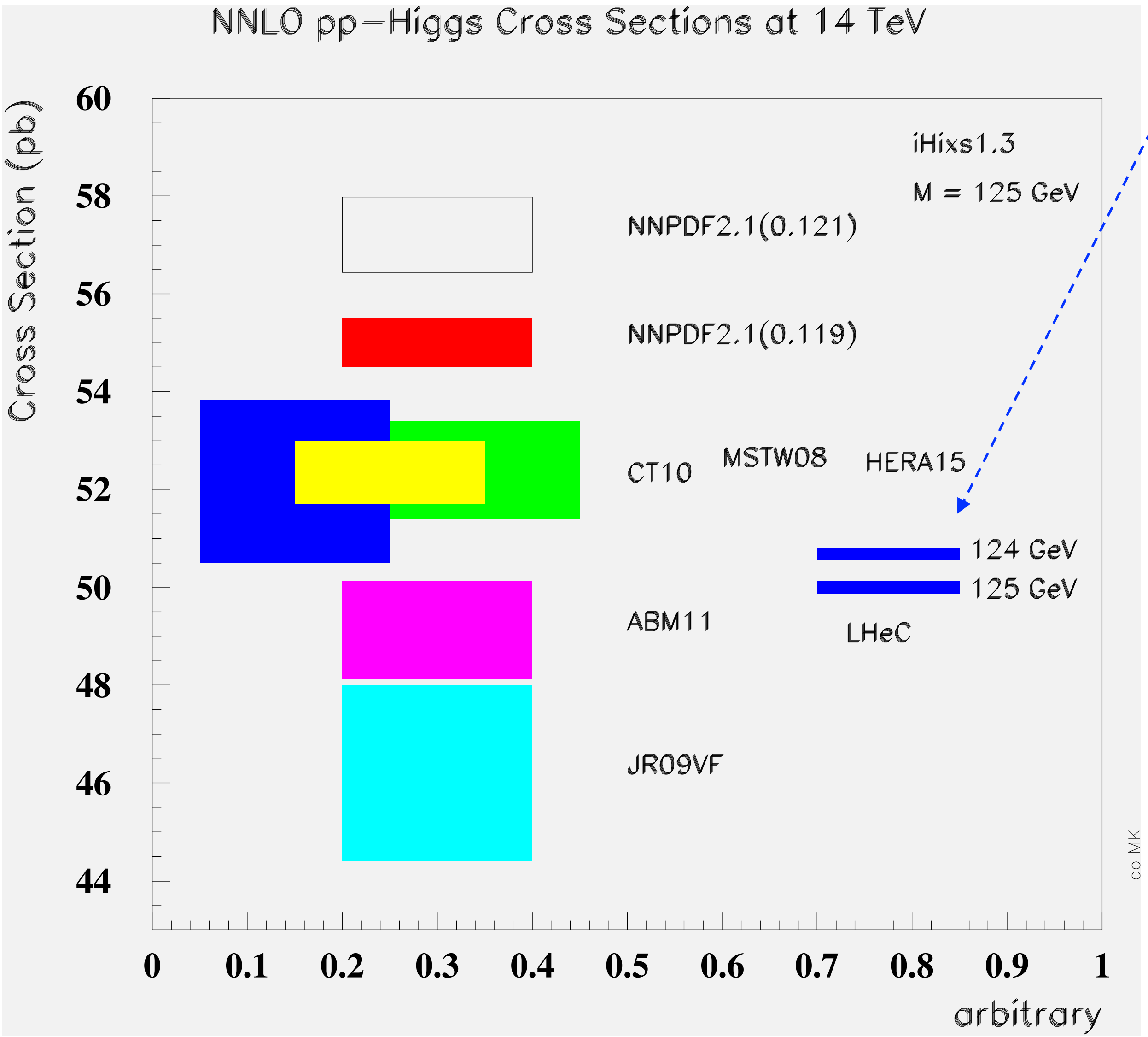
No higher twists, no nuclear corrections, no symmetry assumptions, N^3LO

→ ubar, uv, dbar, dv, s, c, b, t, xg and $alpha_s$

This essentially removes the PDF uncertainties on the electroweak variables, in ep but as well for pp.

For the Higgs this means that ep can turn pp into a precision Higgs facility

Precision PDFs for Higgs at the LHC



O.Brüning and M.K. arXiv:1305.2090, MPLA 2013

LHeC:

Exp uncertainty of predicted H cross section is 0.25% (sys+sta), using LHeC only.

Leads to H mass sensitivity.

Strong coupling underlying parameter (0.005 → 10%). LHeC: 0.0002 !

Needs N^3LO

HQ treatment important …

Determination of EW parameters

On-mass shell scheme used for determination of EW-parameters

- Inclusive NC and CC cross sections
  -> Only indirect determinations of mass parameters
- Explore experimental uncertainty (assume PDF to be known)
- PDF uncertainty (assume PDFs are determined together with the EW-parameters)

Uncertainty on EW parameters from inclusive DIS data

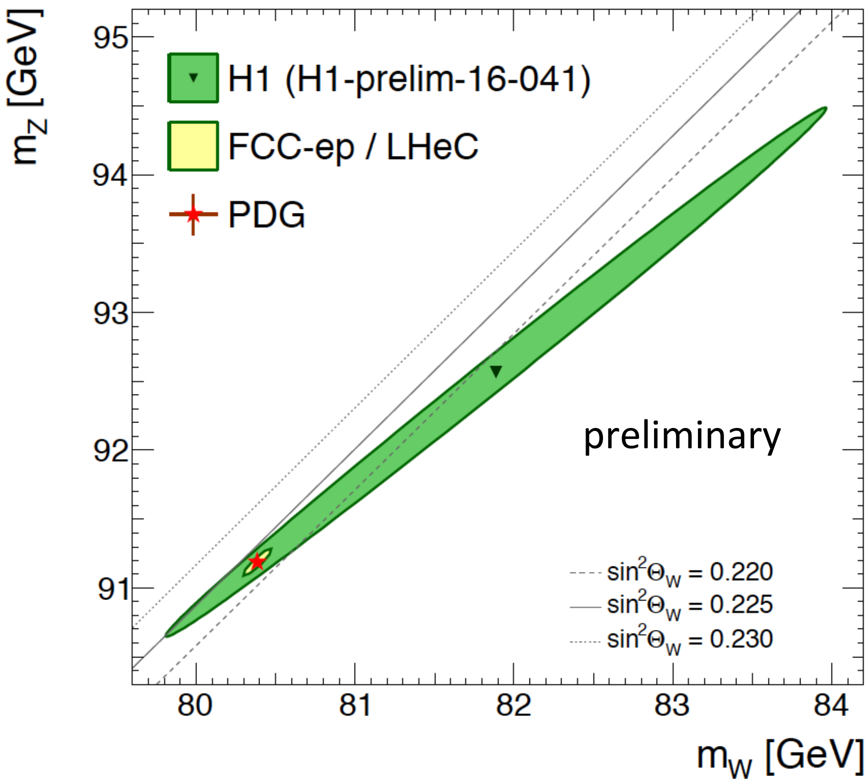
Parameter	HERA	LHeC	FCC	LHeC + FCC
Δm_W [MeV]	$\pm 63_{(\mathrm{exp})} 29_{(\mathrm{pdf})}$	$\pm 14_{(\mathrm{exp})} 10_{(\mathrm{pdf})}$	$\pm 19_{(\mathrm{exp})} 14_{(\mathrm{pdf})}$	$\pm 11_{(\mathrm{exp})} 6_{(\mathrm{pdf})}$
Δm_Z [MeV]	$\pm 56_{(\mathrm{exp})} 25_{(\mathrm{pdf})}$	$\pm 16_{(\mathrm{exp})} 10_{(\mathrm{pdf})}$	$\pm 23_{(\mathrm{exp})} 14_{(\mathrm{pdf})}$	$\pm 13_{(\mathrm{exp})} 6_{(\mathrm{pdf})}$
Δm_t [GeV]	$\pm 10_{(\mathrm{exp})} 5_{(\mathrm{pdf})}$	$\pm 2.6_{(\mathrm{exp})} 1.7_{(\mathrm{pdf})}$	$\pm 3.2_{(\mathrm{exp})} 2.1_{(\mathrm{pdf})}$	$\pm 2.0_{(\mathrm{exp})} 1.0_{(\mathrm{pdf})}$
Δm_H [GeV]	$> \mathcal{O}(100\,\mathrm{GeV})$	$\pm 31_{(\mathrm{exp})} 22_{(\mathrm{pdf})}$	$\pm 38_{(\mathrm{exp})} 25_{(\mathrm{pdf})}$	$\pm 24_{(\mathrm{exp})} 13_{(\mathrm{pdf})}$
Δg_f (MOMS) ($10^{-8}\mathrm{GeV}^{-2}$)	$\pm 4.7_{(\mathrm{exp})} 1.9_{(\mathrm{pdf})}$	$\pm 1.9_{(\mathrm{exp})} 1.2_{(\mathrm{pdf})}$	$\pm 2.8_{(\mathrm{exp})} 1.8_{(\mathrm{pdf})}$	$\pm 1.6_{(\mathrm{exp})} 0.7_{(\mathrm{pdf})}$

g_f: Calculation in 'modified on-shell scheme' (α_{em}, m_Z, g_f, Δr)

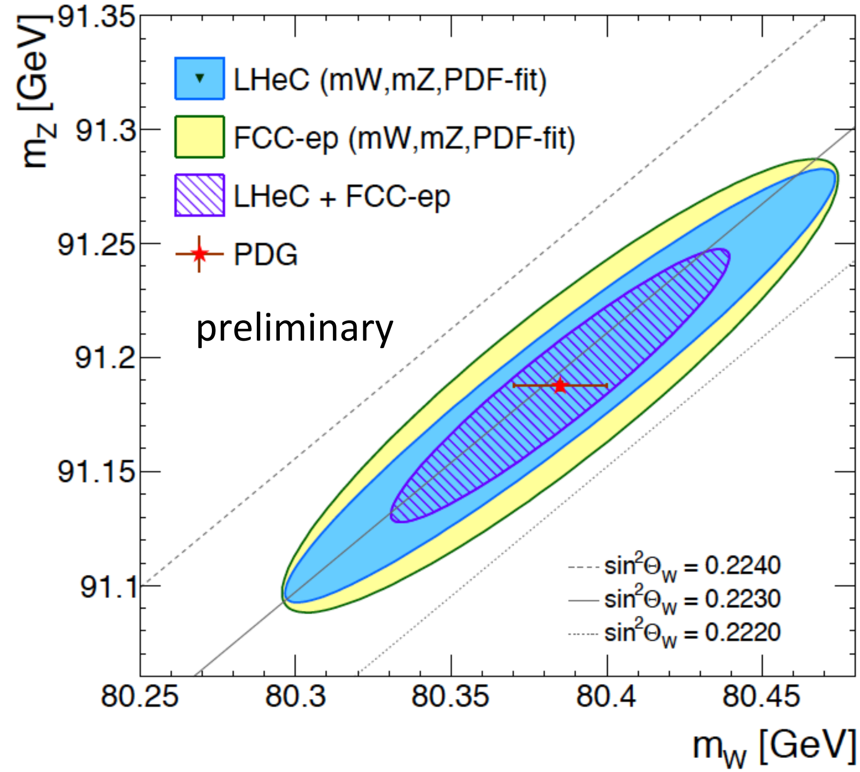
LHeC and FCC

- Greatly improve precision of HERA data
- Uncertainty on W-boson mass will become competitive to best-known value
- Correlation with PDF-determinations will not be the limiting factor !

Determination of W,Z Masses in Deep Inelastic Scattering with FCC-eh



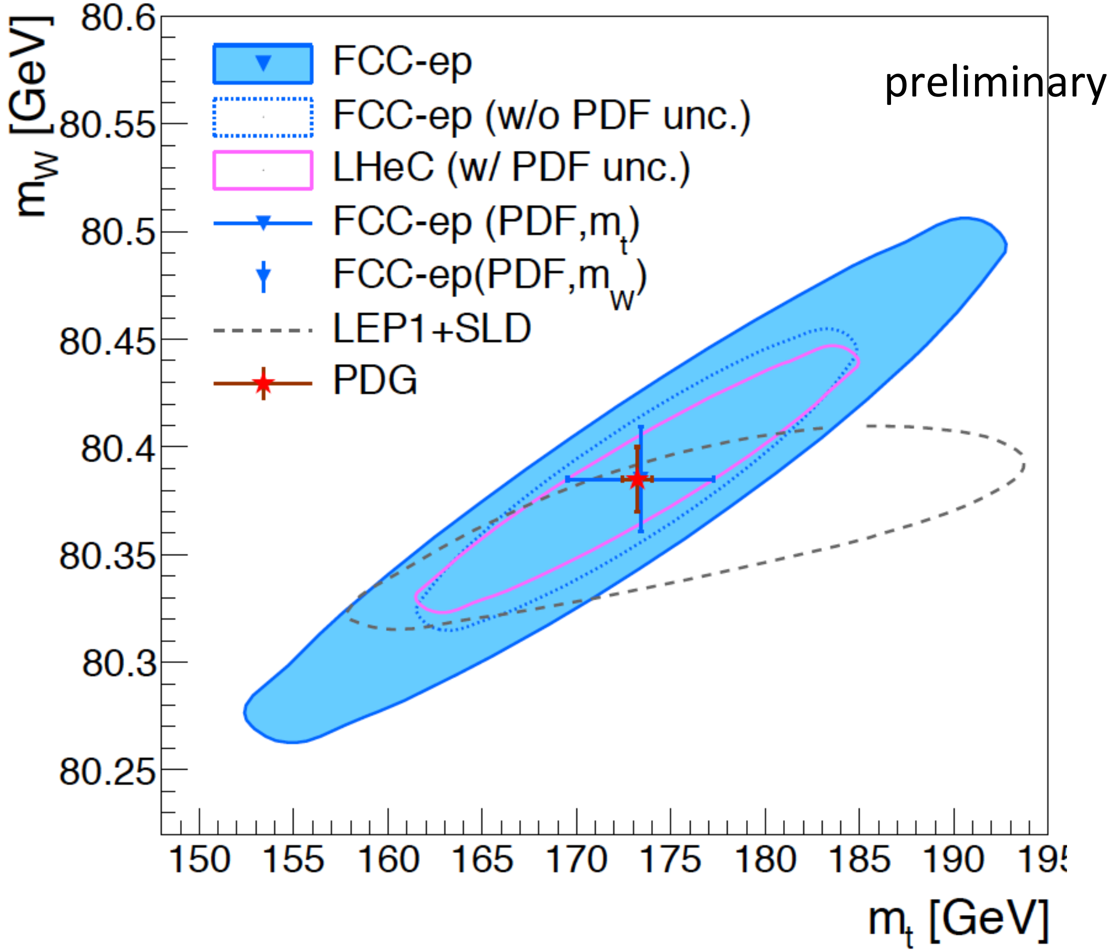
An example study for how LHeC and FCC-eh would improve measurement precision



Huge improvement wrt HERA due to higher energy and luminosity

10 MeV MW error important cross check through spacelike measurement comparable to pp but inferior precision to dedicated timelike ee measurement

W and Top Mass in DIS



Hugely improved wrt HERA. Precision comparable to LEP

FCC-eh (and LHeC) is a top factory. Therefore one can directly measure M_t, still to be studied

Weak mixing angle

Weak mixing angle

- Define $\sin^2\theta_w$ in on-shell scheme

$$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2}$$

- No scale dependence in this definition

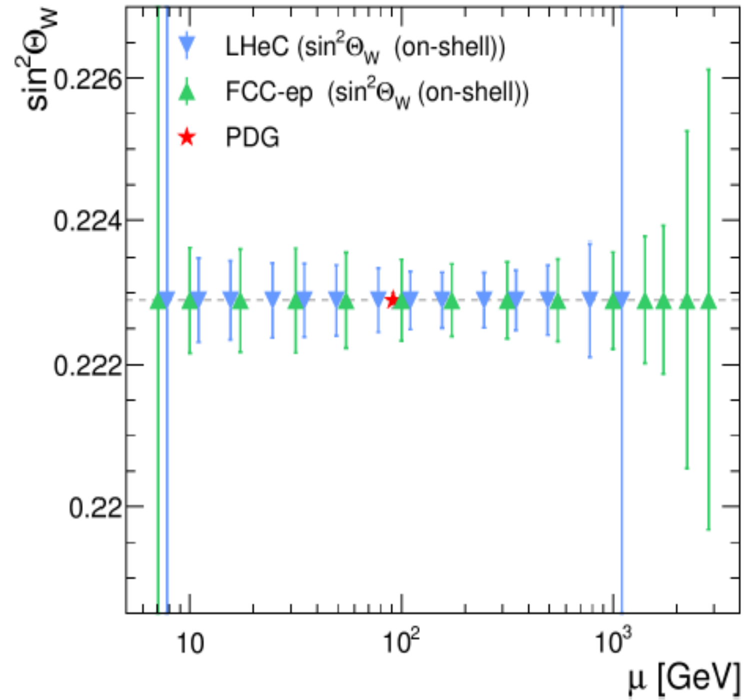
On-shell value can be translated

- into 'effective' weak mixing angle
- into MS-bar definition

Weak mixing angle

- Expected precision:

```
LHeC: ±0.0003(exp) 0.0002(PDF)
FCC:  ±0.0004(exp) 0.0003(PDF)
```



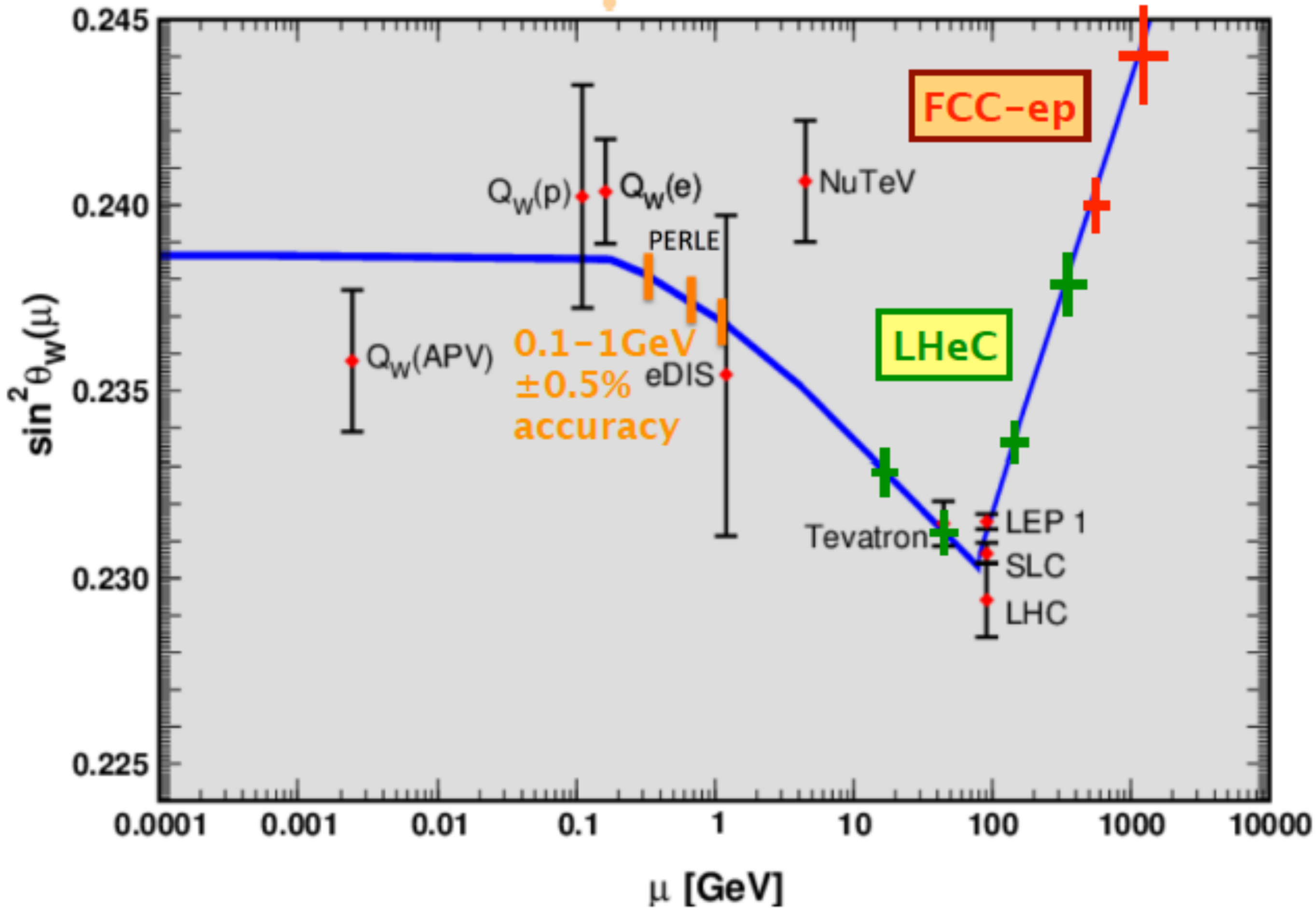
- Inclusive data will only be somewhat competitive with the direct extractions at the Z-pole, but:

- Scale-dependence of EW physics is studied up to TeV range
- Inclusive DIS data from LHeC and FCC probes scale dependence of EW theory in impressive range from 10 GeV up to highest accessible scales

Scale Dependence of $\sin^2\theta_W$

PERLE CDR, Arduini et al, to be published
ICFA BeamNewsletter 68 (January 2016)

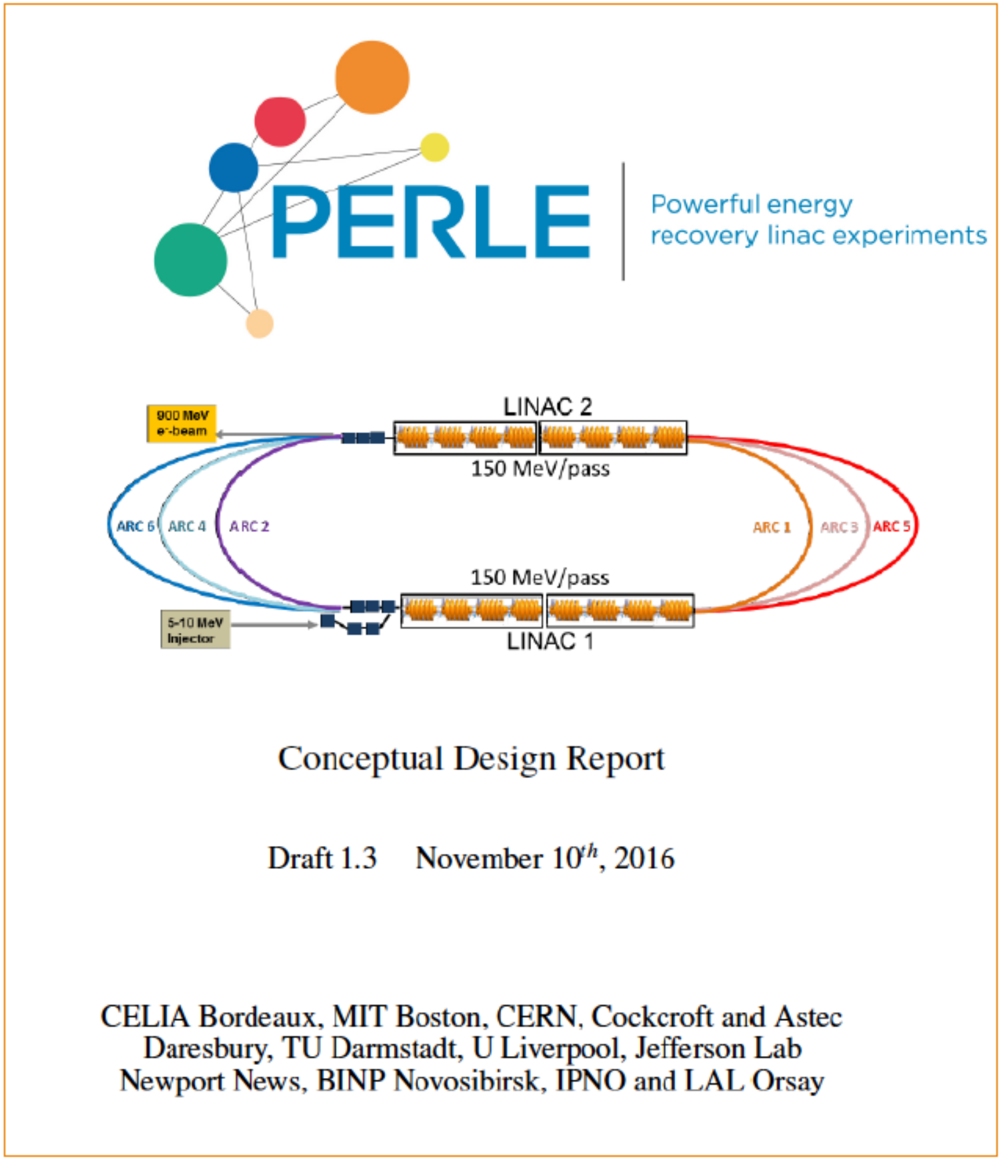
LHeC CDR,
J.Phys. G39,
075001 (2012)



Also
MESA
Jlab
Exp's.

→ **probe large range of scale dependence**

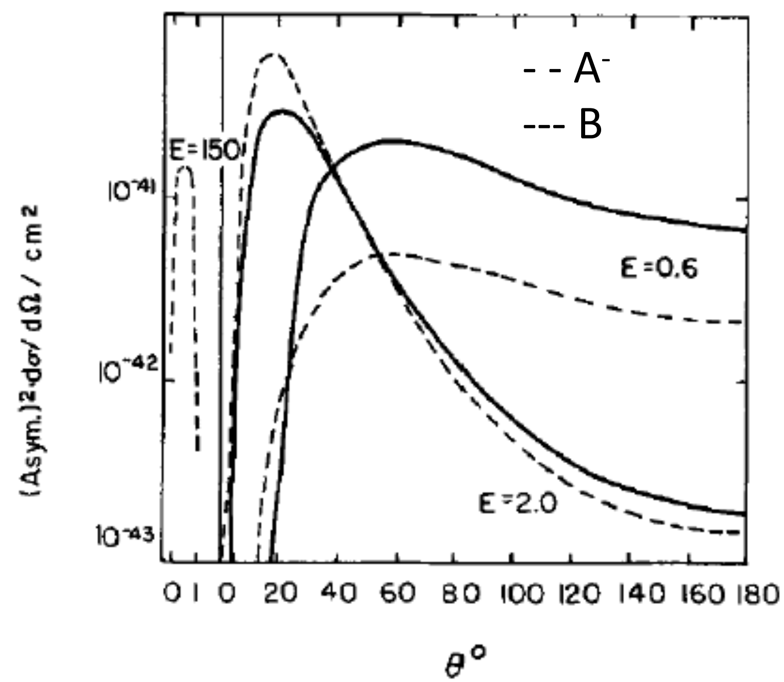
Potential to precisely measure $\sin^2\Theta$ in elastic polarised ep scattering with high intensity ERL test facility.


PERLE
Powerful energy recovery linac experiments

Conceptual Design Report

Draft 1.3 November 10^{th}, 2016

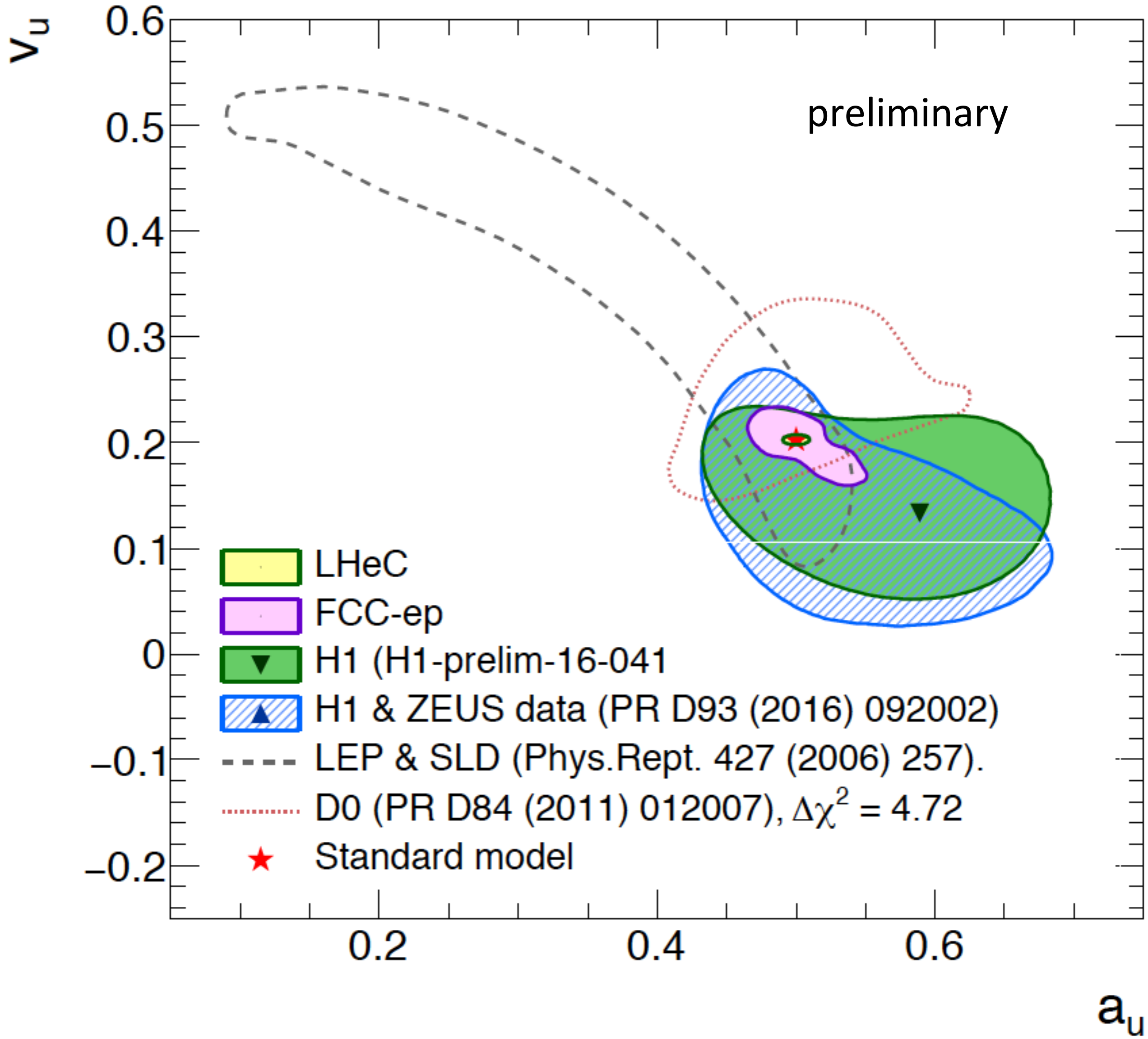
CELIA Bordeaux, MIT Boston, CERN, Cockcroft and Astec Daresbury, TU Darmstadt, U Liverpool, Jefferson Lab Newport News, BINP Novosibirsk, IPNO and LAL Orsay



Optimum signal conditions for E_e O(1) GeV
M.Klein, T. Riemann Zphys C8(81)239

PERLE: 802 MHz 3 turns 15mA. TDR in 2017

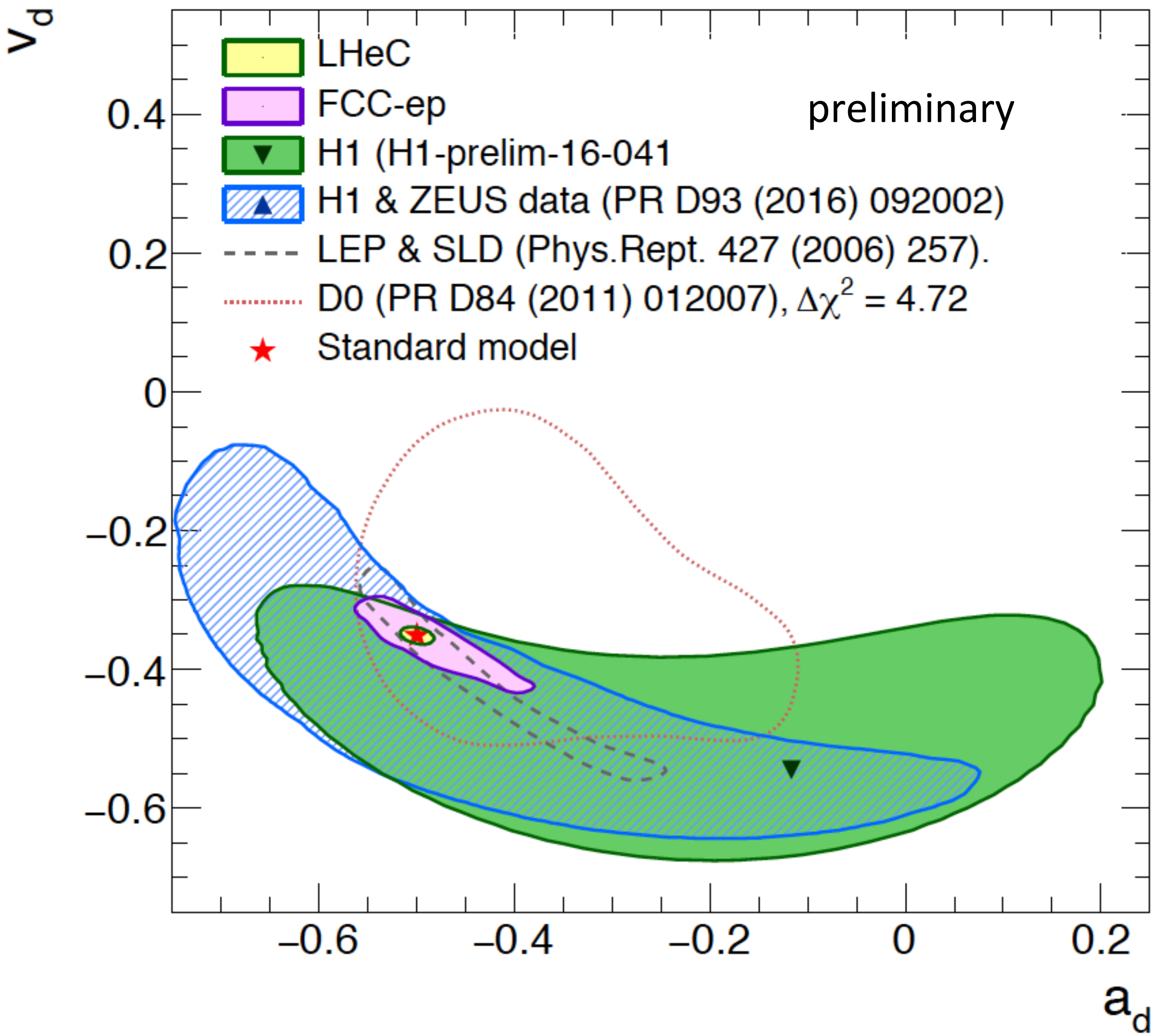
v,a of up Quarks



cf EFT
Adam
Falkowski
today

Note: FCC-eh data set still needs to include P=+0.8 data which for LHeC are considered

v,a of down Quarks



Note: FCC-eh data set still needs to include P=+0.8 data which for LHeC are considered

Summary

- First pass made on electroweak measurements with FCC-eh

- Very high precision with LHeC and FCC-eh: L=1000L(HERA), higher energy offers important and unique tests of eweak SM in the spacelike region

- Systematics included, probably somewhat conservative

- Through its own PDF programme, the p structure uncertainty effects on electroweak measurements at FCC-eh/LHeC is neglible. This is of crucial value also to LHC and FCC-hh measurements, especially Higgs physics

- Eweak effects for the first time can be used to probe nuclear structure

- In general the ew precision is (expected to be) less than that FCCee promises

- Of special value are the scale dependence of the mixing angle and the couplings of u,d

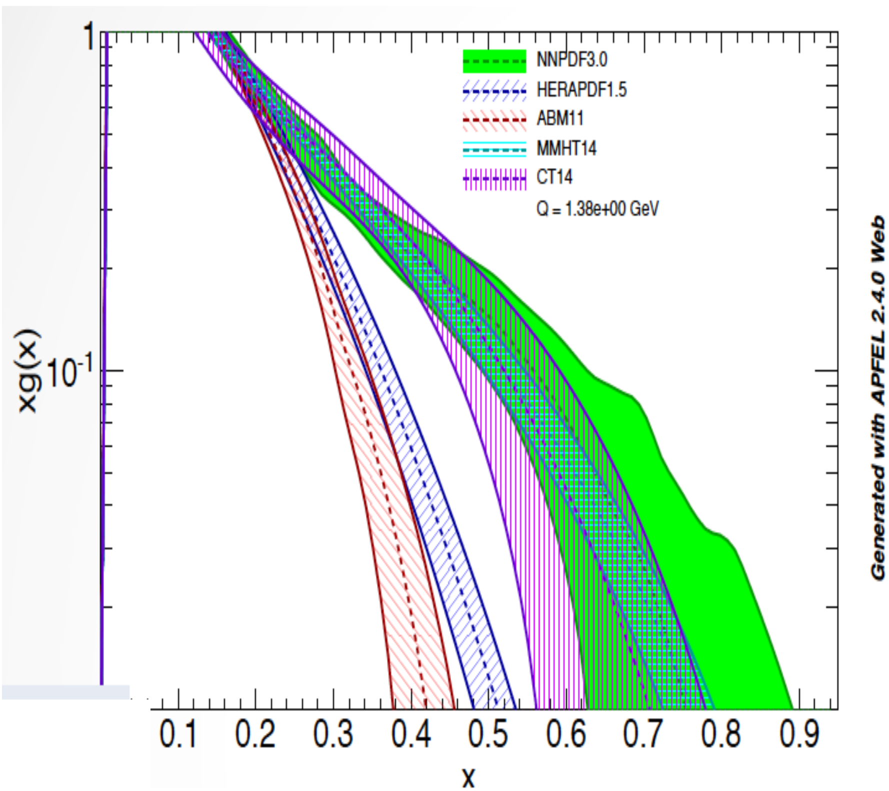
- There is much more to be studied, for example: place of ep for EFT tests, final state (W,Z,t,H masses) or heavy quark couplings + signs through yZ

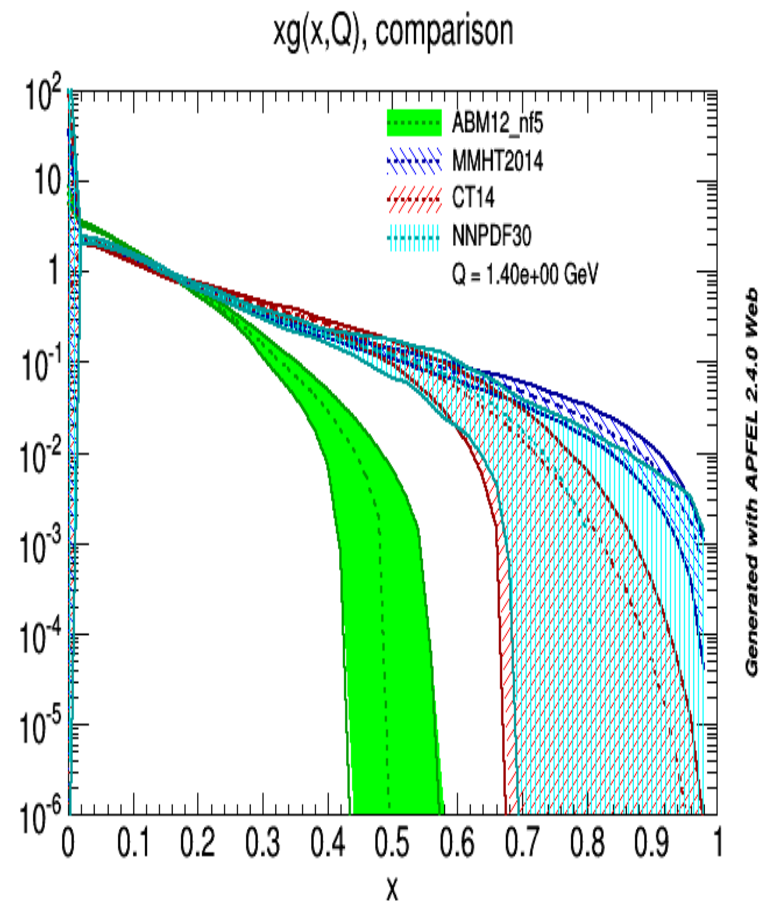
Electron-proton colliders open new horizons on all three of the fundamental questions: the spectroscopy of fundamental fermions, the spectroscopy of gauge bosons, and the problem of hadron structure. In addressing these issues, the ep collider is approaching the same physics as is studied in e^+e^- and $\bar{p}p$ colliders, but in a complementary way, with emphasis on the t-channel. Each technique has its own strengths and weaknesses, which I leave you to contemplate.

Chris Quigg
Fermi National Accelerator Laboratory

FERMILAB-Conf-81/52-THY

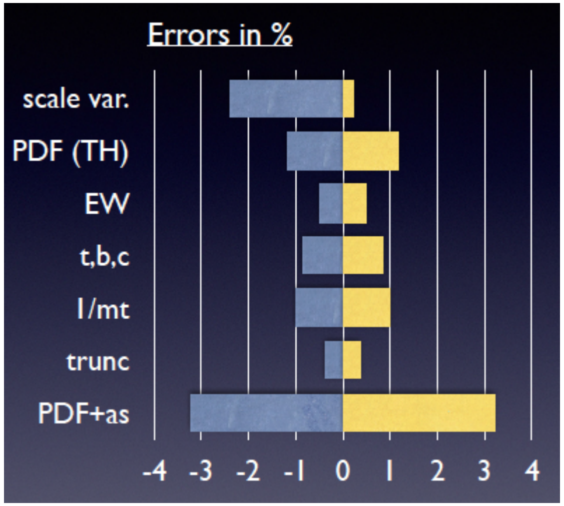
Gluon Distribution at High x





Gluon at large x becomes very small and is hugely uncertain while $M_X^2 = s x_1 x_2$ ..

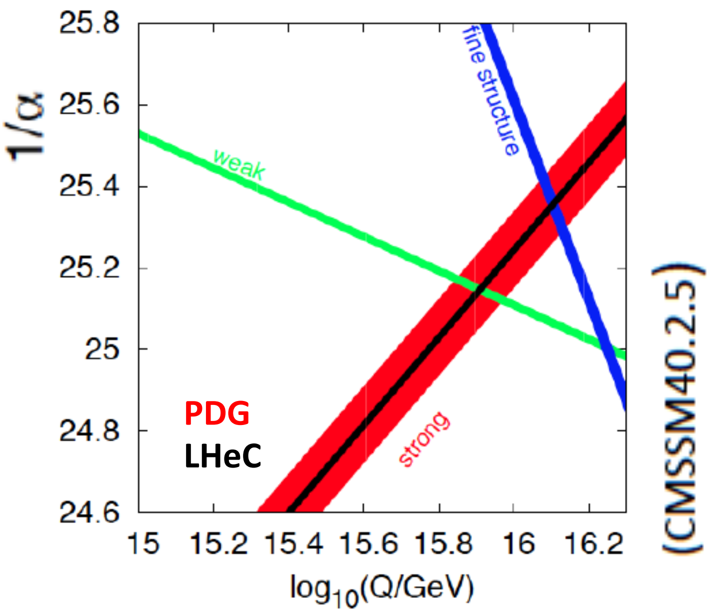
The determination of xg at large x is a severe challenge + not just for one channel



Strong Coupling Constant

- α_s least known of coupling constants
  Grand Unification predictions need smaller $\delta\alpha_s$
- Is α_s(DIS) lower than world average (?)
- LHeC: per mille - independent of BCDMS!
- High precision from inclusive data – α_s(jets)??
- Challenge lattice QCD

Uncertainty on Higgs cross section
Giulia Zanderighi, Vietnam 9/16,
from C.Anastasiou et al, 1602.00695
who also discuss the ABM alpha_s..



LHeC simulation, NC+CC inclusive, total exp error

case	cut [Q^2 in GeV^2]	relative precision in %
HERA only (14p)	$Q^2 > 3.5$	1.94
HERA+jets (14p)	$Q^2 > 3.5$	0.82
LHeC only (14p)	$Q^2 > 3.5$	0.15
LHeC only (10p)	$Q^2 > 3.5$	0.17
LHeC only (14p)	$Q^2 > 20.$	0.25
LHeC+HERA (10p)	$Q^2 > 3.5$	0.11
LHeC+HERA (10p)	$Q^2 > 7.0$	0.20
LHeC+HERA (10p)	$Q^2 > 10.$	0.26

Two independent QCD analyses using LHeC+HERA/BCDMS