PDFs with the LHeC and FCCeh

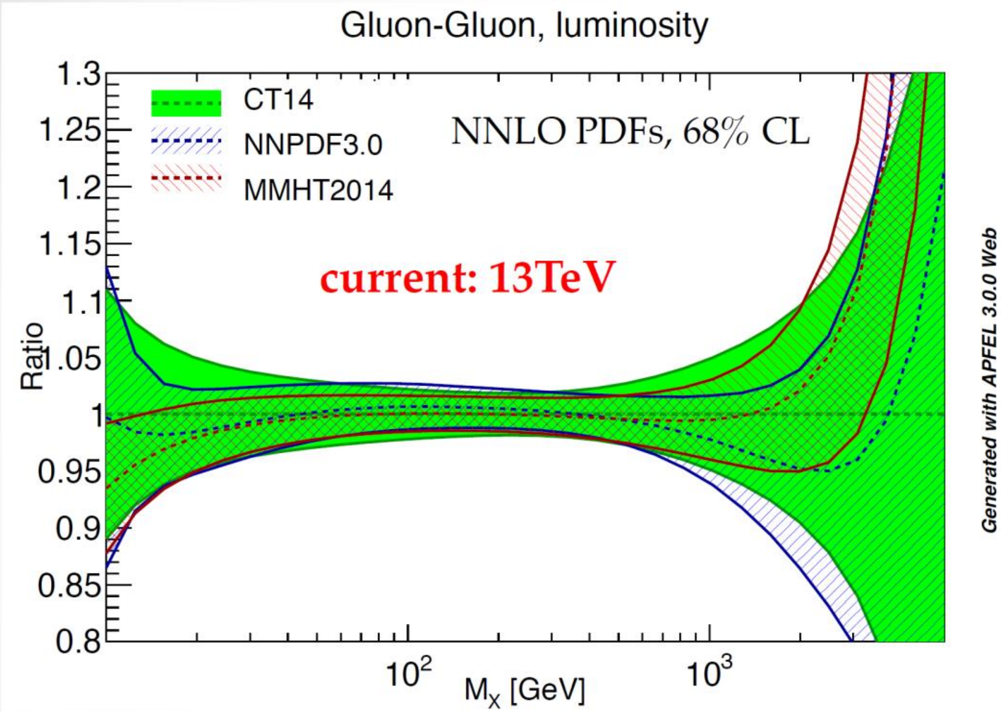
A M Cooper-Sarkar
DIS 2016

The LHeC- a Large Hadron-Electron Collider
~50-100 GeV electrons on 7 TeV protons (Linac- Ring).
Designed such that e-p can operate synchronously with p-p in the HL-LHC phase.
FCC-eh a future ep collider, integrated with FCC-hh

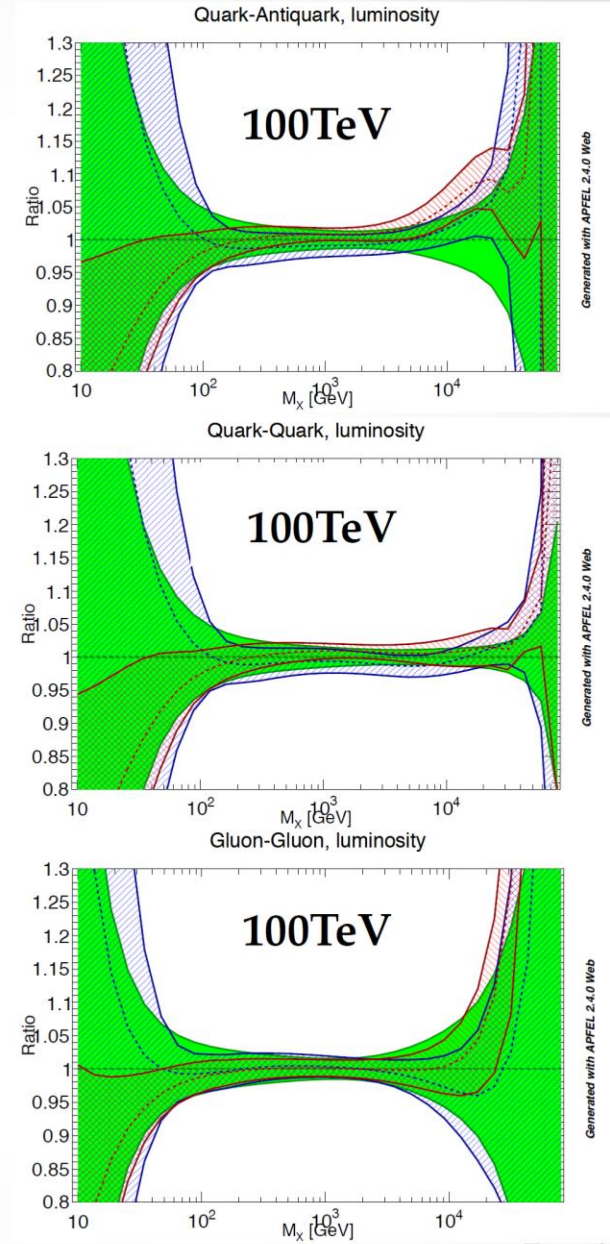
Currently uncertainties on the parton distribution functions (PDFs) limit searches for new heavy particles, dominate the theory uncertainty on Higgs production and limit the precision of M_W α_s, EW parameters

With higher luminosity and higher energy machines on the horizon we will need higher precision PDFs

proton PDFs, today

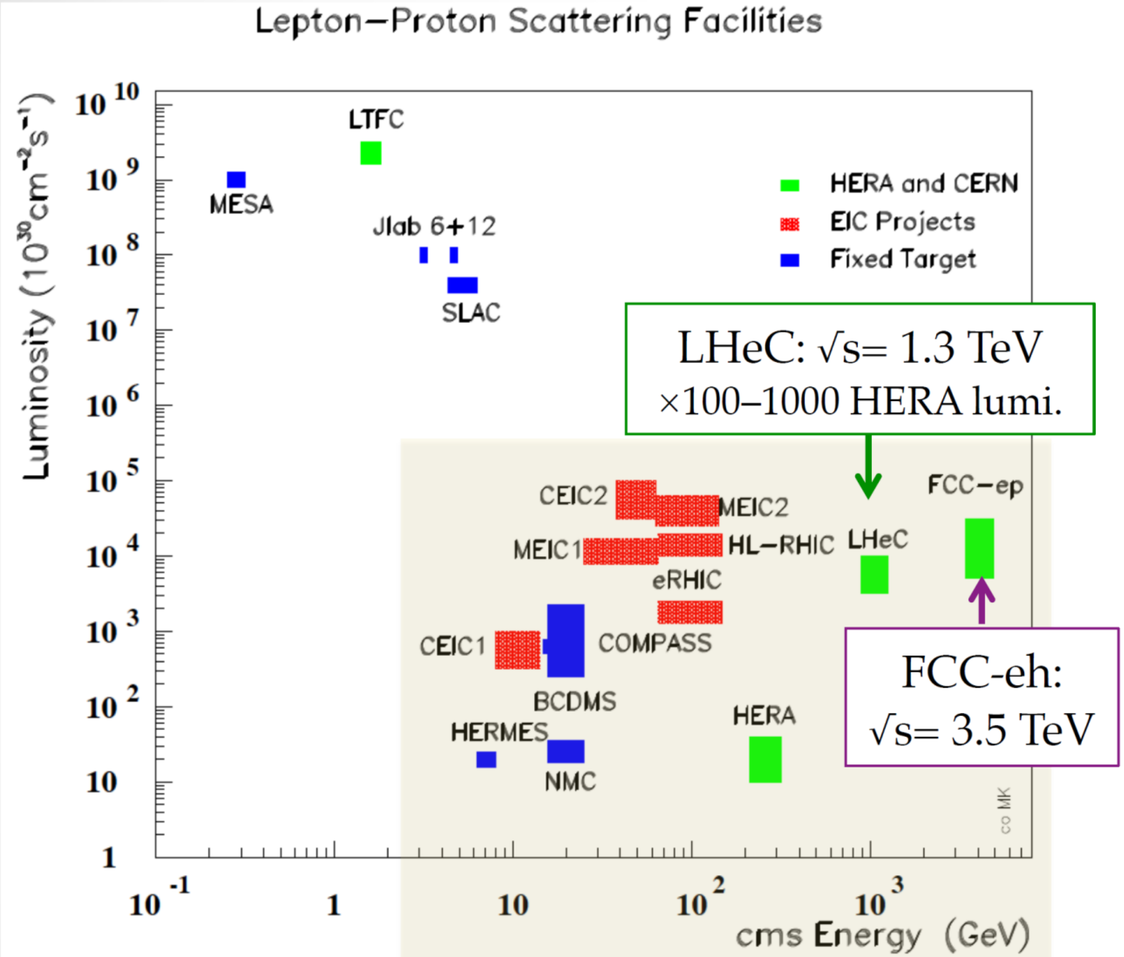


Current level of knowledge of PDFs at 13TeV (including Run-I LHC data) still have considerable uncertainty at high scale BUT at future colliders the low scale region will also have large uncertainties



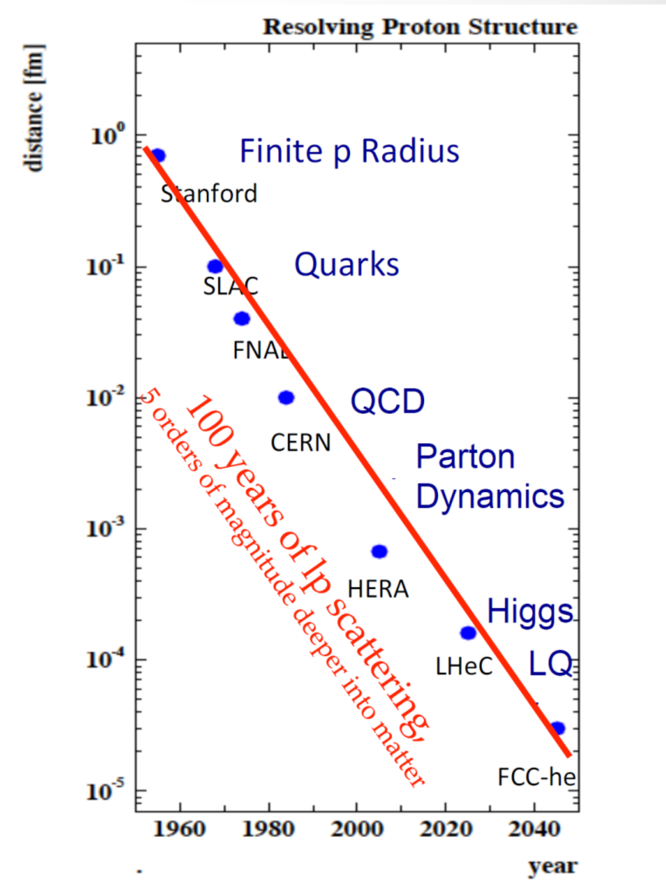
… many thanks to Joey Huston

lepton-proton facilities



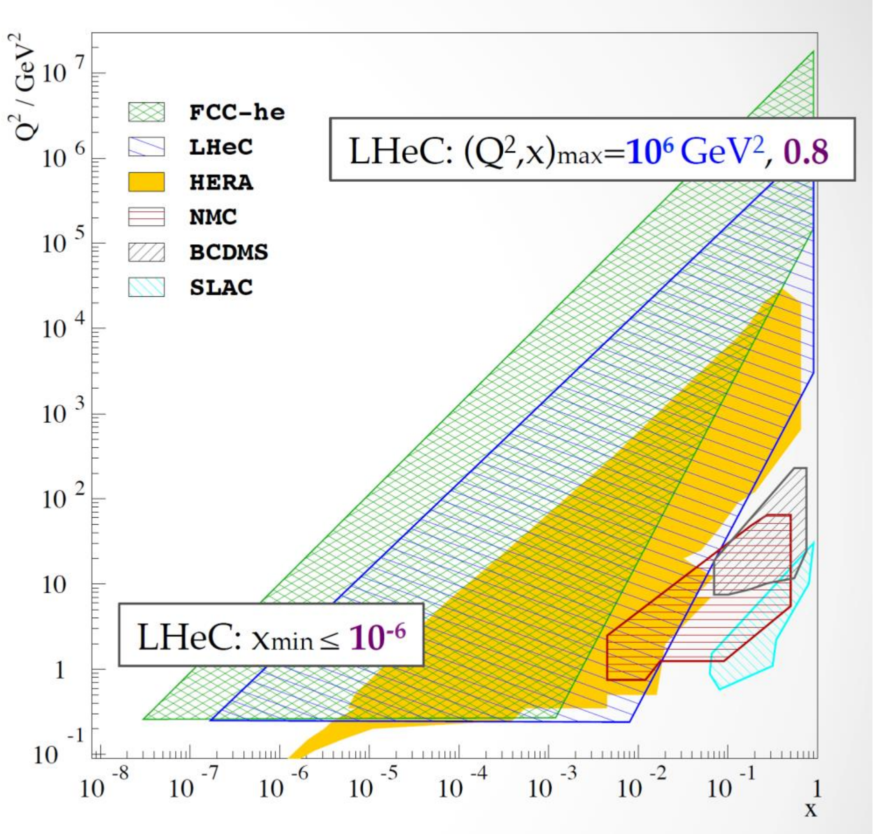
HERA–LHeC–FCC-eh:

finest microscopes, resolution as 1/Q



LHC (and other future machines eg. FCC-pp) is/will be main discovery machine

LHeC not a competitor to these; complementary; synchronous with HL-LHC; transforms them into high precision facilities

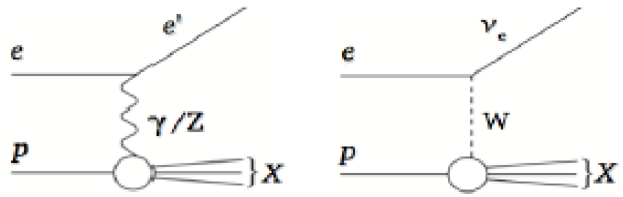


The LHeC/FCC-he option represents an increase in the kinematic reach of Deep Inelastic Scattering and an increase in the luminosity.

- This represents a tremendous increase in the precision of Parton Distribution Functions
- And the exploration of a kinematic region at low-x where we learn more about QCD- e.g. is there gluon saturation?
- Precision PDFs are needed for BSM physics
- PDFs in an extended kinematic region will also be needed for any FCC

DIS is the best tool to probe proton structure

NC : $e\,p \rightarrow e'\,X$ CC : $e\,p \rightarrow \nu_e\,X$



- Kinematic variables:

$Q^2 = -q^2 = -(k-k')^2$ Virtuality of the exchanged boson

$x = \frac{Q^2}{2p\cdot q}$ Bjorken scaling parameter

$y = \frac{p\cdot q}{p\cdot k}$ Inelasticity parameter

$s = (k+p)^2 = \frac{Q^2}{xy}$ Invariant c.o.m.

- Double Differential cross sections:

$$\sigma_r(x,Q^2) = \frac{d^2\sigma(e^{\pm}p)}{dxdQ^2}\frac{Q^4 x}{2\pi\alpha^2 Y_+} = F_2(x,Q^2) - \frac{y^2}{Y_+}F_L(x,Q^2) \mp \frac{Y_-}{Y_+}xF_3(x,Q^2)$$

- F_2 dominates
  - sensitive to all quarks
- xF_3
  - sensitive to valence quarks
- F_L
  - sensitive to gluons

Gluon also comes from the scaling violations

LHeC studies scenarios

CDR, JPhysG39(2012)075001

Set	E_e/GeV	E_N/TeV	N	L^+/fb^{-1}	L^-/fb^{-1}	Pol
A	20	7	7	1	1	0
B	50	7	7	50	50	0.4
C	50	7	7	1	1	0.4
D	100	7	7	5	10	0.9
E	150	7	7	3	6	0.9
F	50	3.5	7	1	1	0
G	50	2.7	7	0.1	0.1	0.4
H	50	1	7	-	1	0

Mostly scenario B is presented here

$2 < Q^2 < 100{,}000$ $0.000002 < x < 0.8$

Typical uncertainties:

Full simulation of NC and CC inclusive cross section measurements including statistics, uncorrelated and correlated uncertainties – based on typical best values achieved by H1

- Statistical it ranges from 0.1% (low Q^2) to ~10% for x=0.7 in CC
- Uncorrelated systematic: 0.7 %
- Correlated systematic: typically 1-3% (for CC high x up to 9%)

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 %

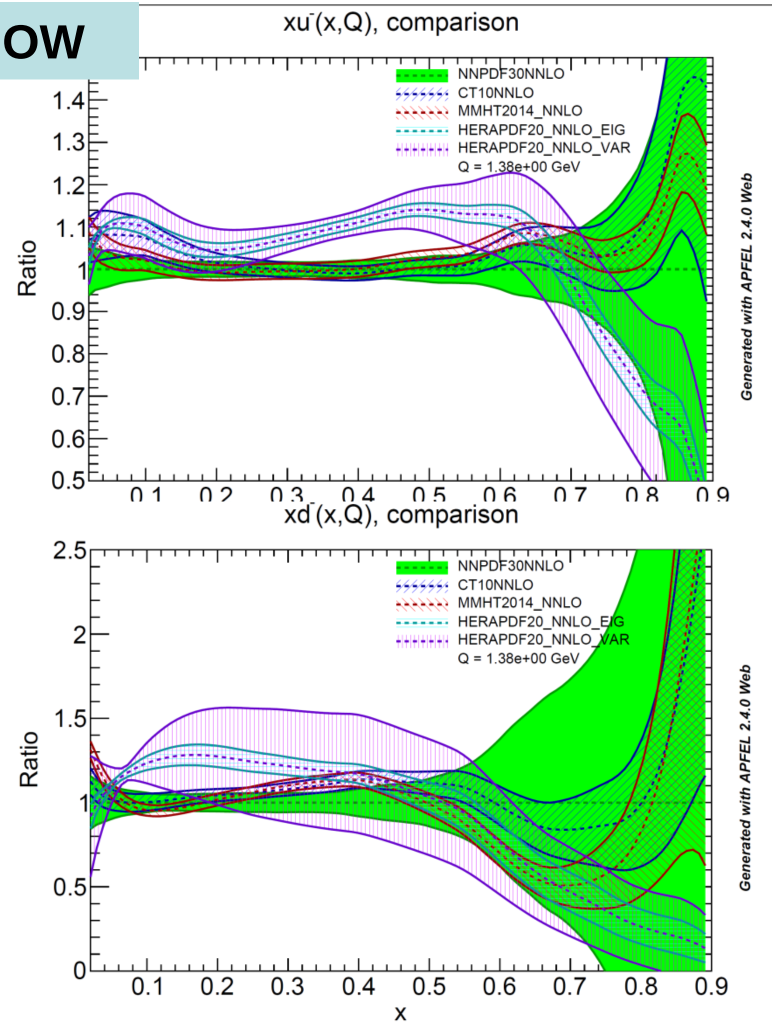
The potential for precision parton distributions at the LHeC is assessed using

- LHeC simulated data (scenario B) on NC, CC e^+p and e^-p cross-sections
- Published HERA-I combined data
- Fixed target data from BCDMS (W^2>15)
- ATLAS 2010W,Z data

HERA/xFitter framework is used, with PDF fit settings as for HERAPDF1.0 NLO

Valence distributions

NOW



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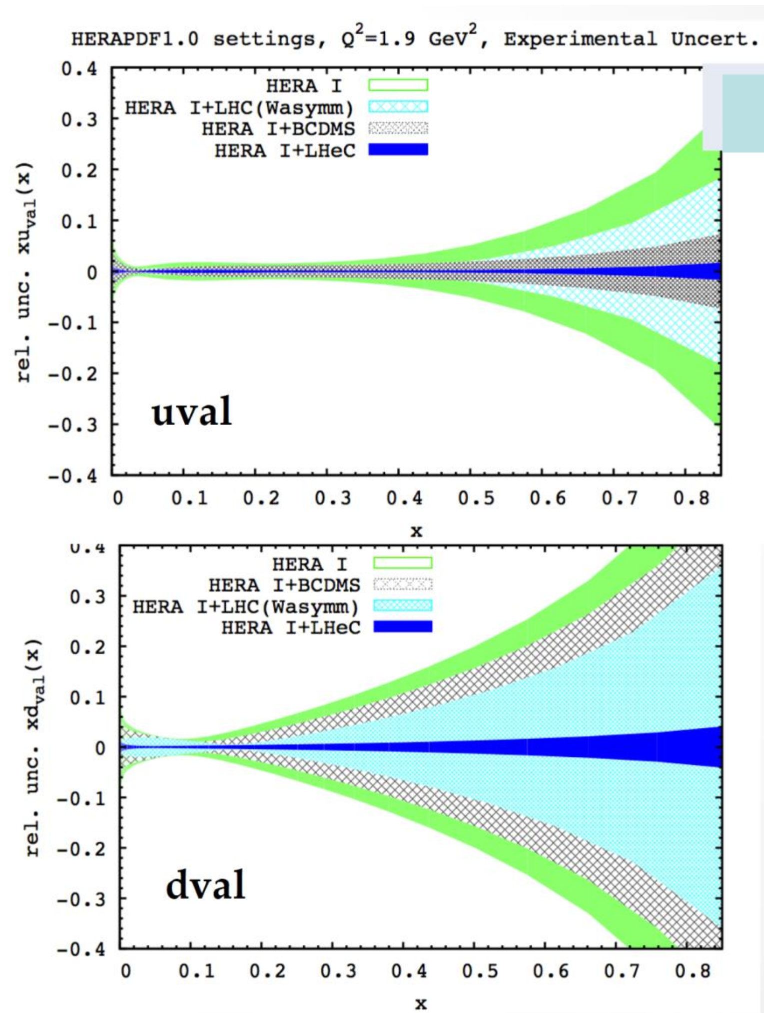
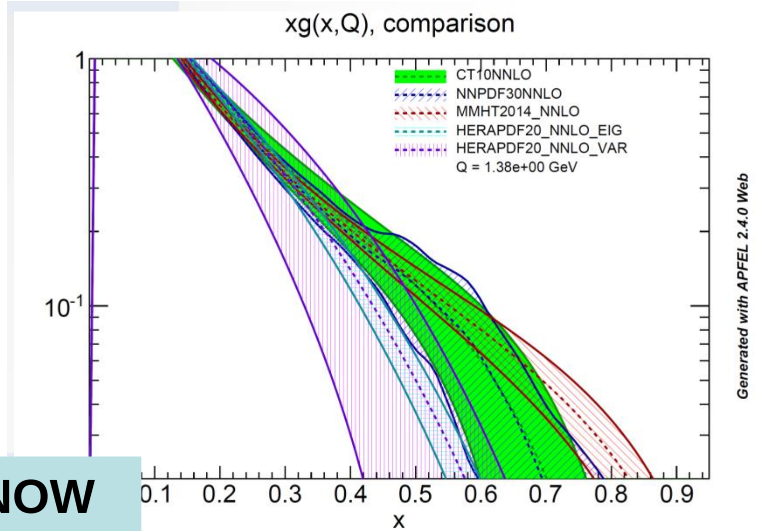
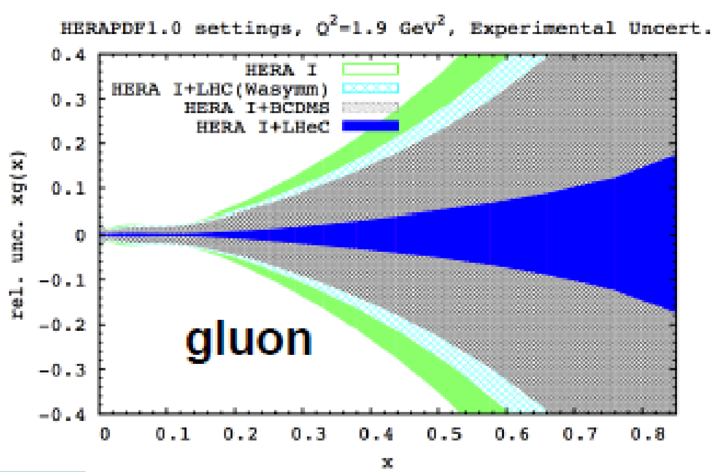


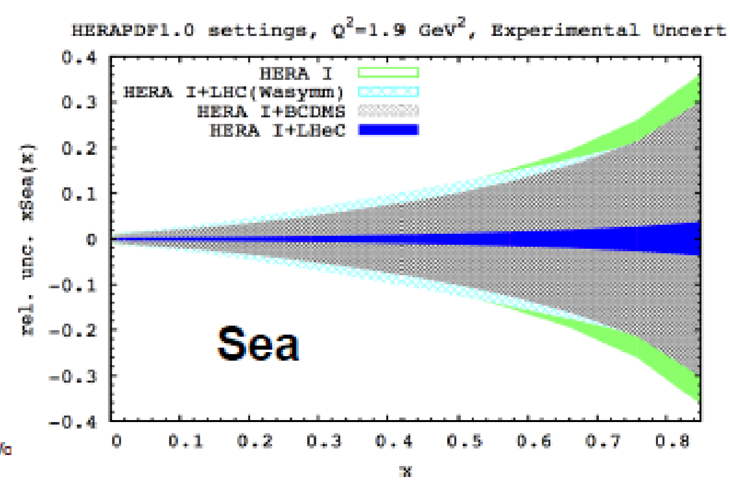
Gluon and sea at high x



NOW

The high x gluon is not well known
Current PDFs differ
The gluon and sea evolution are intimately related.
The LheC can disentangle the sea from the valence at high-x through measurement of CC cross-sections and $F2_{\gamma Z}$, $xF3_{\gamma Z}$

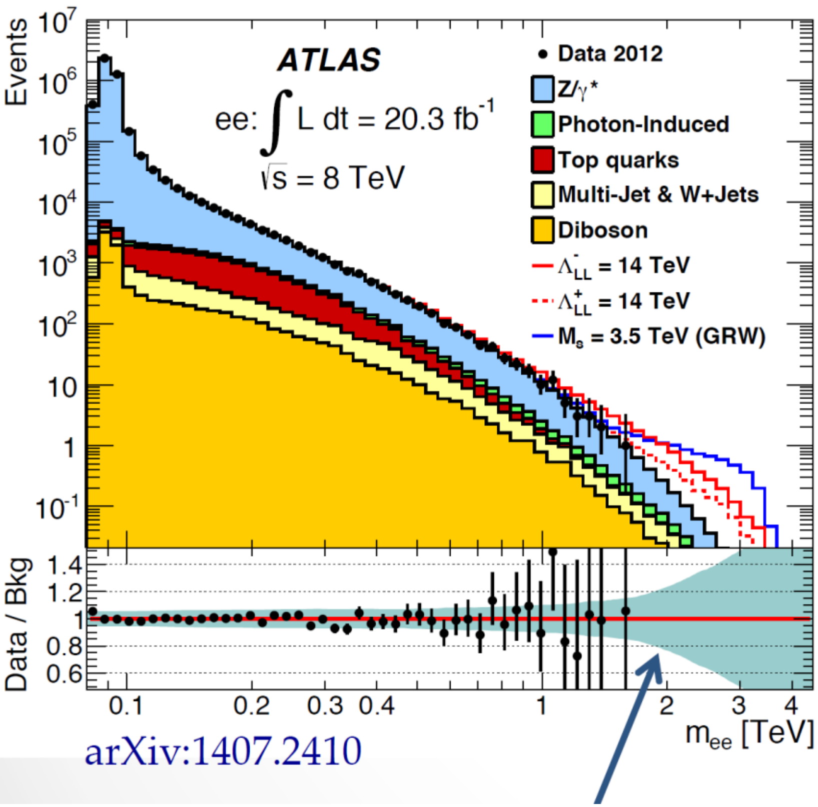




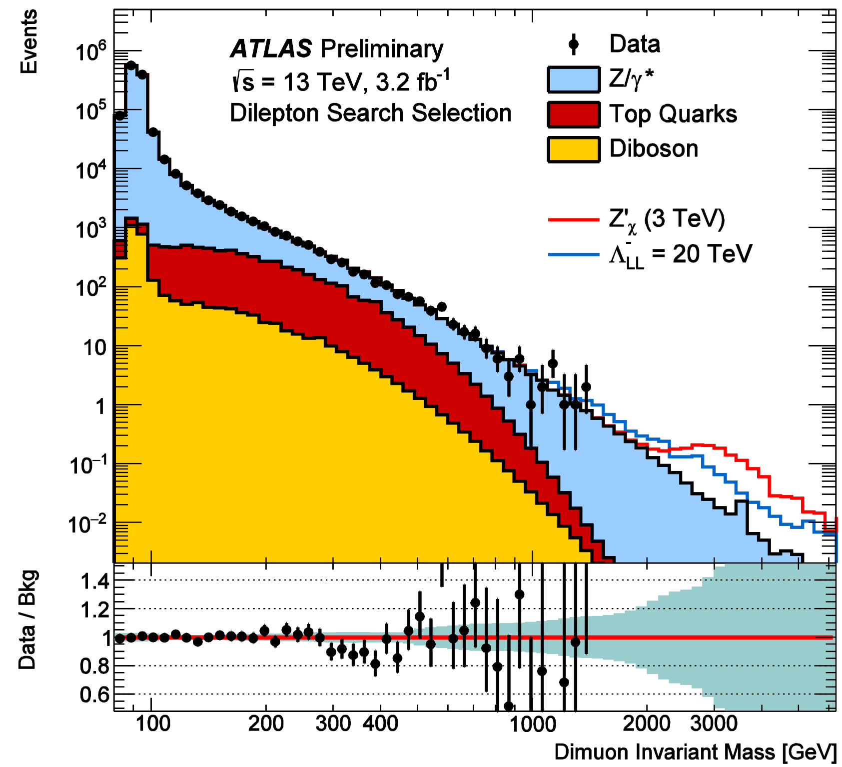
THEN

Why are we interested in the high-x sea?-one example

Current BSM searches in High Mass Drell-Yan are limited by high-x antiquark uncertainties as well as by high-x valence uncertainties



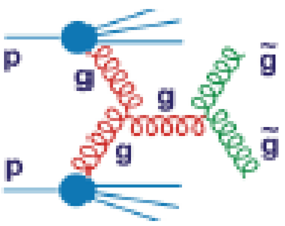
arXiv:1407.2410

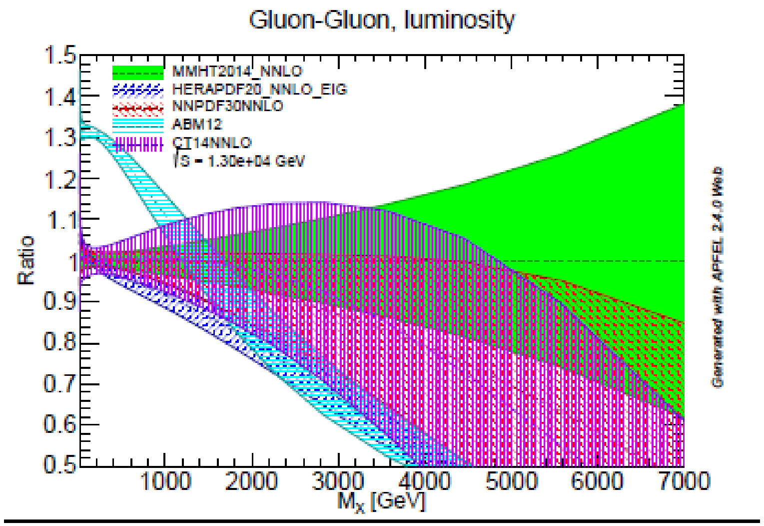


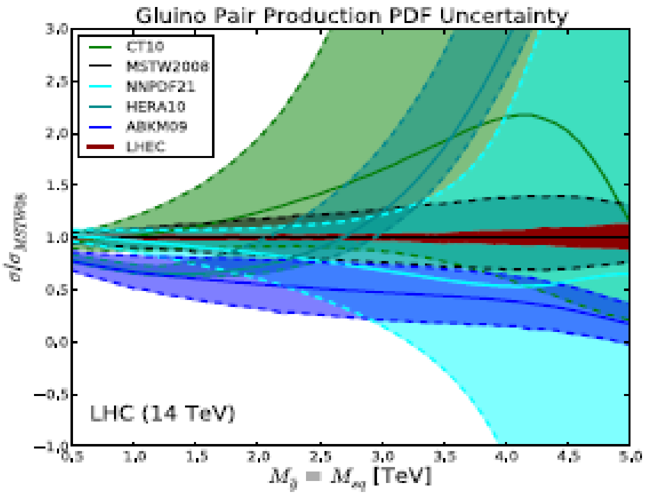
ATLAS CONF-2015-070

Why are we interested in the high-x gluon?-one example

Many interesting processes at the LHC are gluon-gluon initiated
Top, Higgs…BSM processes like gluon-gluon → gluino-gluino
And the high-scale needed for this involves the high-x gluon
The gluon-gluon luminosity at high-scale is not well-known
This leads to uncertainties on the gluino pair production cross section







Which could be considerably reduced using LheC data

Another related uncertainty is the uncertainty on $\alpha_s(M_Z)$

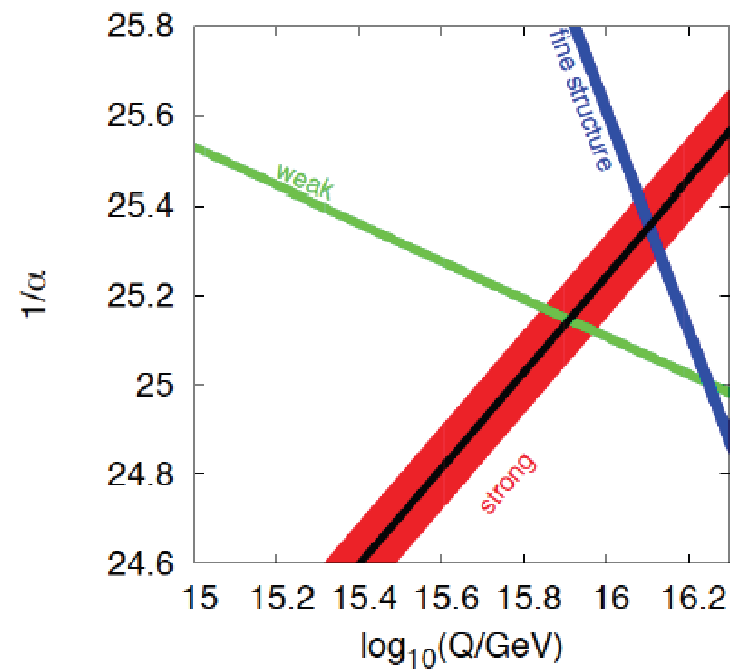
The cross-sections for gluon-gluon initiated processes also depend sensitively on $\alpha_s(M_Z)$, which is also not so well known

DIS data tends to give lower values.

Although the world average looks well determined it is a compromise between many differing determinations.

It is dominated by lattice QCD rather than by experimental measurement

	$\alpha_s(M_Z^2)$	
BBG	$0.1134\ ^{+0.0019}_{-0.0021}$	valence analysis, NNLO [90]
GRS	0.112	valence analysis, NNLO [91]
ABKM	0.1135 ± 0.0014	HQ: FFNS $N_f = 3$ [92]
ABKM	0.1129 ± 0.0014	HQ: BSMN-approach [92]
JR	0.1124 ± 0.0020	dynamical approach [93]
JR	0.1158 ± 0.0035	standard fit [93]
MSTW	0.1171 ± 0.0014	[94]
ABM	0.1147 ± 0.0012	FFNS, incl. combined H1/ZEUS data [95]
BBG	$0.1141\ ^{+0.0020}_{-0.0022}$	valence analysis, N^3LO [90]
world average	0.1181 ±0.0013	



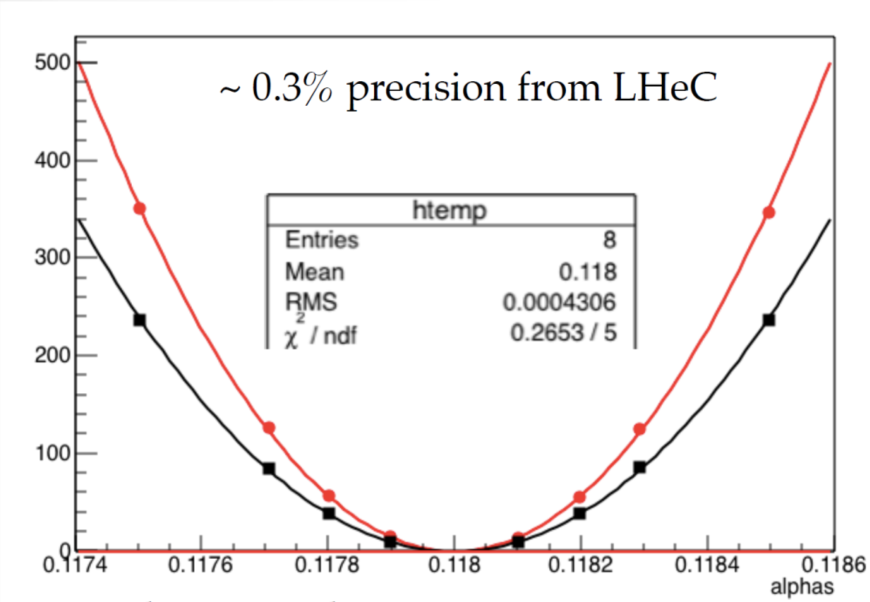
case	cut [Q^2 in GeV^2]	relative precision in %
HERA only (14p)	$Q^2 > 3.5$	1.94
HERA+jets (14p)	$Q^2 > 3.5$	0.82
LHeC only (14p)	$Q^2 > 3.5$	0.15
LHeC only (10p)	$Q^2 > 3.5$	0.17
LHeC only (14p)	$Q^2 > 20.$	0.25
LHeC+HERA (10p)	$Q^2 > 3.5$	0.11
LHeC+HERA (10p)	$Q^2 > 7.0$	0.20
LHeC+HERA (10p)	$Q^2 >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

LHeC promises per mille accuracy on alphas!

A highly accurate $\alpha_s(M_Z)$ is important for GUTS, to know where the couplings unify and under what GUT scenario

strong coupling from LHeC

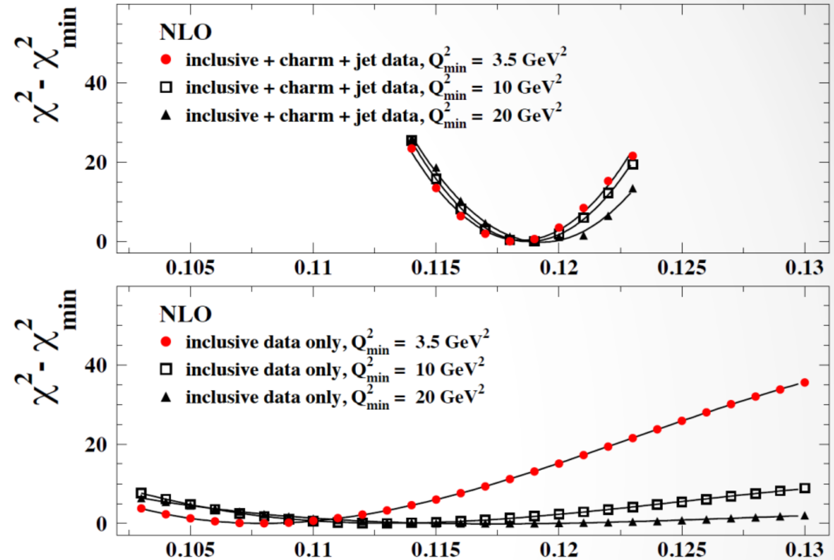
combined fit to PDFs+αs using LHeC data

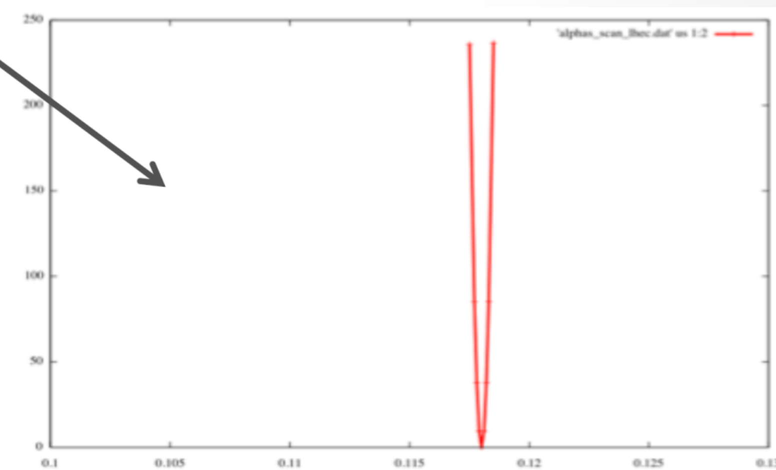


M Klein, V Radescu

NC,CC
NC,CC+F2c

H1 and ZEUS





LHeC could resolve a > 30-year old puzzle:

αs consistent in inclusive DIS, versus jets?

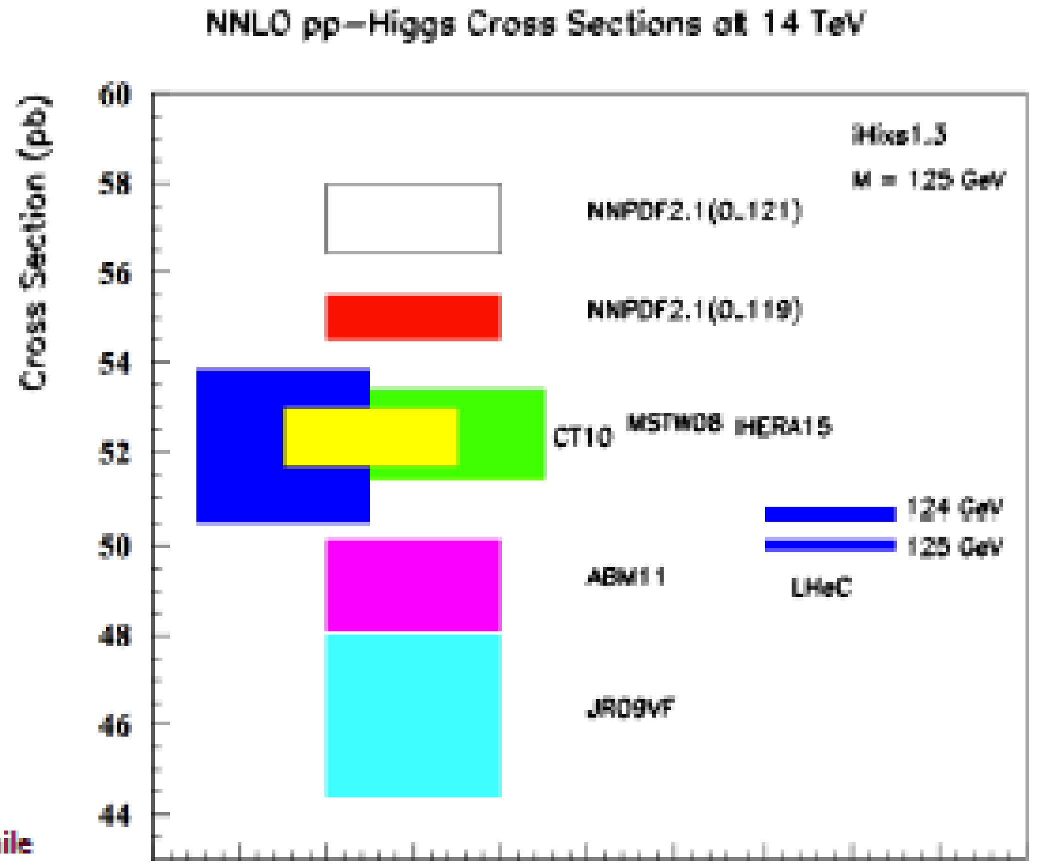
expected 0.1% precision when combined with HERA

LHeC and Higgs

The dominant Higgs production mechanism at LHC is g g→ H

Thus the extra precision on the gluon PDF and $\alpha_s(M_Z)$ which can be obtained at the LHeC improves the precision of SM Higgs cross section predictions-

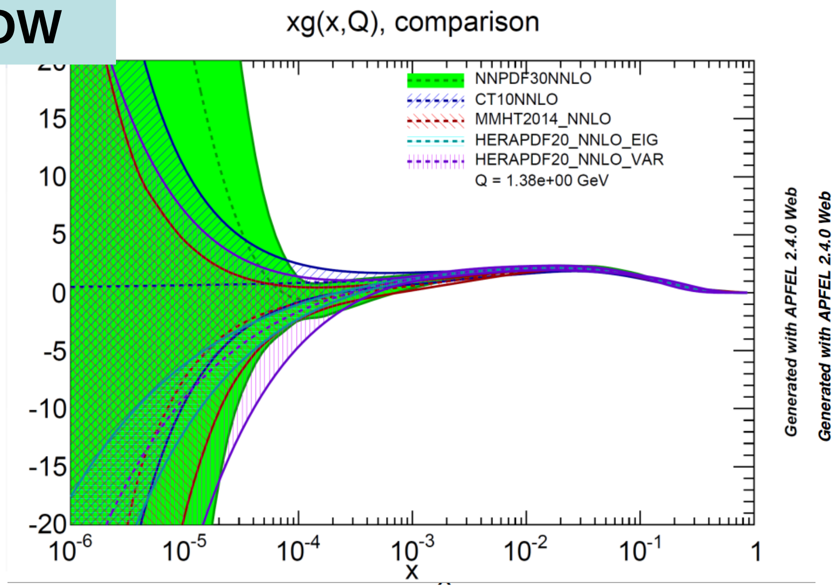
and their dependence on Higgs mass



LHeC at high luminosity is also a Higgs factory, Higgs can be produced by WW, ZZ fusion and H →b-bbar decay is easily identified- O Behnke's talk

Gluon and sea at low x

NOW



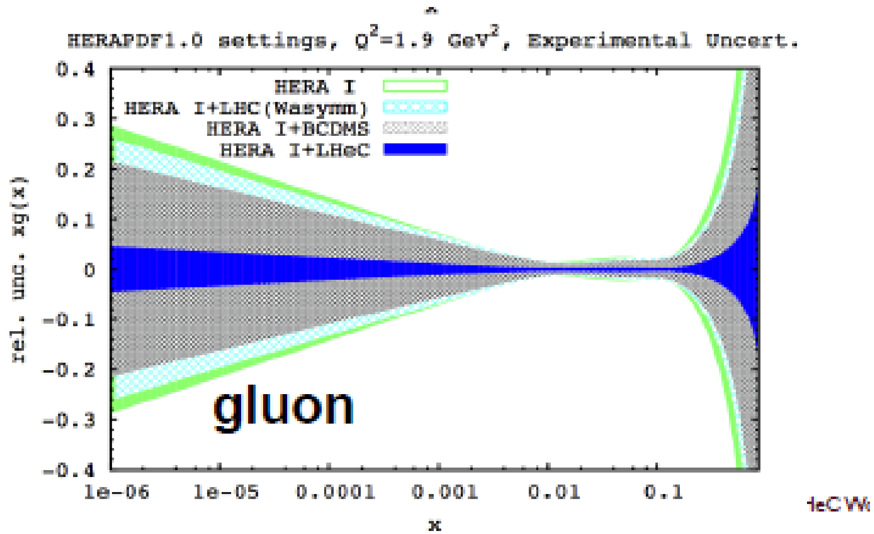
HERA sensitivity stops at $x > 5\ 10^{-4}$

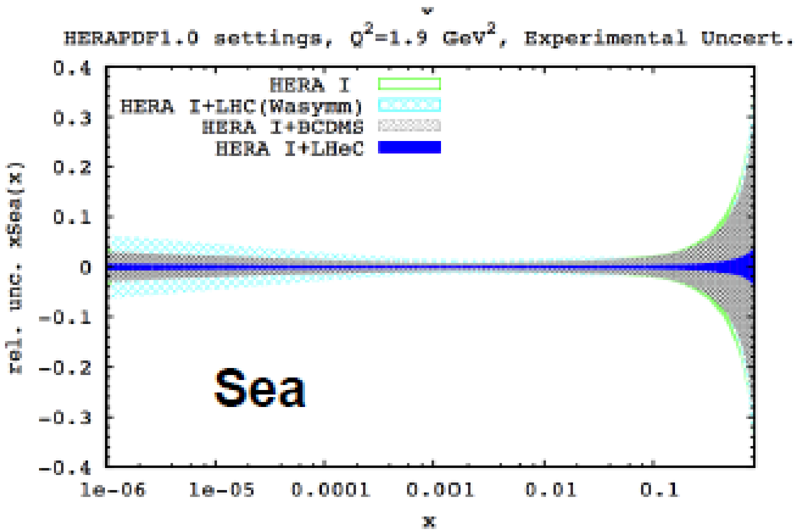
Below that uncertainties depend on the parametrisation

LHeC goes down to 10^{-6}

- FL measurement will also contribute
- Explore low-x QCD DGLAP vs BFKL or non-linear evolution
- Important for high energy neutrino cross sections – Auger etc.

THEN

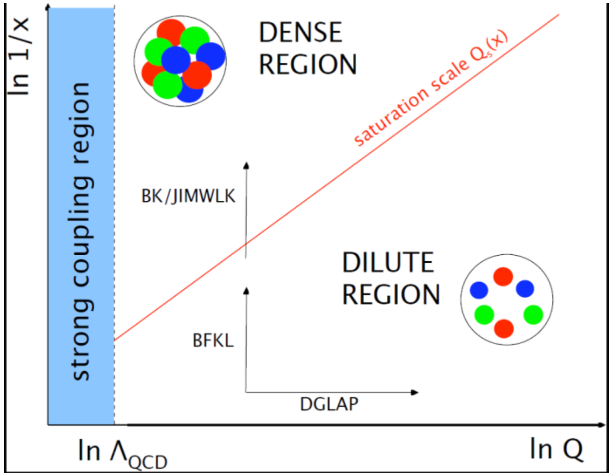


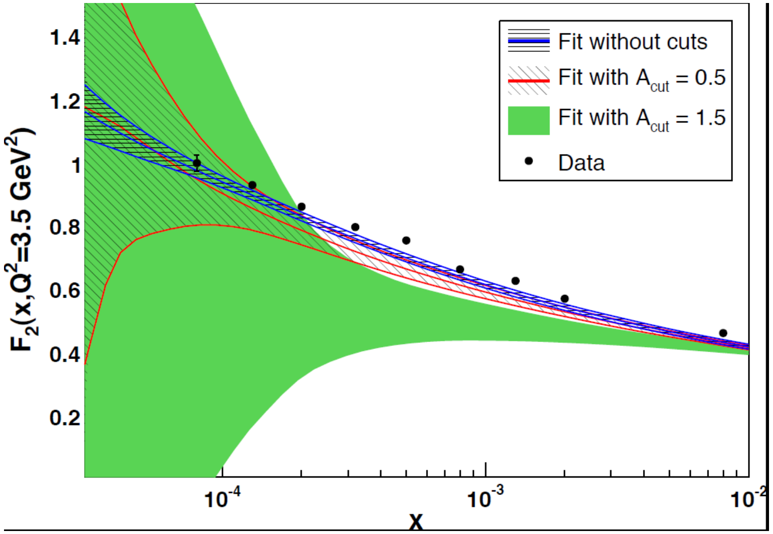


Why are we interested in low-x?

Because the HERA data indicated that there may be something new going on at low x

- New in the sense of a new regime of QCD
- Something that DGLAP evolution at NLO or NNLO cannot describe
- Needing ln(1/x) rather than $\ln Q^2$ resummation (BFKL)
- Or even non-linear evolution (BK, JIMWLK, CGC) and gluon saturation





The rise of the HERA F2 structure function at low x was steeper than expected and continued to lower Q^2 than expected. This gave rise to speculation that one might have entered the BFKL domain.

One way to test this is to make DGLAP QCD fits in which this domain is cut out ($Q^2 > A\, x^{-0.3}$). If physics is the same above and below the cut then these fits will be compatible although the cut fits will have larger uncertainties.

This is not the case….and **this tendency is reconfirmed in the new HERA-I+II final combination data.**

IN DGLAP based fits to inclusive data at low-x, we have
$F_2 \sim xq$ for the sea
$dF_2/d\ln Q^2 \sim Pqg\ xg$ for the gluon

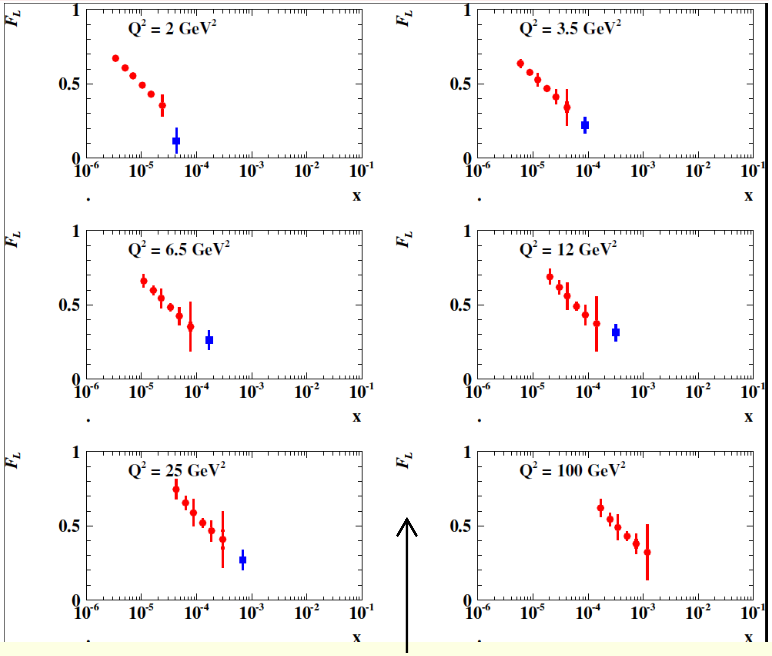
Our deductions about gluon behaviour at low-x come via the DGLAP splitting function Pqg

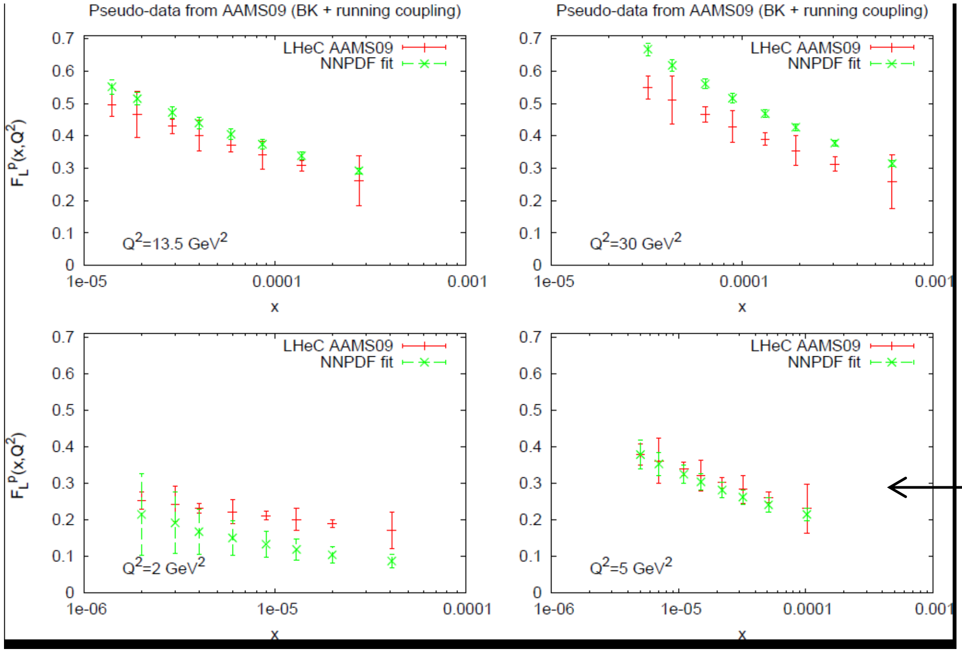
If DGLAP is inadequate then so will our deductions about the shape of the gluon be inadequate. We need other ways to probe it, e.g.

FL is gluon dominated at low-x

$$F_L(x,Q^2) = \frac{\alpha_s}{x}\left[\frac{4}{3}\int_x^1 \frac{dy}{y} z^2 F_2(y,Q^2) + 2\Sigma_i e_i^2 \int_x^1 \frac{dy}{y} z^2(1-z)\, yg(y,Q^2)\right]$$

IF DGLAP is at fault it will be harder for it to explain F2 and FL data simultaneously, but one needs precision data – which can come from the LHeC





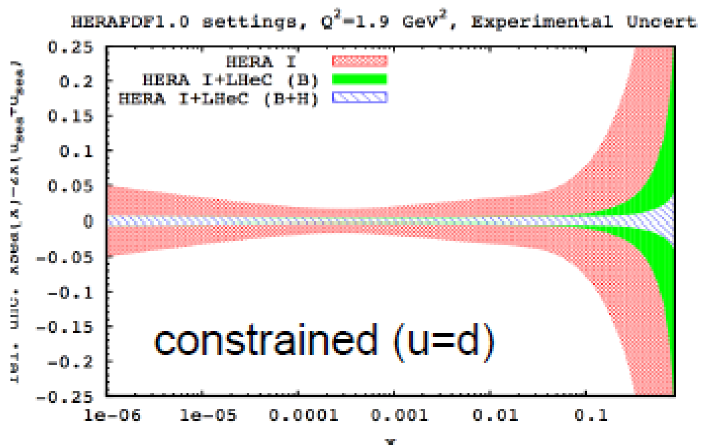
Blue is what we have now averaged over x for each Q2 bin
Red is what we could get from the LHeC
(note that Ee rather than Ep is varied to make this measurement so it does not interfere with p-p)

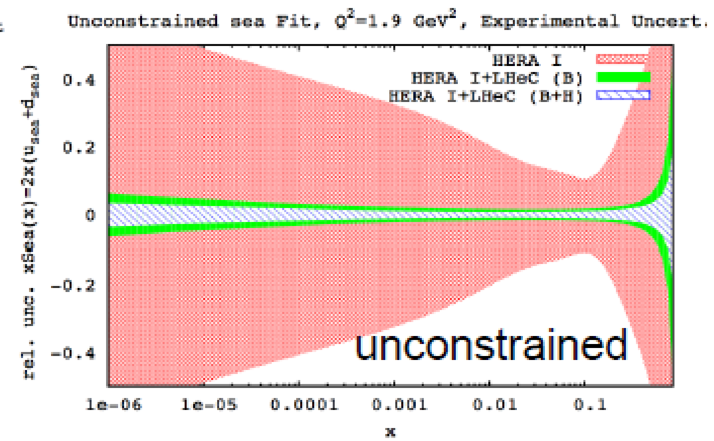
Compare LHeC pseudo-data predicted by a non-linear saturation based model to the DGLAP predictions.

It is usually assumed that ubar=dbar at low-x

If we relax this assumption then PDF errors increase tremendously.
But LHeC data can constrain this.

Here we compare uncertainties on the total sea distribution

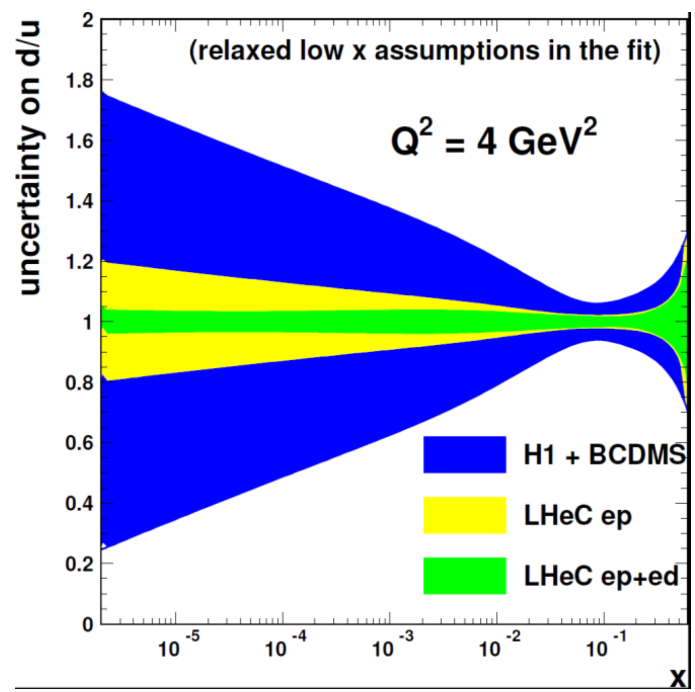




And here we compare uncertainties on the d/u ratio

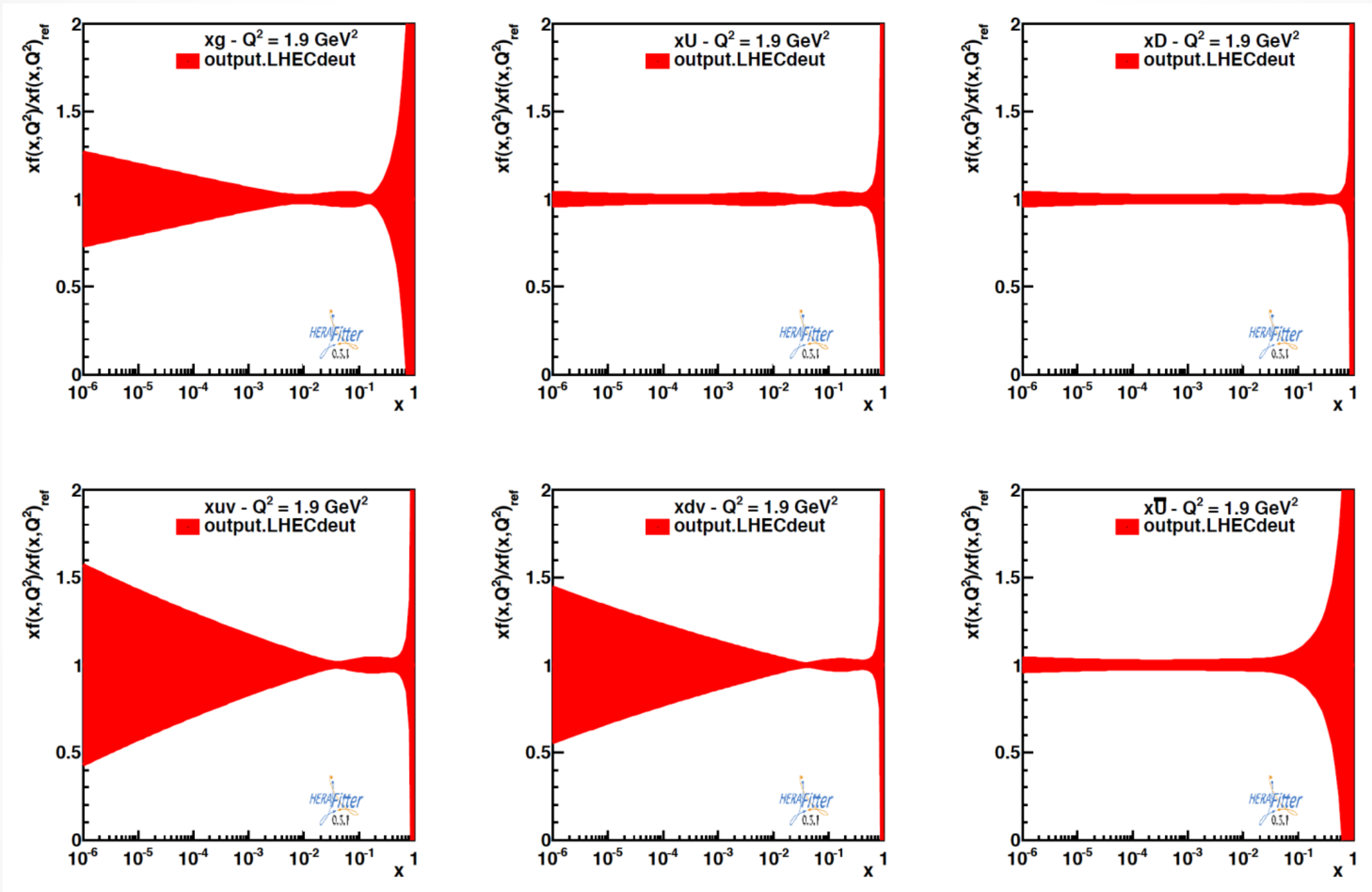
This would improve more if **deuteron target data are used.**

Deuterons can also give information on neutron structure



LHeC deuteron data

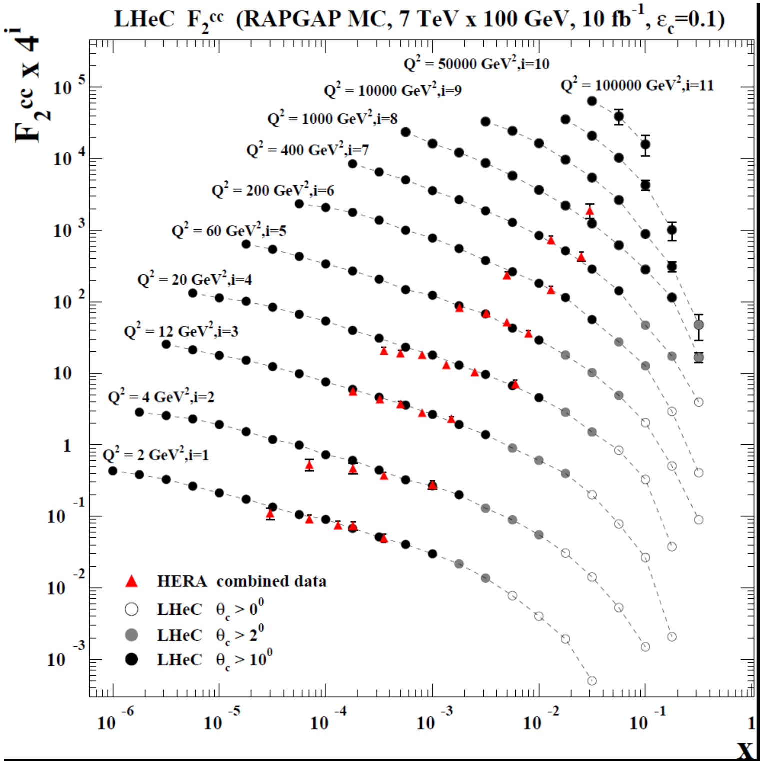
3.5TeV × 60GeV, e-p, P=-80%, 1fb-1, NC and CC, experimental uncertainties

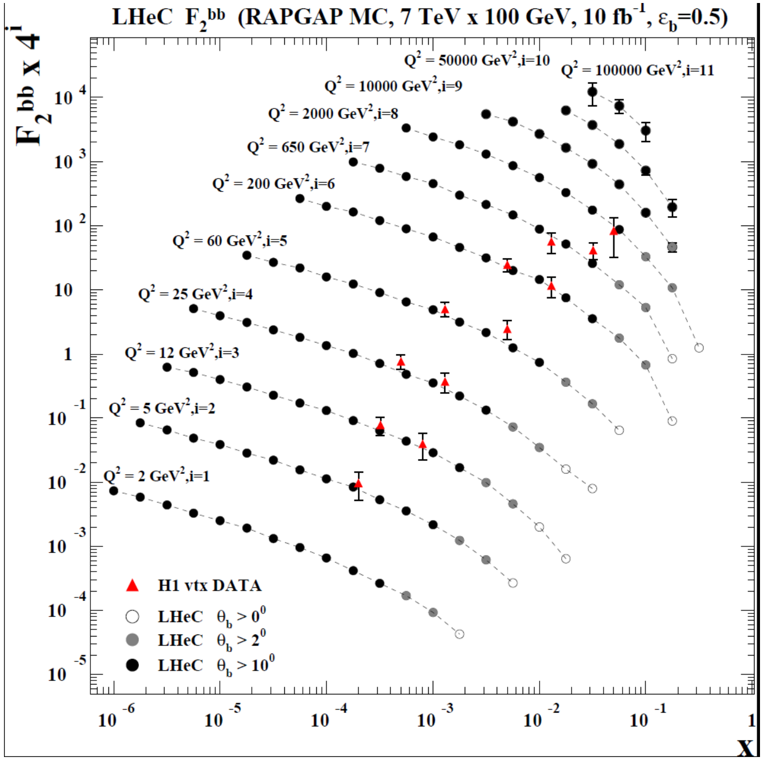


- symmetrised understanding of u-valence and d-valence
- future fits with ep+eD will lead to precise unfolding of u and d

The LHeC would also allow us to improve our knowledge of heavy quarks.

Compare the potential for the measurement of $F2^{c\text{-}cbar}$ and $F2^{b\text{-}bbar}$ with what is currently available from HERA





Why are F2b,c measurements better?

- higher cross section, higher Q^2, higher luminosity (F2b!)
- new generation of Si detectors

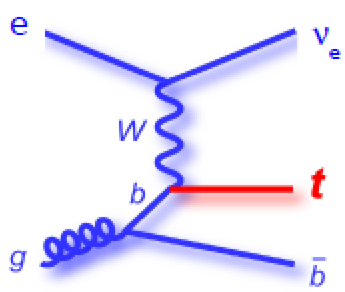
Top quarks and strange quarks could also be studied for the first time

- top: tPDF, cross section few pb at Ee=60GeV, Wb →t

Top Quarks at LHeC

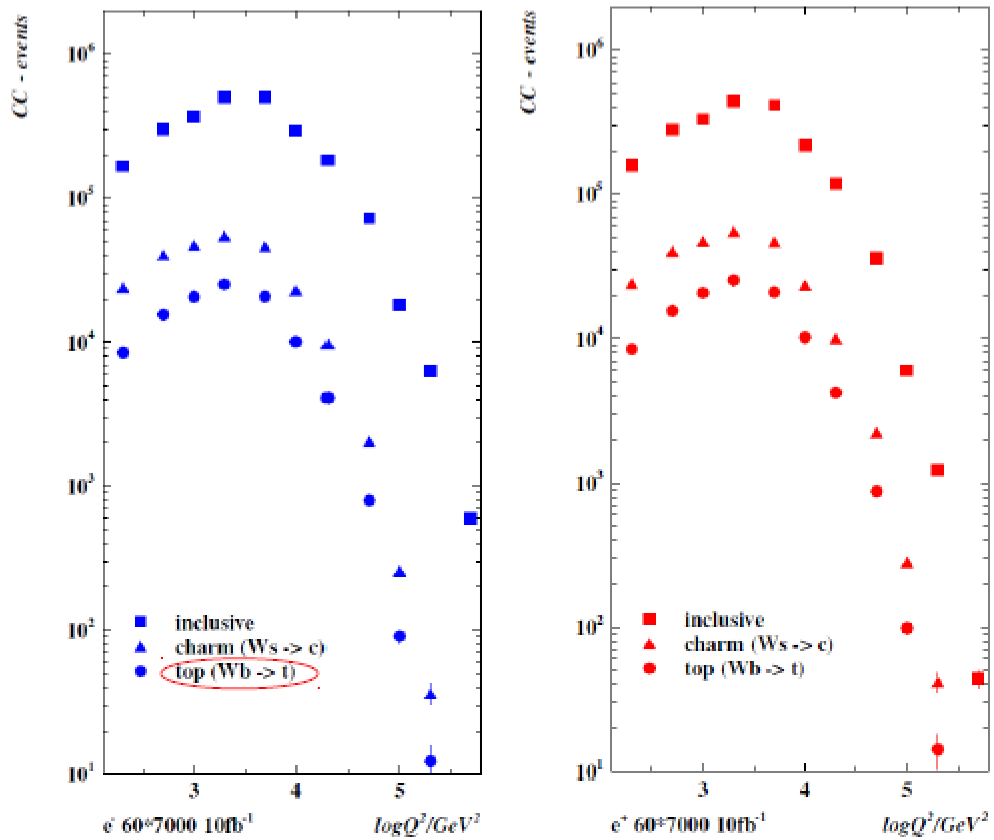
Top quarks can be studied in DIS (negligible cross section at HERA)

CC: Wb → t production
(cross section O(10pb))



NC: ttbar pair production

t and ttbar physics with LHeC still to be studied: precision measurement of top mass, top PDF, ...

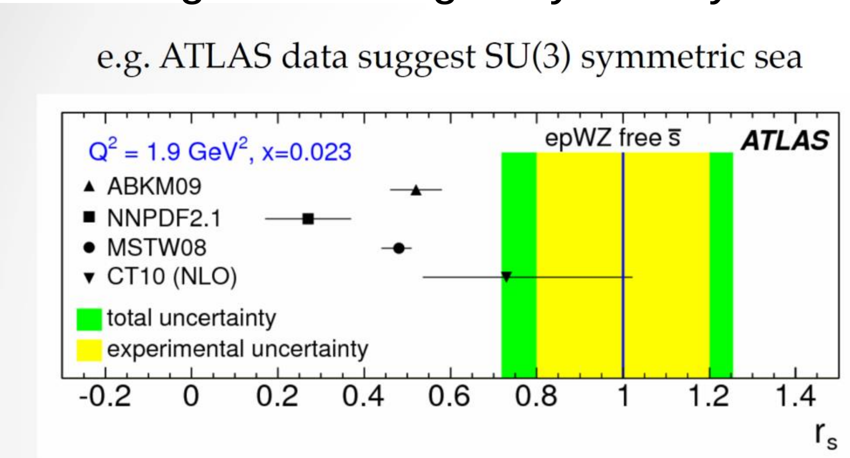


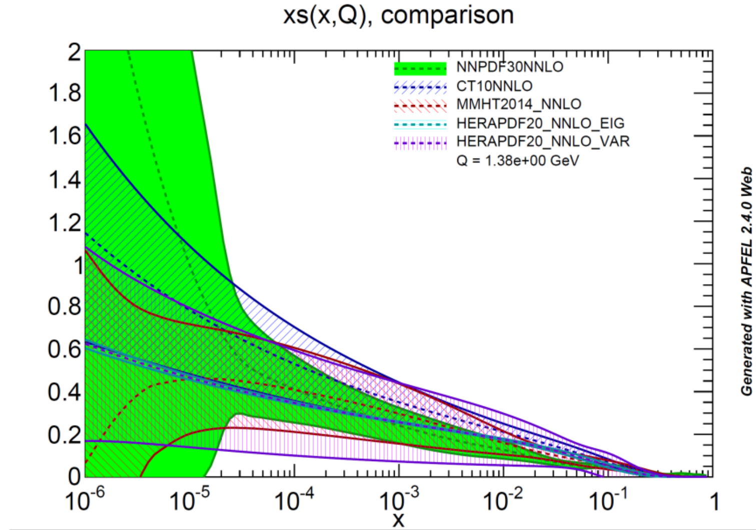
A top PDF could be important at FCC

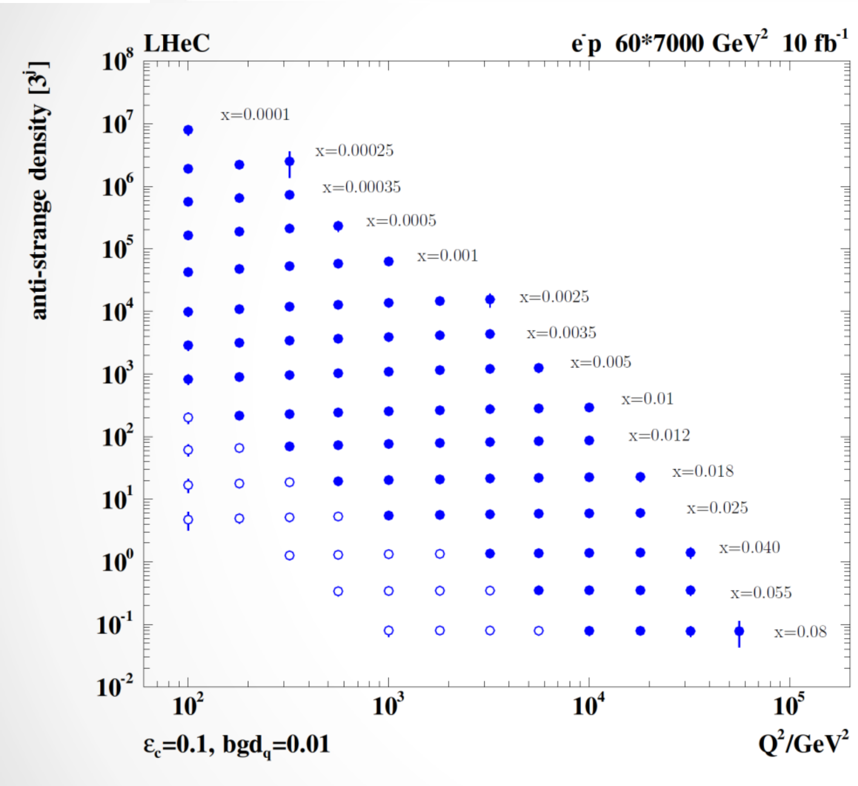
The strange PDF is not well known

Is it suppressed compared to other light quarks?

Is there strange-antistrange asymmetry?







LHeC could give direct sensitivity to strange through charm tagging in CC events.

Results are shown for 10% charm tagging efficiency,

This could give the first x,Q2 measurement of the anti-strange PDF

This also assumes an updated scenario from the CDR .....

impact of different LHeC datasets

new since CDR
ERL scenario; interest in Higgs prefers e-, high polarisation

Ep=7 TeV, E=60 GeV:

NC,CC:

	P	L (fb-1)
e+p	0	5
e-p	+80%	50
e-p	-80%	500

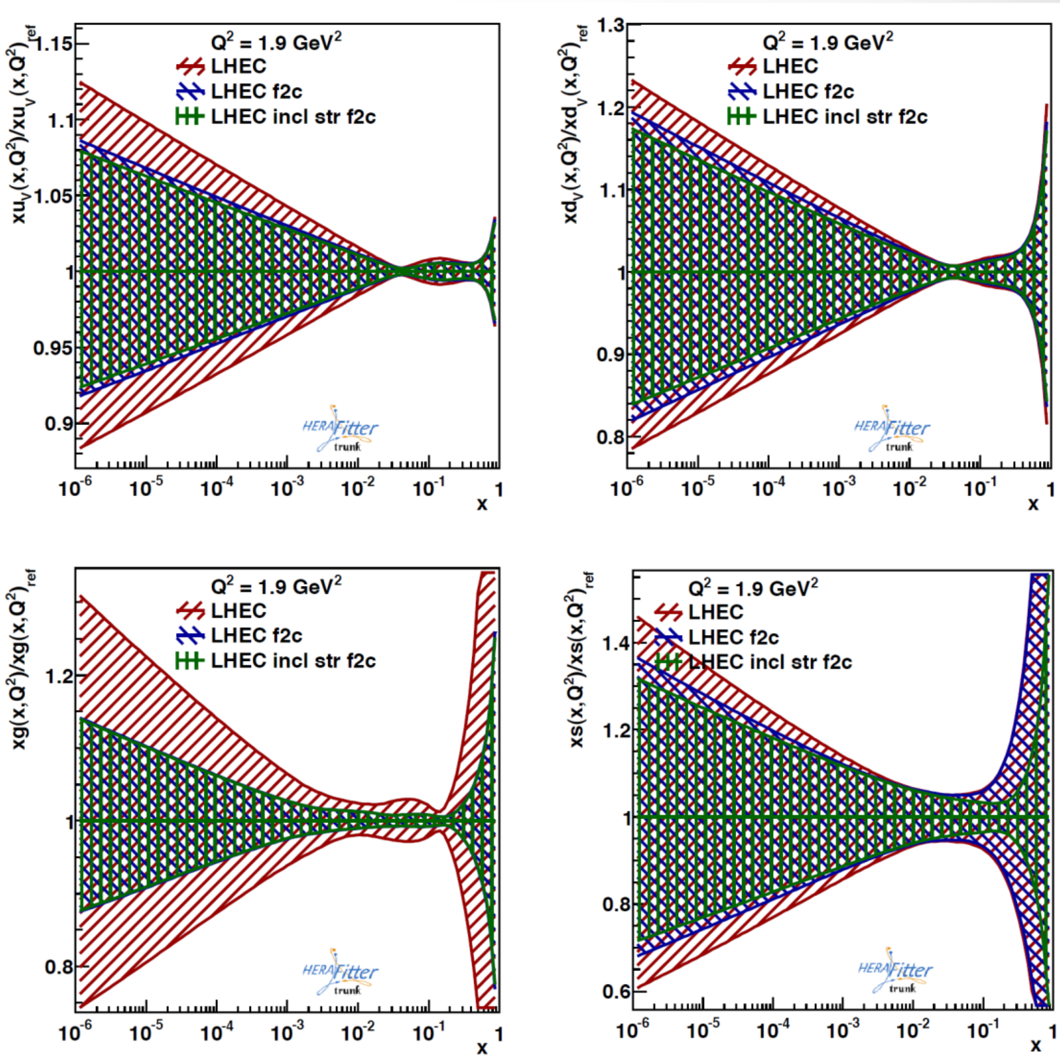
plus, dedicated measurements of strange, anti-strange, F2cc
(not yet F2bb, low Ep data, FL)

more flexible PDF fit:

xg, xuv, xdv, xub, xdb, **xstr**

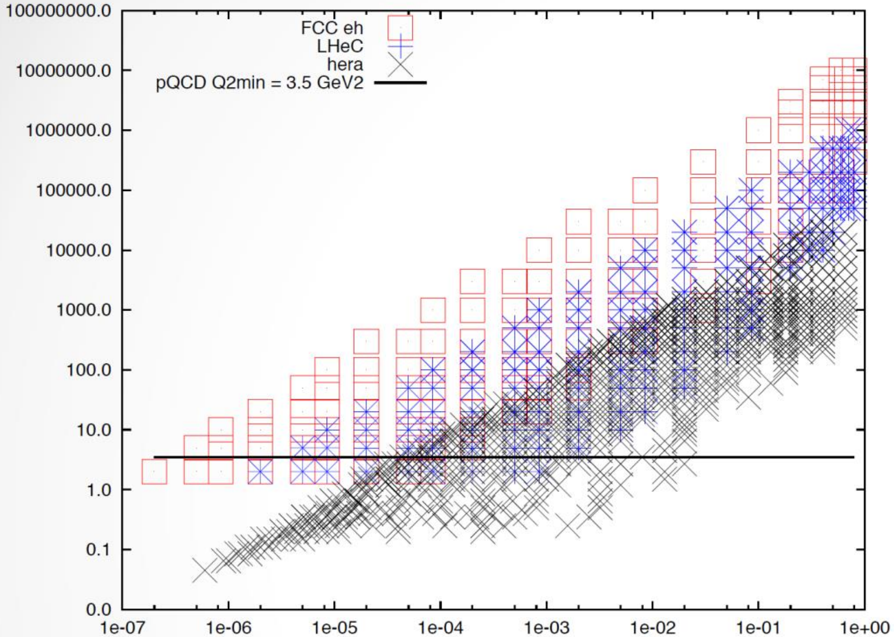
$xf(x) = A\, x^B (1-x)^C (1+Dx+Ex2)$

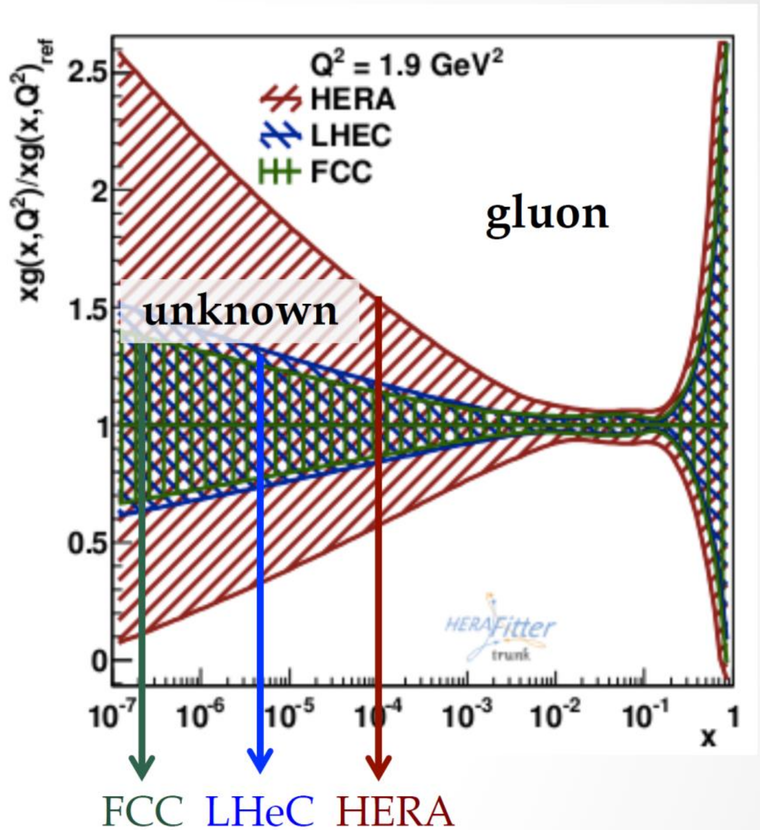
– 14 free parameters



can better constrain all PDFs

FCC-eh vs LHeC vs HERA





FCC-eh: Ep=50 TeV, Ee=100 GeV

NC and CC: e-p, P=80%, 1000 fb^{-1}

stat: 0.1 – 30%, uncor 0.7%, syst 1 – 5%

coverage down to x=2×10-7, up to $Q^2 = 10^7\ GeV^2$

need FCC to constrain much below $x=10^{-5}$

FCC-eh can further improve, and explore low-x phenomenology

Summary

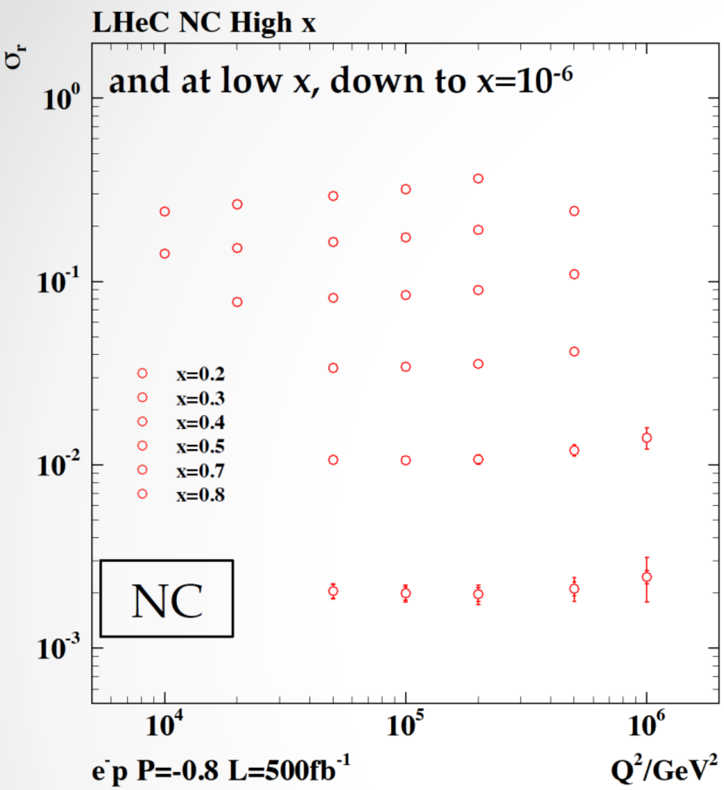
The LHeC represents an increase in the kinematic reach of Deep Inelastic Scattering and an increase in the luminosity.

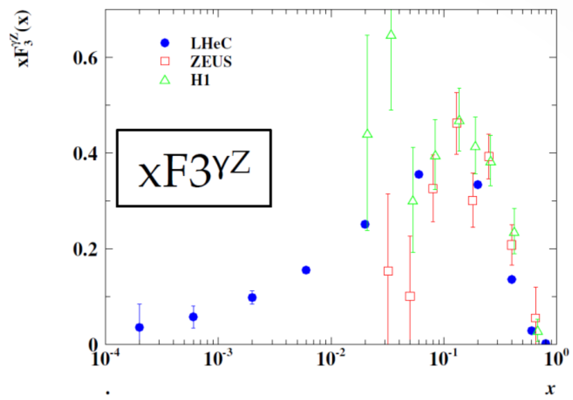
- This represents a tremendous increase in the precision of Parton Distribution Functions
- And the exploration of a kinematic region at low-x where we learn more about QCD beyond linear DGLAP evolution
- Precision PDFs are needed for BSM physics
- The higher luminosity can also provide a precision Higgs ‘factory’

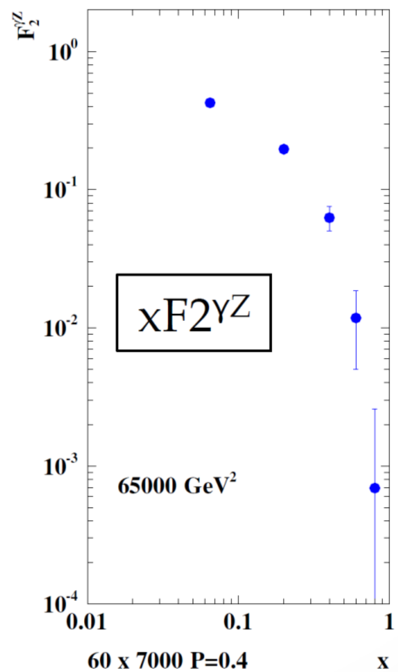
This can run parallel with HL-LHC and the results fed into HL_LHC physics

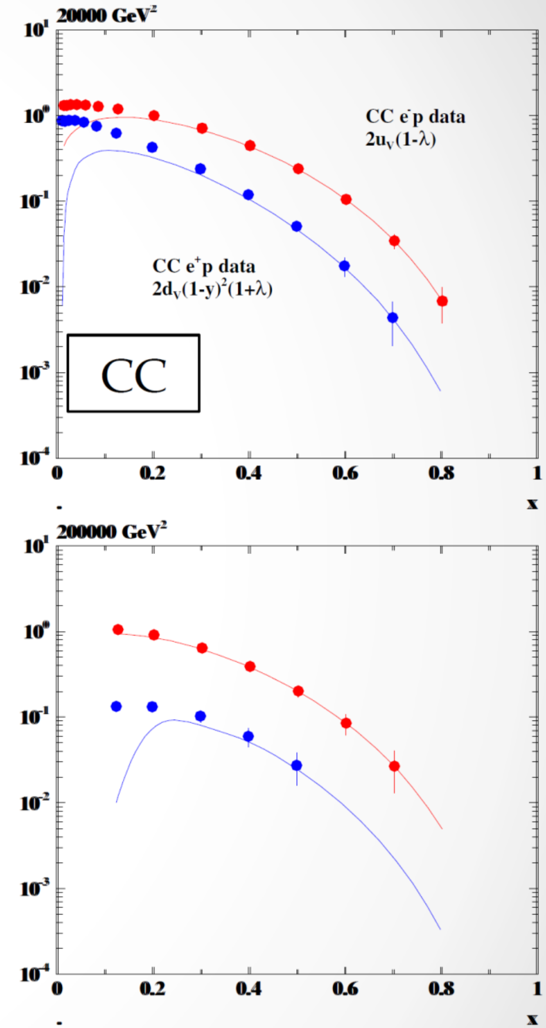
The FCC-eh option extends these possibilities to lower-x and feeds into FCC physics.

primary measurements – simulated – high Q^2







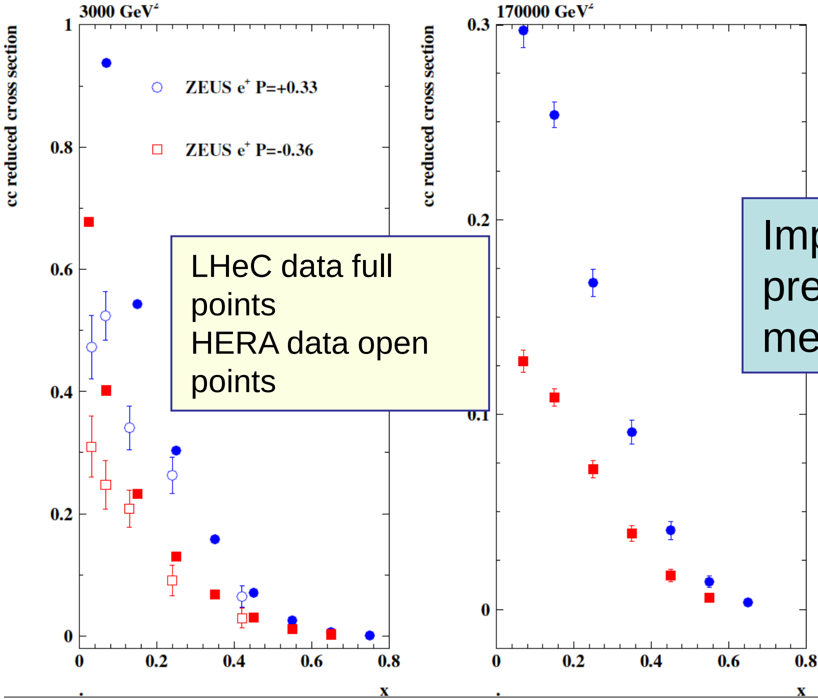


NC/CC cross sections to high precision

- structure functions, sensitive to quarks
- access high x, free from nuclear corrections (via high Q^2, high luminosity)
- different beam charge and polarisation: determination of all quark types

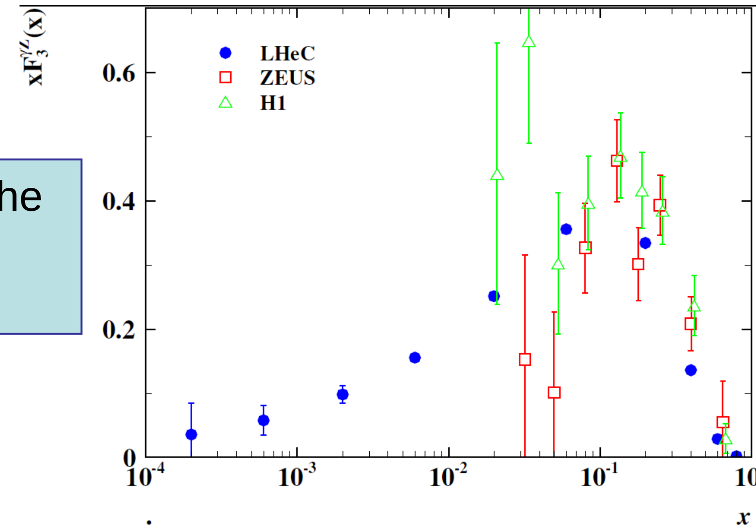
gluon via scaling violation (and F_L)

Electroweak studies

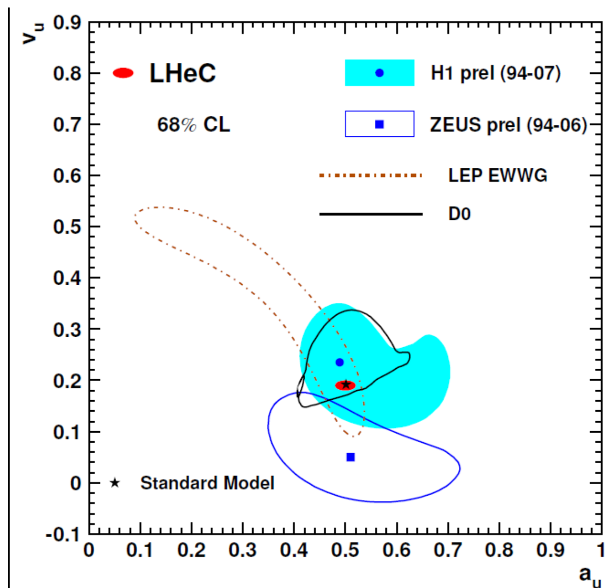


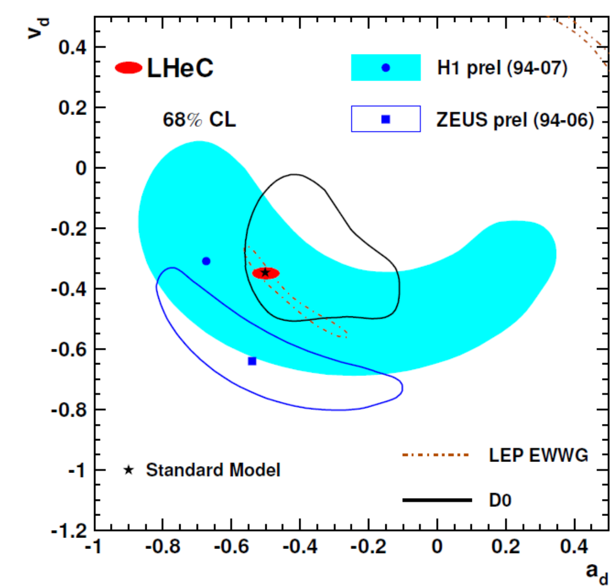
LHeC data full points
HERA data open points

Improvement in the precision of the measurements

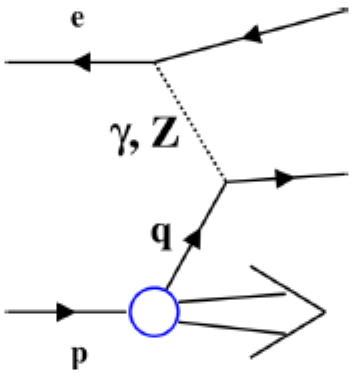


Improvement in the deduced electroweak parameters
Including $\sin^2\theta_W$ from polarisation asymmetry





Master formulae for NC DIS



$$\sigma_{r,NC} = \frac{d^2\sigma_{NC}}{dxdQ^2} \cdot \frac{Q^4 x}{2\pi\alpha^2 Y_+} = \mathbf{F_2} + \frac{Y_-}{Y_+}\mathbf{xF_3} - \frac{y^2}{Y_-}\mathbf{F_L}$$

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

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

$$F_L(x) = \frac{\alpha_s}{4\pi}x^2\int_x^1 \frac{dz}{z^3} \cdot \left[\frac{16}{3}F_2(z) + 8\sum e_q^2\left(1 - \frac{x}{z}\right) zg(z),\right]$$

Vary charge and polarisation and beam energy to disentangle contributions

Charged Currents

$$\sigma_{r,CC} = \frac{2\pi x}{Y_+ G_F^2} \left[\frac{M_W^2 + Q^2}{M_W^2}\right]^2 \frac{\mathrm{d}^2\sigma_{CC}}{\mathrm{d}x\mathrm{d}Q^2}$$

$$\sigma_{r,CC}^{\pm} = \frac{1 \pm P}{2}(W_2^{\pm} \mp \frac{Y_-}{Y_+} x W_3^{\pm} - \frac{y^2}{Y_+} W_L^{\pm})$$

$$W_2^+ = x(\overline{U} + D),\, xW_3^+ = x(D - \overline{U}),\, W_2^- = x(U + \overline{D}),\, xW_3^- = x(U - \overline{D})$$

$$U = u + c \qquad \overline{U} = \overline{u} + \overline{c} \qquad D = d + s \qquad \overline{D} = \overline{d} + \overline{s}$$

$$\sigma_{r,CC}^{+} \sim x\overline{U} + (1-y)^2 xD,$$

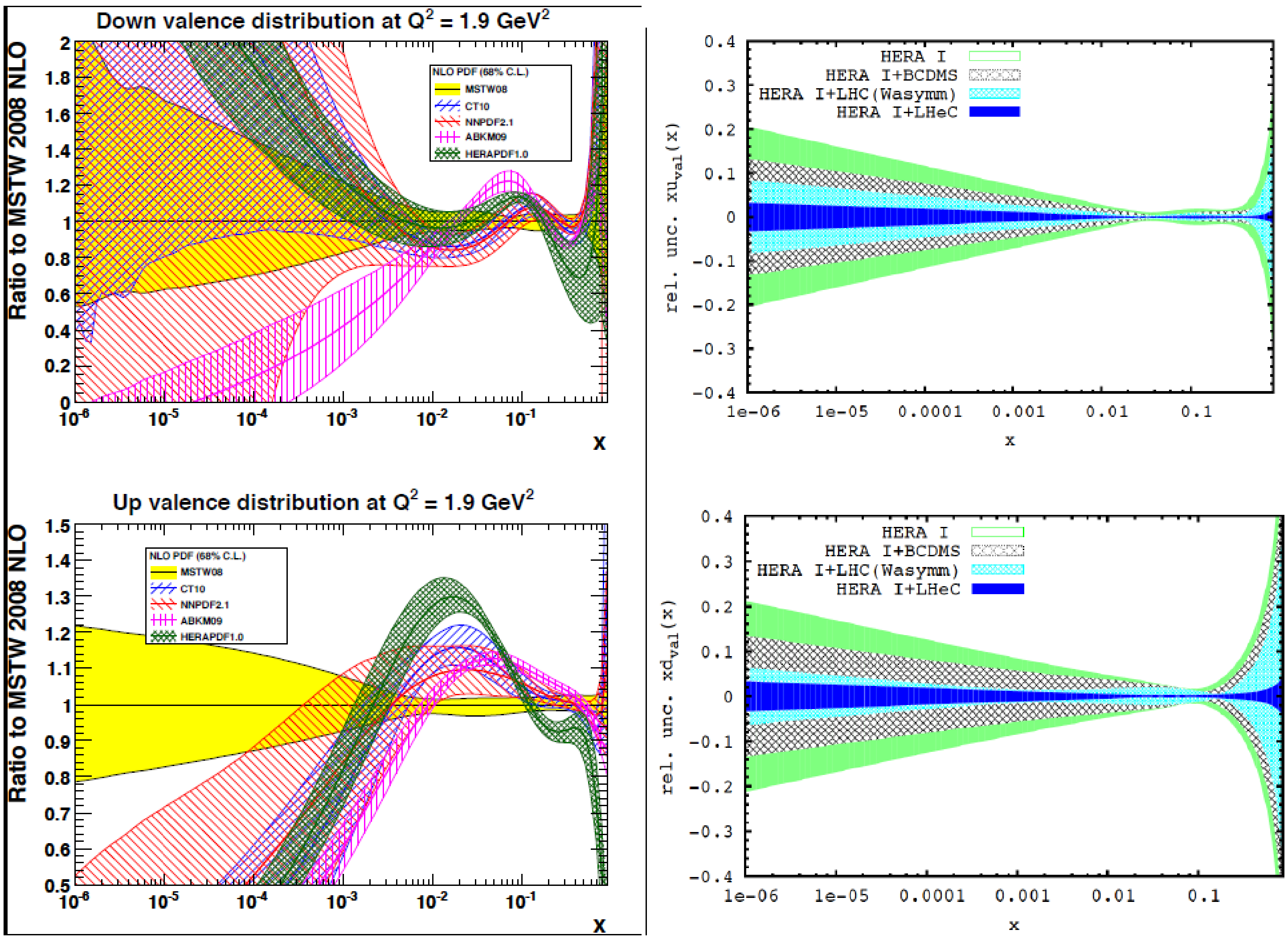
$$\sigma_{r,CC}^{-} \sim xU + (1-y)^2 x\overline{D}$$

$$\sigma_{r,NC}^{\pm} \simeq [c_u(U + \overline{U}) + c_d(D + \overline{D})] + \kappa_Z[d_u(U - \overline{U}) + d_d(D - \overline{D})]$$

with $c_{u,d} = e_{u,d}^2 + \kappa_Z(-v_e \mp P a_e) e_{u,d} v_{u,d}$ and $d_{u,d} = \pm a_e a_{u,d} e_{u,d}$,

Complete unfolding of all parton distributions to unprecedented accuracy

Compare the valence distributions also at low x (maybe cut this)



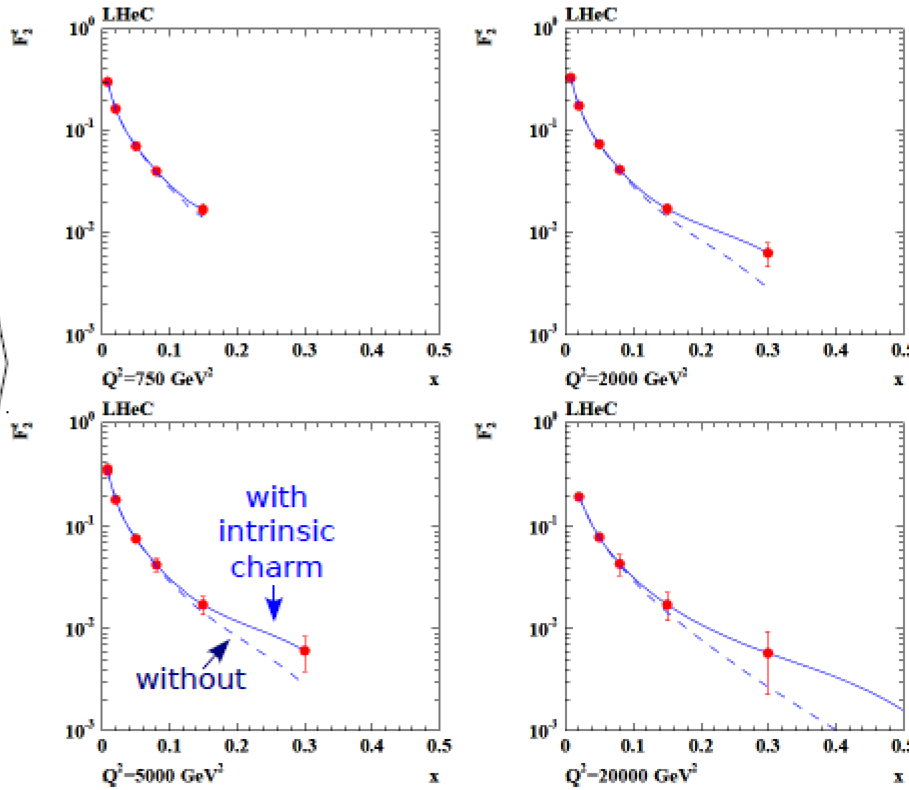
Intrinsic Charm

Intrinsic charm: existence of $c\bar{c}$ pair as non-perturbative component in the bounc state nucleon (Fock state components such as $|uudc\bar{c}>$)

→ may explain certain aspects of the charm data and dominate in some regions of the phase space

for large x very good forward tag acceptance needed (possible with reduced E_p)

simulated measurement of the charm structure function (E_p=1 TeV, L=1 fb^{-1}, CTEQ66)



→ reliable detection of an intrinsic heavy charm component challenging but possible