High Precision DIS with the LHeC

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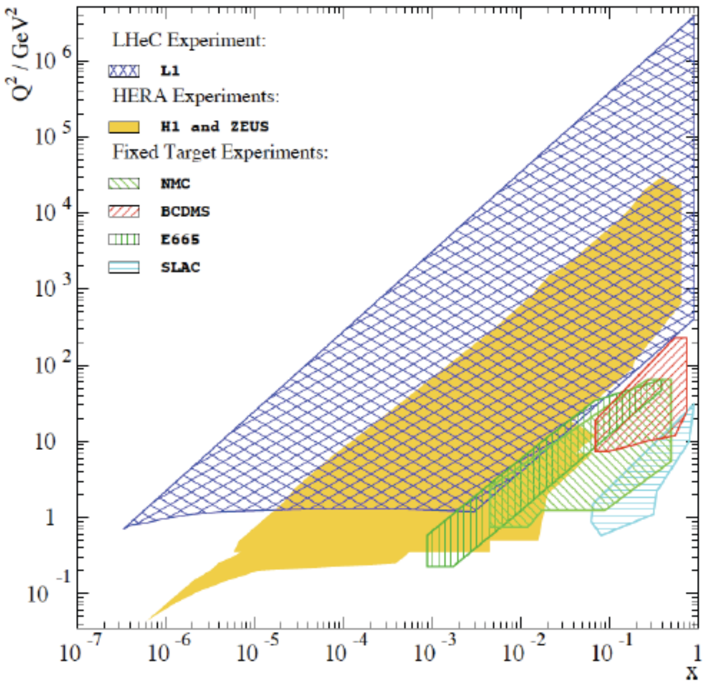
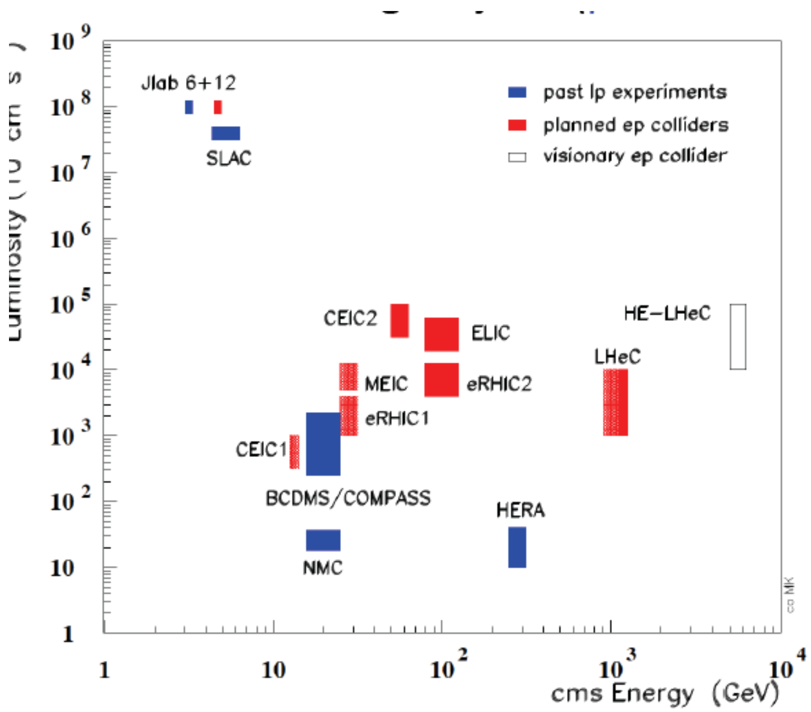
For the LHeC study group

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

Topics:
- Accelerator- talk by Daniel Schulte
- Detector- poster
- eA- talk by Max Klein
- BSM- poster
- Higgs- talk by Uta Kleine
- DIS and low-x– this talk

CDR, JPhysG39(2012)075001



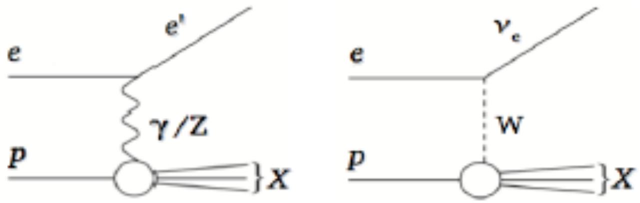


The LHeC represents an increase in the kinematic reach of Deep Inelastic Scattering and an increase in the luminosity.

- 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- e.g. is there gluon saturation?- only the LHeC projects go to high enough energy for this
- Precision PDFs are needed for BSM physics
- The higher luminosity can also provide a precision Higgs ‘factory’– see talk of U Klein

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

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

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%)

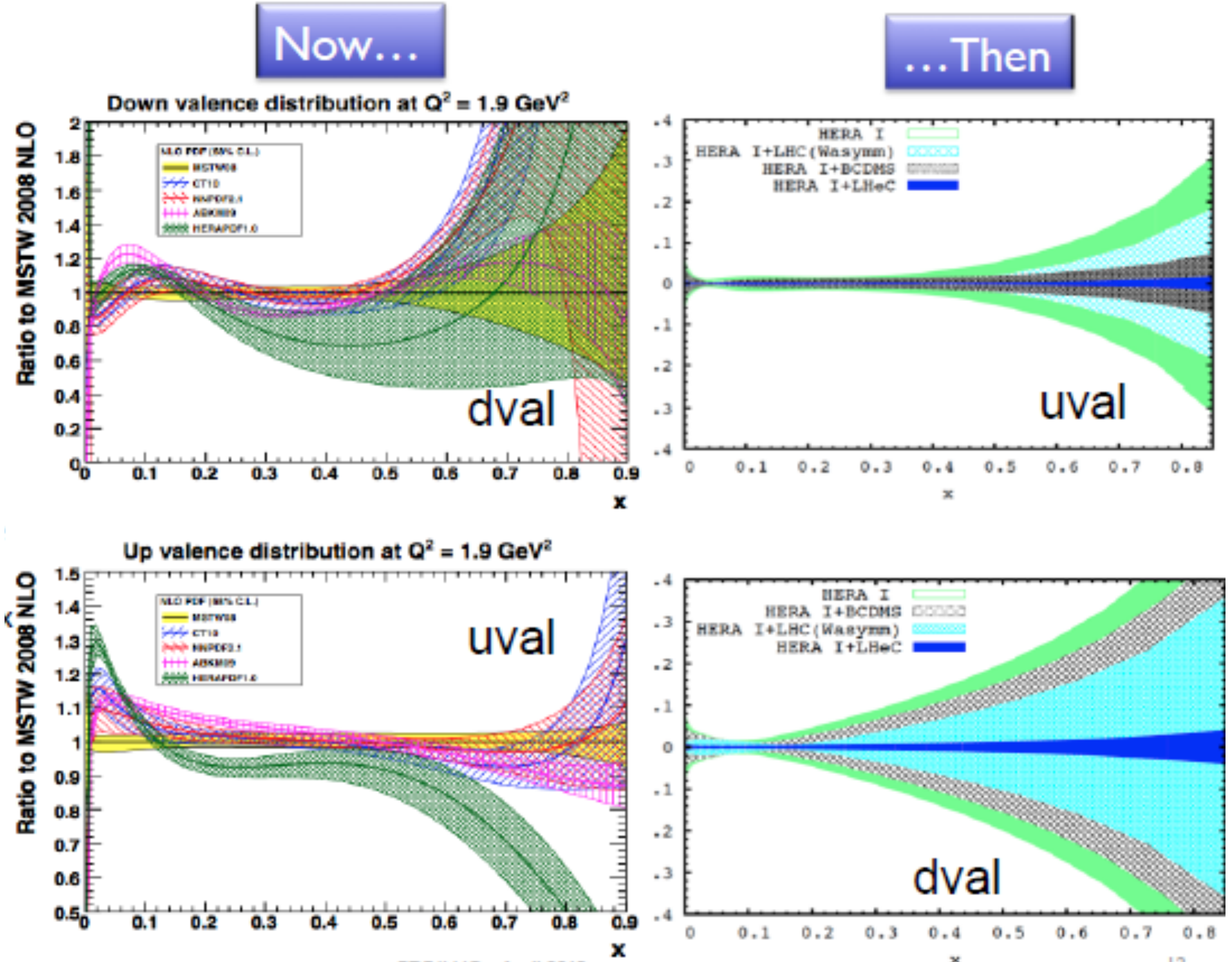
source of uncertainty	error on the source or cross section
scattered electron energy scale $\Delta E'_e/E'_e$	0.1 %
scattered electron polar angle	0.1 mrad
hadronic energy scale $\Delta E_h/E_h$	0.5 %
calorimeter noise (only $y<0.01$)	1-3 %
radiative corrections	0.5%
photoproduction background (only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

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

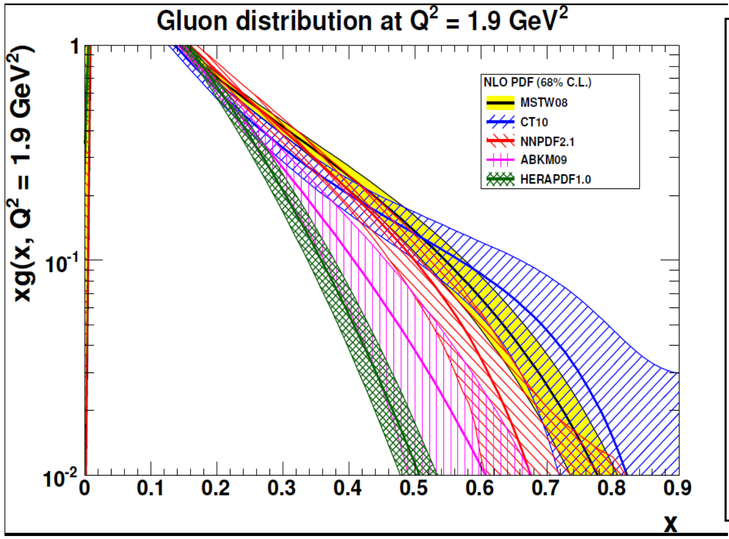
- LHeC simulated data (scenario B) on NC, CC e+p and e-p cross-sections
- Published HERA-I combined data
- Fixed target data from BCDMS (W^2>15)
- ATLAS 2010W,Z data

HERAFitter framework is used, with PDF fit settings as for HERAPDF1.0 NLO

Valence distribution



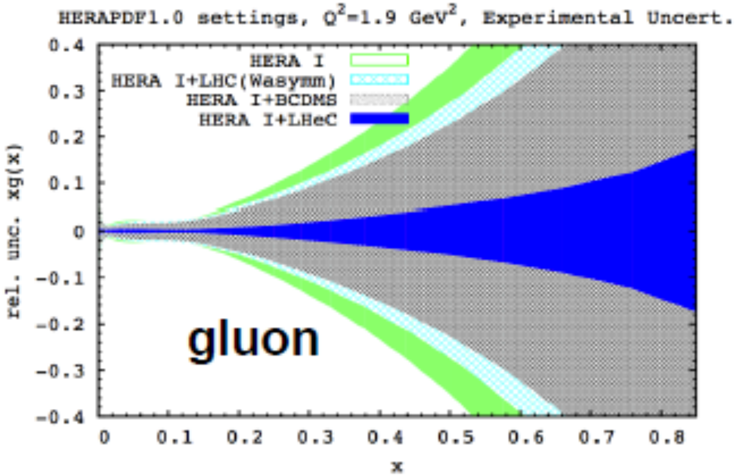
Gluon and sea at high x

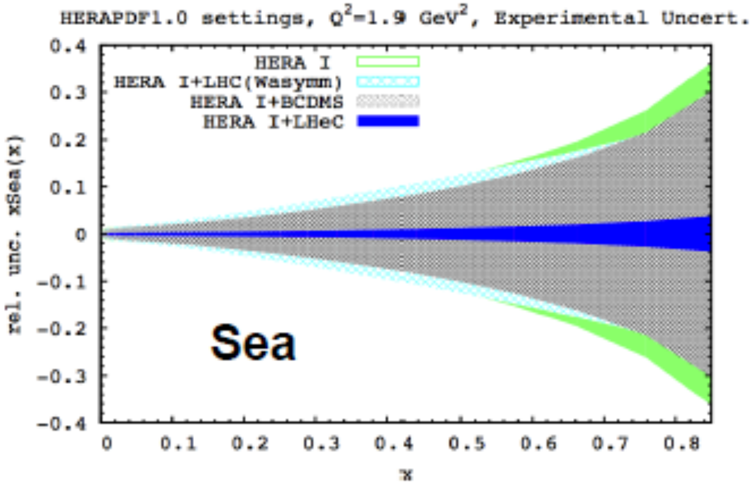


The high x gluon is not well known current PDFs differ

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 $F2_{\gamma Z}$, $xF3_{\gamma Z}$





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

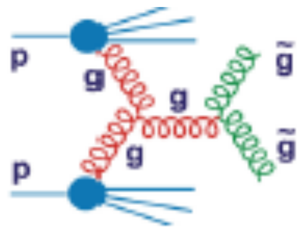
Many interesting processes at the LHC are gluon-gluon initiated

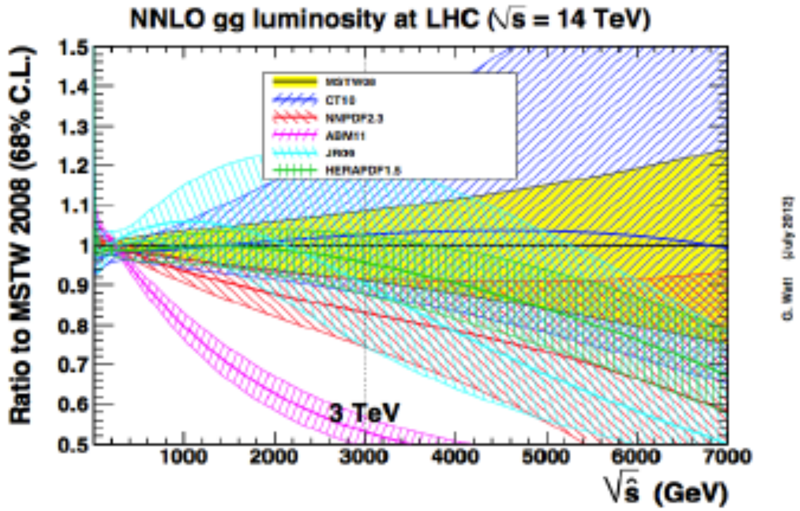
Top, Higgs…BSM processes like gluon-gluon → gluino-gluino

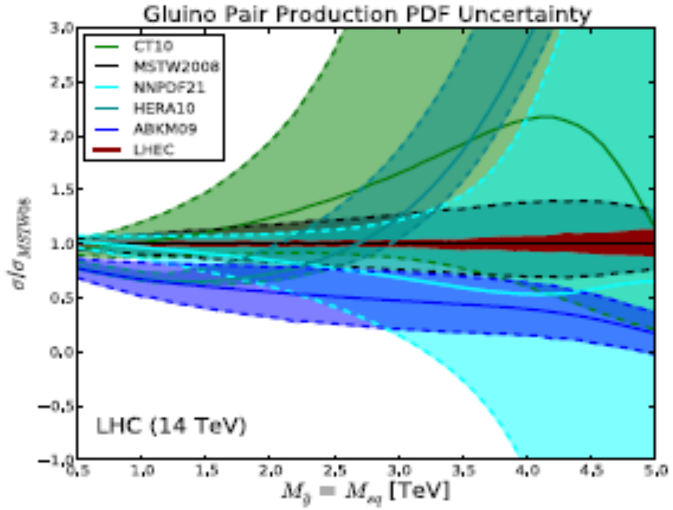
And the high-scale needed for this involves the high-x gluon

The gluon-gluon luminosity at high-scale is thus not well-known

This leads to uncertainties on the gluino pair production cross section







Which could be considerably reduced using LheC data

See poster on BSM physics at LHeC

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

	$\alpha_s(M_Z^2)$	
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	0.1184 ± 0.0007	[96]

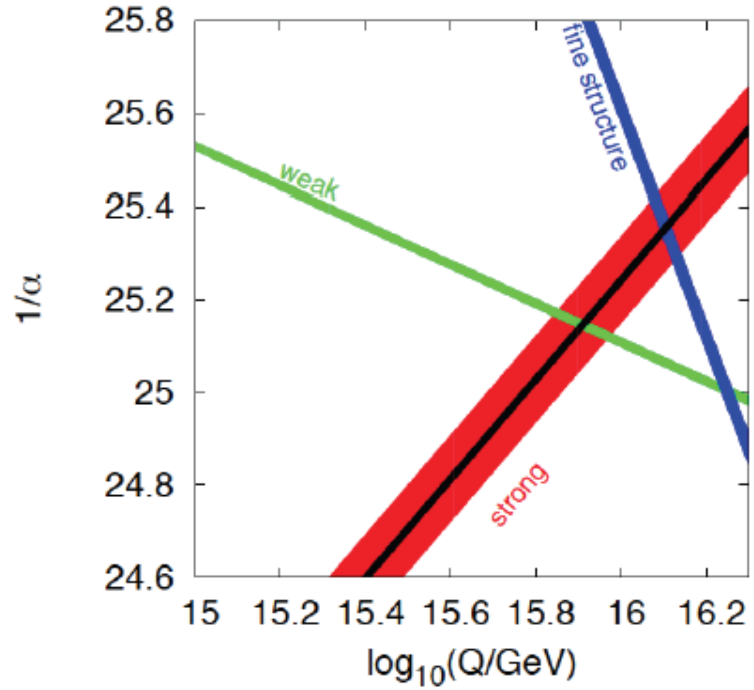
The cross-sections for gluon-gluon initiated processes also depend sensitively on $\alpha_s(M_Z)$, which is also not so well known

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

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!



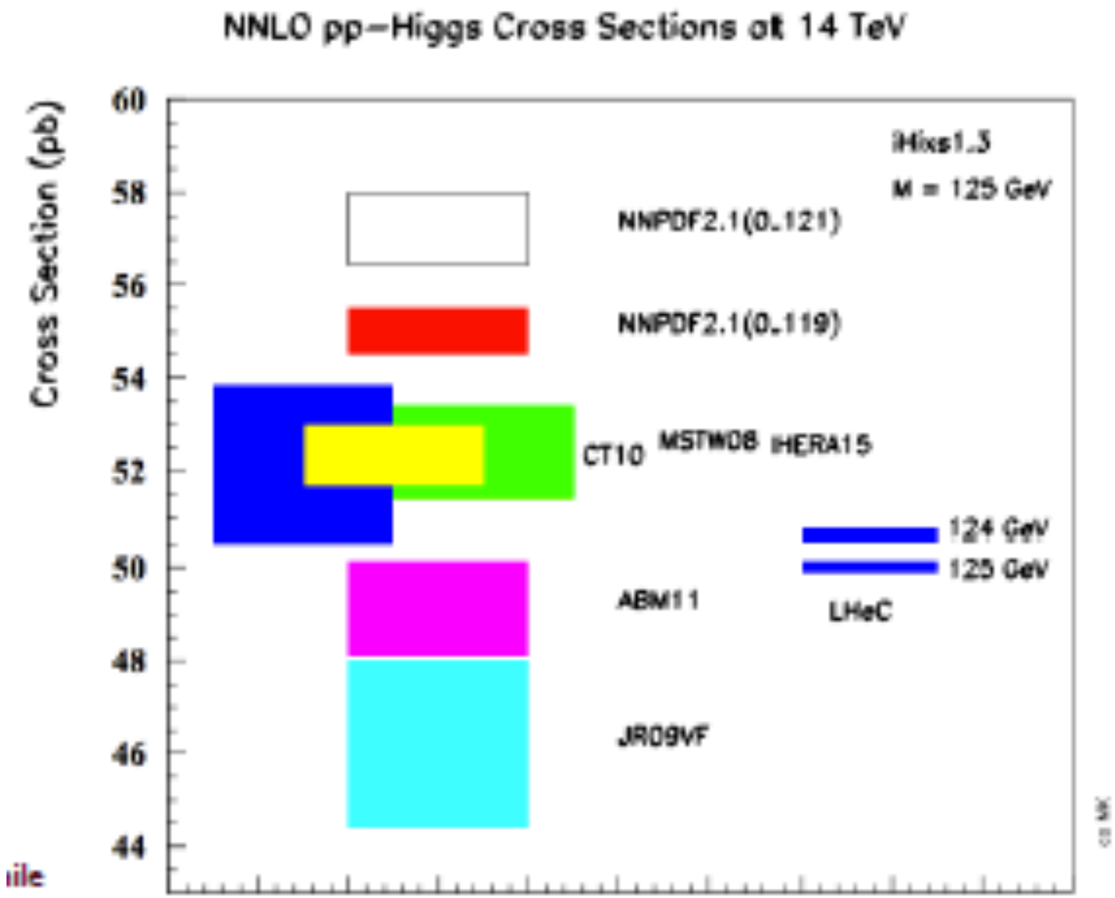
A highly accurate $\alpha_s(M_Z)$ is important for GUTS, to know where the couplings unify and under what GUT scenario

LHeC and Higgs

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

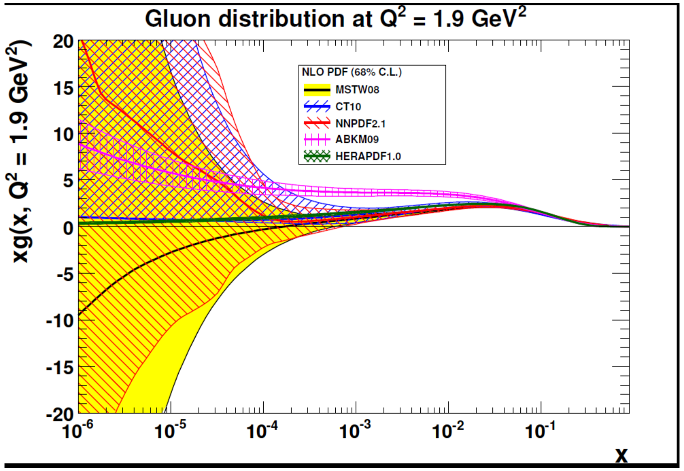
Thus the extra precision on the gluon PDF and $\alpha_s(M_Z)$ which can be obtained at the LHeC improves the precision of SM Higgs cross section predictions-

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- **see talk of Uta Klein**

Gluon and sea at low x

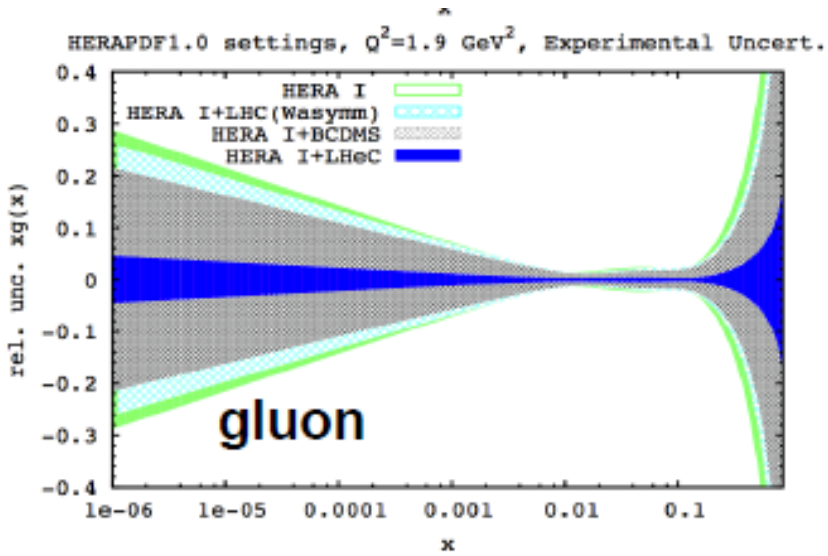


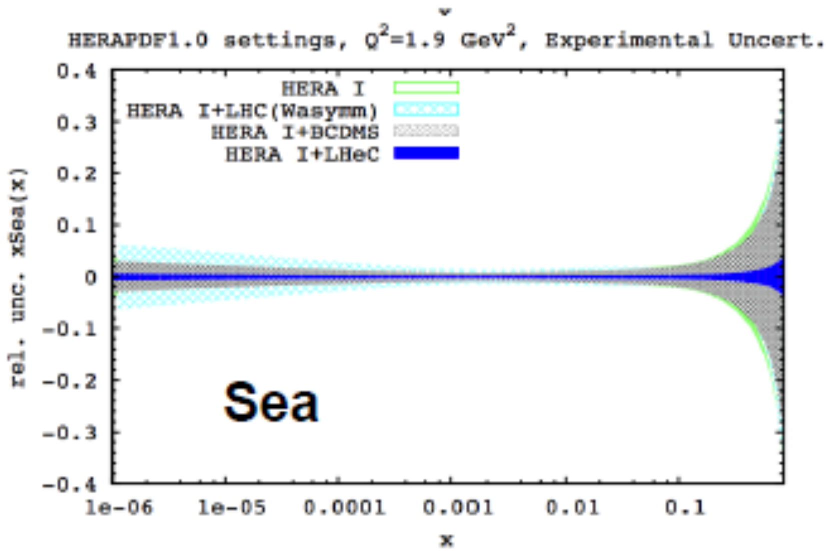
HERA sensitivity stops at $x > 5\ 10^{-4}$

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

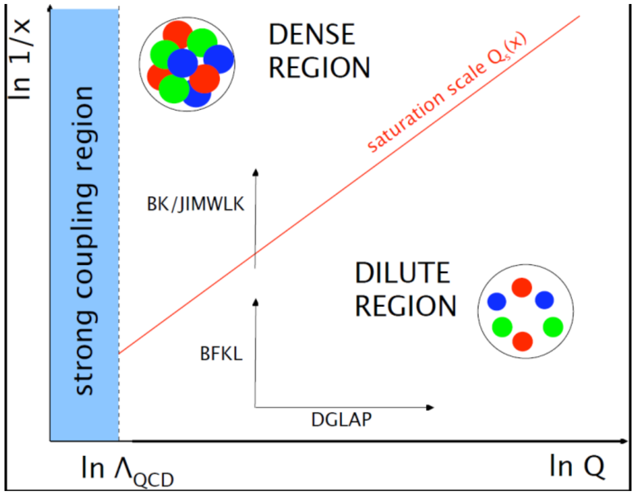


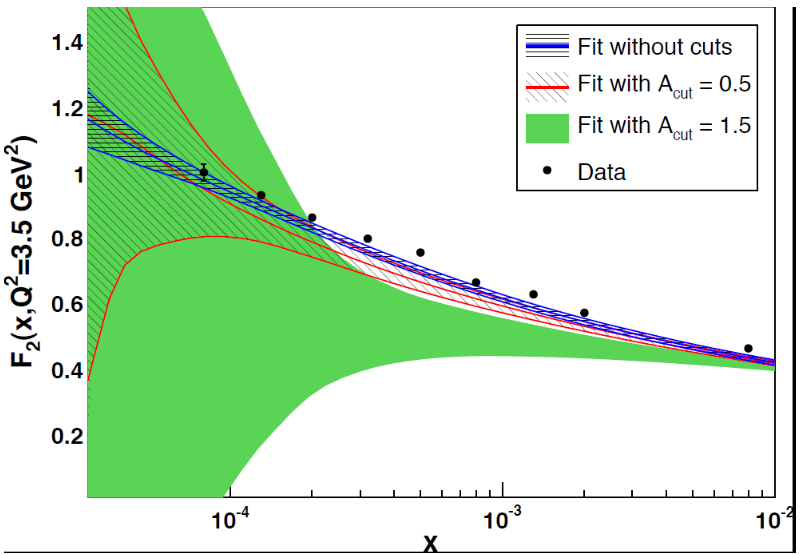


Why are we interested in low-x?

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 lnQ^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, though the evidence is not overwhelming….

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

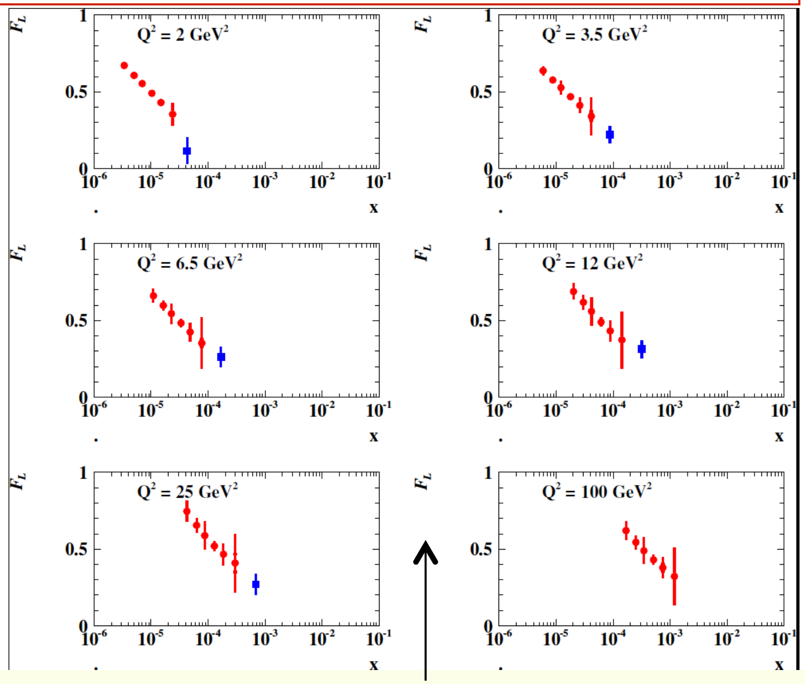
Our deductions about gluon behaviour at low-x come via the DGLAP splitting function Pqg

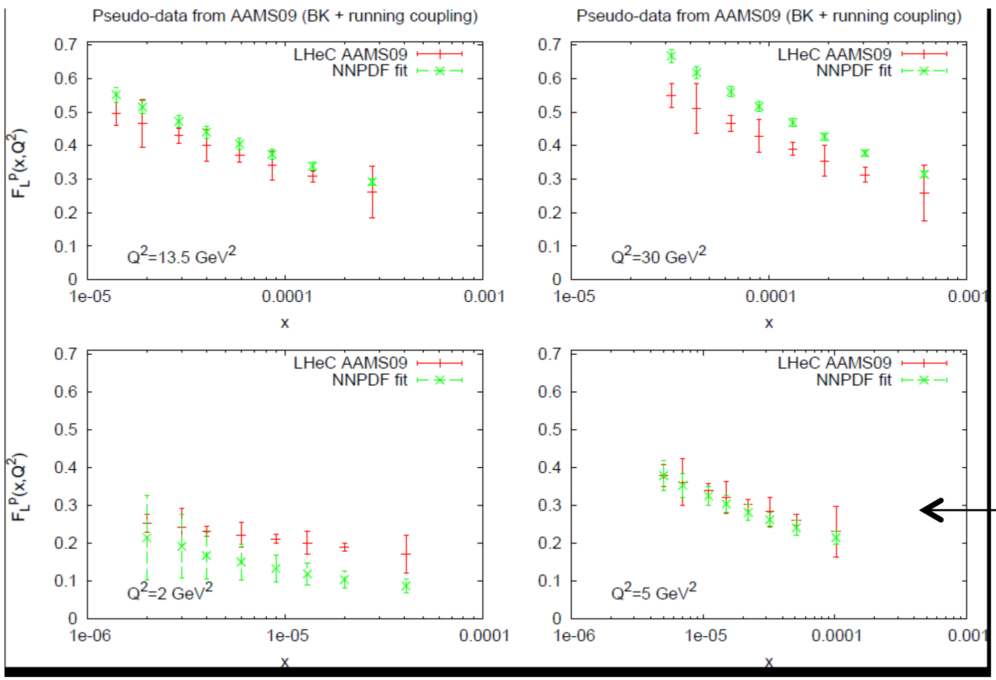
If DGLAP is inadequate then so will our deductions about the shape of the gluon be inadequate. We need other ways to probe it, e.g.

FL is gluon dominated at low-x

$$F_L(x,Q^2) = \frac{\alpha_s}{x}\left[\frac{4}{3}\int_0^1 \frac{dy}{y} z^2 F_2(y,Q^2) + 2\Sigma_i e_i^2 \int_0^1 \frac{dy}{y} z^2 (1-z) y g(y,Q^2)\right]$$

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





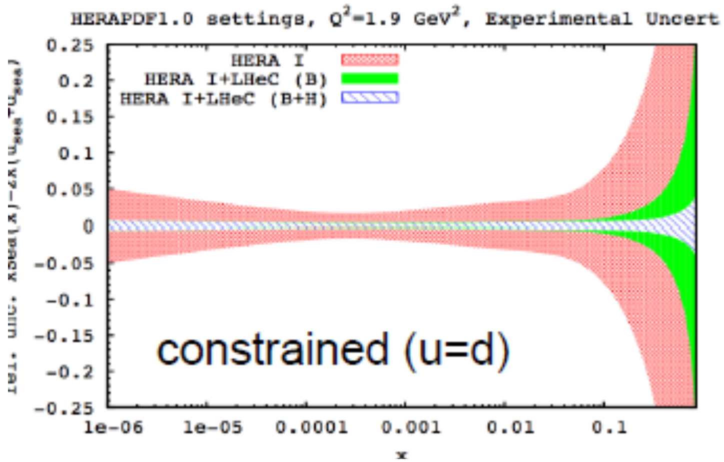
Blue is what we have now averaged over x for each Q2 bin
Red is what we could get from the LHeC
(note thst Ee rather than Ep is varied to make this measurement so it does not interfere with p-p)

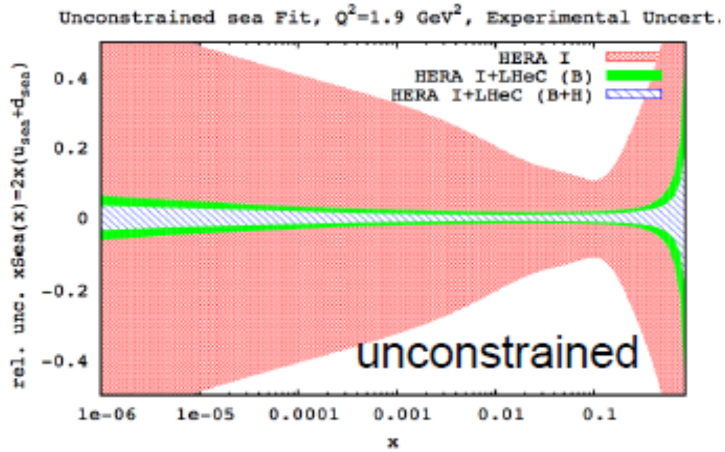
Compare LHeC pseudo-data predicted by a non-linear saturation based model to the DGLAP predictions.

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.

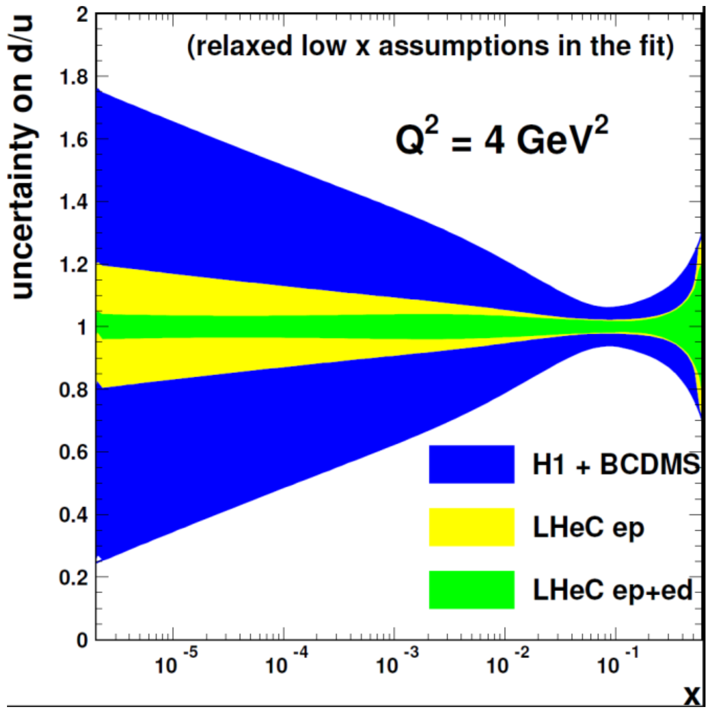
Here we compare uncertainties on the total sea distribution





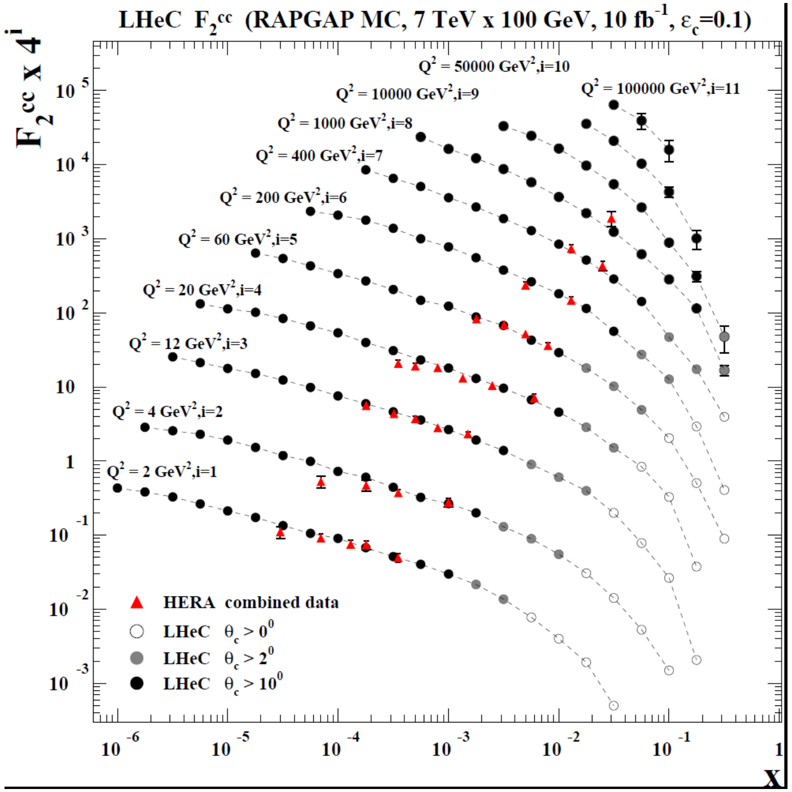
And here we compare uncertainties on the d/u ratio

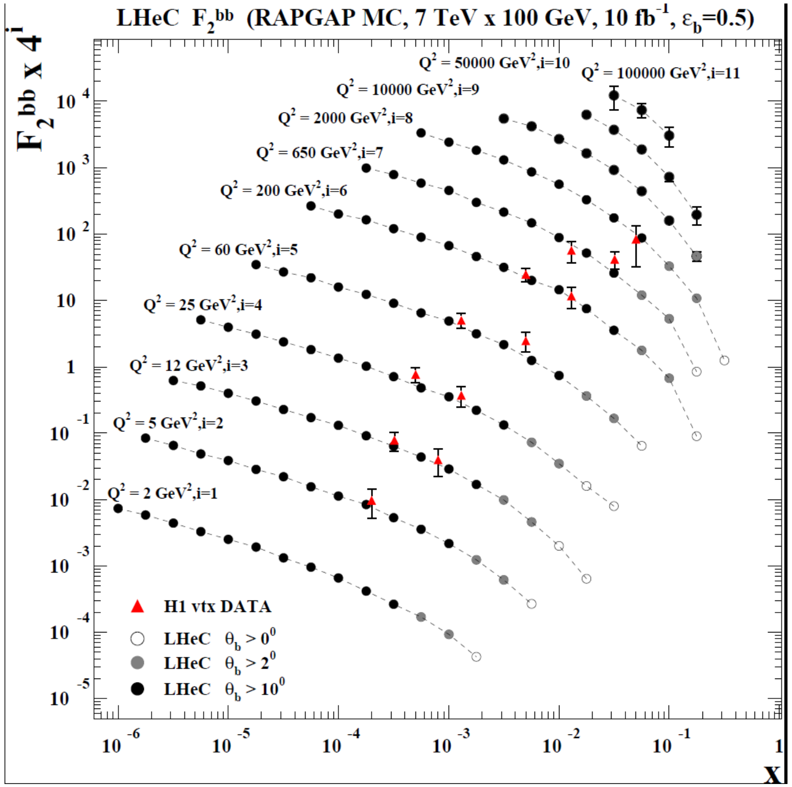
This would improve more if deuteron target data are used.
Deuterons can also give information on neutron structure and on Gribov's relationship between shadowing/diffraction



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?

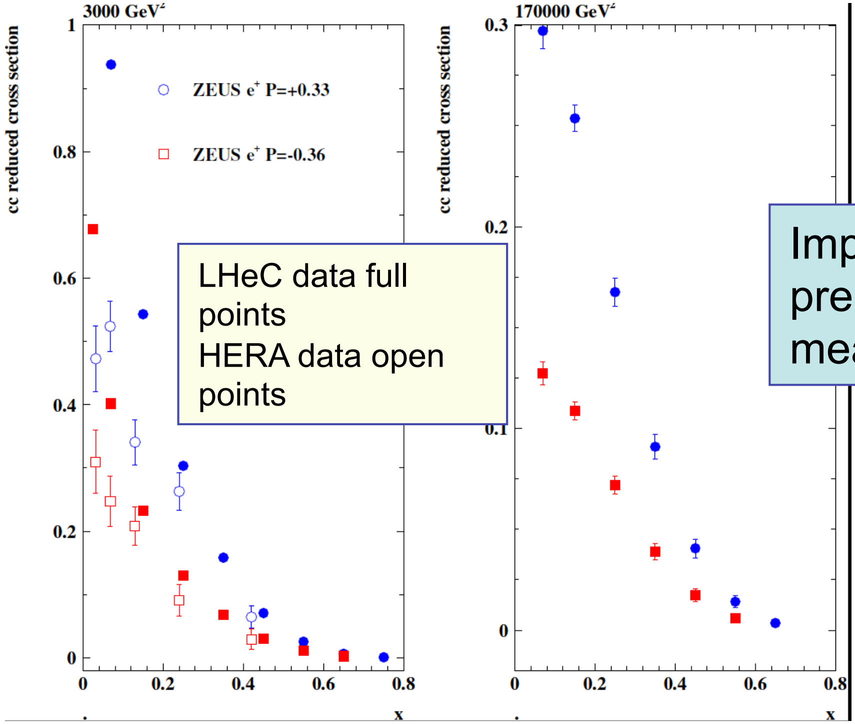
higher cross section, higher Q^2, higher luminosity (F2b!)

smaller envelope of interaction, new generation of Si detectors

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

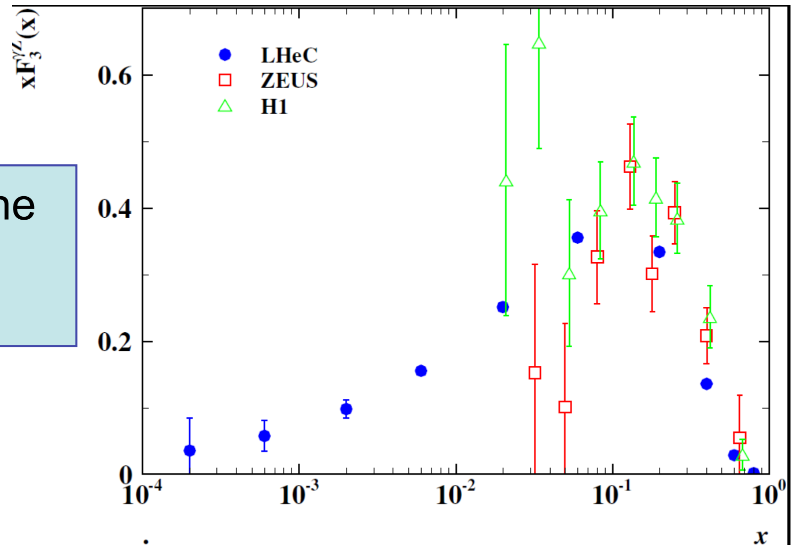
top: tPDF, cross section few pb at Ee=60GeV,

Electroweak studies

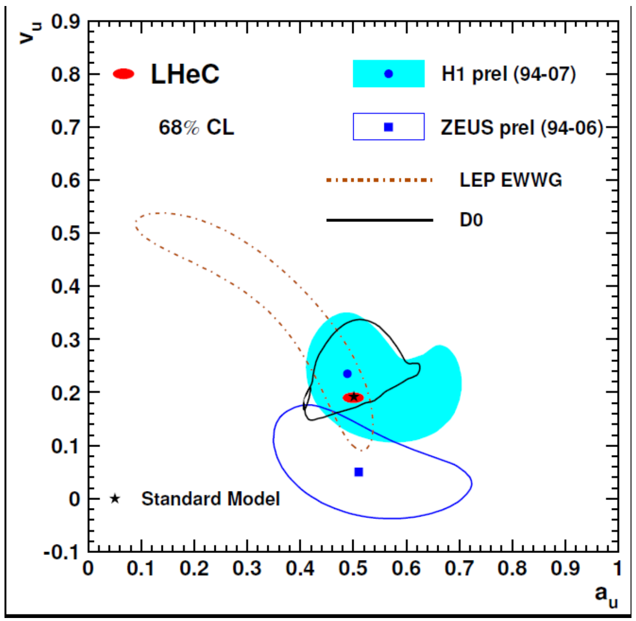


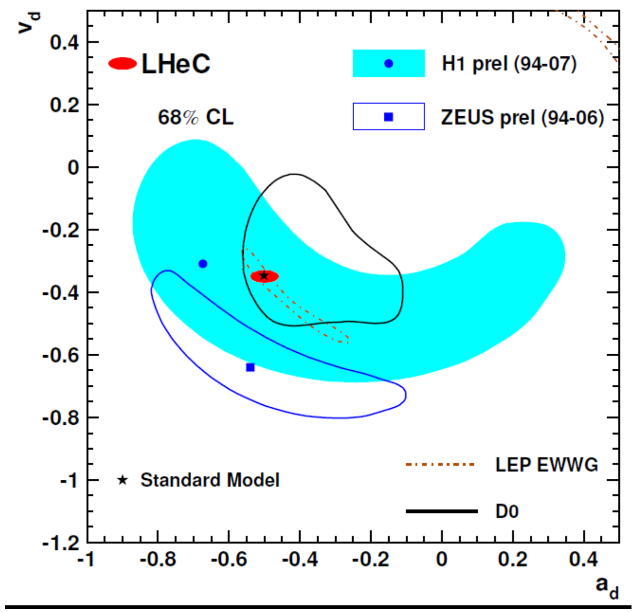
LHeC data full points
HERA data open points

Improvement in the precision of the measurements



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





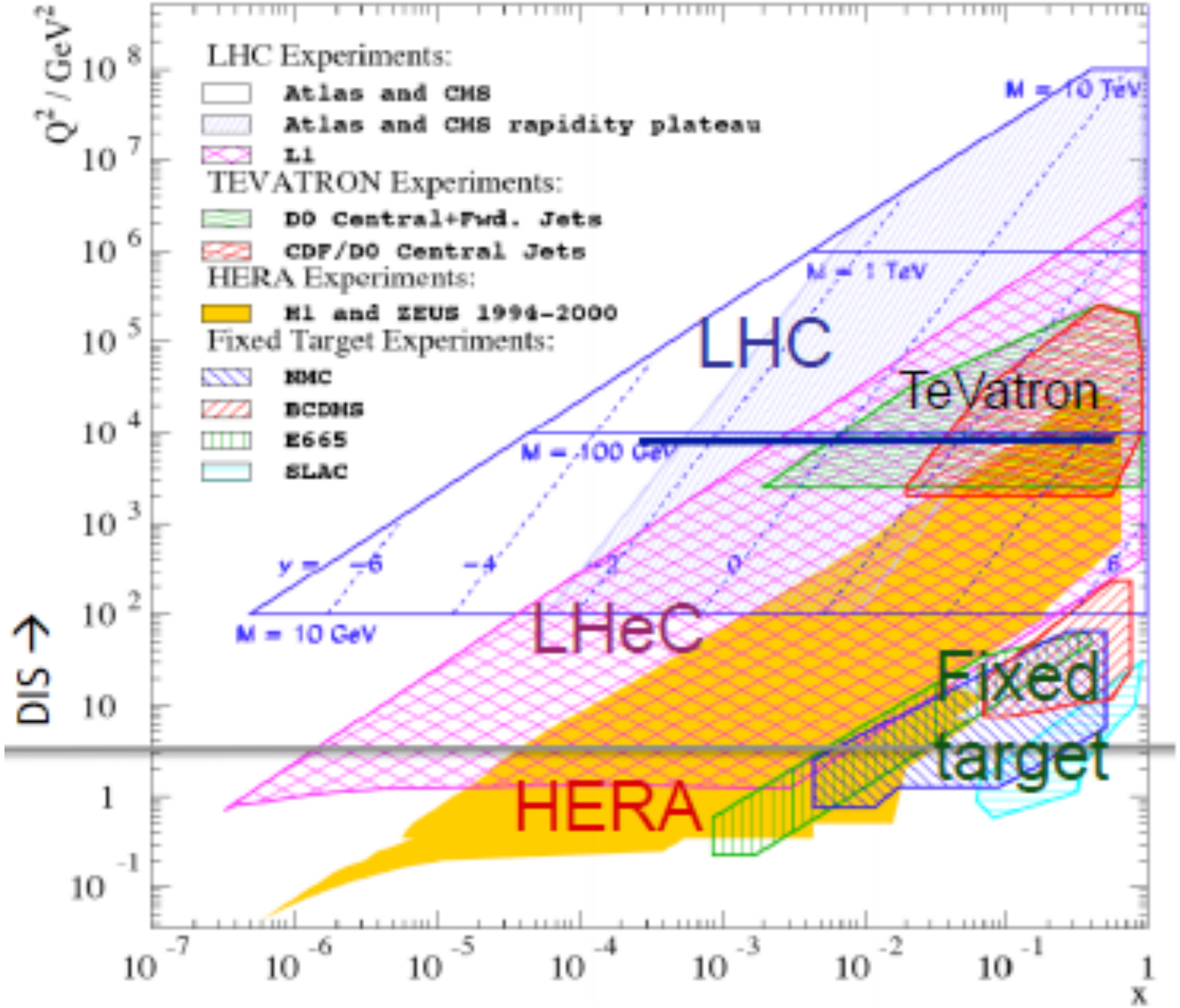
Precision DIS Topics I haven't covered

- Jet production in DIS ET up to 500 GeV
- Forward jets, azimuthal de-correlation between jets
- Forward π^0 production
- Total photo-production cross section
- Connections to ultra-high energy neutrinos
- Inclusive diffraction
- Diffractive jet production
- DVCS
- Vector meson production

Summary

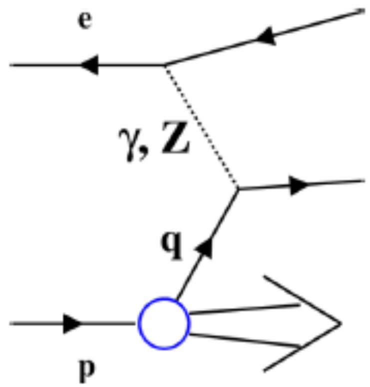
The LHeC represents an increase in the kinematic reach of Deep Inelastic Scattering and an increase in the luminosity.

- 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’



Q^2 / GeV^2
LHC Experiments:
Atlas and CMS
Atlas and CMS rapidity plateau
L1
TEVATRON Experiments:
D0 Central+Fwd. Jets
CDF/D0 Central Jets
HERA Experiments:
H1 and ZEUS 1994-2000
Fixed Target Experiments:
NMC
BCDMS
E665
SLAC
M = 10 TeV
M = 1 TeV
M = 100 GeV
M = 10 GeV
y = 6 4 2 0 -2 -4 -6
LHC
TeVatron
LHeC
Fixed target
HERA
DIS →
x

Master formulae for NC DIS



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

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

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

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

Vary charge and polarisation and beam energy to disentangle contributions

Charged Currents

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

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

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

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

$$\sigma^{+}_{r,CC} \sim x\overline{U} + (1 - y)^2 x D,$$

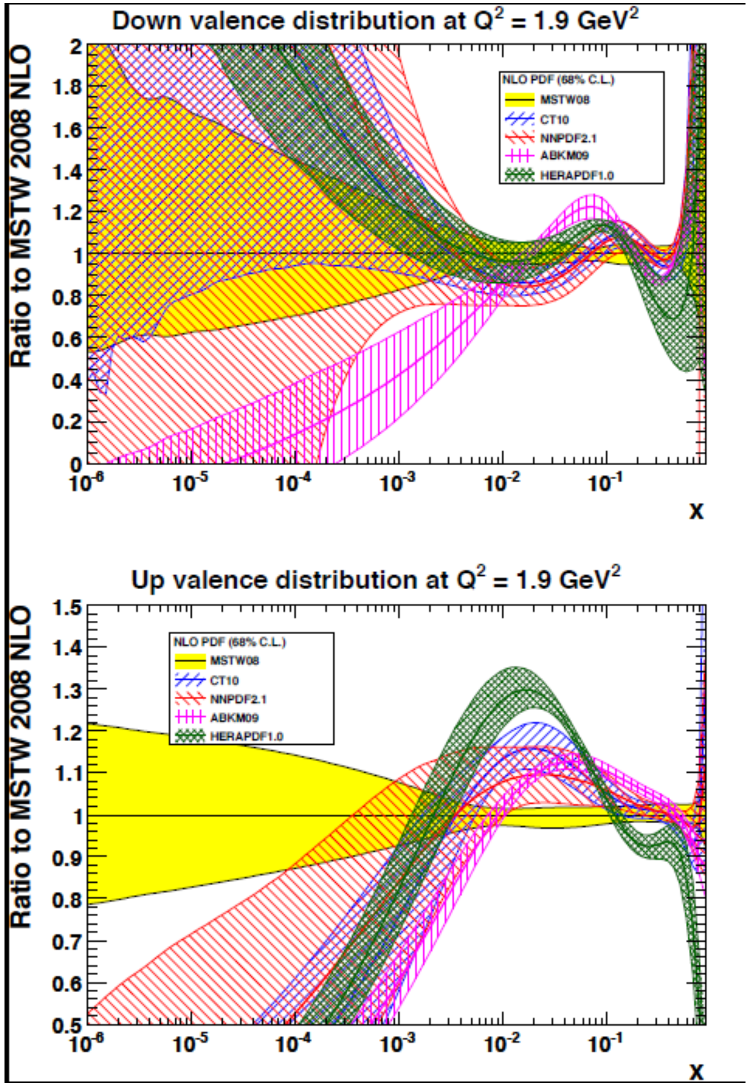
$$\sigma^{-}_{r,CC} \sim xU + (1 - y)^2 x\overline{D}$$

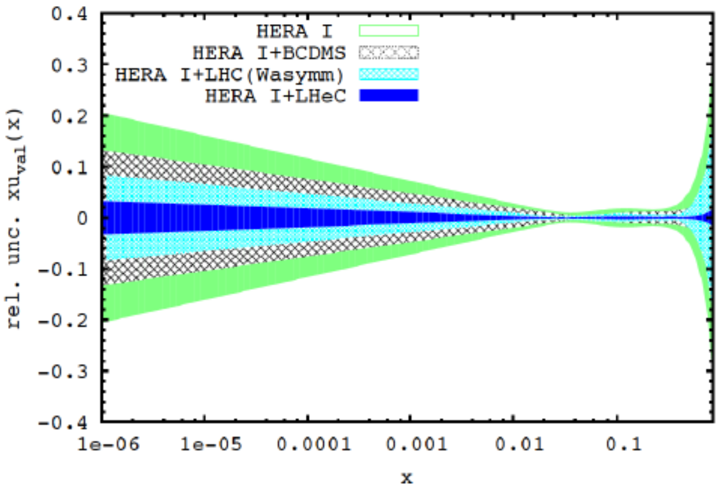
$$\sigma^{\pm}_{r,NC} \simeq [c_u(U + \overline{U}) + c_d(D + \overline{D})] + \kappa_Z[d_u(U - \overline{U}) + d_d(D - \overline{D})]$$

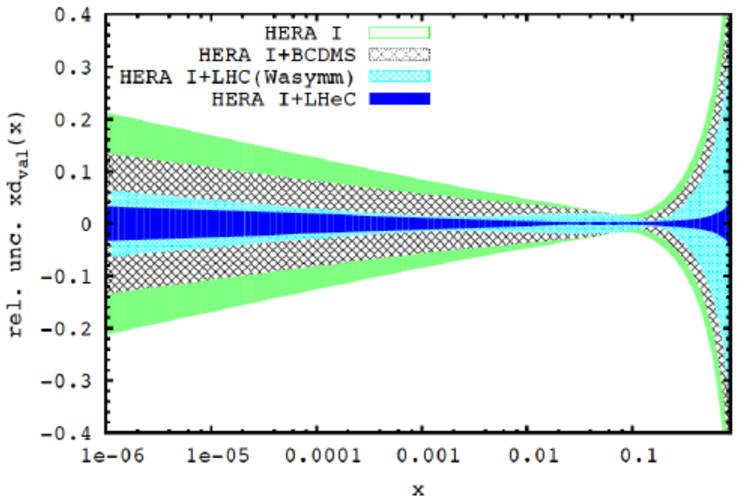
with $c_{u,d} = e^2_{u,d} + \kappa_Z(-v_e \mp P a_e) e_{u,d} v_{u,d}$ and $d_{u,d} = \pm a_e a_{u,d} e_{u,d}$,

Complete unfolding of all parton distributions to unprecedented accuracy

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





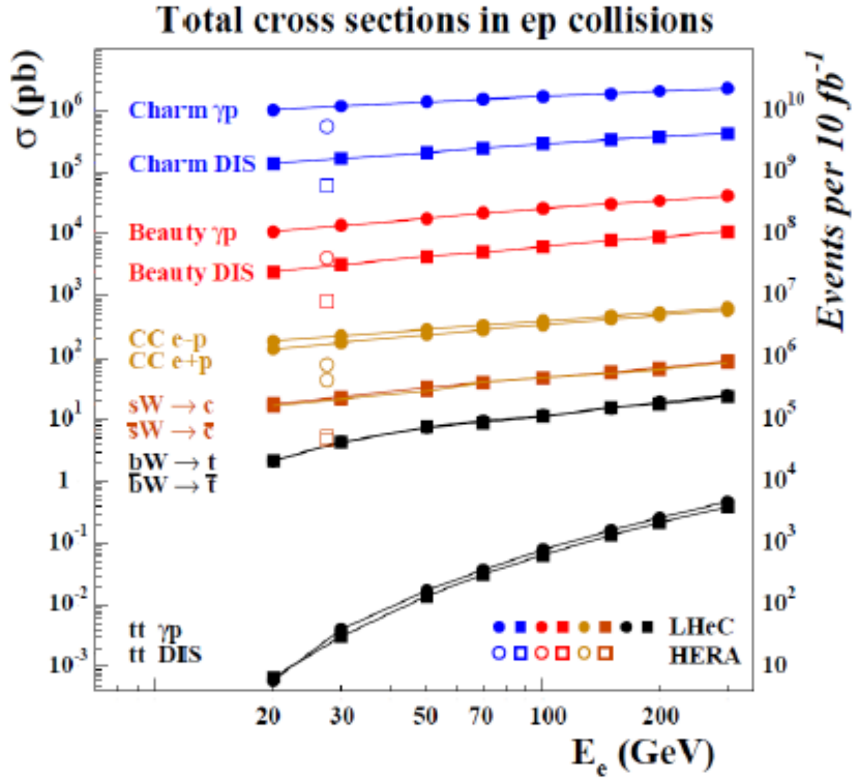


Heavy Quarks

Total production cross section predictions for heavy quark processes at LHeC

simulation:

Process	Monte Carlo	PDF
Charm γp Beauty γp tt γp	PYTHIA6.4 [145]	CTEQ6L [146]
Charm DIS Beauty DIS tt DIS	RAPGAP3.1 [147]	CTEQ5L [148]
CC e^+p CC e^-p $sW \to c$ $\bar{s}W \to \bar{c}$ $bW \to t$ $\bar{b}W \to \bar{t}$	LEPTO6.5 [149]	CTEQ5L
tt DIS	RAPGAP 3.1	CTEQ5L



→ access to all quark flavours with high statistics

Strange Quarks at LHeC

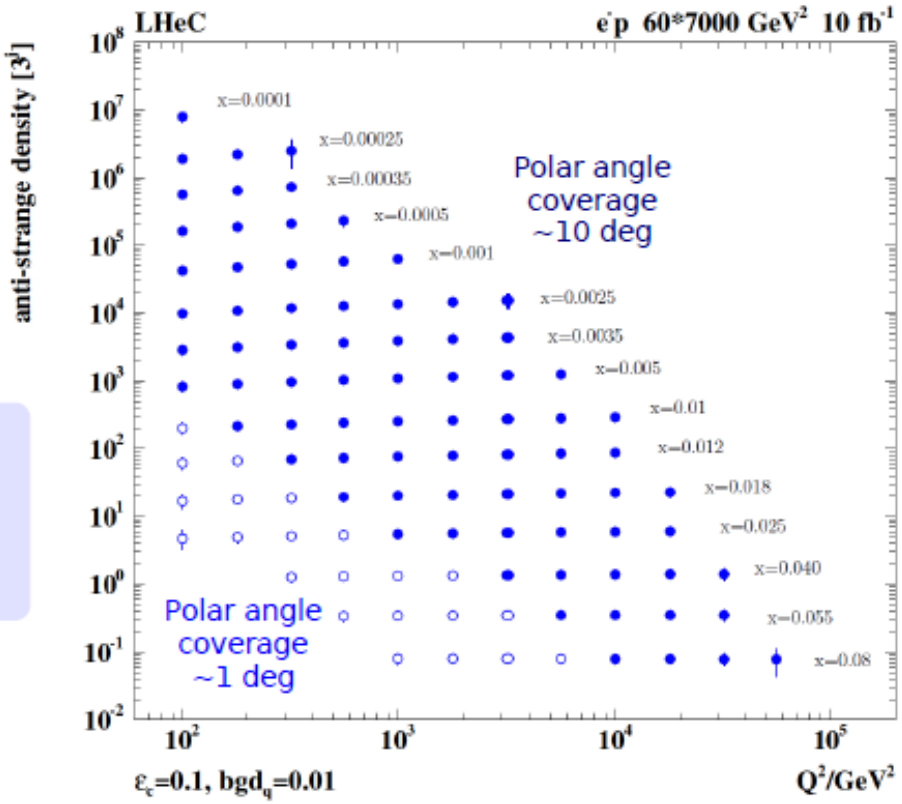
Simulated measurement of the anti-strange quark density in CC e^-p scattering with charm tagging at the LHeC with L = 10 fb^{-1}

→ $\bar{s}$ measurement

$W^- \bar{s} \to \bar{c}$

(similar for s)

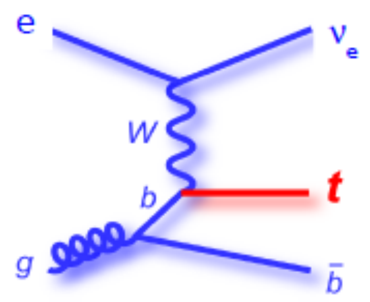
LHeC provides a possibility for precise s quark density measurements for the first time



Top Quarks at LHeC

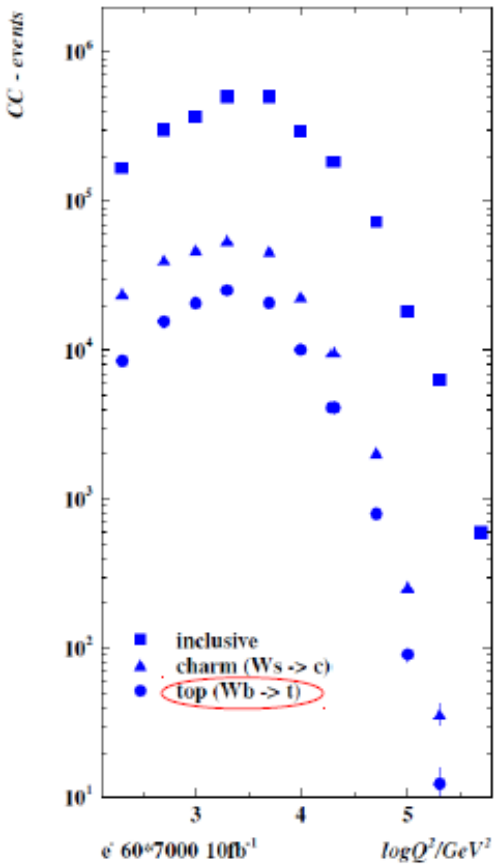
Top quarks can be studied in DIS (negligible cross section at HERA)

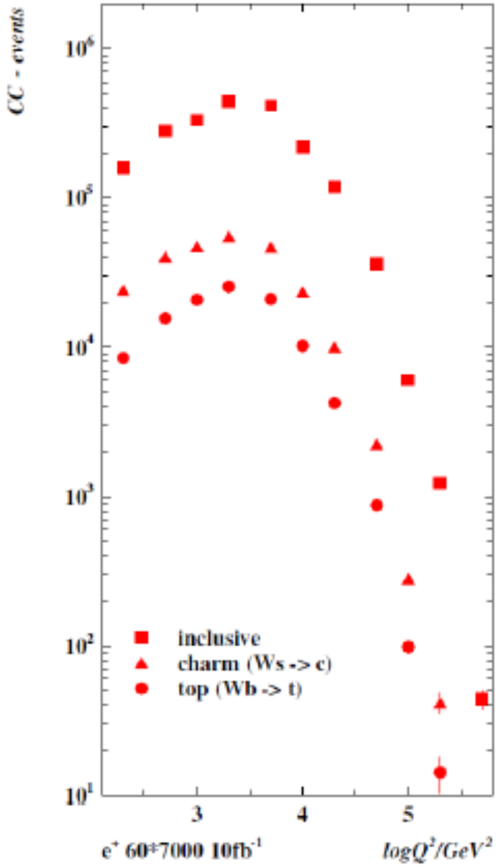
CC: Wb → t production
(cross section O(10pb))



NC: ttbar pair production

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





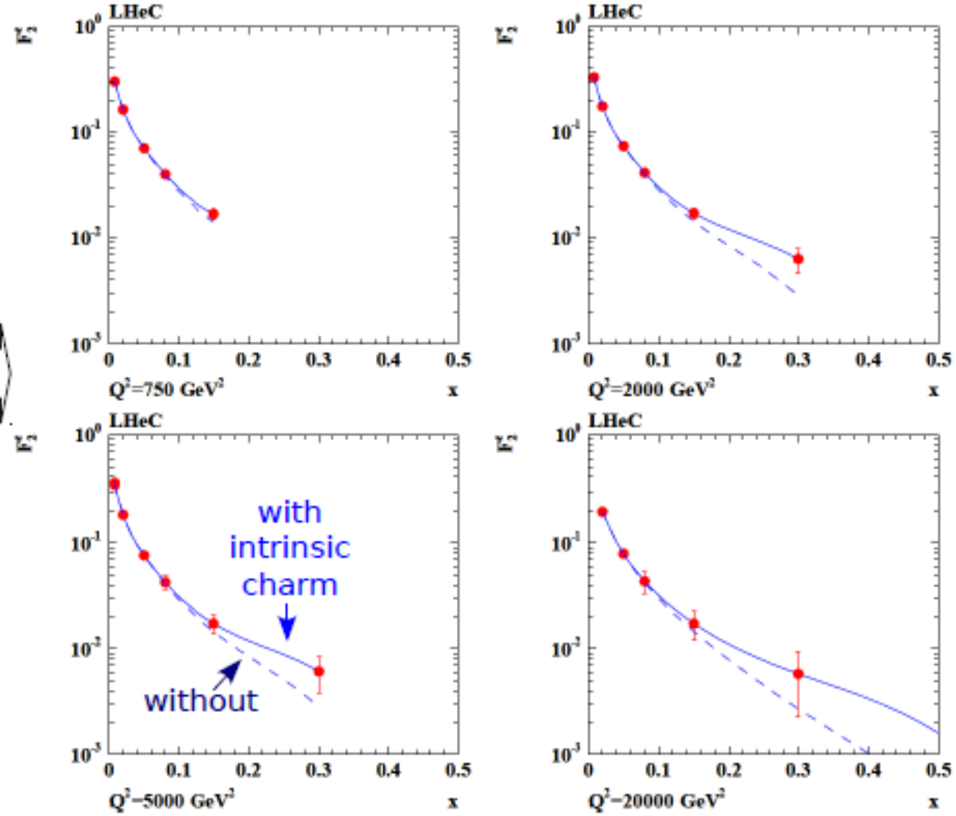
Intrinsic Charm

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

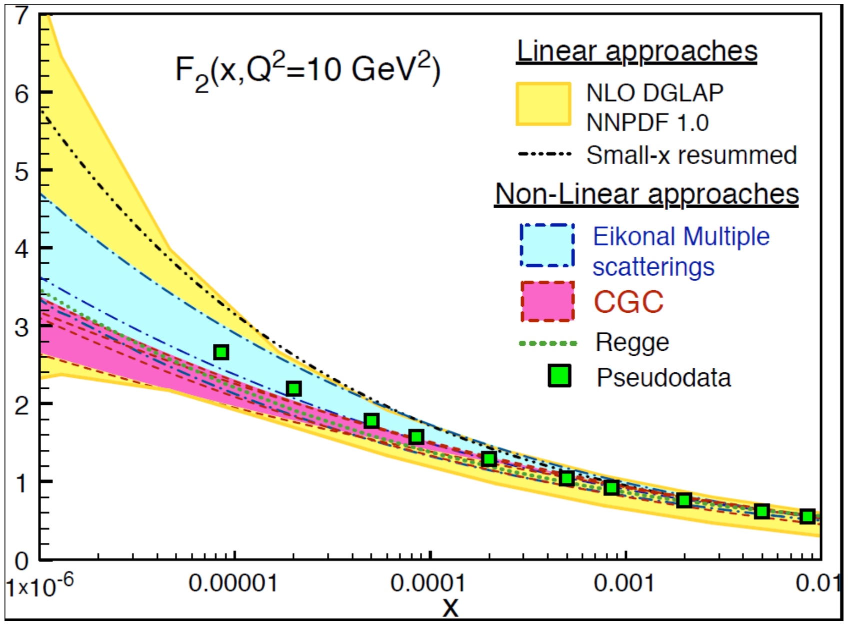
→ may explain certain aspects of the charm data and dominate in some regions of the phase space

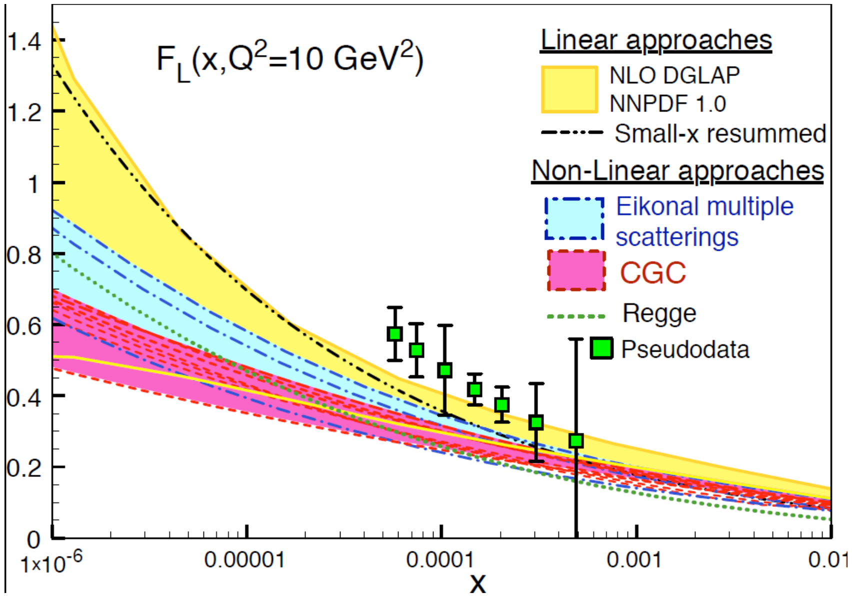
for large x very good forward tag acceptance needed (possible with reduced E_p)

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

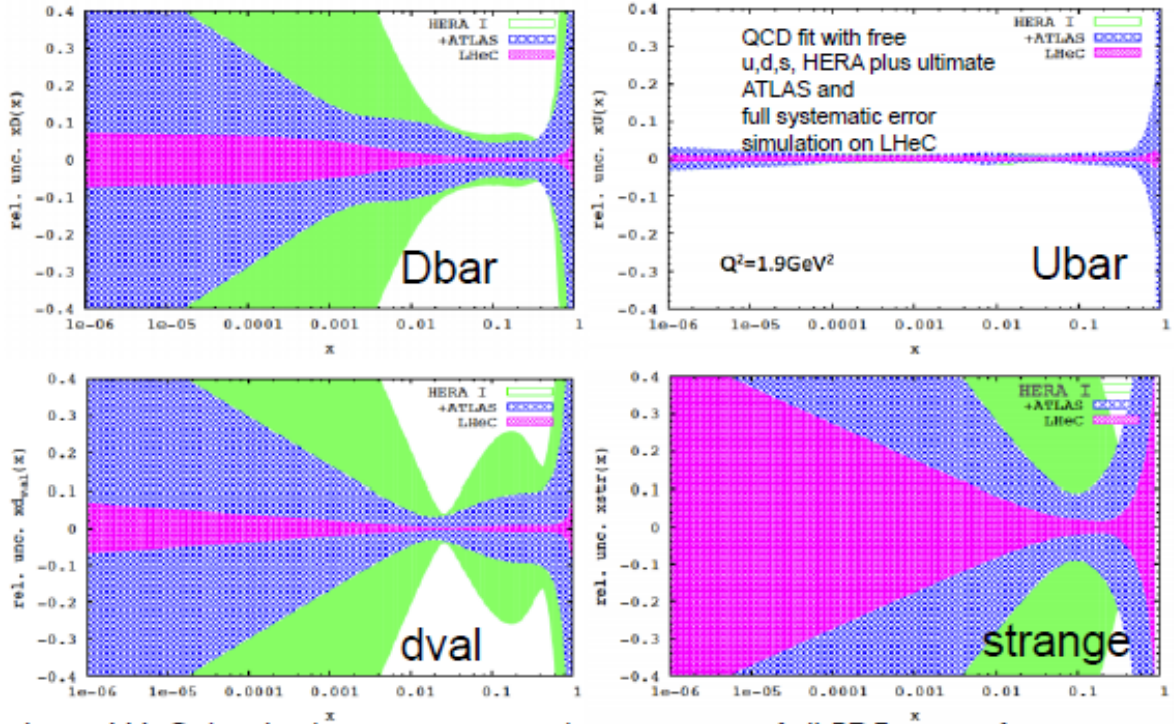


→ reliable detection of an intrinsic heavy charm component challenging but possible


$F_2(x,Q^2=10\ GeV^2)$
Linear approaches
NLO DGLAP
NNPDF 1.0
Small-x resummed
Non-Linear approaches
Eikonal Multiple
scatterings
CGC
Regge
Pseudodata
x


$F_L(x,Q^2=10\ GeV^2)$
Linear approaches
NLO DGLAP
NNPDF 1.0
Small-x resummed
Non-Linear approaches
Eikonal multiple
scatterings
CGC
Regge
Pseudodata
x

Releasing assumptions



Inclusive LHeC data leads to very precise determination of all PDFs even after removing large bulk of assumptions:

LHeC ep data constrain better U than D distributions, however deuteron data would symmetrise our understanding.

Determination of the strange can complement the strange determination from the charm data

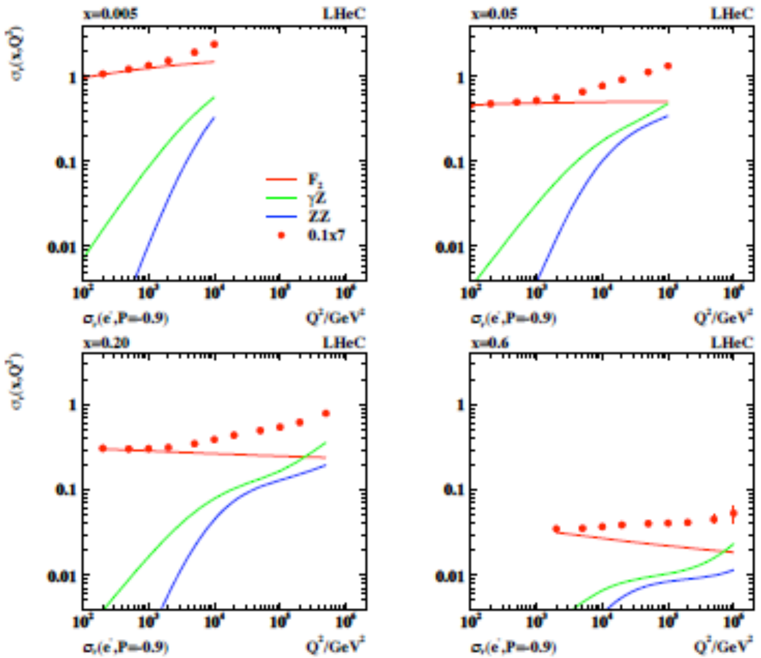


Figure 3.37: Simulated measurement of the neutral current DIS cross section (closed points) with statistical errors for $10\,\mathrm{fb}^{-1}$ shown as a function of Q^2 for different values of Bjorken x. The different curves represent the contributions of pure photon exchange (red), γZ interference (green) and pure Z exchange (blue) as prescribed in Eq. 3.5. Note the high precision of the reduced cross section measurement up to large x and Q^2.

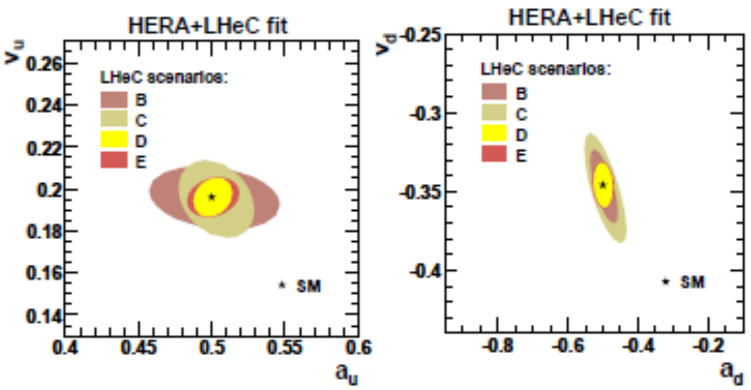


Figure 3.35: Determination of the vector and axial-vector weak neutral couplings of the light quarks at the LHeC, determined from a joint NLO QCD and electroweak χ^2 analysis of simulated NC and CC cross section data using different beam scenarios as are summarised in Table 3.2. The uncertainties comprise the full experimental errors and consider their correlations.

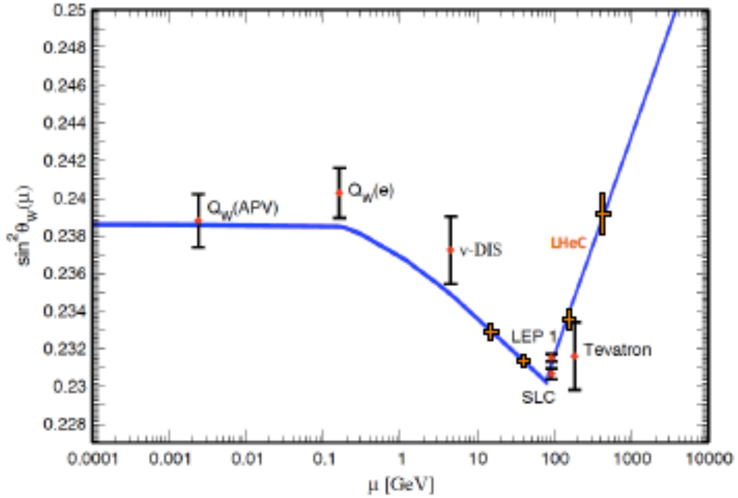


Figure 3.39: Dependence of the weak mixing angle on the energy scale μ, taken from [64]. Four simulated points have been added based on the estimated measurement accuracy using the polarisation asymmetry A^- binned in intervals of $\sqrt{Q^2}$, see text.