PDFs from the LHC and LHeC

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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 as well as the background to BSM searches

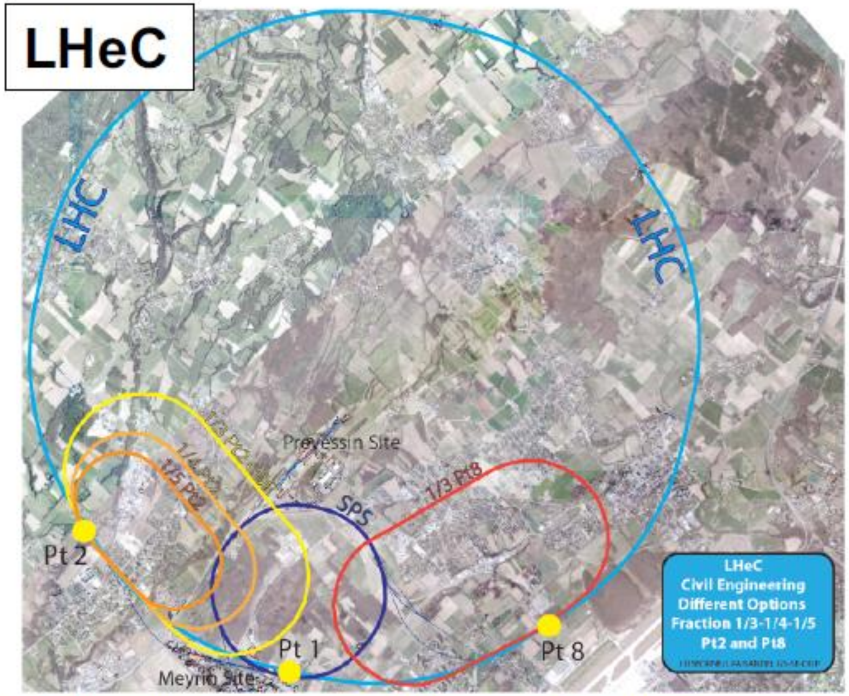
With higher luminosity and higher energy machines on the horizon we will need higher precision PDFs

Do we NEED an LHeC? Will we not improve the precision of the PDFs using LHC data itself?

No time to talk about:

- Improved $\alpha_S(M_Z)$ measurement
- Improved Higgs measurements
- FCCeh

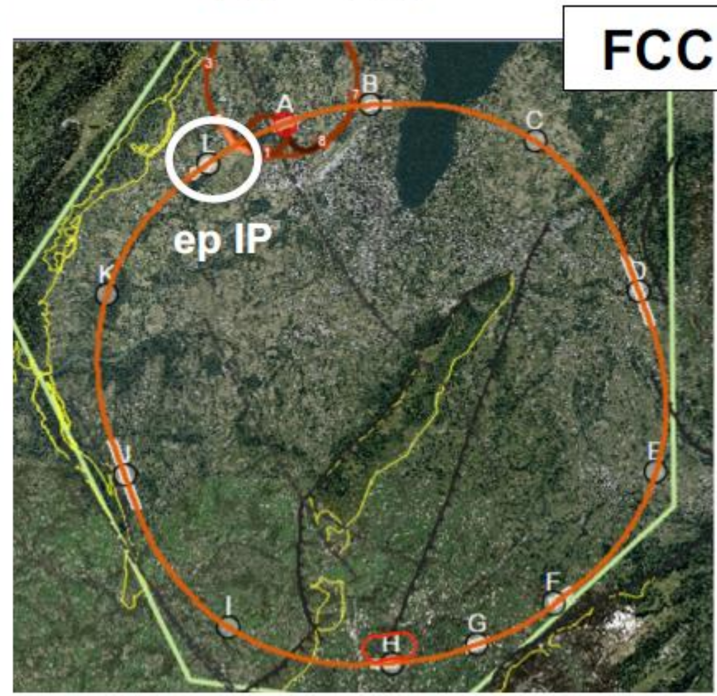
LHeC and FCC-eh



(M Klein, Rencontre du Vietnam, Sept 2017)

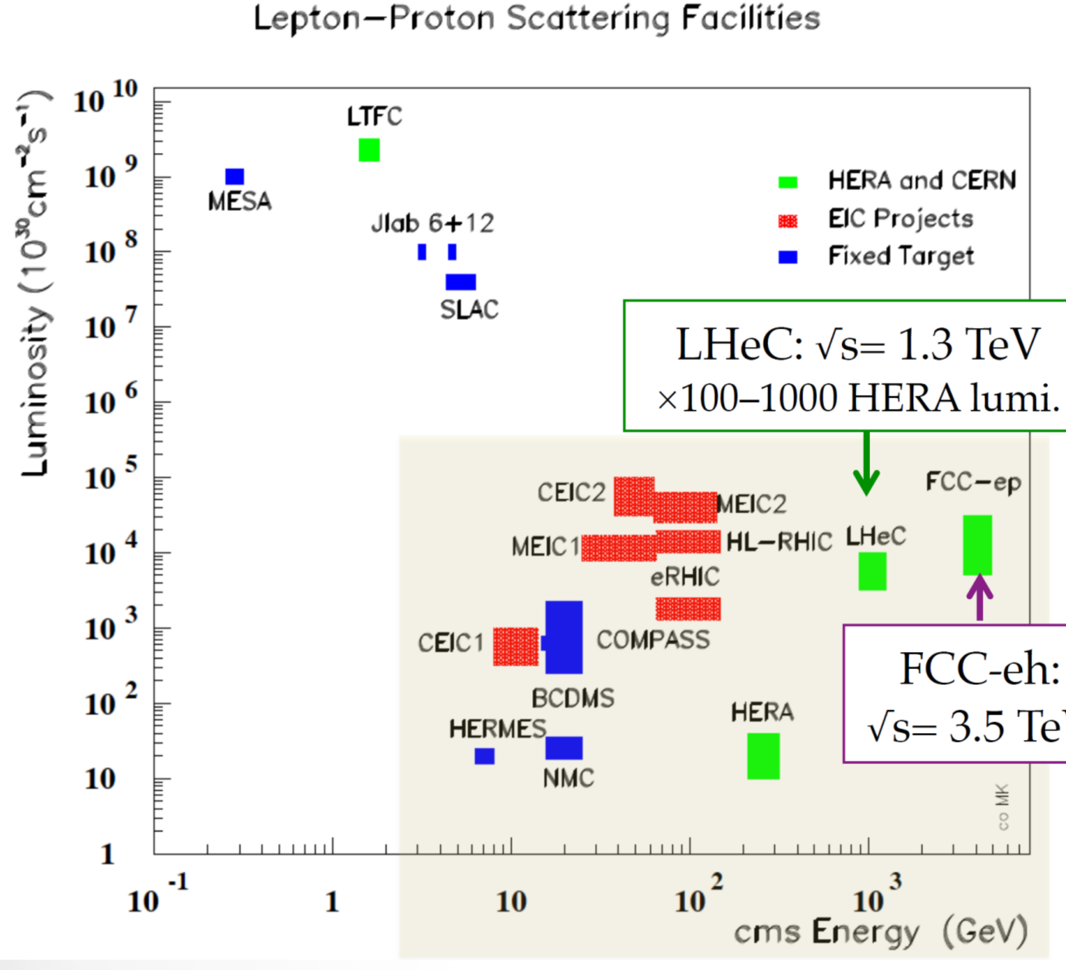
for collider and detector, see talks
by: D Pellegrini, M Klein

LHeC and **FCC-eh**
energy recovery LINAC
e-beam: 60 GeV
$L_{int} \to 1\ ab^{-1}$

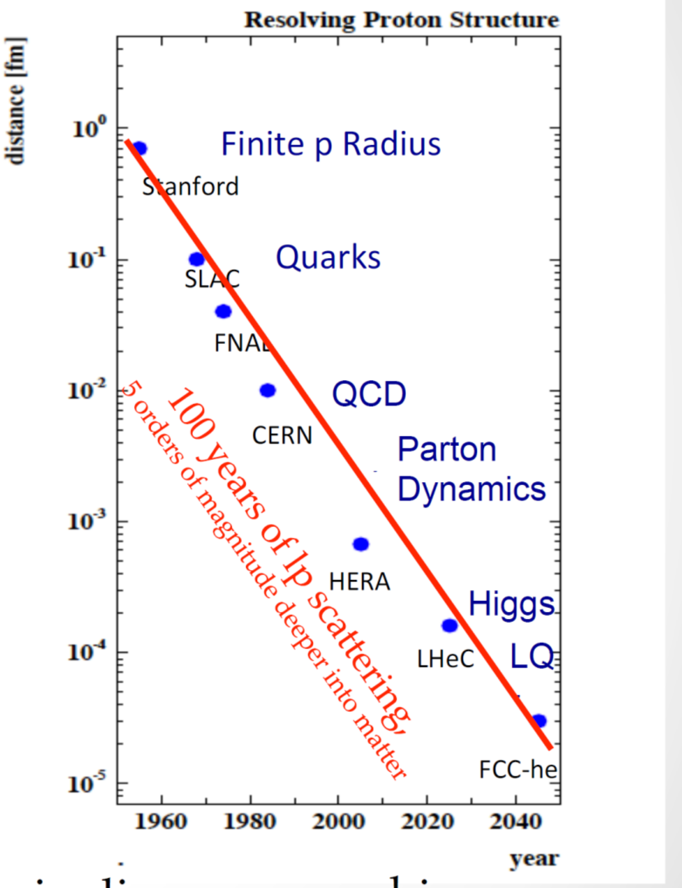


LHeC (**FCC-eh**) complementary to, synchronous with, **HL-LHC** (**FCC**)

lepton-proton facilities

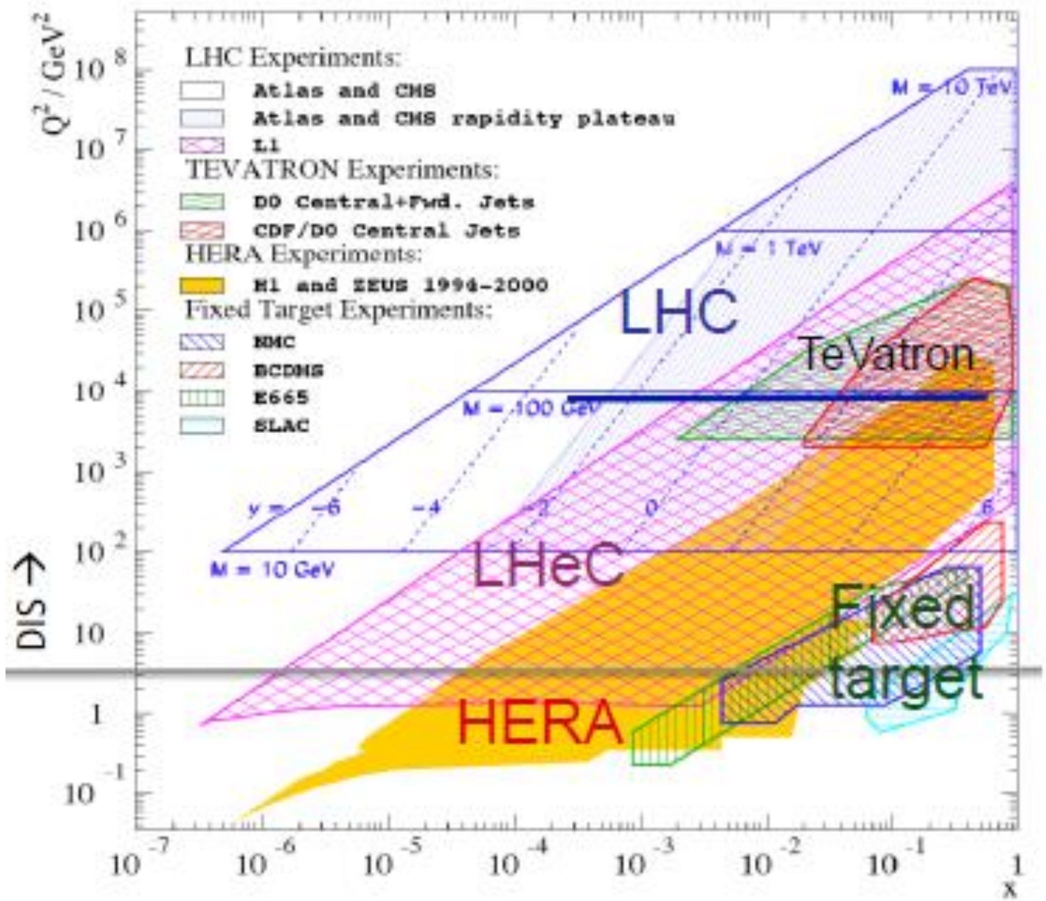


HERA–LHeC–FCC-eh:
finest microscopes, resolution as 1/Q



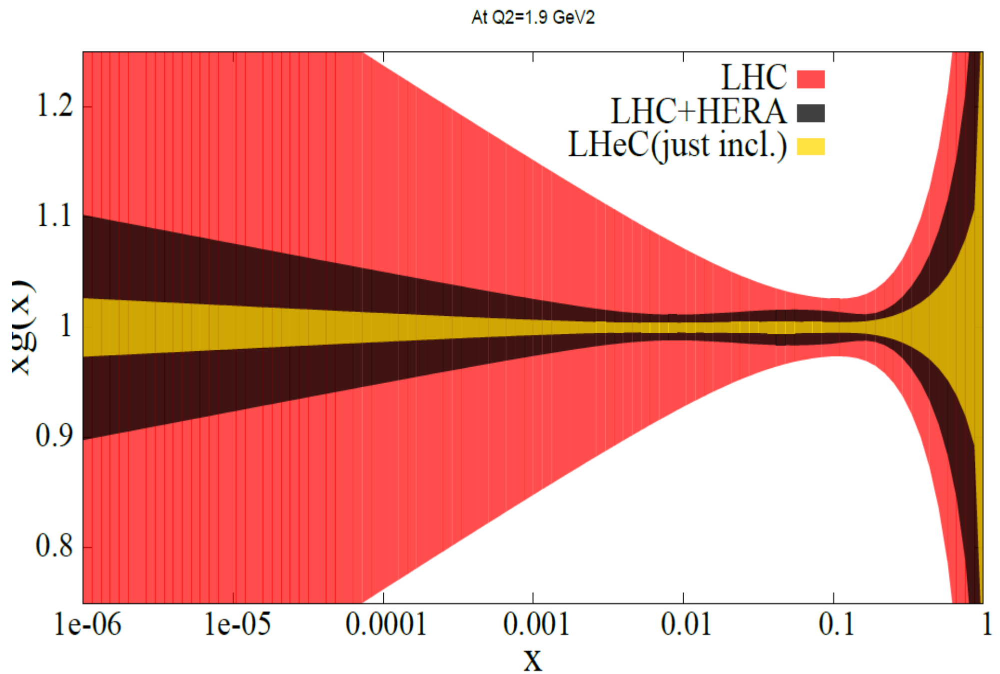
LHC (and other future machines eg. FCC-pp) is/will be main discovery machine

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



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

- This represents a tremendous potential for the 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



Let's ask the question-
Can we determine PDFs just from the LHC?

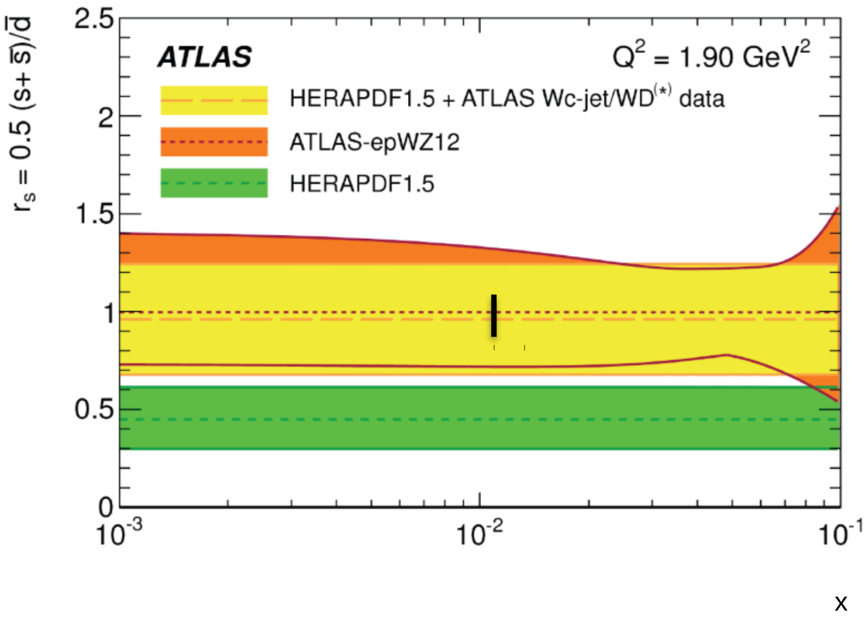
NOT with any precision NO !

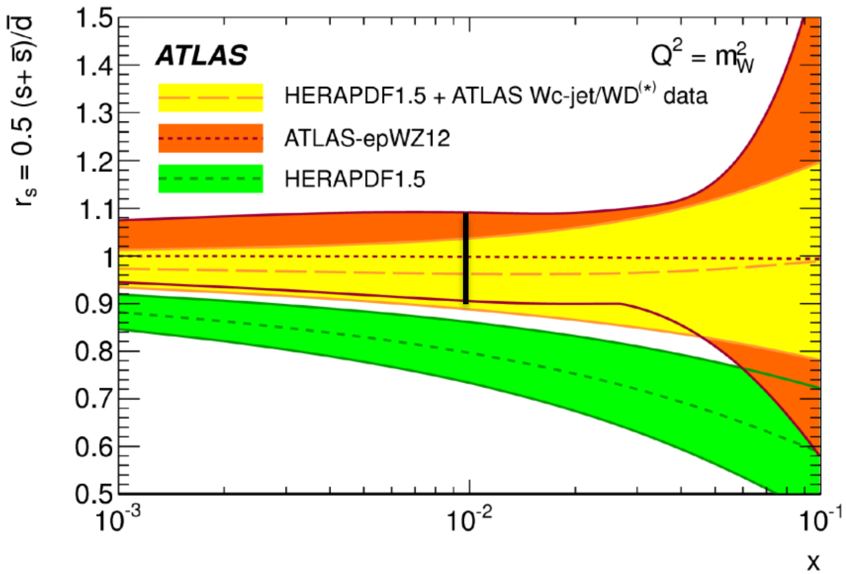
Present LHC W,Z data and jet data are included and LHC ultimate precision is extrapolated according to our current experience– we are systematics limited already

PDFs come from DIS

But this plot is a little old (2014) let us examine:

- Why the DIS data do better
- IF this is still true with our experience of PDF fitting today (2017)





Let us first examine WHY?

For illustration, these are plots of the strangeness fraction in the proton r_s from ATLAS analyses in which it is equal to the light quarks and in the HERAPDF1.5 in which it is ~0.5 of the light quarks.

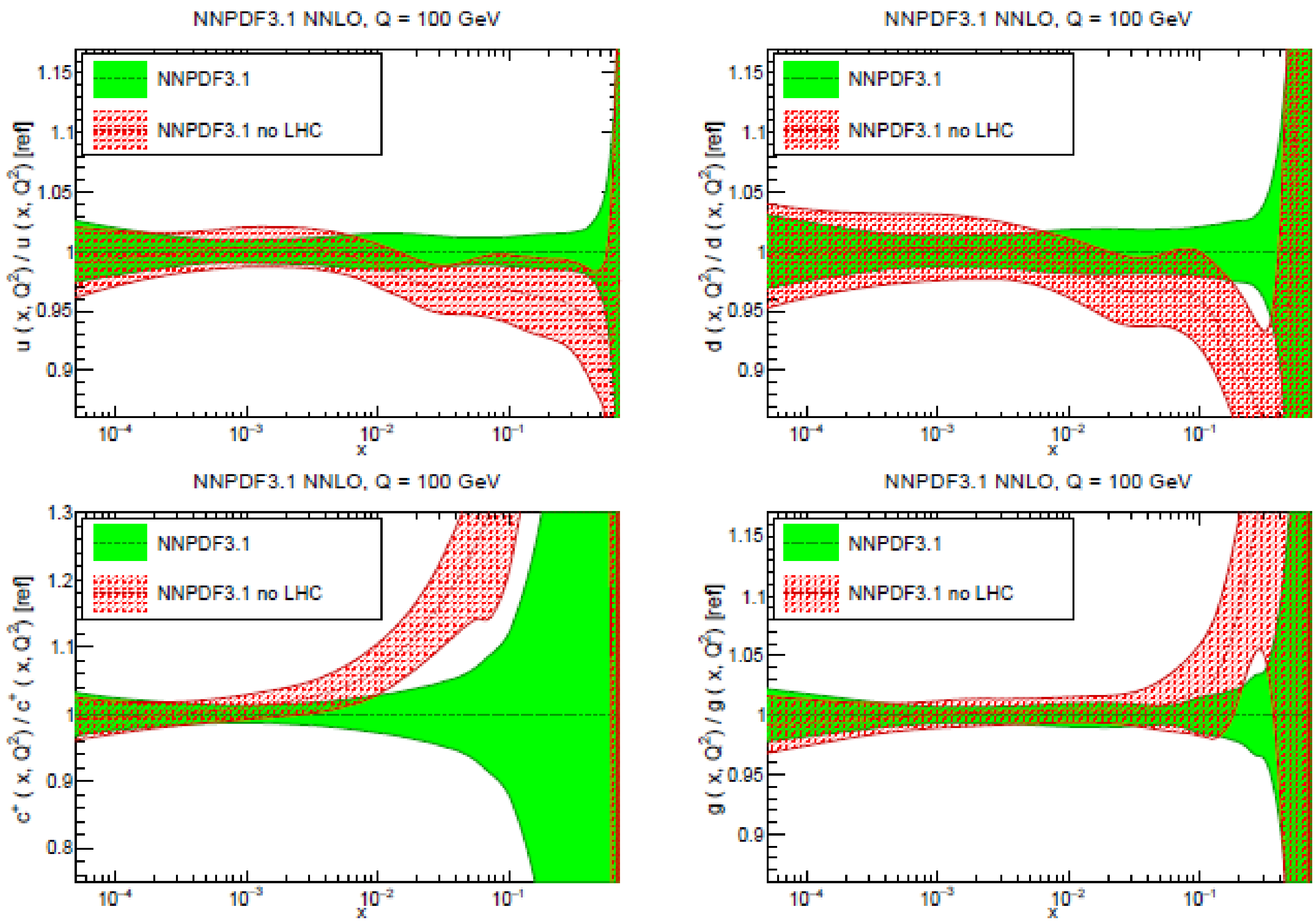
This fraction is shown at the starting scale Q^2_0 ~2 GeV² and at $Q^2=M_W^2$
NOTE the difference in scale.
PDF uncertainties decrease as Q^2 increases because the PDFs depend LESS on the parametrisation at the starting scale and MORE on the known QCD evolution.

On each plot is shown a hypothetical measurement with ±10% accuracy.
Clearly this could distinguish the rs predictions if performed at Q^2_0, but not if performed at high scale.
At high scale we have to have much more accurate measurements.

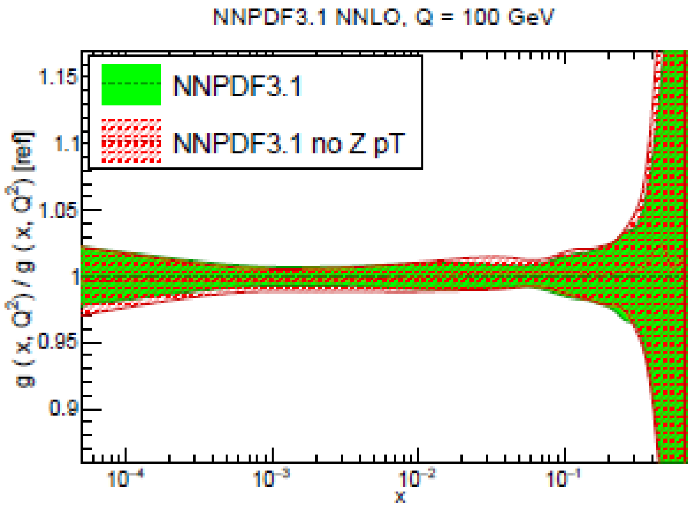
So let’s see how well the LHC is doing

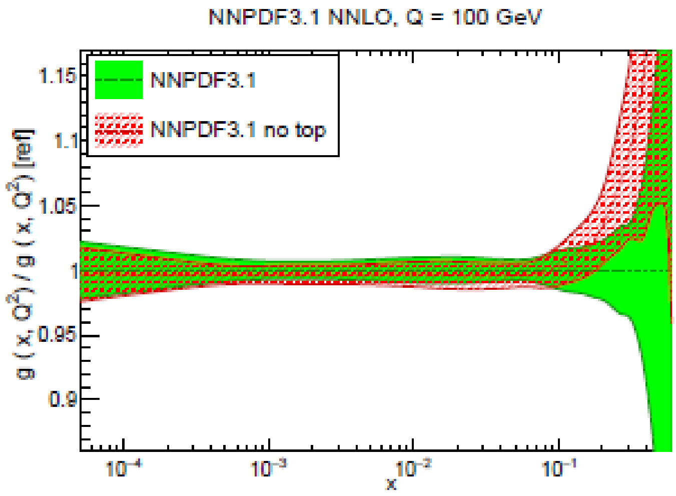
NNPDF3.1 includes modern LHC data on W,Z +jets+top+Zpt from 7 and 8 TeV running

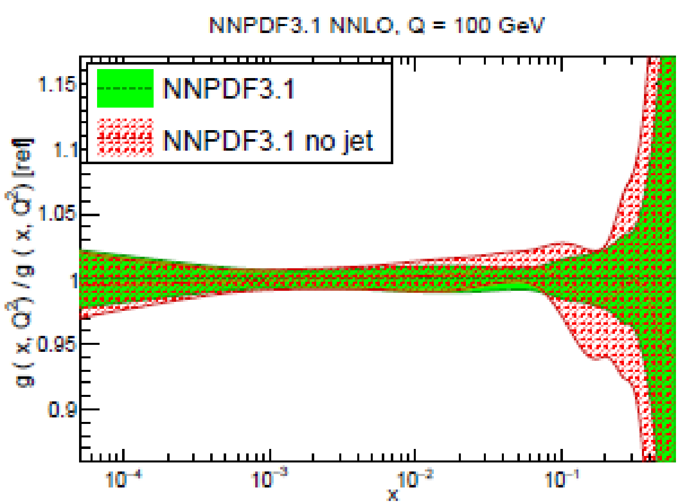
Compare PDFs with and without LHC



Look at some separate LHC data sets from NNPDF3.1 analysis

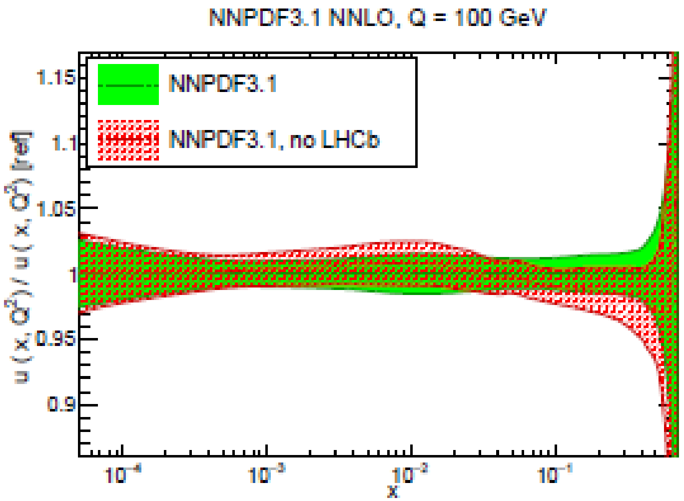


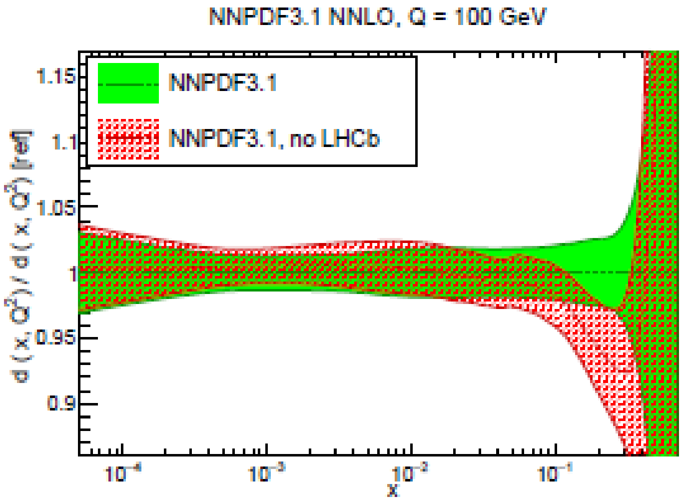


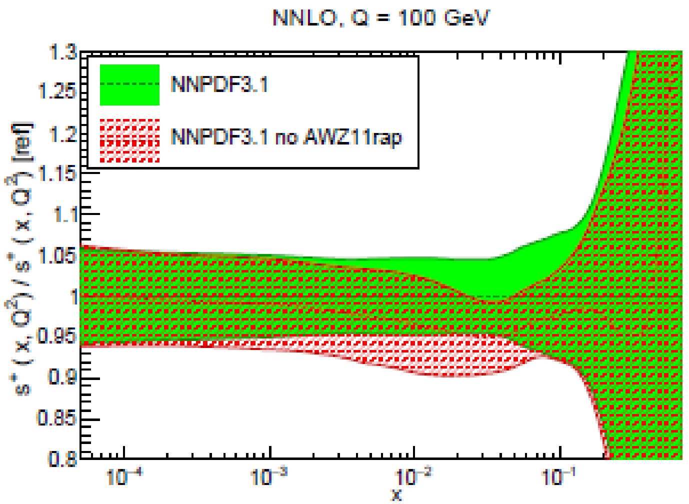


Data sets which affect the gluon:
Zpt
T-tbar differential distributions
Jet production

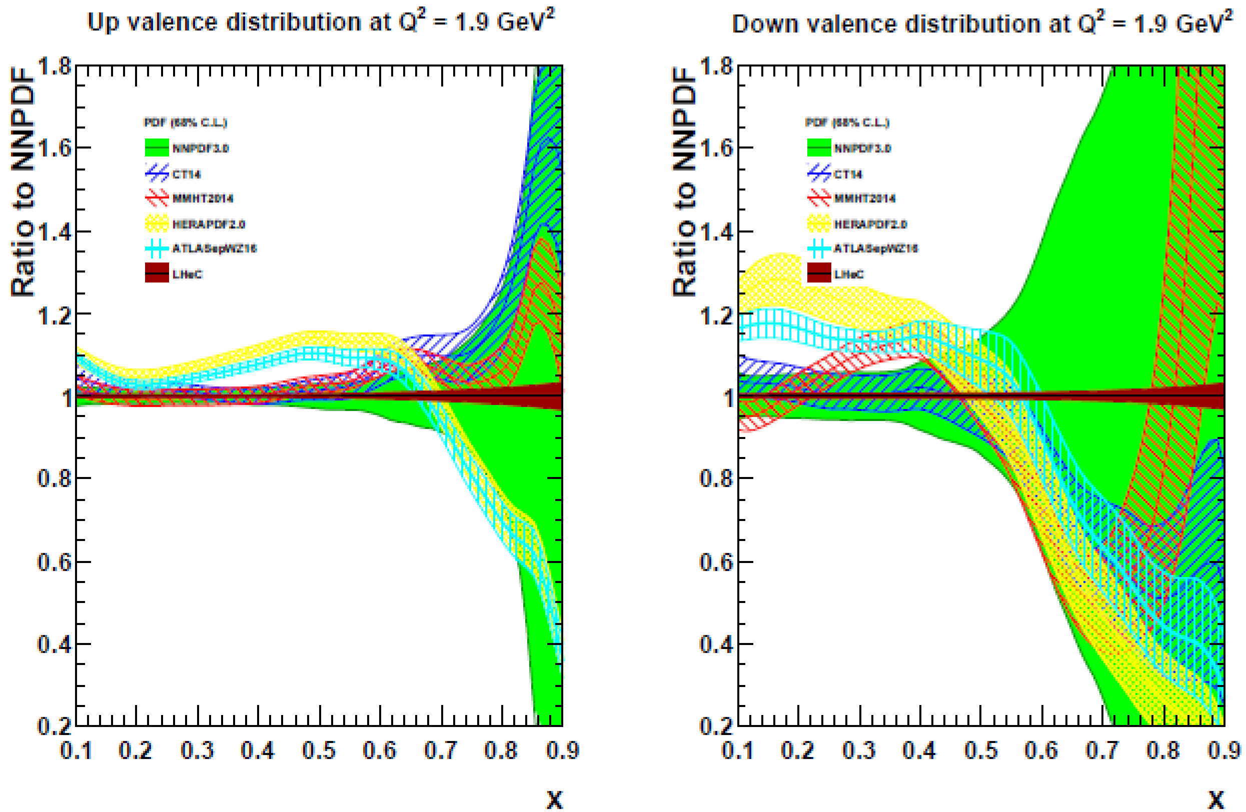
Data sets which affect the quarks
W+, W-, Z production from Tevatron, LHCb, ATLAS, CMS



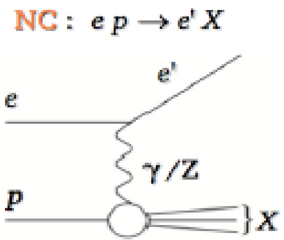


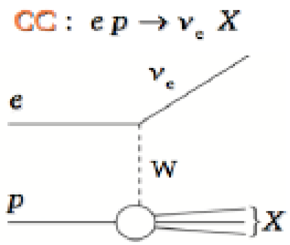


Now let's compare this to the projections for the improvements from an LHeC measurement added to today's data



Let's recap HOW these LHeC predictions are obtained.





- 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:

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

- 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

Studies beyond the LHeC CDR (2012) have now been made. The main difference is in assumptions about luminosity

NC/CC	Name	Ee[GeV]	Ep[TeV]	P(e)	Charge	Lum[ab-1]
nominal, high luminosity data, negative polarisation						
NC	datlhec760ncem	60	7	-0.8	-1	1
CC	datlhec760ccem	60	7	-0.8	-1	1
nominal, high luminosity data, opposite polarisation						
NC	datlhec760ncep	60	7	0.8	-1	0.3
CC	datlhec760ccep	60	7	0.8	-1	0.3
positron data, unpolarised						
NC	datlhec760ncepp	60	7	0	+1	0.1
CC	datlhec760ccepp	60	7	0	+1	0.1

Typical uncertainties:

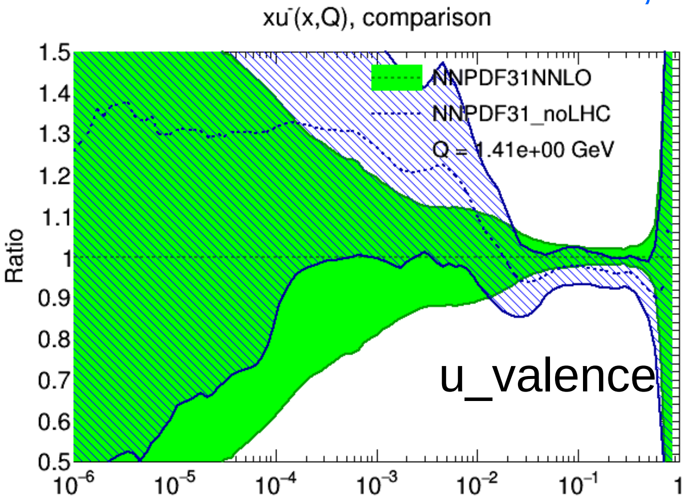
Full simulation of NC and CC inclusive cross section measurements including statistics, uncorrelated and correlated uncertainties – based on typical best values achieved by H1

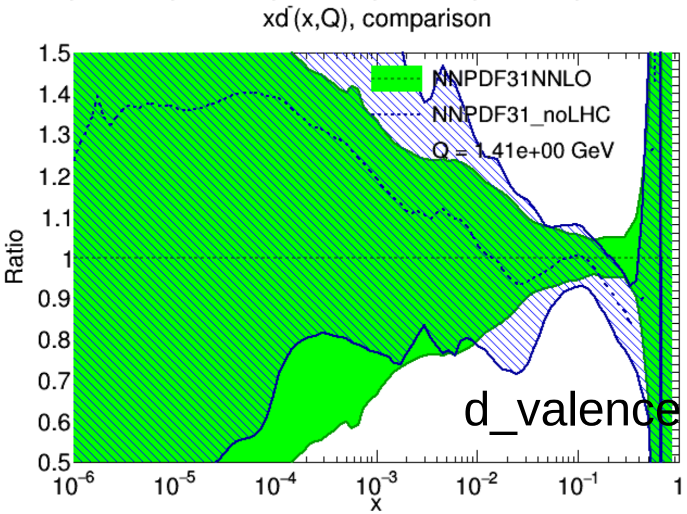
- Statistical it ranges from 0.1% (low Q^2) to ~10% for x=0.7 in CC
- Uncorrelated systematic 0.5%
- Correlated systematic: typically 1-3% (for CC high x up to 9%)

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	0.3%
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
- HERA final combined data plus HERA jet data, BCDMS F2p data
- ATLAS 2010 jet data, CMS jet data 2011, CDF, D0 jet data
- CDF, D0 Z rapidity, CDF,D0 W-asymmetry, CMS Z rapidity, CMS W-lepton asymmetries
- ATLAS total and differential t-tbar 2011, CMS total and differential t-tbar 2011
- ATLAS 2011 W and Z precision data
- xFitter framework is used, with PDF fit settings as for HERAPDF2.0 AG

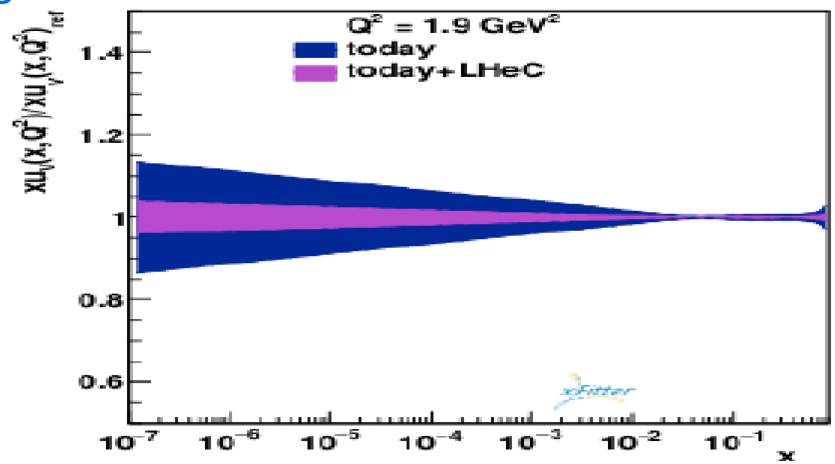


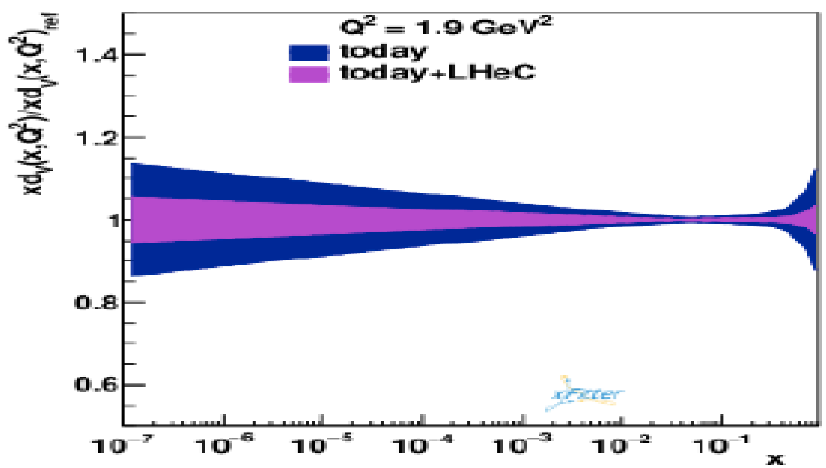


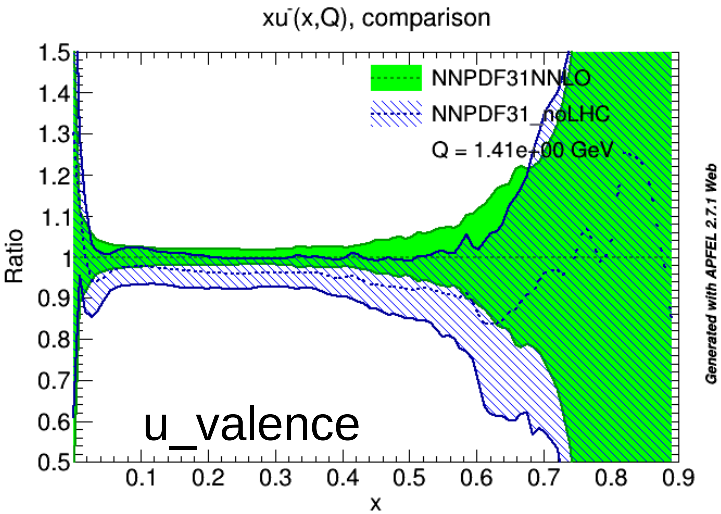
Look at valence distributions at low-x

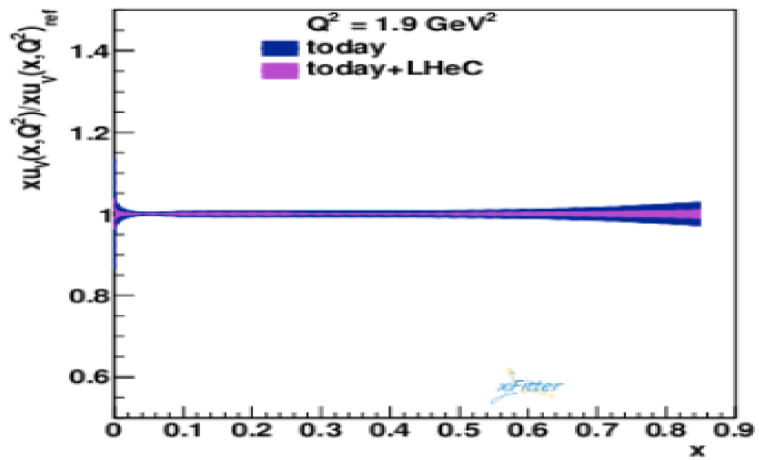
LHC gives improvements from ATLAS and CMS W-asymmetry data

The LHeC does rather better

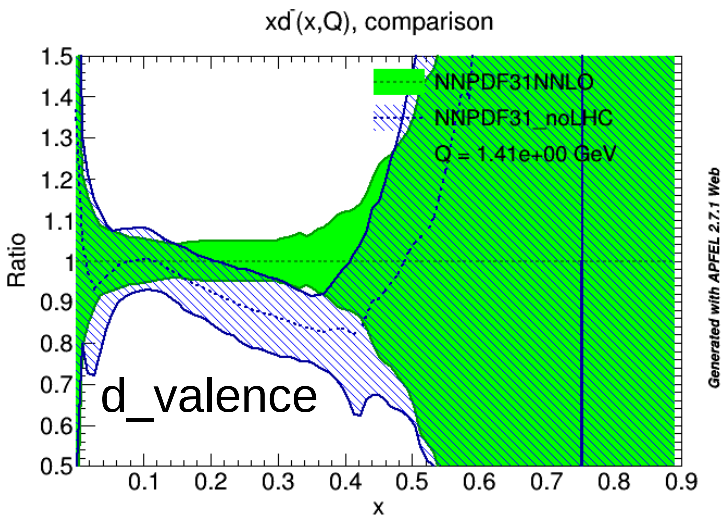


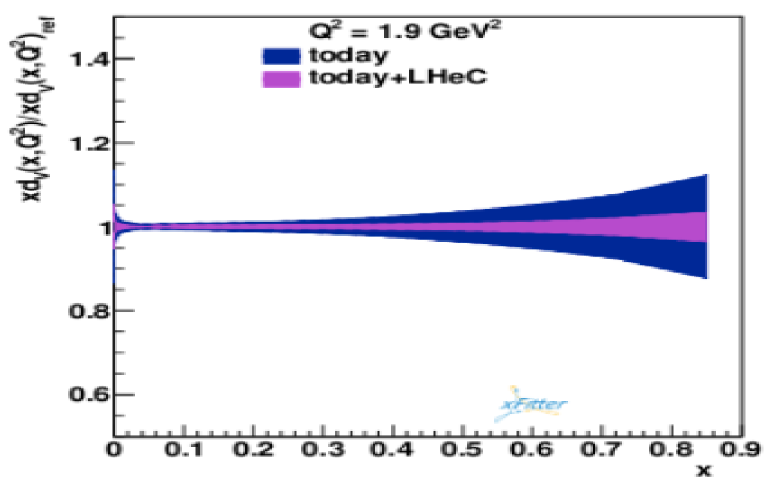






Do not compare the absolute sizes of the uncertainties, compare the level of improvement

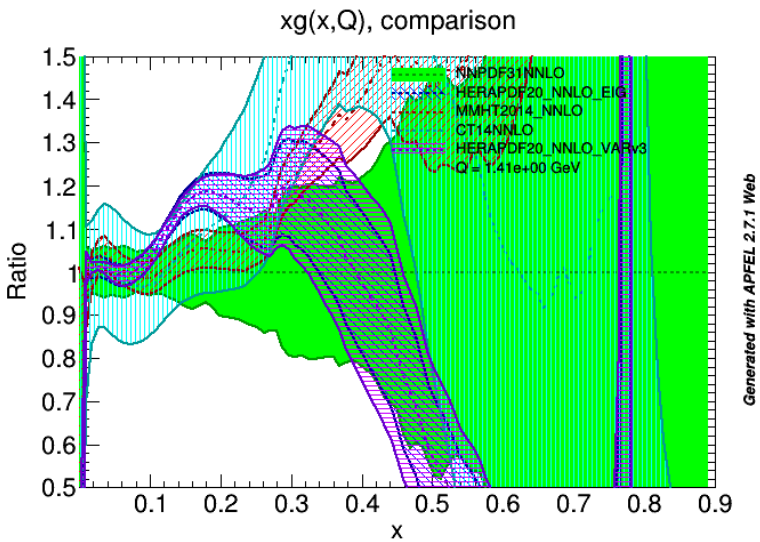


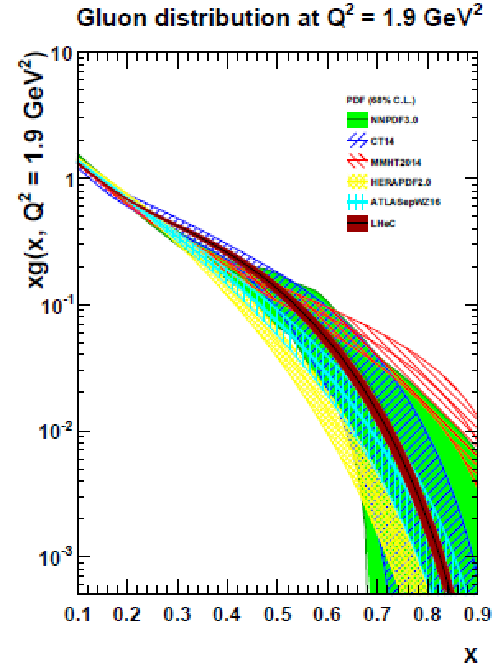


LHC data has made an improvement at x ~0.5 about 30% in d_valence

LHeC data has made an improvement at x ~0.5 about 300% in d_valence

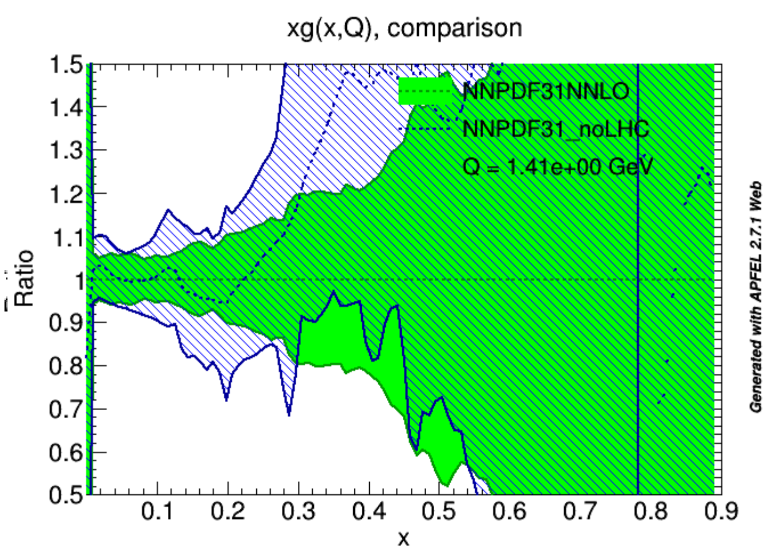
Gluon at high x



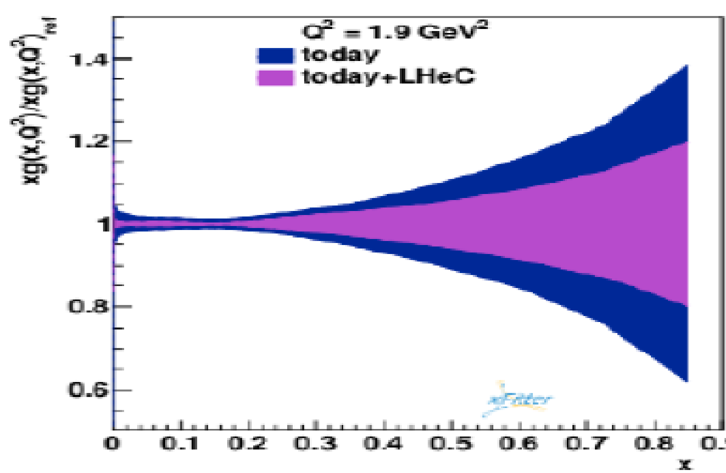


The high x gluon is not well known. Current PDFs differ.

LHC data on jet production has reduced the high-x uncertainty for NNPDF 3.1

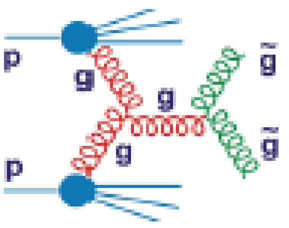


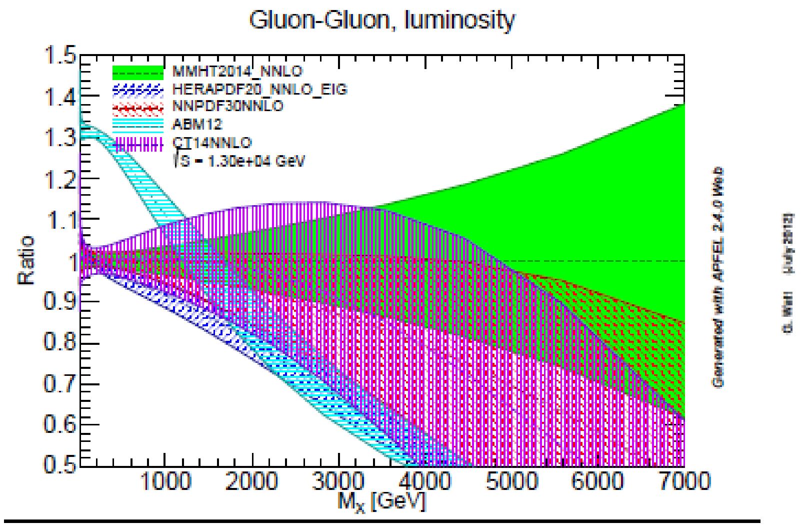
The LHeC does rather better

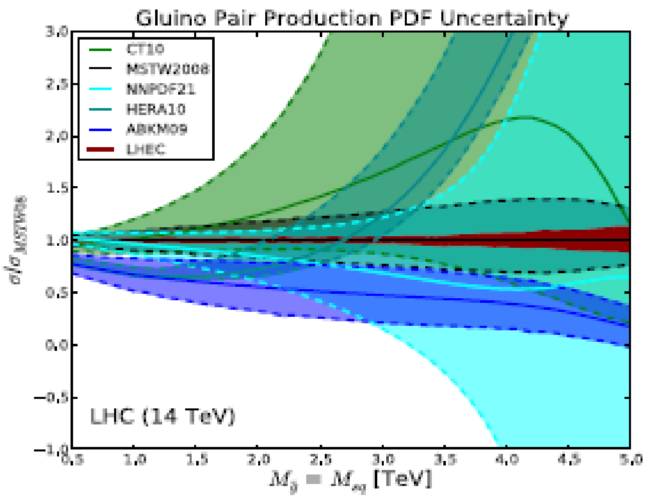


Why are we interested in the high-x gluon?-one example

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



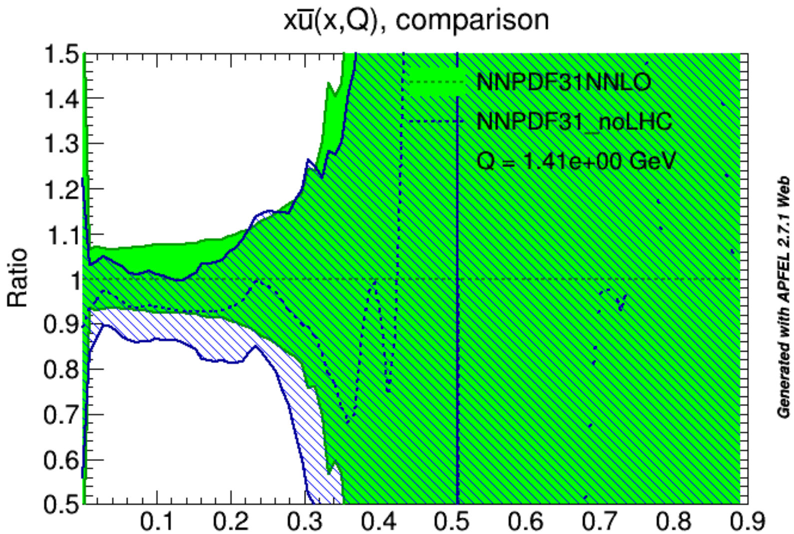


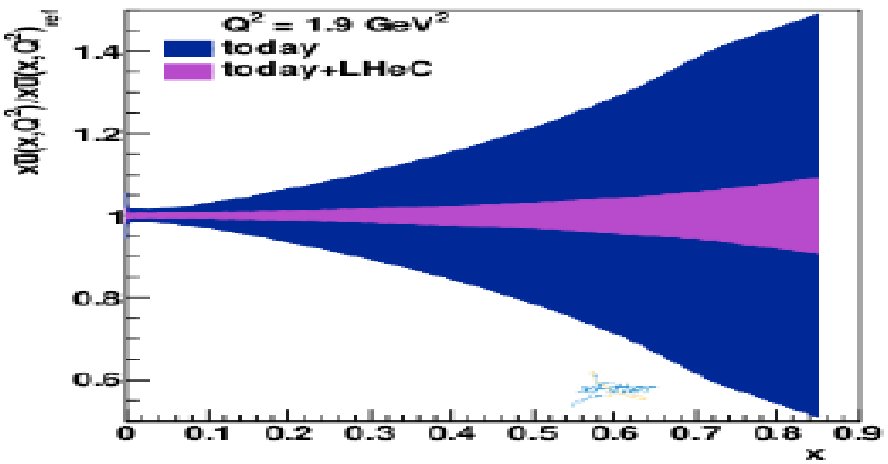


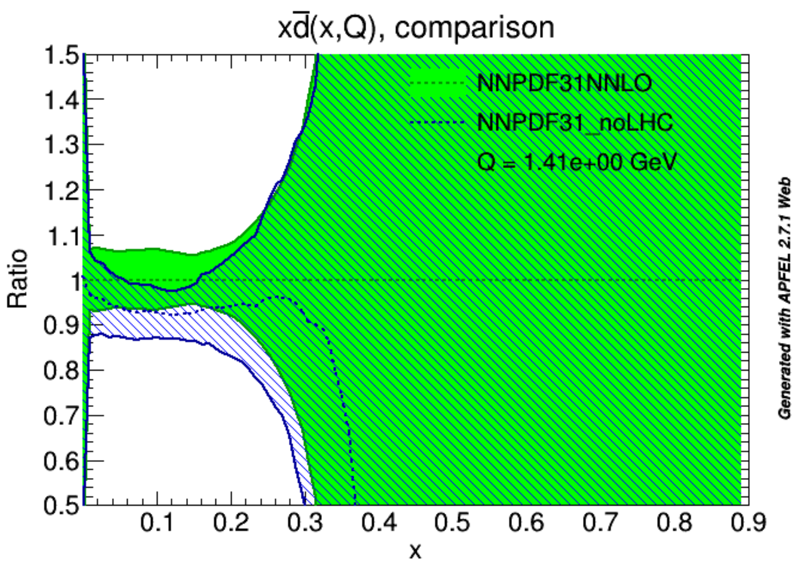
Which could be considerably reduced using LHeC data

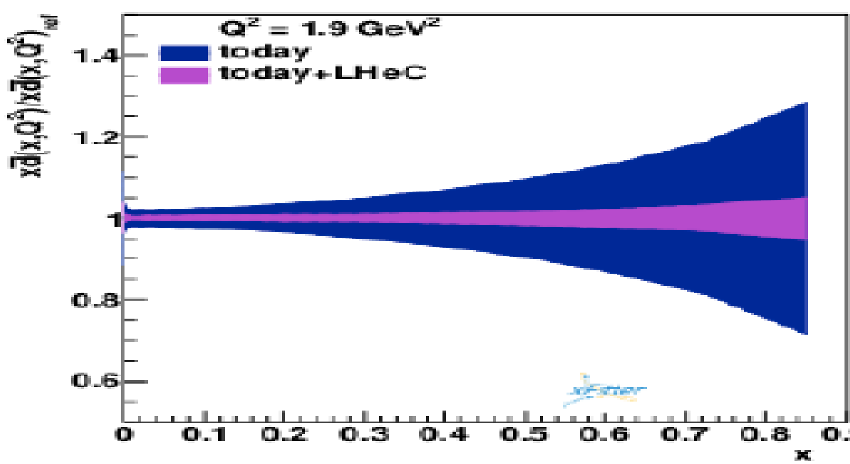
The LHC data have not so far led to big improvements in the **high-x sea PDFs**
This could come from high-mass Drell-Yan data, but is unlikely to compete with the potential improvement
From LHeC PDFs

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



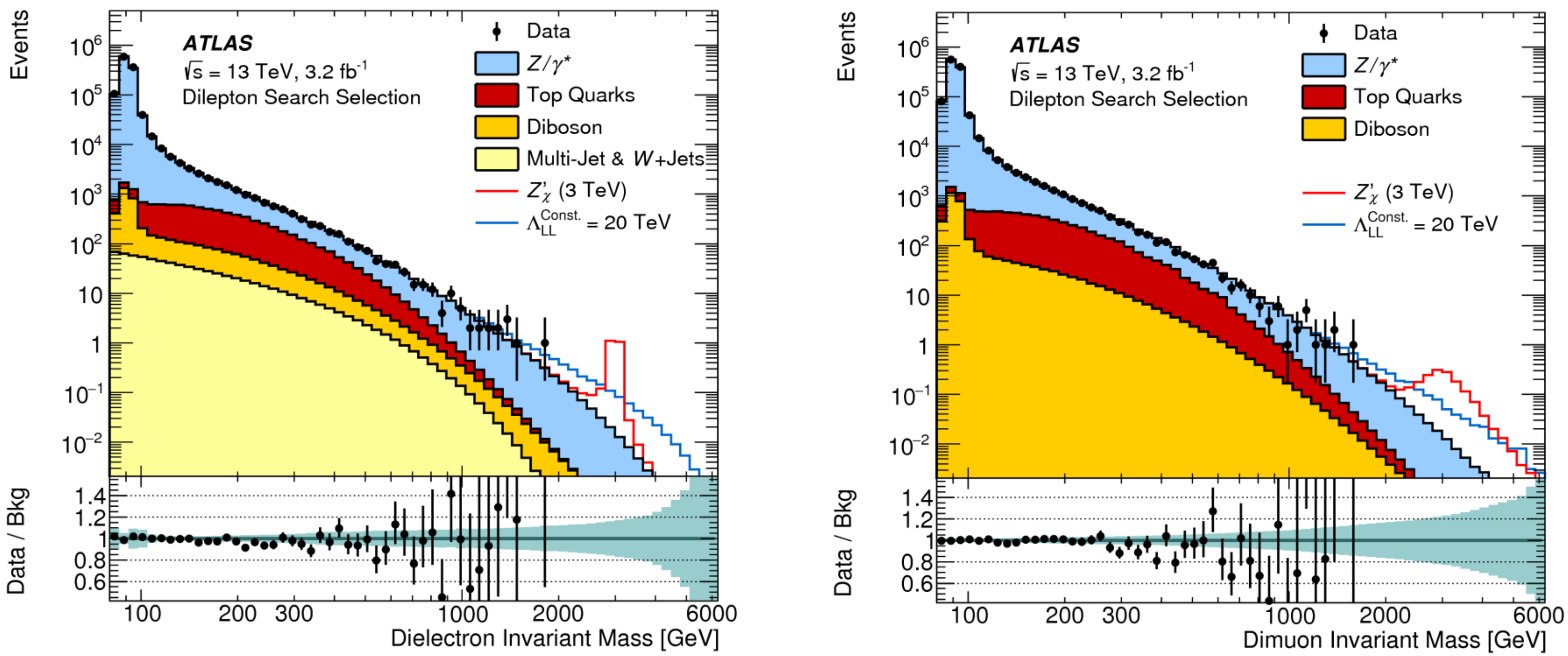






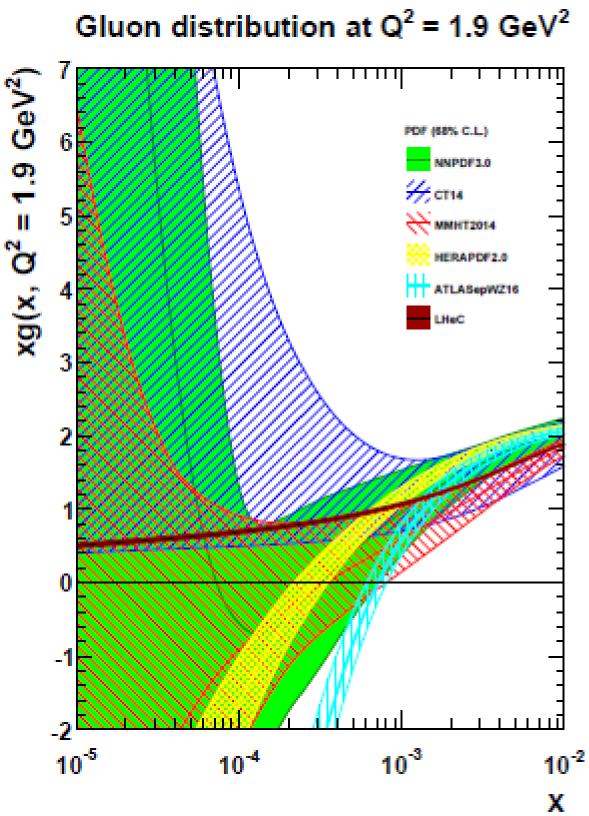
Why are we interested in the high-x sea?-one example

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



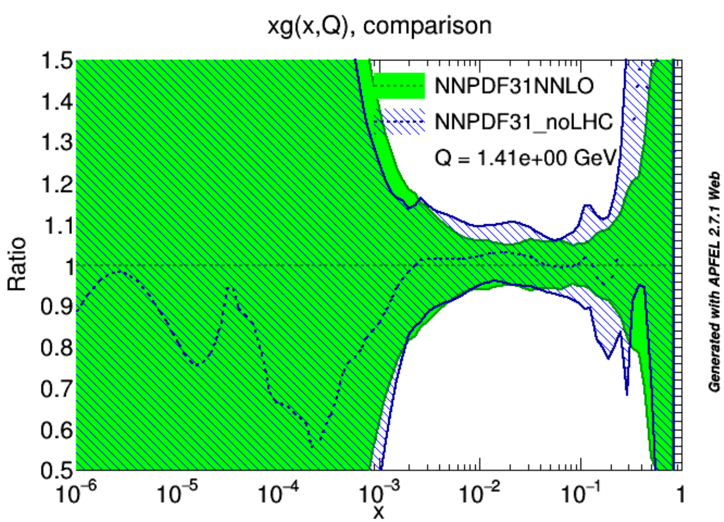
arXiv:1607.03669

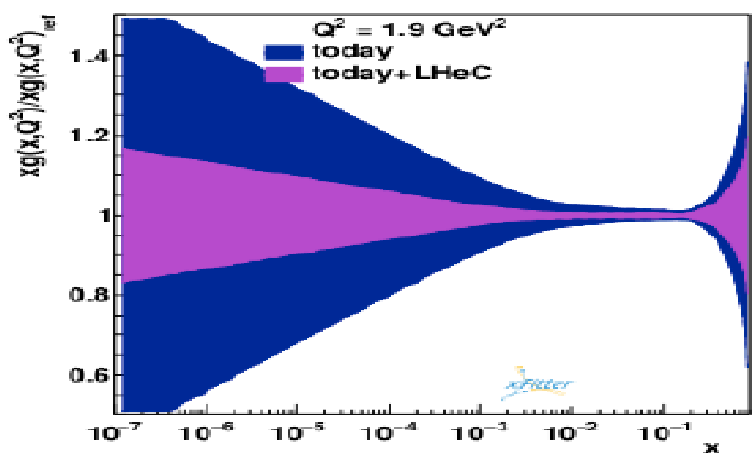
Gluon at low x



The low x gluon is not well known.
LHC data has not contributed much to this for two reasons

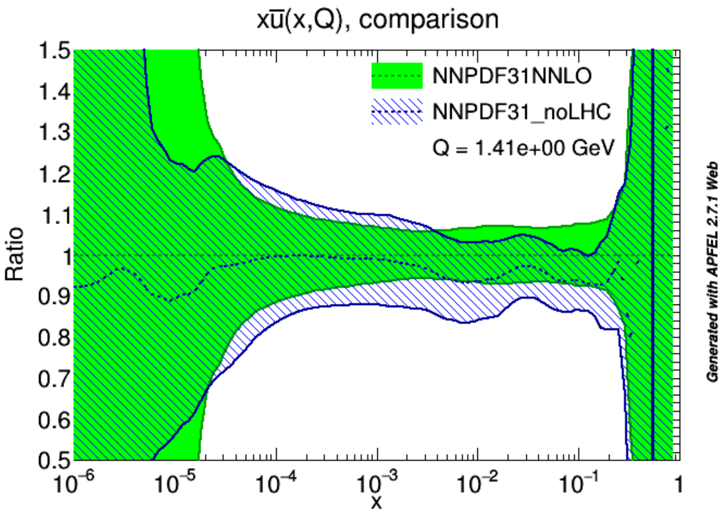
- the data do not reach below x~10^{-3} for ATLAS, CMS
- there is no direct probe of the gluon appropriate at low-x (LHCb data on open charm and beauty COULD help?)
- Our current knowledge comes from HERA. HERA sensitivity stops at x > 5 10^{-4}
- LHeC goes down to 10^{-6}

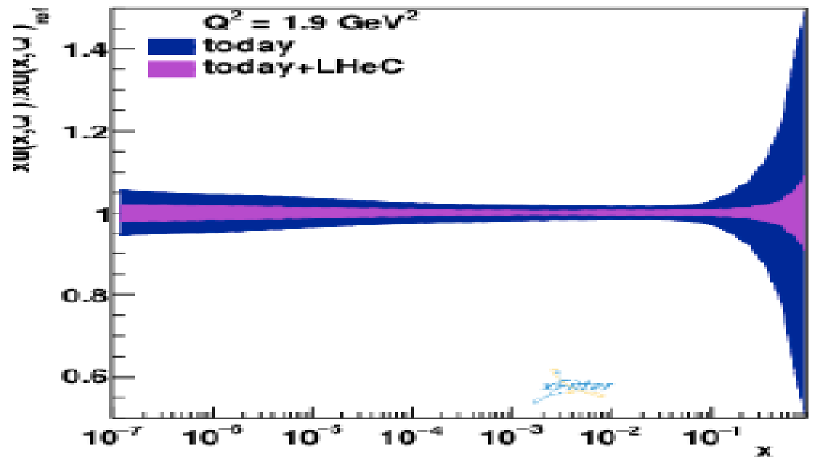


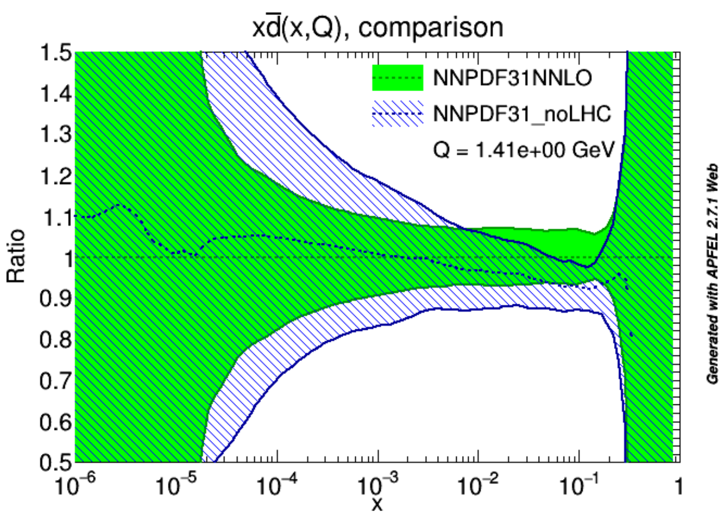


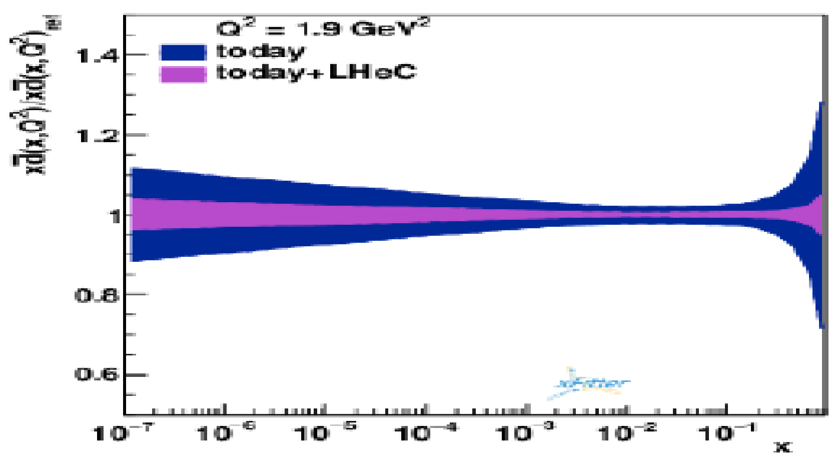
The **low x sea** is better known than the low-x gluon, but still not well known

- LHC data has contributed through the low-mass Drell-Yan data
- However LHeC sensitivity is much better going down to 10^{-6} .The Sea is what DIS measures best





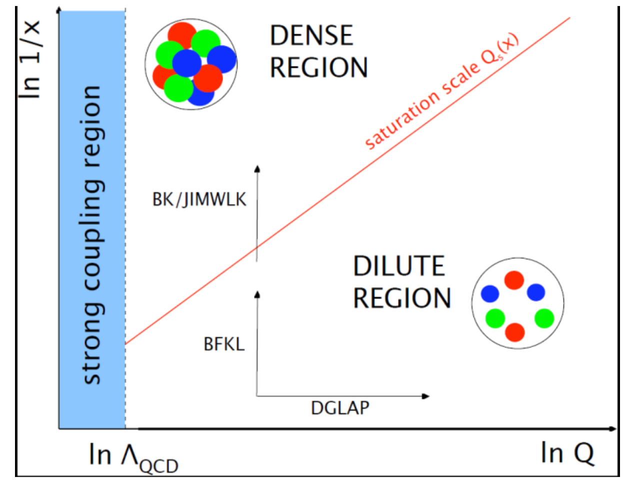




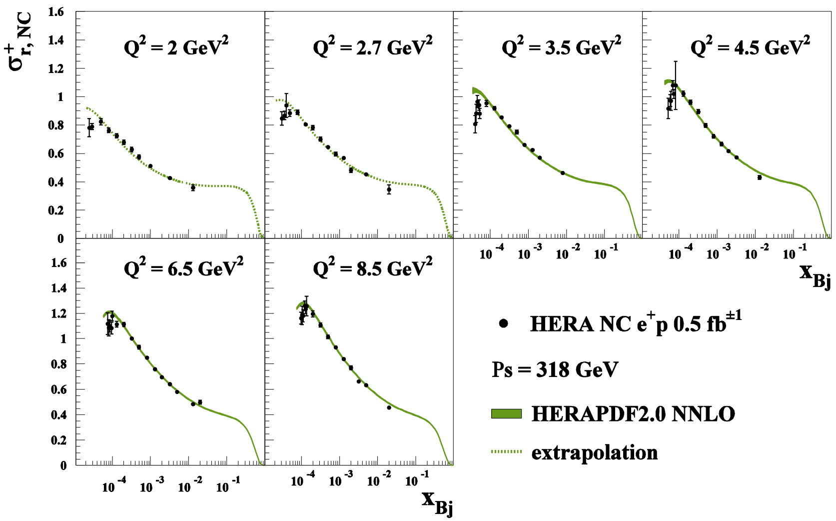
Why are we interested in low-x?

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

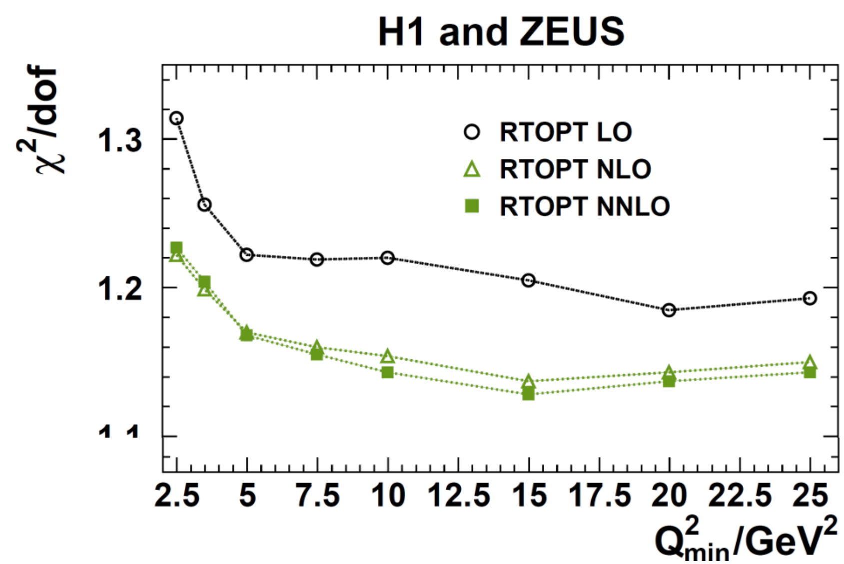
- New in the sense of a new regime of QCD
- Something that DGLAP evolution at NLO or NNLO cannot describe
- Needing ln(1/x) rather than lnQ^2 resummation (BFKL)
- Or even non-linear evolution (BK, JIMWLK, CGC) and gluon saturation



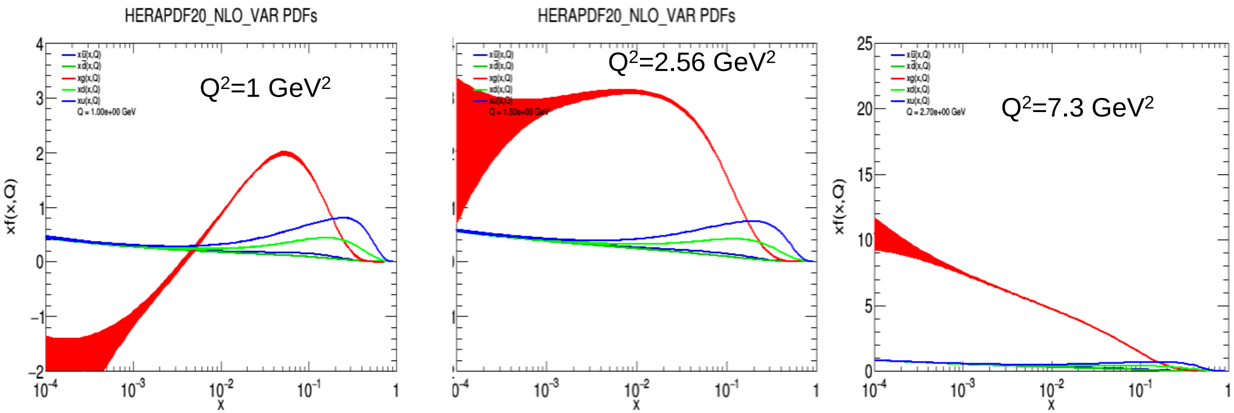
DGLAP describes DIS data down to surprisingly low Q^2



But not quite perfectly, the turn over in $\sigma_{red} = F_2 - y^2/Y_+ F_L$ is not so well described



The χ2 of fits decreases as the Q^2 cut increases



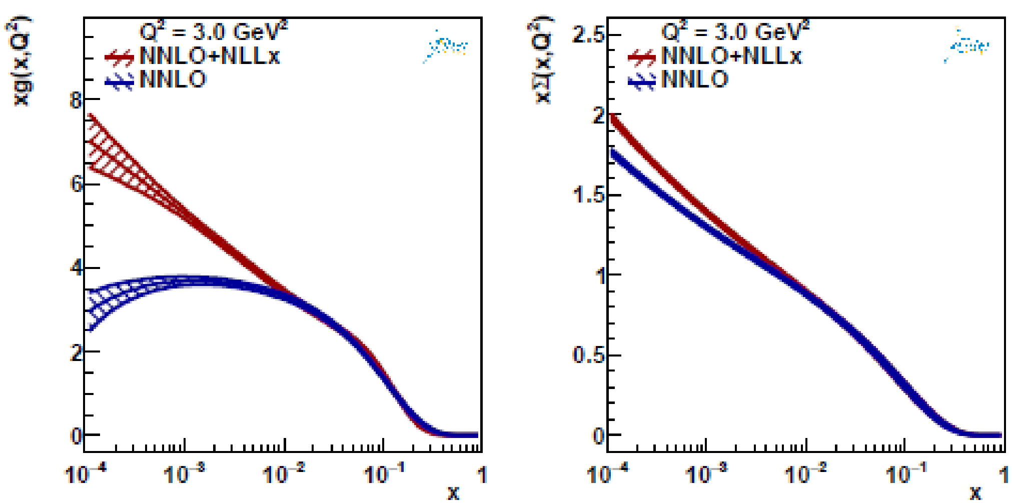
The shape of the gluon compared to the shape of the sea quarks flattens out and then turns over as one goes lower in NLO and NNLO PDF fits

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.

Recently ln(1/x) BFKL resummation has been worked out using the HELL code arXIV:1710.05935

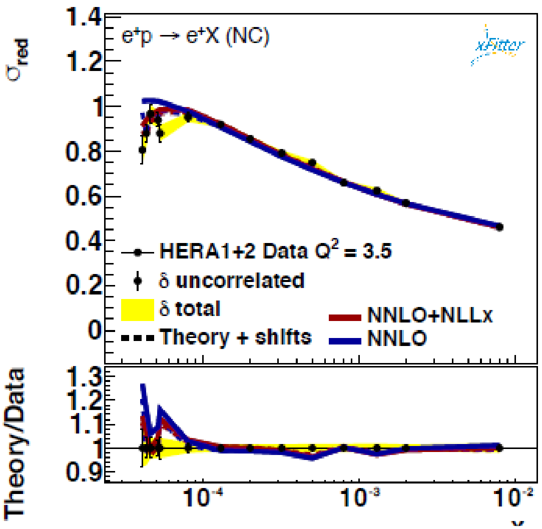


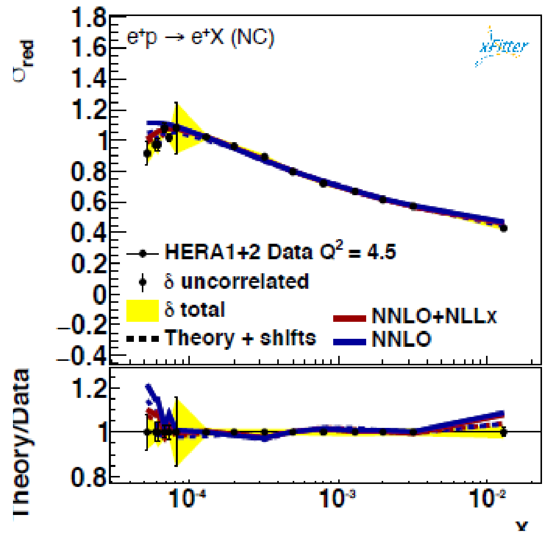
The shape of the gluon becomes singular at low-x and larger than the total sea when next-to-leading log low-x NLLX resummation is applied

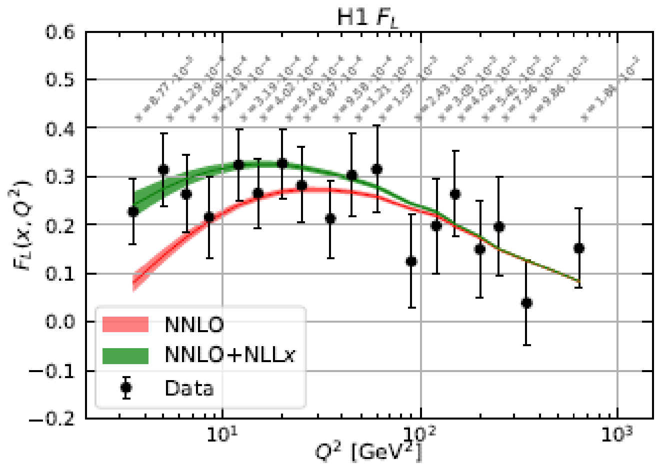
The χ2 is greatly improved

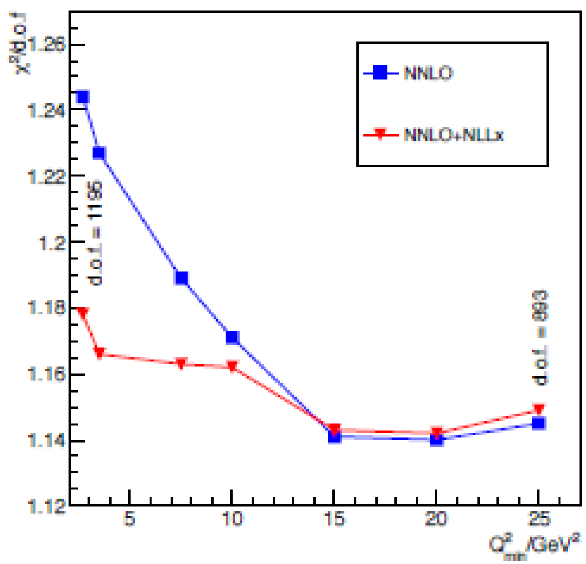
The improvement comes at low-x and low Q2 and the turn over of the data is well described because the gluon is larger and so FL is larger

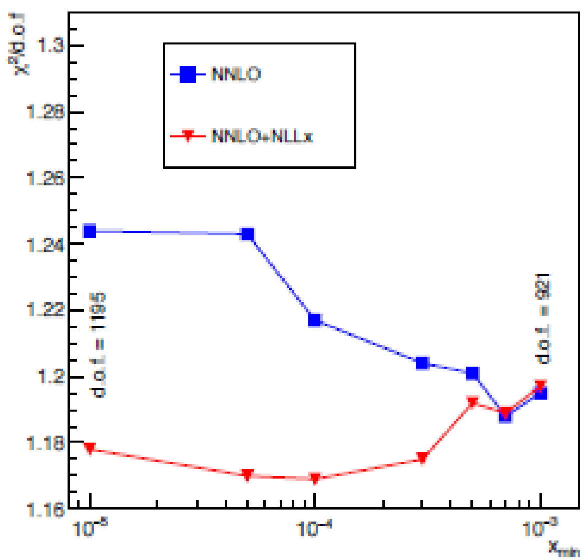
	NNLO fit with new settings	NNLO+NLLx fit with new settings
Total χ^2/d.o.f	1446/1178	1373/1178
subset NC 920 χ^2/n.d.p	446/377	413/377











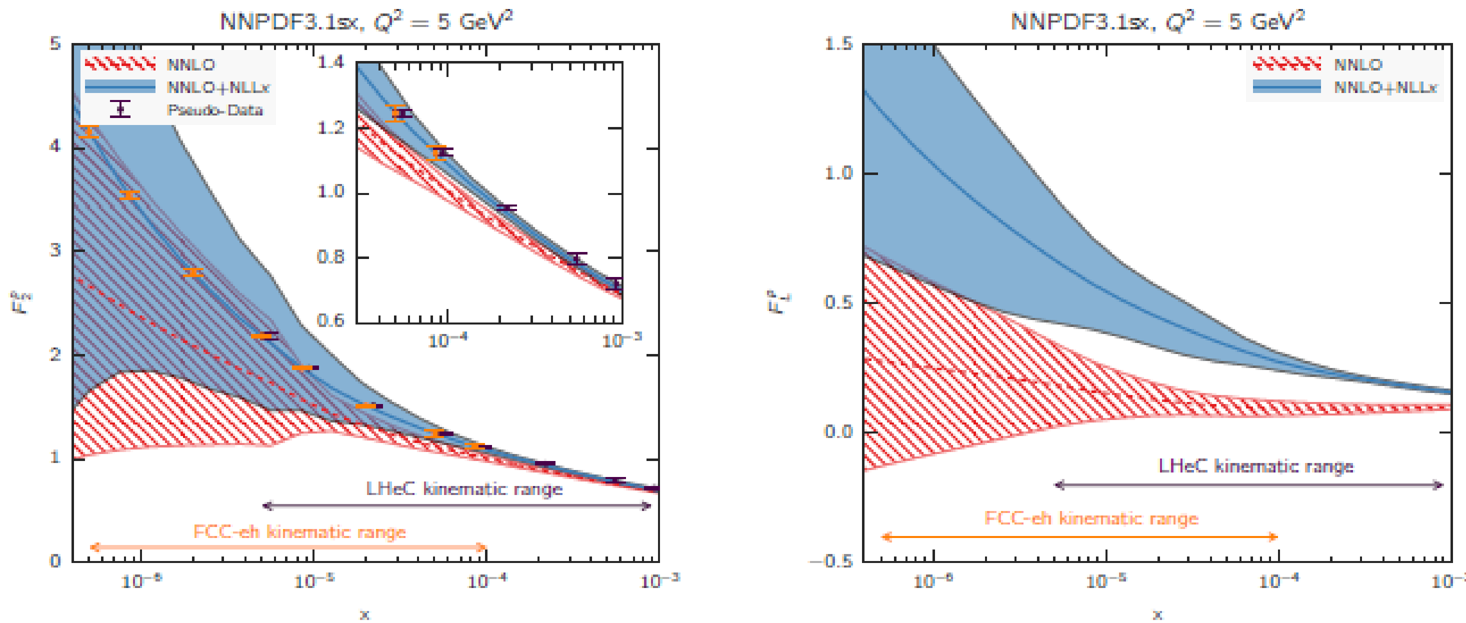
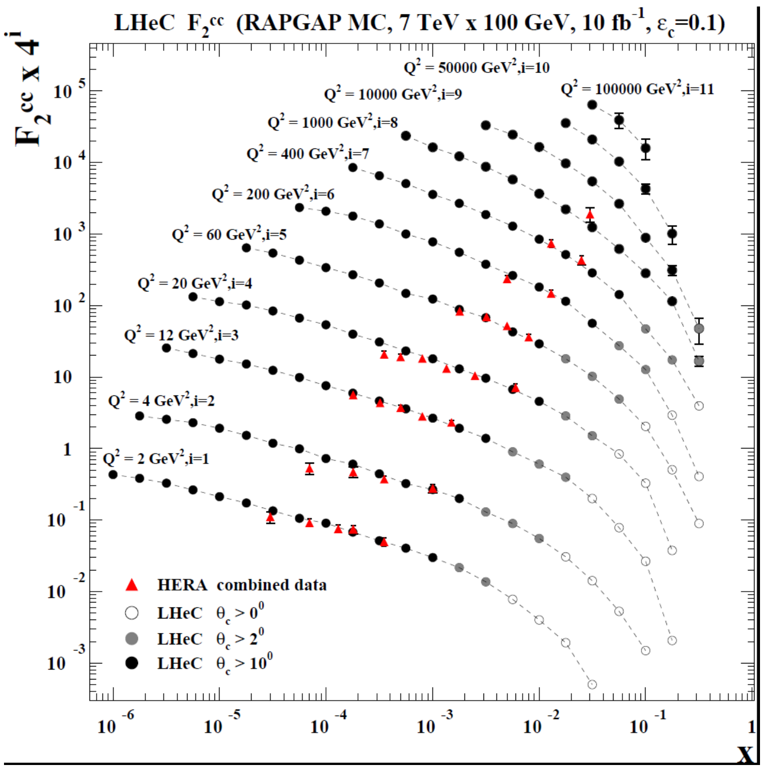
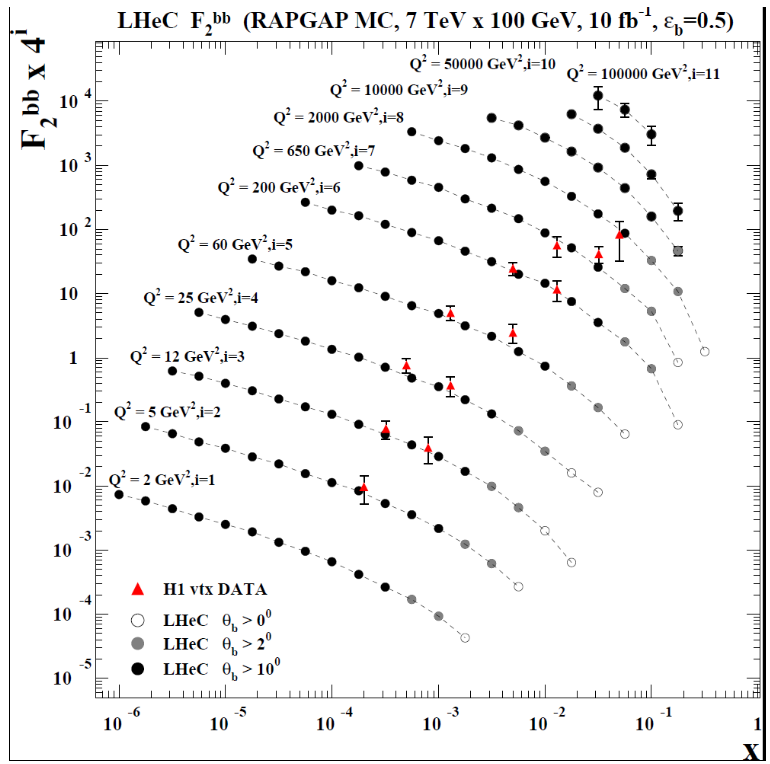


Figure 6.6. Predictions for the F_2 and F_L structure functions using the NNPDF3.1sx NNLO and NNLO+NLLx fits at $Q^2 = 5$ GeV^2 for the simulated kinematics of the LHeC and FCC-eh. In the case of F_2, we also show the expected total experimental uncertainties based on the simulated pseudo-data, assuming the NNLO+NLLx values as central prediction. A small offset has been applied to the LHeC pseudo-data as some of the values of x overlap with the FCC-eh pseudo-data points. The inset in the left plot shows a magnified view in the kinematic region $x > 3 \times 10^{-5}$, corresponding to the reach of HERA data.

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

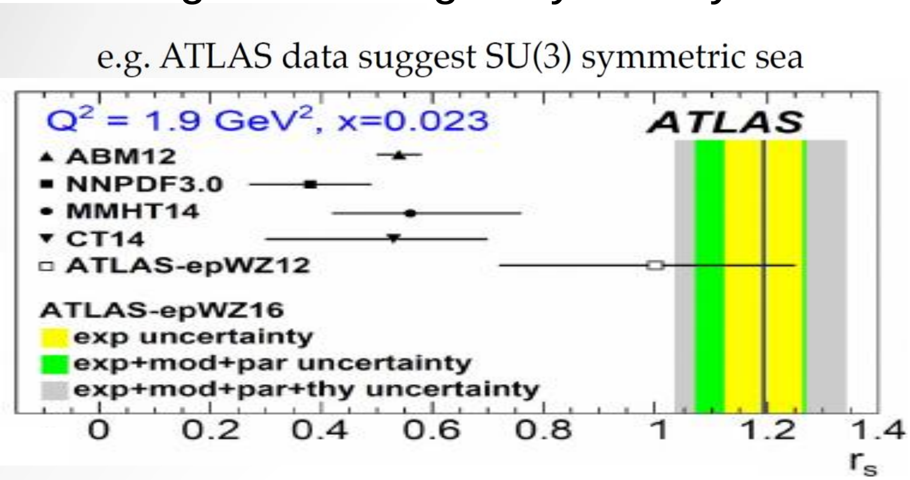
Top quarks and strange quarks could also be studied for the first time

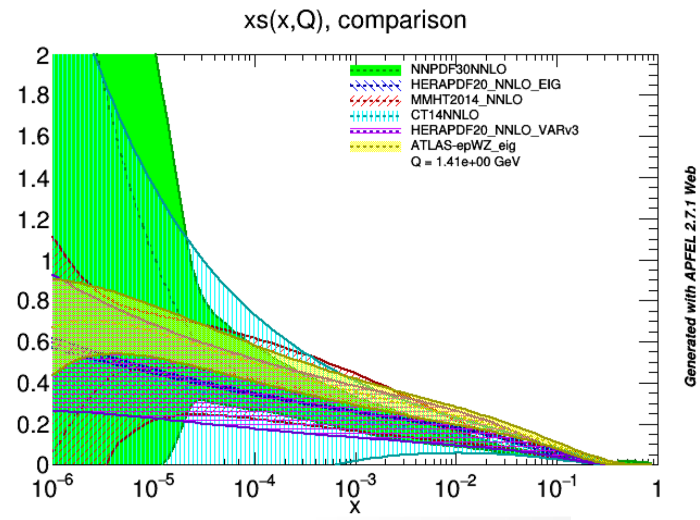
- top: tPDF, cross section few pb at Ee=60GeV, Wb →t

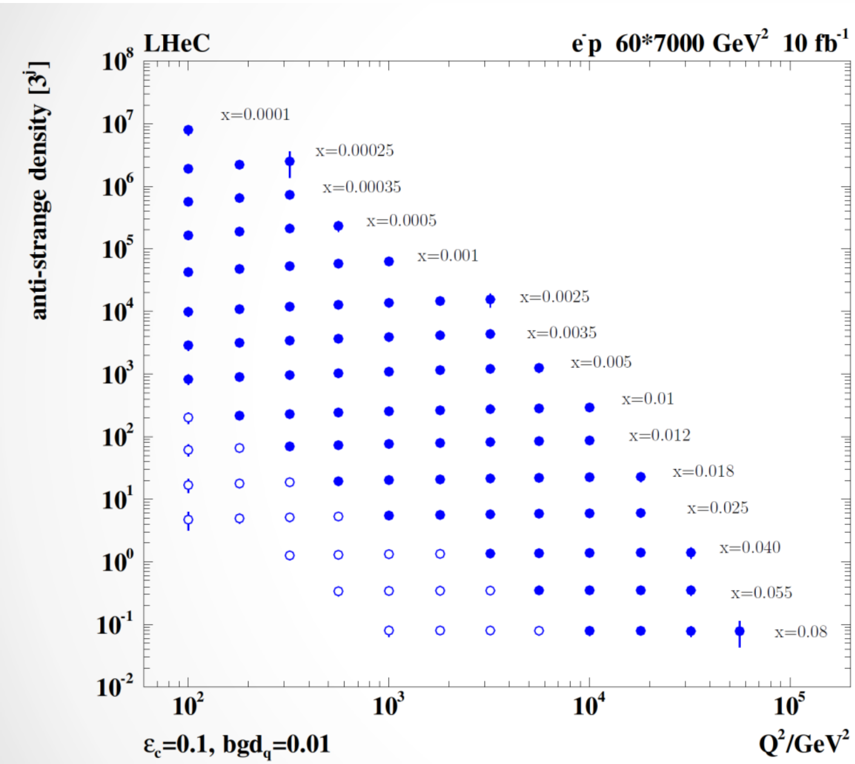
The strange PDF is not well known

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, 1% light quark background in impact parameter.

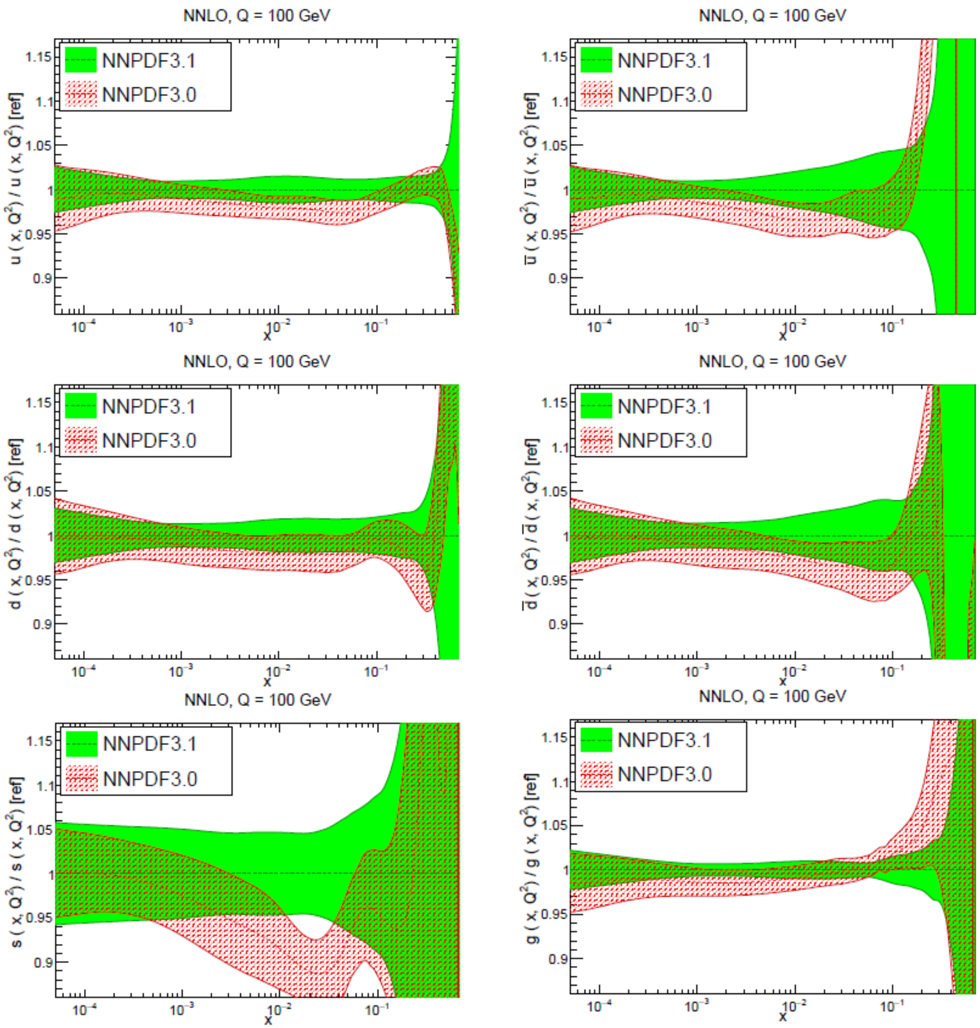
This could give the first x,Q2 measurement of the anti-strange PDF

(This also assumes an updated scenario from the CDR – see backup)

We have been discussing how much better the LheC in terms of PDF precision and comparing to today's LHC results

But how well can the LHC itself do in future-in the next few years?

The change from NNPDF3.0 to 3.1 shows us how much improvement is coming from recent LHC measurements on W,Z+jets+top+Zpt



The improvements are substantial but still modest compared to the potential of the LHeC

But won't this level of improvement keep on happening?

ALMOST CERTAINLY NOT

because we have already hit the ultimate limit of precision- at least with regard to q-qbar.

The NNPDF3.1 already contains the ultimate precision on W,Z production

As remarked earlier, to contribute significantly the measurements at the high-scales of the LHC have to be VERY precise.

Just how precise can we be?

We are already systematics limited.

Consider the most precise measurement there has ever been at LHC: the ATLAS inclusive W and Z differential distributions arXiv:1612.03016

- W: Total (0.6–1.0%), multijet background (0.3–0.7%)
- Z Central: Total (0.4%), reconstruction efficiency (0.2–0.3%)
- Z Forward: Total (2.3%), identification efficiency (1.5%)
- 1.8% luminosity uncertainty

We are unlikely to beat this even with an HL-LHC and the change in kinematic region to from 7/8 to 13/14 TeV does not change the x-region probed for PDFs much.

So this is as good as it gets – at least for q-qbar

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Where can we improve in future at the LHC? Currently High Luminosity and High Energy extensions are being considered

- **W,Z and Drell-Yan distributions** – sensitivity to valence quarks, strangeness, photon PDF.

Some modest improvement at the edges of phase space
The reach to lower x at 13,14 TeV brings more theoretical challenges- need for ln(1/x) resummation

Off-peak Drell-Yan can still improve BUT low-mass brings the same low-x challenges.
This particularly affects the LHCb data
And high-mass requires good understanding of the NLO-EW corrections and photon PDF

- **Inclusive, di-jet and tri-jet distributions**------sensitivity to gluon

Already challenging theoretical understanding -NNLO is here- less sensitivity to choice of **scale- data can improve** in terms of understanding of systematic uncertainties

- **Top-antitop distributions** –sensitivity to gluon

NNLO calculations already required**, data can also improve** (systematics and data consistency?)

Combinations of types of data and different beam energies –accounting for their correlations- can help

This is all likely to give incremental rather than dramatic improvements.

Summary

The LHeC/FCC-eh can give an increase in the kinematic reach of Deep Inelastic Scattering and an increase in the luminosity

- This would yield a tremendous increase in the precision of Parton Distributions
- Data from the LHC itself cannot improve current PDFs to the same degree
- Precision PDFs are needed for BSM physics- both at the LHC and FCC-hh
- Furthermore the LHeC could yield per mille precision on α_S
- Reduction in α_S uncertainty and PDF uncertainty together will reduce the uncertainty predictions for the Higgs cross section substantially
- Finally the LHeC allows the exploration of a kinematic regime at low-x where we learn more about QCD beyond DGLAP evolution and beyond linear evolution. The FCC-eh extends this further.

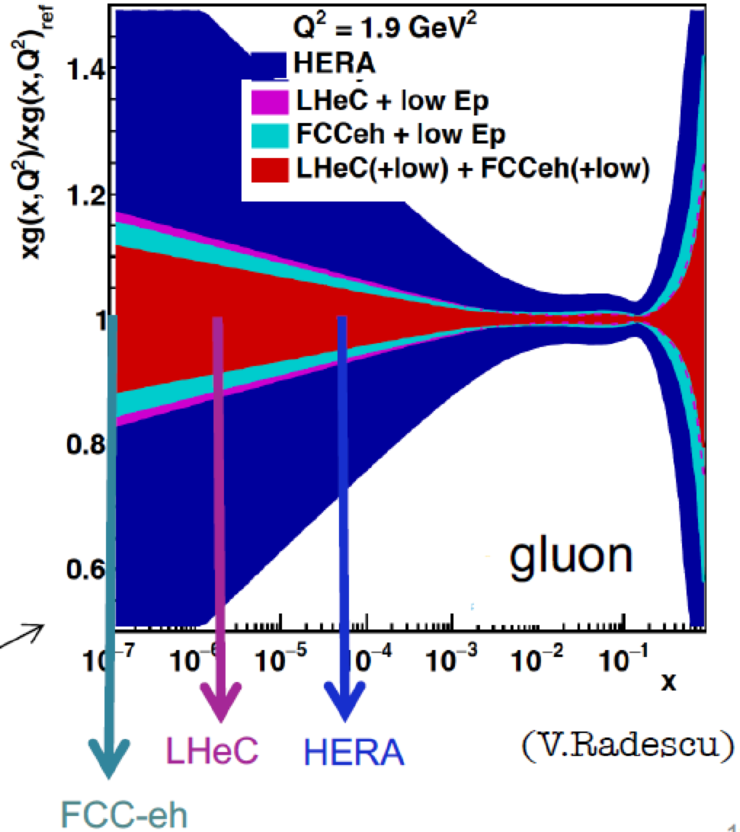
Back ups

FCCeh vs LHeC

- seen already how precisely **LHeC** can control **PDFs**
- need **FCC-eh** to explore below $x=10^{-6}$
- **FCC-eh** may further improve, and explore **small x** phenomenology

(adding low Ep data has small impact here)

NLO QCD fit, using xFitter
parameterisation details in backups



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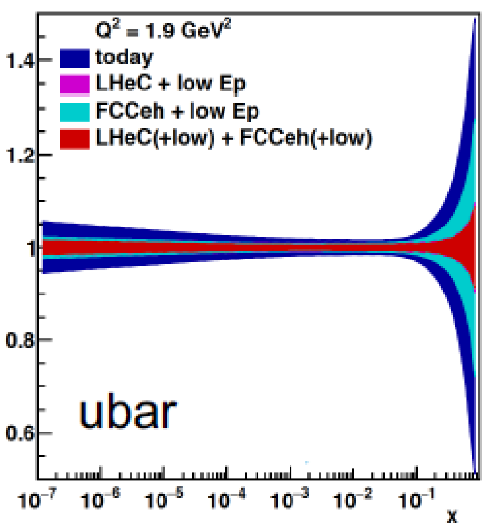
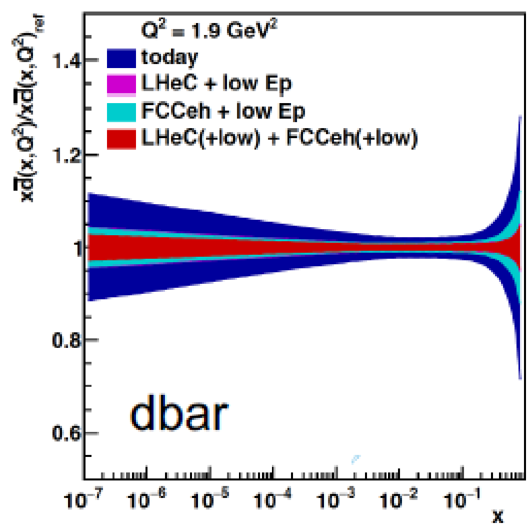
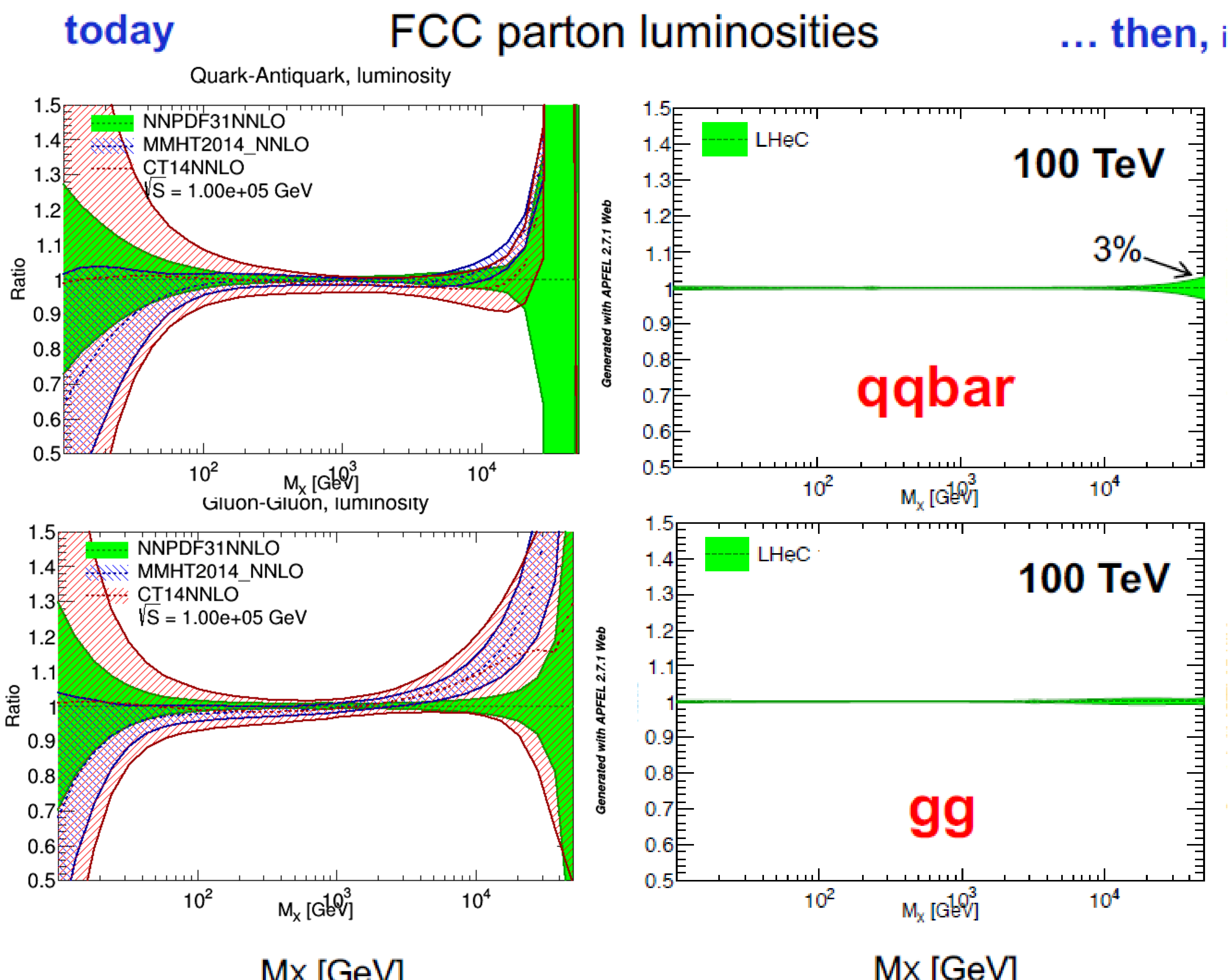




Now let’s consider parton luminosities at future colliders



What if we put the electron LINAC in the FCC ring– how much could we improve on the LHeC?

new

simulated FCC-eh data

new simulated **inclusive NC** and **CC DIS data** for latest running scenarios

NC/CC	E_e [GeV]	E_p [TeV]	P(e)	charge	lumi. [fb^{-1}]	
NC	60 (60)	50 (7)	−0.8	−1	1000	e−, neg. pol.
CC	60 (60)	50 (7)	−0.8	−1	1000	
NC	60 (60)	50 (7)	+0.8	−1	300	e−, pos. pol.
CC	60 (60)	50 (7)	+0.8	−1	300	
NC	60 (60)	50 (7)	0	+1	100	e+, unpol.
CC	60 (60)	50 (7)	0	+1	100	
NC	20 (60)	7 (1)	0	−1	100	low energy
CC	20 (60)	7 (1)	0	−1	100	

* second and third columns show FCC-eh (LHeC)

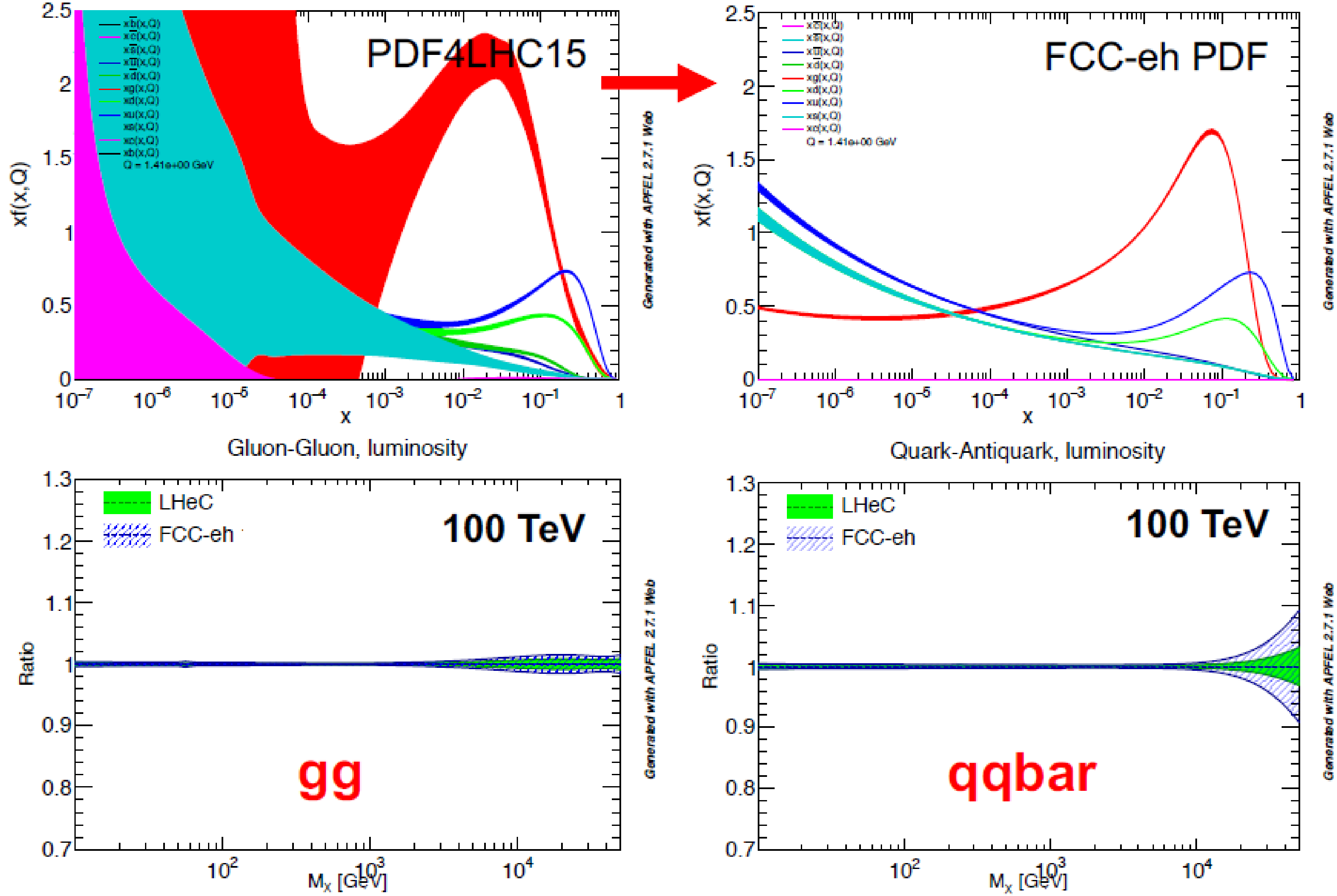
(M.Klein)

error assumptions:
elec. scale: 0.1%; hadr. scale 0.5%
radcor: 0.3%; γp at high y: 1%
uncorrelated extra eff. 0.5%

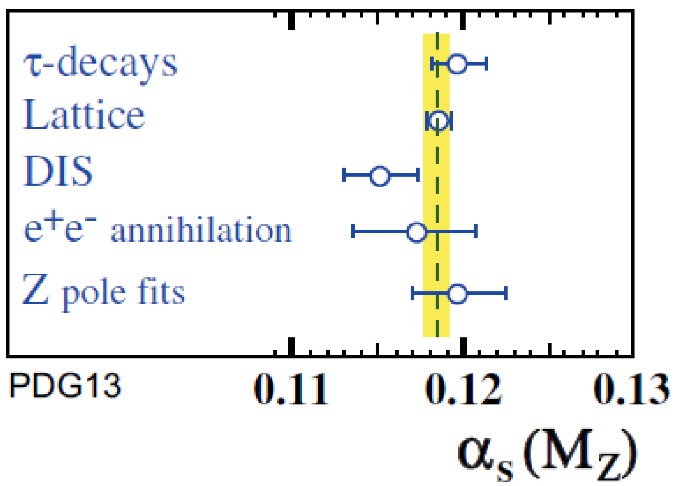
more data, and more options c.f. previous studies

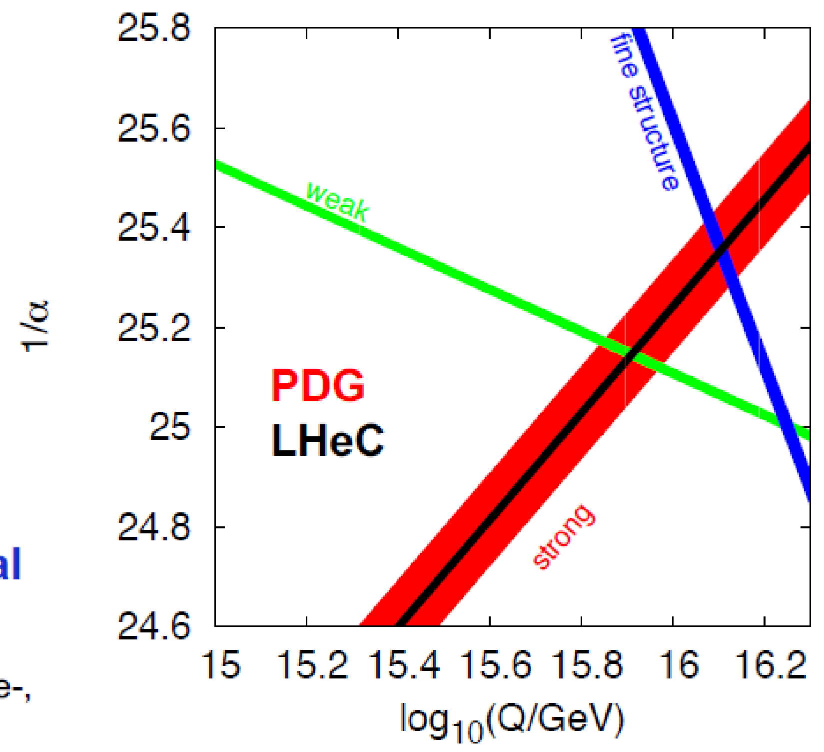
all work in progress

summary of FCC-eh PDFs



strong coupling





strong coupling, α_s, is a fundamental parameter, not given by theory

extracted from experimental measurements in e+e-, ep, pp, and from lattice QCD calculations

> PDG16 world average: $\alpha_s(M_Z)=0.1181\pm0.0011$
>
> cf. PDG13: $\alpha_s(M_Z)=0.1184\pm0.0006$ with QCD lattice treated less conservatively cf. PDG16

BUT measurements **not all consistent**: what is true central value; true uncertainty; role of lattice calculations; is α_s(DIS) smaller than world average?

α_s is least known of coupling constants

precision α_s needed to constrain GUT scenarios

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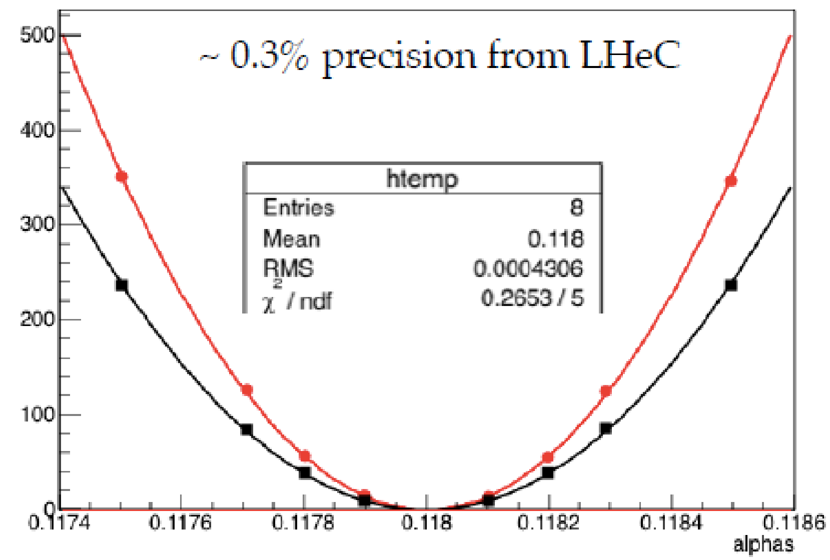
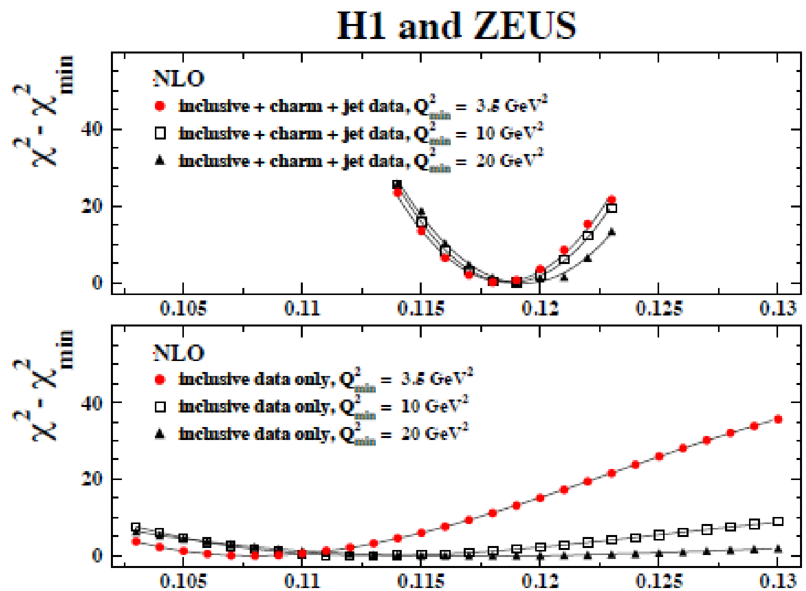
strong coupling from LHeC

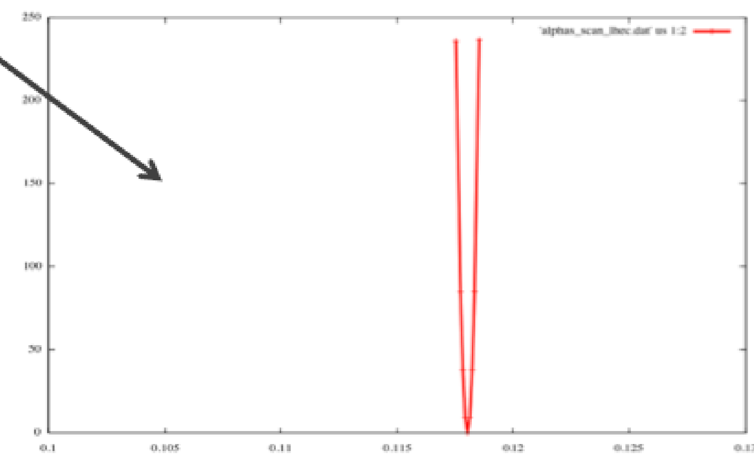
PDF+αs fit using LHeC simulated data



(M Klein, V Radescu)

NC,CC
NC,CC+F2c





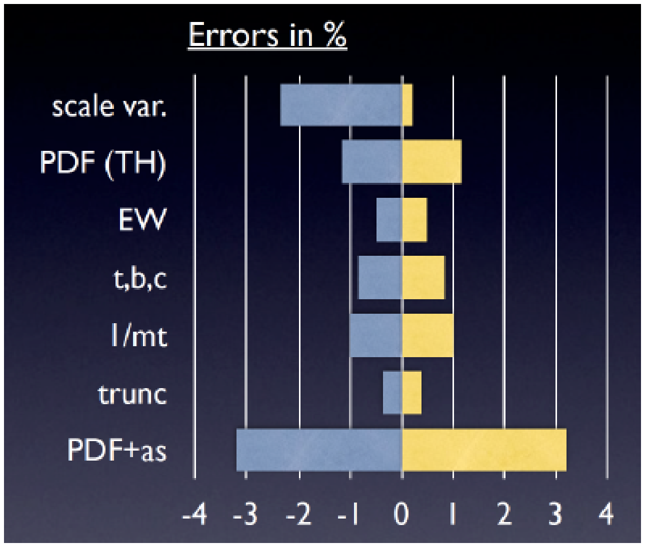
LHeC could resolve a > 30-year old puzzle:

αs consistent in inclusive DIS, versus jets?

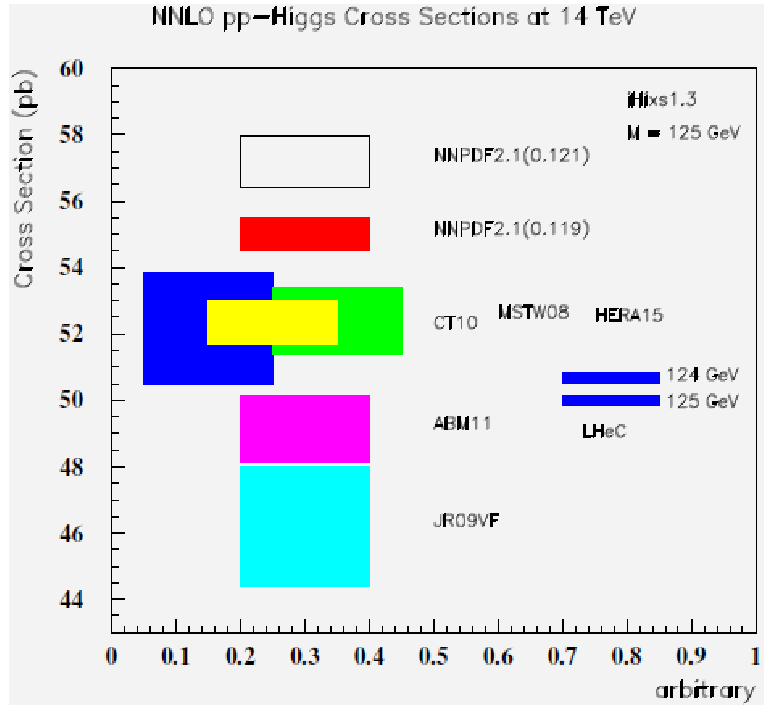
This estimated accuracy of 0.3% comes from te inclusive data scaling violations- there will also be LHeC jet data, to improve on this

Furthermore PDF uncertainties and α_S DOMINATE the Higgs cross-section

strong coupling, and Higgs



uncertainty on inclusive Higgs production
G. Zanderighi, Moriond, March 2016
(from C. Anastasiou et al., arXiv:1602.00695)



The LHeC can give a tremendous improvement on this– see talks in the Higgs session

impact of different LHeC datasets

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

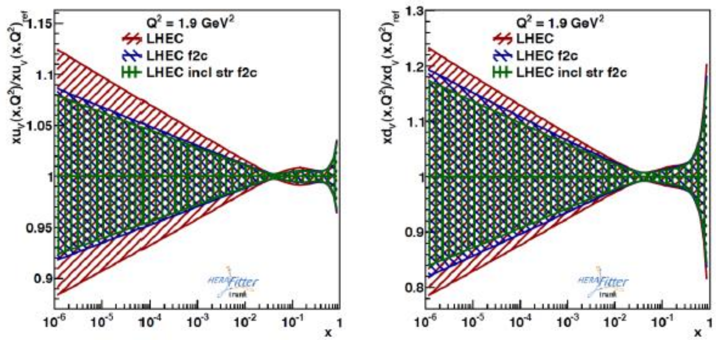
Ep=7 TeV, E=60 GeV:

NC,CC:

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

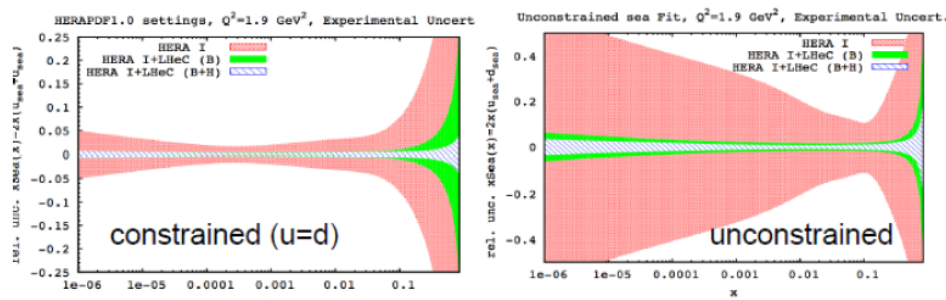
plus, dedicated measurements of strange, anti-strange, F2cc
(not yet F2bb, low Ep data, FL)

more flexible PDF fit:
xg, xuv, xdv, xub, xdb, **xstr**
$xf(x) = A x^B (1-x)^C (1+Dx+Ex2)$
– 14 free parameters

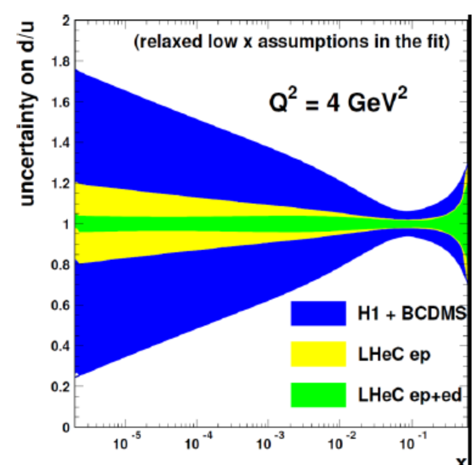


Further thoughts on low-x sea.
It is often assumed that ubar=dbar at low-x
If we relax this assumption then PDF errors increase tremendously.
But LHeC data can constrain this.

Here we compare uncertainties on the total sea distribution



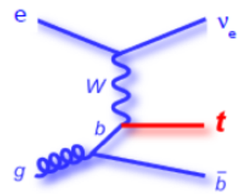
And here we compare uncertainties on the d/u ratio
This would improve more if **deuteron target data are used.**
Deuterons can also give information on neutron structure



Top Quarks at LHeC

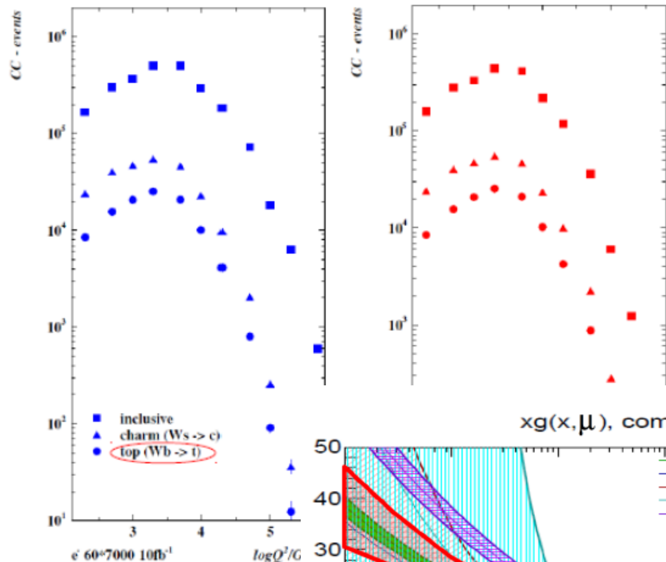
Top quarks can be studied in DIS (negligible cross section at HERA)

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

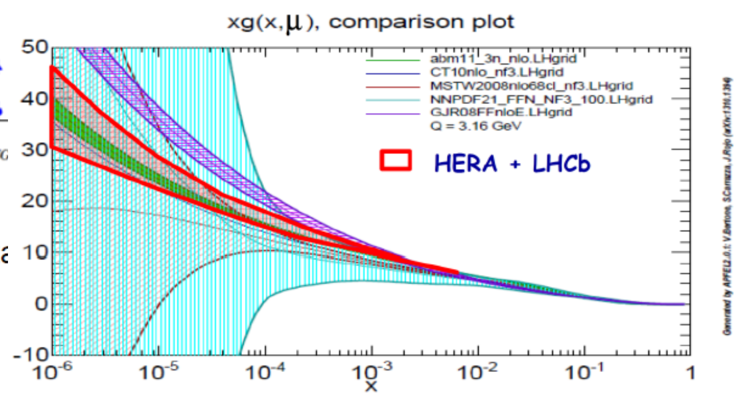


NC: ttbar pair production

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

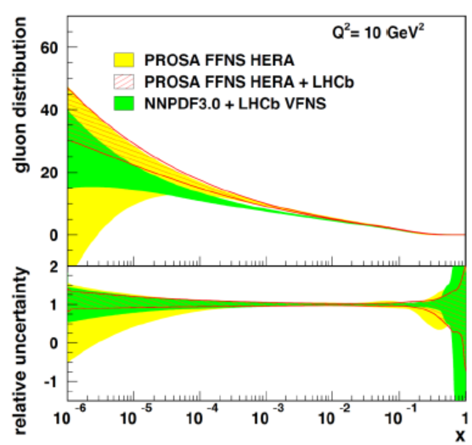


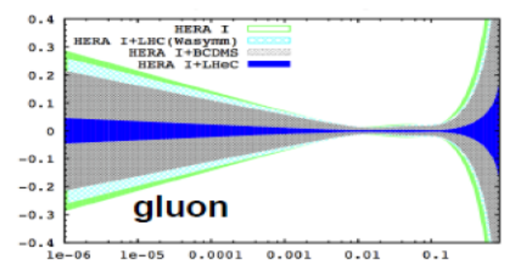
A top PDF could be importa



Can LHCb data on open charm and beauty help?
YES
But not as much as an LHeC

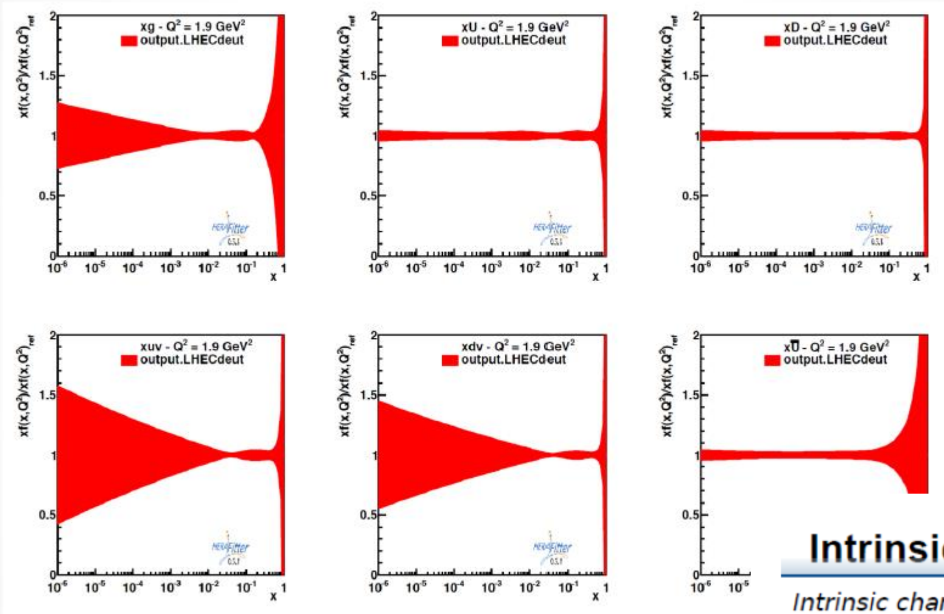
These LHCb data probe the ln(1/x) resummation region– and so the theory for the open b and c production would need some modification





LHeC deuteron data

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



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

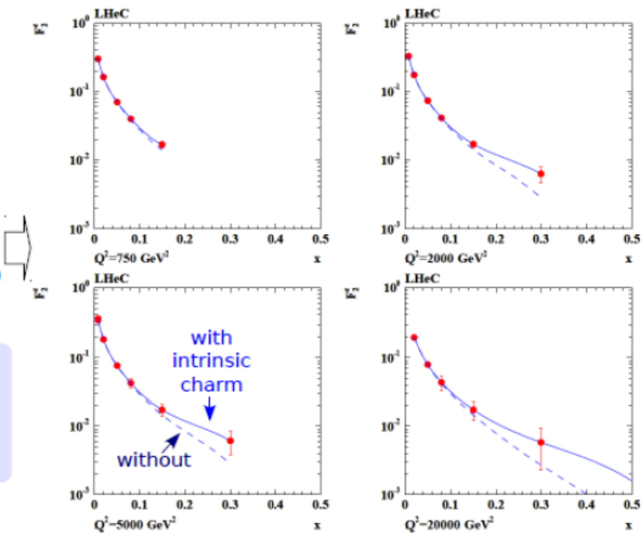
Intrinsic Charm

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

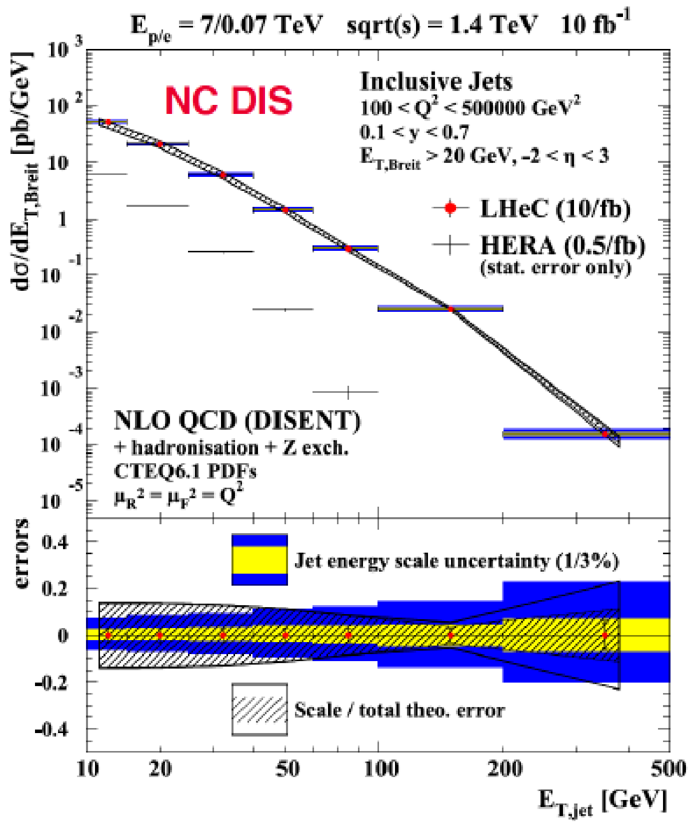
for large x very good forward tag acceptance needed (possible with reduced E_p)

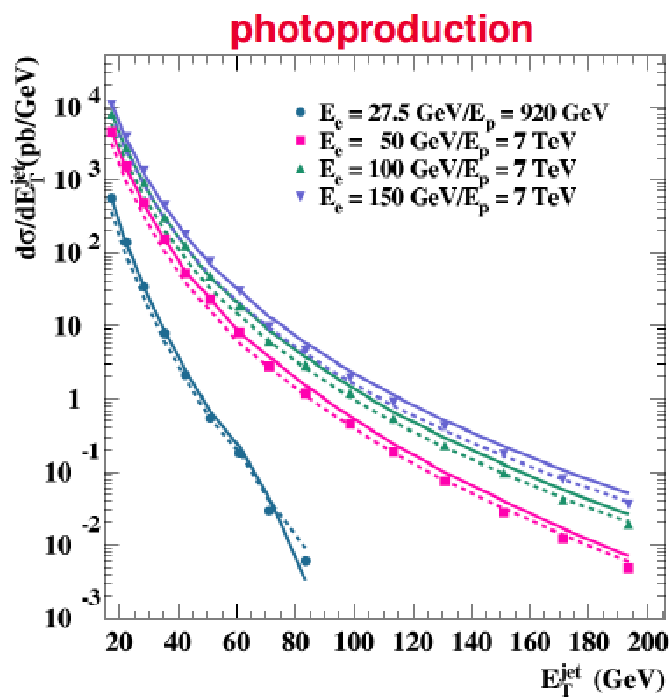
simulated measurement of the charm structure function (E_p=1 TeV, L=1 fb^{-1}, CTEQ66)



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

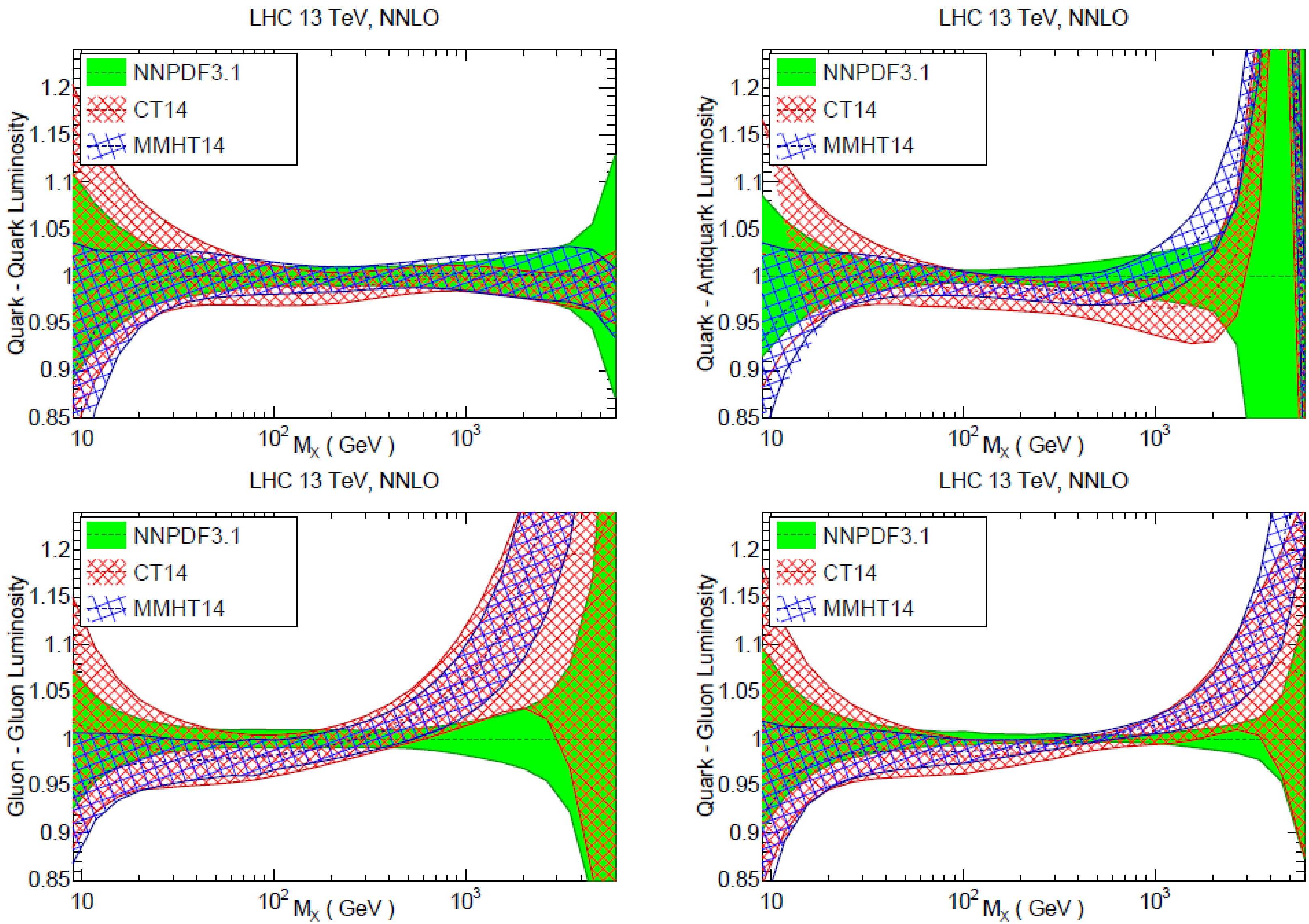
LHeC jet data





(plots from LHeC CDR – illustrative)

impact of **LHeC jet data** on α_s (and PDFs) expected to be substantial


LHC 13 TeV, NNLO
NNPDF3.1
CT14
MMHT14
Quark - Quark Luminosity
M_X (GeV)
LHC 13 TeV, NNLO
NNPDF3.1
CT14
MMHT14
Quark - Antiquark Luminosity
M_X (GeV)
LHC 13 TeV, NNLO
NNPDF3.1
CT14
MMHT14
Gluon - Gluon Luminosity
M_X (GeV)
LHC 13 TeV, NNLO
NNPDF3.1
CT14
MMHT14
Quark - Gluon Luminosity
M_X (GeV)

This will affect those LHC results which probe low-x
Dominantly those from low-mass Drell-Yan production, and for LHCb even W, and Z production can be affected because of the reach to high rapidity/low-x