

# PDFs with the LHeC and LHC

A M Cooper-Sarkar on behalf of the LHeC study group

with special thanks to Voica Radescu

DIS 2017

## 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.

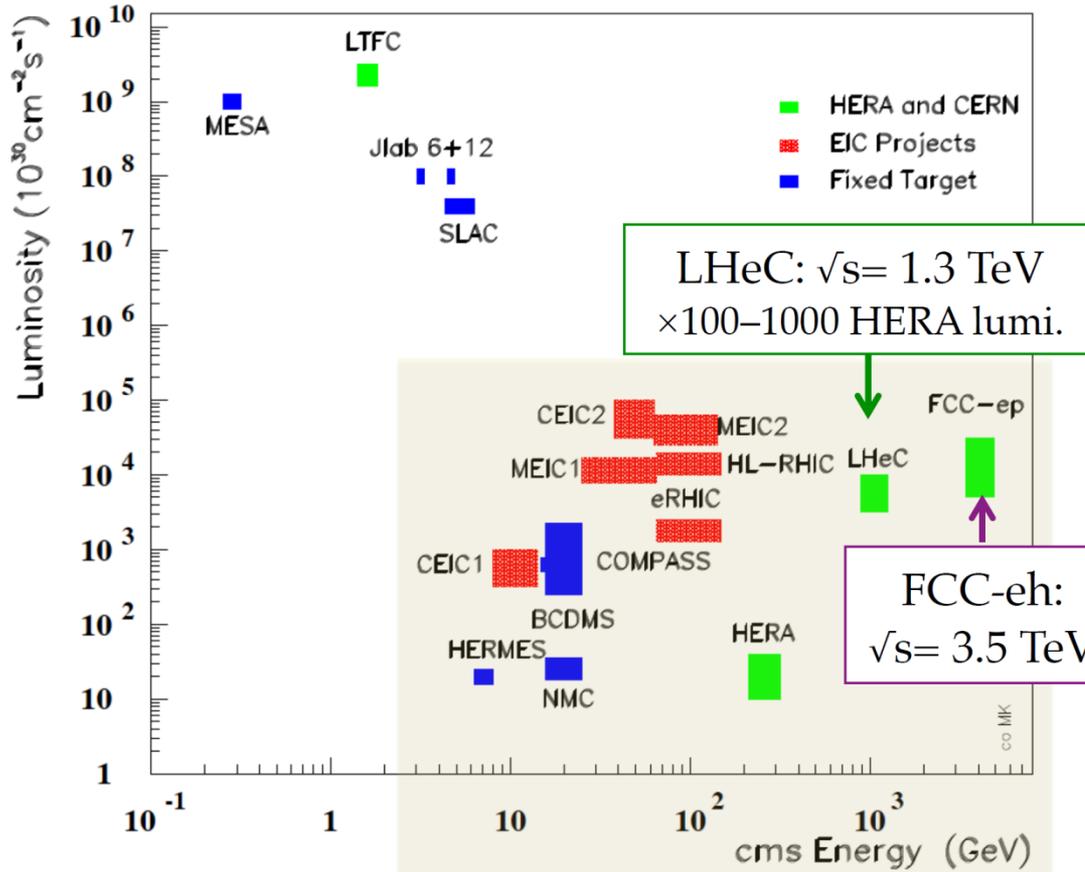
Currently uncertainties on the parton distribution functions (PDFs) limit searches for new heavy particles, dominate the theory uncertainty on Higgs production and limit the precision of  $M_W$  as well as the background to BSM searches

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

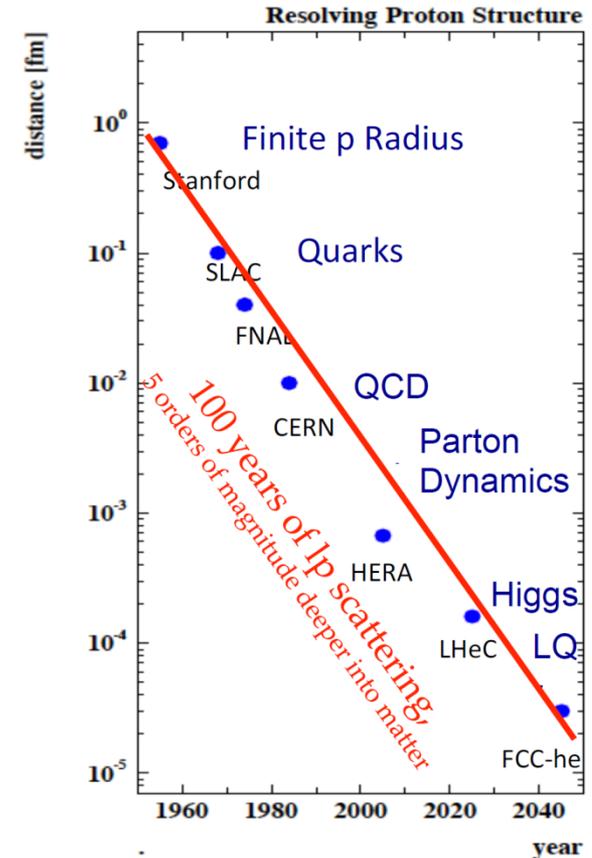
**BUT do we NEED an LHeC? Will we not improve the precision of the PDFs using LHC data itself?**

# lepton-proton facilities

Lepton-Proton Scattering Facilities

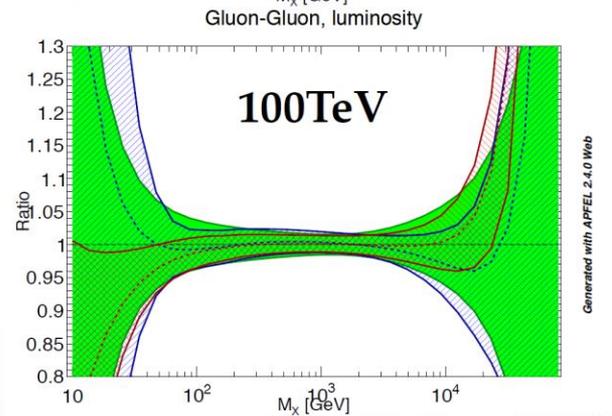
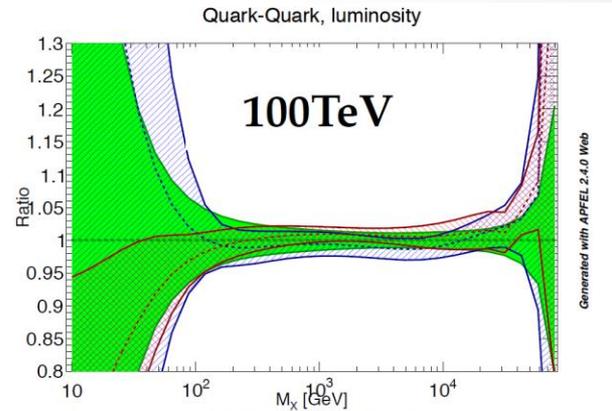
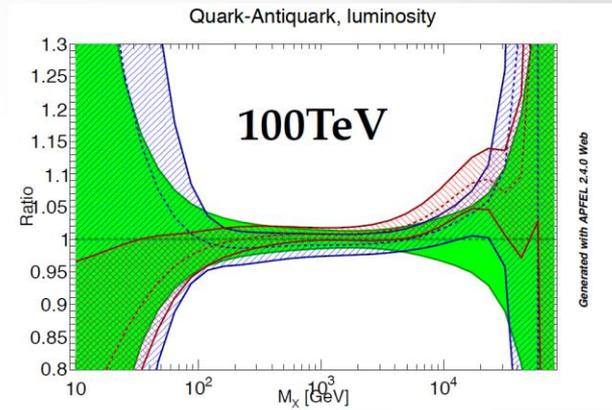
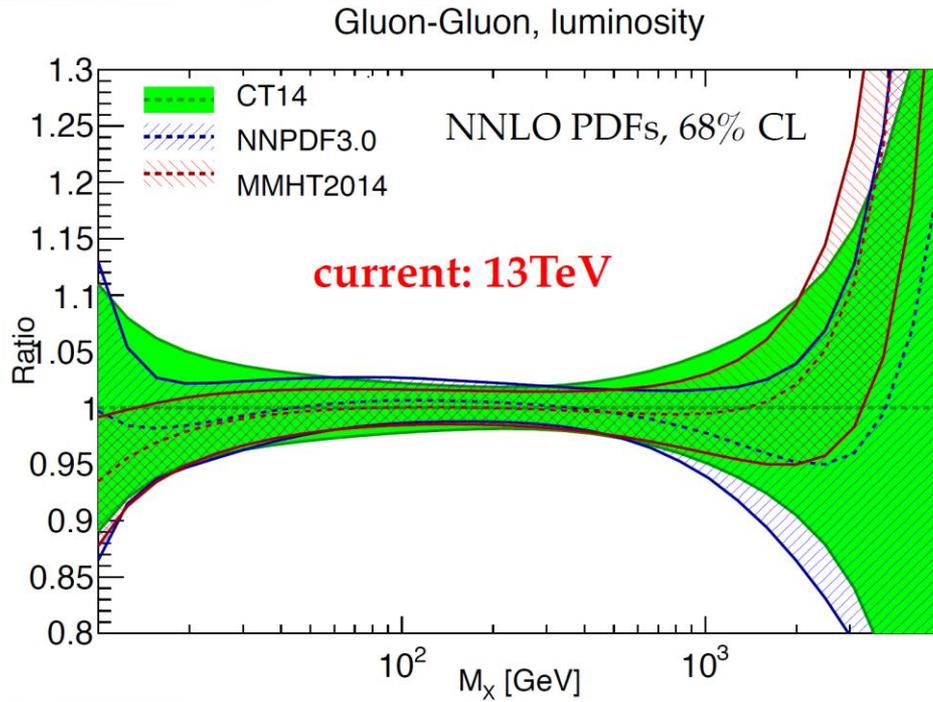


HERA-LHeC-FCC-eh:  
finest microscopes, resolution as  $1/Q$



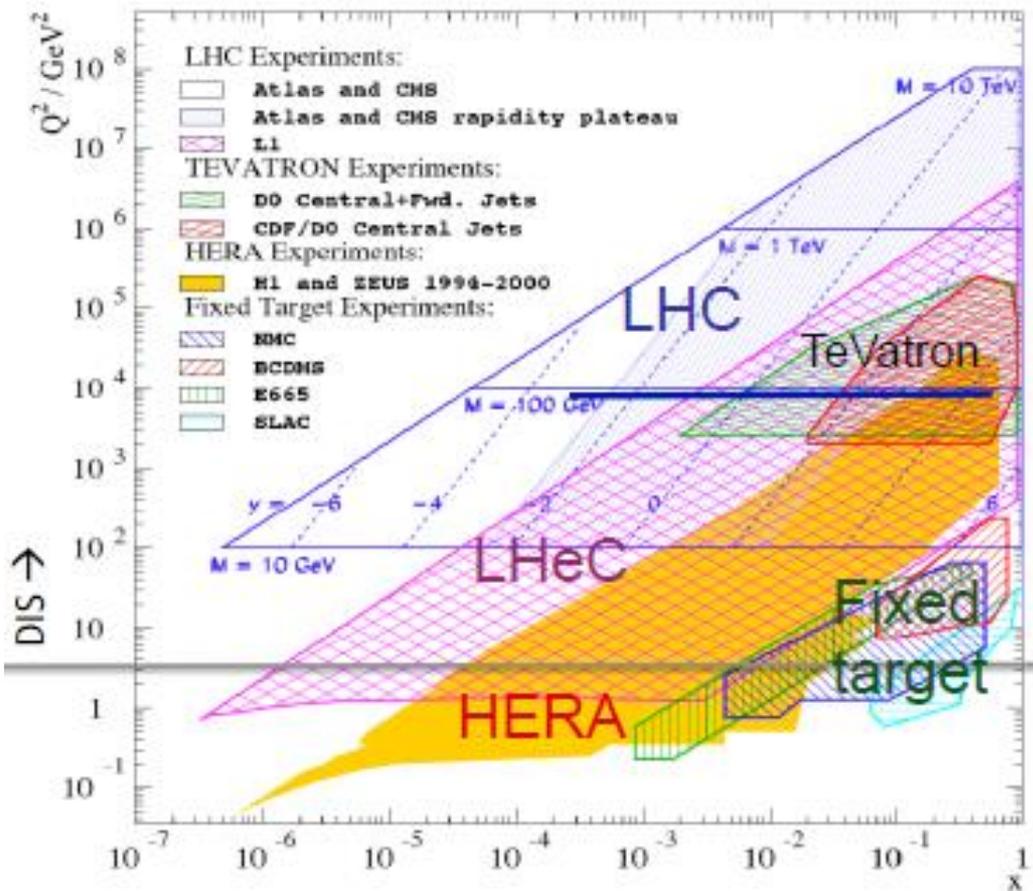
LHC (and other future machines eg. FCC-pp) is/will be main discovery machine  
**LHeC not a competitor to these**; complementary; synchronous with HL-LHC;  
 transforms them into high precision facilities

# proton PDFs, today



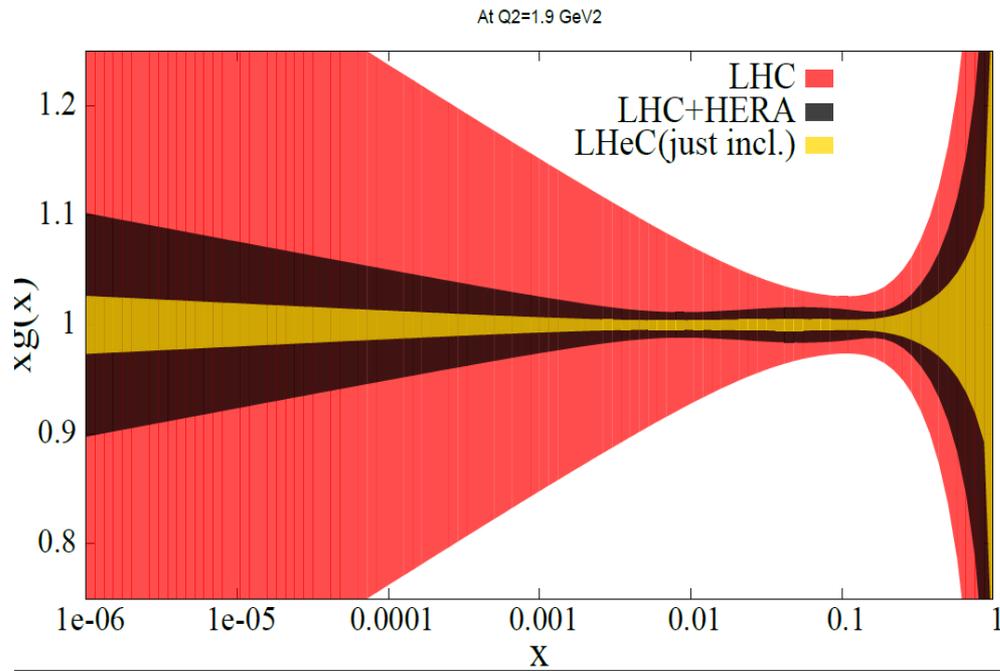
Current level of knowledge of PDFs at 13TeV (including Run-I LHC data) still have considerable uncertainty at high scale BUT at future colliders the low scale region will also have large uncertainties

... many thanks to Joey Huston



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  $\sim 0.5$  of the light quarks.

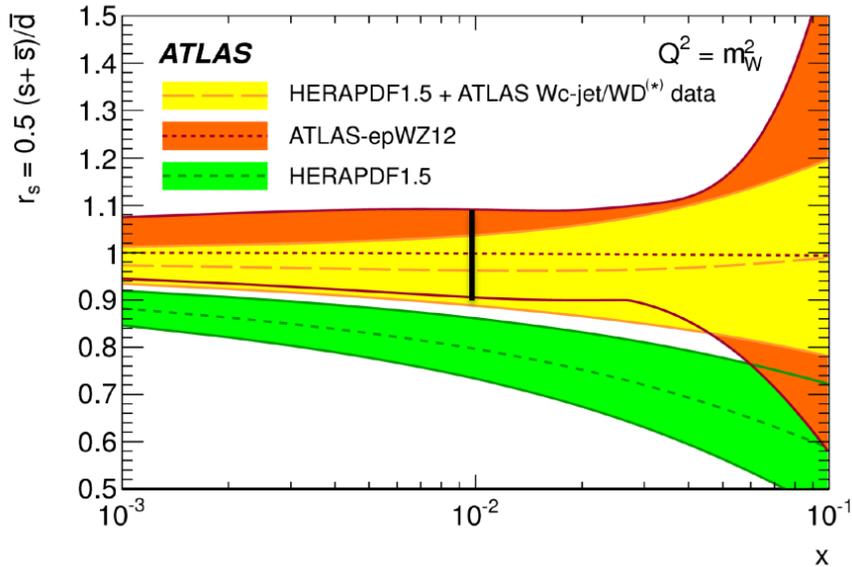
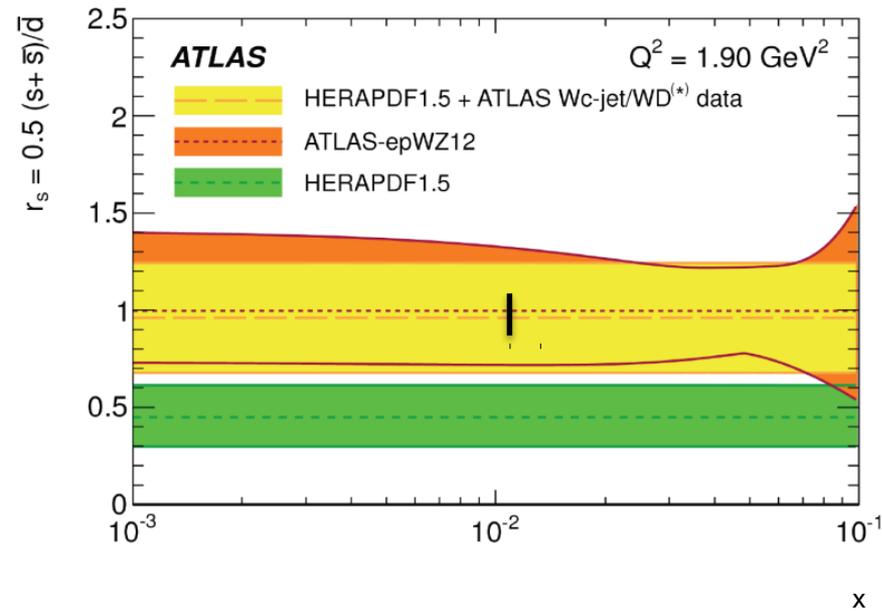
This fraction is shown at the starting scale  $Q^2_0 \sim 2 \text{ GeV}^2$  and at  $Q^2 = M_W^2$

**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  $\pm 10\%$  accuracy. Clearly this could distinguish the  $r_s$  predictions if performed at  $Q^2_0$ , but not if performed at high scale.

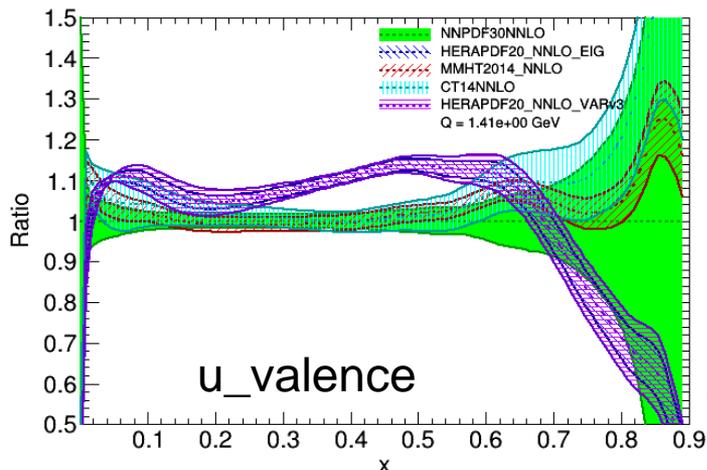
**At high scale we have to have much more accurate measurements.**



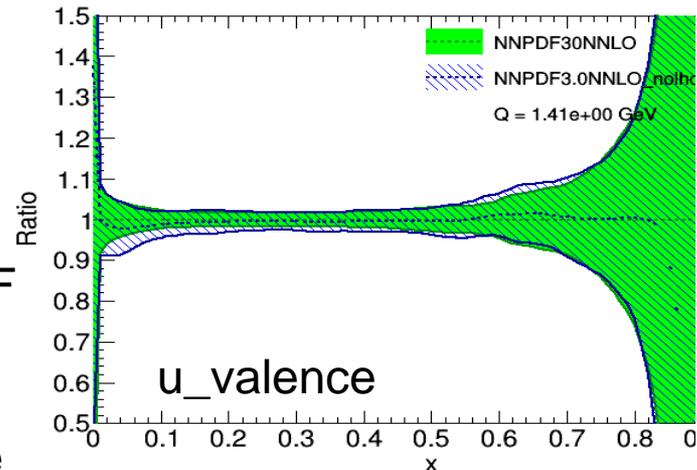
# So let's see how well the LHC is doing

Use the NNPDF3.0 PDF sets **with and without LHC data**

$xu^-(x,Q)$ , comparison

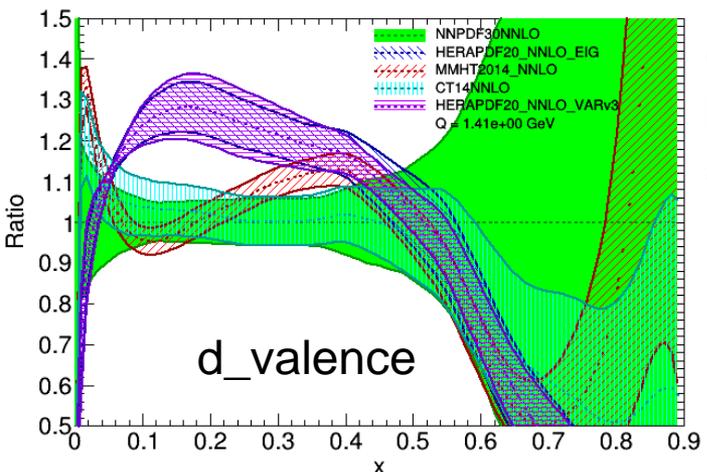


$xu^-(x,Q)$ , comparison

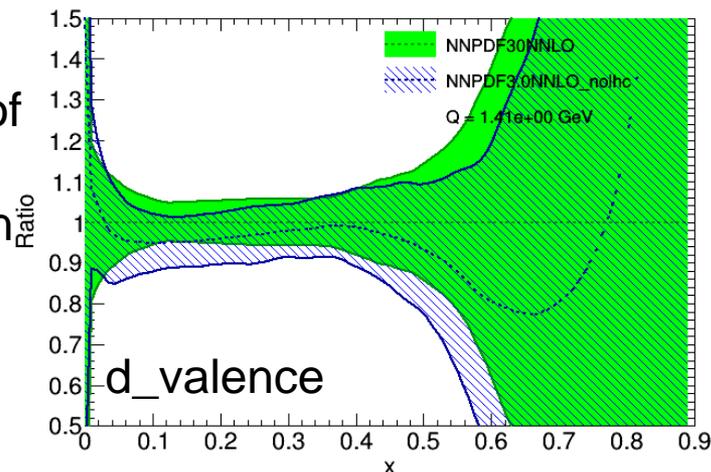


Note that the NNPDF is the PDF analysis with the largest uncertainties outside the  $x$  region of constraining data because of the use of a neural net rather than a parametrization

$xd^-(x,Q)$ , comparison



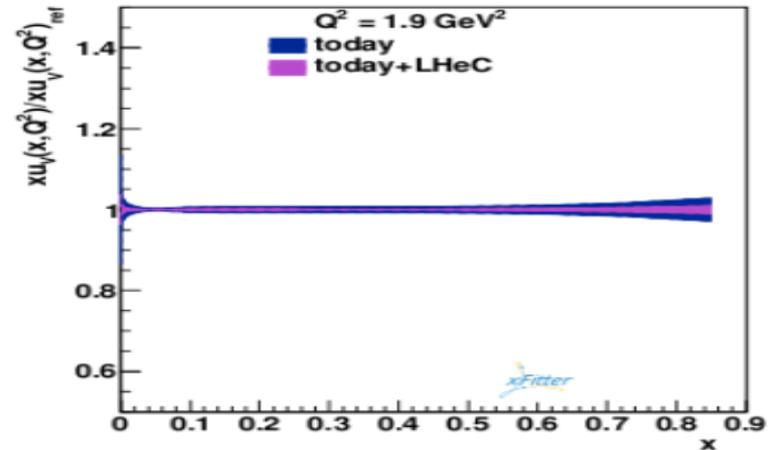
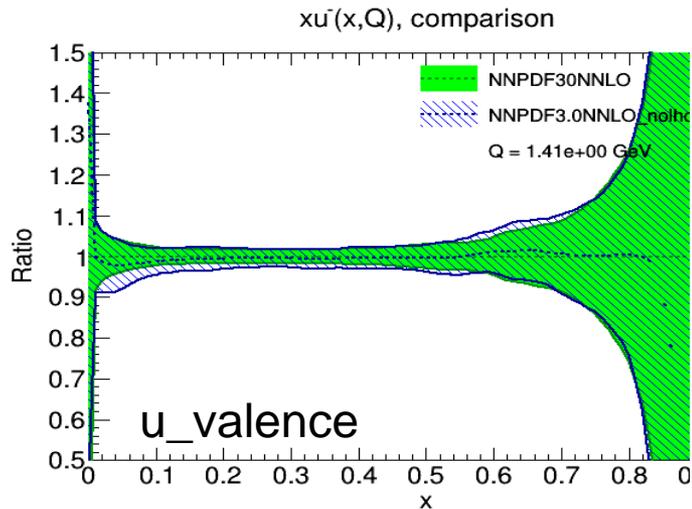
$xd^-(x,Q)$ , comparison



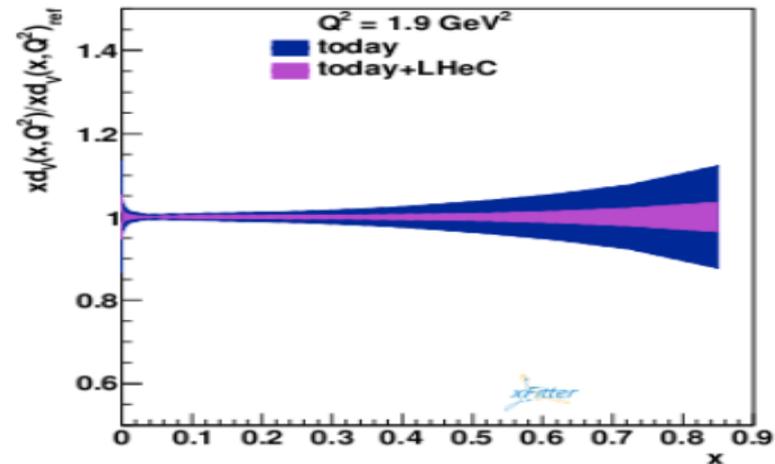
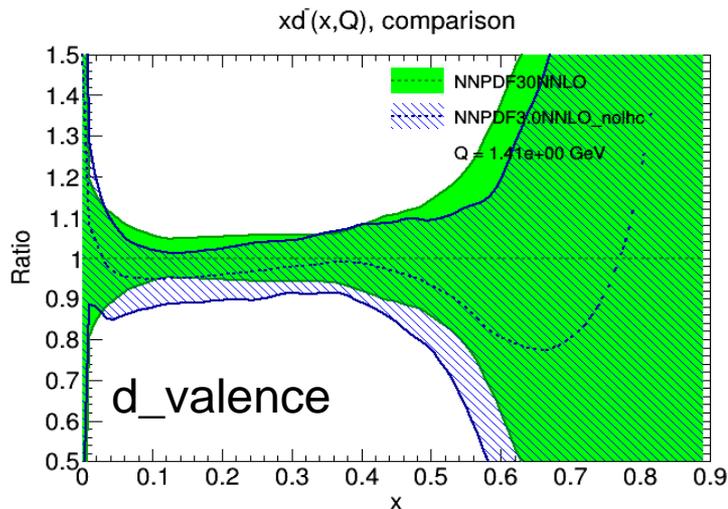
Here we see predictions for u and d valence in ratio to the NNPDF3.0 prediction for CT14, MMHT14, HERAPDF2.0

Here we see predictions for u and d valence from NNPDF3.0 **with and without the LHC data**. At high- $x$  there is some reduction in uncertainty from LHCb  $W^{+/-}$  data

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



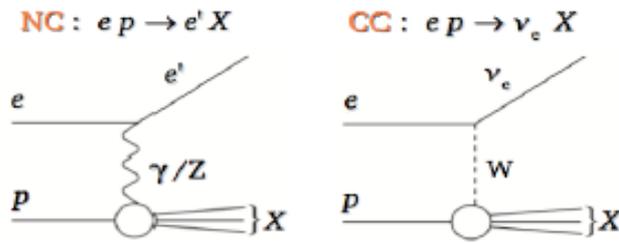
Do not compare the absolute sizes of the uncertainties, compare the level of improvement



LHC data has made an improvement at  $x \sim 0.5$  about 30% in  $d_{\text{valence}}$

LHeC data has made an improvement at  $x \sim 0.5$  about 300% in  $d_{\text{valence}}$

# Let's recap HOW these LHeC predictions are obtained.



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

- o 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.

NC/CC	Name	Ee[GeV]	Ep[TeV]	P(e)	Charge	Lum[ab <sup>-1</sup> ]
nominal, high luminosity data, negative polarisation						
NC	datlhe760ncem	60	7	-0.8	-1	1
CC	datlhe760ccem	60	7	-0.8	-1	1
nominal, high luminosity data, opposite polarisation						
NC	datlhe760ncep	60	7	0.8	-1	0.3
CC	datlhe760ccep	60	7	0.8	-1	0.3
positron data, unpolarised						
NC	datlhe760ncepp	60	7	0	+1	0.1
CC	datlhe760ccepp	60	7	0	+1	0.1

$$\sigma_r(x, Q^2) = \frac{d^2\sigma(e^\pm p)}{dx dQ^2} \frac{Q^4 x}{2\pi\alpha^2 Y_\pm} = F_2(x, Q^2) - \frac{y^2}{Y_+} F_L(x, Q^2) \mp \frac{Y_-}{Y_+} x F_3(x, Q^2)$$

### 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

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

- **F<sub>2</sub> dominates**
  - sensitive to all quarks
- **xF<sub>3</sub>**
  - sensitive to valence quarks
- **F<sub>L</sub>**
  - sensitive to gluons

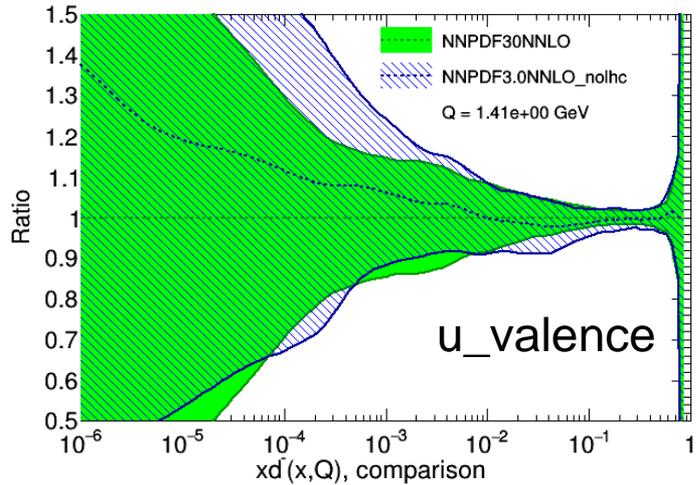
source of uncertainty	error on the source or cross section
scattered electron energy scale $\Delta E'_e/E'_e$	0.1 %
scattered electron polar angle	0.1 mrad
hadronic energy scale $\Delta E_h/E_h$	0.5 %
calorimeter noise (only $y < 0.01$ )	1-3 %
radiative corrections	0.3 %
photoproduction background (only $y > 0.5$ )	1 %
global efficiency error	0.7 %

Gluon also comes from the scaling violations

# 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**

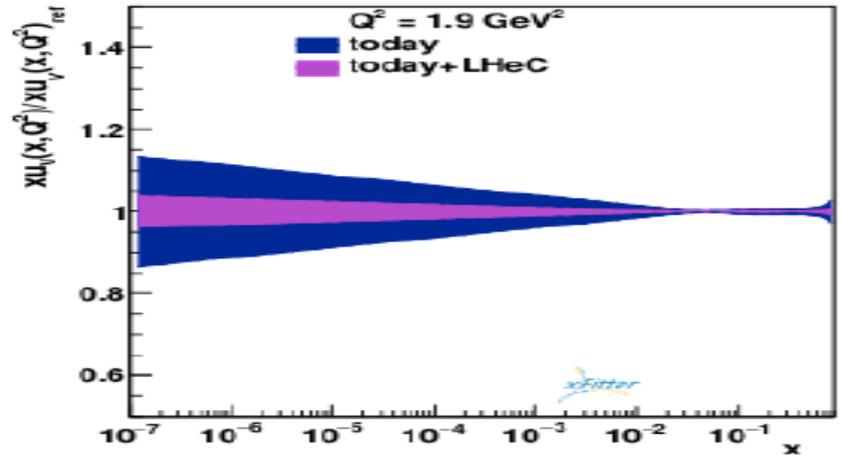
$xu(x,Q)$ , comparison



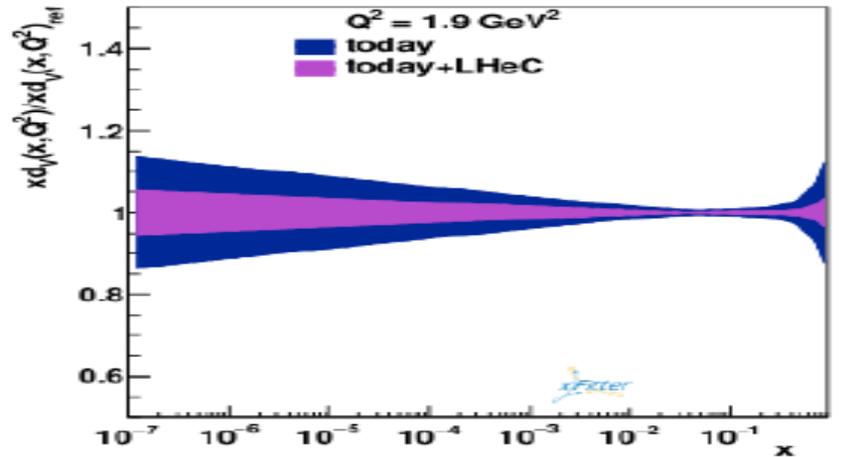
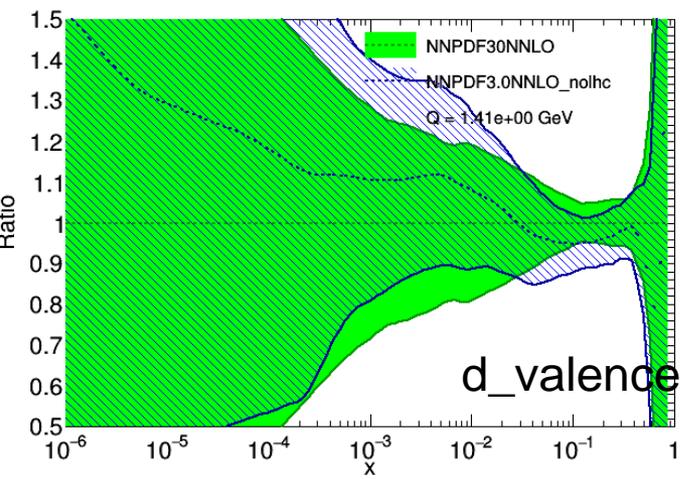
Now look at valence distributions at low-x

LHC gives improvements from ATLAS and CMS W-asymmetry data

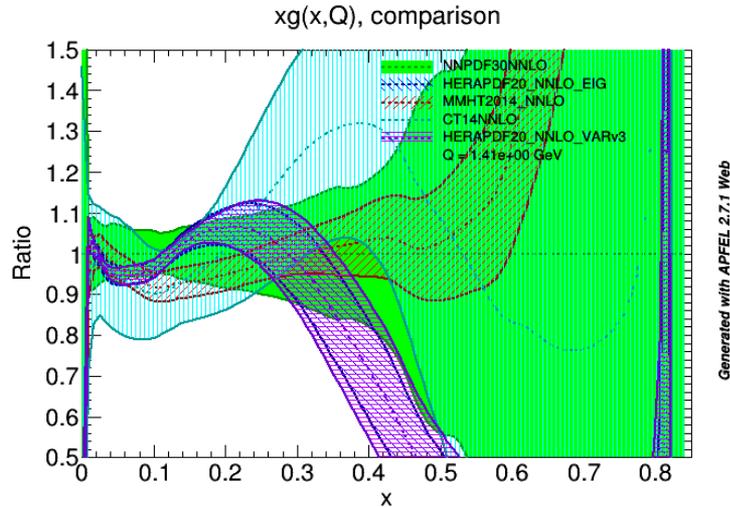
The LHeC does rather better



$xd(x,Q)$ , comparison

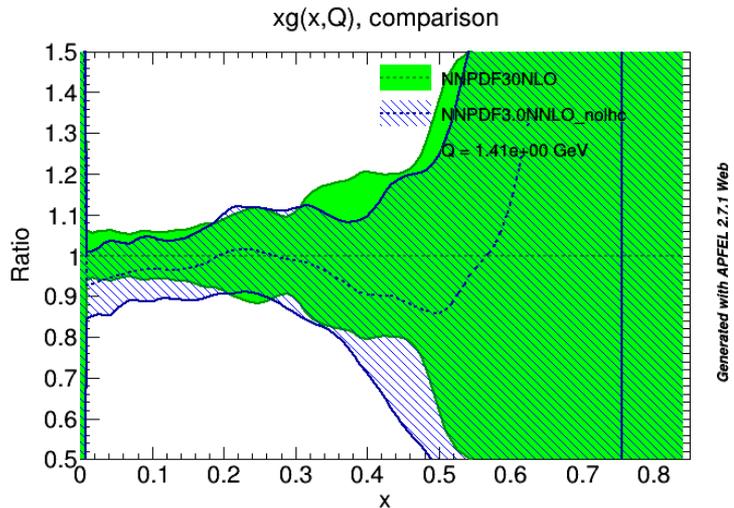


# Gluon at high x

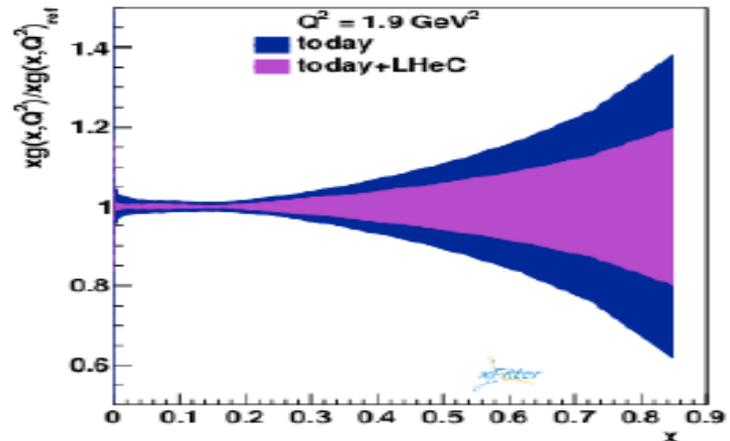


The high x gluon is not well known. Current PDFs differ.

LHC data on jet production has reduced the high-x uncertainty for NNPDF3.0.



The LHeC does rather better



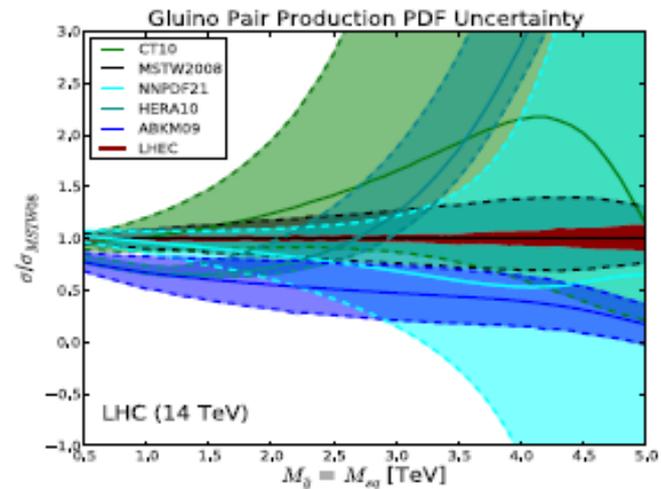
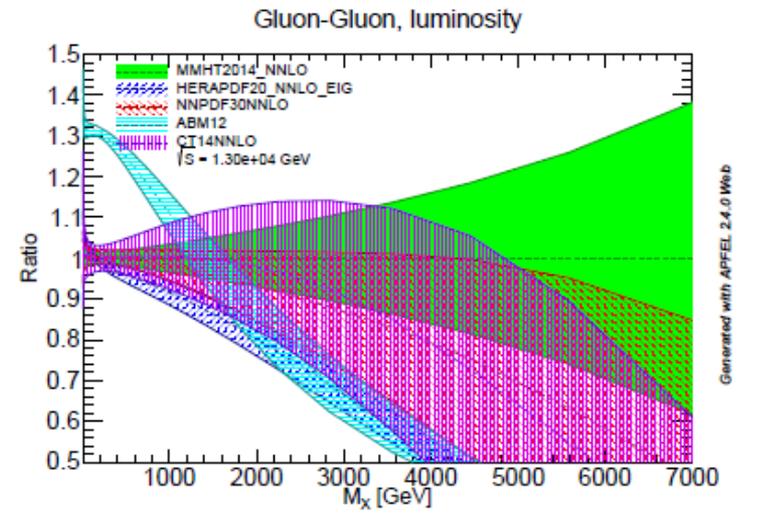
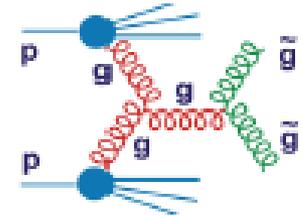
# Why are we interested in the high-x gluon?-one example

Many interesting processes at the LHC are gluon-gluon initiated  
Top, Higgs...BSM processes like gluon-gluon  $\rightarrow$  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

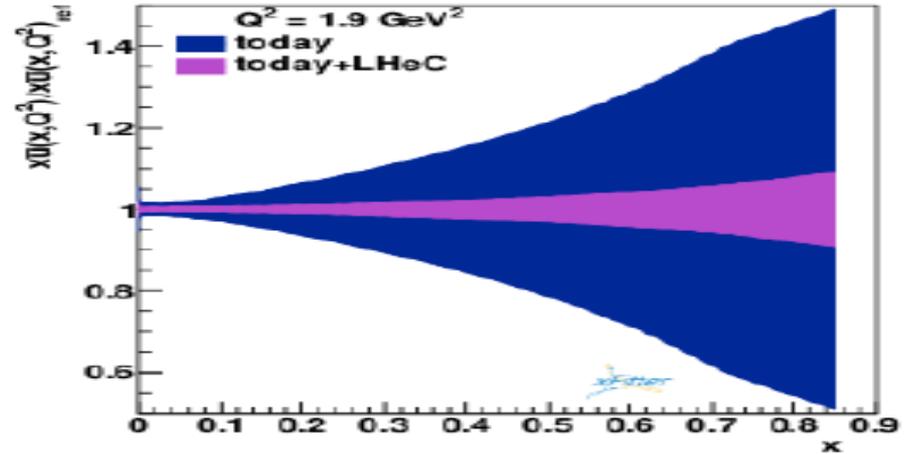
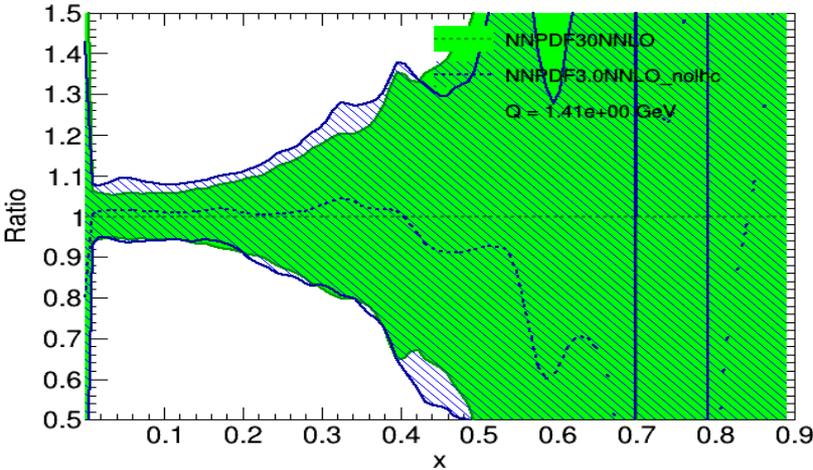


Which could be considerably reduced using LHeC data

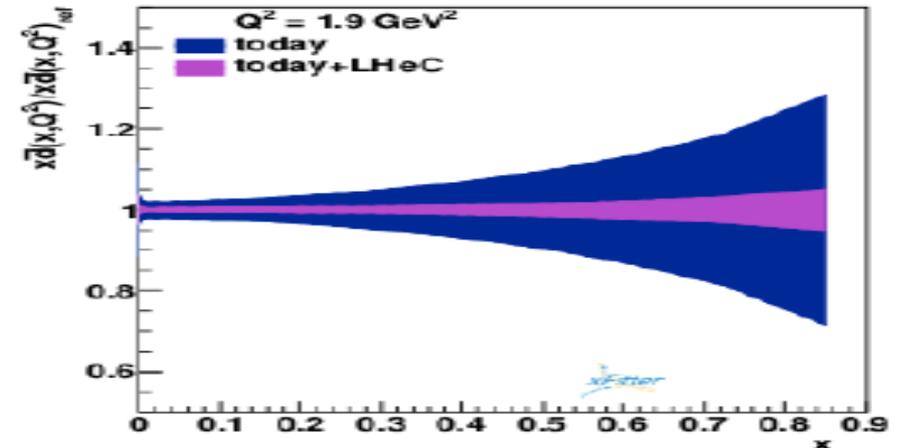
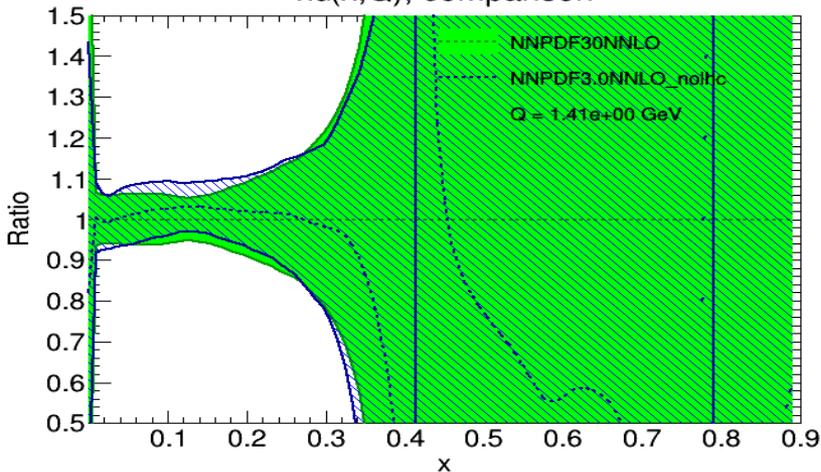
The LHC data have not so far led to big improvements in the **high-x sea PDFs**  
 This could come from high-mass Drell-Yan data, but is unlikely to compete with the potential improvement  
 From LHeC PDFs

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  $F_{2,YZ}$ ,  $x F_{3,YZ}$

$x\bar{u}(x,Q)$ , comparison

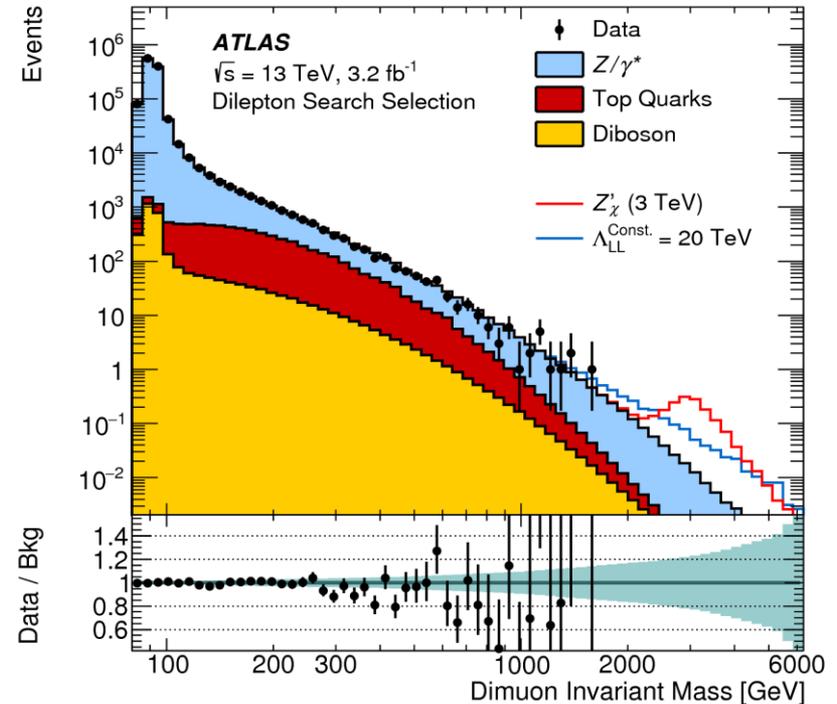
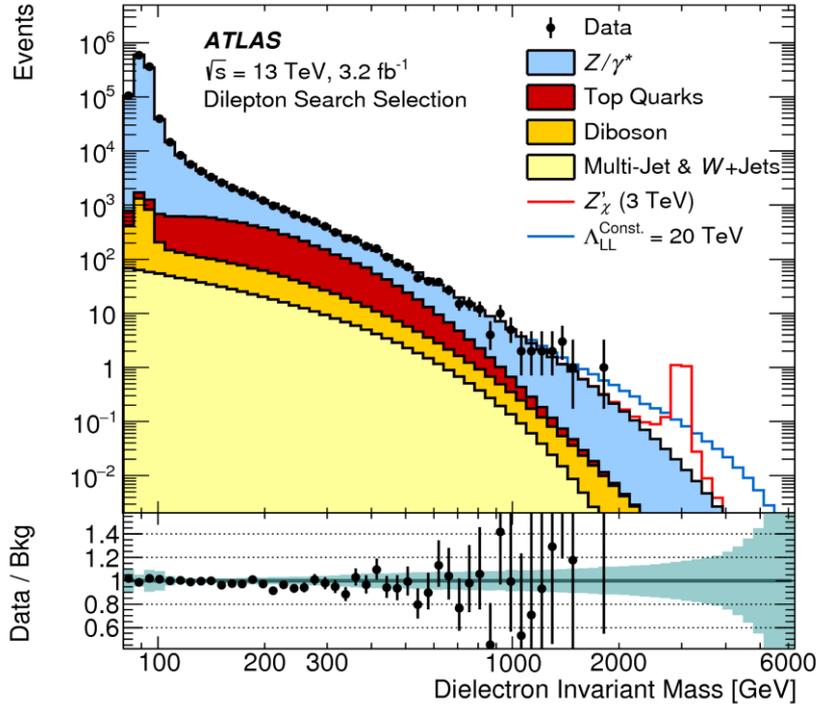


$x\bar{d}(x,Q)$ , comparison



# 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



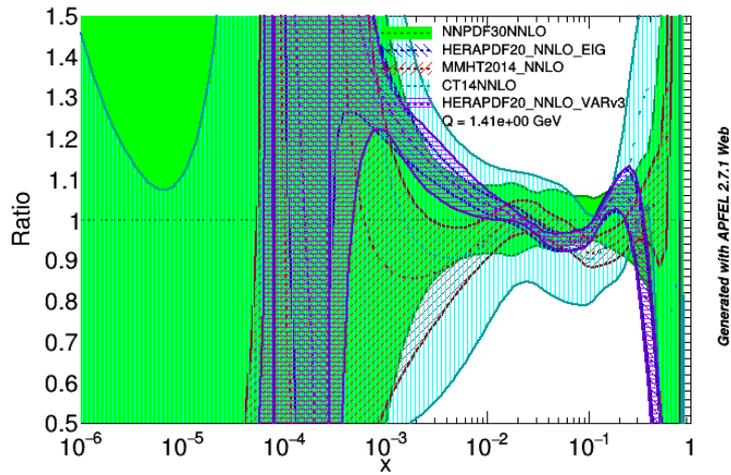
arXiv:1607.03669

# Gluon at low x

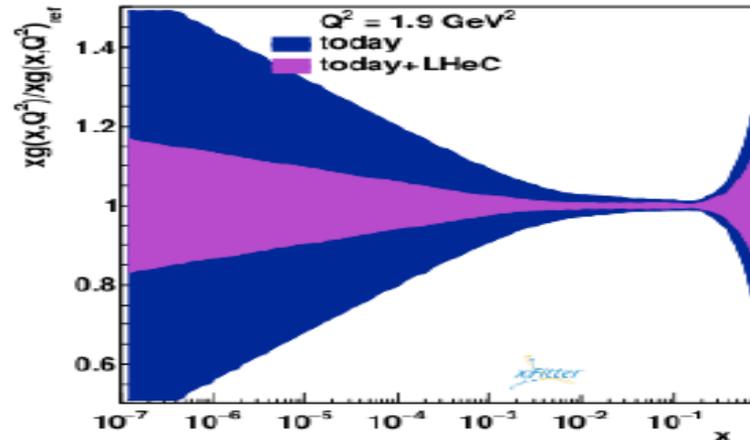
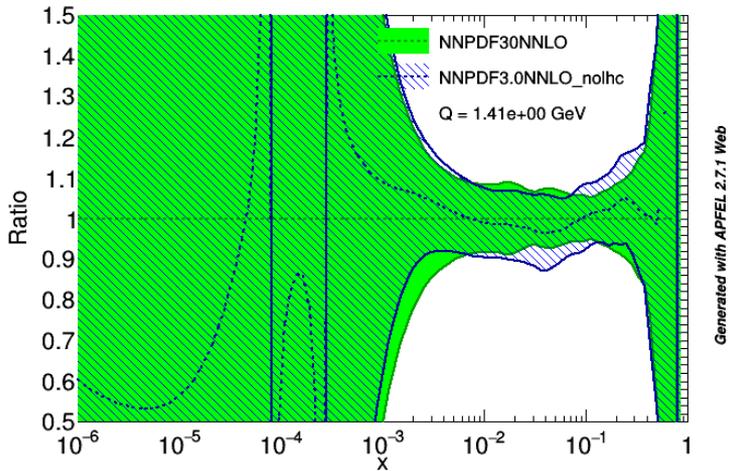
The low x gluon is not well known.  
LHC data has not contributed much to this for two reasons

- the data do not reach below  $x \sim 10^{-3}$  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  $x > 5 \cdot 10^{-4}$
- LHeC goes down to  $10^{-6}$

xg(x,Q), comparison



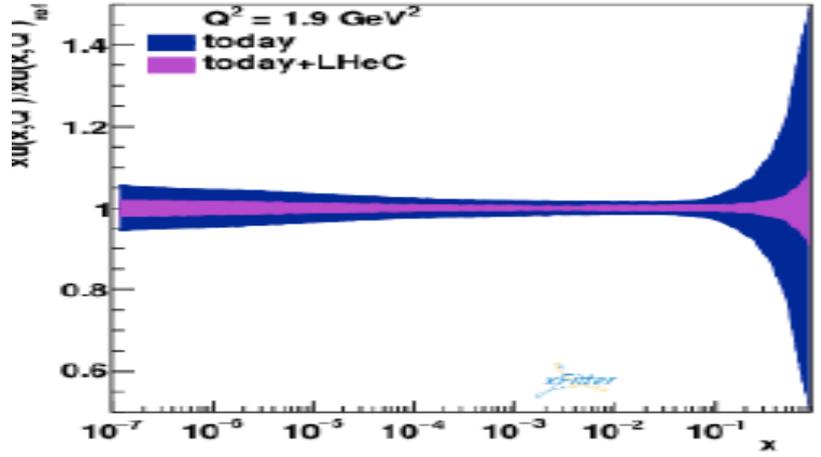
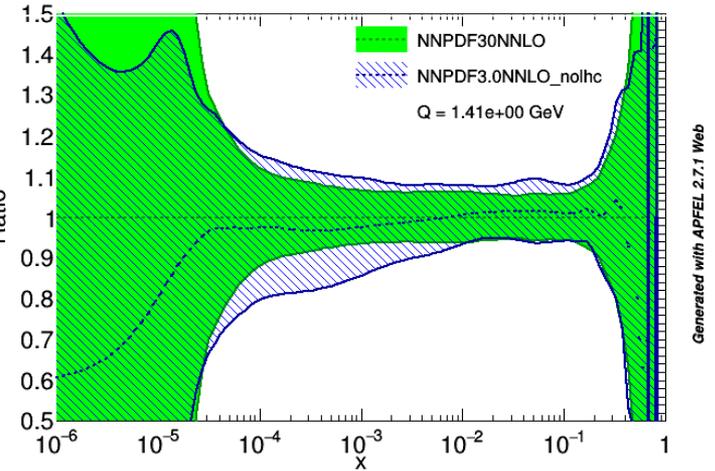
xg(x,Q), comparison



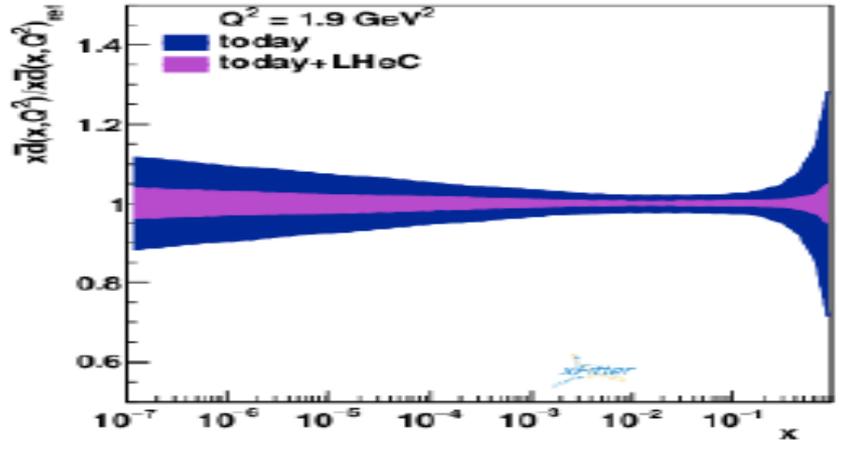
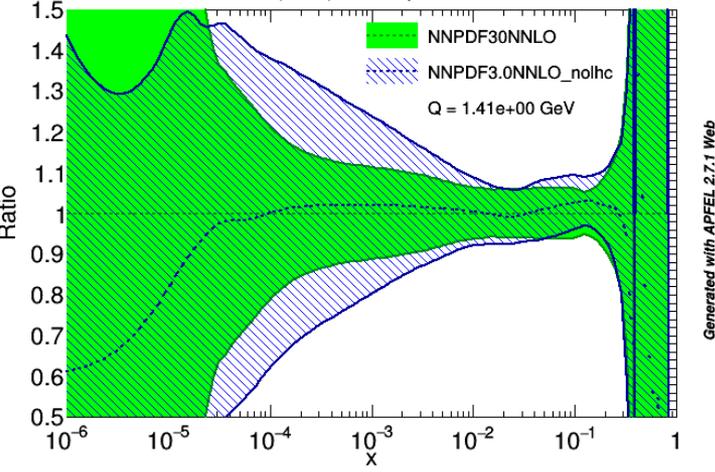
The **low x sea** is better known than the low-x gluon, but still not well known

- 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

$x\bar{u}(x,Q)$ , comparison



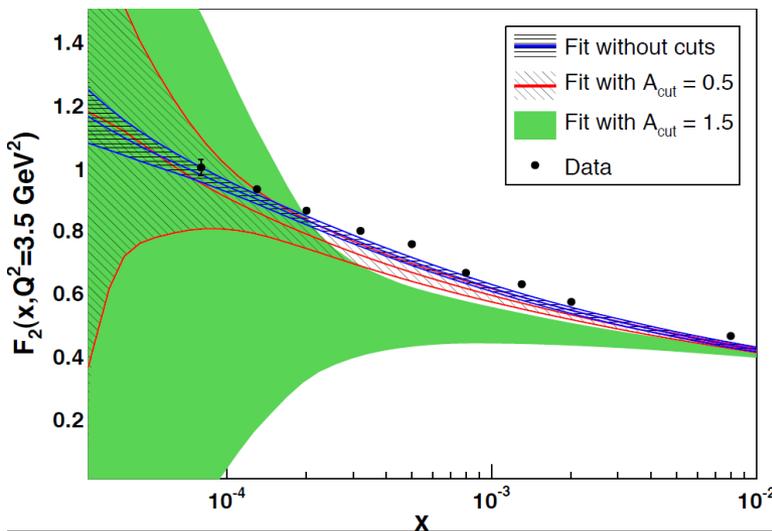
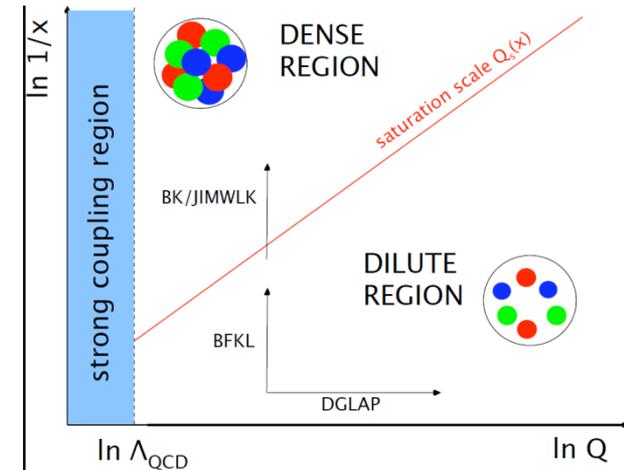
$x\bar{d}(x,Q)$ , comparison



## 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  $F_2$  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.

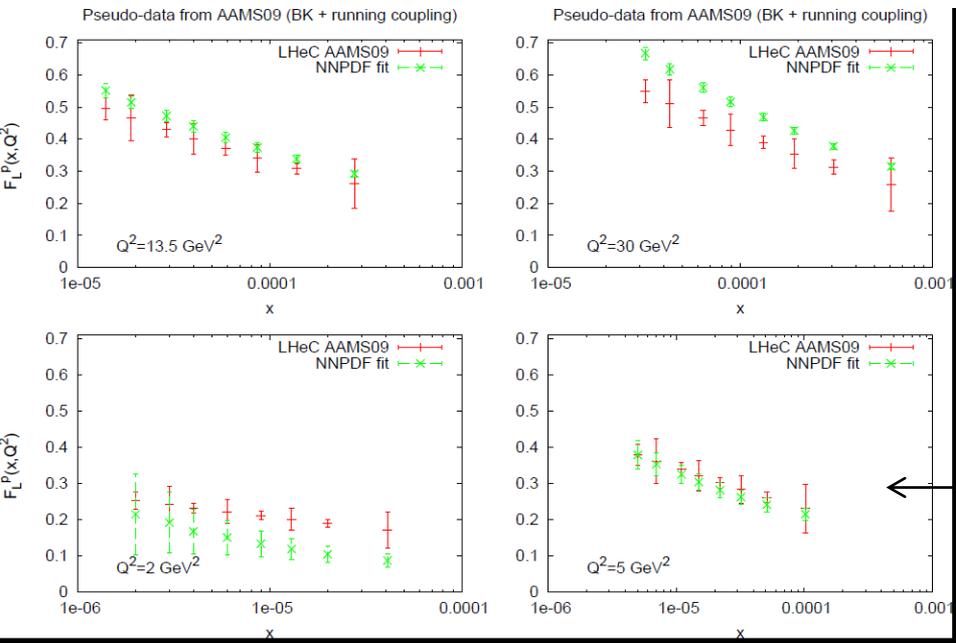
IN DGLAP based fits to inclusive data at low-x, we have  
 $F_2 \sim xq$  for the sea  
 $dF_2/d\ln Q^2 \sim P_{qg} xg$  for the gluon

Our deductions about gluon behaviour at low-x come via the DGLAP splitting function  $P_{qg}$

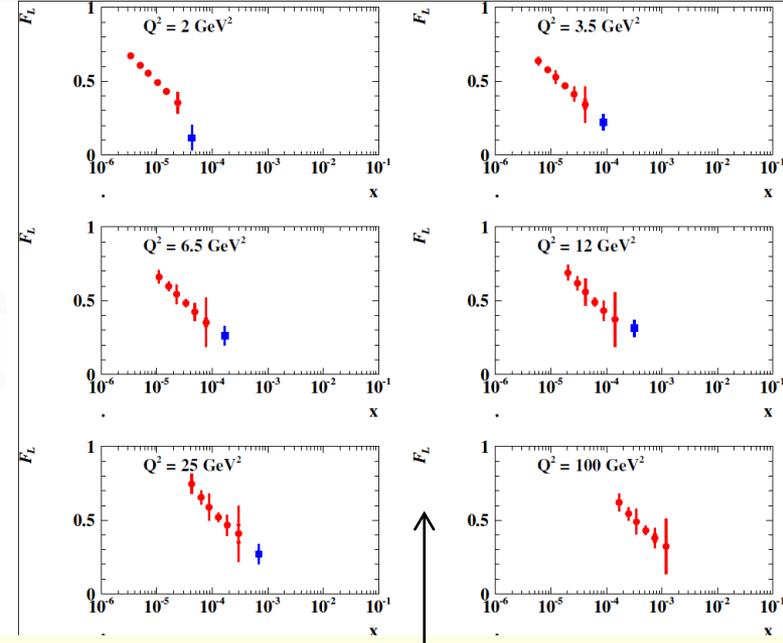
If DGLAP is inadequate then so will our deductions about the shape of the gluon be inadequate. We need other ways to probe it, e.g.

FL is gluon dominated at low-x

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



IF DGLAP is at fault it will be harder for it to explain  $F_2$  and  $F_L$  data simultaneously, but one needs precision data – which can come from the LHeC --a low energy run is planned



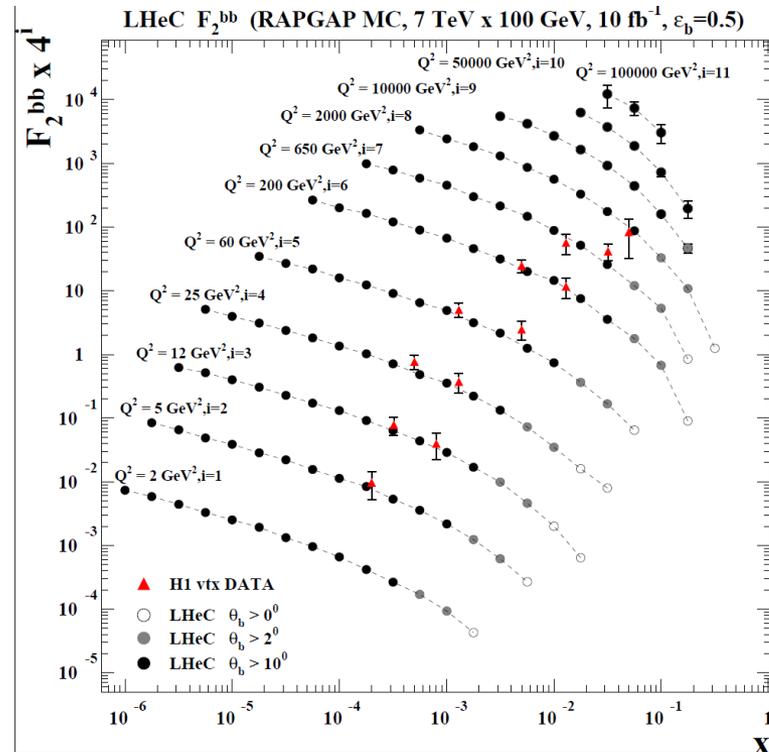
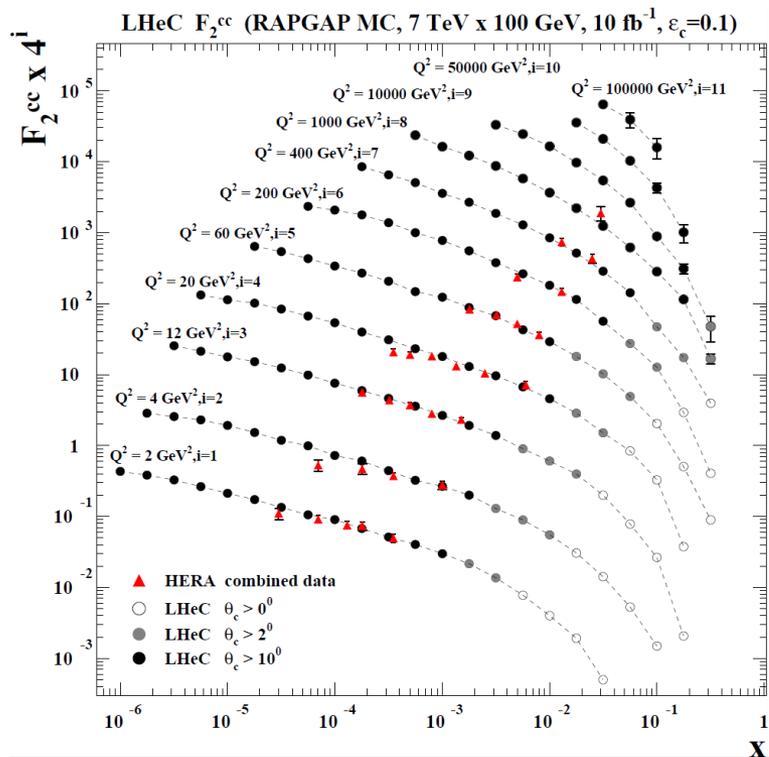
Blue is what we have now averaged over x for each Q2 bin

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.

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

Compare the potential for the measurement of  $F_2^{c\text{-cbar}}$  and  $F_2^{b\text{-bbar}}$  with what is currently available from HERA



## Why are $F_2^{b,c}$ measurements better?

- higher cross section, higher  $Q^2$ , higher luminosity ( $F_2^b$ )
- new generation of Si detectors

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

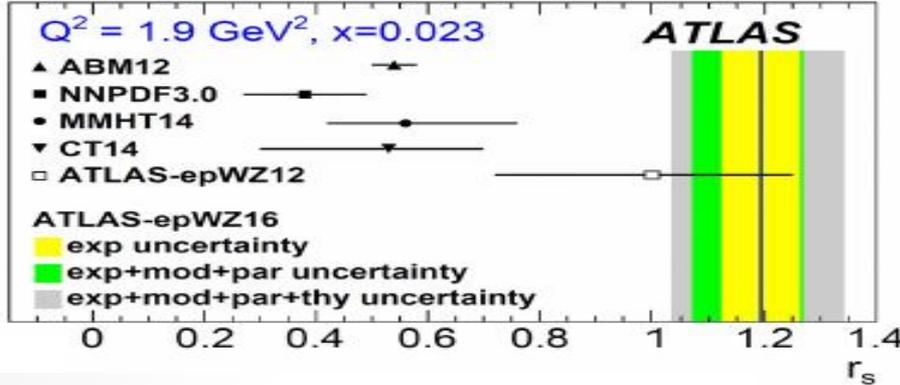
top: tPDF, cross section few pb at  $E_e=60\text{GeV}$ ,  $W_b \rightarrow t$

# The strange PDF is not well known

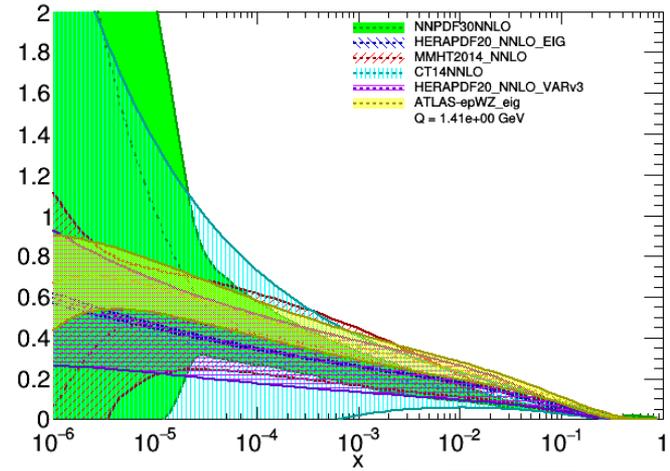
Is it suppressed compared to other light quarks?

Is there strange-antistrange asymmetry?

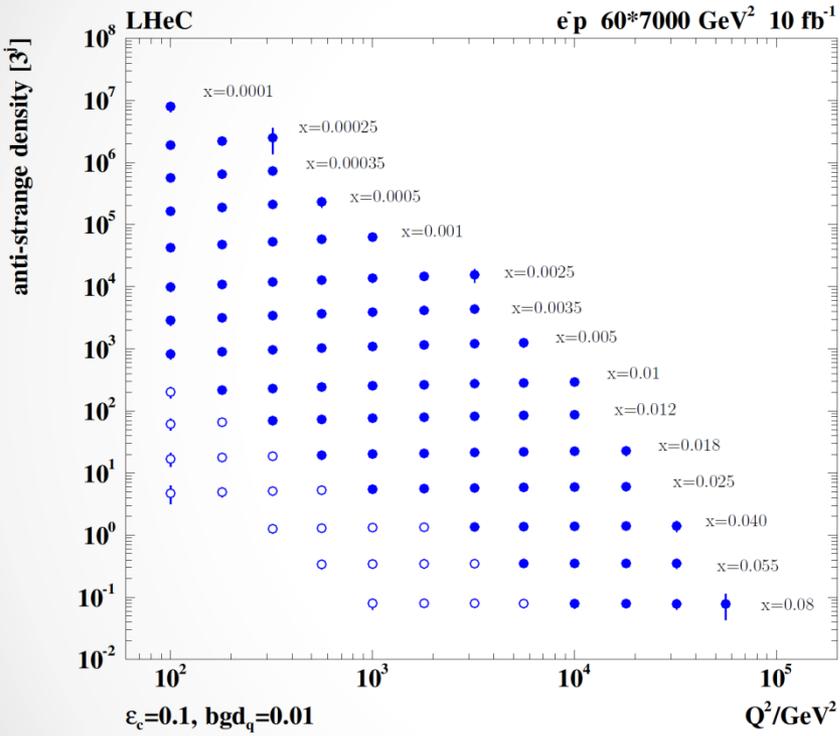
e.g. ATLAS data suggest SU(3) symmetric sea



xs(x,Q), comparison



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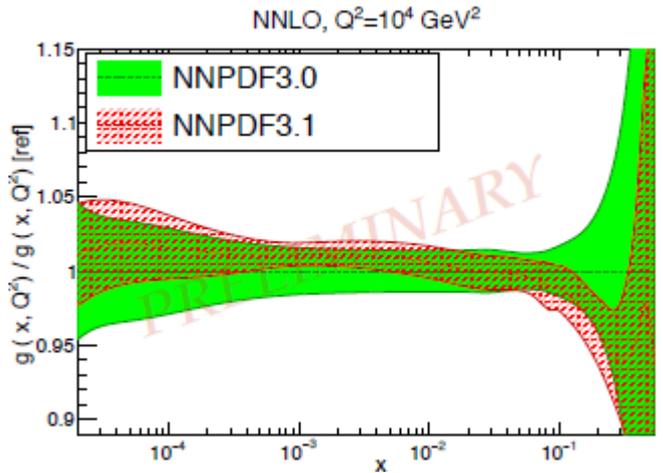
**LHeC could give direct sensitivity to strange through charm tagging in CC events.**

Results are shown for 10% charm tagging efficiency, 1% light quark background in impact parameter.

**This could give the first  $x, Q^2$  measurement of the anti-strange PDF** (This also assumes an updated scenario from the CDR – see backup)

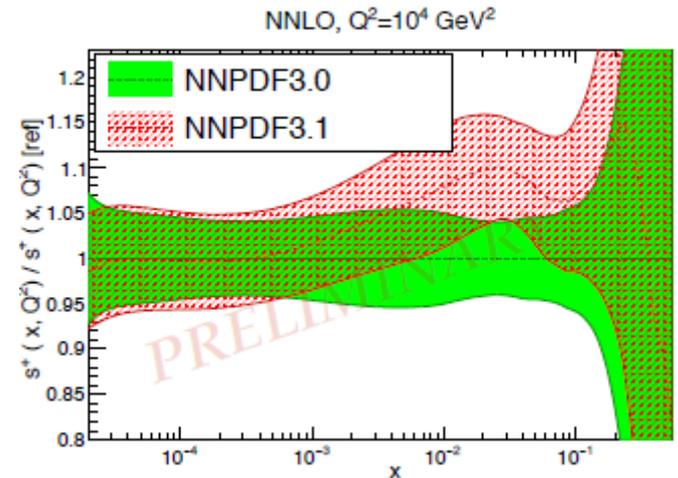
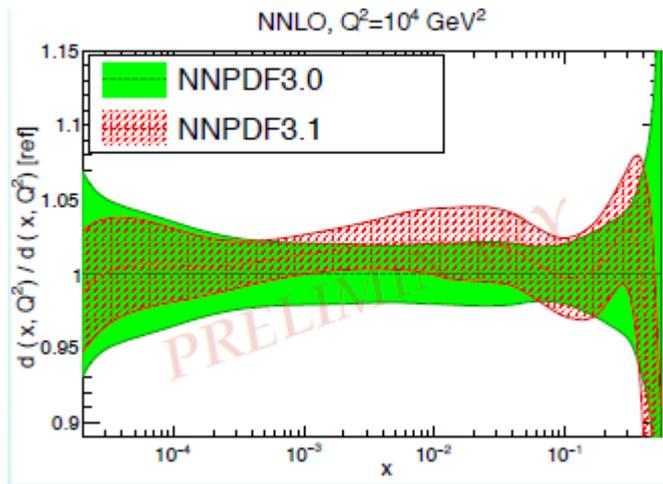
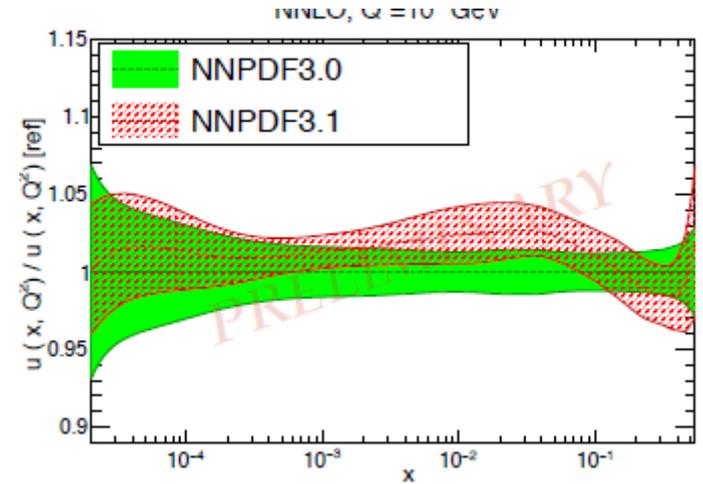
But all of this was based on knowledge of how the LHC contributes to our knowledge of PDFs TODAY.

How about tomorrow? The NNPDF3.1 contains more LHC data including the most precise data set there has ever been on W,Z data



Further high-x gluon improvement from t-tbar and Zpt as well as jets

Further quark improvement from Drell-Yan particularly the ATLAS W,Z precision measurement



Improvements are significant but still modest

**But all of this was based on knowledge of how the LHC contributes to our knowledge of PDFs TODAY.**

**How about in several years time.**

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.

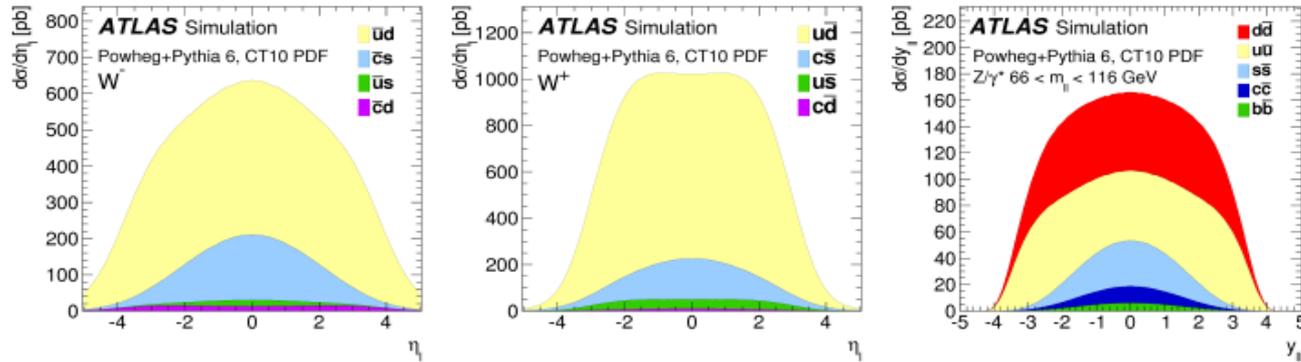
Consider the most precise measurement there has ever been at LHC:  
the ATLAS inclusive  $W$  and  $Z$  differential distributions arXiv:1612.03016

- $W$ : 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

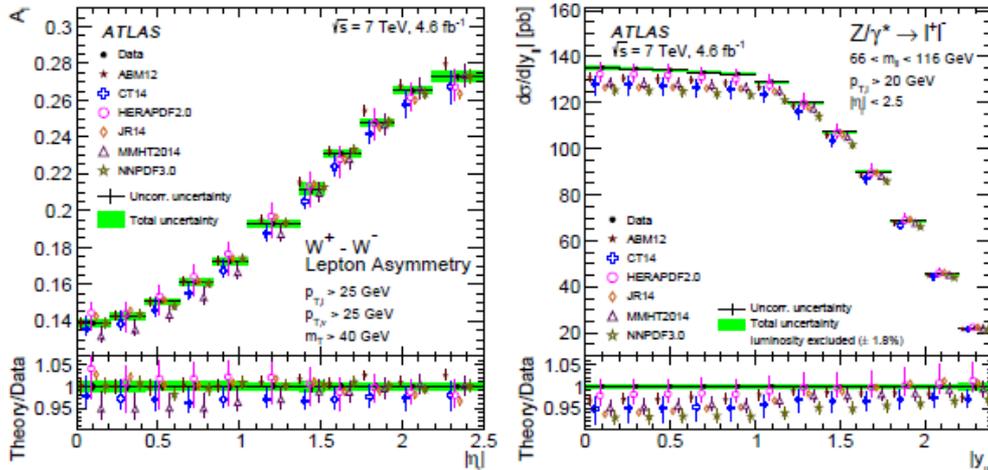
We are unlikely to beat this even with an HL-LHC and the change in kinematic region to from 7/8 to 13/14 TeV does not change the  $x$ -region probed for PDFs much.

**So this is as good as it gets – at least for  $q$ - $q$ bar**

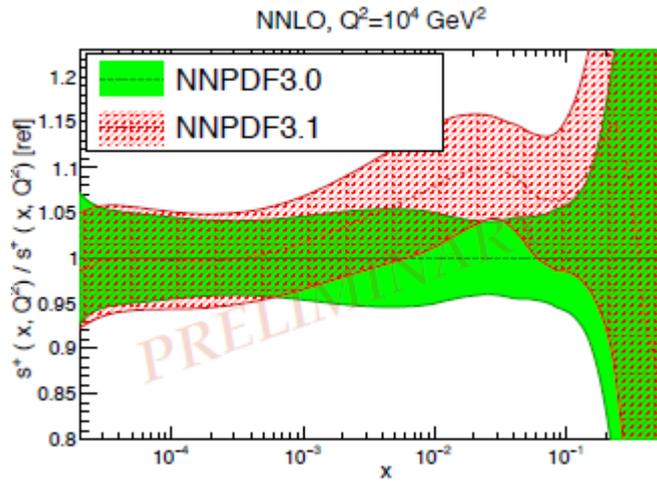
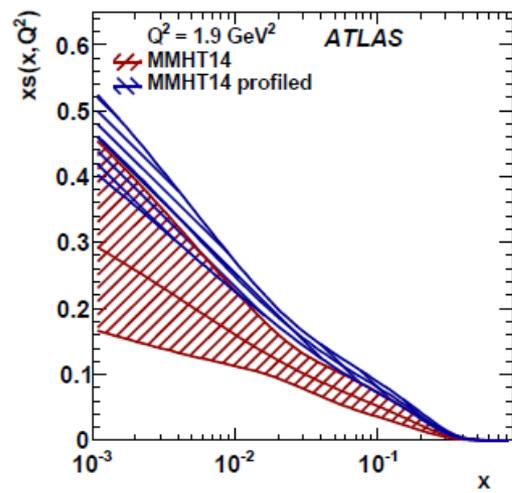
# What does this precise $W, Z$ measurement do for us?



- Inclusive rapidity-differential measurements of  $W^\pm$  and  $Z/\gamma^*$  production probe different combinations of PDFs. They provide constraints on the light flavour sea decomposition and the valence PDFs
- $W$  charge asymmetry measurements provide constraints on the  $u$  and  $d$  valence PDFs
- The shape of the  $Z$  rapidity distribution, and the  $W/Z$  cross-section ratio probe the strange PDF

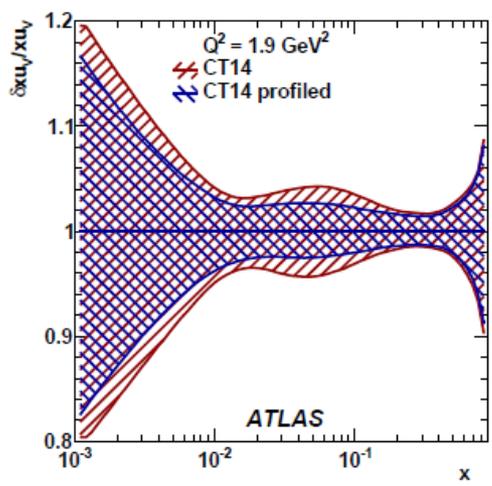
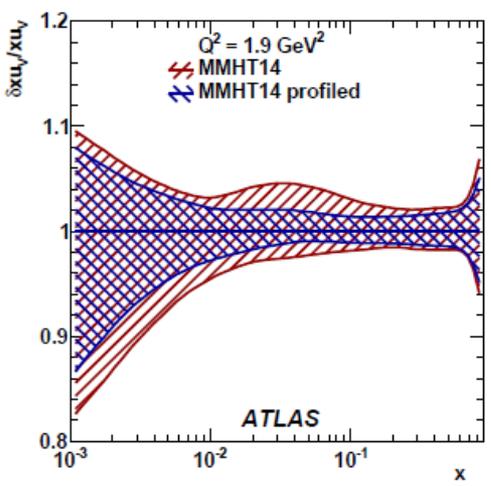


The measurement uncertainties are smaller than the uncertainties on current PDF predictions SO...

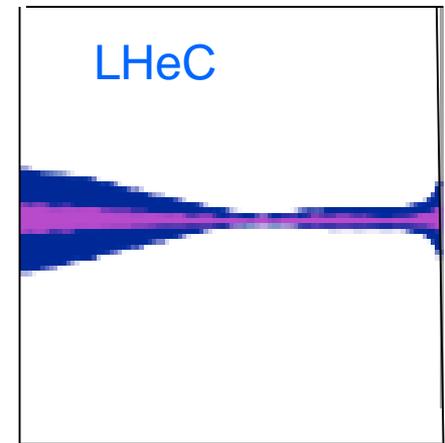


It reduces the uncertainties on the strange sea- as well as pulling up its absolute value at low-x. Strange measurements can be much improved at the LHeC

It is already included in NNPDF3.1, as seen on slide 21, with only modest improvement to uncertainties and it is already included in the 'todays' data of the LHeC studies



e.g It improves valence PDF uncertainties BUT does not compete with an LHeC



# 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
- Such Precision PDFs are needed for BSM physics
- Data from the LHC itself cannot improve current PDFs to anything like the same degree

Backup

# impact of different LHeC datasets

**new** since CDR

ERL scenario; interest in Higgs

prefers e-, high polarisation

$E_p=7$  TeV,  $E=60$  GeV:

NC,CC:

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

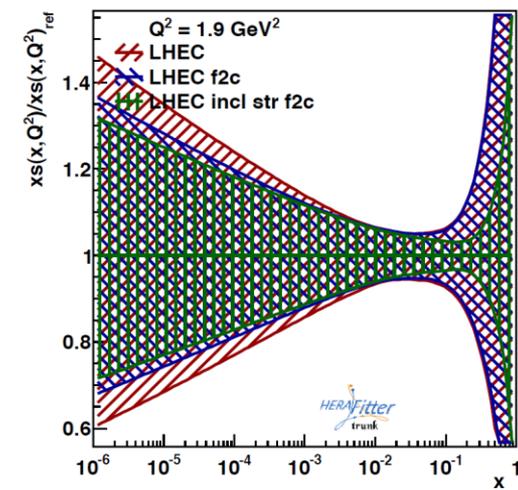
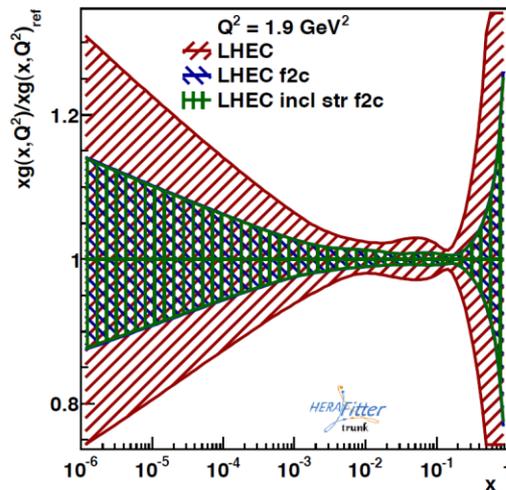
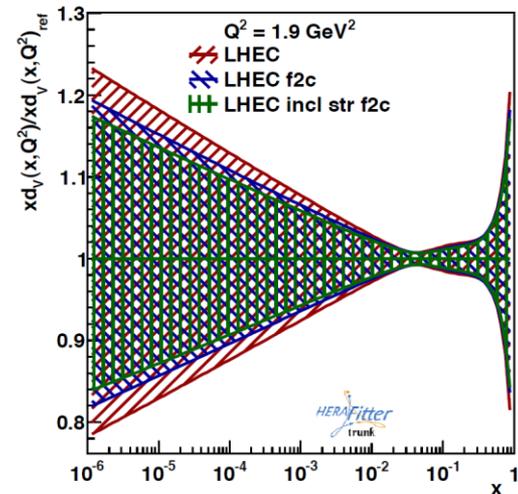
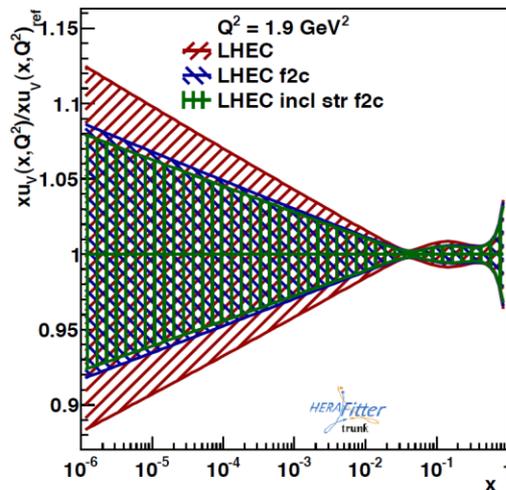
plus, dedicated measurements of strange, anti-strange, F2cc (not yet F2bb, low  $E_p$  data, FL)

more flexible PDF fit:

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

$xf(x) = A x^B (1-x)^C (1+Dx+Ex^2)$

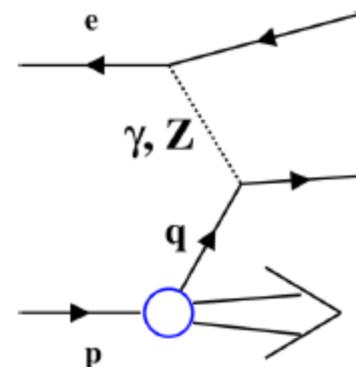
- 14 free parameters



can better constrain all PDFs

## Master formulae for NC DIS

$$\sigma_{r,NC} = \frac{d^2\sigma_{NC}}{dx dQ^2} \cdot \frac{Q^4 x}{2\pi\alpha^2 Y_+} = \mathbf{F}_2 + \frac{Y_-}{Y_+} \mathbf{xF}_3 - \frac{y^2}{Y_-} \mathbf{F}_L$$



$$\begin{aligned} \mathbf{F}_2^\pm &= F_2 + \kappa_Z(-v_e \mp P a_e) \cdot F_2^{\gamma Z} + \kappa_Z^2(v_e^2 + a_e^2 \pm 2P v_e a_e) \cdot F_2^Z \\ \mathbf{xF}_3^\pm &= \kappa_Z(\pm a_e + P v_e) \cdot x F_3^{\gamma Z} + \kappa_Z^2(\mp 2v_e a_e - P(v_e^2 + a_e^2)) \cdot x F_3^Z \end{aligned}$$

$$(F_2, F_2^{\gamma Z}, F_2^Z) = x \sum (e_q^2, 2e_q v_q, v_q^2 + a_q^2)(q + \bar{q})$$

$$(x F_3^{\gamma Z}, x F_3^Z) = 2x \sum (e_q a_q, v_q a_q)(q - \bar{q}),$$

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

Vary charge and polarisation and beam energy to disentangle contributions

## Charged Currents

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

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

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

$$U = u + c \quad \bar{U} = \bar{u} + \bar{c} \quad D = d + s \quad \bar{D} = \bar{d} + \bar{s}$$

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

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

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

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

**Complete unfolding of all parton distributions  
to unprecedented accuracy**

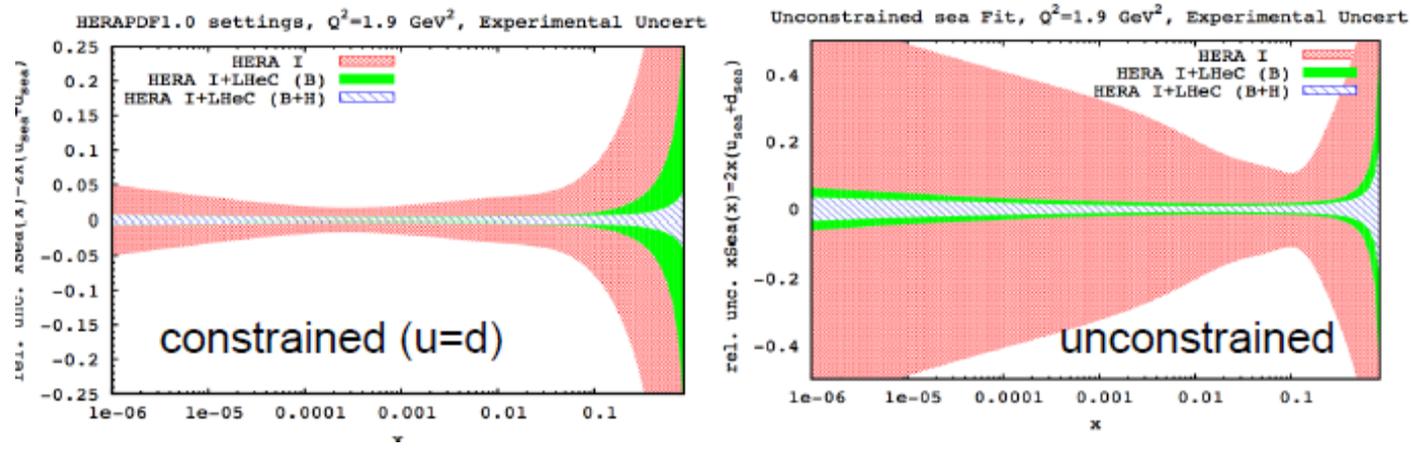
# Further thoughts on low-x sea.

It is often assumed that  $\bar{u}=\bar{d}$  at low-x

If we relax this assumption then PDF errors increase tremendously.

But LHeC data can constrain this.

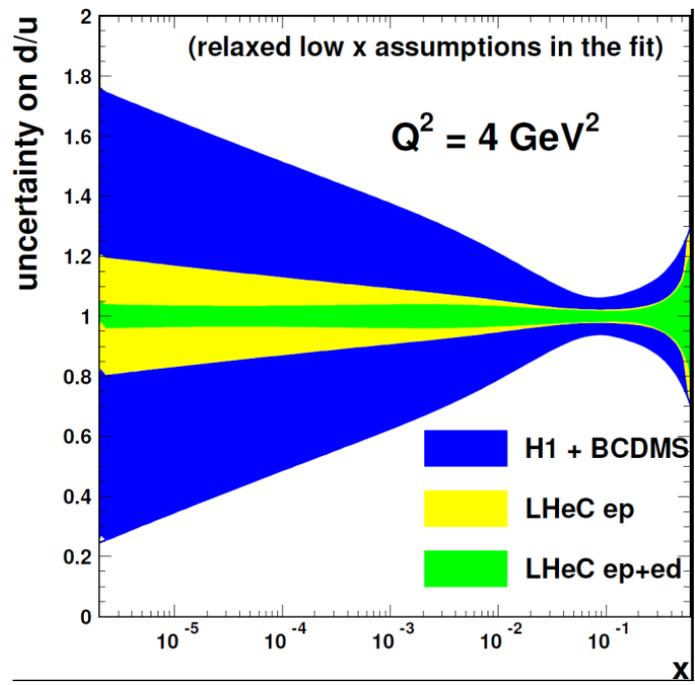
Here we compare uncertainties on the total sea distribution



And here we compare uncertainties on the d/u ratio

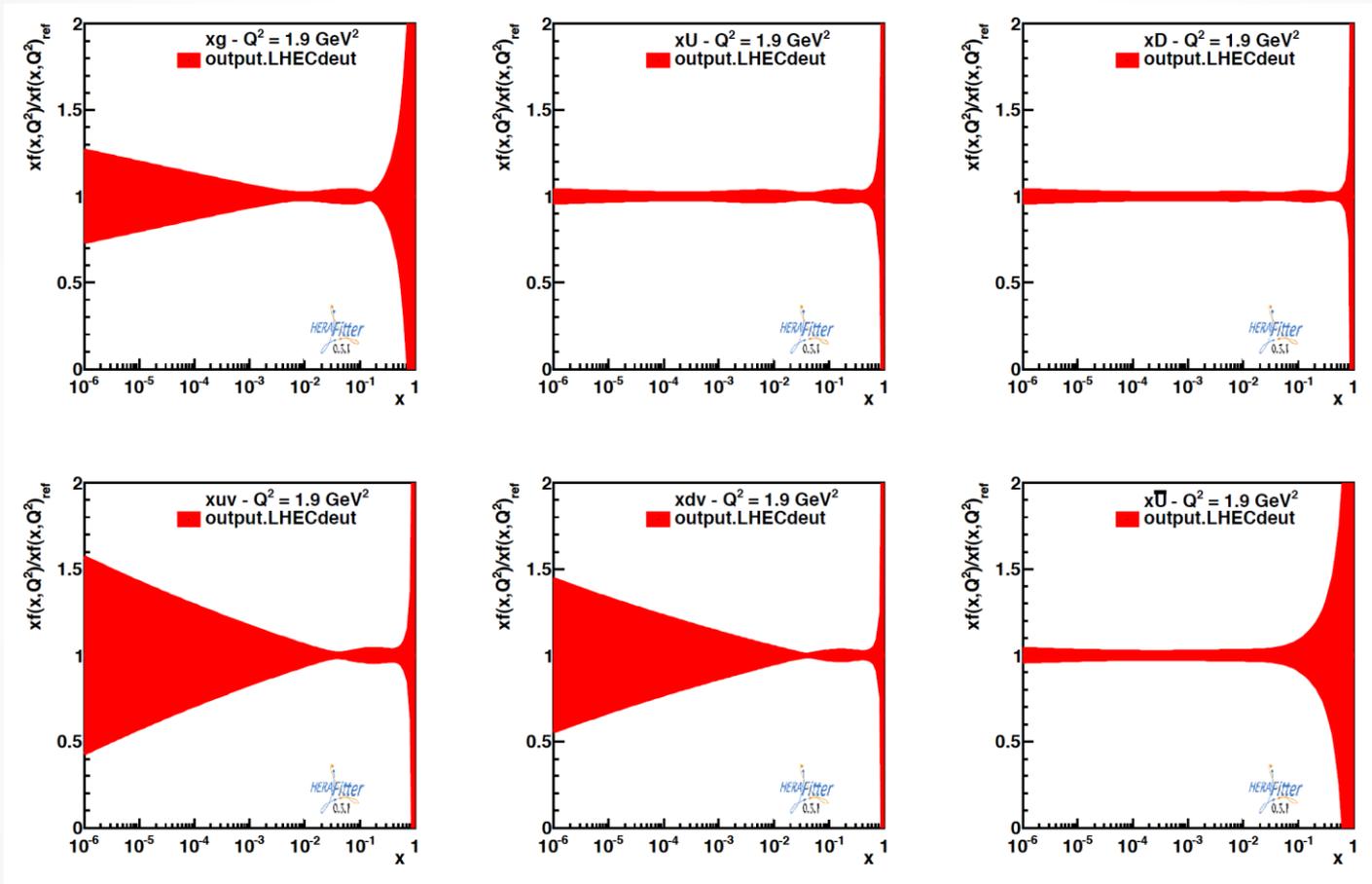
This would improve more if **deuteron target data** are used.

Deuterons can also give information on neutron structure



# LHeC deuteron data

3.5TeV  $\times$  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

# Intrinsic Charm

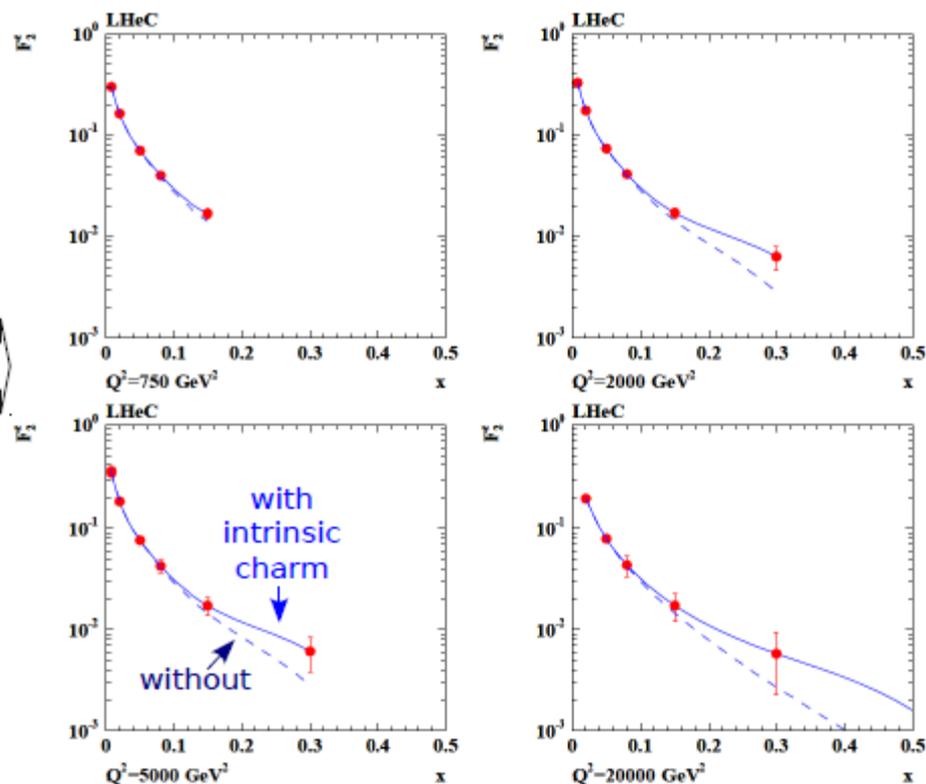
*Intrinsic charm*: existence of  $c\bar{c}$  pair as non-perturbative component in the bound state nucleon (Fock state components such as  $|uudc\bar{c}\rangle$ )

→ 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 ( $E_p=1\text{ TeV}$ ,  $L=1\text{ fb}^{-1}$ , CTEQ66)

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



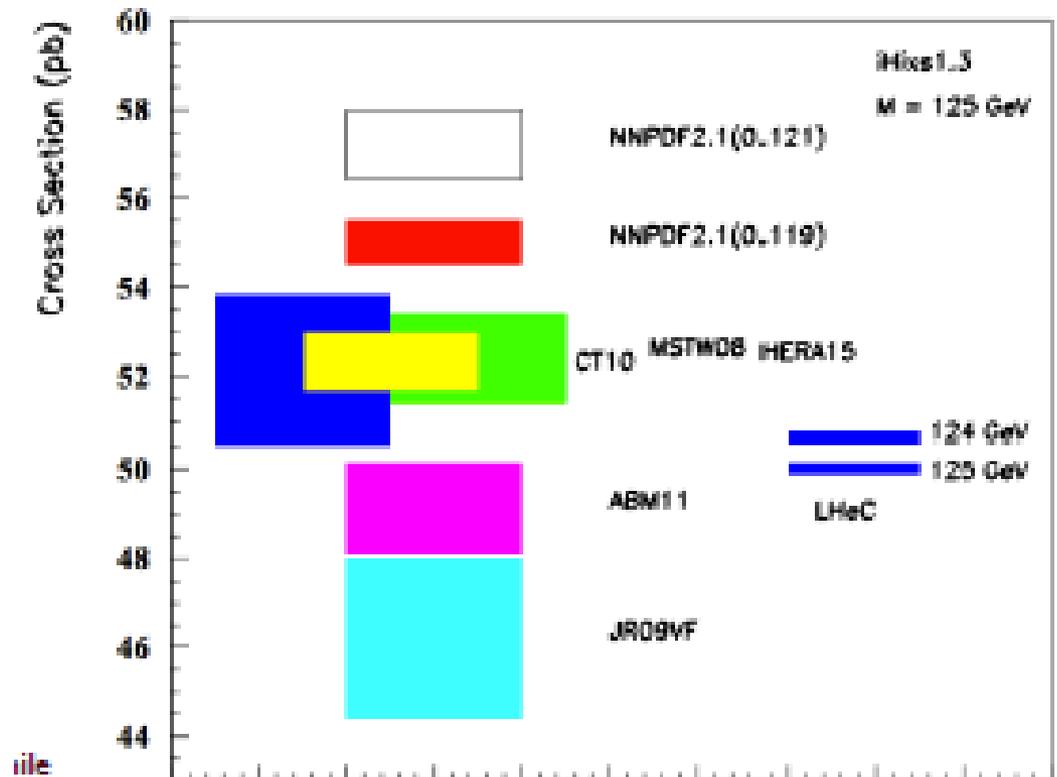
# LHeC and Higgs

The dominant Higgs production mechanism at LHC is  $g g \rightarrow H$

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

NNLO pp-Higgs Cross Sections at 14 TeV

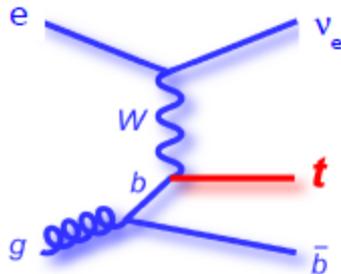


LHeC at high luminosity is also a Higgs factory, Higgs can be produced by WW, ZZ fusion and  $H \rightarrow b\text{-}b\text{bar}$  decay is easily identified

# Top Quarks at LHeC

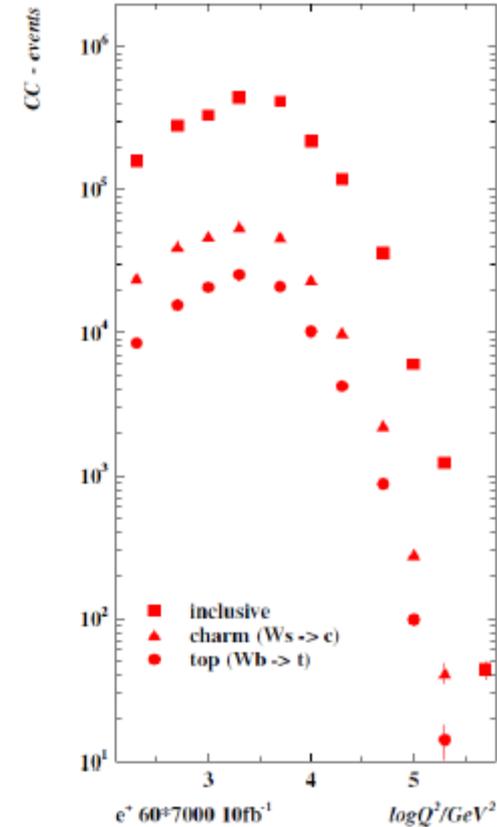
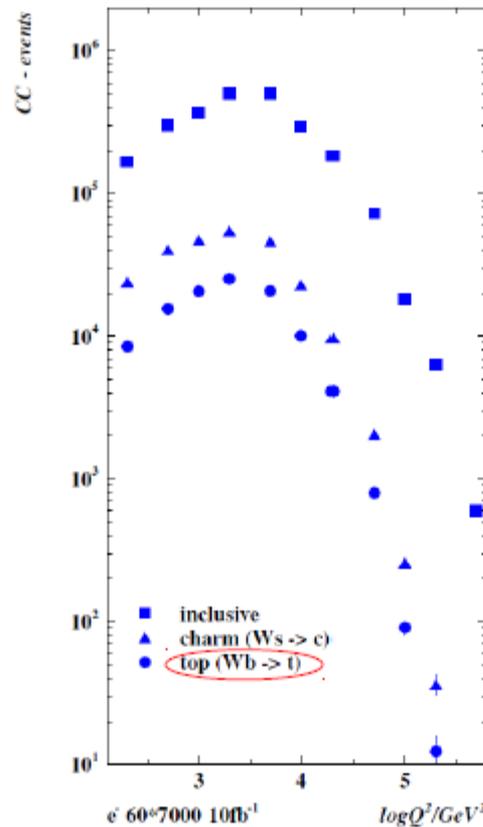
Top quarks can be studied in DIS (negligible cross section at HERA)

CC:  $Wb \rightarrow t$  production  
( cross section  $O(10\text{pb})$  )



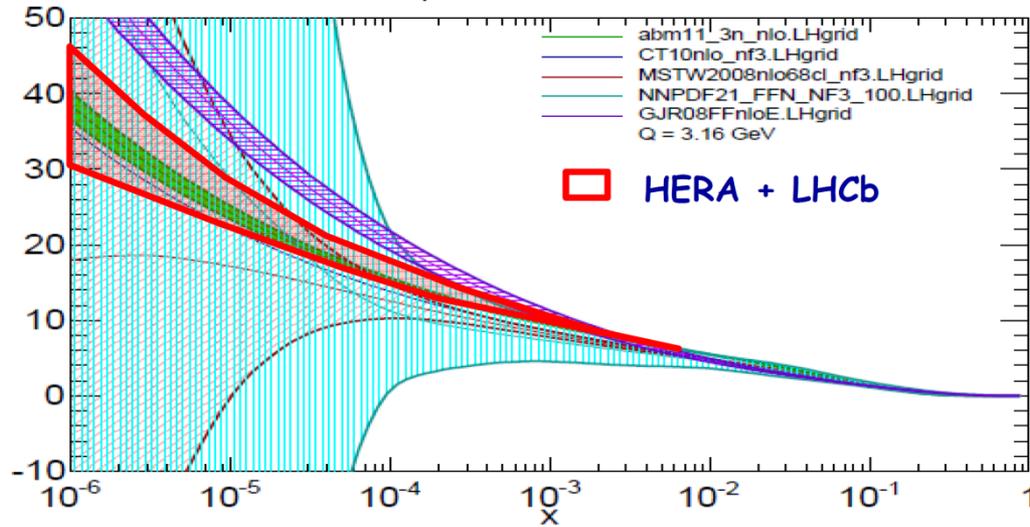
NC:  $t\bar{t}$  pair production

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



A top PDF could be important at FCC

$xg(x, \mu)$ , comparison plot



Generated by JFELD.0.1: V.Berone, S.Carranza, J.Rope (arXiv:1301.194)

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

