Further Future e-p

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arXiv:1206.2913

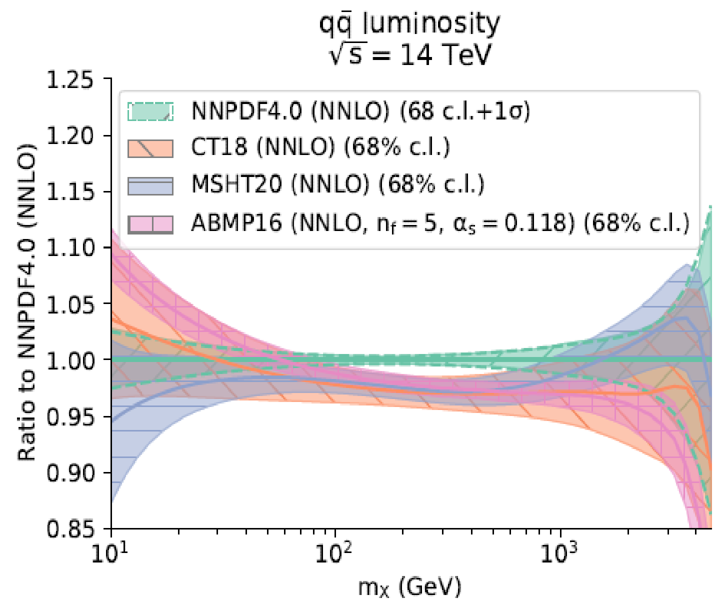
J. Phys. G 48 (2021) 11, 110501

(arXiv:2007.14491)

see also, FCC CDR, vols 1 and 3:

physics, EPJ C79 (2019), 6, 474

FCC with eh integrated, EPJ ST 228 (2019), 4, 755



Why an LHeC? Many reasons

One of them is to improve precision of proton PDFs

Today PDFs, from each of the big groups CT, MSHT, NNPD,F are each heading towards percent level precision BUT the differences between them are at the few percent level– even in the 'well-known' central x region

This is not good enough if we aim to find deviations from the SM in the deviations of the values of SM parameters M_W, $\sin^2\theta_W$, $\alpha_S(M_Z)$

What could help?

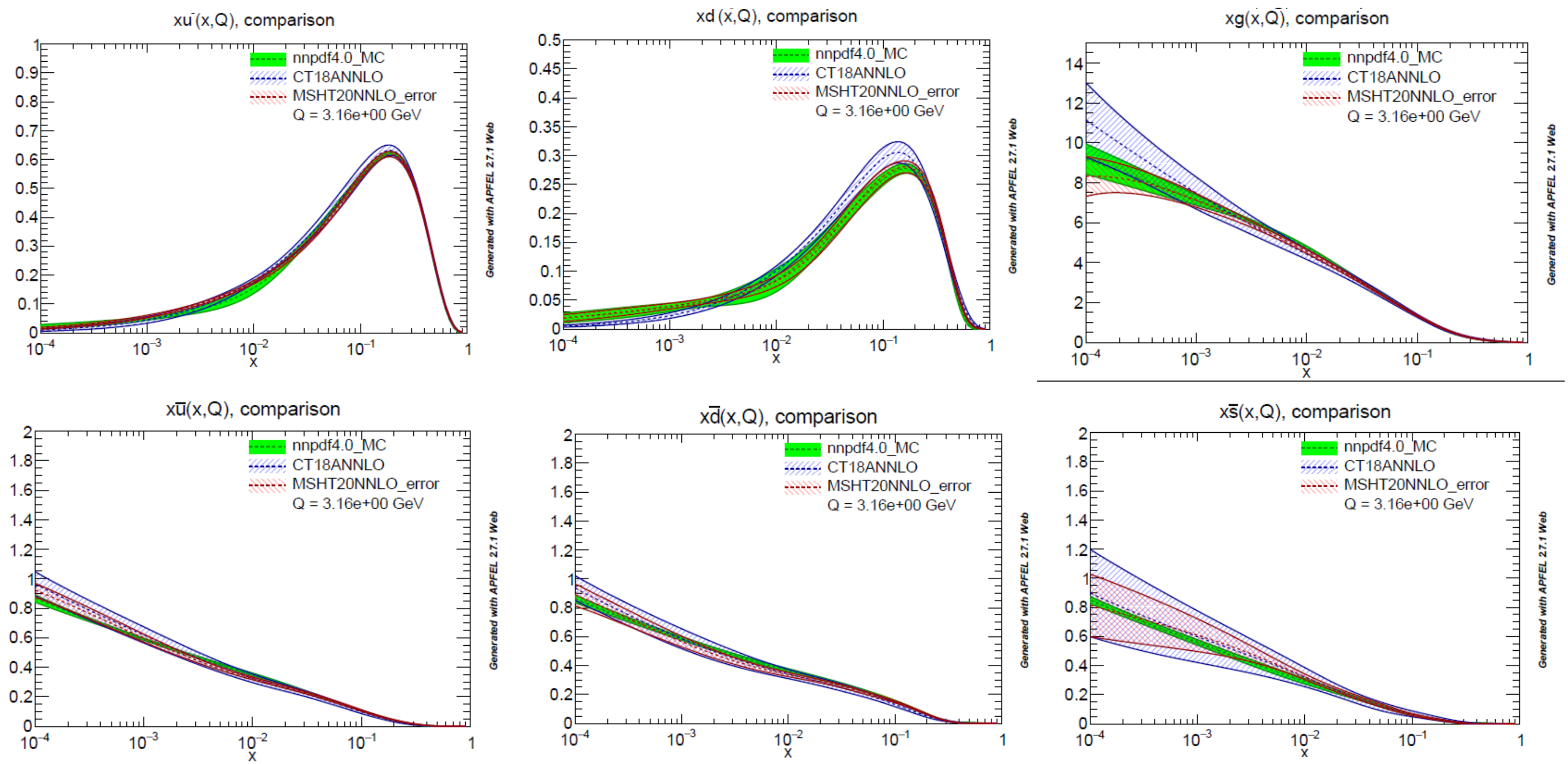
A precise new data set over a very wide kinematic range with consistent correlated systematics--- that's what the LHeC could provide

The ‘big three’ of PDF fitting groups are CT, NNPDF and MSHT

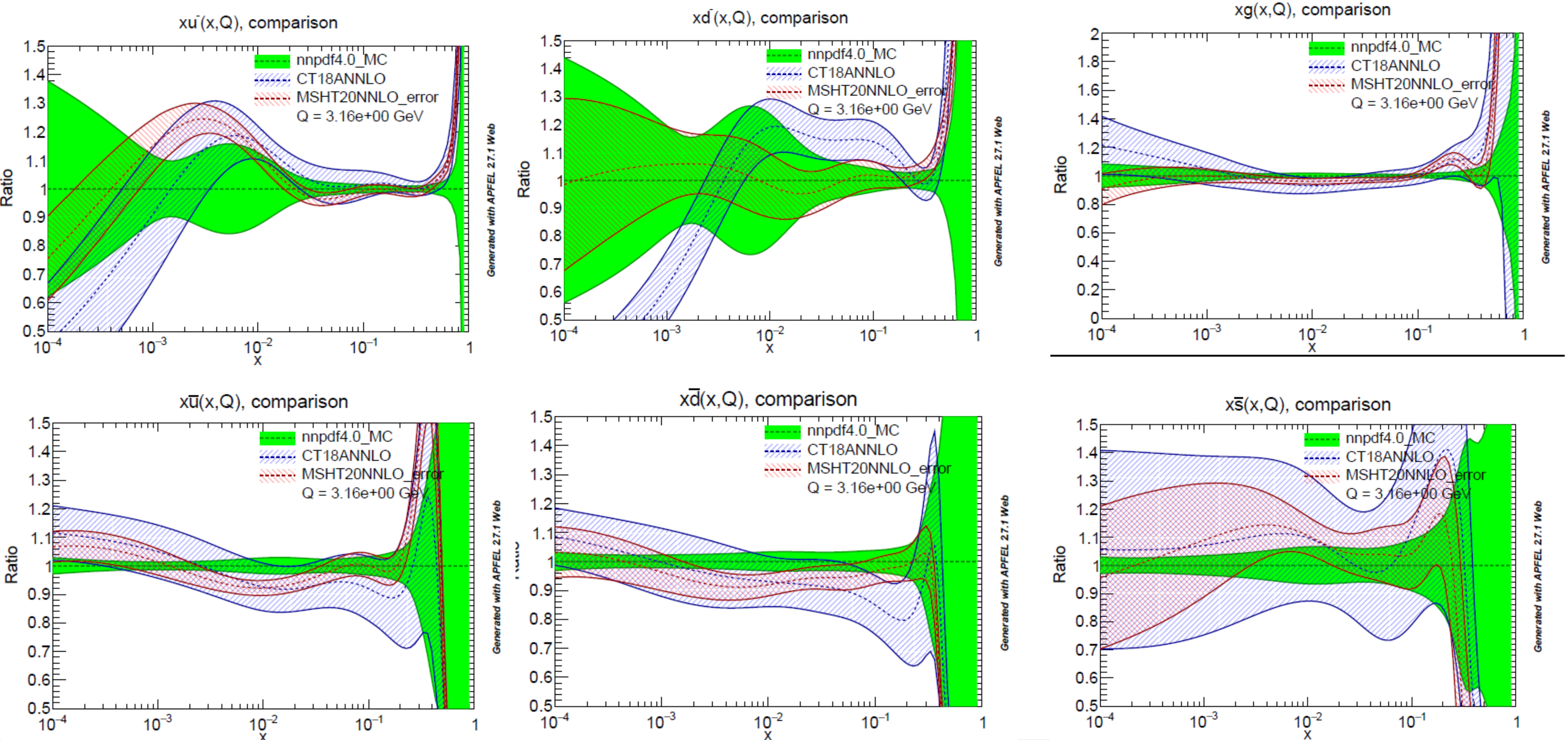
The latest CT18, NNPDF4.0, MSHT20. Be agnostic in the choice between these.

The one with the smallest uncertainties is not necessary the best.

Note CT18 actually came out end 2019 (1912.10053), MSHT came out end 2020 (2012.04684), NNPDF4.0 in 2021(2109.02653). NNPDF3.1 in 2017



This looks as if we are doing reasonably well –but look at ratios….



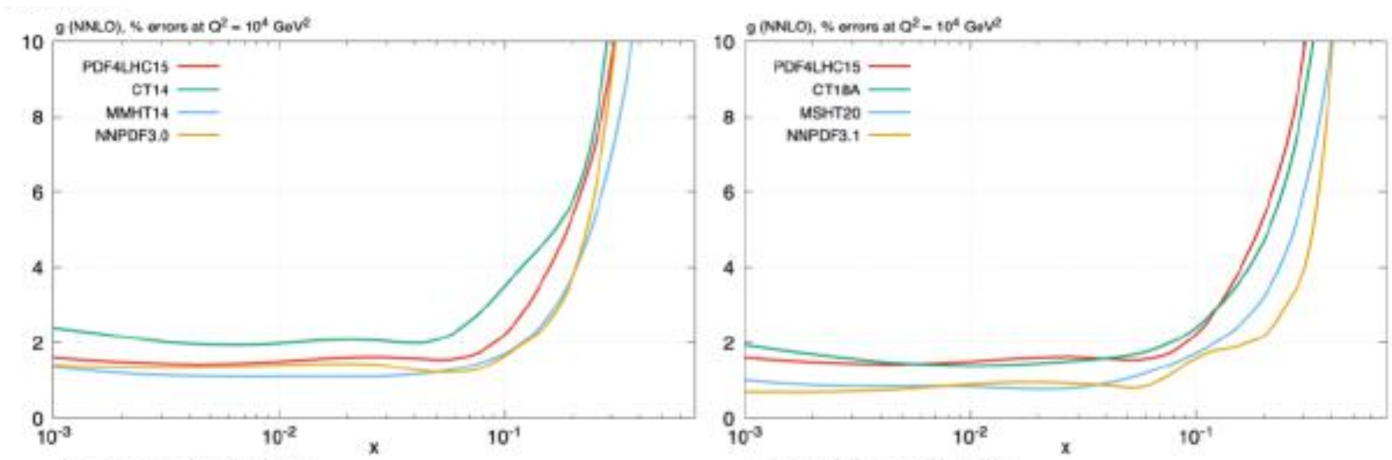
Differences are more obvious in ratio. They are large at small-x and at high-x, where there is less data. **The differing model choices matter.** Like exactly which data sets are used and what cuts are applied on them, what is the parametrisation (or NN), what is the treatment of heavy quarks, what is the starting scale for evolution, what are the values of heavy quark masses, $\alpha_S(M_Z)$ etc

So also do theory choices, standard is NNLO, often using NNLO/NLO ‘k-factors’ but such calculations are mostly done by each group separately. Even when using direct NNLO grids - treatment of grid uncertainties can differ.

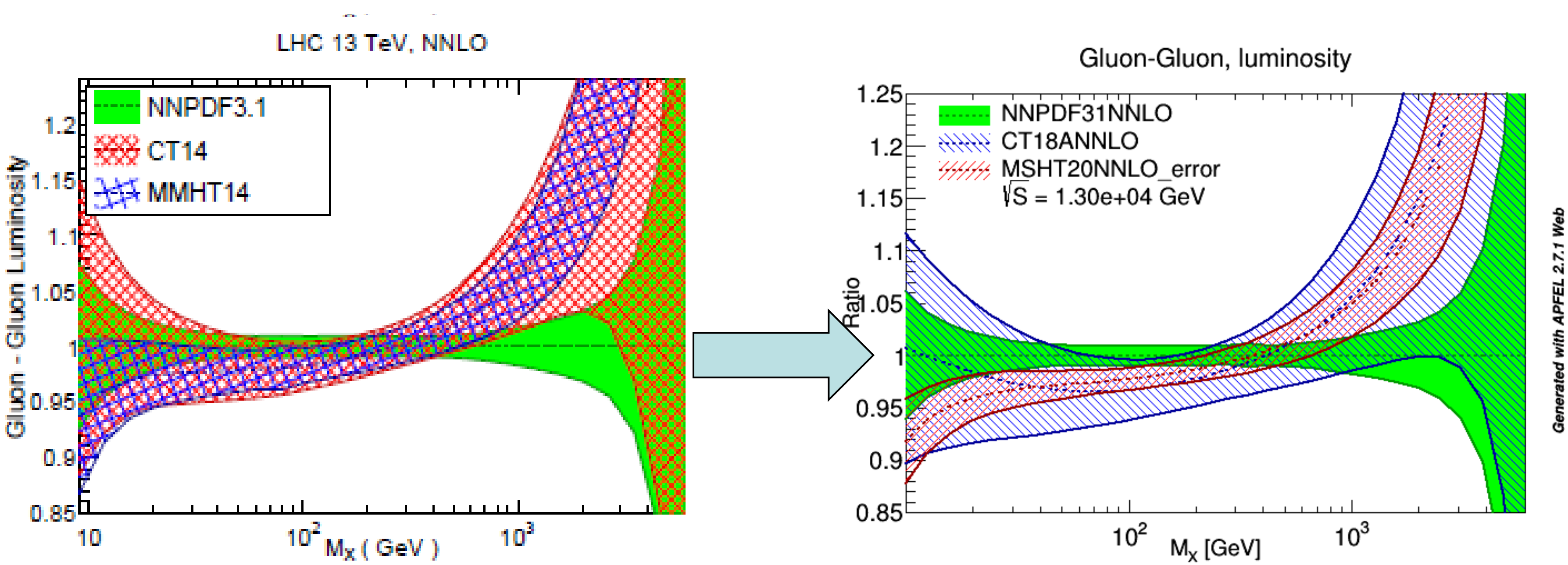
PDFs also differ in how they evaluate their uncertainties some use enhanced $\chi 2$ tolerances -- closer to the hypothesis testing criterion– but this is a whole lecture series in itself.

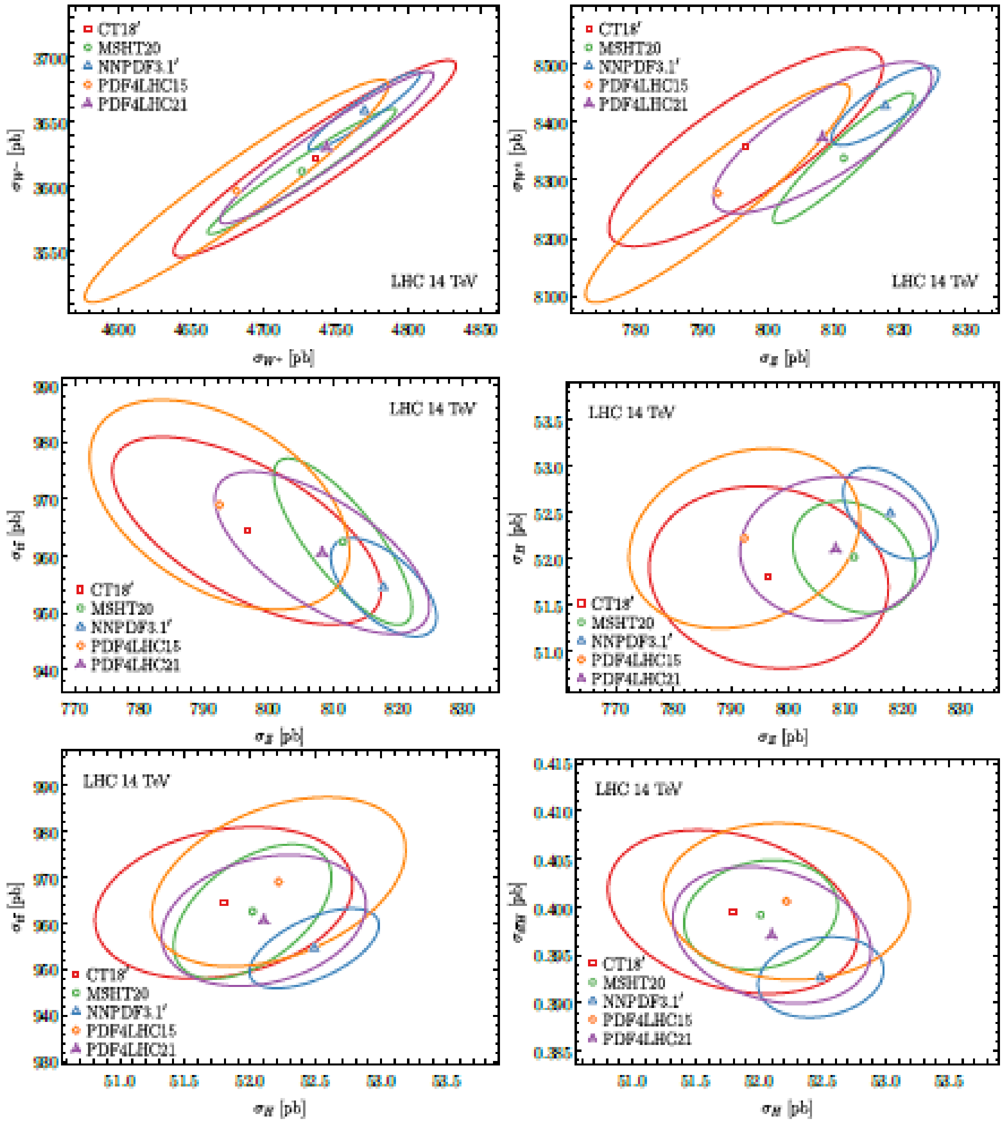
Has there been progress in recent years?

Gluon Uncertainties



As the uncertainties of each individual PDF decrease with the input of more information, the divergence of the PDFs from each other has increased





The PDF4LHC group makes combinations of the PDFs from the three main fitting groups NNPDF, CT and MSHT

The PDF4LHC15 combination has just been superseded by the PDF4LHC21 combination

There IS an improvement in uncertainty BUT this is not enough to reduce the PDF uncertainty on LHC measurement of m_W, $\sin^2\theta_W$, $\alpha_S(M_Z)$ dramatically

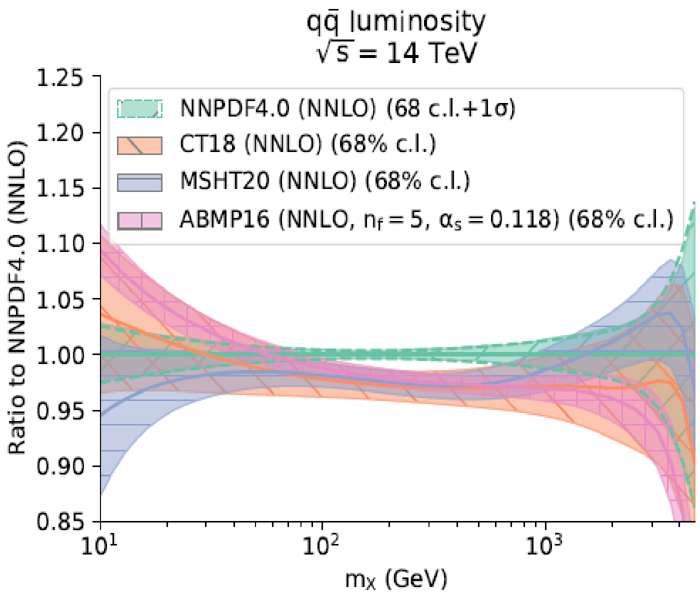
Since the issue of PDF4LHC21 there has been the new PDF set from NNPDF4.0

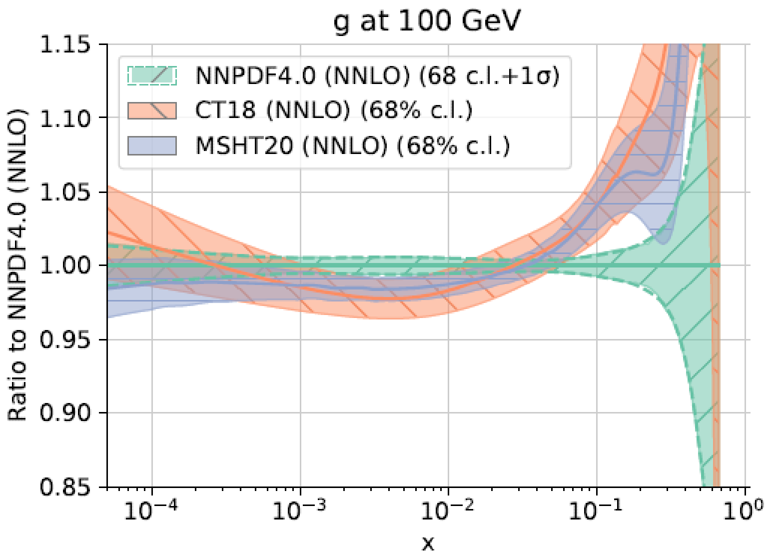
This has a lot of new data from the LHC and considerable decrease in uncertainty, with respect to NNPDF3.1.

BUT the improvements in uncertainty are **not so much due to the new data**, they are more **due to improvements in their procedure.**

Unfortunately decrease in uncertainty of a single PDF does not help much if there are discrepancies with other PDFs.

The uncertainty on combination of PDFs will remain higher than the uncertainty of any individual PDF set





And there are other PDFs eg ABMP, which does not use jet data,
HERAPDF which uses only HERA data,
And ATLAS itself produces PDFs…

Most significantly for this meeting the values of $\alpha_S(M_Z)$ determined by the PDF fitters also differ by more than their quoted uncertainty

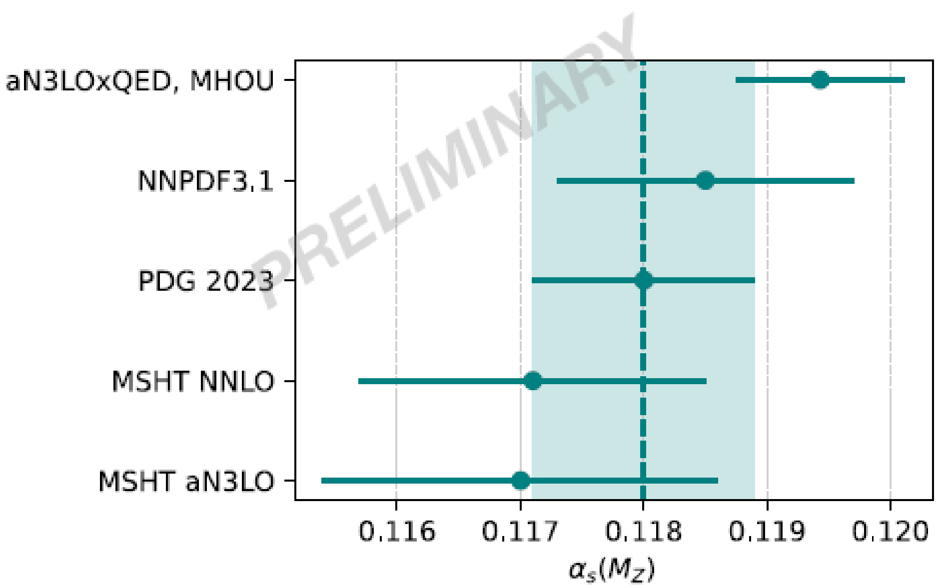
MSHT values

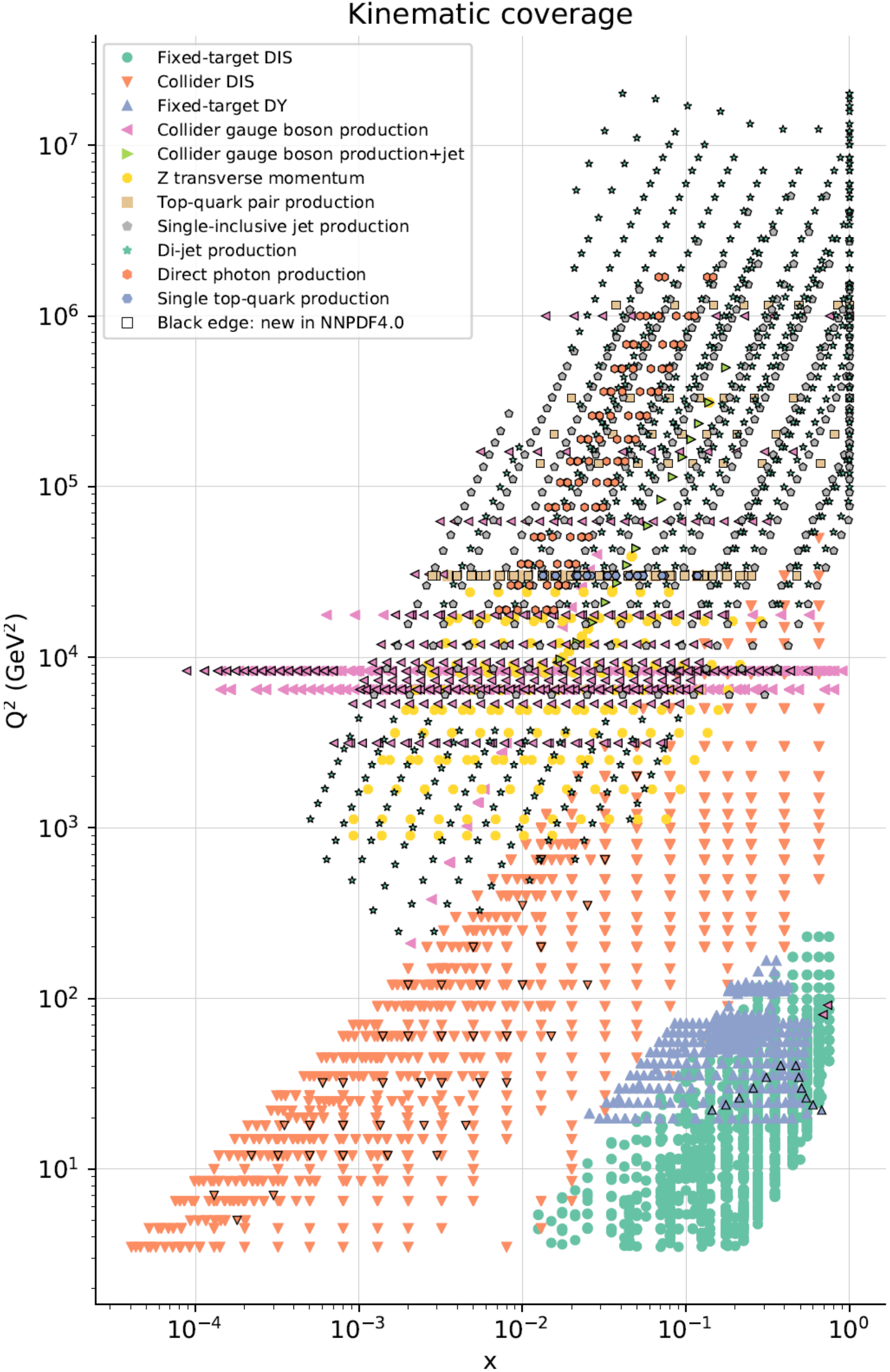
$$\alpha_S(M_Z^2) = 0.1171 \pm 0.0014 \text{ NNLO}$$

$$\alpha_S(M_Z^2) = 0.1170 \pm 0.0016 \text{ aN}^3\text{LO}$$

NNPDF

- $\alpha_s(M_Z)^{\text{aN3LO,QED,MHOU}} = 0.1194(7)$





SO how to improve?

We now use many other processes than deep-inelastic scattering for the determination of PDFs

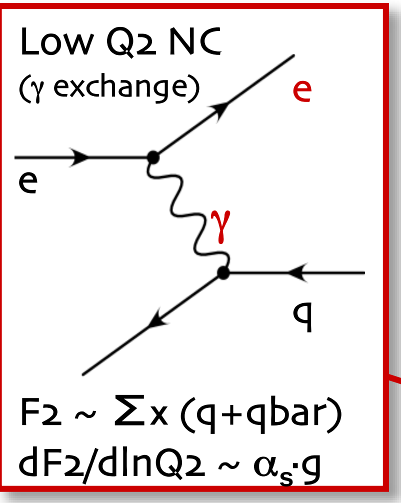
- Beware: IS the factorisation theorem proven?-only for DY!
- Beware: there may be new physics at high scale that we 'fit away'

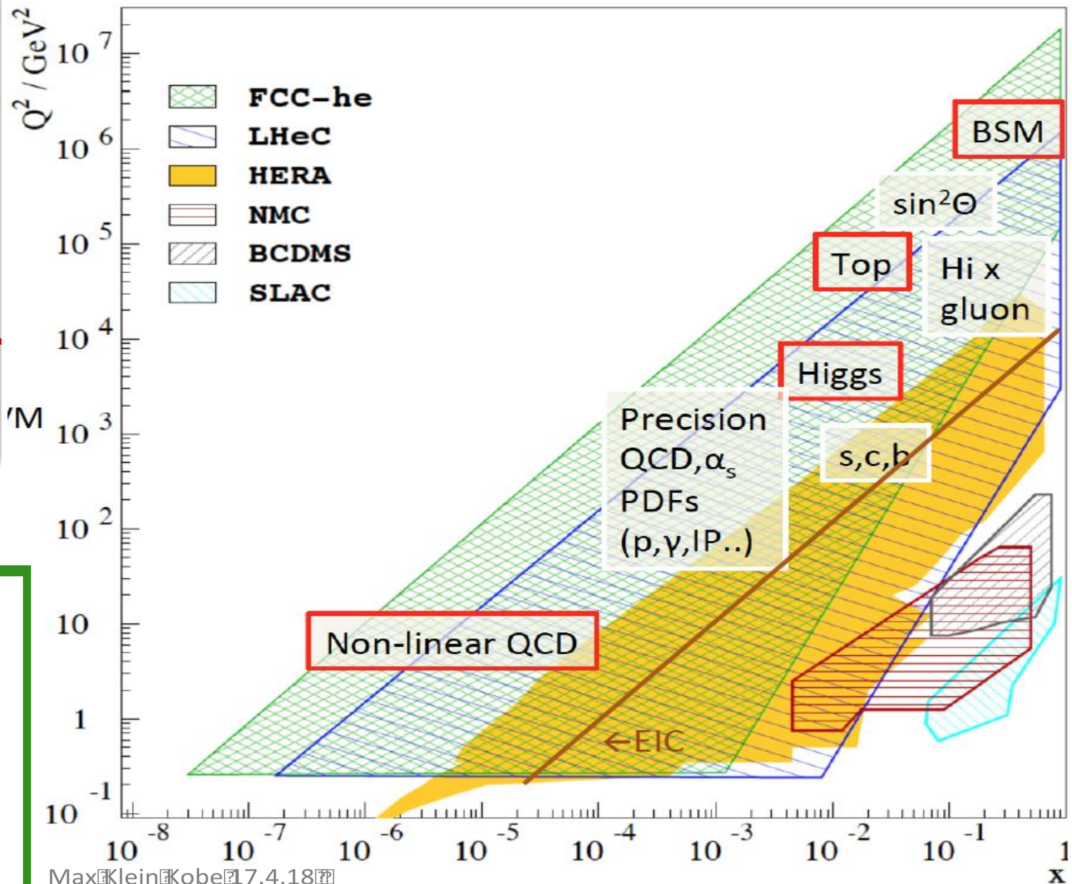
BUT MOSTLY BEWARE…

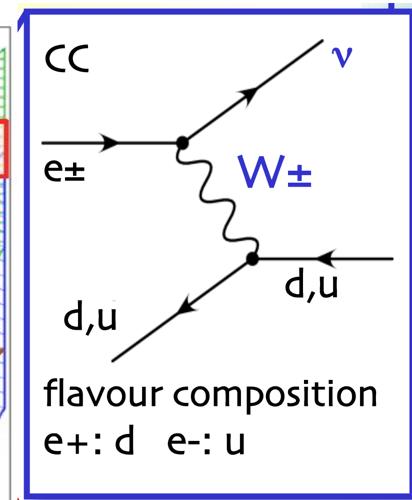
The additional information comes from many different groups– even within a single experiment---often there is no clarity on the correlations of experimental systematic uncertainties between differing LHC measurements.

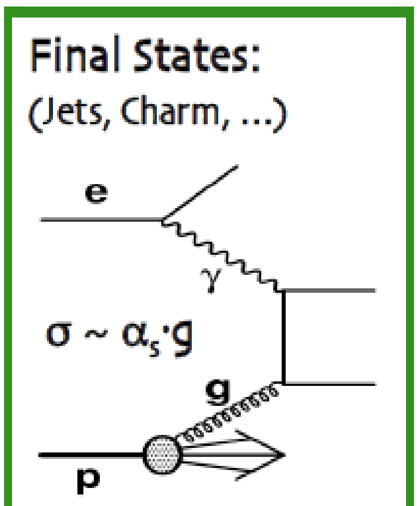
The HERA combination (in orange) of ZEUS and H1 experiments spent years trying to resolve the differing systematics of the two experiments. It's the best DIS information we have ...but it's not as good as a dedicated effort to unify systematic uncertainties across the whole kinematic plane

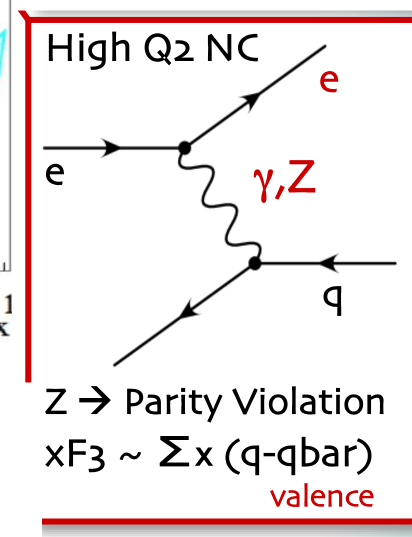
We need more DIS, the EIC will be great, but we could also extend the kinematic range at low x with an LHeC







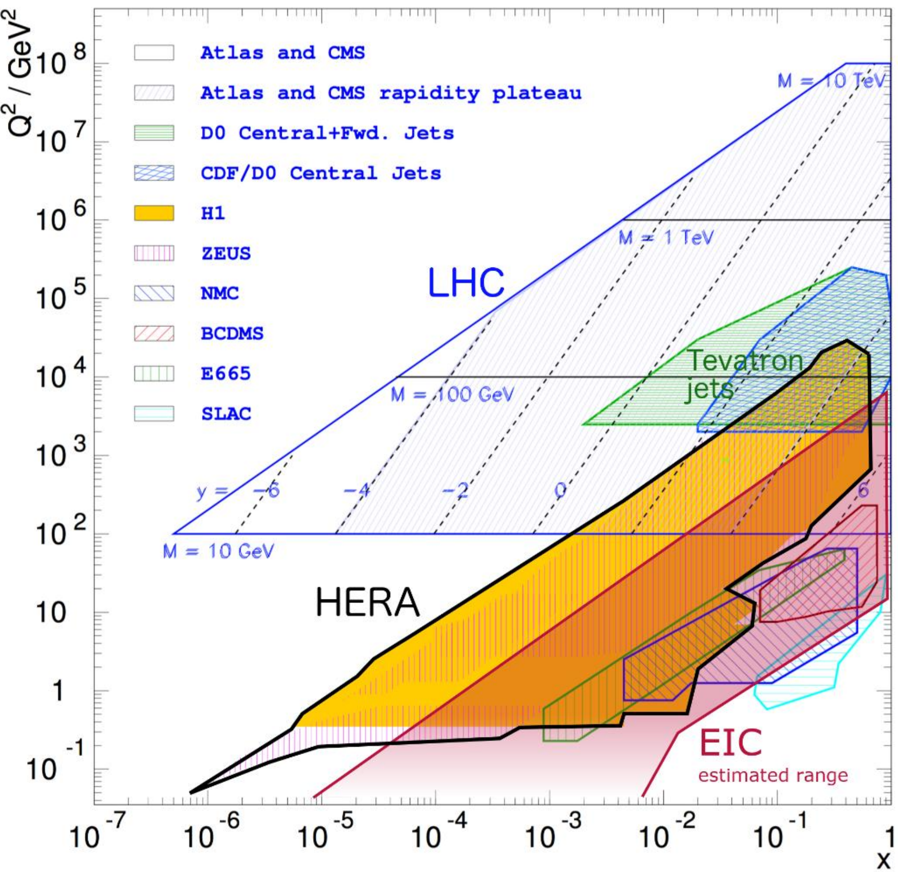


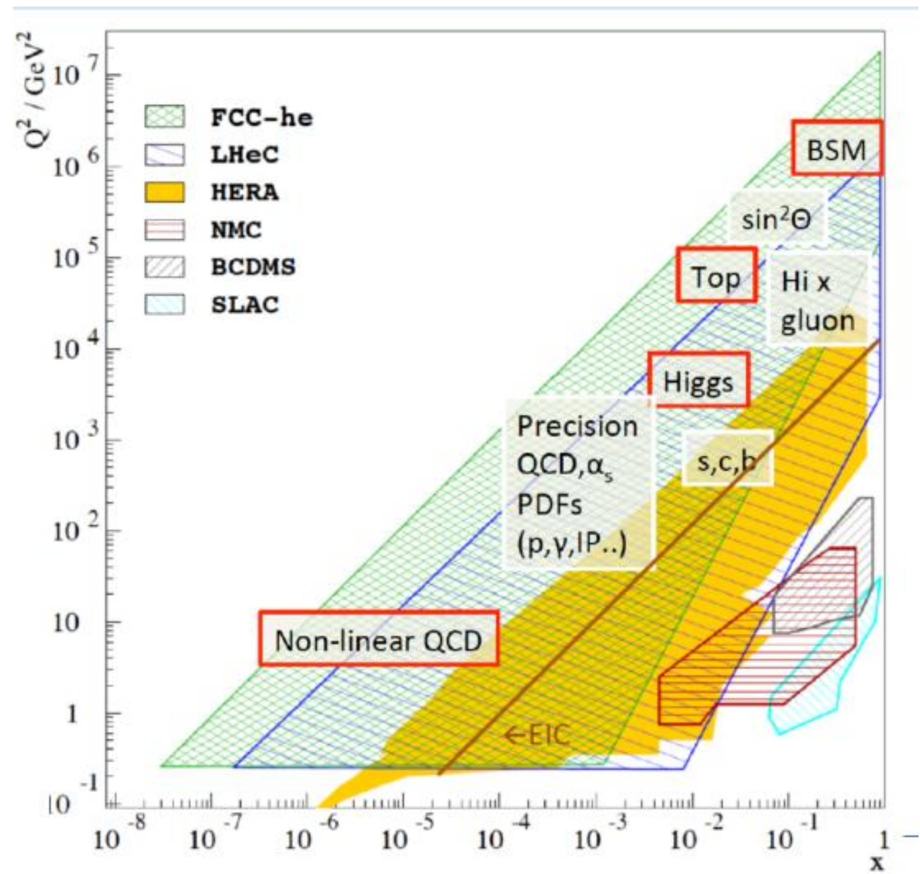


A future DIS machine would be a vast improvement on HERA in both luminosity and kinematic reach

×**15**/**120** extension in Q^2,1/x reach vs **HERA**

Consider the kinematic reach of each of these





The EIC will reach higher x than HERA could reach

The proposed LHeC and FCC-eh machines reach lower x than HERA could reach

LHeC ep simulated data and QCD fits

NEW: LHeC simulations (e: **50 GeV***, p: 7 TeV†)

simulation: M. Klein

dataset	e charge	e pol.	lumi (fb-1)	
NC/CC	–	–0.8	5,50,1000	**luminosity**
NC/CC	+	0	1,10	**positron**
NC/CC	–	0	50	**polarisation** (important for EW)
NC/CC	–	+0.8	10,50	
NC/CC	–	0	1	**low-E** (p: 1 TeV)

uncert. assumptions:
elec. scale: 0.1%
hadr. scale 0.5%
radcor: 0.3%
γp at high y: 1%
uncorrelated uncert.: 0.5%
CC syst.: 1.5%
luminosity: 0.5%

*corresponds to possibility of smaller ERL cf. previous 60 GeV simulations †except for low-E

various combinations studied;
shown frequently in following slides:

LHeC 1st Run (50 fb^{-1} e– only; 3 yrs)

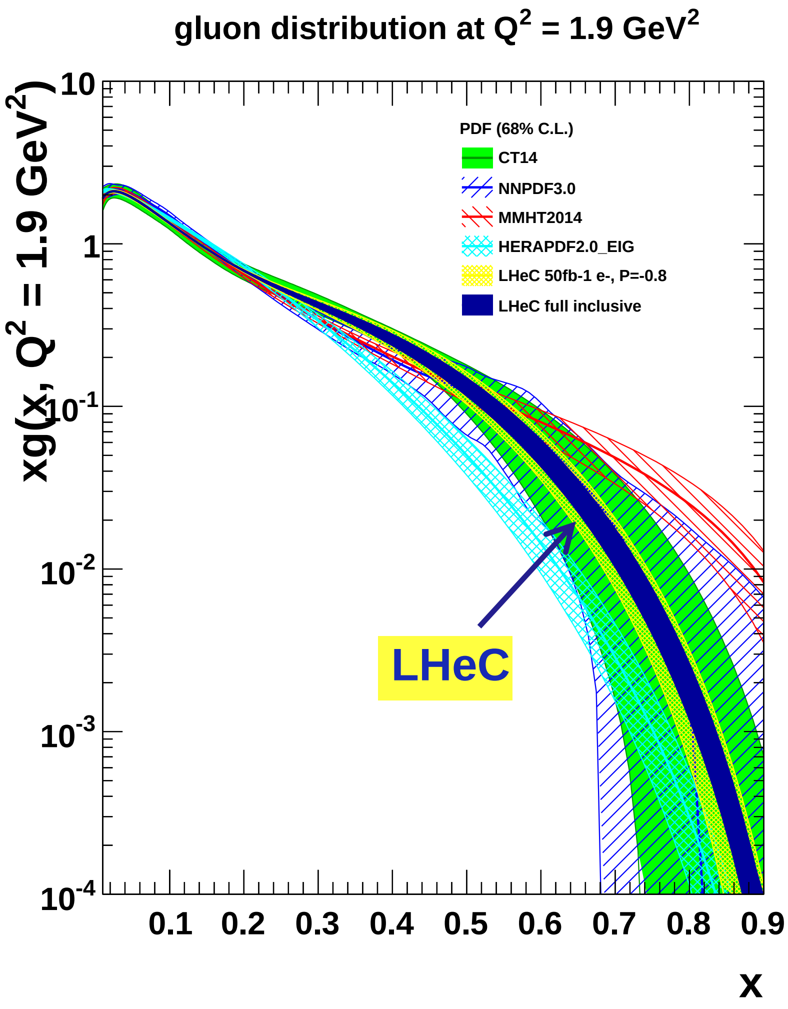
LHeC full inclusive

QCD analysis a la HERAPDF2.0, except **more flexible**, notably in **NO constraint** requiring dbar=ubar at small x;

4+1 xuv, xdv, xUbar, xDbar and **xg** (**14 free parameters**, cf. 10 by default in CDR)

5+1 xuv, xdv, xUbar, xdbar, xsbar and **xg** (if strange and HQ included; **17 free parameters**)

Gluon at large x



gluon at large x is small and currently very poorly known;
crucial for new physics searches

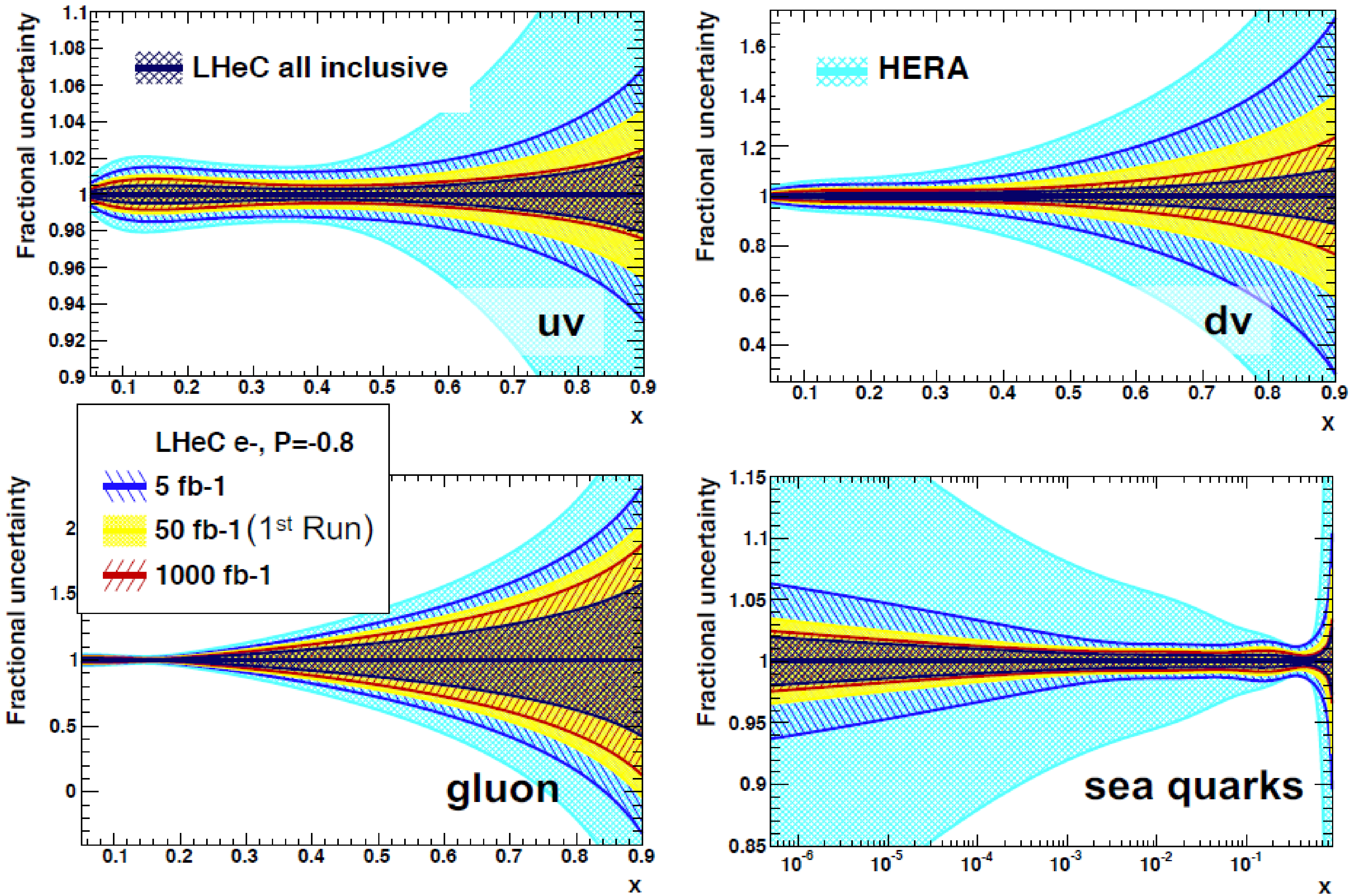
LHeC sensitivity at large x comes as part of overall package

high luminosity (×50–1000 HERA);
fully constrained quark pdfs; small x;
momentum sum rule

gluon and sea intimately related

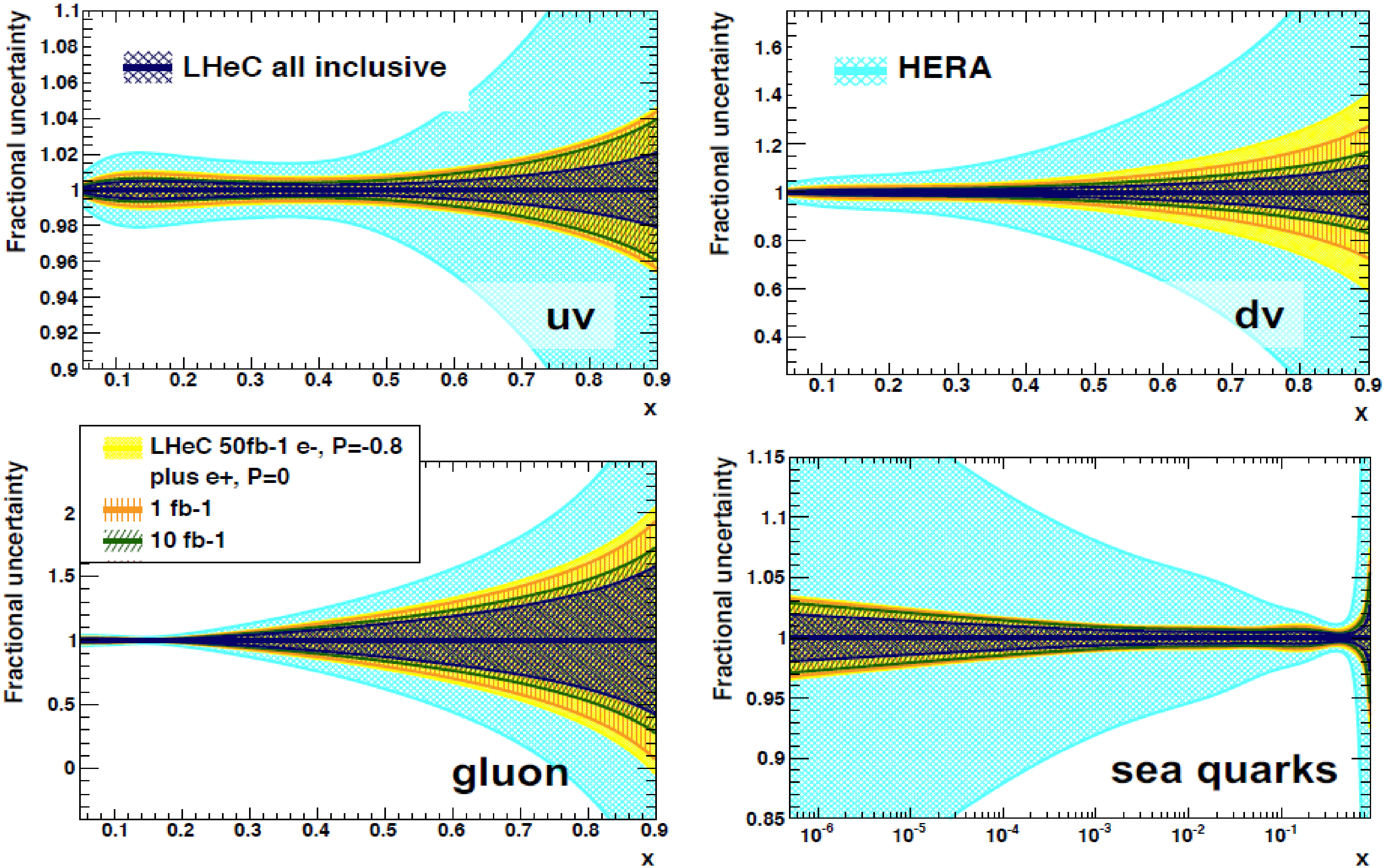
LHeC can disentangle sea from valence quarks at large x, with precision measurements of **CC** and **NC** $F2^{\gamma Z}$, $xF3^{\gamma Z}$

Impact of luminosity on PDFs



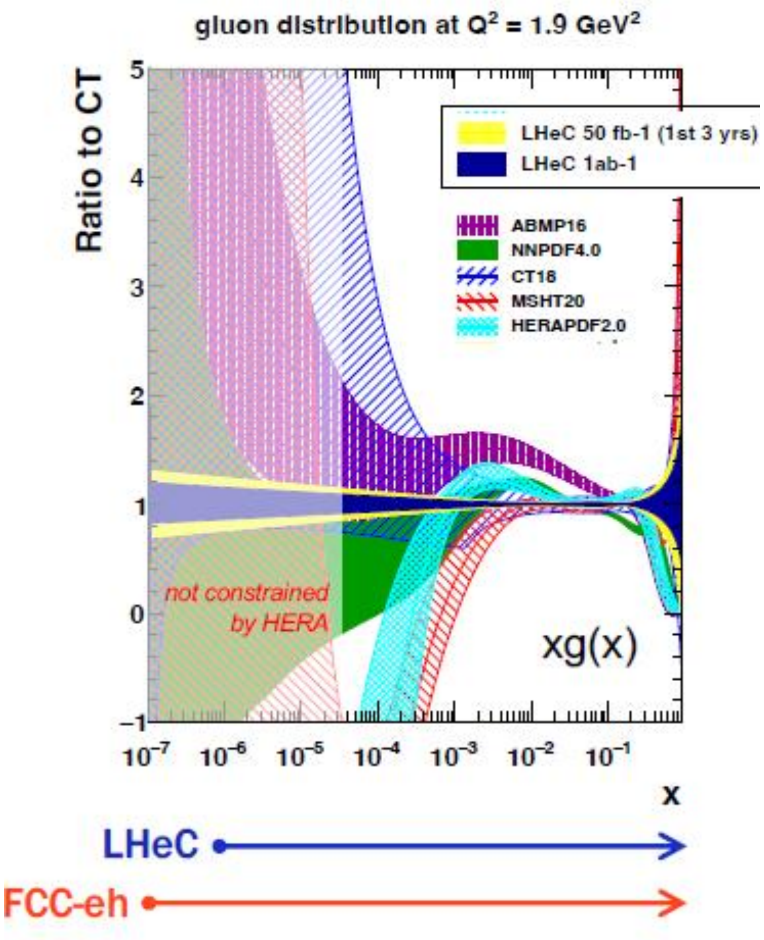
small and medium x quickly constrained (5 fb-1 ≡ ×5 HERA ≡ 1 year LHeC)

Impact of positrons on PDFs



CC: e+ sensitive to d; **NC**: e± asymmetry gives $xF3^{\gamma Z}$, sensitive to valence

Gluon at small x



no current data much below $x=5\times10^{-5}$

LHeC provides single, precise and unambiguous dataset down to $x=10^{-6}$

FCC-eh probes to even smaller $x=10^{-7}$

explore low x QCD:

DGLAP vs BFKL; non-linear evolution;

gluon saturation; implications

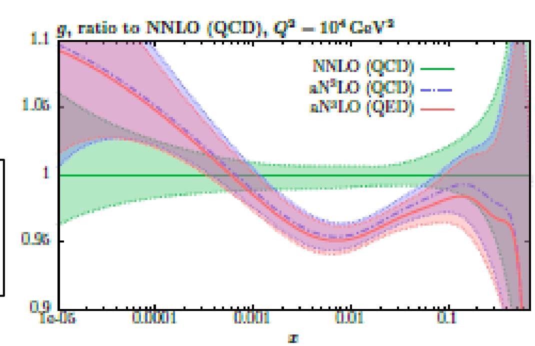
for ultra high energy neutrino cross sections

Even if your specific interest is not in low-x physics do not be complacent in thinking that this region does not affect you…

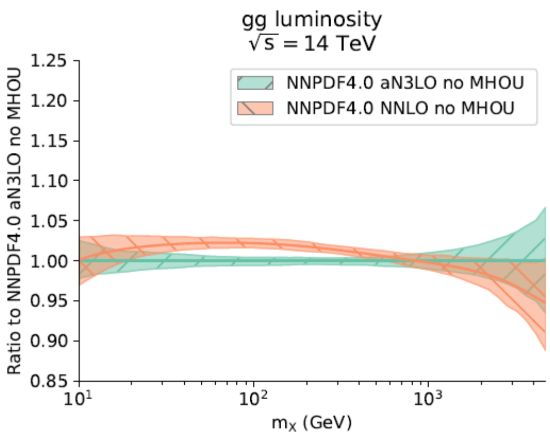
PDFs are going to N3LO –

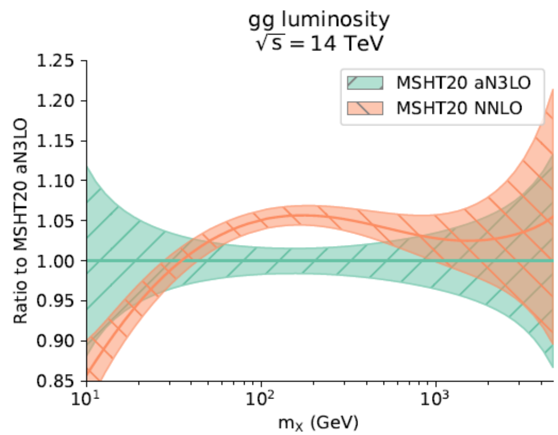
where the first of the BFKL (ln(1/x) resummation) terms matter..

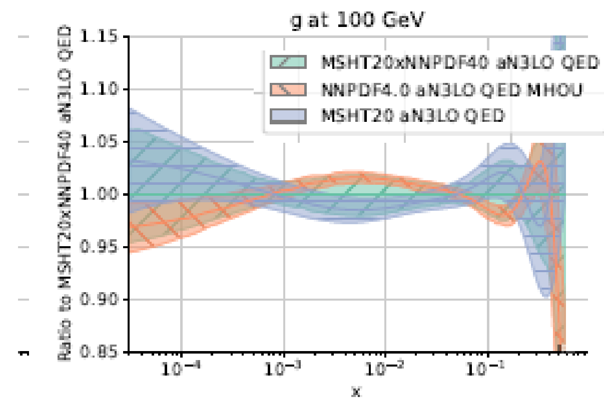
This has a significant effect on the low-x gluon



And that translates to an effect on the low Mx region for the gluon-gluon luminosity and has a ‘knock-on effect’ on the luminosity in the Higgs region Mx =125 GeV







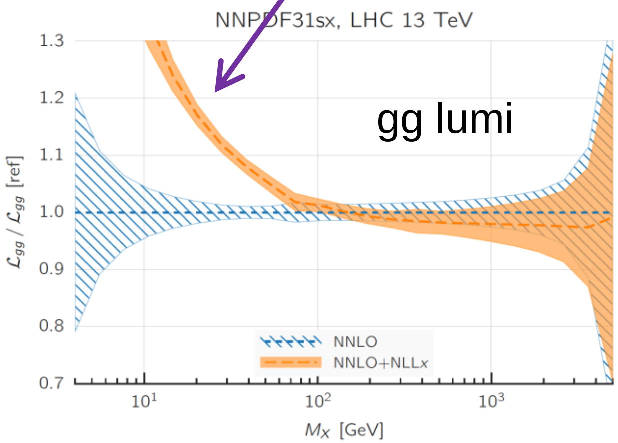
We now have two approximate N3LO PDFs from NNPDf and MSHT
Differing groups have different ways of implementing the aN3LO

For MSHT there is a 5% decrease in luminosity at the Higgs mass, for NNPDF this is more like 2%... BUT either way there is a significant difference.
These come together a bit more with recent updates on N3LO and with QED corrections, which are larger for NNPDF than for MSHT.
There is also a combination of NNPDF and MSHT aN3LO which covers their differences 2411.05373

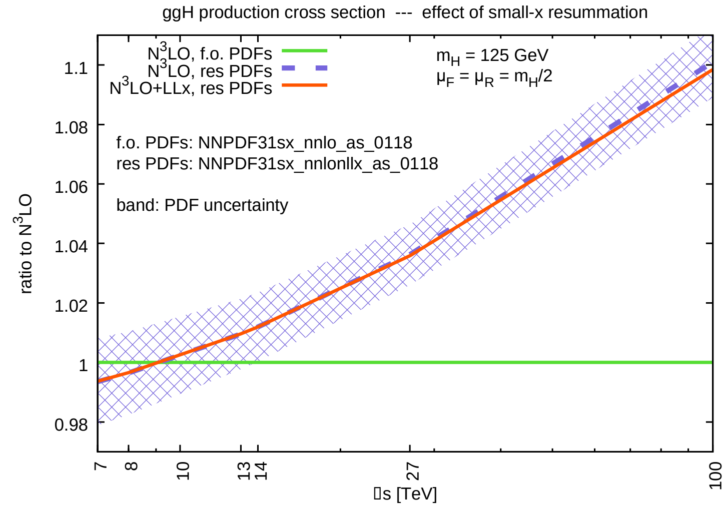
Low-x cannot be ignored…

Full ln(1/x) BFKL resummation

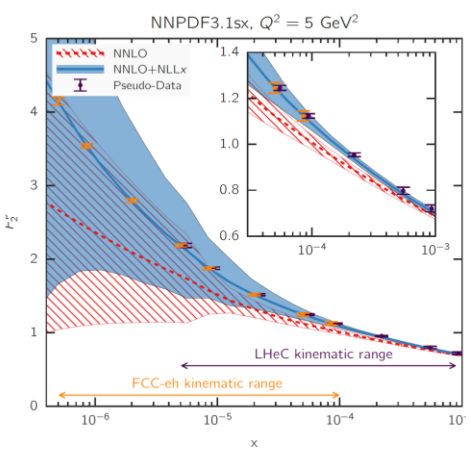
effect of small x resummation on LHC luminosity

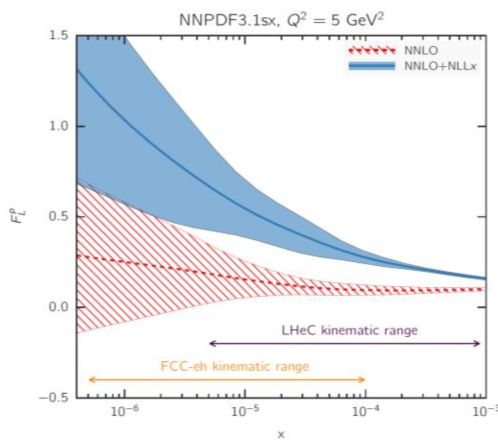


effect of small x resummation on ggH cross section for LHC, HE-LHC, FCC

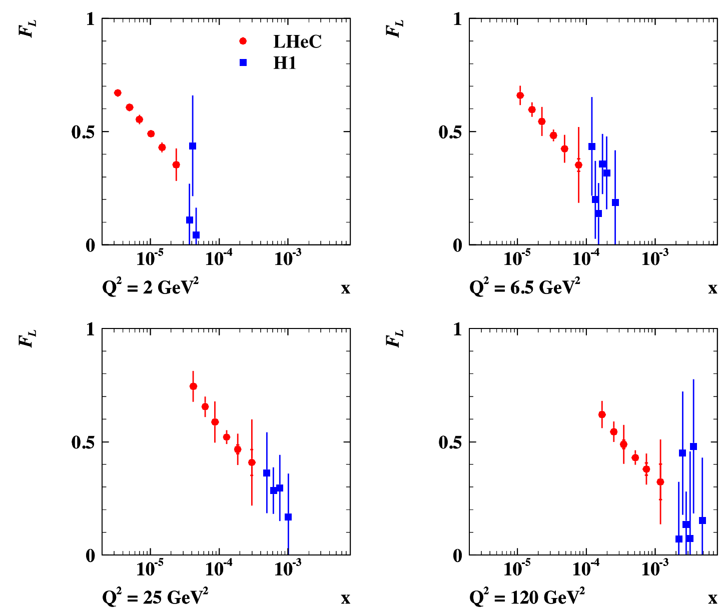


Effect of small x resummation on predictions for DIS F2 and FL

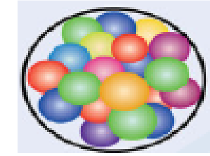




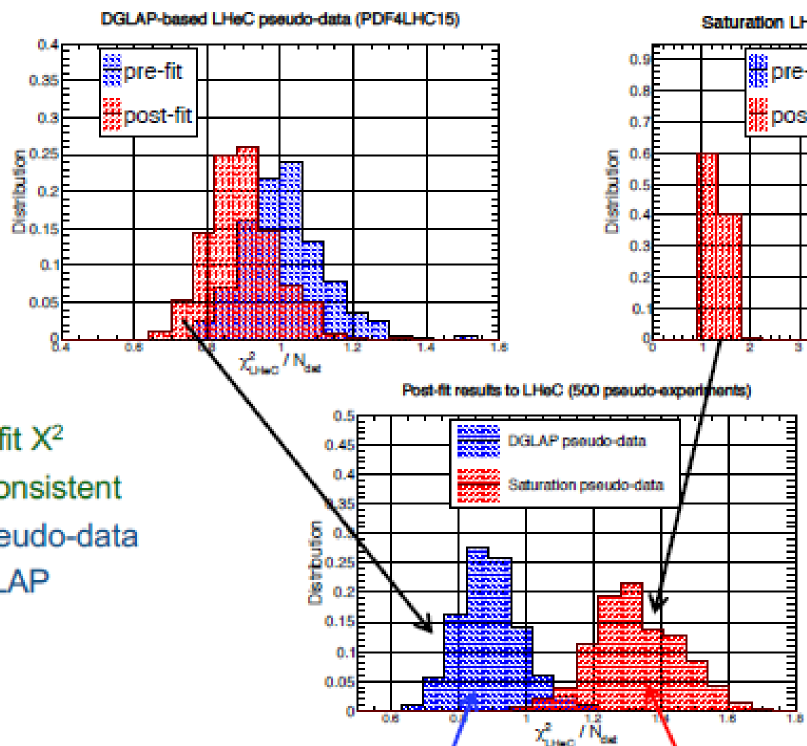
Prospects for FL measurement at LHeC



Novel dynamics at small x: saturation



- studies show linear evolution **cannot accommodate saturation**, even at NNLO or NNLO+NLLx
- EG, **DGLAP-** vs **saturation-** based simulated data fitted with NNLO DGLAP



pre- and post-fit X^2 distributions consistent for DGLAP pseudo-data fitted with DGLAP

pre- and post-fit distributions very different for DGLAP fit to saturation-based ($x \leq 10^{-4}$, GBW model) pseudo-data

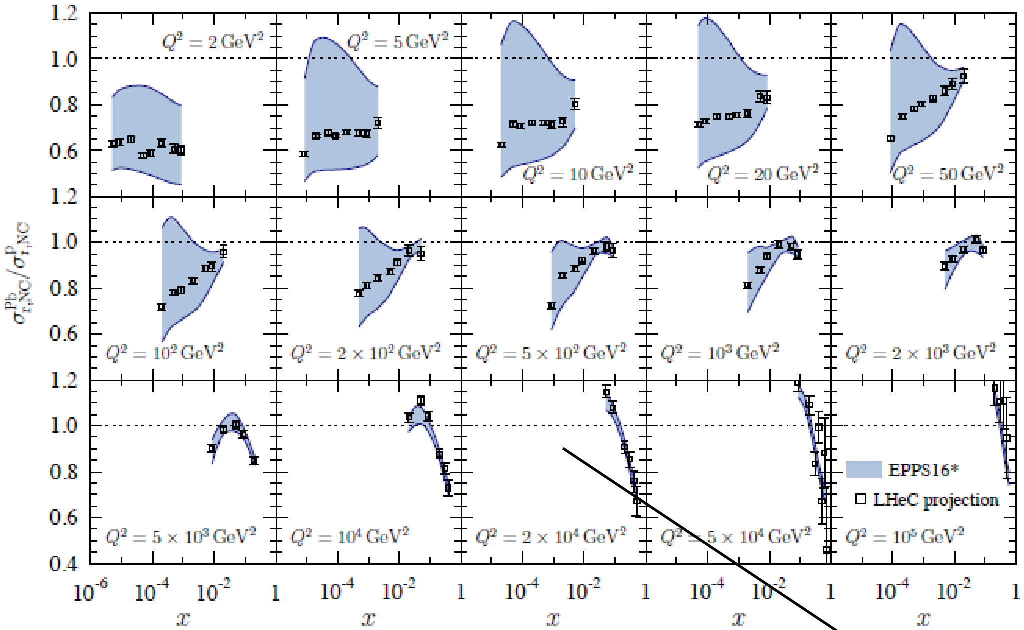
DGLAP can not absorb all saturation effects

LHeC can distinguish between **DGLAP** and **saturation**

(NB, large lever arm in Q^2 crucial, see also arXiv:1702.00839)

arXiv:2007.14491

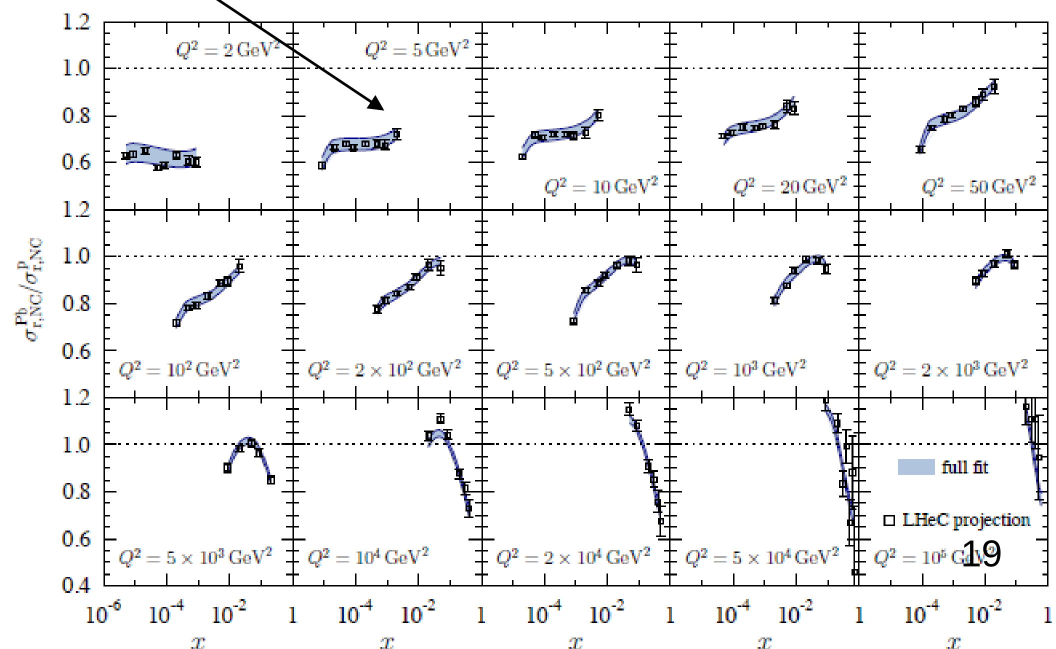
(more detail in EXTRAS)



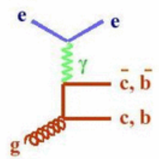
But saturation effects will show up most strongly in heavy nuclei

And LHeC can also measure ePb

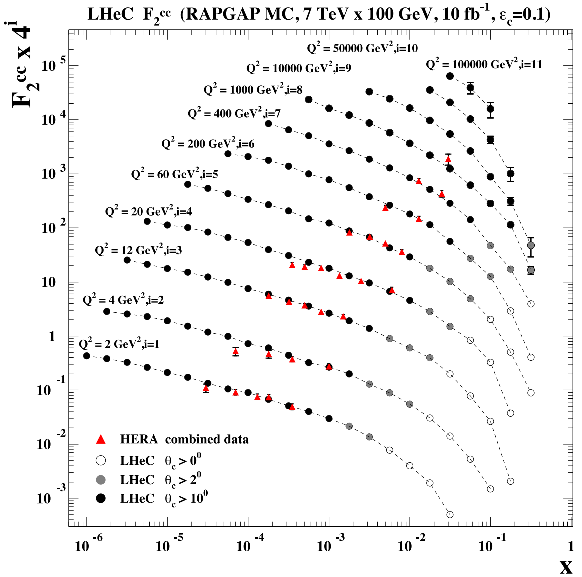
Pseudo data based on EPPS16 eA analysis bring vast improvement in previously unmeasured kinematic ranges

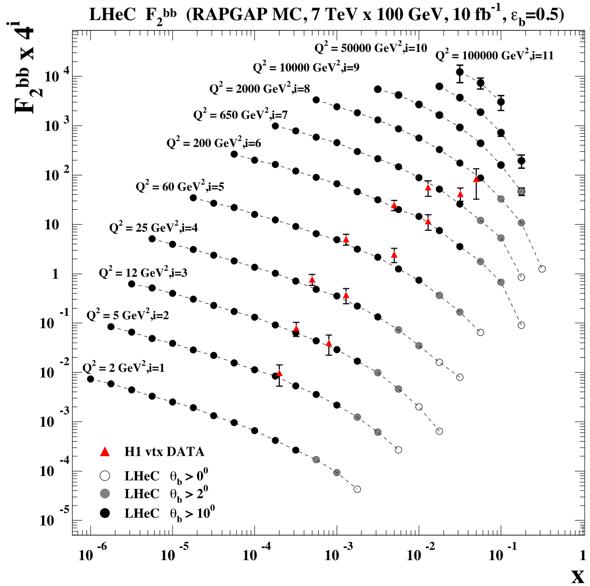


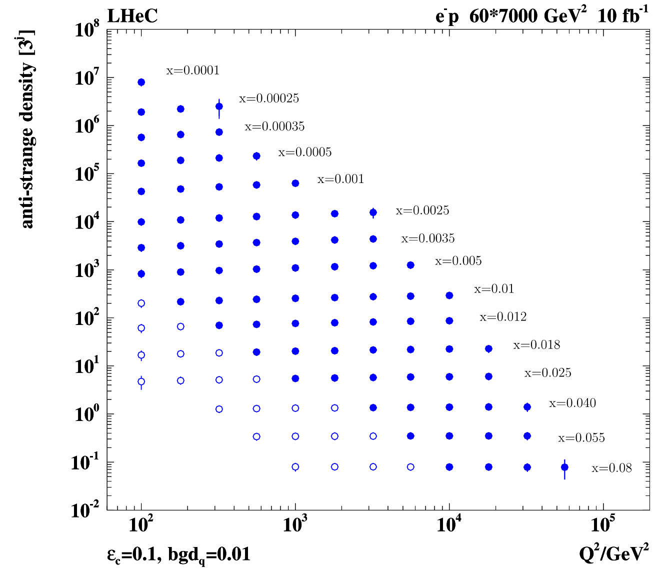
c, b quarks



strange







LHeC: enormously extended range and much improved precision c.f. HERA

- **δMc = 50 (HERA)** to **3 MeV**: impacts on αs, regulates ratio of charm to light, crucial for precision t, H
- **δMb** to **10 MeV**; MSSM: Higgs produced dominantly via bb → A

strange pdf poorly known; how suppressed cf. other light quarks? s ≠ sbar ?

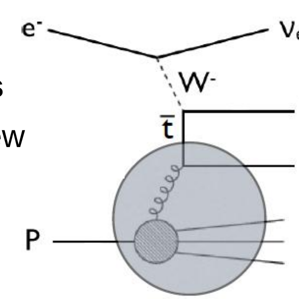
LHeC: direct sensitivity to **strange** via W+s → c

(x,Q^2) mapping of (anti) strange for first time

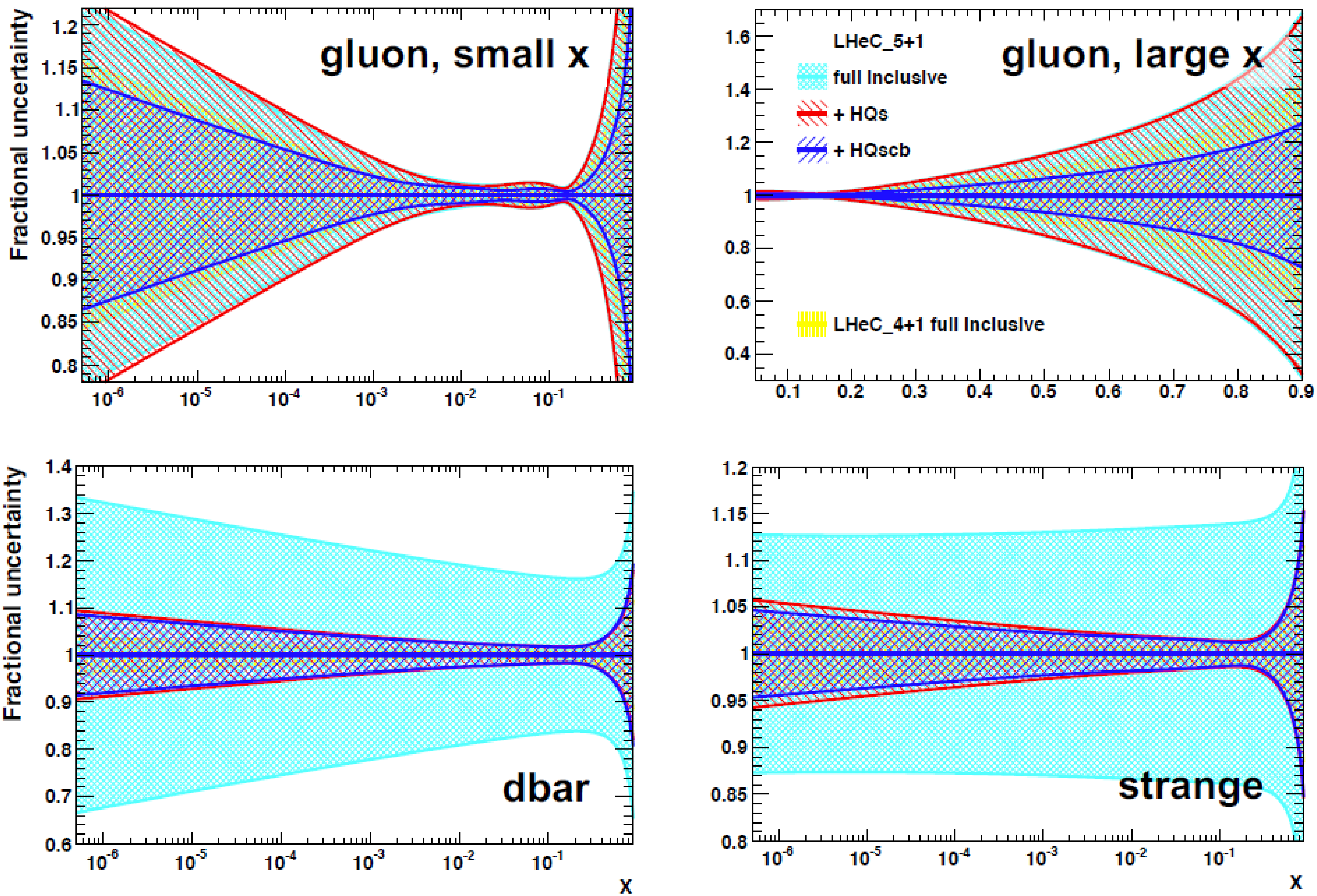
-

also top PDF

top quark becomes light at large Q^2: new field of research opens for top PDFs!

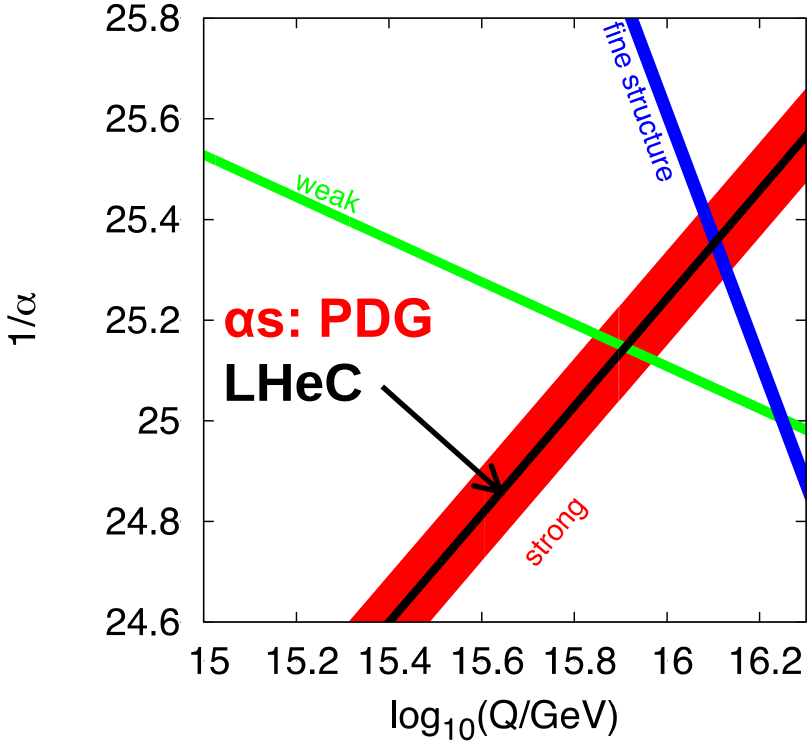


impact of HQ data on LHeC pdfs



more flexible parameterisation (5+1): **xuv, xdv,** $x\bar{U}$, $x\bar{d}$, $x\bar{s}$ and **xg**

And there will be further information from jet production at the LHeC…… which will mostly contribute to the precision of the gluon PDF and thus to the determinations of strong coupling, α_S (MZ)



precise αs needed:
to constrain GUT scenarios; for cross section predictions, including Higgs; …

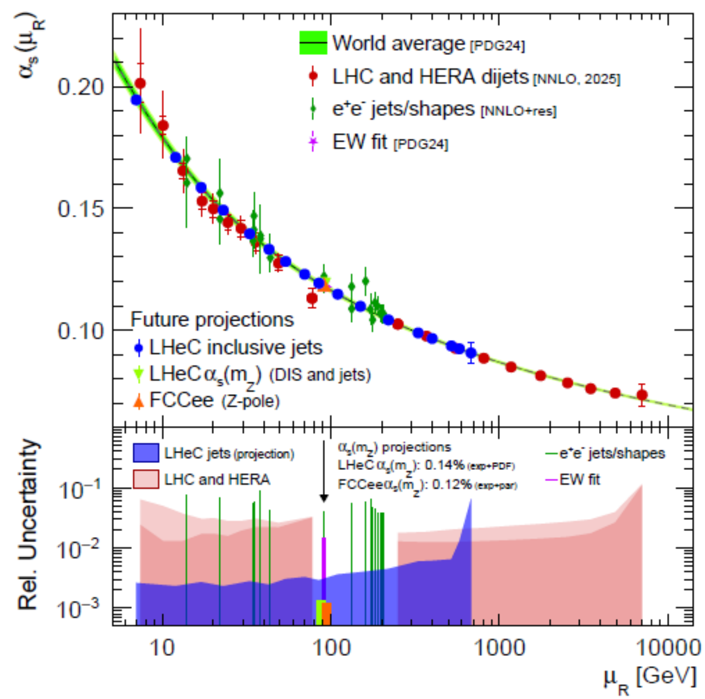
LHeC: permille precision possible in **combined QCD fit for pdfs+αs**

Strong Coupling

arXiv:2007.14491
featured in Snowmass α_s White Paper,
arXiv:2203.08271

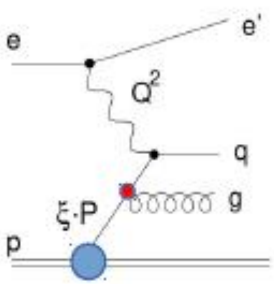
- α_s: least known coupling constant
- current state-of-the-art: $\delta\alpha_s/\alpha_s = \mathcal{O}(1\%)$

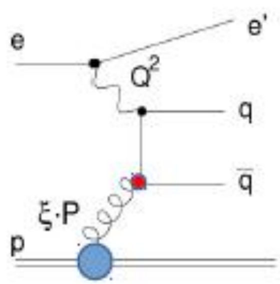
- simultaneous **PDF+α_s** fits:
- **EIC** (arXiv:2307.01183): $\mathcal{O}(0.4\%)$ (exp+PDF)
- **LHeC**:
- $\Delta\alpha_s(M_Z)$[incl. DIS] = ±0.00022 (exp+PDF)
- $\Delta\alpha_s(M_Z)$= ± 0.00018 for incl. DIS together with **ep jets**
- achievable precision: $\mathcal{O}(0.1\text{–}0.2\%)$
  ×5–10 better than today



$= \sqrt{(Q^2 + p_T^2)}$

ep jets:





- α_s from fits to **ep** jet production (**LHeC**)
- connects τ-decays to Z-pole and beyond
- **FCC-eh** further increases precision and range

8

Summary

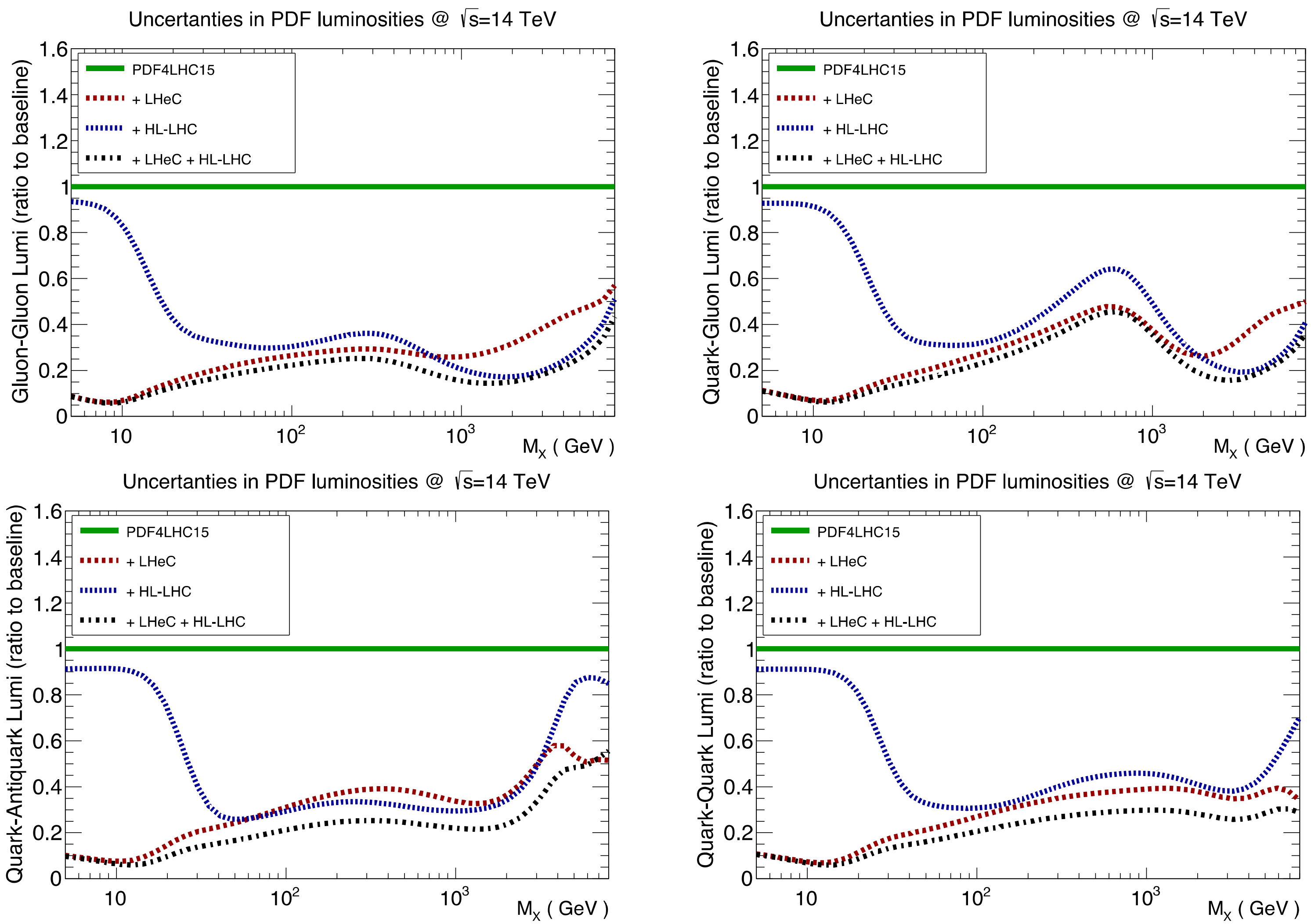
- PDF improvement is not just a matter of more data, consistency of data matters, consistency across a broad kinematic range is what LHeC/FCCeh offers
- A single team would analyse the whole kinematic region producing a consistent set of correlated systematic uncertainties----we have learnt our lessons at HERA
- This is also theoretically cleaner + less subject to new physics contamination at high scale

- Improvement in PDFs at high-x important for direct discoveries, improvement in high-x gluon also brings improvement in $\alpha_S(M_Z)$
- Improvement at middling x important for SM precision measurements like M_W and $\sin^2\theta_W$ which may reveal BSM physics
- Improvement at low-x is necessary to be sure of this, but is interesting in its own right for studying QCD beyond DGLAP: BFKL resummation and saturation

- The LHeC offers dramatic improvement for all of this and probes low-x, thus it is complementary to the EIC, which probes to high-x.

Backup

Just in case you worry that a study of LHeC improvements based on a simple HERAPDF procedure may be optimistic. A study was done comparing future improvements from the HL-LHC to those from the LHeC in an 'apples to apples' manner. Profiling the PDF4LHC15 with HL-LHC pseudo-data or LHeC pseudo-data With consistent tolerance T=3



Abdul Khalek et al
arXiv:1810.03639
+ 1906.10127

QCD fit parameterisation

QCD fit ansatz based on HERAPDF2.0, with following differences

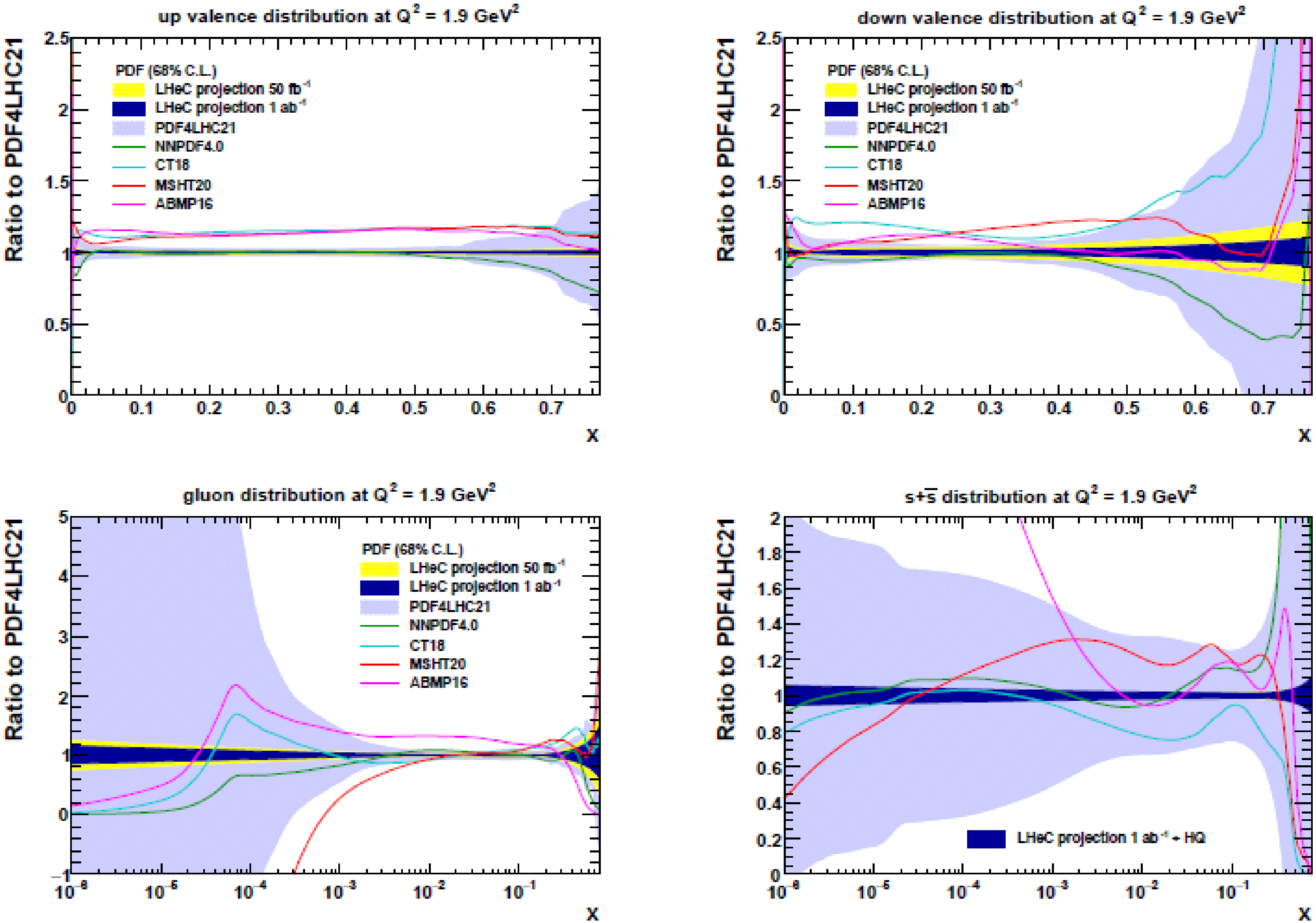
much more relaxed sea ie. no requirement that ubar=dbar at small x

no negative gluon term (simply for the aesthetics of ratio plots – it has been checked that this does not impact size of projected uncertainties)

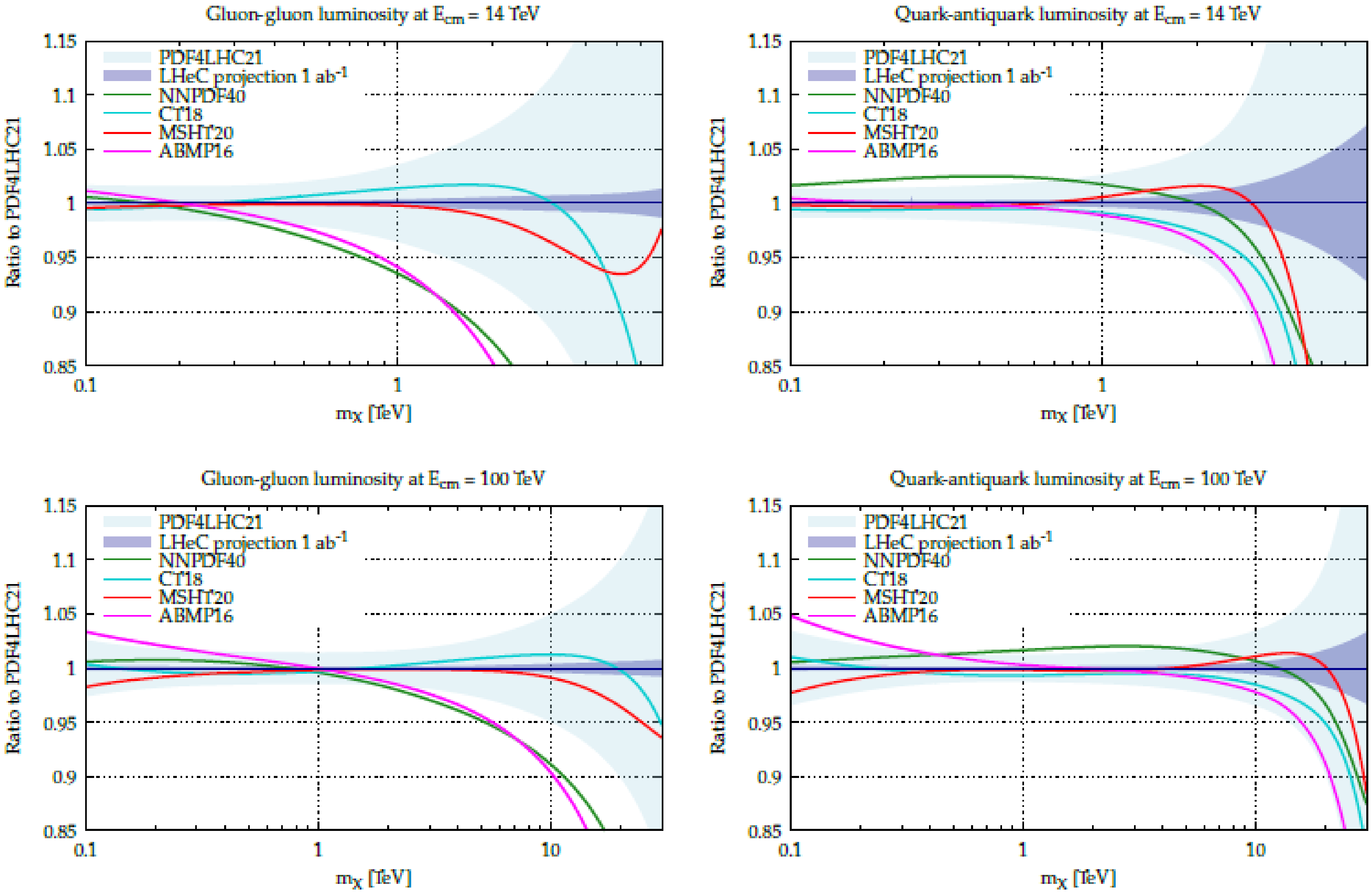
$$
\begin{aligned}
xg(x) &= A_g x^{B_g}(1-x)^{C_g}(1+D_g x) \\
xu_v(x) &= A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}(1+E_{u_v}x^2) \\
xd_v(x) &= A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}} \\
x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}} \\
x\bar{D}(x) &= A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}
\end{aligned}
$$

4+1 pdf fit (above) has 14 free parameters

5+1 pdf fit for HQ studies parameterises dbar and sbar separately, and has 17 free parameters

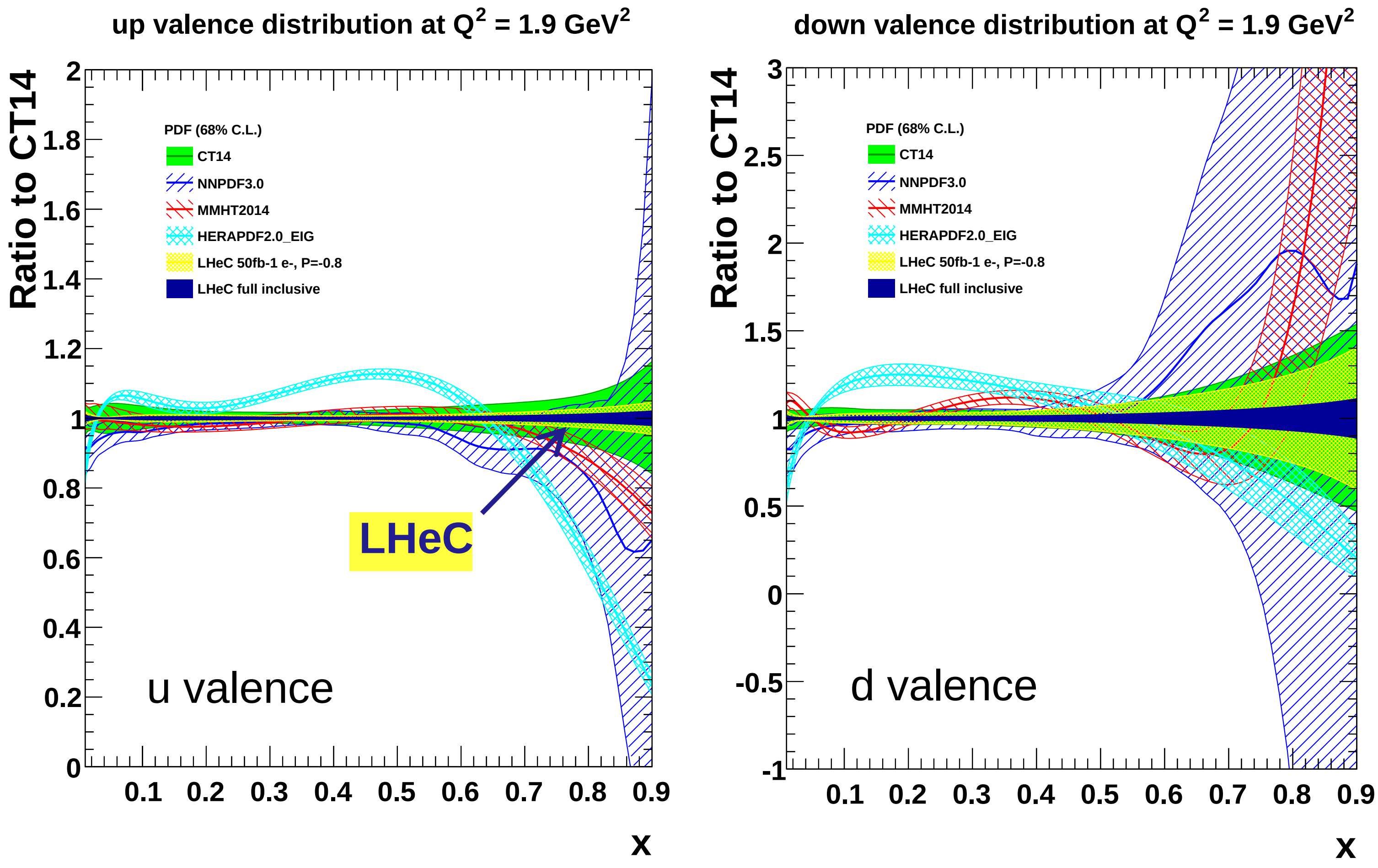


And in comparison to modern PDFs



Then in terms of luminosities at LHC energies and beyond

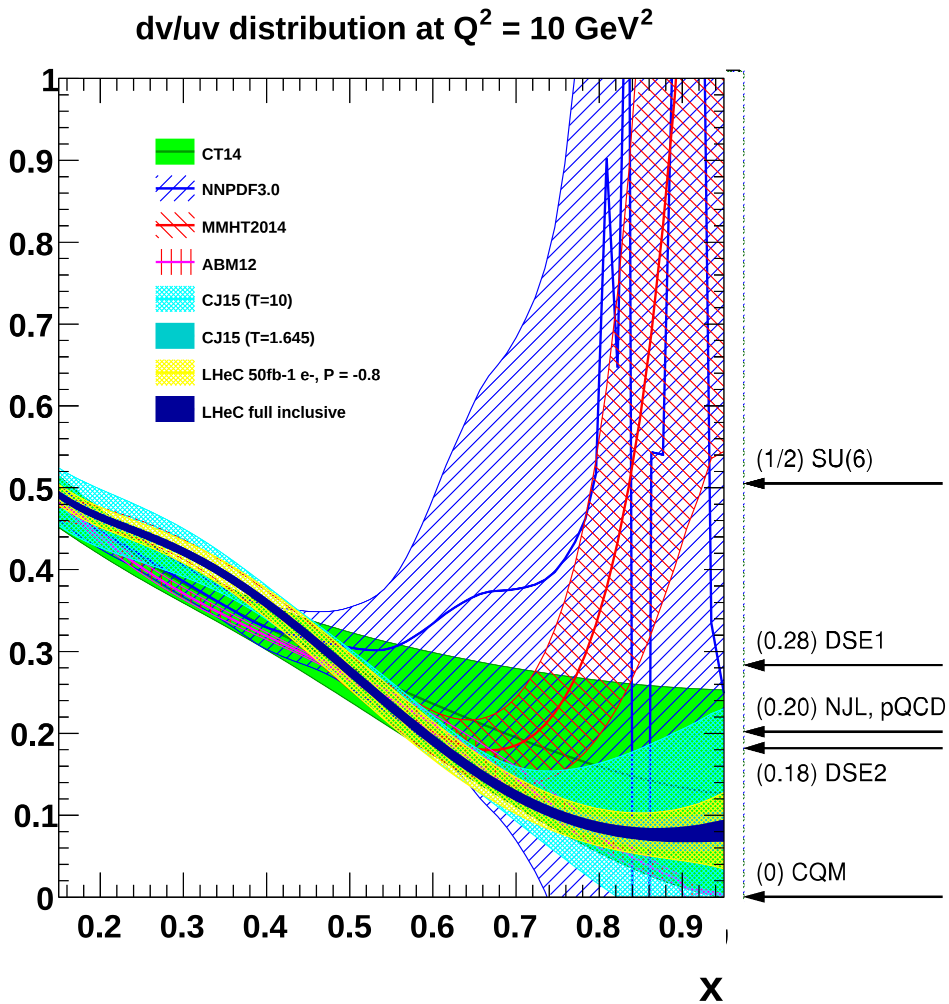
valence quarks from LHeC



precision determination, free from higher twist corrections and nuclear uncertainties

large x crucial for HL/HE–LHC and FCC searches; also relevant for DY, MW etc.

d/u at large x



d/u essentially unknown at large x

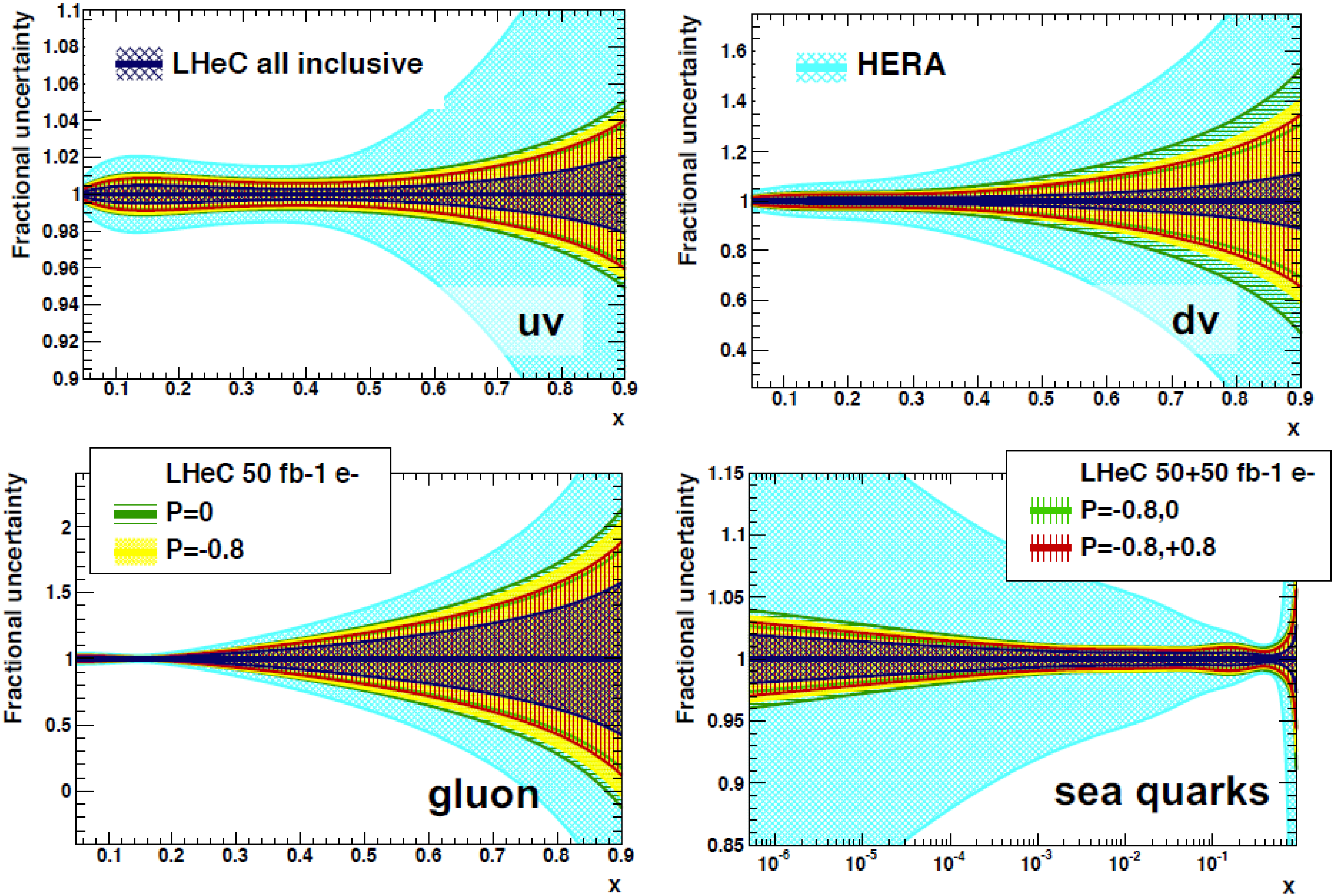
no predictive power from current pdfs;

conflicting theory pictures;

data inconclusive, large nuclear uncerts.

resolve long-standing mystery of d/u ratio at large x

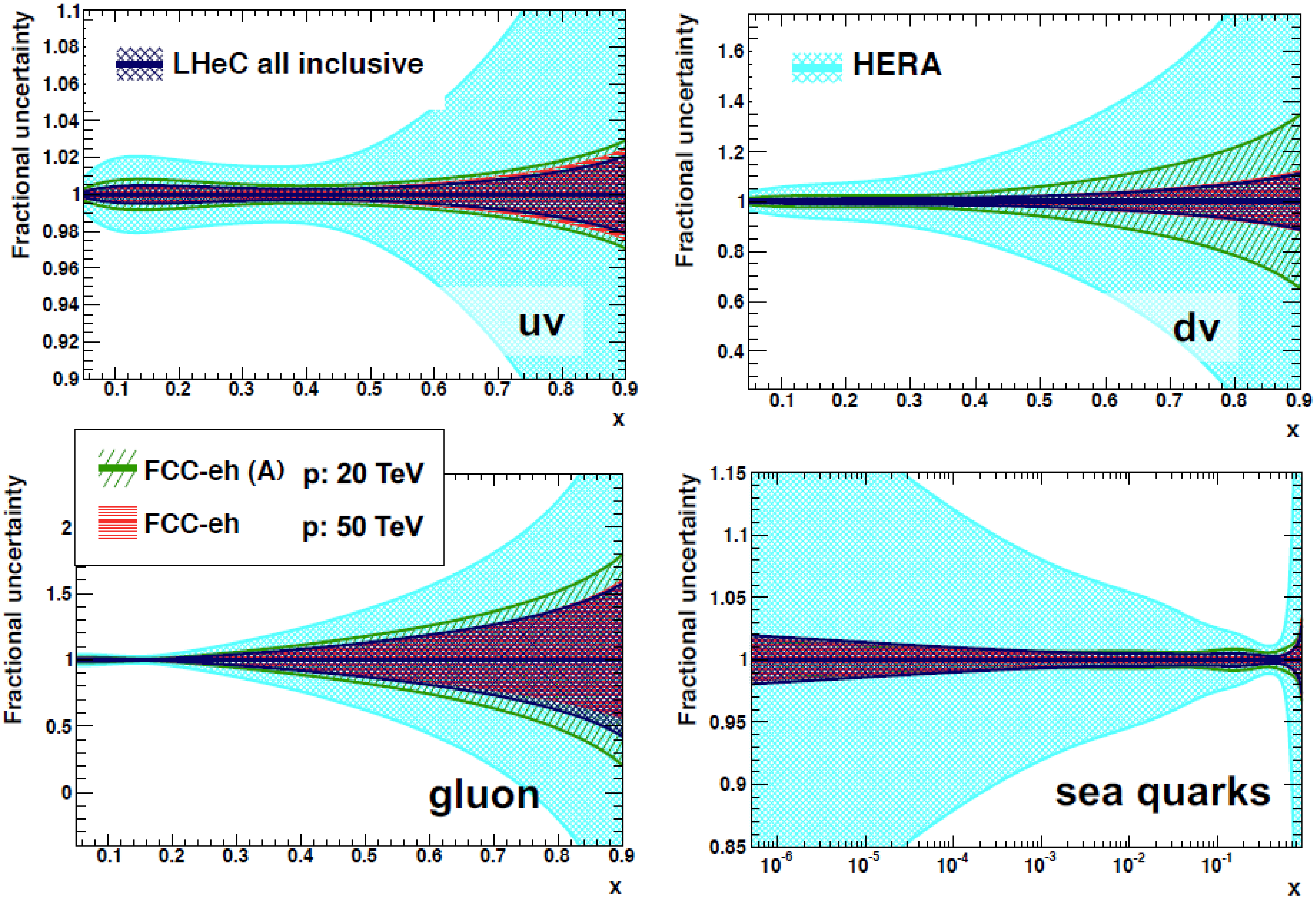
impact of polarisation on LHeC pdfs



impact of polarisation on pdfs generally small (but pol. important for ew)

(**CC**: σ(e±) scales as (1±P) ; **NC**: effects subtle; pol. asym. gives access to $F2^{\gamma Z}$, new quark combinations)

Collider configurations



FCC-eh (A): new preliminary simulation with 2 ab^{-1} polarised e– (NO e+ yet; impact especially in d at large x)