PDFs from LHeC

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arXiv:1206.2913

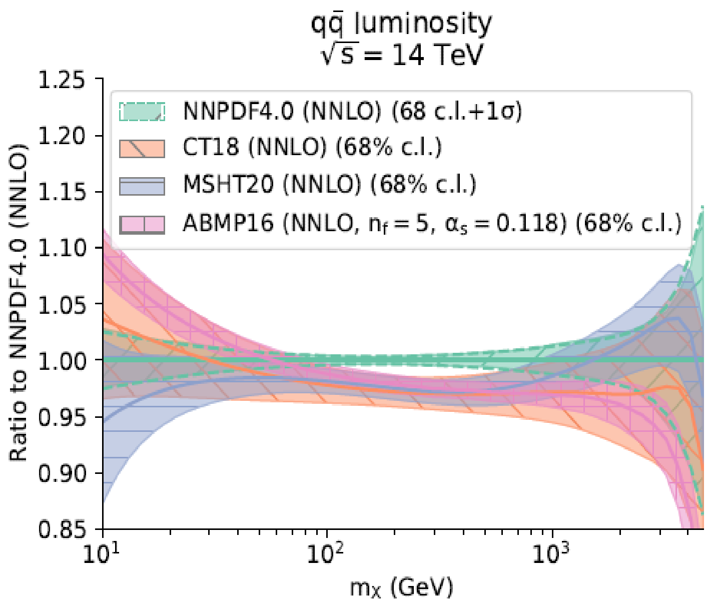
J. Phys. G 48 (2021) 11, 110501

(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

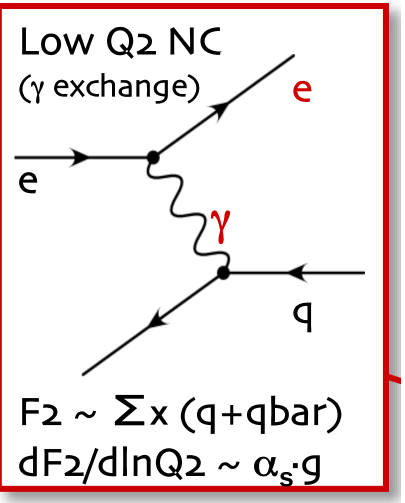
Today PDFs from each of the big groups CT, MSHT, NNPDF are each heading towards percent level precision BUT the differences between them are at the few percent level– even in the 'well-known' central x region

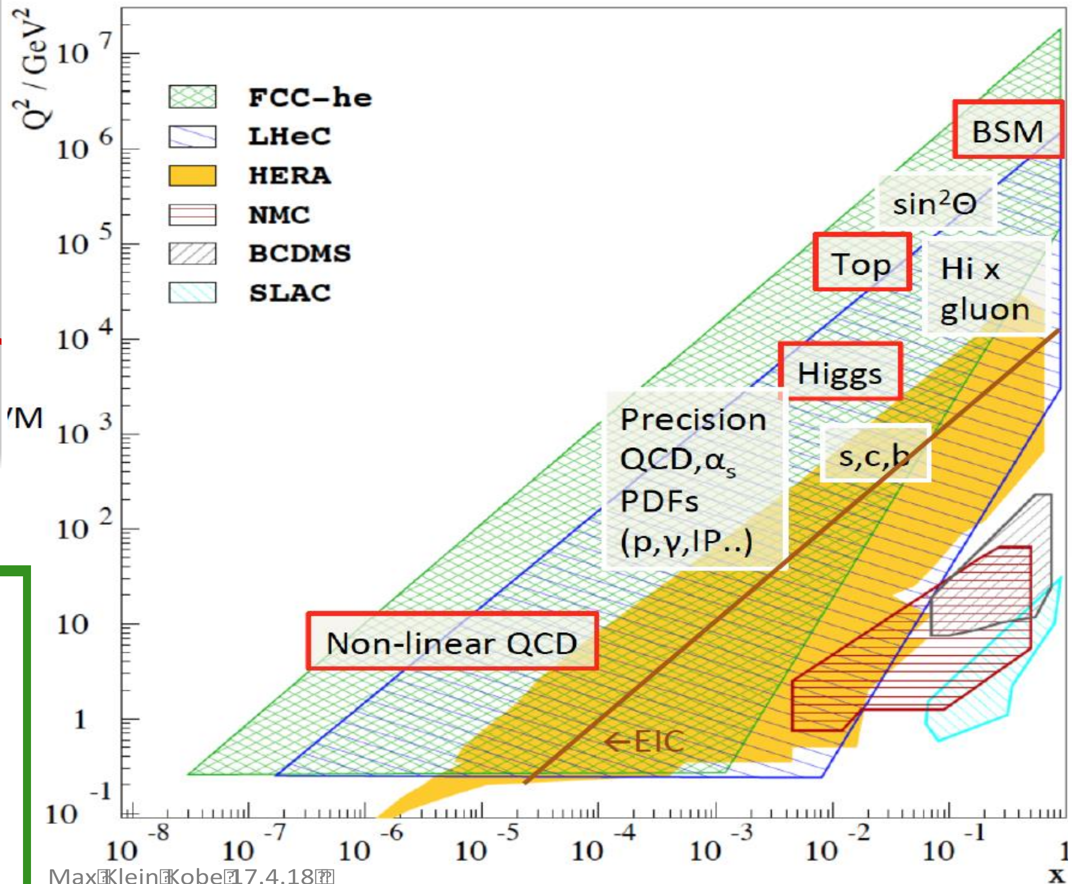
This is not good enough if we aim to find deviations from the SM in the deviations of the values of SM parameters M_W, $\sin^2\theta_W$

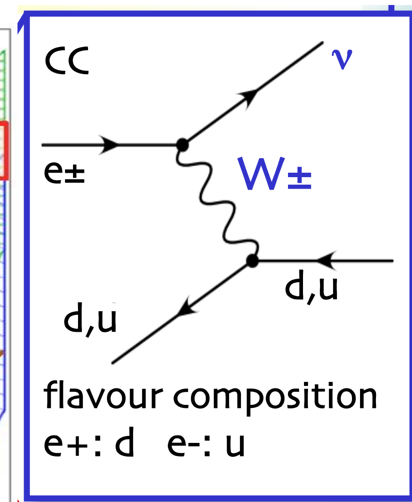
What could help?

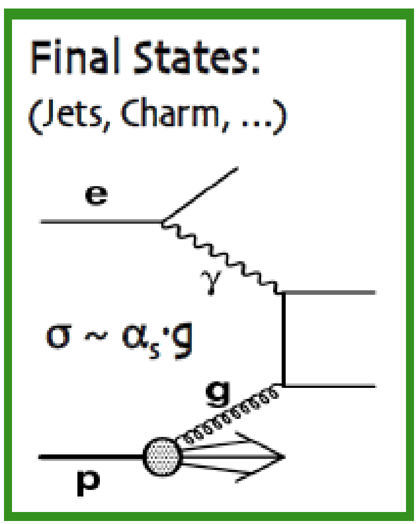
A precise new data set over a very wide kinematic range with consistent correlated systematics--- that's what the LHeC could provide

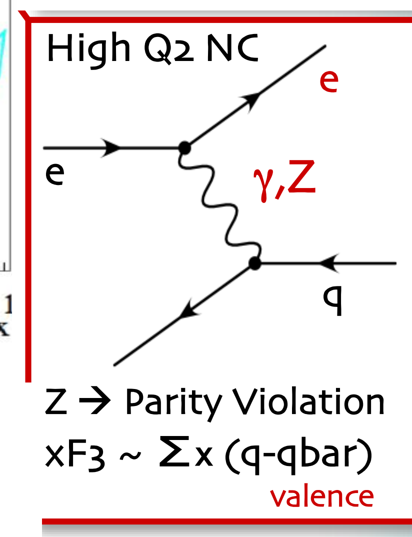
Where does the information come from?











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**

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)

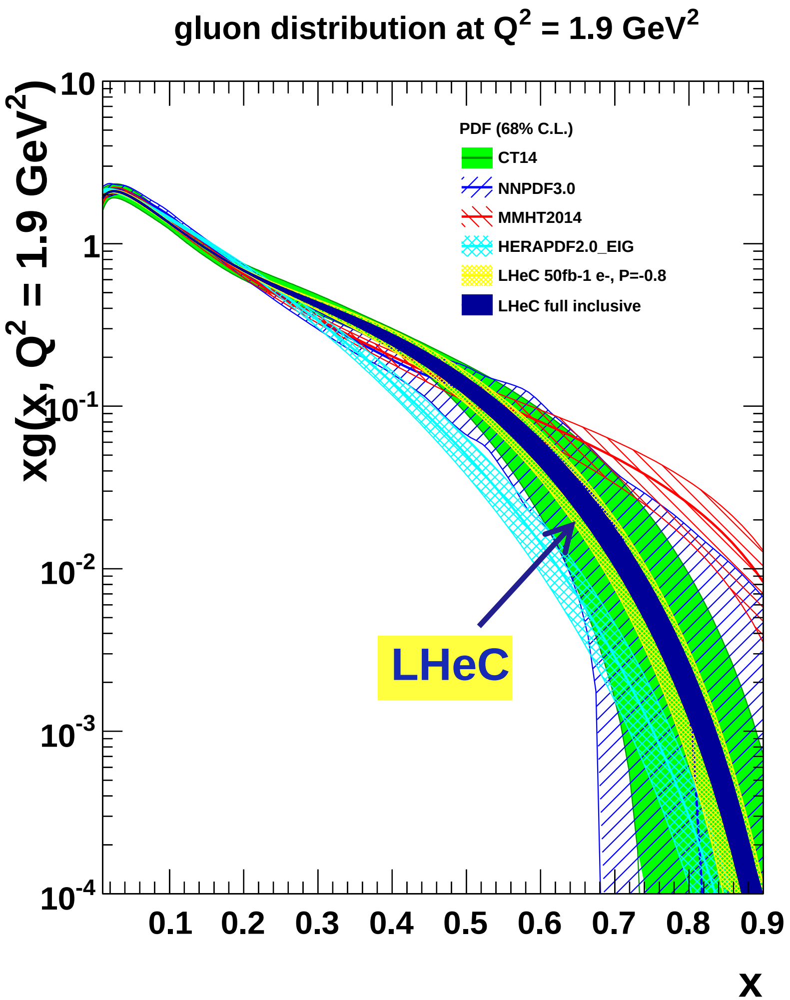
LHeC full inclusive

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

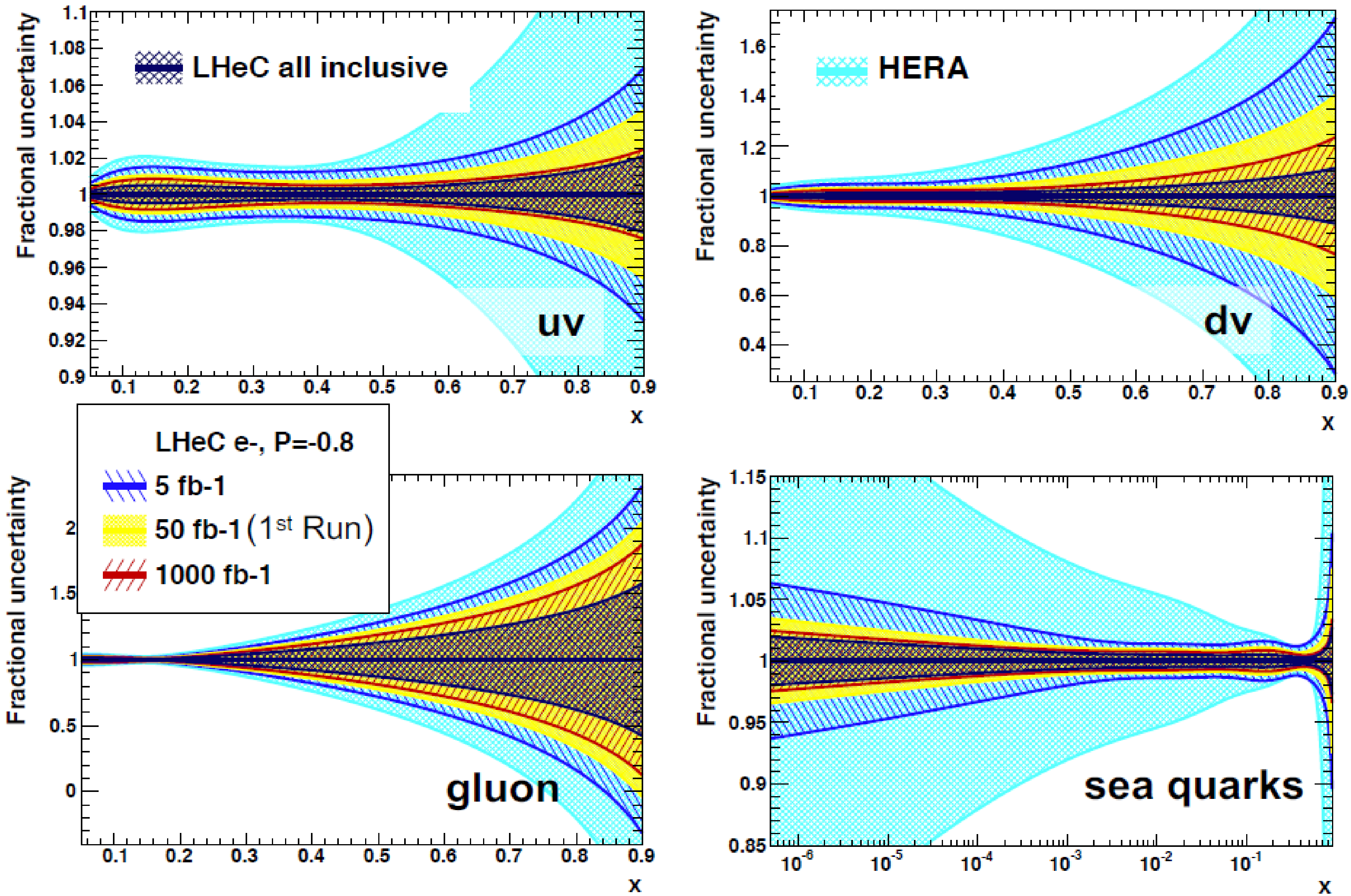
LHeC sensitivity at large x comes as part of overall package

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

gluon and sea intimately related

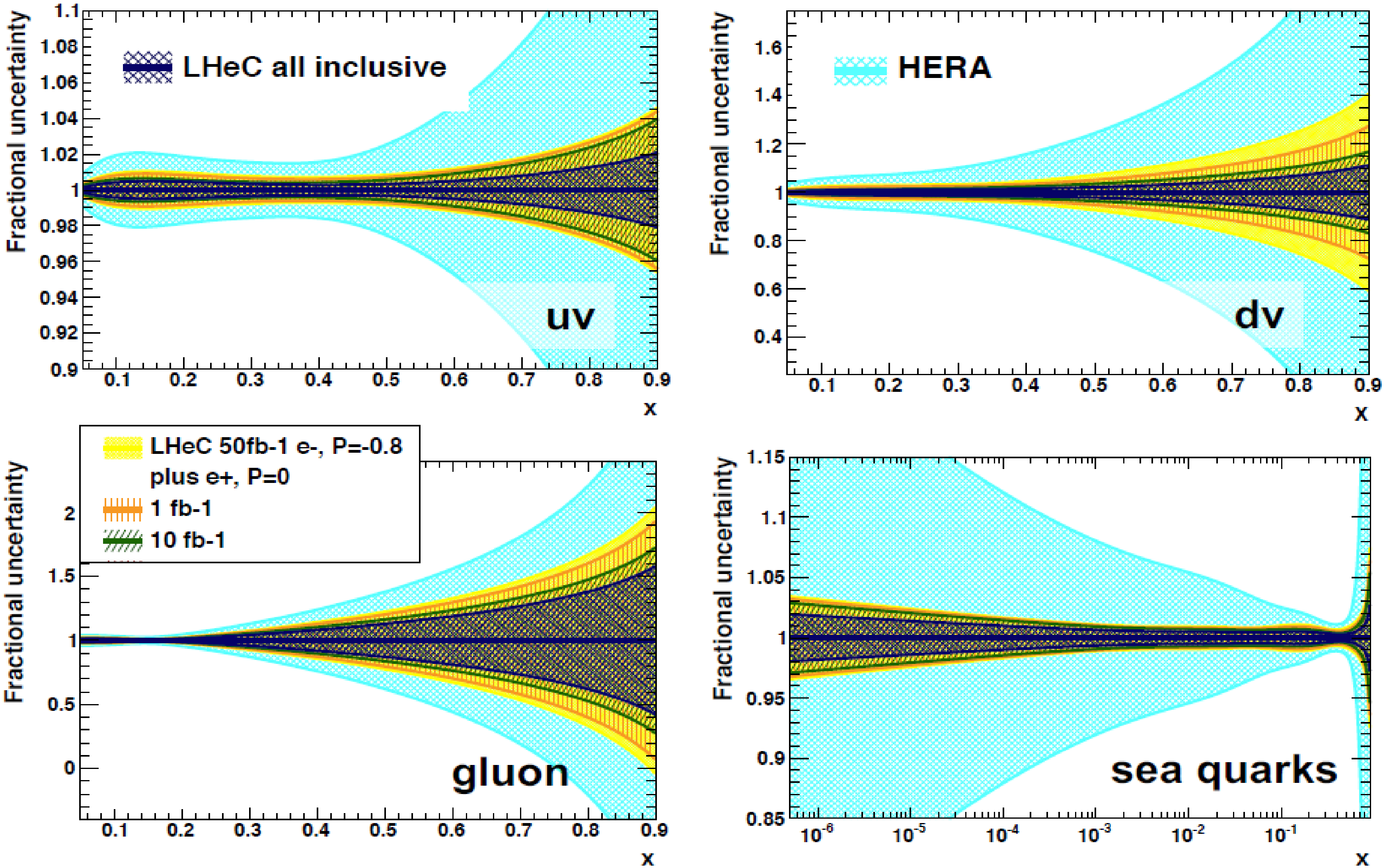
LHeC can disentangle sea from valence quarks at large x, with precision measurements of **CC** and **NC** $F2^{\gamma Z}$, $xF3^{\gamma Z}$

Impact of luminosity on PDFs



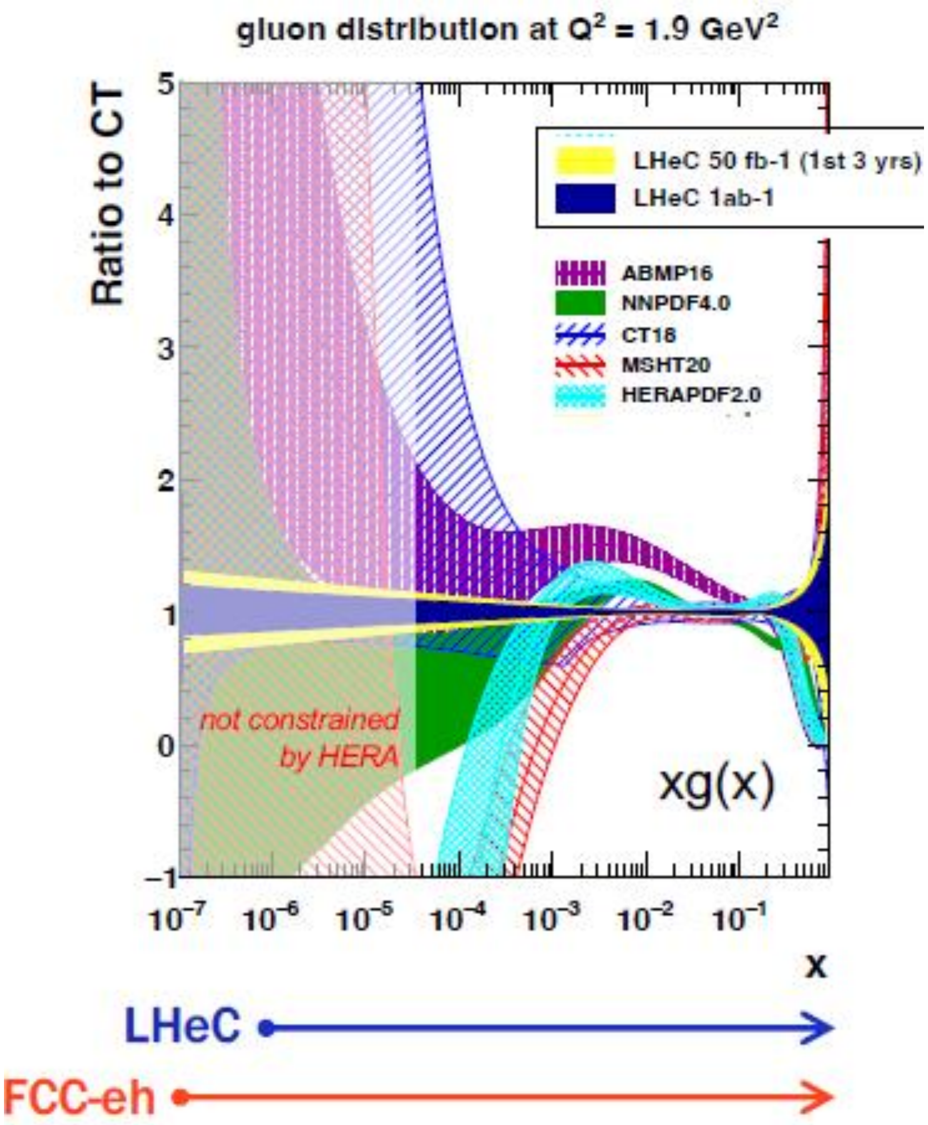
small and **medium x** quickly constrained (5 fb-1 ≡ ×5 HERA ≡ 1 year LHeC)

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 $x=10^{-7}$

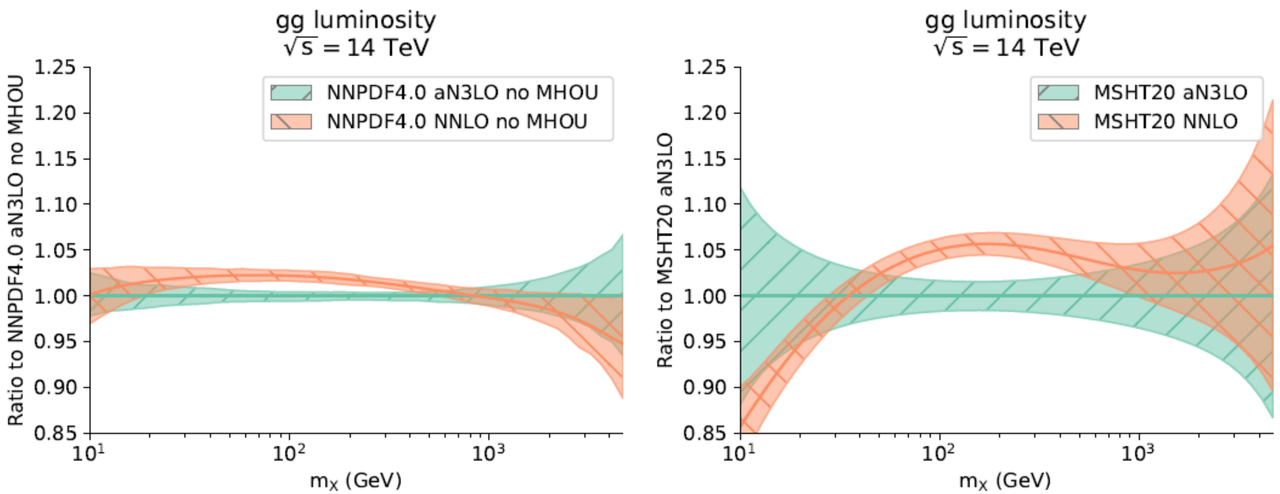
explore low x QCD:
DGLAP vs BFKL; non-linear evolution;
gluon saturation; implications
for ultra high energy neutrino cross sections

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..

We now have N3LO predictions..

-----Well at least approximately

This has a significant effect on the low-x gluon at low scales

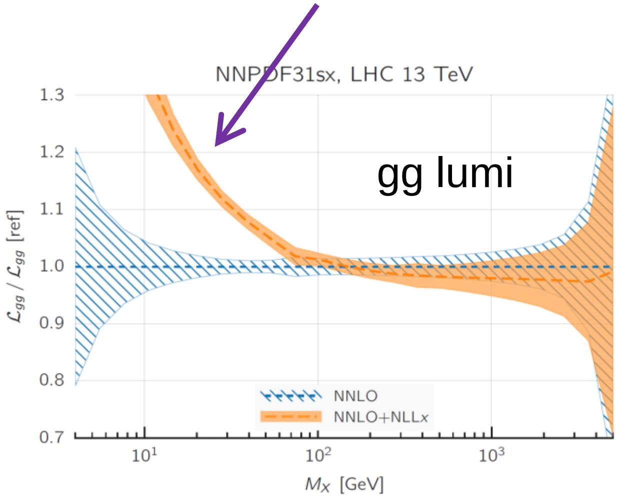


And that translates to an effect on the low Mx region for the gluon-gluon luminosity
BUT this also has a ‘knock-on effect’ on the luminosity in the Higgs region Mx =125 GeV

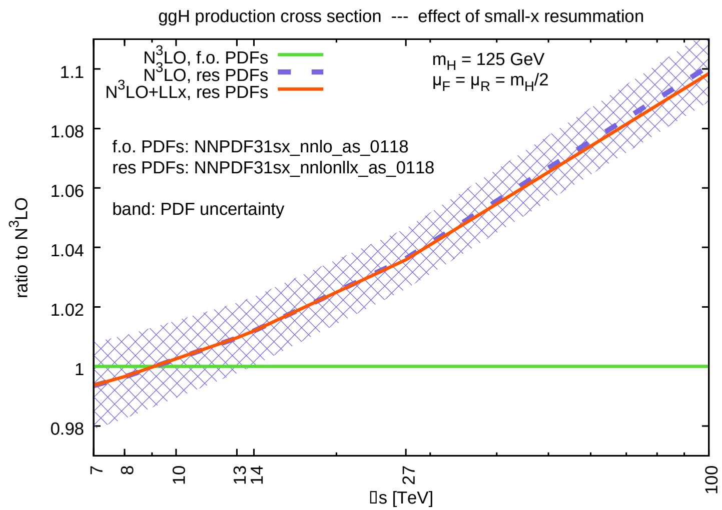
Differing groups have different ways of implementing the aN3LO
For MSHT there is a 5% decrease in luminosity at the Higgs mass, for NNPDF this is more like 2%... BUT either way there is a significant difference
BEWARE of low-x effects!!

Full ln(1/x) BFKL resummation

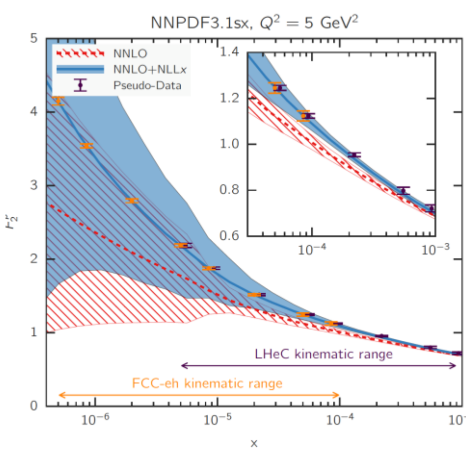
effect of small x resummation on LHC luminosity

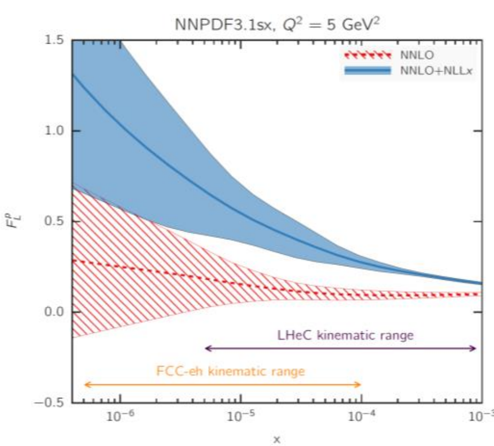


effect of small x resummation on ggH cross section for LHC, HE-LHC, FCC

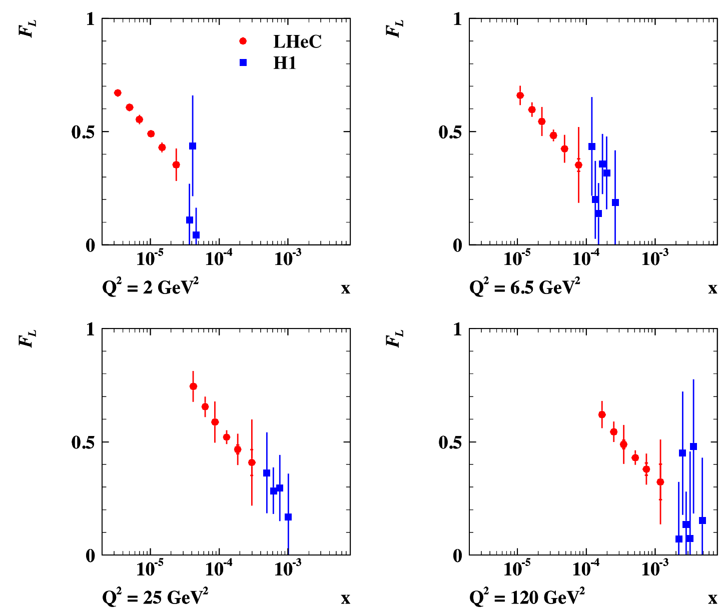


Effect of small x resummation on predictions for DIS F2 and FL



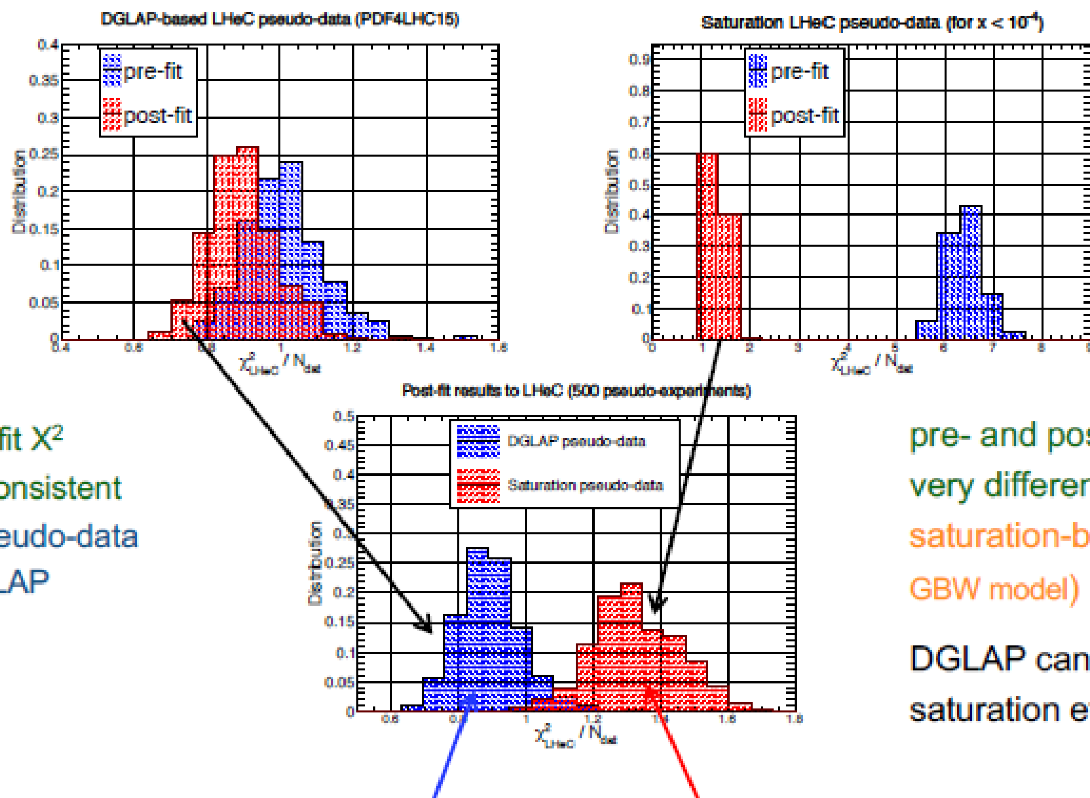


Prospects for FL measurement at LHeC



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

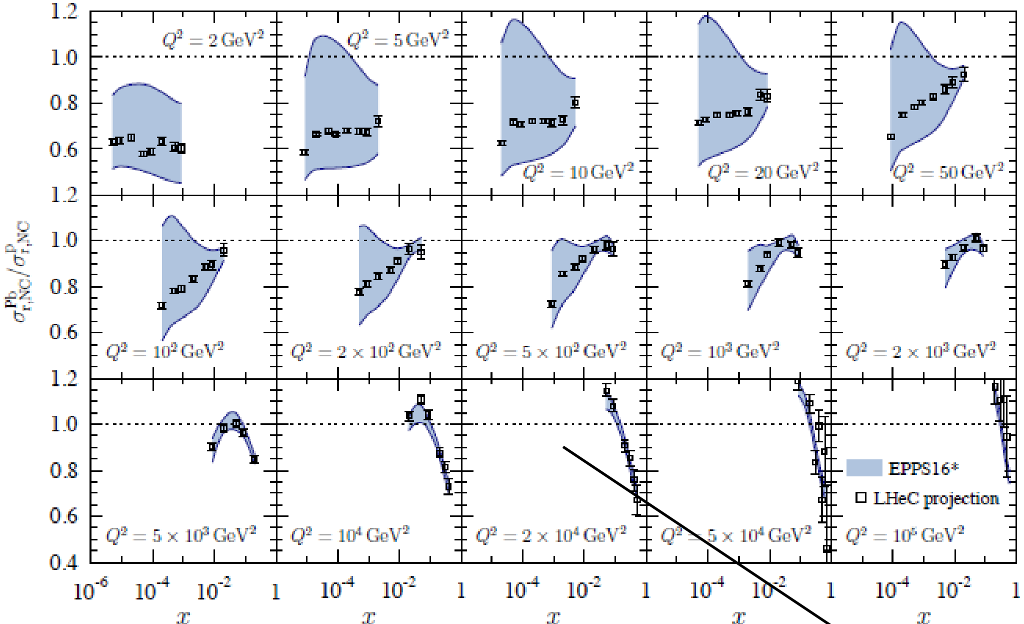
LHeC can distinguish between **DGLAP** and **saturation**

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

arXiv:2007.14491

(more detail in EXTRAS)

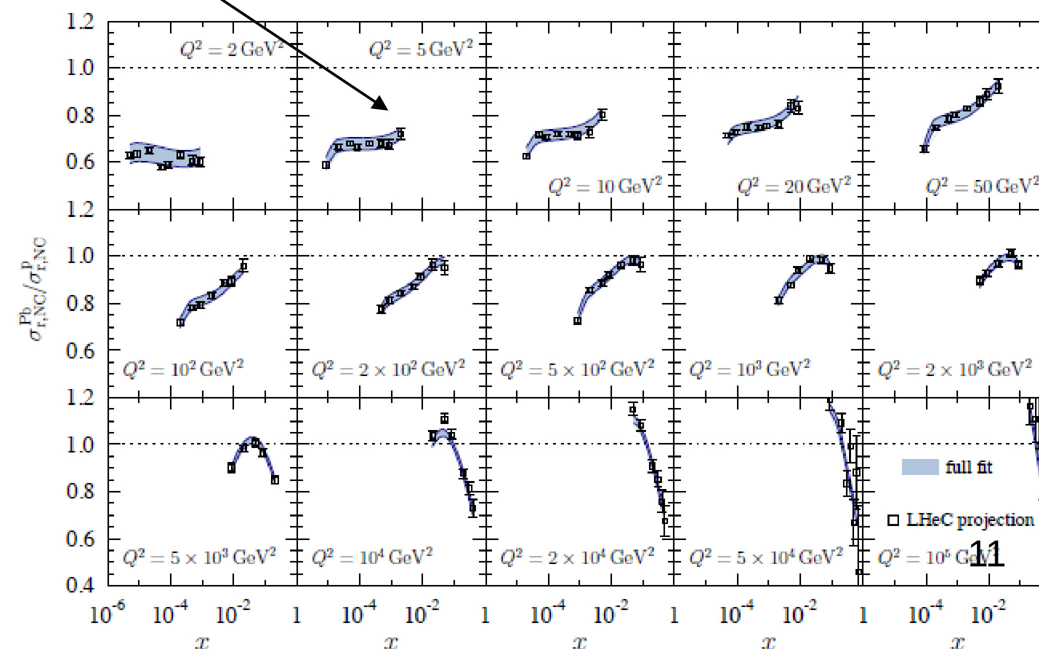
18



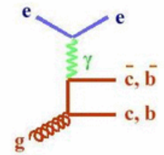
But saturation effects will show up most strongly in heavy nuclei

And LHeC can also measure ePb

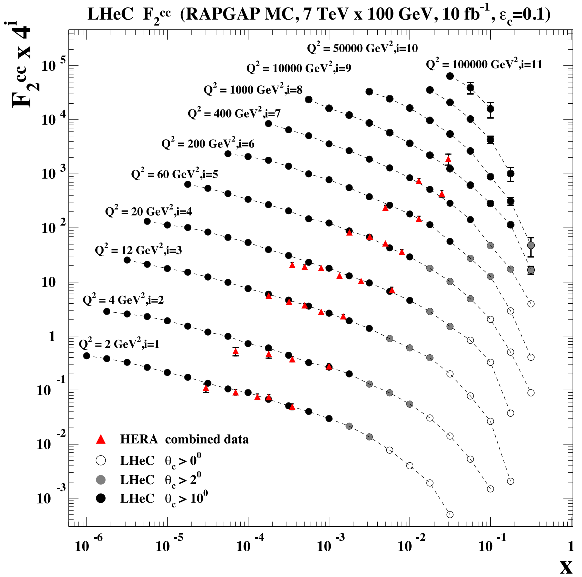
Pseudo data based on EPPS16 eA analysis bring vast improvement in previously unmeasured kinematic ranges

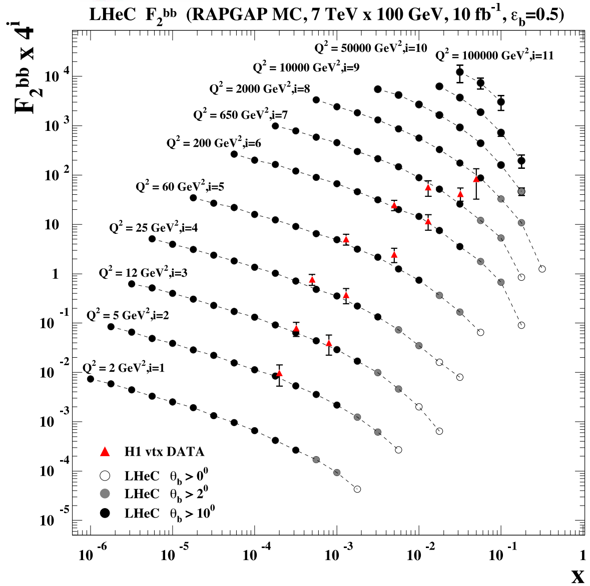


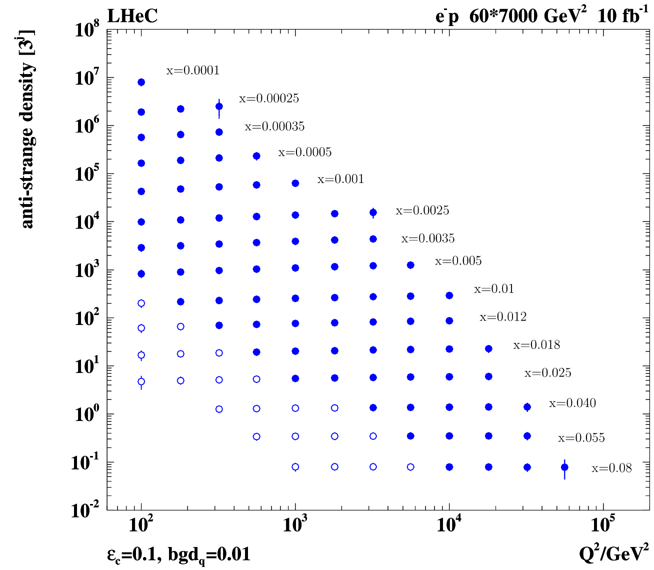
c, b quarks



strange







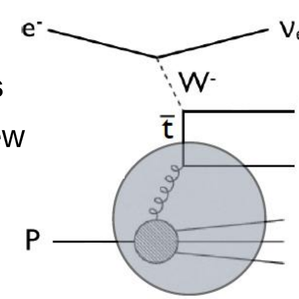
LHeC: enormously extended range and much improved precision c.f. HERA

- **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

-

also top PDF

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

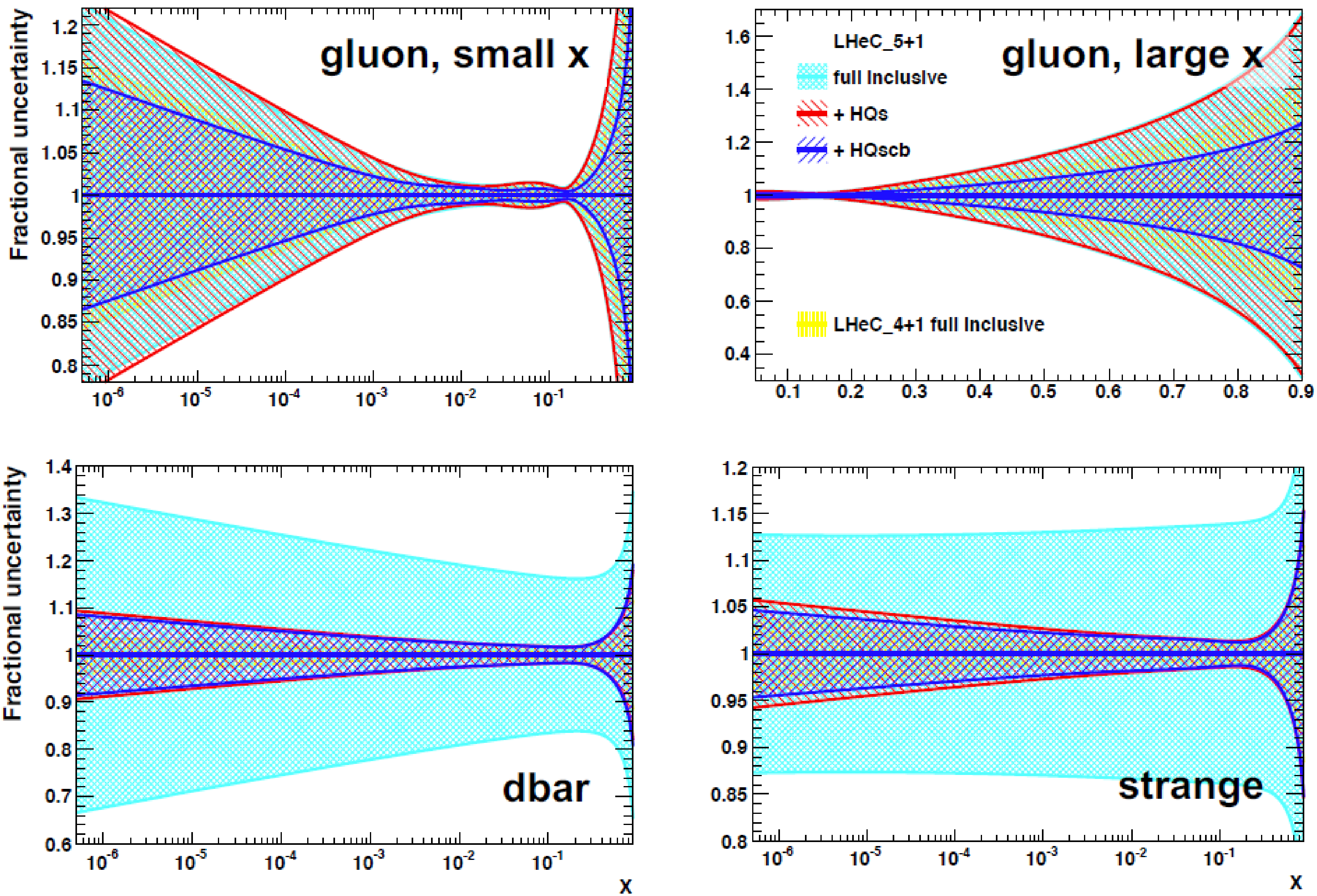


strange pdf poorly known; how suppressed cf. other light quarks? s ≠ sbar ?

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

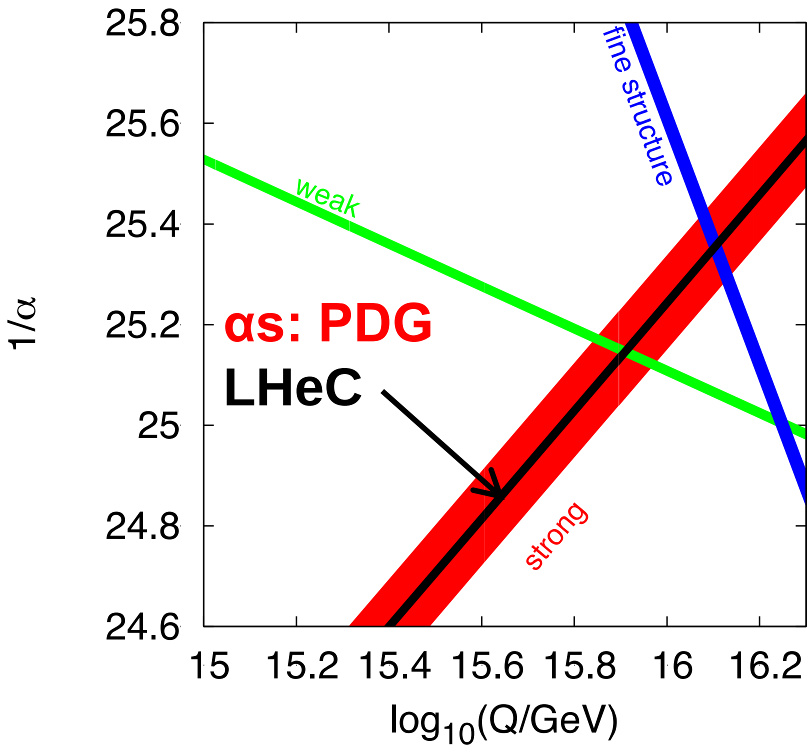
(x,Q^2) mapping of (anti) strange for first time

impact of HQ data on LHeC pdfs



more flexible parameterisation (5+1): **xuv, xdv, x$\overline{\text{U}}$, x$\overline{\text{d}}$, x$\overline{\text{s}}$** 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 **α_S** **needed**:
to constrain GUT scenarios; for cross section predictions, including Higgs; …

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

$\alpha_S(M_Z)$

- LHeC simultaneous PDF+α_S fit:
  - $\Delta\alpha_S(m_Z) = \pm 0.00022$ (exp.+PDF)
  - $\Delta\alpha_S(m_Z) = \pm 0.00018$ (with ep jets)
- Achievable precision: $\mathcal{O}$**(0.1%)** - **x5-10** better than today

Summary

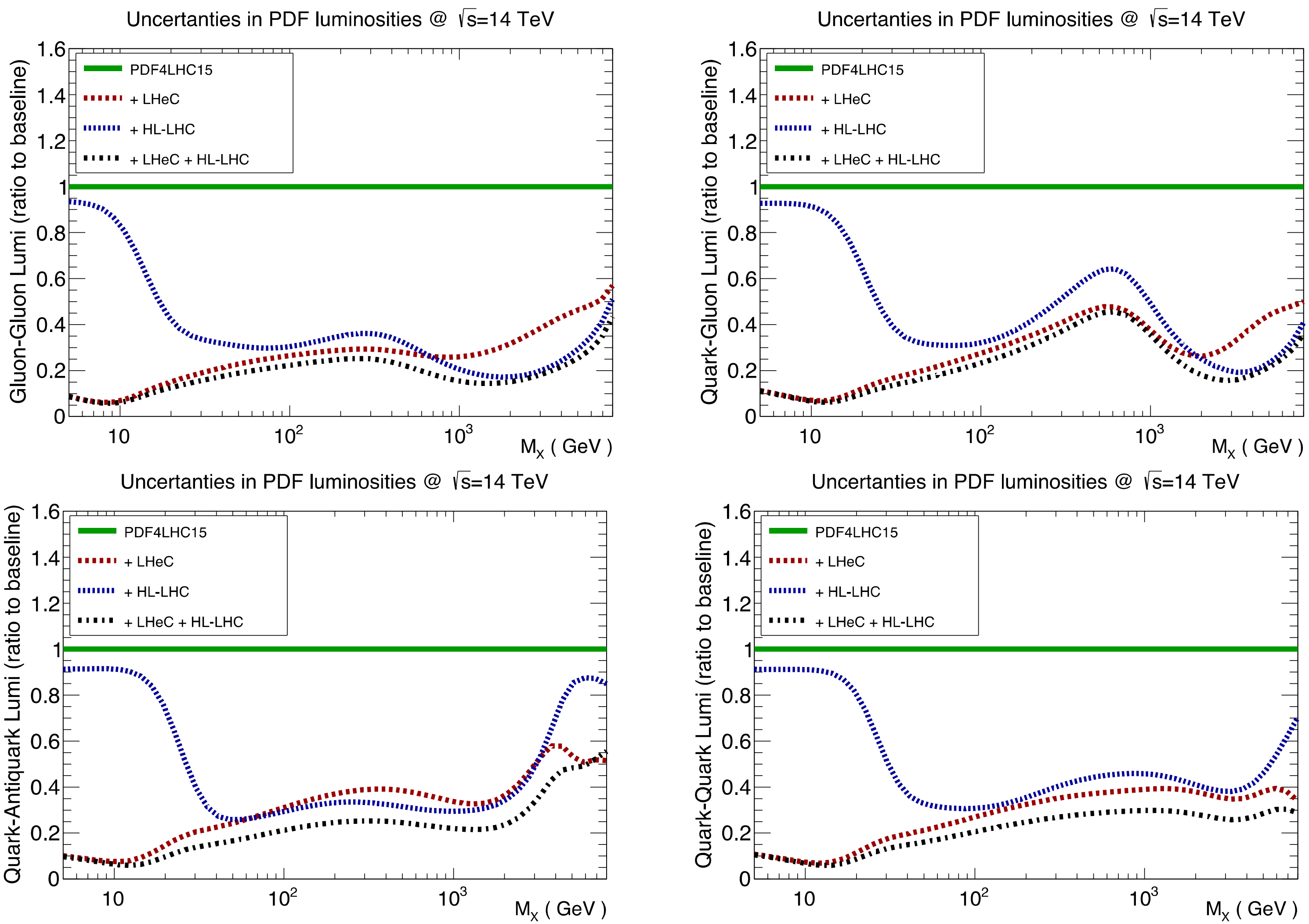
- PDF improvement is not just a matter of more data, consistency of data matters, consistency across a broad kinematic range is what LHeC/FEEeh offers
- A single team would analyse the whole kinematic region producing a consistent set of correlated systematic uncertainties----we have learnt our lessons 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
- Saturation is stronger at eA

- The LHeC offers dramatic improvement for all of this (and more) and is complementary to the EIC

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

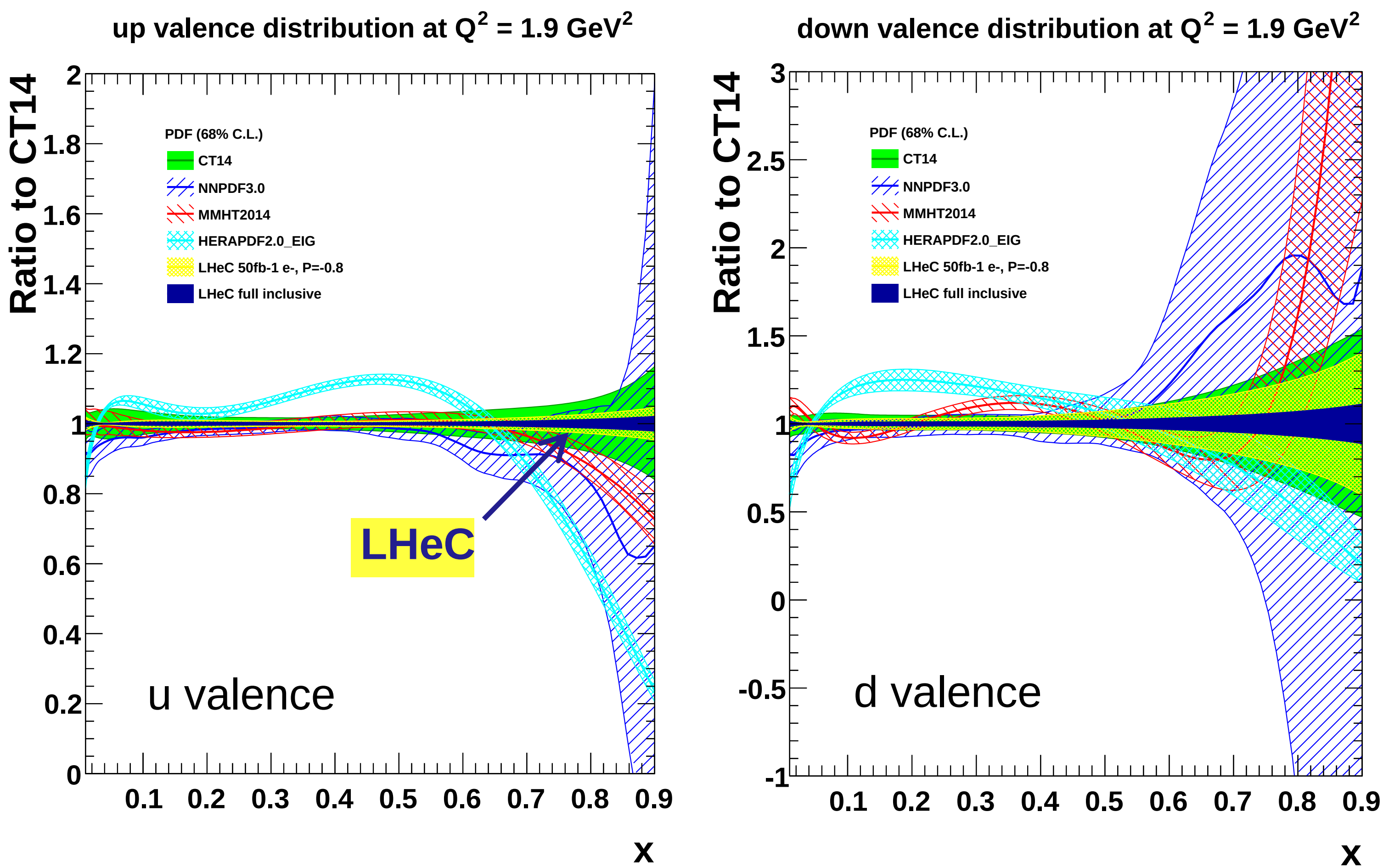
no negative gluon term (simply for the aesthetics of ratio plots – it has been checked that this does not impact size of projected uncertainties)

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

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

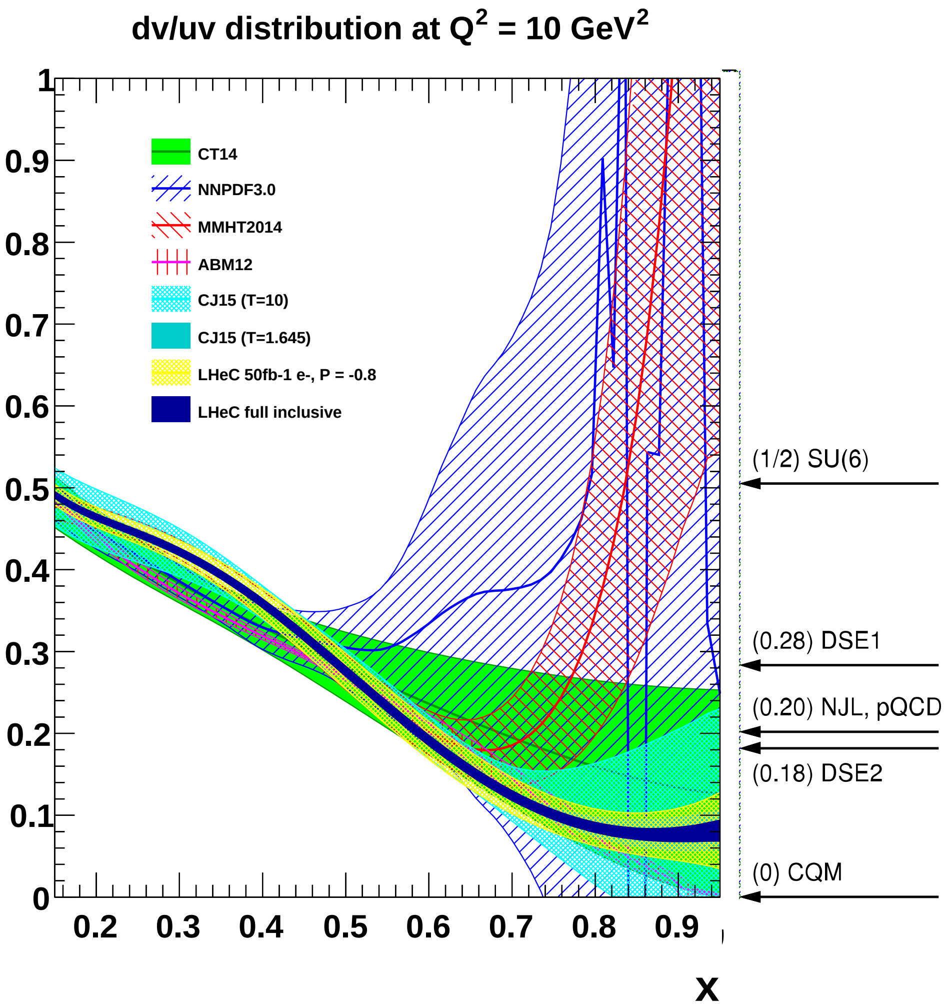
valence quarks from LHeC



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

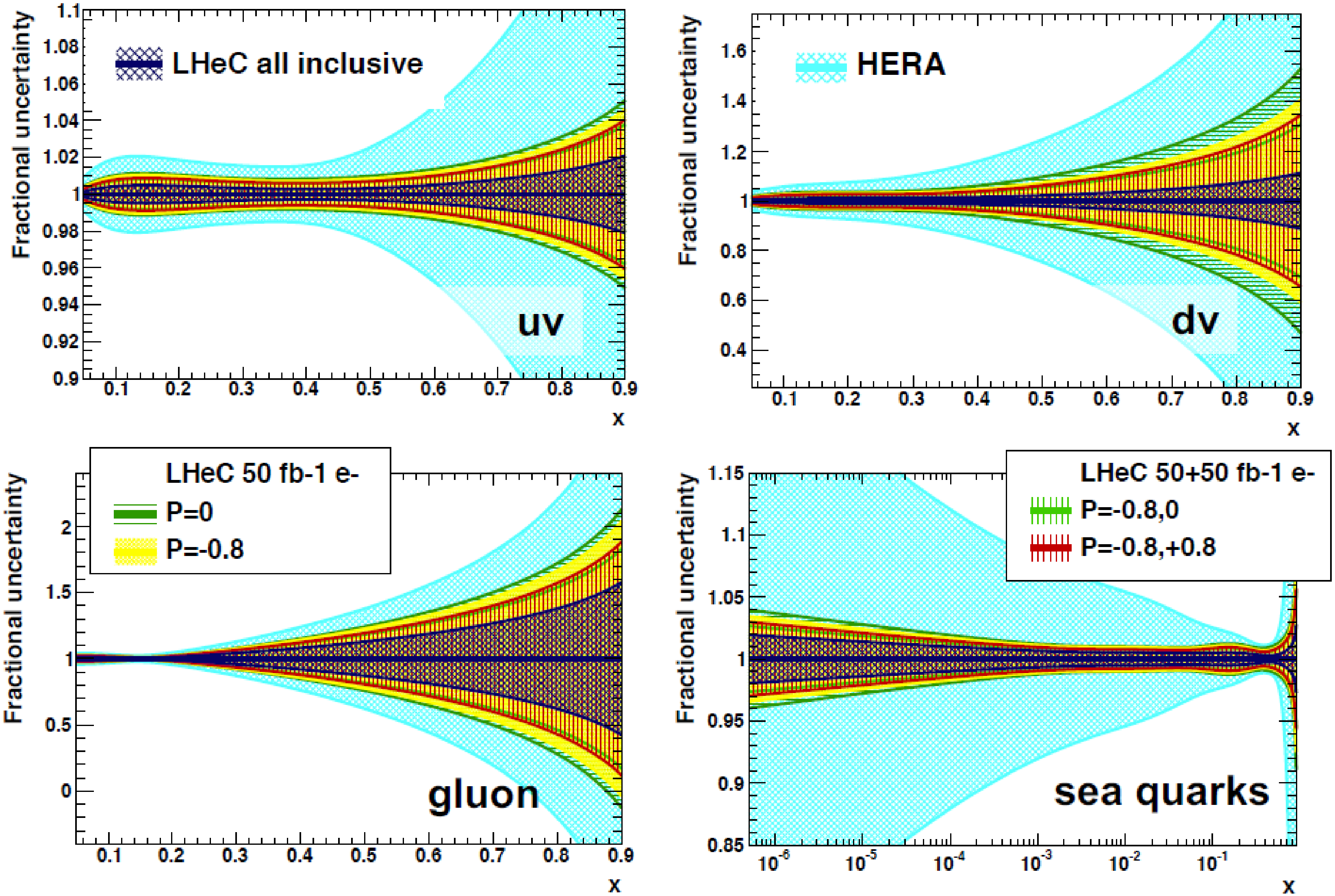


d/u essentially unknown at large x

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

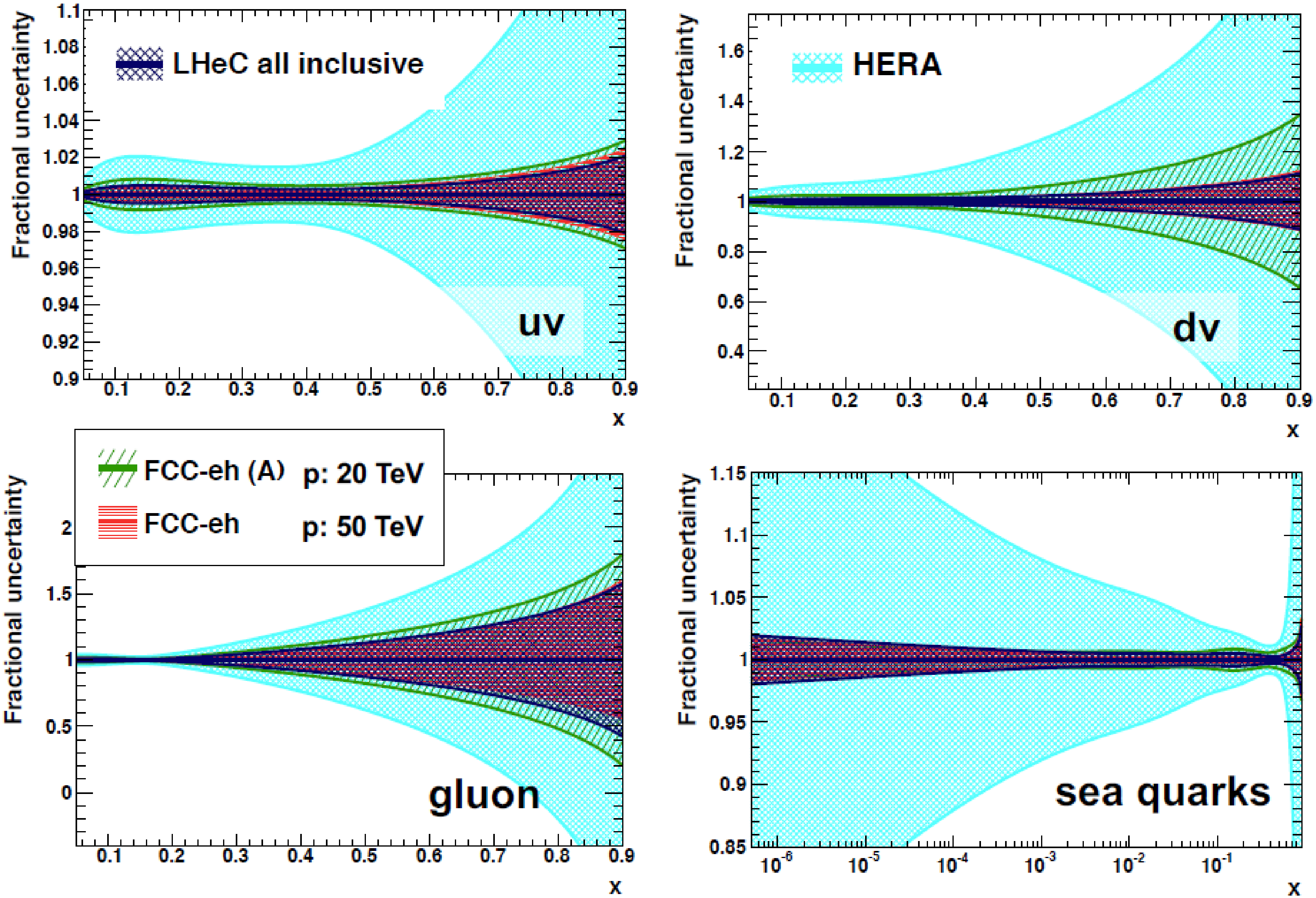
impact of polarisation on LHeC pdfs



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

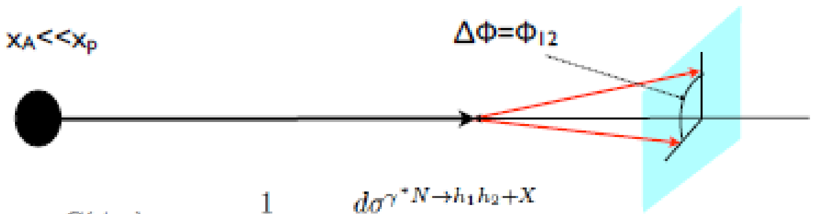


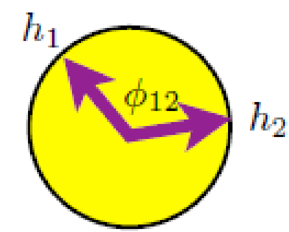
FCC-eh (A): new preliminary simulation with 2 ab^{-1} polarised e– (NO e+ yet; impact especially in d at large x)

Novel small x dynamics: exclusive observables

other key probes of saturation:

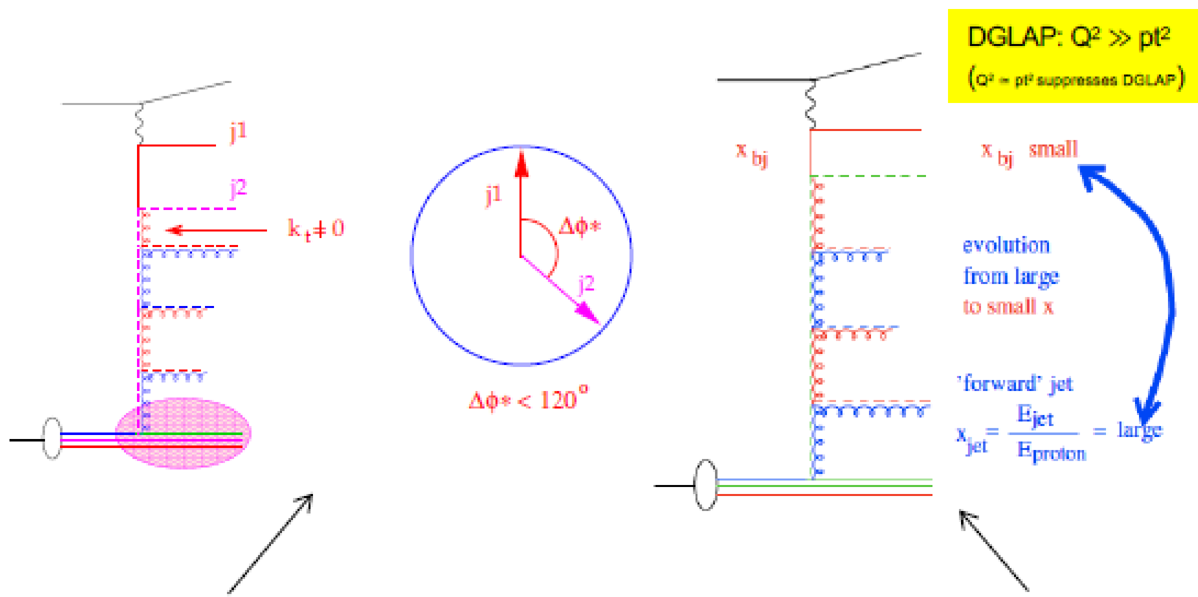
- **dihadron azimuthal decorrelation**
- currently discussed at RHIC as suggestive of saturation (see also **SMALL x** plenary, A. Dumitru, MON, 11:30)





$$C(\phi_{12}) = \frac{1}{\frac{d\sigma(\gamma^* N \to h_1 X)}{dz_{h1}}} \frac{d\sigma^{\gamma^* N \to h_1 h_2 + X}}{dz_{h1} dz_{h2} d\phi_{12}}$$

- **nuclear** and **saturation effects** on usual BFKL signals, EG. dijet azimuthal decorrelation, Mueller-Navelet jets
- **A dependence?**



if incoming gluon has sizeable kt, jets no longer back-to-back; must balance kt of incoming virtual gluon

measurements with large rapidity separations and different (Q,pt) combinations to systematically test parton dynamics