EUROPEAN PHYSICAL SOCIETY HEP2019

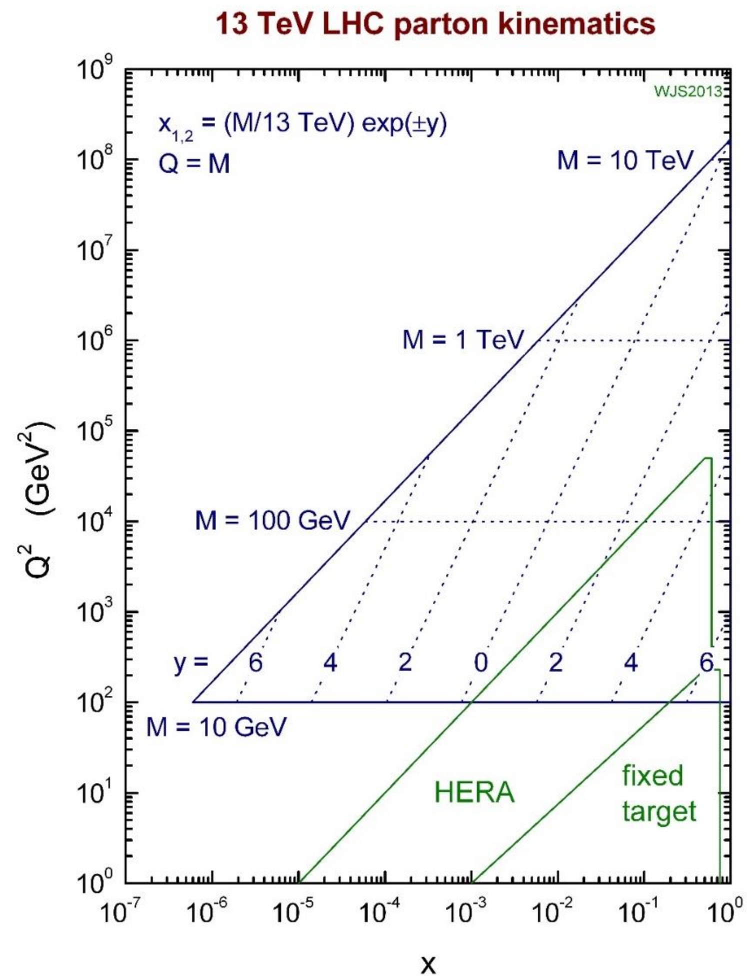
Precision QCD at the LHeC and FCC-eh

Amanda Cooper-Sarkar, Oxford

on behalf of the LHeC and FCC-eh WGs

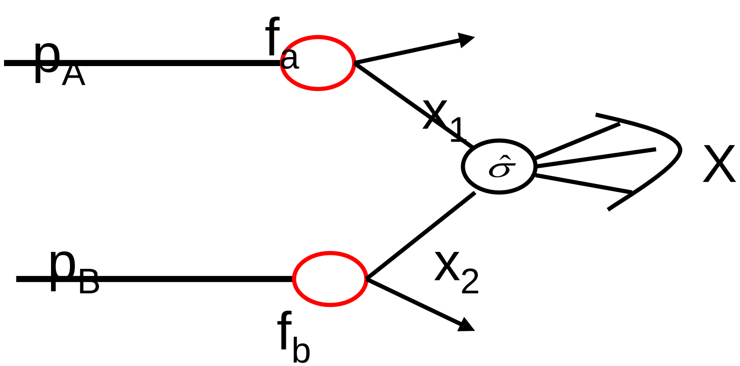
The Standard Model is not as well known as you might think

In the QCD sector the uncertainties on Parton Distribution Functions (PDFs) limit our knowledge of cross sections-



$$\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2\, f_a(x_1, \mu_F^2)\, f_b(x_2, \mu_F^2)$$
$$\times\ \hat{\sigma}_{ab\to X}\left(x_1, x_2, \{p_i^\mu\}; \alpha_S(\mu_R^2), \alpha(\mu_R^2), \frac{Q^2}{\mu_R^2}, \frac{Q^2}{\mu_F^2}\right)$$

where X=W, Z, D-Y, H, high-E_T jets, prompt-γ and σ is known to some fixed order in pQCD and EW or in some leading logarithm approximation (LL, NLL, …) to all orders via resummation

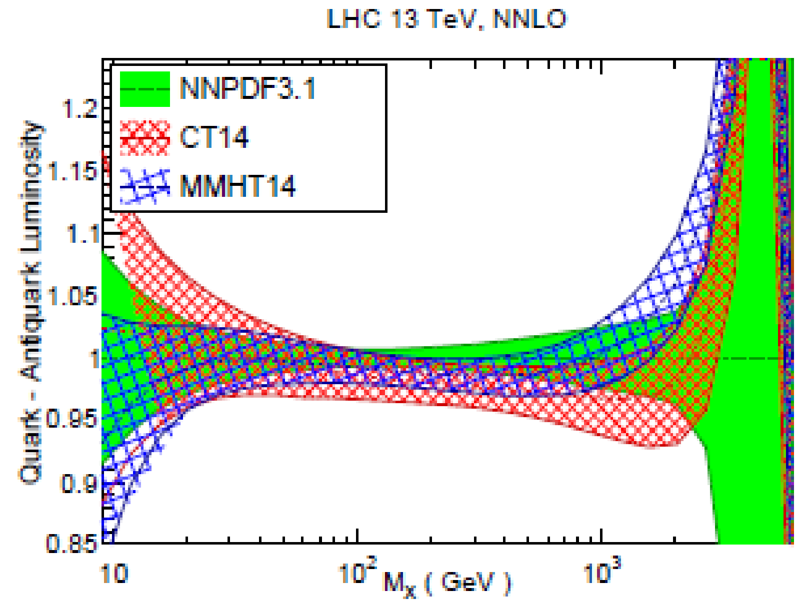


Our knowledge of PDFs in the LHC kinematic region mostly comes from evolving the results from HERA and other Deep Inelastic Scattering experiments in Q^2 using the QCD DGLAP formalism

How well do we know PDFs today ?

This is best evaluated in terms of parton-parton luminosities, which are the convolution of the purely partonic part of the sub-process cross-section.

The quark-antiquark and gluon-gluon luminosities for various PDFs are compared here for 13 TeV LHC running in terms of the centre of mass energy of the parton sub- process M_X

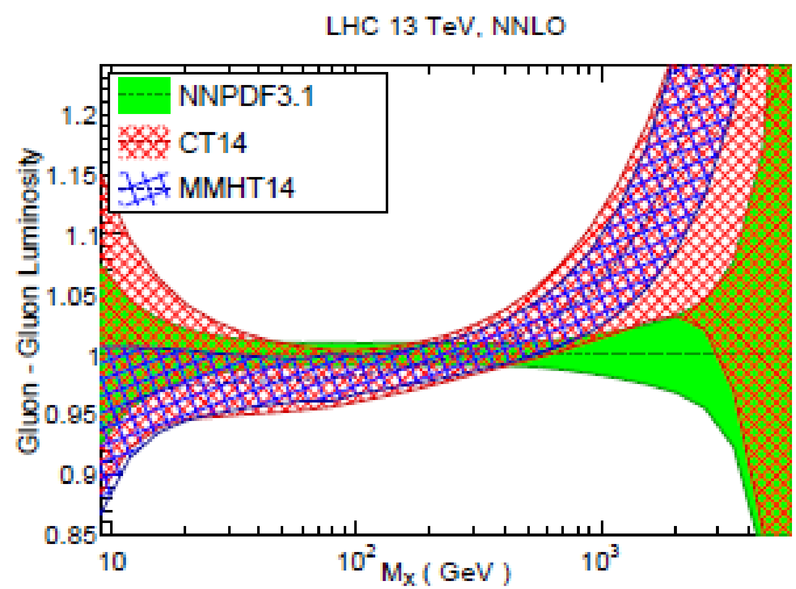


So for Drell-Yan production of W or Z at Mx ~80,90 GeV

Or for gluon-gluon production of Higgs at Mx~125 GeV

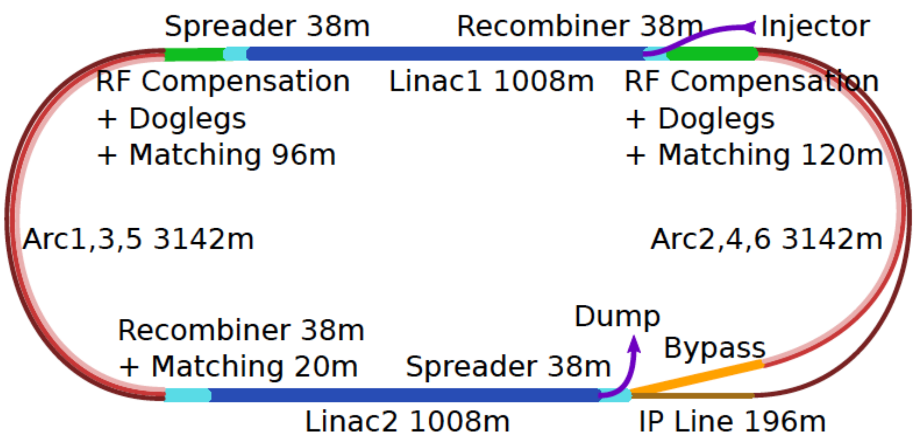
the parton-parton luminosities are fairly well known

$$\mathcal{L}_{ij}(M^2, s) = \int_\tau^1 \frac{dx}{x} x f_i(x, M^2) \frac{\tau}{x} f_j\left(\frac{\tau}{x}, M^2\right) \qquad \tau \equiv \frac{M^2}{s}$$



- This is not so for higher mass BSM particles where we need improved PDFs at high-x
- It is also not so for low-scales/ low-x where we may learn more about QCD in the non-linear regime
- We also need to know PDFs better in the regiosn where they are best known today in order to reduce the uncertainty on precision SM measurements like M_W and $\sin^2\theta_W$

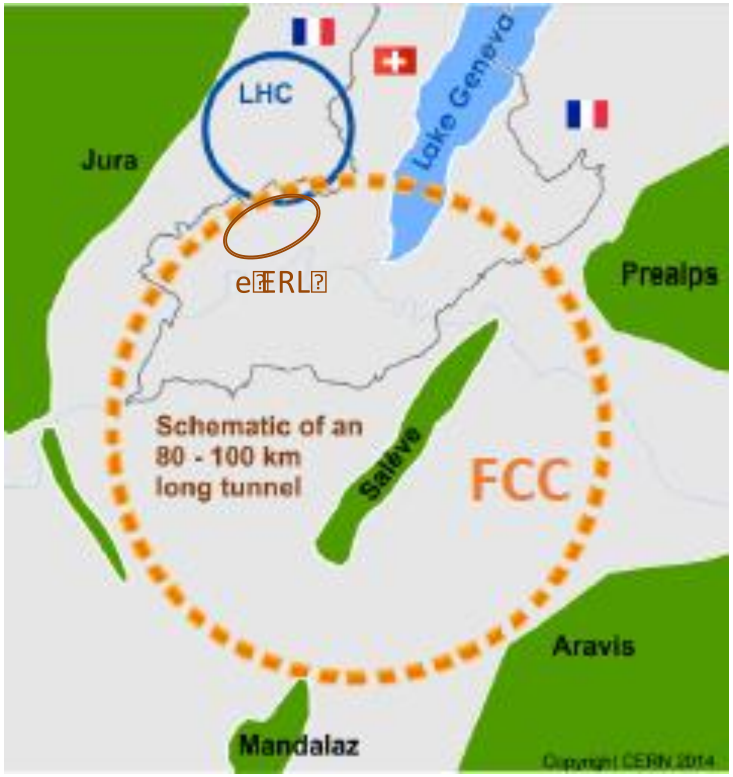
How could one improve knowledge?
LHeC and FCC-eh



energy recovery LINAC

e beam: up to 60 GeV

Lint ⟶ 1 ab^{-1} (1000× HERA ; per 10 yrs)



operating **synchronously** :

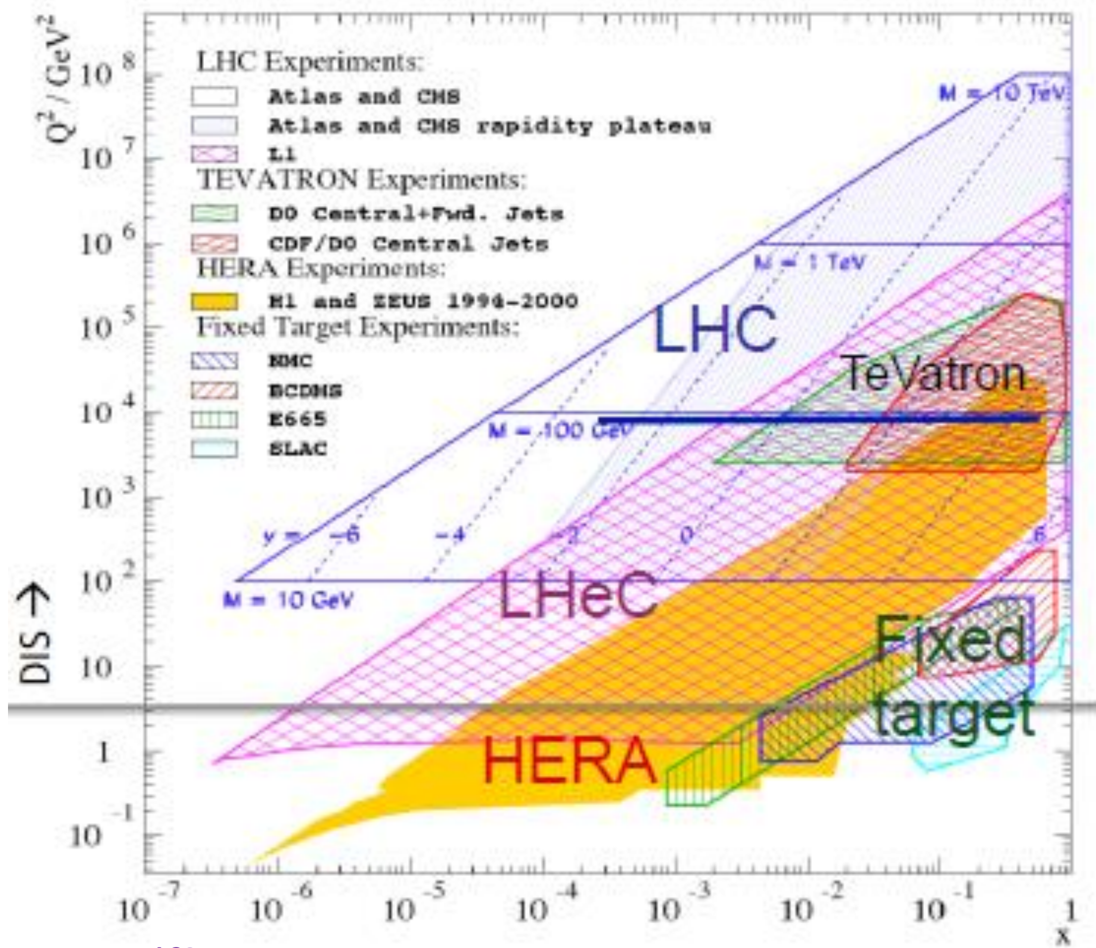
- with **HL-LHC** (or HE-LHC)
  p: 7 (14) **TeV, √s ≈ 1.3** (1.8) **TeV**
- and/or later with an **FCC** (A)
  p: 50 (20) **TeV, √s ≈ 3.5** (2.2) **TeV**

† **FCC (A):** a lower energy configuration that could operate earlier, in an FCC tunnel, using current magnet technology

Kinematic coverage

The LHeC option represents an increase in the kinematic reach of Deep Inelastic Scattering and an increase in the luminosity ~500 fold

- 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



But can't we get precision PDFs from the LHC itself?

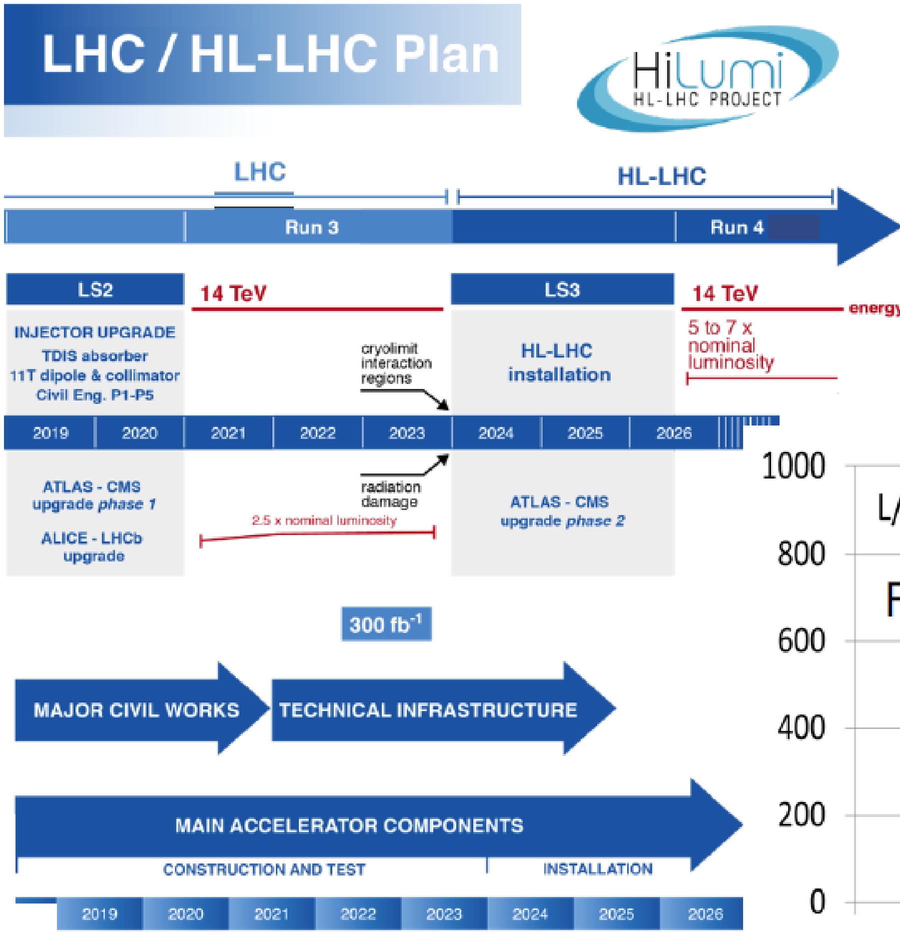
Future projections suggest we may get some way towards it.

But future projections live in an ideal world where many different types of data from the LHC have completely well understood systematics, well understood correlations and no inconsistencies.

The single consistent data set of deep inelastic scattering at an LHeC is a tried and tested reliable way to achieve this.

Plus there are questions of timing……

Timelines

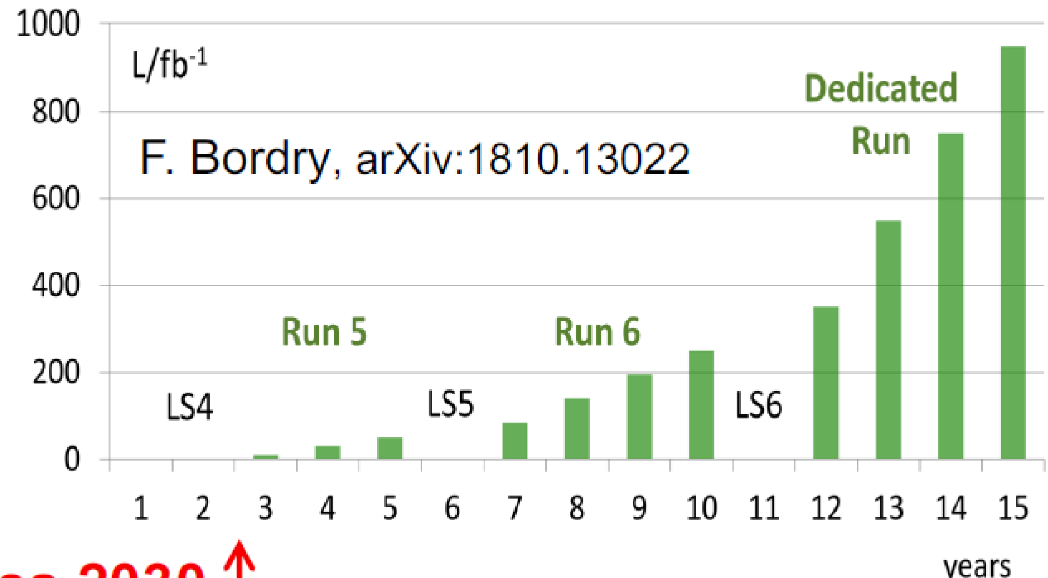


today

LHeC 1st run, Lint approx. 50 fb^{-1}

total Lint ⟶ 1 ab^{-1}

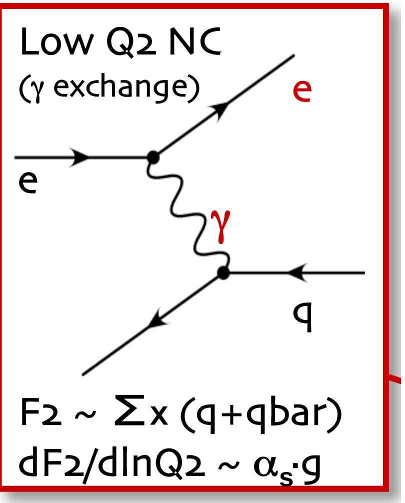
LHeC projected Integrated Luminosity:

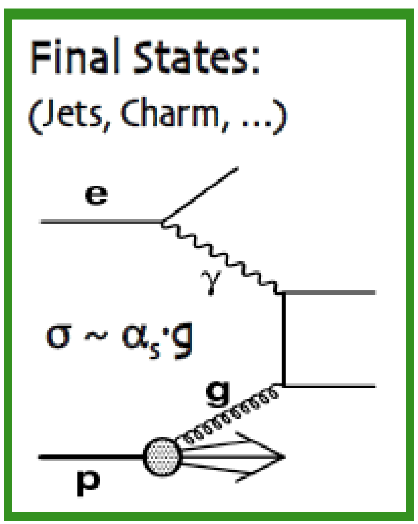


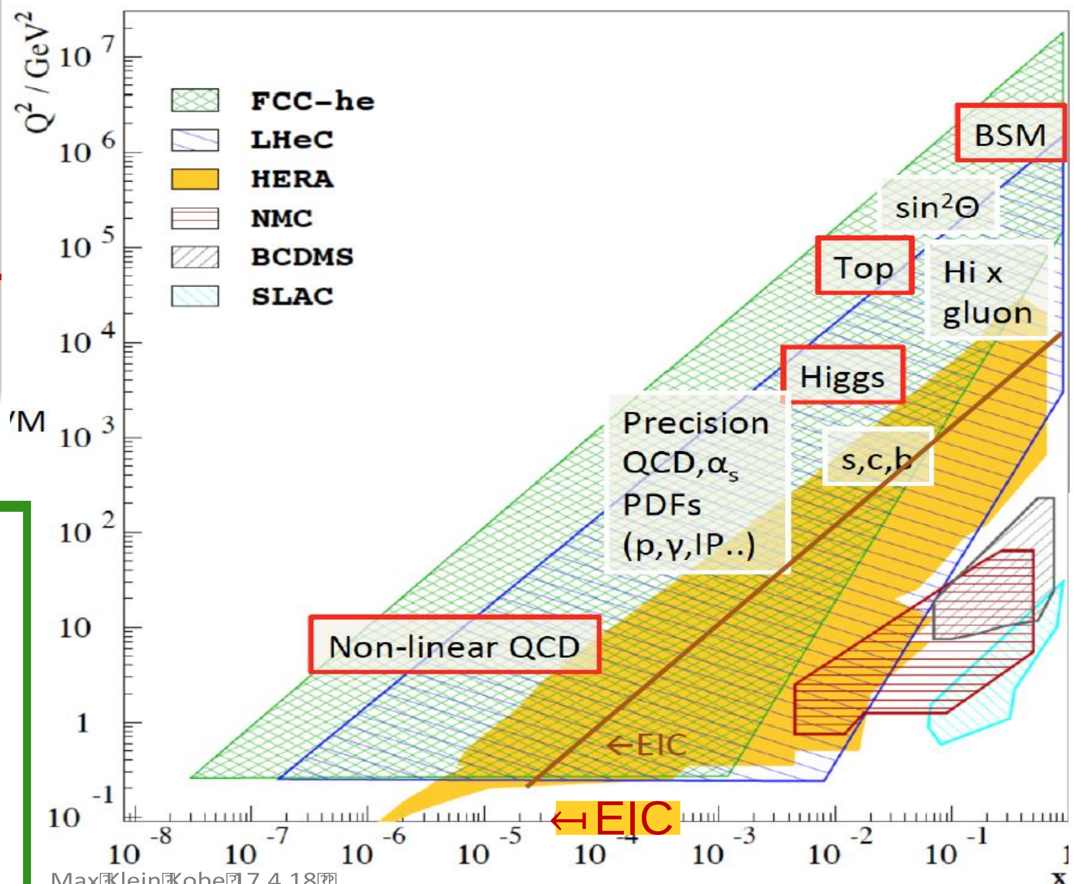
circa 2030

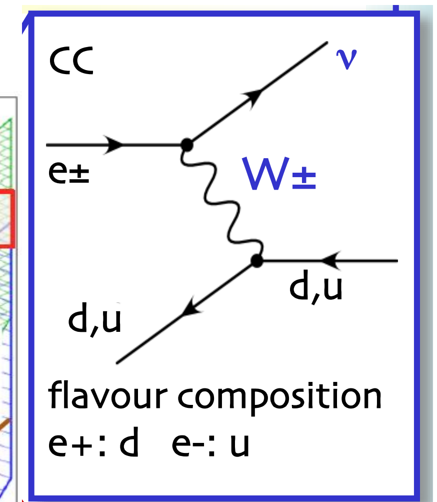
50 fb-1 can be achieved in 3years before LS5 and long before the end of HL-LHC running

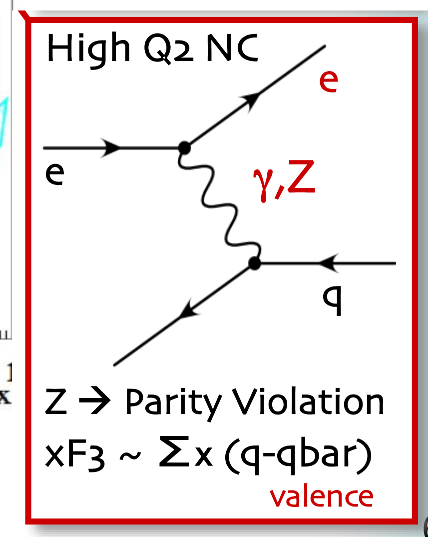
Where does the information come from?











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

LHeC pdf programme

simulation and pdf fit studies:
M. Klein,
C. Gwenlan

completely resolve all **proton pdfs**, and **α_s** to permille precision

→ **ubar, uv, dbar, dv, s, c, b, t, xg** and **α_s**

unprecedented kinematic range;
no higher twist, no nuclear corrs.,
free of symmetry assumptions,
N3LO theory possible, …

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

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**
NC/CC	–	+0.8	10,50	

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

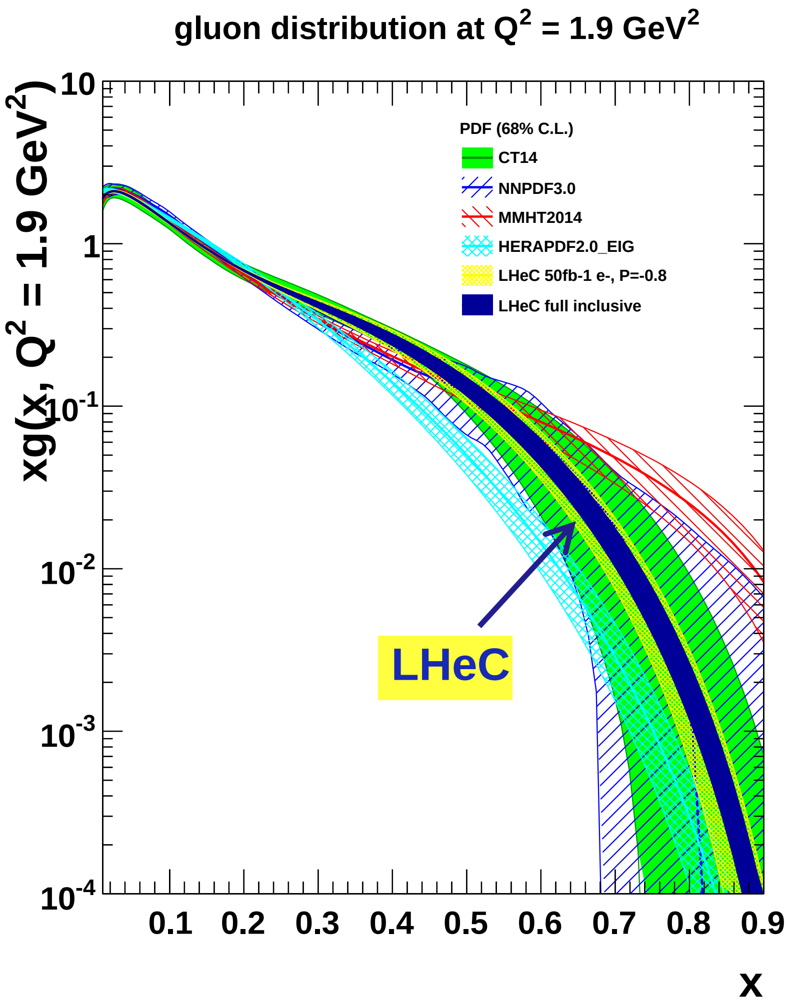
NB, I will frequently refer to the following:

LHeC 1st Run **(e-, 50 fb-1, P=-0.8)**

LHeC full inclusive **(e-, 1000 fb-1, P=-0.8) + (e-, 50 fb-1, P=+0.8) + (e+,10 fb-1)**

QCD analysis a la HERAPDF, BUT no constraint that dbar=ubar at small x;
4+1 xuv, xdv, xUbar, xDbar and **xg**

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);

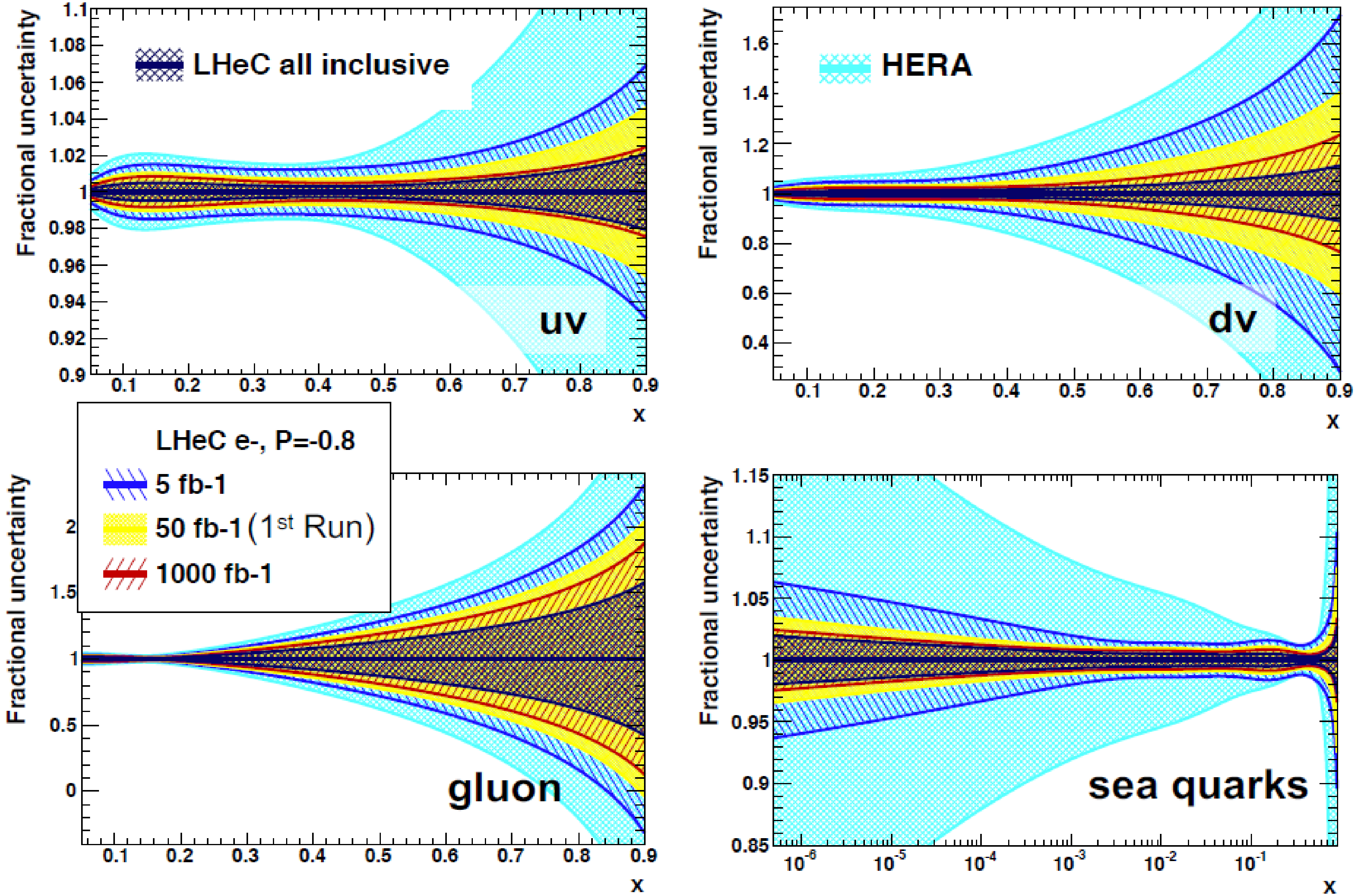
fully constrained quark pdfs; small x;

momentum sum rule

gluon and sea intimately related

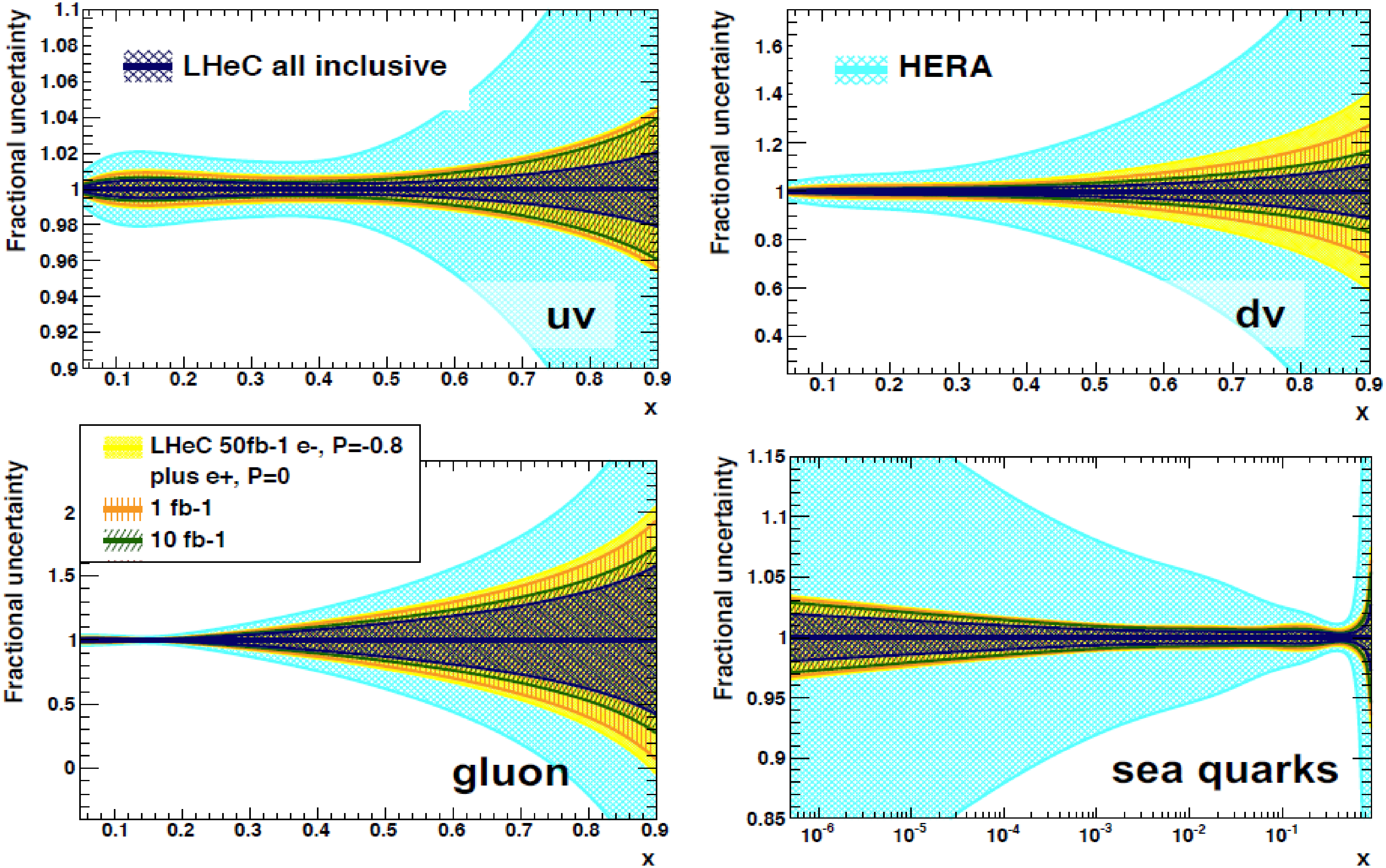
LHeC can disentangle sea from valence quarks at large x, with precision measurements of **CC** and **NC** $F2^{\gamma Z}$, $xF3^{\gamma Z}$

Impact of luminosity on PDFs



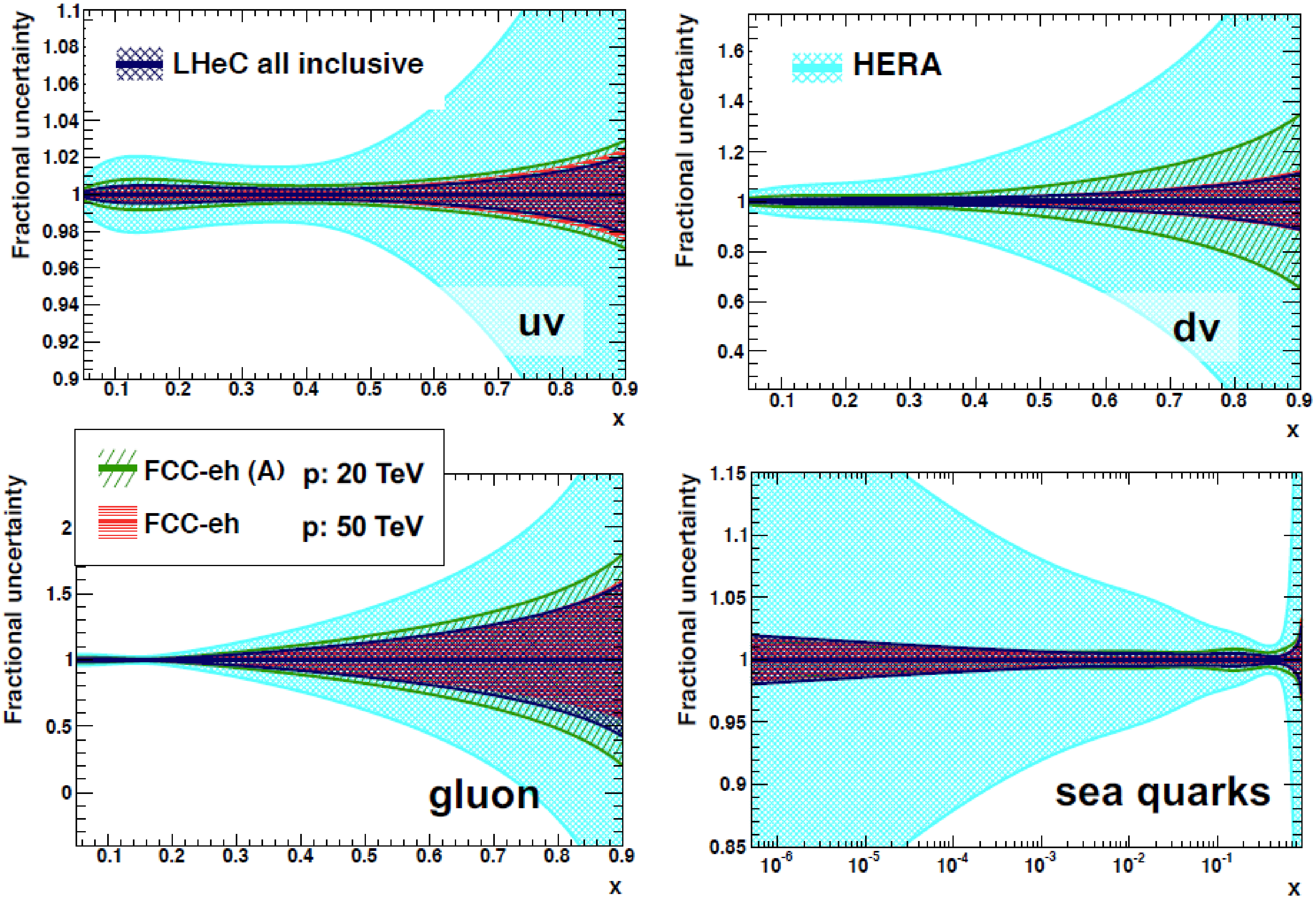
small and **medium x** quickly constrained (5 fb-1 ≡ ×5 HERA ≡ 1 year LHeC)

Impact of positrons on PDFs



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

Collider configurations



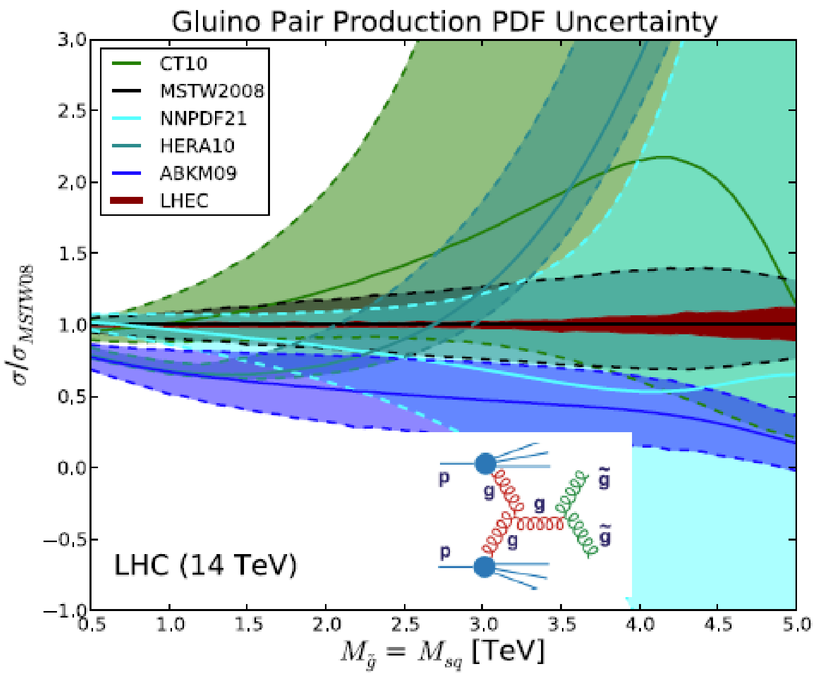
FCC-eh (A): new preliminary simulation with 2 ab^{-1} polarised e– (NO e+ yet; impact especially in d at large x)

And why do we want to improve high-x gluon and quarks?

external, reliable **pdfs** needed for range extension and interpretation

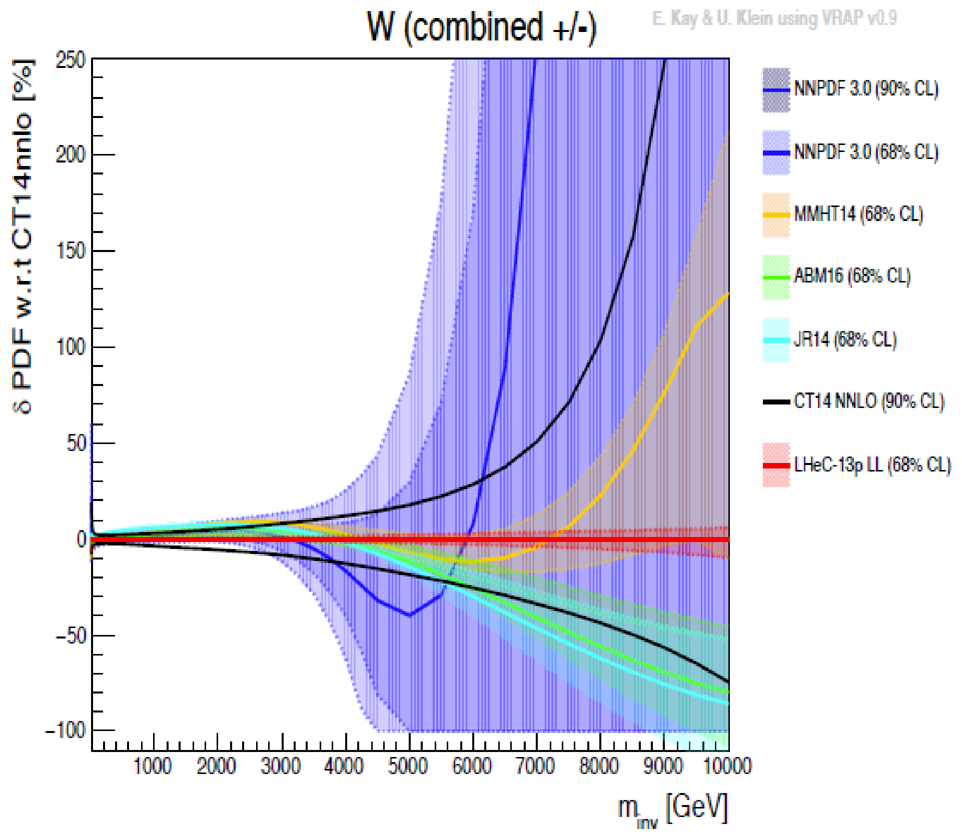
gluons

SUSY (RPC, RPV), LQs, …

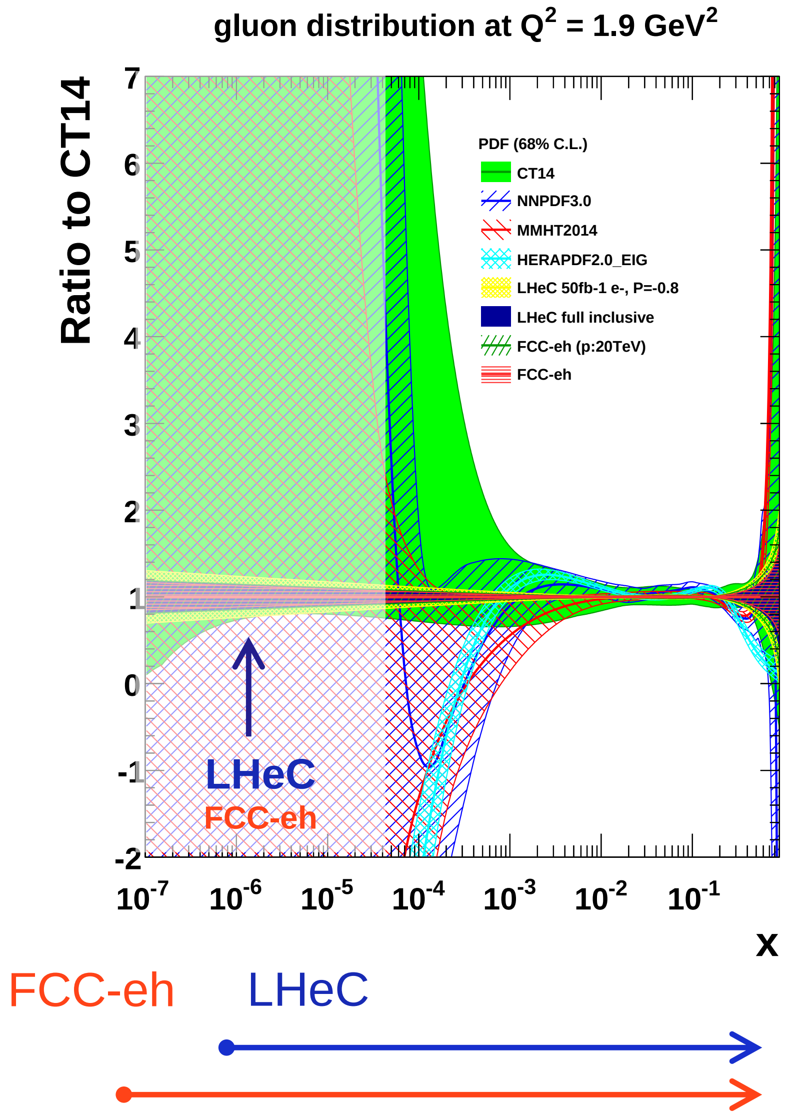


quarks

exotic and extra boson searches at high mass



Gluon at small x



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

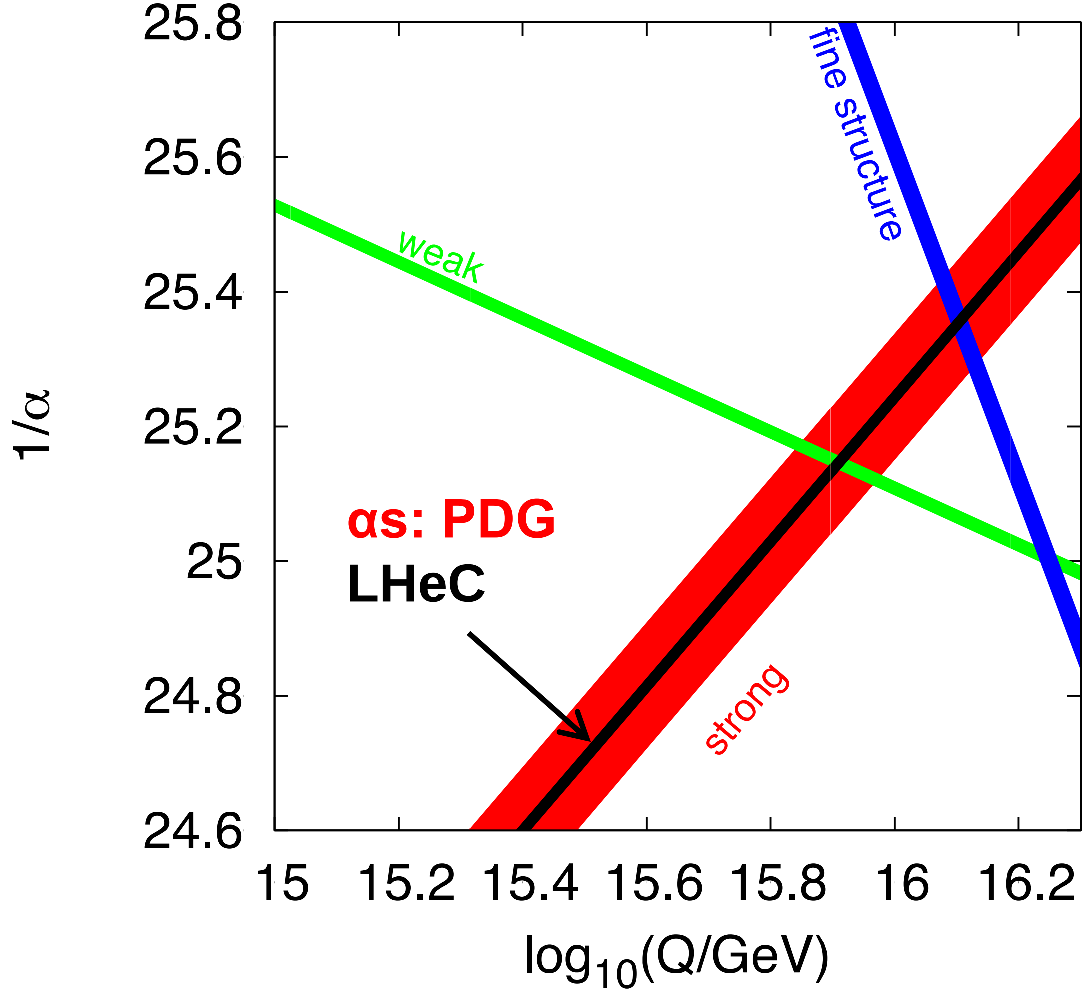
LHeC provides single, precise and unambiguous dataset down to $x=10^{-6}$

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

strong coupling, α_s (MZ)



arXiv:1206.2913,1211.5102, **new studies underway**

α_s is least known coupling constant

PDG2018:
α_s = 0.1174 ± 0.0016
(w/o lattice QCD, 1.5% uncertainty)

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**

Summary

Precision determination of quark and gluon structure of proton and α_s
of fundamental importance for future hadron collider physics programme (Higgs, BSM, …)

Deep inelastic scattering e-p colliders essential for full exploitation

External precision pdf input; complete q,g unfolding, high luminosity x ⟶ 1, s, c, b, (t); N3LO; small x; strong coupling to permille precision; …

NEW pdf studies presented (all work in progress)

All critical pdf information can be obtained early with LHeC (~50 fb-1 ≡×50 HERA), in parallel with HL-LHC operation

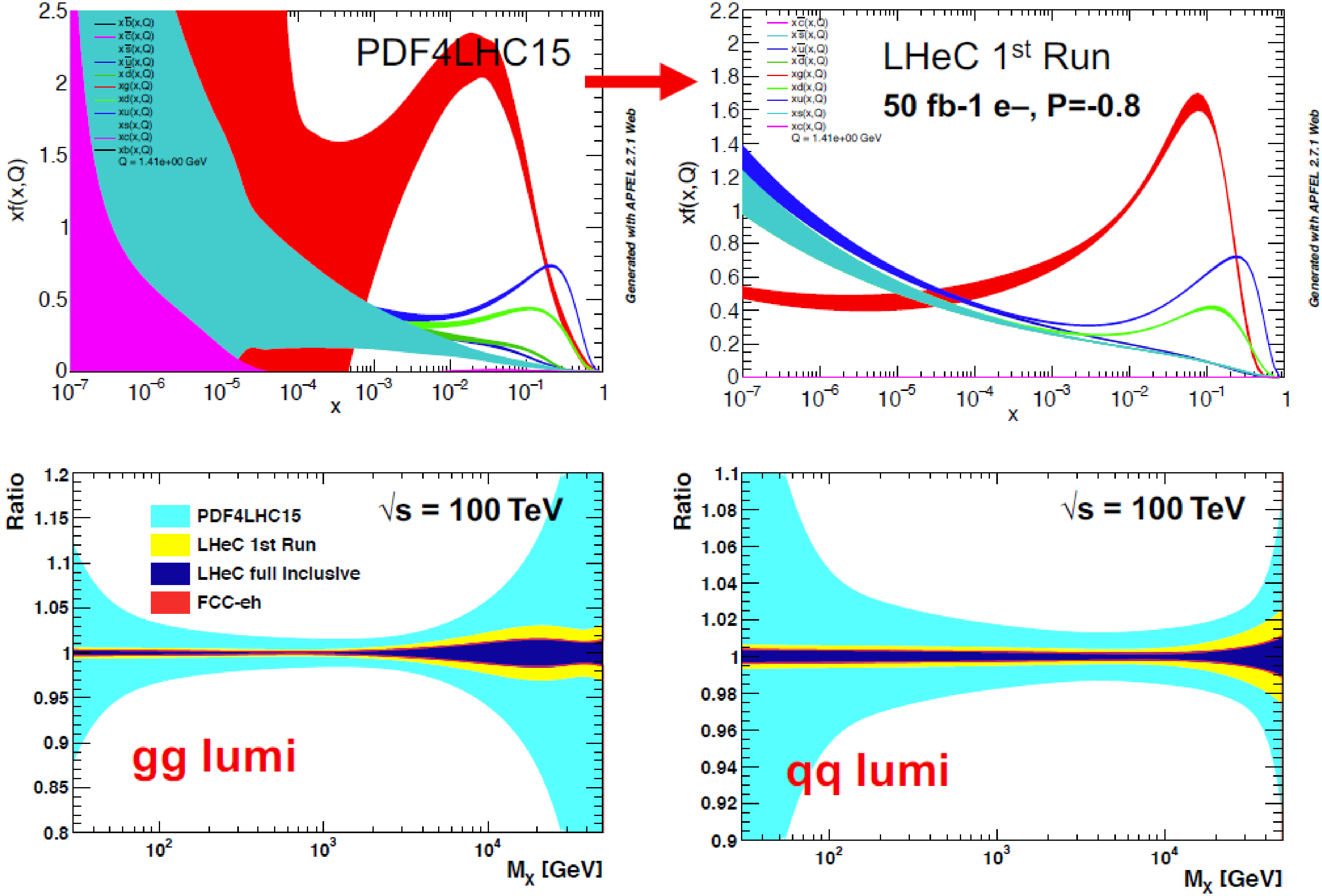
studies for potential new collider configurations underway

LHeC, PERLE and FCC documents submitted to european strategy update

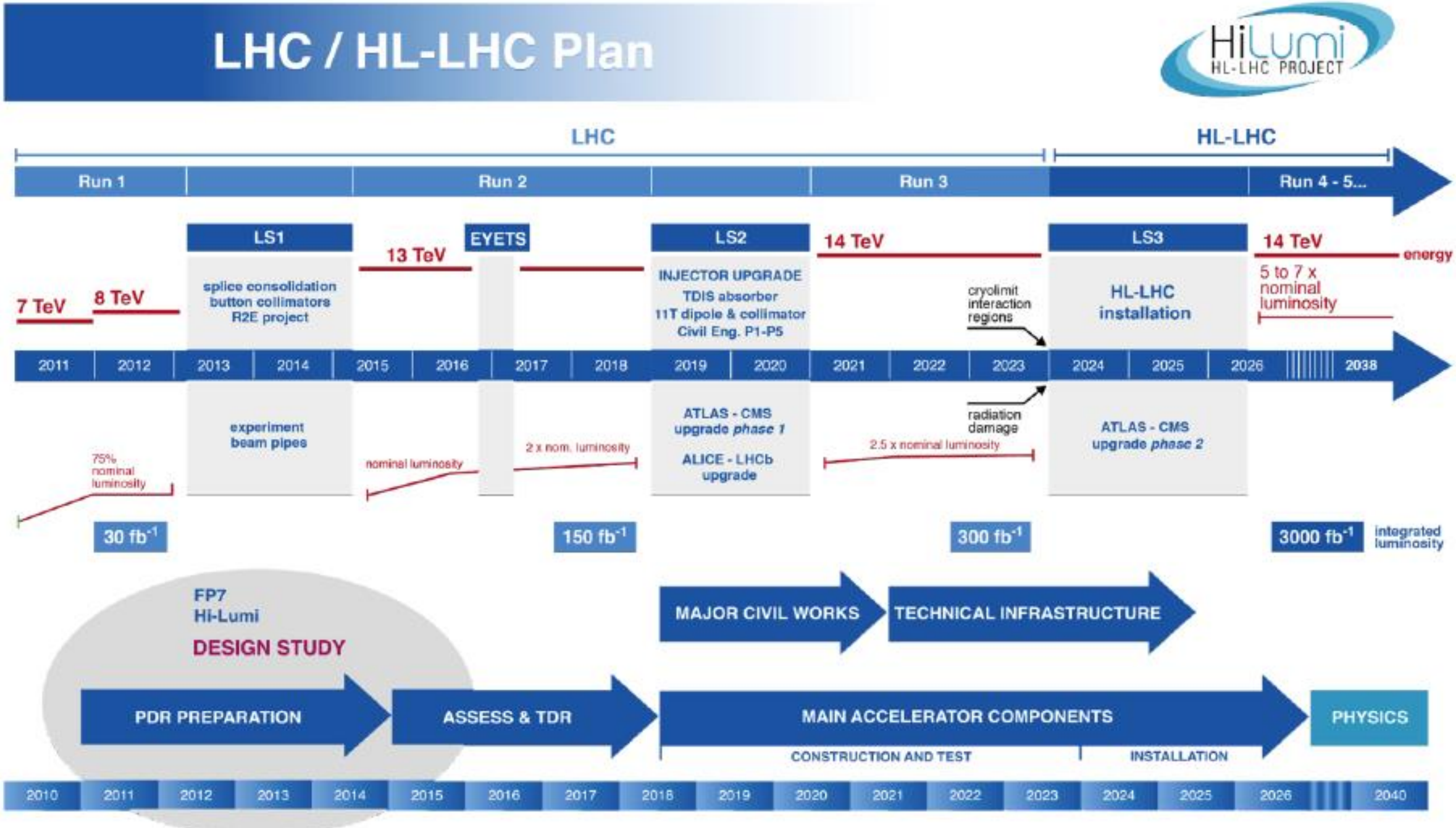
Next steps: ongoing parallel and complementary studies EG. arXiv:1906.10127; major new summary paper later this year; workshop in the autumn, 24 – 25 Oct 2019

extras

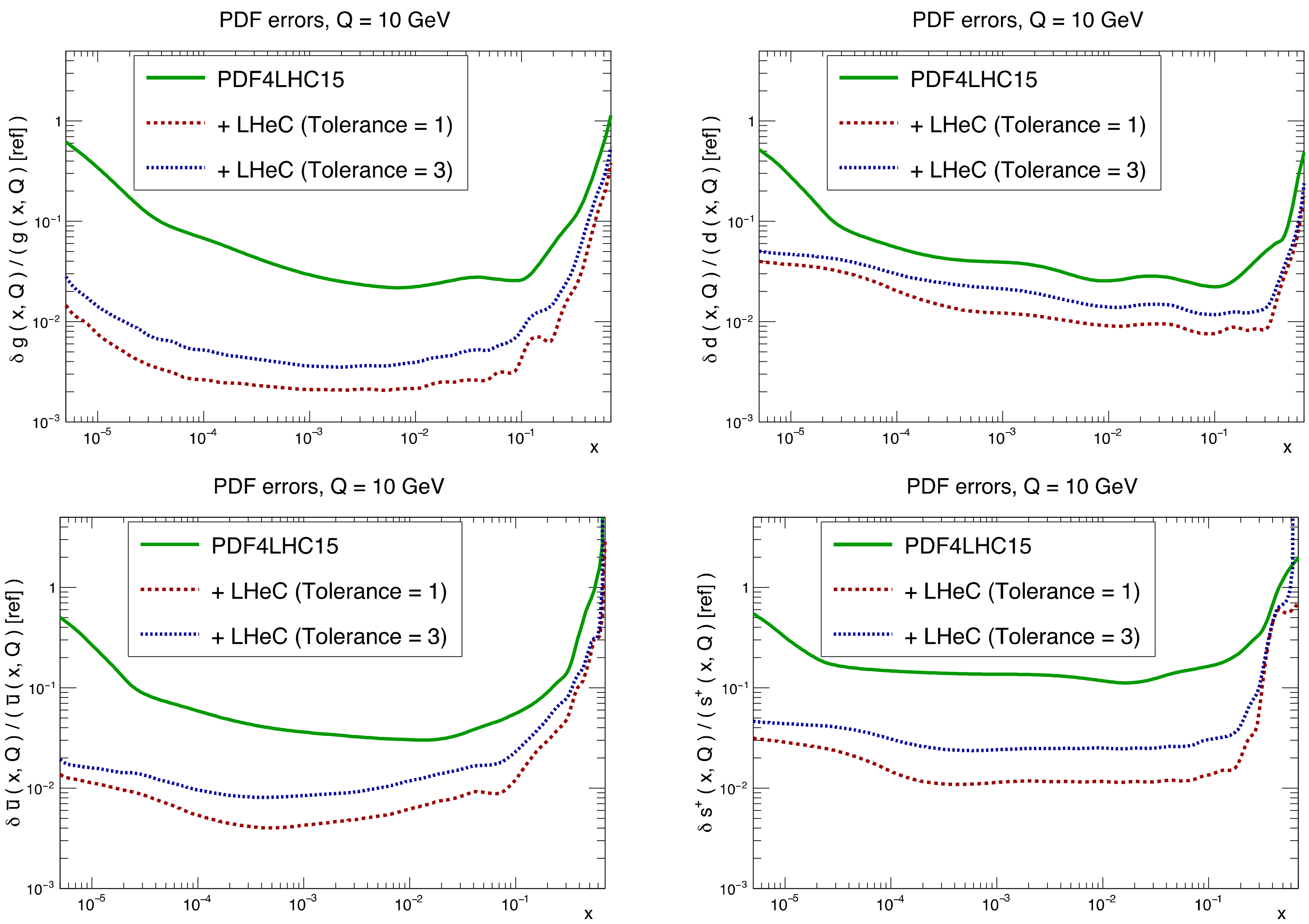
summary of pdfs



LHC / HL-LHC Plan

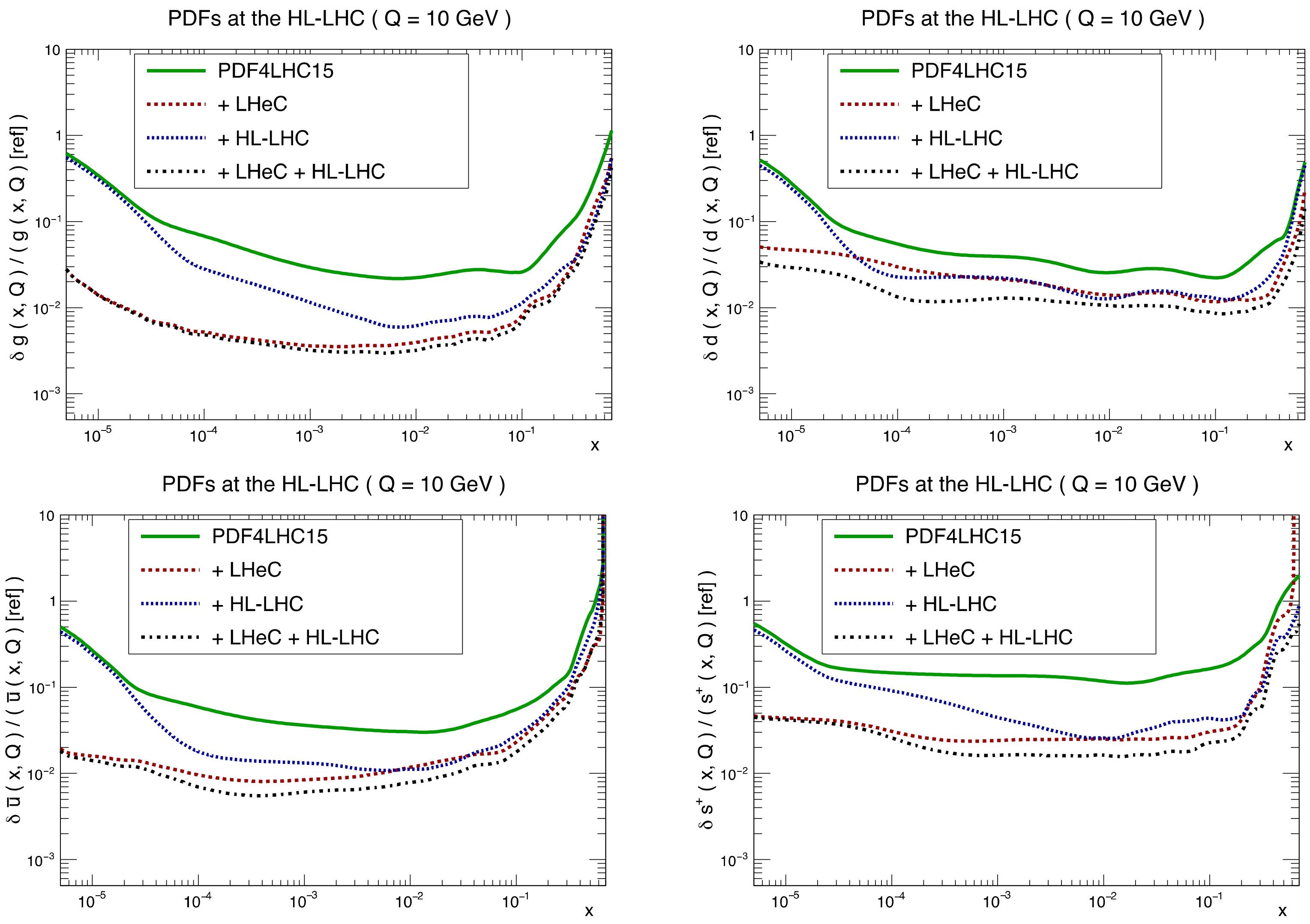


arXiv:1906.10127



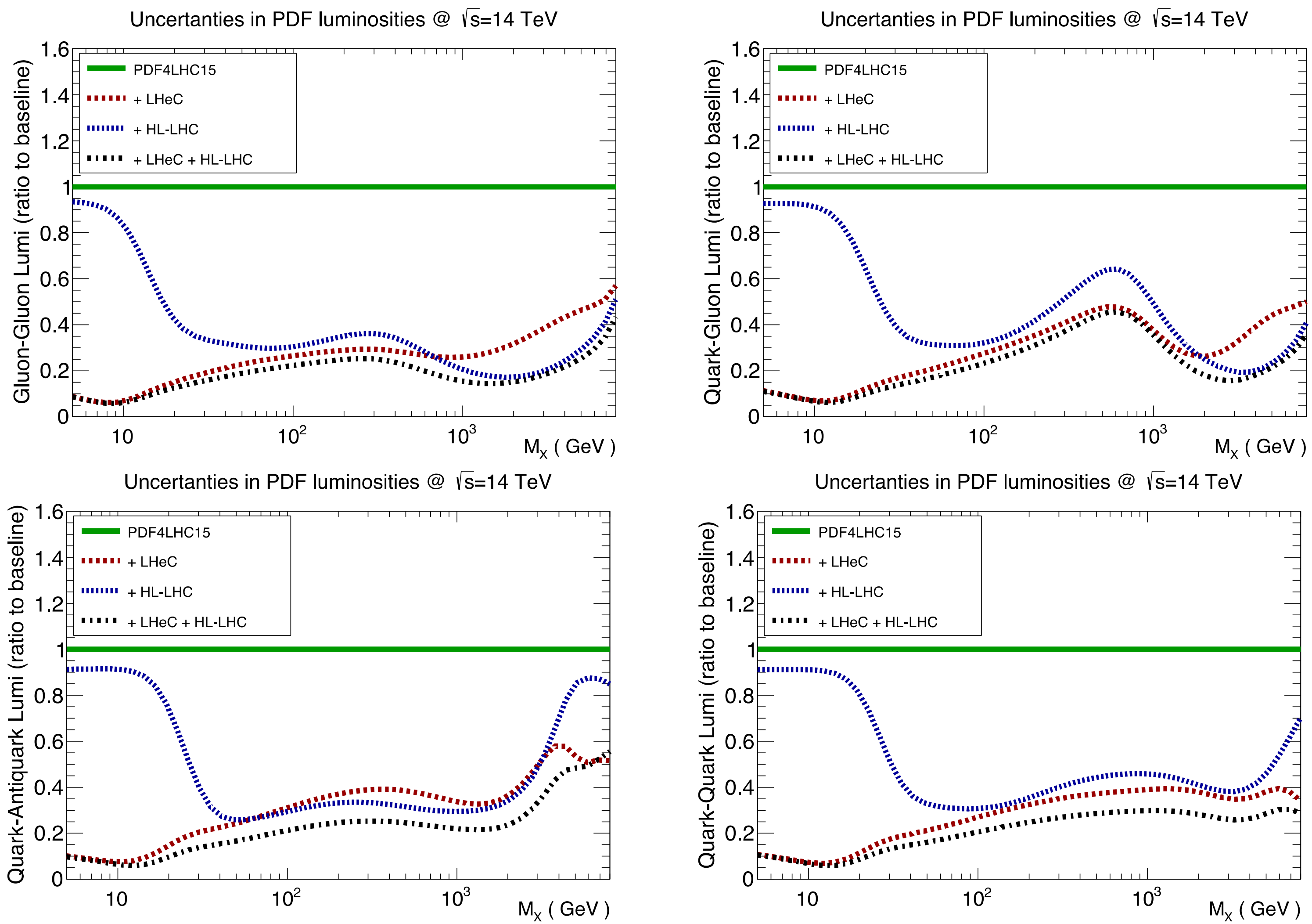
PDF4LHC15 profiled with (previous iteration of) LHeC inclusive+HQ simulated data

arXiv:1810.03639 + 1906.10127



PDF4LHC15 profiled with LHeC inclusive+HQ and HL-LHC simulated data

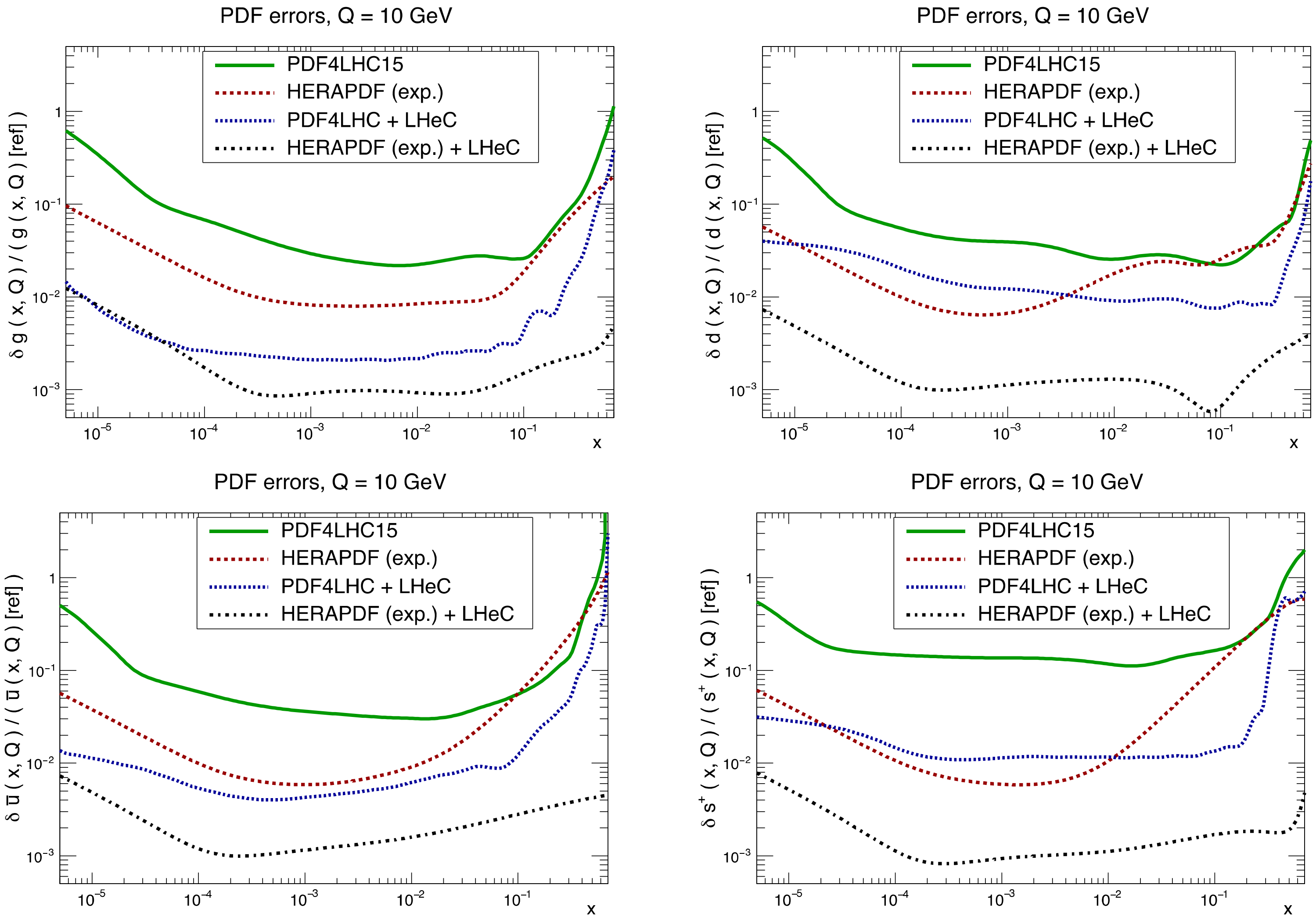
arXiv:1810.03639 + 1906.10127



PDF4LHC15 profiled with LHeC inclusive+HQ and HL-LHC simulated data

arXiv:1906.10127

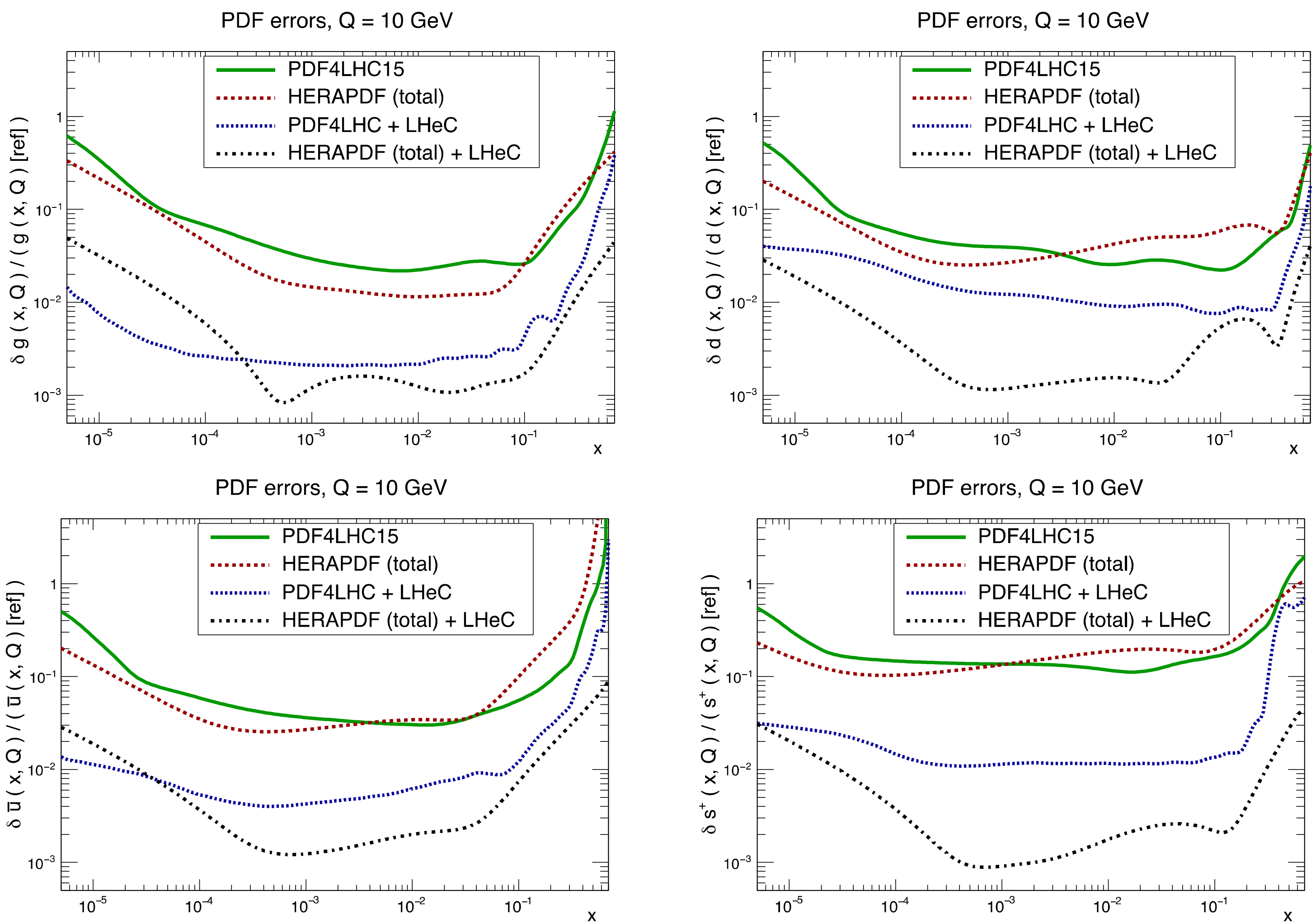
T=1



PDF4LHC15 and HERAPDF profiled with LHeC inclusive+HQ simulated data

arXiv:1906.10127

T=1



PDF4LHC15 and HERAPDF (total uncerts) profiled with LHeC inclusive+HQ simulated data

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

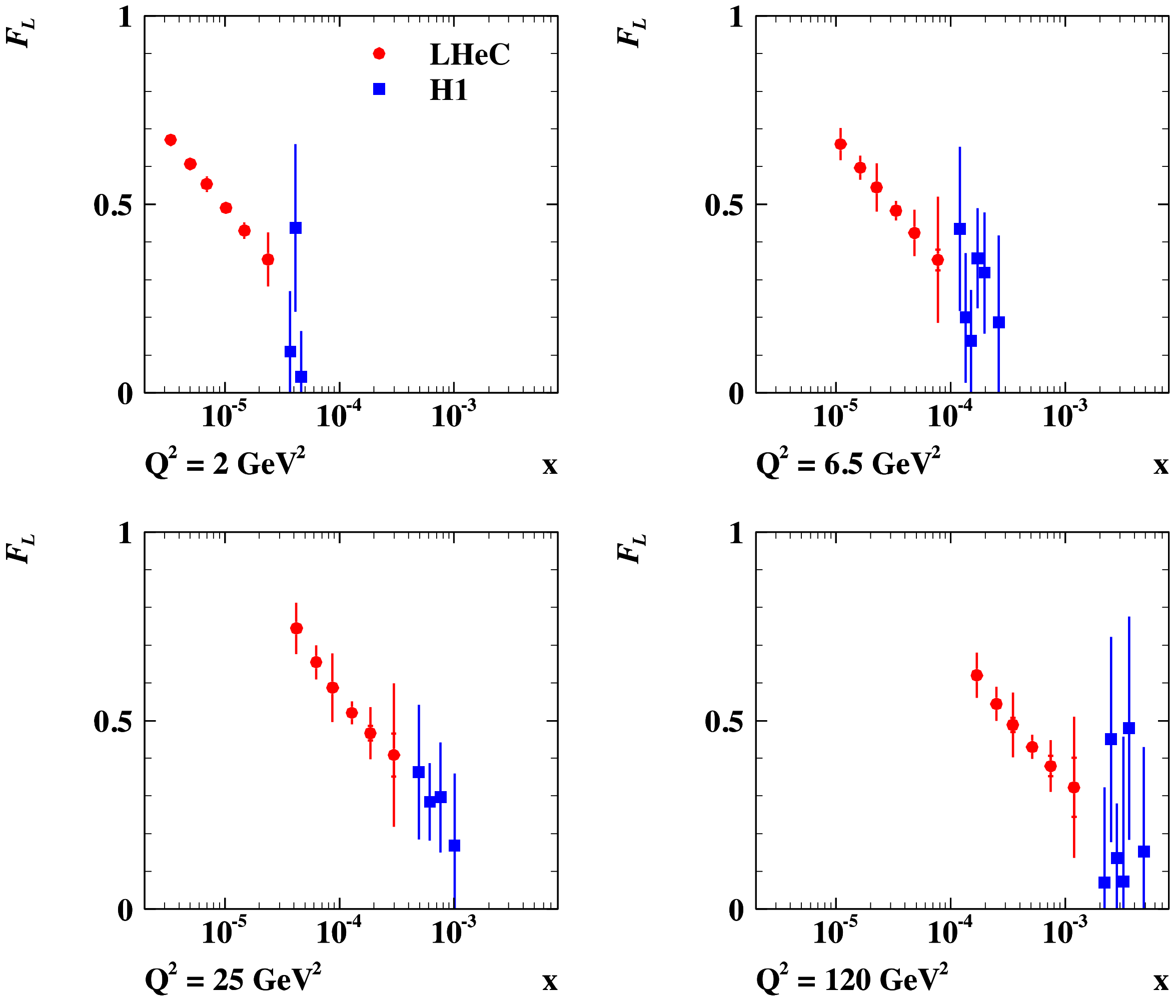
no negative gluon term (simply for the aesthetics of ratio plots – it has been checked that this does not impact size of projected uncertainties)

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

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

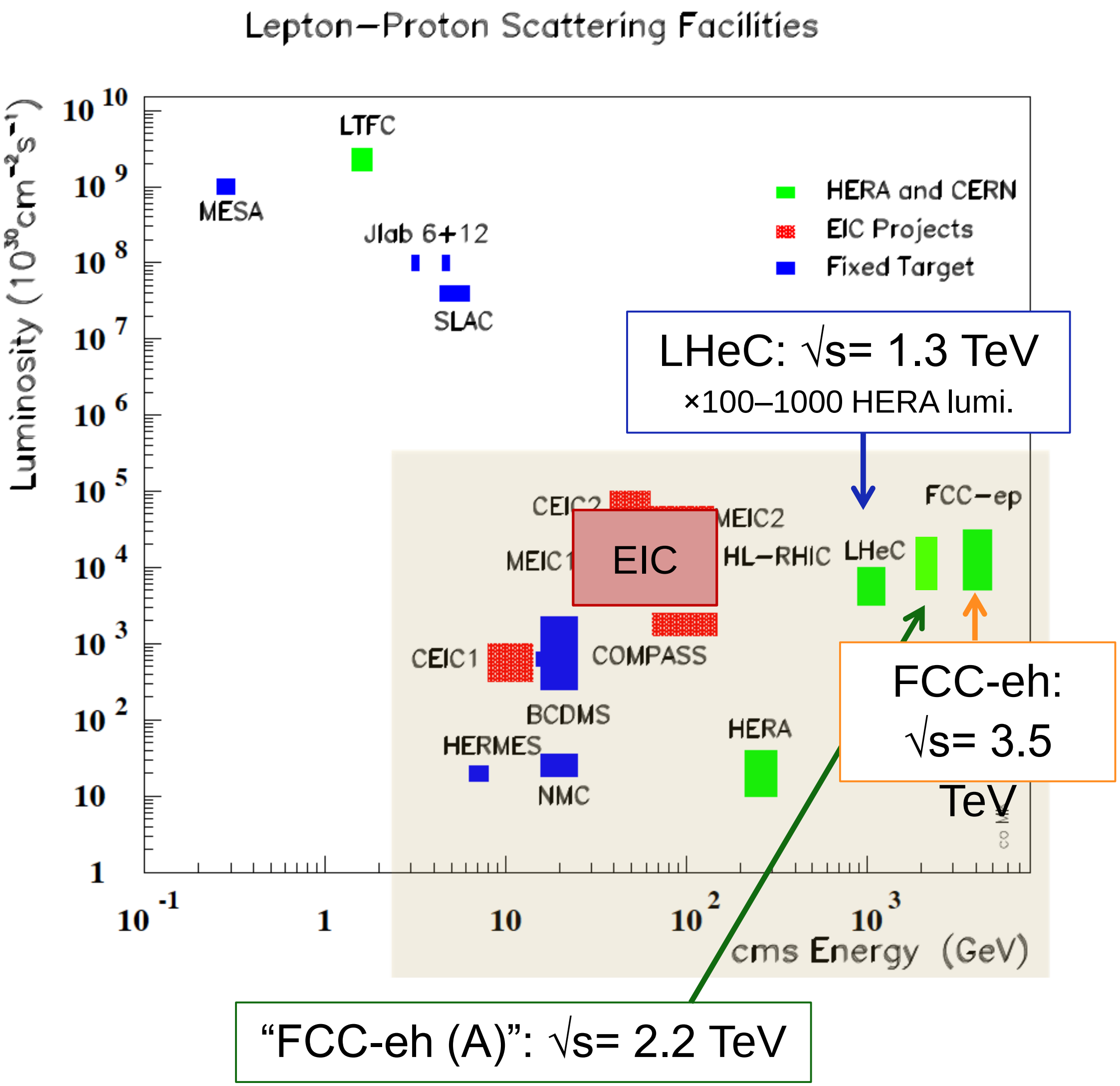
5+1 pdf fit for HQ studies parameterises dbar and sbar separately, and has 17 free parameters

FL at LHeC



M. Klein, arXiv:1802.04317

ep colliders

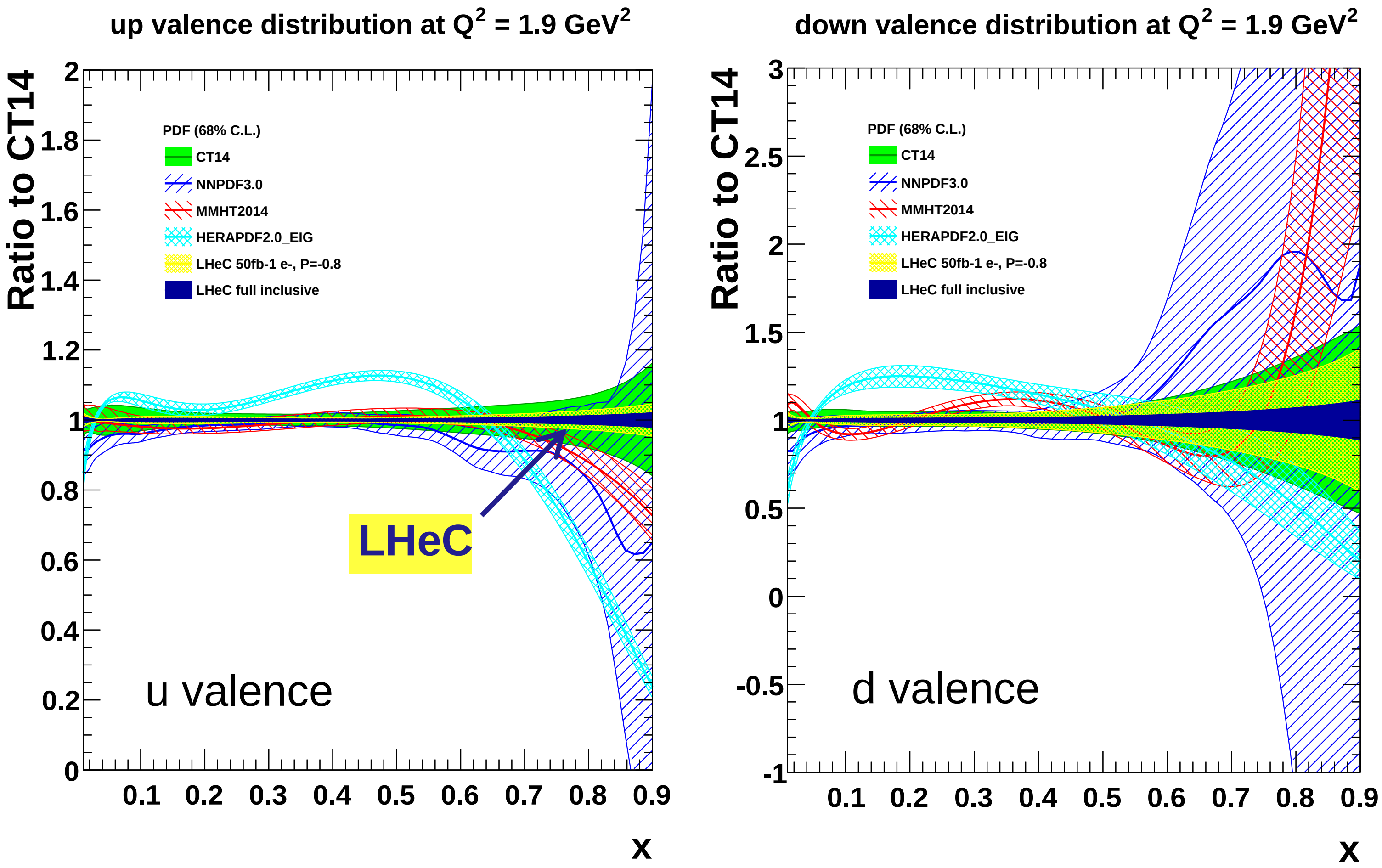


HERA: world's first and still only **ep** collider (√s ≃ 300 GeV)

LHeC: future **ep** (eA) collider, proposed to run concurrently with HL/HE-LHC; CDR arXiv:1206.2913 (complementary to LHC; extra discovery channels; Higgs; precision pdfs and **α**s)

FCC-eh: further future **ep** (eA) collider, integrated with FCC; CDR, volume 1, EPJ C79 (2019) no.6, 474 (further kinematic extension wrt **LHeC**)

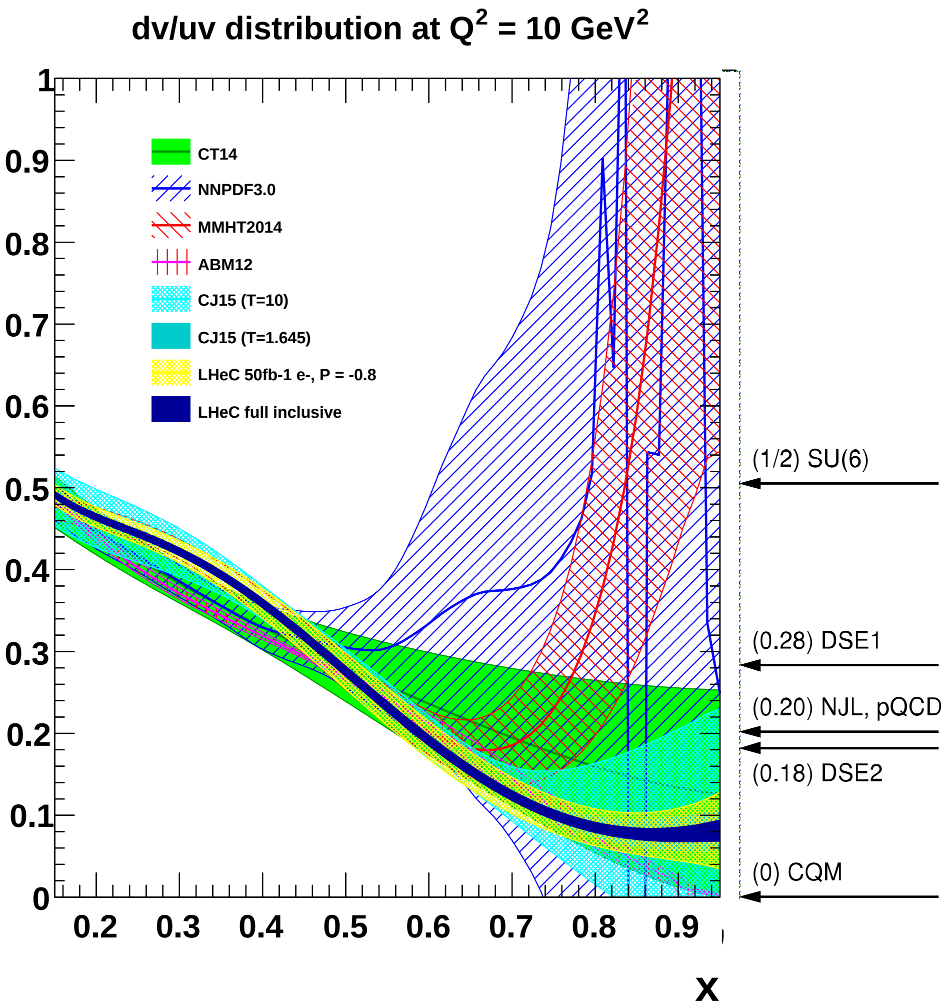
valence quarks from LHeC



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



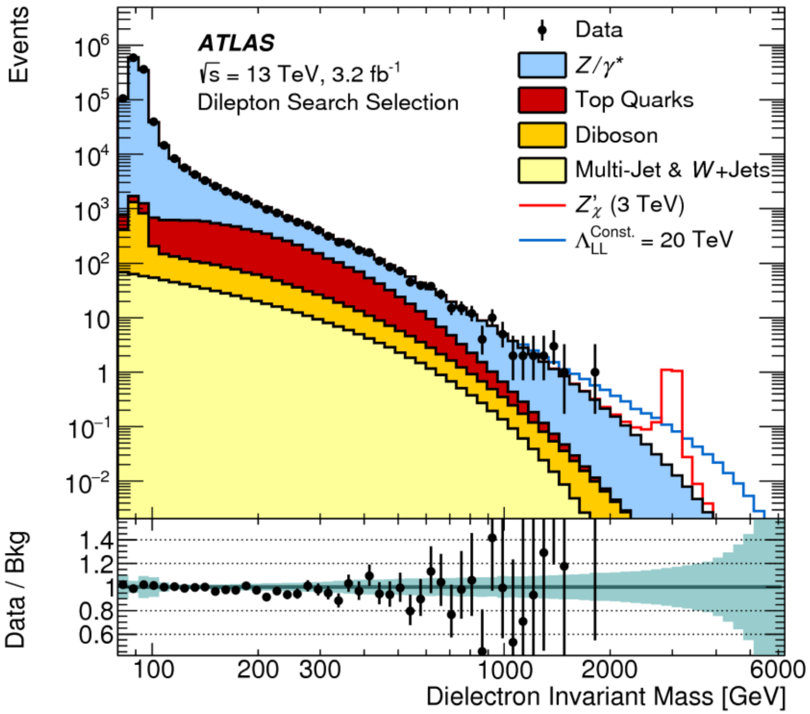
d/u essentially unknown at large x

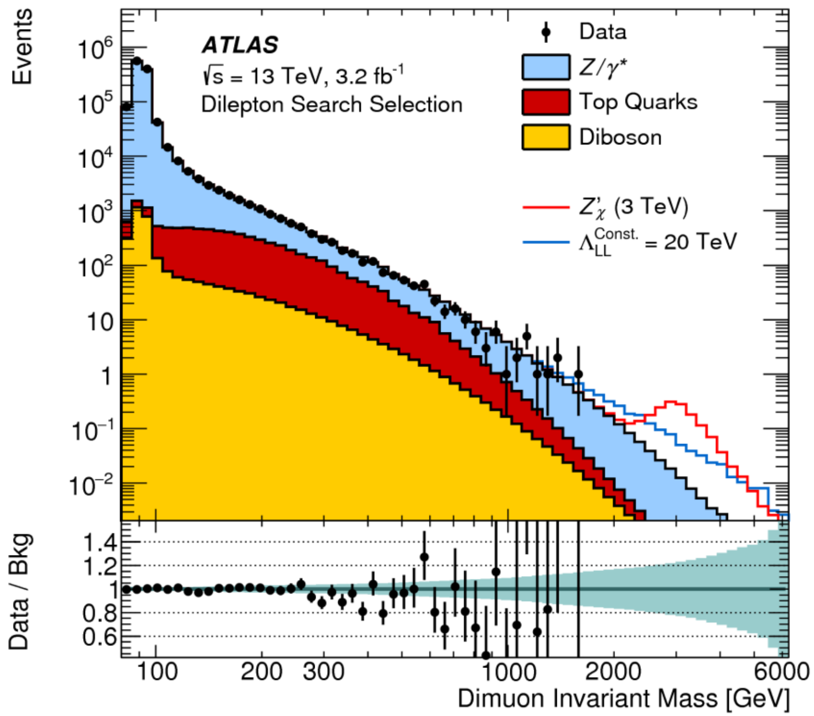
no predictive power from current pdfs;
conflicting theory pictures;
data inconclusive, large nuclear uncerts.

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

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

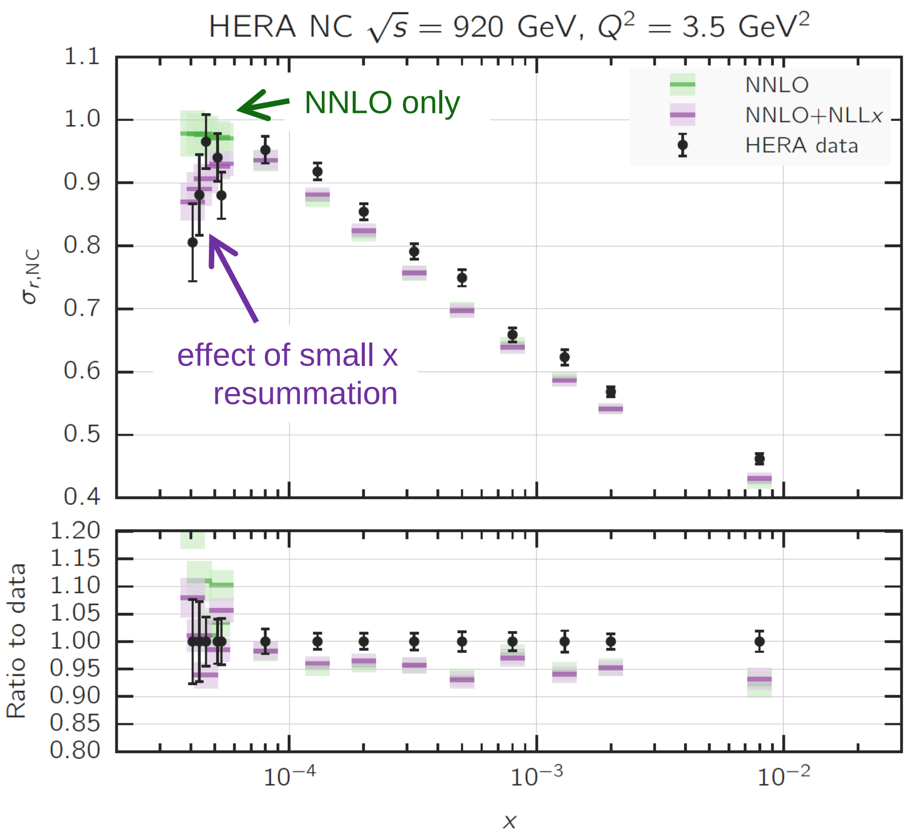
Current BSM searches in High Mass Drell-Yan are limited by high-x antiquark uncertainties as well as by high-x valence uncertainties

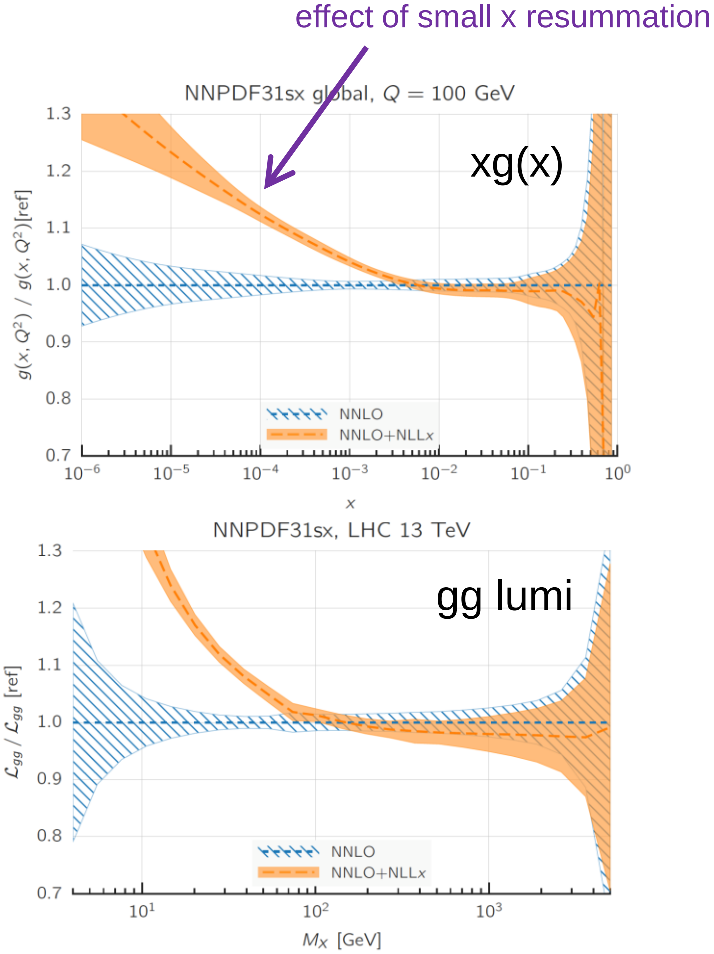




gluon at small x

R. Ball et al, arXiv:1710.05935

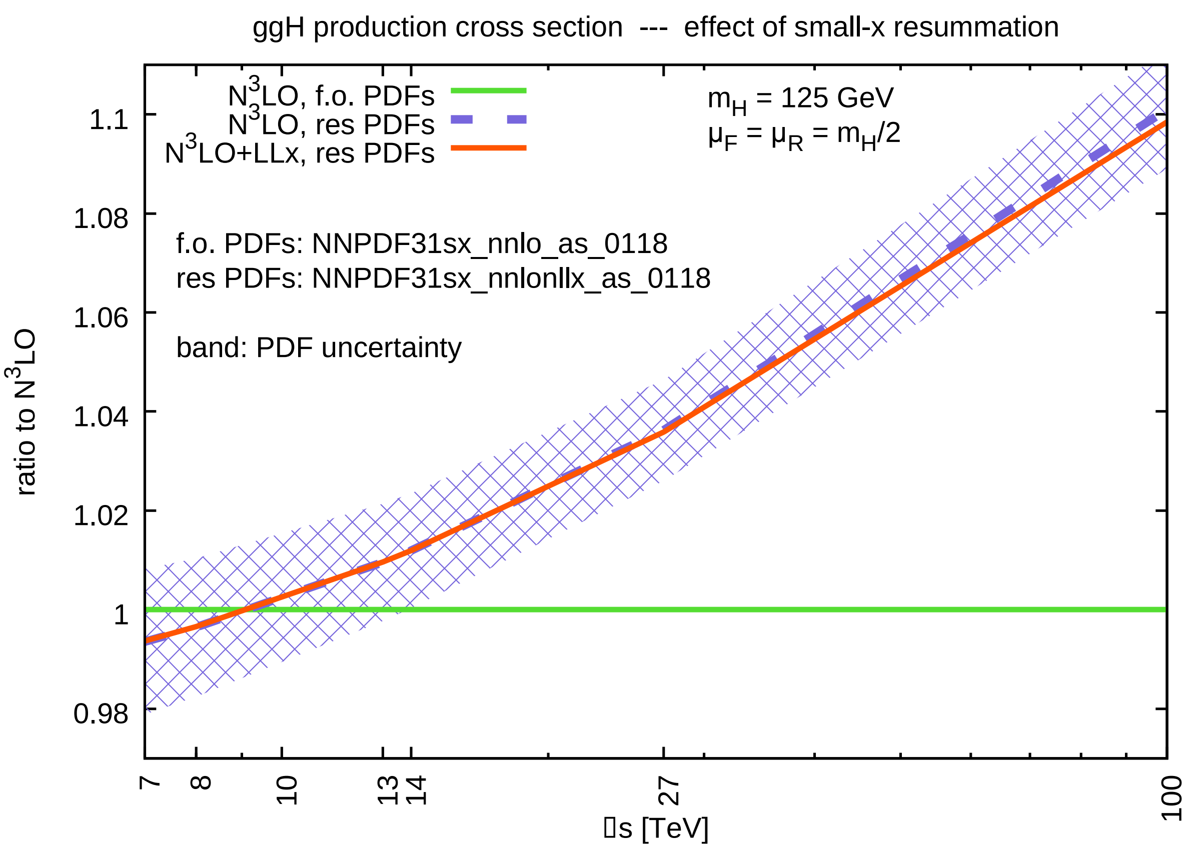




- recent evidence for onset of BFKL dynamics in HERA inclusive data
- **impact for LHC and most certainly at ultra low x values probed at FCC**

confirmed in xFitter study, arXiv:1802.00064

gluon at small x matters



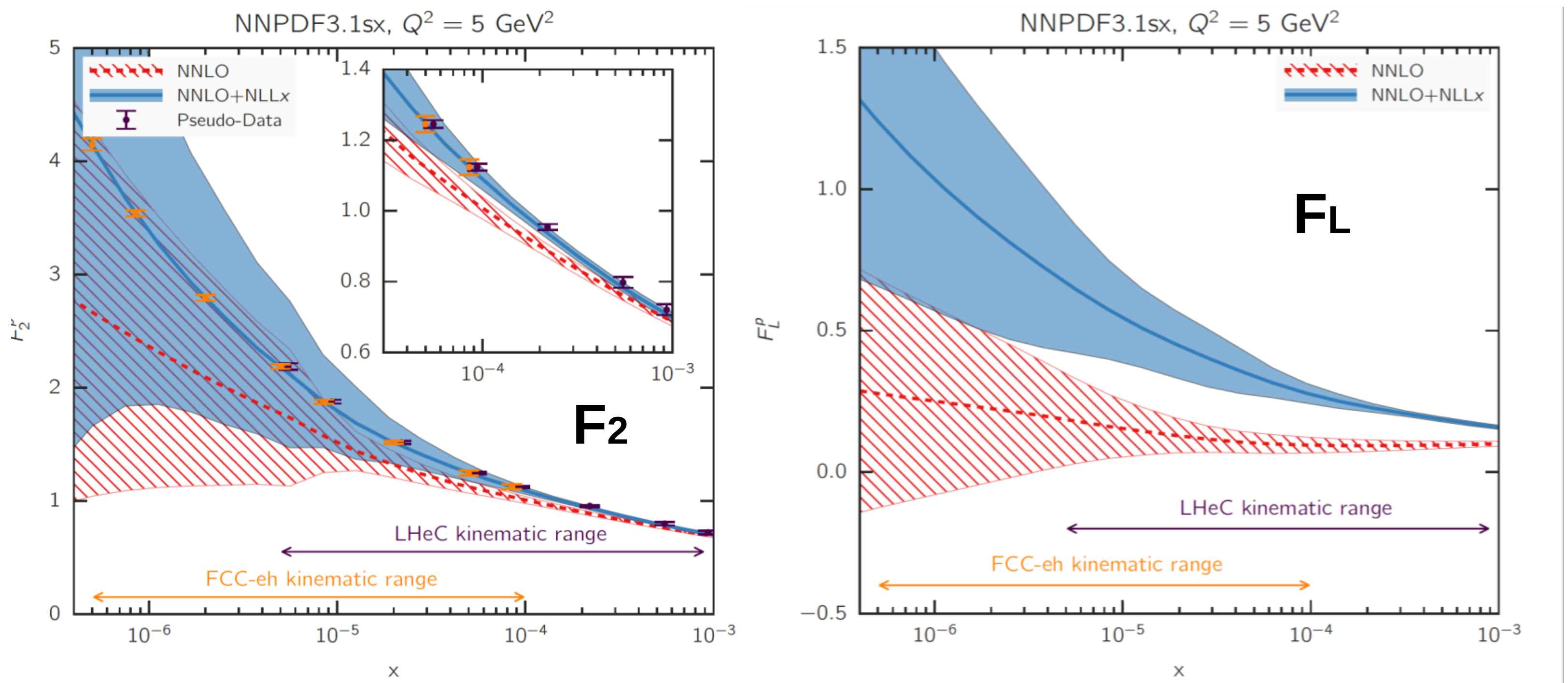
effect of small x resummation on ggH cross section for LHC, HE-LHC, FCC

impact on other EW observables could be of similar size

M. Bonvini and S. Marzani, arXiv:1802.07758

gluon at small x

arXiv:1710.05935



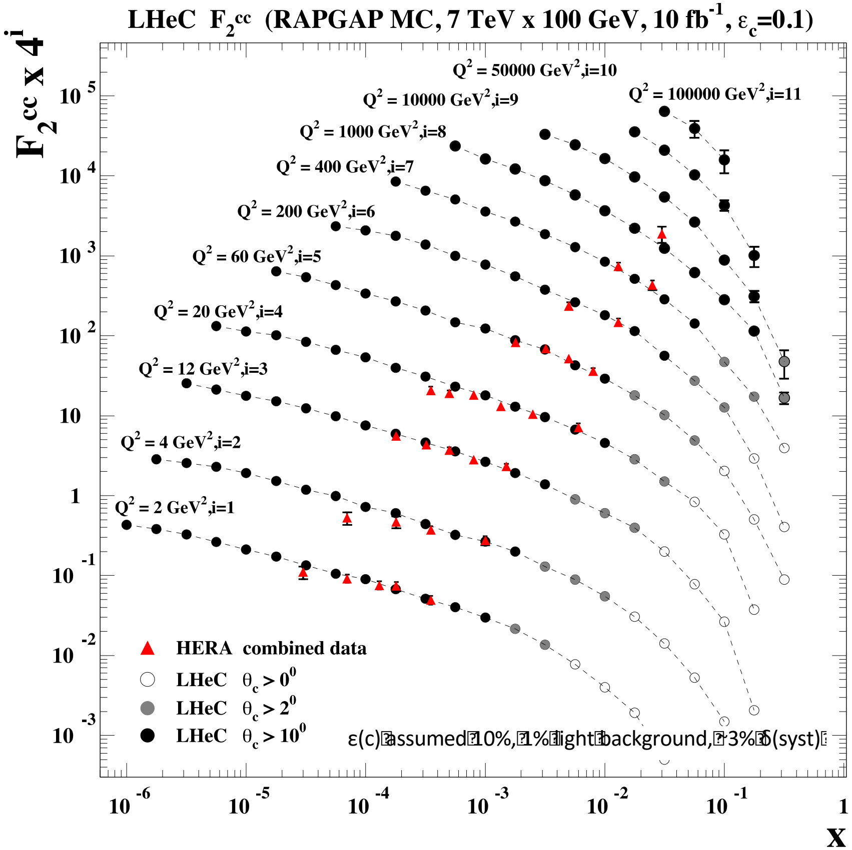
F2 and FL predictions for simulated kinematics of **LHeC** and **FCC-eh**

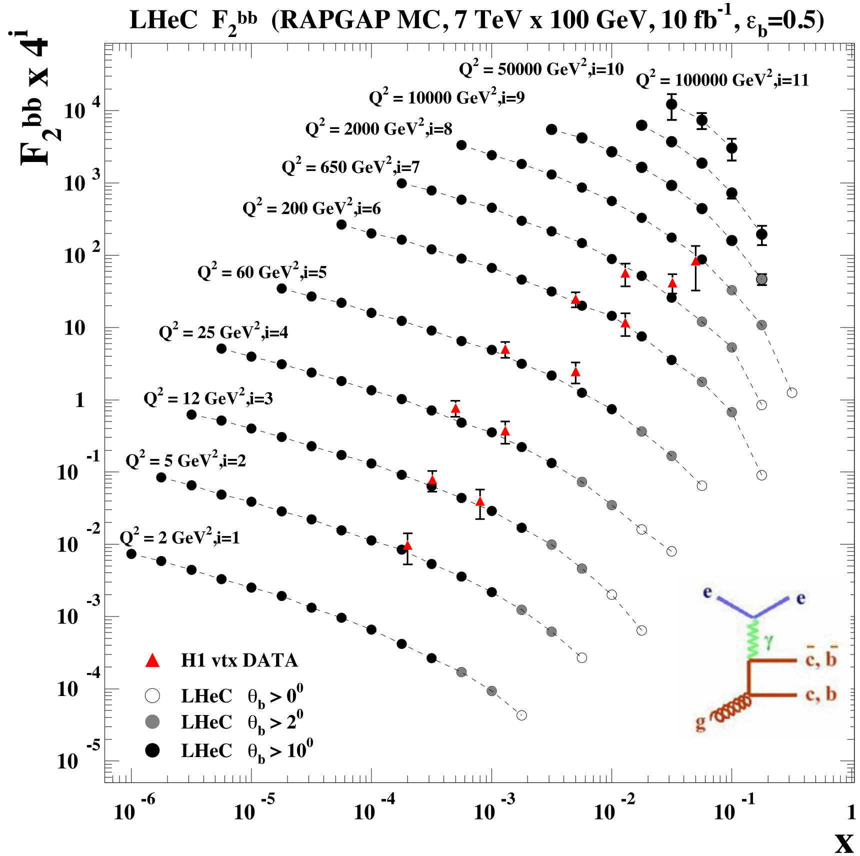
ep simulated data very precise – significant constraining power to discriminate between theoretical scenarios of small x dynamics

measurement of FL has a critical role to play

see also M. Klein, arXiv:1802.04317

c, b quarks



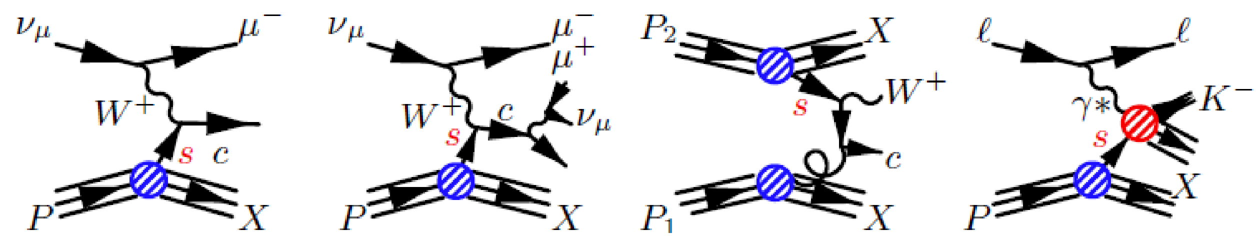


LHeC: enormously extended range and much improved precision c.f. HERA

- **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 $b\bar{b} \rightarrow A$

strange

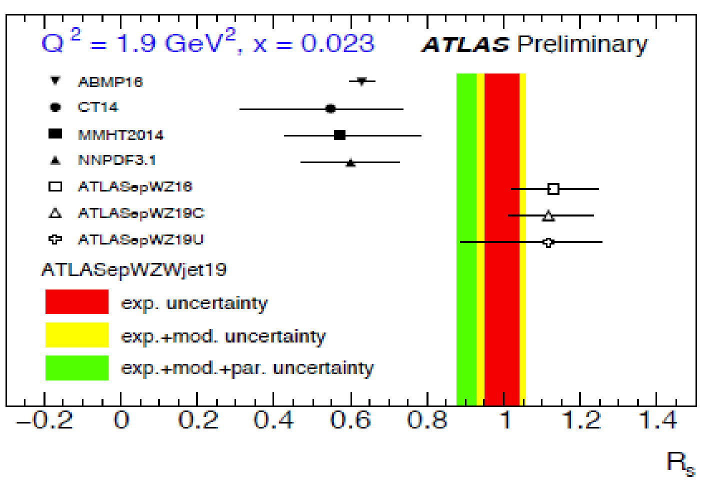
strange pdf poorly known; suppressed cf. other light quarks? strange valence?

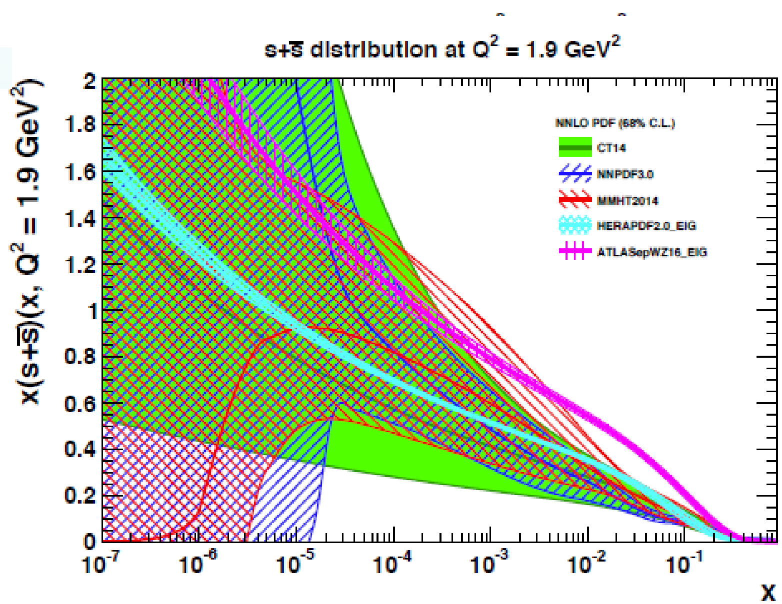


EG. CHORUS NuTeV ATLAS/CMS HERMES

ATLAS† observe large strange fraction at mean Bjorken x around 0.01

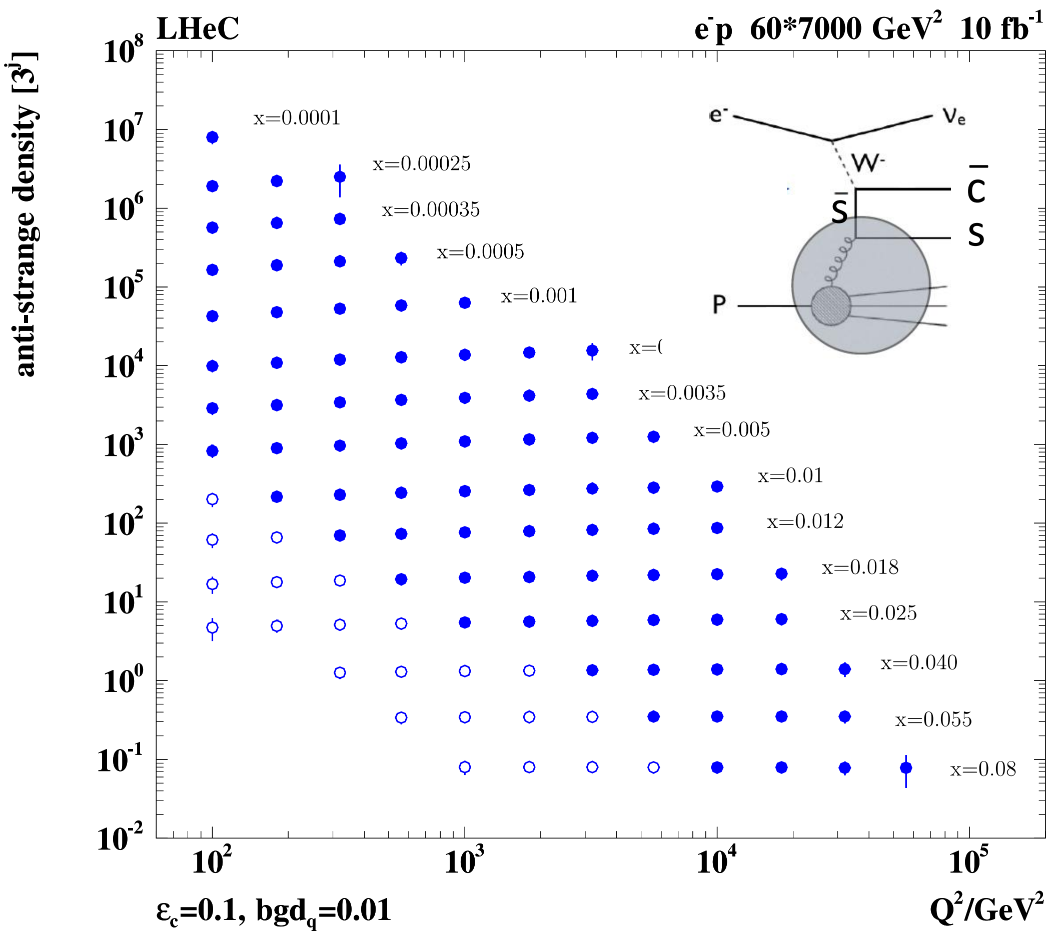
$$R_s(x,Q^2) = \frac{s(x,Q^2)+\bar{s}(x,Q^2)}{\bar{u}(x,Q^2)+\bar{d}(x,Q^2)} \begin{cases} \approx 0.5 \text{ (from neutrinc)} \\ \approx 1.0 \text{ (from ATLAS W,Z)} \end{cases}$$





†ATLAS arXiv:1203.4051, confirmed in 1612.03016, ATL-PHYS-PUB-2019-016; and by global fitters EG. 1706.00428, 1708.00047

strange



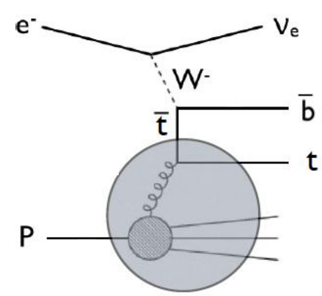
LHeC: direct sensitivity to **strange** via W+s → c

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

also top PDF

top quark becomes light at large Q2:

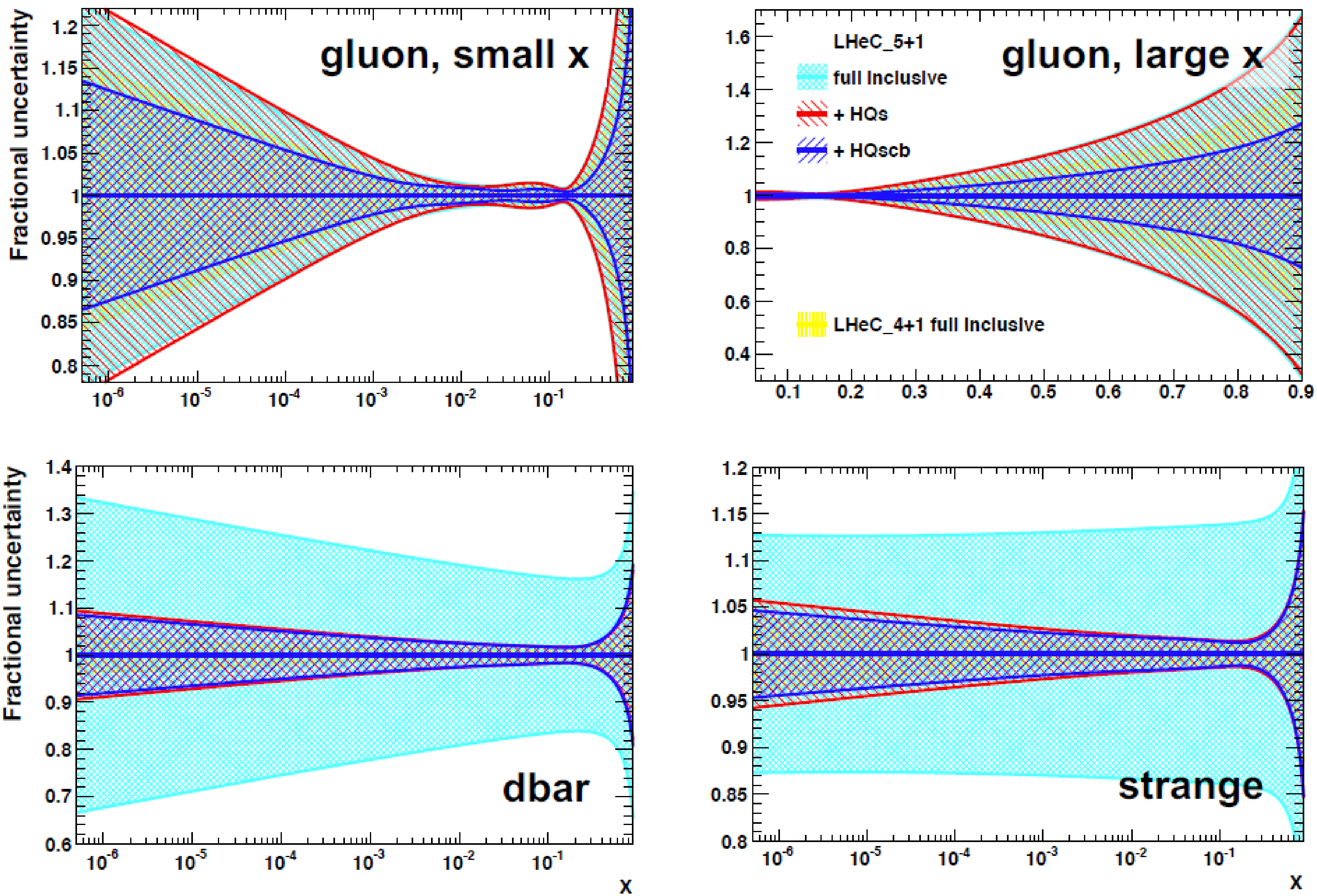
new field of research opens for top PDFs!



G.R. Boroun, PLB 744 (2015) 142

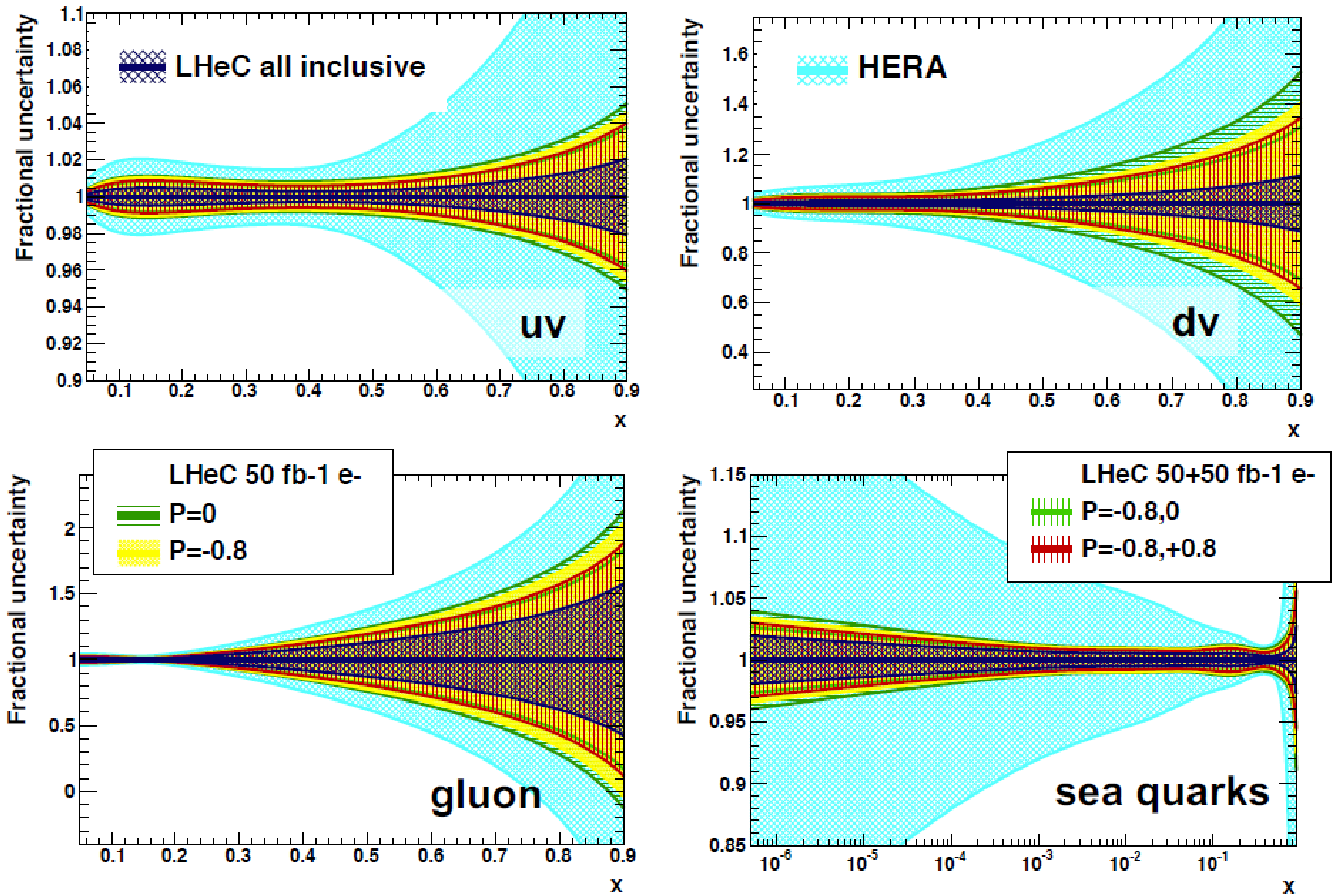
G.R. Boroun, PLB 741 (2015) 197

impact of HQ data on LHeC pdfs



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

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)