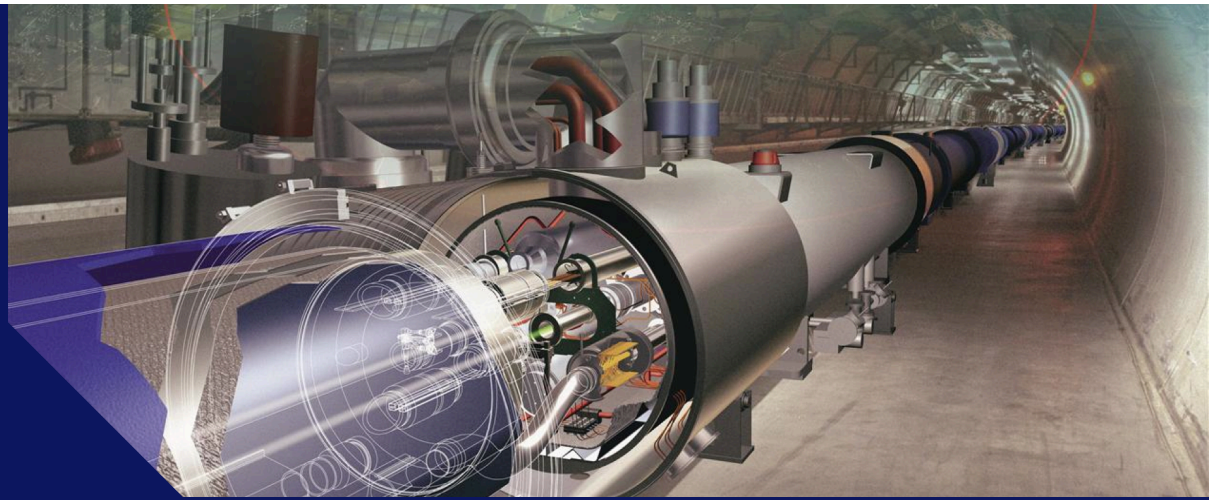
QCD@LHC 2019

Buffalo, New York

15 – 19 July 2019



Precision PDFs at Future Colliders

Claire Gwenlan, Oxford

on behalf of the LHeC and FCC-eh WGs

outline

- **pdfs from future ep high energy colliders, LHeC and FCC-eh**

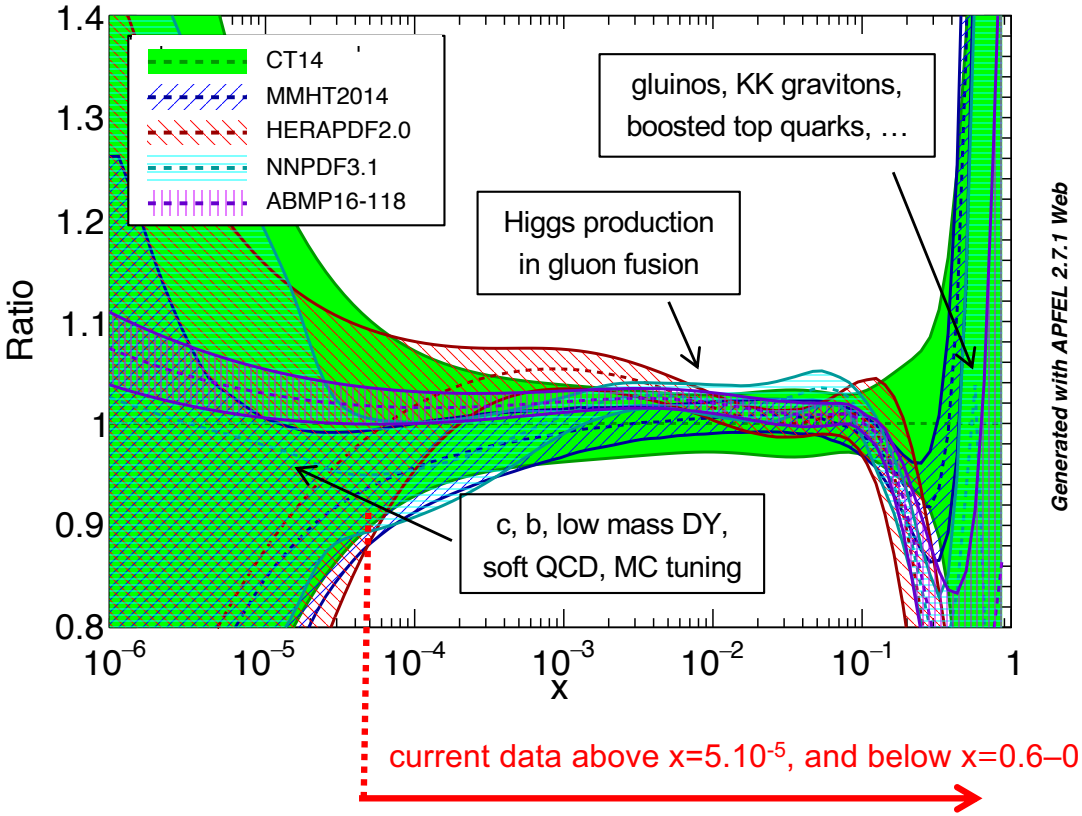
  summary of ongoing studies towards update of LHeC CDR (arXiV:1206.2913);
  FCC-eh pdf studies from FCC CDR, volume 1 (EPJ C79 (2019), no.6, 474),
  plus some ongoing studies on a lower energy FCC configuration

- **pdfs from the HL-LHC**

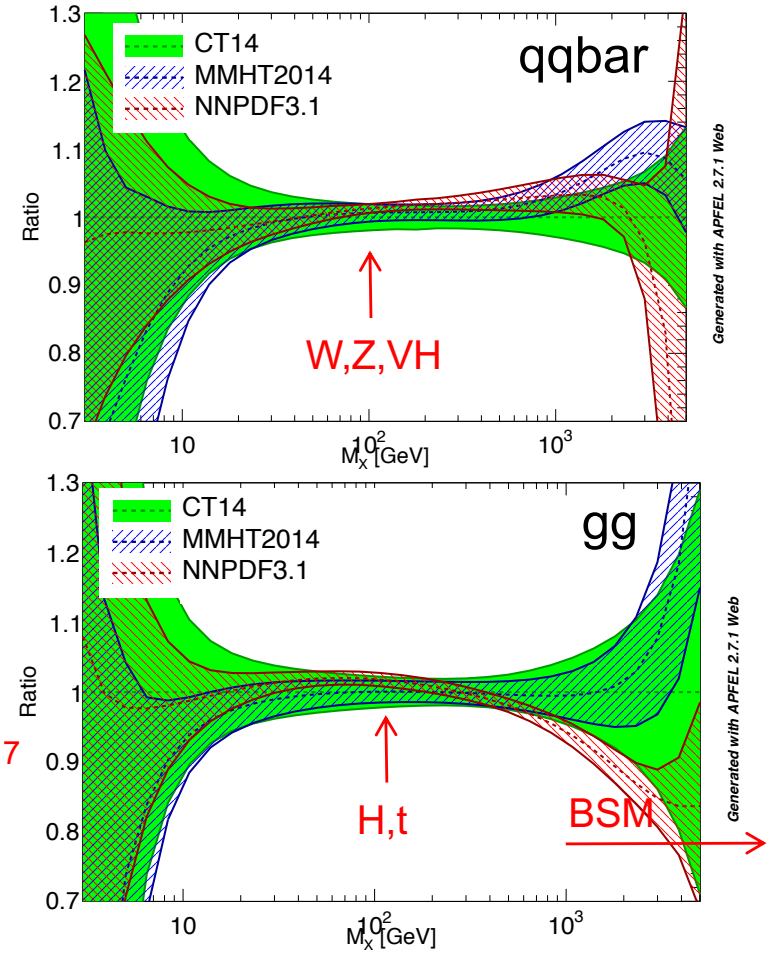
  summary of Khalek et al., arXiv:1810.03639;
  contribution to CERN yellow report on Standard Model Physics at the HL-LHC and HE-LHC,
  arXiv:1902.04070

pdfs: the situation today

xg(x,Q), NNLO, Q^2=100 GeV^2, $\alpha_s(M_Z)$=0.118



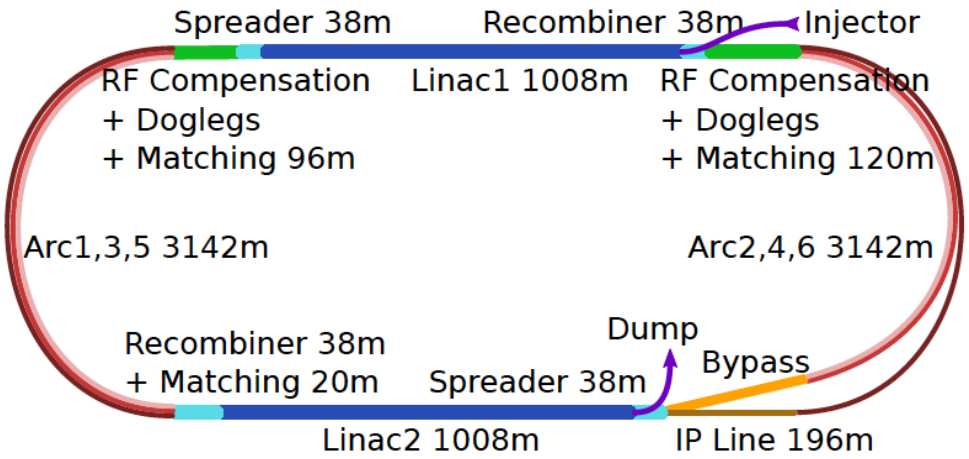
pdf luminosities (LHC@14TeV)



pdfs poorly known at large and small x

higher precision needed also for H, W, t

improving knowledge: LHeC and FCC-eh



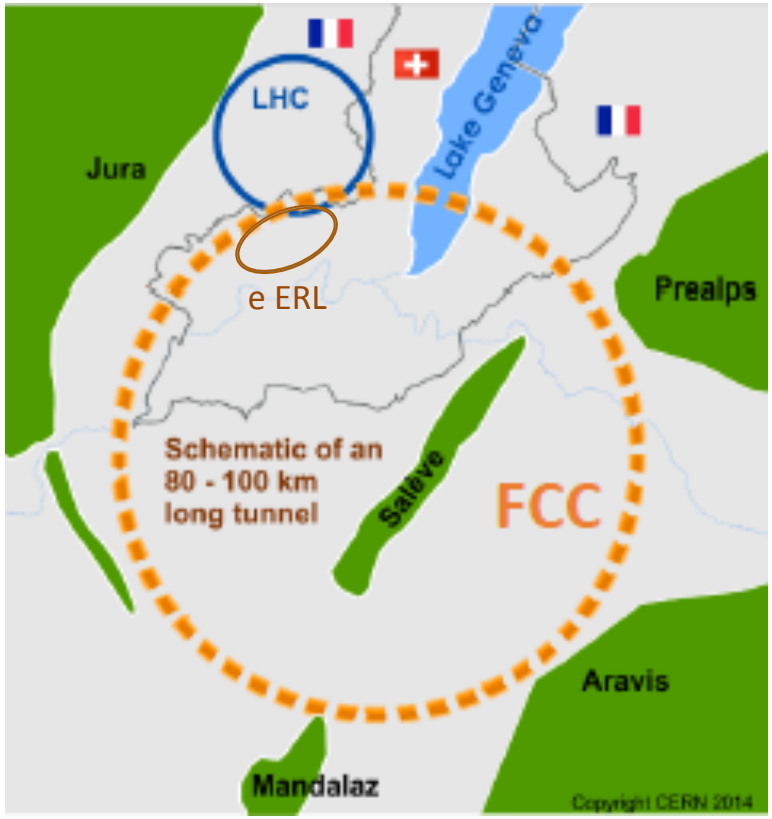
energy recovery LINAC

e beam: up to 60 GeV

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

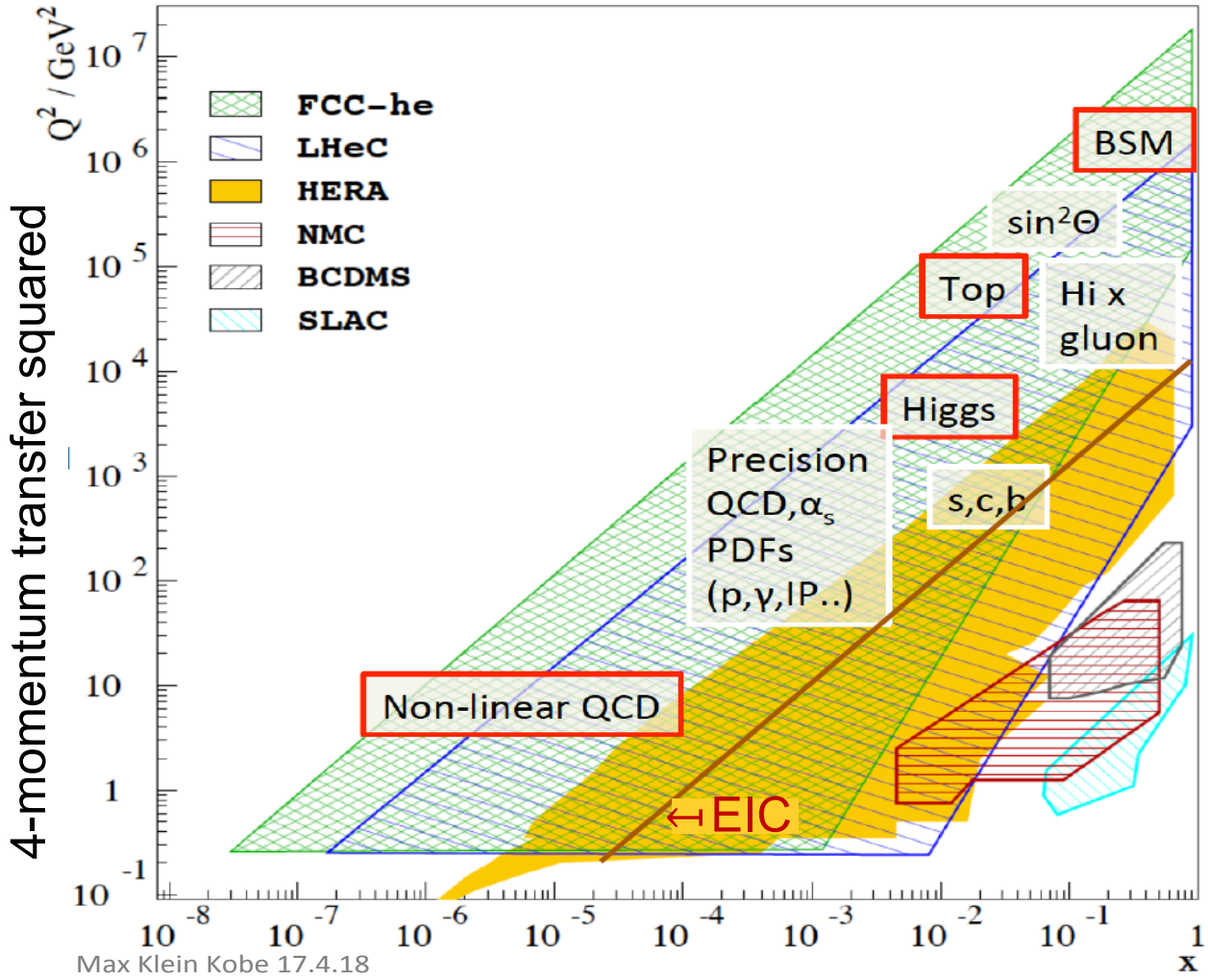
operating **synchronously** :

- 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



opportunity for **unprecedented increase in DIS kinematic reach**; ×1000 increase in lumi.

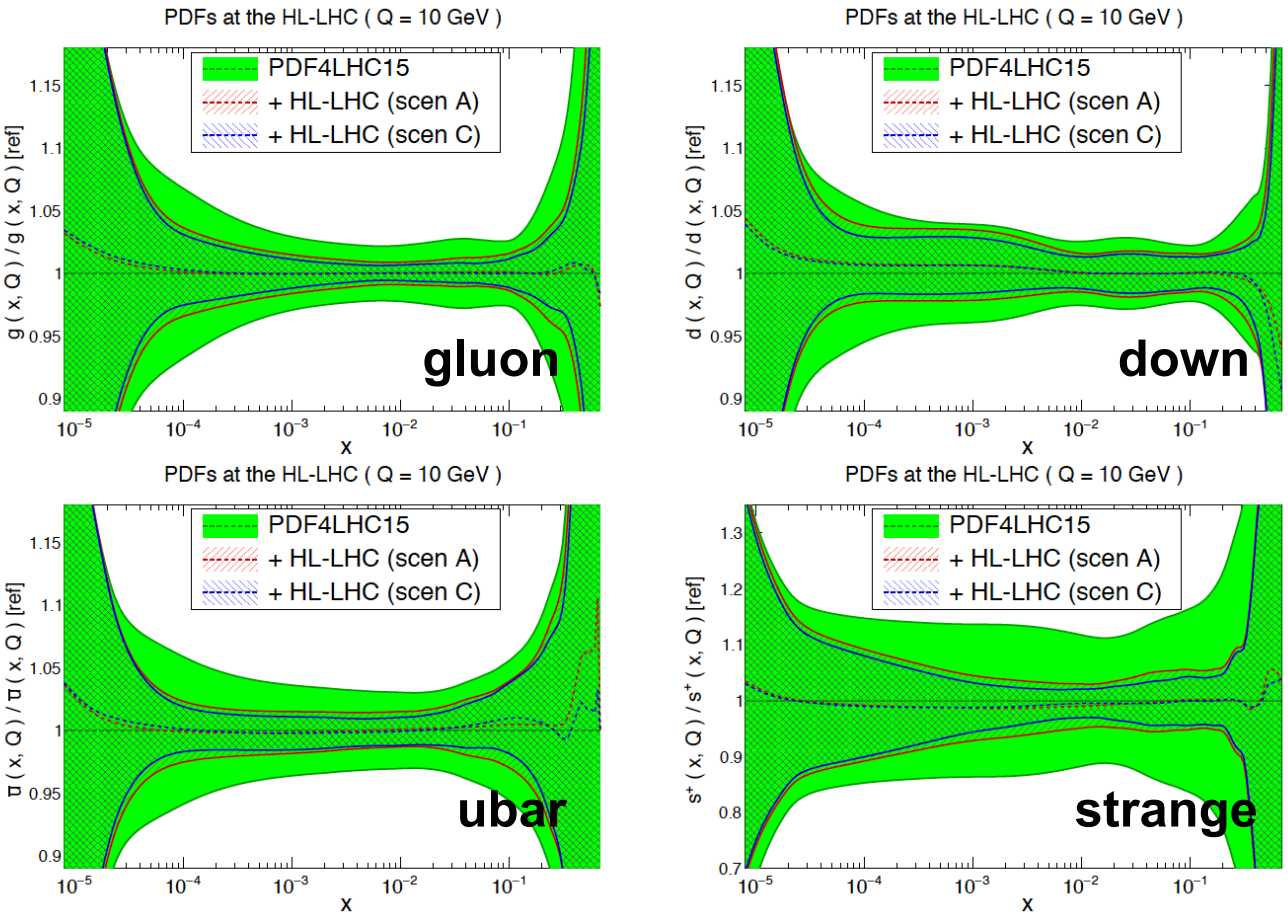
no higher twist, no nuclear corrections, free of symmetry assumptions, N3LO theory possible, …

precision pdfs, and exploration of low x regime; plus extensive physics program in its own right

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

HL-LHC pdfs

BUT can't we get precision pdfs from the LHC itself?



HL-LHC projections suggest it can go quite some way!

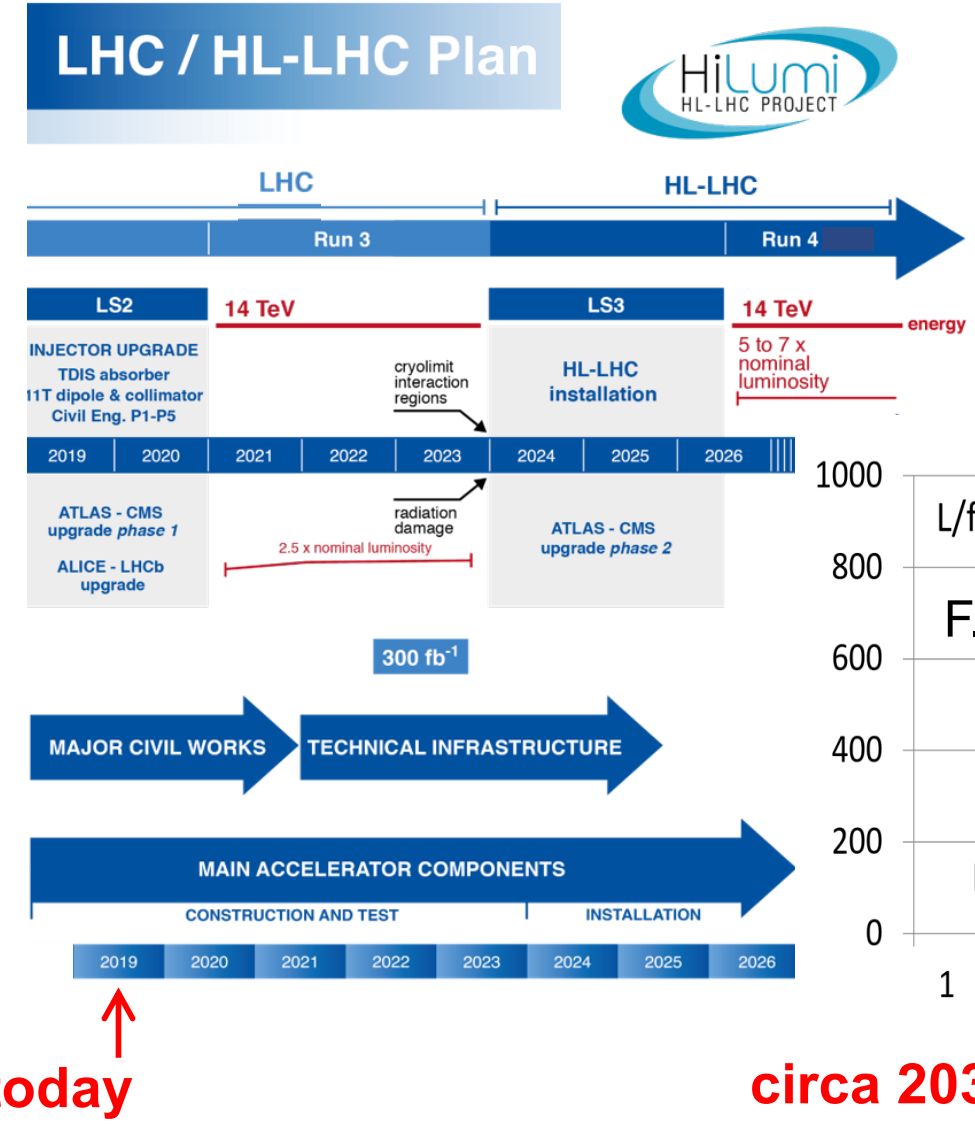
arXiv:1810.03639

BUT projections are in an ideal world, where **many different types of LHC measurements** have well understood systematics, correlations, and no data inconsistencies

single, consistent DIS data set is a tried and tested reliable way to achieve precision

also, possible issues of timing …

timelines

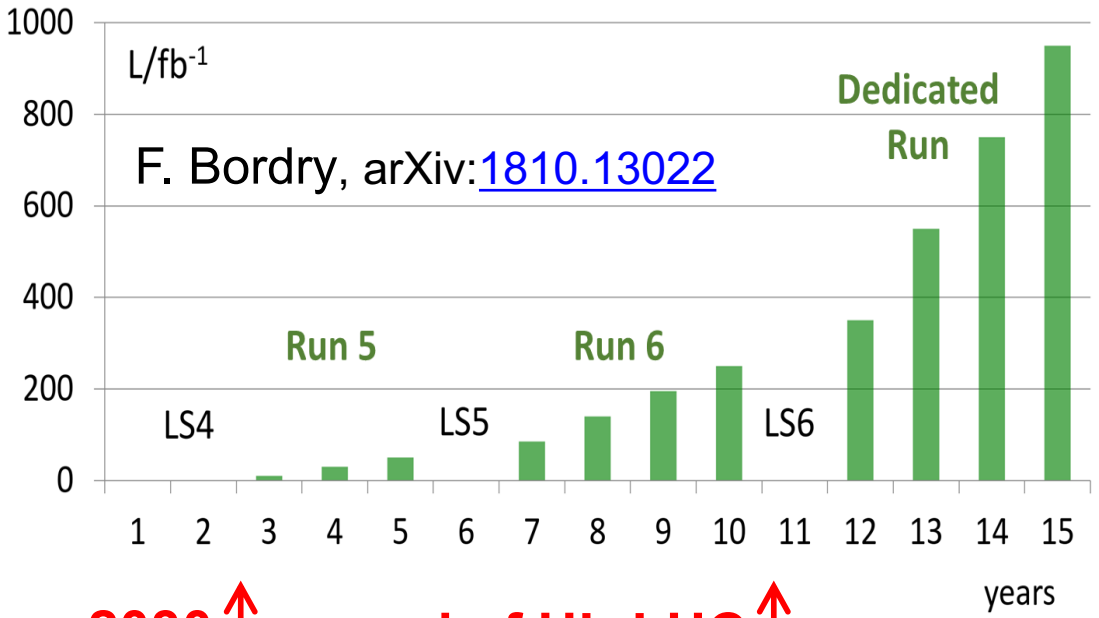


today

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

total Lint ⟶ 1 ab^{-1}

LHeC projected Integrated Luminosity:

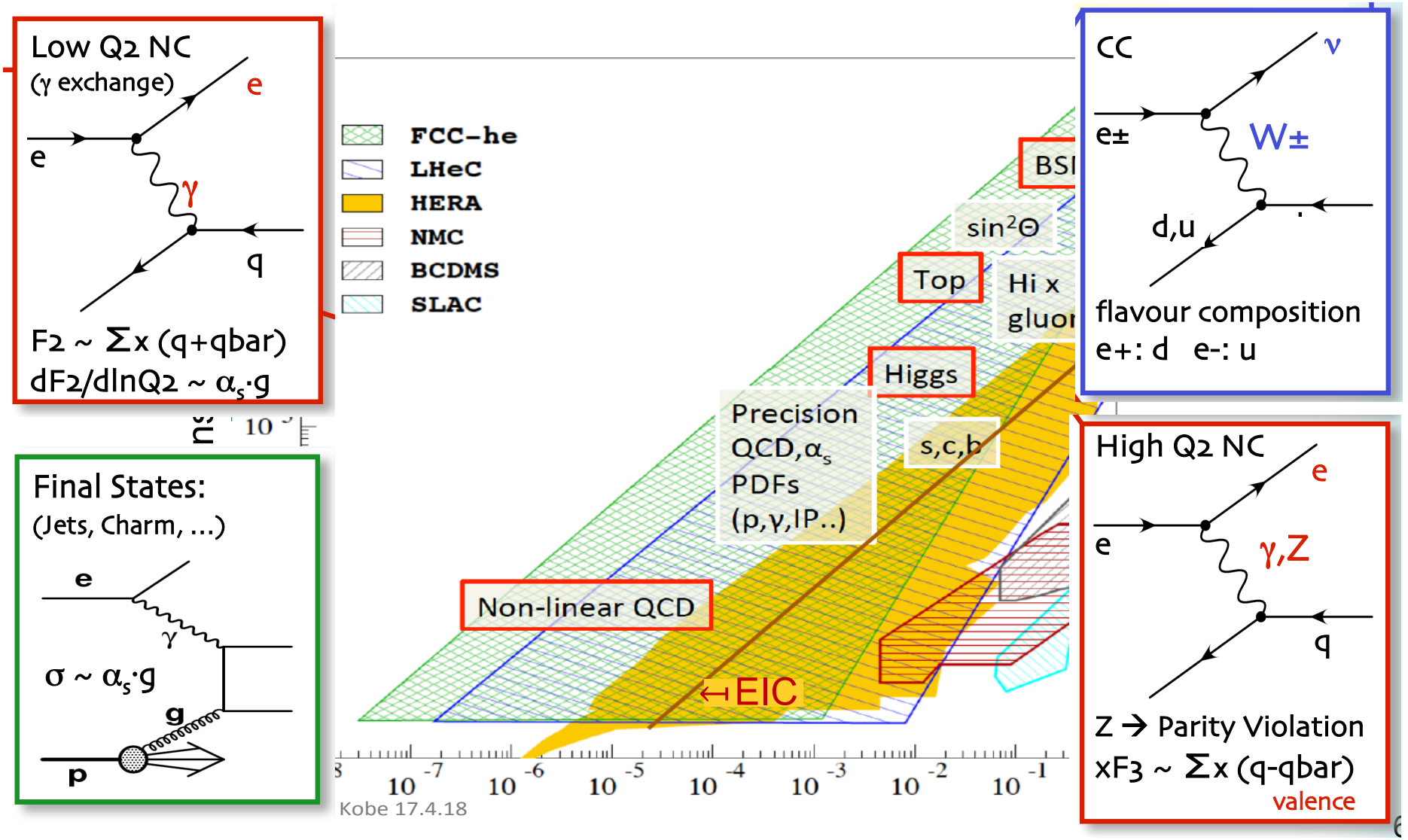


circa 2030

end of HL-LHC

50 fb^{-1} could be achieved in 3 years before LS5 and long before the end of HL-LHC running

pdfs from ep colliders



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

LHeC pdf programme

simulation and pdf fit studies:
M. Klein, CG

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

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

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** (important for EW physics)
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%

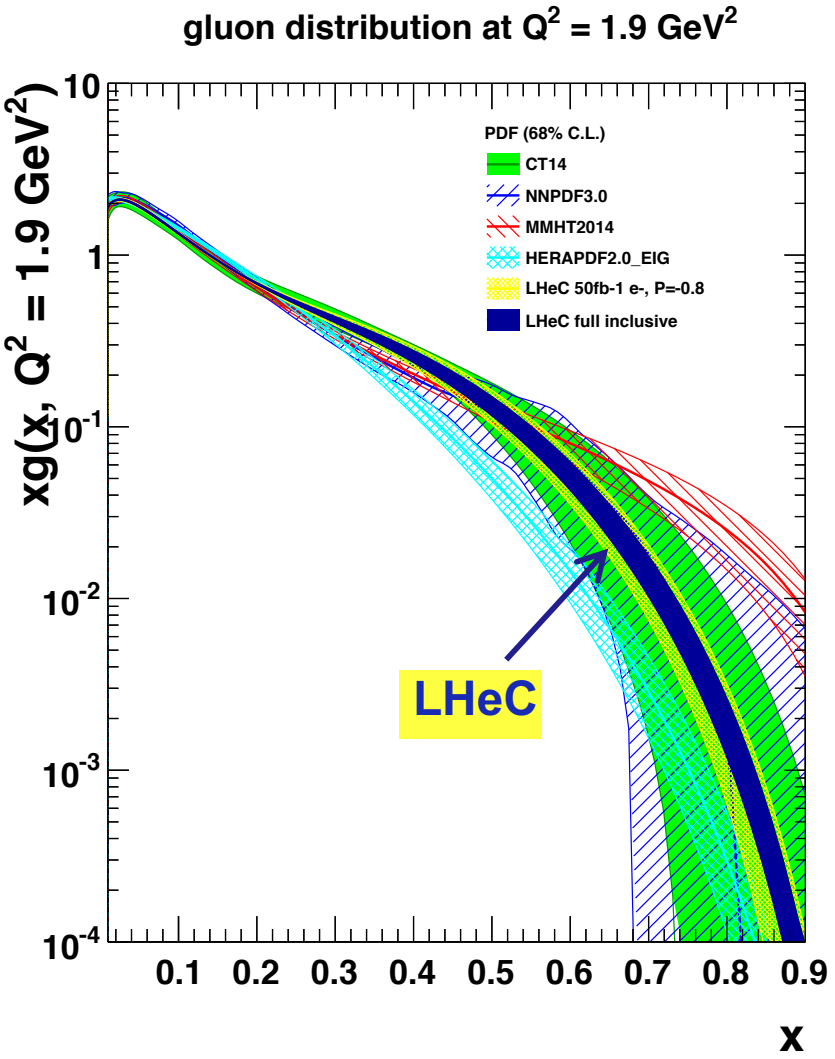
NB, I will frequently refer to the following:

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

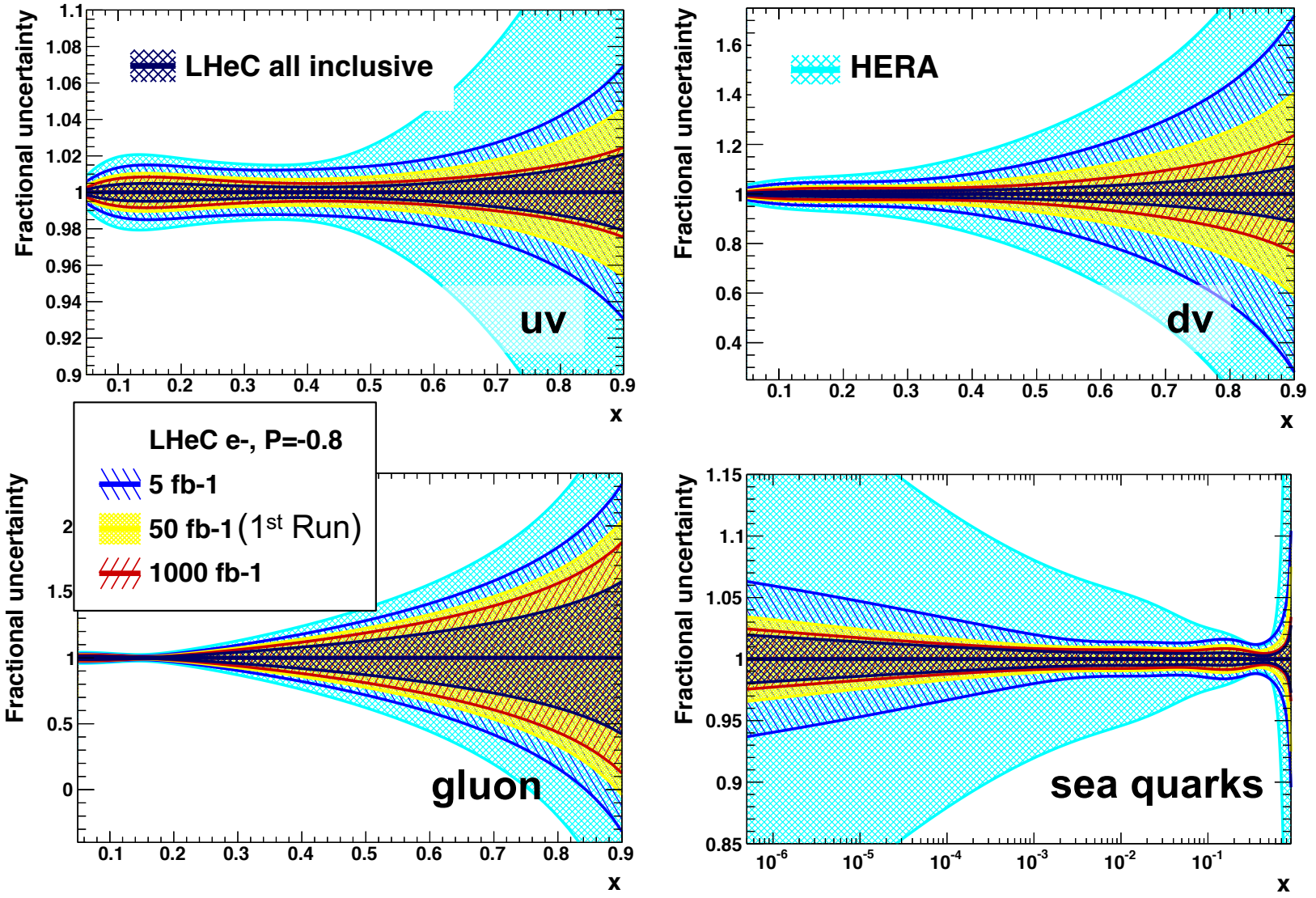
LHeC sensitivity at large x comes as part of overall package

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** $F2^{\gamma Z}$, $xF3^{\gamma Z}$

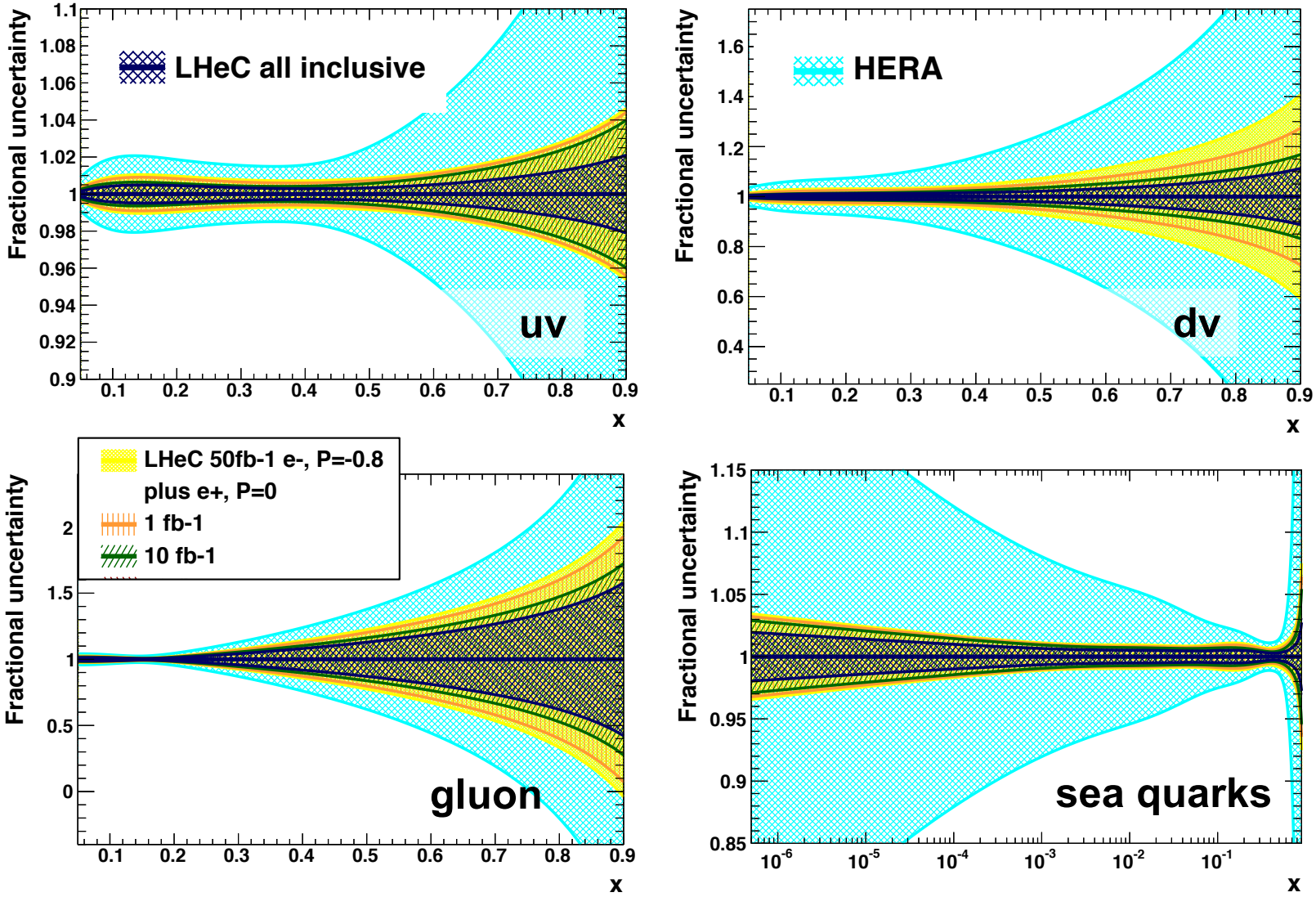
impact of luminosity on LHeC pdfs



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

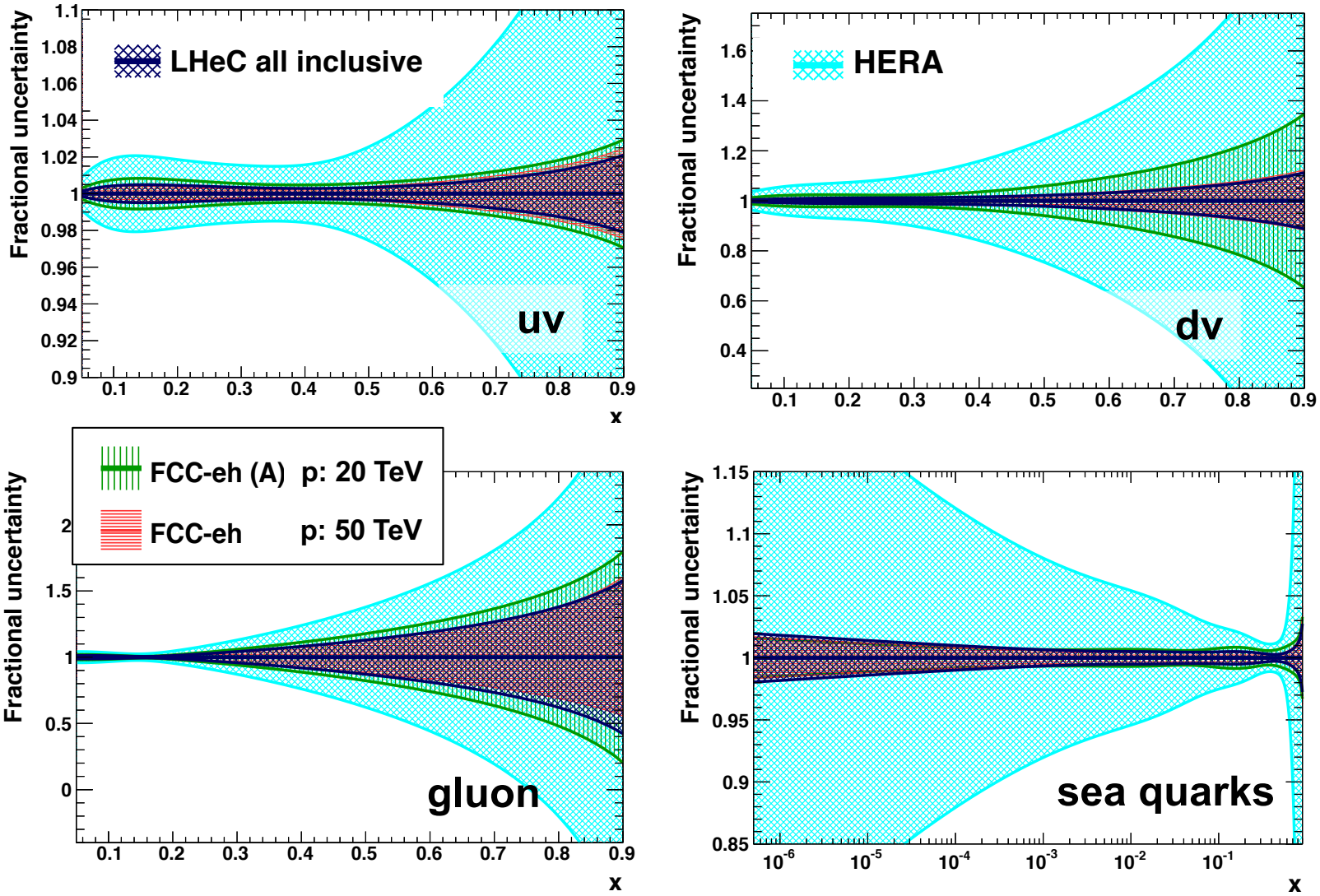
large x (≡ large Q2), gain from increased Lint

impact of positrons on LHeC 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– (**NB, NO e+ yet; impact especially in dv**)

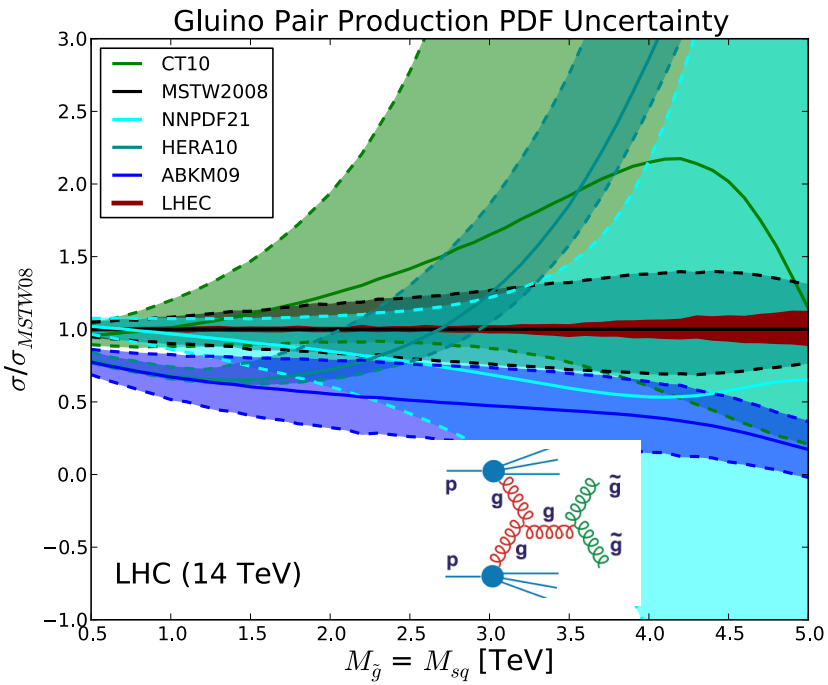
FCC-eh: CDR, volume 1, EPJ C79 (2019), no.6, 474

empowering LHC searches

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

gluons

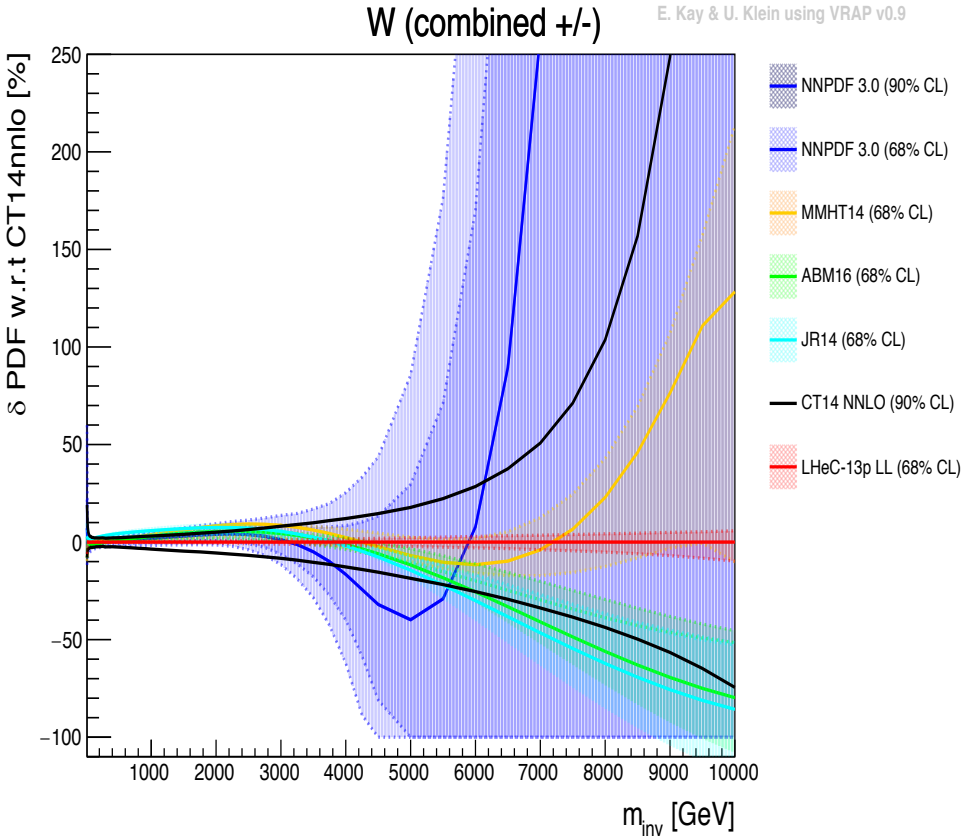
SUSY (RPC, RPV), LQs, …



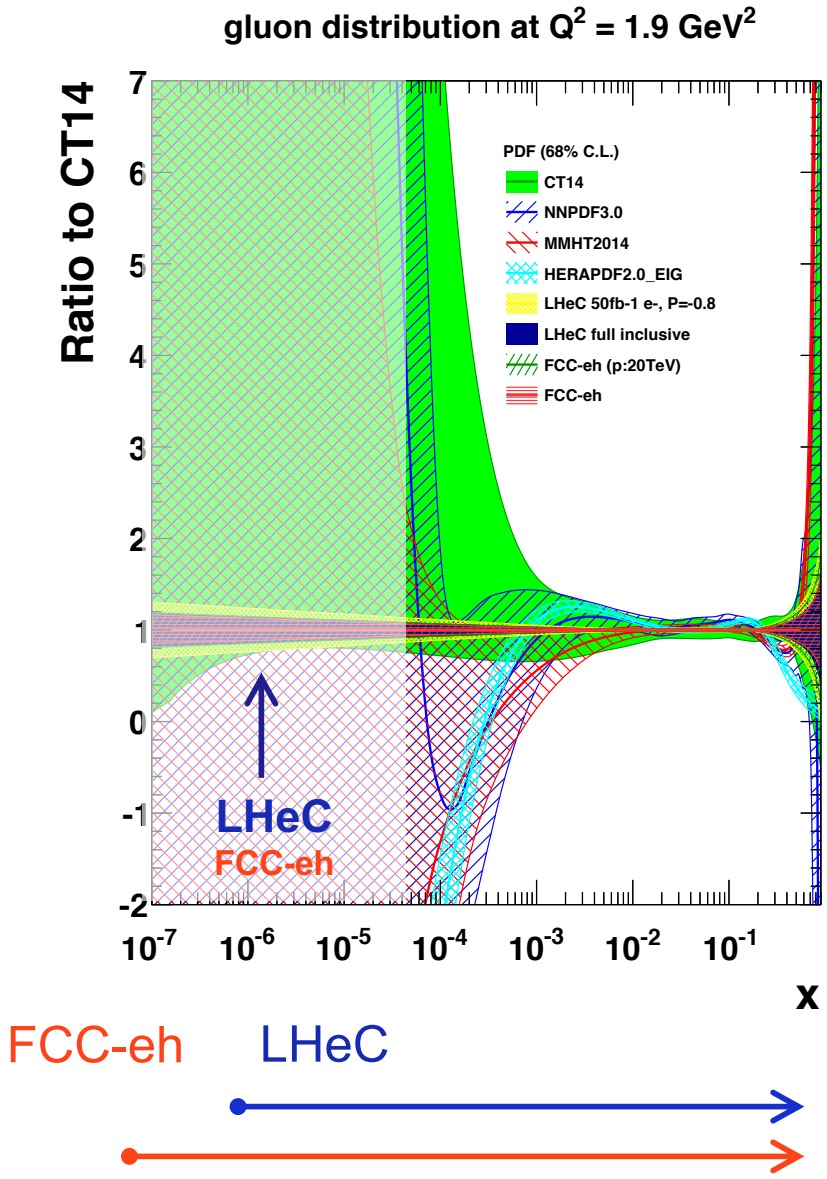
arXiv:1211.5102

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 $x=10^{-6}$

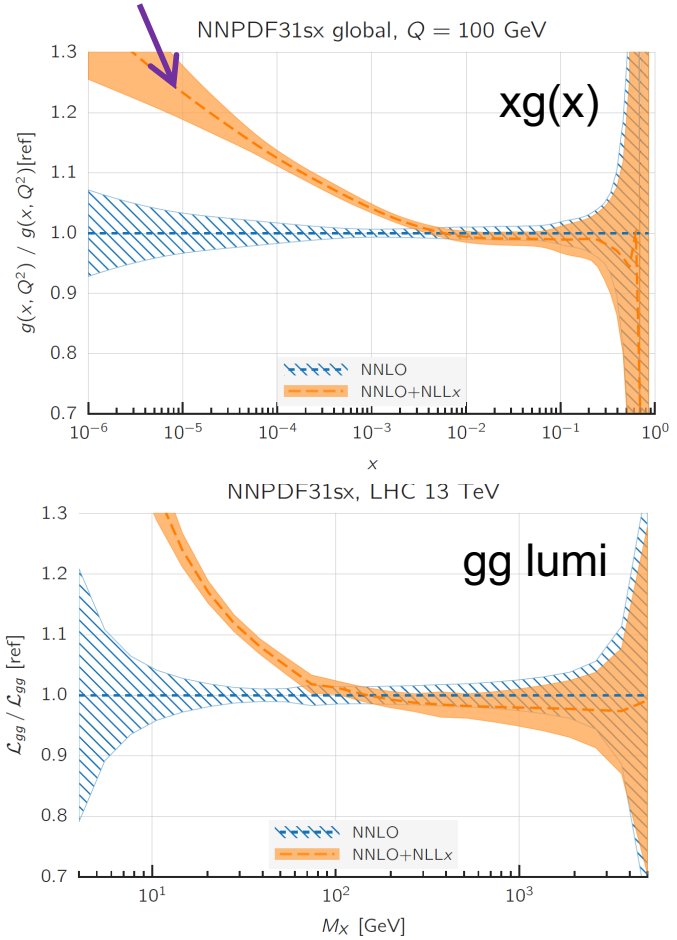
FCC-eh probes to even smaller $x=10^{-7}$

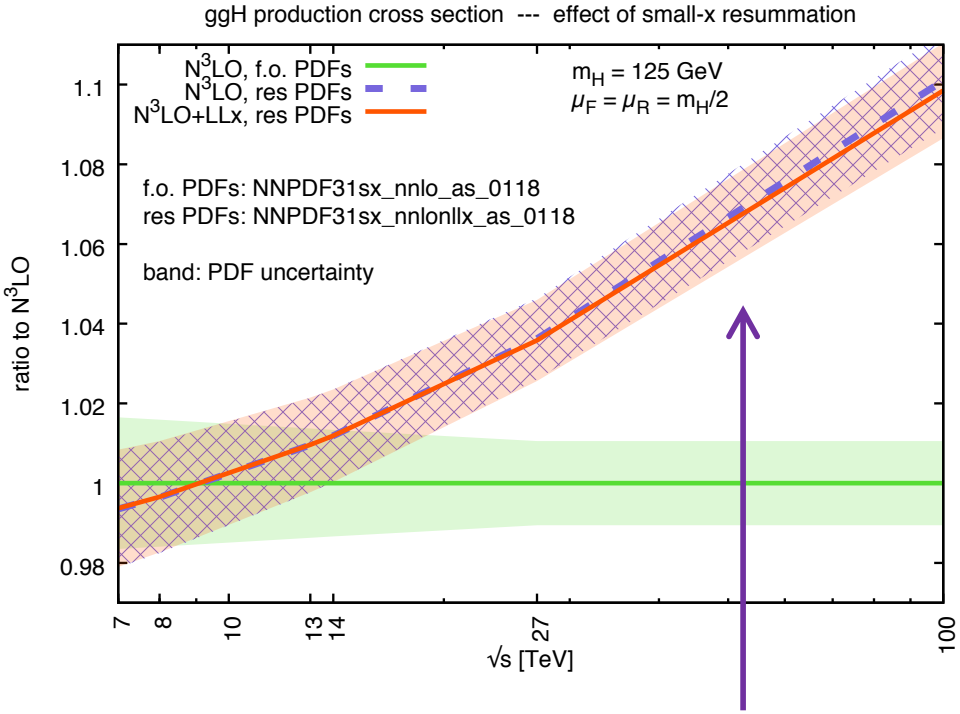
explore low x QCD:

DGLAP vs BFKL; non-linear evolution;
gluon saturation; implications
for ultra high energy neutrino cross sections

gluon at small x matters

effect of small x resummation





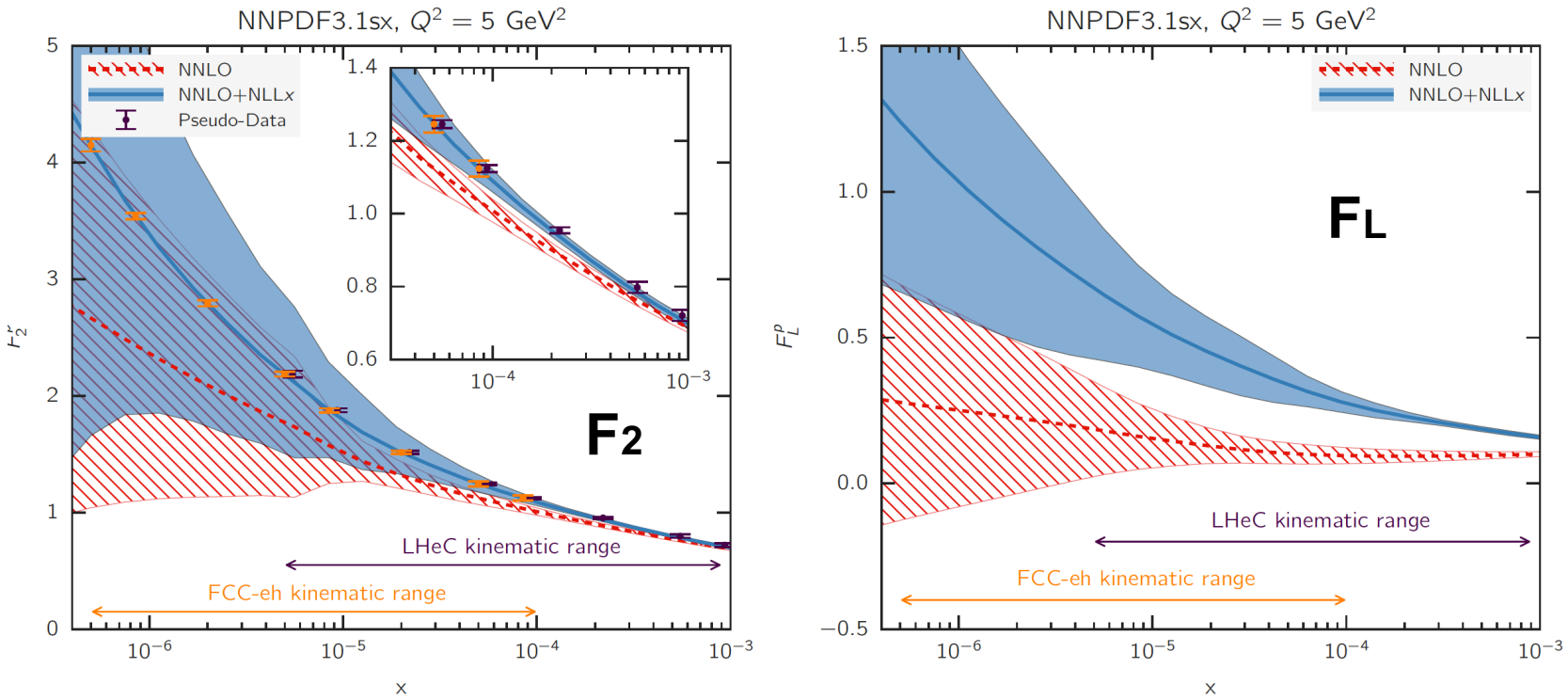
effect of small x resummation on ggH cross section

impact on other EW observables could be as large

- recent evidence for onset of BFKL dynamics in HERA inclusive data
  arXiv:1710.05935; confirmed in xFitter study, arXiv:1802.00064
- **impact for LHC and most certainly at ultra low x values probed at FCC**

gluon at small x

arXiv:1710.05935



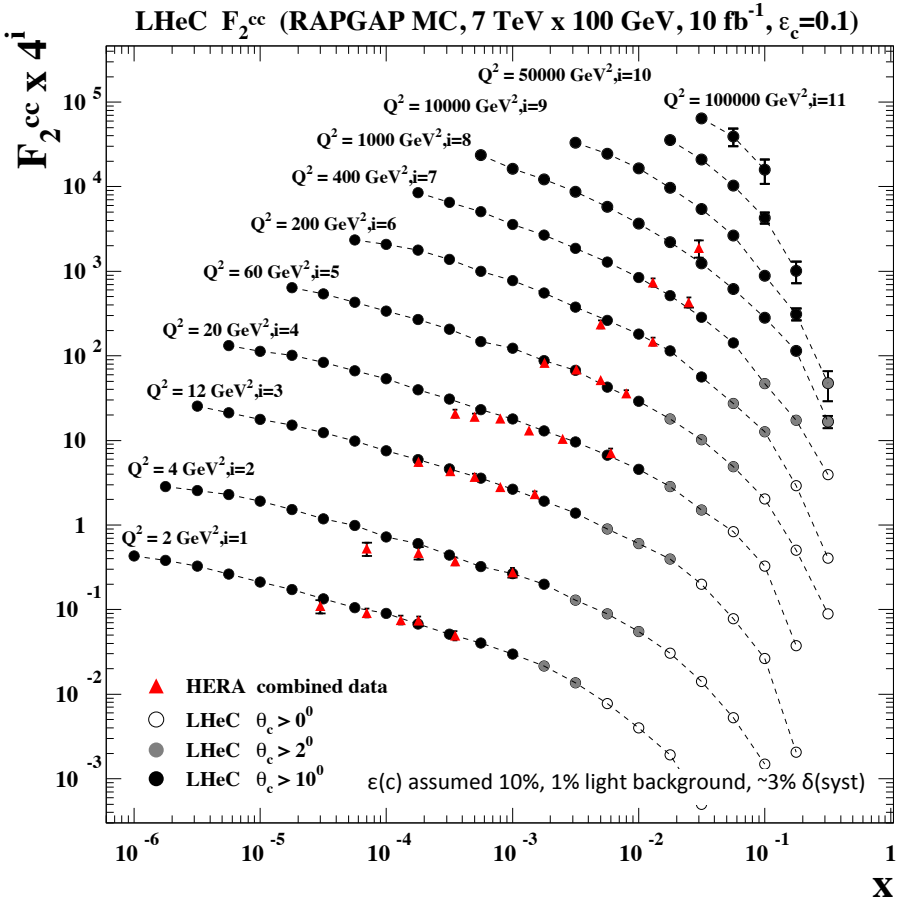
F2 and FL predictions for simulated kinematics of **LHeC** and **FCC-eh**

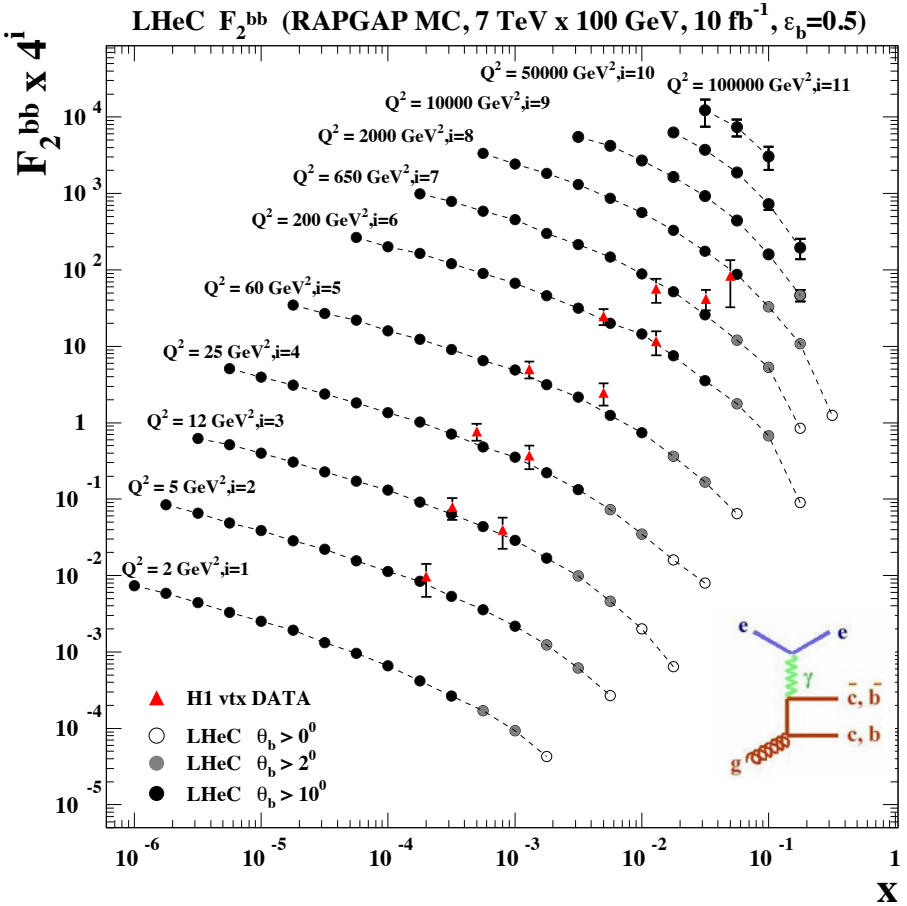
ep simulated data very precise – significant constraining power to discriminate between theoretical scenarios of small x dynamics

measurement of FL has a critical role to play

see also M. Klein, arXiv:1802.04317

c, b quarks

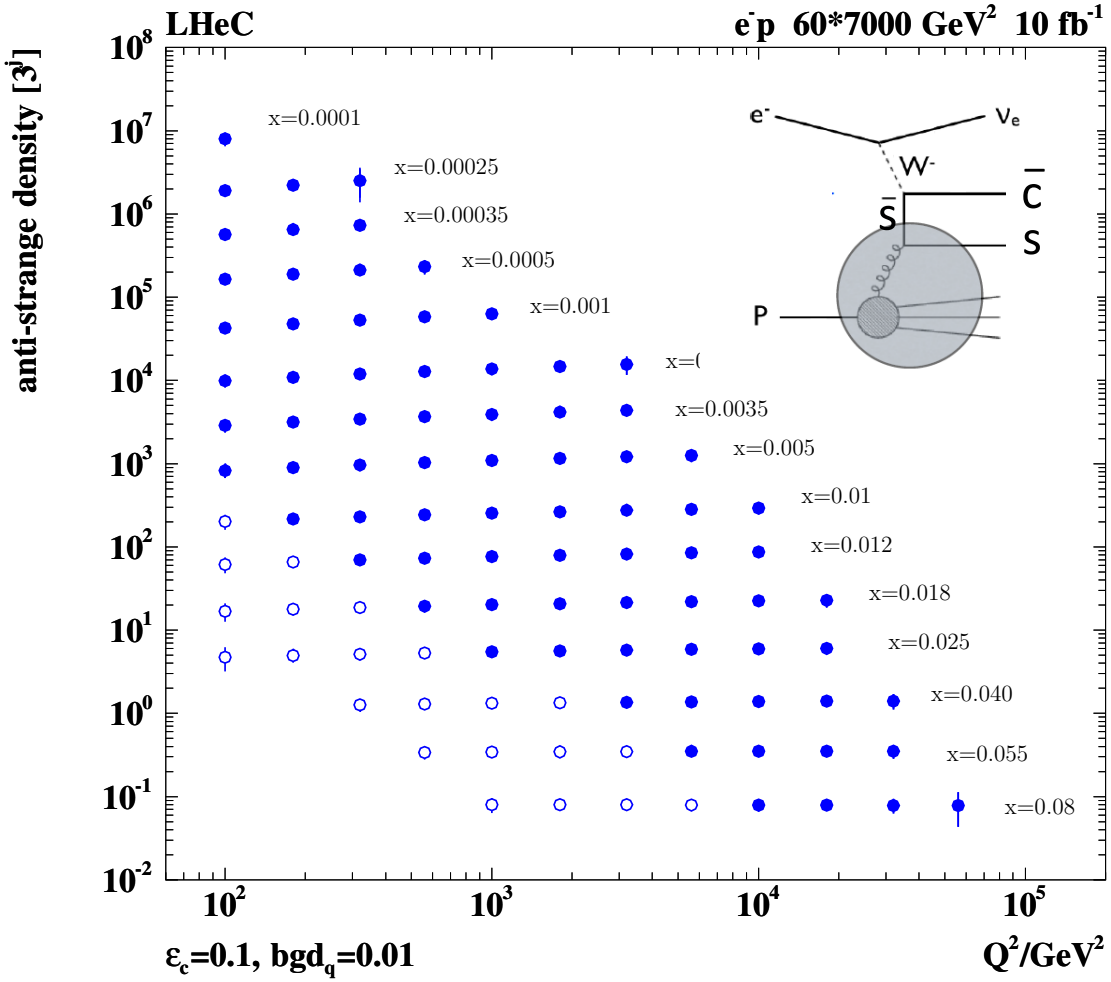




LHeC: enormously extended range and much improved precision c.f. HERA

- **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

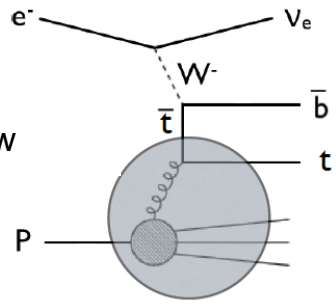


strange pdf poorly known;
suppressed cf. other light quarks?
strange valence?

LHeC: direct sensitivity to **strange** via W+s → c
(x,Q^2) mapping of (anti) strange for first time

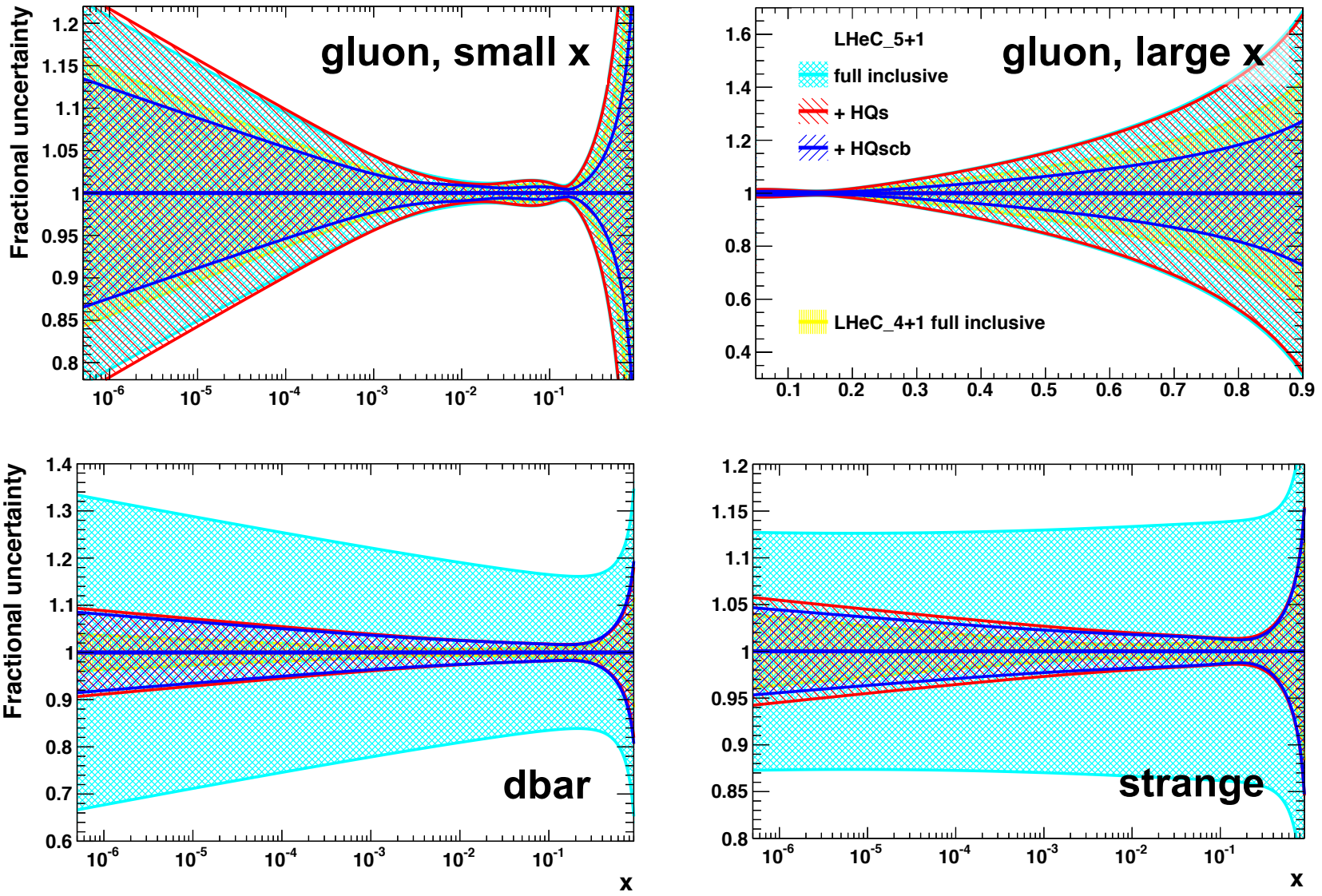
also top PDF

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



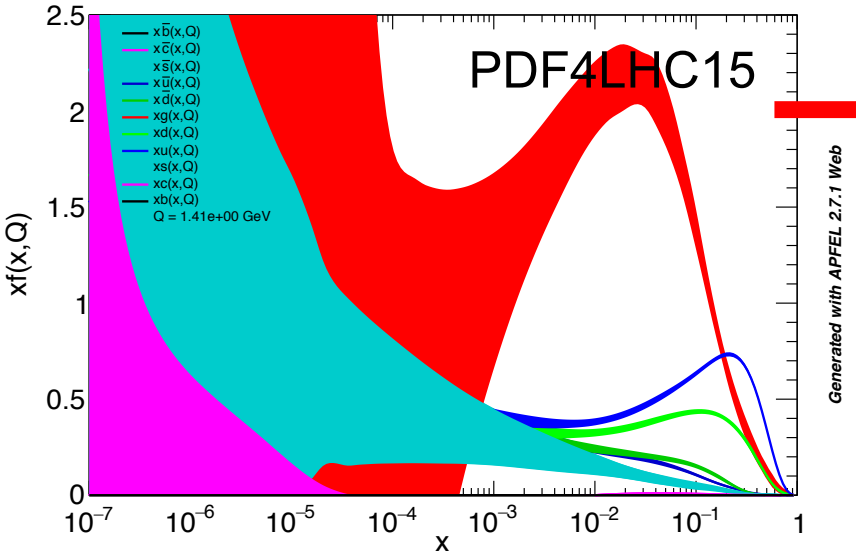
G.R. Boroun, PLB 744 (2015) 142
G.R. Boroun, PLB 741 (2015) 197

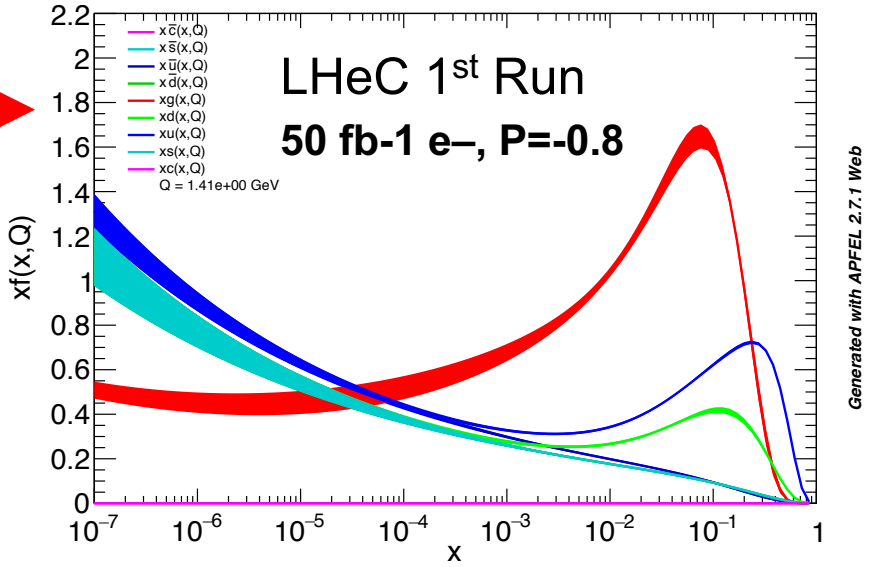
impact of HQ data on LHeC pdfs

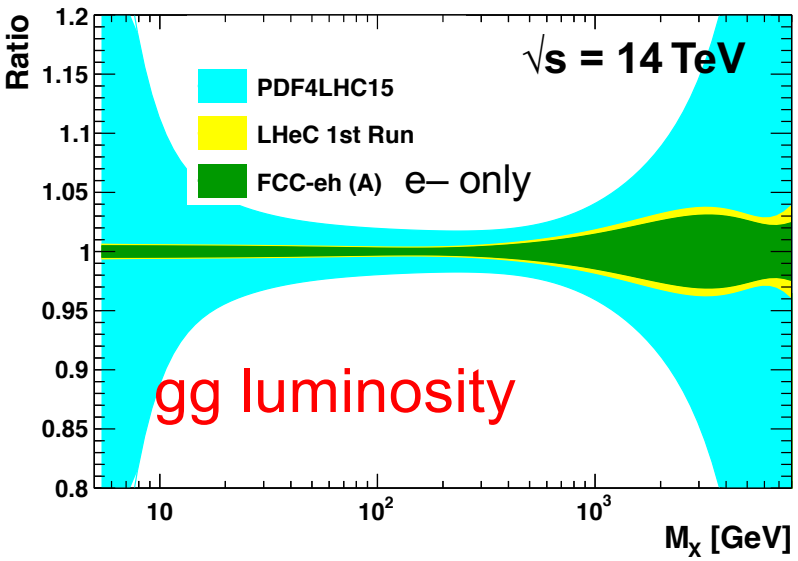


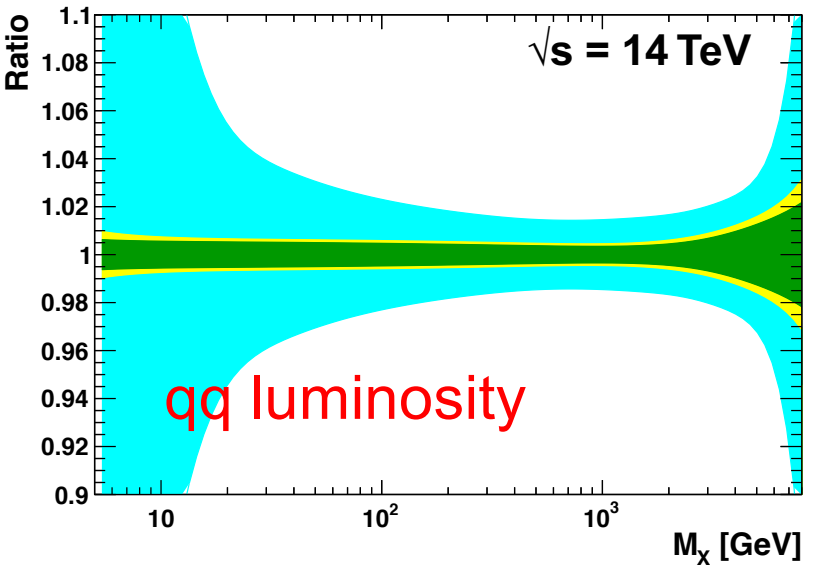
more flexible parameterisation (5+1): **xuv, xdv, $x\bar{U}$, $x\bar{d}$, $x\bar{s}$** and **xg**

summary of pdfs from ep

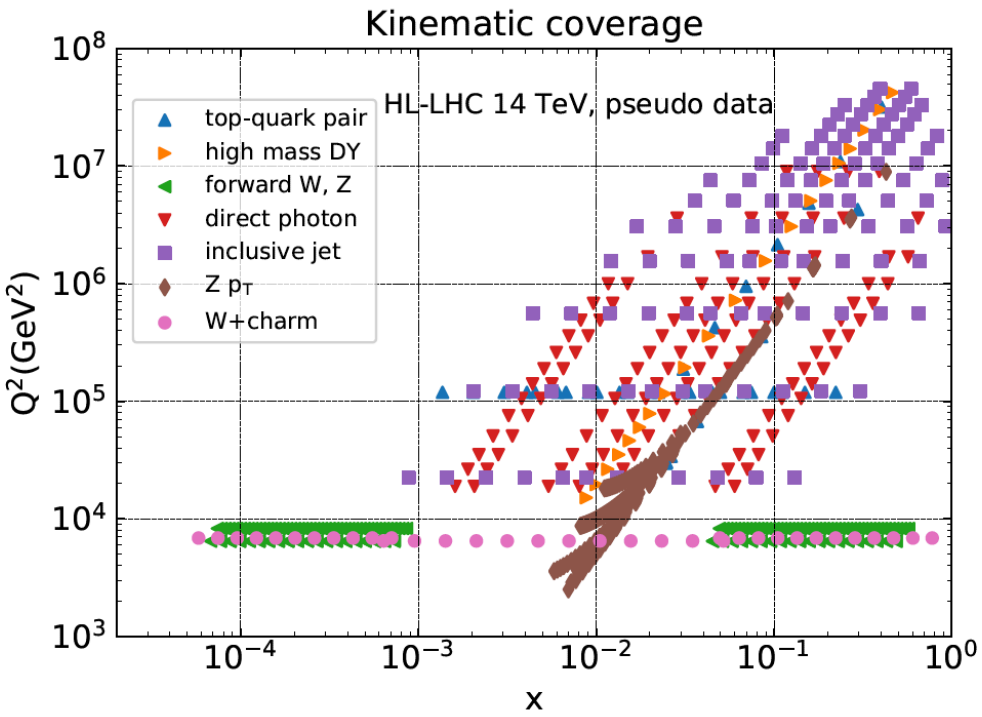








HL-LHC pdfs



study pdf constraints expected from LHC measurements **by end of HL-LHC phase**

ATLAS+CMS **3 ab^{-1}**

LHCb **0.3 ab^{-1}**

(studies in arXiv:1810.03639; prepared for CERN Yellow Report, arXiv:1902.04070)

concentrate on datasets sensitive to mid-to-high-x; and not already systematics dominated

$$\mathrm{sys}(14\ \mathrm{TeV}) \sim f_{\mathrm{corr}} \times f_{\mathrm{red}} \times \mathrm{sys}(8/13\ \mathrm{TeV})$$

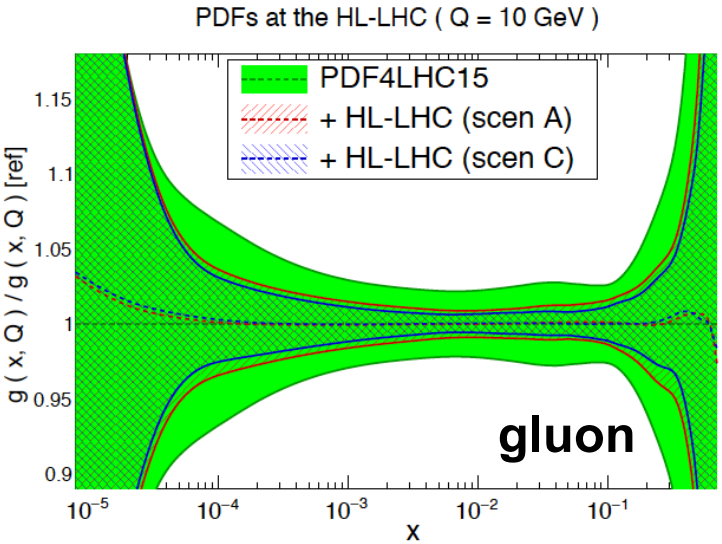
- systematic uncertainties taken from existing data;
- treated as uncorrelated, with factor **fcorr=0.5**, chosen to approximately reproduce effect of syst. correlations in existing measurements;
- variable factor **fred** to estimate improvement to systs.

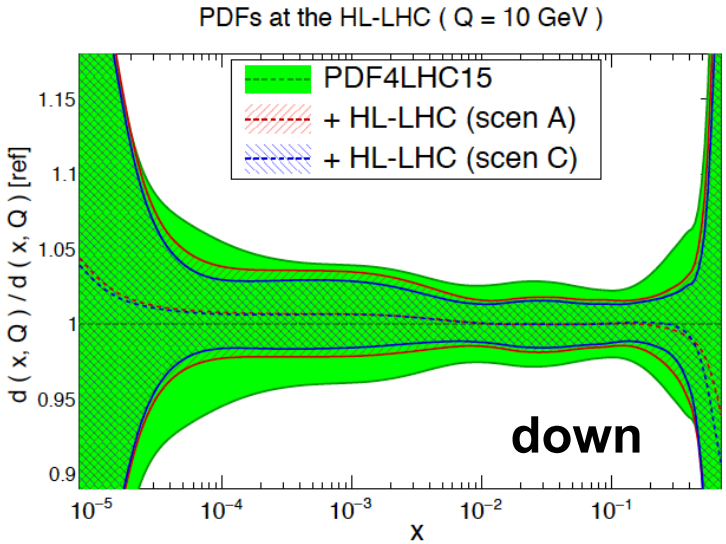
Hessian profiling of PDF4LHC15

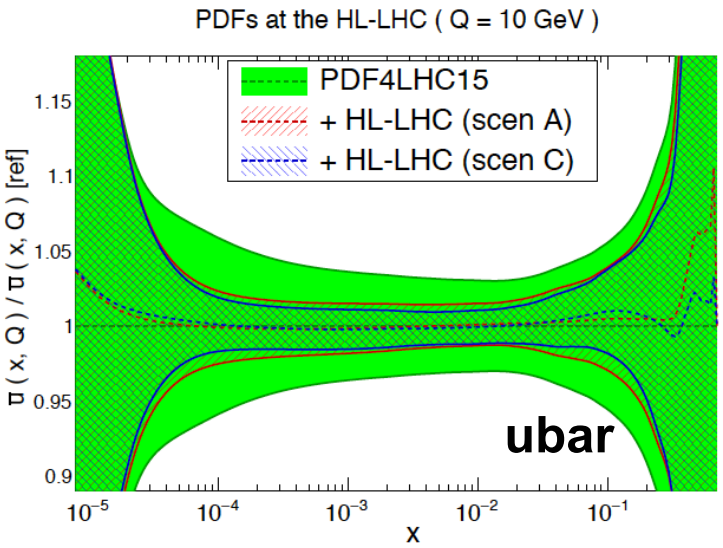
with tolerance T=3

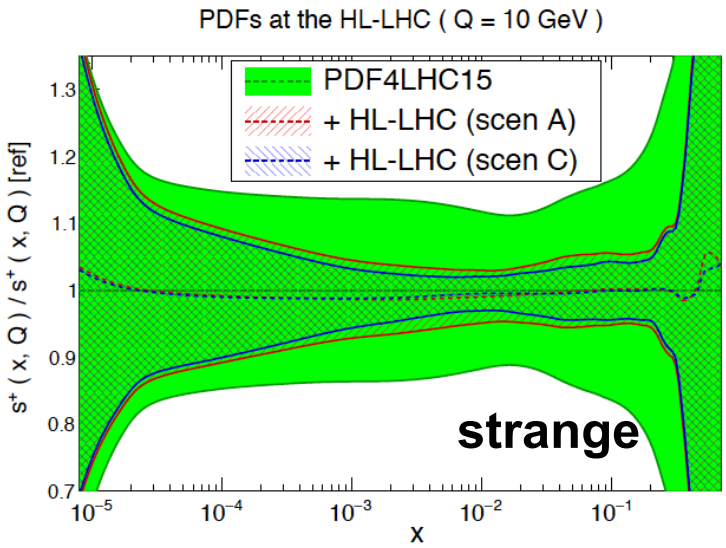
HL-LHC pdfs

arXiv:1810.03639







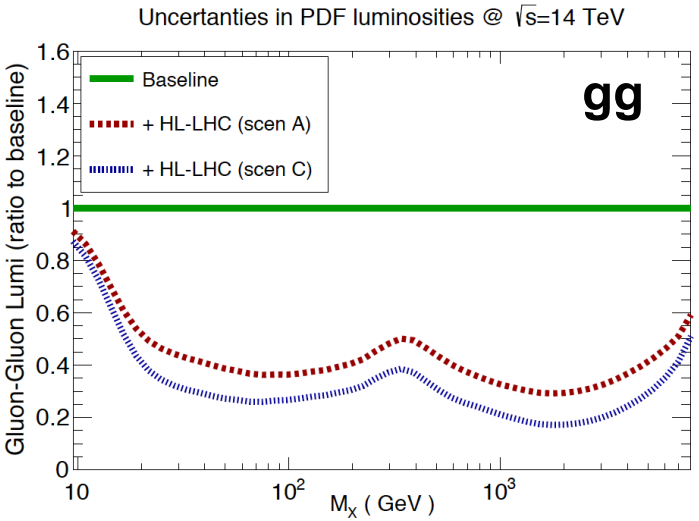


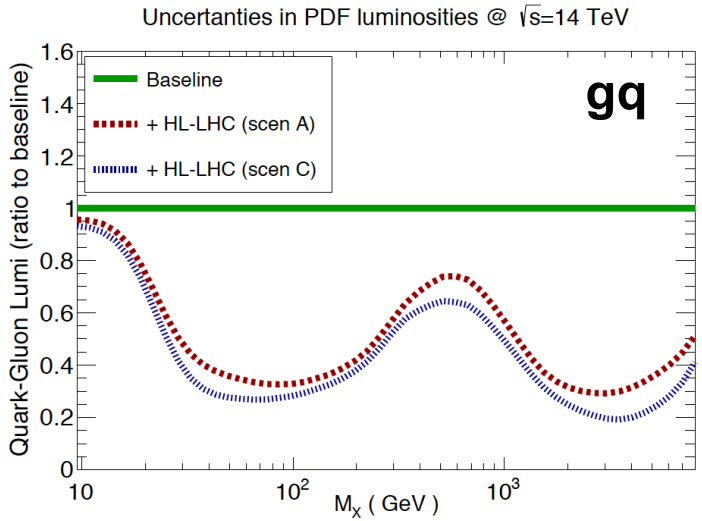
$$f_{red} = \begin{cases} 1/0.5\ (8/13)\mathrm{TeV} & \text{scenario A: } \textbf{conservative} \\ 0.4/0.2\ (8/13)\mathrm{TeV} & \text{scenario C: } \textbf{optimistic} \end{cases}$$

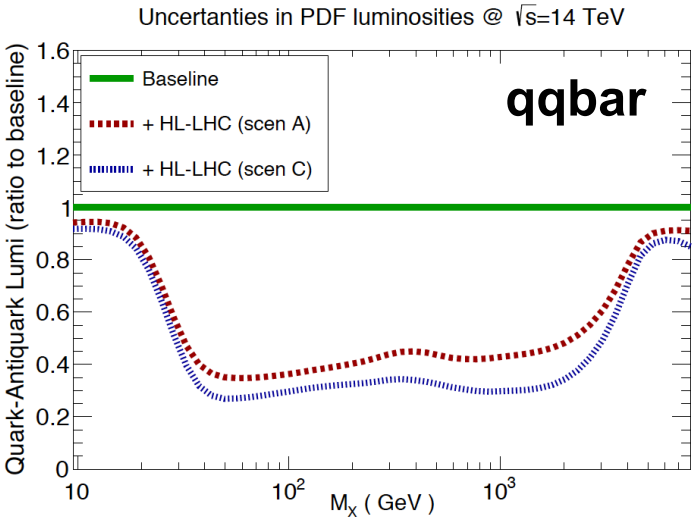
(together with **intermediate** scenario B, all are available in lhapdf format)

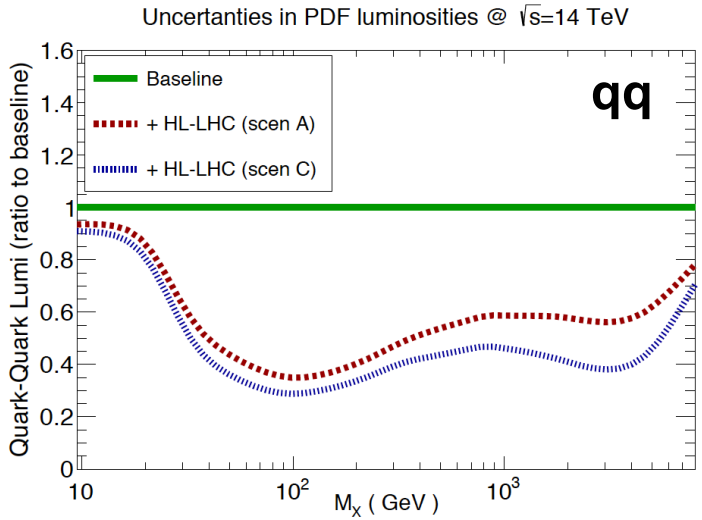
parton luminosities

arXiv:1810.03639

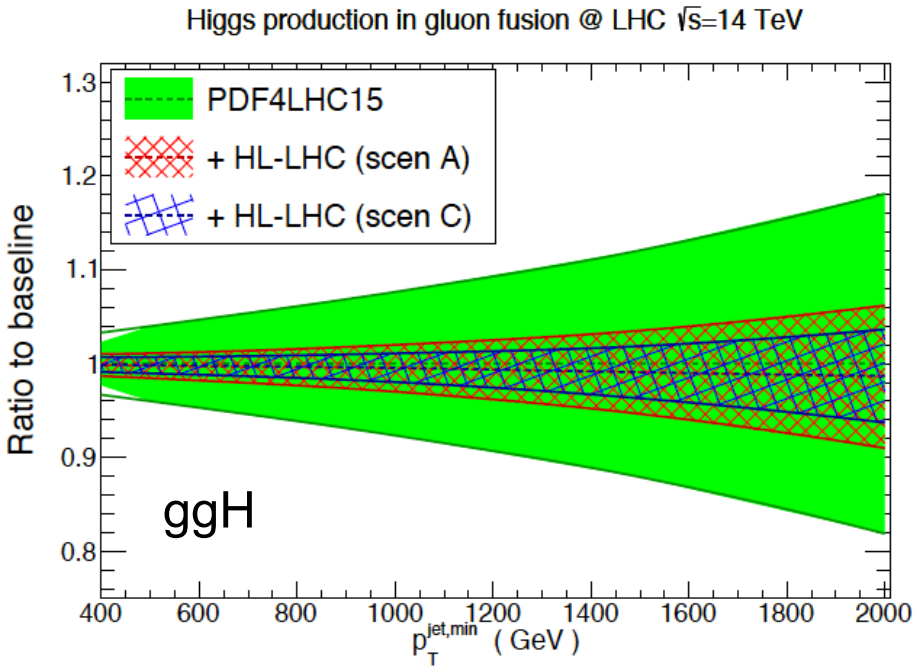


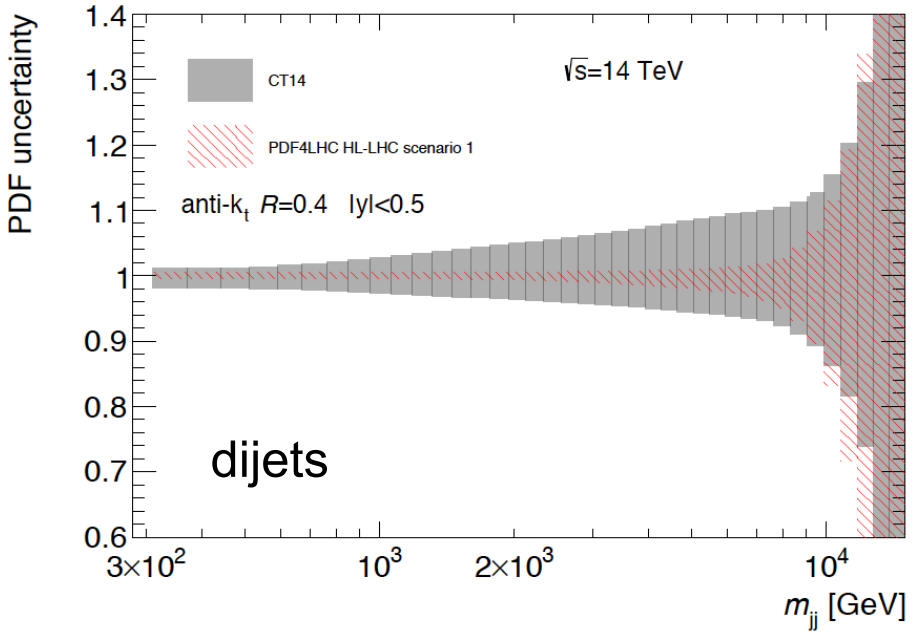






impact on LHC phenomenology





arXiv:1810.03639, and CERN yellow report, arXiv:1902.04070

summary

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

NEW ep pdf studies presented (work in progress)
all critical pdf information can be obtained early with LHeC (~50 fb-1 ≡×50 HERA), in parallel with HL-LHC operation
major new summary paper later this year;
next workshop 24 – 25 Oct.

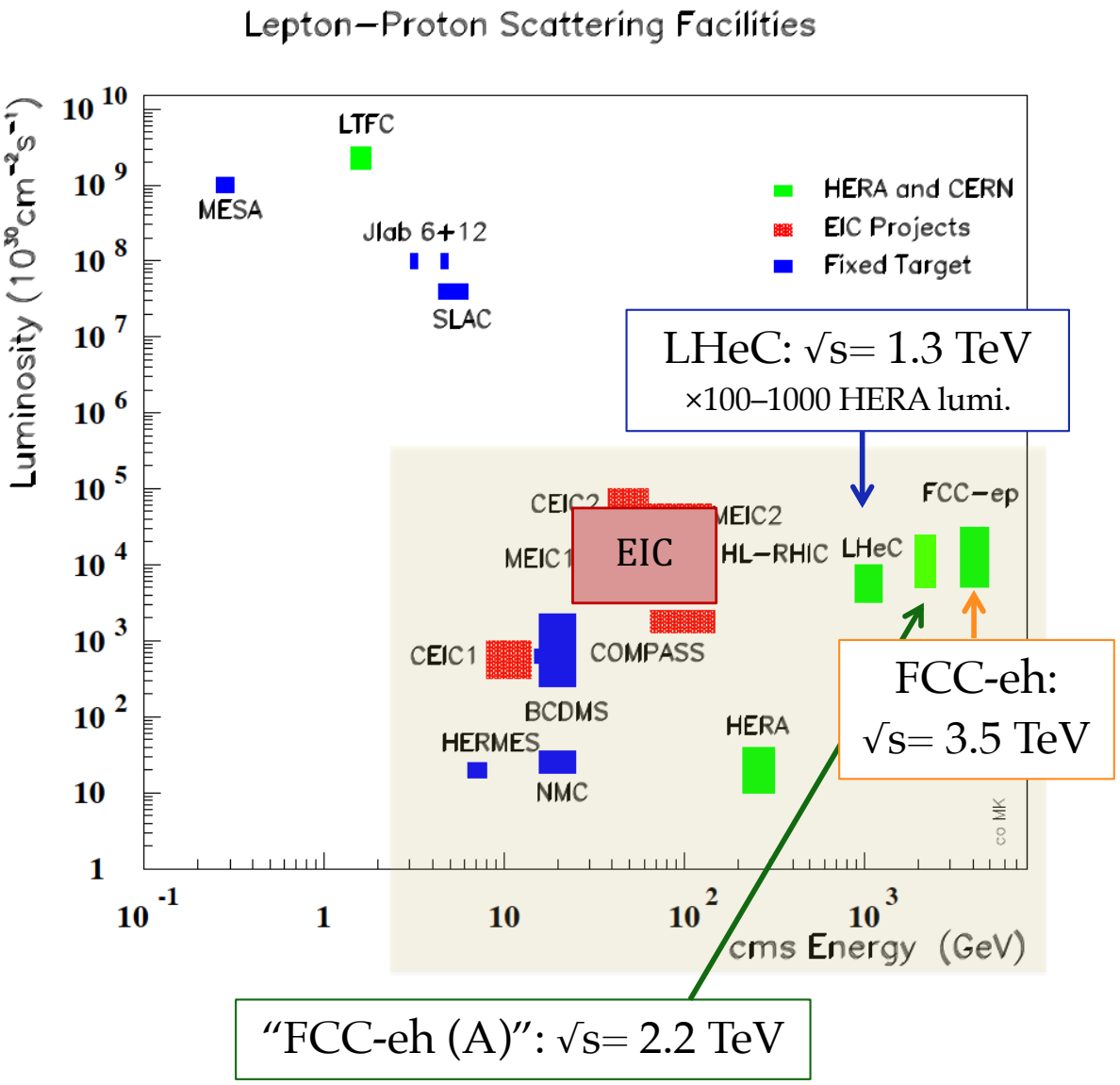
HL-LHC pdf studies indicate significant constraints;
complementarity between HL-LHC and LHeC (see also arXiv:1906.10127)

caveats: ignored issues relating to correlation models; incompatible data sets; …
not all possible data sets included in either study (EG. LHeC jet data, for further constraints on gluon at large x; HL-LHC data probing lower x; …)

electron-proton colliders essential for full exploitation of hadron machines
external precision pdf input; complete q,g unfolding, high luminosity x ⟶ 1, s, c, b, (t); N3LO; small x; strong coupling to permille precision; …

extras

ep colliders

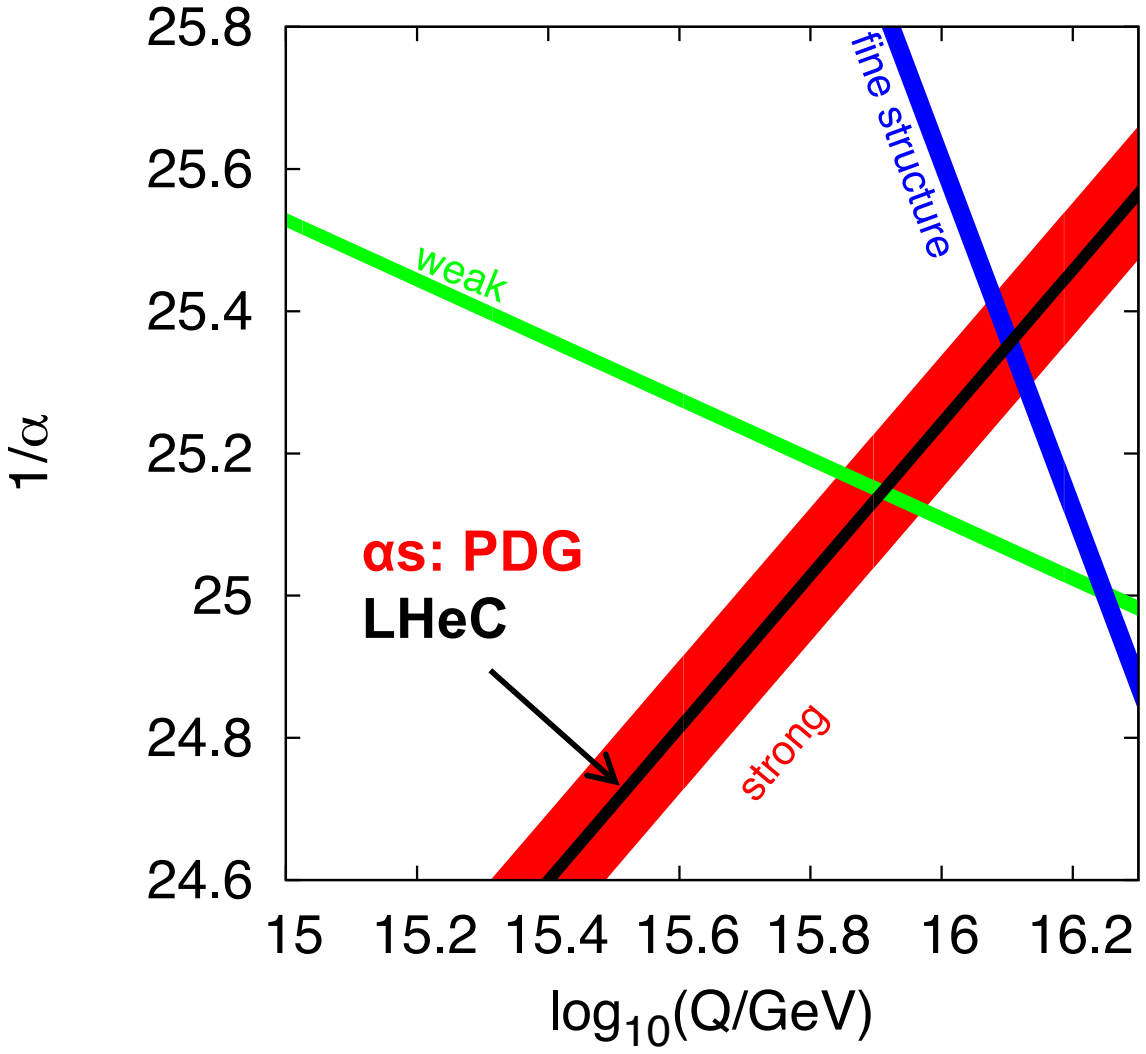


HERA: world's first and still only ep collider ($\sqrt{s} \simeq 300$ GeV)

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**)

strong coupling, αs



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

αs is least known coupling constant

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

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 α_s

case	cut $[Q^2$ in $\mathrm{GeV}^2]$	relative precision in %
HERA only (14p)	$Q^2 > 3.5$	1.94
HERA+jets (14p)	$Q^2 > 3.5$	0.82
LHeC only (14p)	$Q^2 > 3.5$	0.15
LHeC only (10p)	$Q^2 > 3.5$	0.17
LHeC only (14p)	$Q^2 > 20$	0.25
LHeC+HERA (10p)	$Q^2 > 3.5$	0.11
LHeC+HERA (10p)	$Q^2 > 7.0$	0.20
LHeC+HERA (10p)	$Q^2 > 10.$	0.26

LHeC: NC+CC inclusive; total exp. uncertainties; independent of BCDMS

arXiv:1512.05194

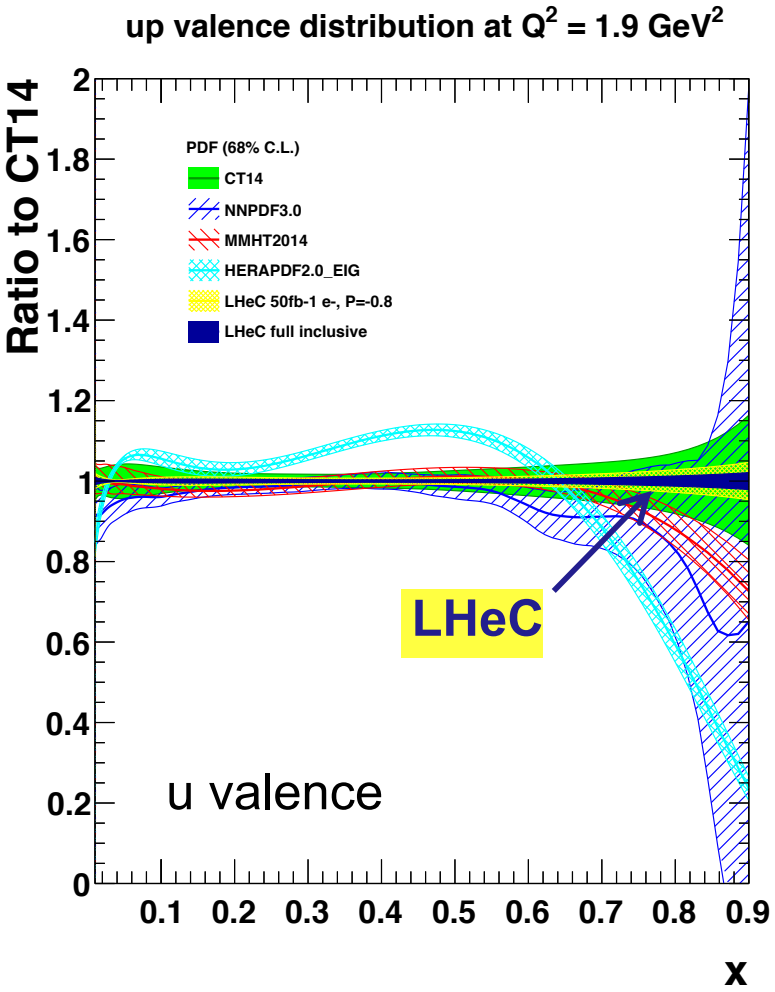
Method	Current $\delta\alpha_s(m_Z^2)/\alpha_s(m_Z^2)$ uncertainty (theory & experiment state-of-the-art)	Future $\delta\alpha_s(m_Z^2)/\alpha_s(m_Z^2)$ uncertainty (theory & experiment progress)
lattice	$\approx 1\%$ (latt. stats/spacing, N^{3}LO pQCD)	$\approx 0.1\%$ (~10 yrs) (improved computing power, N^{4}LO pQCD)
π decay factor	$1.5\%_{\rm th} \oplus 0.05\%_{\rm exp} \approx 1.5\%$ (N^{3}LO RGOPT)	$1\%_{\rm th} \oplus 0.05\%_{\rm exp} \approx 1\%$ (few yrs) (N^{4}LO RGOPT, explicit $m_{u,d,s}$)
τ decays	$1.4\%_{\rm th} \oplus 1.4\%_{\rm exp} \approx 2\%$ (N^{3}LO CIPT vs. FOPT)	$0.7\%_{\rm th} \oplus 0.7\%_{\rm exp} \approx 1\%$ (+B-factories), <1% (FCC-ee) (N^{4}LO, ~10 yrs. Improved spectral function data)
$Q\overline{Q}$ decays	$4\%_{\rm th} \oplus 4\%_{\rm exp} \approx 6\%$ (NLO only. Υ only)	$1.4\%_{\rm th} \oplus 1.4\%_{\rm exp} \approx 2\%$ (few yrs) (NNLO. More precise LDME and $R_\gamma^{\rm exp}$)
soft FFs	$1.8\%_{\rm th} \oplus 0.7\%_{\rm exp} \approx 2\%$ (NNLO* only (+NNLL), npQCD small)	$0.7\%_{\rm th} \oplus 0.7\%_{\rm exp} \approx 1\%$ (~2 yrs), <1% (FCC-ee) (NNLO+NNLL. More precise e^+e^- data: 90–350 GeV)
hard FFs	$1\%_{\rm th} \oplus 5\%_{\rm exp} \approx 5\%$ (NLO only. LEP data only)	$0.7\%_{\rm th} \oplus 2\%_{\rm exp} \approx 2\%$ (+B-factories), <1% (FCC-ee) (NNLO. More precise e^+e^- data)
global PDF fits	$1.5\%_{\rm th} \oplus 1\%_{\rm exp} \approx 1.7\%$ (Diff. NNLO PDF fits. DIS+DY data)	$0.7\%_{\rm th} \oplus 0.7\%_{\rm exp} \approx 1\%$ (few yrs), 0.15% (LHeC/FCC-eh) (N^{3}LO. Full DIS+hadronic data fit)
jets in $e^\pm$p, γ-p	$2\%_{\rm th} \oplus 1.5\%_{\rm exp} \approx 2.5\%$ (NNLO* only)	$1\%_{\rm th} \oplus 1\%_{\rm exp} \approx 1.5\%$ (few yrs), < 1% (FCC-eh) (NNLO. Combined DIS + (extra?) γ-p data)
F_2^γ in γ-γ	$3.5\%_{\rm th} \oplus 3\%_{\rm exp} \approx 4.5\%$ (NLO only)	$1\%_{\rm th} \oplus 2\%_{\rm exp} \approx 2\%$ (~2 yrs), <1% (FCC-ee) (NNLO. More precise new F_2^γ data)
e^+e^- evt shapes	$(1.5–4)\%_{\rm th} \oplus 1\%_{\rm exp} \approx (1.5–4)\%$ (NNLO+N$^{(3)}$LL, npQCD significant)	$1\%_{\rm th} \oplus 1\%_{\rm exp} \approx 1.5\%$ (+B-factories), < 1% (FCC-ee) (NNLO+N^{3}LL. Improved npQCD via $\sqrt{s}$-dep. New data)
jets in e^+e^-	$(2–5)\%_{\rm th} \oplus 1\%_{\rm exp} \approx (2–5)\%$ (NNLO+NLL, npQCD moderate)	$1\%_{\rm th} \oplus 1\%_{\rm exp} \approx 1.5\%$ (few yrs), < 1% (FCC-ee) (NNLO+NNLL. Improved npQCD. New high-$\sqrt{s}$ data)
W decays	$0.7\%_{\rm th} \oplus 37\%_{\rm exp} \approx 37\%$ (N^{3}LO, npQCD small. Low-stats data)	$(0.7–0.1)\%_{\rm th} \oplus (10–0.1)\%_{\rm exp} \approx (10–0.15)\%$ (LHC,FCC-ee) (N^{4}LO, ~10 yrs. High-stats/precise W data)
Z decays	$0.7\%_{\rm th} \oplus 2.4\%_{\rm exp} \approx 2.5\%$ (N^{3}LO, npQCD small)	$0.1\%_{\rm th} \oplus (0.5–0.1)\%_{\rm exp} \approx (0.5–0.15)\%$ (ILC,FCC-ee) (N^{4}LO, ~10 yrs. High-stats/precise Z data)
jets in p-p, p-$\overline{\rm p}$	$3.5\%_{\rm th} \oplus (2–3)\%_{\rm exp} \approx (4–5)\%$ (NLO only. Combined exp. observables)	$1\%_{\rm th} \oplus 1\%_{\rm exp} \approx 1.5\%$ (Tevatron+LHC, ~2 yrs) (NNLO. Multiple datasets+observables)
$t\bar{t}$ in p-p, p-$\overline{\rm p}$	$1.5\%_{\rm th} \oplus 2\%_{\rm exp} \approx 2.5\%$ (NNLO+NNLL. CMS only)	$1\%_{\rm th} \oplus 1\%_{\rm exp} \approx 1.5\%$ (Tevatron+LHC, ~2 yrs) (Improved $m_{\rm top}^{\rm pole}$ & PDFs. Multiple datasets)

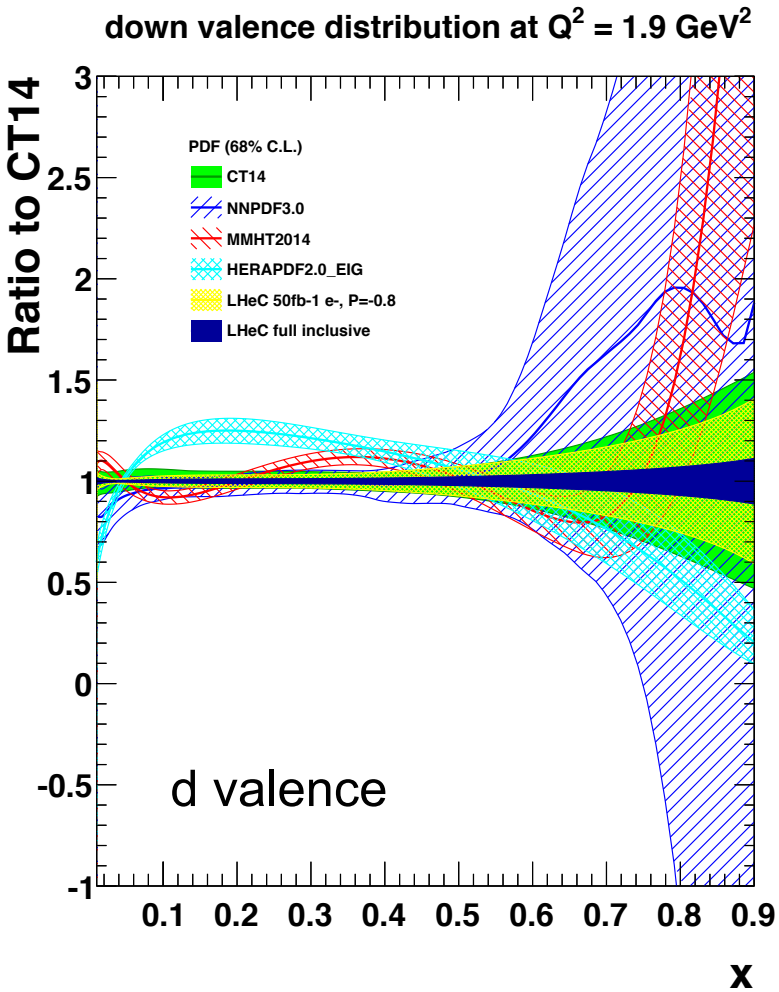
lattice QCD

ep: per mille level (LHeC/FCC-eh combined with HERA)

ee: order **per mille** with an FCC-ee

valence quarks from LHeC



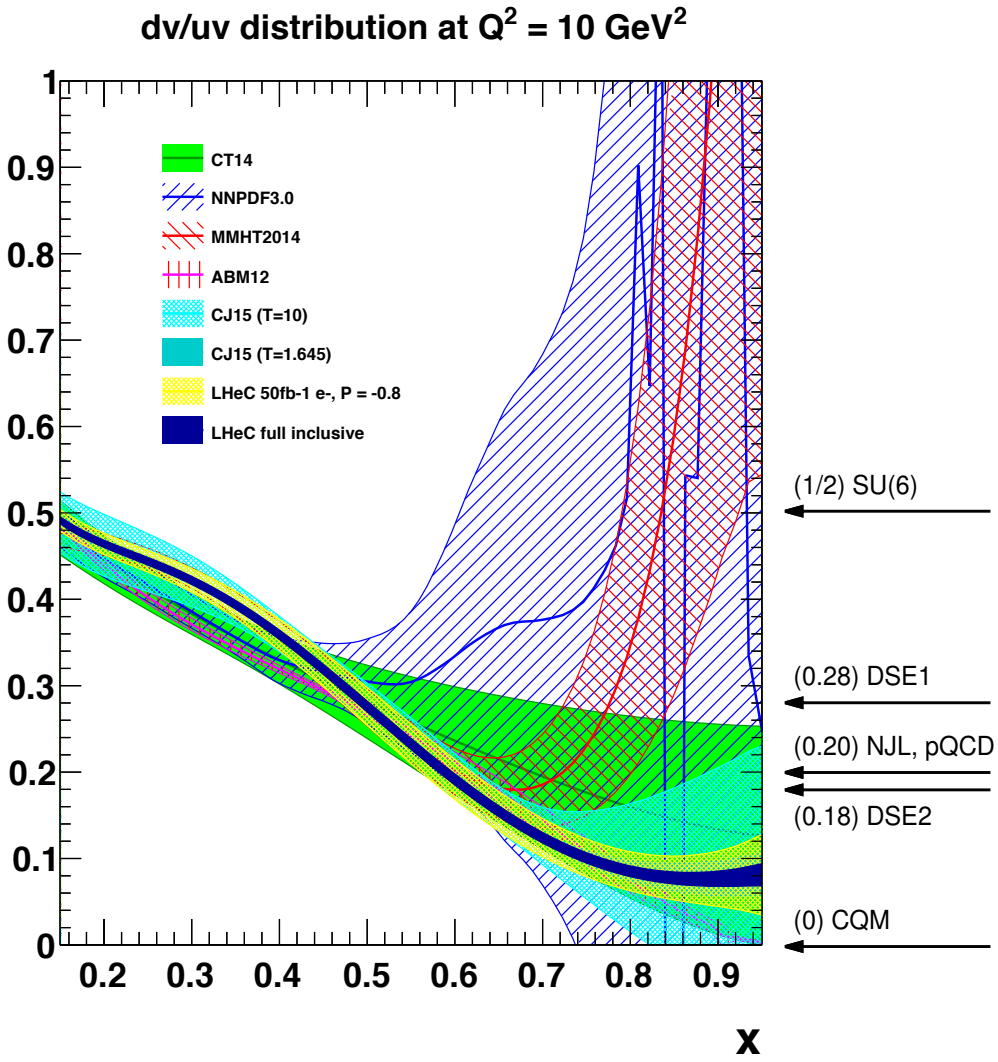


precision determination; free from higher twist corrections and nuclear uncertainties

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

resolve long-standing mystery of d/u ratio; …

d/u at large x

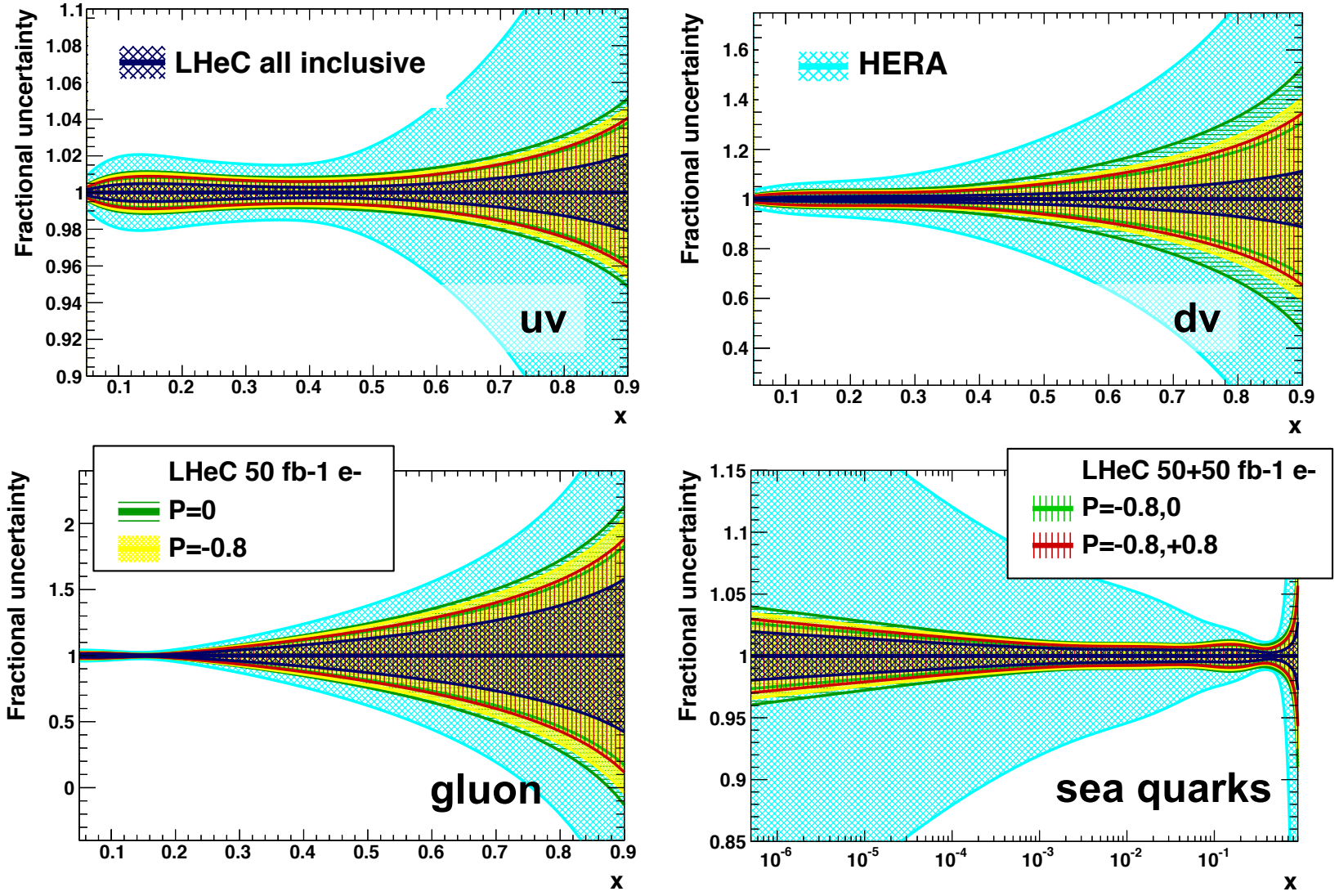


d/u essentially unknown at large x

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)

LHeC studies: 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

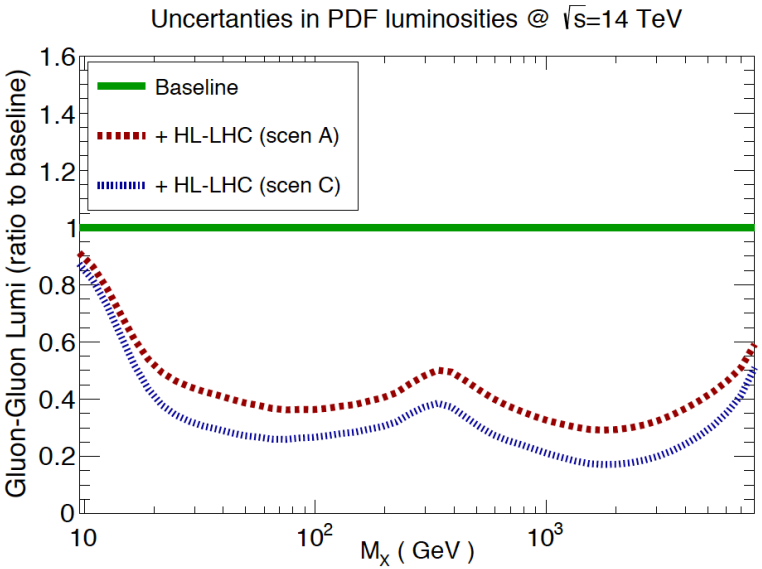
5+1 pdf fit for HQ studies parameterises dbar and sbar separately, and has 17 free parameters

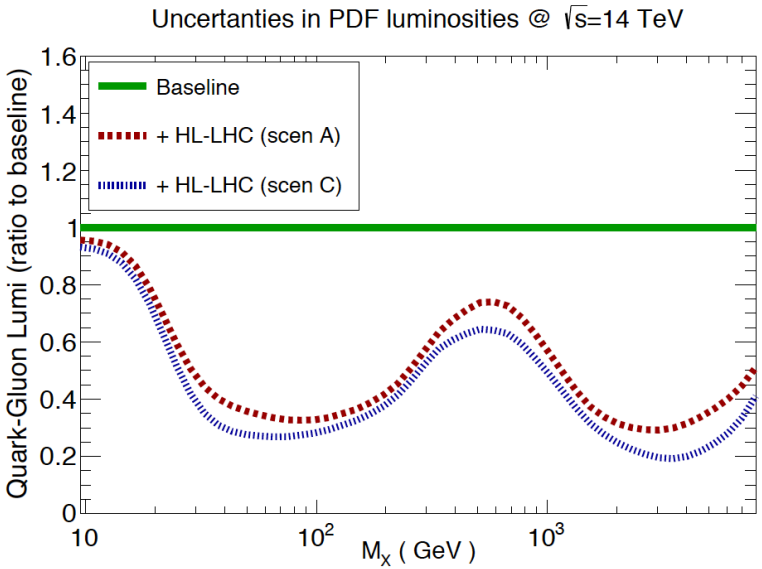
HL-LHC pdfs

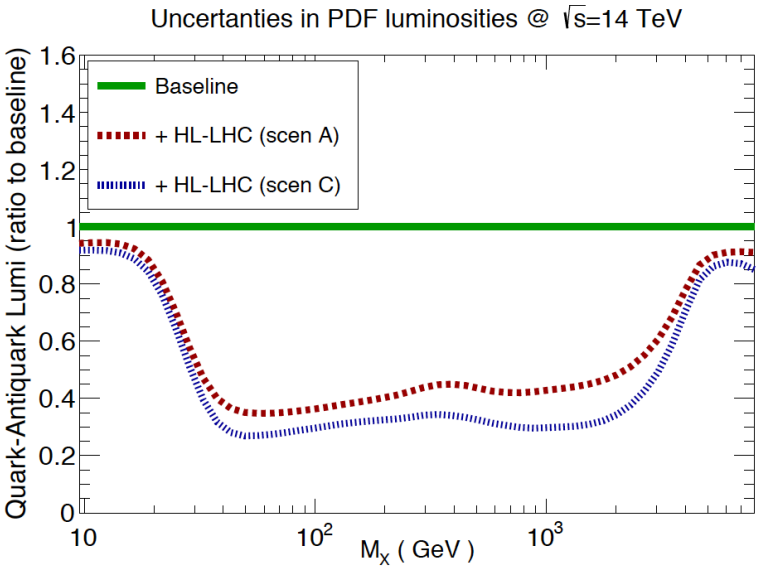
Scenario	$f_{\rm red}$ (8 TeV)	$f_{\rm red}$ (13 TeV)	LHAPDF set	Comments
A	1	0.5	PDF4LHC_nnlo_hllhc_scen1	Conservative
B	0.7	0.36	PDF4LHC_nnlo_hllhc_scen2	Intermediate
C	0.4	0.2	PDF4LHC_nnlo_hllhc_scen3	Optimistic

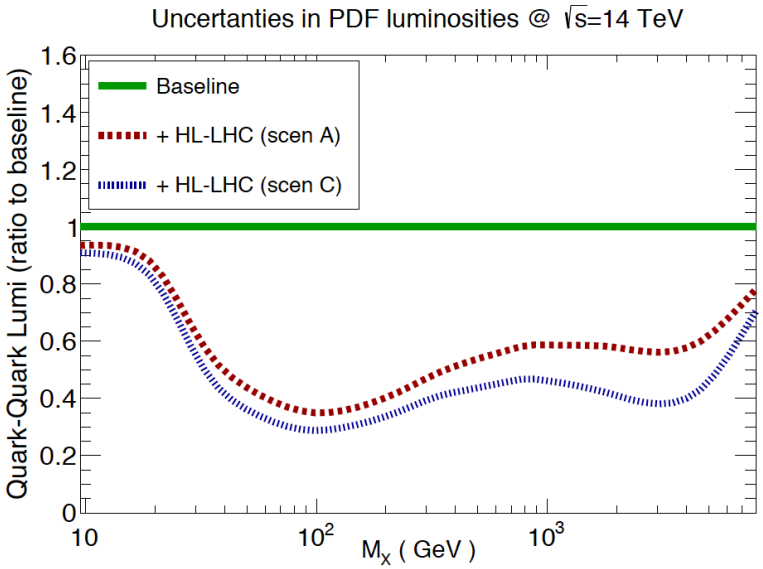
Table 4.1. The three scenarios for the systematic uncertainties of the HL–LHC pseudo–data that we assume in the present study. These scenarios, ranging from conservative to optimistic, differ among them in the reduction factor $f_{\rm red}$, Eq. (2.2), applied to the systematic errors of the reference 8 TeV or 13 TeV measurements. We also indicate in each case the name of the corresponding LHAPDF grid.

arXiv:1810.03639

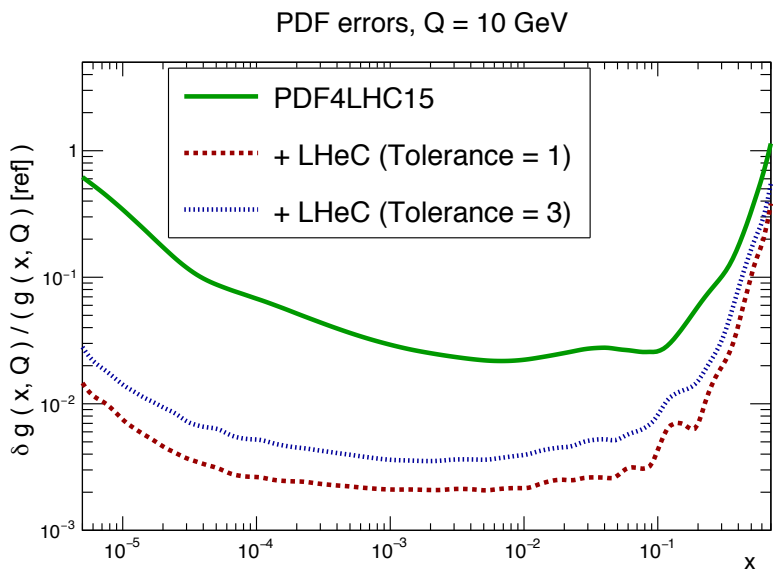


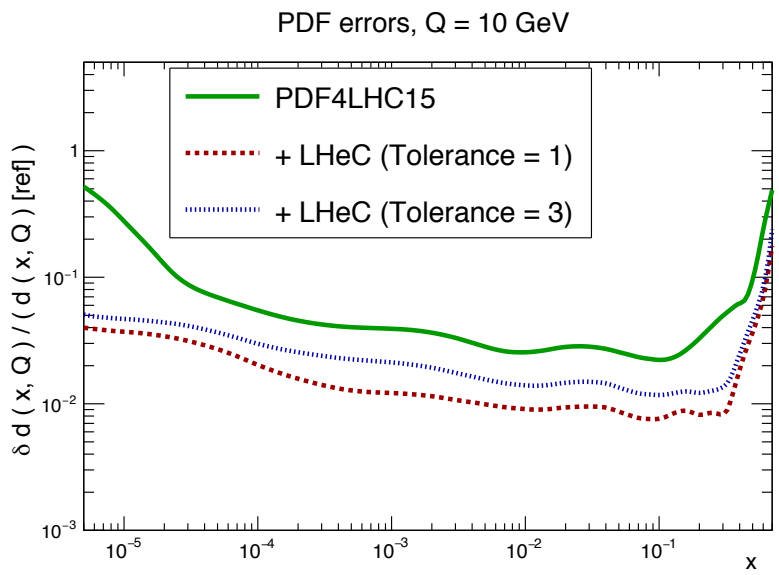


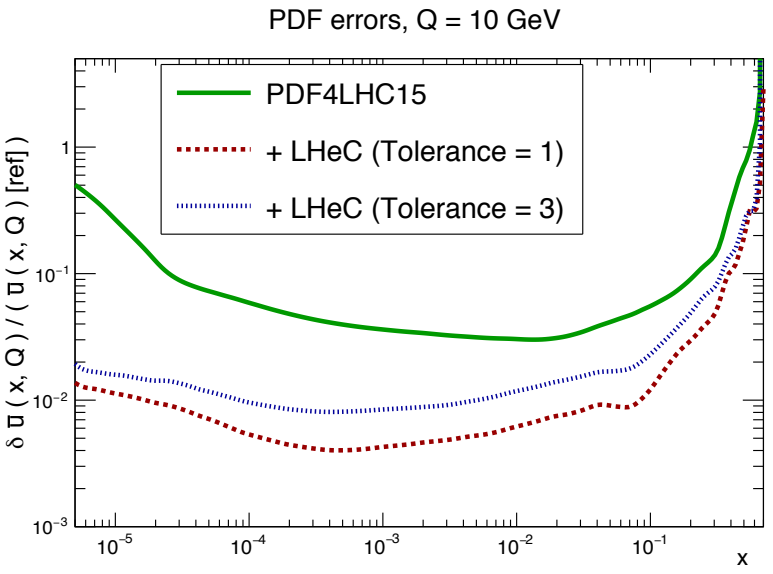


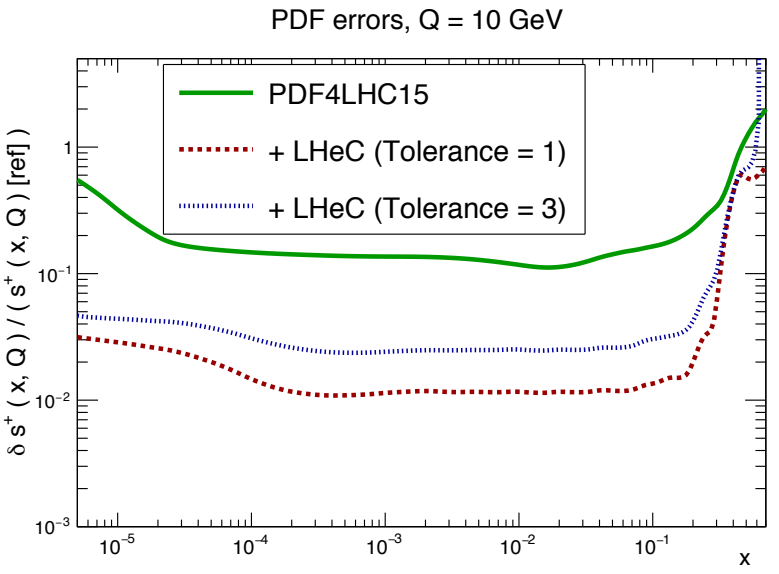


arXiv:1906.10127



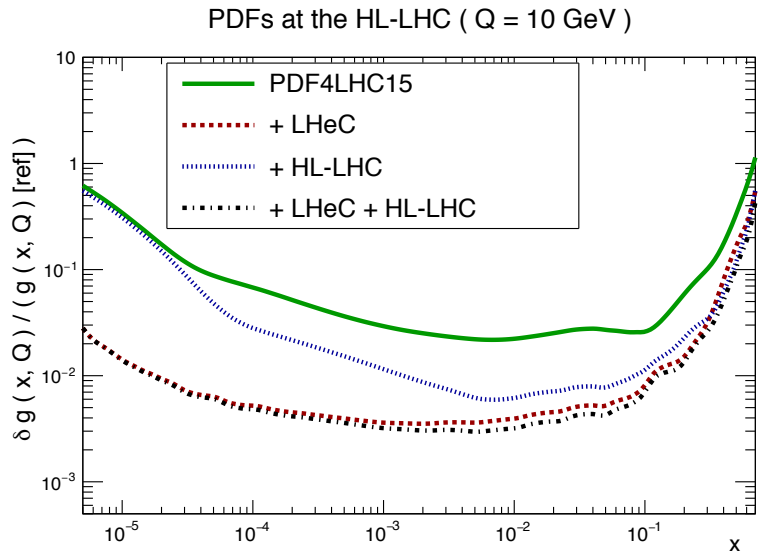


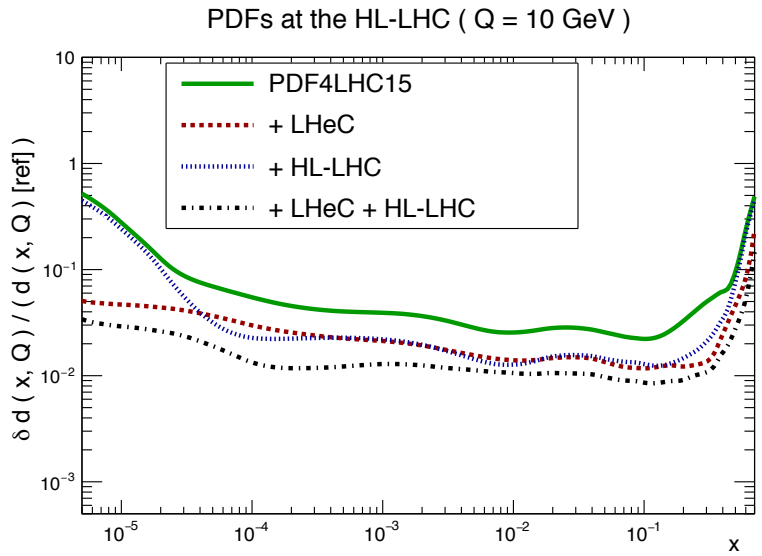


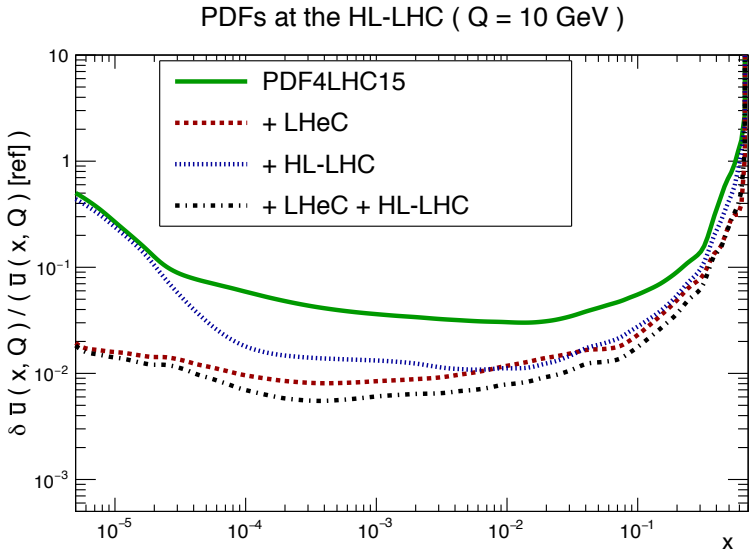


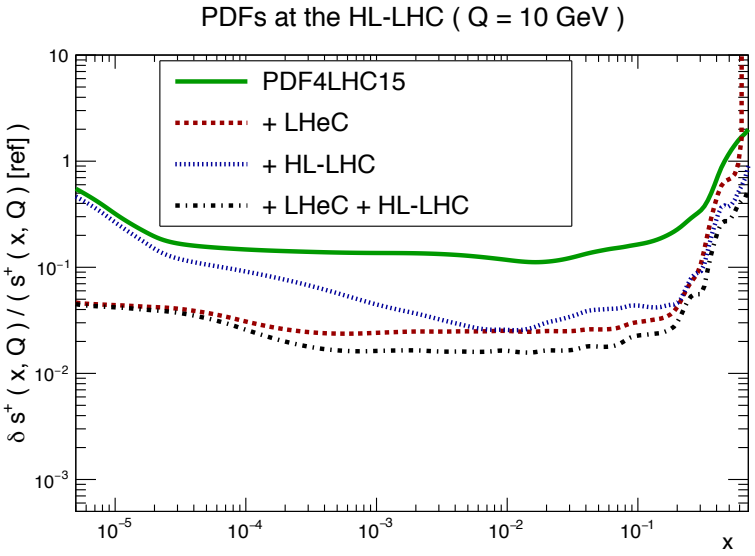
PDF4LHC15 profiled with (previous iteration of) LHeC inclusive+HQ simulated data

arXiv:1906.10127



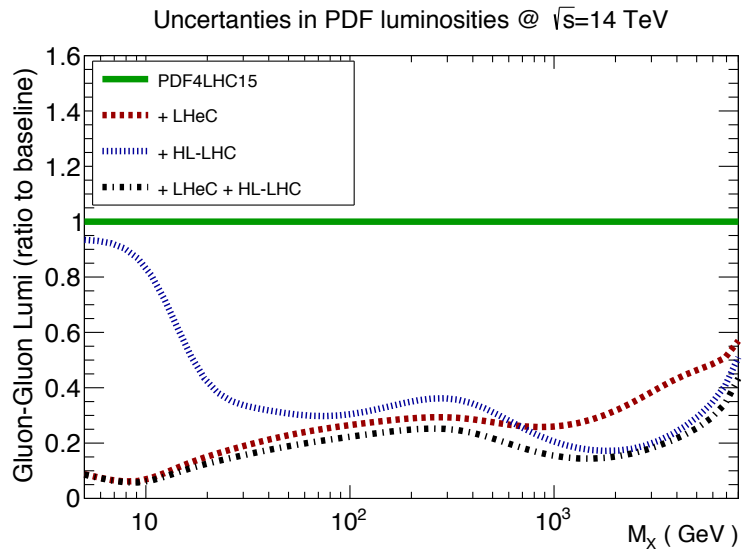


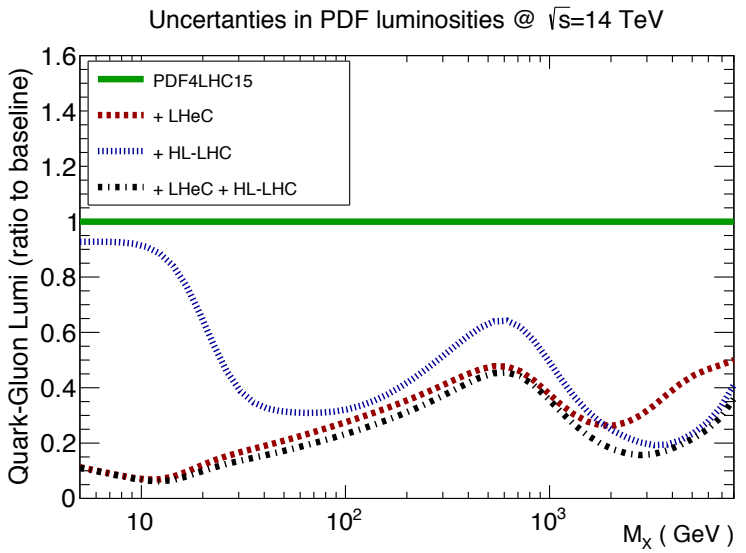


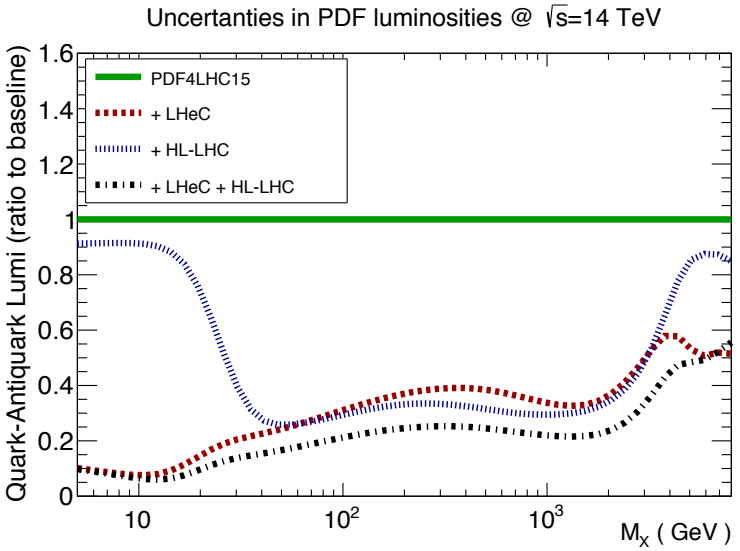


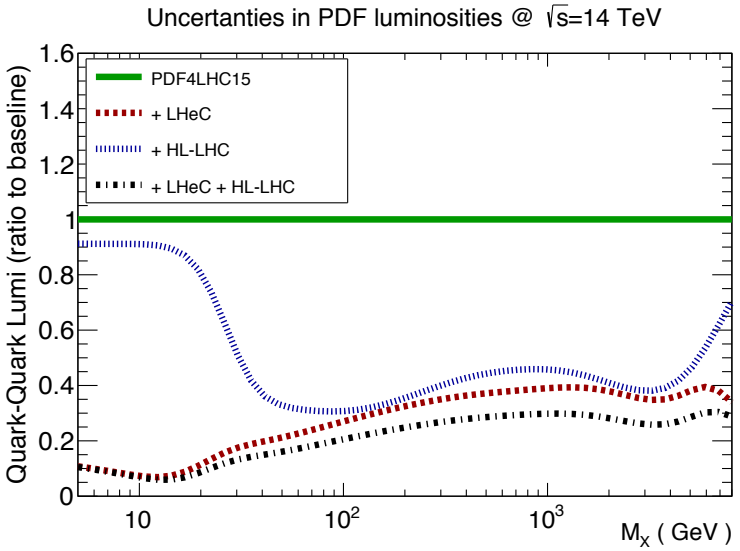
PDF4LHC15 profiled with LHeC inclusive+HQ and HL-LHC simulated data

arXiv:1906.10127





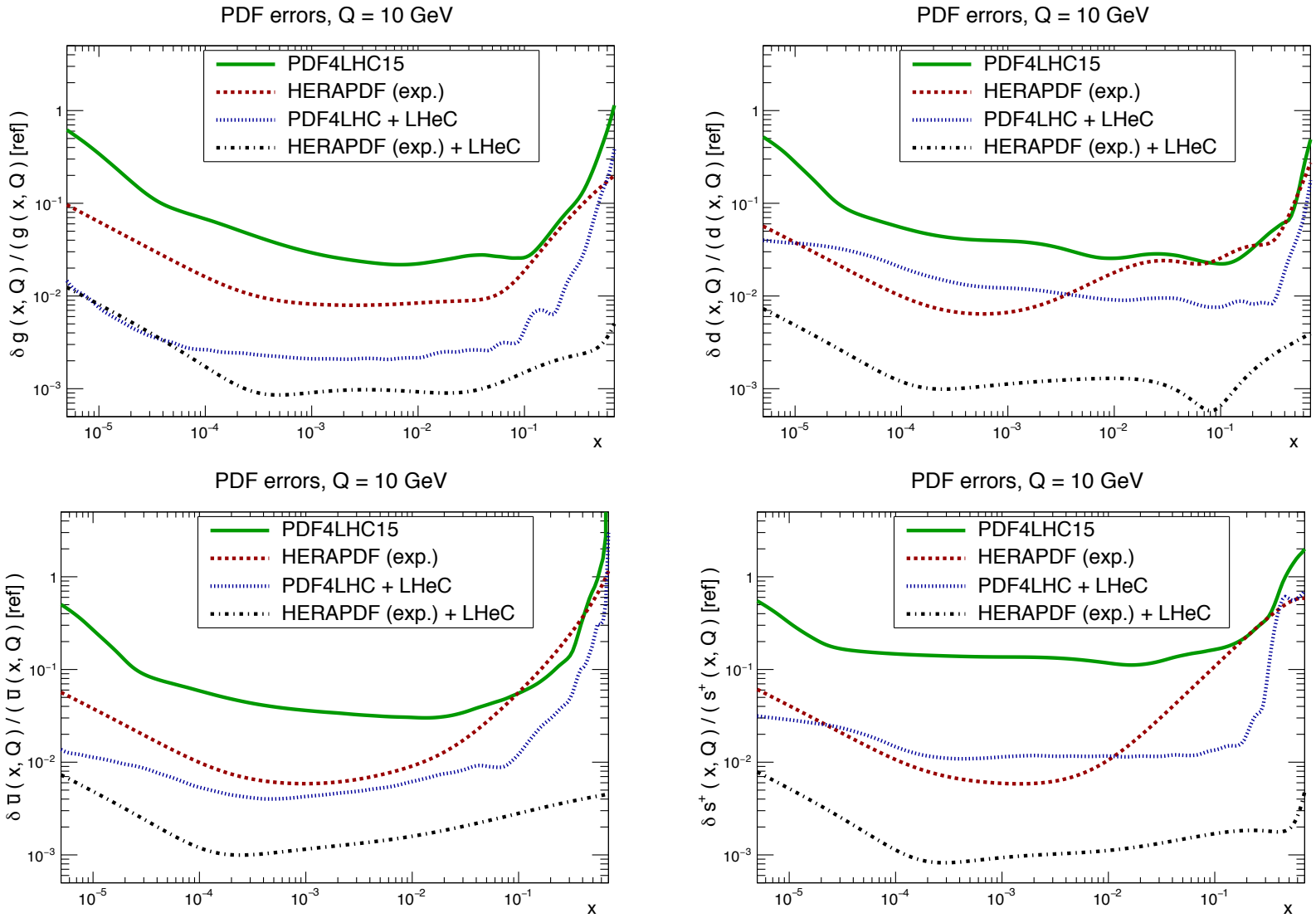




PDF4LHC15 profiled with LHeC inclusive+HQ and HL-LHC simulated data

arXiv:1906.10127

T=1



PDF4LHC15 and HERAPDF profiled with LHeC inclusive+HQ simulated data

arXiv:1906.10127

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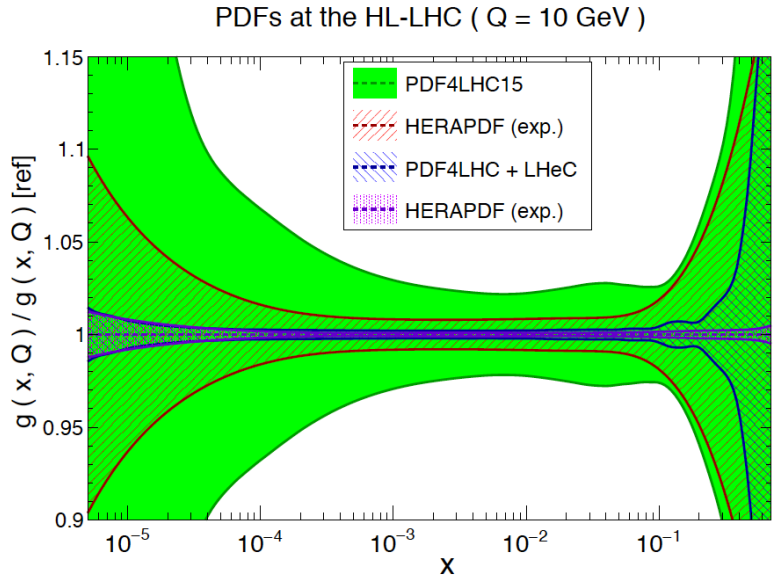
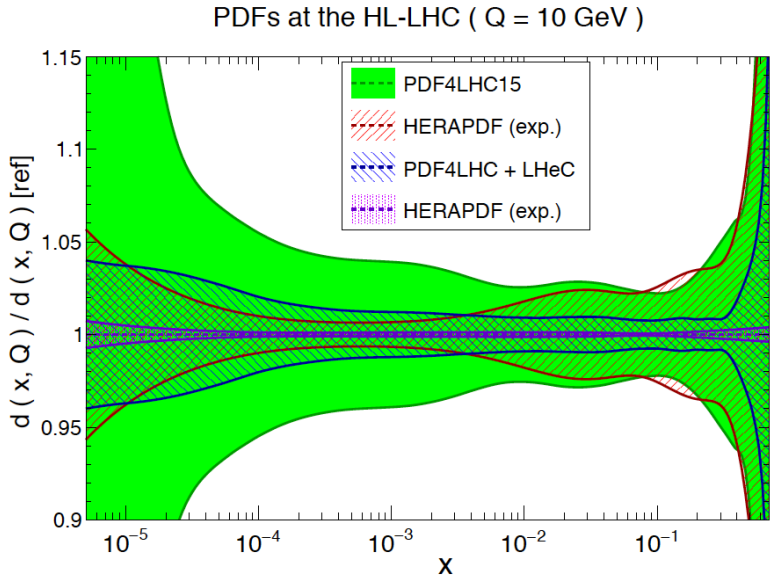
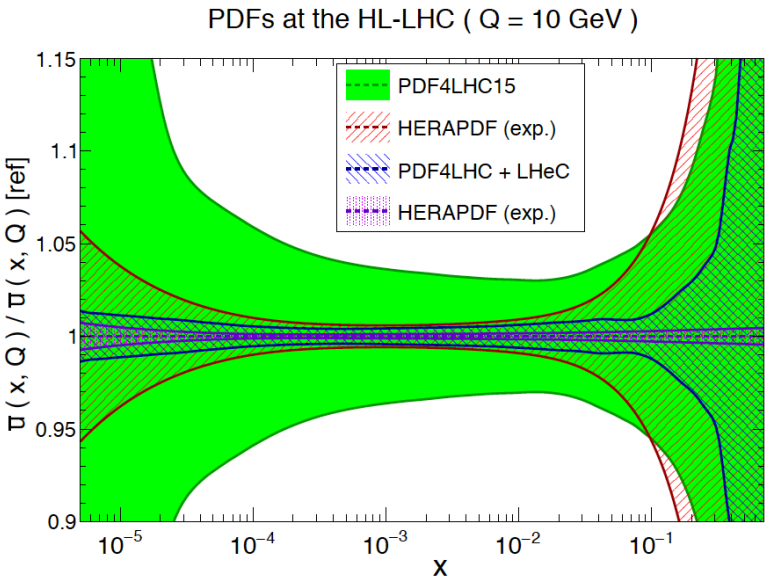
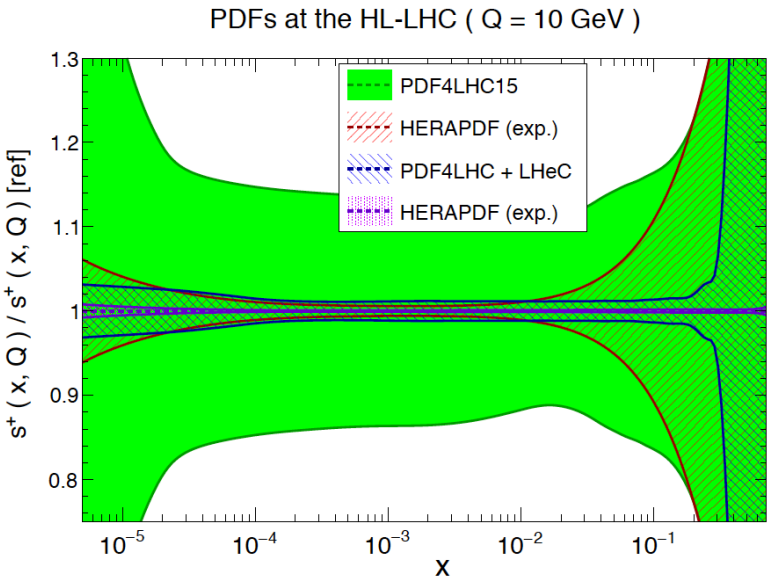




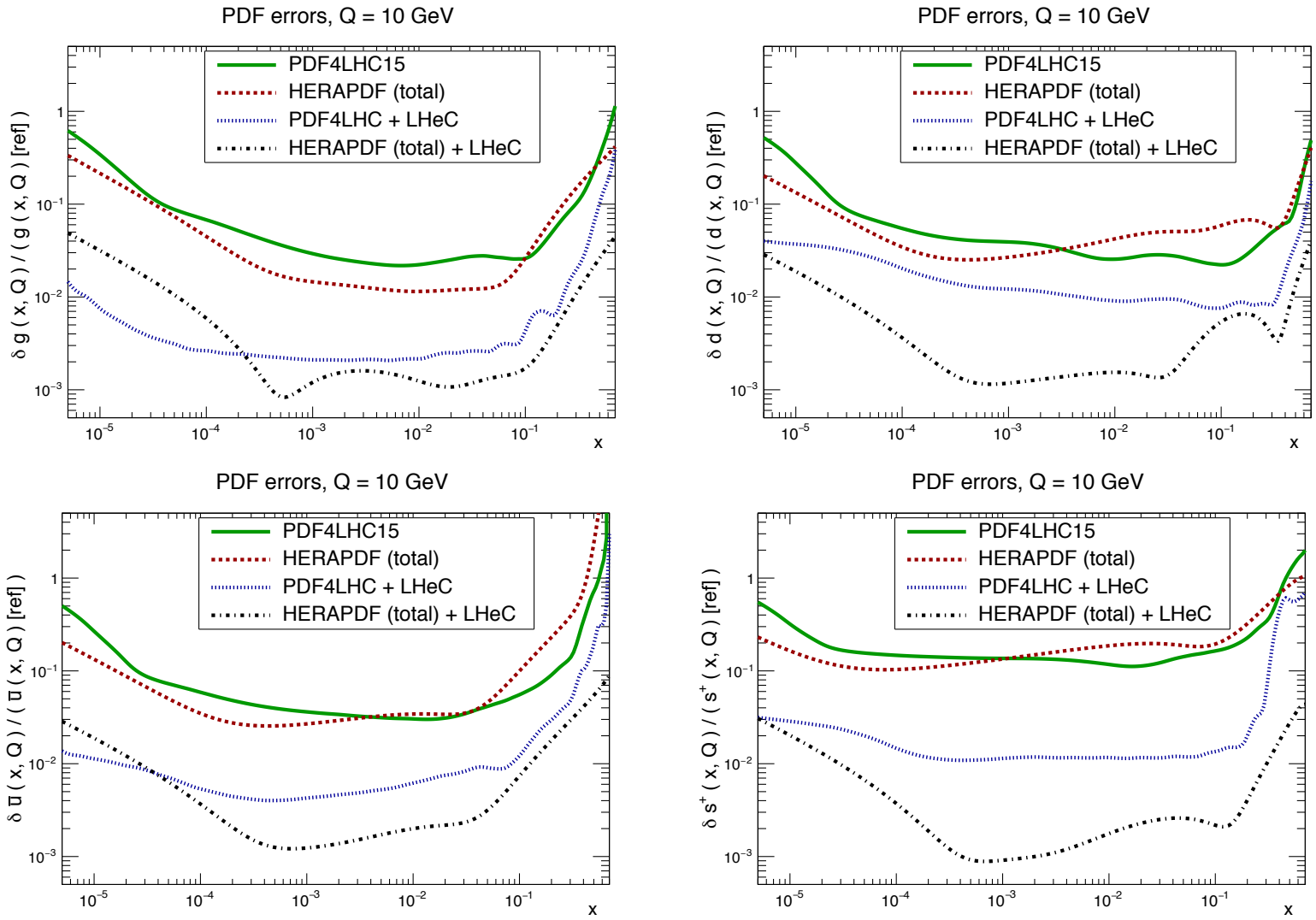




PDF4LHC15 and HERAPDF profiled with LHeC inclusive+HQ simulated data

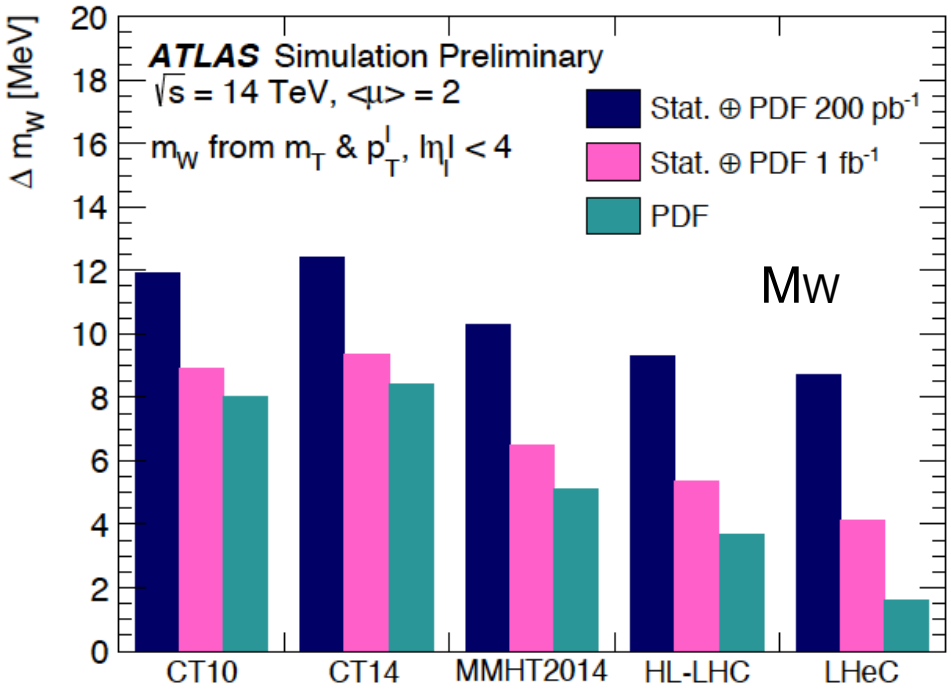
arXiv:1906.10127

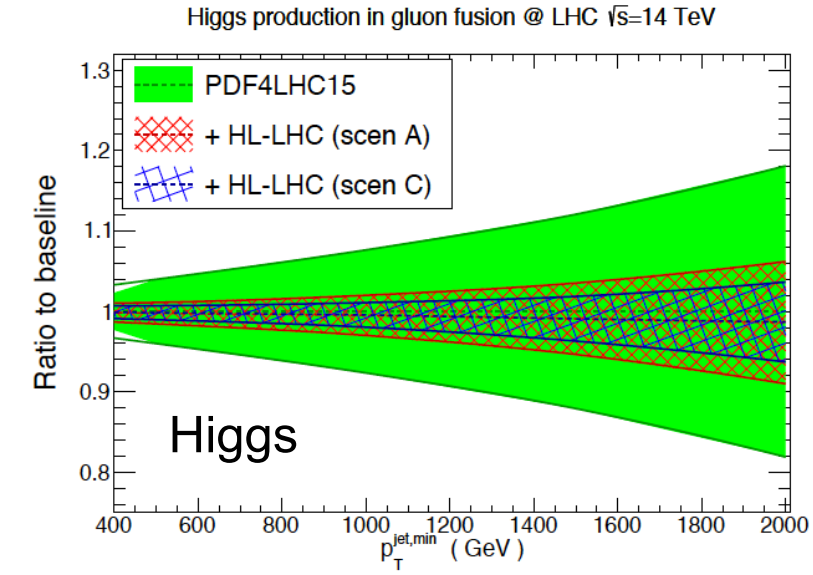
T=1

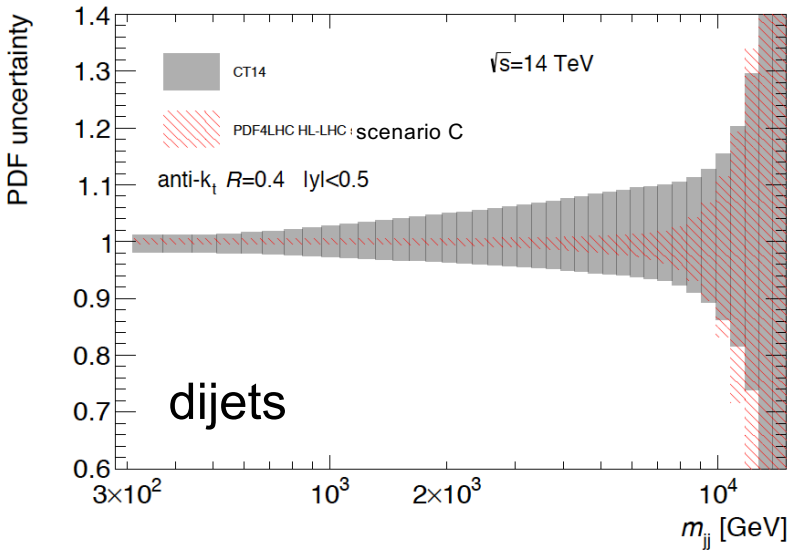


PDF4LHC15 and HERAPDF (total uncerts) profiled with LHeC inclusive+HQ simulated data

impact on LHC phenomenology



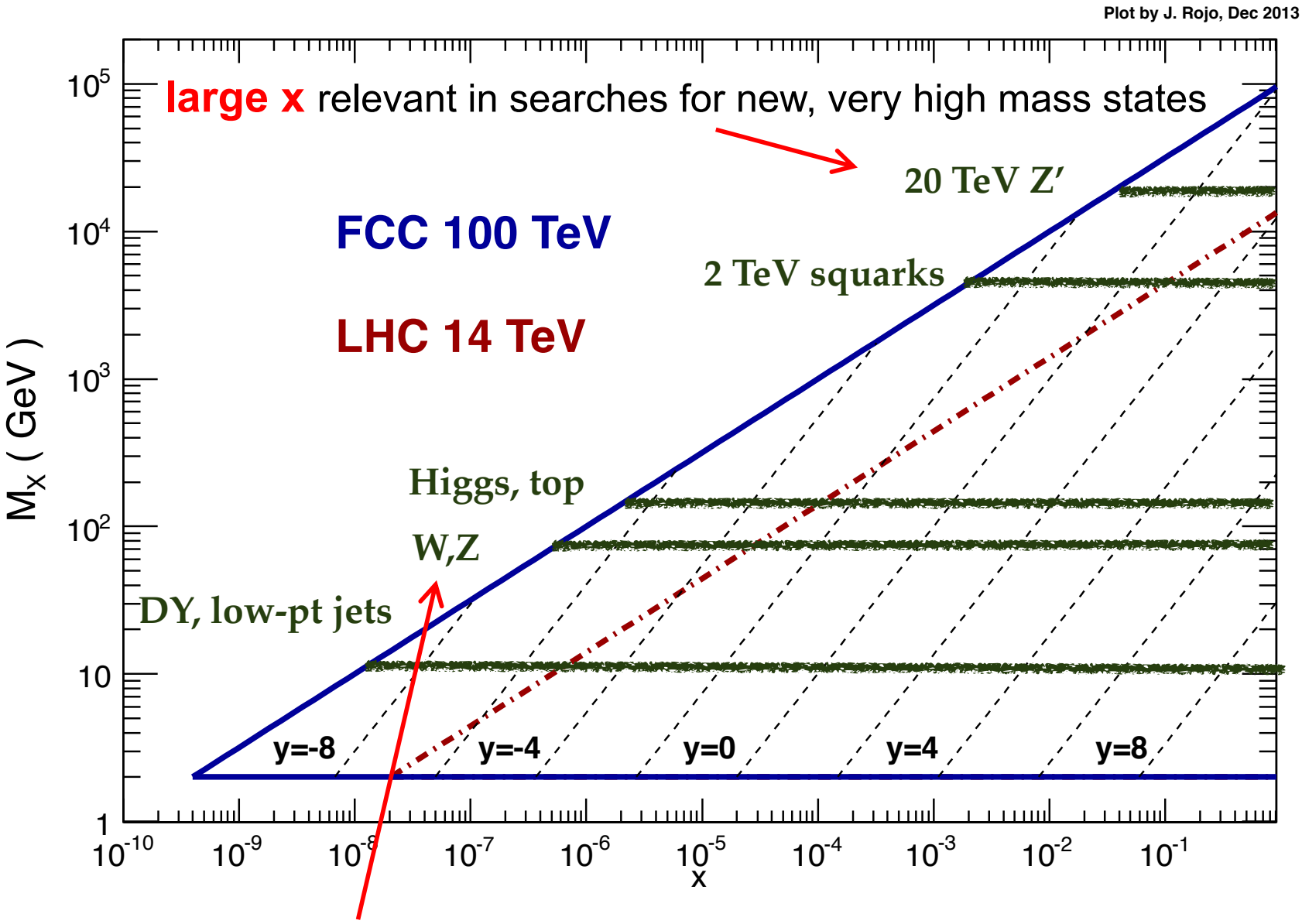




arXiv:1810.03639,

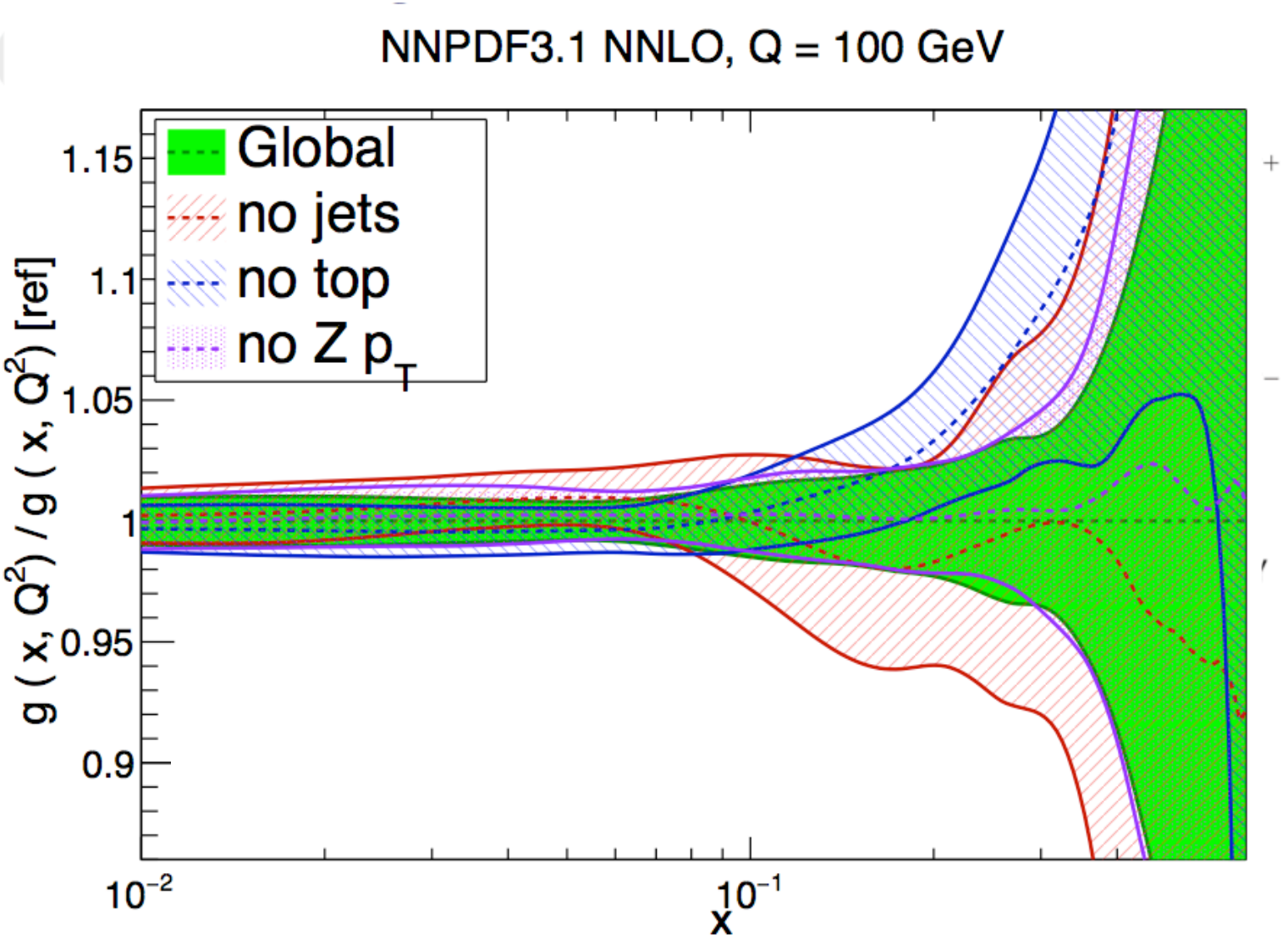
and CERN yellow report, arXiv:1902.04070

Kinematics of a 100 TeV FCC

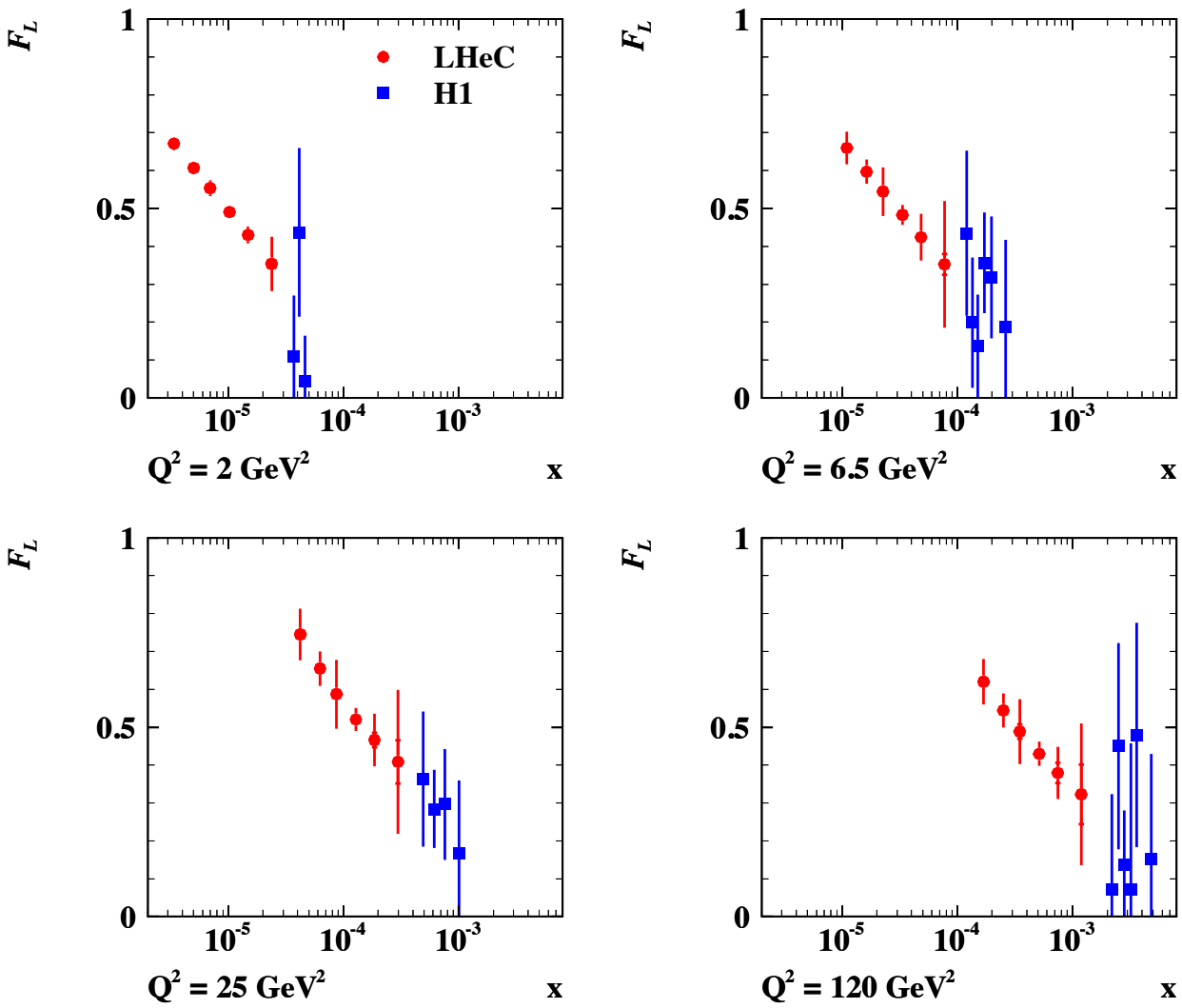


small x becomes relevant even for "common" physics (EG. W, Z, H, t)

impact of LHC on today's pdfs



FL at LHeC



M. Klein, arXiv:1802.04317