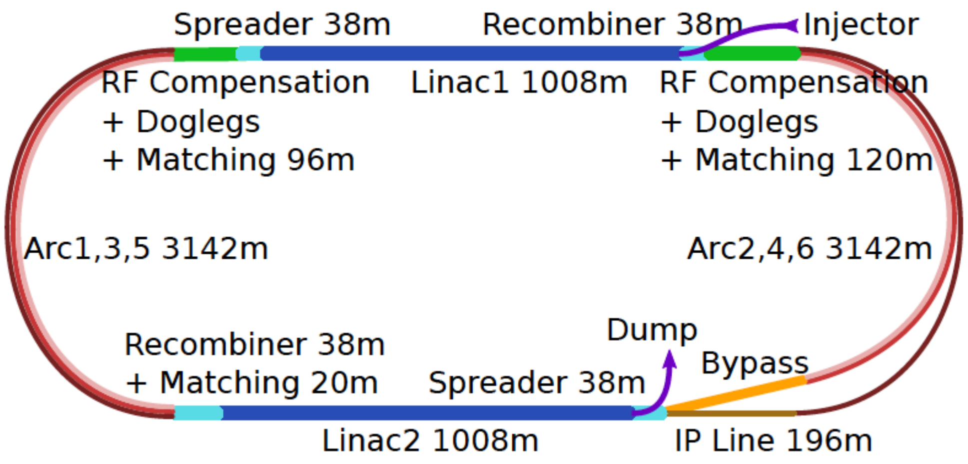
precision QCD with the LHeC and FCC-eh

Claire Gwenlan, Oxford

with special thanks to M. Klein, U. Klein, G. Pownall

UNIVERSITY OF OXFORD

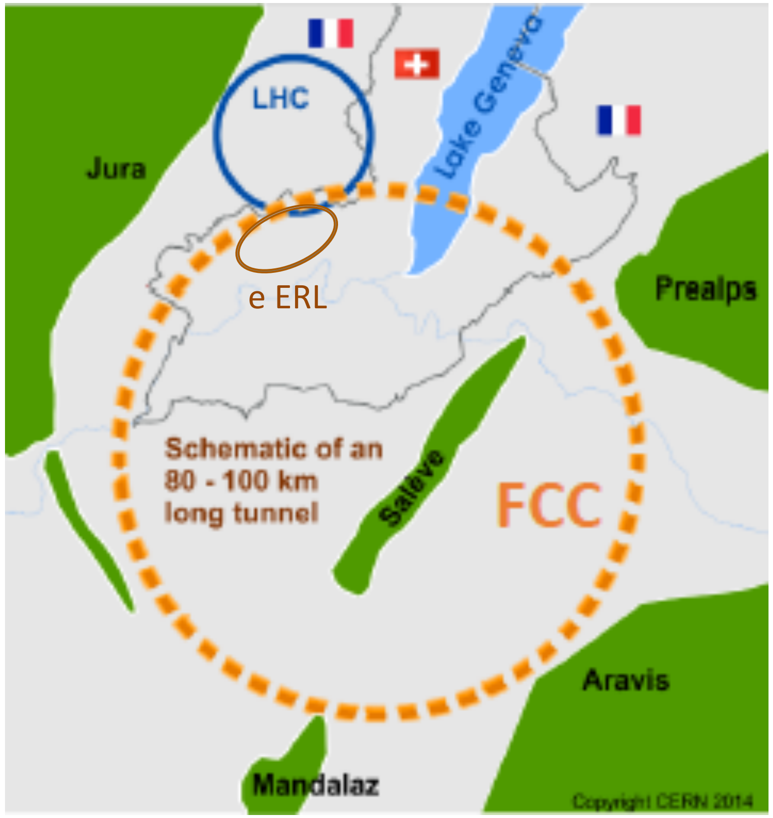
LHeC and FCC-eh



energy recovery LINAC

e beam: up to 60 GeV

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

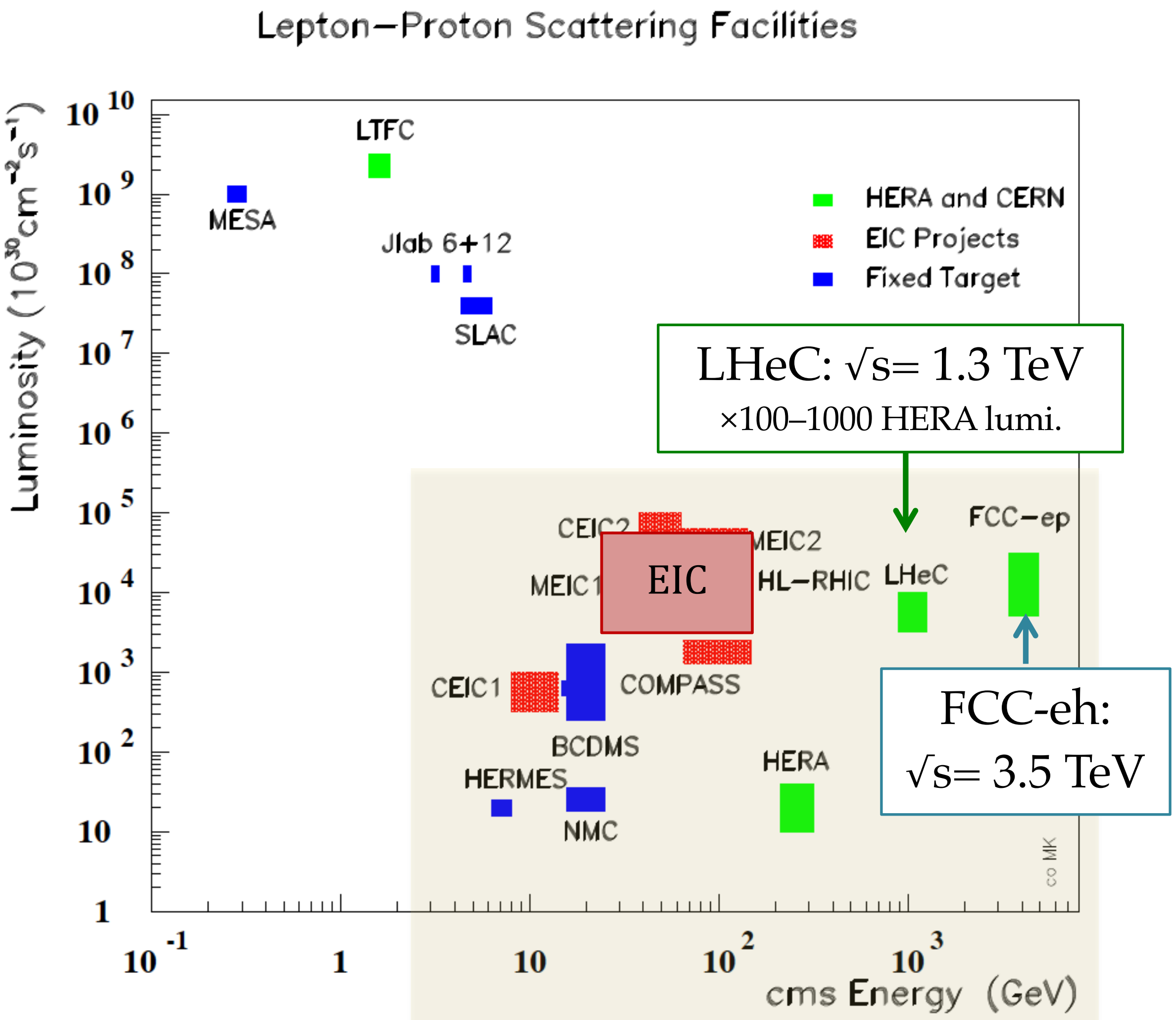


operating **synchronously** :

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

(×15/120 (LHeC/FCCeh) extension in Q^2,1/x reach)

ep colliders



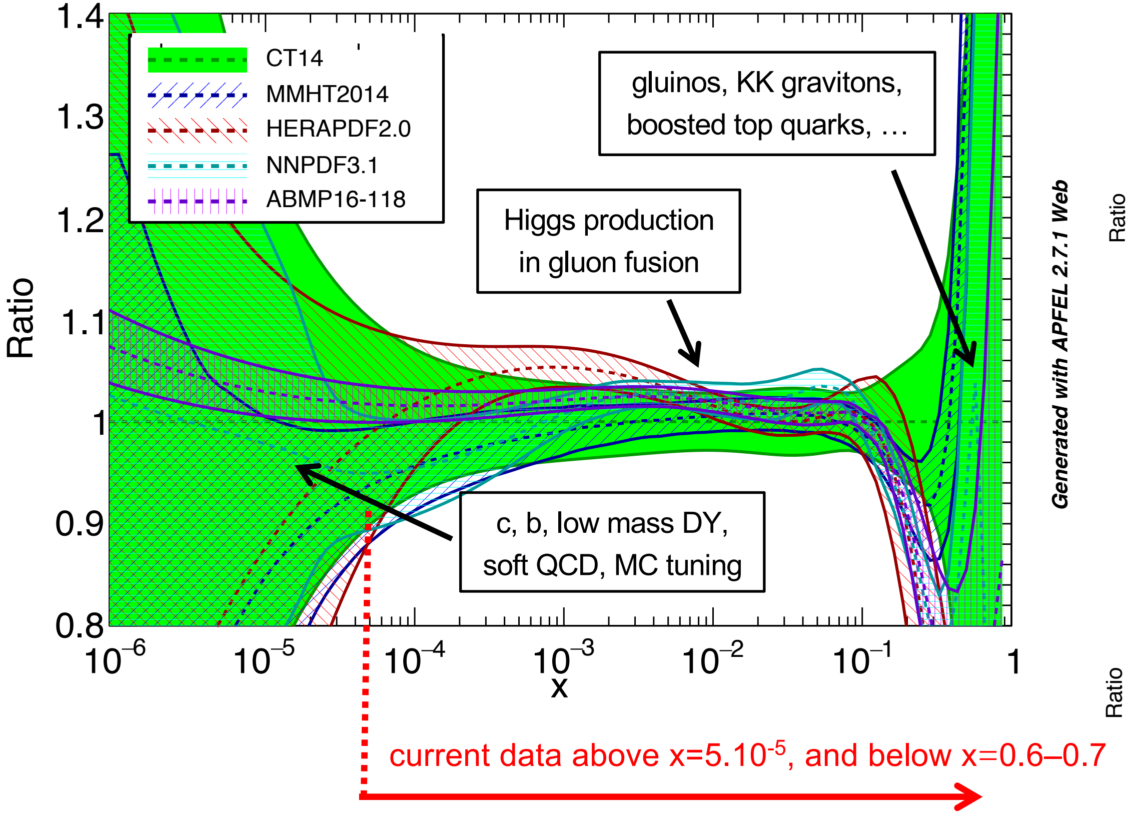
HERA: world's first and still only **ep** collider ($\sqrt{s} \simeq 300$ GeV)

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)

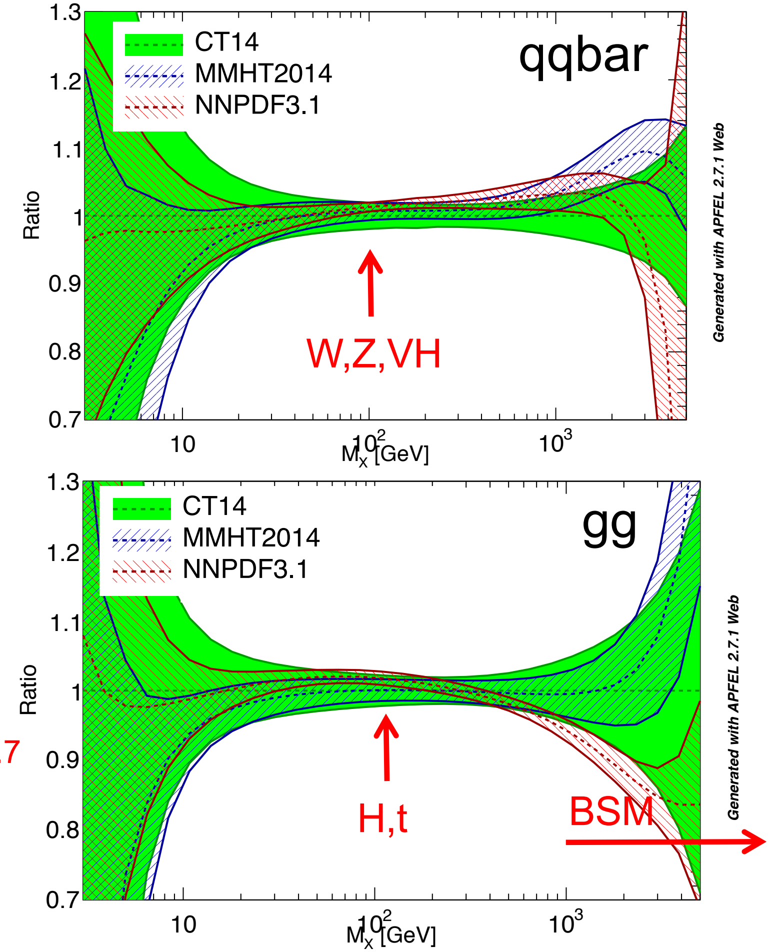
FCC-eh: further future **ep** (eA) collider, integrated with FCC (further kinematic extension wrt **LHeC**)

situation today

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



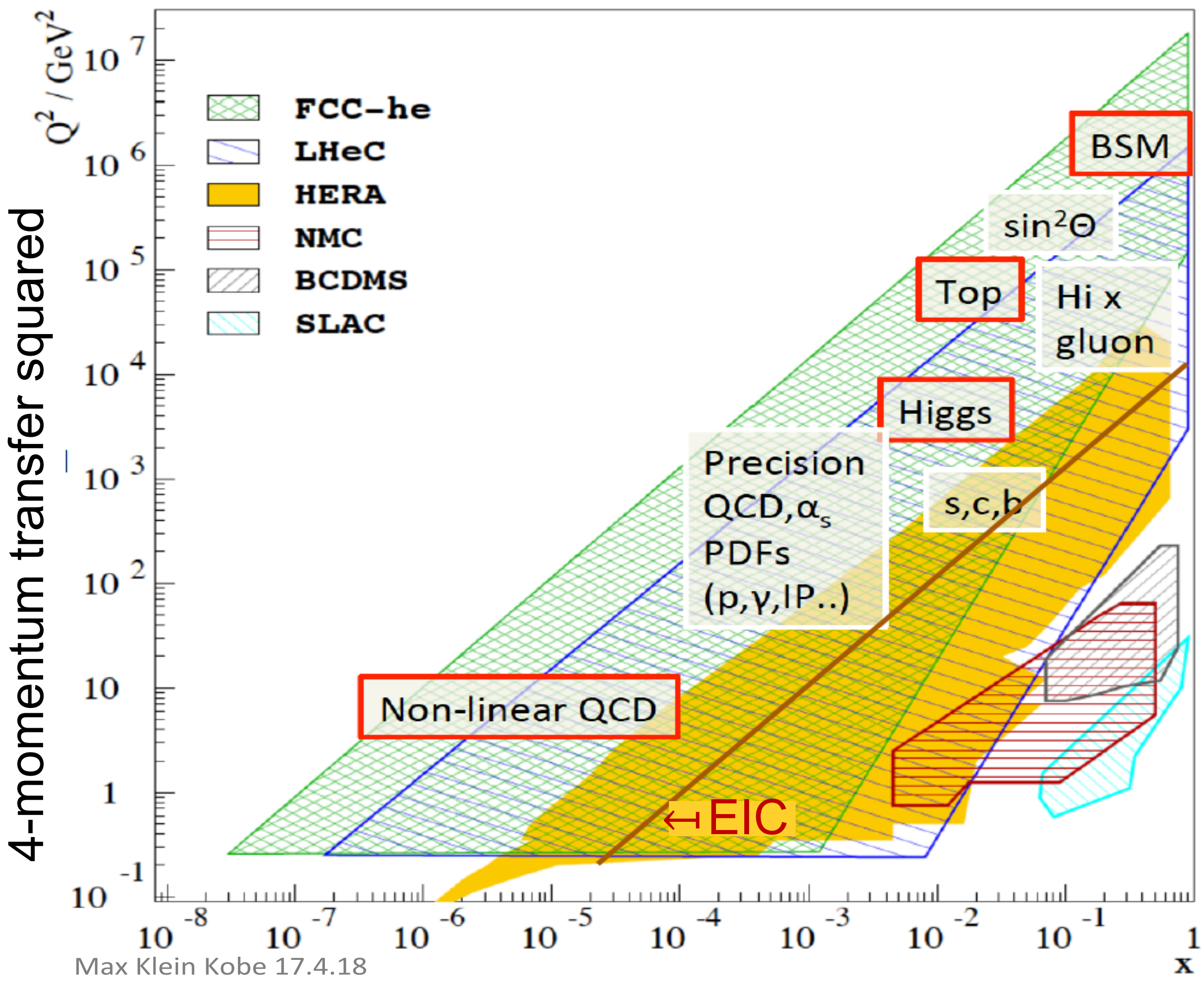
pdf luminosities (LHC@14TeV)



pdfs poorly known at large and small x

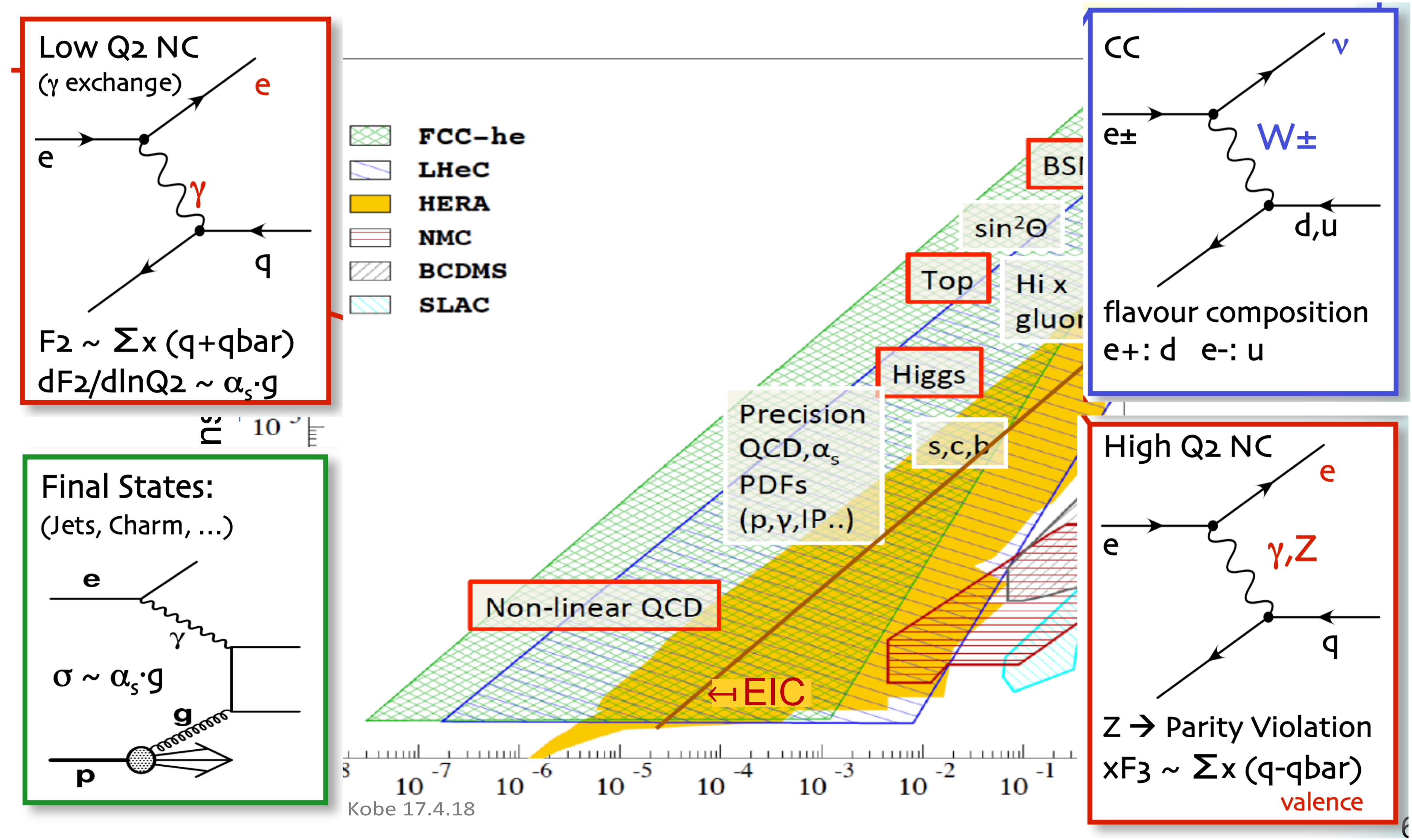
higher precision needed also for H, W, t

kinematic coverage



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

kinematic coverage

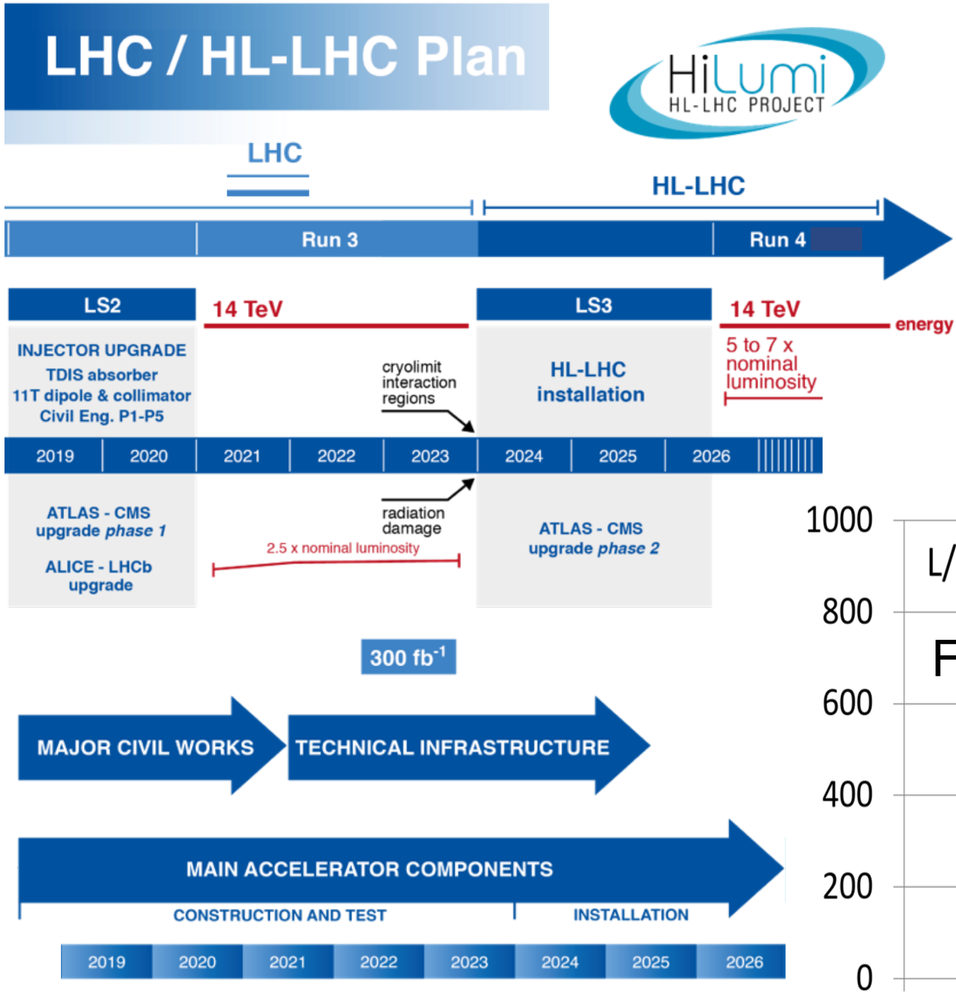


×**15**/**120** extension in Q^2,1/x reach vs **HERA**

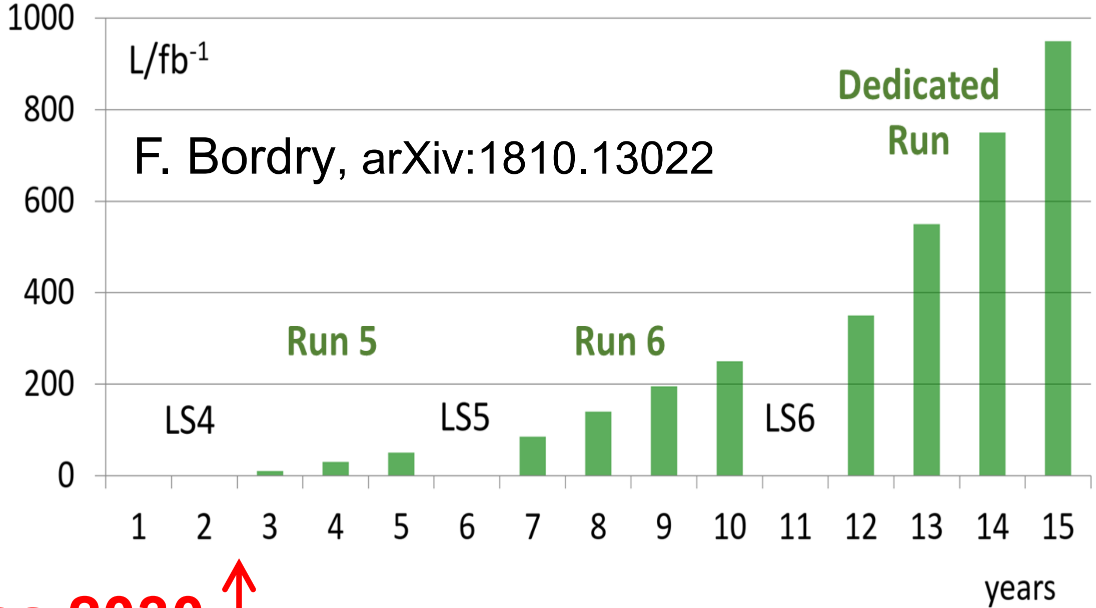
visualising the LHeC timeline

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

total Lint ⟶ 1 ab^{-1}



LHeC projected Integrated Luminosity



↑ **today**

circa 2030 ↑

LHeC pdf programme

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; …

LHeC pdf programme

simulation and pdf fit studies:
M. Klein,
CG, G. Pownall

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

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

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	1,10,50	**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%

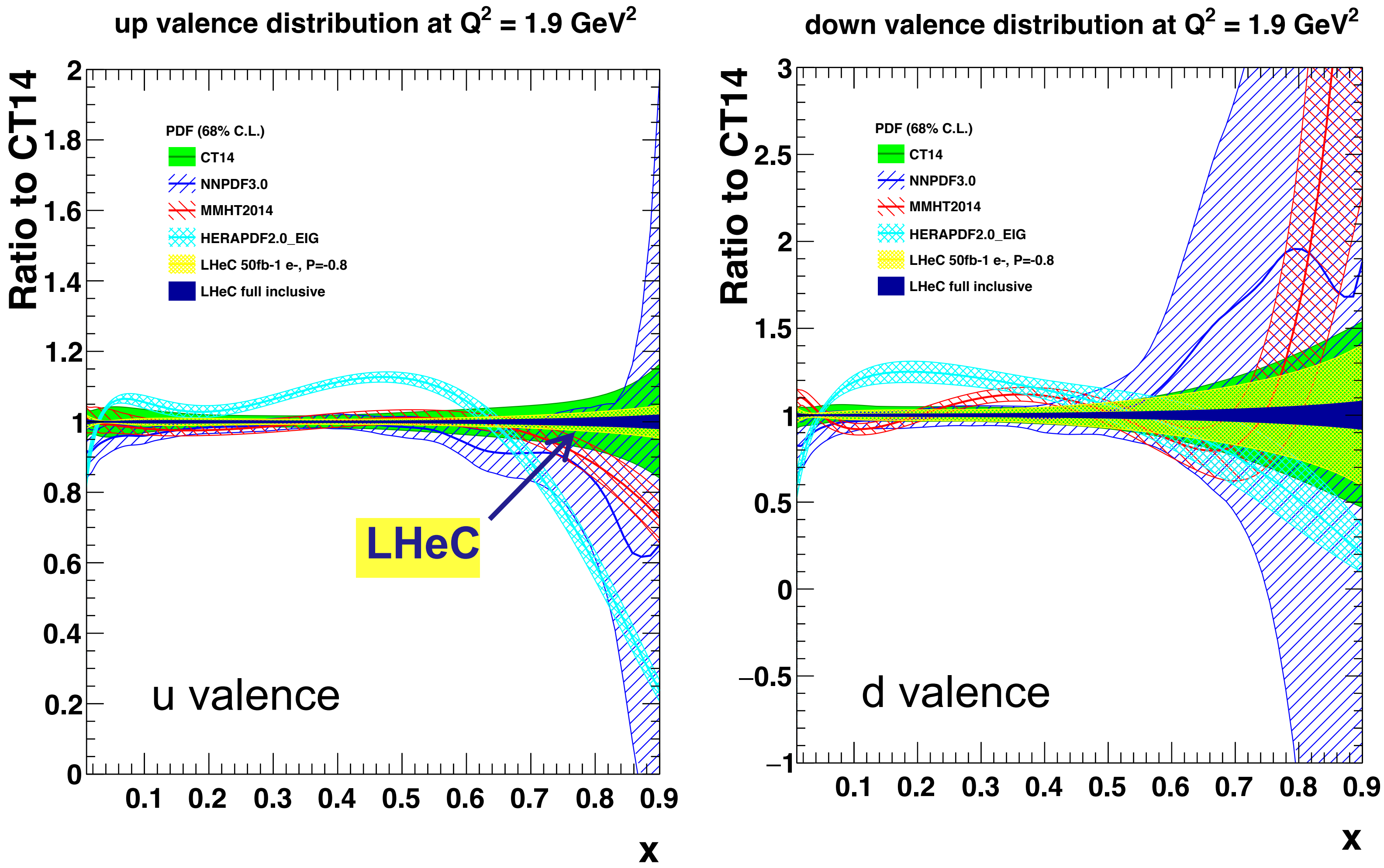
NB, I will frequently refer to the following:

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+,50 fb-1)**

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

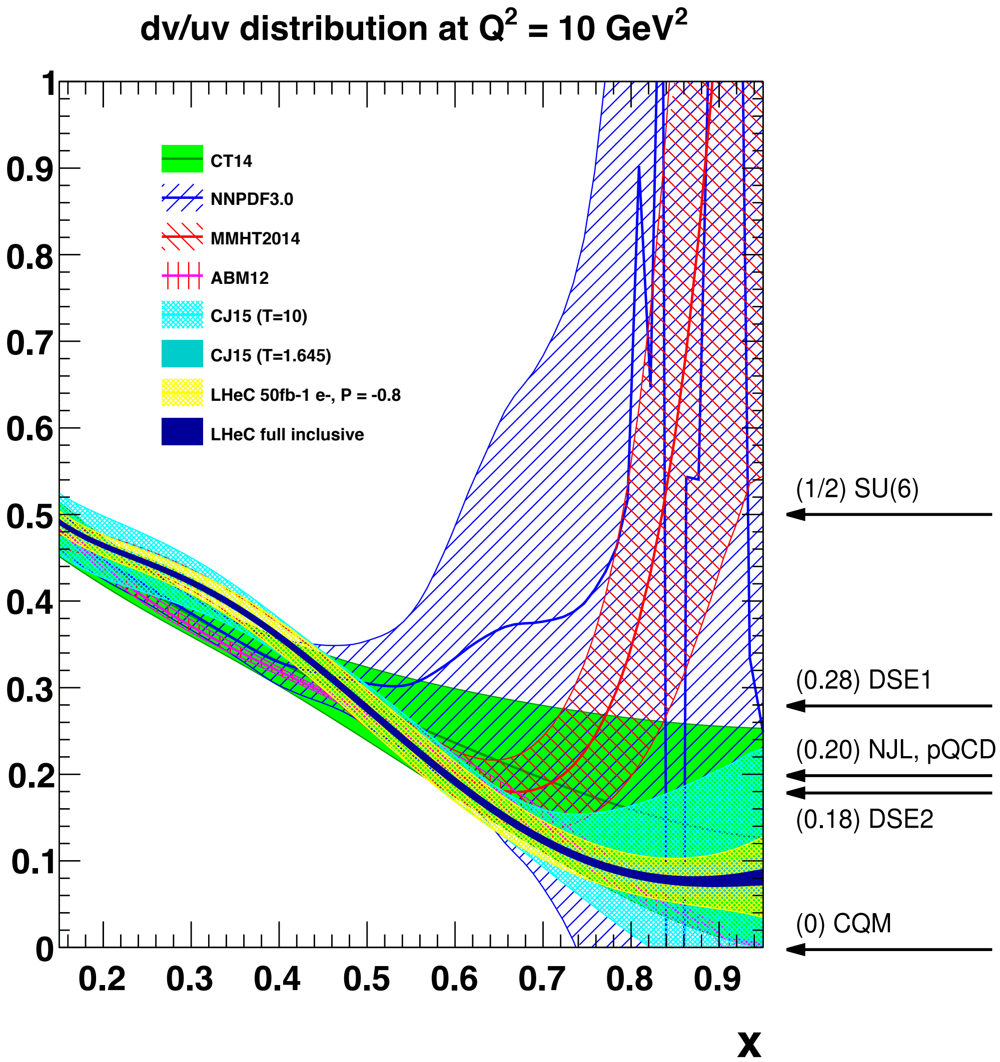
valence quarks from LHeC



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

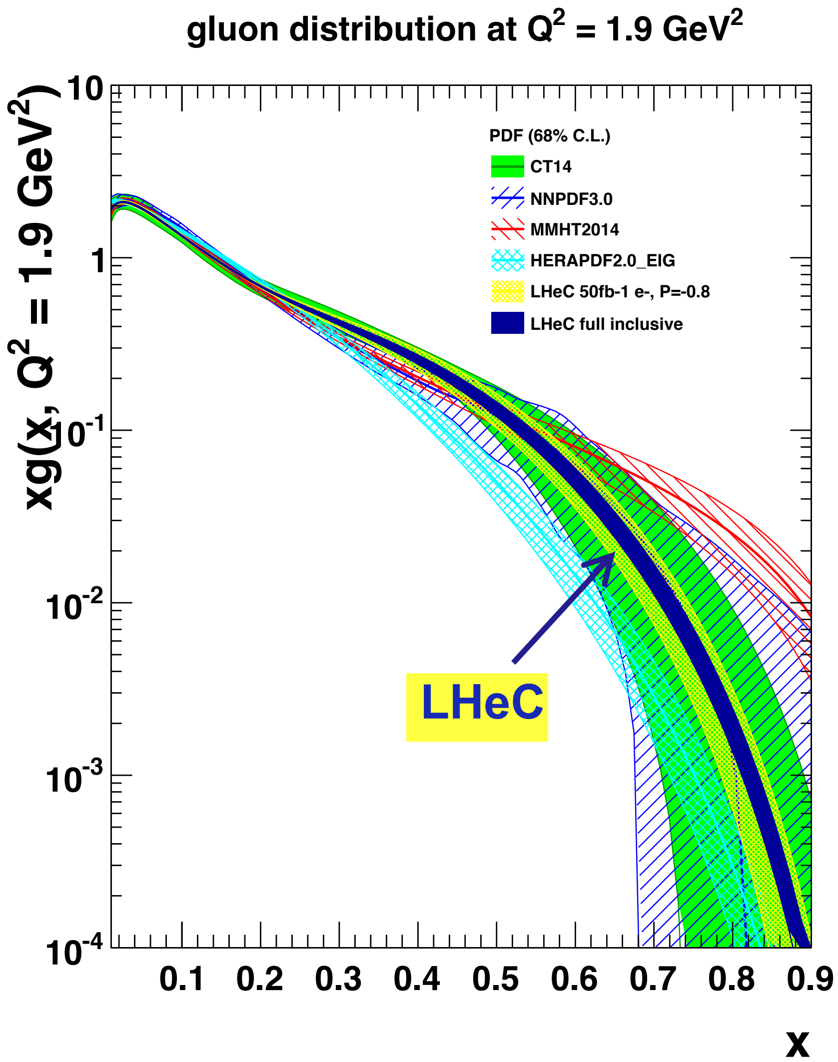


d/u essentially unknown at large x

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

gluon at large x



gluon at large x is small and currently very poorly known;

crucial for new physics searches

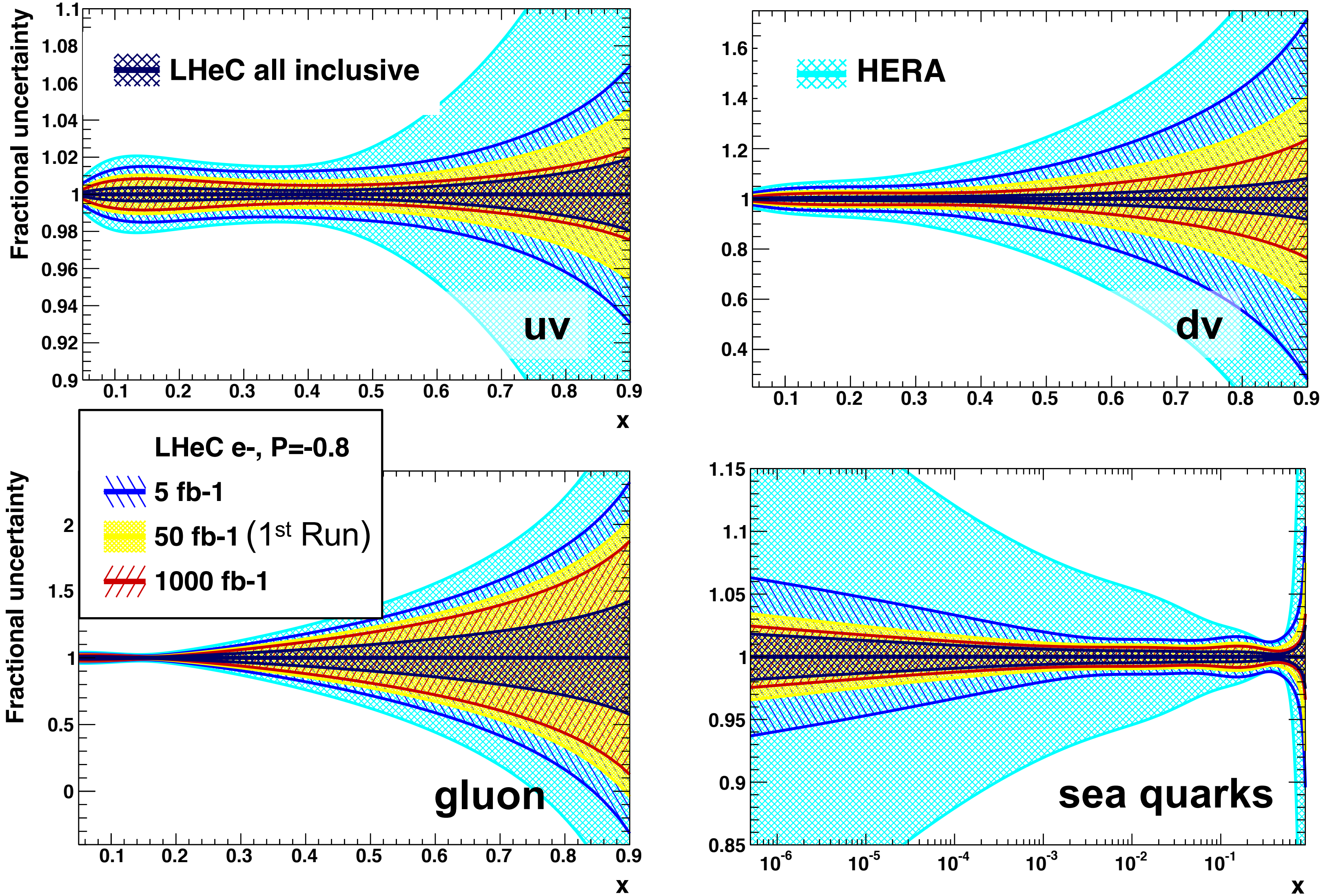
LHeC sensitivity at large x comes as part of overall package

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

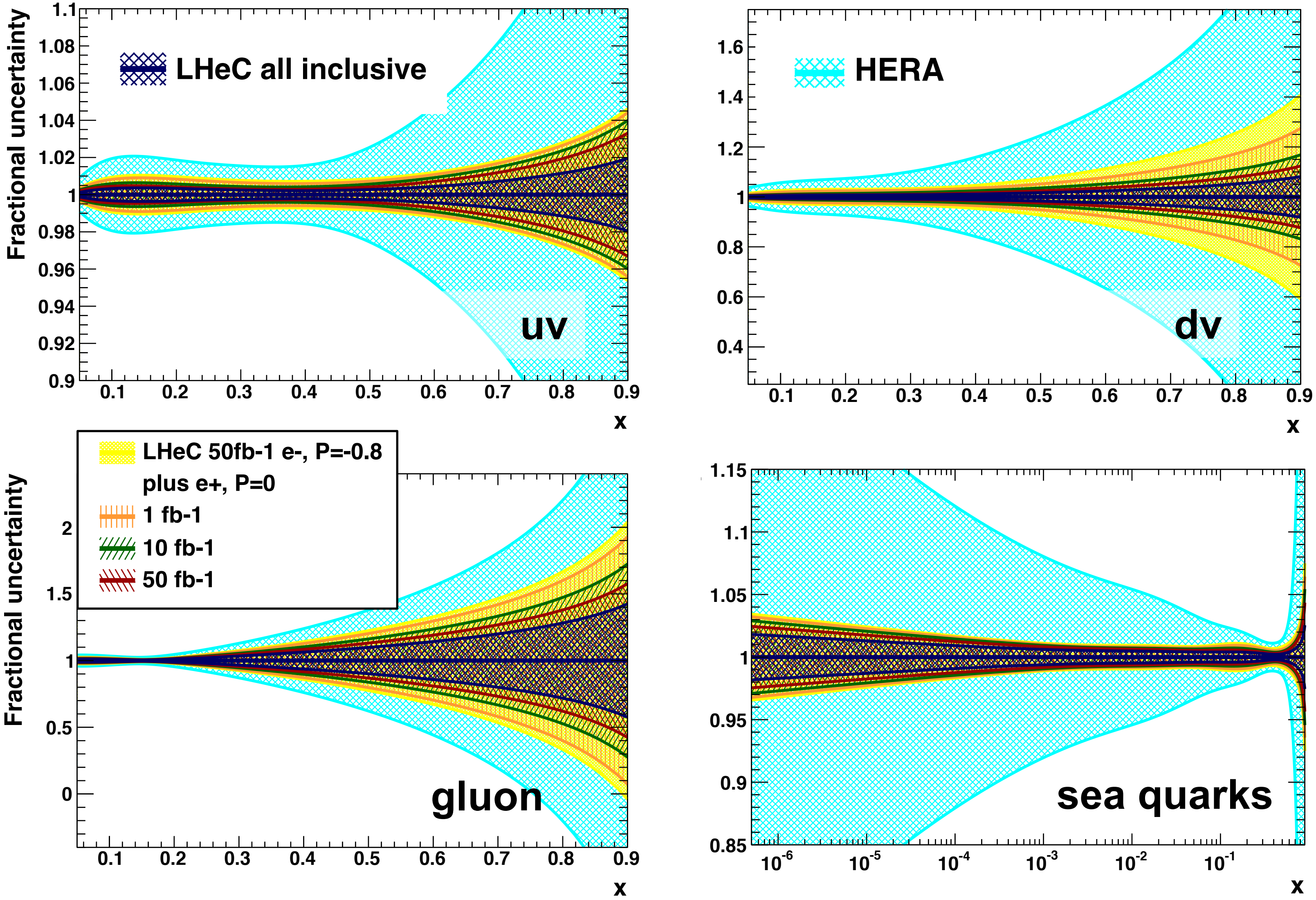
impact of luminosity on LHeC pdfs



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

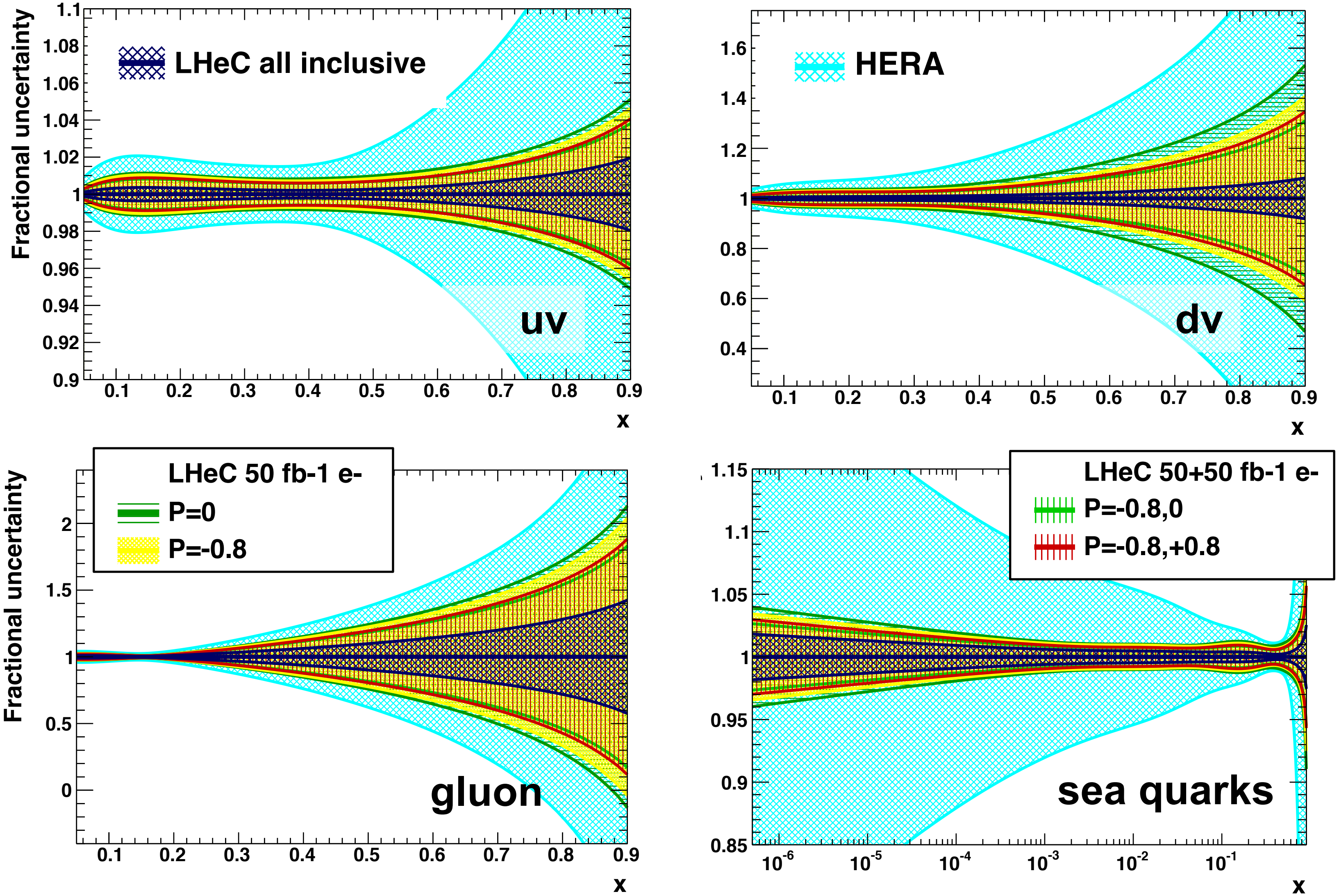
large x (≡ large Q2), gain from increased Lint

impact of positrons on LHeC pdfs



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

impact of polarisation on LHeC pdfs



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

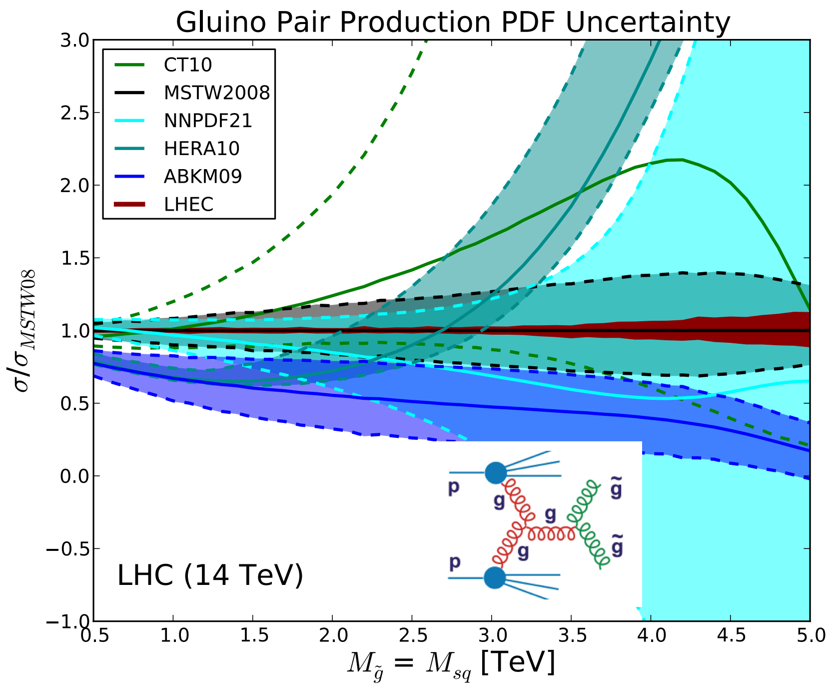
(**CC**: σ(e±) scales as (1±P) ; **NC**: effects subtle; pol. asym. gives access to $F2^{\gamma Z}$, new quark combinations)

empowering LHC searches

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

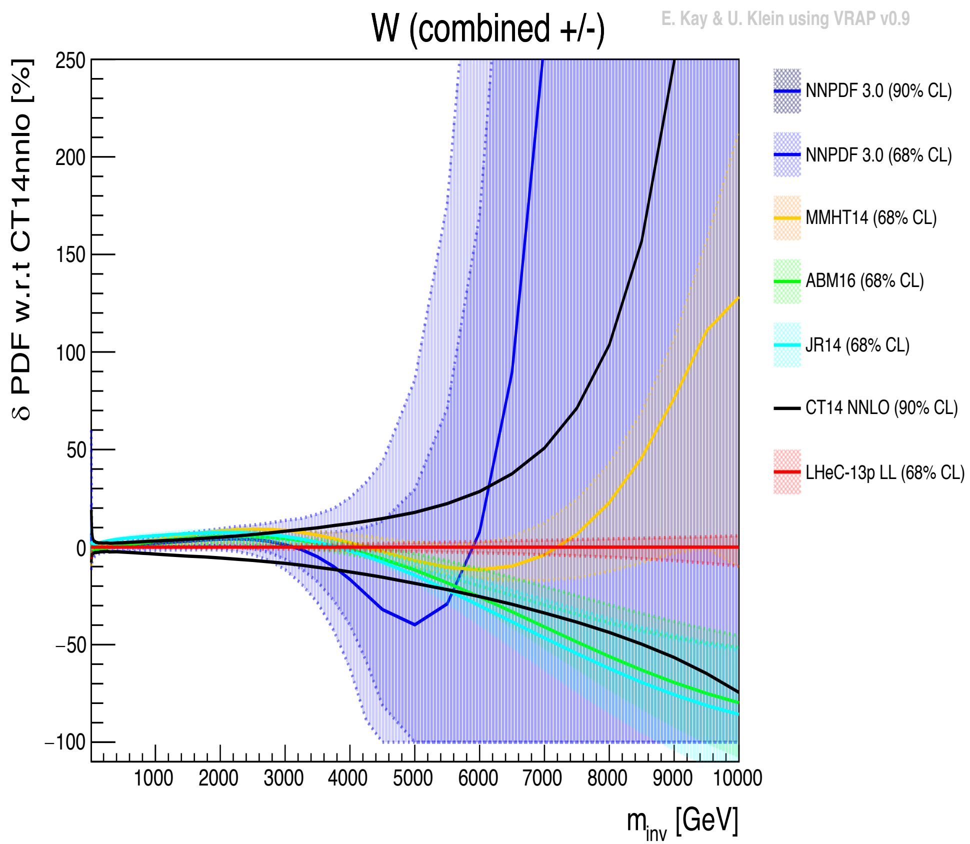
gluons

SUSY (RPC, RPV), LQs, …

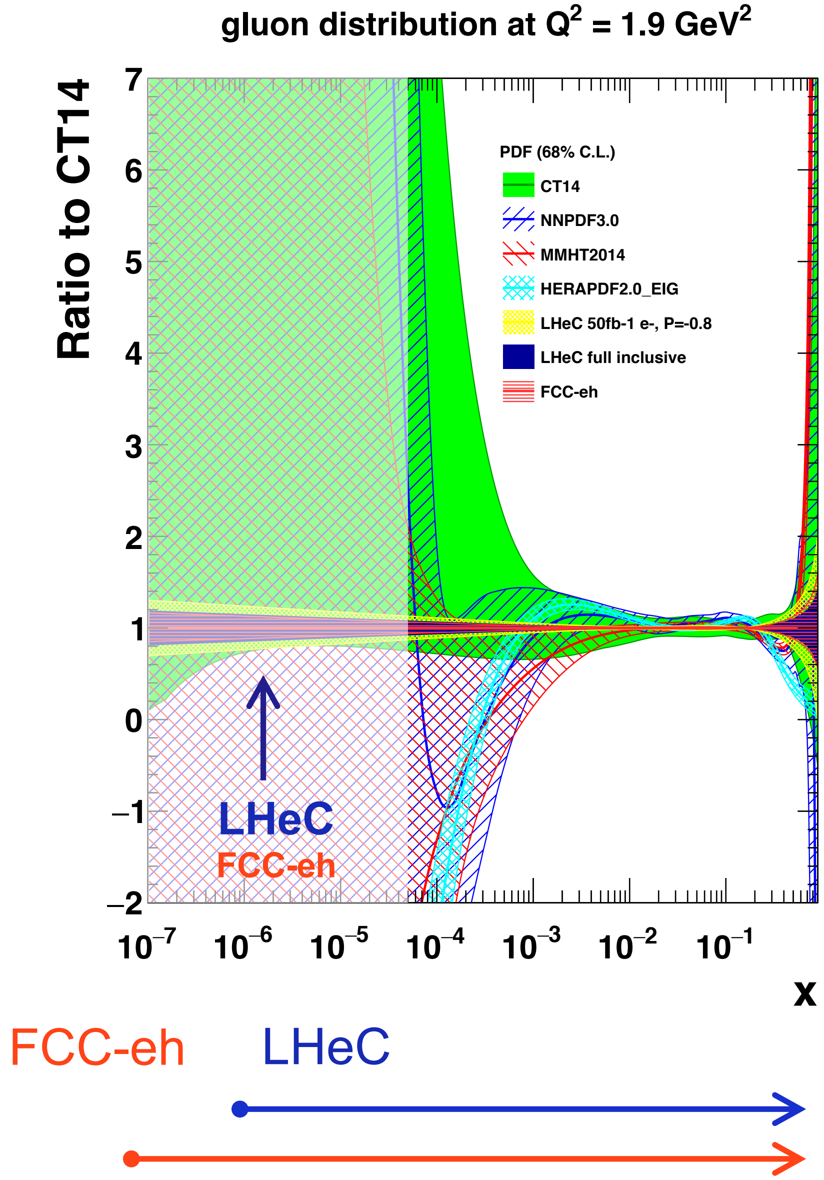


quarks

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 $x=10^{-6}$

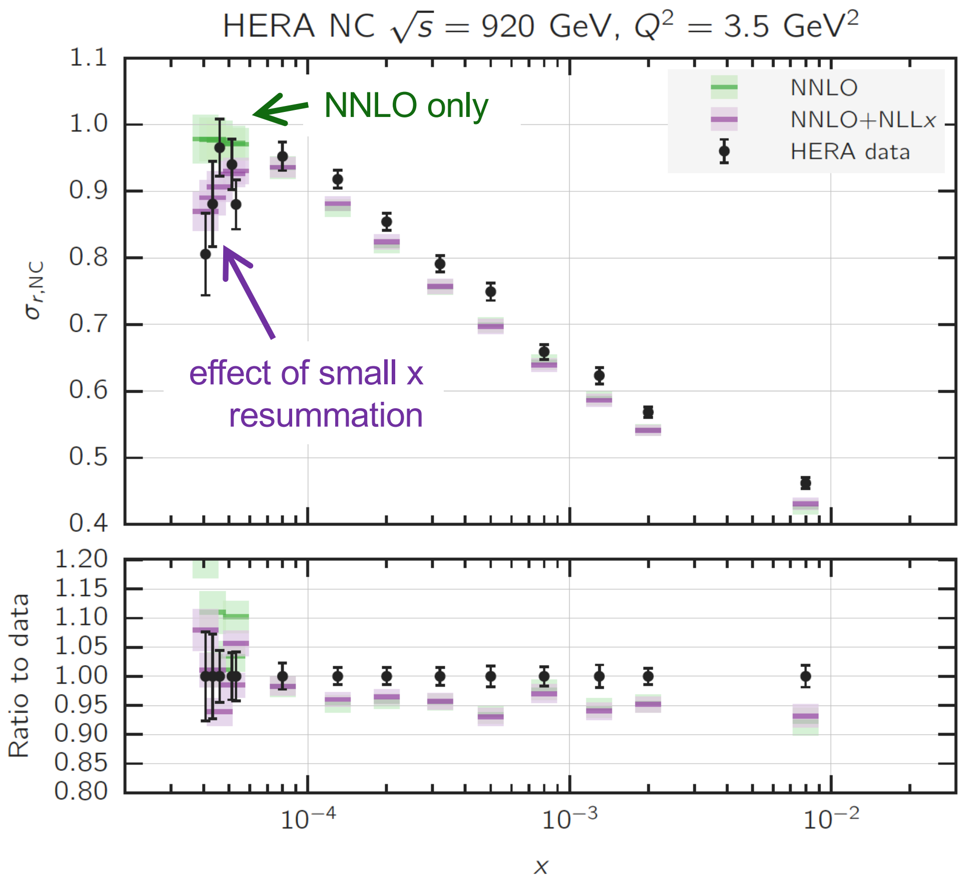
FCC-eh probes to even smaller $x=10^{-7}$

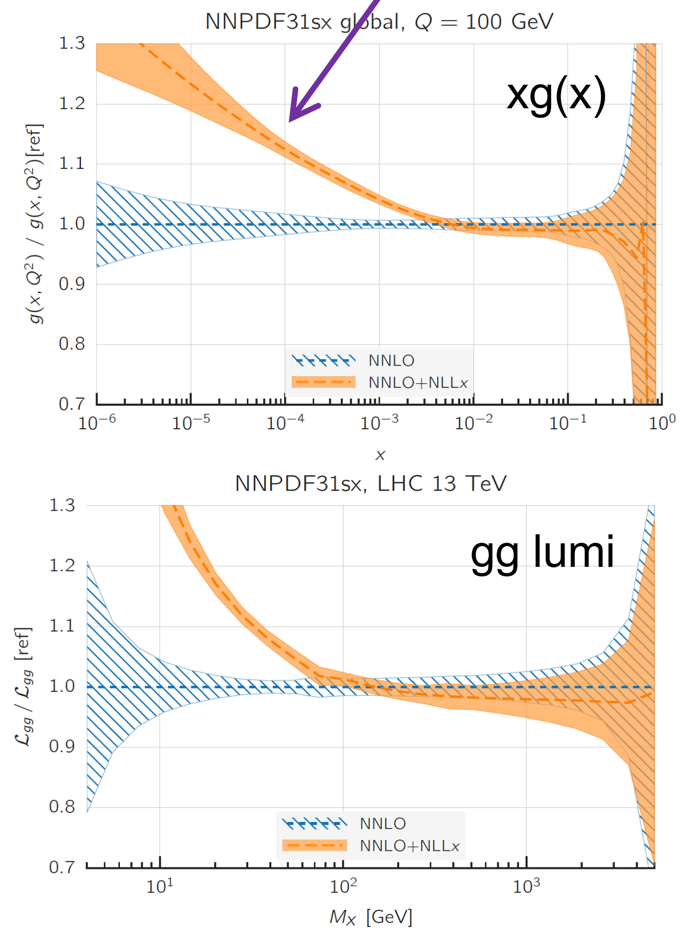
explore low x QCD:

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

gluon at small x

R. Ball et al, arXiv:1710.05935

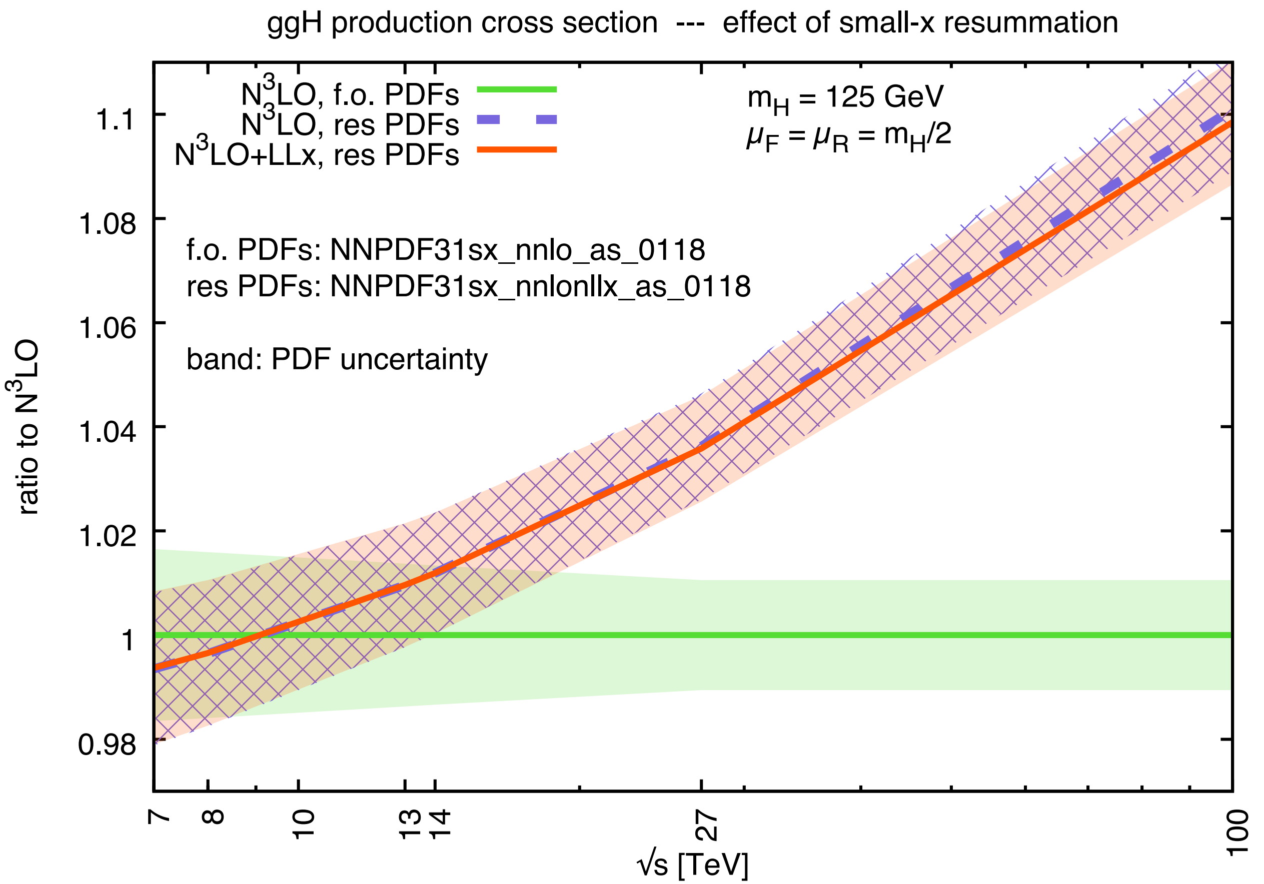




- recent evidence for onset of BFKL dynamics in HERA inclusive data
- **impact for LHC and most certainly at ultra low x values probed at FCC**

confirmed in xFitter study, arXiv:1802.00064

gluon at small x matters



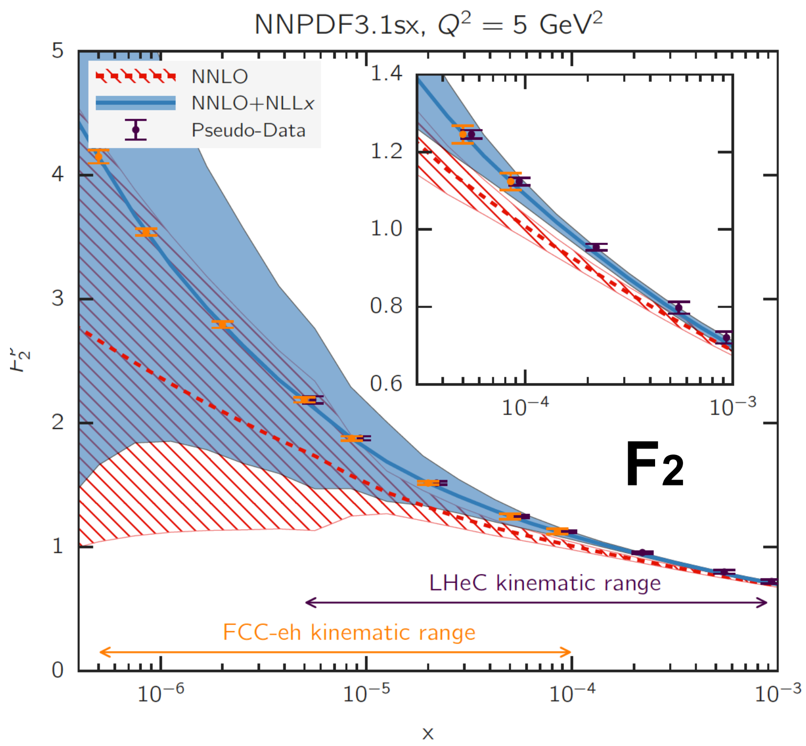
effect of small x resummation on ggH cross section for LHC, HE-LHC, FCC

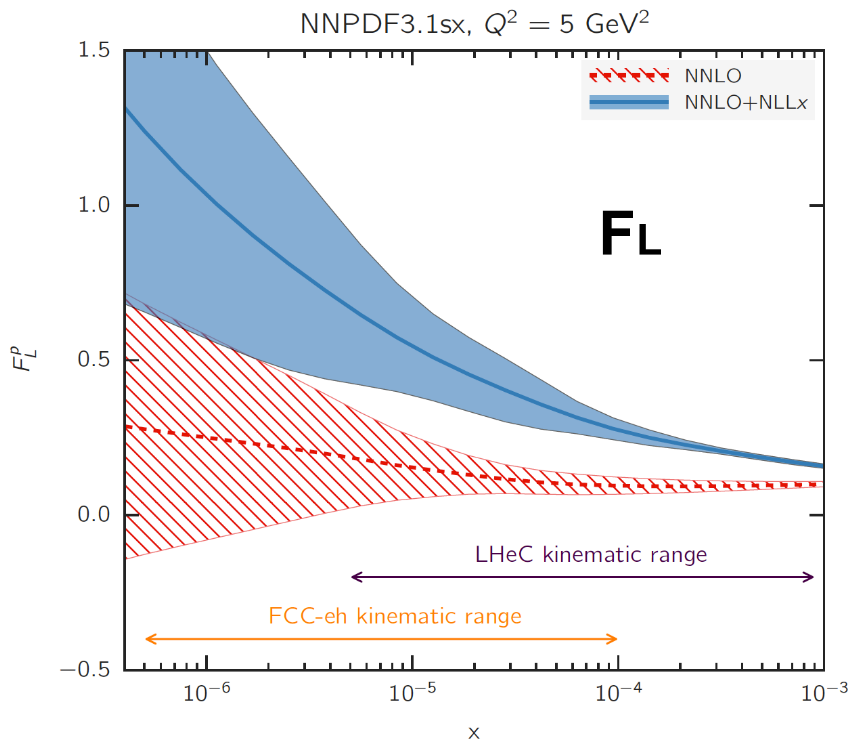
impact on other EW observables could be of similar size

M. Bonvini and S. Marzani, arXiv:1802.07758

gluon at small x

arXiv:1710.05935





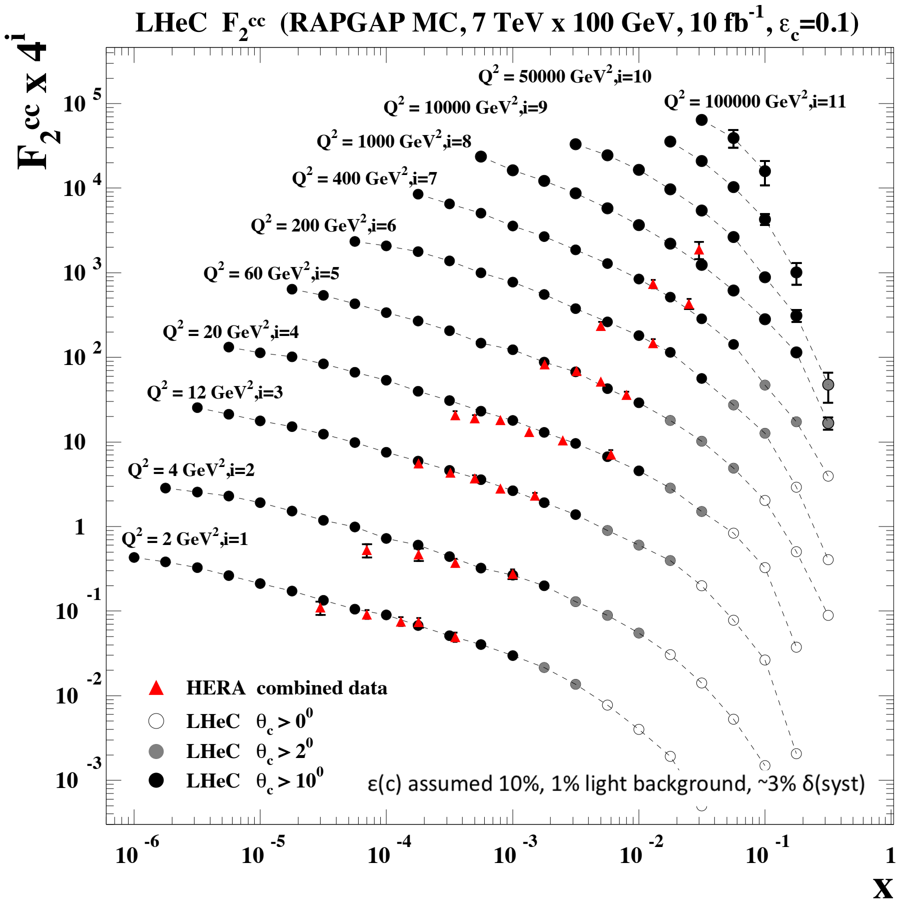
F2 and FL predictions for simulated kinematics of **LHeC** and **FCC-eh**

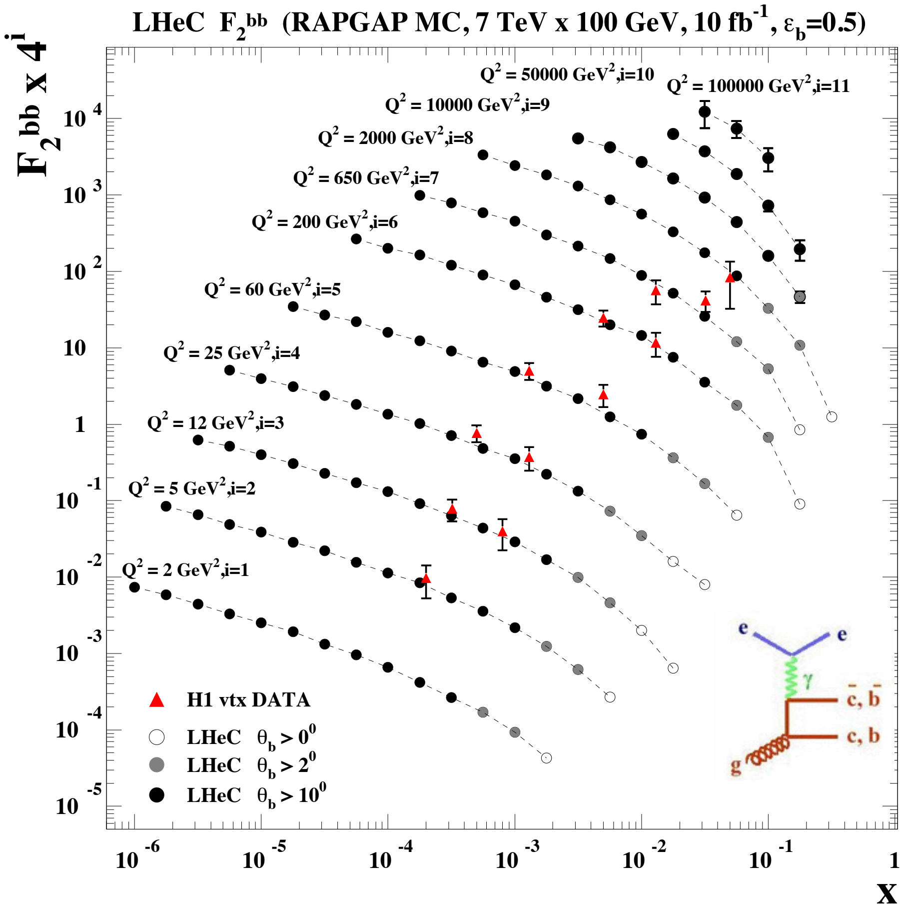
ep simulated data very precise – significant constraining power to discriminate between theoretical scenarios of small x dynamics

measurement of FL has a critical role to play

see also M. Klein, arXiv:1802.04317

c, b quarks



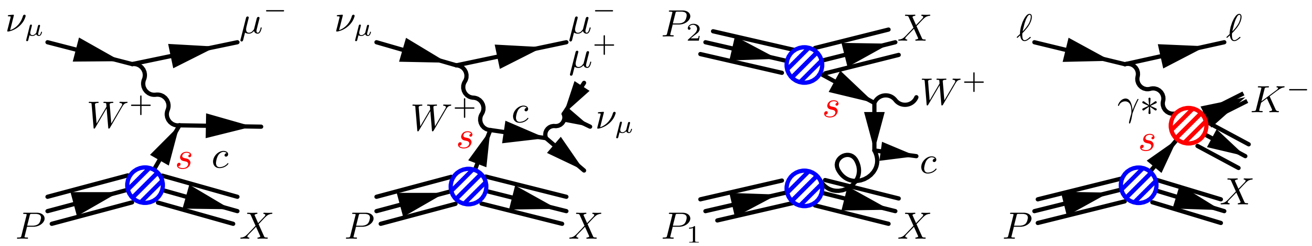


LHeC: enormously extended range and much improved precision c.f. HERA

- **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

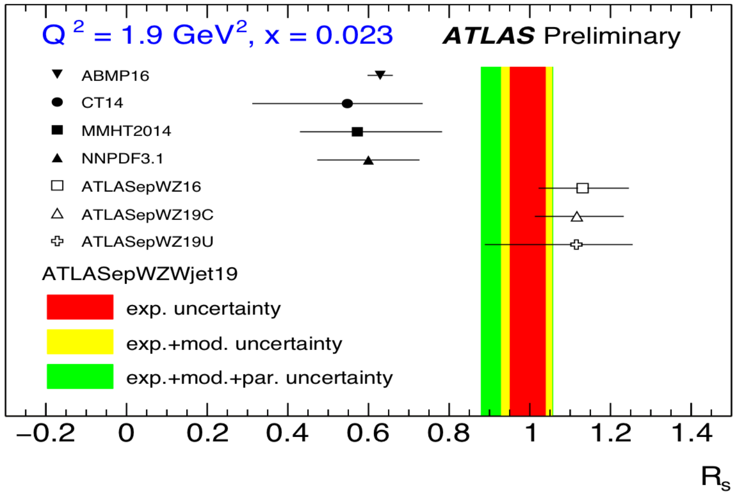
strange pdf poorly known; suppressed cf. other light quarks? strange valence?

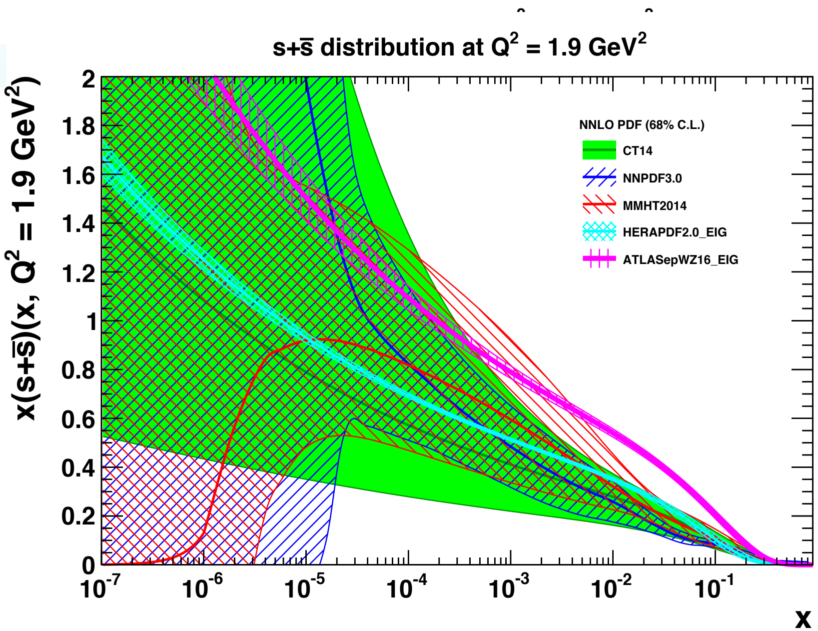


EG. CHORUS NuTeV ATLAS/CMS HERMES

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

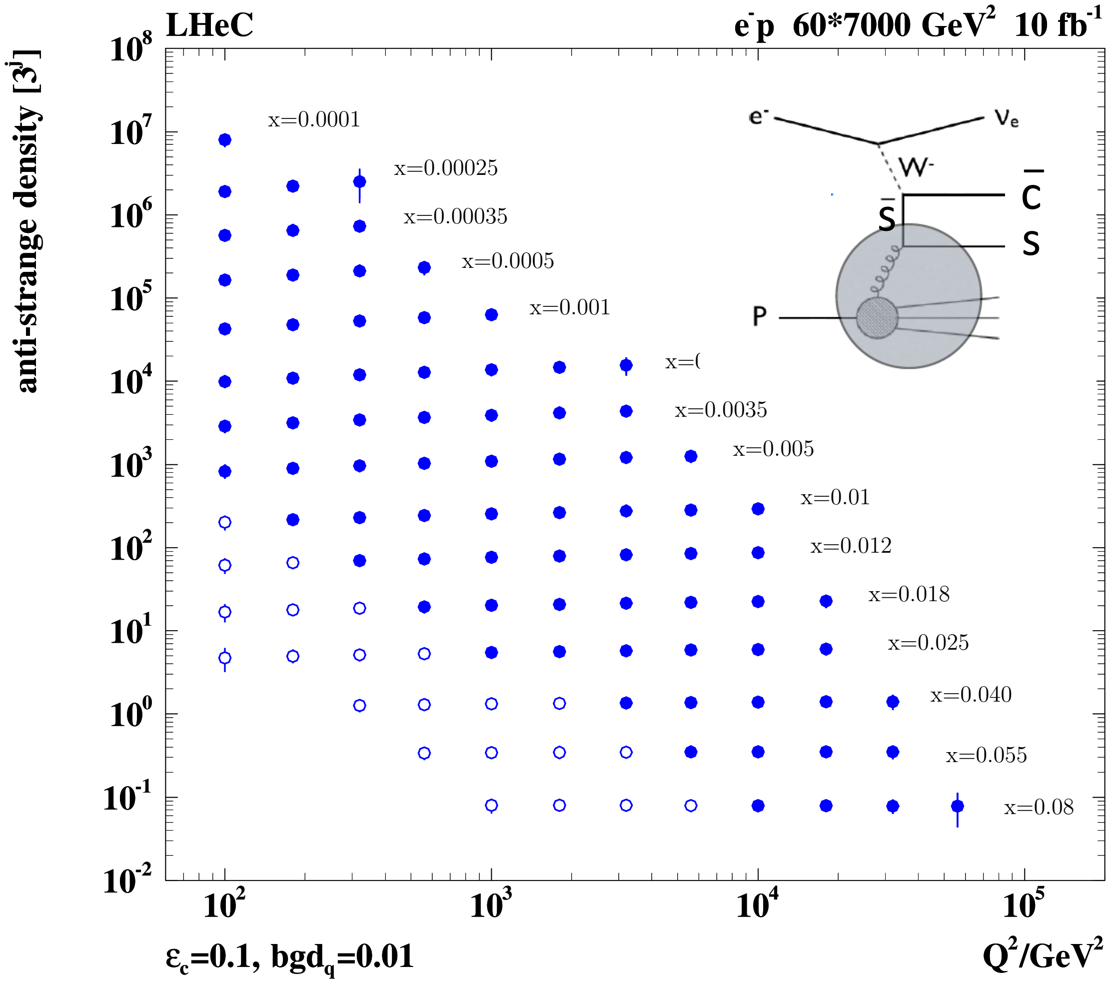
$$R_s(x,Q^2) = \frac{s(x,Q^2)+\bar{s}(x,Q^2)}{\bar{u}(x,Q^2)+\bar{d}(x,Q^2)} \begin{cases} \approx 0.5 \text{ (from neutrino)} \\ \approx 1.0 \text{ (from ATLAS W,Z)} \end{cases}$$





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

strange



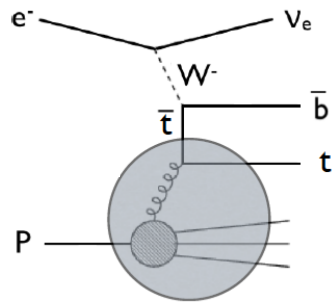
LHeC: direct sensitivity to **strange** via $W+s \rightarrow c$

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

also top PDF

top quark becomes light at large Q2:

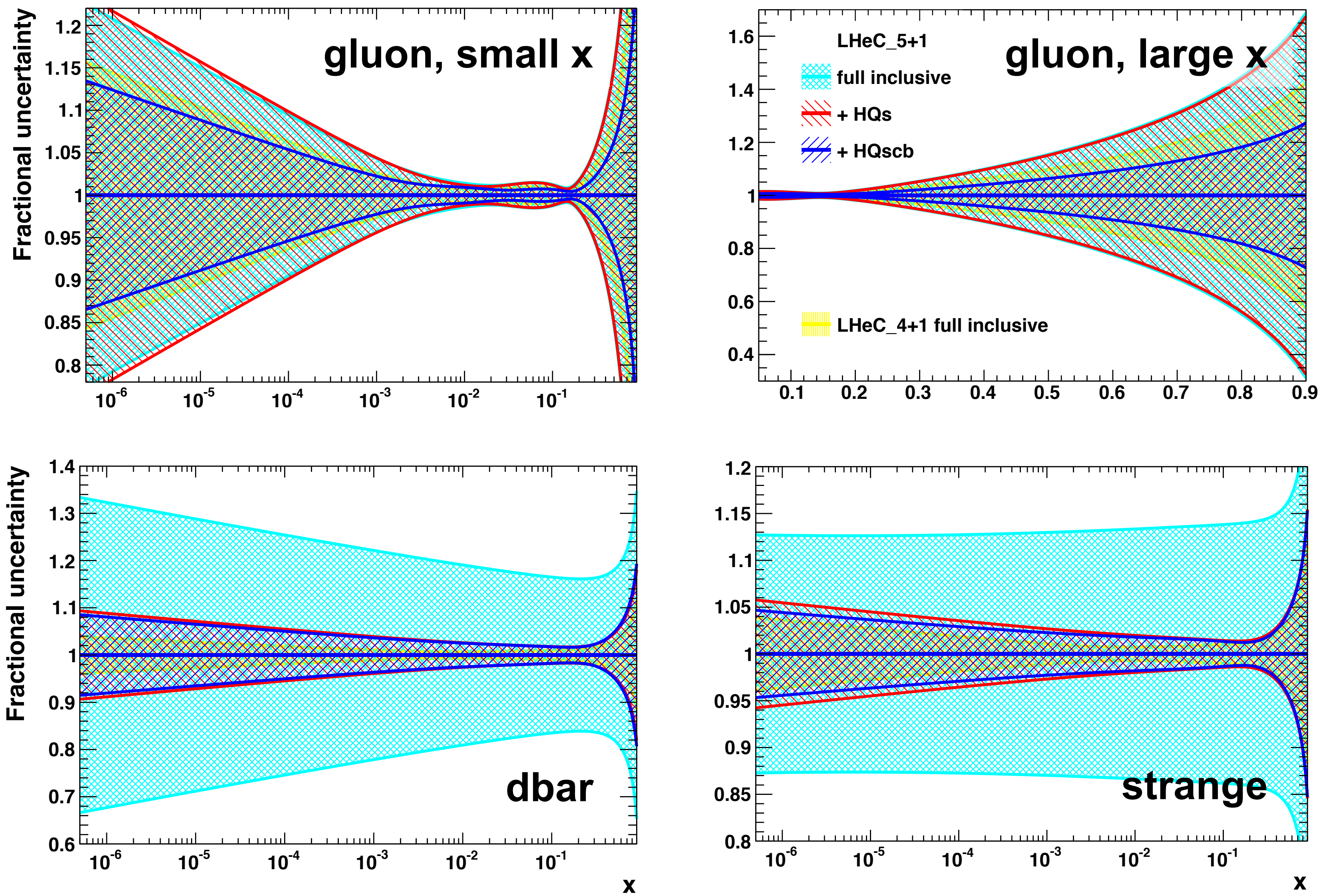
new field of research opens for top PDFs!



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

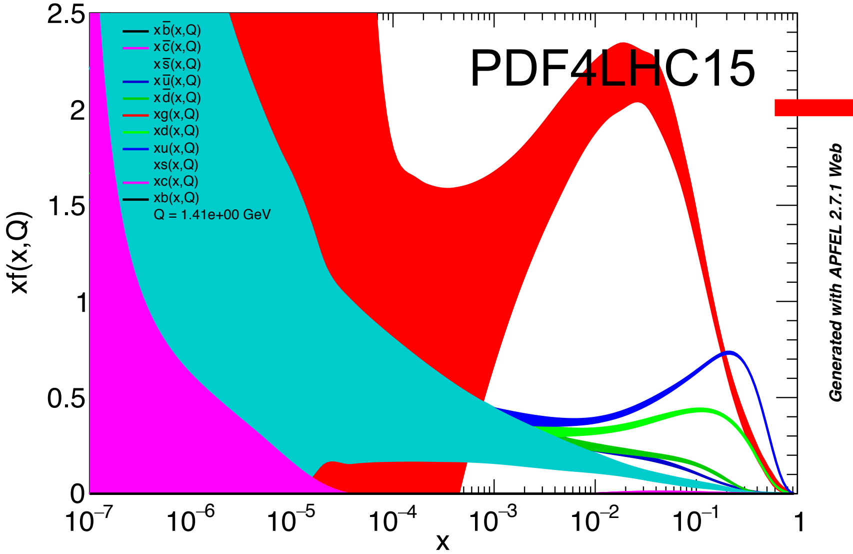
G.R. Boroun, PLB 741 (2015) 197

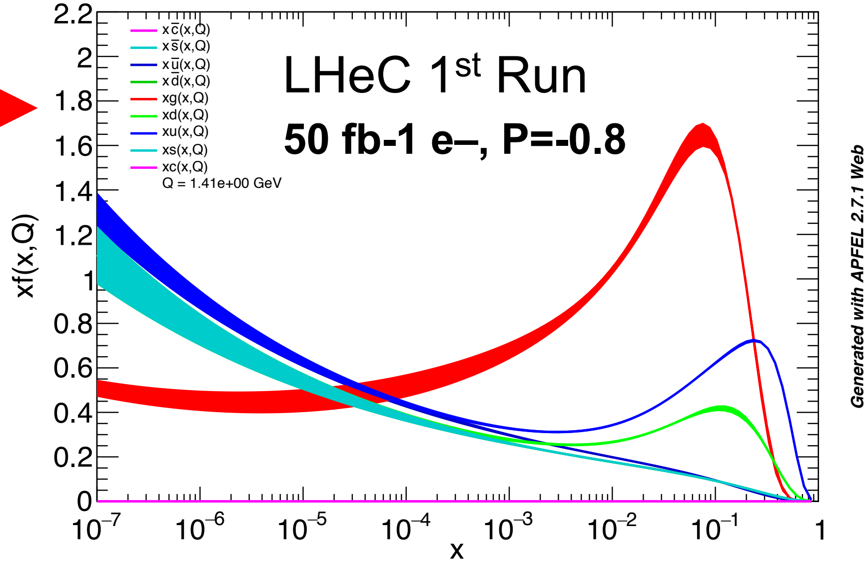
impact of HQ data on LHeC pdfs

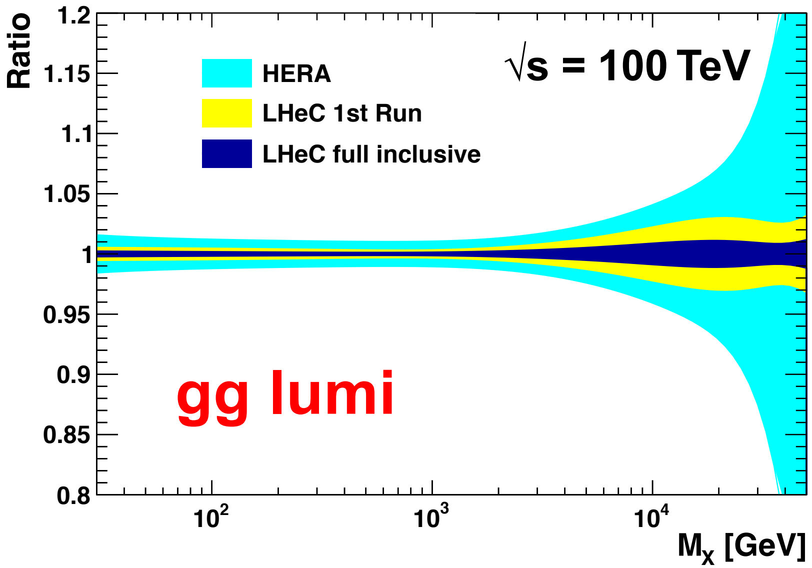


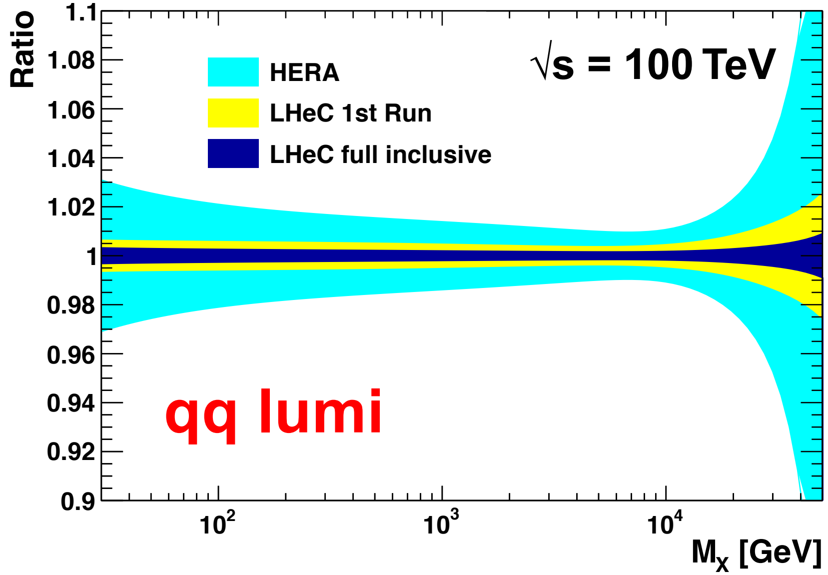
more flexible parameterisation (5+1): **xuv, xdv, $x\bar{U}$, $x\bar{d}$, $x\bar{s}$** and **xg**

summary of LHeC pdfs

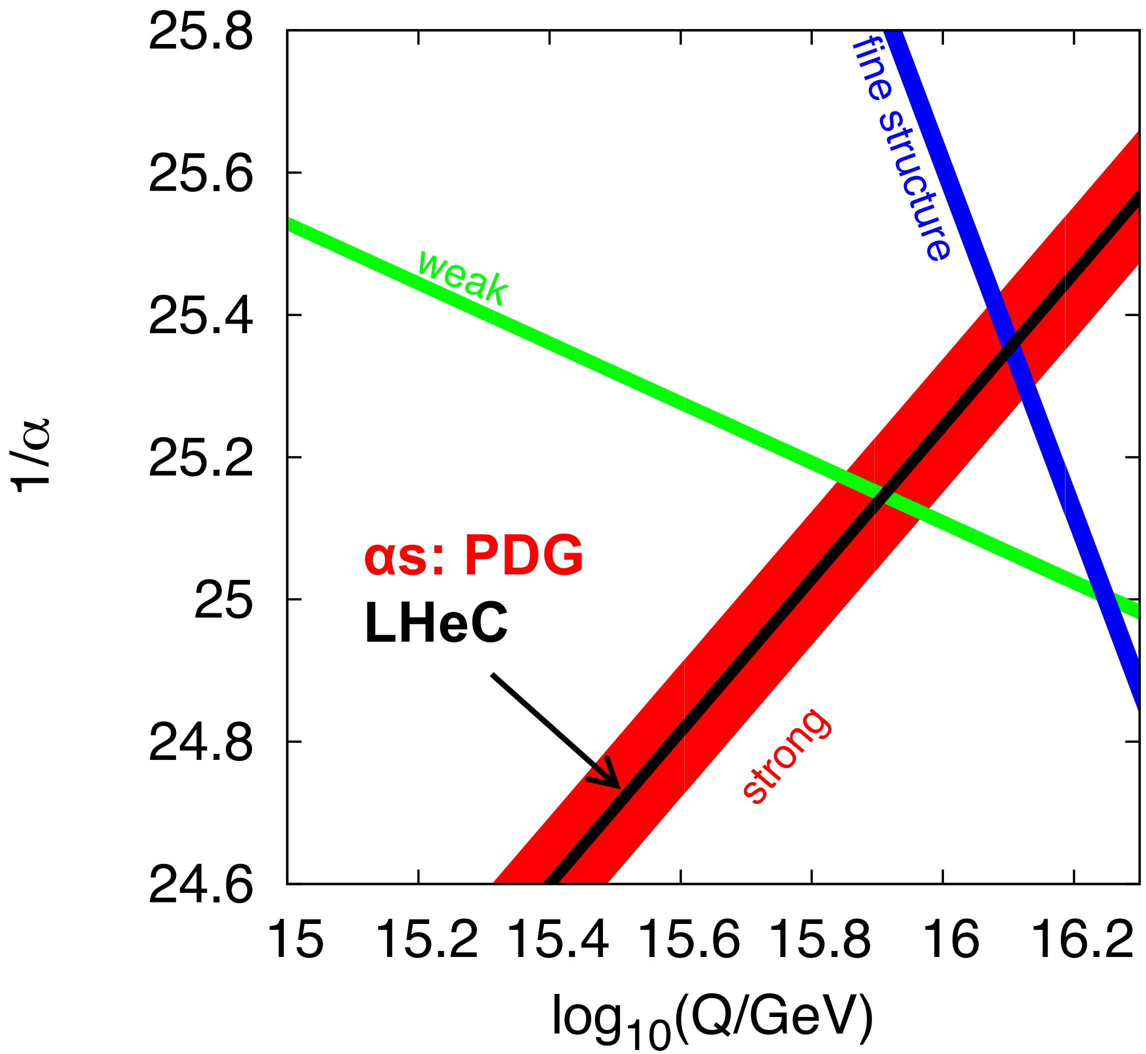








strong coupling, αs



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

αs is least known coupling constant

PDG2018:
$\alpha_s = 0.1174 \pm 0.0016$
(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**

summary

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

electron-proton colliders essential for full exploitation of these 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; …

NEW LHeC pdf studies presented (all work in progress)

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

LHeC and PERLE documents submitted to european strategy update

next steps: ongoing collaborative studies with various groups; major new summary paper later this year; workshop in the autumn

extras

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)

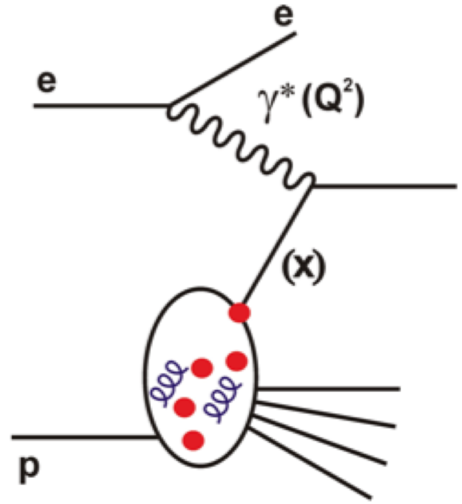
$$
\begin{aligned}
xg(x) &= A_g x^{B_g}(1-x)^{C_g}(1+D_g x) \\
xu_v(x) &= A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}(1+E_{u_v} x^2) \\
xd_v(x) &= A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}} \\
x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}} \\
x\bar{D}(x) &= A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}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

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

DIS formalism with polarisation

$$\sigma_{r,NC} = \mathbf{F_2} + \frac{Y_-}{Y_+}\mathbf{xF_3} - \frac{y^2}{Y_+}\mathbf{F_L}, \qquad Y_\pm = 1 \pm (1-y)^2$$



$$\begin{aligned}
\mathbf{F_2^\pm} &= F_2 + \kappa_Z(-v_e \mp P a_e)\cdot F_2^{\gamma Z} + \kappa_Z^2(v_e^2 + a_e^2 \pm 2P v_e a_e)\cdot F_2^Z \\
\mathbf{xF_3^\pm} &= \kappa_Z(\pm a_e + P v_e)\cdot xF_3^{\gamma Z} + \kappa_Z^2(\mp 2 v_e a_e - P(v_e^2 + a_e^2))\cdot xF_3^Z.
\end{aligned}$$

$$\begin{aligned}
(F_2, F_2^{\gamma Z}, F_2^Z) &= x\sum(e_q^2, 2e_q v_q, v_q^2 + a_q^2)(q + \bar{q}) \\
(xF_3^{\gamma Z}, xF_3^Z) &= 2x\sum(e_q a_q, v_q a_q)(q - \bar{q}),
\end{aligned}$$

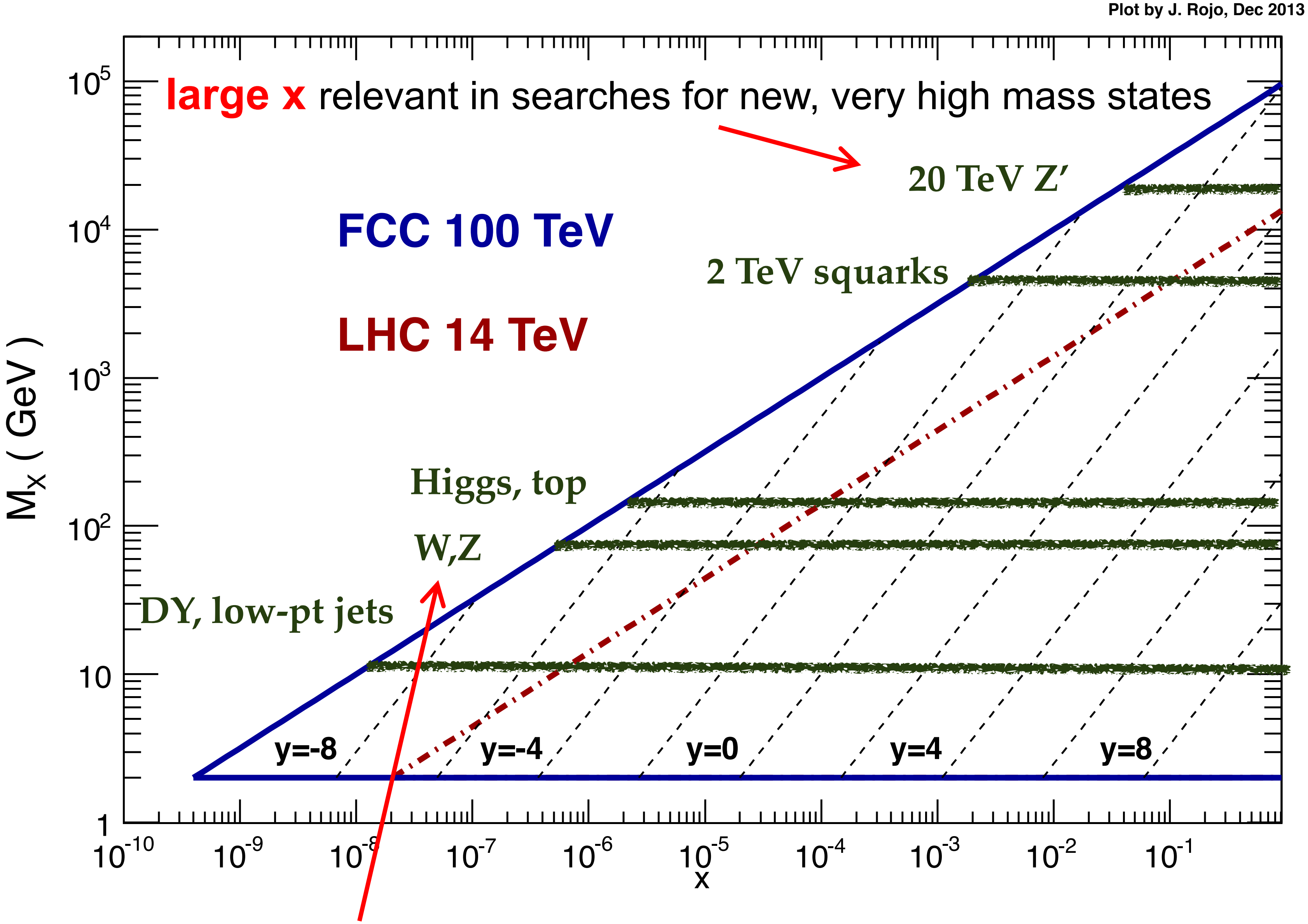
$$\sigma^+_{r,NC}(P_+) - \sigma^-_{r,NC}(P_-) = -\kappa_Z a_e(P_+ + P_-)\cdot F_2^{\gamma Z} + \frac{Y_-}{Y_+}\kappa_Z a_e\cdot[2xF_3^{\gamma Z} + (P_+ - P_-)\kappa_Z a_e xF_3^Z]$$

$$xF_3^{\gamma Z} \simeq (2u_v + d_v)/3$$

$$\frac{\sigma^\pm_{r,NC}(P_L) - \sigma^\pm_{r,NC}(P_R)}{P_L - P_R} = \kappa_Z[\mp a_e F_2^{\gamma Z} + \frac{Y_-}{Y_+}v_e xF_3^{\gamma Z}] \simeq \mp\kappa_Z a_e F_2^{\gamma Z}$$

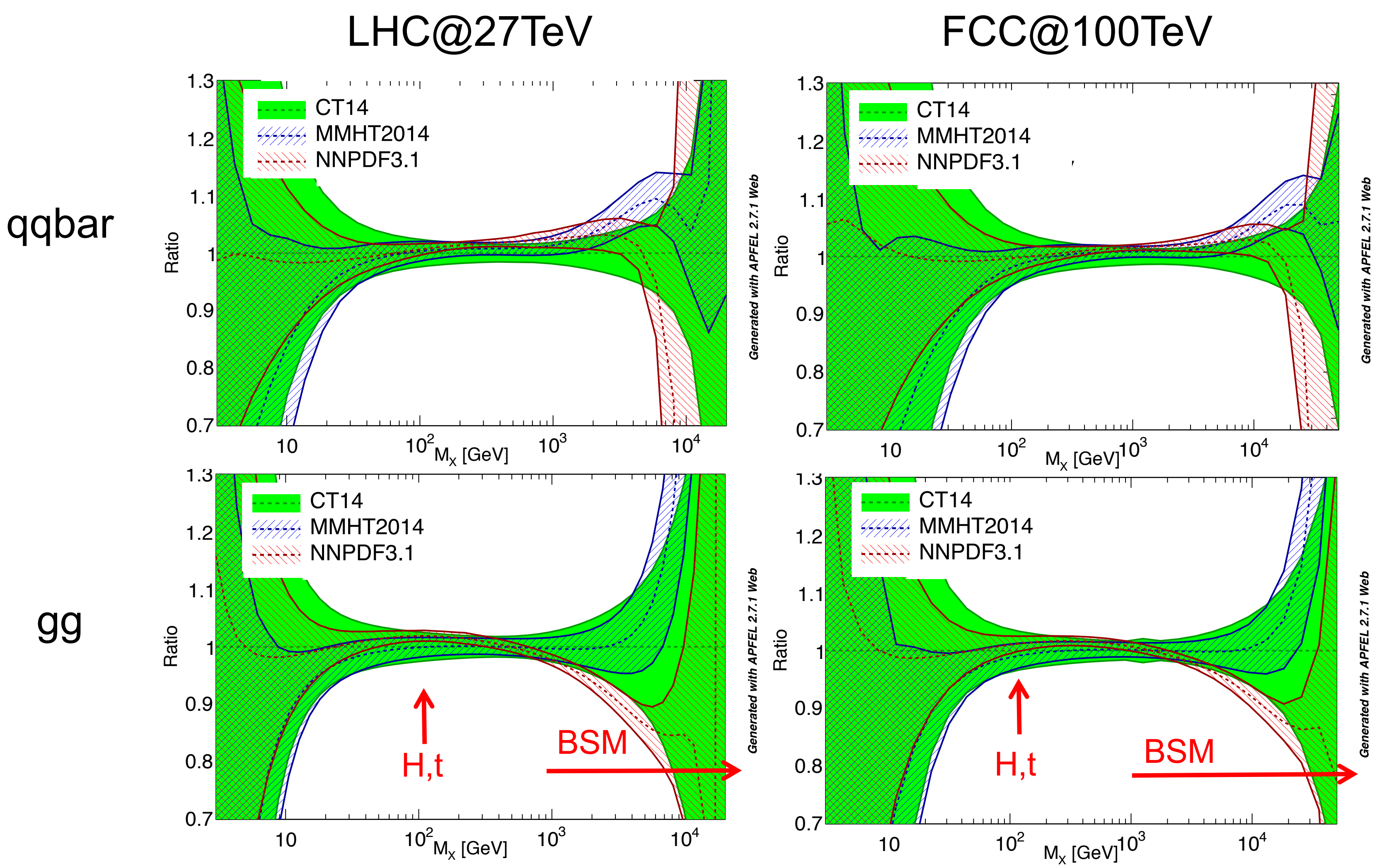
$$\begin{aligned}
\sigma^+_{r,CC} &\sim x\overline{U} + (1-y)^2 xD, \\
\sigma^-_{r,CC} &\sim xU + (1-y)^2 x\overline{D}.
\end{aligned}$$

Kinematics of a 100 TeV FCC

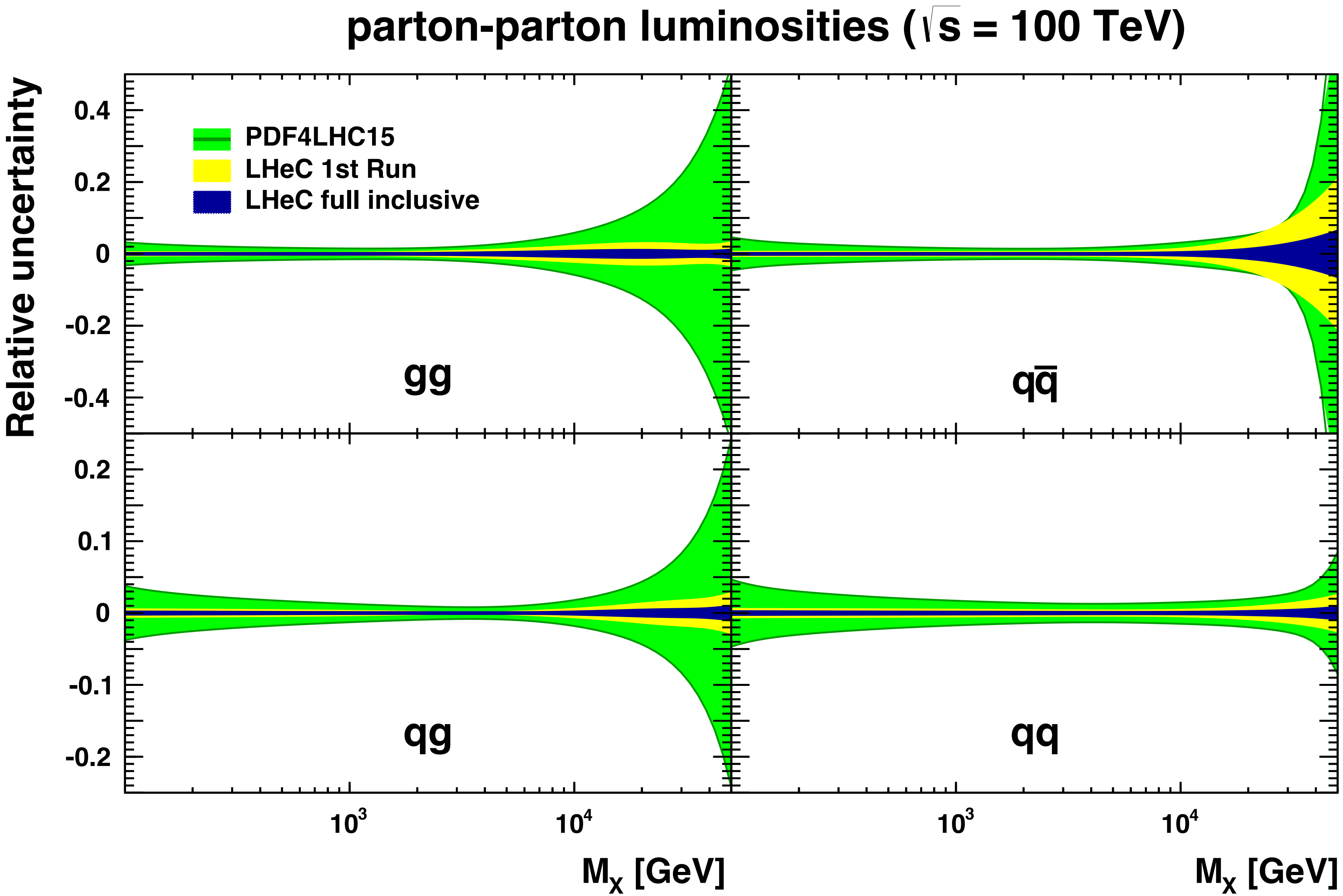


small x becomes relevant even for “common” physics (EG. W, Z, H, t)

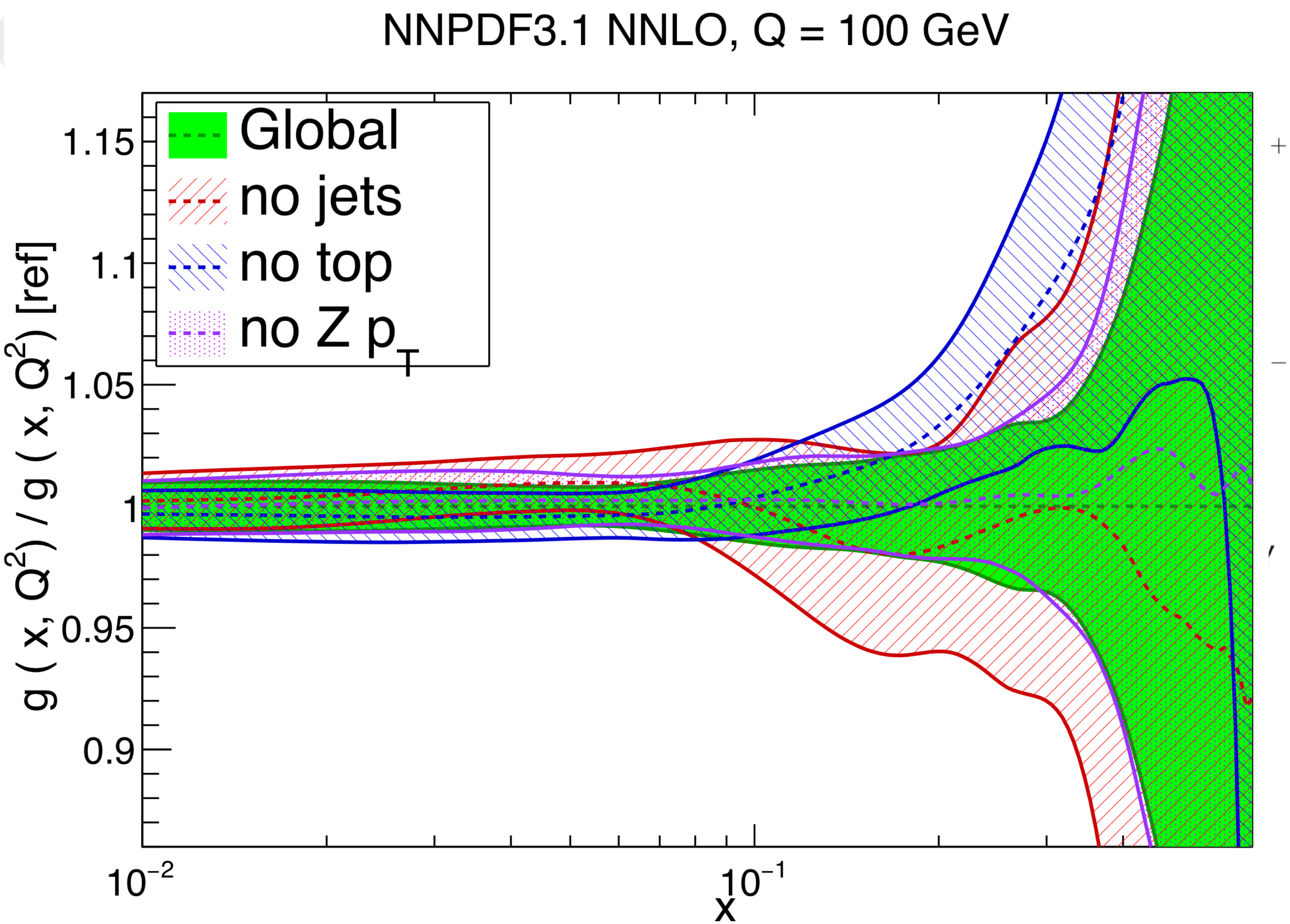
pdf luminosities for HE-LHC and FCC



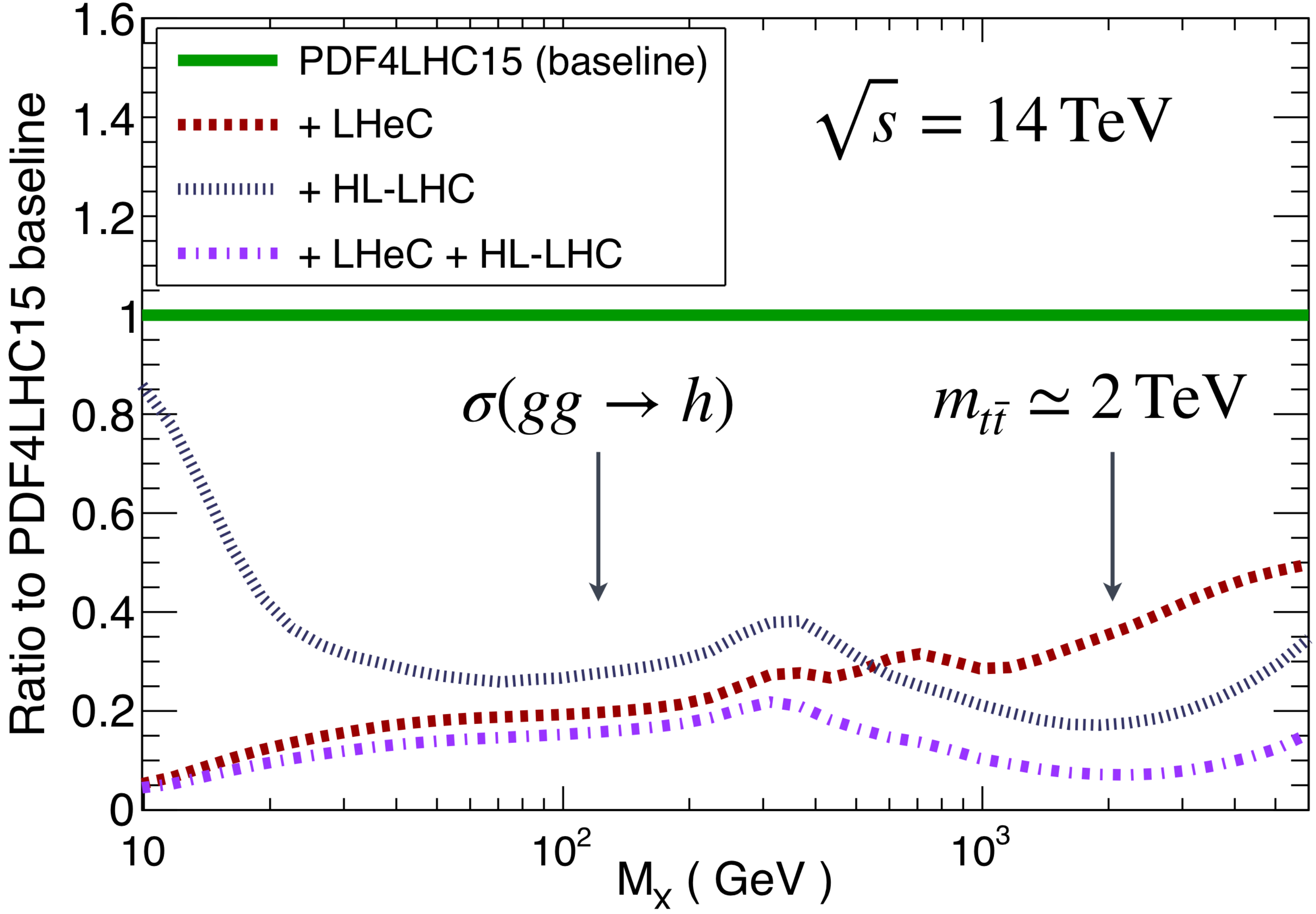
pdf luminosities



impact of LHC on today's pdfs

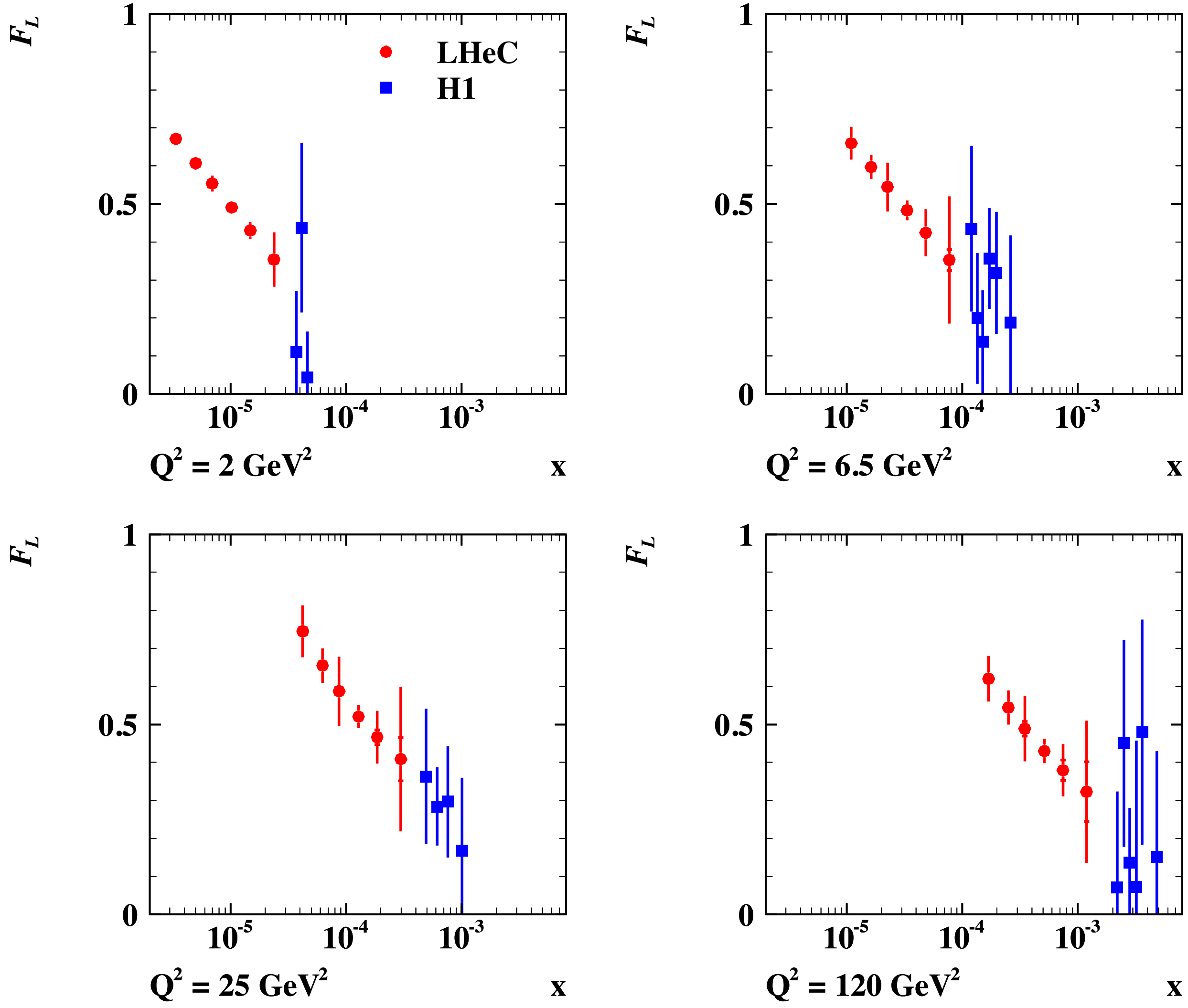


PDF uncertainties in gluon-gluon luminosity



arXiv:1810.03639 + ongoing work

FL at LHeC



M. Klein, arXiv:1802.04317

strong coupling α_s

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

lattice QCD

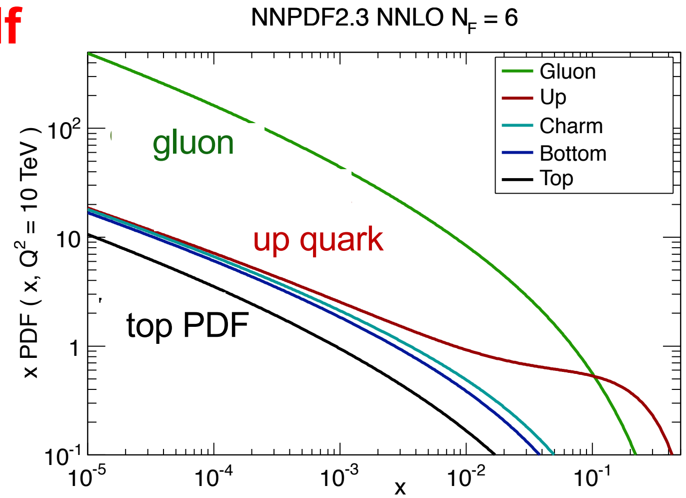
ep: per mille level
(LHeC/FCC-eh combined with HERA)

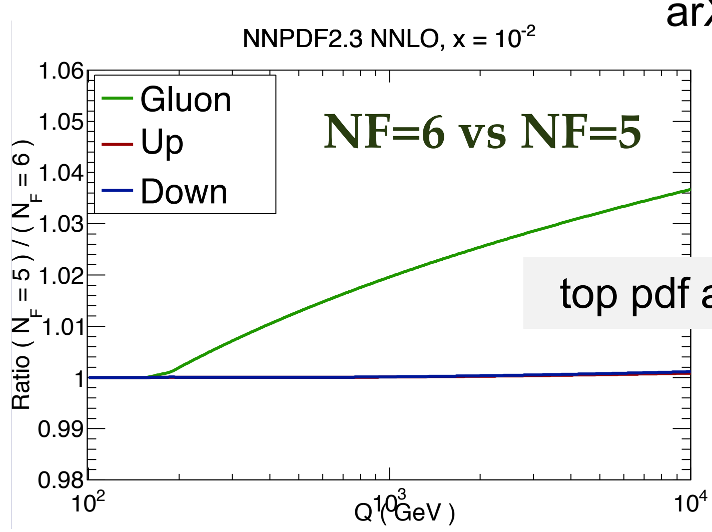
ee: order **per mille** with an FCC-ee

some other considerations

arXiv:1607.01831

top pdf



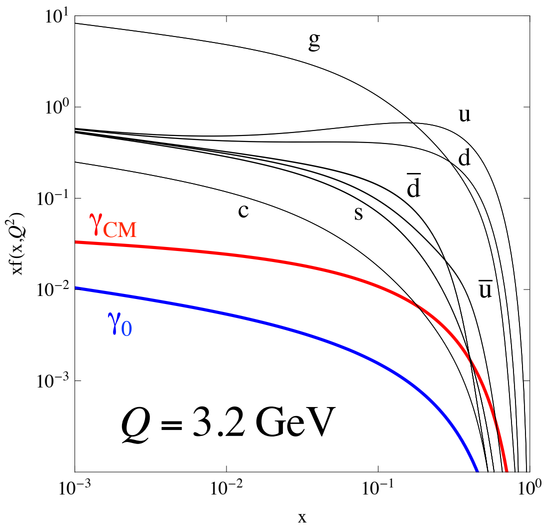


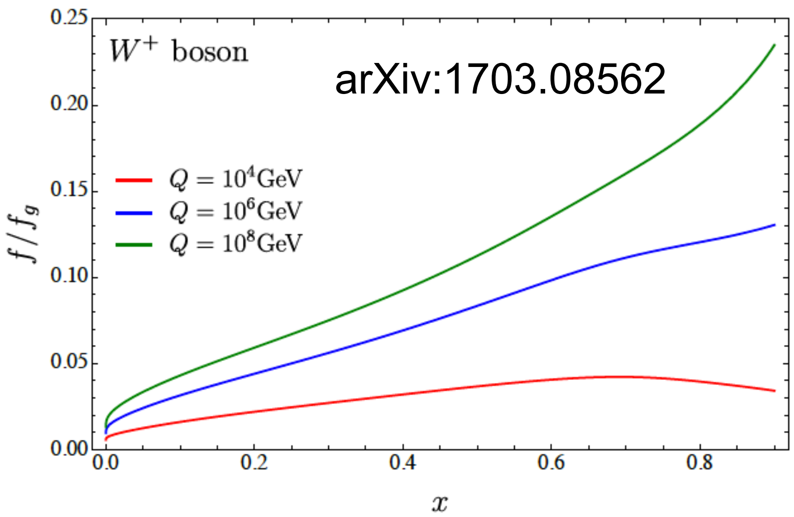
photon pdf

already visible

impact on high

scale LHC data





EW pdfs

also contribute

at FCC

FCC not simply a scaled version of **LHC** (qualitatively new phenomena introduced)

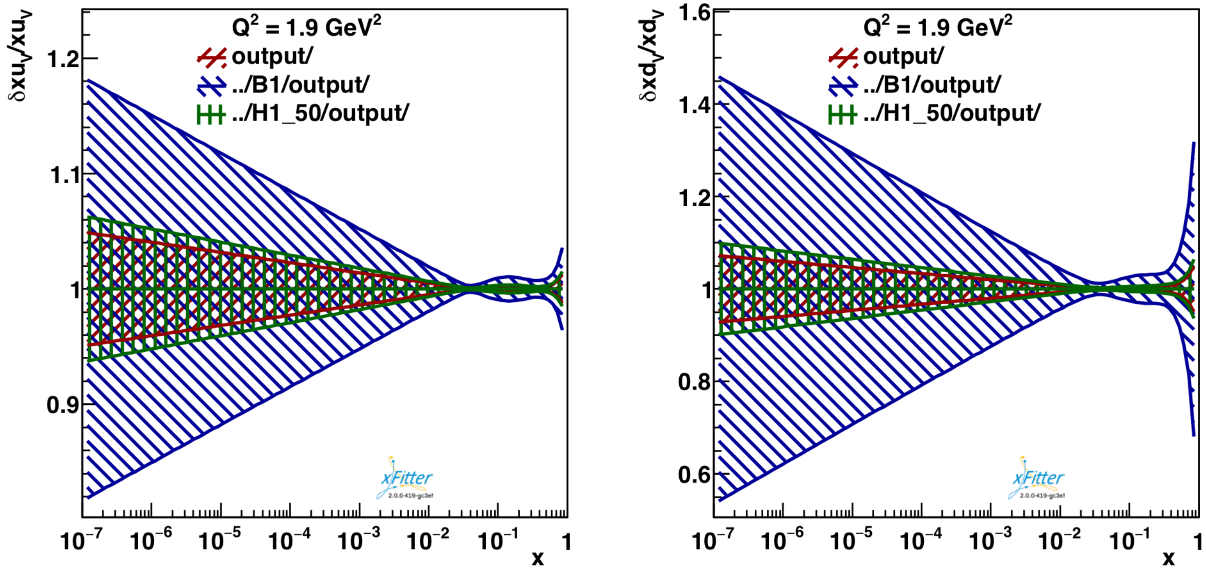
FCC-eh and previous LHeC simulation

NC/CC	E_e [GeV]	E_p [TeV]	P(e)	charge	lumi. [fb^{-1}]
NC	60 (60)	50 (7)	−0.8	−1	1000
CC	60 (60)	50 (7)	−0.8	−1	1000
NC	60 (60)	50 (7)	+0.8	−1	300
CC	60 (60)	50 (7)	+0.8	−1	300
NC	60 (60)	50 (7)	0	+1	100
CC	60 (60)	50 (7)	0	+1	100
NC	20 (60)	7 (1)	0	−1	100
CC	20 (60)	7 (1)	0	−1	100

error assumptions:
elec. scale: 0.1%; hadr. scale 0.5%
radcor: 0.3%; **γ**p at high y: 1%
uncorrelated extra eff. 0.5%

M.Klein

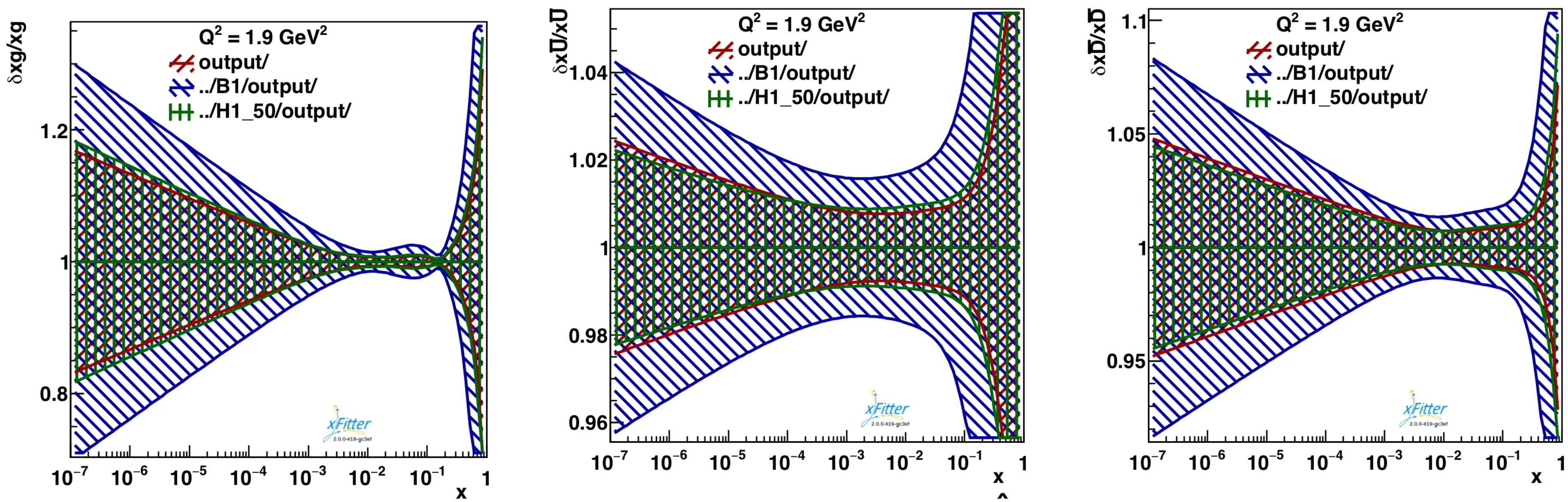
LHeC pdfs: previous versus new



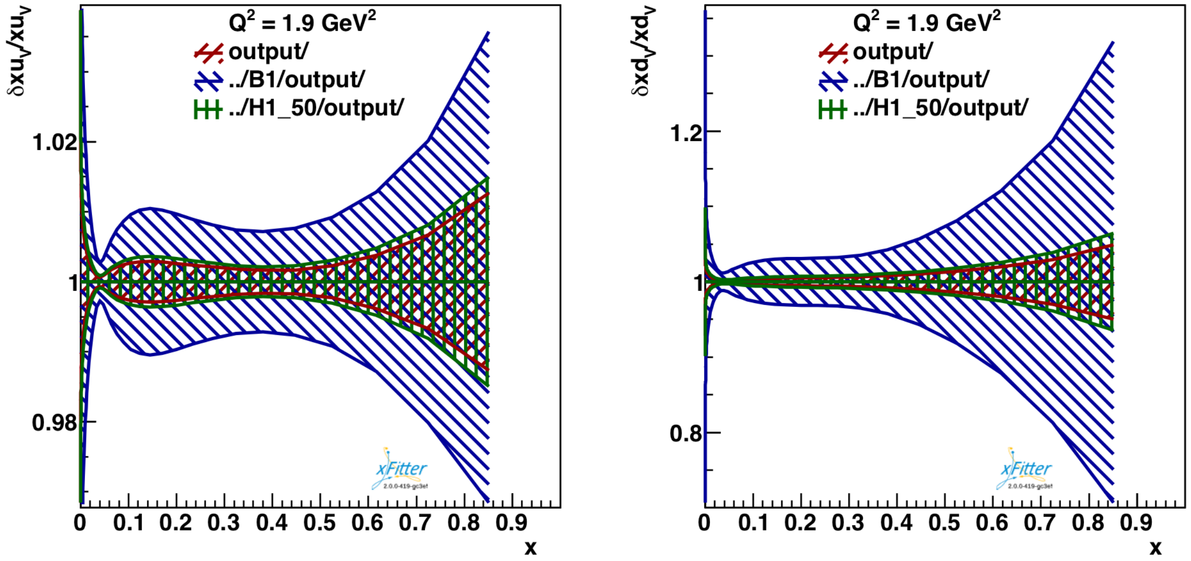
RED = previous full inclusive
(shown in DIS17 and subsequently)

BLUE = new 1st Run

GREEN = new full inclusive



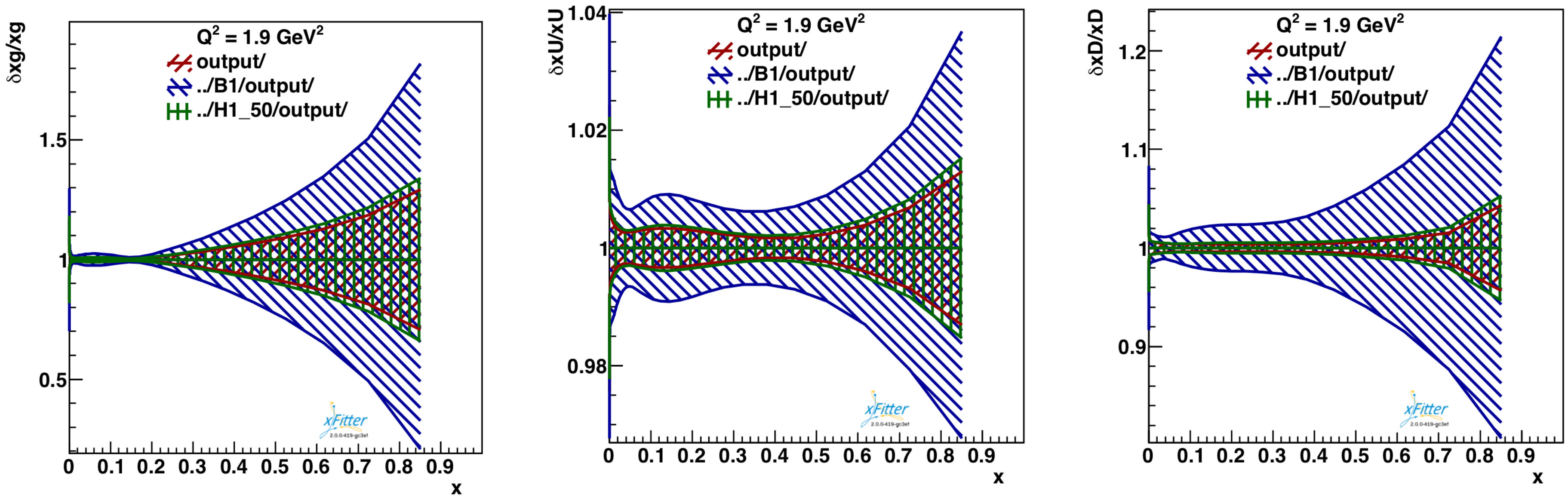
LHeC pdfs: previous versus new



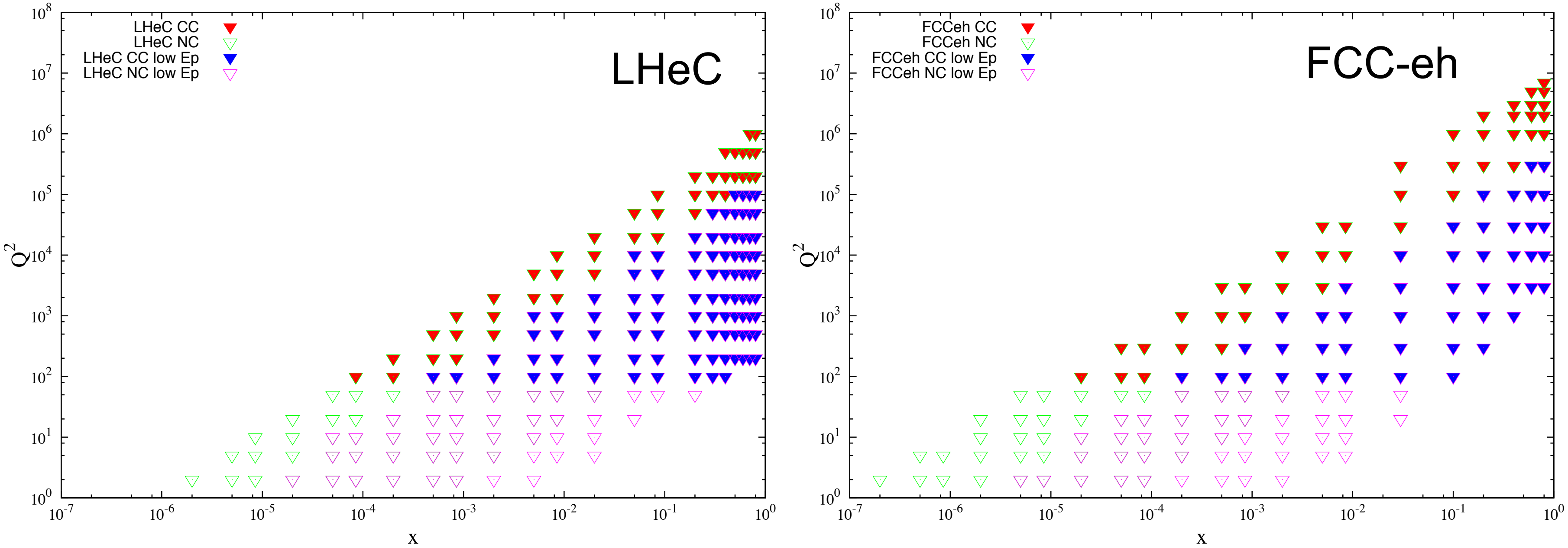
RED = previous full inclusive
(shown in DIS17 and subsequently)

BLUE = new 1st Run

GREEN = new full inclusive



kinematic coverage previous simulations



strange

ATLAS coll.,
arXiv:1612.0301

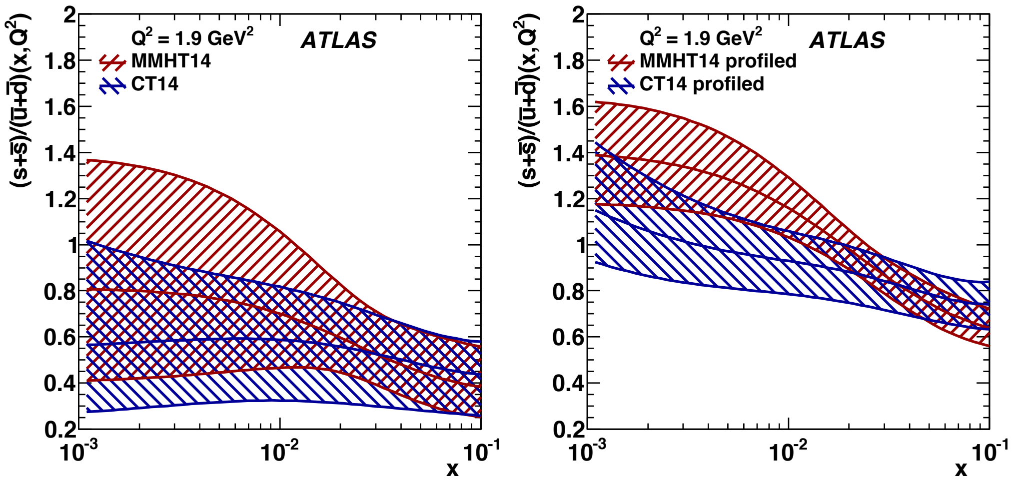


Figure 25: Ratio $R_s(x) = (s(x) + \bar{s}(x))/(\bar{u}(x) + \bar{d}(x))$ as a function of Bjorken-x at a scale of $Q^2 = 1.9$ GeV^2 for the original MMHT14 and CT14 PDF sets (left) and for the MMHT14 and CT14 sets when profiled with the new W, Z differential cross-section data (right).

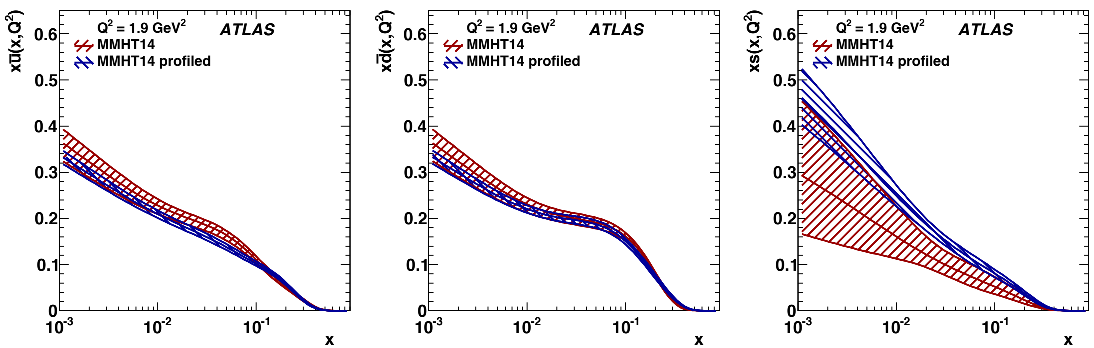
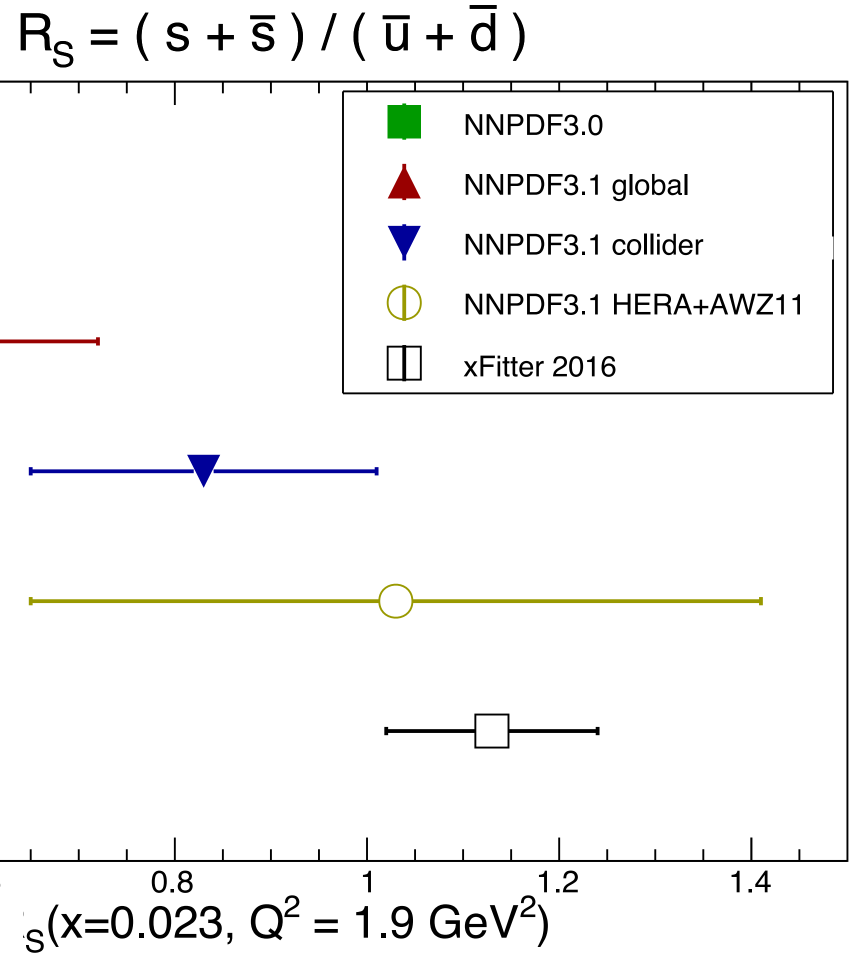


Figure 26: Distribution of $x\bar{u}$ (left), $x\bar{d}$ (middle) and xs (right) PDFs as a function of Bjorken-x at a scale of $Q^2 =$ 1.9 GeV^2 for the MMHT14 PDF set before and after profiling.

strange

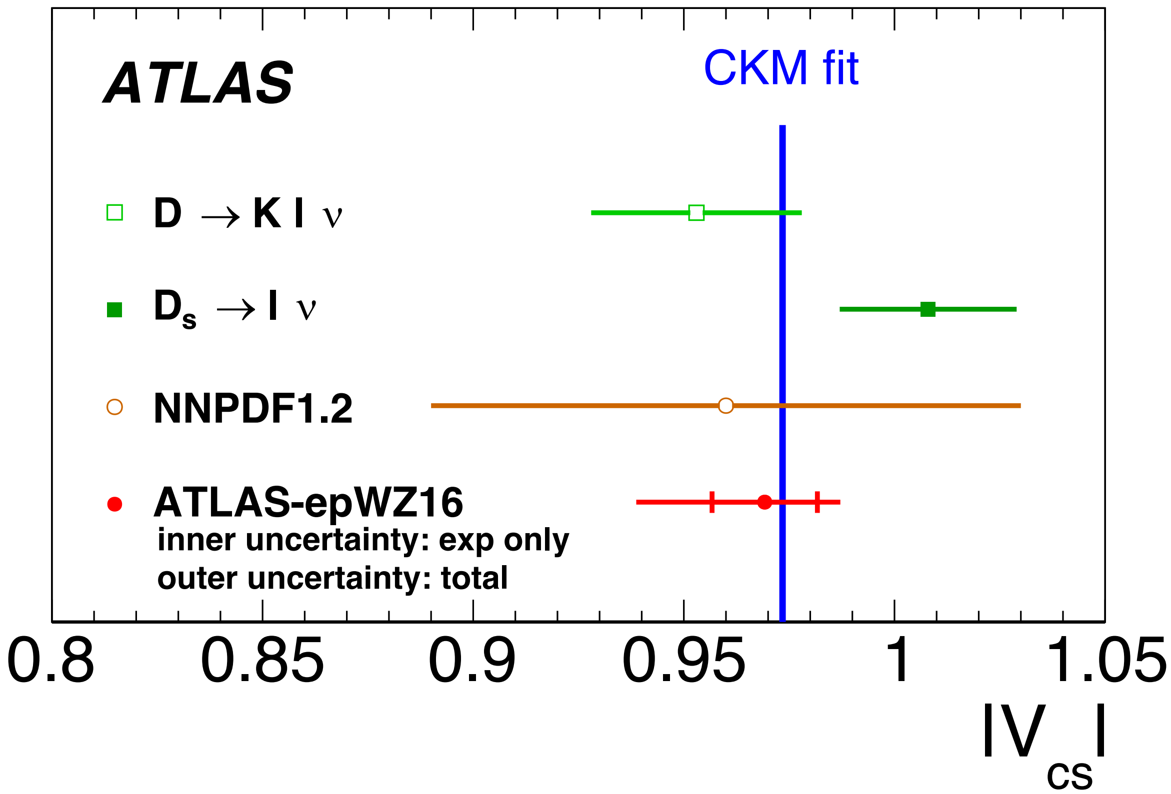
NNPDF3.1, arXiv:1706.00428



* “xFITTER16” = ATLAS arXiv:1612.0301

Vcs

ATLAS coll., arXiv:1612.03016



HERA+ATLAS ⟶ Vcs

expect much better precision from **LHeC** or **FCC-eh** (×10 or more)