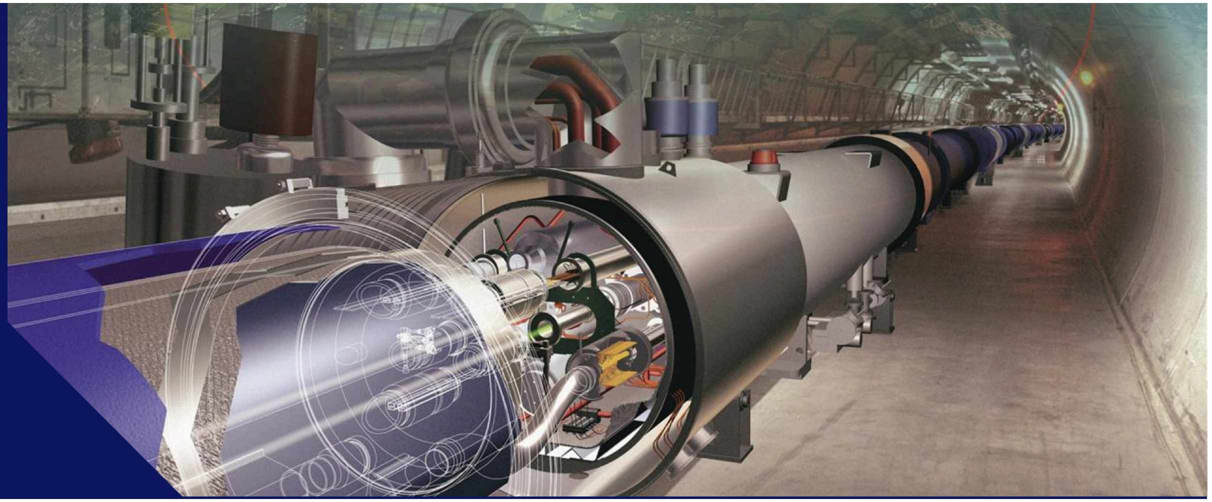
HiX 2019

Kolympari, Crete

16 – 21 August 2019



PDFs at the HL-LHC and LHeC

Claire Gwenlan, Oxford

on behalf of the LHeC and HL-/HE-LHC SM WGs

outline

- **pdfs at the LHC and the importance of large x**

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

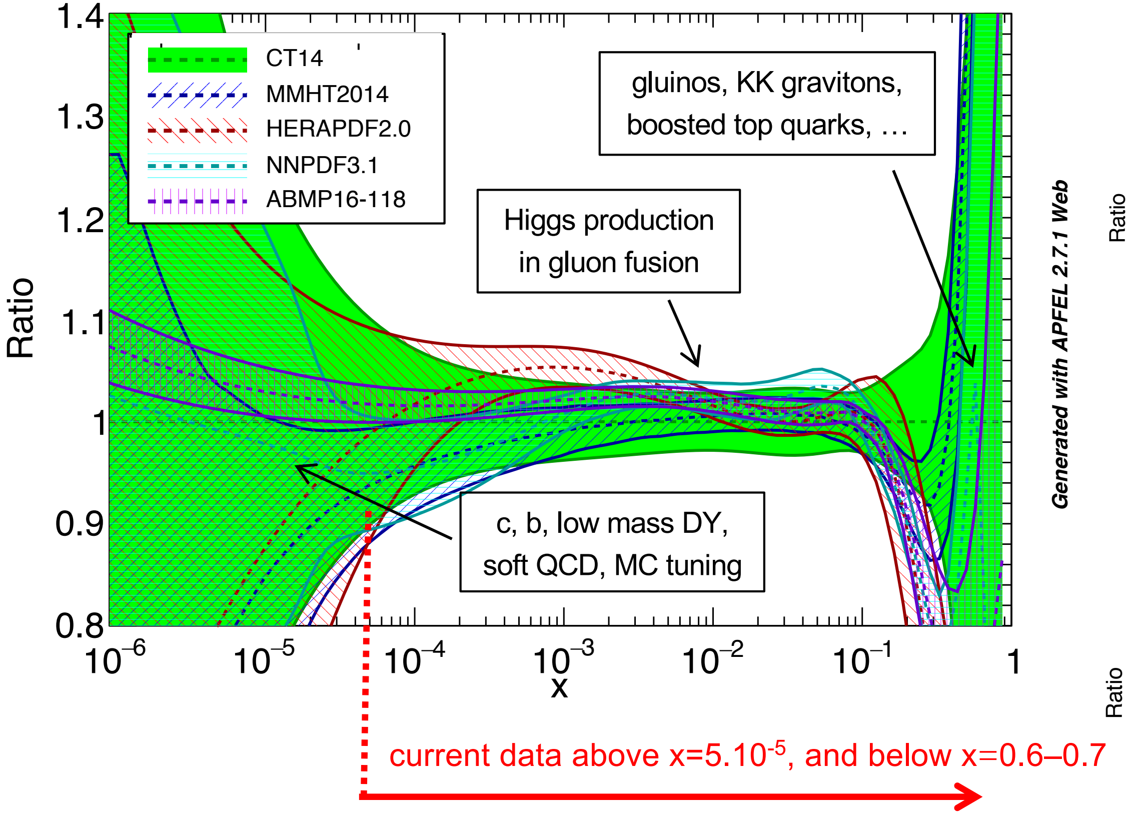
  summary of ongoing studies towards update of LHeC CDR (arXiV:1206.2913);

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

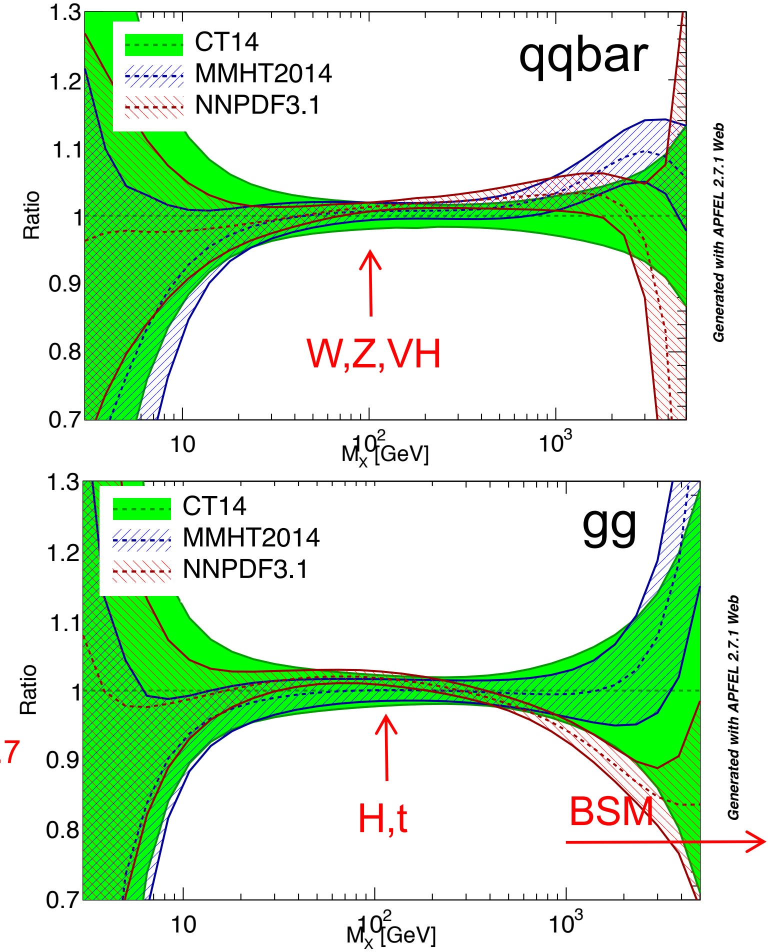
  plus some ongoing studies on a lower energy FCC configuration

pdfs: the situation today

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



pdf luminosities (LHC@14TeV)

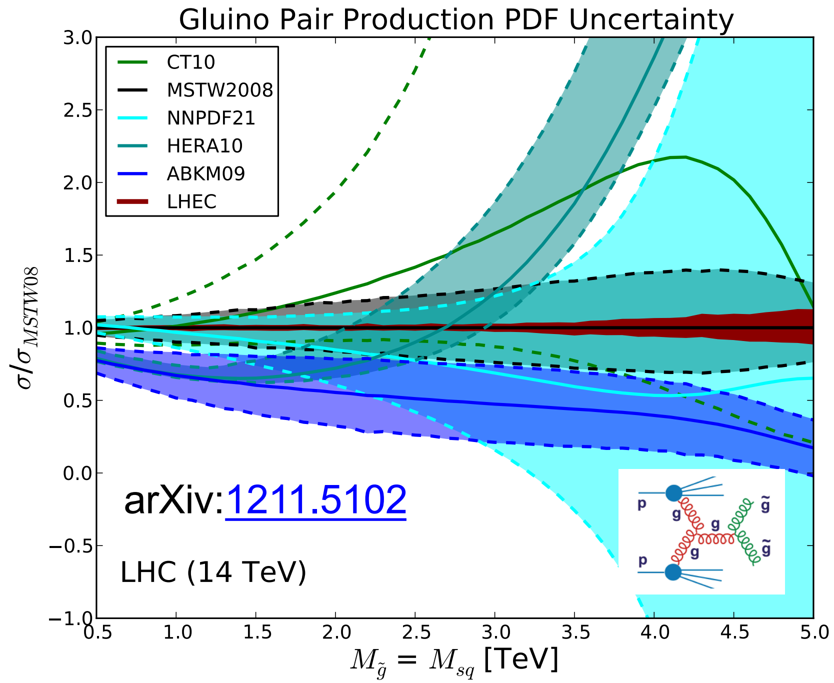


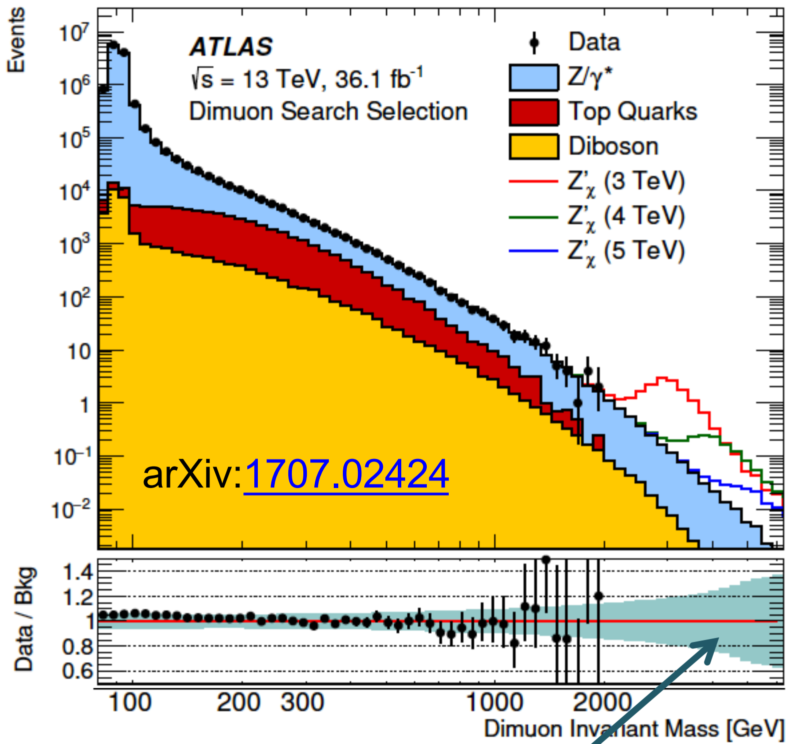
pdfs poorly known at **large** and **small x**

higher precision needed also for H, W, t

why large x pdfs matter at the LHC

BSM searches at high scales limited by (lack of) knowledge of large x pdfs





pdf uncertainty dominates

many interesting processes at LHC are **gg** initiated – top; Higgs; BSM, EG. gluino pair production, LQs etc.; …

current BSM searches at high mass also limited by **large x valence** and **sea quark** uncertainties

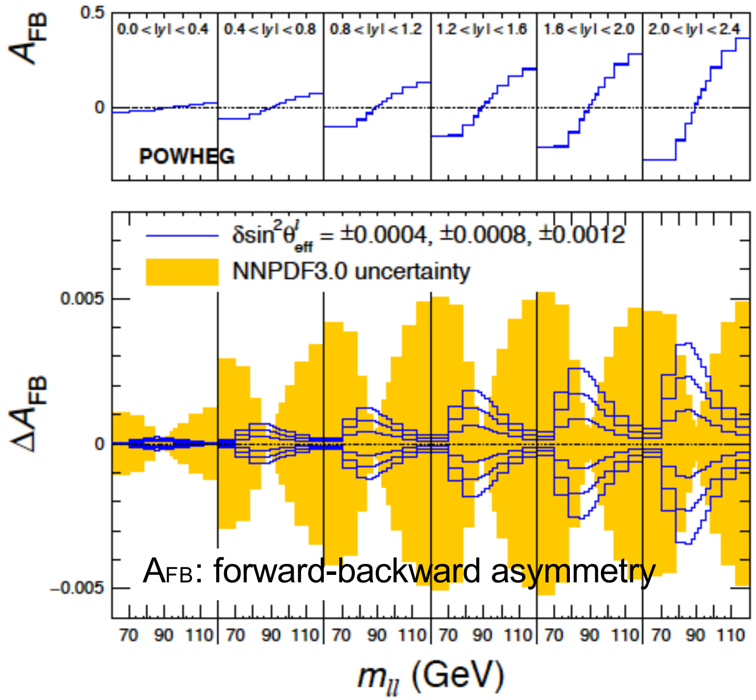
and other LHC measurements…

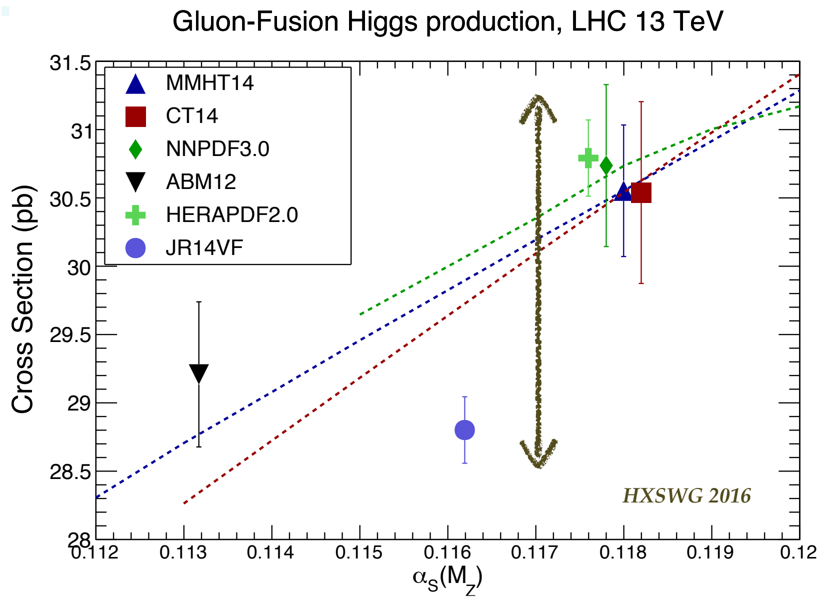
… such as precision M_W, $\sin^2\vartheta_W$ (where small discrepancies may indicate BSM physics) and Higgs, are also limited by **pdf uncertainties** at medium x, where we know pdfs best!

ATLAS M_W, arXiv:[1701.07240](1701.07240)

Channel	$m_{W^+} - m_{W^-}$ [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.
$W \to e\nu$	−29.7	17.5	0.0	4.9	0.9	5.4	0.5	0.0	24.1	30.7
$W \to \mu\nu$	−28.6	16.3	11.7	0.0	1.1	5.0	0.4	0.0	26.0	33.2
Combined	−29.2	12.8	3.3	4.1	1.0	4.5	0.4	0.0	23.9	28.0

CMS $\sin^2\vartheta_W$, arXiv:[1806.00863](1806.00863)





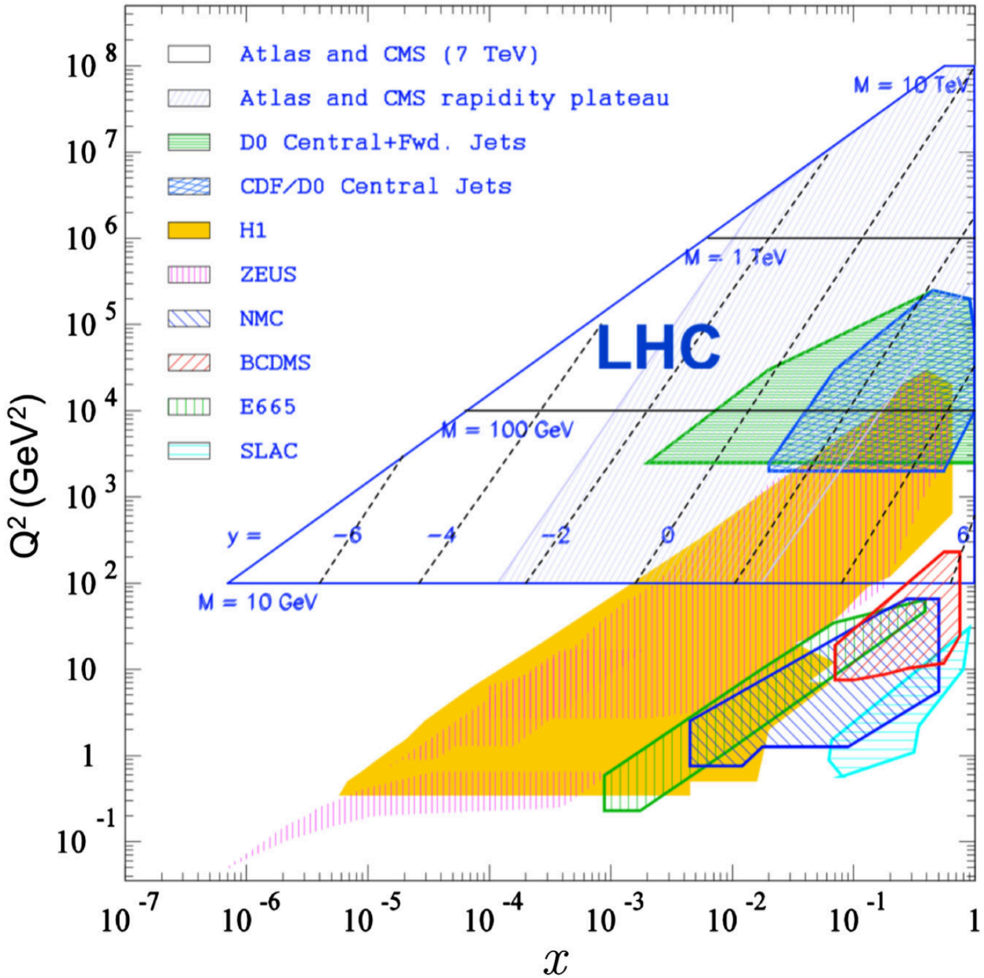
BLUE: vary $\sin^2\vartheta_{eff}$ for fixed pdf

ORANGE: NNPDF3.0 pdf uncertainty for fixed $\sin^2\vartheta_{eff}$

pdf constraints from the LHC

HERA inclusive DIS (NC and CC) provide most important baseline for any current pdf determination

sensitive to **valence quarks**; constraints on **small x quarks**; **gluon** via scaling violations



LHC measurements increase range in (x,μ^2), and provide information on quark flavour separation

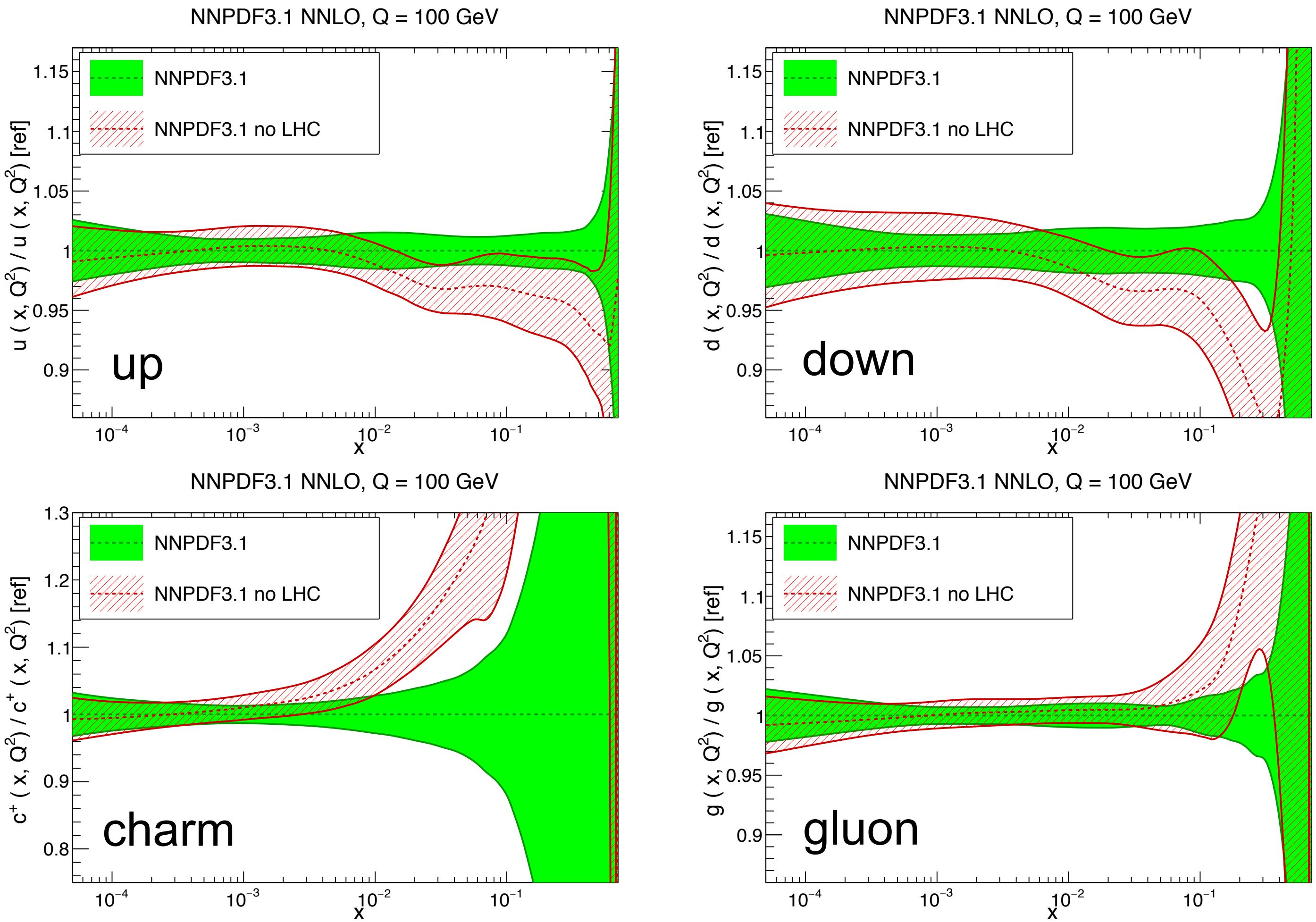
LHC measurements are sensitive to:

gluon at large x: jets; top; ZPt; W,Z+jets; direct γ

quarks at large x: HM Drell Yan

medium and smaller x: W,Z production; LM Drell Yan; W,Z,γ+c,b

impact of LHC on today's pdfs



arXiv:[1706.00428]

(**NNPDF3.1** includes modern LHC data on W,Z+top+jets+ZPt)

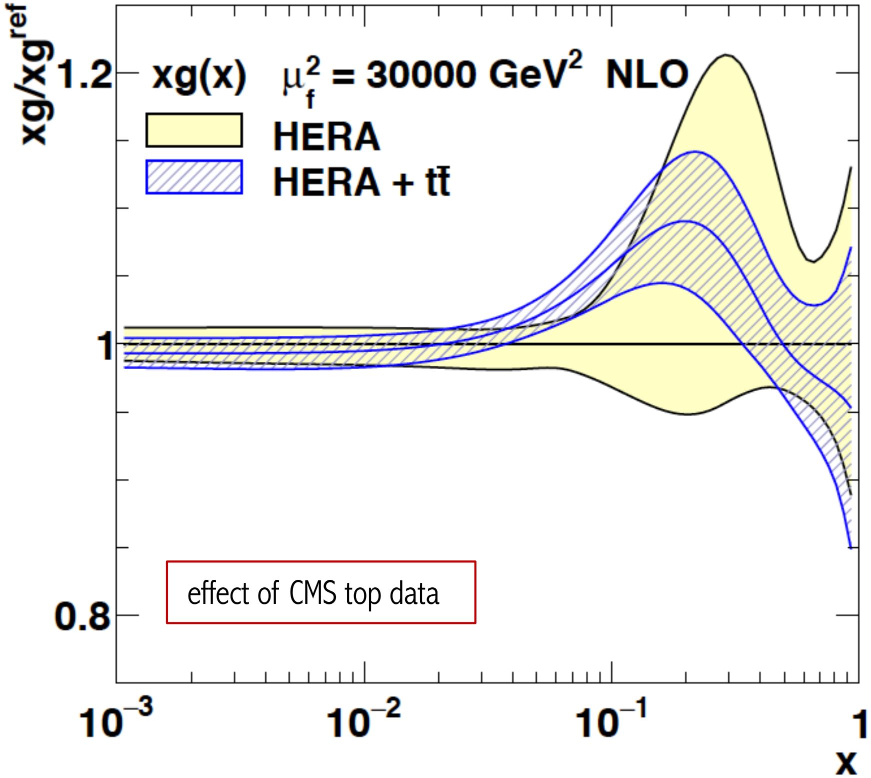
updates to main global pdf fits, including more LHC data, expected soon

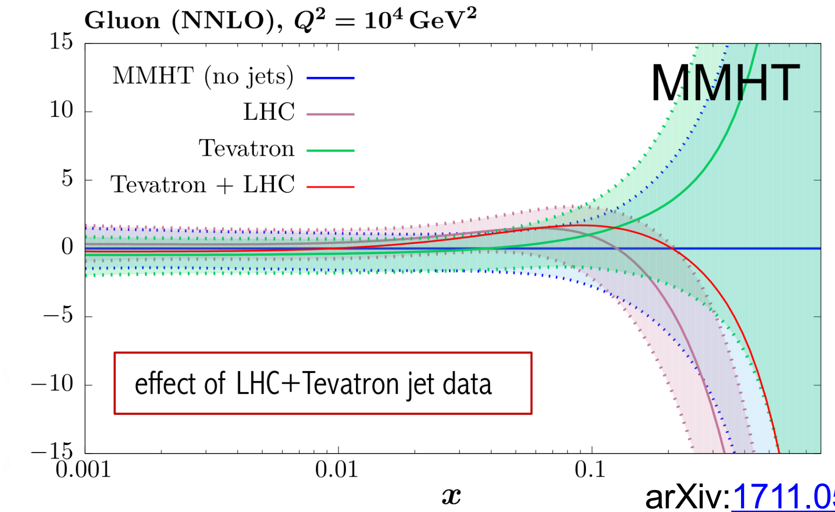
LHC: large x gluon

direct **γ** : arXiv:1802.03021

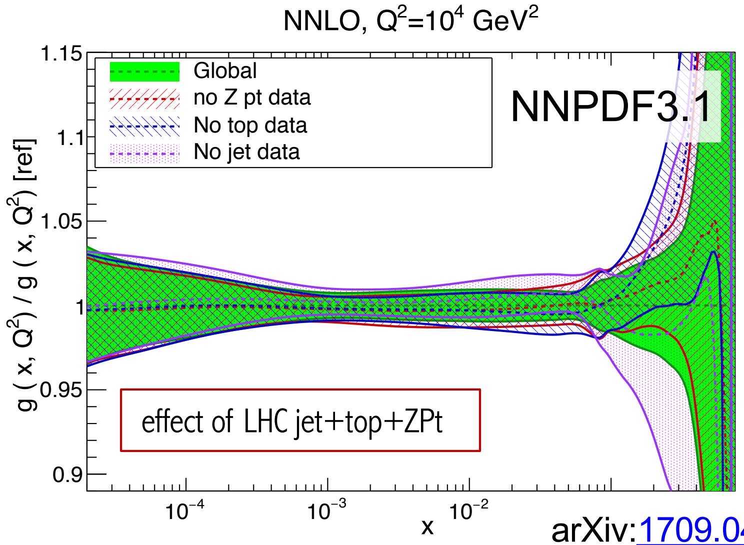
arXiv:1904.05237; see also ATLAS-PHYS-PUB-2018-017

CMS





arXiv:1711.05757



arXiv:1709.04922

jet, **top quark pair**, **ZPt** and **γ** measurements constrain **gluon** at medium and **large x**

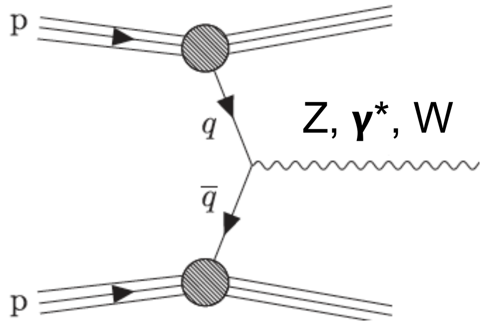
numerous studies from ATLAS, CMS, xFitter and global fitters

NNLO QCD calculations now available in all cases

(**LHCb forward charm and beauty** COULD also help at small and large x?)

LHC: large x quarks and flavour separation

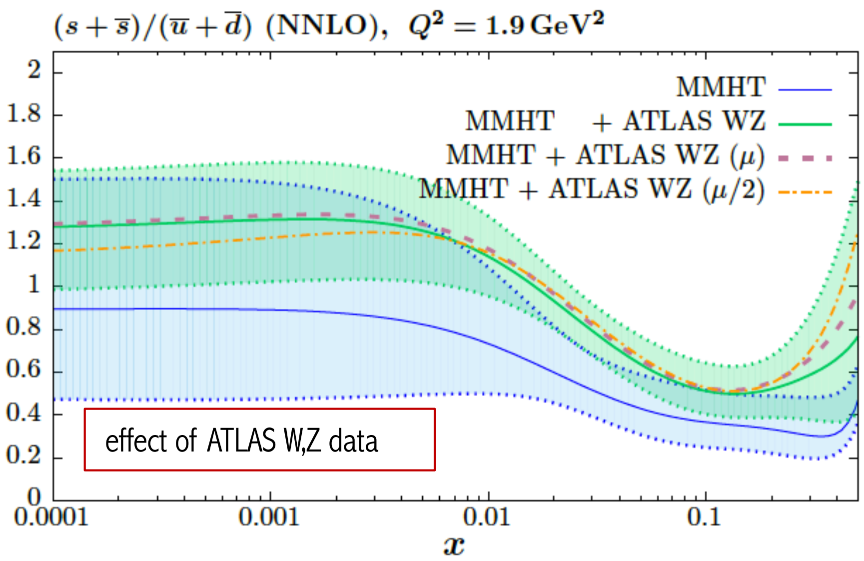
electroweak gauge boson measurements give information on **quark** and **anti-quark** flavour separation



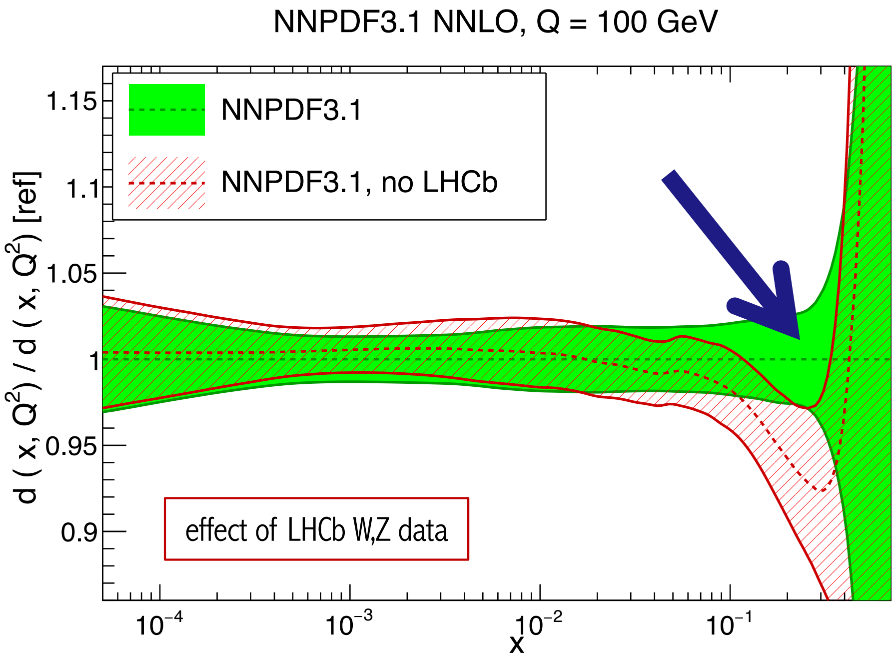
HM DY gives access to **large x** (also sensitive to proton's **γ** pdf)

LHCb measurements extend to **forward** region (small & **large x**)

W,Z & W+c also sensitive to **strange pdf**



R. Thorne, DIS19

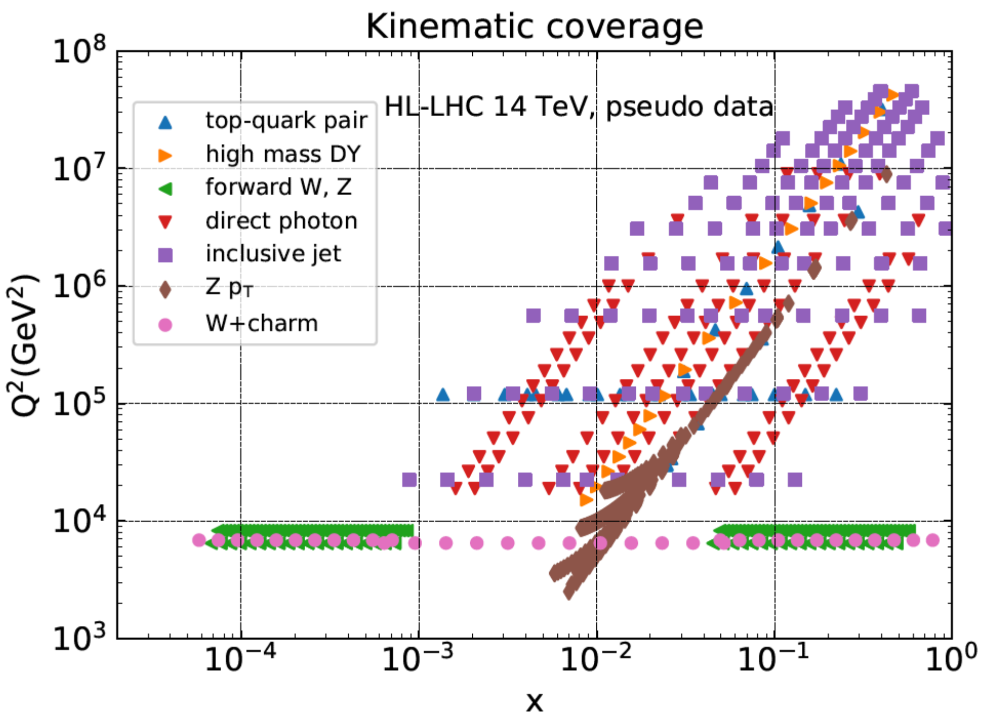


arXiv:1706.00428

numerous studies from ATLAS, CMS, xFitter and global fitters, using combinations of:

W,Z including HM & LM DY; W+c; and most recently W+jets [ATLAS-PHYS-PUB-2019-016]

HL-LHC pdfs



study pdf constraints expected from LHC measurements **by end of HL-LHC phase** (2026 to mid-2030s)

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-large-x; and not already systematics limited

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

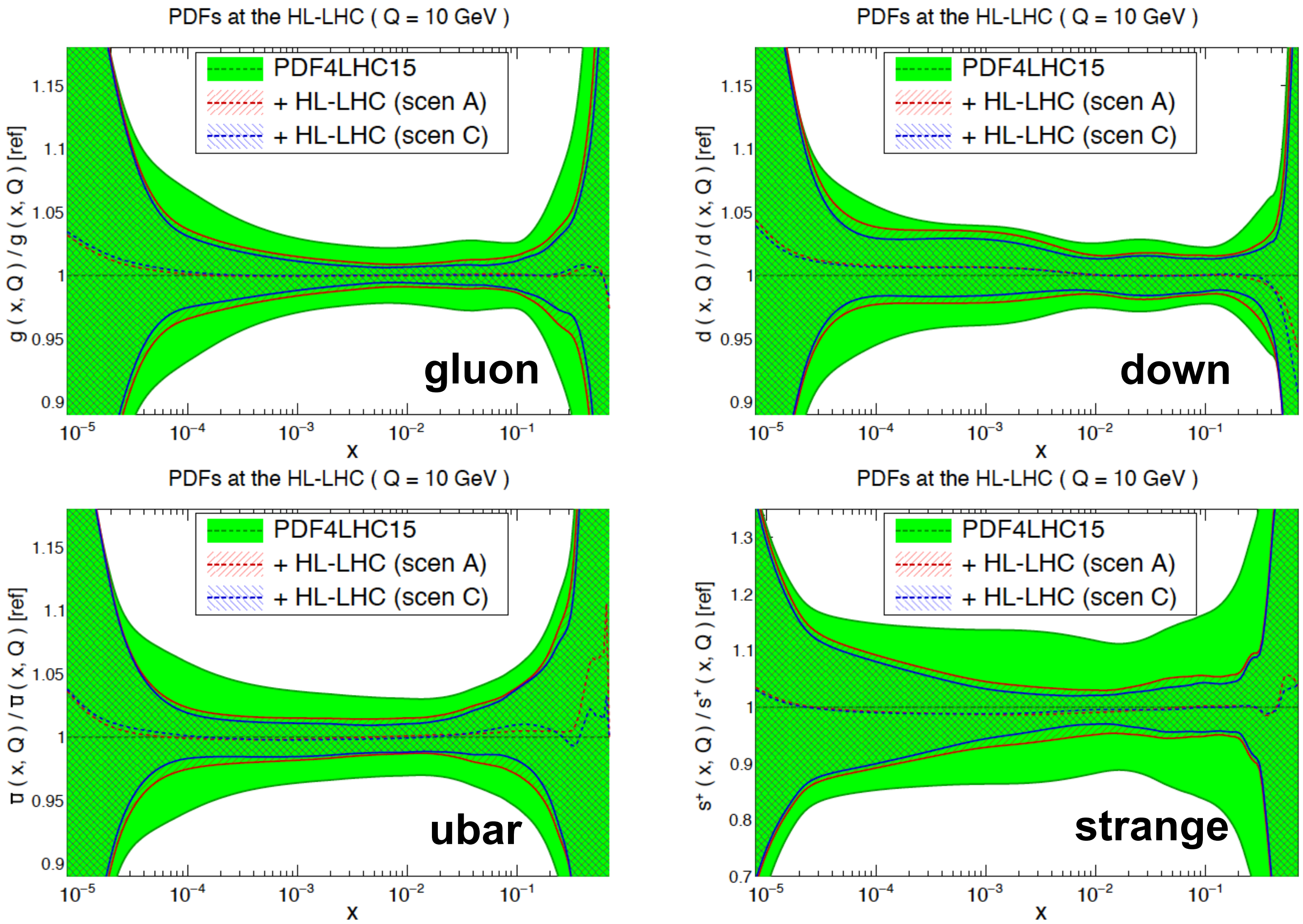
- systematic uncertainties taken from existing data;
- treated as **uncorrelated**, with factor **fcorr=0.5**, chosen to approximately reproduce effect of syst. correlations in existing measurements;
- variable factor **fred** to estimate improvement to systs.

Hessian profiling of PDF4LHC15

with tolerance T=3

arXiv:[1810.03639](https://arxiv.org/abs/1810.03639)

HL-LHC pdfs



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

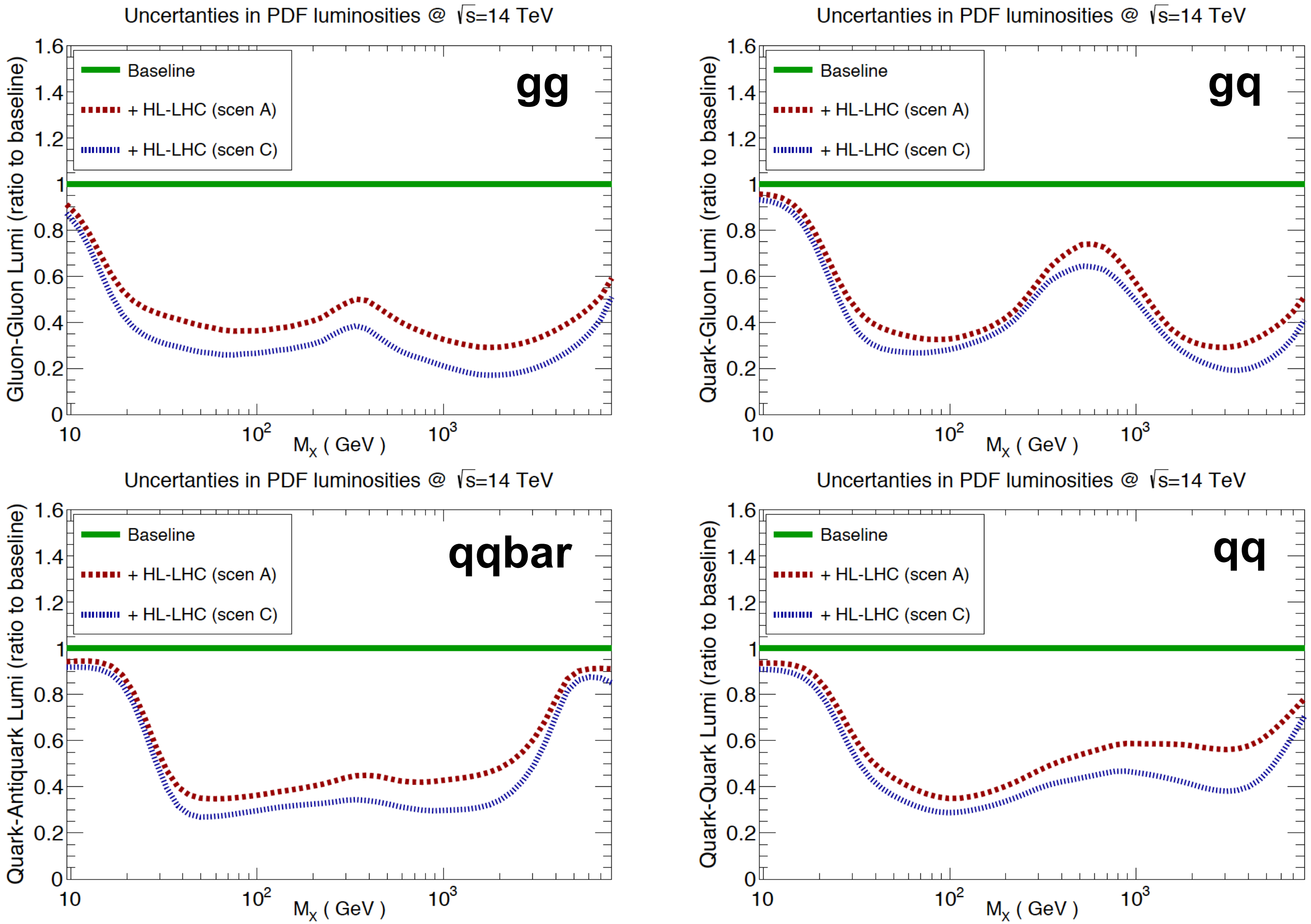
scenario A: **conservative**

scenario C: **optimistic**

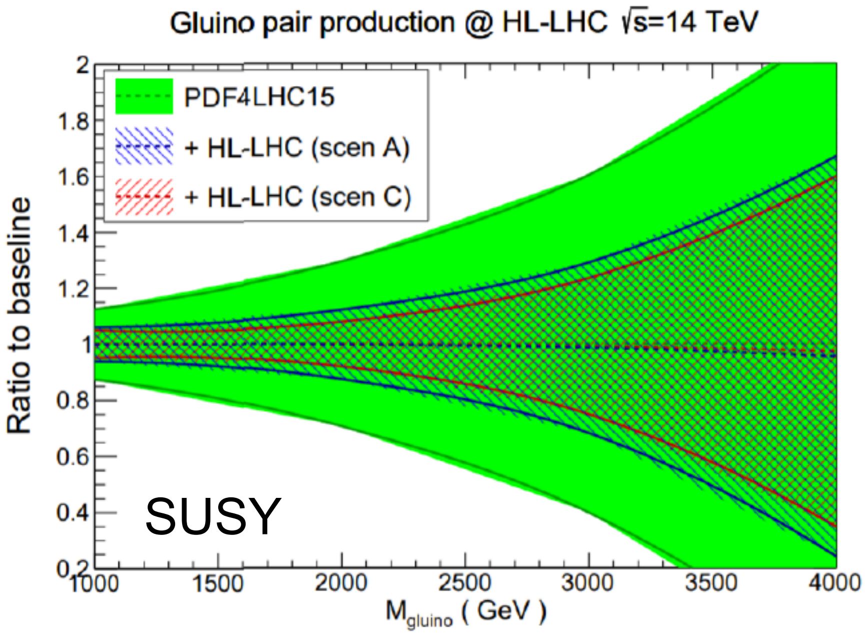
(together with **intermediate** scenario B, all are available in lhapdf format)

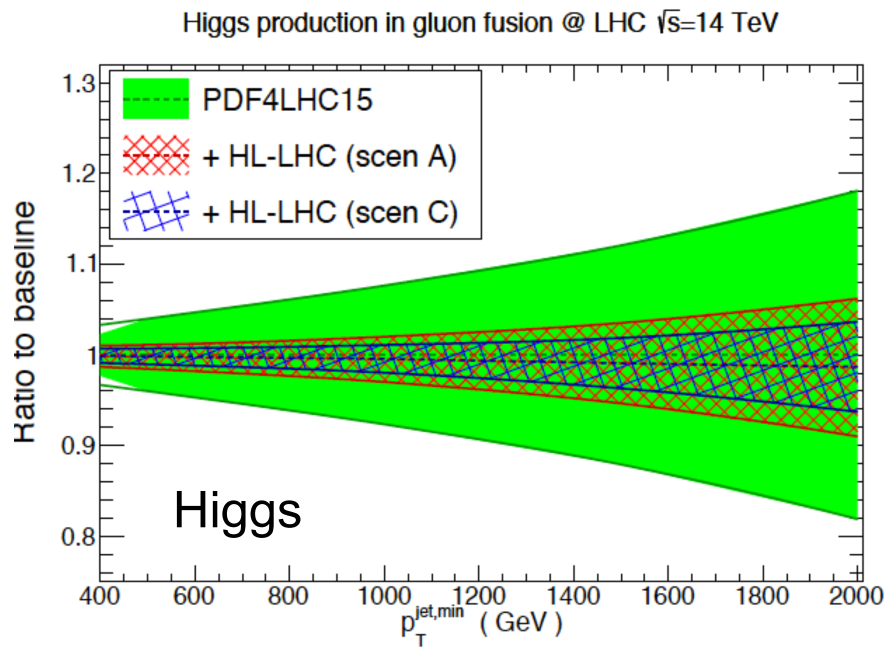
arXiv:1810.03639

parton luminosities



impact on LHC phenomenology

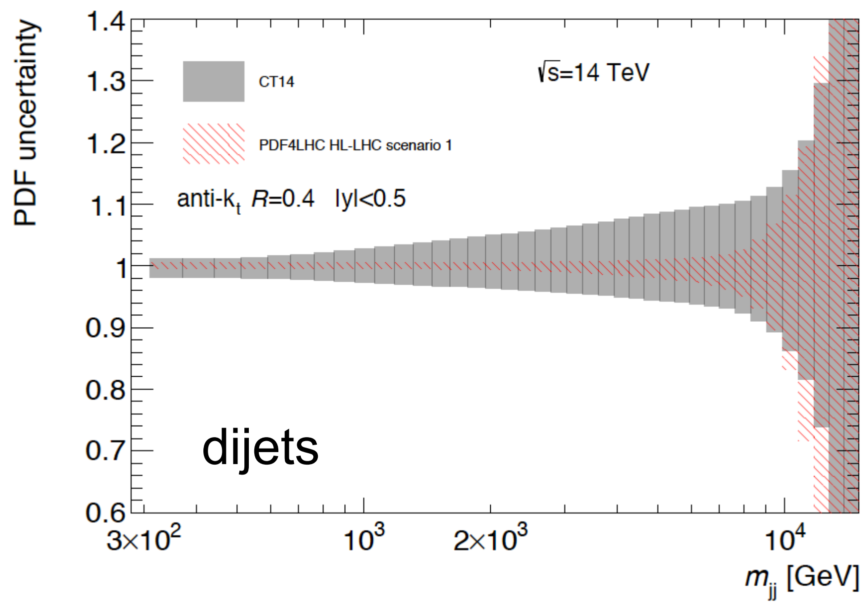




arXiv:[1810.03639]

and CERN yellow report,

arXiv:[1902.04070]



caveats

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

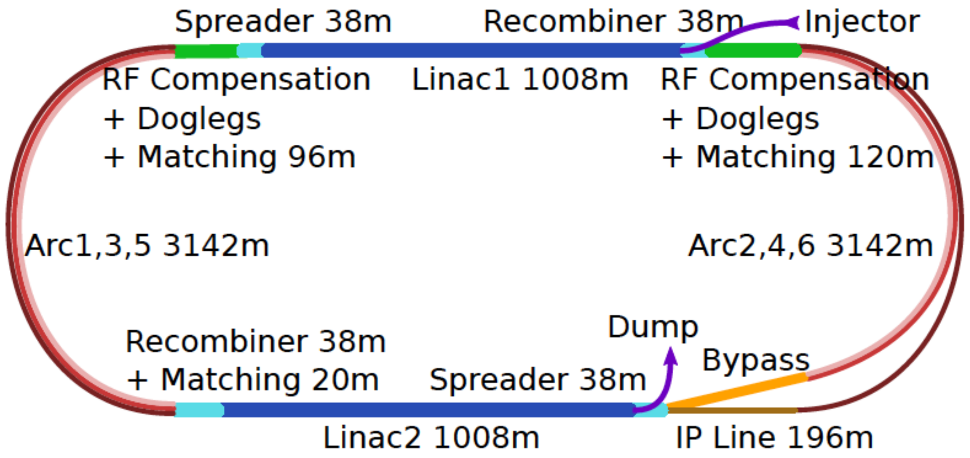
experience to date at the LHC tells us that these issues present major challenges

EG. difficulty in fitting **ATLAS inclusive jet data** in all rapidity bins, now well known, seen by both ATLAS and global fitters; fit quality sensitive to exact choice of correlation model (see EG. arXiv:1706.03192)

similar issues seen elsewhere, for example in fitting **top quark pair** distributions; along with other issues such as that ATLAS and CMS not always consistent with each other for same spectra, nor are their uncertainty estimates; and within same experiment different spectra not always compatible (EG. arXiv:1611.08609, ATLAS-PHYS-PUB-2018-017 , MMHT update DIS19)

also theoretical challenges: reach to small x – need for ln(1/x) resummation, arXiv:1710.05935, arXiv:1802.00064 ; reach to large x, EG. HM DY, requires good understanding of NLO electroweak corrections and **γ** content of proton (considerable recent progress); …

can we do better?



operating **synchronously** with and using p beam from:

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

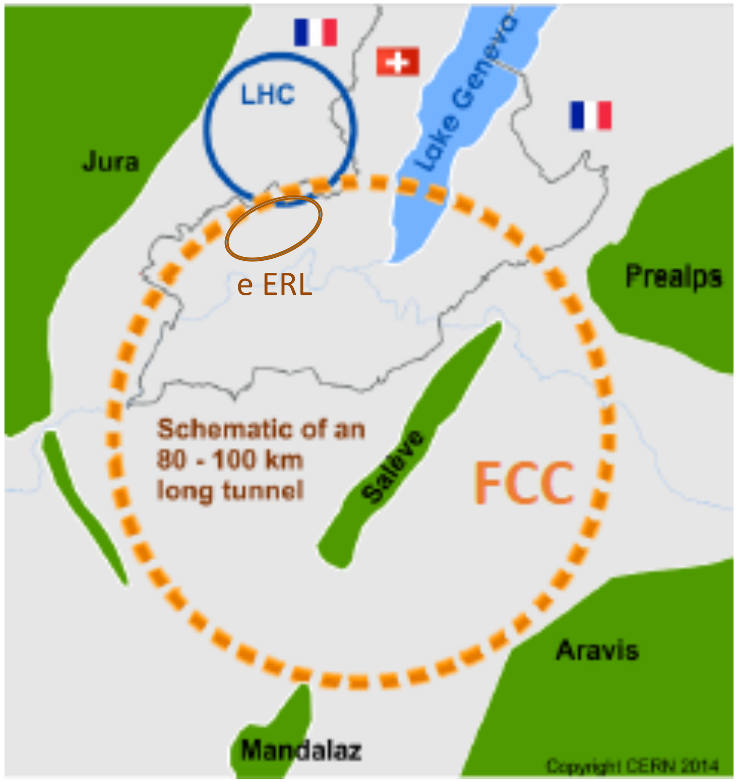
† **FCC (A):** a lower energy configuration that could operate earlier in an FCC tunnel, using current magnet technology

ep colliders: LHeC or **FCC-eh**

energy recovery LINAC

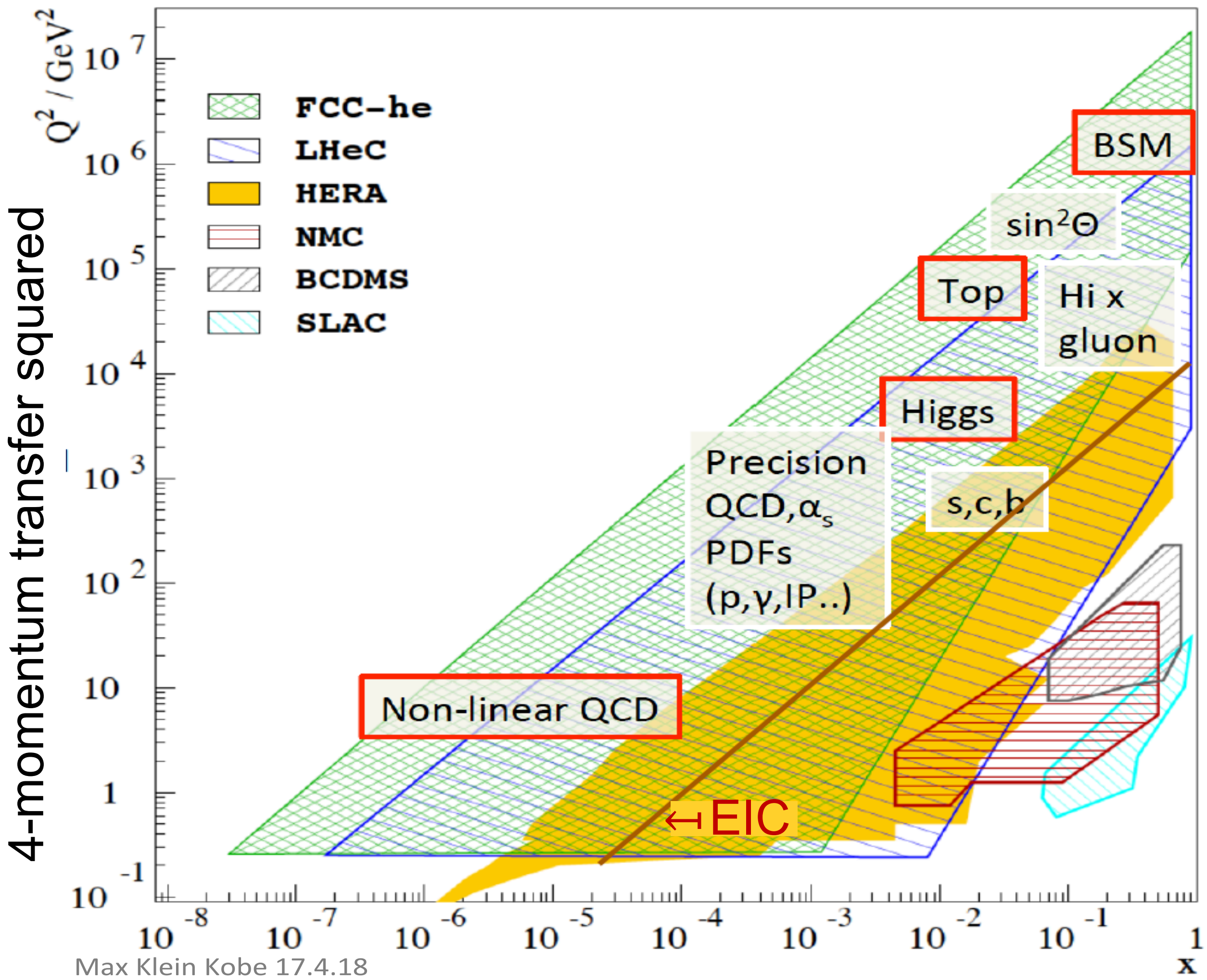
e beam: up to 60 GeV

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



kinematic coverage

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



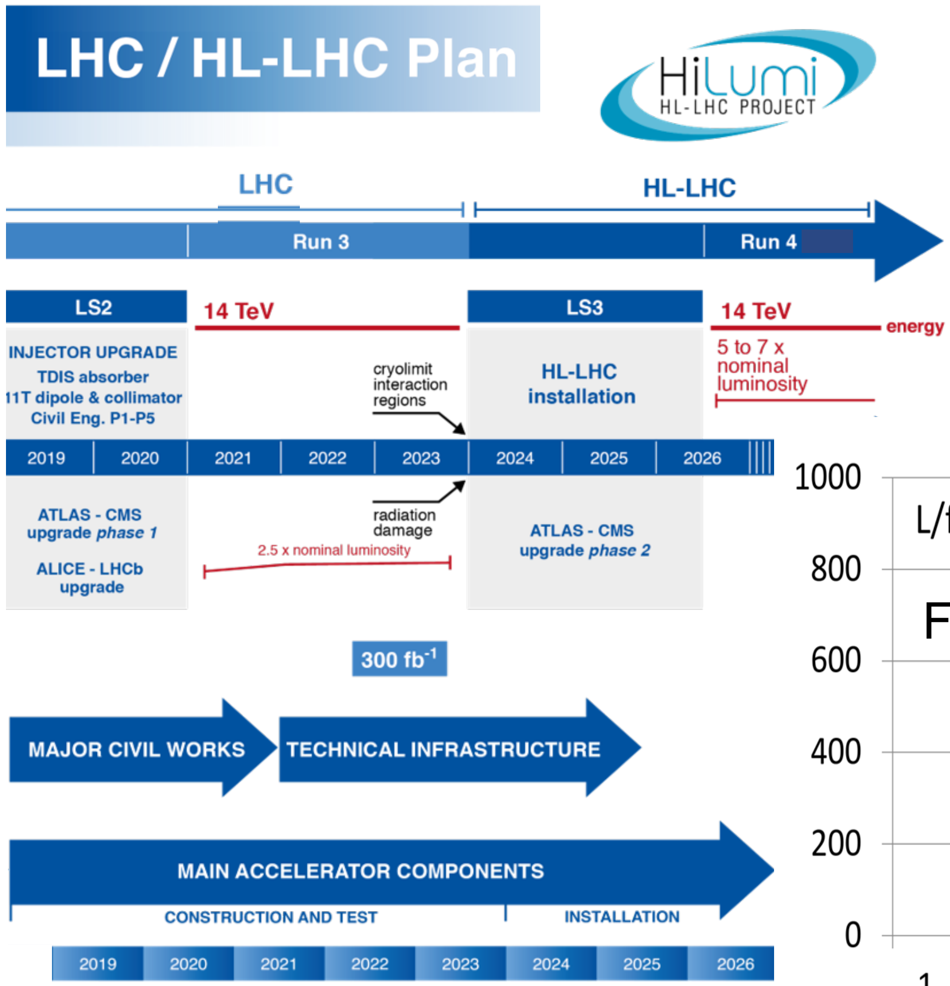
opportunity for **unprecedented increase in DIS kinematic reach**; ×1000 increase in lumi.

no higher twist, no nuclear corrections, free of symmetry assumptions, N^3LO theory possible, …

precision pdfs up to x→1, and exploration of low x regime; plus extensive physics program in its own right

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

timelines



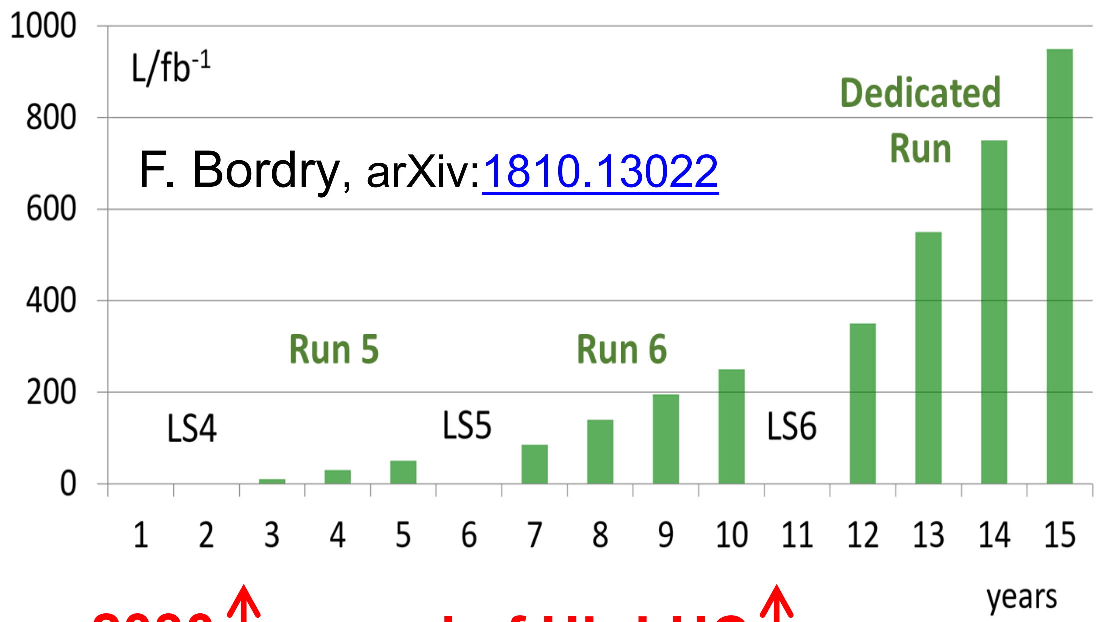
today

also, consider timing …

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

total Lint ⟶ 1 ab^{-1}

LHeC projected Integrated Luminosity:



F. Bordry, arXiv:1810.13022

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

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**

simulation and pdf fit studies:
M. Klein, CG

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%

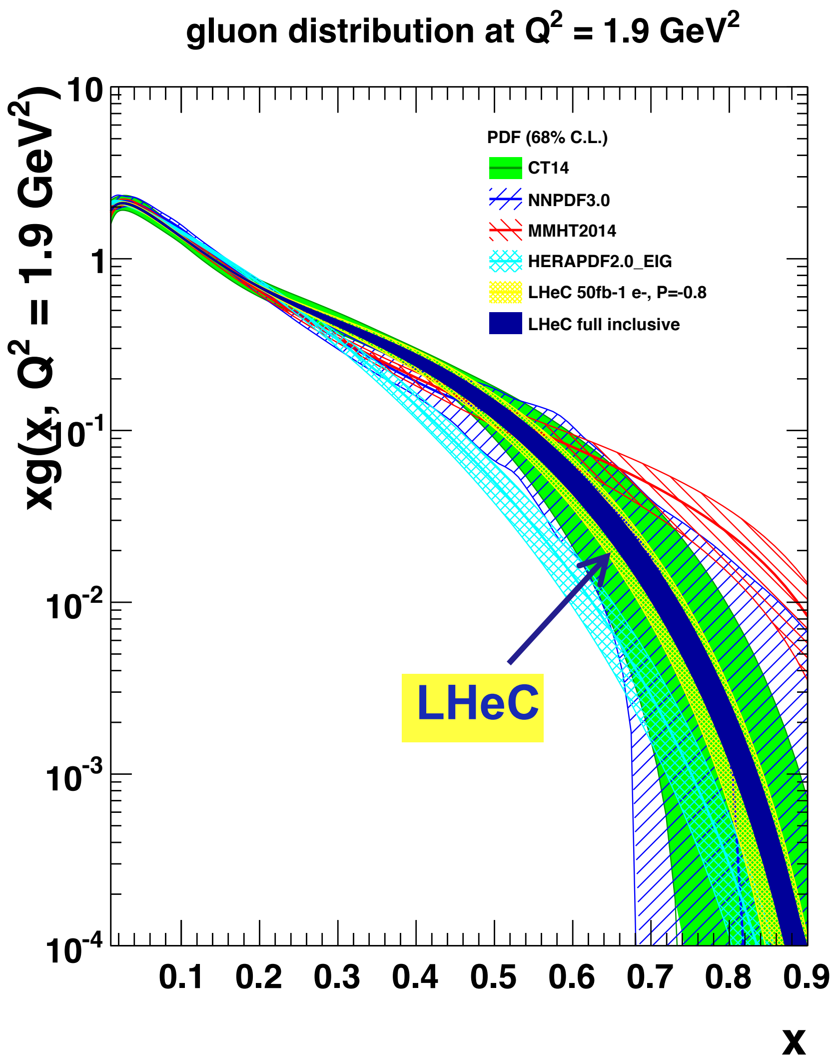
NB, I will frequently refer to the following:

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

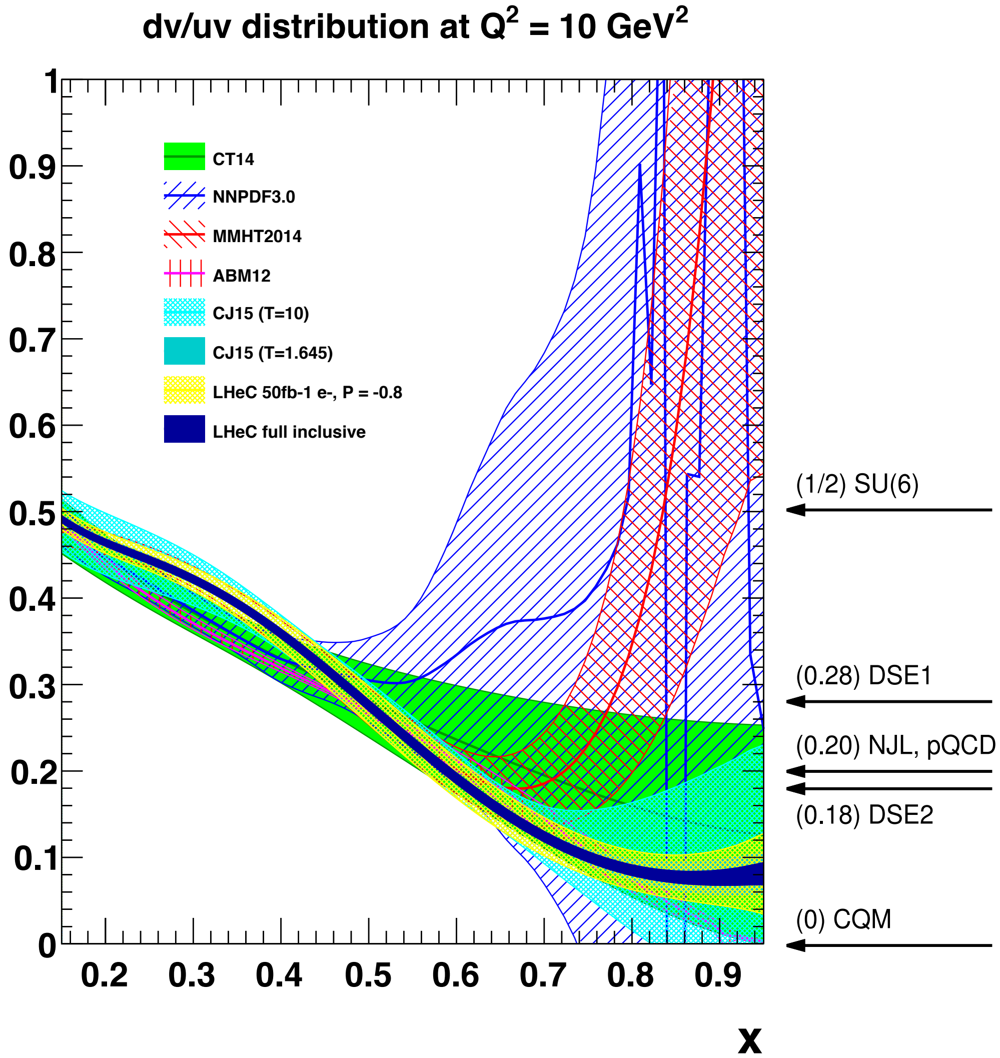
LHeC sensitivity at large x comes as part of overall package

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

d/u at large x



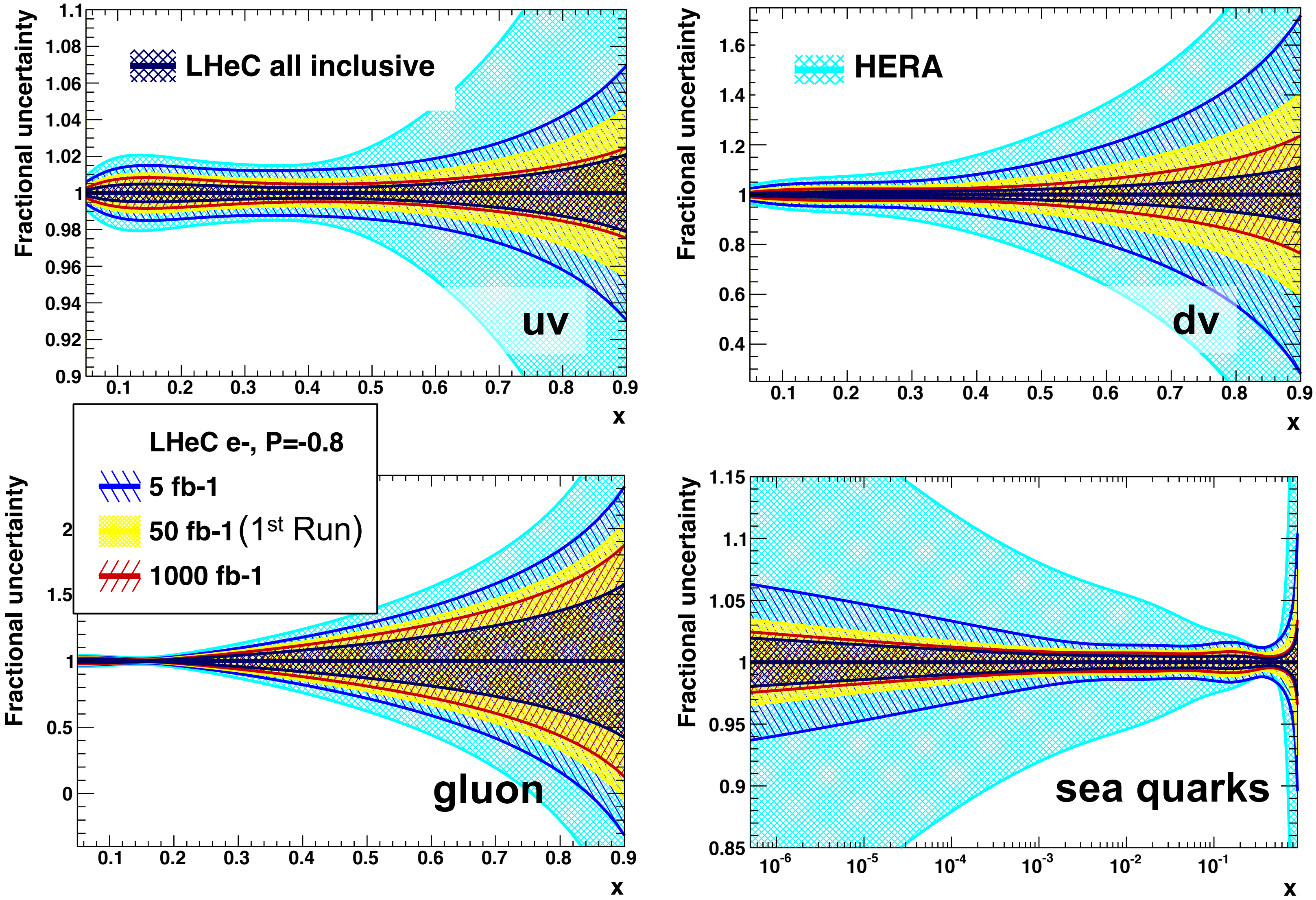
valence quarks: precision determination; free from higher twist corrections and nuclear uncertainties

d/u essentially unknown at large x

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

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

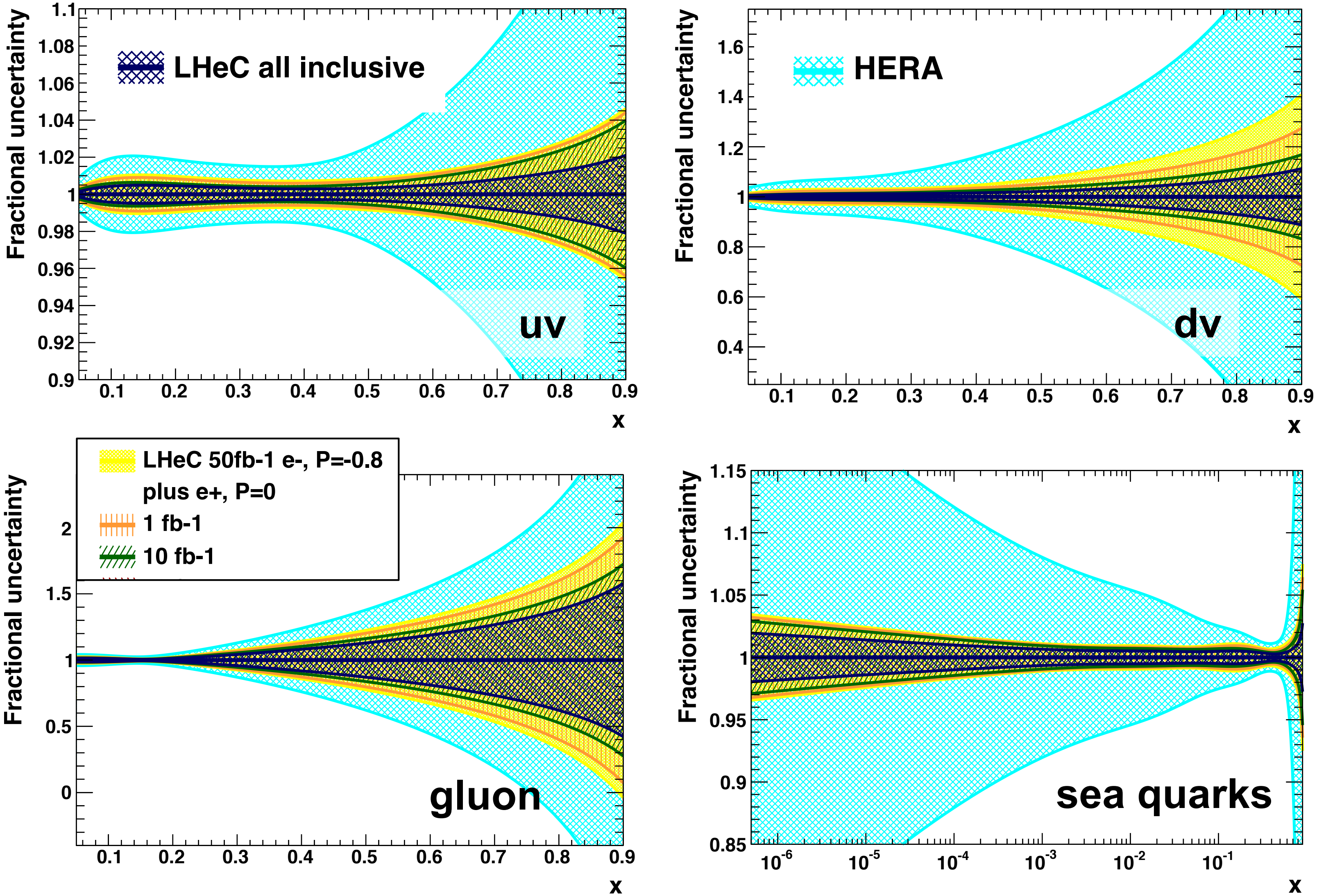
impact of luminosity on LHeC pdfs



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



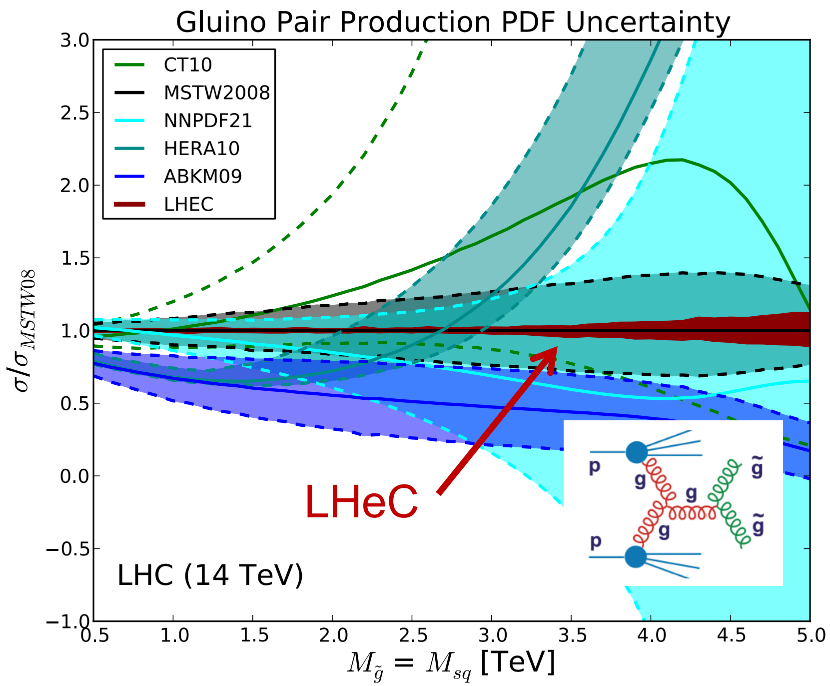
CC: e+ sensitive to d; **NC**: e± asymmetry gives $xF3^{\gamma Z}$, sensitive to valence

empowering LHC searches

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

gluons at large x

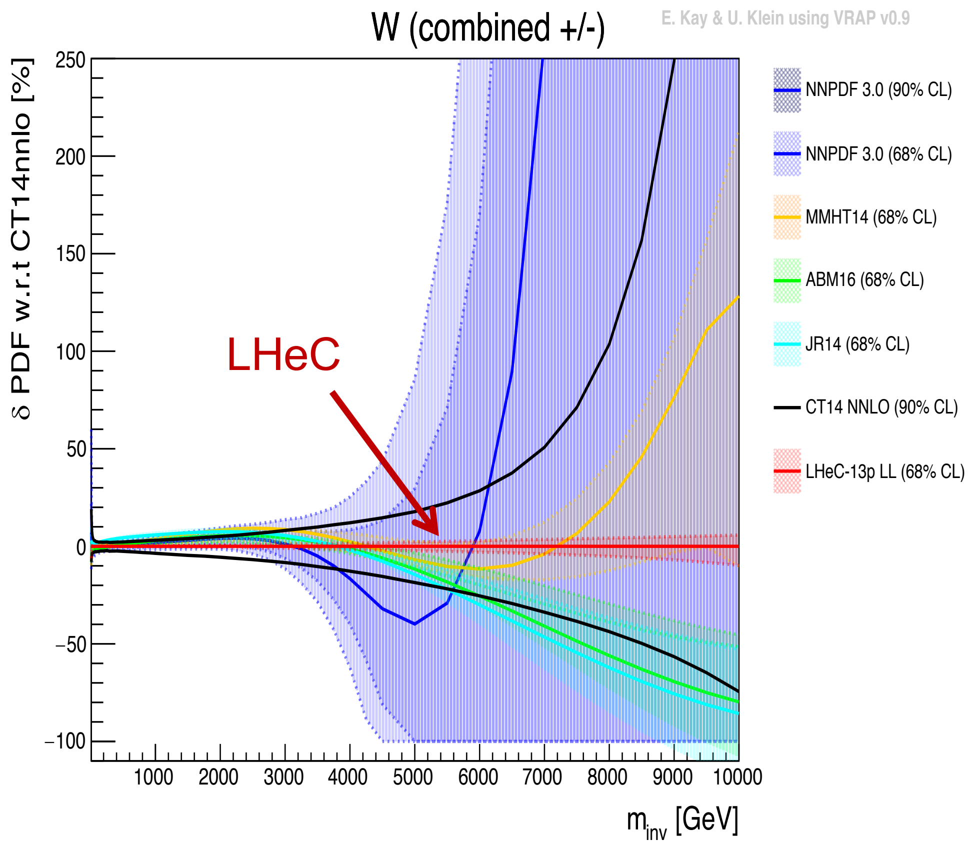
SUSY (RPC, RPV), LQs, …



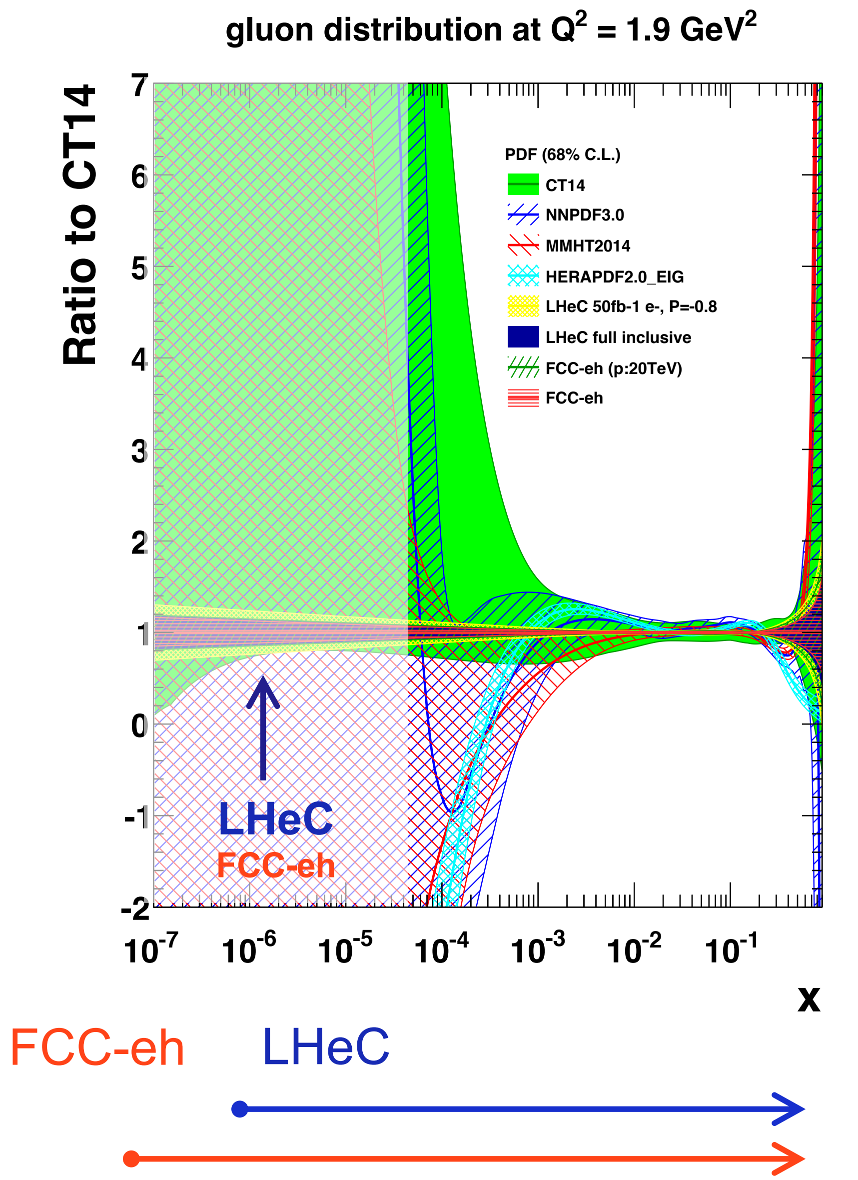
arXiv:[1211.5102](1211.5102)

quarks at large x

exotic and extra boson searches at high mass



gluon at small x



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

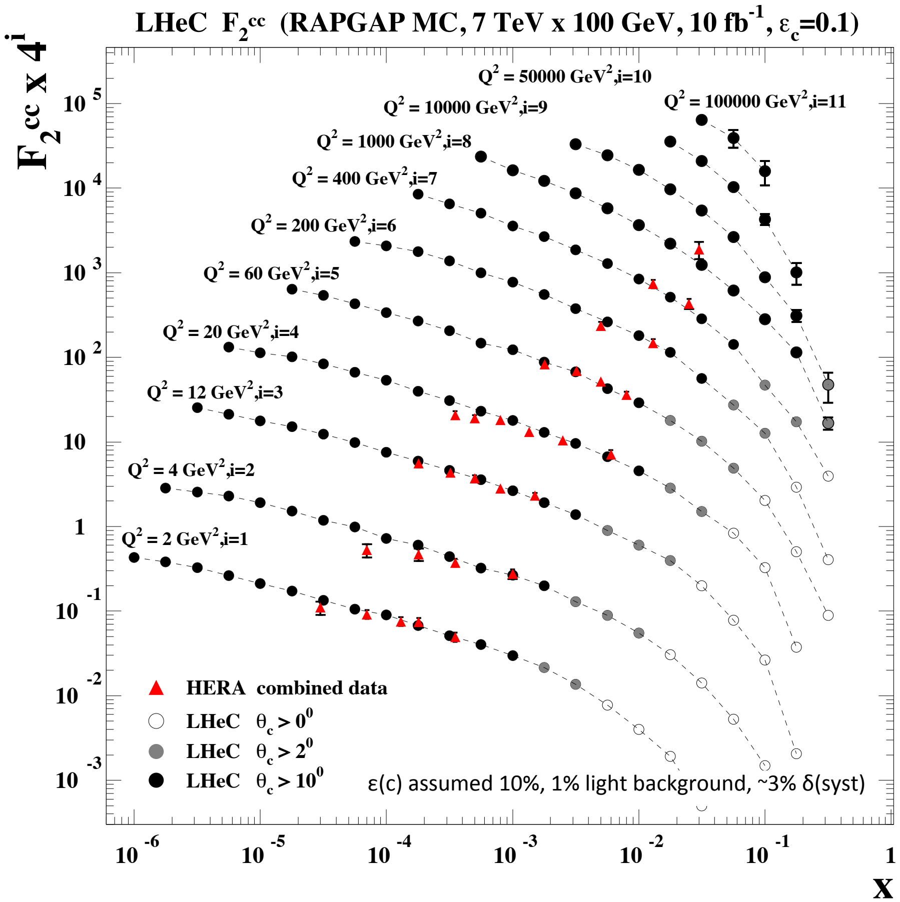
LHeC provides single, precise and unambiguous dataset down to $x=10^{-6}$

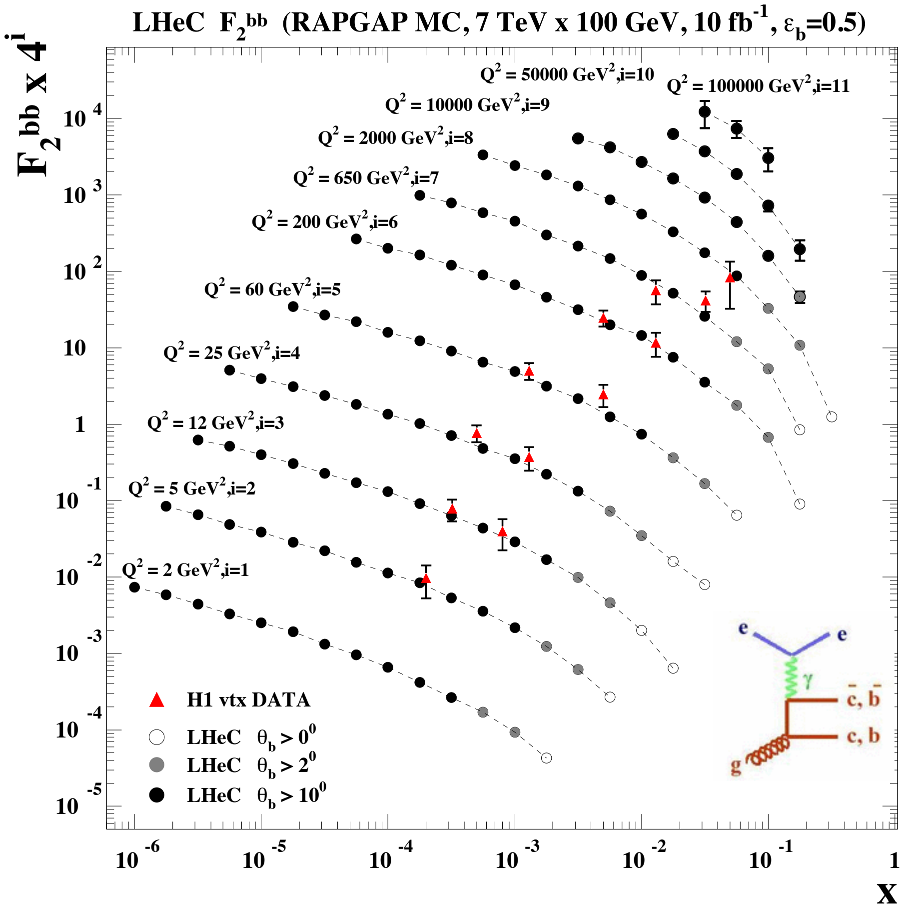
FCC-eh probes to even smaller $x=10^{-7}$

explore small x QCD:

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

c, b quarks

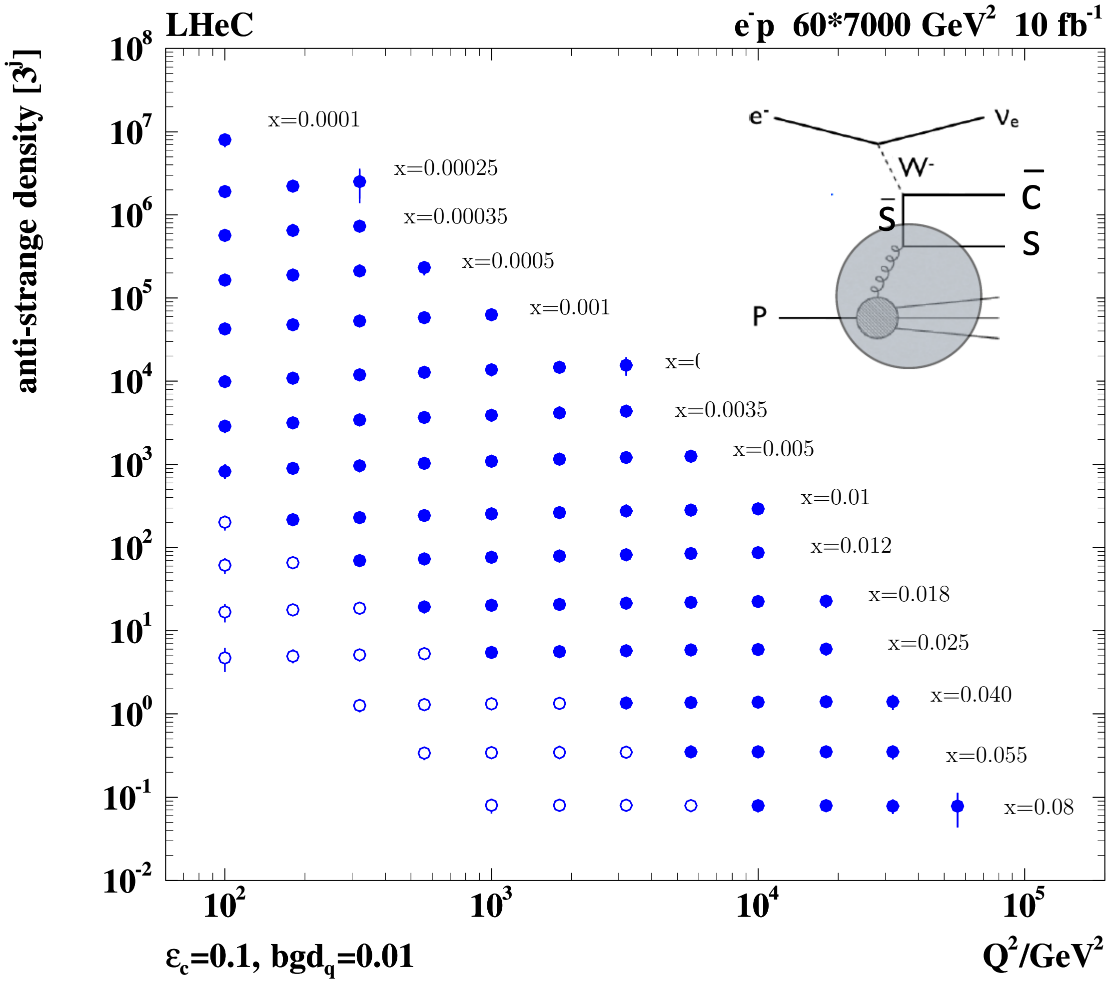




LHeC: enormously extended range and much improved precision c.f. HERA

- **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

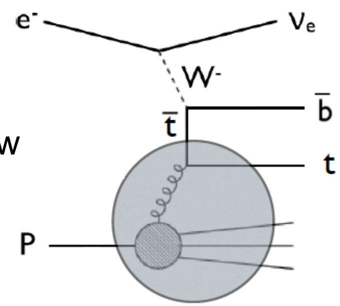


strange pdf poorly known;
suppressed cf. other light quarks?
strange valence?

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

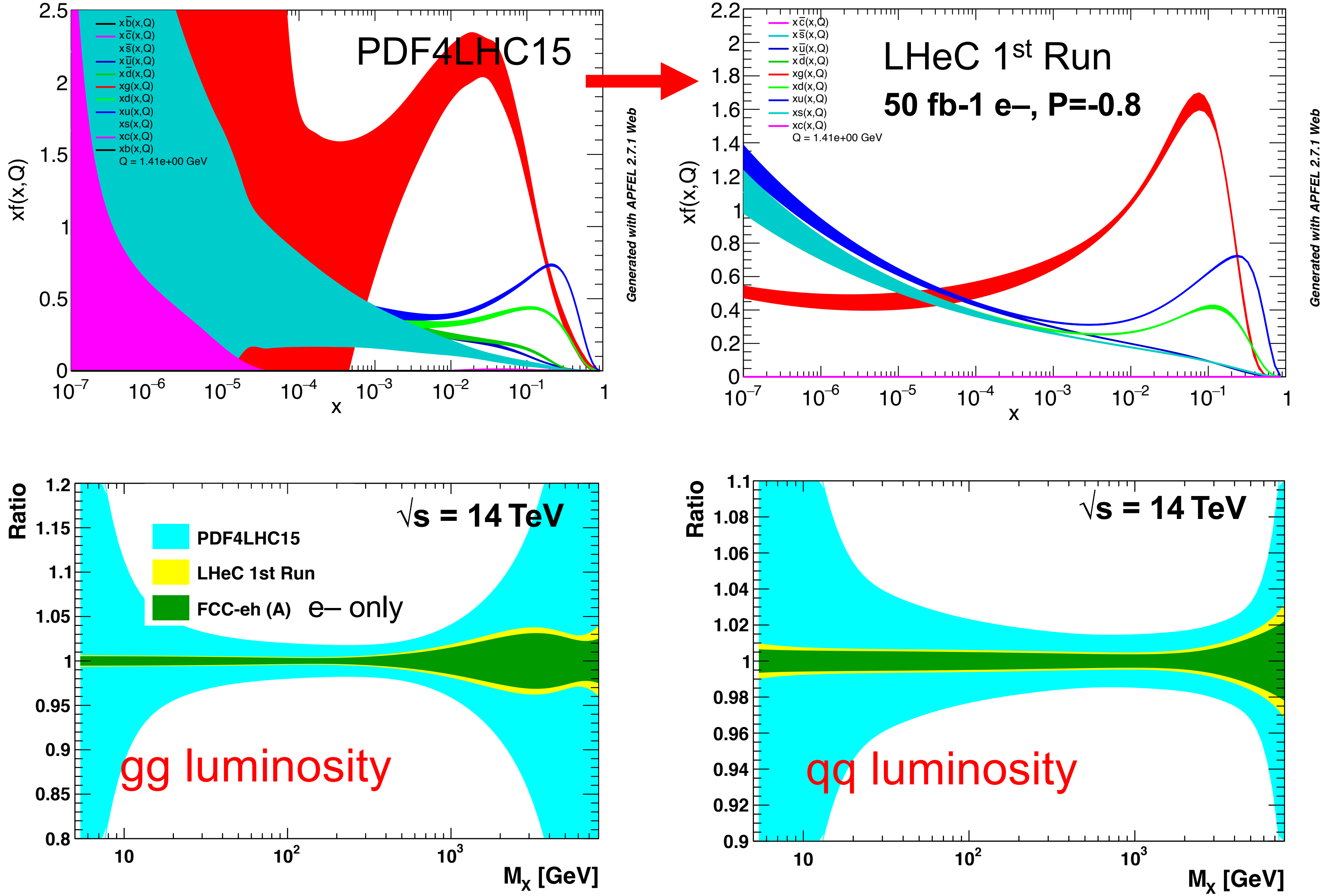
also top PDF

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

summary of pdfs from ep



summary

precision determination of quark and gluon structure of proton and α_s

of fundamental importance for future hadron collider physics programme (Higgs, BSM, …)

HL-LHC pdf studies indicate significant constraints;

complementarity between HL-LHC and LHeC (see also arXiv:1906.10127)

caveats: studies ignore issues related to correlation models; incompatible datasets; …

NEW pdf studies presented for the LHeC

all critical pdf information can be obtained early in 1st Run ($\sim 50\ fb^{-1} \equiv \times 50$ HERA), in parallel with HL-LHC operation

also, note: neither study yet includes all possible datasets, EG. HL-LHC data probing smaller x; LHeC jet data for further constraints on gluon at large x; …

electron-proton colliders essential for full exploitation of hadron machines

external precision pdf input; complete q,g unfolding, high luminosity $x \longrightarrow 1$, s, c, b, (t); N^3LO; small x; strong coupling to permille precision; …

extras

LHC datasets used in NNPDF3.1

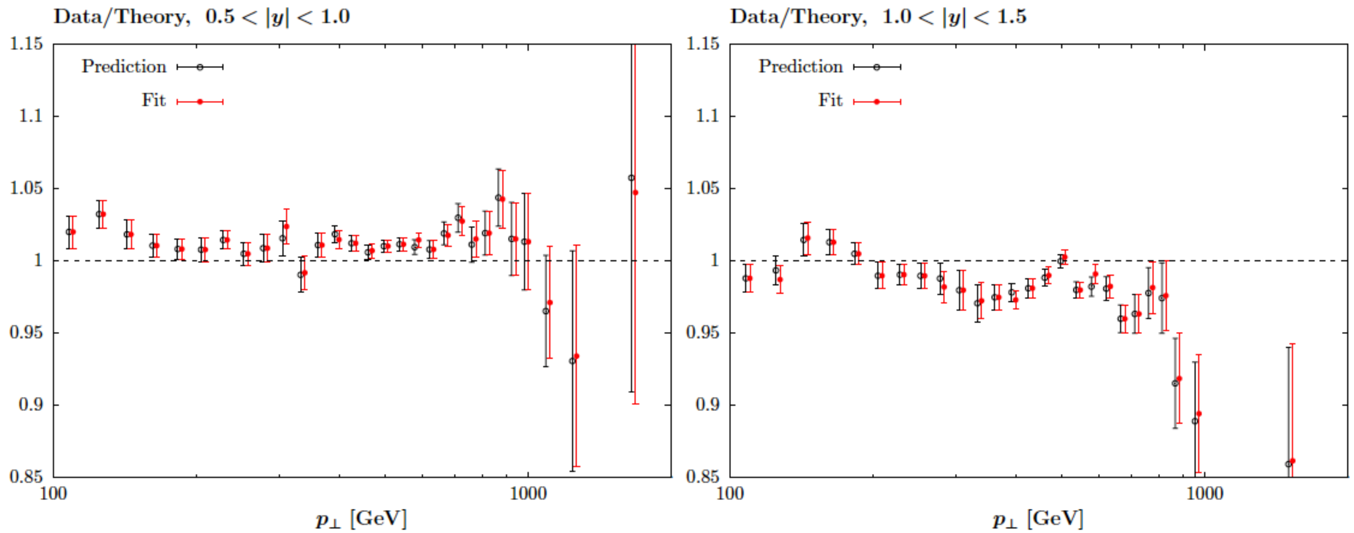
Exp.	Obs.	Ref.	N_{dat}	Kin$_1$	Kin$_2$ (GeV)	Theory
ATLAS	W,Z 2010	[49]	30 (30/30)	$0 \le \lvert\eta_l\rvert \le 3.2$	$Q = M_W, M_Z$	MCFM+FEWZ
	W,Z 2011 (*)	[72]	34 (34/34)	$0 \le \lvert\eta_l\rvert \le 2.3$	$Q = M_W, M_Z$	MCFM+FEWZ
	high-mass DY 2011	[50]	11 (5/5)	$0 \le \lvert\eta_l\rvert \le 2.1$	$116 \le M_{ll} \le 1500$	MCFM+FEWZ
	low-mass DY 2011 (*)	[77]	6 (4/6)	$0 \le \lvert\eta_l\rvert \le 2.1$	$14 \le M_{ll} \le 56$	MCFM+FEWZ
	[Z p_T 7 TeV (p_T^Z, y_Z)] (*)	[78]	64 (39/39)	$0 \le \lvert y_Z\rvert \le 2.5$	$30 \le p_T^Z \le 300$	MCFM+NNLO
	Z p_T 8 TeV (p_T^Z, M_{ll}) (*)	[71]	64 (44/44)	$12 \le M_{ll} \le 150$ GeV	$30 \le p_T^Z \le 900$	MCFM+NNLO
	Z p_T 8 TeV (p_T^Z, y_Z) (*)	[71]	120 (48/48)	$0.0 \le \lvert y_Z\rvert \le 2.4$	$30 \le p_T^Z \le 150$	MCFM+NNLO
	7 TeV jets 2010	[57]	90 (90/90)	$0 \le \lvert y^{\mathrm{jet}}\rvert \le 4.4$	$25 \le p_T^{\mathrm{jet}} \le 1350$	NLOjet++
	2.76 TeV jets	[58]	59 (59/59)	$0 \le \lvert y^{\mathrm{jet}}\rvert \le 4.4$	$20 \le p_T^{\mathrm{jet}} \le 200$	NLOjet++
	7 TeV jets 2011 (*)	[76]	140 (31/31)	$0 \le \lvert y^{\mathrm{jet}}\rvert \le 0.5$	$108 \le p_T^{\mathrm{jet}} \le 1760$	NLOjet++
	$\sigma_{\mathrm{tot}}(t\bar{t})$	[74, 75]	3 (3/3)	-	$Q = m_t$	top++
	$(1/\sigma_{t\bar{t}})d\sigma(t\bar{t})/y_t$ (*)	[73]	10 (10/10)	$0 < \lvert y_t\rvert < 2.5$	$Q = m_t$	Sherpa+NNLO
CMS	W electron asy	[52]	11 (11/11)	$0 \le \lvert\eta_e\rvert \le 2.4$	$Q = M_W$	MCFM+FEWZ
	W muon asy	[53]	11 (11/11)	$0 \le \lvert\eta_\mu\rvert \le 2.4$	$Q = M_W$	MCFM+FEWZ
	$W+c$ total	[60]	5 (5/0)	$0 \le \lvert\eta_l\rvert \le 2.1$	$Q = M_W$	MCFM
	$W+c$ ratio	[60]	5 (5/0)	$0 \le \lvert\eta_l\rvert \le 2.1$	$Q = M_W$	MCFM
	2D DY 2011 7 TeV	[54]	124 (88/110)	$0 \le \lvert\eta_{ll}\rvert \le 2.2$	$20 \le M_{ll} \le 200$	MCFM+FEWZ
	[2D DY 2012 8 TeV]	[84]	124 (108/108)	$0 \le \lvert\eta_{ll}\rvert \le 2.4$	$20 \le M_{ll} \le 1200$	MCFM+FEWZ
	$W^{\pm}$ rap 8 TeV (*)	[79]	22 (22/22)	$0 \le \lvert\eta_l\rvert \le 2.3$	$Q = M_W$	MCFM+FEWZ
	Z p_T 8 TeV (*)	[83]	50 (28/28)	$0.0 \le \lvert y_Z\rvert \le 1.6$	$30 \le p_T^Z \le 170$	MCFM+NNLO
	7 TeV jets 2011	[59]	133 (133/133)	$0 \le \lvert y^{\mathrm{jet}}\rvert \le 2.5$	$114 \le p_T^{\mathrm{jet}} \le 2116$	NLOjet++
	2.76 TeV jets (*)	[80]	81 (81/81)	$0 \le \lvert y_{\mathrm{jet}}\rvert \le 2.8$	$80 \le p_T^{\mathrm{jet}} \le 570$	NLOjet++
	$\sigma_{\mathrm{tot}}(t\bar{t})$	[82, 88]	3 (3/3)	-	$Q = m_t$	top++
	$(1/\sigma_{t\bar{t}})d\sigma(t\bar{t})/y_{t\bar{t}}$ (*)	[81]	10 (10/10)	$-2.1 < y_{t\bar{t}} < 2.1$	$Q = m_t$	Sherpa+NNLO
LHCb	Z rapidity 940 pb	[55]	9 (9/9)	$2.0 \le \eta_l \le 4.5$	$Q = M_Z$	MCFM+FEWZ
	$Z \to ee$ rapidity 2 fb	[56]	17 (17/17)	$2.0 \le \eta_l \le 4.5$	$Q = M_Z$	MCFM+FEWZ
	$W,Z \to \mu$ 7 TeV (*)	[85]	33 (33/29)	$2.0 \le \eta_l \le 4.5$	$Q = M_W, M_Z$	MCFM+FEWZ
	$W,Z \to \mu$ 8 TeV (*)	[86]	34 (34/30)	$2.0 \le \eta_l \le 4.5$	$Q = M_W, M_Z$	MCFM+FEWZ

Table 2.3: Same as Table 2.1, for ATLAS, CMS and LHCb data from the LHC Run I at $\sqrt{s} = 2.76$ TeV, $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV. The ATLAS 7 TeV Z p_T and CMS 2D DY 2012 are in brackets because they are only included in a dedicated study but not in the default PDF set. The total number of LHC data points after cuts is 848/854 for NLO/NNLO fits (not including ATLAS 7 TeV Z p_T and CMS 2D DY 2012).

arXiv:1706.00428

Fit to high luminosity ATLAS $7\ \mathrm{TeV}$ inclusive jet data – MMHT (JHEP 02 (2015) 153)

Difficulty simultaneously fitting data in all rapidity bins. Mismatch in one bin different in form to neighbouring bin constraining PDFs of similar x, Q^2.



Similar results also seen by other groups.

Qualitative conclusion shown to be independent of jet radius R, choice of scale or inclusion of NNLO corrections.

slide from R Thorne, DIS19

arXiv:1711.05757

Exercise on decorrelating uncertainties

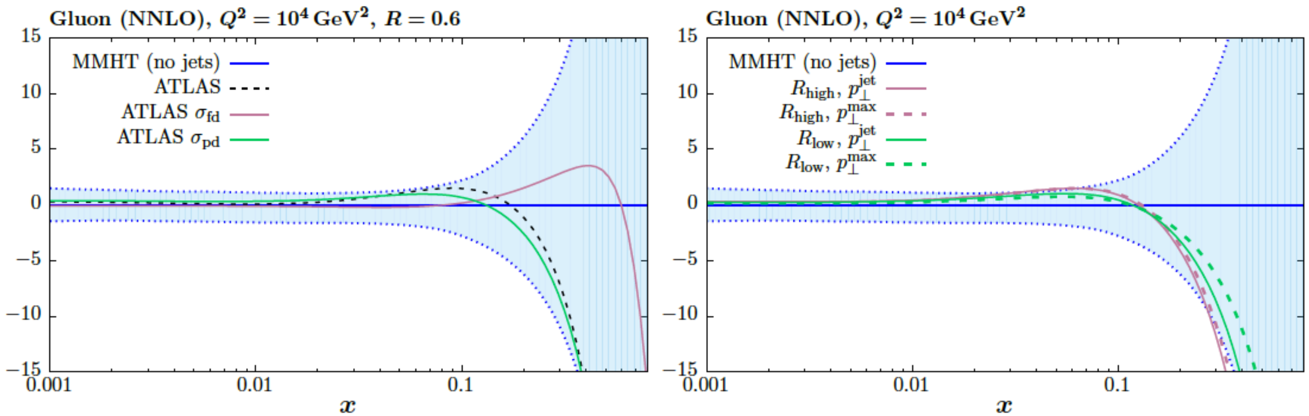
We consider the effect of decorrelating two uncertainty sources, i.e. making them independent between the 6 rapidity bins. More extensive decorrelation study in ATLAS – JHEP 09 020 (2017).

	Full	21	62	21,62
$\chi^2/N_{\text{pts.}}$	2.85	1.56	2.36	1.27

Similar results using new NNLO results.

	$R_{\text{low}},\, p_\perp^{\text{jet}}$	$R_{\text{low}},\, p_\perp^{\text{max}}$	$R_{\text{high}},\, p_\perp^{\text{jet}}$	$R_{\text{high}},\, p_\perp^{\text{max}}$
NLO	210.0 (187.1)	189.1 (181.7)	175.1 (193.5)	164.9 (191.2)
NNLO	172.3 (177.8)	199.3 (187.0)	149.8 (182.3)	152.5 (185.4)

ATLAS (CMS)

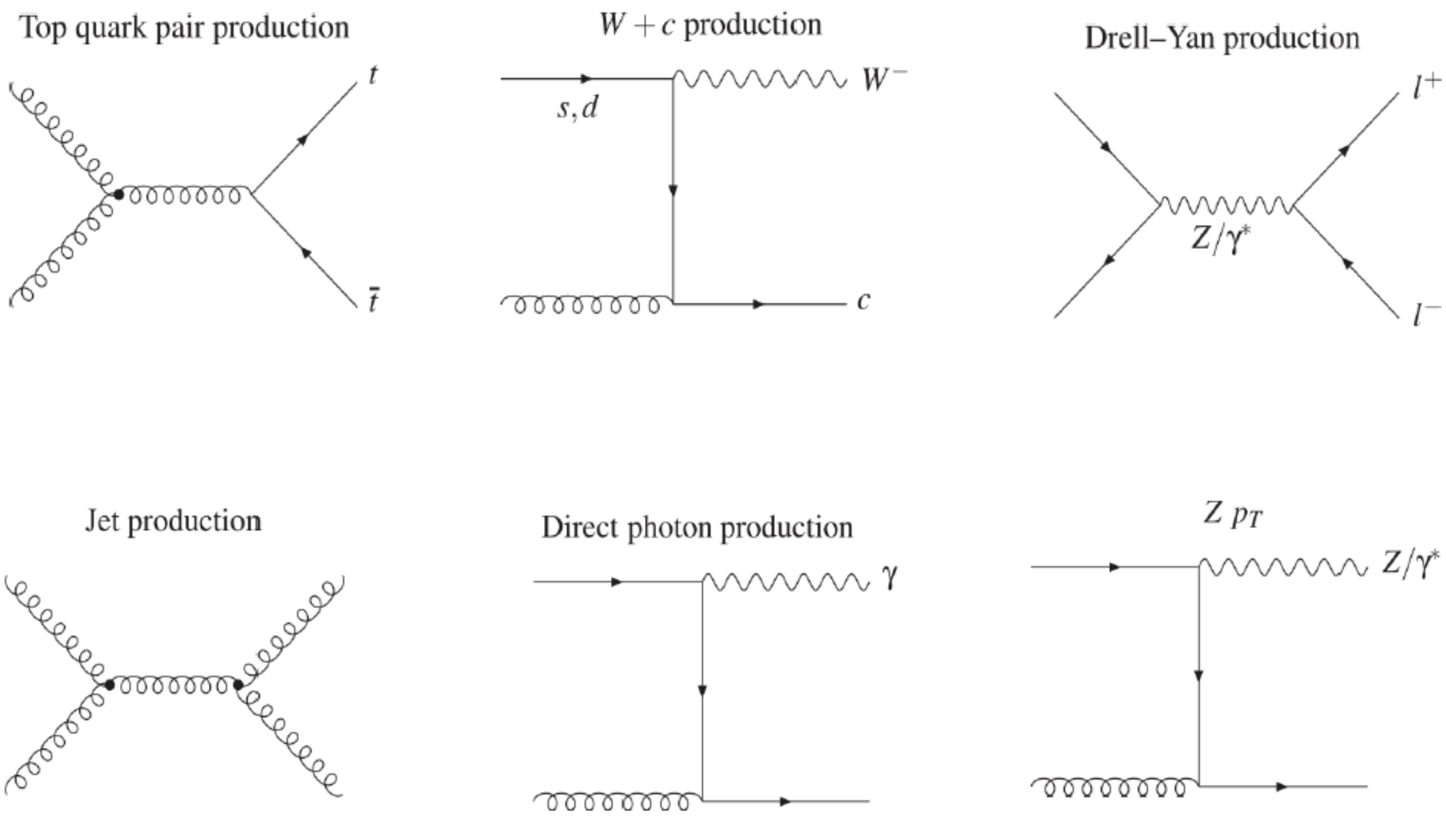


Results insensitive to decorrelation. Find softer gluon, reduced uncertainty. Also relatively little sensitivity to scales and jet radius.

slide from R Thorne, DIS19

arXiv:1711.05757

HL-LHC pdfs: datasets



arXiv:1810.03639

HL-LHC datasets

arXiv:1810.03639

Process	Kinematics	$N_{\rm dat}$	$f_{\rm corr}$	$f_{\rm red}$	Baseline
$Z\ p_T$	$20\,\text{GeV} \le p_T^{ll} \le 3.5$ TeV $12\,\text{GeV} \le m_{ll} \le 150$ GeV $\lvert y_{ll}\rvert \le 2.4$	338	0.5	(0.4, 1)	[52] (8 TeV)
high-mass Drell-Yan	$p_T^{l1(2)} \ge 40(30)$ GeV $\lvert\eta^l\rvert \le 2.5$, $m_{ll} \ge 116$ GeV	32	0.5	(0.4, 1)	[47] (8 TeV)
top quark pair	$m_{t\bar{t}} \simeq 5$ TeV, $\lvert y_t\rvert \le 2.5$	110	0.5	(0.4, 1)	[50] (8 TeV)
W+charm (central)	$p_T^\mu \ge 26$ GeV, $p_T^c \ge 5$ GeV $\lvert\eta^\mu\rvert \le 2.4$	12	0.5	(0.2, 0.5)	[24] (13 TeV)
W+charm (forward)	$p_T^\mu \ge 20$ GeV, $p_T^c \ge 20$ GeV $p_T^{\mu+c} \ge 20$ GeV $2 \le \eta^\mu \le 4.5$, $2.2 \le \eta^c \le 4.2$	10	0.5	(0.4, 1)	LHCb projection
Direct photon	$E_T^\gamma \lesssim 3$ TeV, $\lvert\eta_\gamma\rvert \le 2.5$	118	0.5	(0.2, 0.5)	[55] (13 TeV)
Forward W, Z	$p_T^l \ge 20$ GeV, $2.0 \le \eta^l \le 4.5$ $60\,\text{GeV} \le m_{ll} \le 120$ GeV	90	0.5	(0.4, 1)	[49] (8 TeV)
Inclusive jets	$\lvert y\rvert \le 3$, $R = 0.4$	58	0.5	(0.2, 0.5)	[61] (13 TeV)
Total		768			

Table 2.1. Summary of the features of the HL–LHC pseudo–data generated for the present study. For each process we indicate the kinematic coverage, the number of pseudo–data points used across all detectors $N_{\rm dat}$, the values of the correction factors $f_{\rm corr}$ and $f_{\rm red}$; and finally the reference from the 8 TeV or 13 TeV measurement used as baseline to define the binning and the systematic uncertainties of the HL–LHC pseudo–data, as discussed in the text.

arXiv:1810.03639

HL-LHC pdfs

Scenario	f_{red} (8 TeV)	f_{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_{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.

parton luminosities

arXiv:[1810.03639]

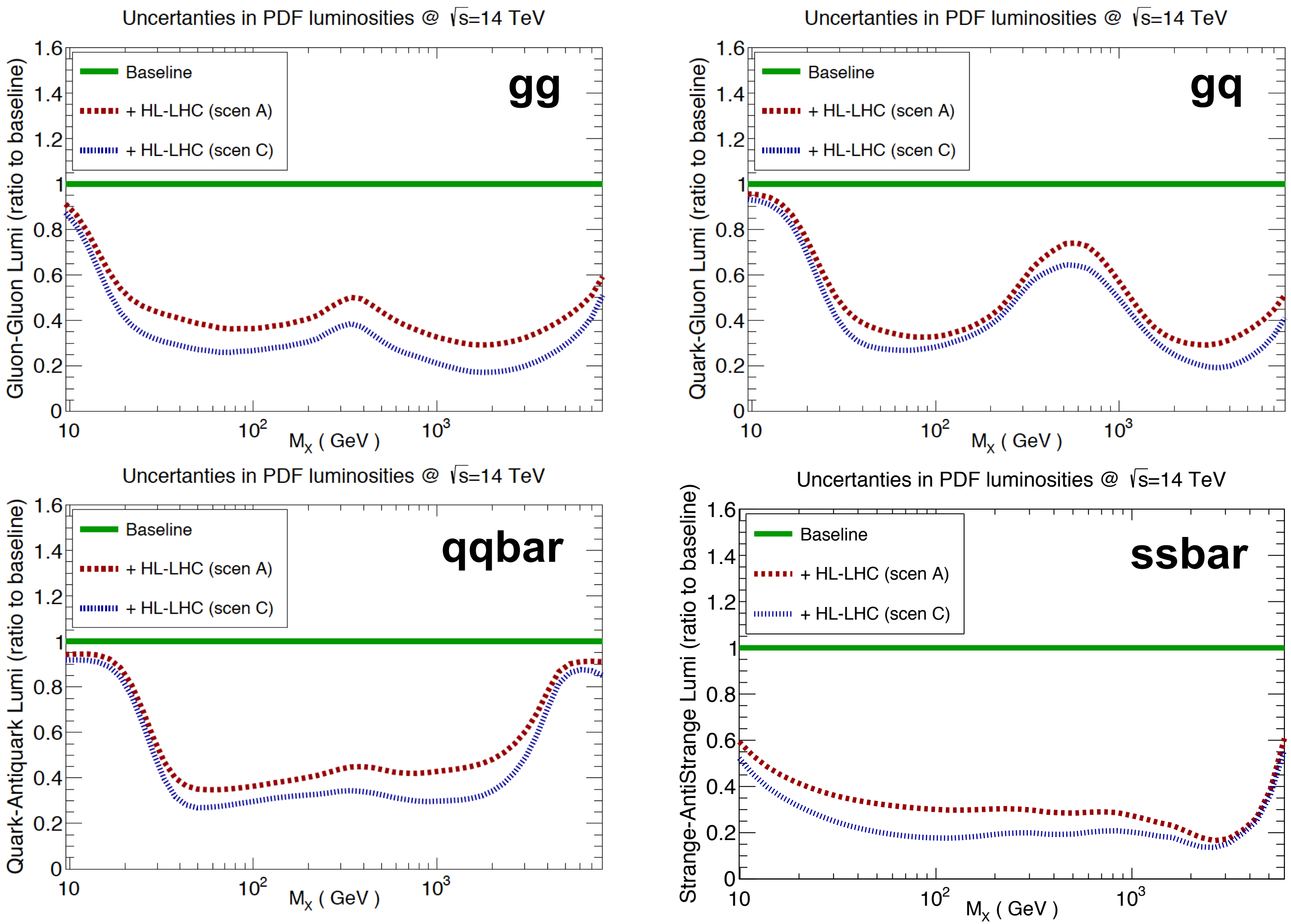
Ratio to baseline	10 GeV $\leq M_X \leq$ 40 GeV	40 GeV $\leq M_X \leq$ 1 TeV	1 TeV $\leq M_X \leq$ 6 TeV
gluon–gluon	0.50 (0.60)	0.28 (0.40)	0.22 (0.34)
gluon–quark	0.66 (0.72)	0.42 (0.45)	0.28 (0.37)
quark–quark	0.74 (0.79)	0.37 (0.46)	0.43 (0.59)
quark–antiquark	0.71 (0.76)	0.31 (0.40)	0.50 (0.60)
strange–antistrange	0.34 (0.44)	0.19 (0.30)	0.23 (0.27)
strange–antiup	0.67 (0.73)	0.27 (0.38)	0.38 (0.43)

overall factor of 2 – 4 improvement over wide range of kinematics

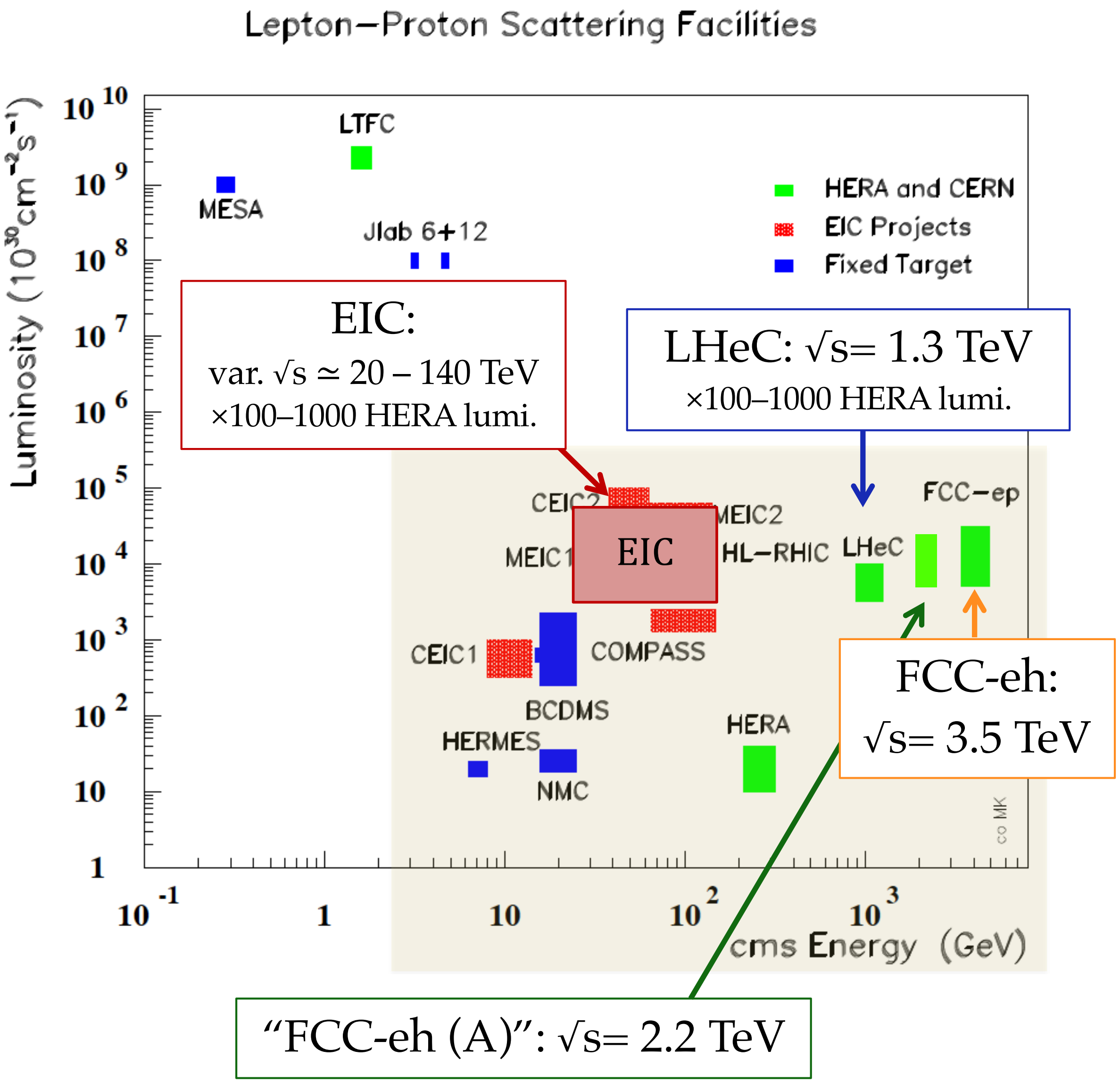
not a large difference between optimistic and conservative (brackets) scenarios

parton luminosities

arXiv:1810.03639



ep colliders



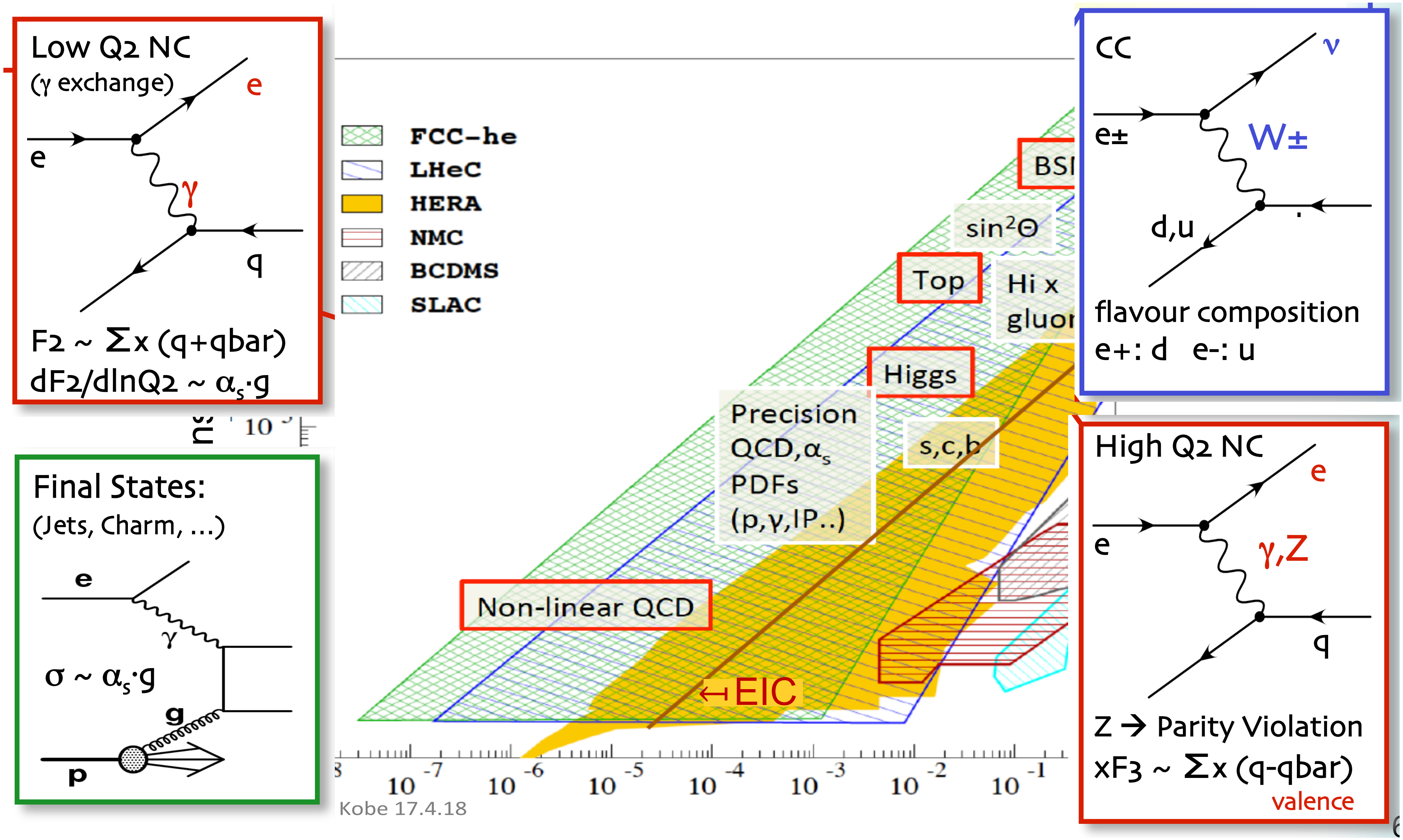
HERA: world's first and still only ep collider (√s ≃ 300 GeV)

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**)

complementary to **EIC**: world's first polarised ep/eA future collider (image structure/interactions of nucleons and nuclei in multi-dimensions (x, bt, kt, spin)) EG. arXiv:1108.1713, 1212.1701, 1708.01527

pdfs from ep colliders



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

also, to be of maximum benefit to HL-LHC programme, consider timing …

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

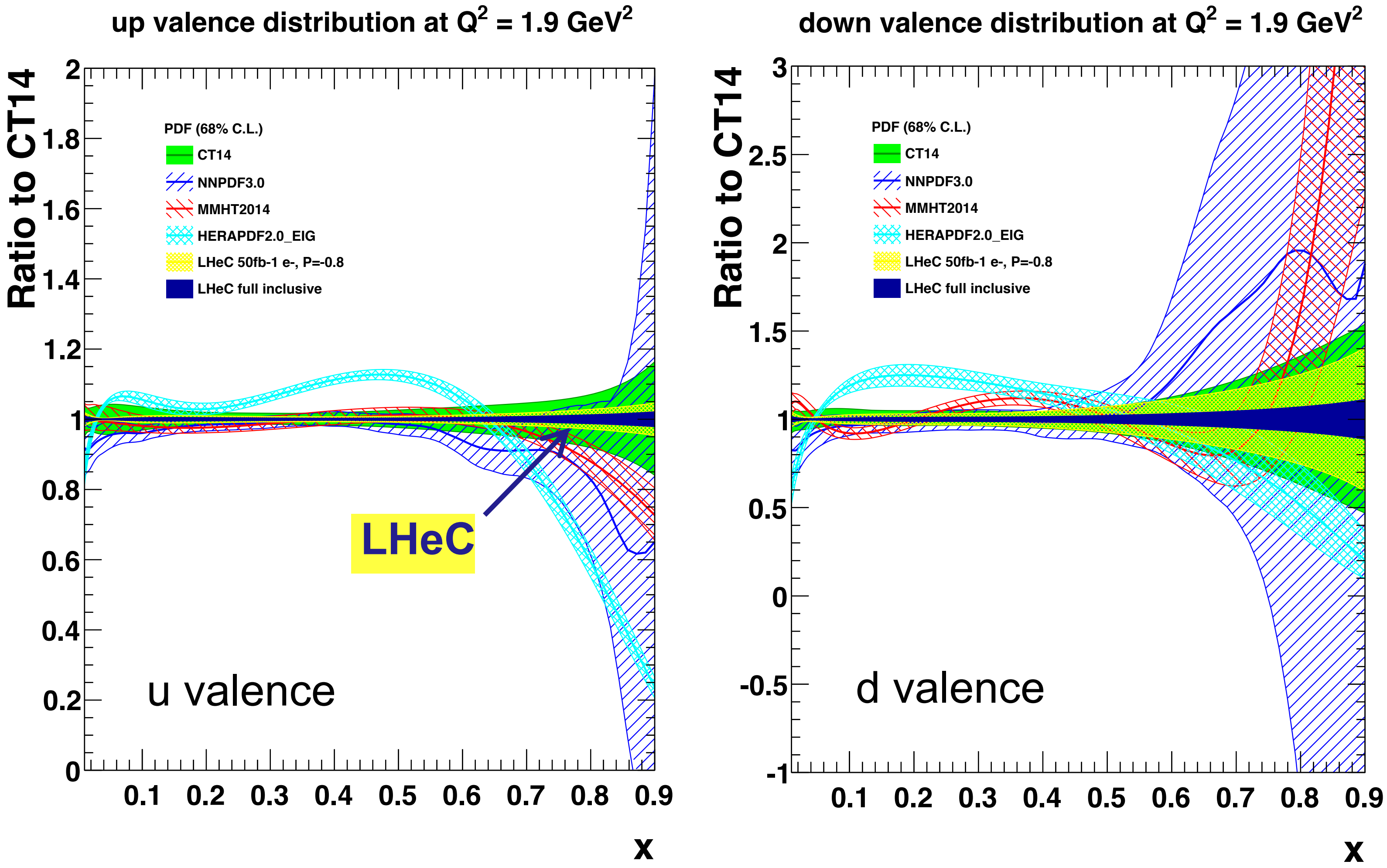
no negative gluon term (simply for the aesthetics of ratio plots – it has been checked that this does not impact size of projected uncertainties)

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

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**

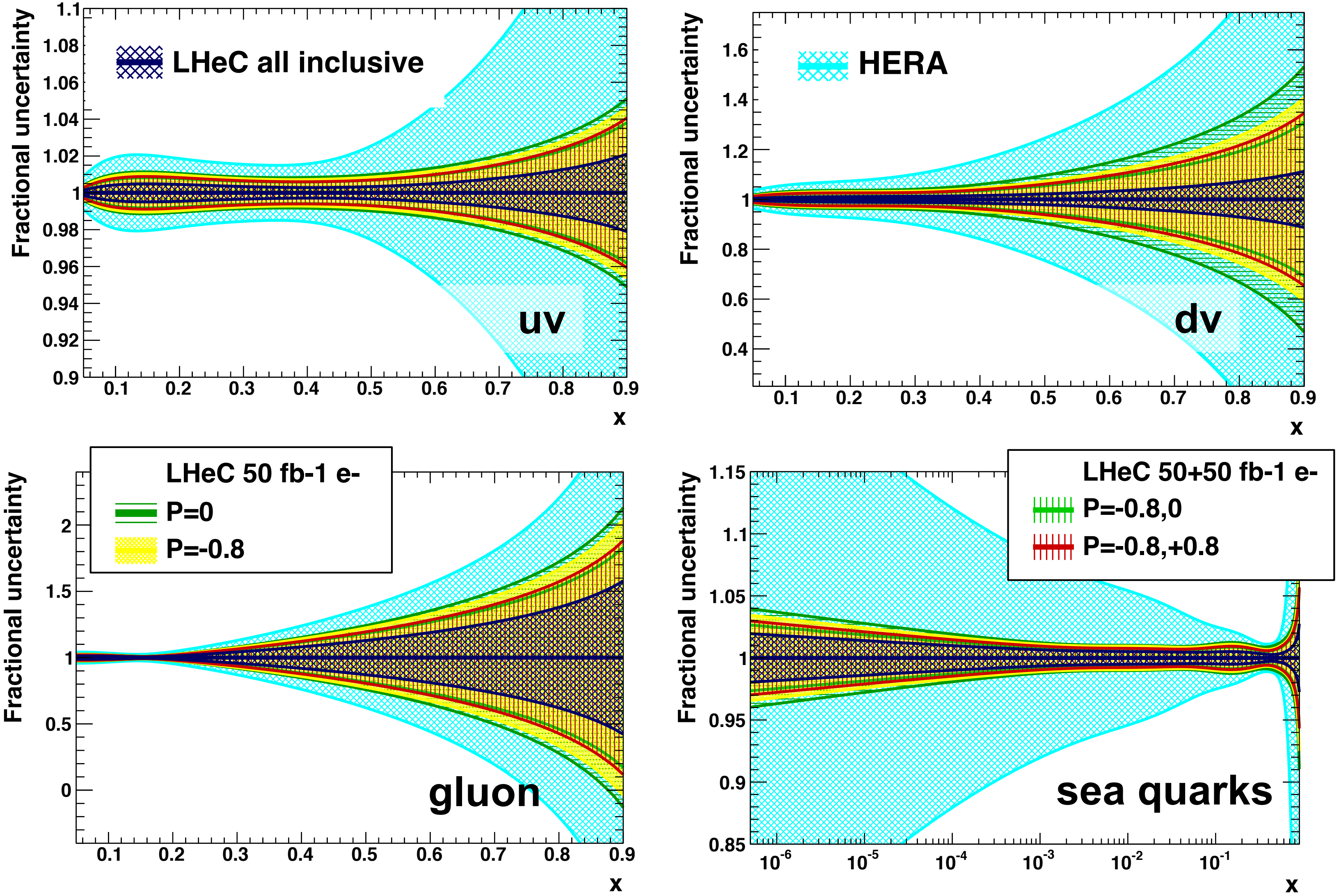
valence quarks



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.;

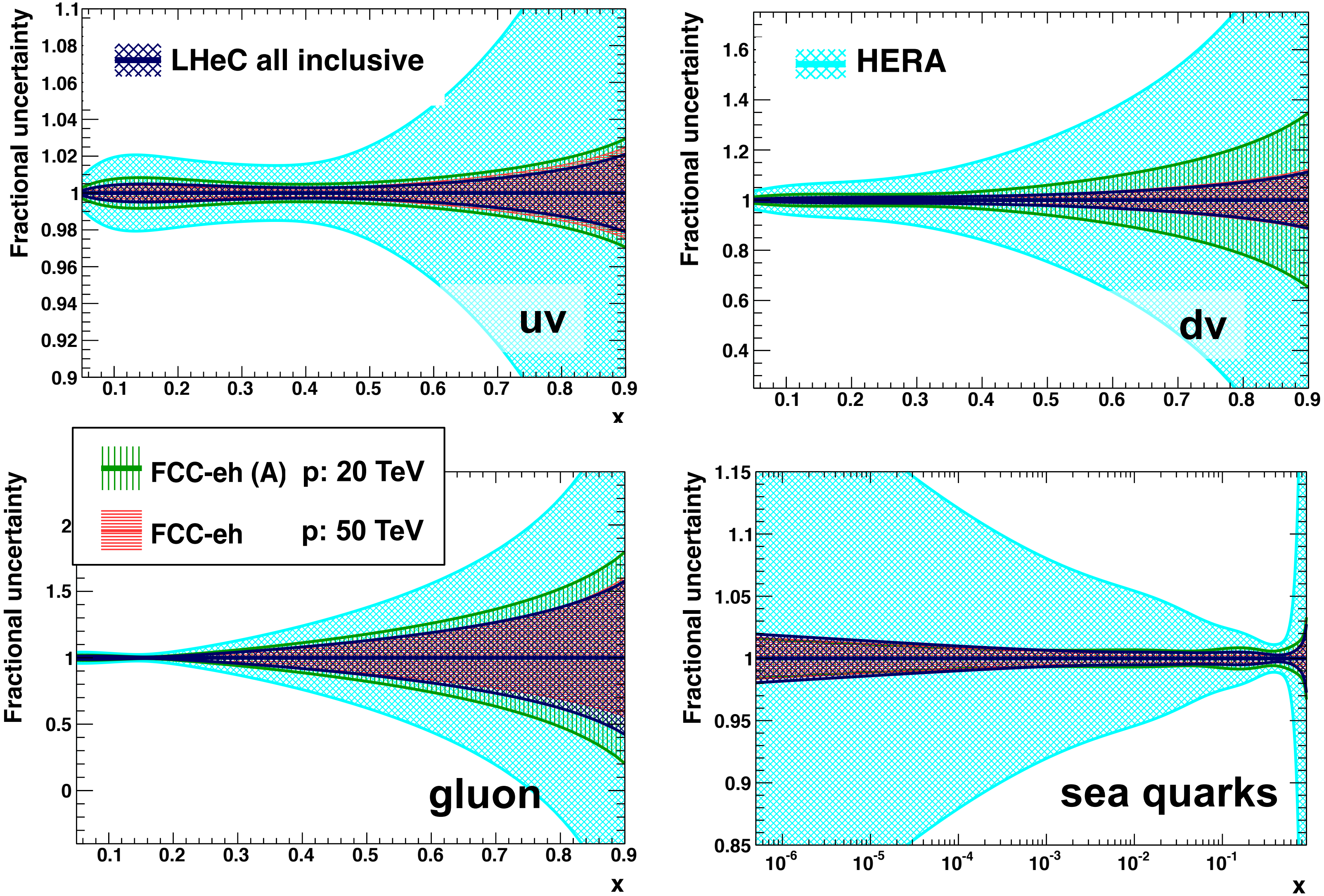
impact of polarisation on LHeC pdfs



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)

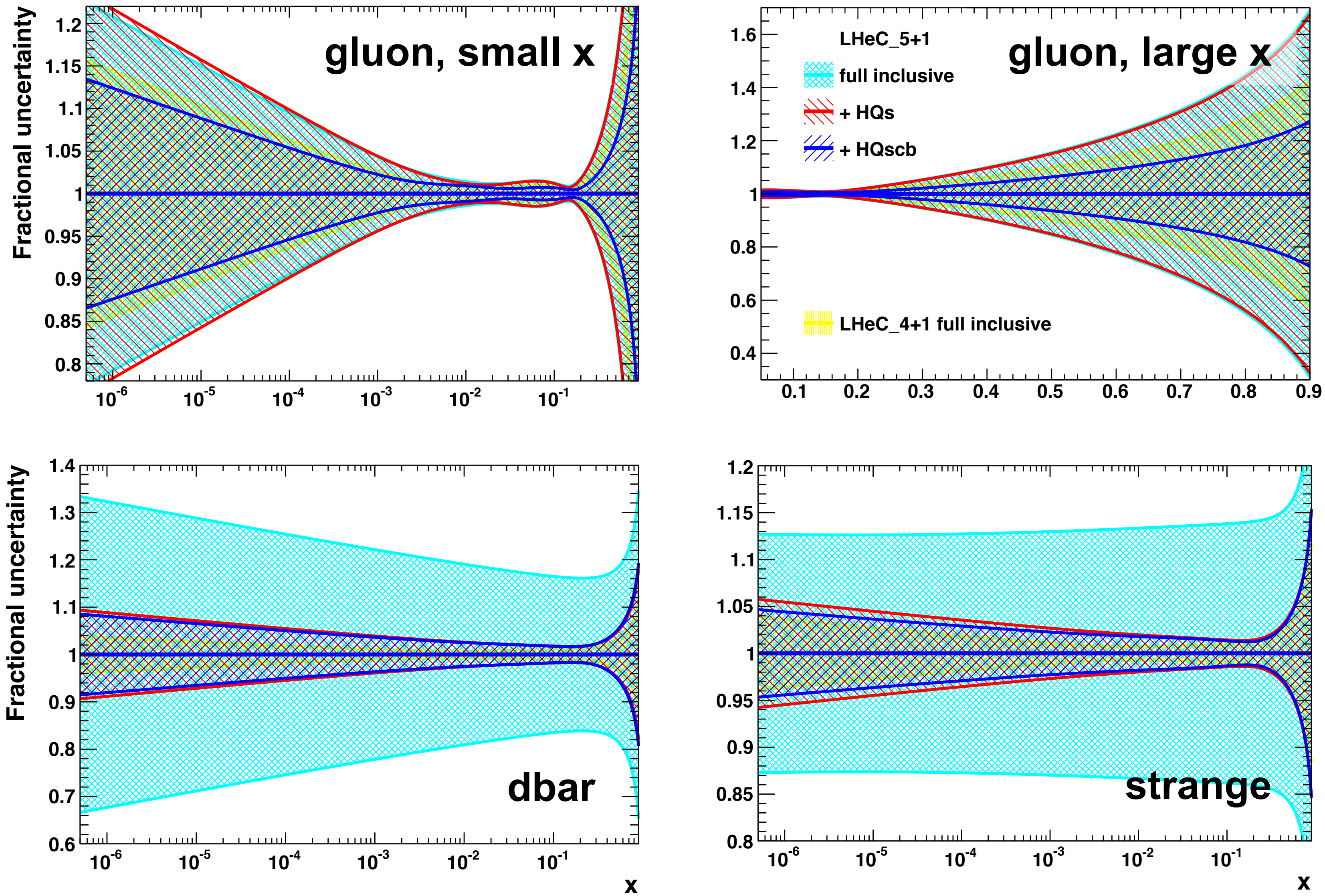
collider configurations



FCC-eh (A): new preliminary simulation with 2 ab^{-1} polarised e– (**NB, NO e+ yet; impact especially in dv**)

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

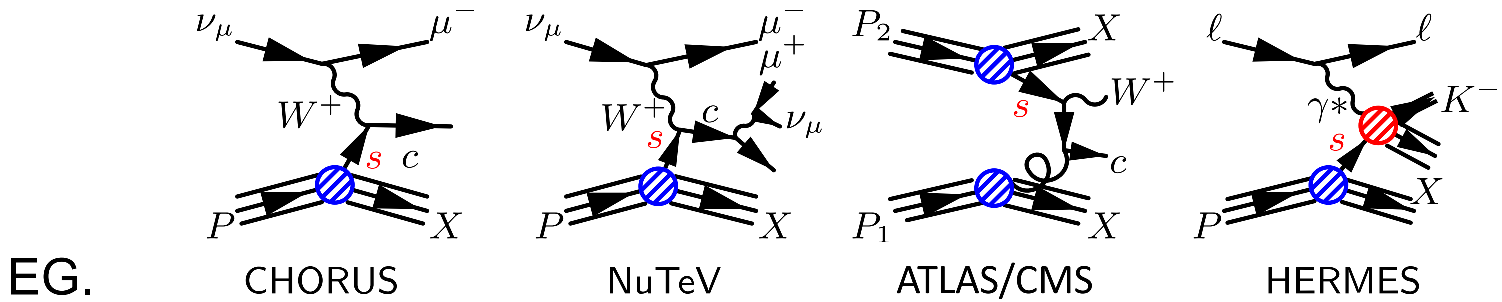
impact of HQ data on LHeC pdfs



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

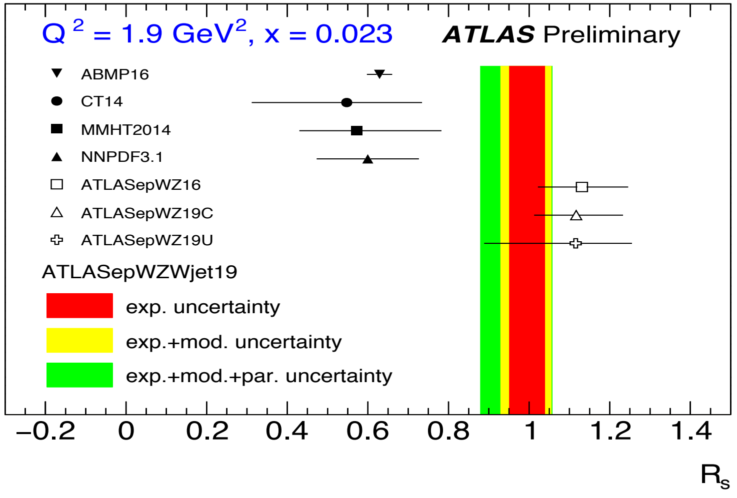
strange

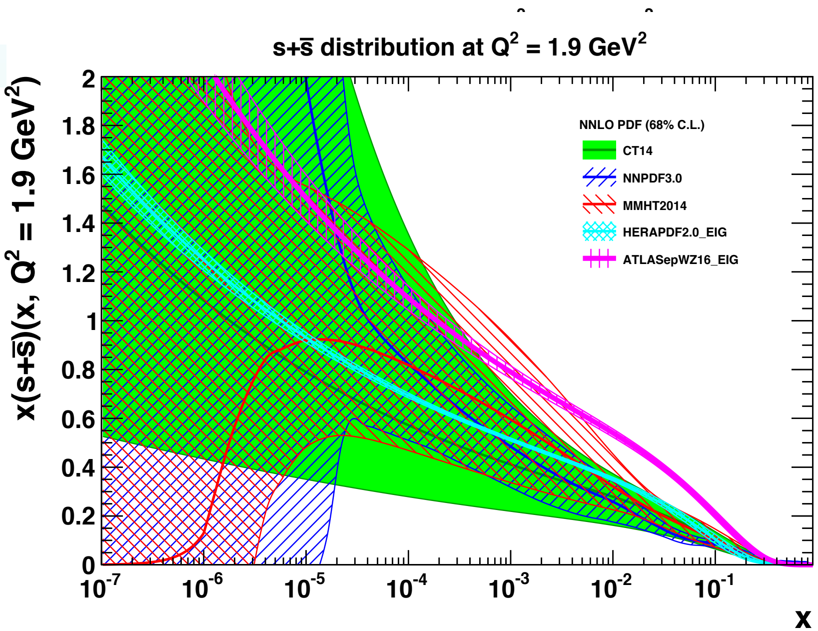
strange pdf poorly known; suppressed cf. other light quarks? strange valence?



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

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

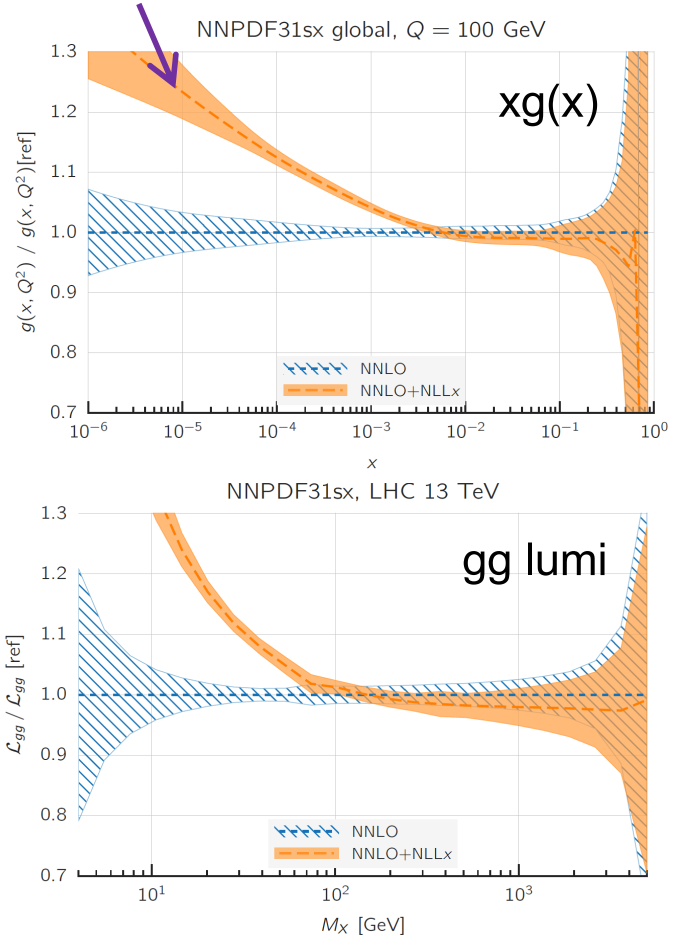


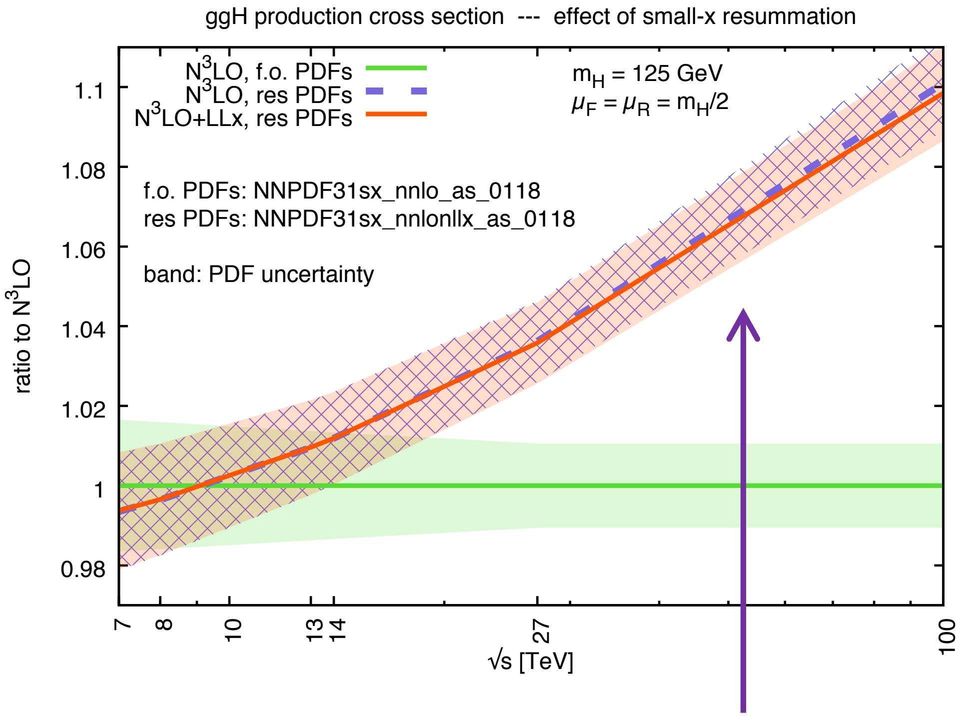


†ATLAS arXiv:1203.4051, confirmed in 1612.03016, ATL-PHYS-PUB-2019-016; and by global fitters EG. 1706.00428, 1708.00047

gluon at small x matters

effect of small x resummation





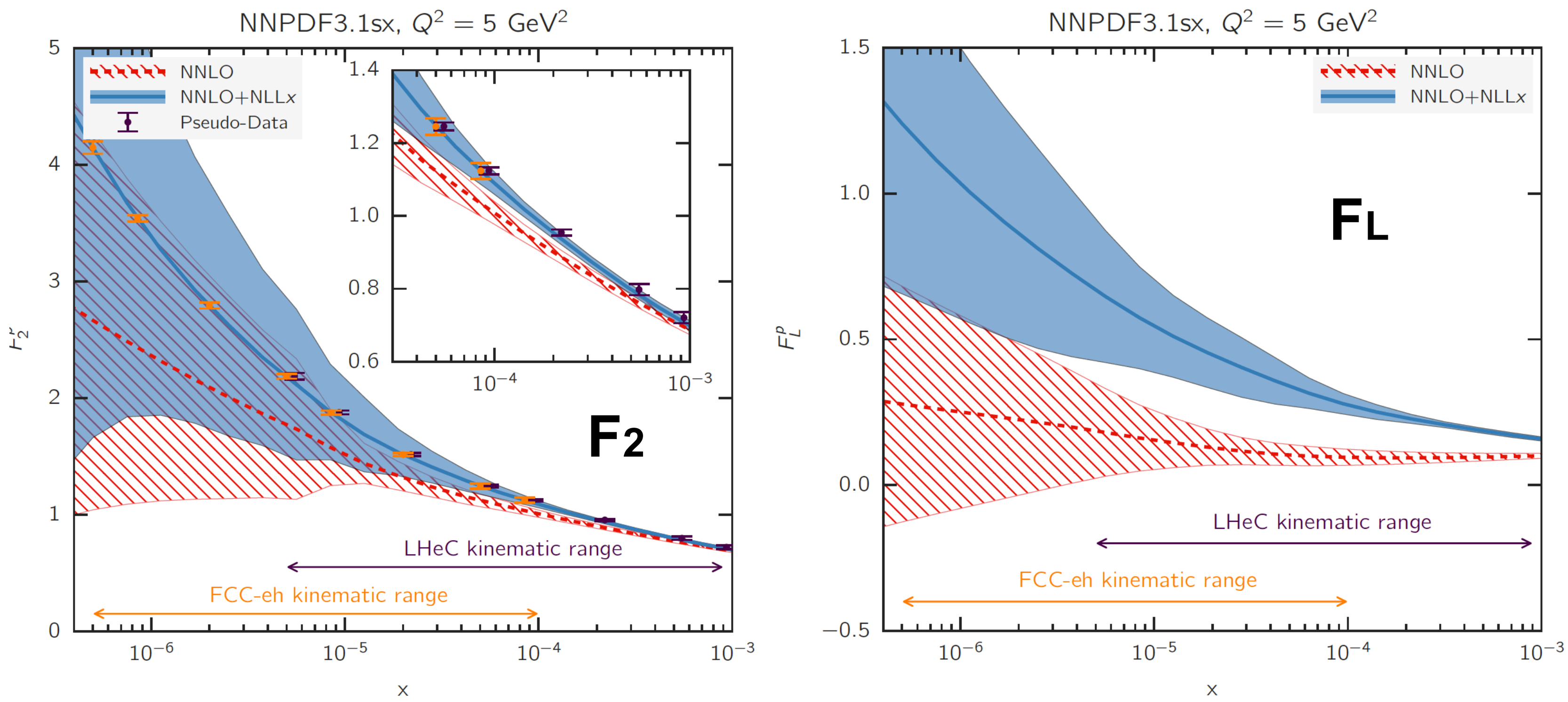
effect of small x resummation on ggH cross section

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



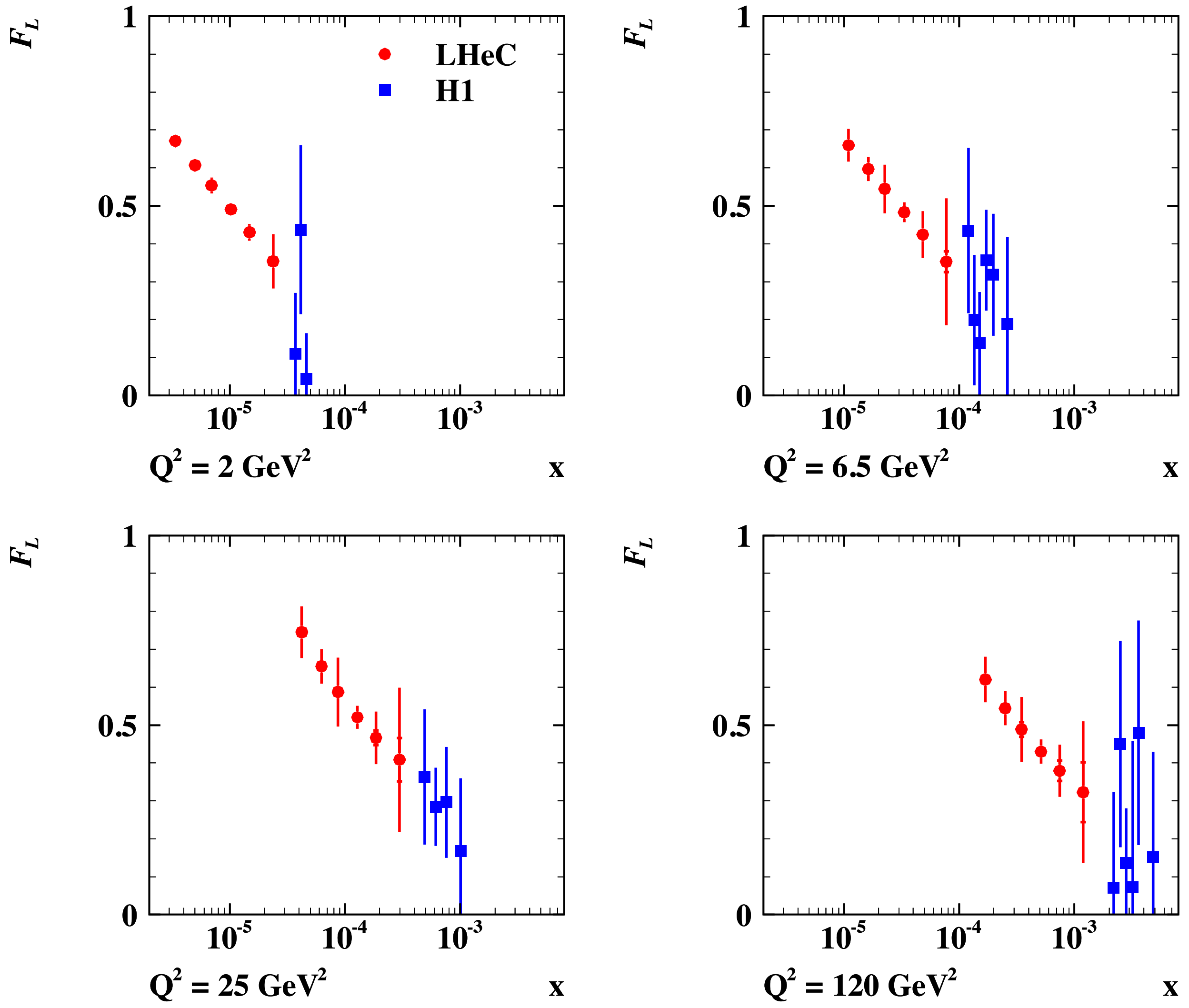
F2 and FL predictions for simulated kinematics of **LHeC** and **FCC-eh**

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

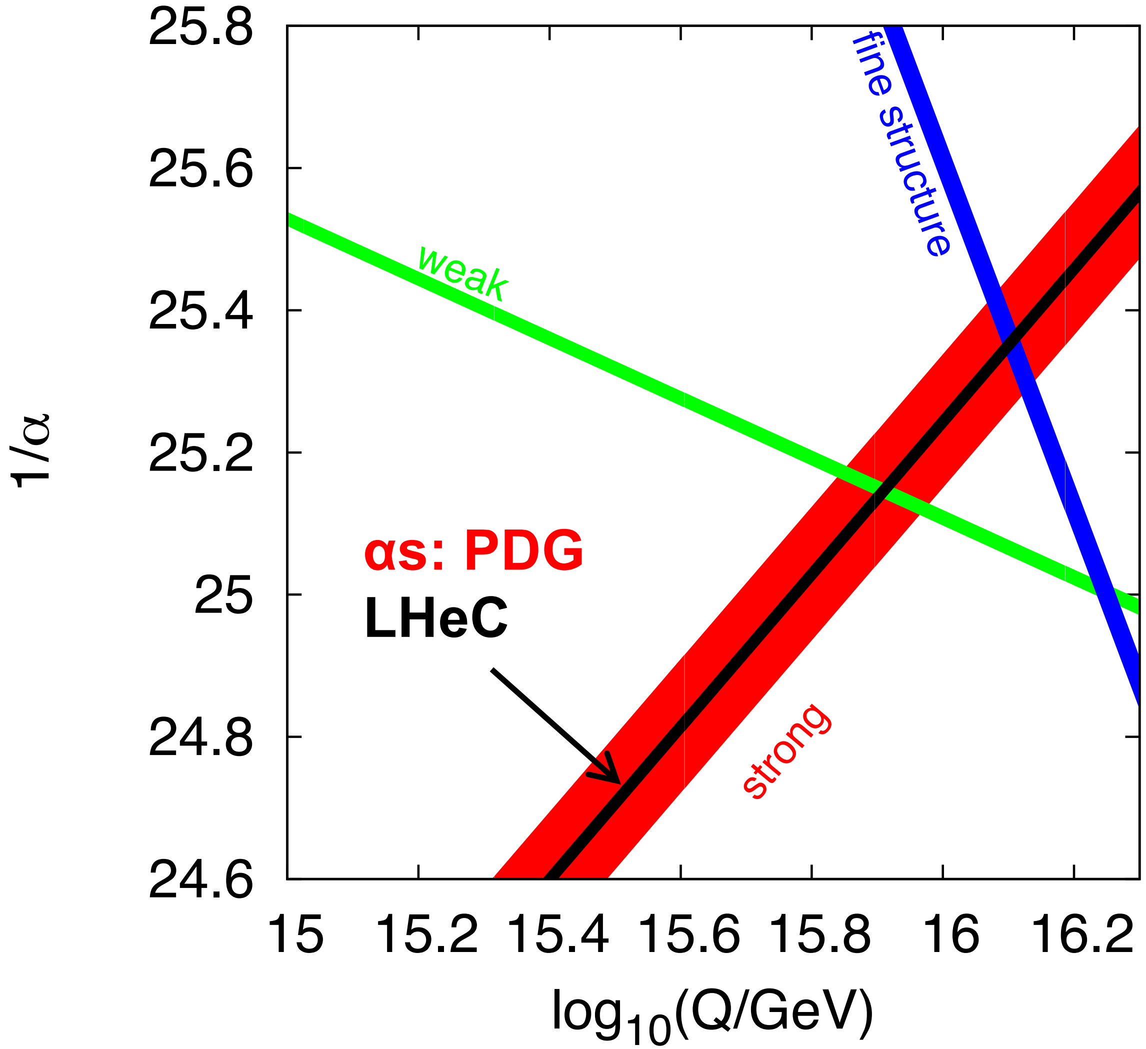
see also M. Klein, arXiv:1802.04317

FL at LHeC



M. Klein, arXiv:1802.04317

strong coupling, αs



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

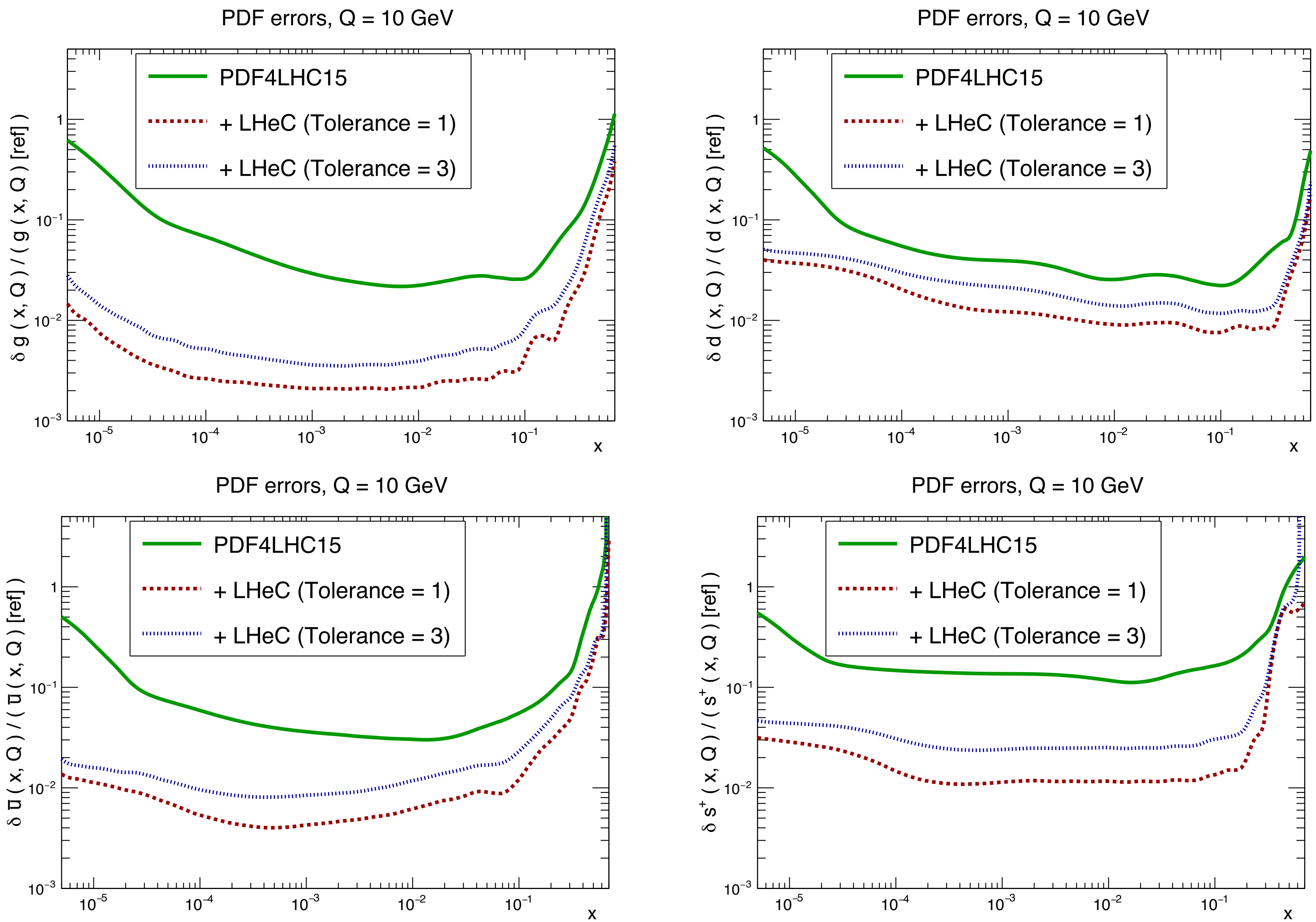
αs is least known coupling constant

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; …

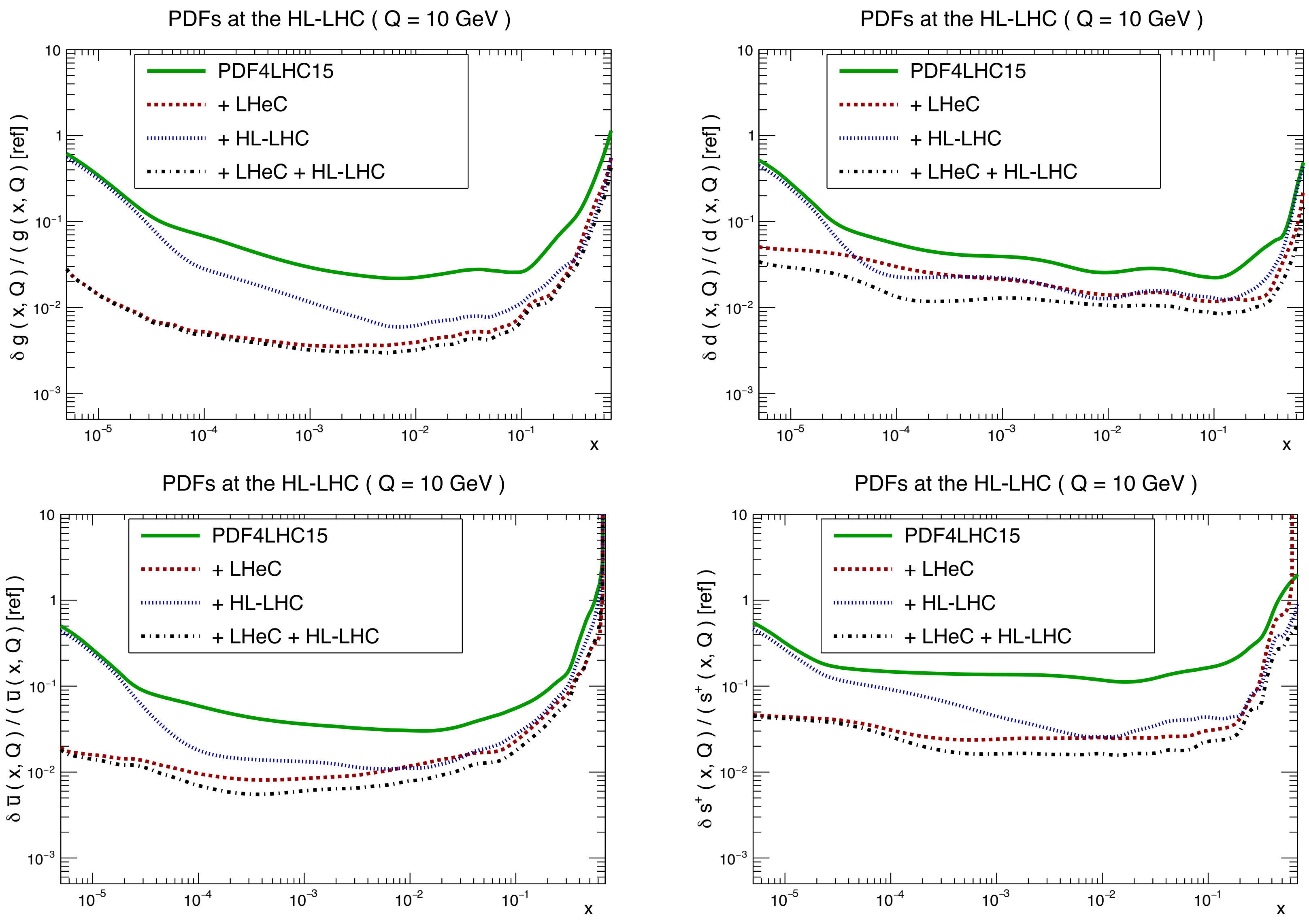
LHeC: permille precision possible in **combined QCD fit for pdfs+αs**

arXiv:[1906.10127](https://arxiv.org/abs/1906.10127)



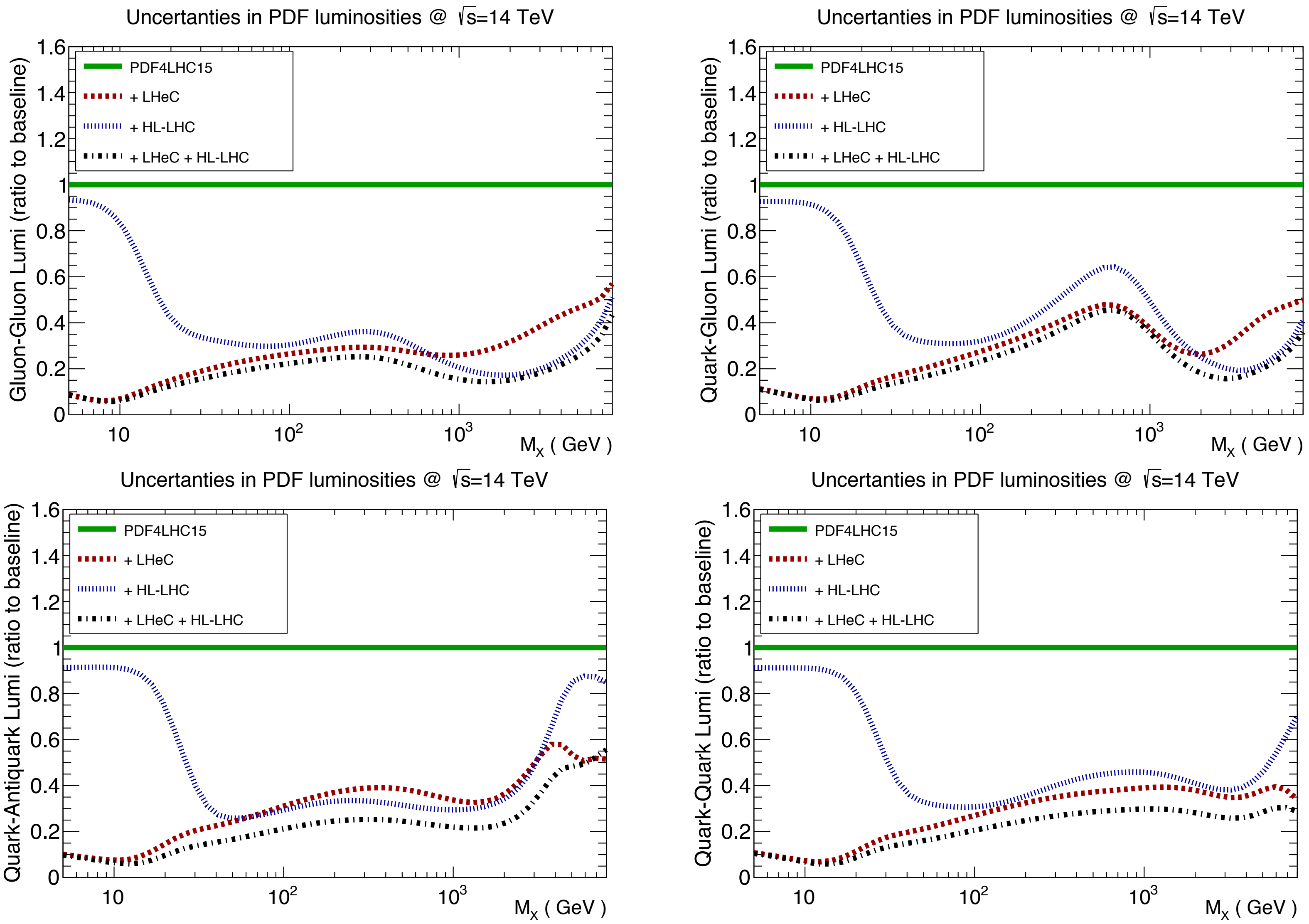
PDF4LHC15 profiled with (previous iteration of) LHeC inclusive+HQ simulated data

arXiv:[1906.10127](https://arxiv.org/abs/1906.10127)



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

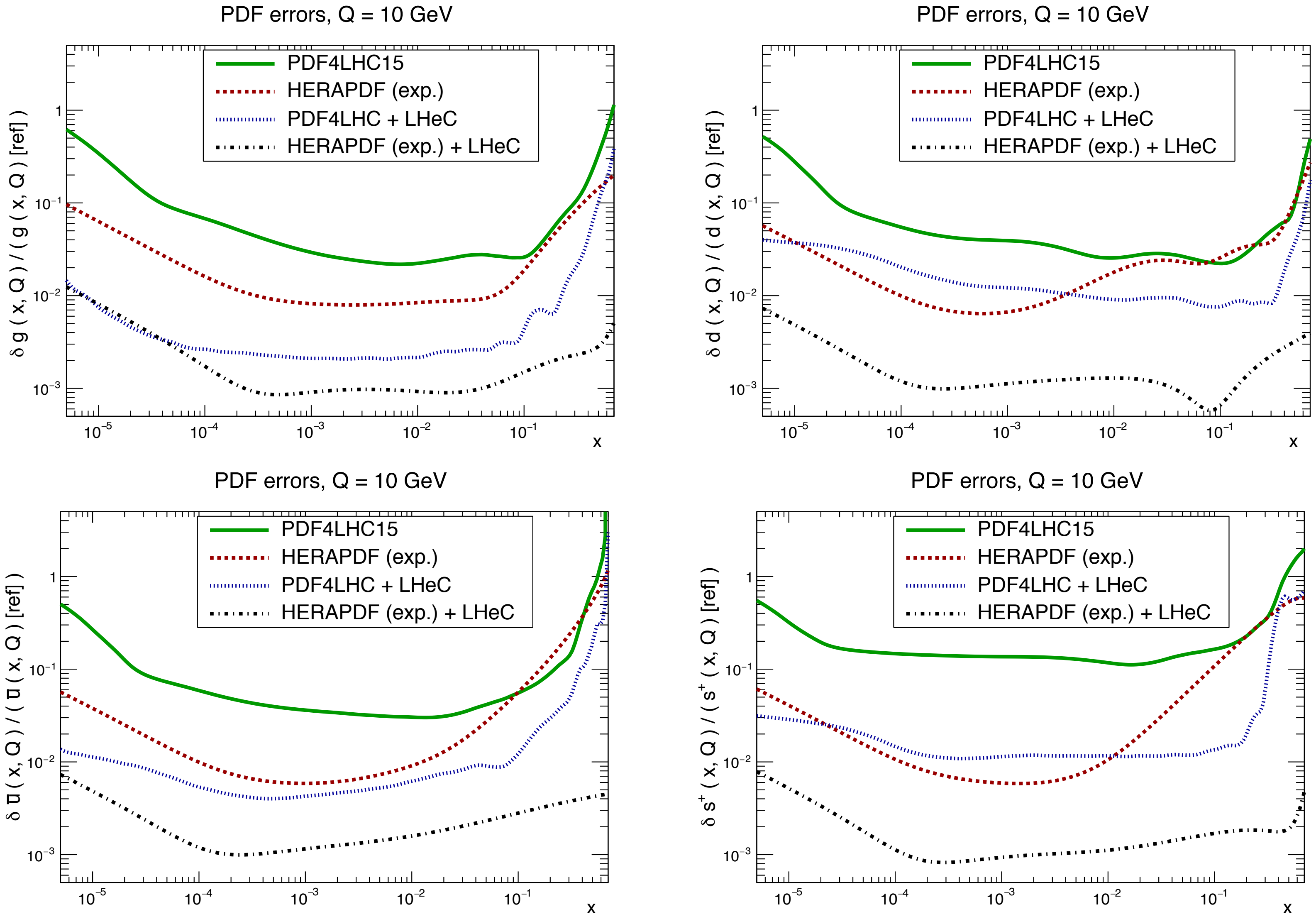
arXiv:1906.10127



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

arXiv:1906.10127

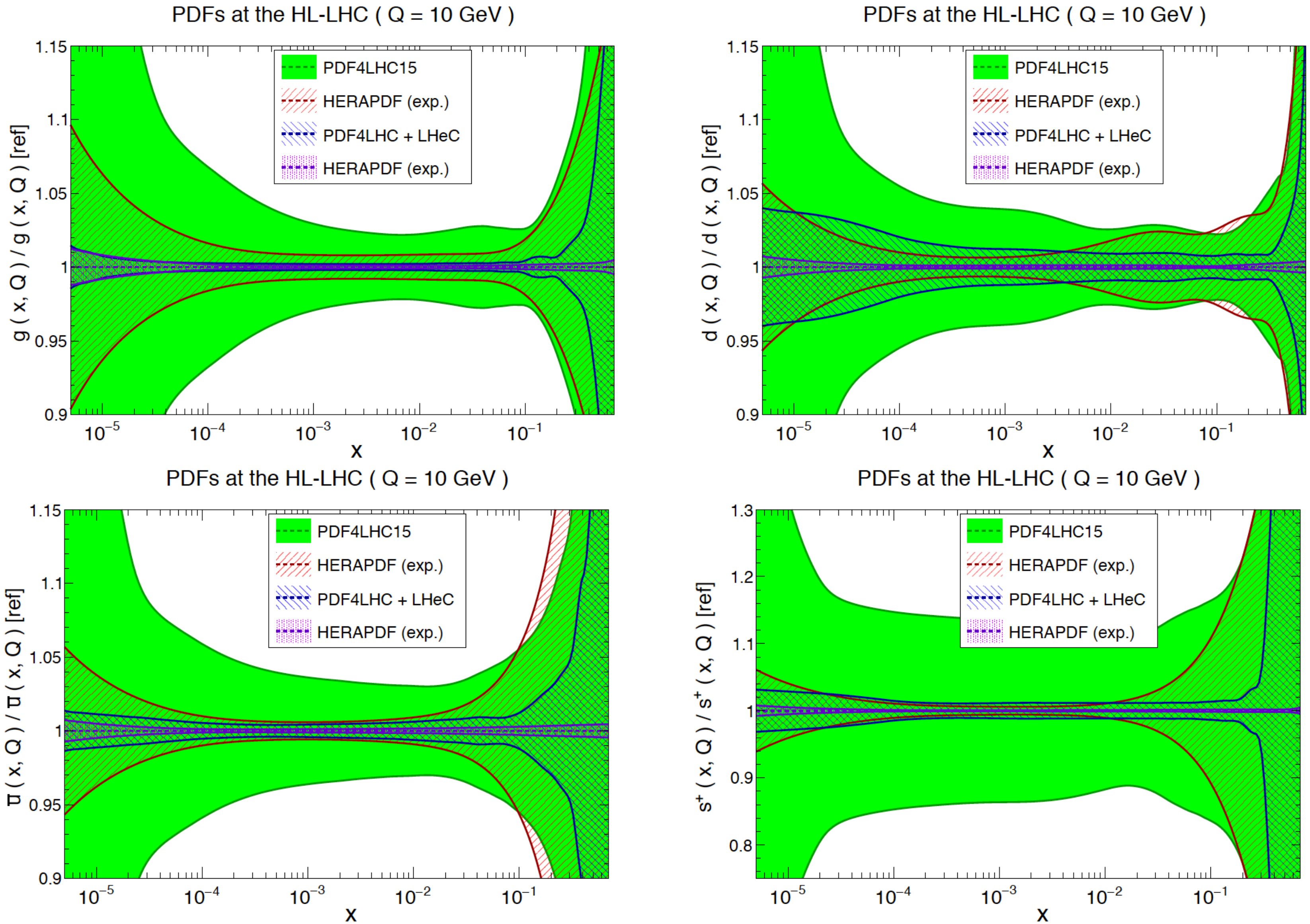
T=1



PDF4LHC15 and HERAPDF profiled with LHeC inclusive+HQ simulated data

arXiv:[1906.10127](https://arxiv.org/abs/1906.10127)

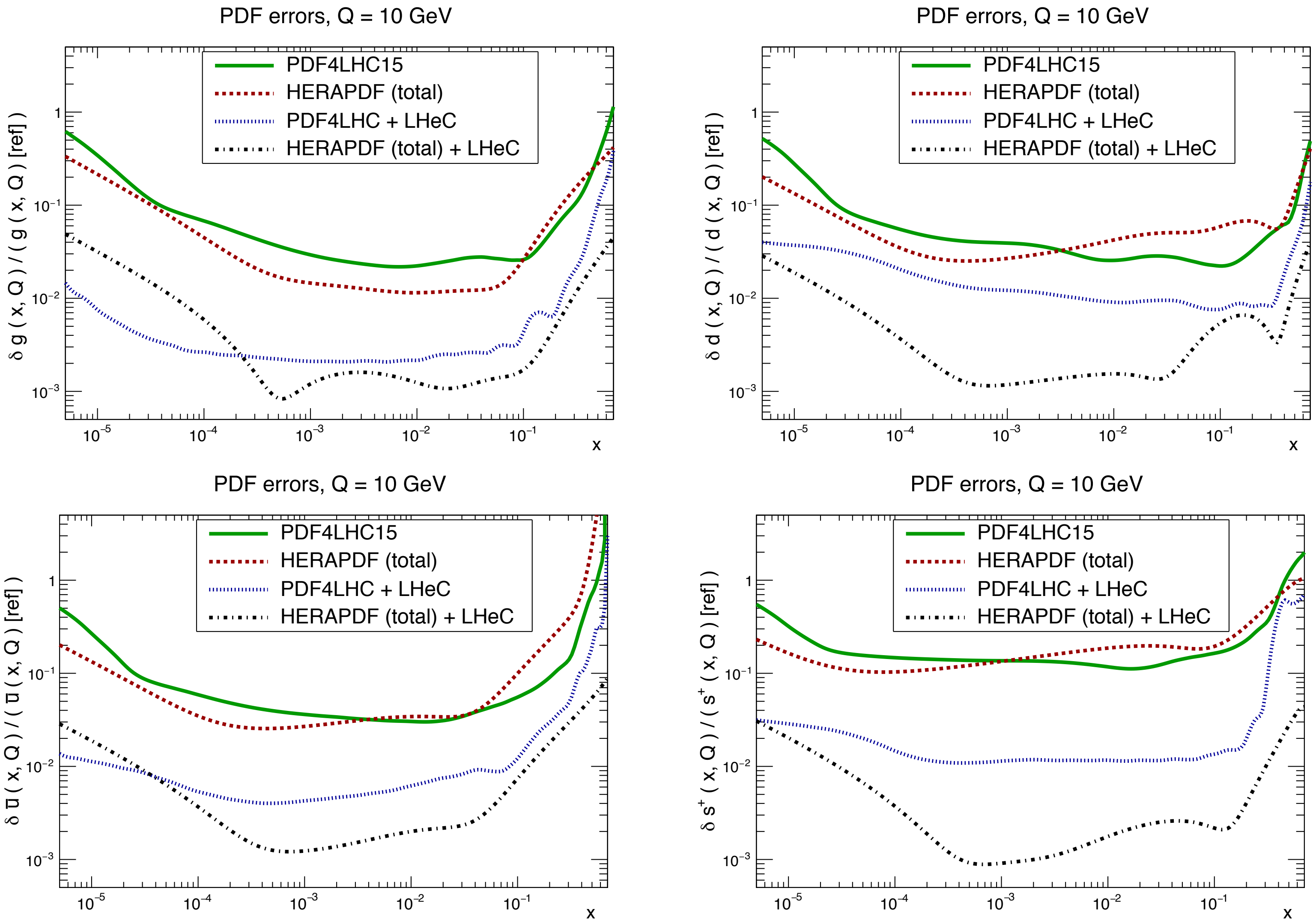
T=1



PDF4LHC15 and HERAPDF profiled with LHeC inclusive+HQ simulated data

arXiv:[1906.10127](https://arxiv.org/abs/1906.10127)

T=1



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