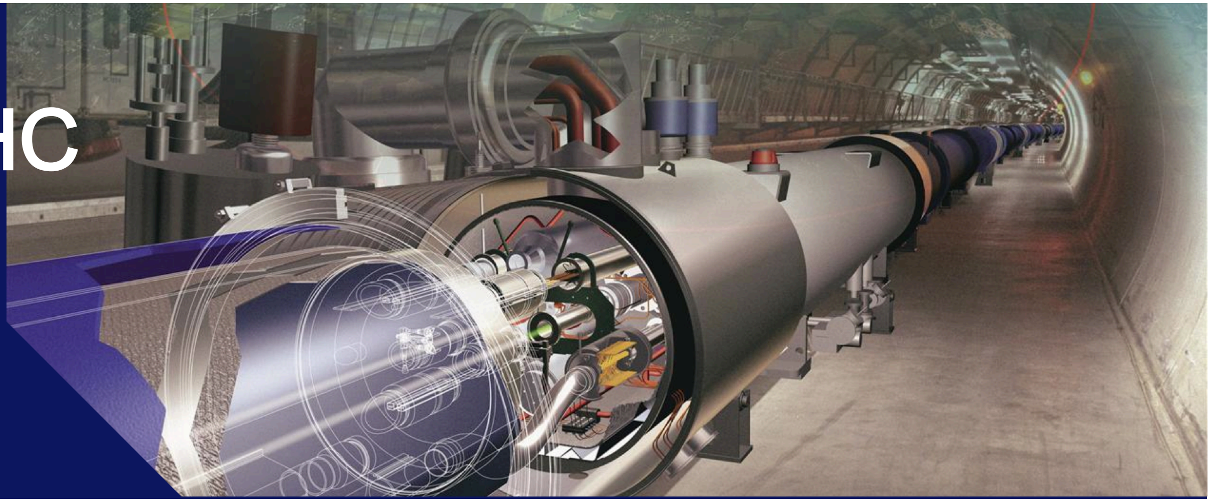
electrons for the LHC

Chavannes de Bogis

24 – 25 October 2019



Proton PDFs and αs

Claire Gwenlan, Oxford

Fred Olness, SMU

on behalf of the PDFs and QCD WG

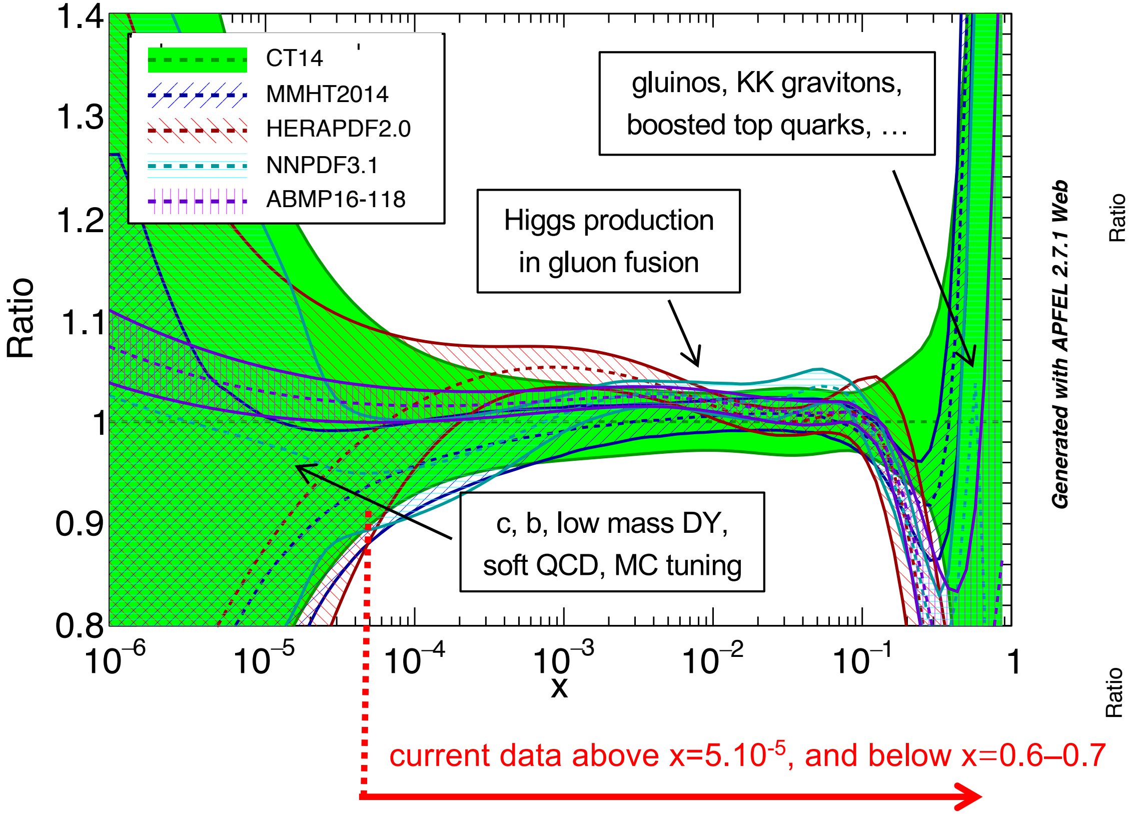
with special thanks to Max Klein and Daniel Britzger

UNIVERSITY OF OXFORD

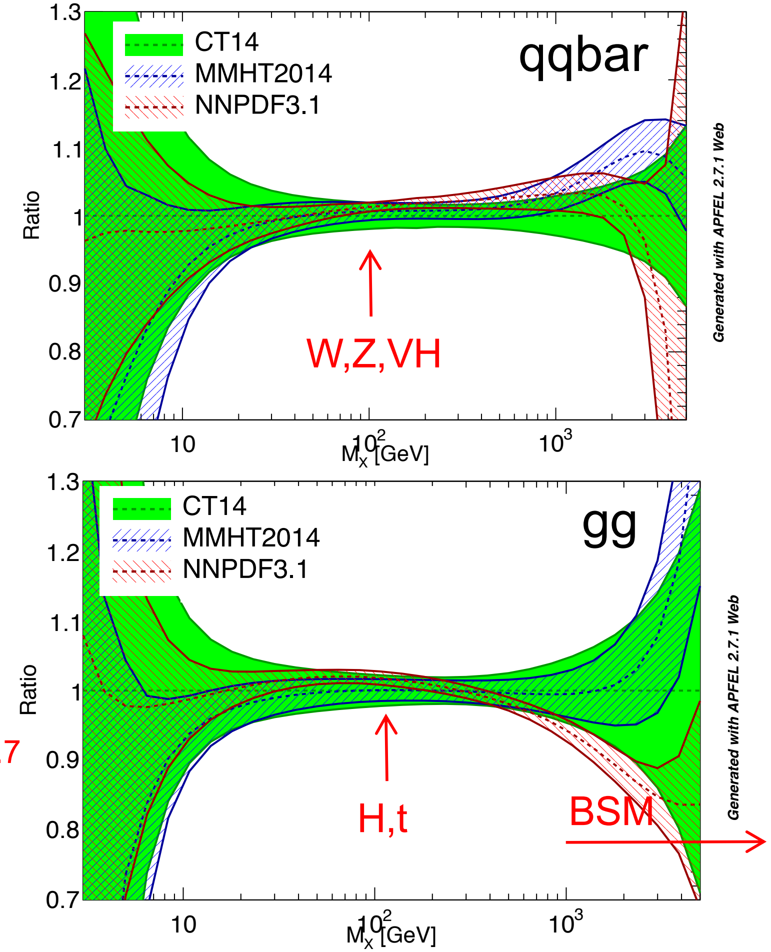
LHeC PERLE FCC hh ee he CERN

pdfs: the situation today

xg(x,Q), NNLO, Q^2=100 GeV^2, α_s(Mz)=0.118



pdf luminosities (LHC@14TeV)

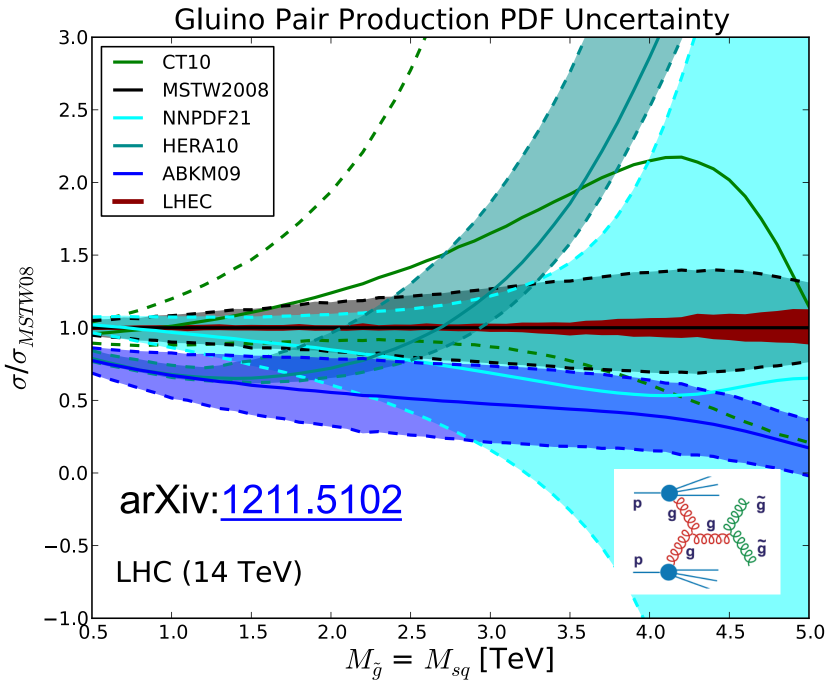


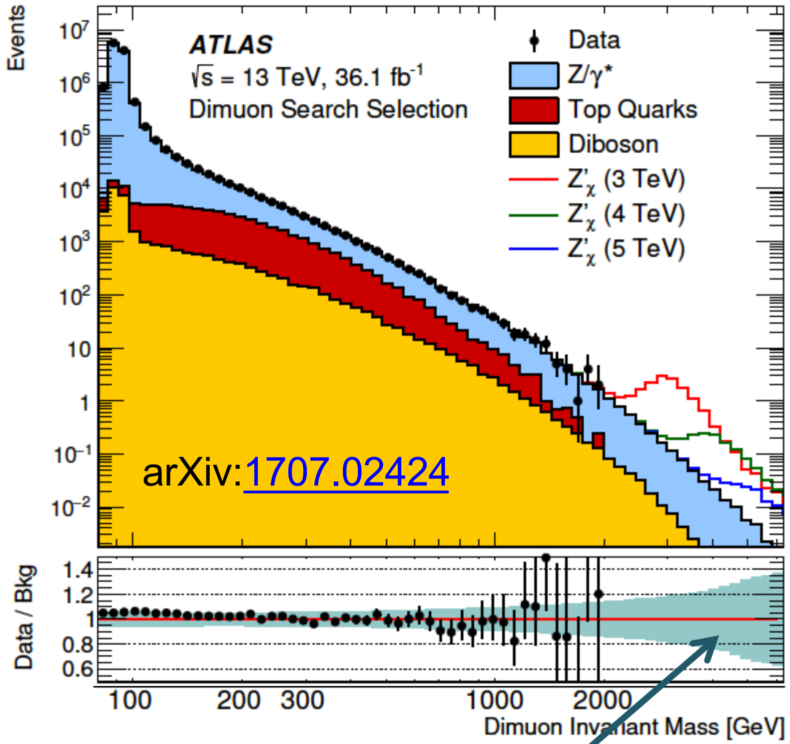
pdfs poorly known at **large** and **small x**

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

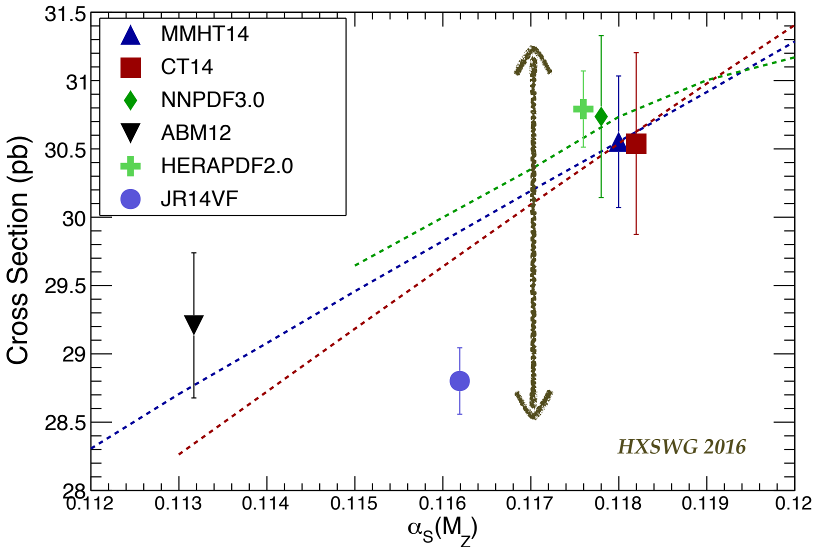
and other LHC measurements…

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

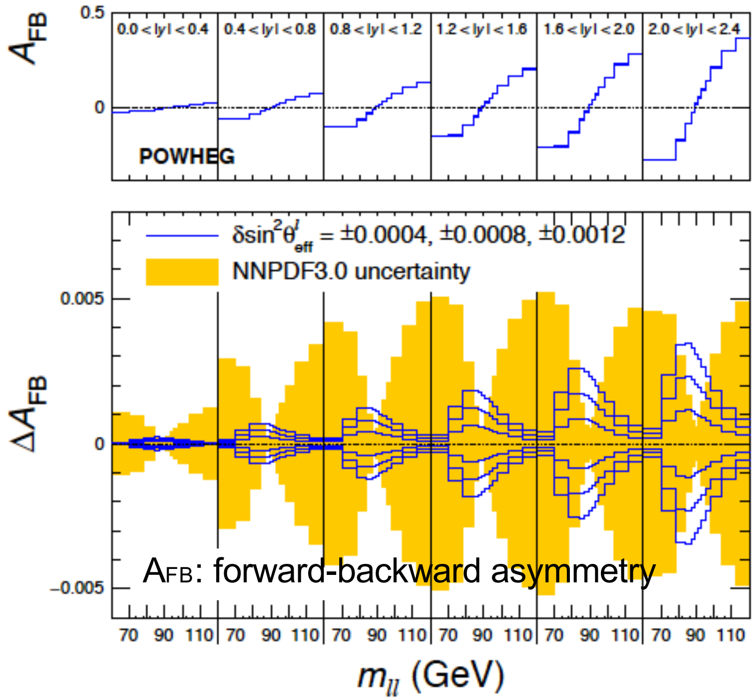
ATLAS MW, arXiv:1701.07240

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

Gluon-Fusion Higgs production, LHC 13 TeV



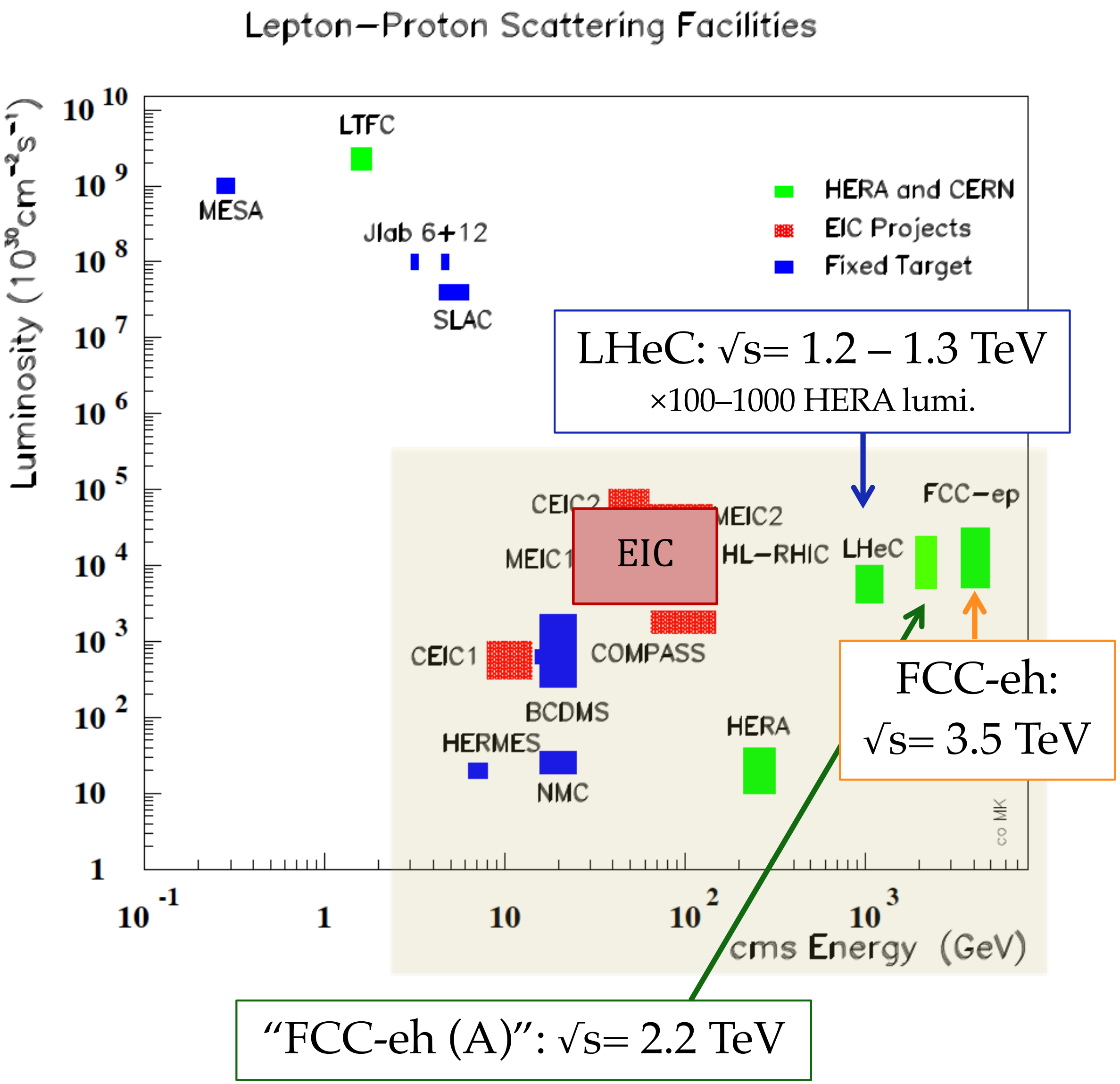
CMS $\sin^2\vartheta_W$, arXiv:1806.00863



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

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

ep collider configurations



LHeC and FCC-eh

ERL, Ee: ⟶ 60 GeV

LHeC

Ep: 7 TeV (or more, with a HE-LHC)

LHeC CDR, arXiV:1206.2913

FCC-eh

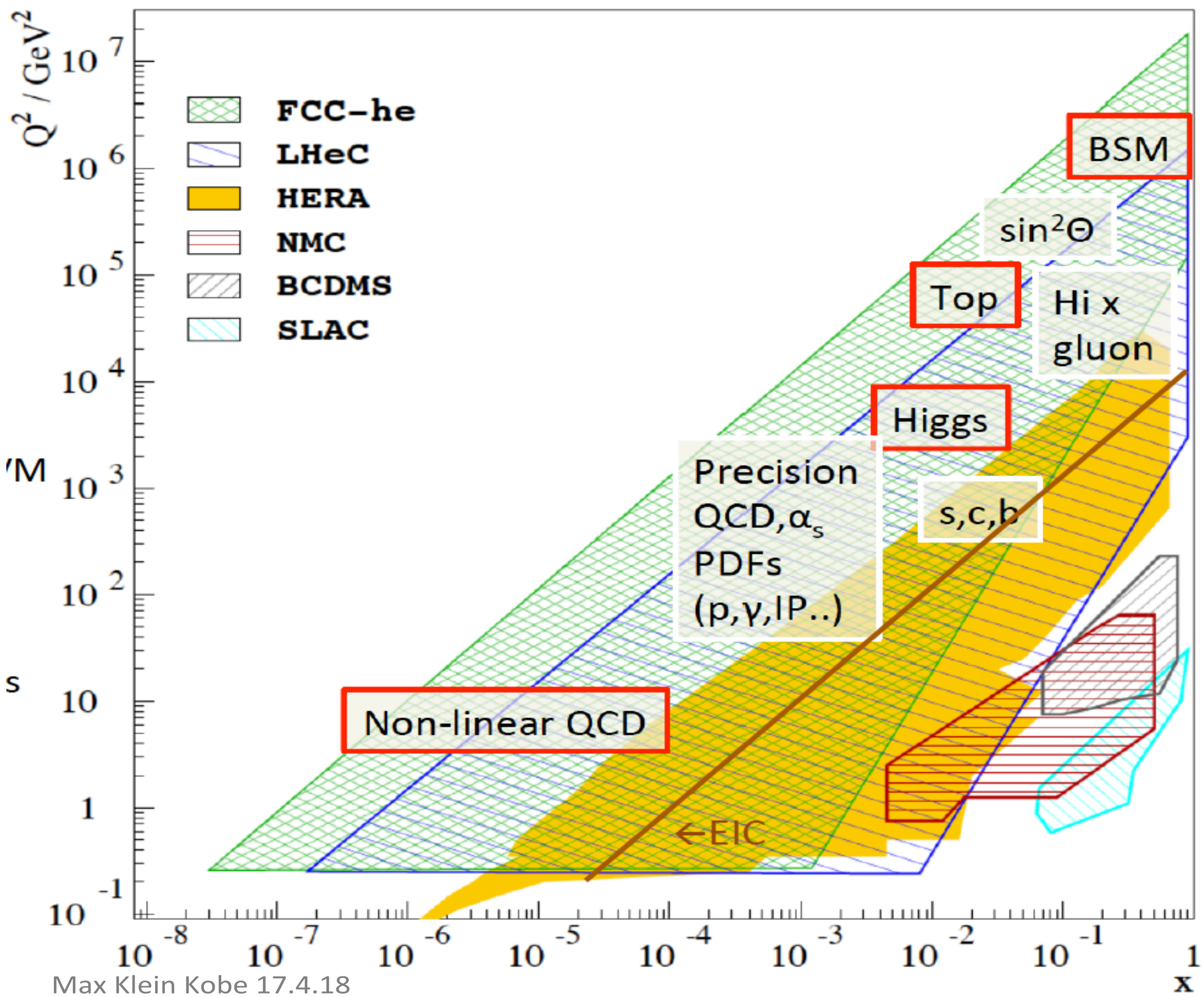
Ep: 50 TeV

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

or possible earlier FCC configuration,

Ep: 20 TeV

kinematic coverage



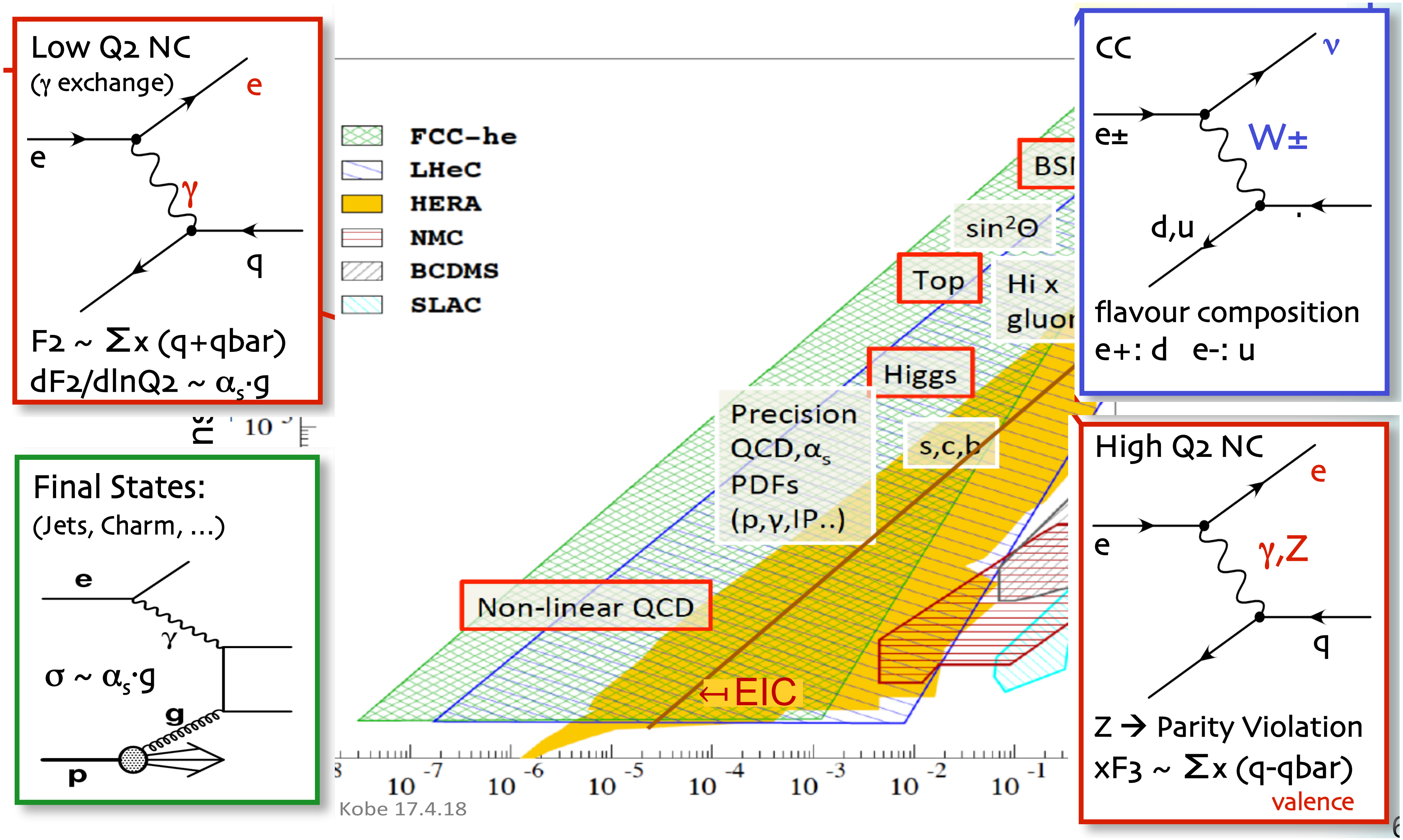
opportunity for **unprecedented increase in DIS kinematic reach**; ×1000 increase in lumi. cf. HERA

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

precision pdfs up to x→1, and exploration of small x regime; plus extensive additional physics programme

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

pdfs from LHeC or FCC-eh

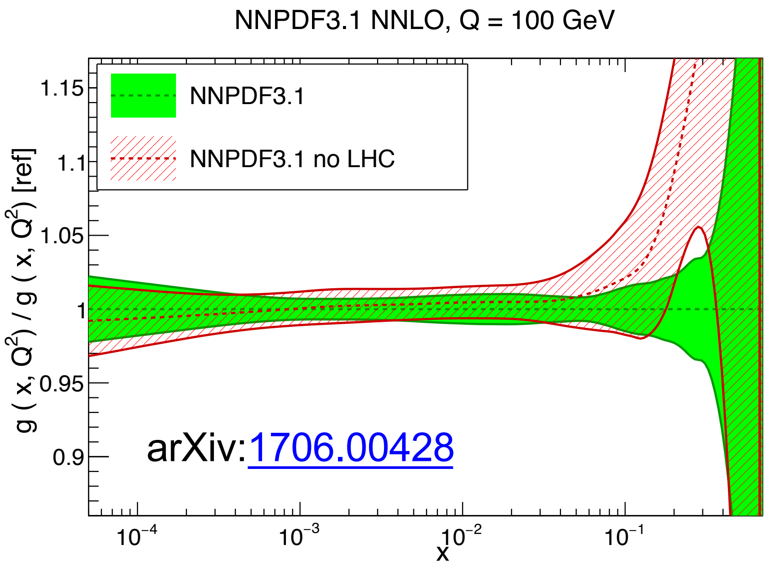


completely resolve all proton **pdfs** and **αs** → **ubar, uv, dbar, dv, s, c, b, t, xg** and **αs**

pp vs ep ?

(slide based on one from M. Klein)

LHC data constrain **pdfs**, BUT do not precisely **determine** them



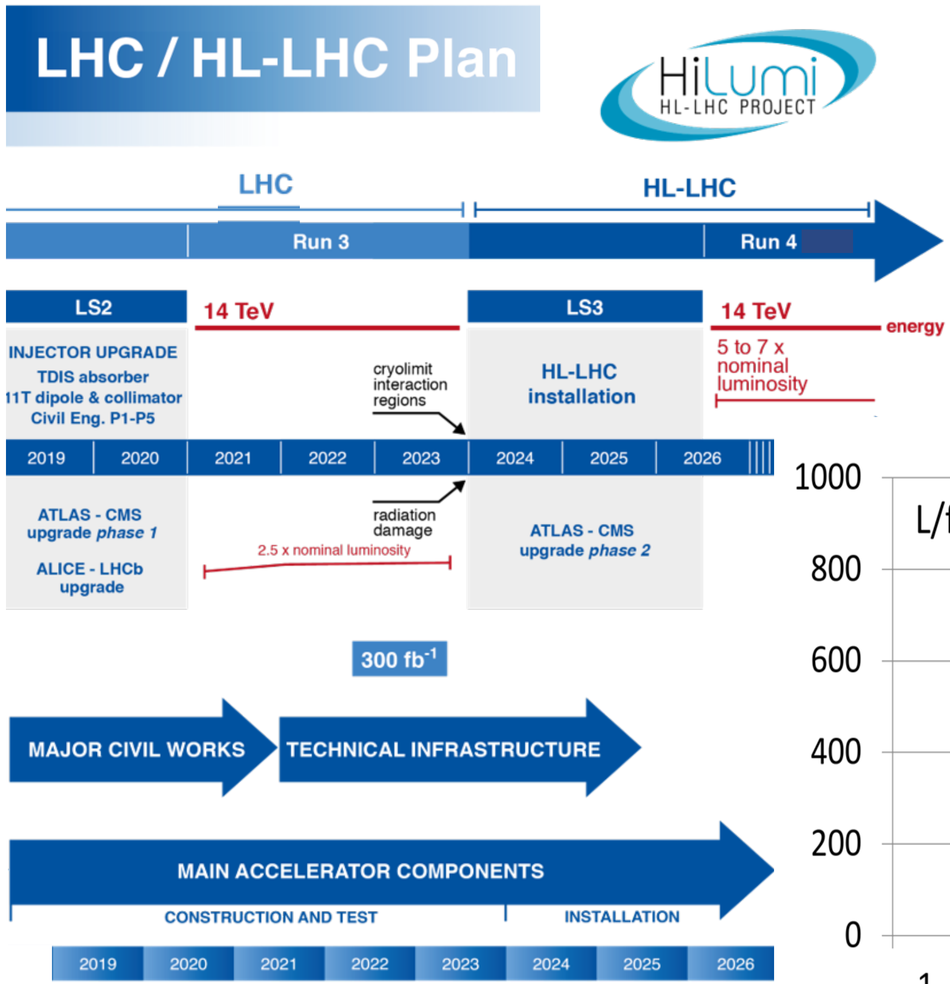
pp: providing useful constraints in global fits and also interesting results (EG. non-suppressed strange at x ~ 0.01 from ATLAS); must nevertheless be aware that it is not **ep** …

see also talk by **L. Harland-Lang**

cf. ep

- complete q,g unfolding at all x
- **α_s** to order permille precision (not in pp)
- clear theory (EG. N3LO, scale choice, hadronisation)
- strong effects from Q^2 variation (which cannot come from EG. W, Z at $Q^2=10^4$ GeV^2)
- HQ separation: s,c,b,(t)
- understanding of small x dynamics, EG. BFKL, saturation, … (comes from F_2 and F_L)
- gives external precision input for QCD subtleties (EG. factorisation, resummation), and for subtle discoveries
- single DIS dataset a tried and tested reliable way to achieve precision (**$\Delta\chi^2$**=1; cf. current LHC measurements; issues understanding systematics, correlations, data inconsistencies, …)

… plus, issues of timing?



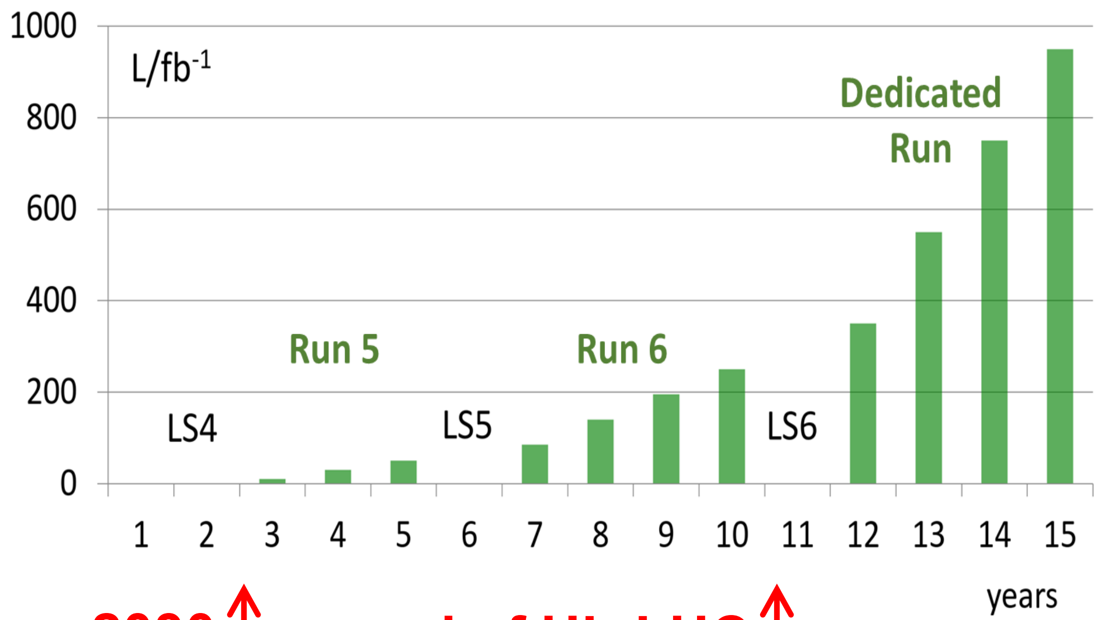
today

LHeC: first 3 yrs: Lint ~ 50 fb^{-1}

total: Lint ⟶ 1 ab^{-1}

F. Bordry et al. arXiv:1810.13022

LHeC projected Integrated Luminosity:



circa 2030 ↑ **end of HL-LHC** ↑

50 fb^{-1} (×50 HERA) achievable by LHeC in 3 yrs, **long before end** of **HL-LHC** operation

LHeC and FCC-eh pdfs WG

lhec.web.cern.ch
fcc.web.cern.ch

PDFs and Low x Working Groups

LHeC and FCC-eh

Conveners:

- Nestor Armesto Perez (Universidade de Santiago de Compostela (ES))
- Paul Newman (University of Birmingham (UK))
- Anna Stasto (Penn State (US))
- Claire Gwenlan (University of Oxford (GB))
- Fred Olness (Southern Methodist University (US))

Working Group Meetings

A list of all LHeC+FCC-eh related Indico meetings is here https://indico.cern.ch/category/1874/

everyone is welcome!

contributions:
(partial list)
L. Bella
M. Bonvini
D. Britzger
S. Camarda
A. Cooper-Sarkar
F. Giuli
A. Guffanti
C. Gwenlan
T. Hobbs
M. Klein
U. Klein
P. Nadolsky
F. Olness
R. Placakyte
G. Pownall
V. Radescu
J. Rojo
W. Slominski

see talks in this WS by:
Anna Stasto
Lucian Harland-Lang
Oleksandr Zenaiev
Nestor Armesto Perez
Paul Newman
Daniel Britzger

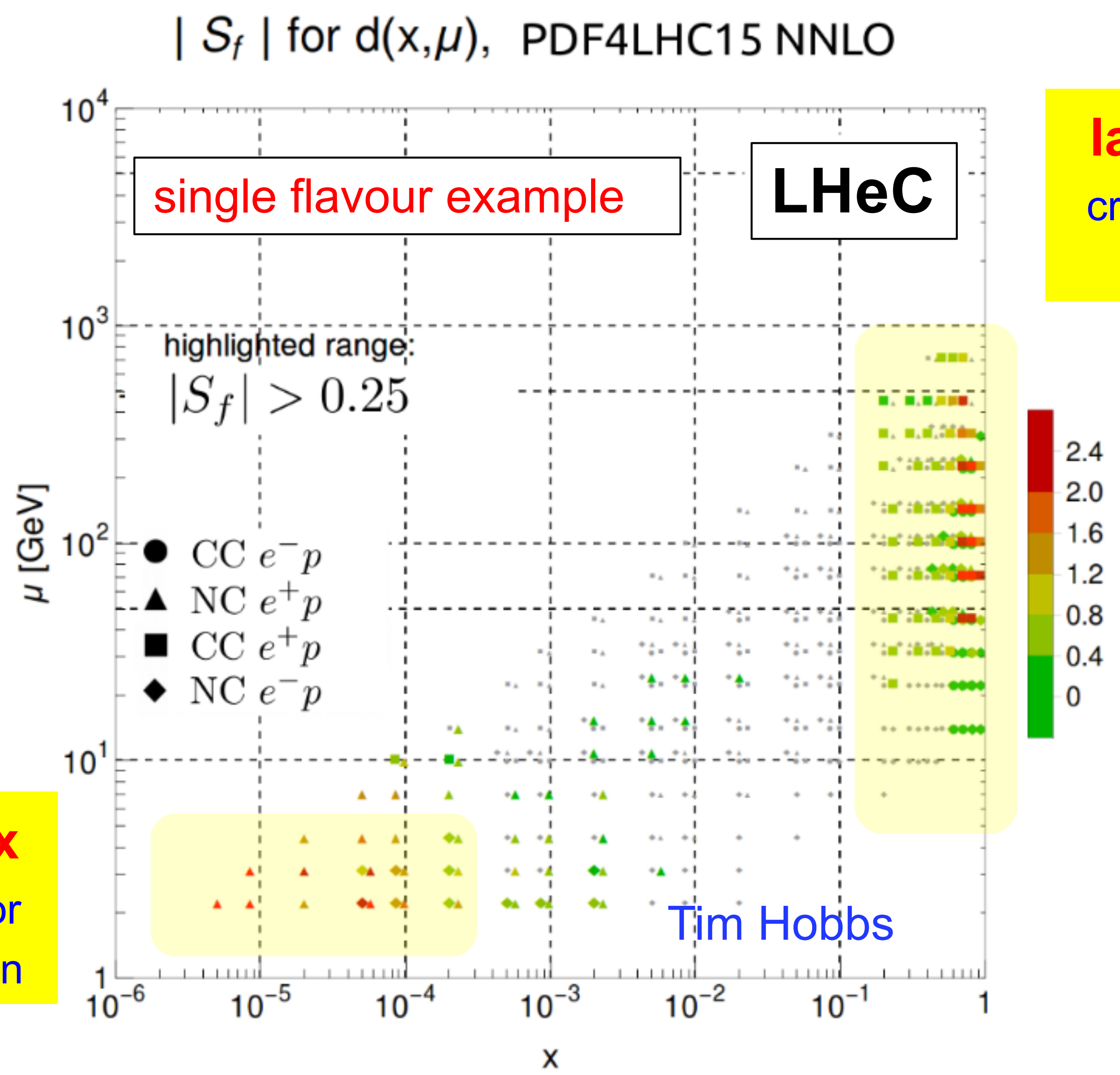
since the LHeC (arXiV:1206.2913) and FCC (vol1, EPJ C79 (2019), no.6, 474) CDRs,
many additional studies, with updated running scenarios etc.

LHeC sensitivity to pdfs

B.-T. Wang et al.
arXiv:1803.02777

"sensitivity" Sf
= **C**orrelation ×
scaled **r**esidual

$$S_f(x_i,\mu_i) \equiv \frac{\delta^{(\mathrm{PDF})} r_i}{\sqrt{\frac{1}{N}\sum_{i=1}^{N} r_i^2}} C_f(x_i,\mu_i).$$



large-(x,Q²)
crucial for BSM searches

small-x
crucial for saturation

enormous sensitivity in regions currently poorly constrained

PDFSENSE: tool for quickly quantifying potential impact of experimental (pseduo)data

LHeC simulated data and QCD fits

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

simulation: M. Klein

dataset	e charge	e pol.	lumi (fb-1)	
NC/CC	–	–0.8	5,50,1000	**luminosity**
NC/CC	+	0	1,10	**positron**
NC/CC	–	0	50	**polarisation** (important for EW)
NC/CC	–	+0.8	10,50	
NC/CC	–	0	1	**low-E** (p: 1 TeV)

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

*corresponds to possibility of smaller ERL cf. previous 60 GeV simulations †except for low-E

various combinations studied;
shown frequently in following slides:

LHeC 1st Run
(50 fb^{-1} e– only; 3 yrs)

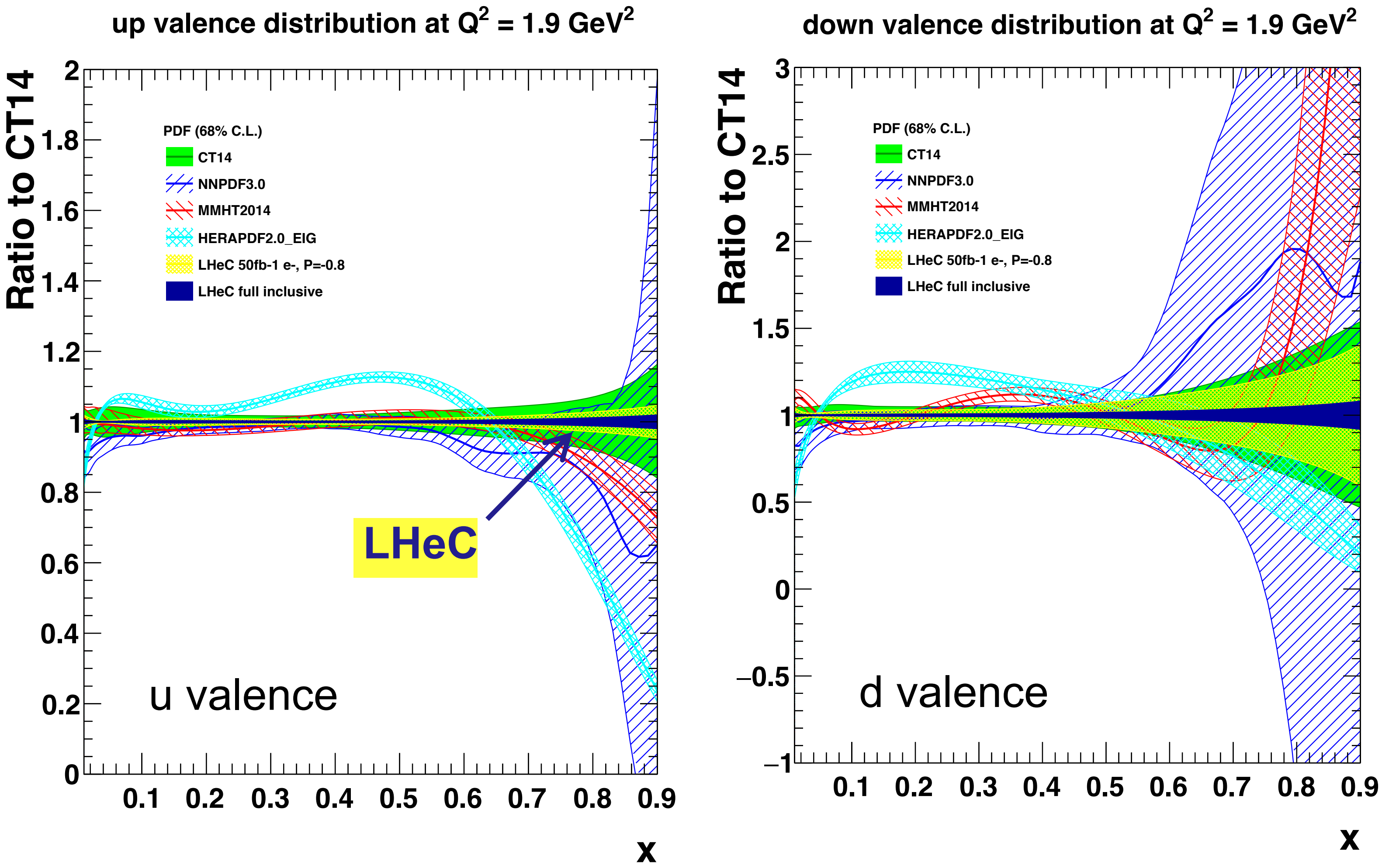
LHeC full inclusive

QCD analysis a la HERAPDF2.0, except **more flexible**, notably in **NO constraint** requiring dbar=ubar at small x;

4+1 xuv, xdv, xUbar, xDbar and **xg** (**14 free parameters**, cf. 10 by default in CDR)

5+1 xuv, xdv, xUbar, xdbar, xsbar and **xg** (if strange and HQ included; **17 free parameters**)

valence quarks from LHeC

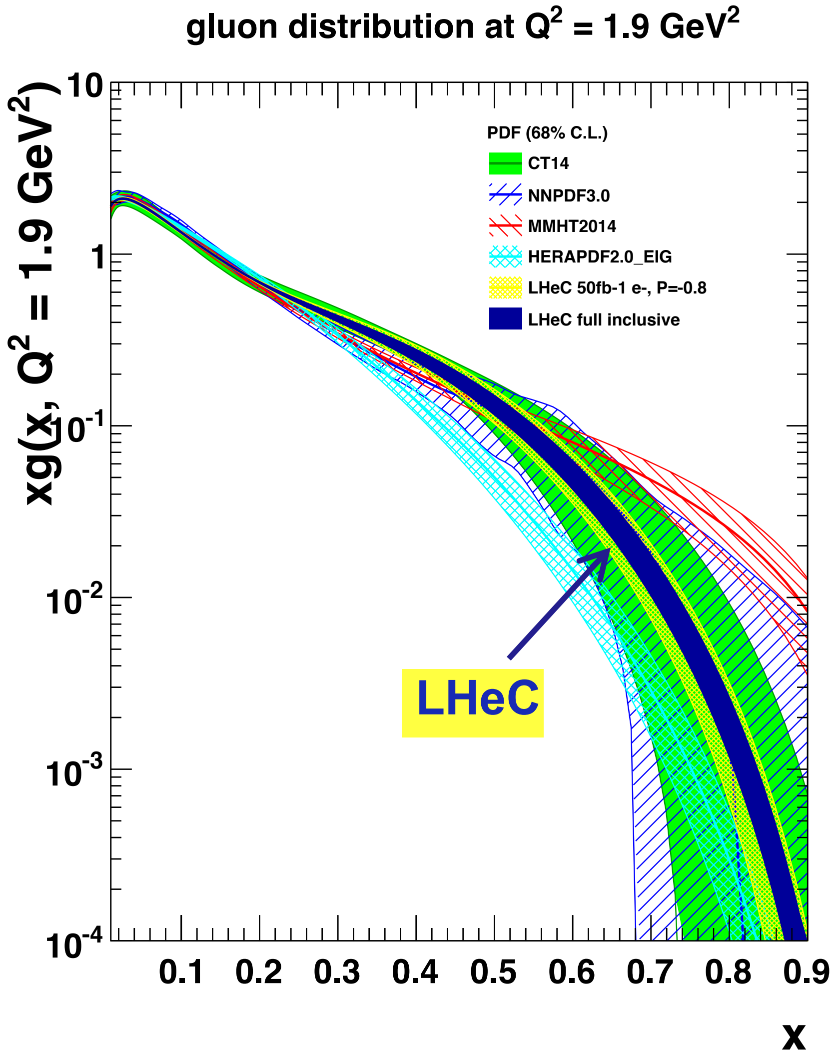


precision determination, free from higher twist corrections and nuclear uncertainties

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

and 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

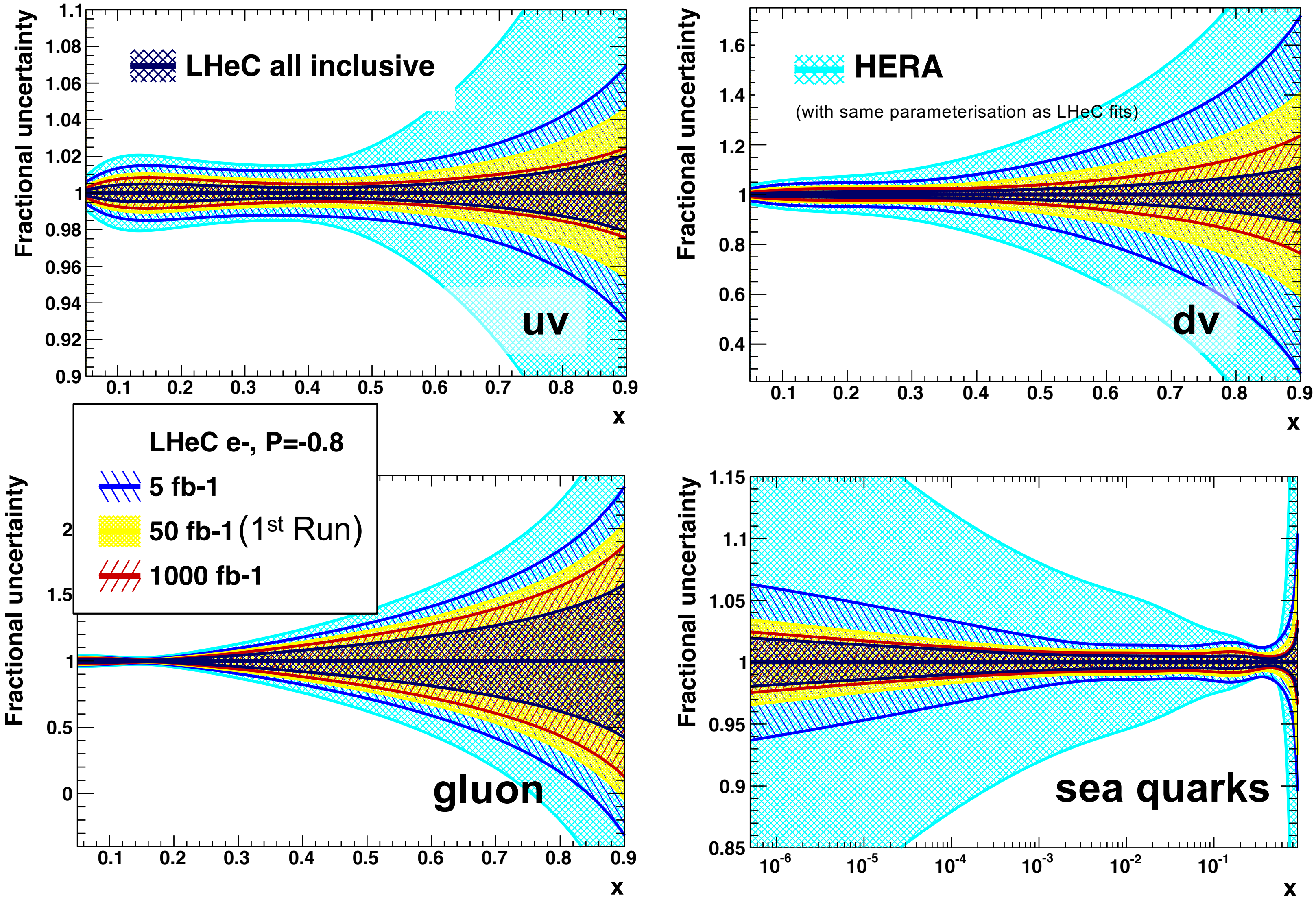
LHeC sensitivity at large x comes as part of overall package

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

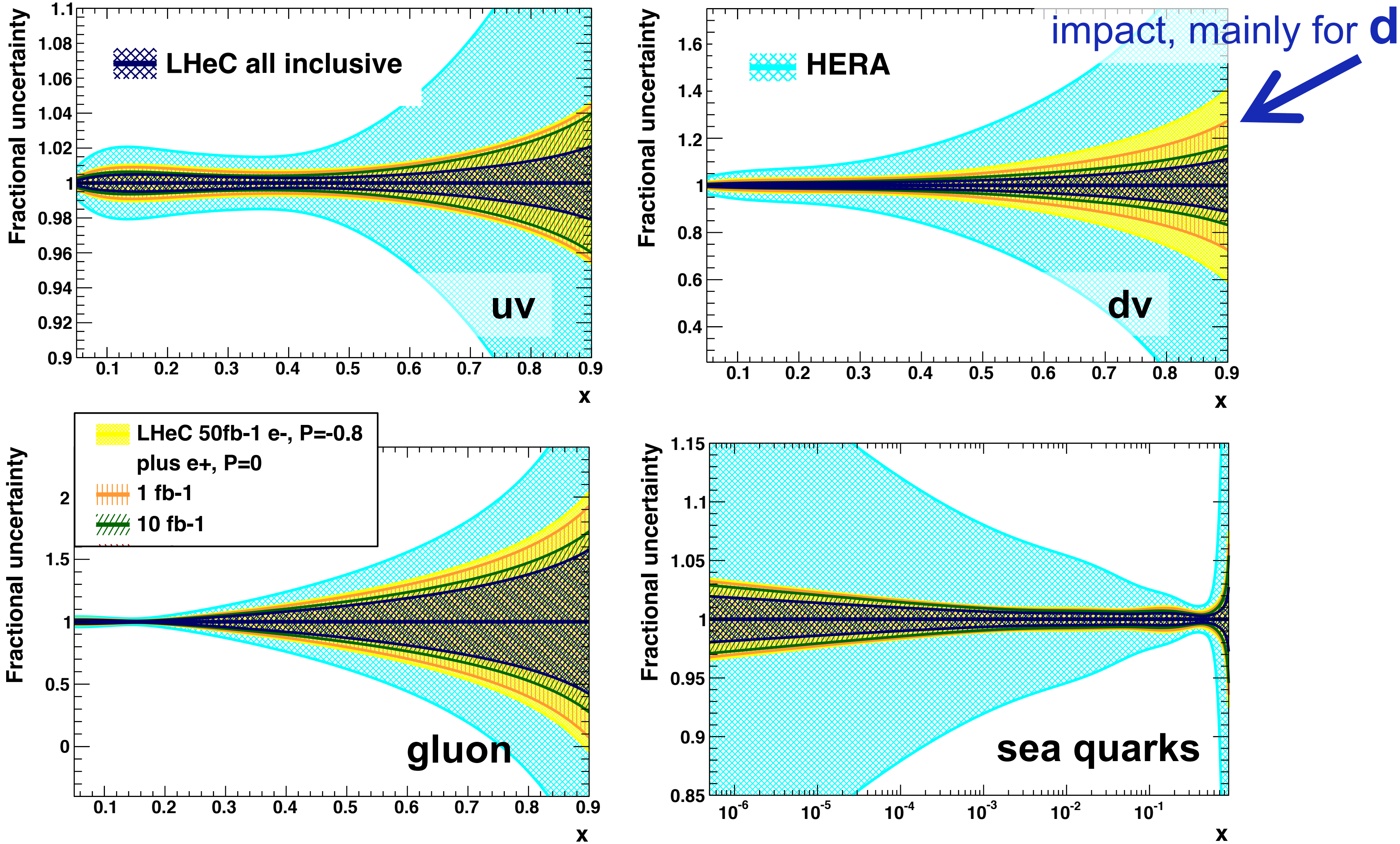
impact of luminosity on LHeC pdfs



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

large x (≡ large Q2), gain from increased Lint; still, early massive improvement cf. today

impact of positrons on LHeC pdfs



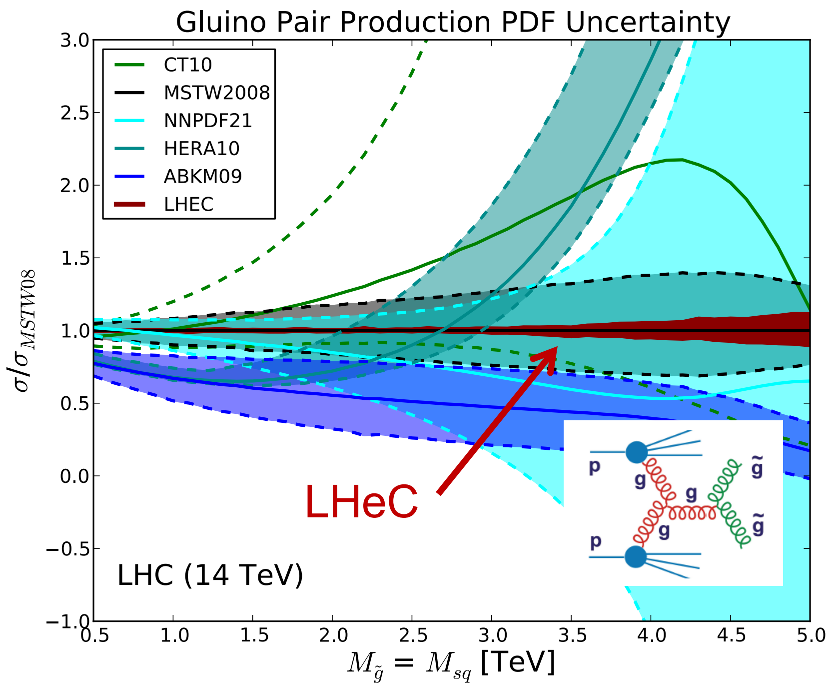
CC: e+ sensitive to d; **NC**: e± asymmetry gives $xF3^{\gamma Z}$, sensitive to valence

empowering LHC searches

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

gluons at large x

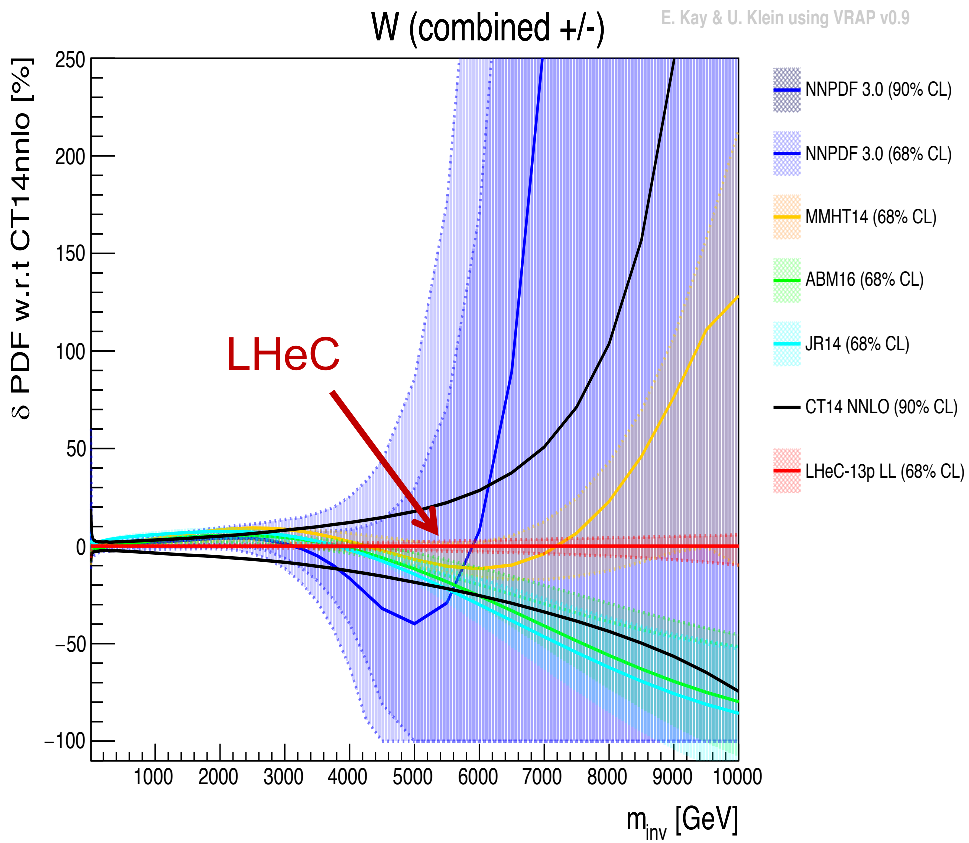
SUSY (RPC, RPV), LQs, …



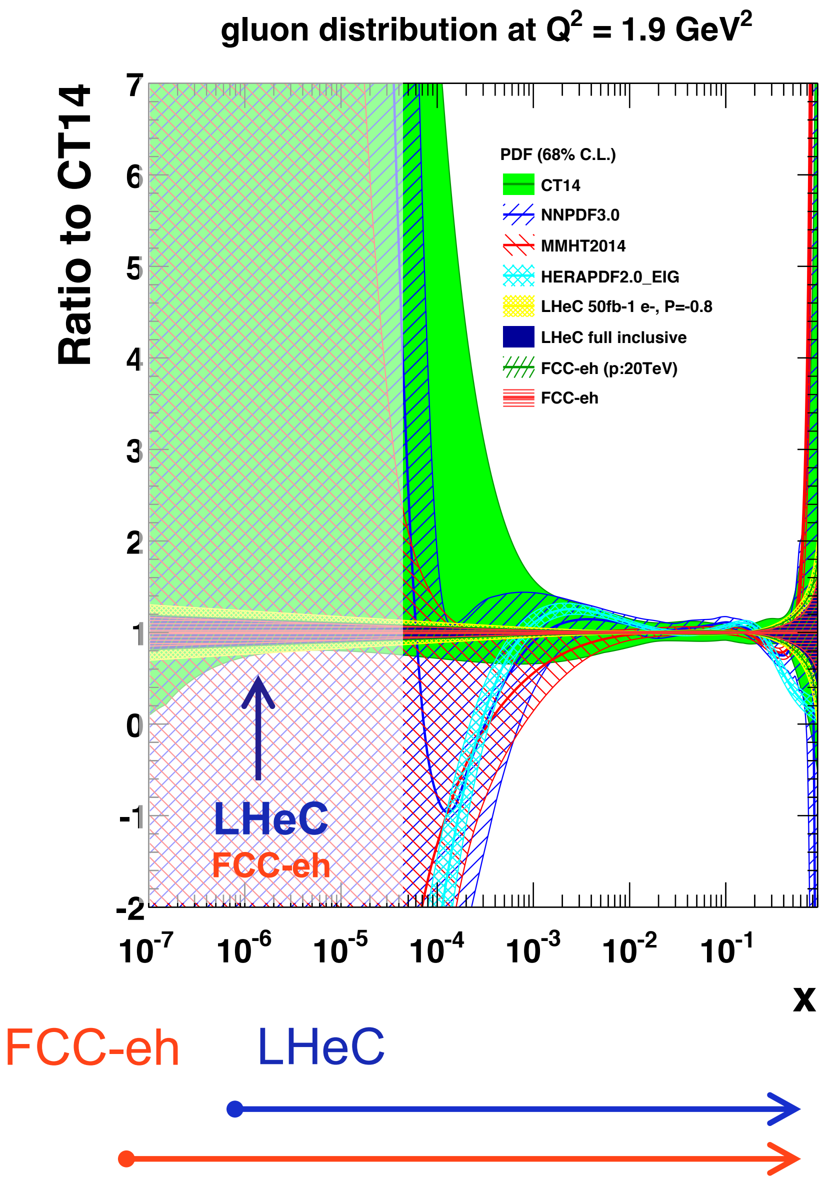
arXiv:[1211.5102](https://arxiv.org/abs/1211.5102)

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:

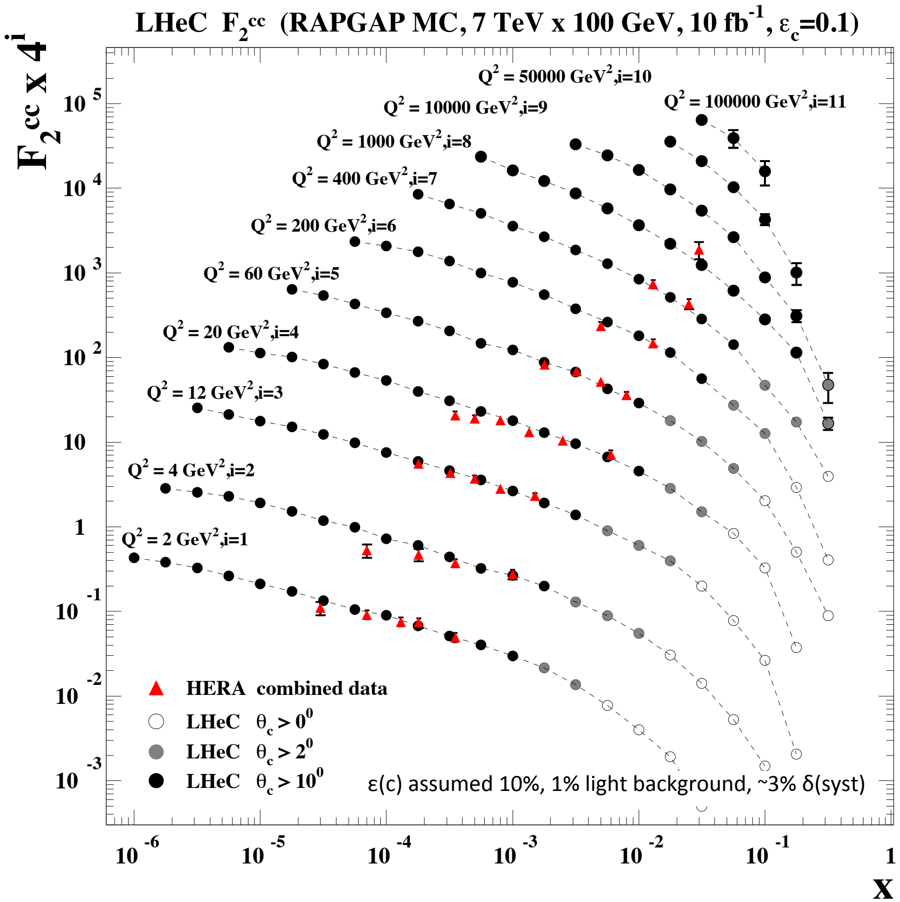
DGLAP vs BFKL; non-linear evolution; gluon saturation; implications for ultra high energy neutrino cross sections

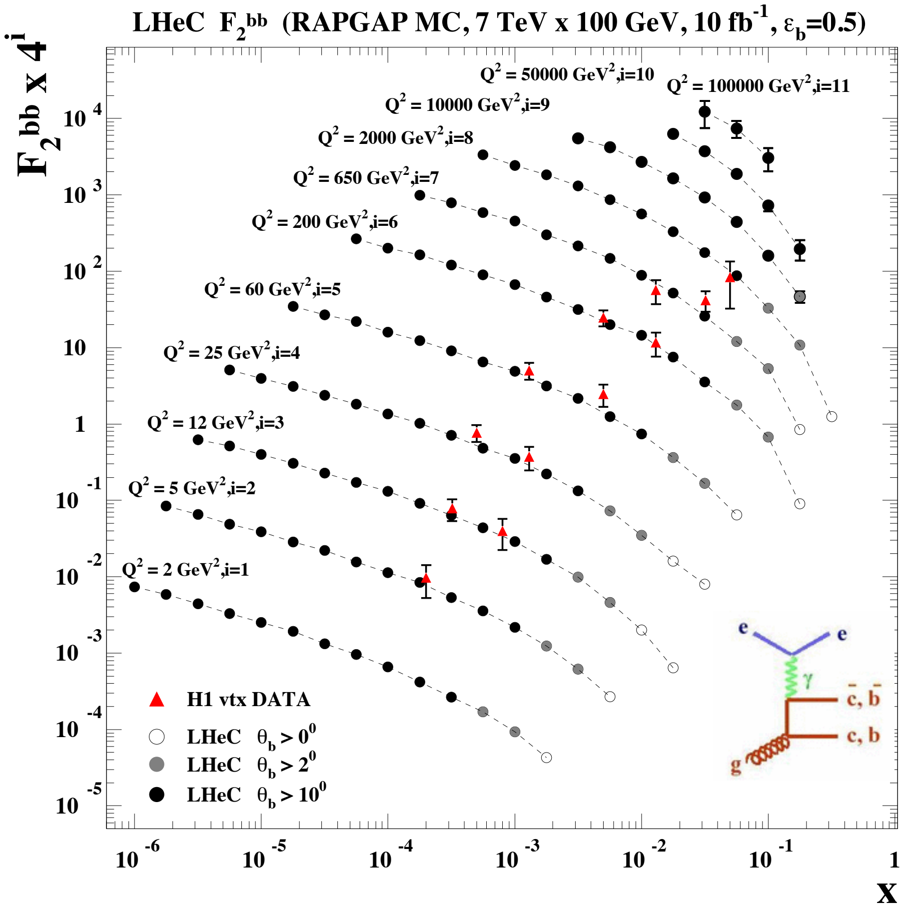
small x also important for **pp** phenomenology, especially as collider energy increases, EG. arXiv:1802.07758

see talk by **A. Stasto**

c, b quarks

arXiV:1206.2913

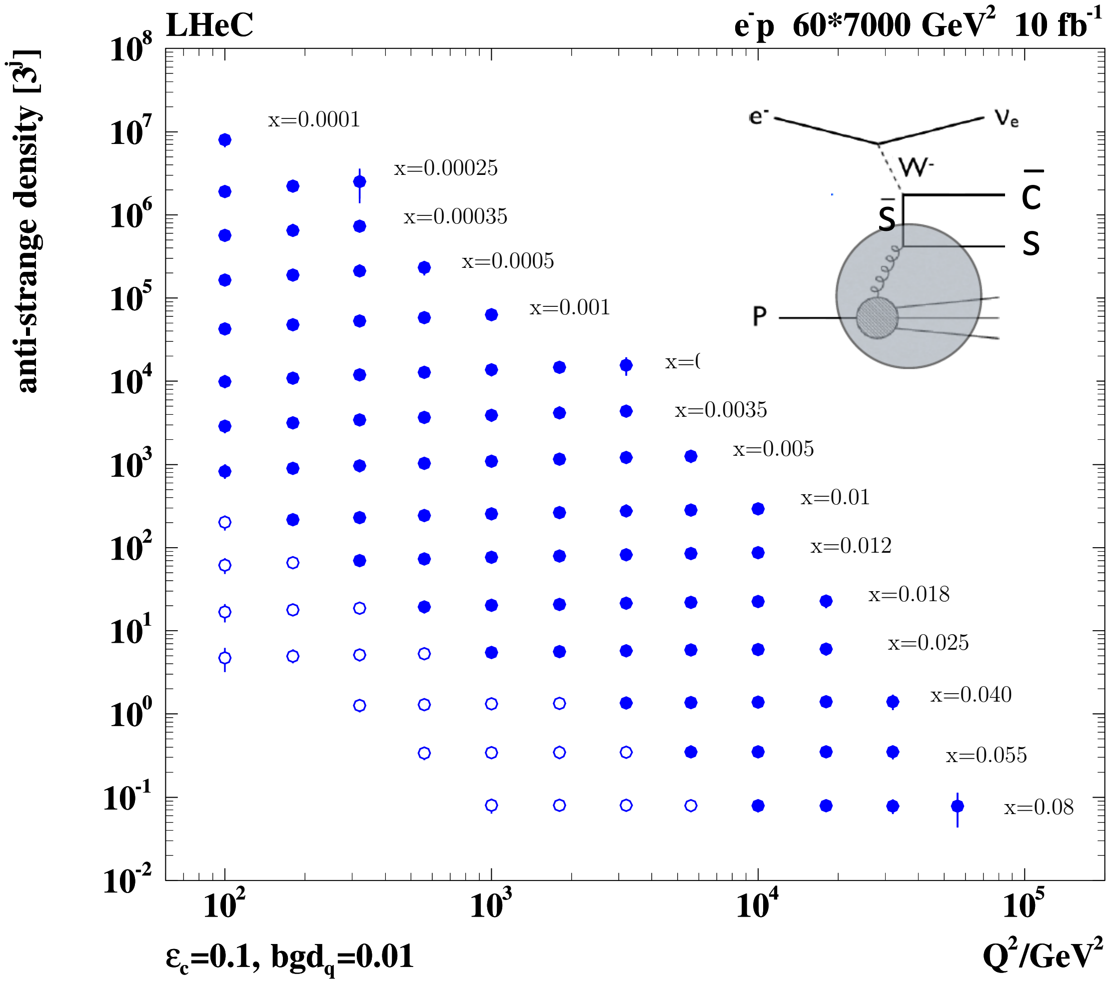




LHeC: enormously extended range and much improved precision c.f. HERA

- **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

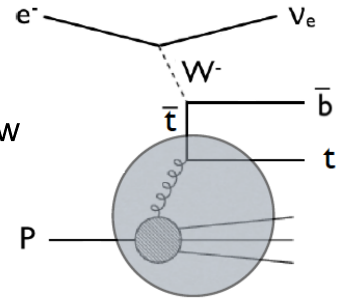


strange pdf poorly known;
suppressed cf. other light quarks?
strange valence?

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

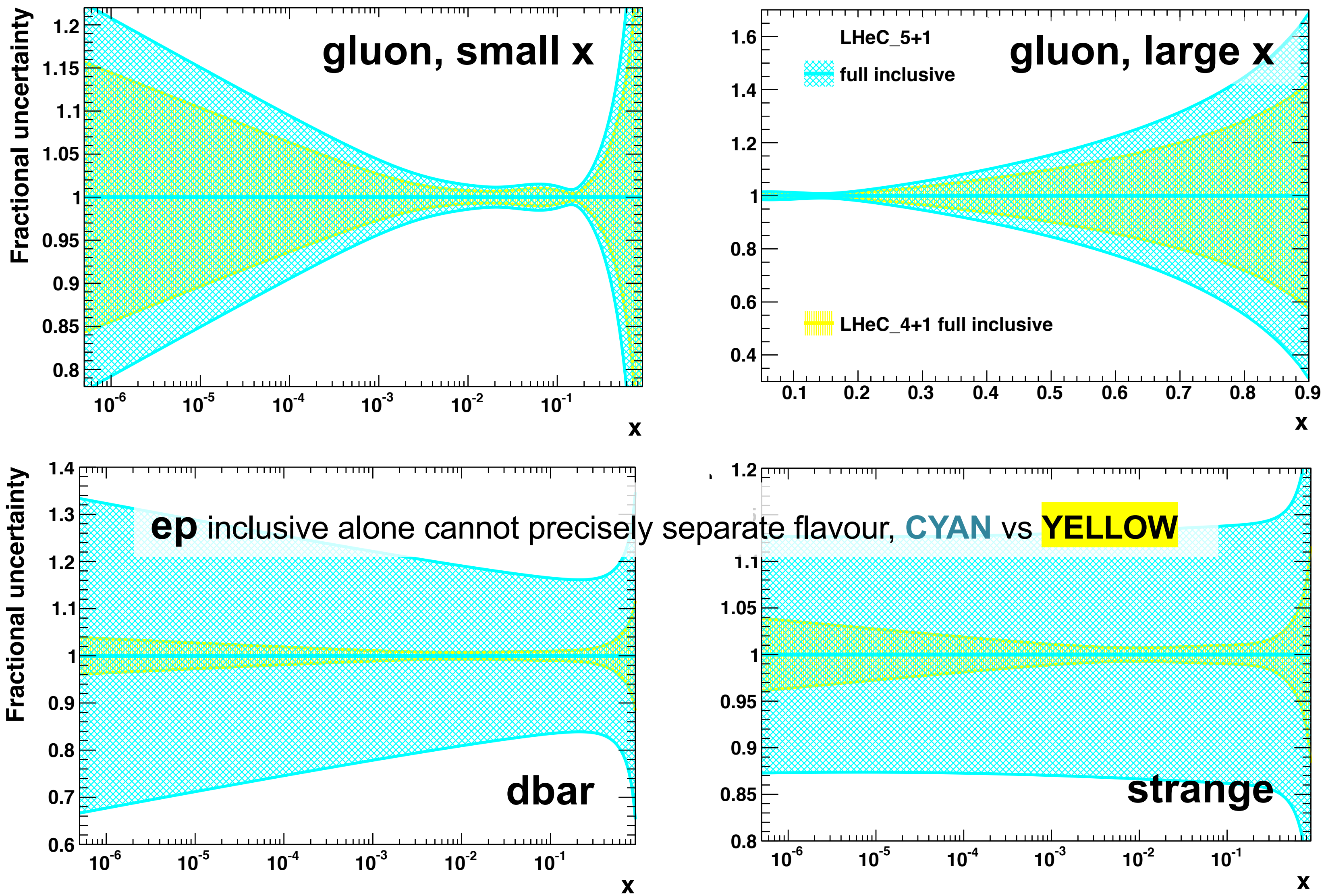
also top PDF

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

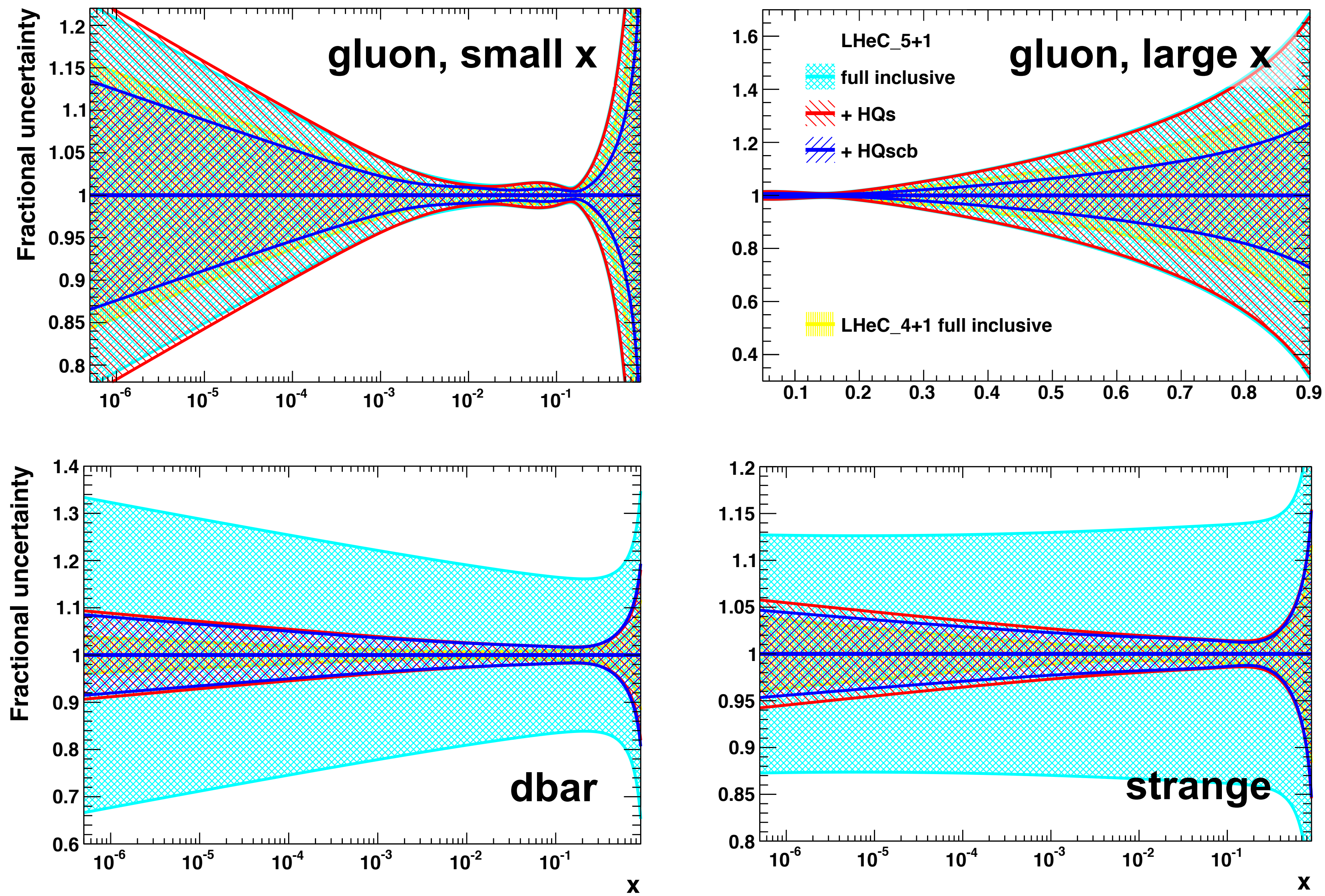
pdf flavour separation



ep inclusive alone cannot precisely separate flavour, **CYAN** vs **YELLOW**

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

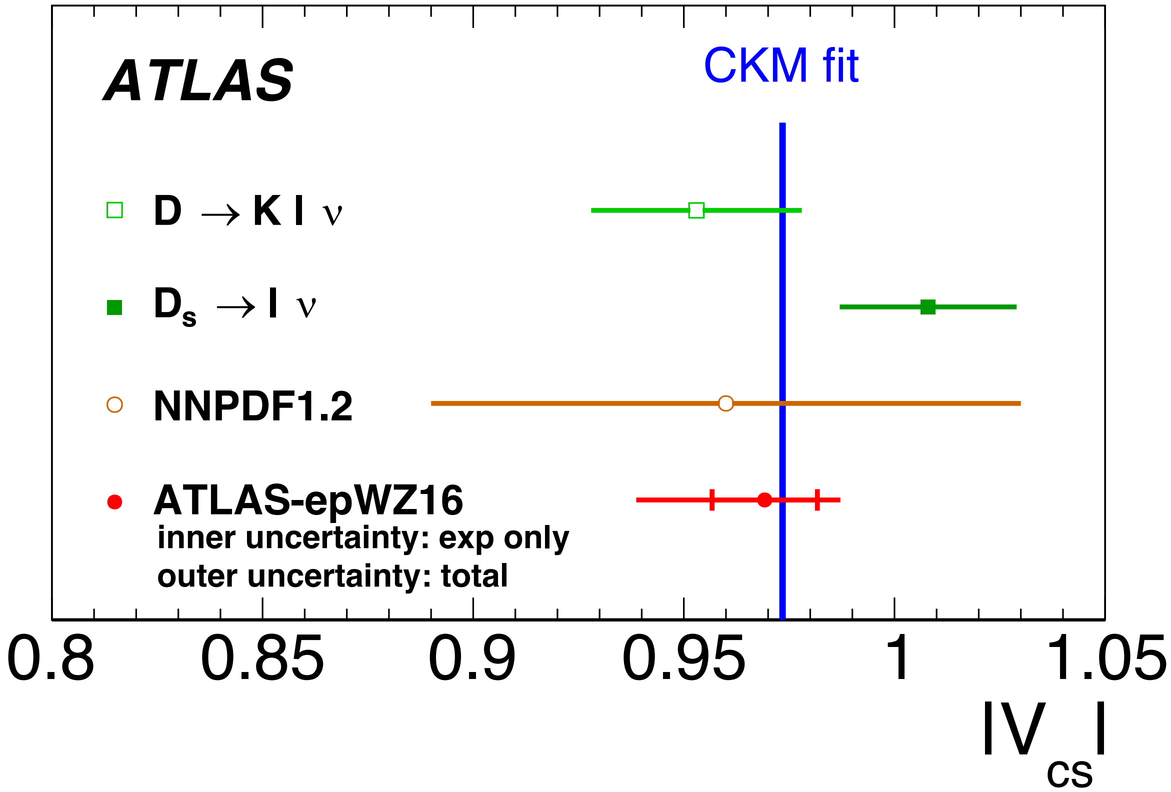
impact of HQ data on LHeC pdfs



s and b,c in addition to inclusive **ep** data gives flavour separation!

Vcs

ATLAS coll., arXiv:[1612.03016]



HERA+ATLAS ⟶ Vcs

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

other LHeC pdf studies

M. Bonvini, F. Giuli

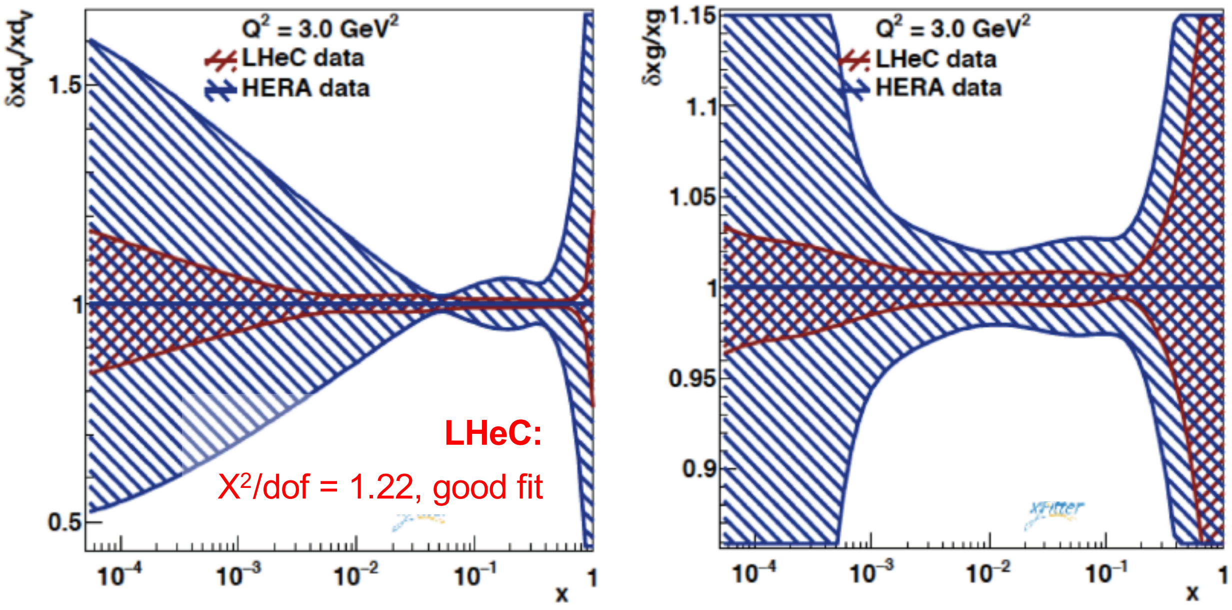
see also poster in this **WS** for more

ongoing study to understand **pdf uncertainty dependence** on:

- pseudo-data set choice — created new LHeC dataset starting from different input pdf
- parameterisation bias — QCD fits using new, flexible parameterisation, arXiv:1902.11125
- tolerance criteria

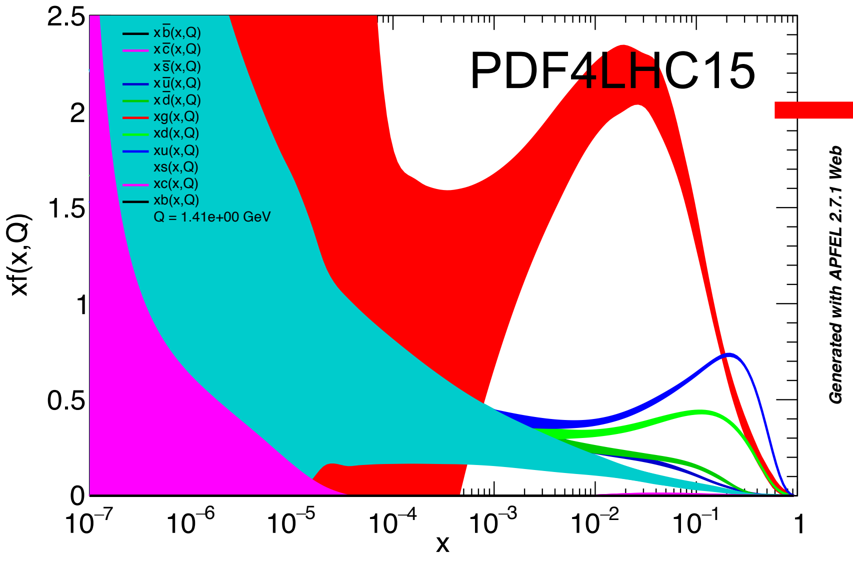
comparison of fits with **LHeC** vs **HERA** data →

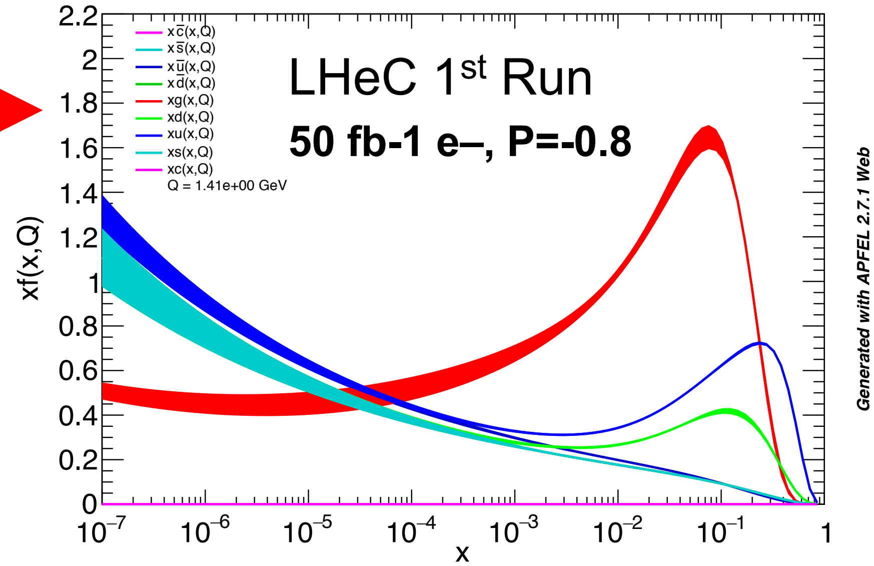
(remarkable uncertainty reduction, also when cf. modern global pdfs)

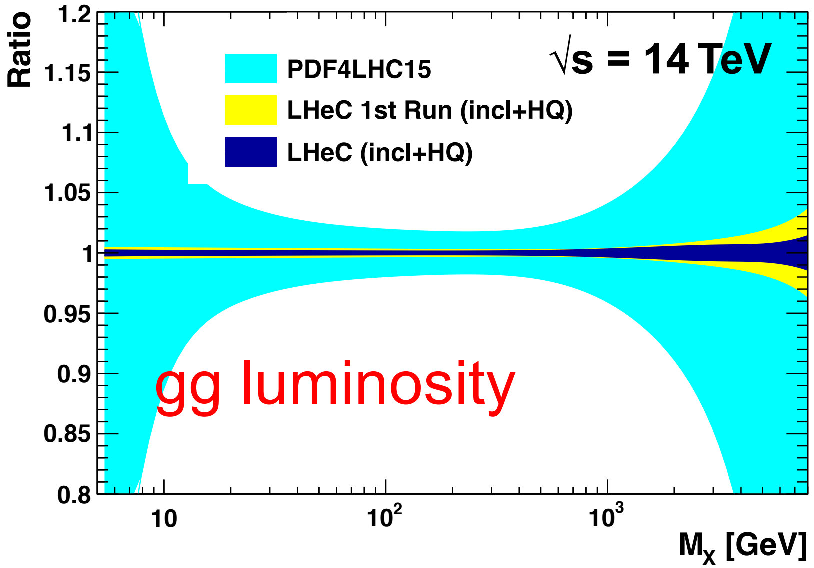


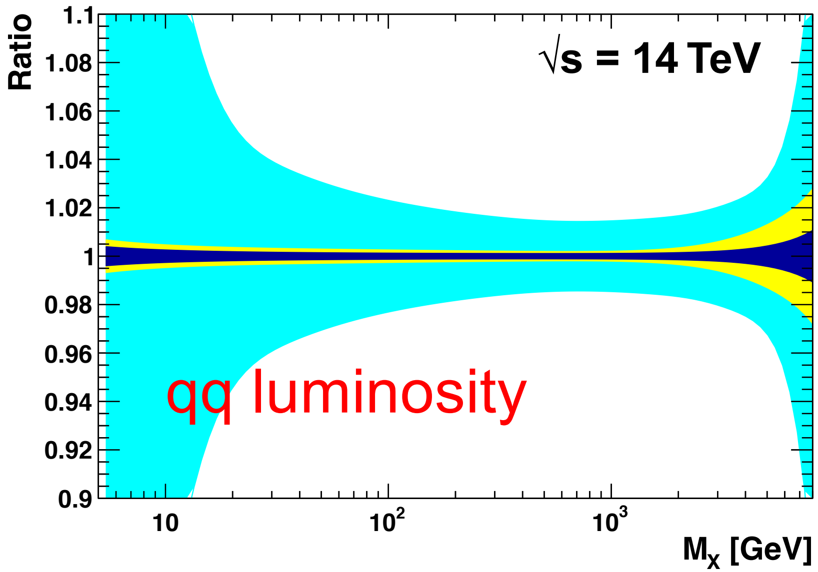
see also talk by **L. Harland-Lang**, for summary of Khalek et al., arXiv:1906.10127

summary of pdfs from ep

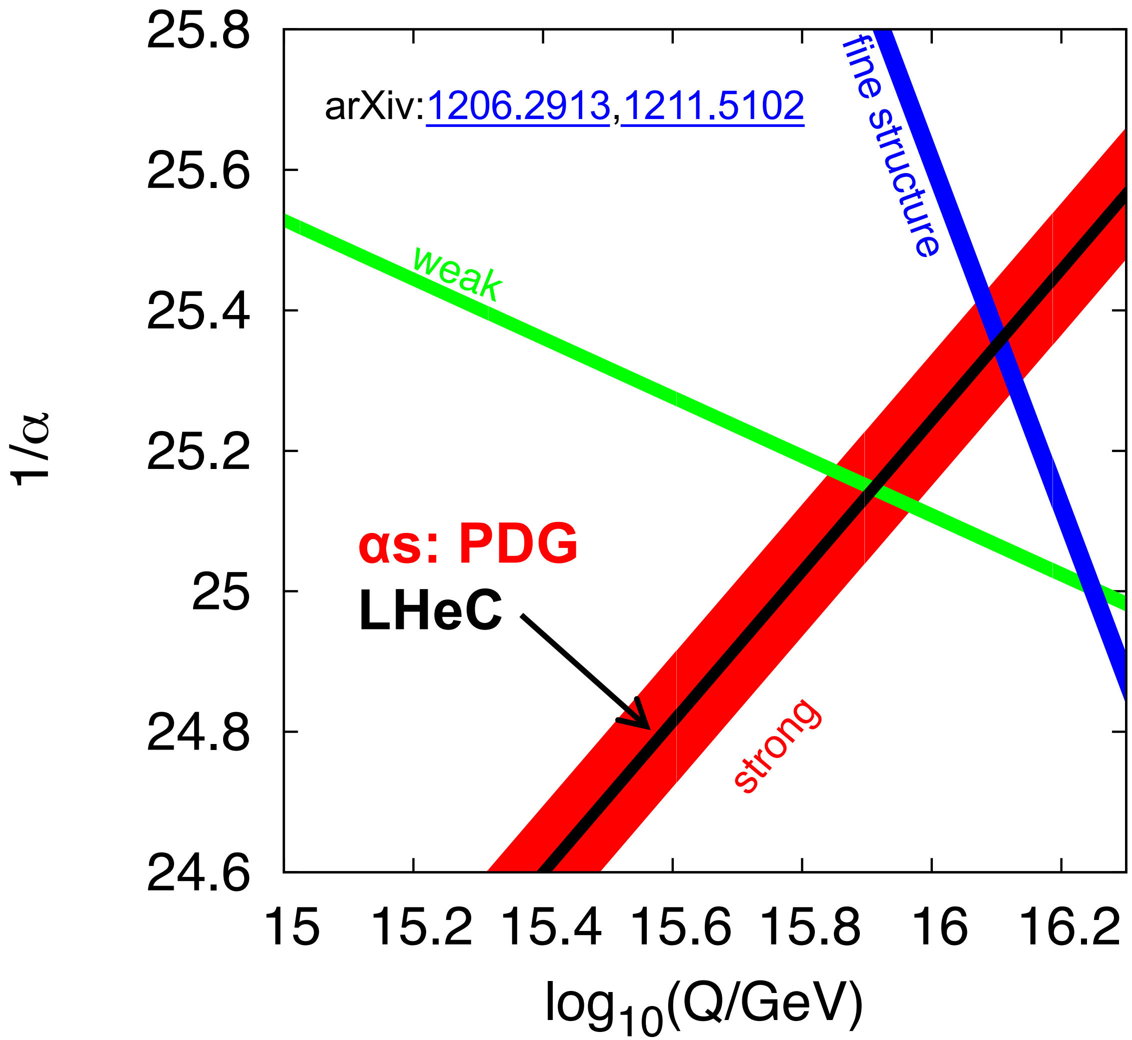








strong coupling, αs



αs is least known coupling constant

PDG 2018:

α_s = 0.1181 ± 0.0011

or α_s = 0.1174 ± 0.0016
w/o lattice QCD, 1.4% uncertainty

current measurements not all consistent!

accurate and precise **αs** needed:

to constrain GUT scenarios;
for cross section predictions, including Higgs; …

NEW updated studies performed and ongoing …

αs from LHeC jets

D. Britzger, J. Hessler et al.
see also **poster** in this WS

NEW **LHeC αs** studies using **NC DIS jet** (pseudo) data for the first time

NNLO calculations used for **αs** fit

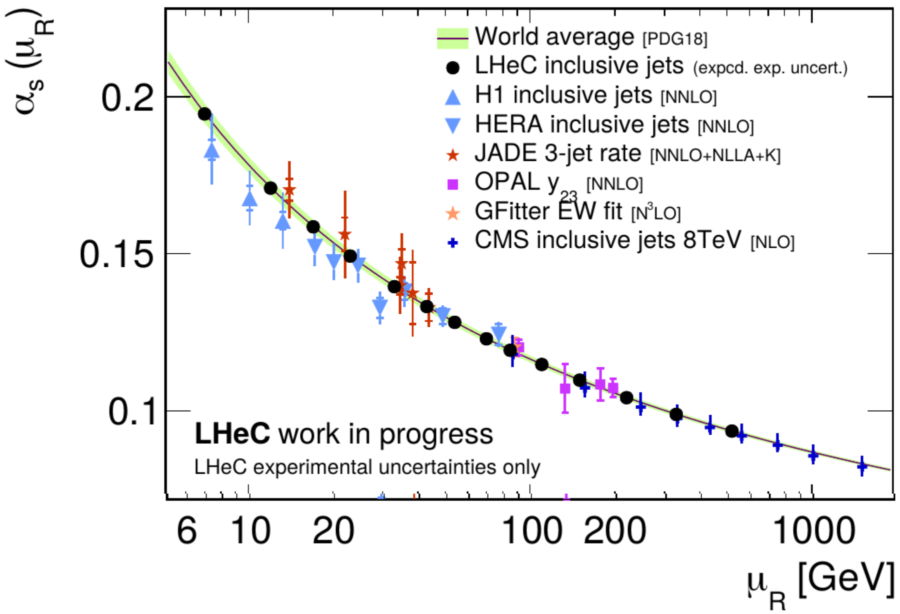
methodology as for arXiv:[1709.07251](), [1906.05303]()

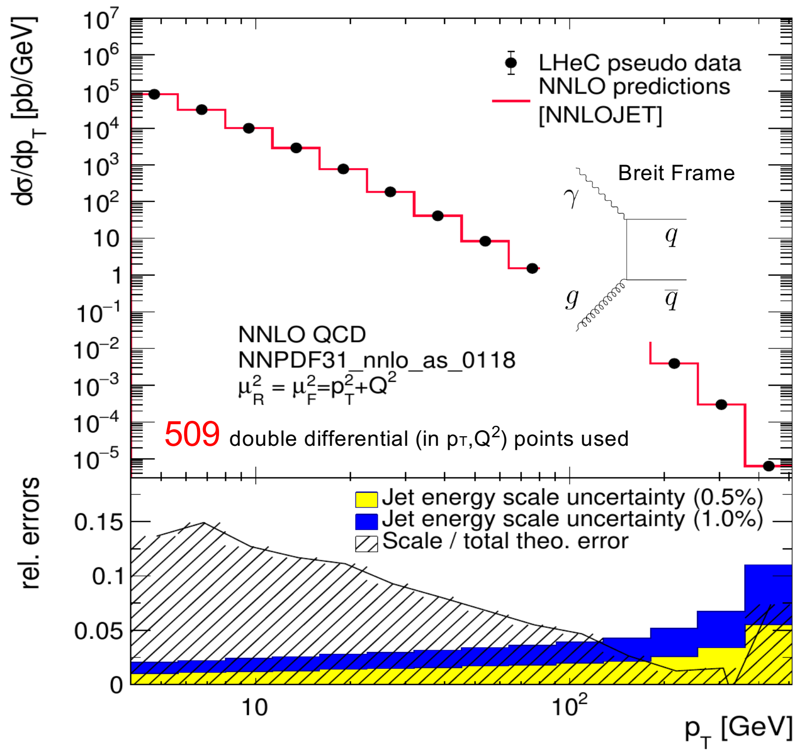
δαs(MZ)= ± 0.00018 (exp.⊕pdf)

extraordinary experimental precision

scale uncertainty dominates; need improved theory

αs running tested over two orders of magnitude in μR ↓

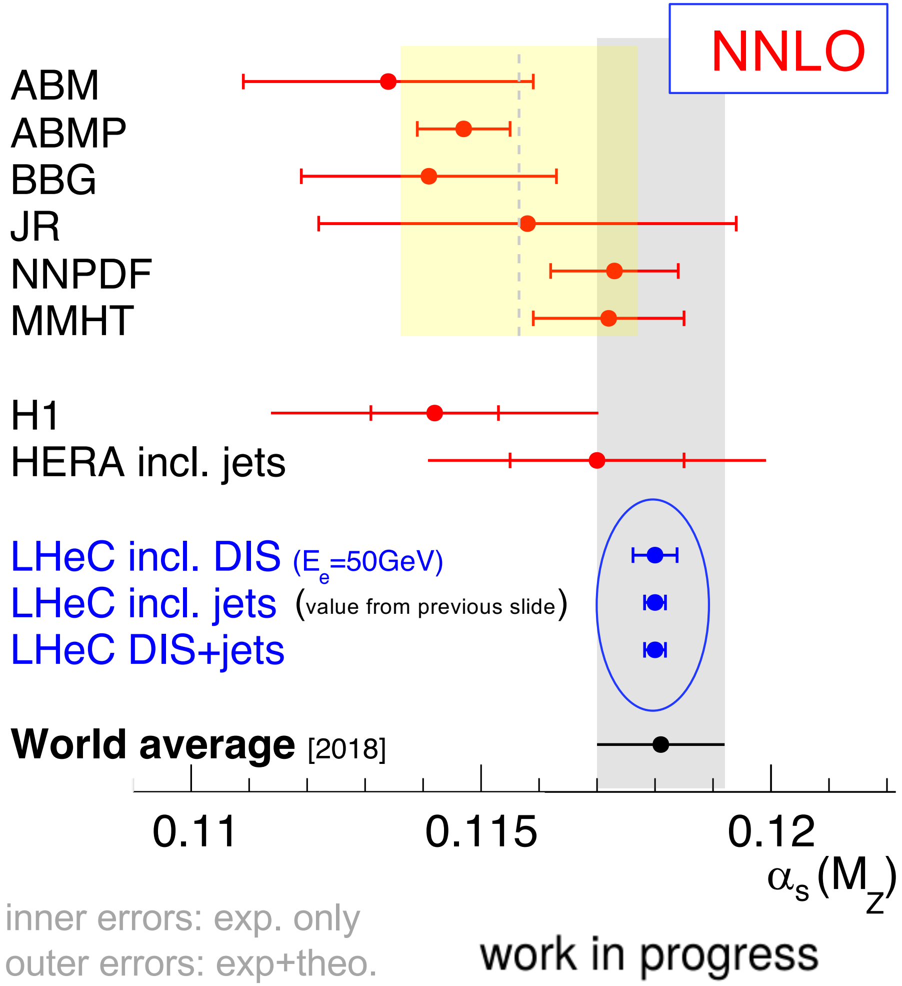


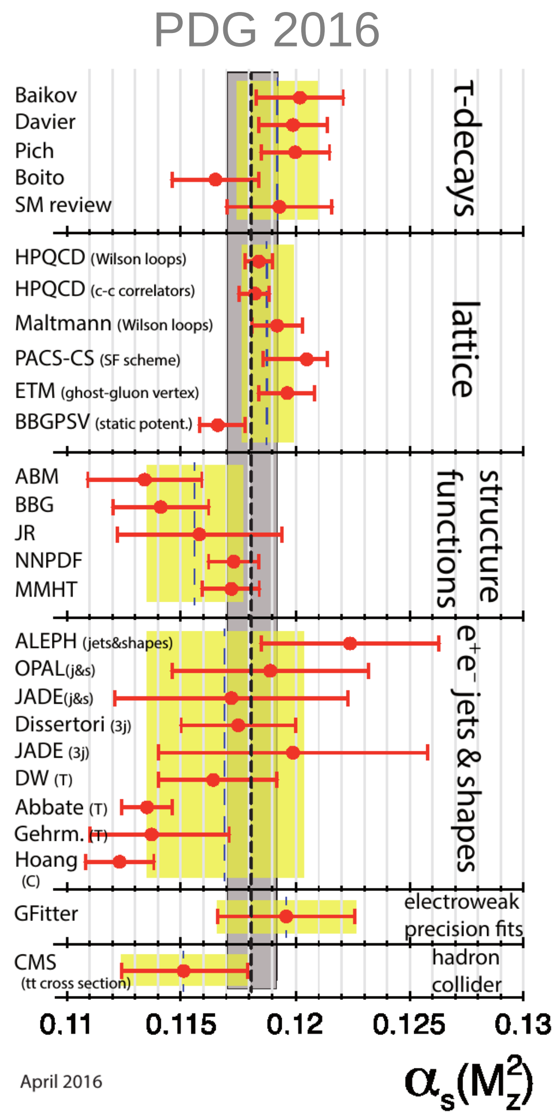


Exp. uncertainty	Shift	Size on σ [%]
Statistics with 1 ab^{-1}	min. 0.15 %	0.15 – 5
Electron energy	0.1 %	0.02 – 0.62
Polar angle	2 mrad	0.02 – 0.48
Calorimeter noise	±20 MeV	0.01 – 0.74
JES	0.5 %	0.2 – 4.4
Uncorrelated uncert.	0.6 %	0.6
Normalisation uncert.	1.0 %	1.0

D. Britzger, J. Hessler et al.
see also **poster** in this WS

pdf+αs fits





pdf+αs fit studies in progress (inclusive only, incl.+jets)

δαs sensitive to size of uncorrelated systematic uncertainty – studies underway…

summary

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

much activity since CDR(s), on both LHeC and FCC studies, and work still ongoing… **(writing for LHeC CDR update in progress!)**

NEW pdf studies presented for the LHeC

all critical pdf information can be obtained early from LHeC 1st Run (~50 fb^{-1} ≡×50 HERA; 3 years), **in parallel** with **HL-LHC** operation

αs : order of magnitude improved experimental precision over "today"

ep colliders essential for full exploitation of pp machines

external precision pdf input; complete q,g unfolding; high luminosity, x ⟶ 1, s, c, b, (t); N^3LO theory; small x; **αs** to extraordinary experimental precision; …

extras

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

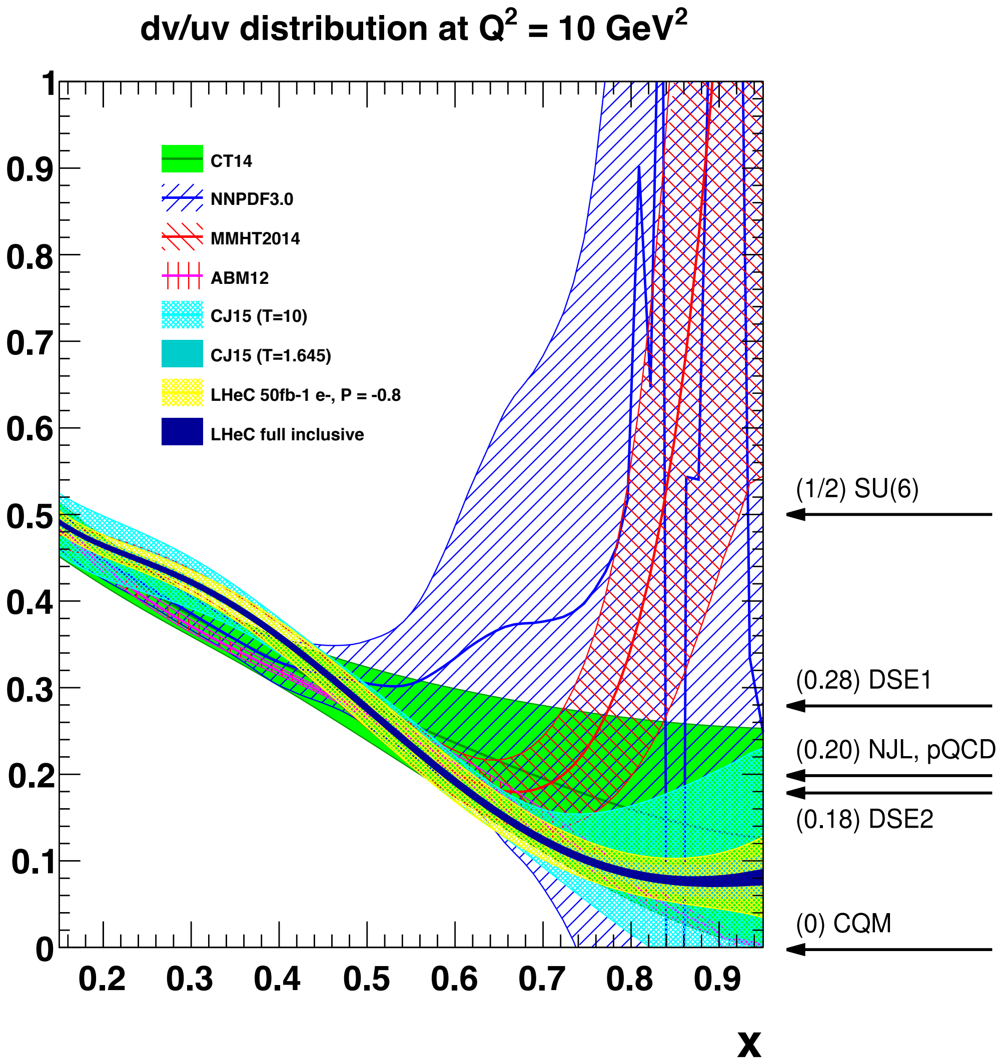
no negative gluon term (simply for the aesthetics of ratio plots – it has been checked that this does not impact size of projected uncertainties)

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

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**

d/u at large x



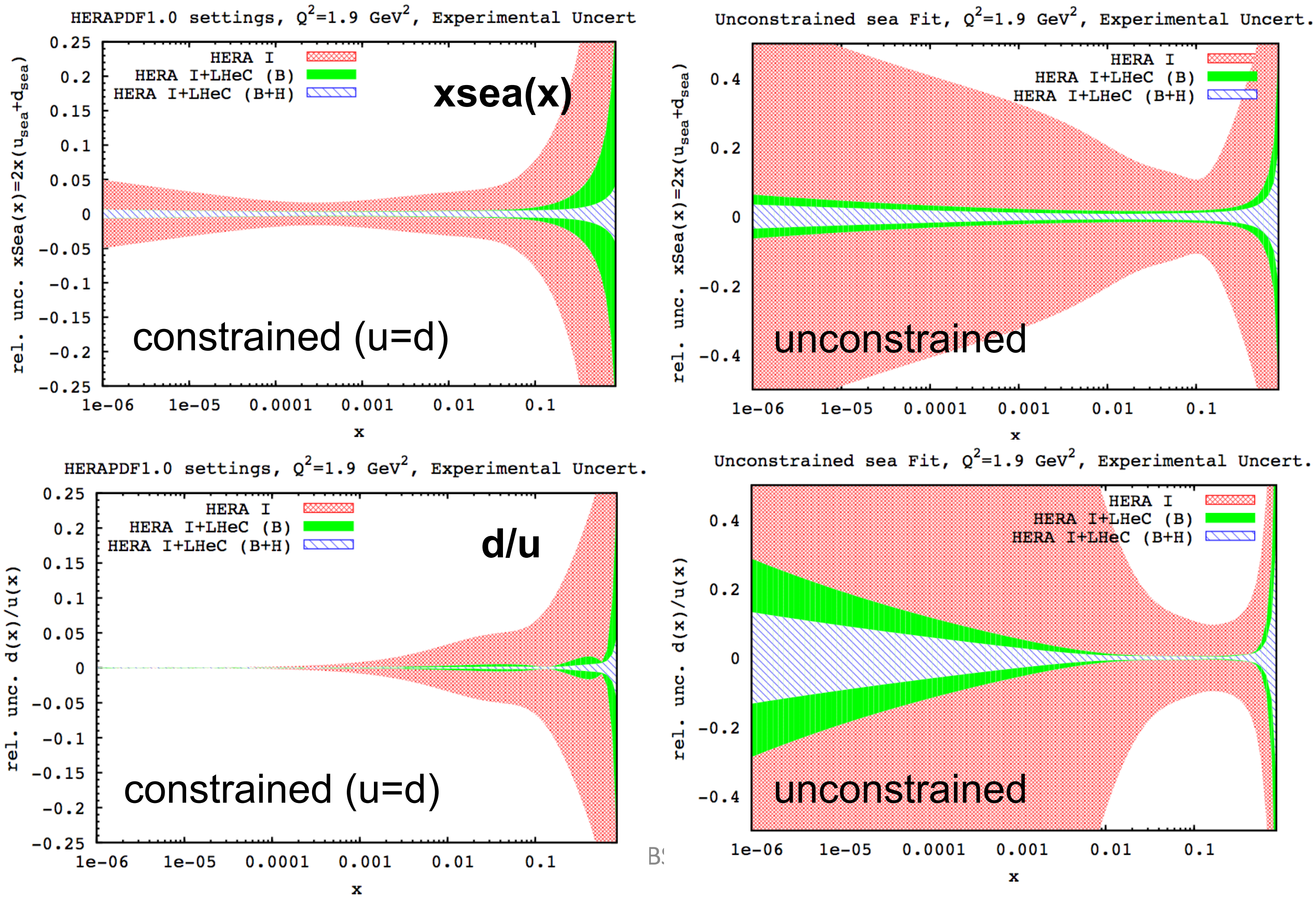
d/u essentially unknown at large x

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

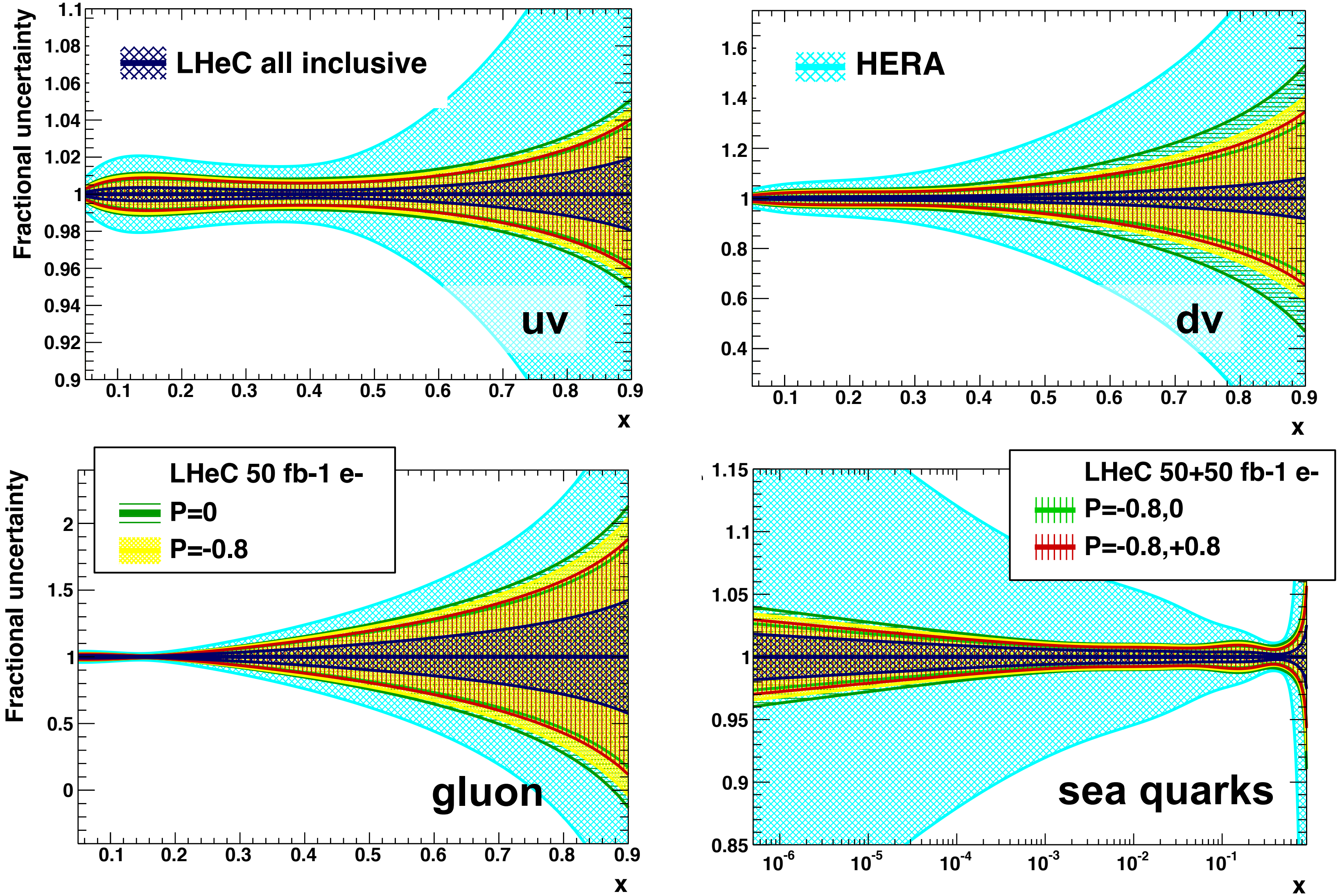
resolve long-standing mystery of **d/u ratio** at **large x**

(old) LHeC pdfs with released assumptions

- LHeC does not need to rely on 'usual' constraint that ubar=dbar at small x, which **may not be valid** (all new QCD fits shown in this talk use an 'unconstrained' version)



impact of polarisation on LHeC pdfs

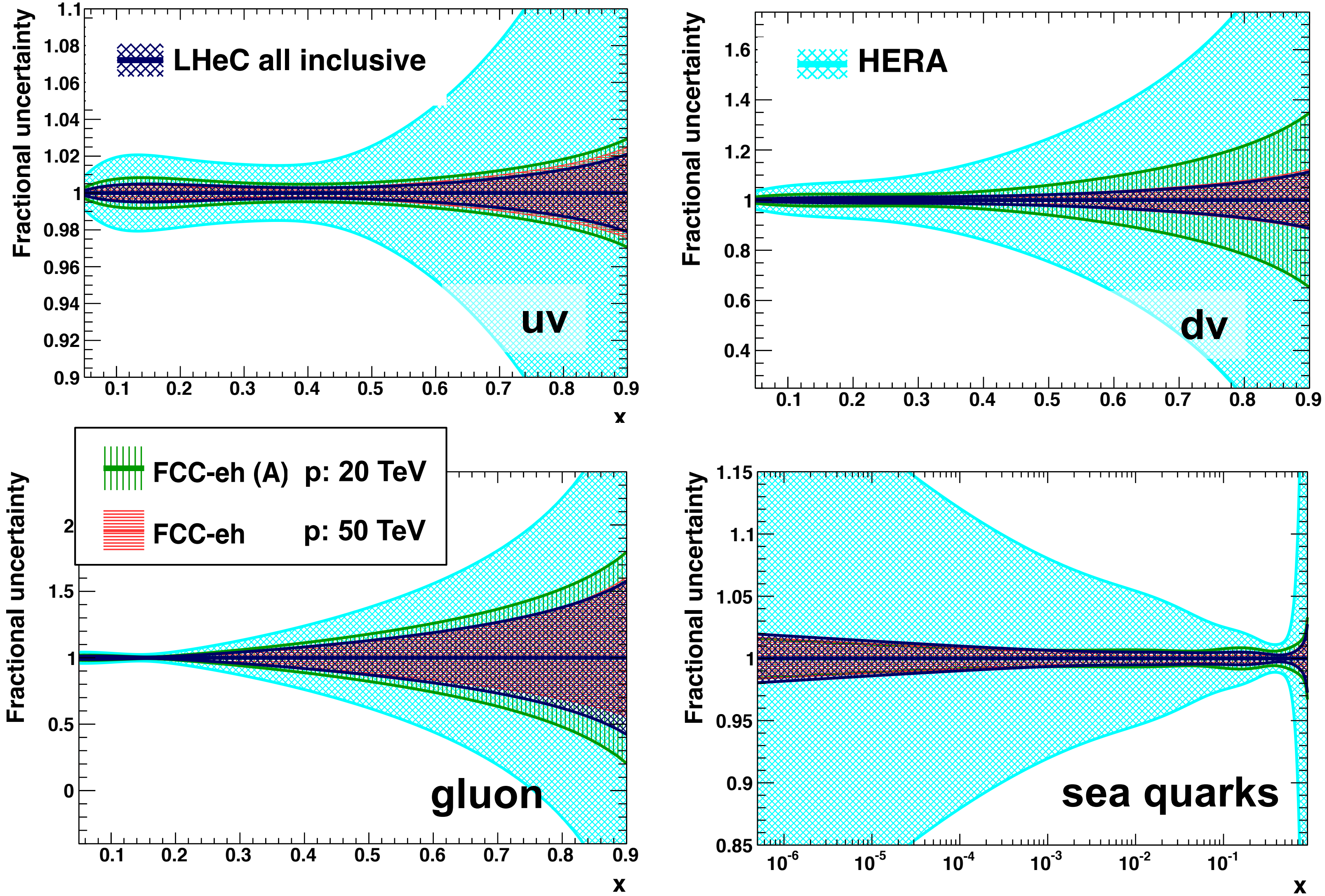


impact of polarisation on pdfs generally small (but pol. important for ew)

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

collider configurations

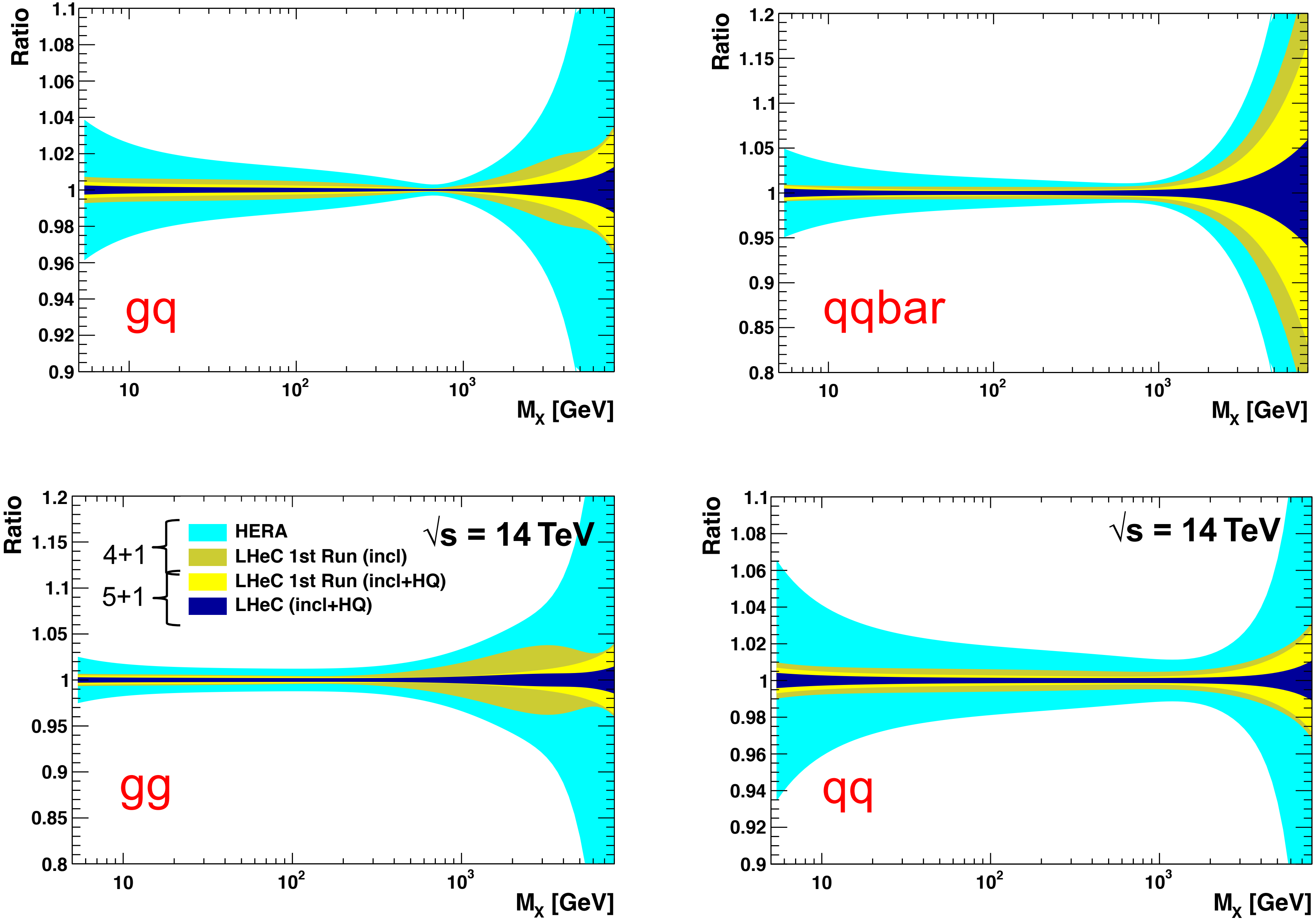
work in progress



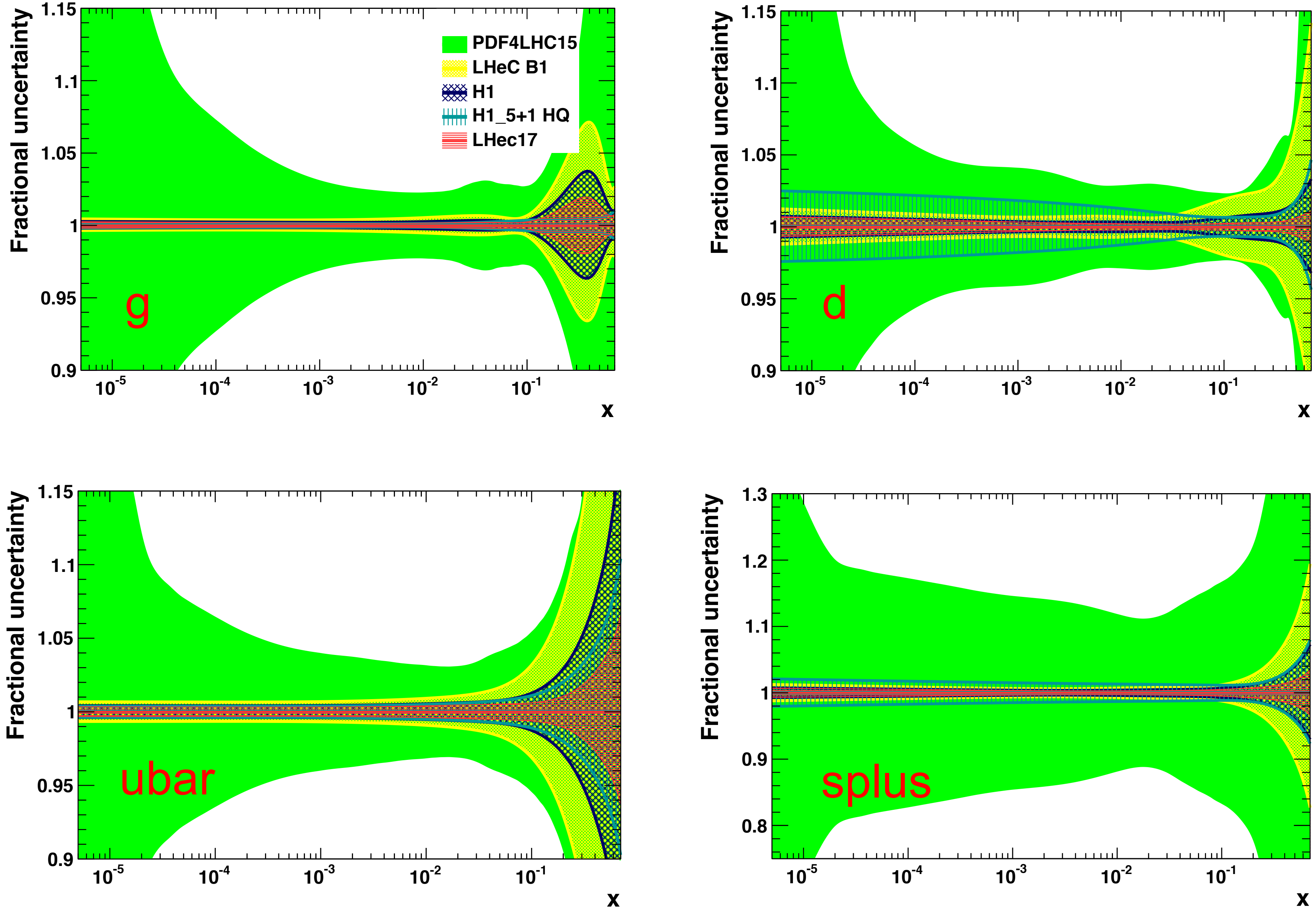
FCC-eh (A): new preliminary simulation with 2 ab^{-1} polarised e– (**NB, NO e+ yet; impact especially in dv**)

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

pdf luminosities



pdfs at Q=10 GeV

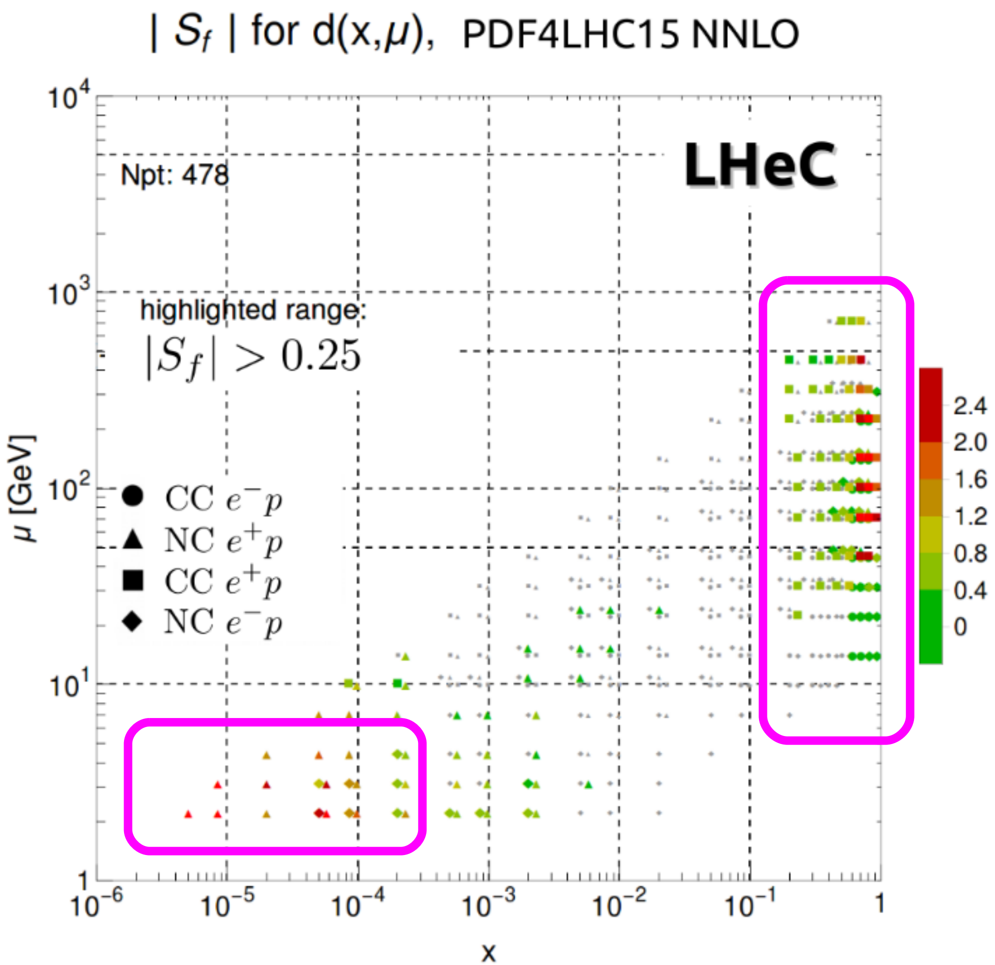


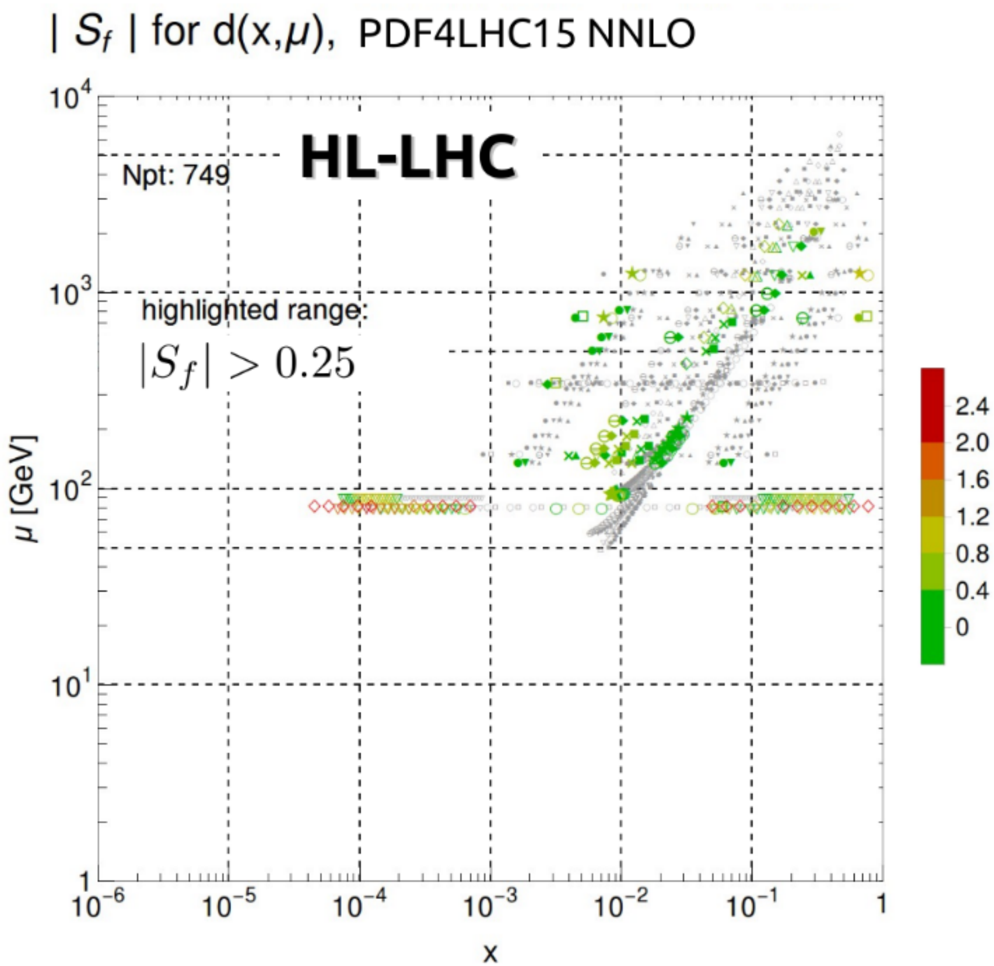
PDFSense: Kinematic Reach of LHeC *(single flavor sample)*

Sensitivity S^F:

Correlation times the scaled residual:

$$S_F \sim C_f \frac{\delta r}{\langle r \rangle_{exp}} \qquad \delta r \sim \frac{T - D}{\sigma}$$





Different Kinematic Regions
LHeC Reach is **Crucial**!!!

Tim Hobbs

PDFSense: B.-T. Wang, et al., Phys.Rev. D98 (2018) no.9, 094030

α_s with inclusive jets

D. Britzger, J. Hessler, et al.
see poster

$\alpha_s(M_Z)$ with inclusive jets

- double-differential pseudo-data with 509 data points
- NNLO predictions for α_s-fit

$$\delta\alpha_s(M_Z) = \pm 0.00013_{(exp)} \pm 0.00010_{(PDF)} = \pm 0.00018$$

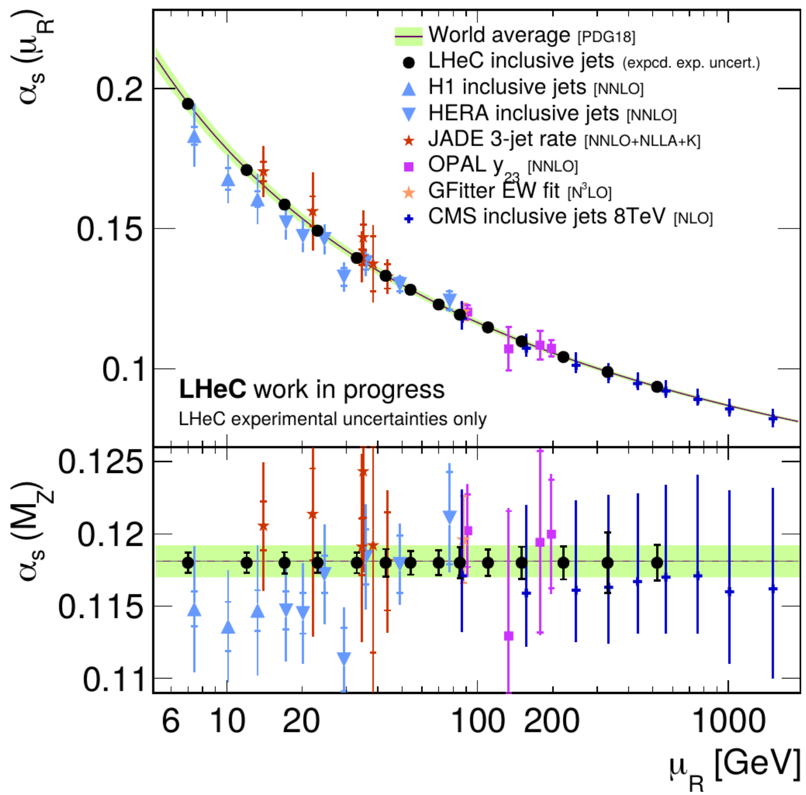
- Improvement by factor 6 w.r.t. world average value
- (LHeC)-PDF uncertainties small

Test running of α_s

- Fit to ranges of the pseudo-data
- Experimental uncertainty smaller than 1% over huge kinematic range

Scale/theory uncertainties

- NNLO scale uncertainties are dominant (not shown)
- Improved predictions, or other observables will be studied



D. Britzger, J. Hessler et al.

α_s from inclusive DIS

LHeC with E_e=50GeV

- Simultaneous determination of α_s and PDFs
- Inclusive NC and CC DIS pseudo-data

Three scenarios

- 1st year data taking: e^- with L~50fb^{-1}
- 1st year data: e- (L~50fb^{-1}) and e+ with 1fb^{-1}
- All data: 1ab-1 e-, 10fb e+ + Low-E data

Uncertainty of α_s

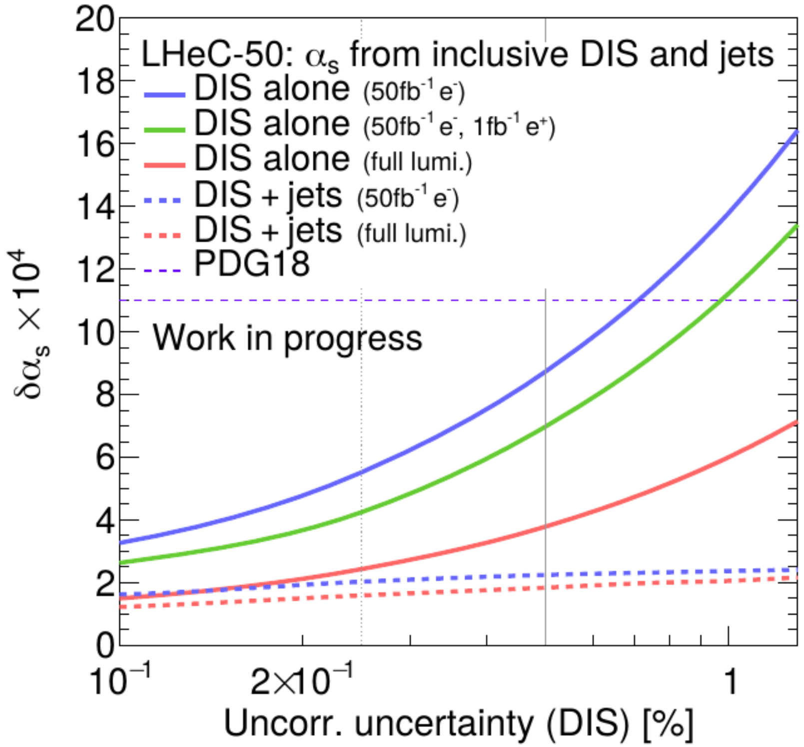
- With 1 year data: $\delta\alpha_s(M_Z)$ = 4 – 8 ‰
- With full data: $\delta\alpha_s(M_Z)$ = 2 – 3 ‰

→ Sizeable dependence on uncorrelated uncertainty complicates the estimate

Using inclusive jets in addition

- Inclusive jets will have superior sensitivity to α_s

→ but likely larger theo. unertainties (to be studied)



D. Britzger, J. Hessler et al.

α_s with inclusive jets

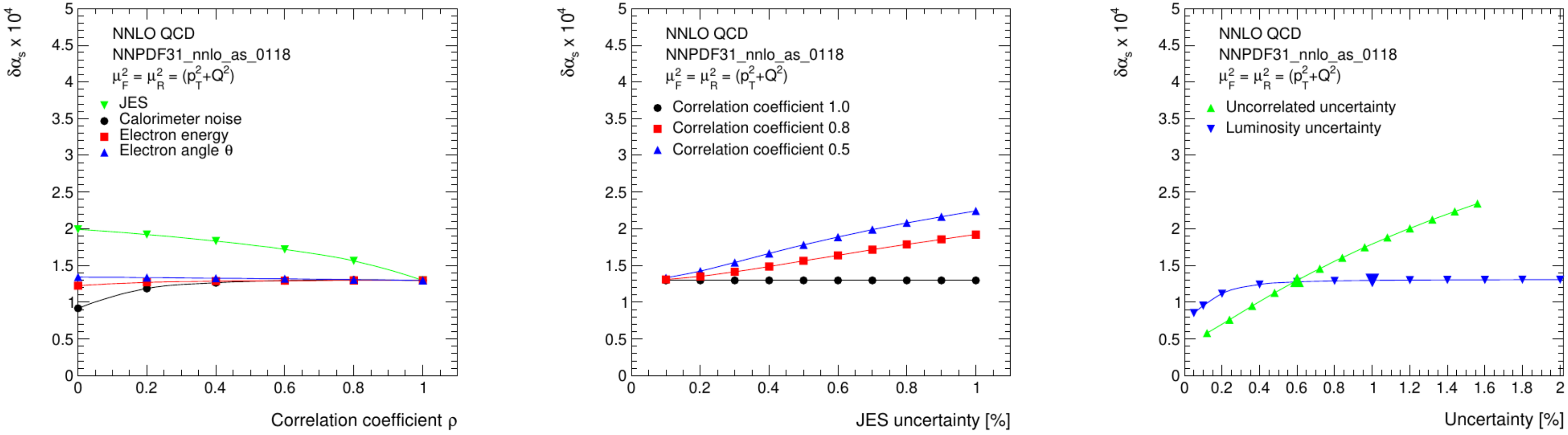
$\alpha_s(M_Z)$ with inclusive jets

- double-differential pseudo-data with 509 data points
- NNLO predictions for α_s-fit

$$\delta\alpha_s(M_Z) = \pm 0.00013(\text{exp}) \pm 0.00010(\text{PDF}) \quad = \quad \pm 0.00018$$

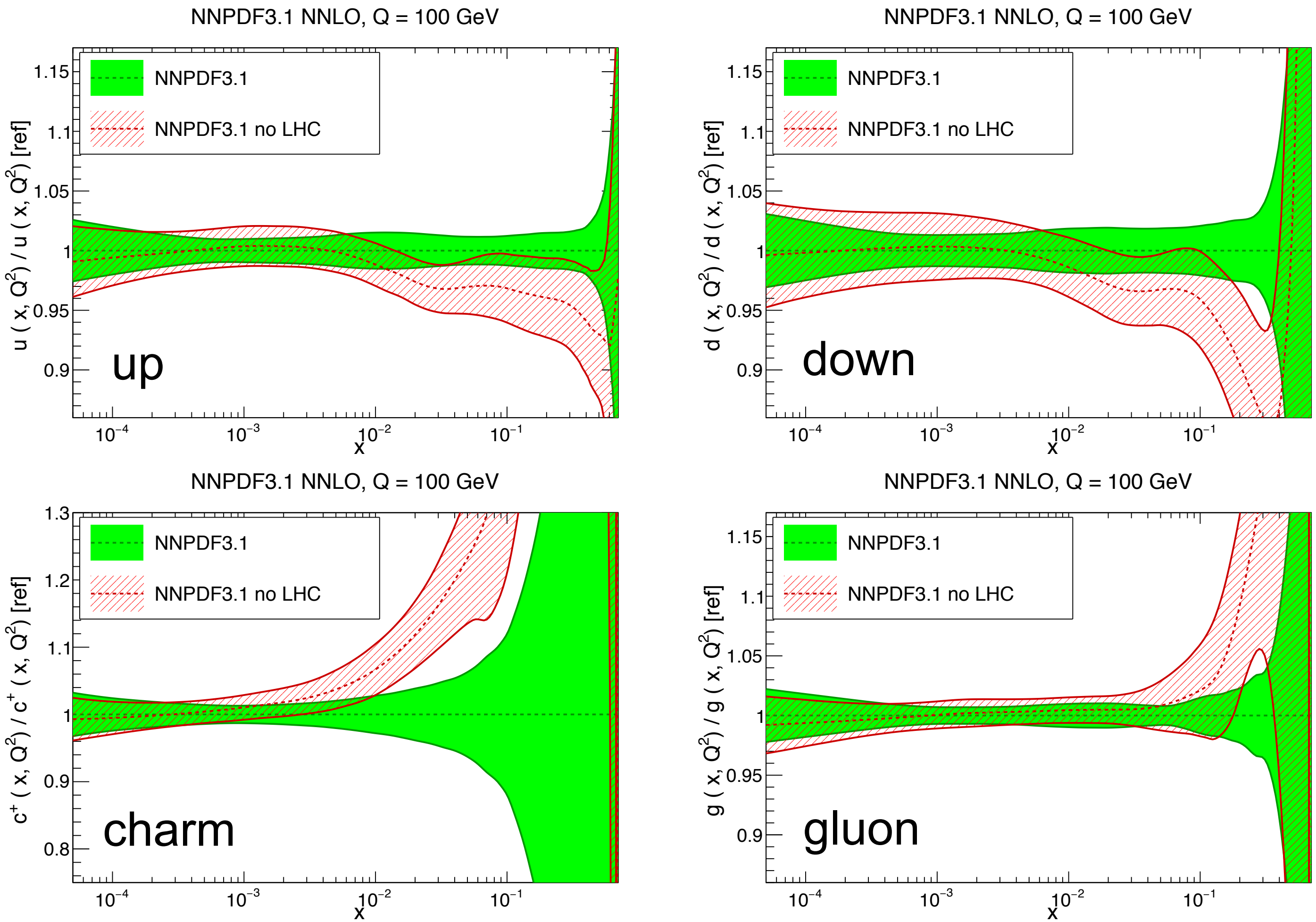
Study of uncertainties

- Even with more conservative uncertainty estimates $\delta\alpha_s < 2‰$



D. Britzger, J. Hessler et al.

impact of LHC on today’s pdfs



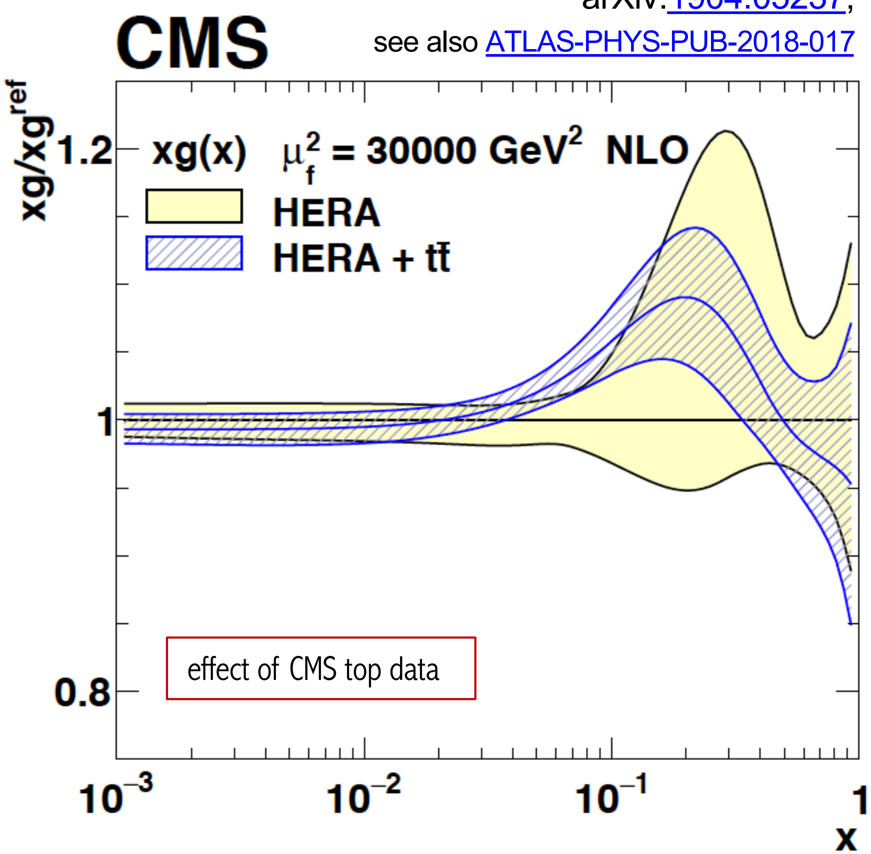
arXiv:[1706.00428](1706.00428)

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

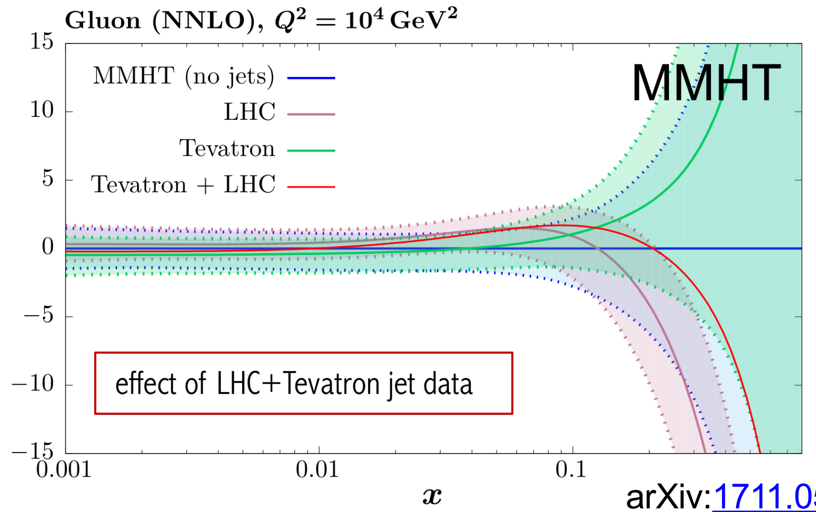
updates to main global pdf fits, including more LHC data, expected soon

LHC: large x gluon

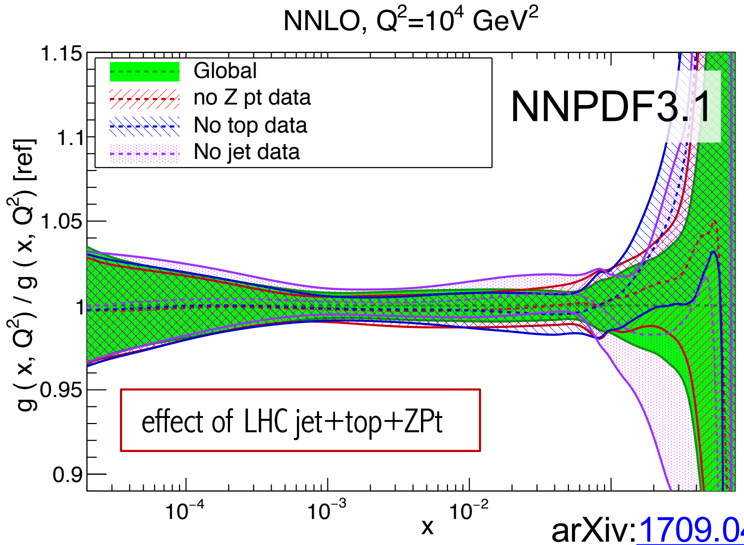
arXiv:1904.05237;
see also ATLAS-PHYS-PUB-2018-017



direct γ : arXiv:1802.03021



arXiv:1711.05757



arXiv:1709.04922

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

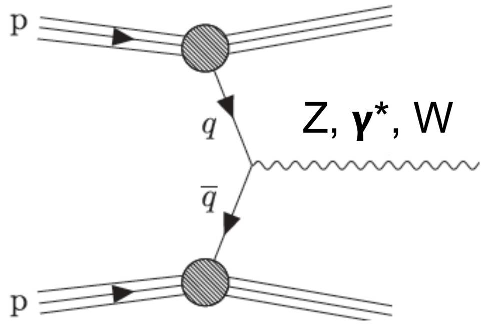
numerous studies from ATLAS, CMS, xFitter and global fitters

NNLO QCD calculations now available in all cases

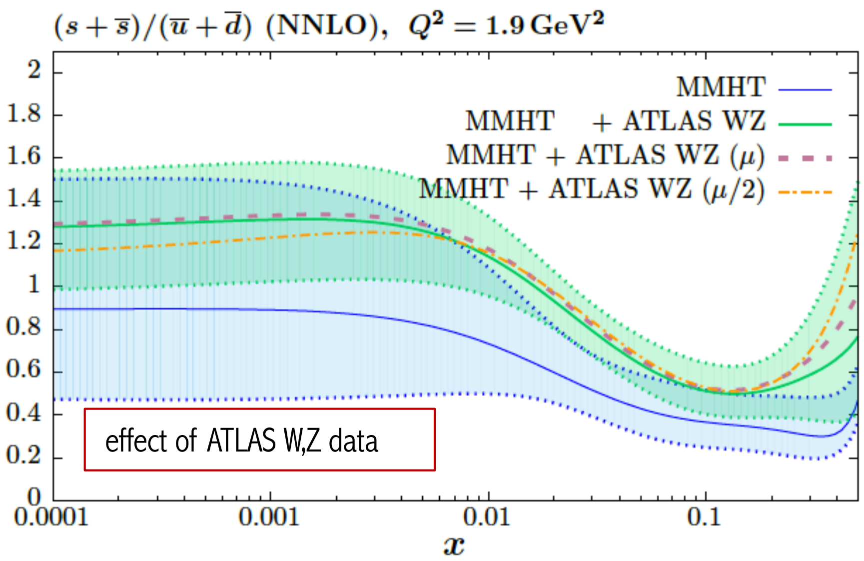
(**LHCb forward charm and beauty** COULD also help at small and large x?)

LHC: large x quarks and flavour separation

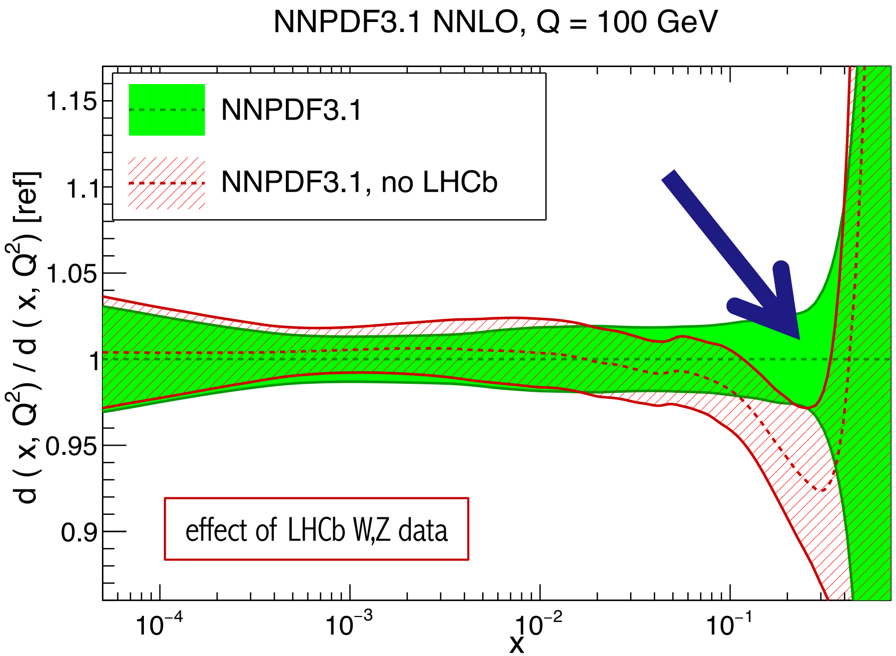
electroweak gauge boson measurements give information on **quark** and **anti-quark** flavour separation



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]

LHC datasets used in NNPDF3.1

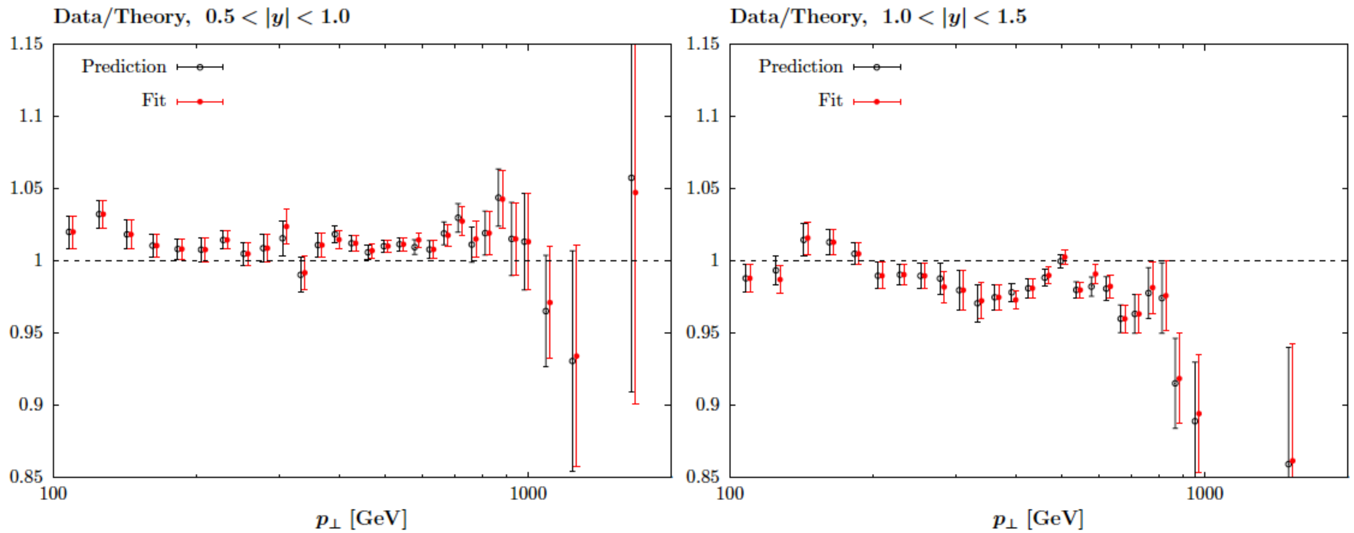
Exp.	Obs.	Ref.	$N_{\mathbf{dat}}$	Kin$_1$	Kin$_2$ (GeV)	Theory
ATLAS	W, Z 2010	[49]	30 (30/30)	$0 \leq \|\eta_l\| \leq 3.2$	$Q = M_W, M_Z$	MCFM+FEWZ
	W, Z 2011 (*)	[72]	34 (34/34)	$0 \leq \|\eta_l\| \leq 2.3$	$Q = M_W, M_Z$	MCFM+FEWZ
	high-mass DY 2011	[50]	11 (5/5)	$0 \leq \|\eta_l\| \leq 2.1$	$116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

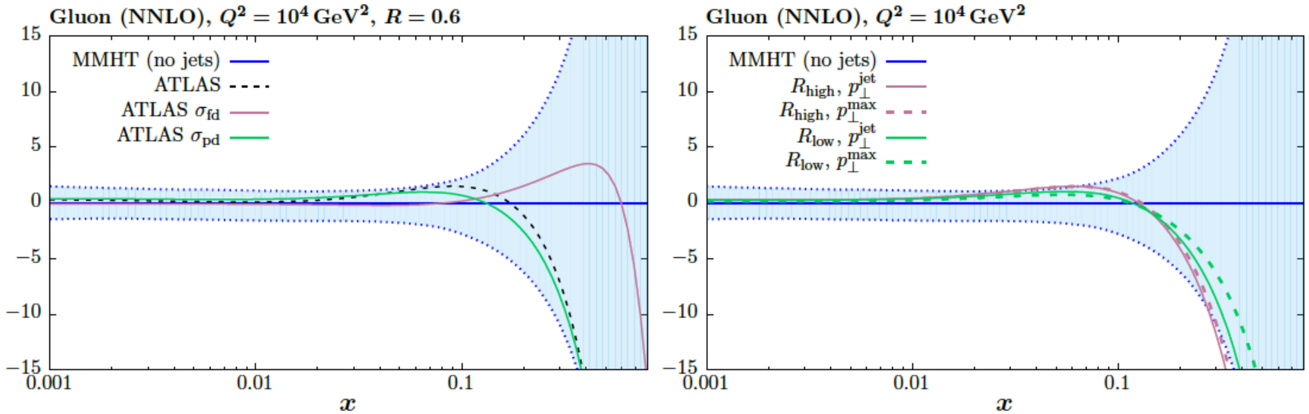
We consider the effect of decorrelating two uncertainty sources, i.e. making them independent between the 6 rapidity bins. More extensive decorrelation study in ATLAS – JHEP 09 020 (2017).

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

Similar results using new NNLO results.

	$R_{\rm low},\ p_\perp^{\rm jet}$	$R_{\rm low},\ p_\perp^{\rm max}$	$R_{\rm high},\ p_\perp^{\rm jet}$	$R_{\rm high},\ p_\perp^{\rm max}$
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)



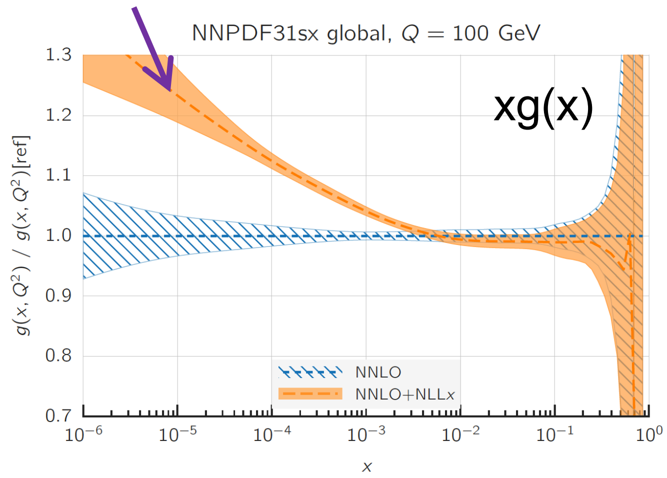
Results insensitive to decorrelation. Find softer gluon, reduced uncertainty. Also relatively little sensitivity to scales and jet radius.

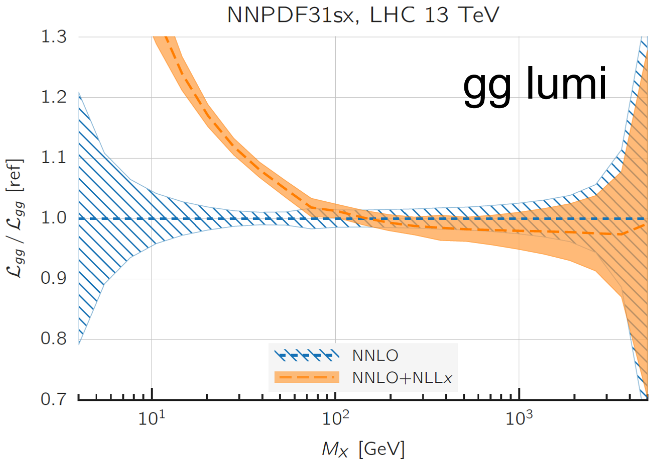
slide from R Thorne, DIS19

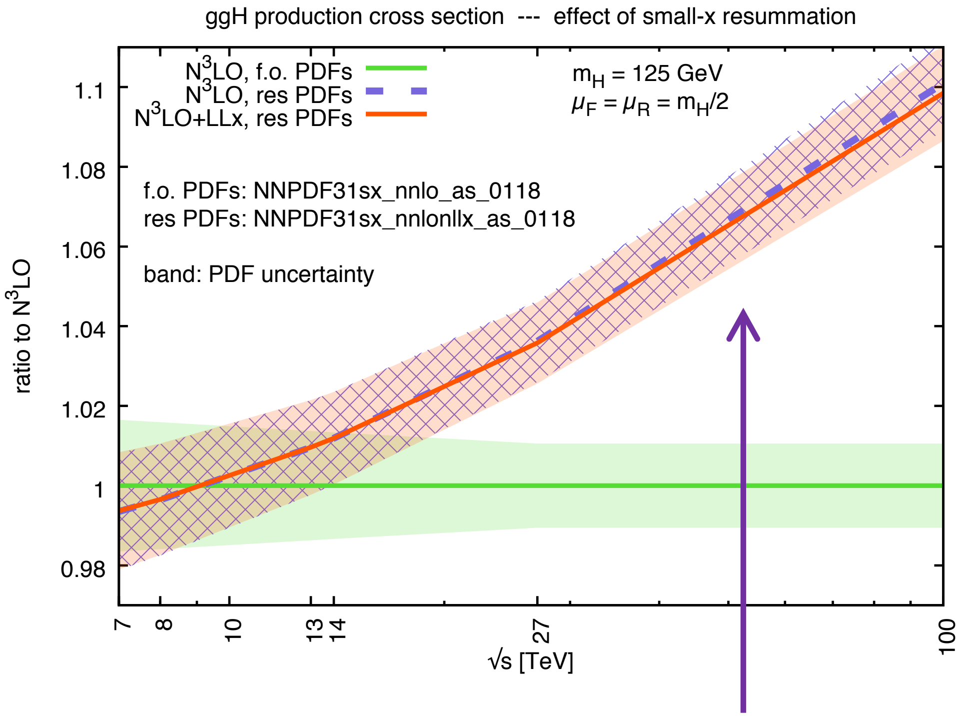
arXiv:1711.05757

gluon at small x matters

effect of small x resummation







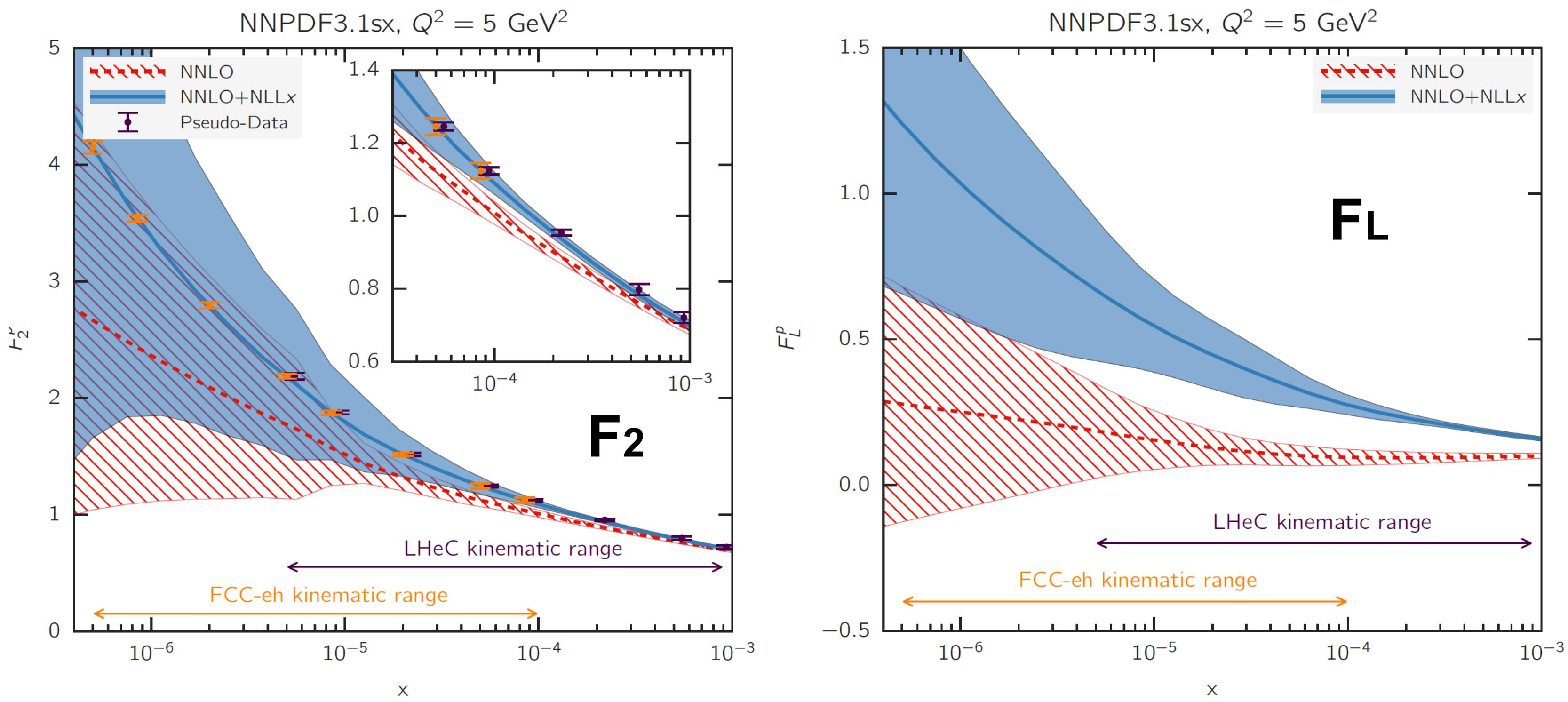
effect of small x resummation on ggH cross section

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



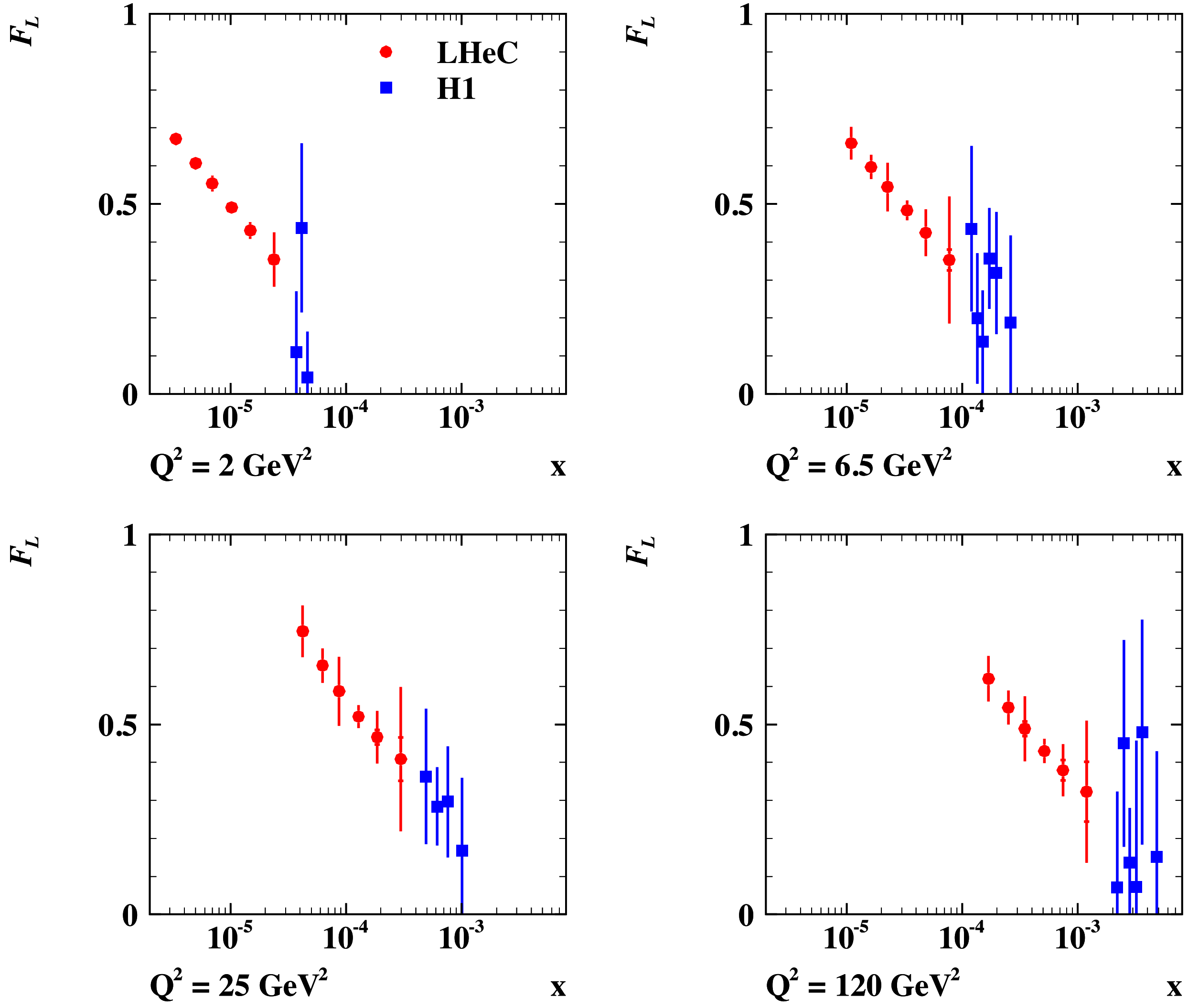
F2 and FL predictions for simulated kinematics of **LHeC** and **FCC-eh**

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