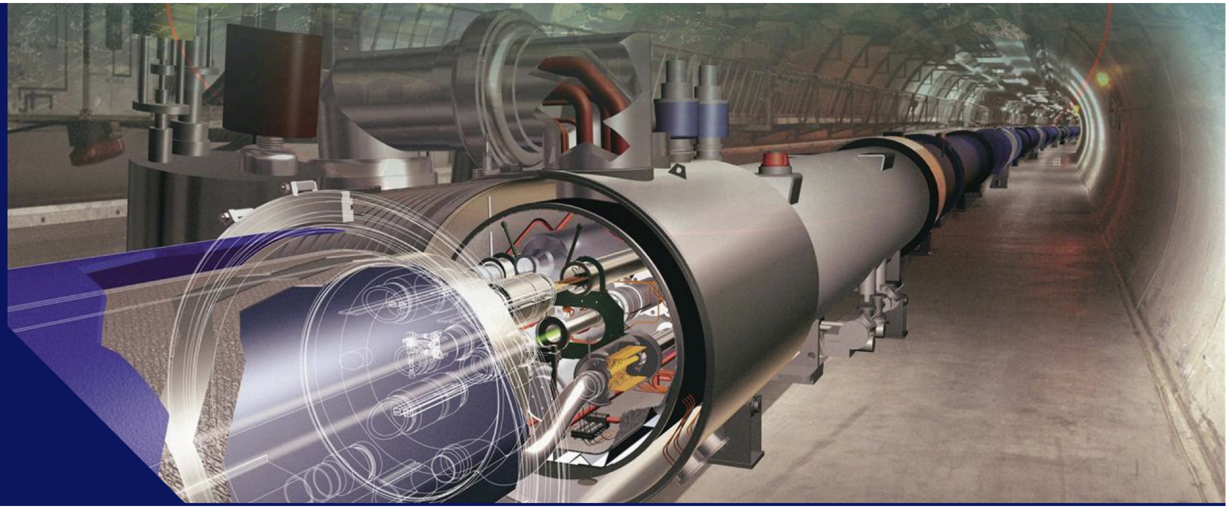
PDF4LHC meeting

2nd October 2020



Precision QCD at the LHeC and FCC-eh

Claire Gwenlan, Oxford

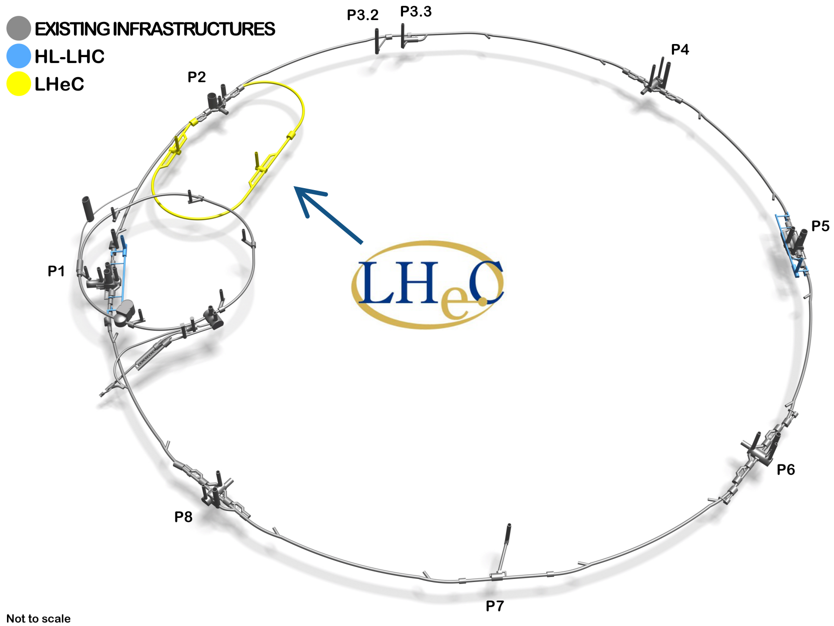
on behalf of the LHeC and FCC-eh study groups

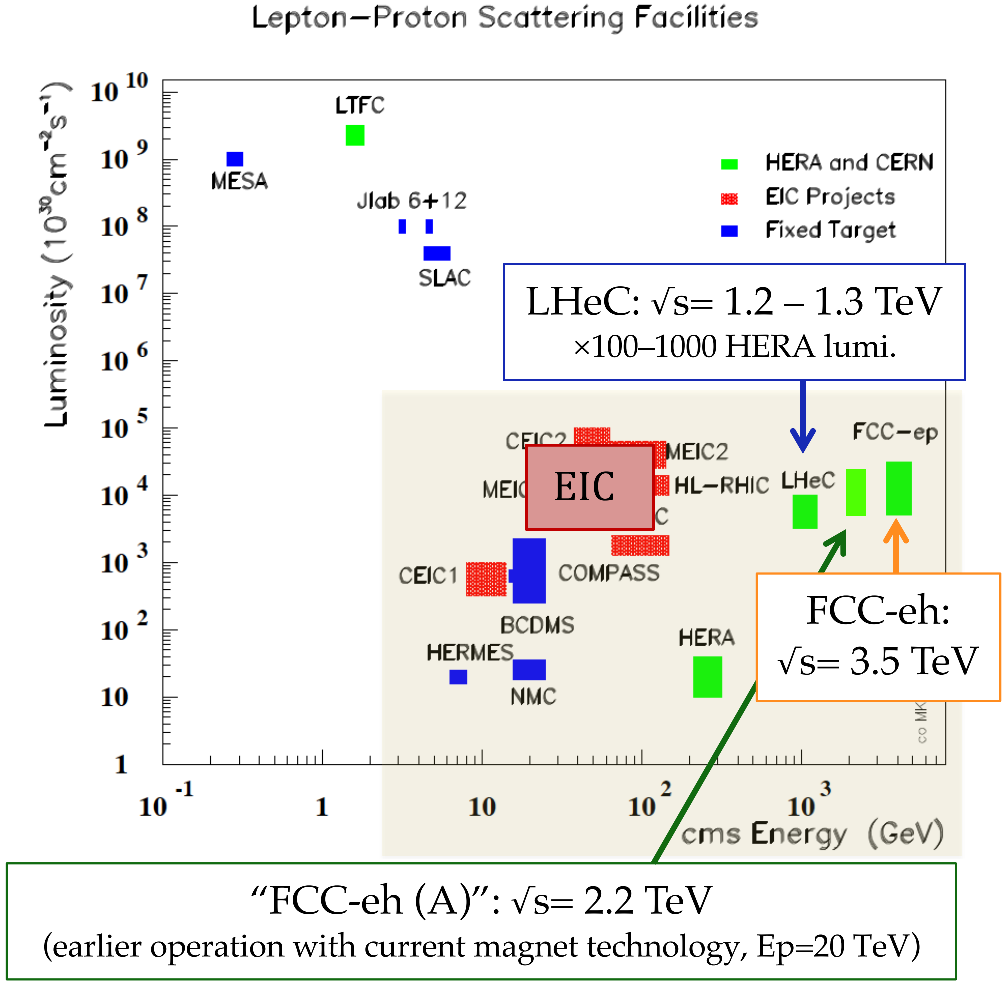
UNIVERSITY OF OXFORD

focus on results from new LHeC white paper, [arXiv:2007.14491](https://arxiv.org/abs/2007.14491)

LHeC PERLE FCC hh ee he CERN

LHeC and FCC-eh





energy recovery LINAC (ERL)

attached to HL-LHC (or FCC)

e beam: ⟶ **50 or 60 GeV**

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

ESPPU: ERL is a “high-priority future initiative” for CERN

LHeC white paper

CERN-ACC-Note-2020-0002
Geneva, July 28, 2020

LHeC

The Large Hadron-Electron Collider at the HL-LHC

LHeC and FCC-he Study Group

To be submitted to J. Phys. G

LHeC white paper: arXiv:2007.14491

update to LHeC CDR, arXiV:1206.2913

compilation of new and updated studies over the past two years, from > 330 authors

this talk:

QCD and **proton structure** – Ch. 3, 4

very wide-ranging additional physics programme:

BSM

EW

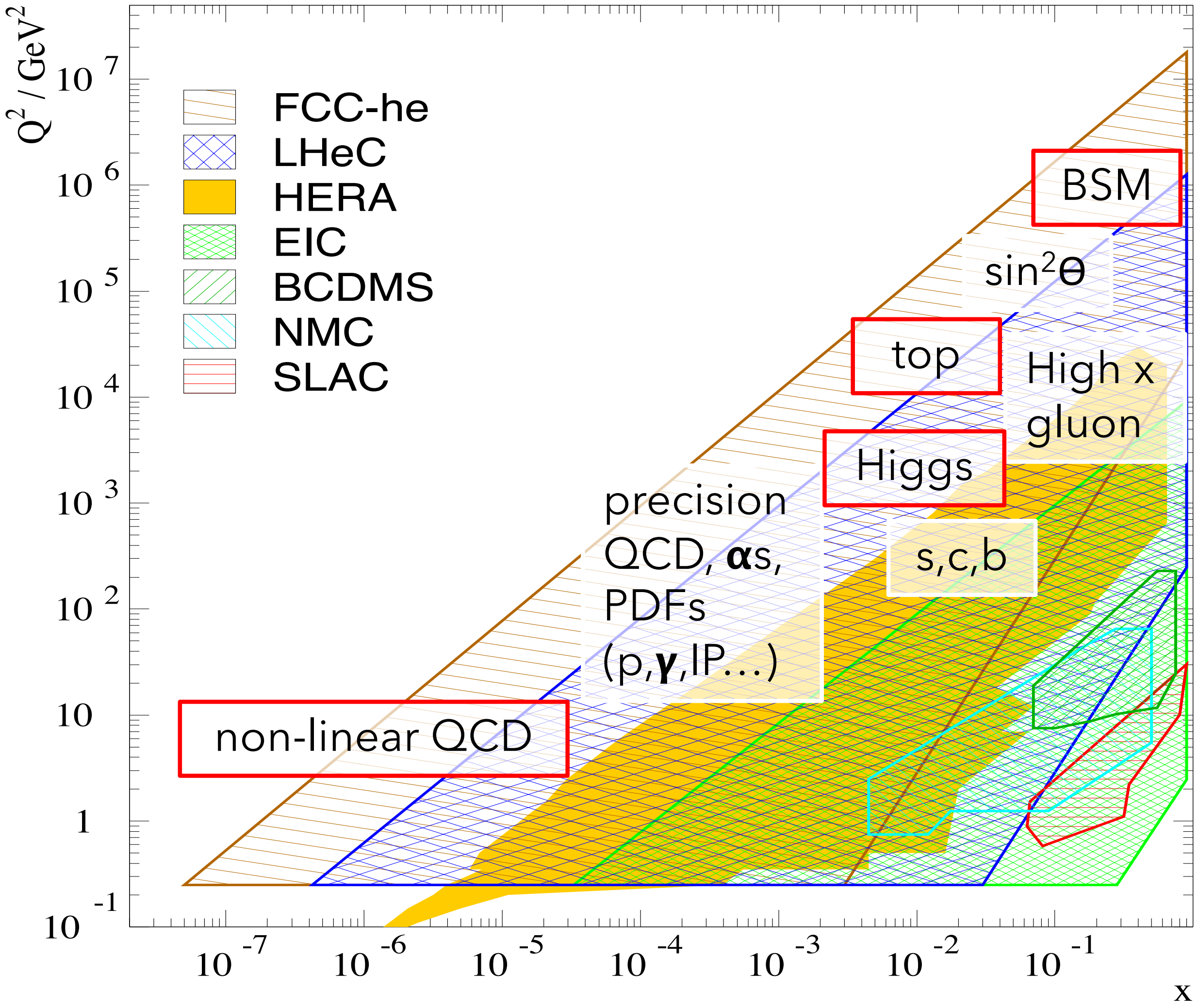
Heavy Ions

Higgs

Top quark

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

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^{3}LO 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**

LHeC simulated data and QCD fits

- LHeC projected timeline (several years concurrent operation, plus dedicated run), see arXiv:[1810.13022](https://arxiv.org/abs/1810.13022)

LHeC 1st Run

50 fb^{-1} e– only; 3 yrs;

concurrent with HL-LHC

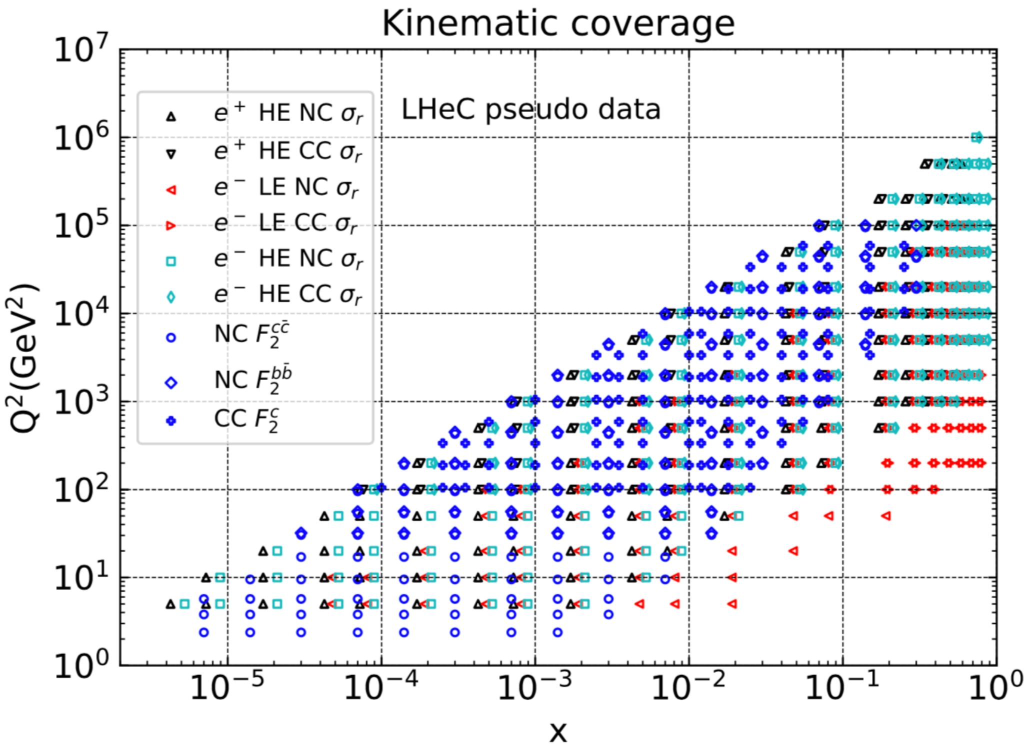
LHeC full incl.

1000 fb^{-1} e– (P_e=–0.8)

50 fb^{-1} e– (P_e=+0.8)

1 fb^{-1} e+

1 fb^{-1} e– (Ep=1 TeV)



Ee: **50** GeV

HE: Ep=**7** TeV

LE: Ep=**1** TeV

full set of systematic uncertainties considered:

elec. energy scale: 0.1%

hadr. energy scale 0.5%

radiative corrs.: 0.3%

γp at high y: 1%

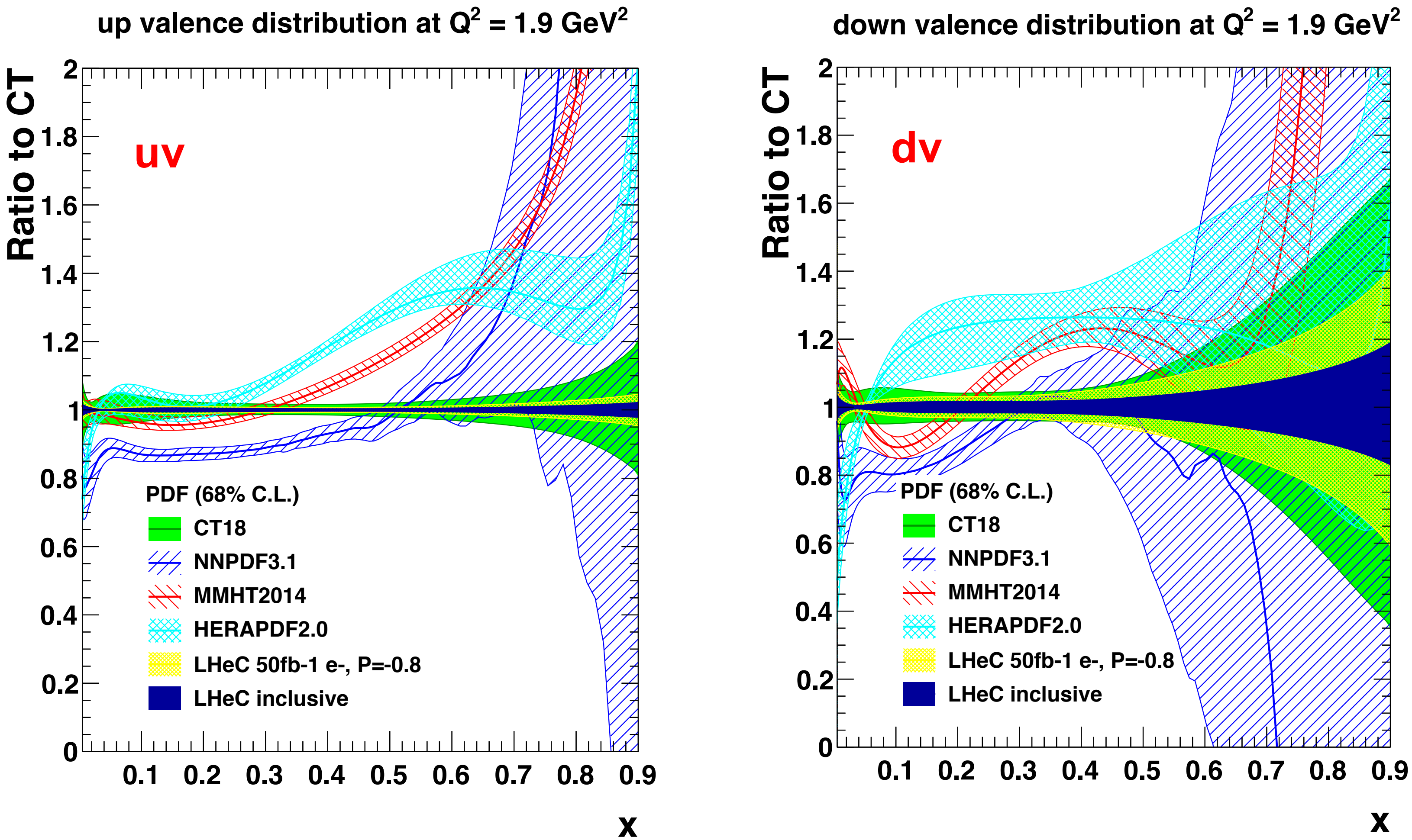
uncorrelated uncert.: 0.5%

CC syst.: 1.5%

luminosity: 0.5%

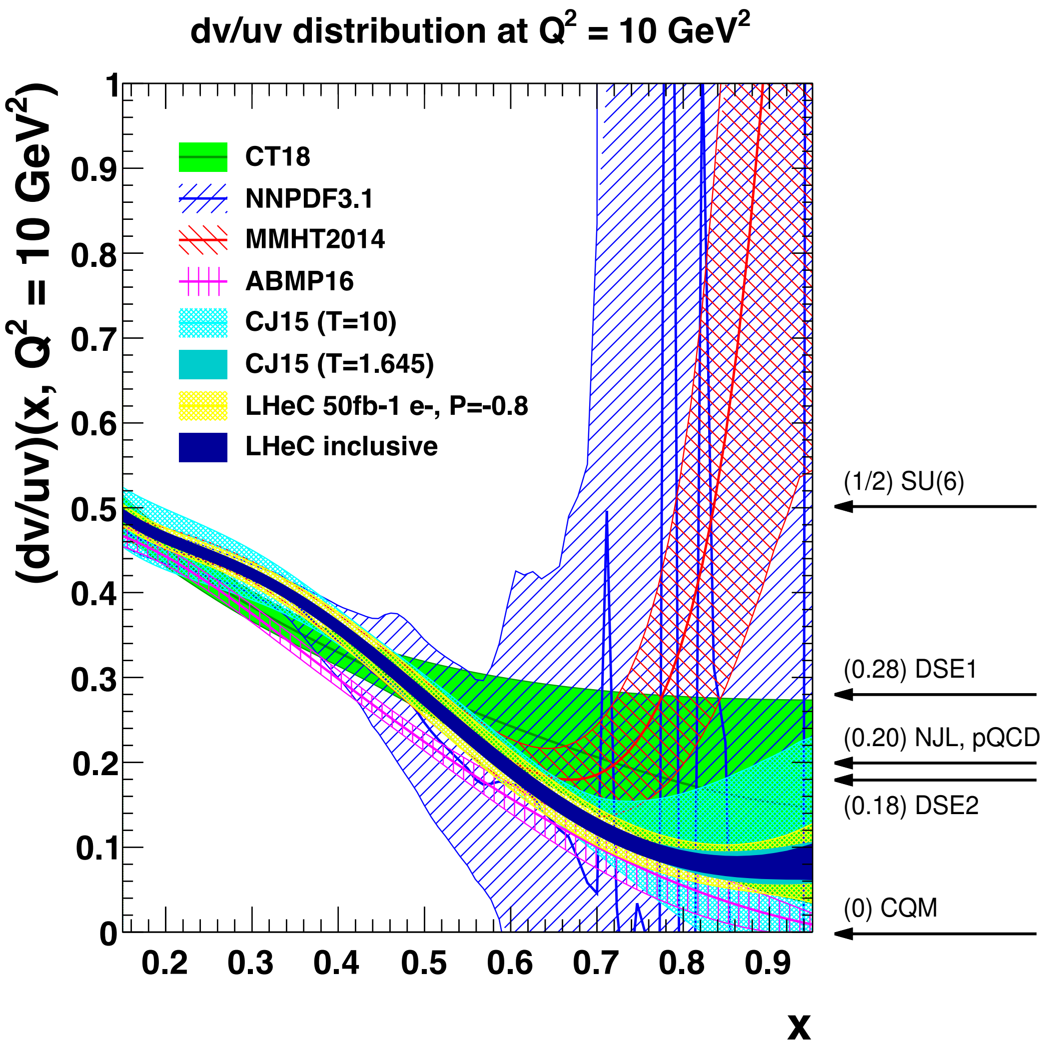
- QCD analysis a la HERAPDF2.0, except more flexible, notably in **NO constraint** requiring dbar=ubar at small x;
- **4+1 xuv, xdv, xUbar, xDbar** and **xg** (**14 free parameters**, cf. 10 by default in CDR)
- **5+1 xuv, xdv, xUbar, xdbar, xsbar** and **xg** (if strange and HQ included; **17 free parameters**)

valence quarks



- 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

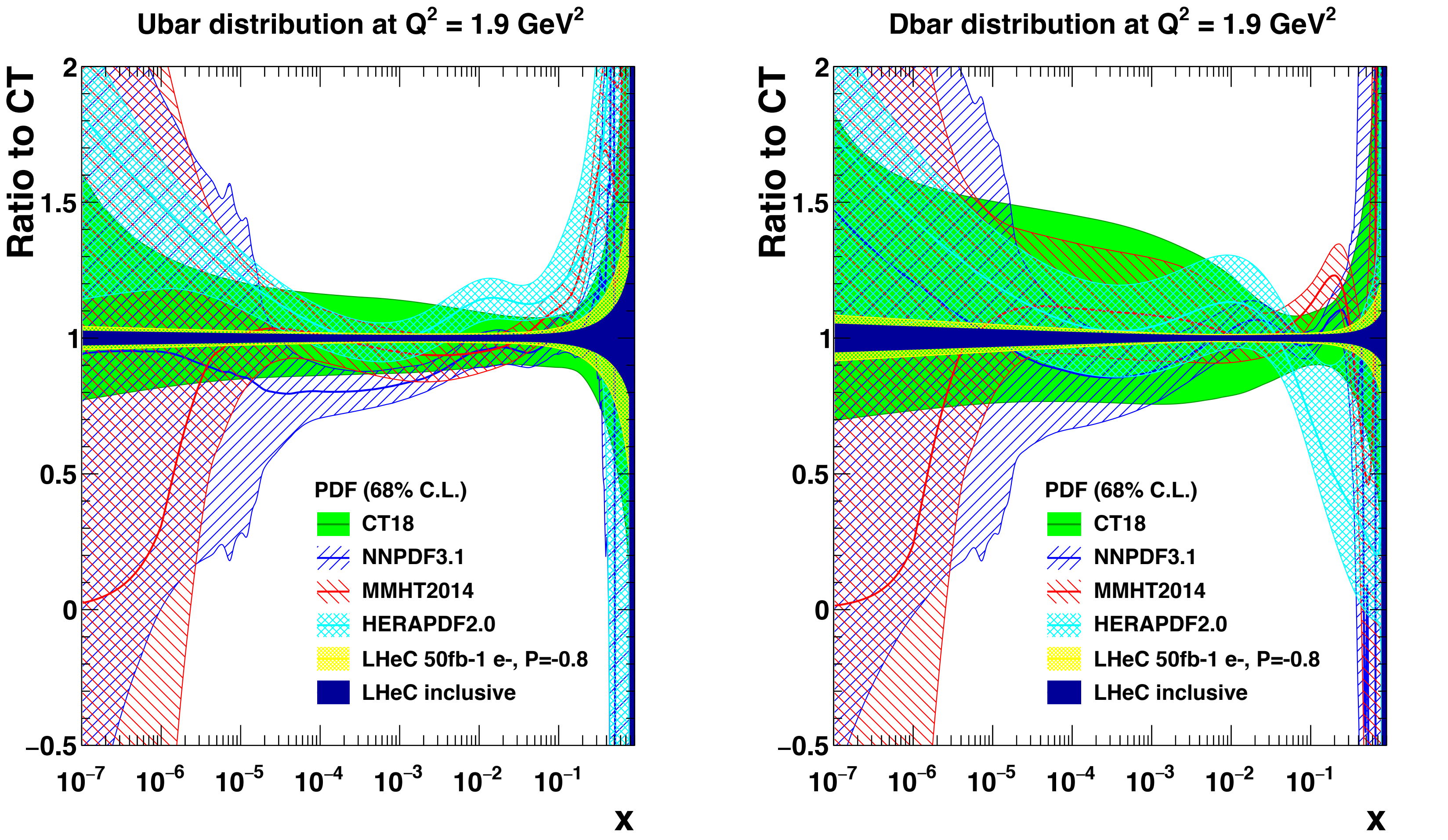
no predictive power from current pdfs;

conflicting theory pictures;

data inconclusive, large nuclear uncertainties

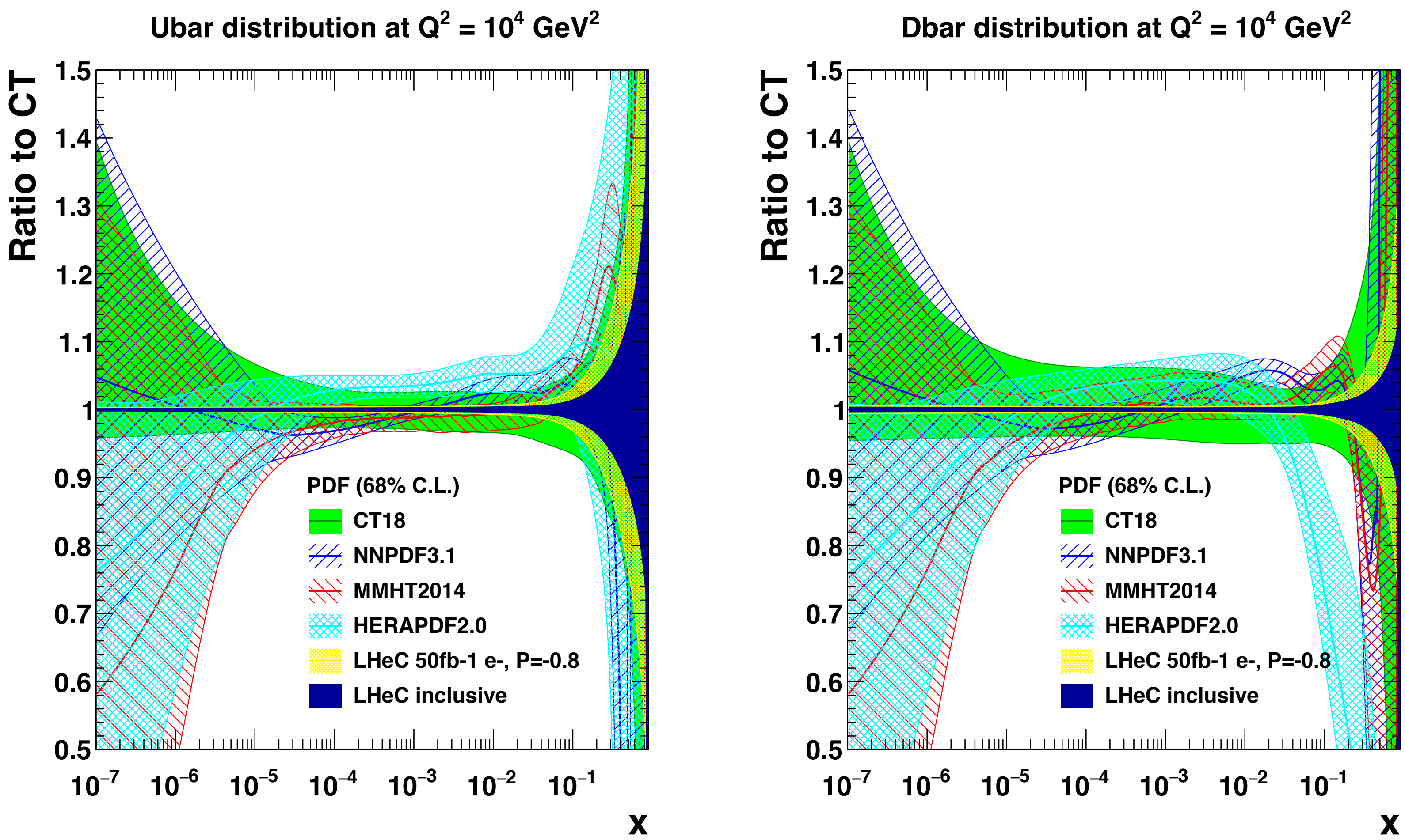
can resolve long-standing mystery of d/u ratio at large x

sea quarks

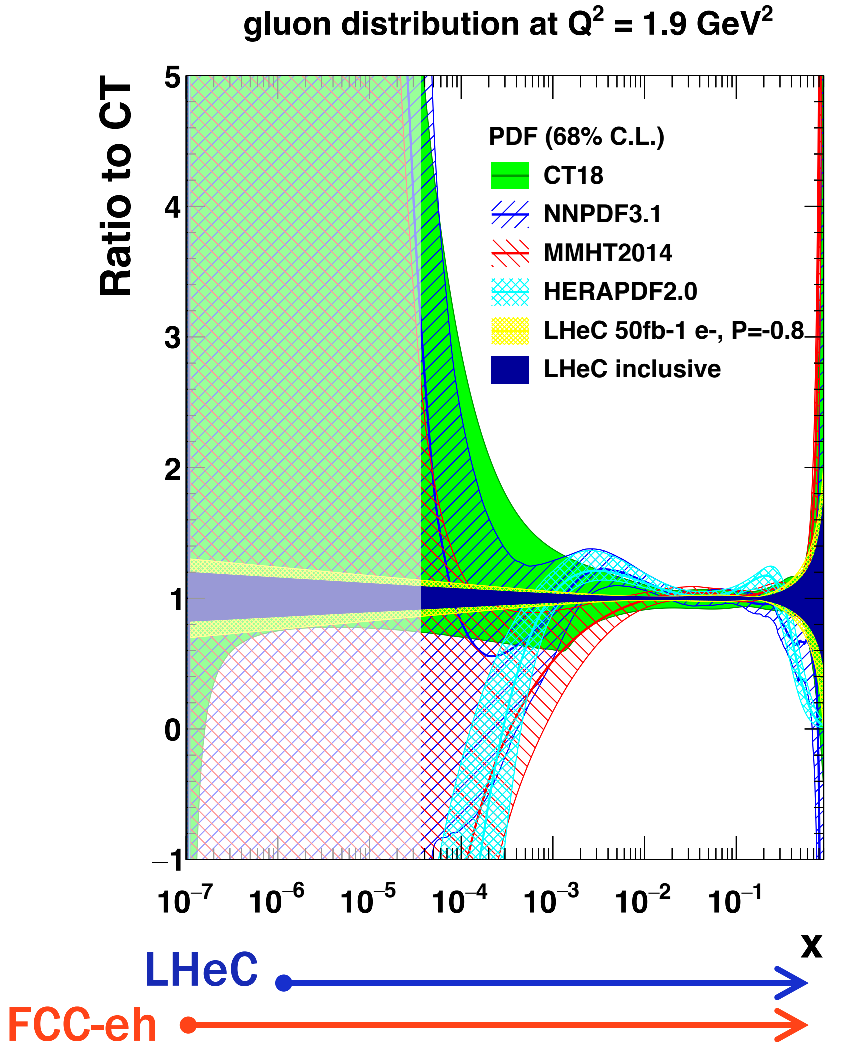


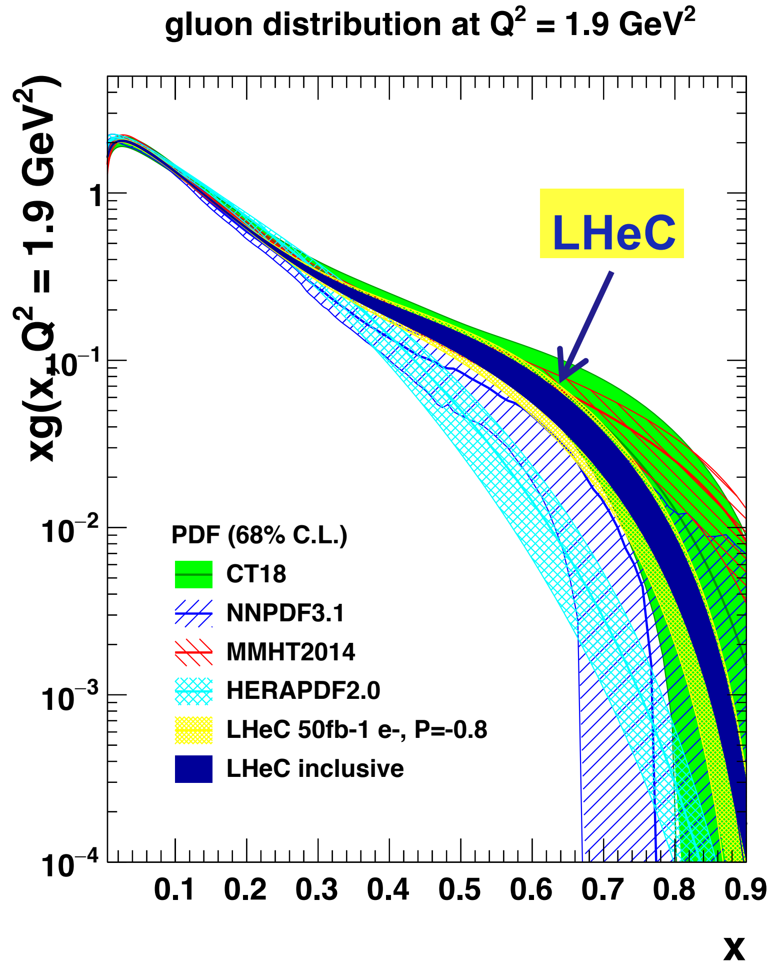
Ubar distribution at Q2 = 1.9 GeV2
Ratio to CT
2
1.5
1
0.5
0
−0.5
10−7 10−6 10−5 10−4 10−3 10−2 10−1
x
PDF (68% C.L.)
CT18
NNPDF3.1
MMHT2014
HERAPDF2.0
LHeC 50fb-1 e-, P=-0.8
LHeC inclusive
Dbar distribution at Q2 = 1.9 GeV2
Ratio to CT
2
1.5
1
0.5
0
−0.5
10−7 10−6 10−5 10−4 10−3 10−2 10−1
x
PDF (68% C.L.)
CT18
NNPDF3.1
MMHT2014
HERAPDF2.0
LHeC 50fb-1 e-, P=-0.8
LHeC inclusive

sea quarks @ $Q^2=10^4$ GeV^2



gluon



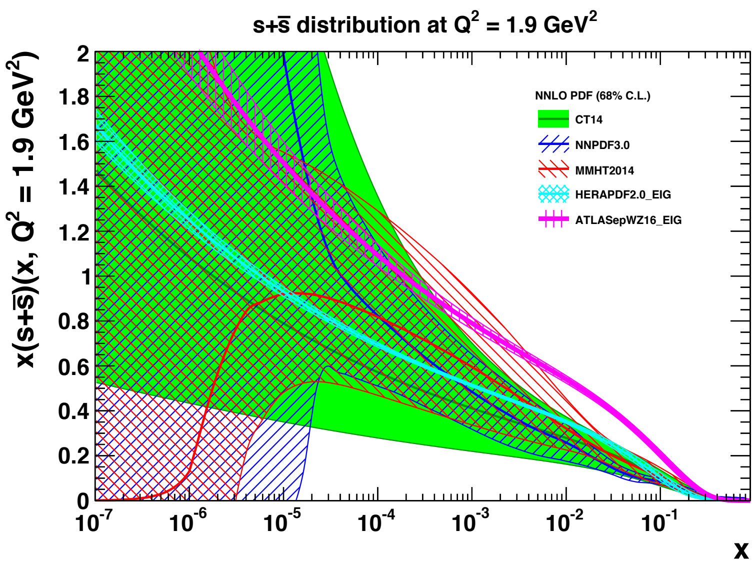


exploration of small x QCD: DGLAP vs BFKL; non-linear evolution; gluon saturation; implications for ultra high energy neutrinos

gluon at large x is small and currently poorly known; **crucial for BSM searches**

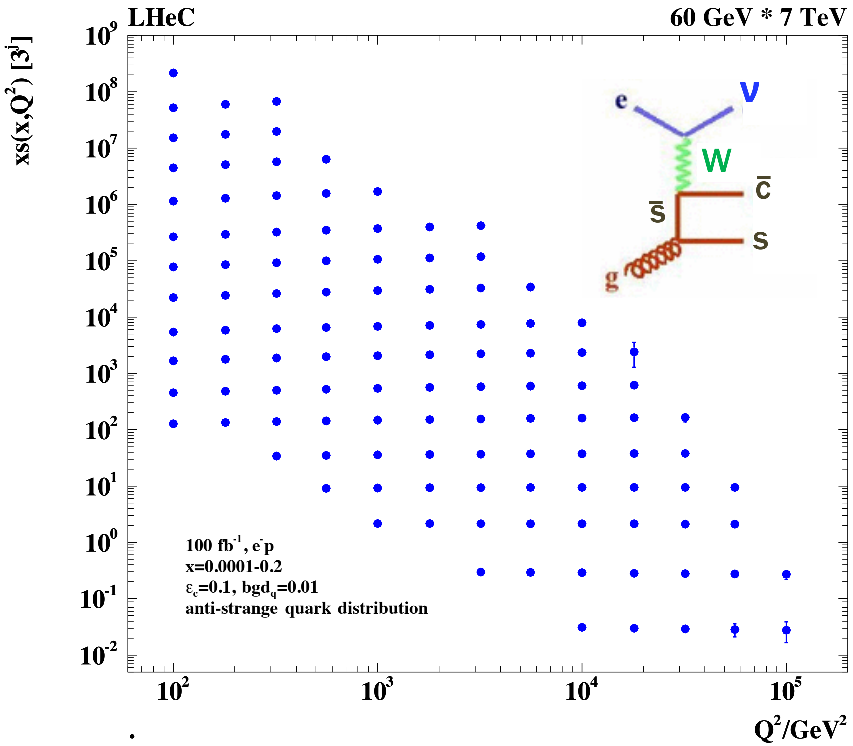
strange, c, b

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

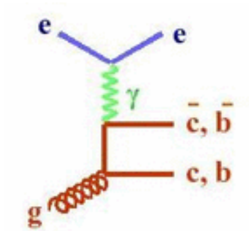


➜ **LHeC:** direct sensitivity via charm tagging in Ws→c

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

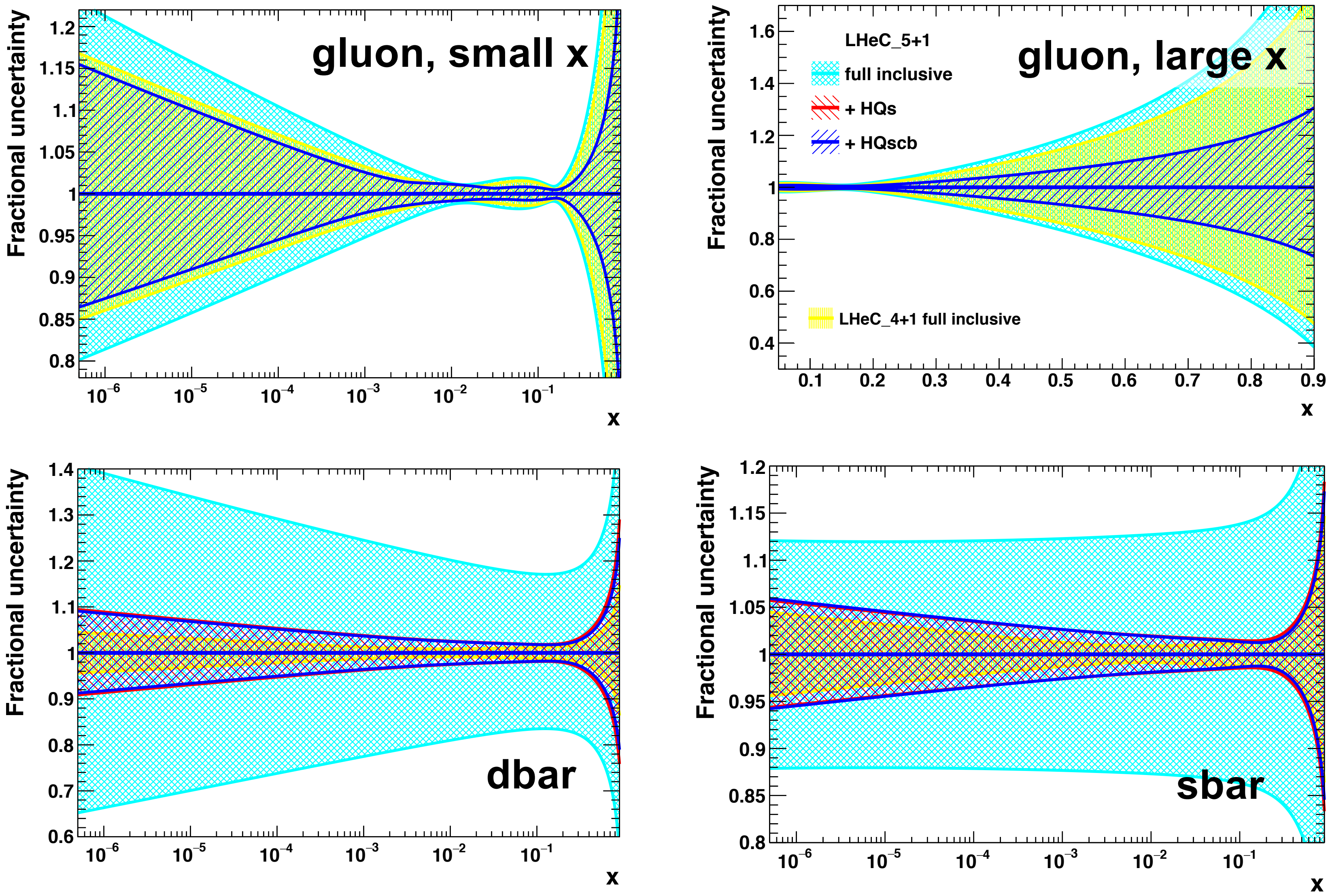


- **c, b:** enormously extended range and much improved precision c.f. HERA



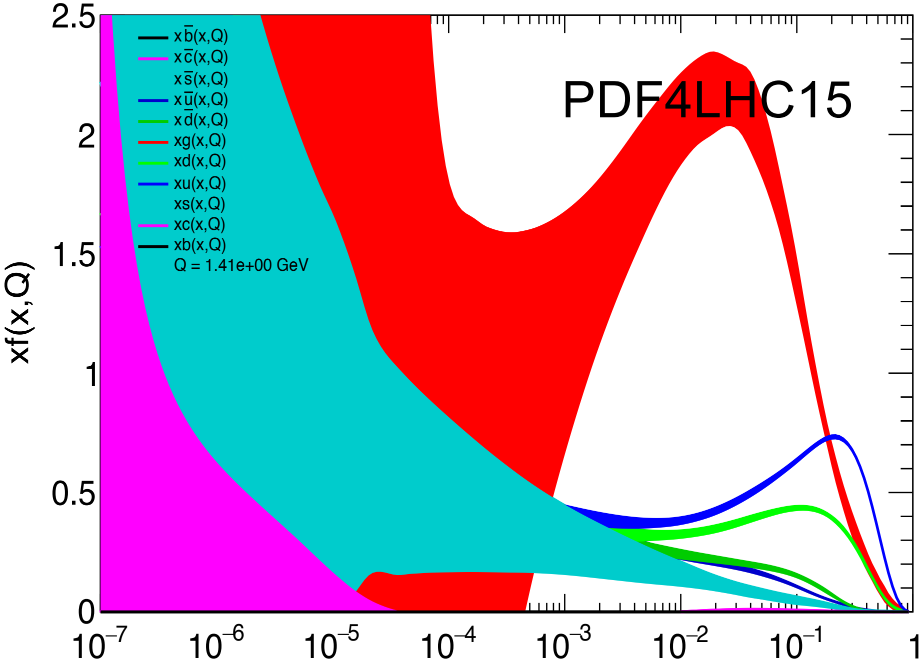
- **δMc = 50 (HERA)** to **3 MeV**: impacts on **α**s, regulates ratio of charm to light, crucial for precision t, H
- **δMb** to **10 MeV**; MSSM: Higgs produced dominantly via b$\bar{b}$ → A

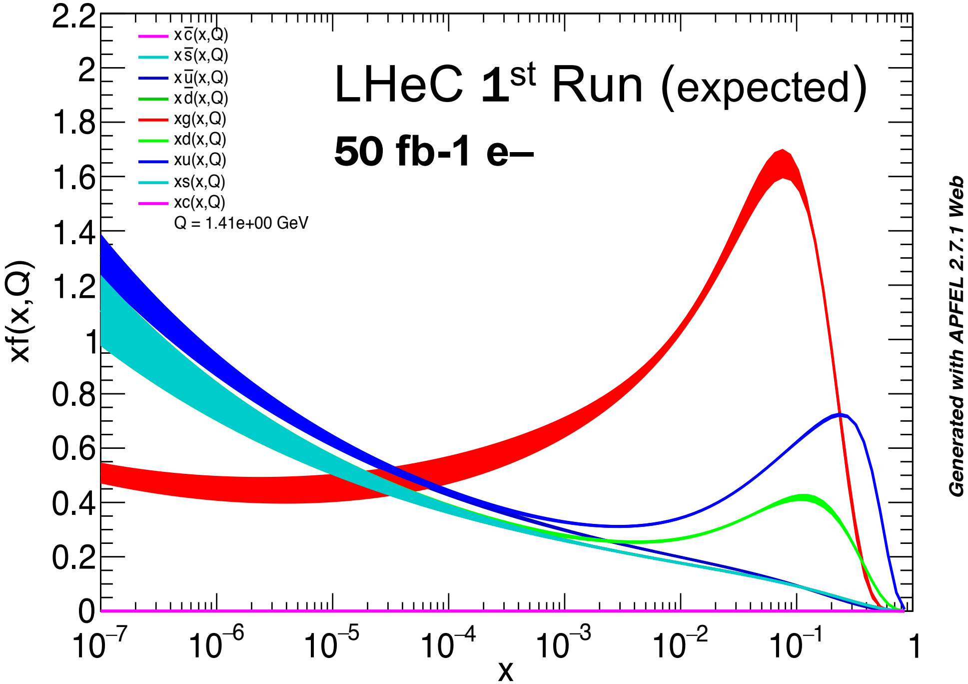
impact of s, c, b



- **4+1** xuv, xdv, xUbar, xDbar + xg **(14)**
- **5+1** xuv, xdv, xUbar, xdbar, xsbar + xg **(17)**

summary of LHeC pdfs

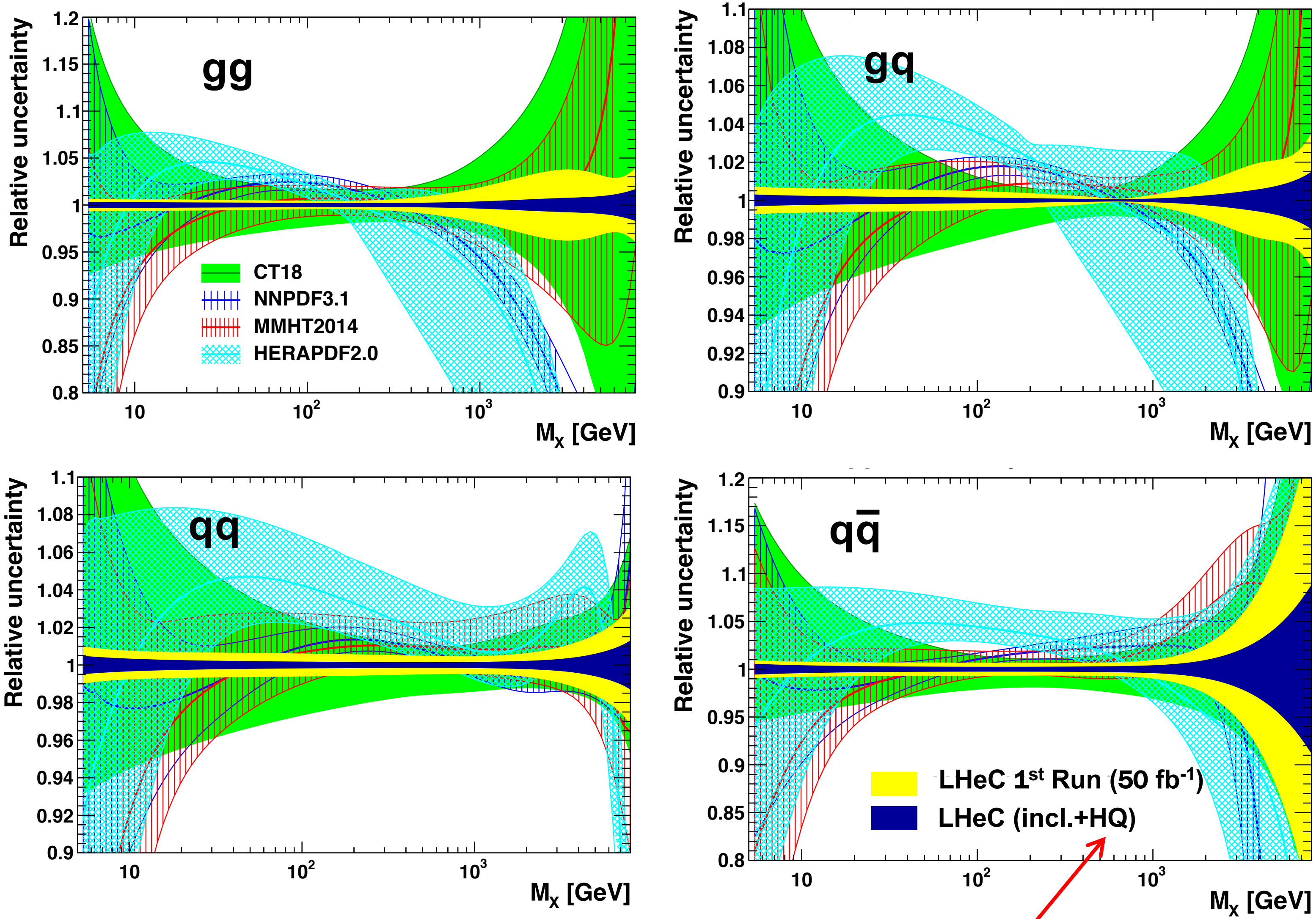




situation today → after 1st LHeC Run

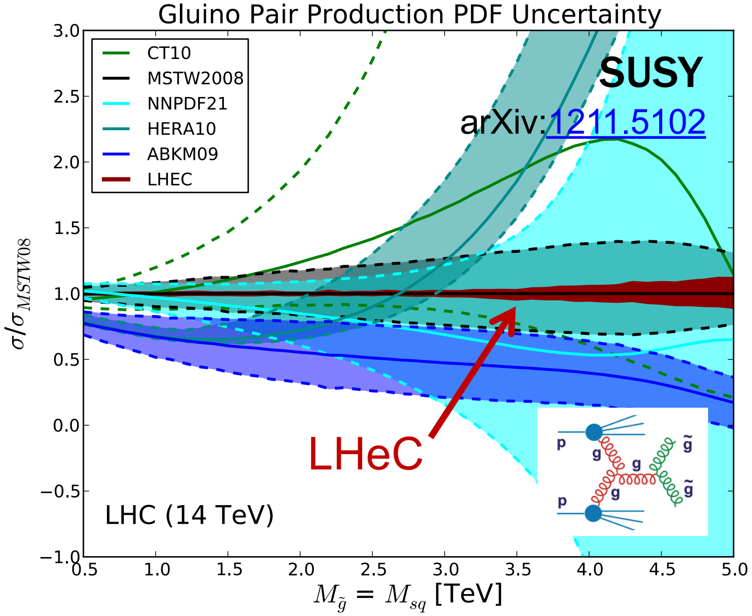
with further improvements after full running period, plus HQs, (DIS jets, …)

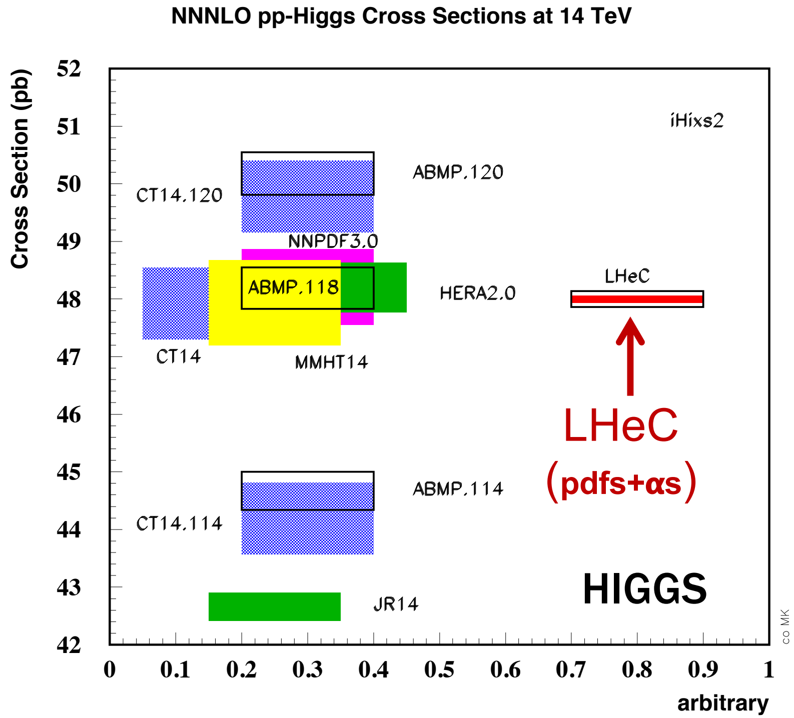
pdf luminosities @ 14TeV

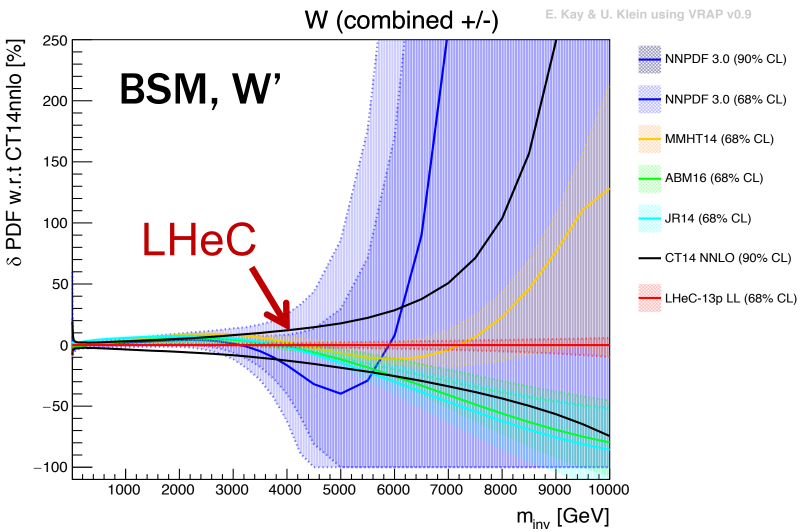


(s,c,b) also included, with more flexible (5+1) fit

empowering the LHC

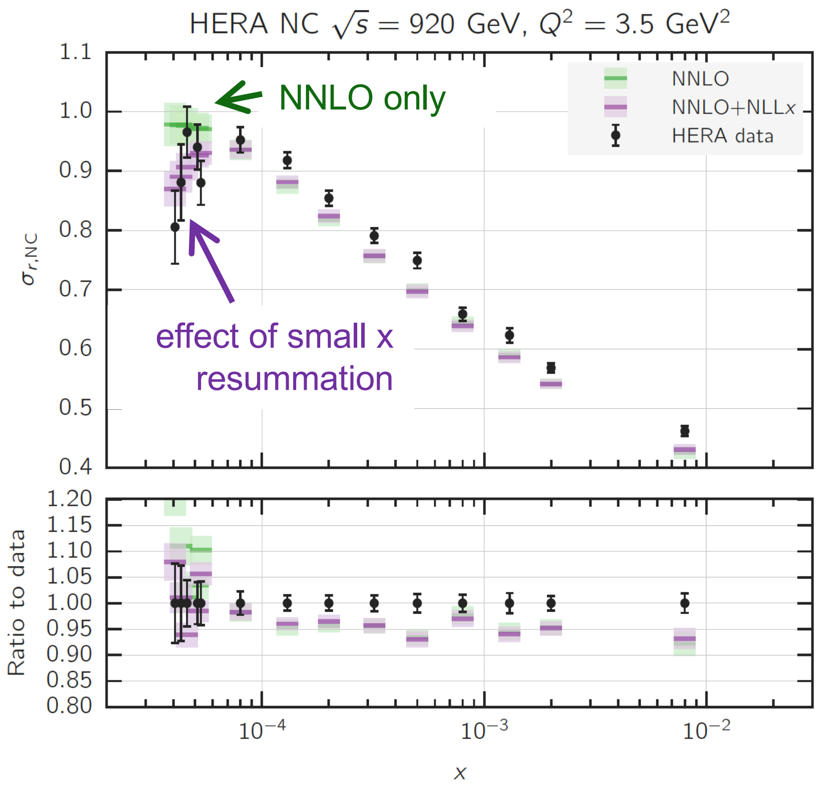


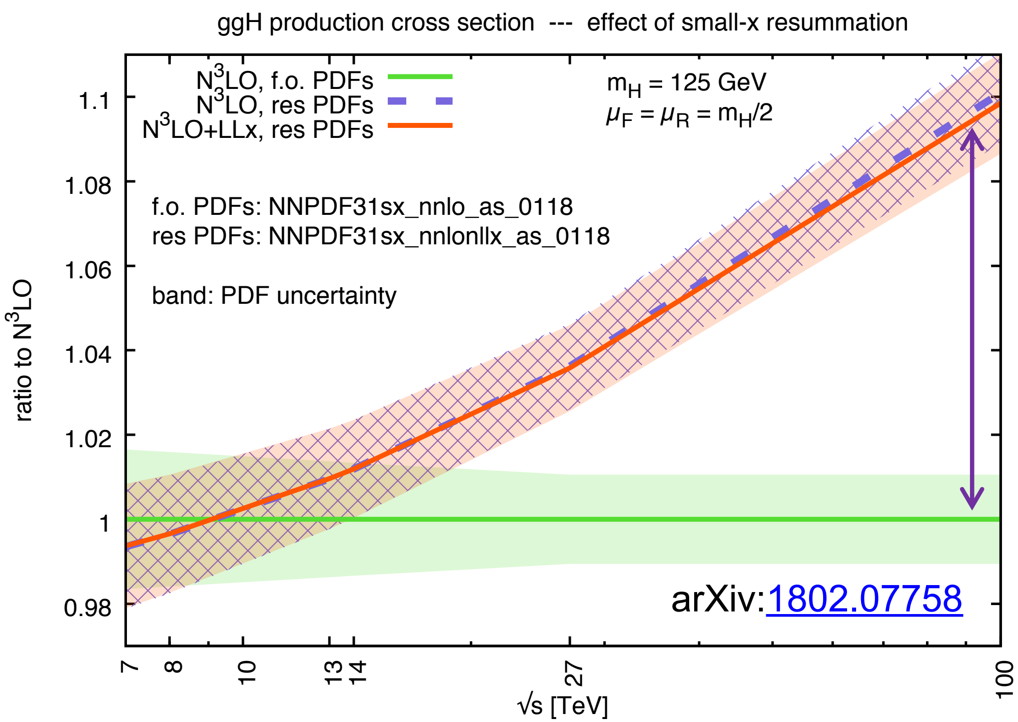




- external, reliable, precise pdfs needed for range extension and interpretation
- **BSM**, gluons and quarks at large x (SUSY, LQs, additional high mass bosons, …)
- **Higgs**, theory uncert. dominated by **pdfs+αs**
- SM parameters, EG. **MW**, **$\sin^2\vartheta W$** (see white paper)

more on small x QCD



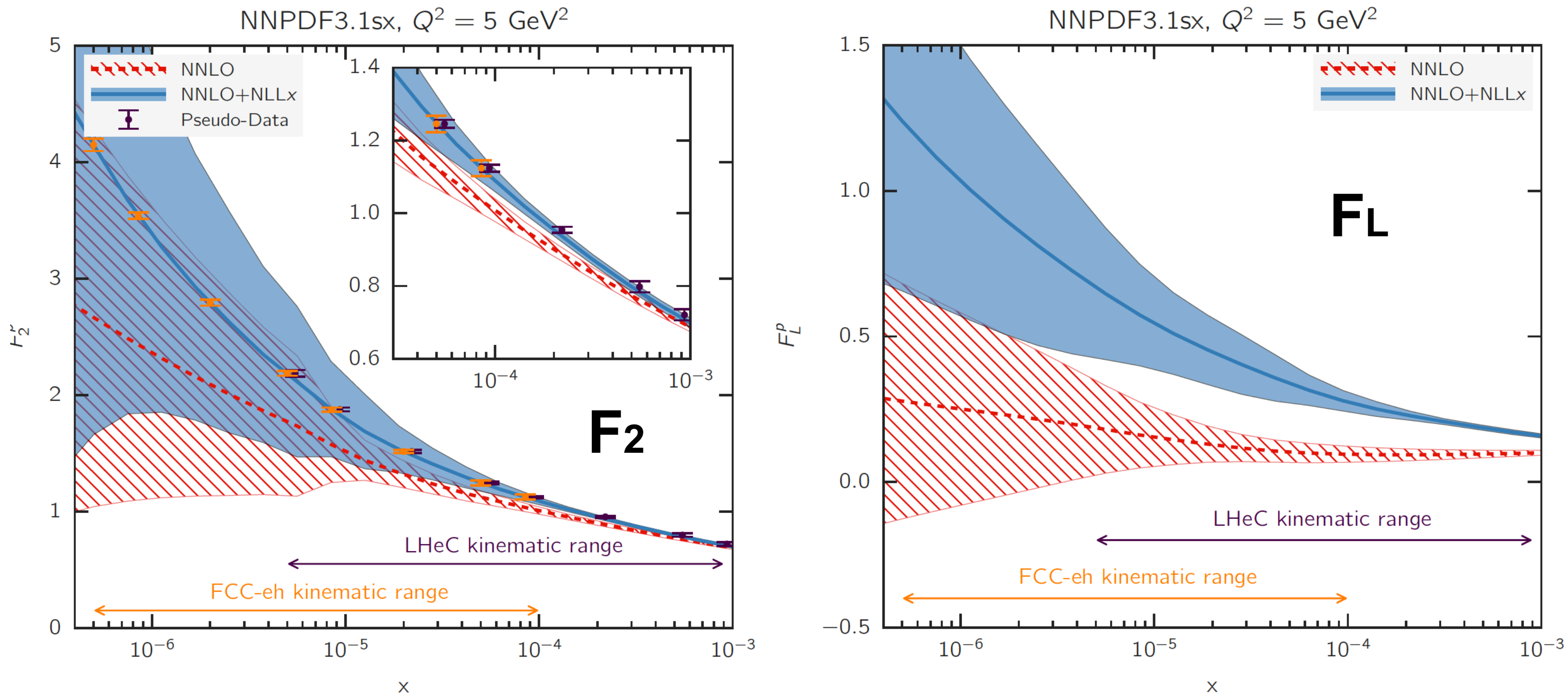


- evidence for onset of BFKL dynamics in HERA inclusive data,
- arXiv:1710.05935; confirmed in xFitter study, arXiv:1802.00064

- effect of small x resummation on ggH cross section for LHC, HE-LHC, FCC
- impact for LHC, and most certainly at ultra low x values probed at FCC

- LHeC and FCC-eh have unprecedented kinematic reach to **explore small x** phenomena

LHeC sensitivity to small x phenomena



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, arXiv:1710.05935
- **measurement of FL has a critical role to play**

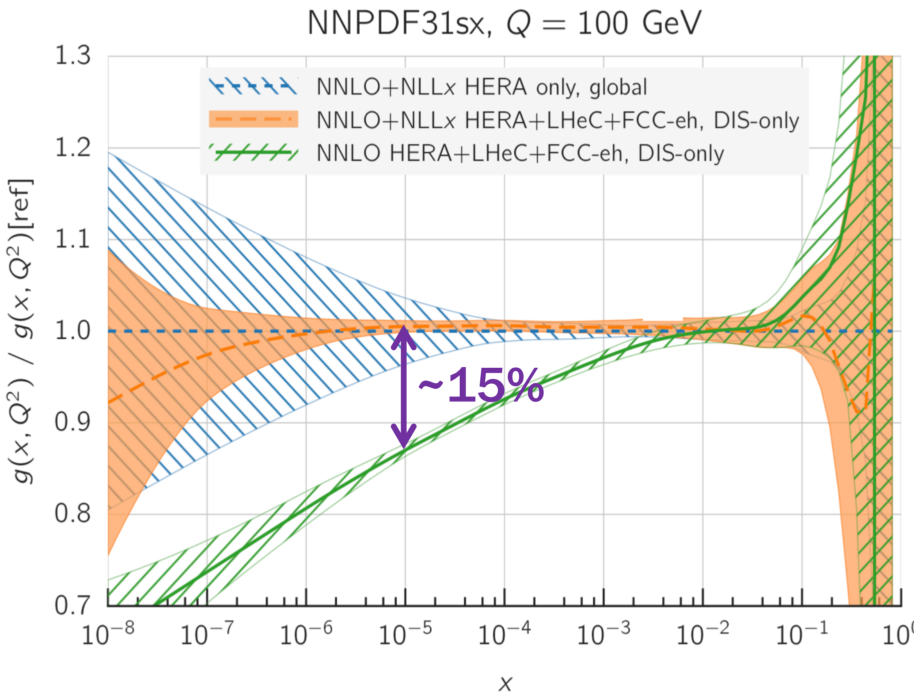
  see, EG. arXiv:1802.04317

small x resummation

- NNLO+NLLx resummed calculation used to produce **LHeC** and **FCC-eh** simulated inclusive NC and CC pseudo-data
- then, fitted using **NNLO (DGLAP only)** vs. **NNLO+NLLx**

X^2 per DOF	LHeC / FCC-eh
NNLO:	**1.71 / 2.72**
NNLO+NLLx	**1.22 / 1.34**

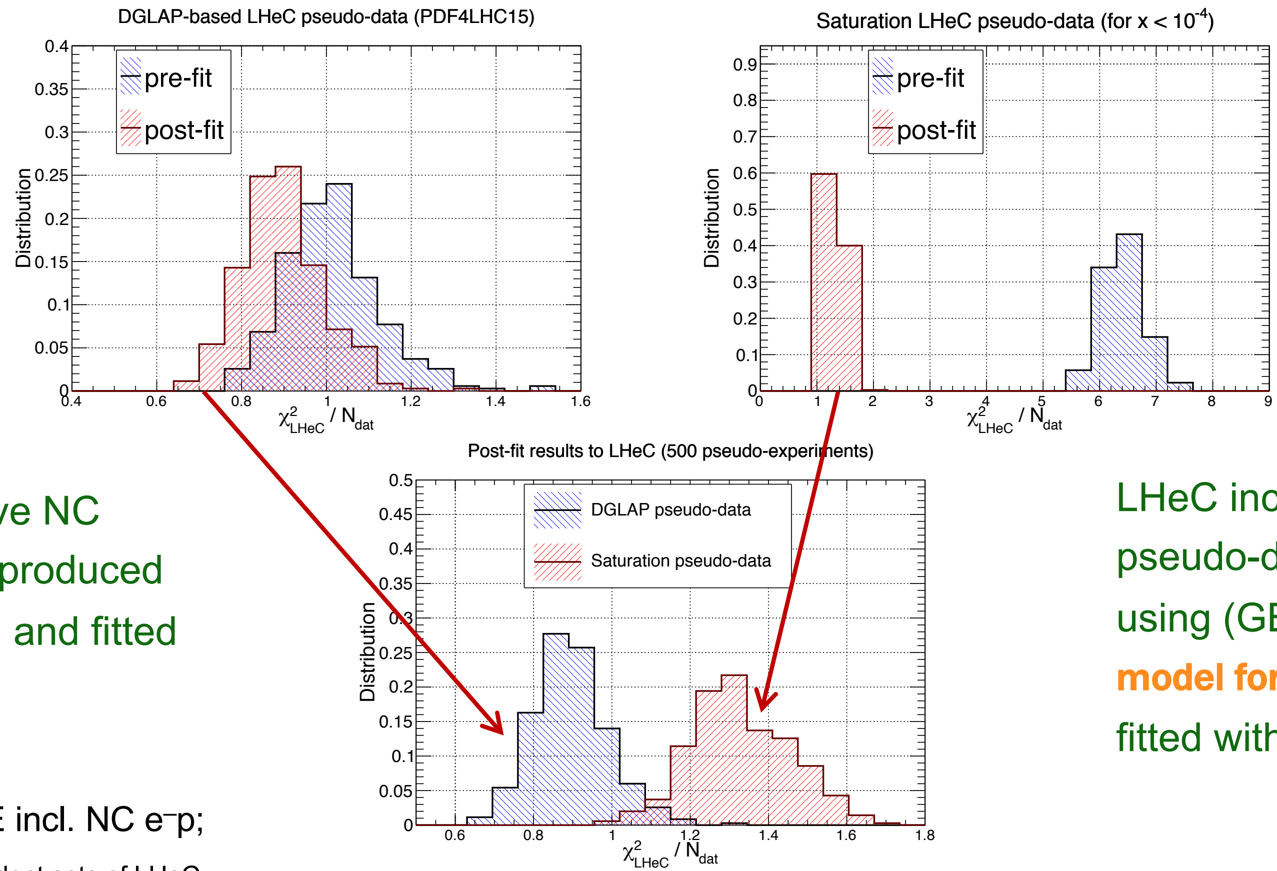
- substantial difference in extracted gluon (**10** (**15**)% at x=**10^{-4}** (**10^{-5}**))
- much larger than precision with which gluon can be determined using LHeC or FCC-eh DIS data



- large sensitivity and discriminatory power to pin down details of **small x QCD dynamics**

non-linear QCD dynamics

- with the unprecedented small-x reach, **gluon recombination / parton saturation may also be expected**, manifesting as deviation from linear DGLAP



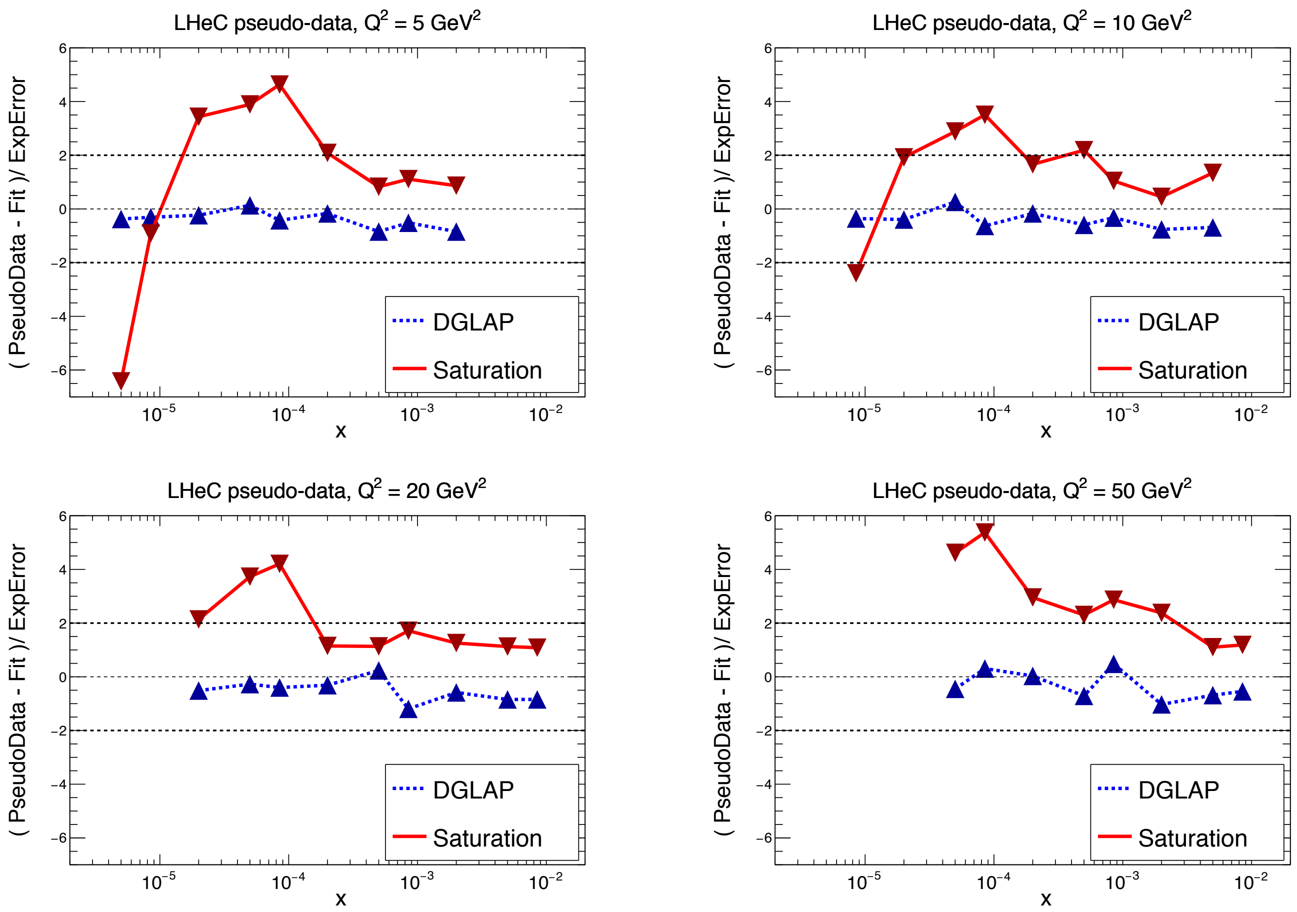
LHeC inclusive NC pseudo-data produced using **DGLAP**, and fitted with **DGLAP**

LHeC inclusive NC pseudo-data produced using (GBW) **saturation model for x ≲ 10^{-4}**, and fitted with **DGLAP**

LHeC HE and LE incl. NC e⁻p;

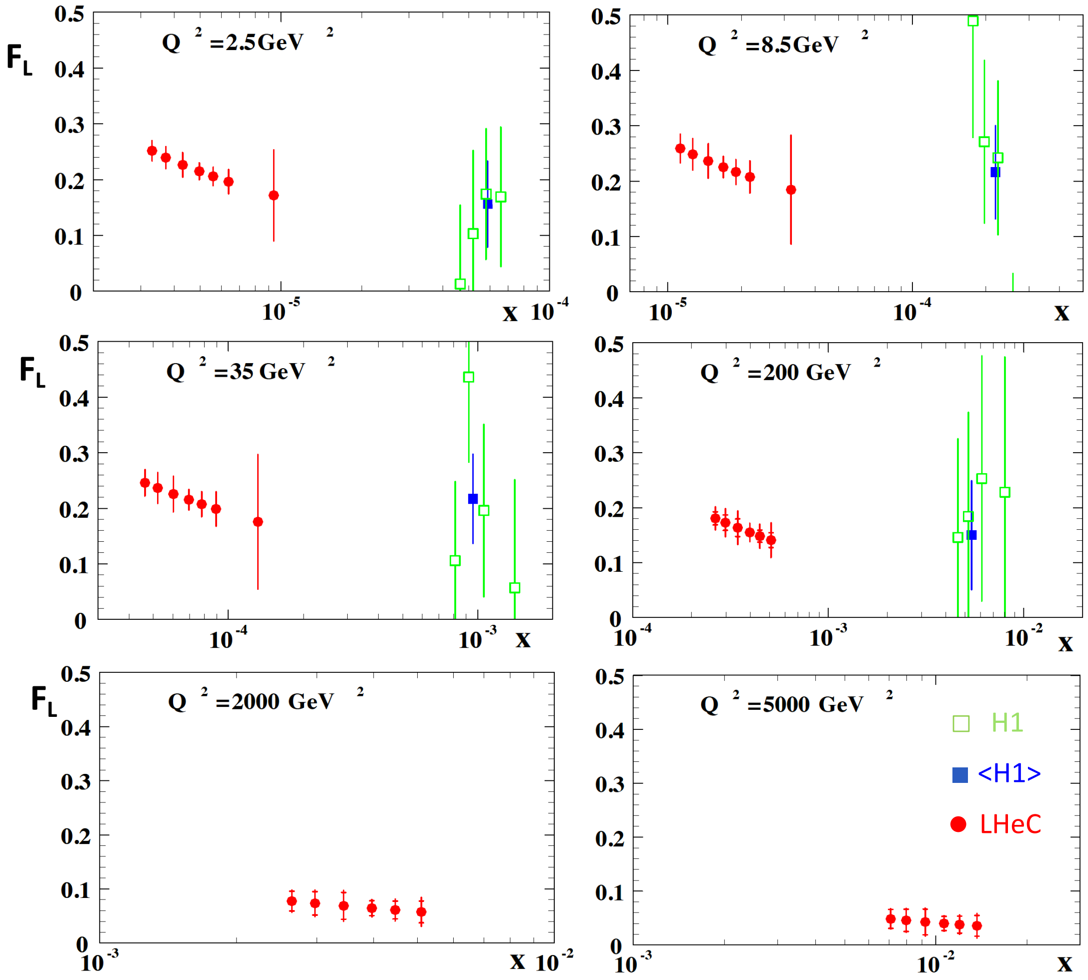
(Nexp=500 independent sets of LHeC pseudodata, each characterised by different random fluctuations)

non-linear QCD dynamics



- inspect **PULLS** to highlight origin of worse agreement: in **saturation case (fitted with DGLAP)**, theory wants to overshoot data at smallest x, and undershoot at higher x
- while a different x dependence might be absorbed into PDFs at scale Q_0, this is not possible with a Q^2 dependence – **large Q^2 lever arm crucial**

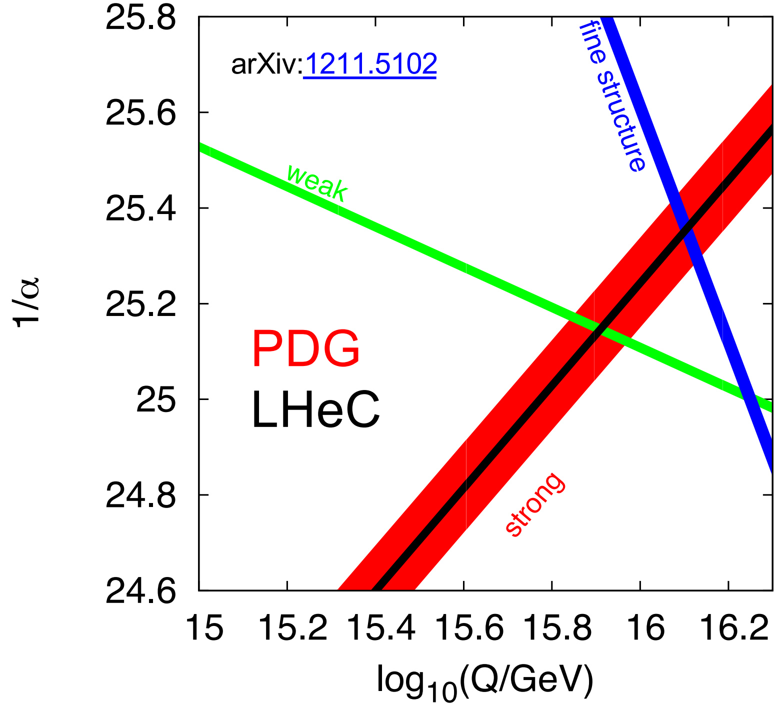
FL from the LHeC



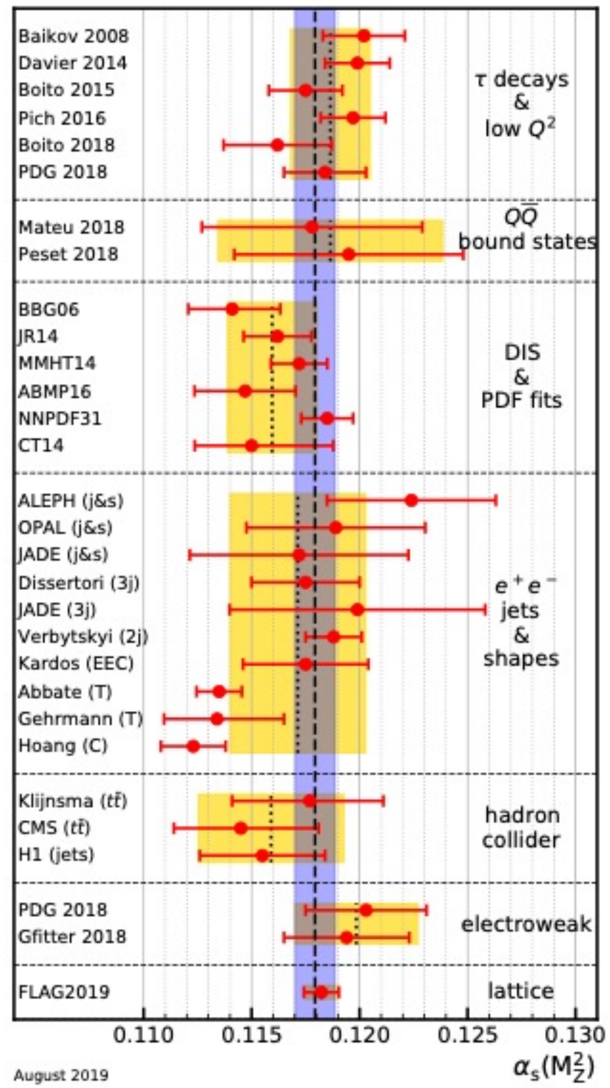
- **expect significant additional discrimination from dedicated precision measurement of FL**

  (not yet included in shown studies); incorrect **small x** treatment unlikely to accommodate both F2 **and** FL

strong coupling, αs



PDG19



world ave. $\alpha_s(M_Z^2) = 0.1179 \pm 0.0010$

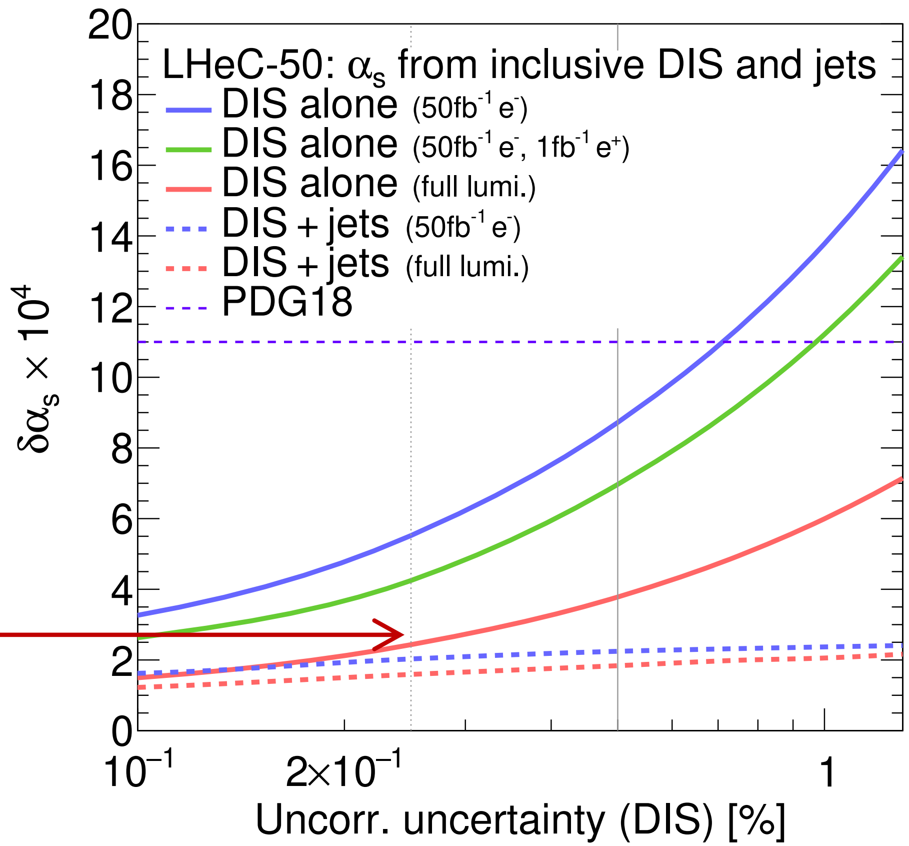
- **αs is the least known coupling**
- needed: for cross section predictions, including Higgs; to constrain GUT scenarios, etc.
- measurements not all consistent:– what is true central value, uncertainty? is **αs**(DIS) lower than world average? role of lattice QCD?

αs from LHeC inclusive NC/CC DIS

- αs from inclusive NC/CC DIS:
- simultaneous determination of **pdfs** and **αs** in **NNLO QCD** fit

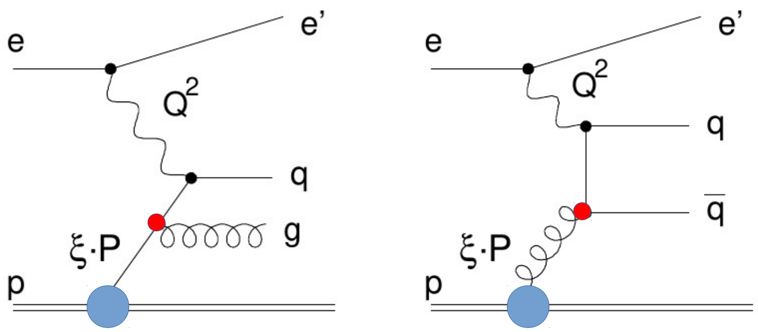
- **3** LHeC scenarios:
- LHeC **1**st Run (**50** fb^{-1} e-p)
- plus **1** fb^{-1} positron data
- full inclusive LHeC dataset (**1** ab^{-1})

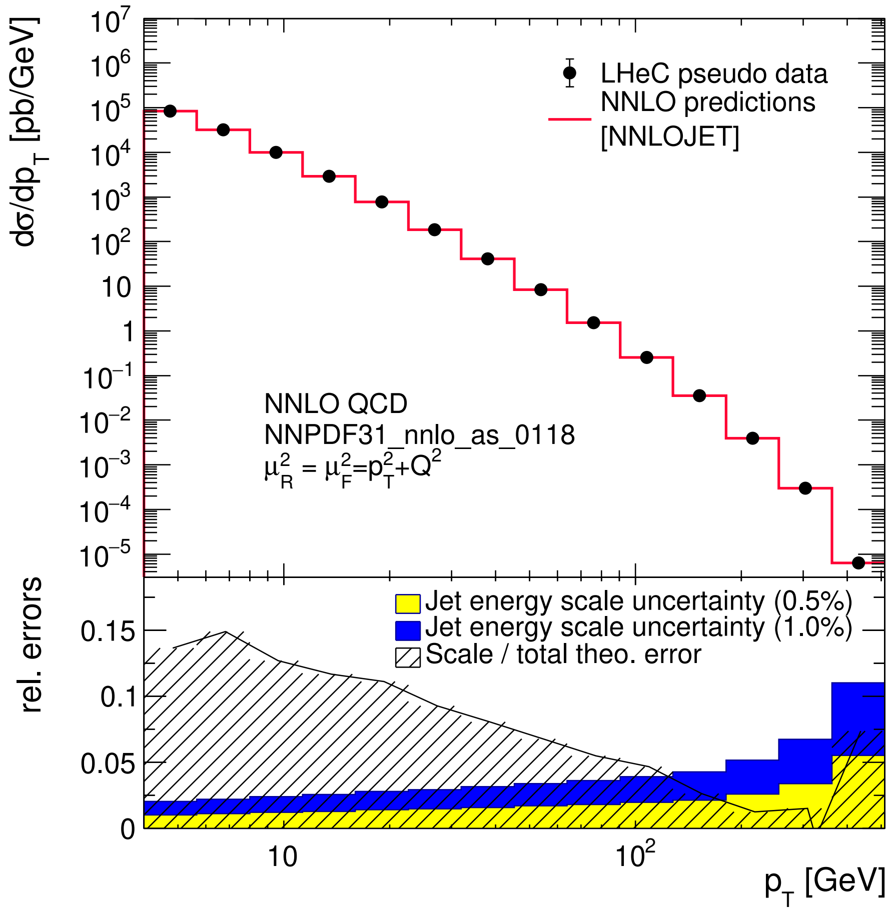
$$\Delta\alpha_s(M_Z)(\text{incl. DIS}) = \pm 0.00022_{(\text{exp+PDF})}$$



- **αs** to better than **2** permille experimental uncertainty!
- inclusion of jet cross sections yields further improvement, and stabilises against uncorrelated uncertainty scenario →

NC DIS jet production at the LHeC





- **sensitive to αs at lowest order**
- different dependencies on **xg(x)** and **αs** c.f. inclusive DIS; improved constraints on both, when used in simultaneous **pdf+αs** fit
- NNLO QCD calculations for DIS jets available in NNLOJet (arXiv:1606.03991, 1703.05977), and implemented in APPLfast (arXiv:1906.05303)
- full set of systematic uncertainties considered; benchmarked with H1, ZEUS, ATLAS, CMS

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
Jet energy scale (JES)	0.5 %	0.2 – 4.4
Uncorrelated uncert.	0.6 %	0.6
Normalisation uncert.	1.0 %	1.0

αs from LHeC NC DIS jet production

- **αs** extracted in **NNLO QCD** fit to LHeC simulated jet data only
- methodology as for arXiv:[1709.07251](https://arxiv.org/abs/1709.07251), [1906.05303](https://arxiv.org/abs/1906.05303)

$$\Delta\alpha_s(M_Z)(\text{jets}) = \pm 0.00013_{(\text{exp})} \pm 0.00010_{(\text{PDF})}$$

- extraordinary experimental precision
- scale uncertainty dominates $\Delta\alpha_s(M_Z) = 0.0035\,(\text{NNLO})$

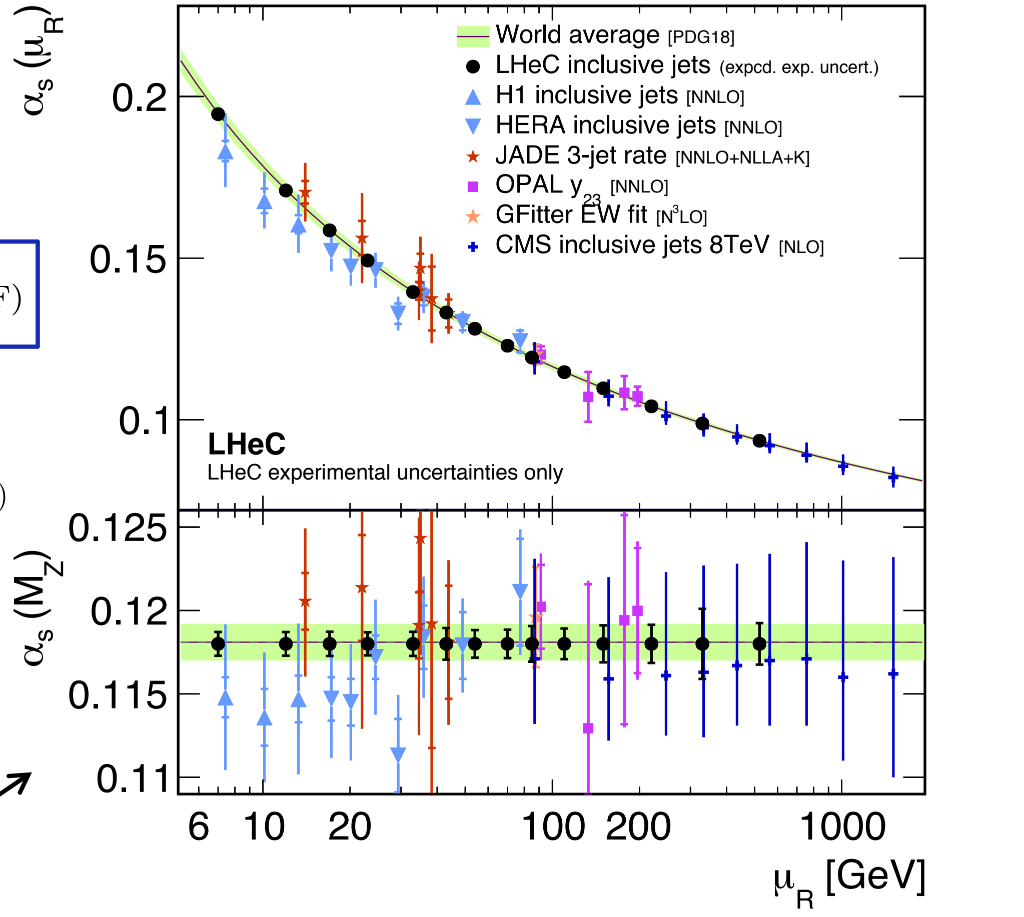
  restricting to higher pt or Q^2 can reduce to

  $\Delta\alpha_s(M_Z) \approx 0.0010$

  trade off with increased experimental uncertainties

  (N^3LO by **2030**s ?)

- **αs** running tested over two orders of magnitude in μR



= √ $(Q^2 + p_T^2)$

- enormous improvement over other jet-based measurements
- LHeC uniquely connects low 𝒪(GeV) scales with high 𝒪(MZ) scales

LHeC αs summary

- LHeC is an ideal QCD laboratory
- connects low-scale to **Z**-pole and beyond with high experimental precision

- **inclusive NC/CC DIS only:**

$$\Delta\alpha_s(M_Z)(\text{incl. DIS}) = \pm 0.00022_{(\text{exp+PDF})}$$

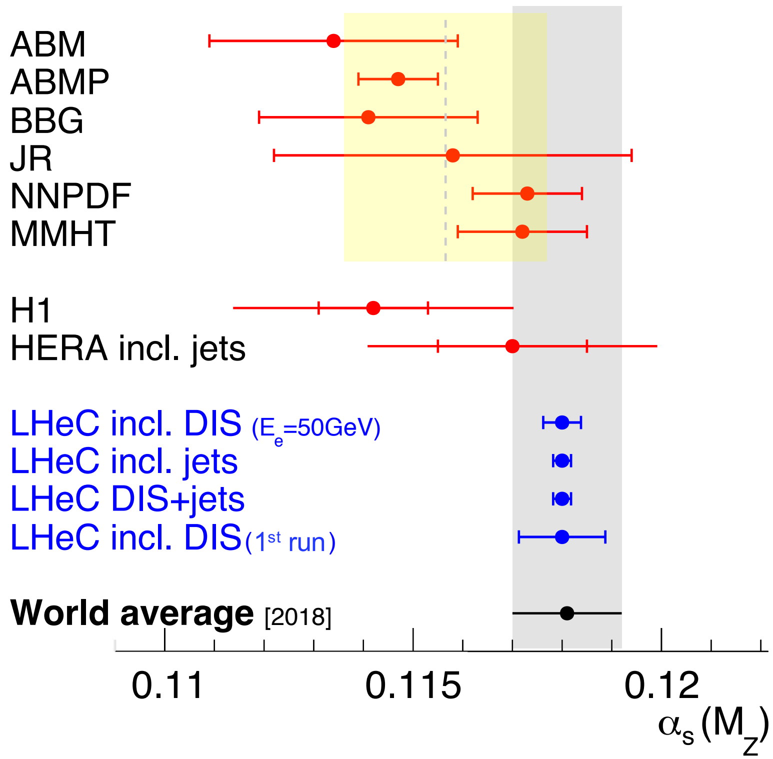
- **inclusive jet cross sections only:**

$$\Delta\alpha_s(M_Z)(\text{jets}) = \pm 0.00013_{(\text{exp})} \pm 0.00010_{(\text{PDF})}$$

- **inclusive DIS <u>and</u> jet cross sections:**

$$\Delta\alpha_s(M_Z)(\text{incl. DIS \& jets}) = \pm 0.00018_{(\text{exp+PDF})}$$

αs determinations at NNLO:



- achievable precision on same level as αs determination from FCC-ee
- QCD theory uncertainties will be limiting factor for ultimate precision

- other sensitive processes/measurements: dijets, multijets, HQs, jets in γp, event shapes, …

summary

- energy frontier **electron-proton colliders** essential for full exploitation of current and future hadron colliders (Higgs, BSM, electroweak, …)
- **external precision pdf input**; complete q,g unfolding, high luminosity $x \longrightarrow 1$, s, c, b, (t); N3LO; small x; strong coupling to permille precision; …

- NEW LHeC white paper summarises wealth of new and updated studies, arXiv:2007.14491
- enormously rich physics programme both in **own right**, and for **transformation of proton-proton machines** into precision facilities

- **all critical pdf information can be obtained early** (~ **50** fb^{-1} ≡ ×**50** HERA), in parallel with HL-LHC operation
- **α_s** to permille exp. precision also achievable early, with use of NC DIS jets
- unprecedented access to novel kinematic regime, with **unique potential to explore novel small x phenomena**