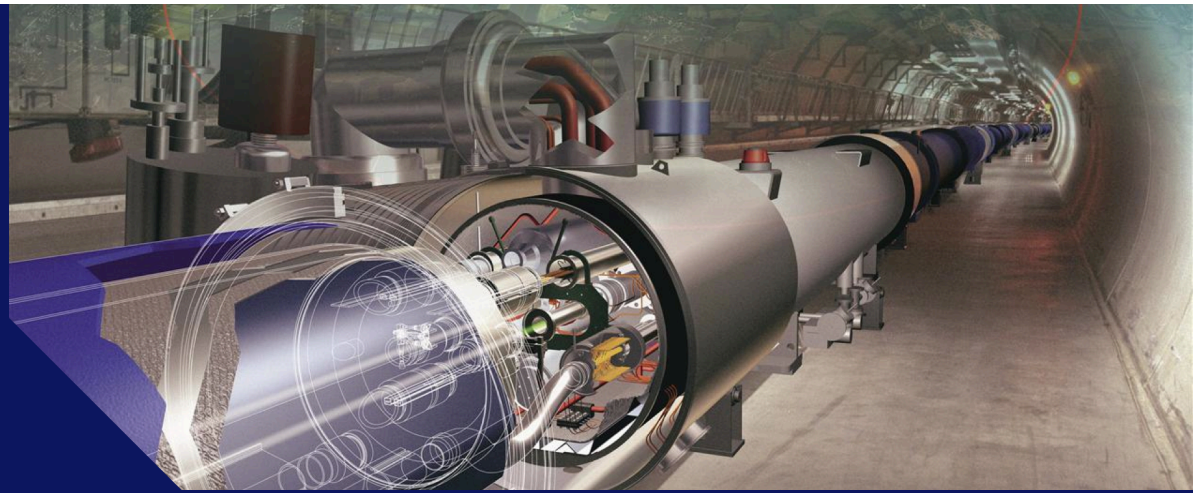
12 – 16 April 2021

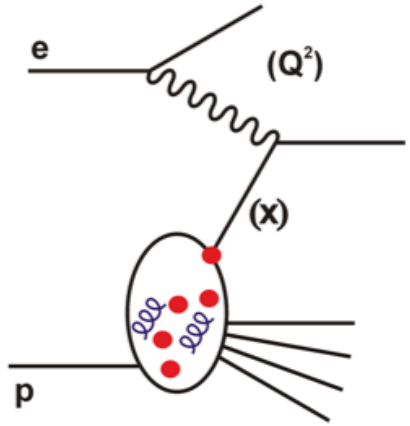


PROTON PDF DETERMINATION AT THE LHeC

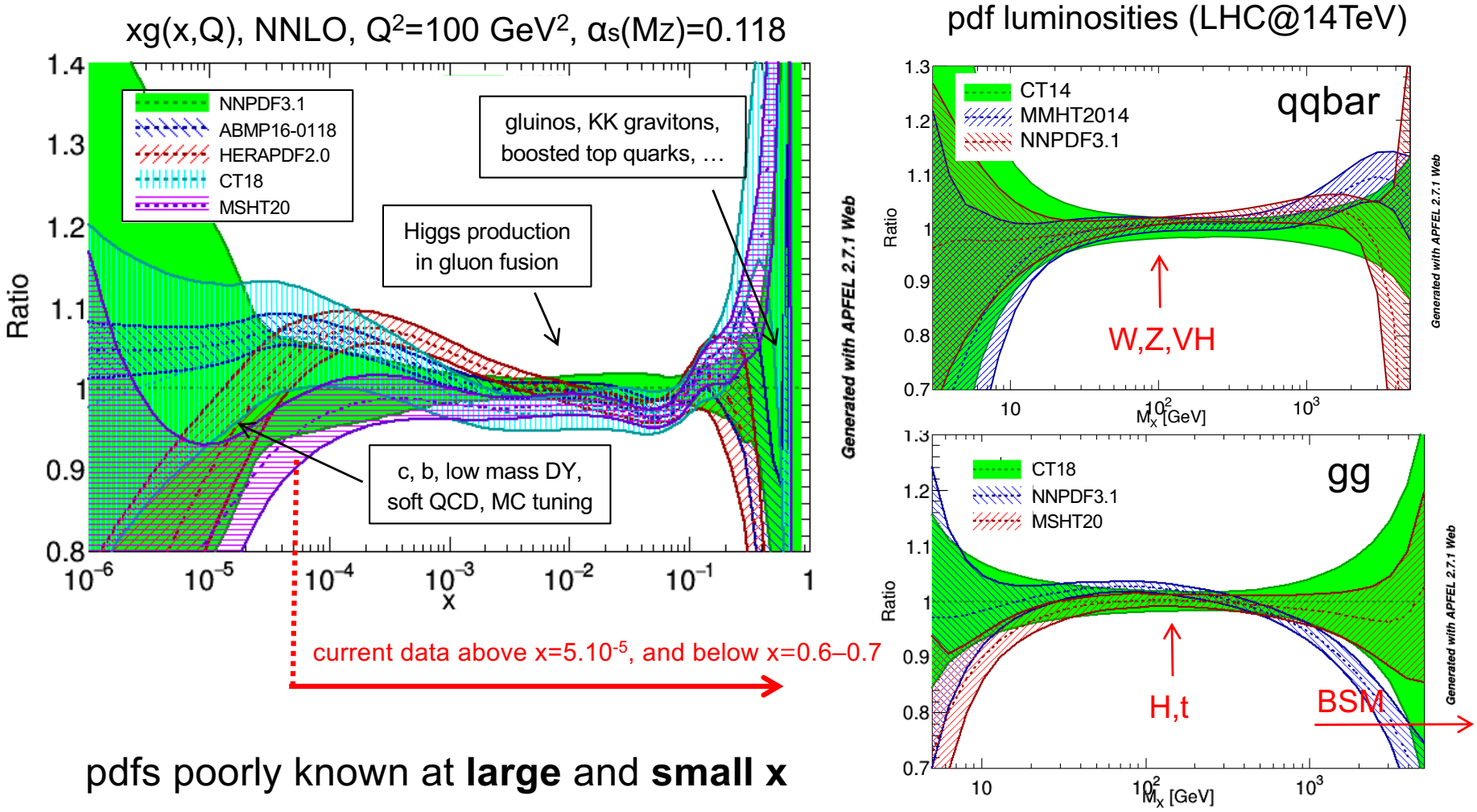
Claire Gwenlan, Oxford

on behalf of the LHeC and FCC-eh study groups

with focus on results from LHeC CDR update, arXiv:2007.14491



pdfs: the situation today



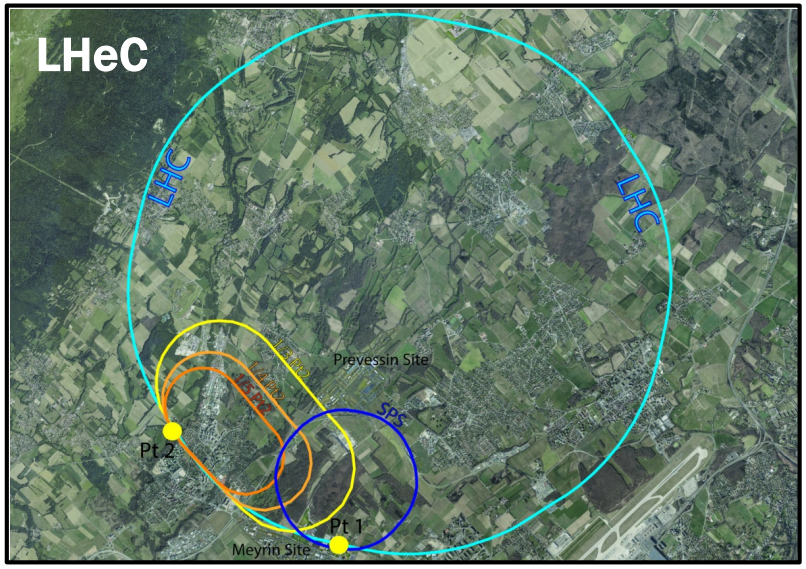
pdfs poorly known at **large** and **small x**

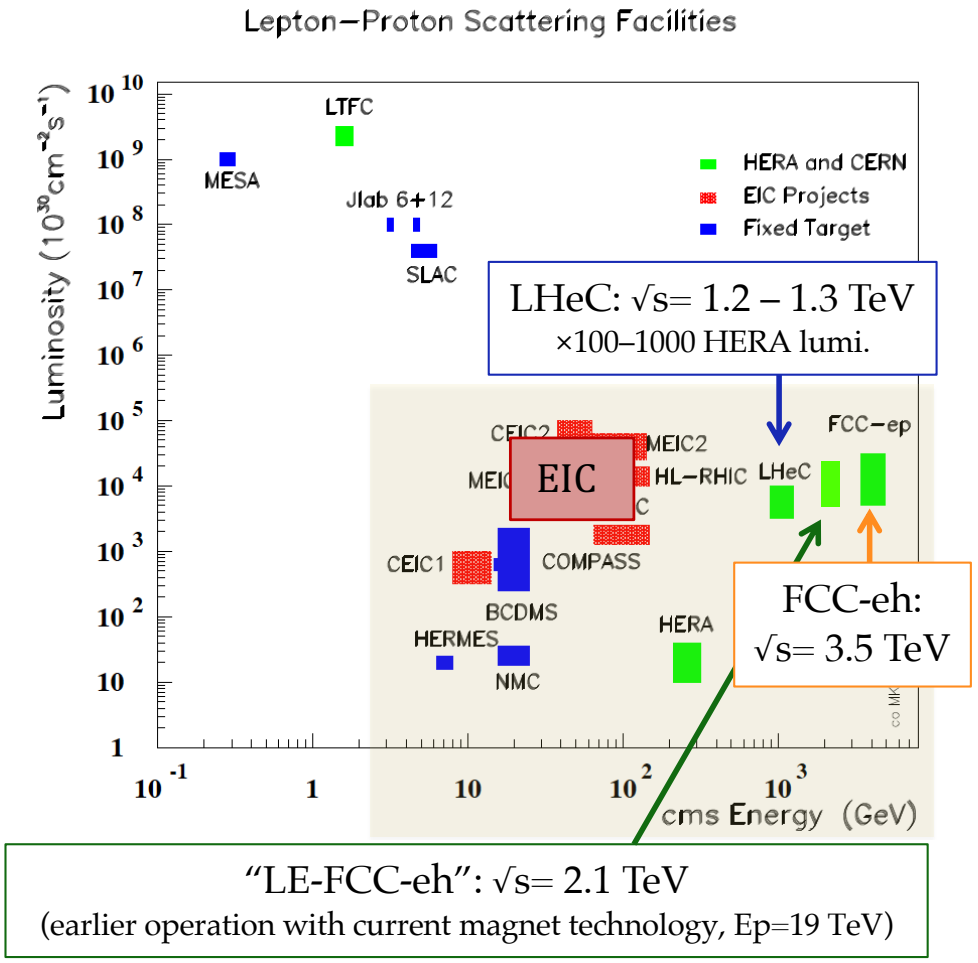
BSM searches limited by (lack of) knowledge of **large x gluon** and **quark pdfs**

… plus precision **MW**, **sin²ϑW** (where small discrepancies may indicate BSM physics) and **Higgs**,

also limited by **pdf uncertainties** at medium x, where we know pdfs best!

LHeC and FCC-eh





energy recovery LINAC (ERL)

attached to HL-LHC (or FCC)

e beam: ⟶ **50** or **60** GeV

e pol.: P= **±0.8**

Lint ⟶ **1–2** ab^{-1} (1000× HERA!)

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

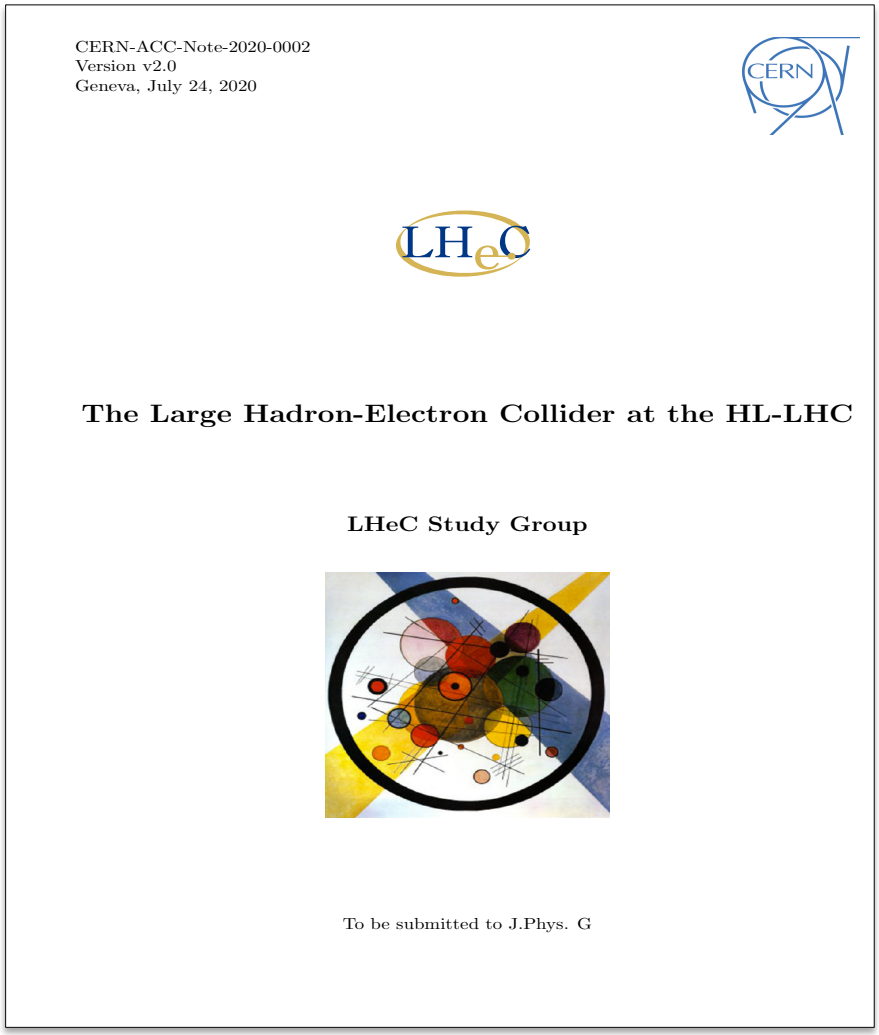
see also talks:

ERL facility **PERLE**, A Bogacz

LHeC at **CERN**, C. Schwanenberger

LHeC as part of **HL-LHC**, L. Aperio Bella

LHeC CDR update



LHeC white paper: arXiv:**2007.14491**

accepted by J.Phys.G

update to CDR, arXiV:**1206.2913** (600 citations)

compilation of new and updated studies over the past years,

400 pages, 300 authors, 156 institutions

this talk:

QCD and proton structure – Ch. 3, 4

see also other talks in this conference:

BSM, O. Fischer

HI, H. Mantysaari

Top Quark, M. Kumar

Higgs, U. Klein

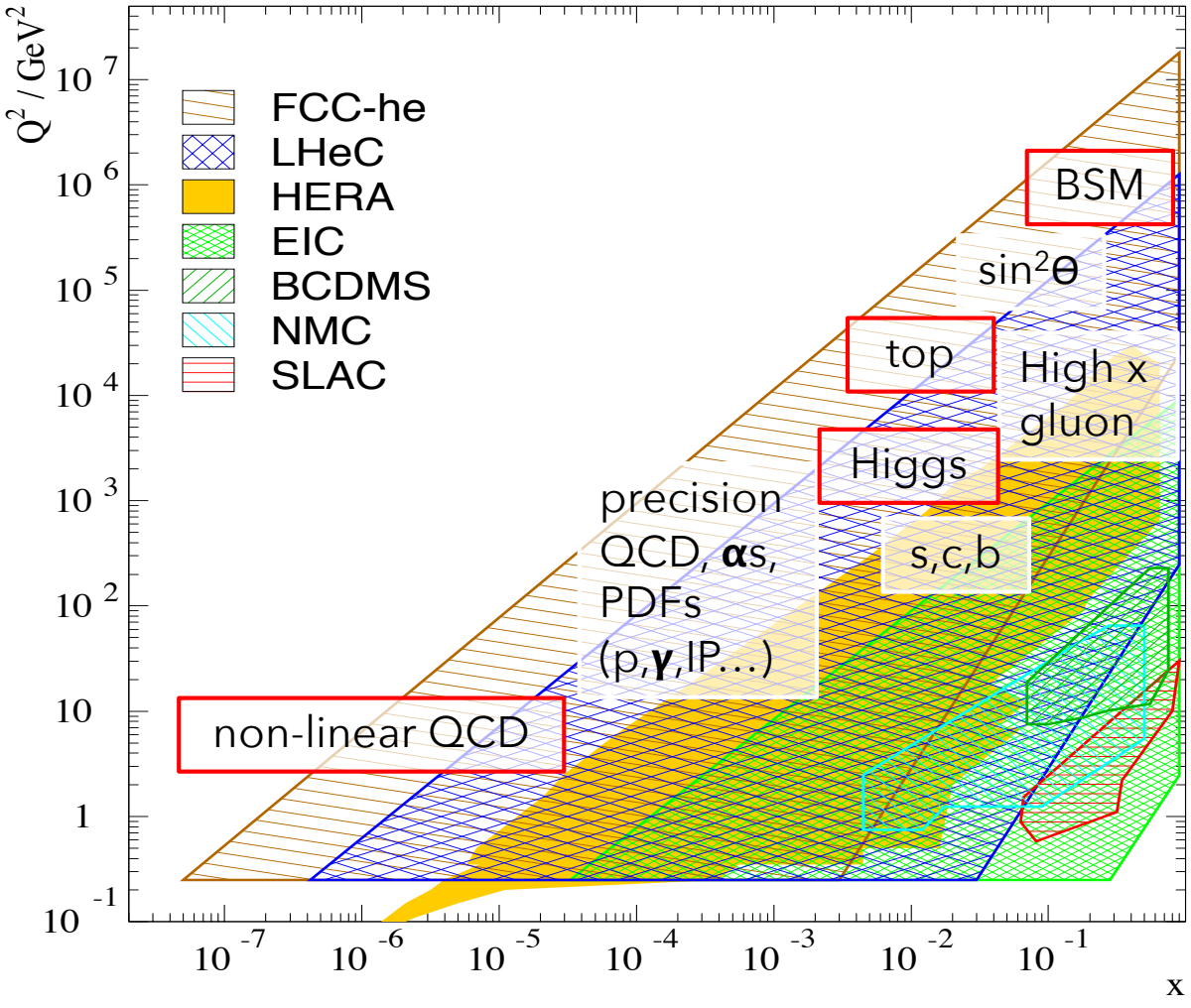
EW, D. Britzger

small x, A. Stasto

DIS and connections to the LHC, T. Hobbs (plenary)

(see also FCC CDR, vols 1 and 3: physics **EPJ C79 (2019), 6, 474** ; FCC with eh integrated **EPJ ST 228 (2019), 4, 755**)

physics with energy frontier DIS



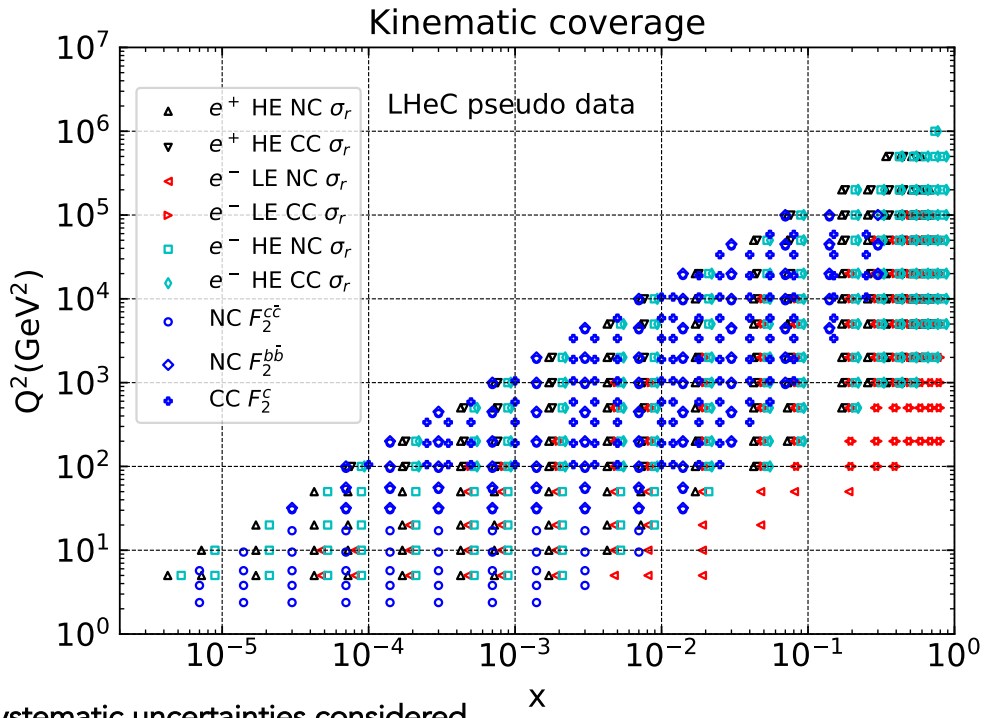
opportunity for **unprecedented increase in DIS kinematic reach**; **×1000** increase in lumi. cf. HERA

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

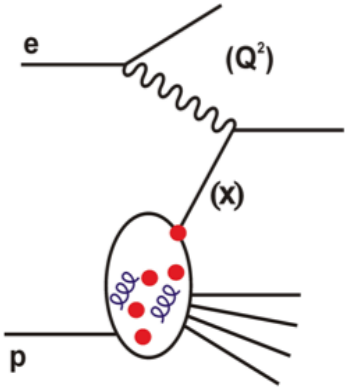
×15/120 extension in Q^2,1/x reach vs **HERA**

LHeC pdf programme



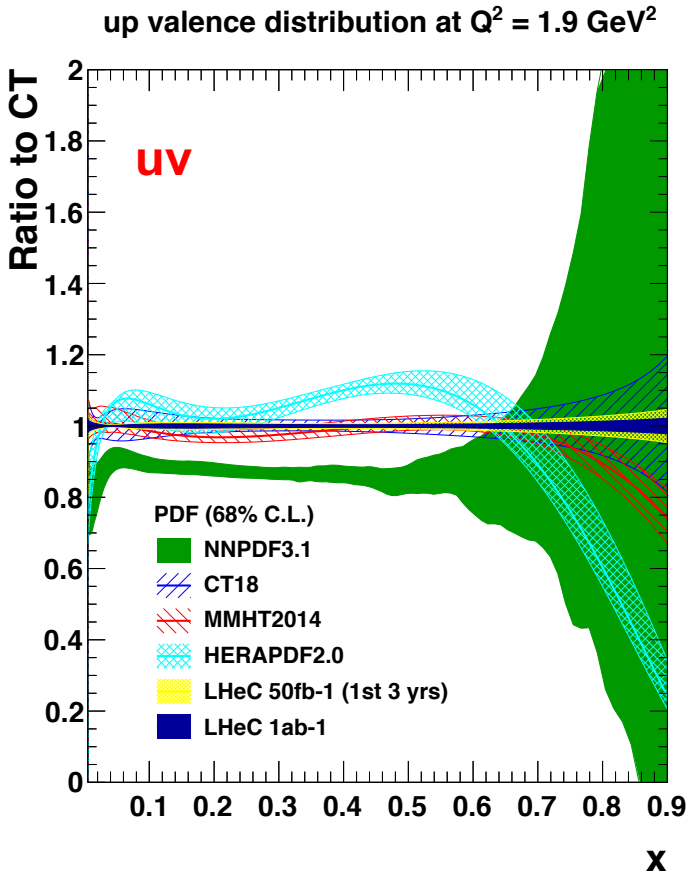
full set of systematic uncertainties considered,
see arXiv: 2007.14491 for full details

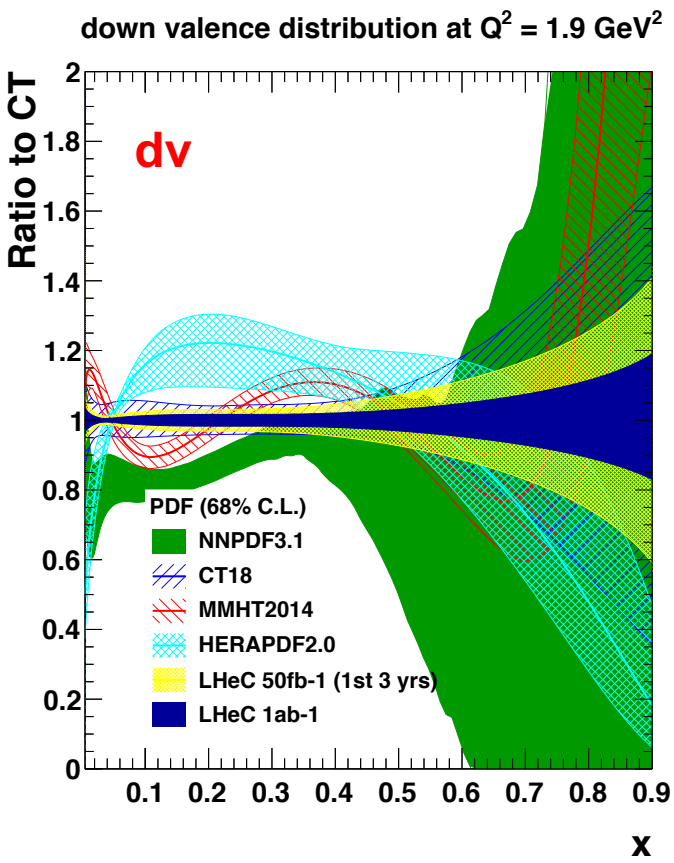
- completely resolve **all proton pdfs**, and **αs** to permille precision
- unprecedented kinematic (x,Q^2) range and precision for NC and CC measurements; tagging of c,b with high efficiency



- LHeC projected timeline, several years concurrent HL-LHC operation, plus dedicated run, arXiv:1810.13022
- LHeC **1st 3** yrs (**50** fb^{-1} e– , concurrent with HL-HLC)
  LHeC **1** ab^{-1} (**1** ab^{-1} e– , and additional P=+0.8, low energy, and **e+ data**)
- QCD analysis a la HERAPDF2.0, with greater flexibility
- 4+1 xuv, xdv, xUbar, xDbar and xg (14 params.), or 5+1 (including HQs) xuv, xdv, xUbar, xdbar, xsbar and xg (17 params.)

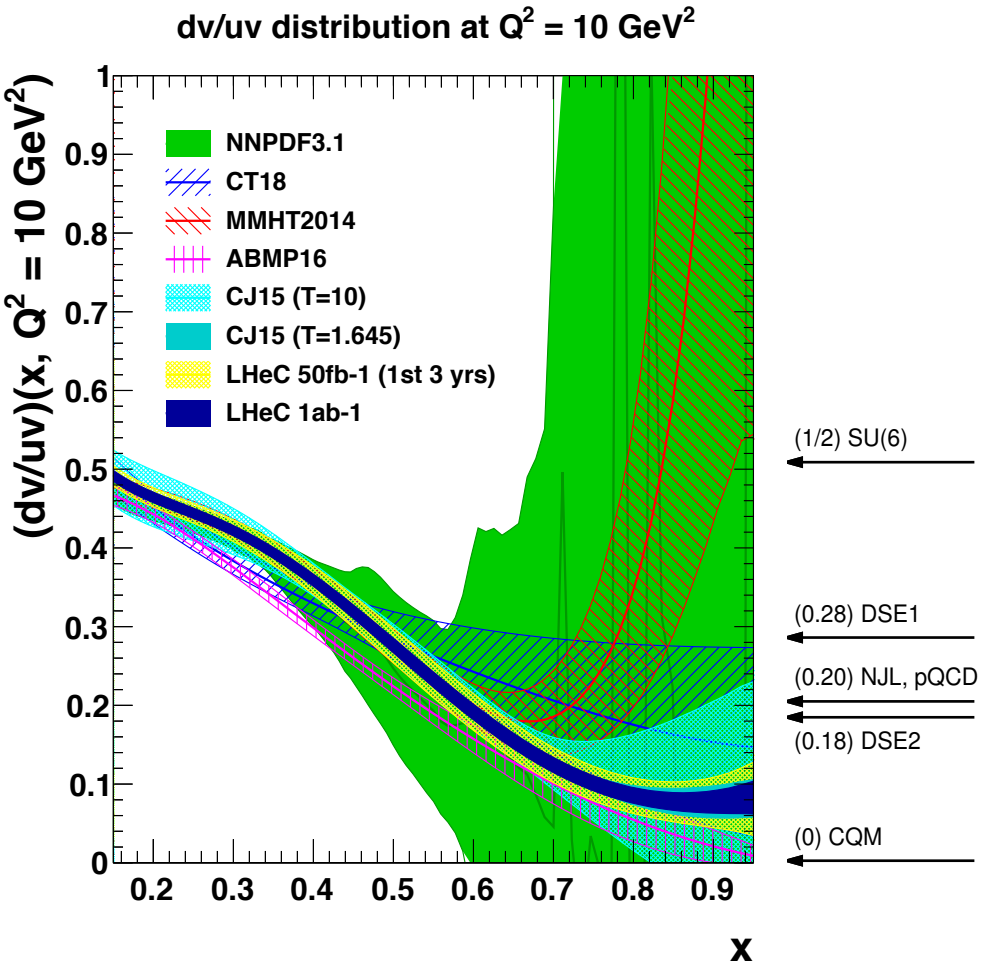
quarks





- 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

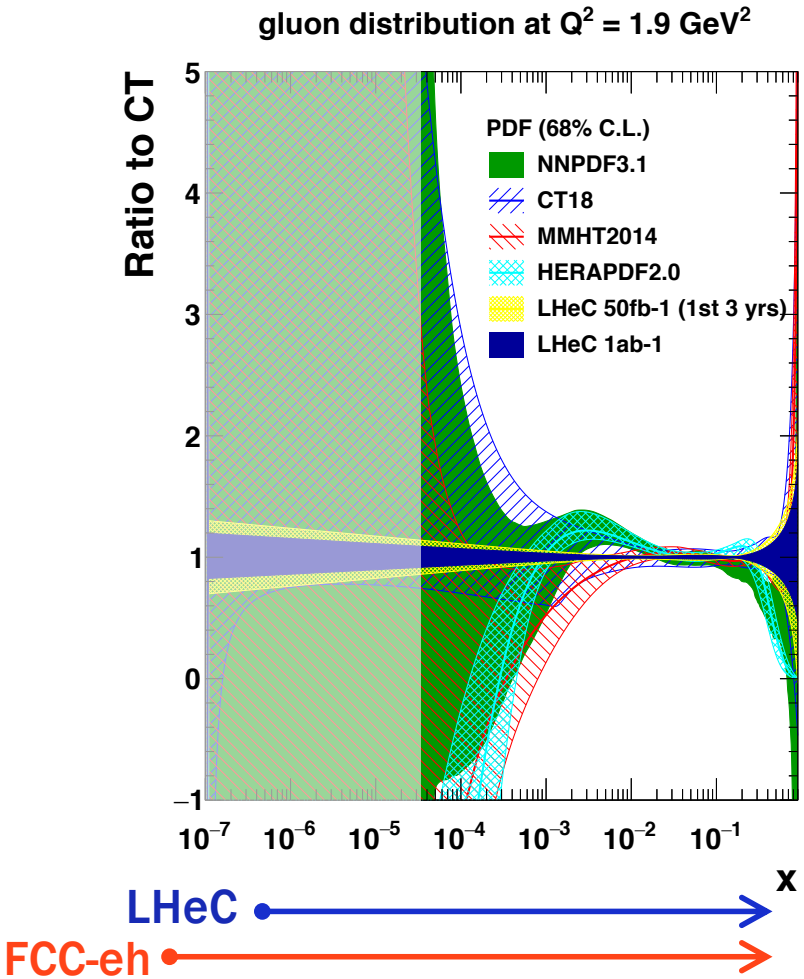


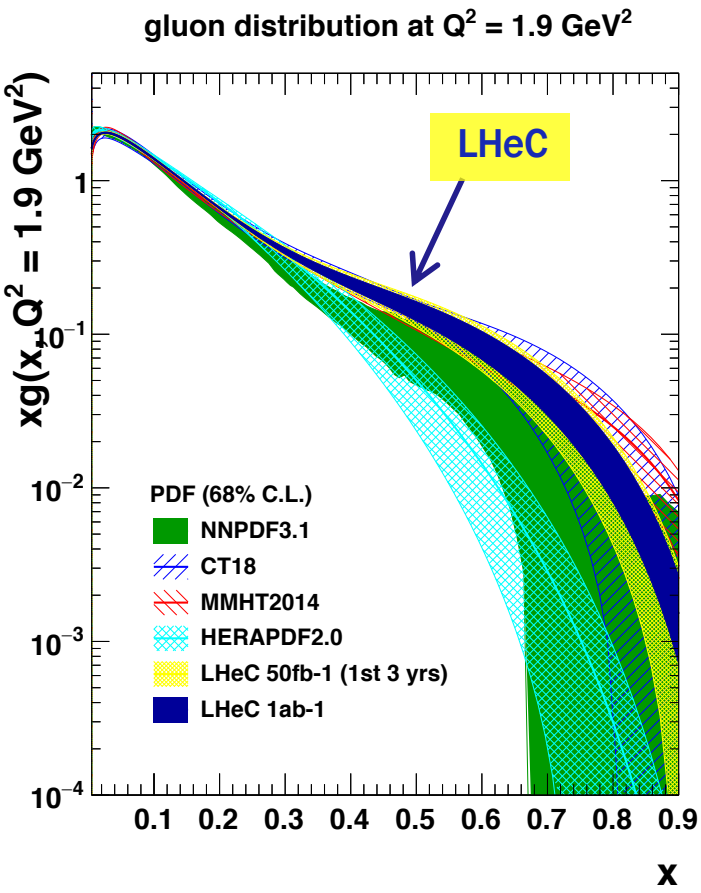
d/u essentially unknown at large x

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

gluon





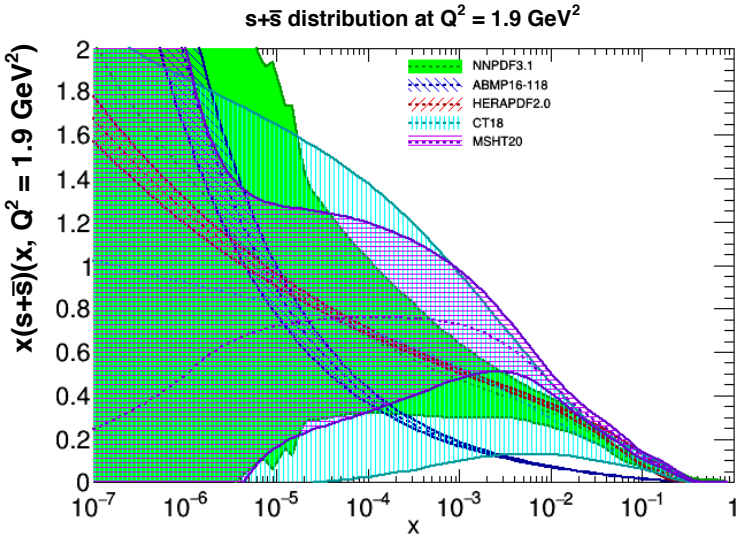
- **exploration of small x QCD**: DGLAP vs BFKL; non-linear evolution; saturation; with implications for UHE vs
- **gluon at large x** small and poorly known; **crucial for BSM searches**

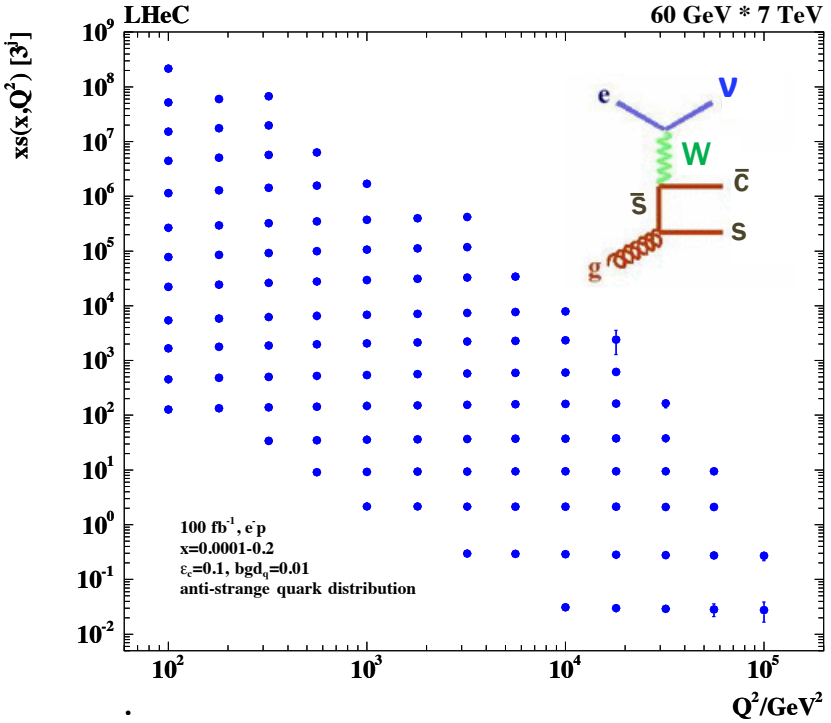
strange, c, b

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

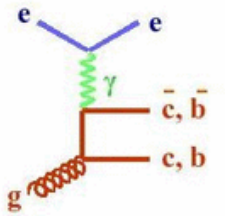
→ **LHeC:** direct sensitivity via charm tagging in Ws→c

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

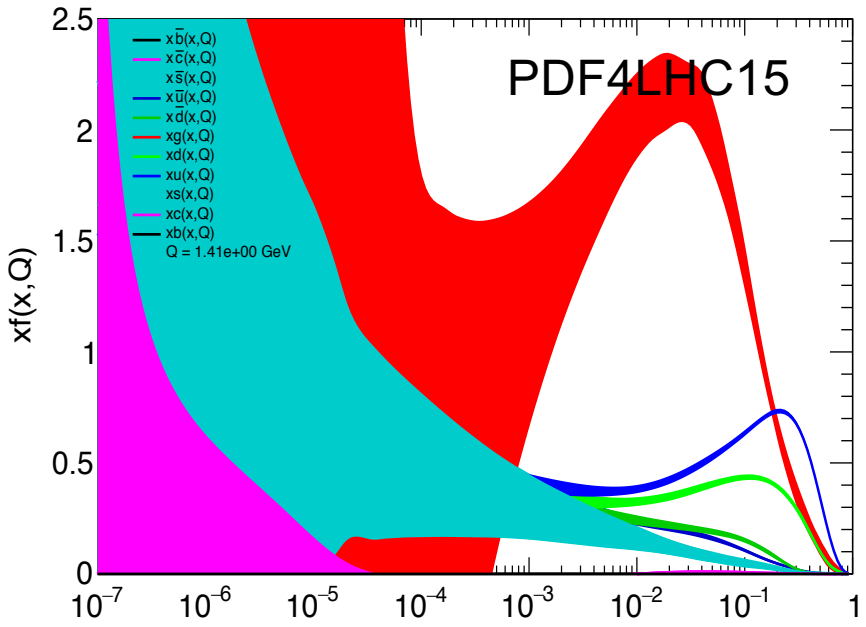


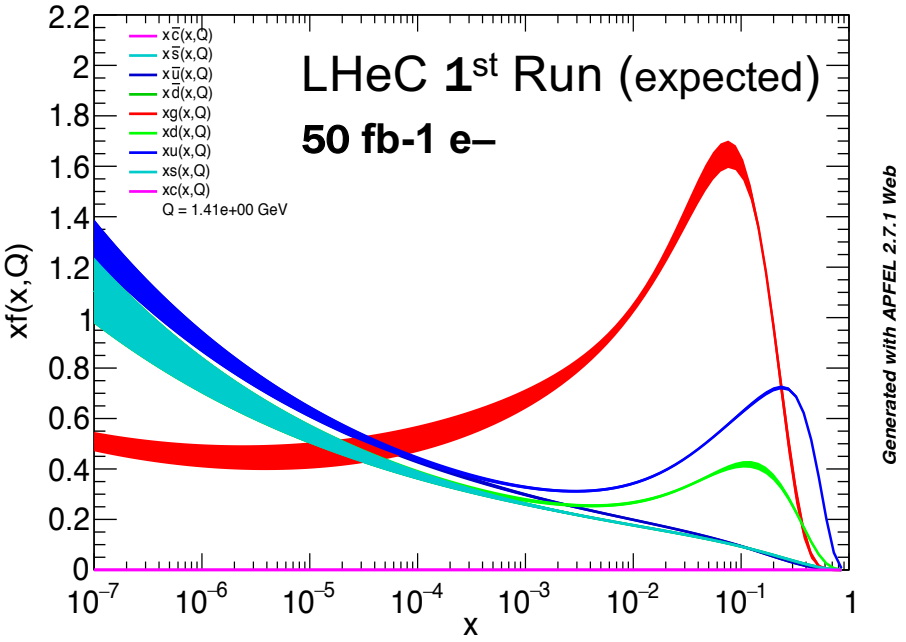


- **c, b:** enormously extended range and much improved precision c.f. HERA
- **δMc = 50 (HERA)** to **3 MeV**: impacts on **α**s, regulates ratio of charm to light, crucial for precision t, H
- **δMb** to **10 MeV**; MSSM: Higgs produced dominantly via $b\bar{b} \rightarrow A$



summary of LHeC pdfs



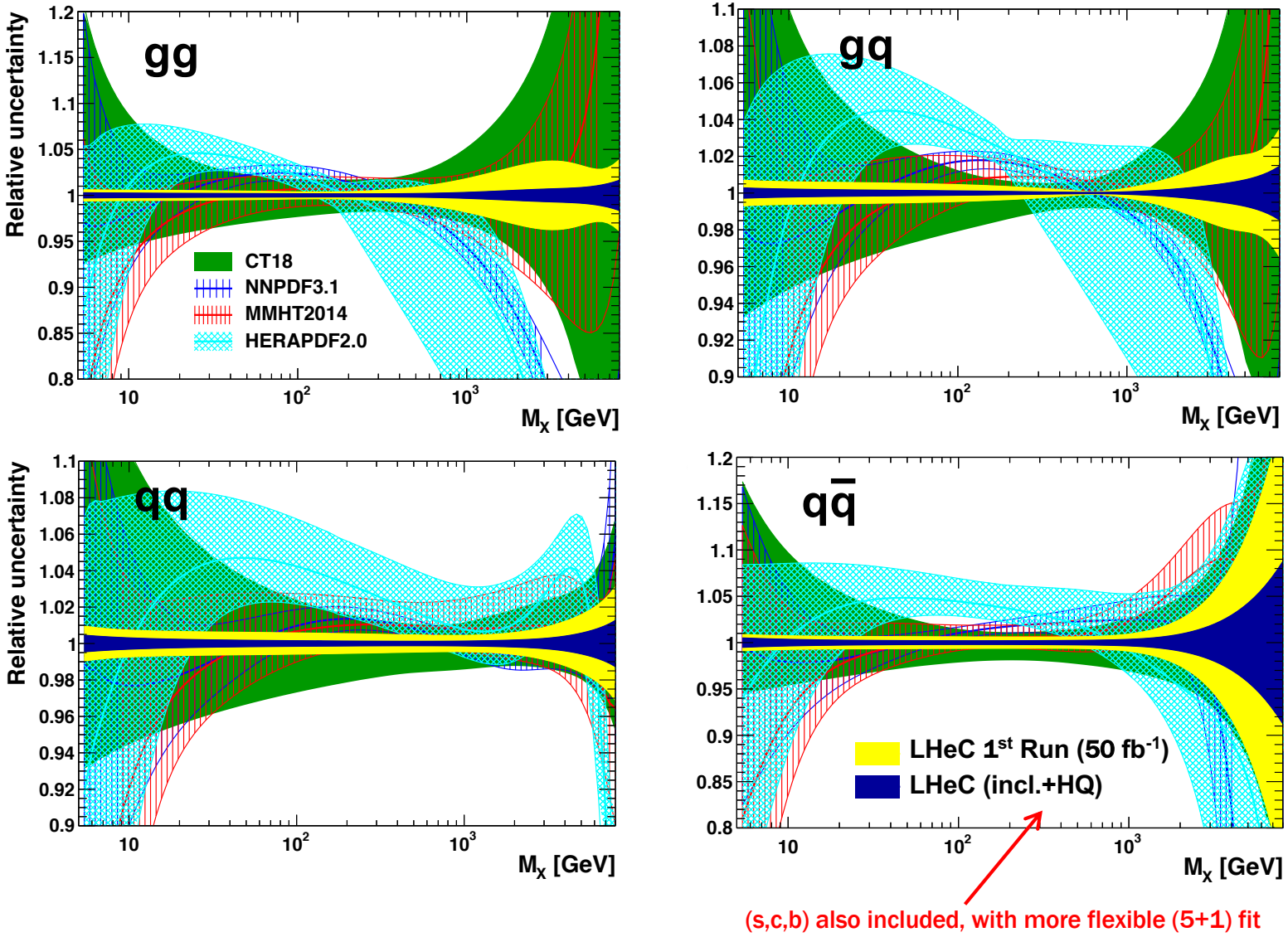


situation today

after 1st LHeC Run

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

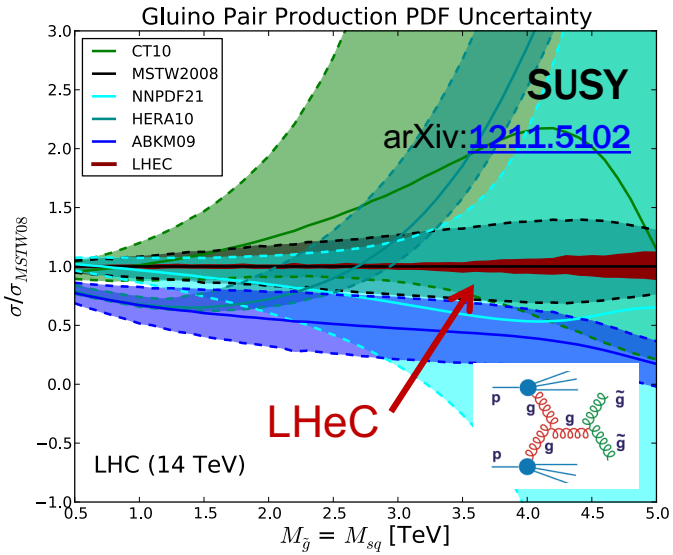
pdf luminosities @ 14TeV

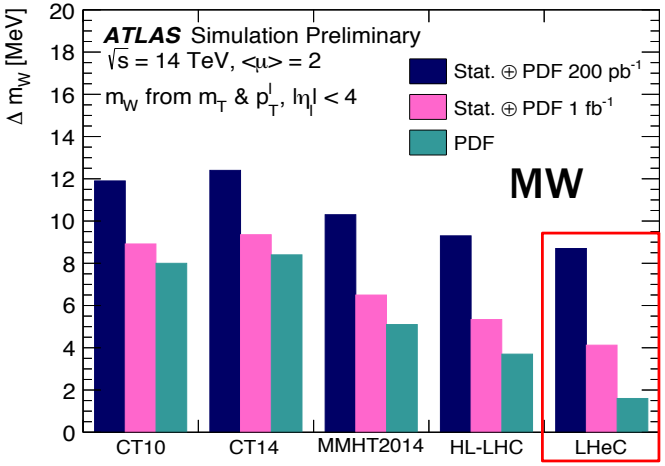


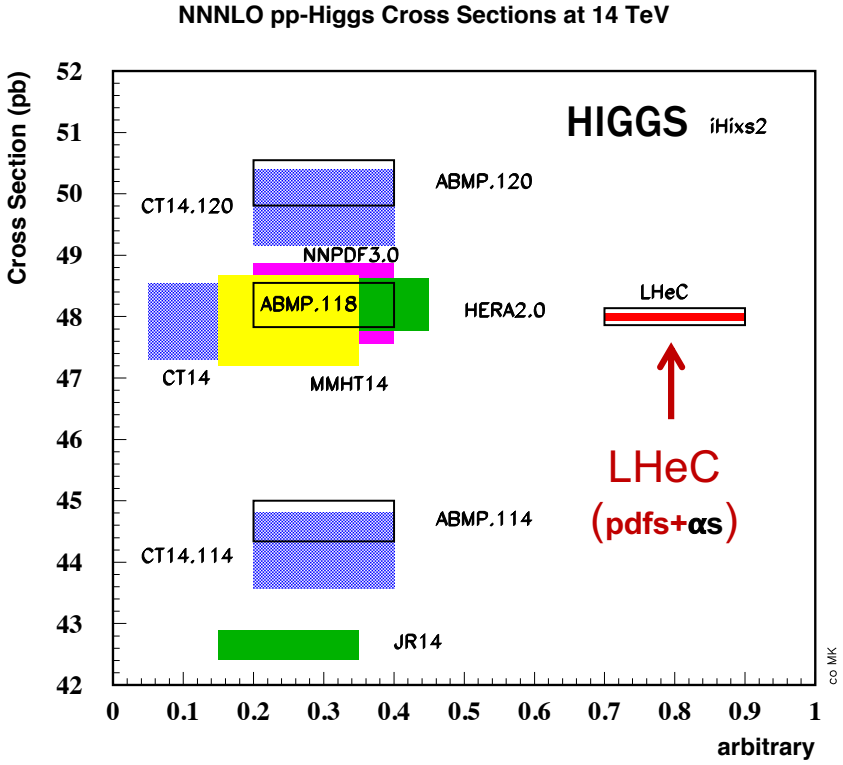
empowering the LHC

arXiv:2007.14491
arXiv:1902.04070

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



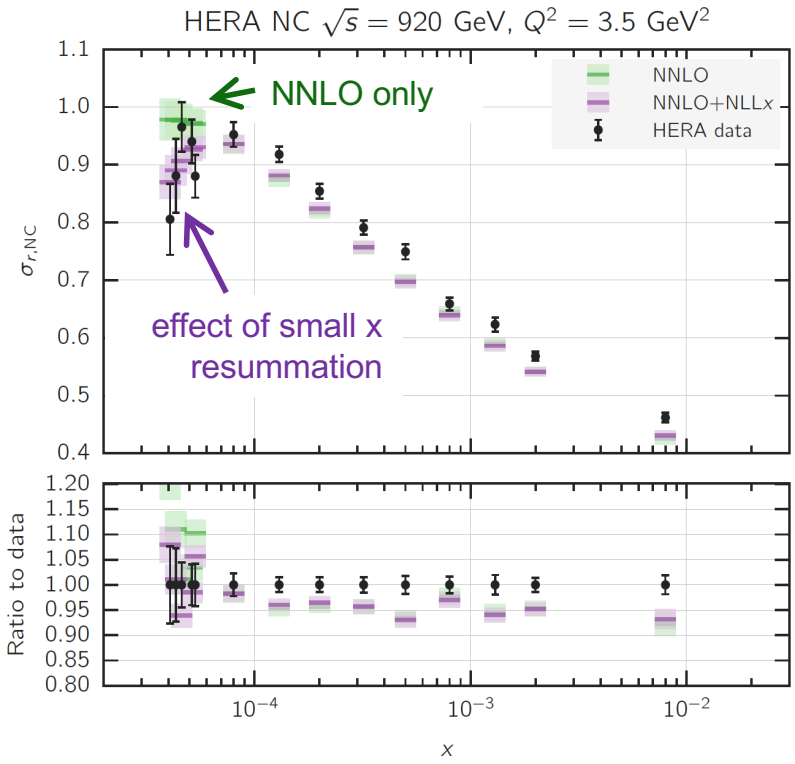


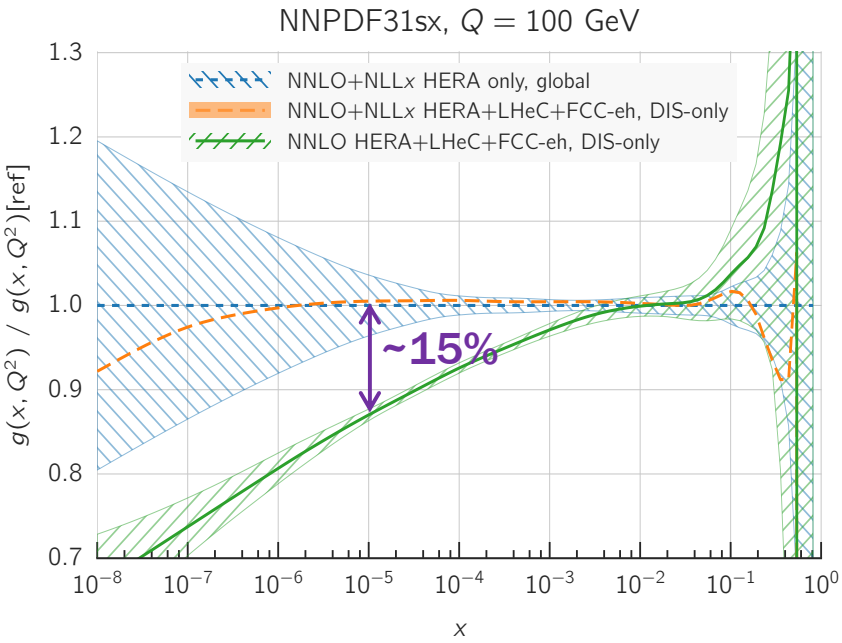


CONTACT INTERACTIONS: $\mathcal{L}_{\rm CI} = \dfrac{g^2}{\Lambda^2}\eta_{ij}(\bar{q}_i\gamma_\mu q_i)(\bar{\ell}_i\gamma^\mu \ell_i)$

Model	ATLAS (Ref. [702])	HL-LHC	
	$\mathcal{L} = 36\,\text{fb}^{-1}$ (CT14nnlo)	$\mathcal{L} = 3\,\text{ab}^{-1}$ (CT14nnlo)	$\mathcal{L} = 3\,\text{ab}^{-1}$ (LHeC)
LL (constr.)	28 TeV	58 TeV	96 TeV
LL (destr.)	21 TeV	49 TeV	77 TeV
RR (constr.)	26 TeV	58 TeV	84 TeV
RR (destr.)	22 TeV	61 TeV	75 TeV
LR (constr.)	26 TeV	49 TeV	81 TeV
LR (destr.)	22 TeV	45 TeV	62 TeV

more on small x QCD





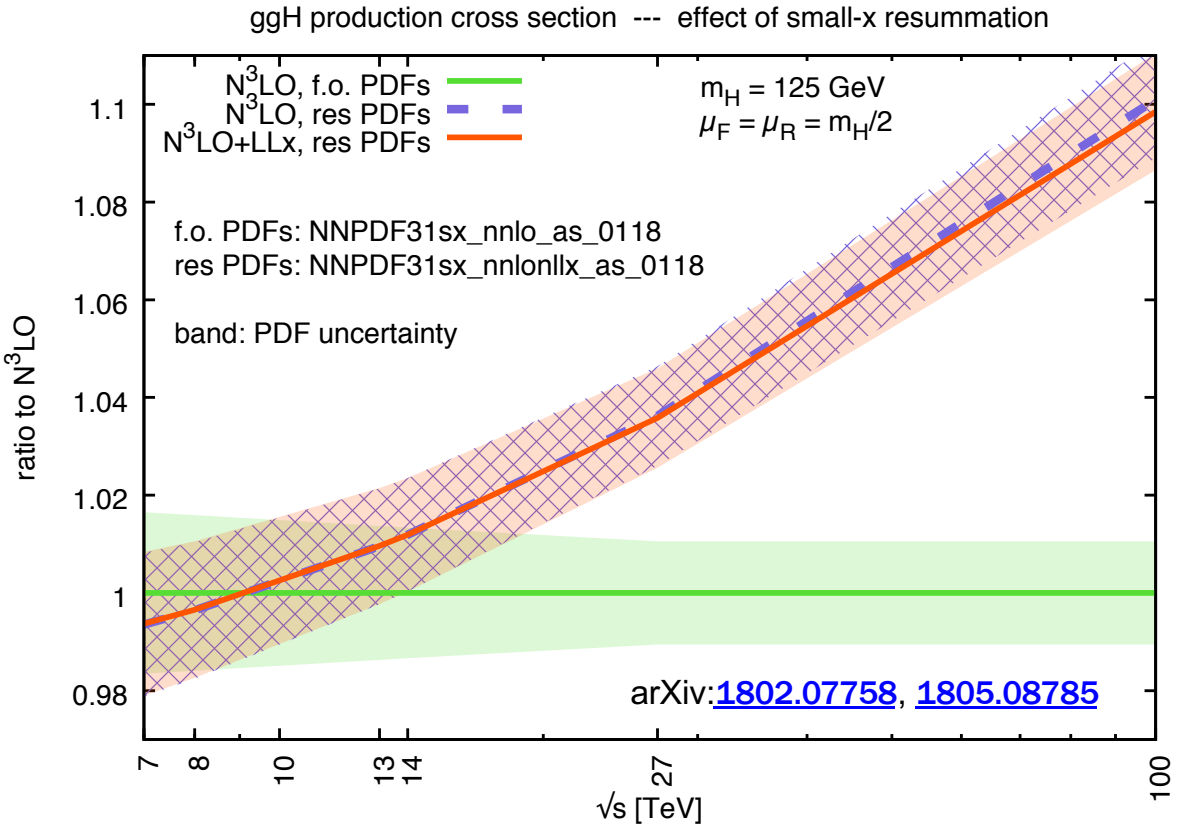
- recent evidence for onset of BFKL dynamics in HERA inclusive data,
- arXiv:1710.05935; 1802.00064

(see also, arXiv:1604.02299)

- mainly affects **gluon pdf** – dramatic effect for **x** $\lesssim$ **10^{-3}**
- impact for LHC and FCC phenomenology

- NB, gluon pdf obtained with small x resummation grows more quickly – **saturation** at some point!

impact on pp phenomenlogy

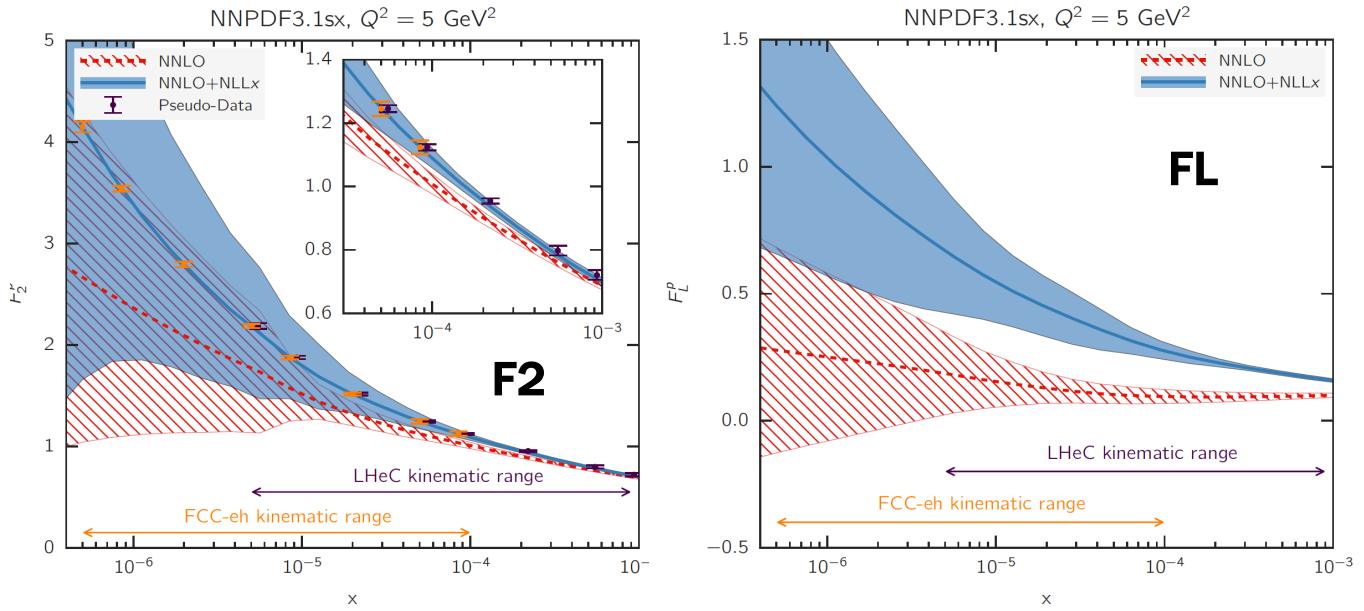


- effect of small x resummation on gg→H cross section for LHC, HE-LHC, FCC
- significant impact, especially at ultra low x values probed at FCC

(see also recent work on forward Higgs production, arXiv:2011.03193; other processes in progress)

arXiv:1710.05935

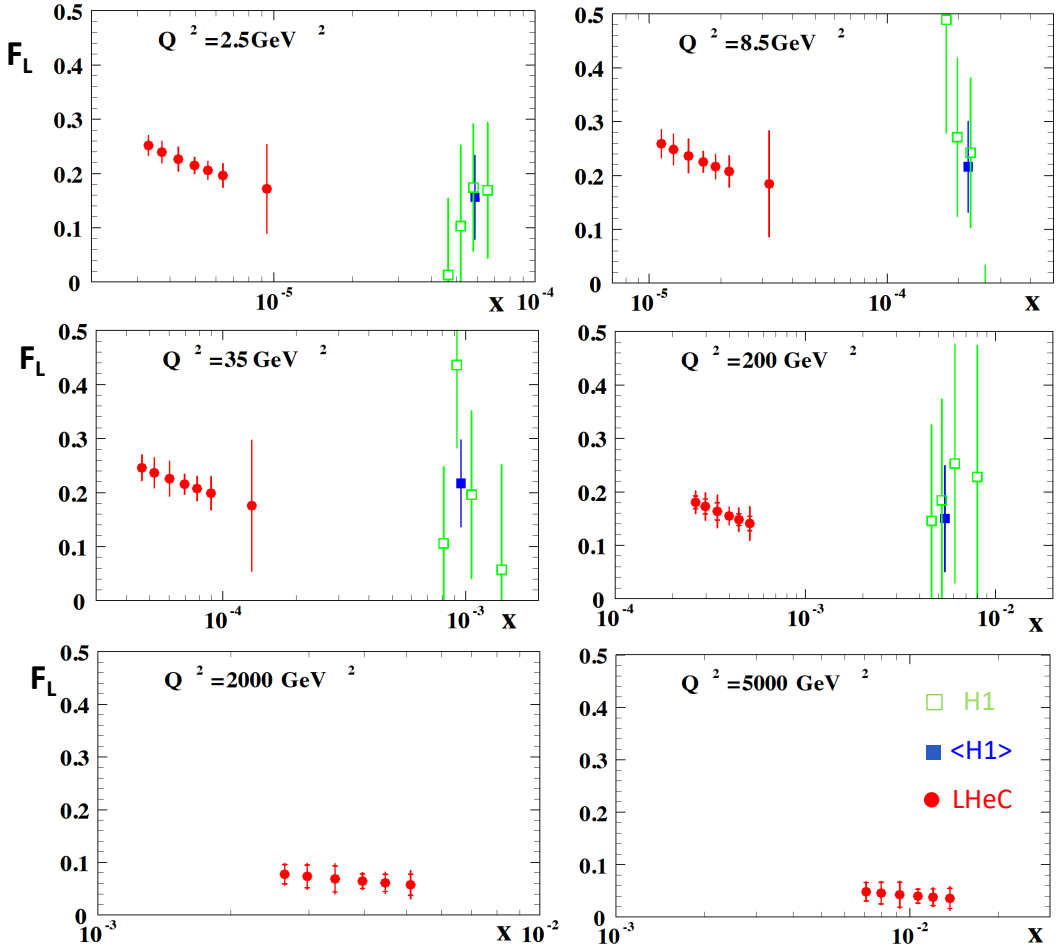
LHeC sensitivity to small x



NC cross section: $\sigma_{r,\mathrm{NC}} = F_2(x,Q^2) - \frac{y^2}{1+(1-y)^2} F_L(x,Q^2)$ $\qquad y = \frac{Q^2}{x\,s}$

- LHeC and FCC-eh have unprecedented kinematic reach to **small x**; very large sensitivity and discriminatory power to pin down details of **small x QCD dynamics**
- measurement of FL has a significant role to play, arXiv:1802.04317

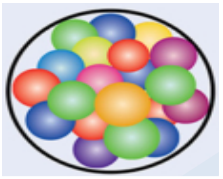
F_L from the LHeC



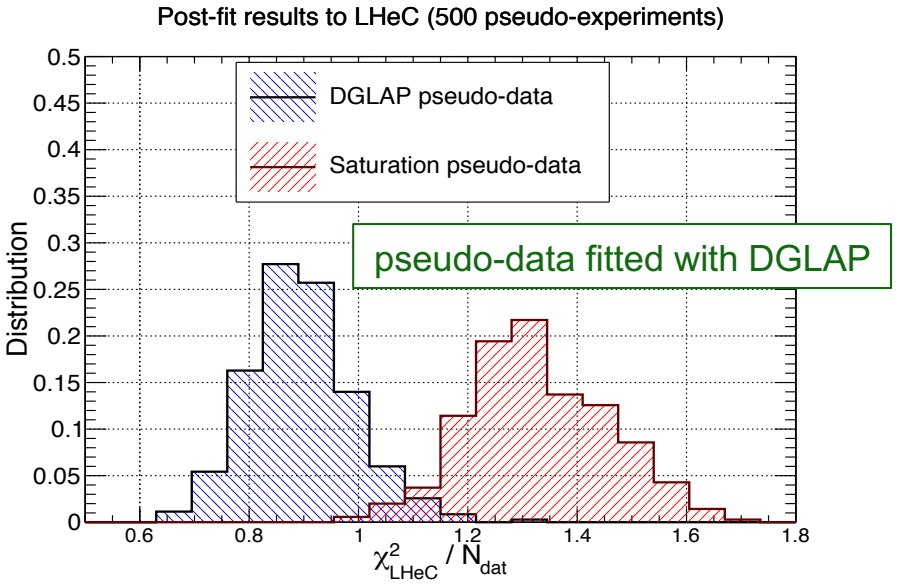
- **expect significant additional discrimination from dedicated precision measurement of FL**

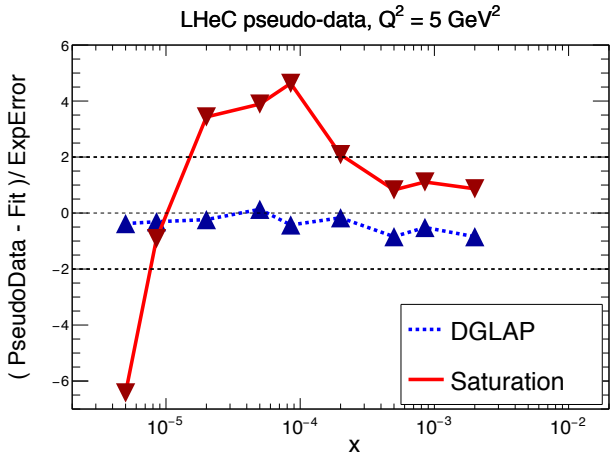
  (not yet included in shown studies); incorrect **small x** treatment unlikely to accommodate both F2 **and** FL

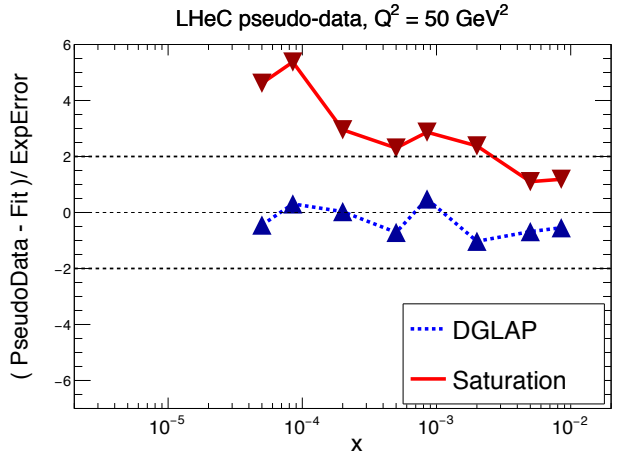
non-linear QCD dynamics



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

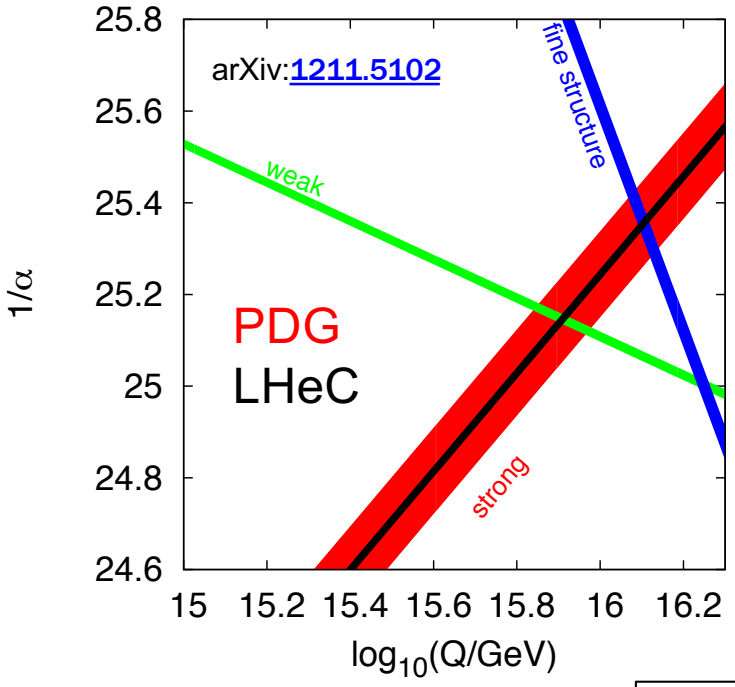


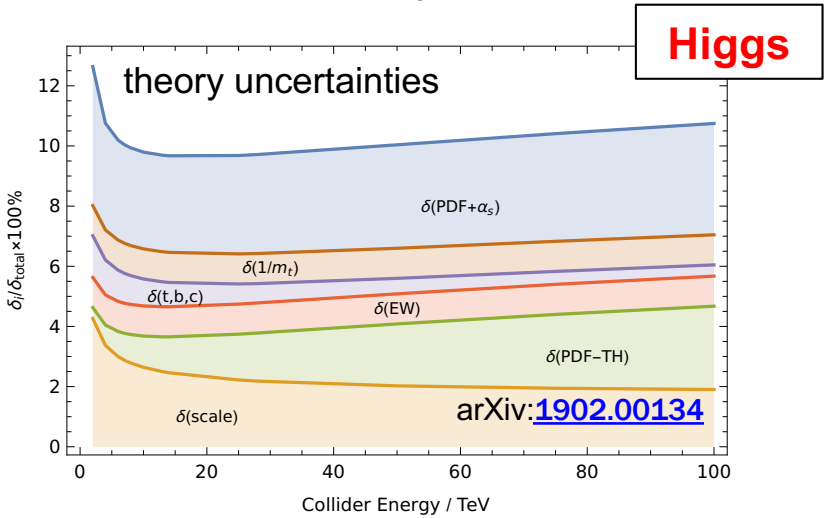




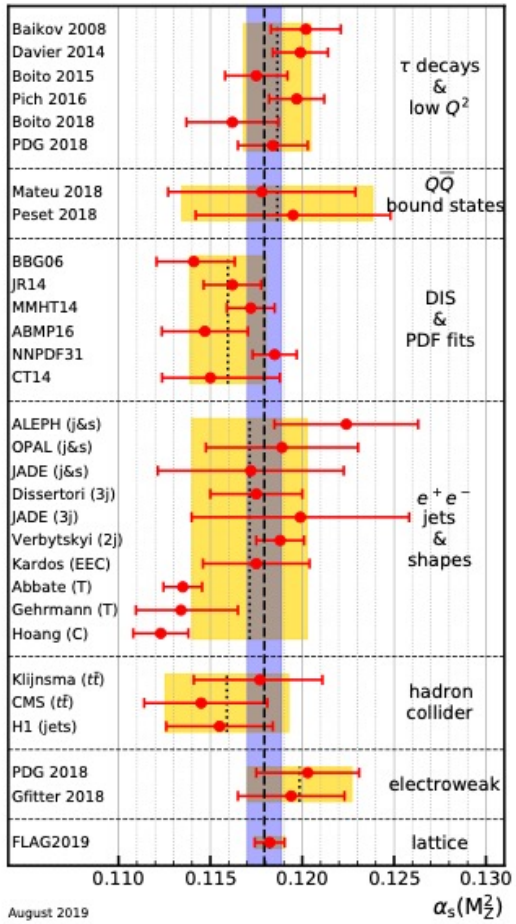
- QCD DGLAP **cannot** absorb all effects of saturation
- **possible to identify saturation by distortions in pulls** → DGLAP fits cannot absorb a non-DGLAP Q^2 dependence

strong coupling, αs





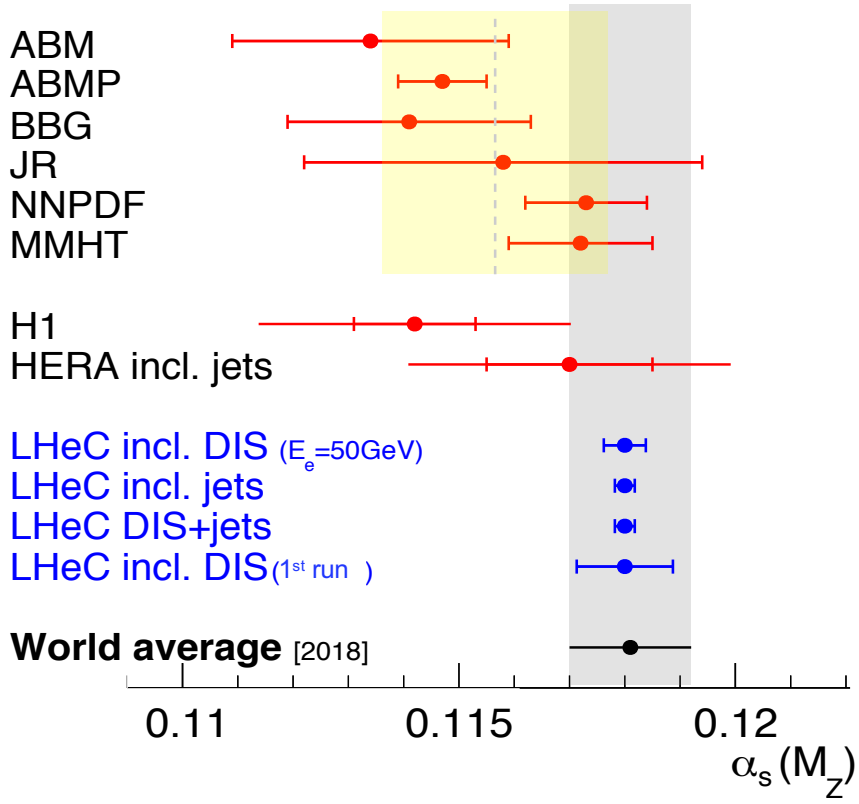
PDG20



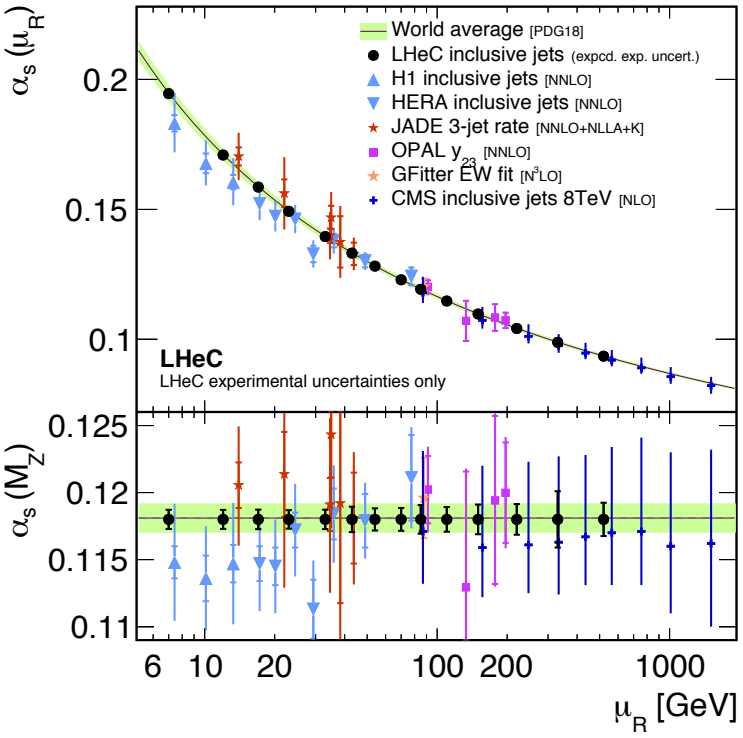
- αs is least known coupling constant
- world av.: $\alpha_s(M_Z^2) = 0.1179 \pm 0.0010$
- current state-of-the-art: δαs/αs = $\mathcal{O}(1\%)$

αs from the LHeC

αs determinations at NNLO QCD:



fit to subsets of ep jet data



LHeC simultaneous **PDF+αs** fit:

Δαs(MZ) (exp.+pdf) = **±0.00022** (inclusive DIS)

Δαs(MZ) (exp.+pdf) = **±0.00018** (incl. DIS & jets)

- **αs** running testable over two orders of magnitude in scale
- **QCD theory uncerts.** will be limiting factor

- achievable precision $\mathcal{O}(0.1\%)$ at same level as **αs** from FCC-ee

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 ⟶ 1, s, c, b, (t); N3LO; small x; strong coupling to permille precision; …

- LHeC CDR update (arXiv:**2007.14491**) summarises wealth of new and updated studies

- 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
- **αs** 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**

extras