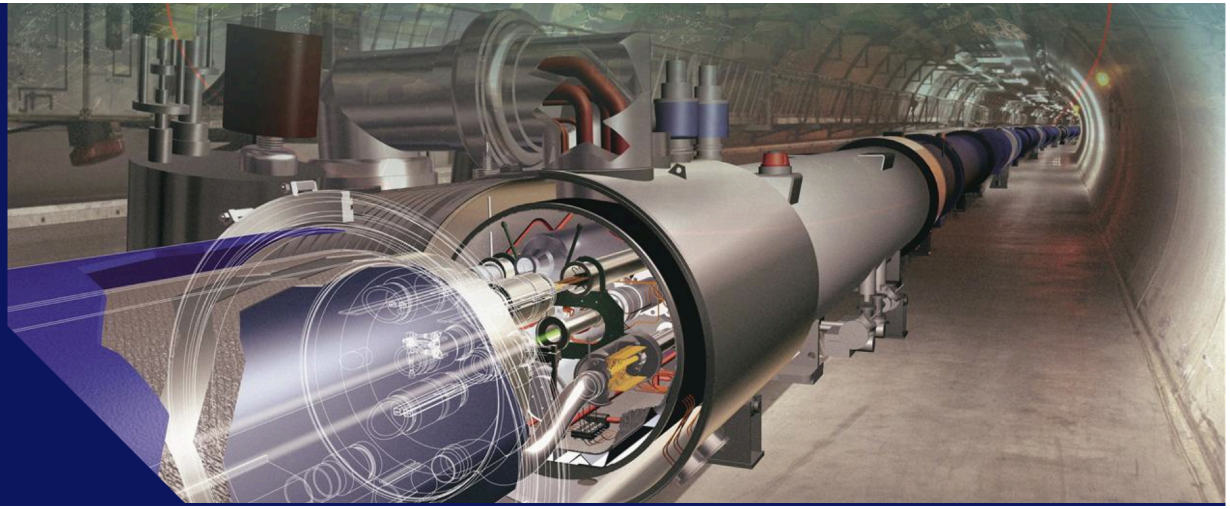
12 – 16 April 2021



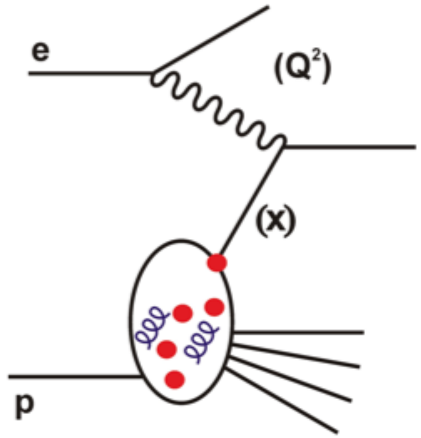
PROTON PDF DETERMINATION AT THE LHeC

Claire Gwenlan, Oxford

on behalf of the LHeC and FCC-eh study groups

UNIVERSITY OF OXFORD

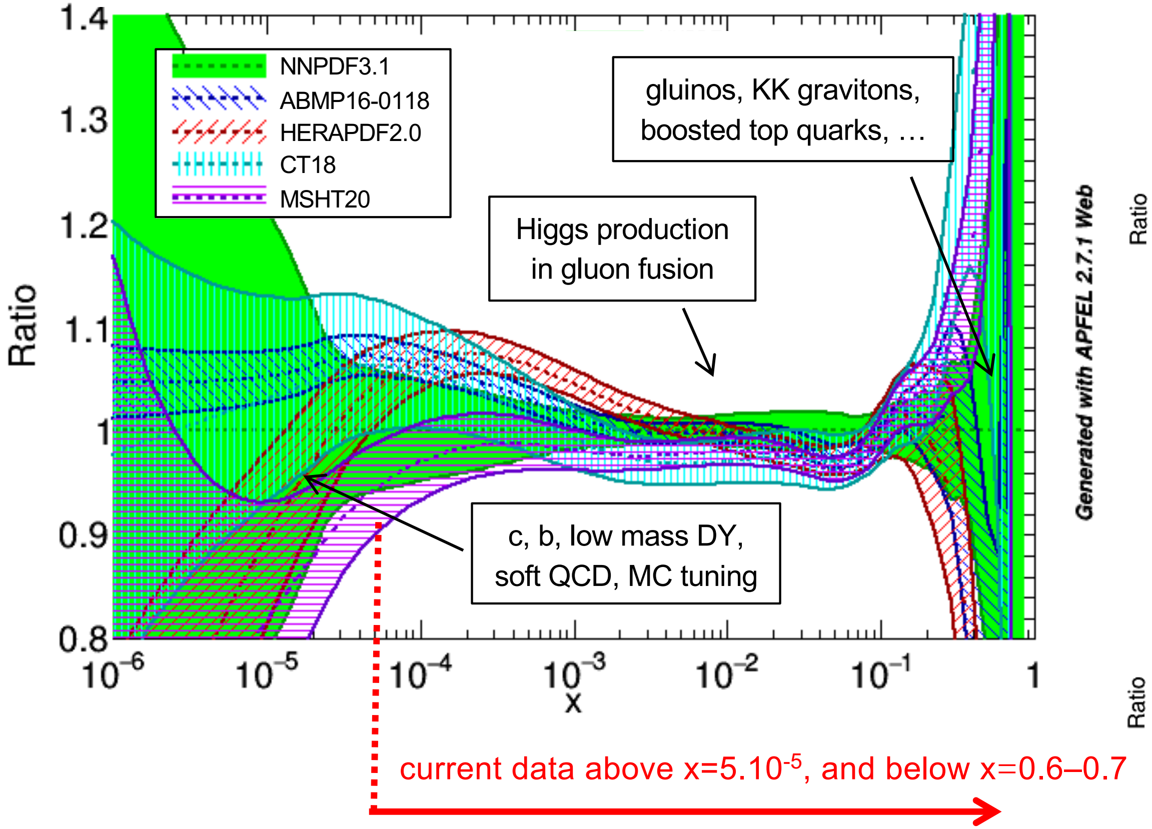
with focus on results from LHeC CDR update, arXiv:2007.14491



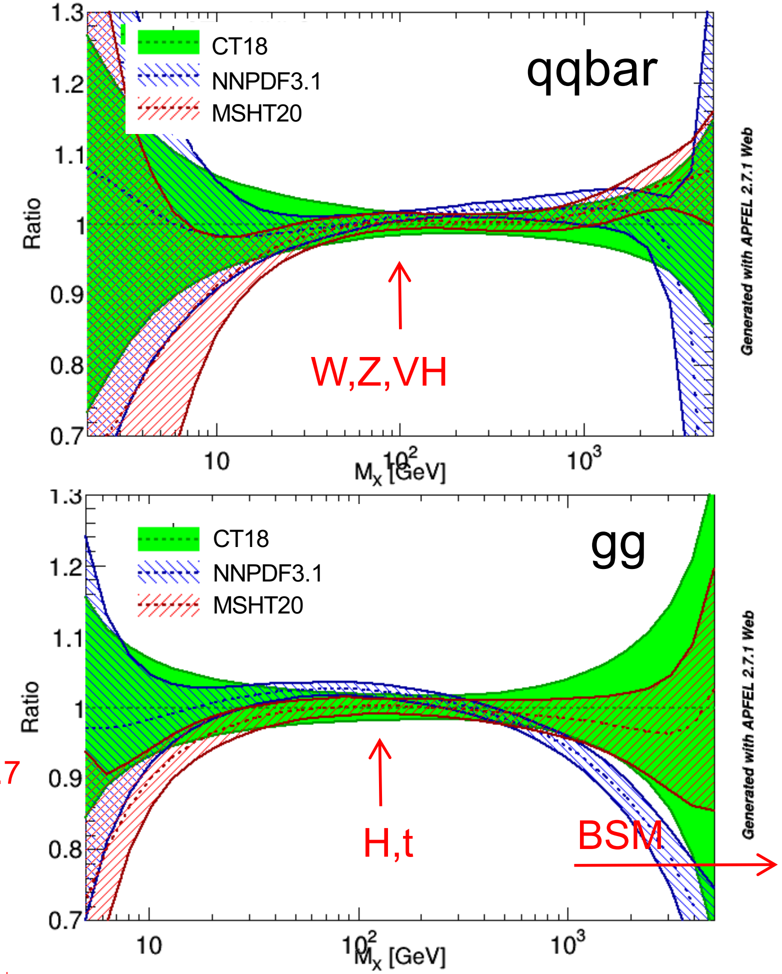
LHeC PERLE FCC hh ee he CERN

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**

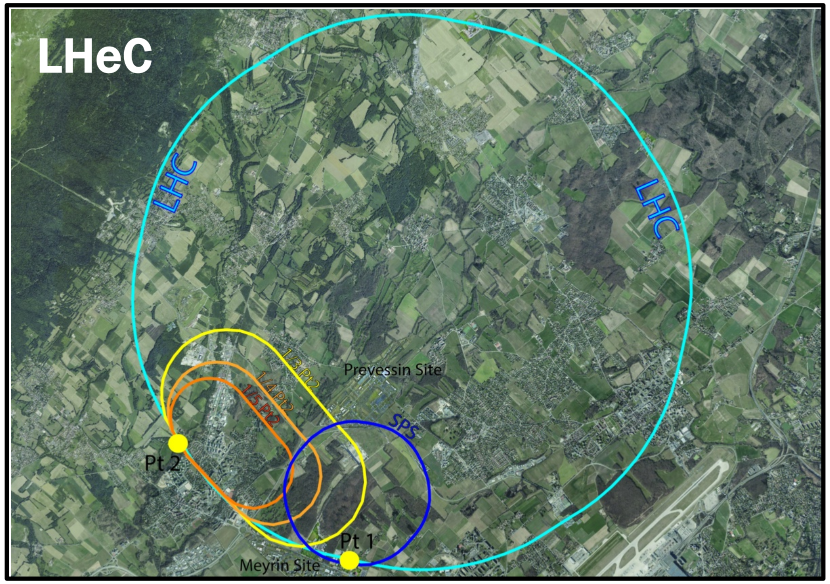
BSM searches limited by (lack of) knowledge of **large x gluon** and **quark pdfs**

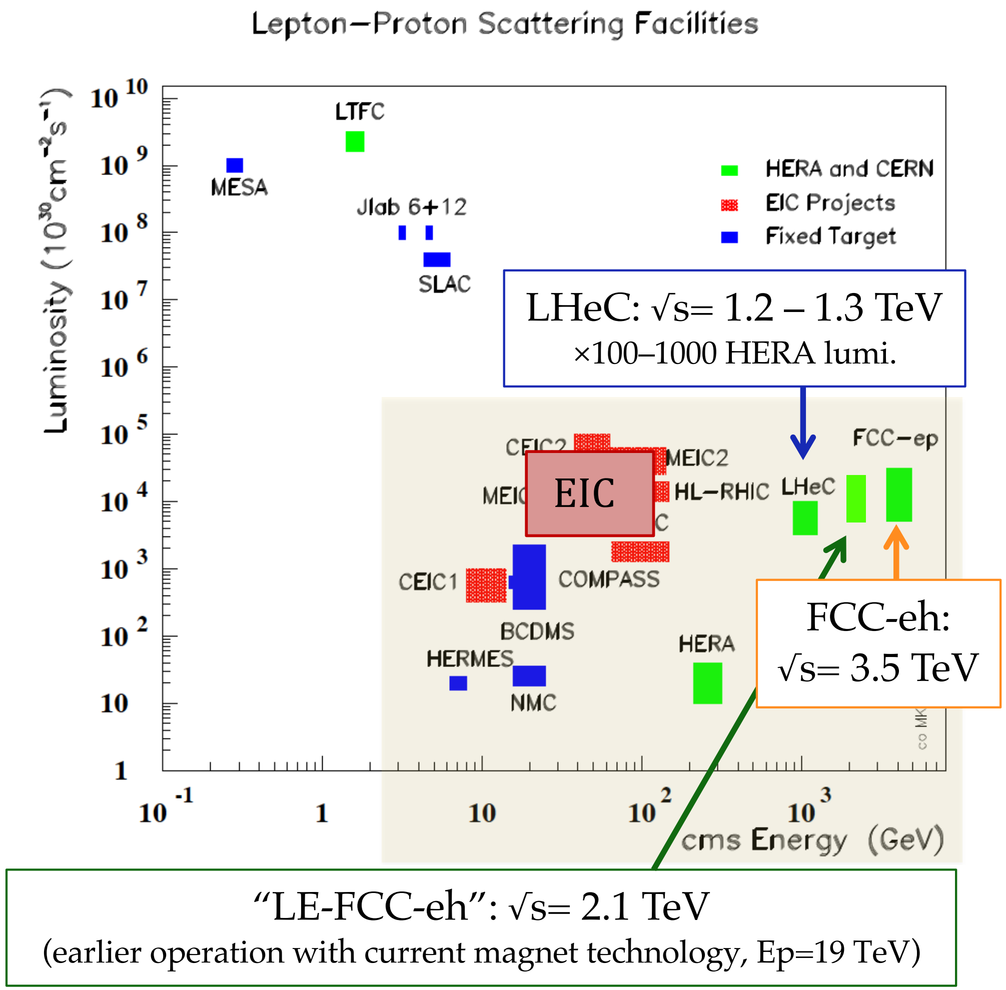
… plus precision **MW**, **sin^{2}θW** (where small discrepancies may indicate BSM physics) and **Higgs**,

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

crucial also to ensure **BSM deviations not inadvertently absorbed into pdfs**, see EG. arXiv:2104.02723 , 1905.05215

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!)

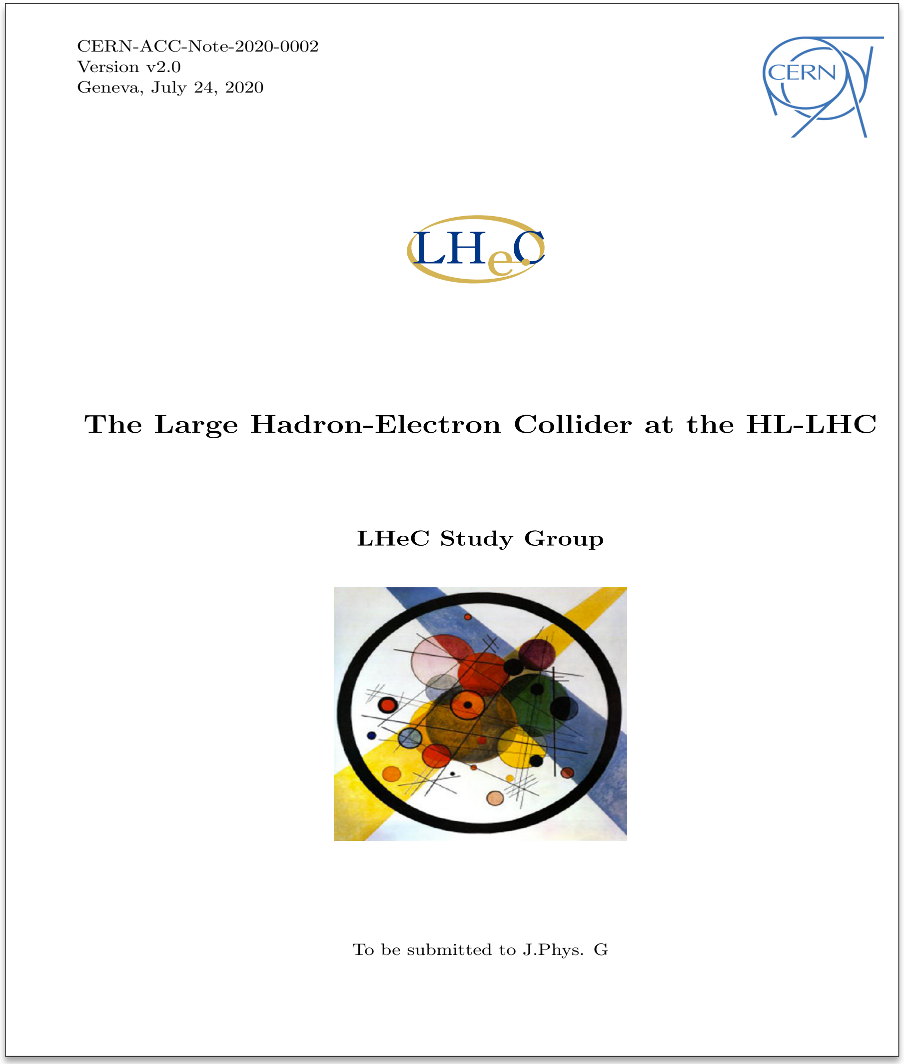
ESPPU: ERL is a high-priority future initiative for CERN

see also talks:

ERL facility PERLE, *A Bogacz*

LHeC at CERN, *C. Schwanenberger*

LHeC CDR update


CERN-ACC-Note-2020-0002
Version v2.0
Geneva, July 24, 2020

CERN

LHeC

The Large Hadron-Electron Collider at the HL-LHC

LHeC Study Group

To be submitted to J.Phys. G

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:

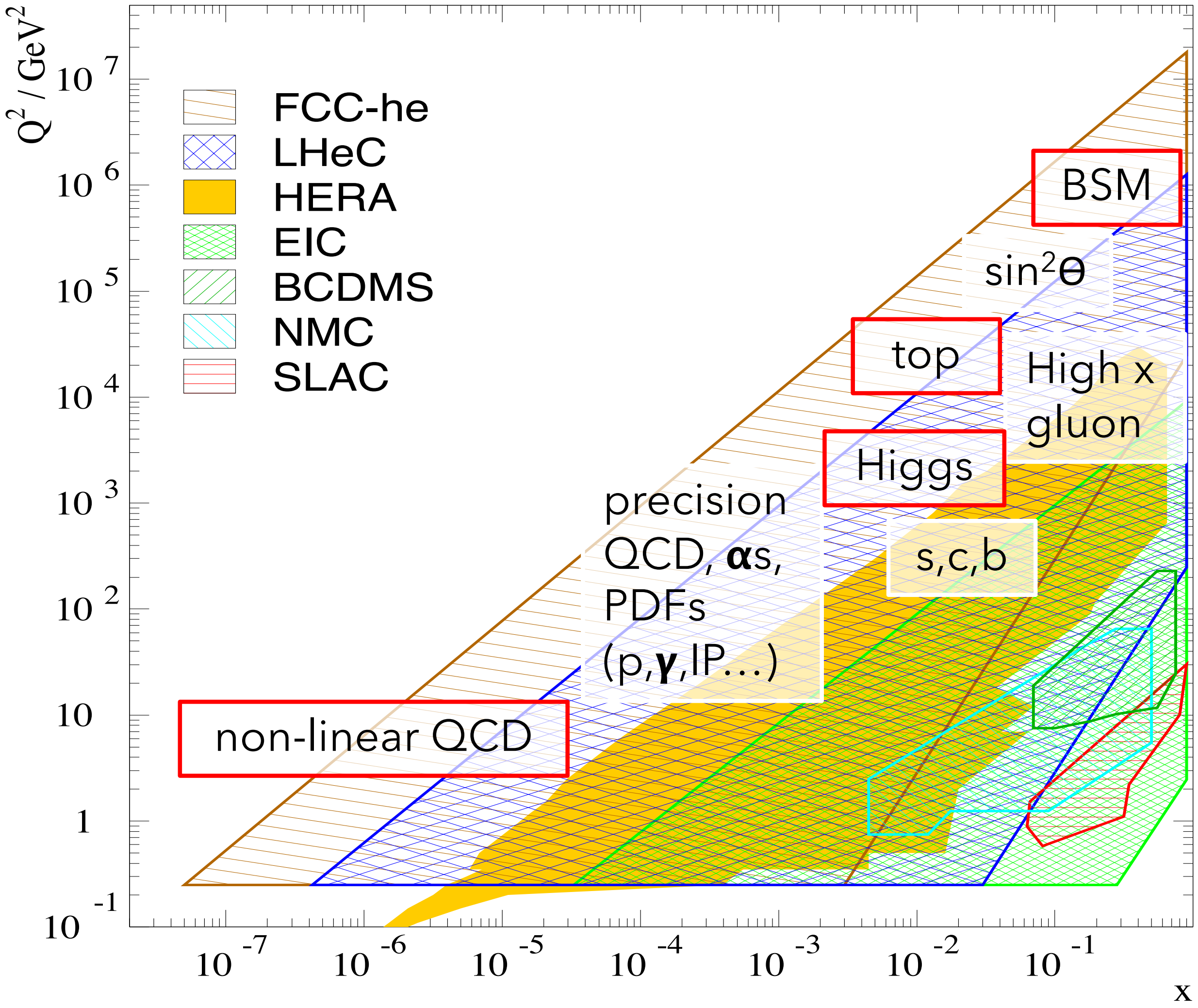
QCD and proton structure – Ch. 3, 4

see also other physics talks in this conference:

BSM, *O. Fischer*
eA, *H. Mantysaari*
Top Quark, *M. Kumar*
Higgs, *U. Klein*
EW, *D. Britzger*
small x, *A. Stasto*
LHeC as part of HL-LHC, *L. Aperio Bella*
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**;

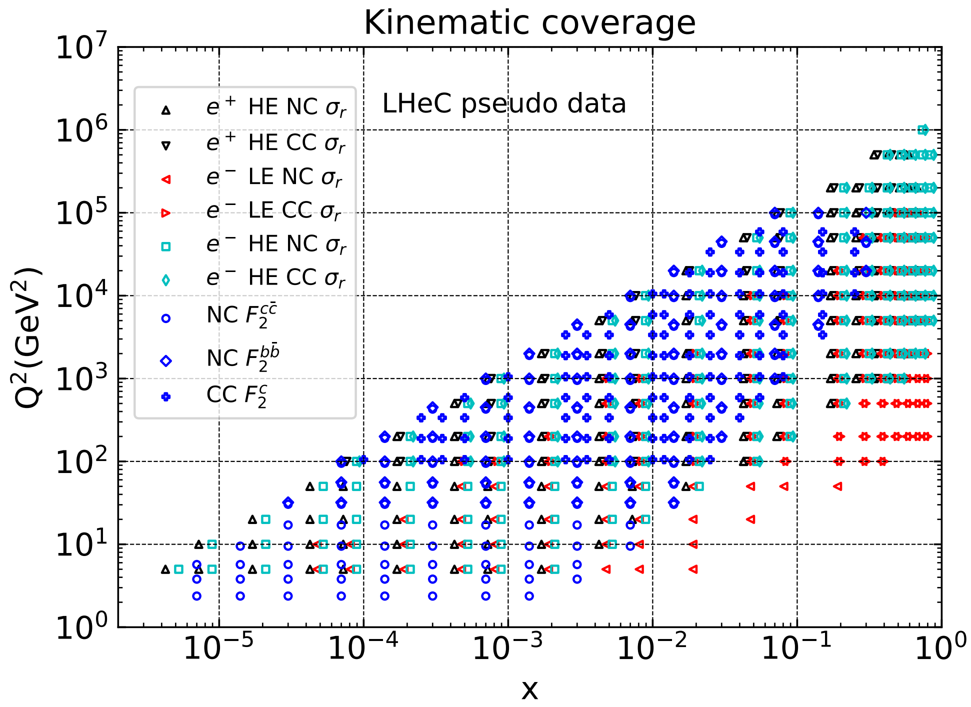
×1000 increase in lumi. cf. HERA

no higher twist, no nuclear corrections, free of symmetry assumptions, N^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**

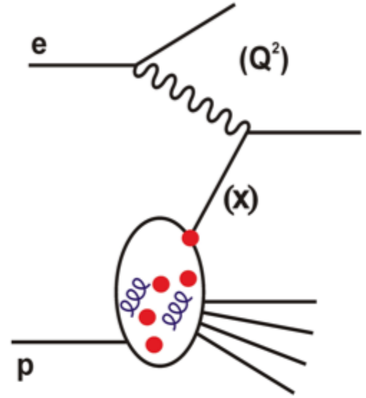
LHeC pdf programme



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

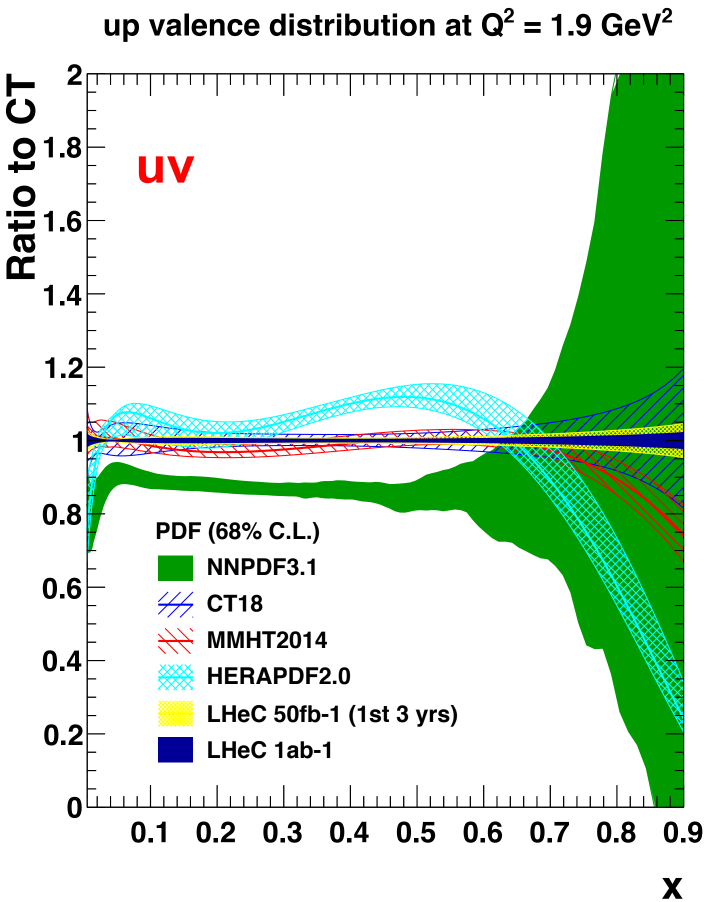


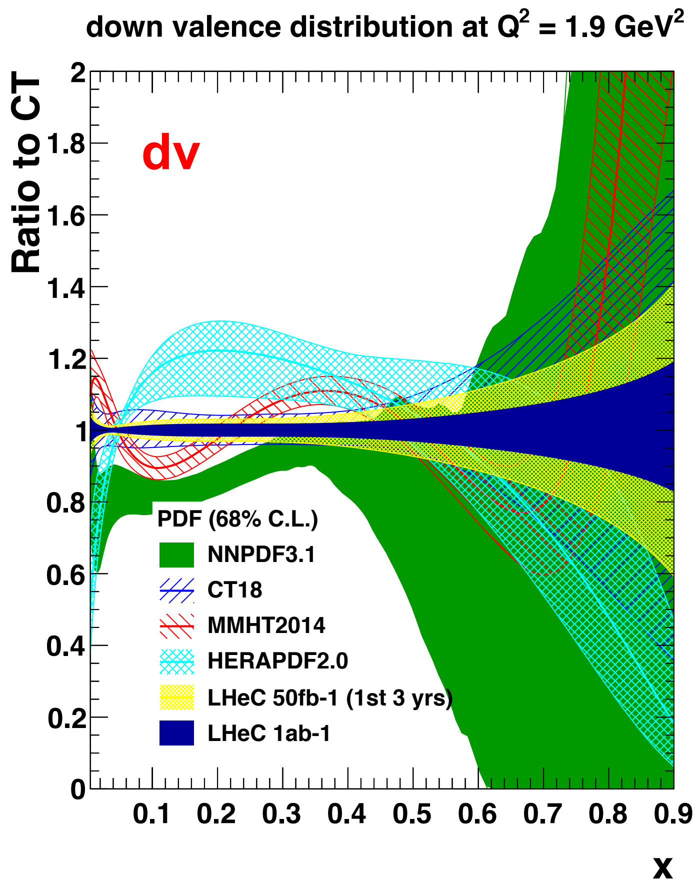
- LHeC projected timeline, several years concurrent HL-LHC operation, plus dedicated run, arXiv:1810.13022

- **LHeC 1st 3 yrs (50** fb^{-1} e– , concurrent with HL-LHC)
  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.)

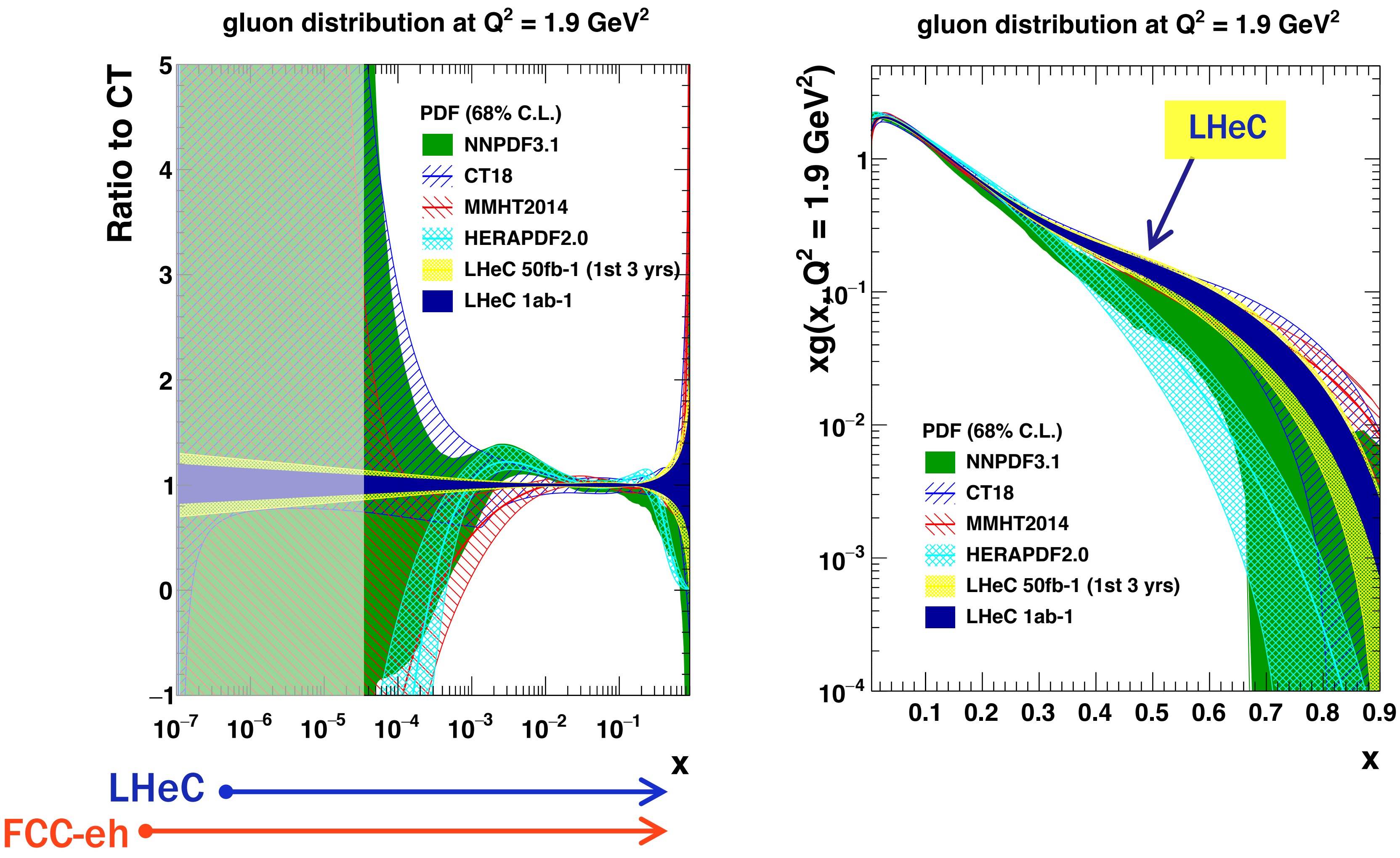
valence quarks





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

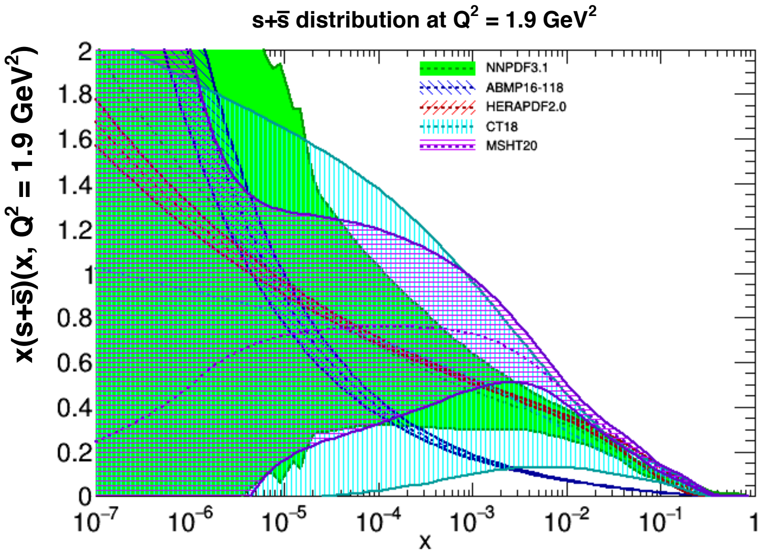
gluon



- **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**

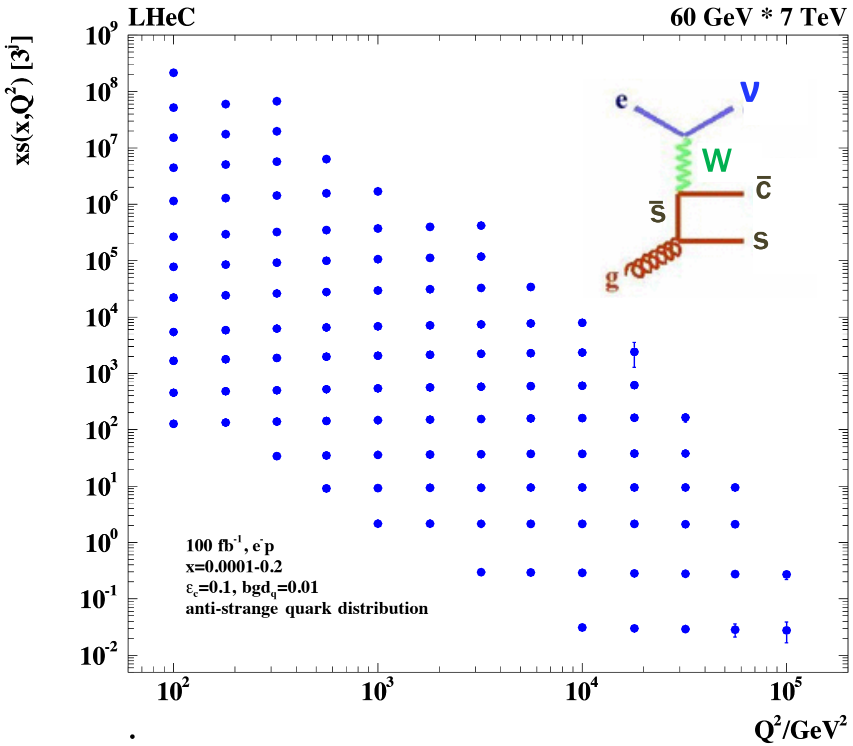
strange, c, b

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

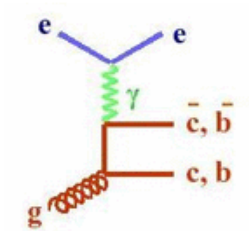


➜ **LHeC:** direct sensitivity via charm tagging in Ws→c

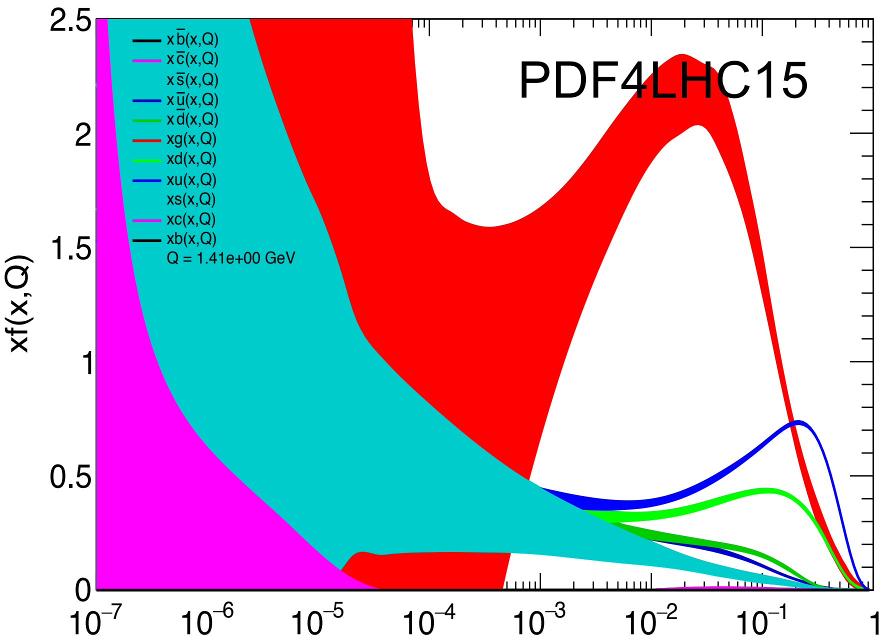
(x,Q^2) mapping of strange density for first time

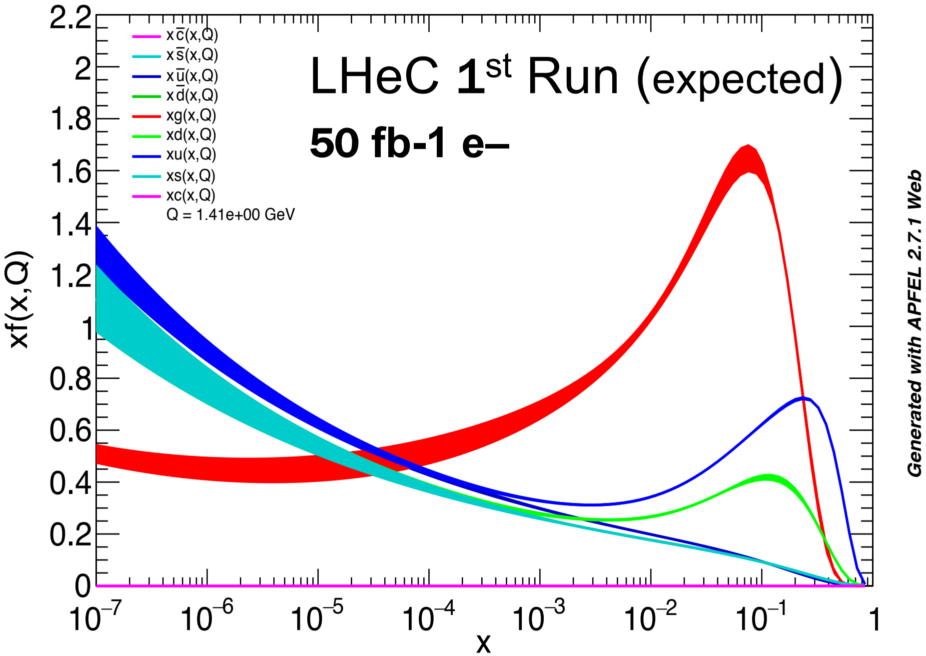


- **c, b:** enormously extended range and much improved precision c.f. HERA
- **δMc = 50 (HERA)** to **3 MeV**: impacts on **α**s, regulates ratio of charm to light, crucial for precision t, H
- **δMb** to **10 MeV**; MSSM: Higgs produced dominantly via $b\bar{b} \to A$



summary of LHeC pdfs

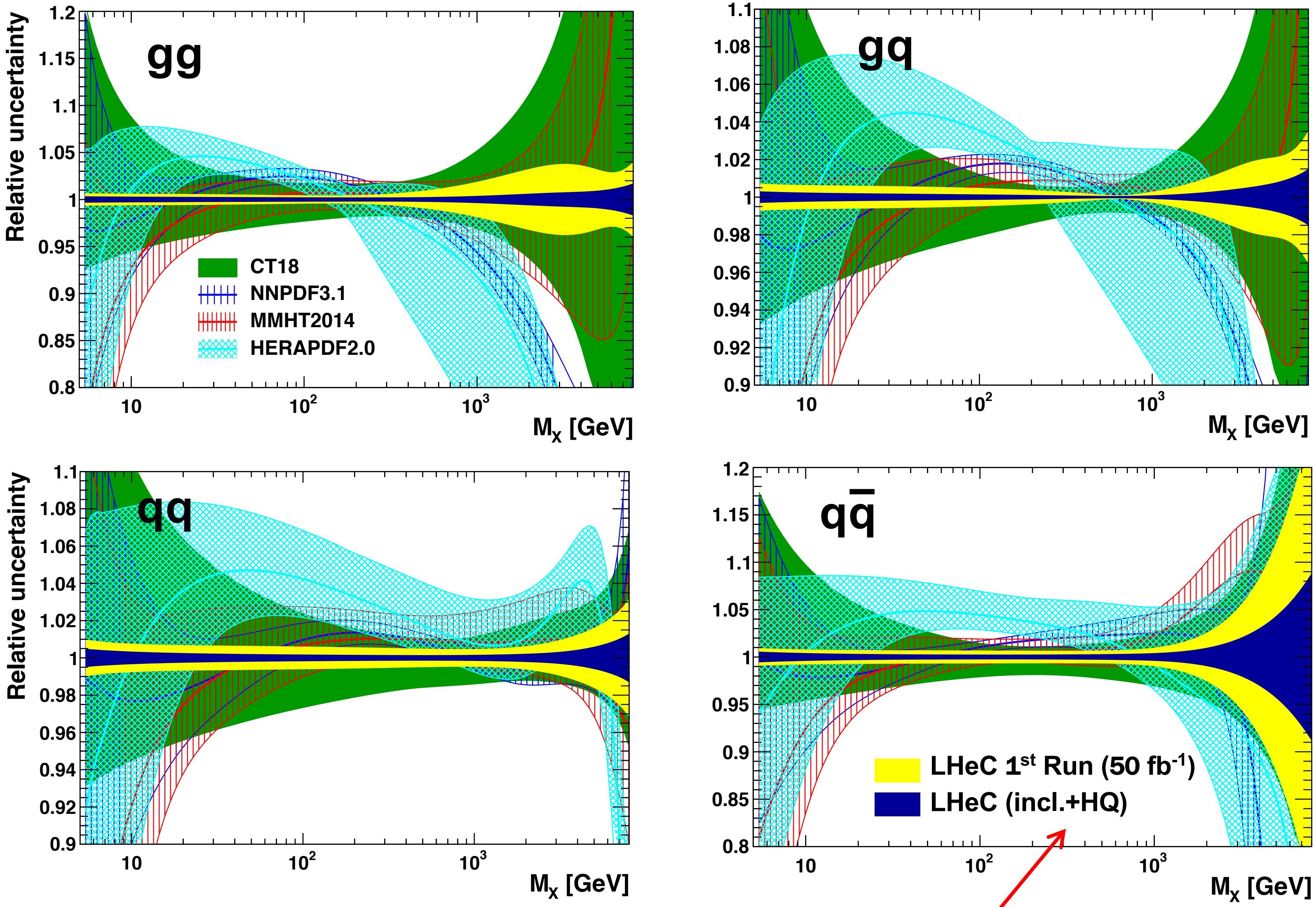




situation today → after 1st LHeC Run

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

pdf luminosities @ 14TeV

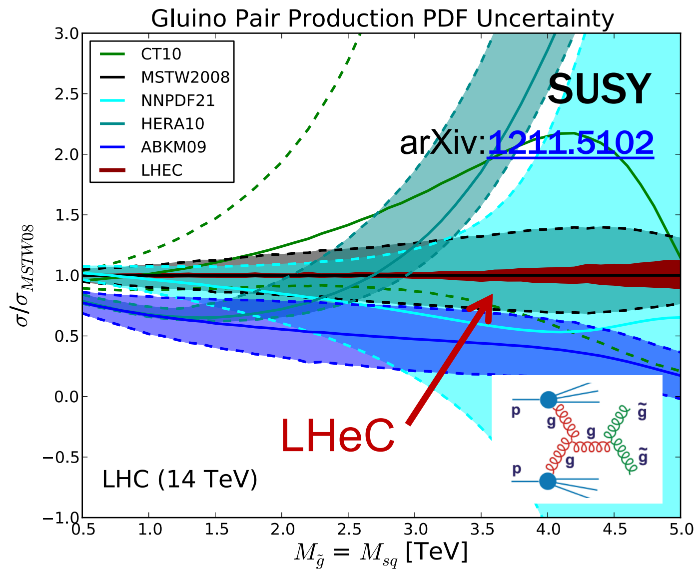


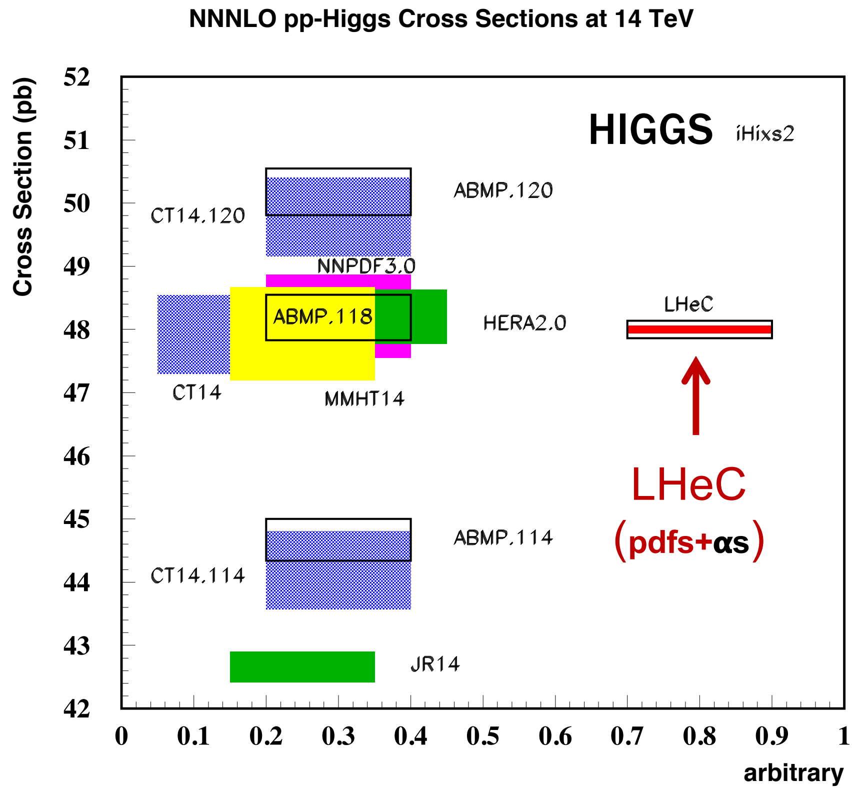
(s,c,b) also included, with more flexible (5+1) fit arXiv:2007.14491; 1902.04070

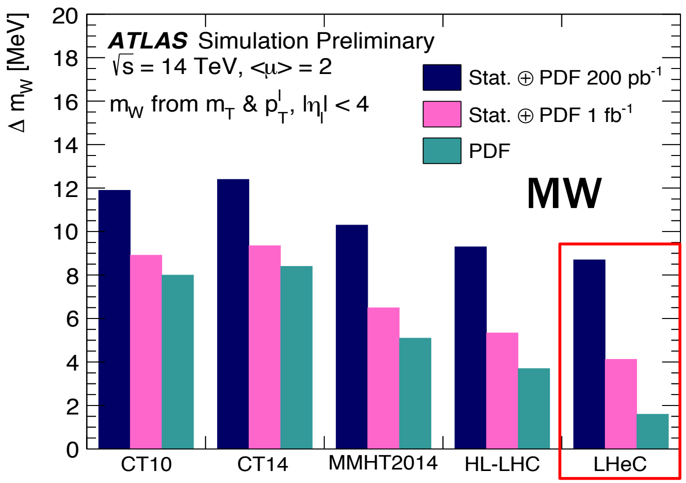
empowering the LHC

see also talk by:
L. Aperio Bella

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





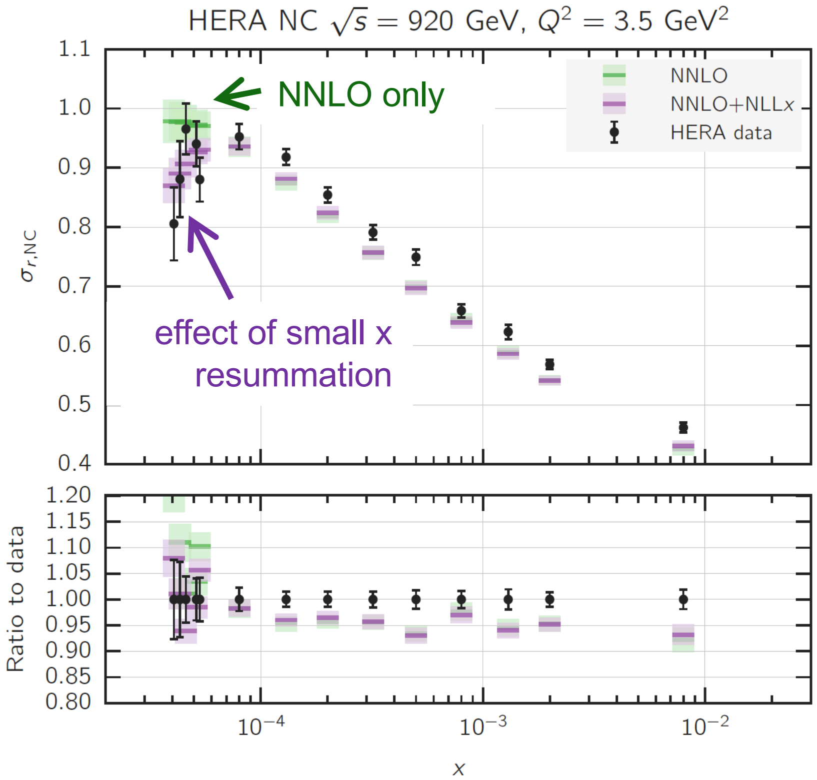


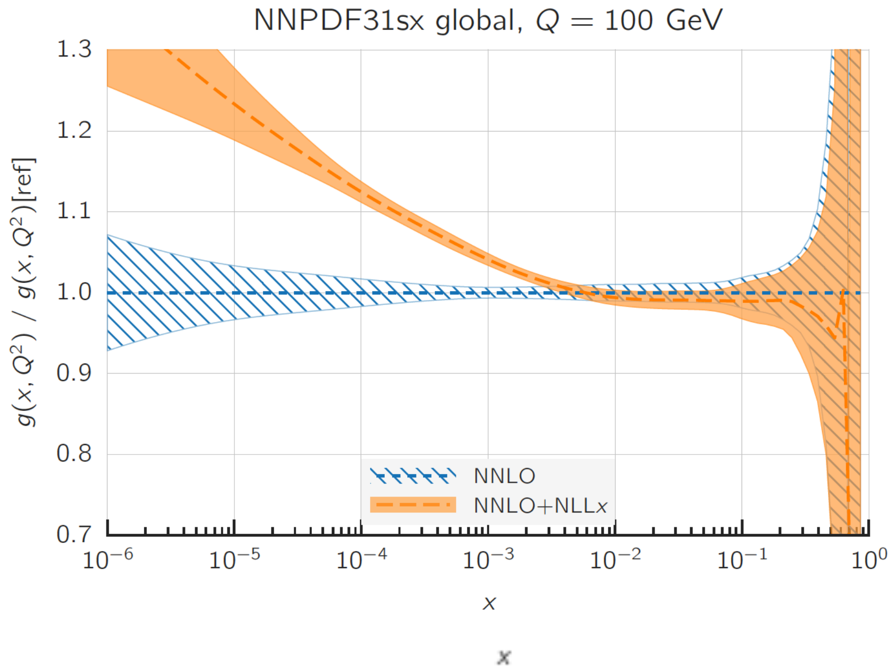
CONTACT INTERACTIONS: $\mathcal{L}_{CI} = \frac{g^2}{\Lambda^2}\eta_{ij}(\bar{q}_i\gamma_\mu q_i)(\bar{\ell}_i\gamma^\mu \ell_i)$

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

see also talk on:
small x, *A. Stasto*

more on small x QCD





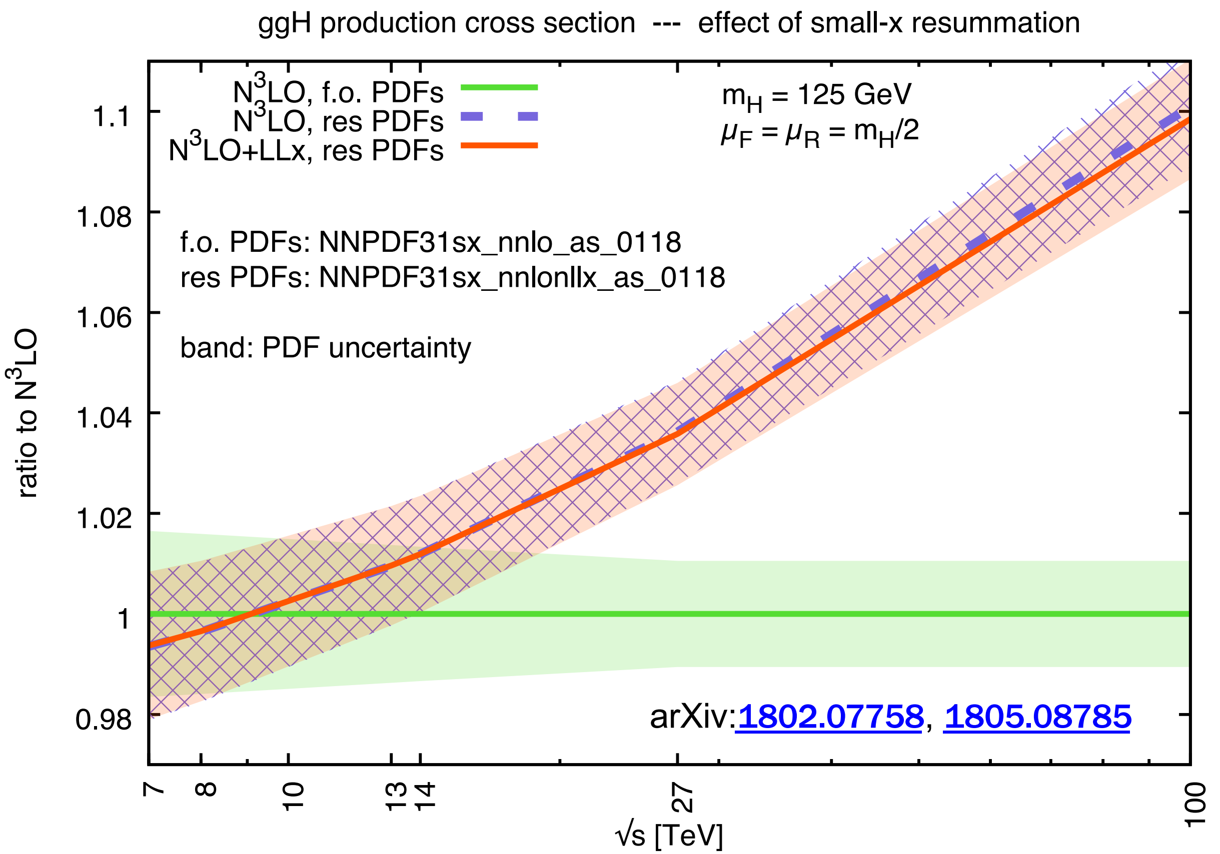
- recent evidence for onset of BFKL dynamics in HERA inclusive data,
- arXiv:[1710.05935](); [1802.00064]()

(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!

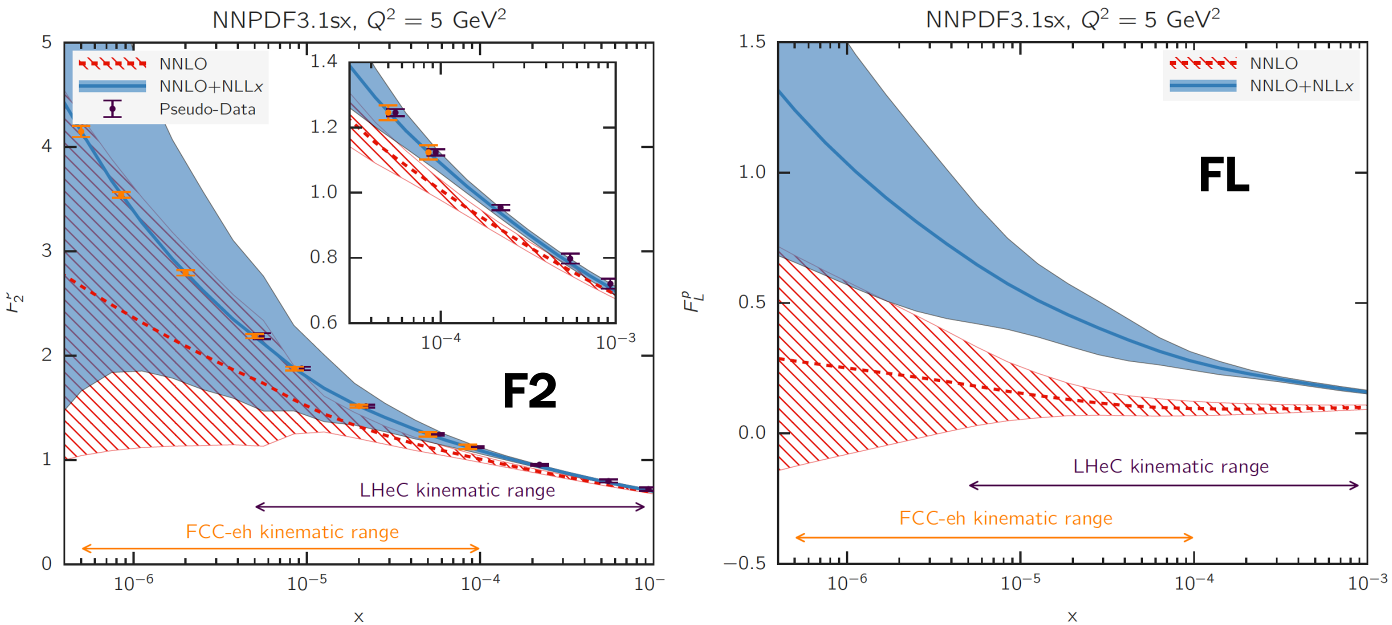
impact on pp phenomenlogy



- 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

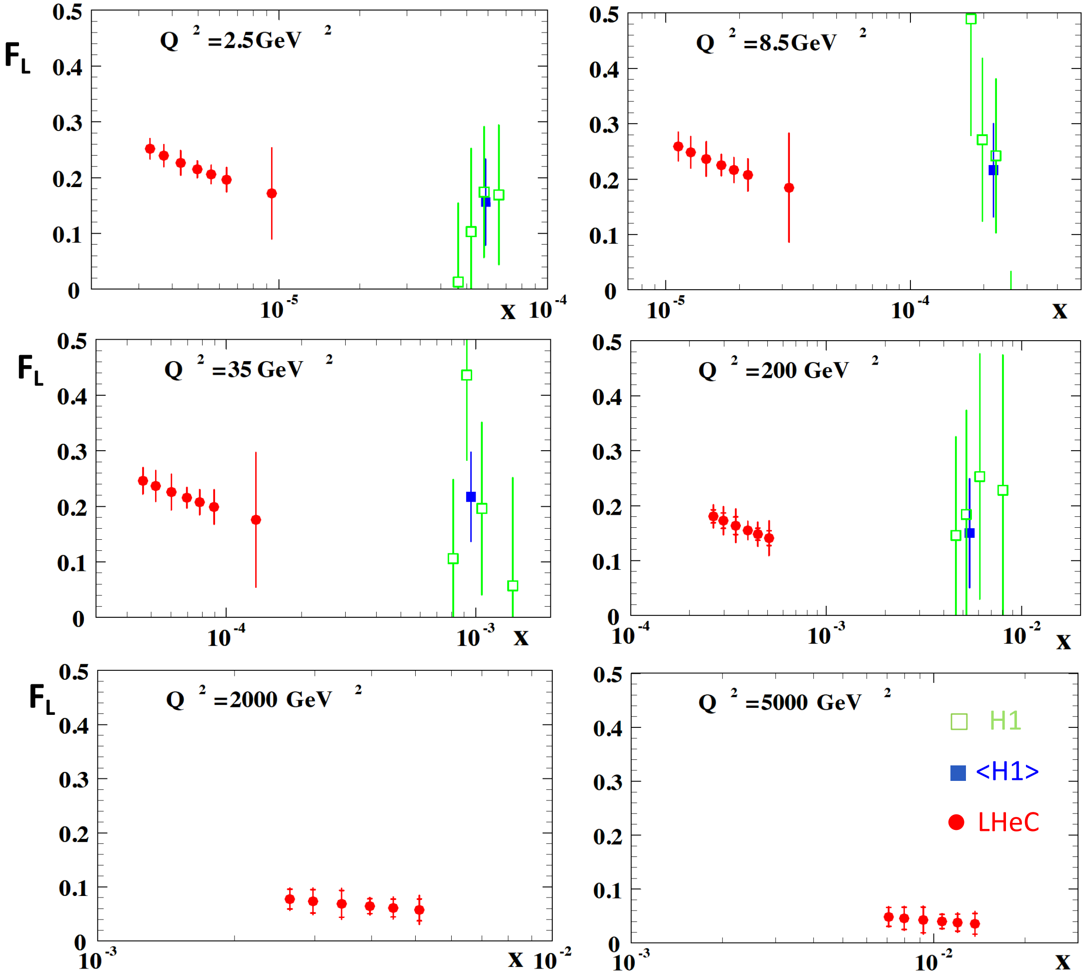
LHeC sensitivity to small x



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

- 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

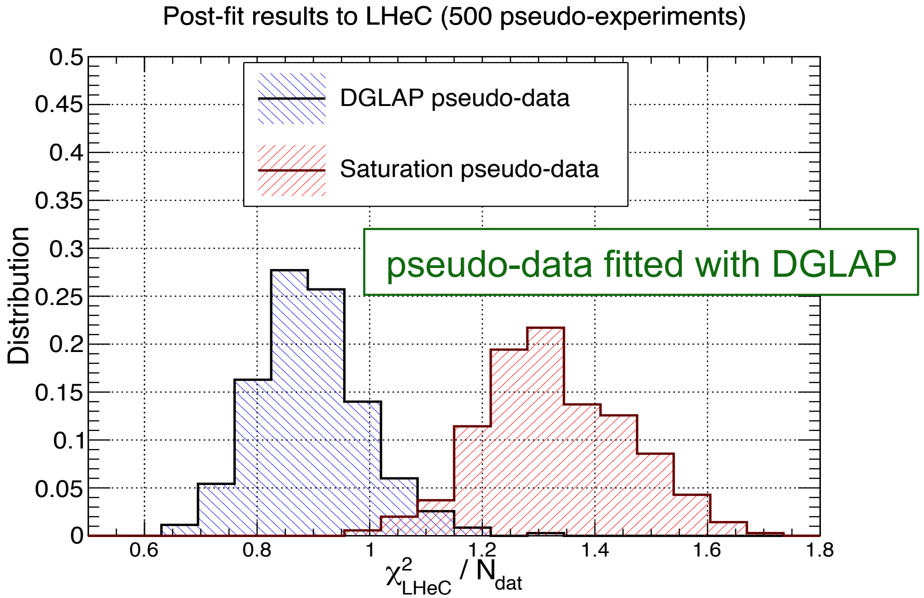
FL from the LHeC

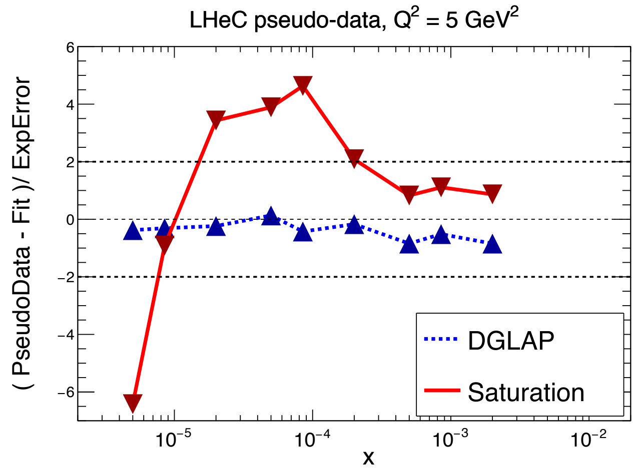


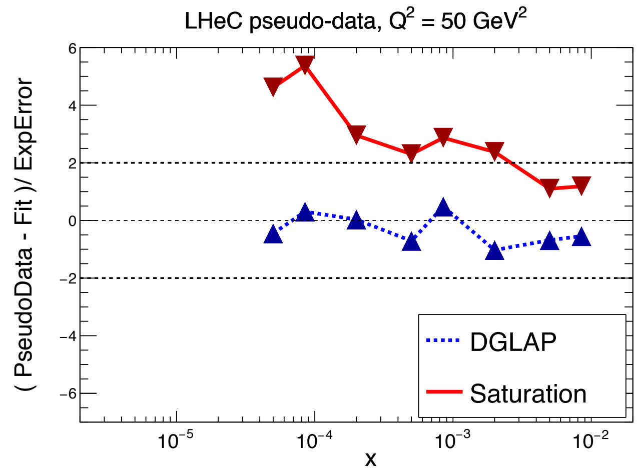
- **expect significant additional discrimination from dedicated precision measurement of FL** (not yet included in shown studies); incorrect **small x** treatment unlikely to accommodate both F2 **and** FL see talk by A. Stasto, (tomorrow) small x WG

non-linear QCD dynamics

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

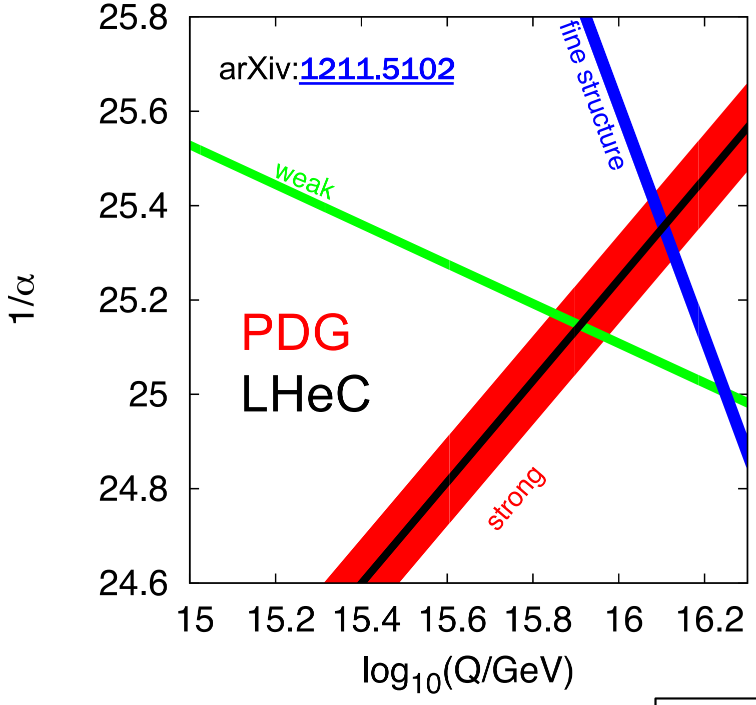




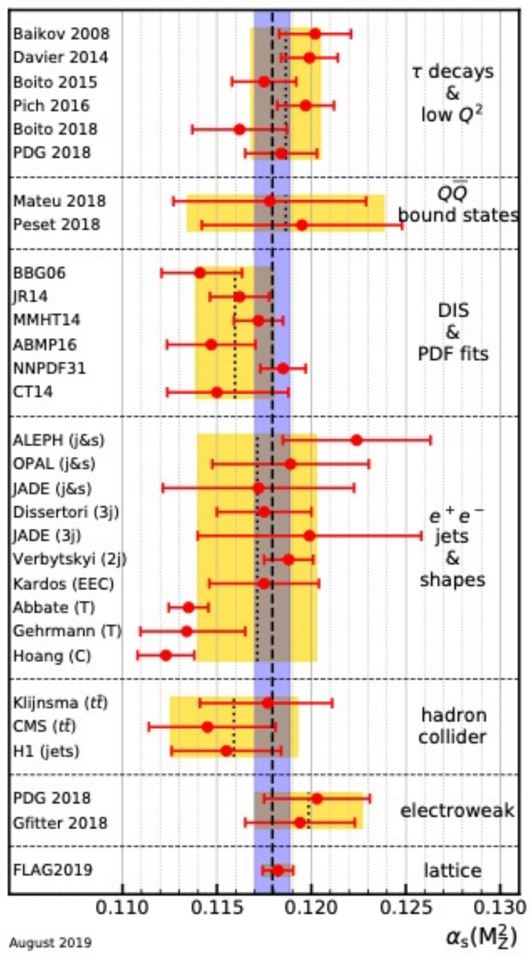


- QCD DGLAP **cannot** absorb all effects of saturation
- **possible to identify saturation by distortions in pulls** → DGLAP fits cannot absorb a non-DGLAP Q^2 dependence

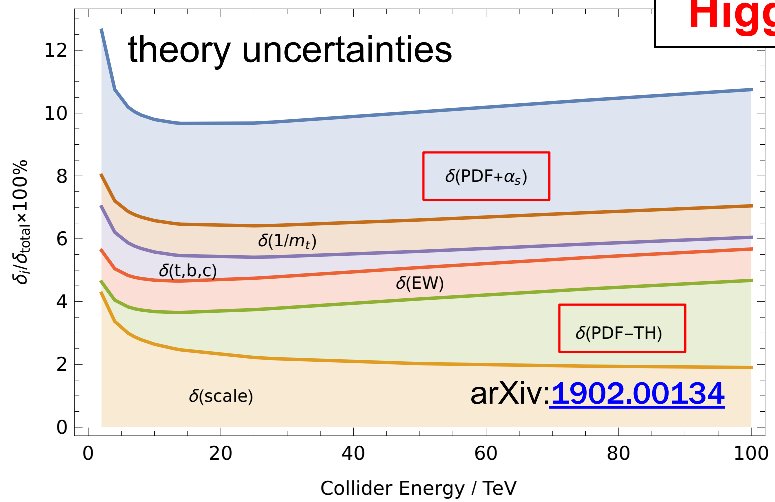
strong coupling, αs



PDG20



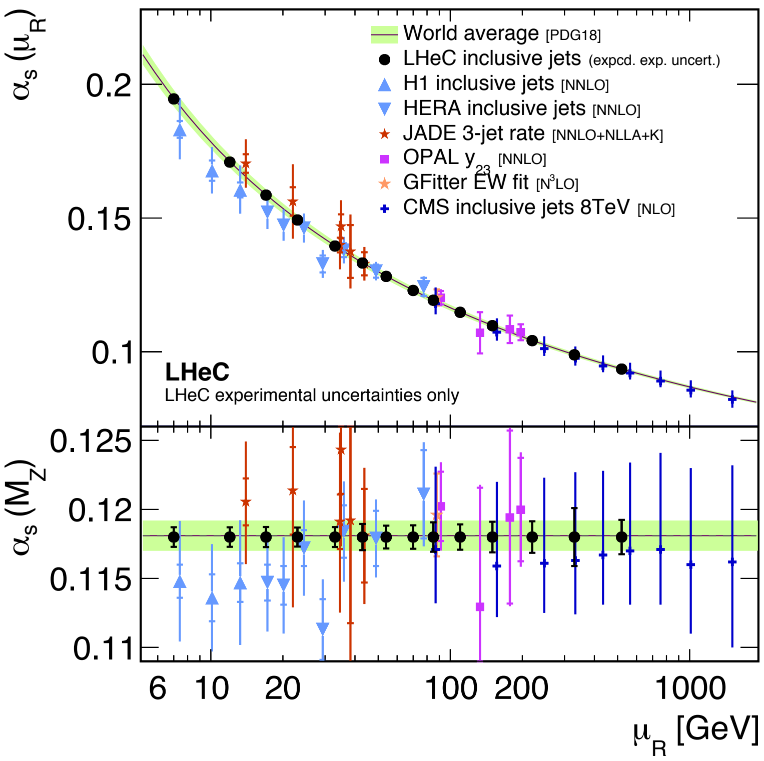
Higgs



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

αs from the LHeC

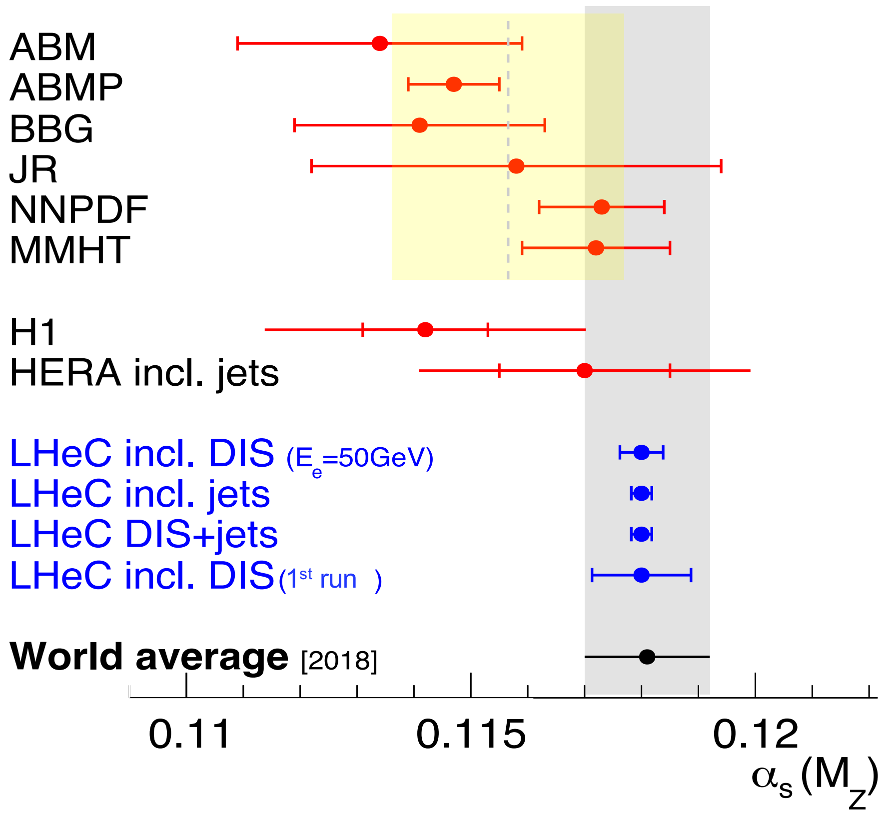
fit to subsets of ep jet data



Δαs(MZ) (exp.+pdf) = **±0.00013±0.00010**

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

αs determinations at NNLO QCD:



LHeC simultaneous **PDF+αs** fit:

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

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

- achievable precision $\mathcal{O}$**(0.1%)**

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; …

- 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
- $\boldsymbol{\alpha_s}$ to permille exp. precision also achievable early, with use of NC DIS jets
- unprecedented access to novel kinematic regime, with **unique potential to explore small x phenomena**

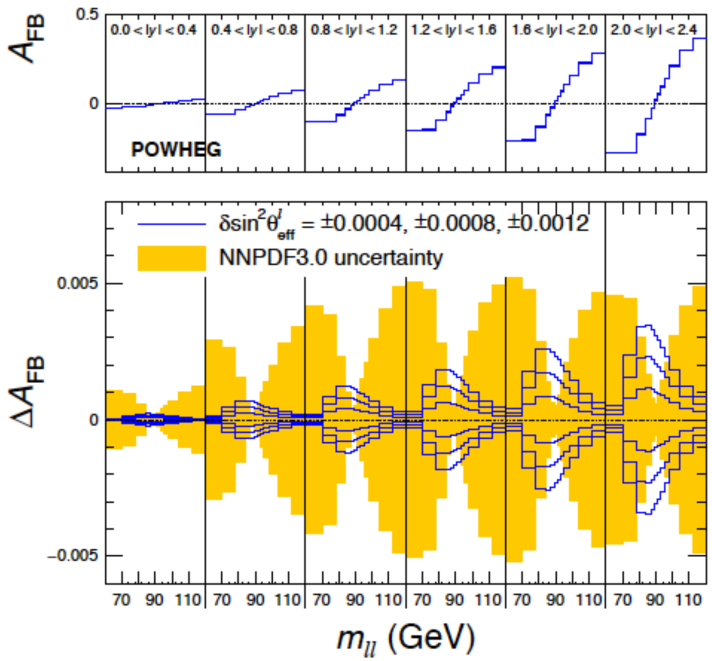
extras

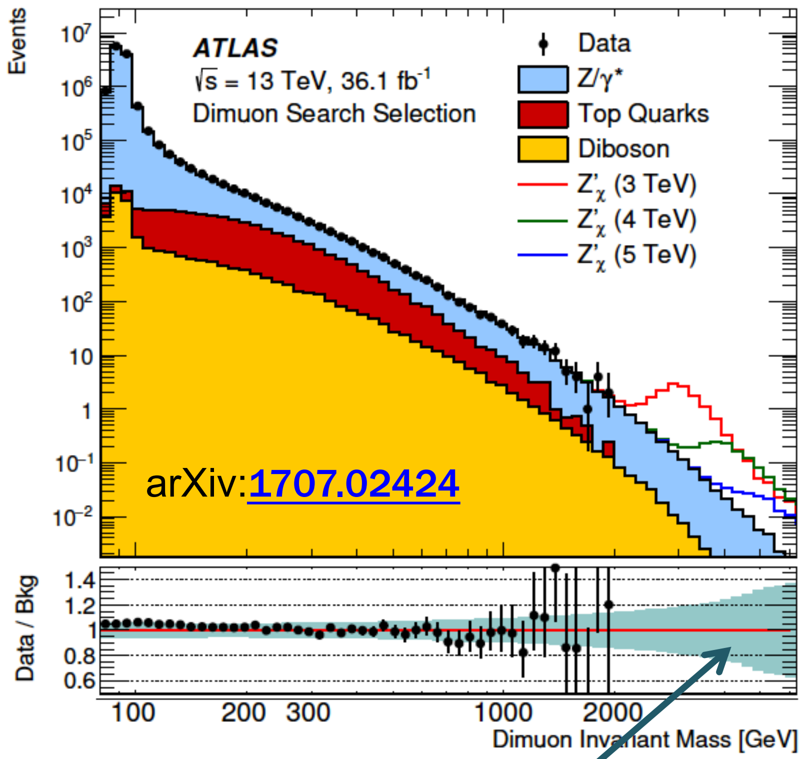
why pdfs matter

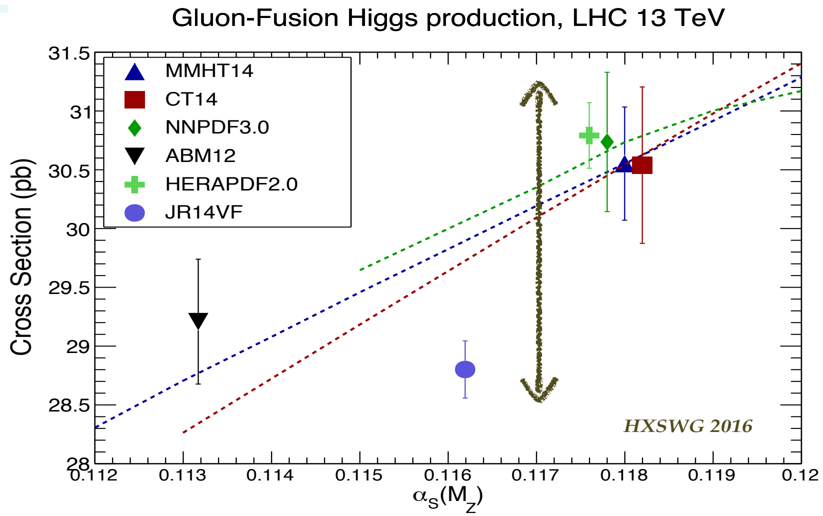
CMS $\sin^2\vartheta_W$, arXiv:[1806.00863](1806.00863)

ATLAS Mw, 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

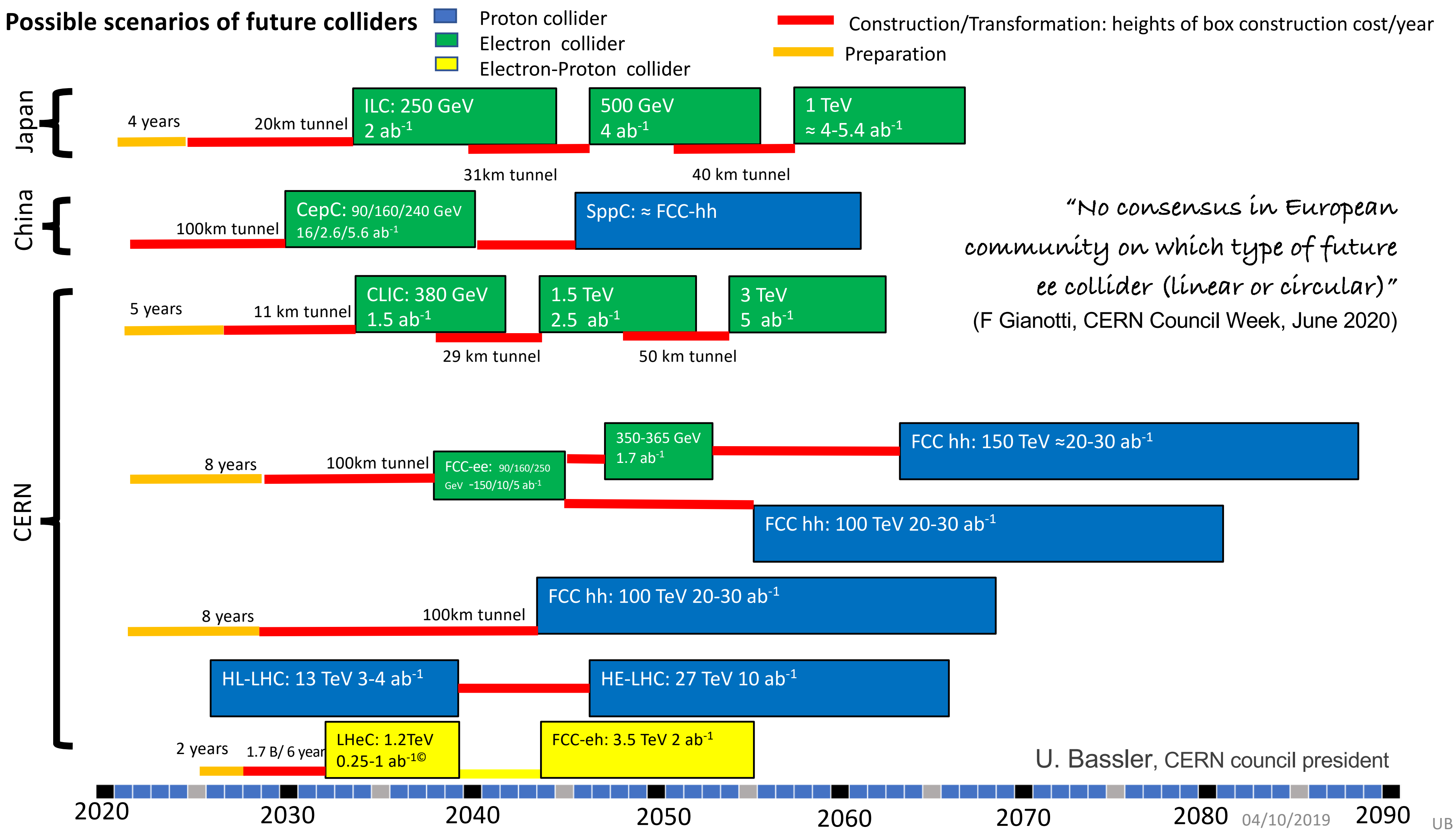






pdf uncertainty dominates

CERN/ESG/05



LHeC: installation during **LS4**;

concurrent operation through LHC **Runs 5/6**; and period of **dedicated running**, arXiv:1810.13022

LHeC simulated data

Source of uncertainty	Uncertainty
Scattered electron energy scale $\Delta E'_e/E'_e$	0.1 %
Scattered electron polar angle	0.1 mrad
Hadronic energy scale $\Delta E_h/E_h$	0.5 %
Radiative corrections	0.3 %
Photoproduction background (for $y > 0.5$)	1 %
Global efficiency error	0.5 %

Table 3.1: Assumptions used in the simulation of the NC cross sections on the size of uncertainties from various sources. The top three are uncertainties on the calibrations which are transported to provide correlated systematic cross section errors. The lower three values are uncertainties of the cross section caused by various sources.

Parameter	Unit	Data set								
		D1	D2	D3	D4	D5	D6	D7	D8	D9
Proton beam energy	TeV	7	7	7	7	1	7	7	7	7
Lepton charge		−1	−1	−1	−1	−1	+1	+1	−1	−1
Longitudinal lepton polarisation		−0.8	−0.8	0	−0.8	0	0	0	+0.8	+0.8
Integrated luminosity	fb^{-1}	5	50	50	1000	1	1	10	10	50

Table 3.2: Summary of characteristic parameters of data sets used to simulate neutral and charged current $e^\pm$ cross section data, for a lepton beam energy of $E_e = 50\,\text{GeV}$. Sets D1-D4 are for $E_p = 7\,\text{TeV}$ and e^-p scattering, with varying assumptions on the integrated luminosity and the electron beam polarisation. The data set D1 corresponds to possibly the first year of LHeC data taking with the tenfold of luminosity which H1/ZEUS collected in their lifetime. Set D5 is a low Ep energy run, essential to extend the acceptance at large x and medium Q^2. D6 and D7 are sets for smaller amounts of positron data. Finally, D8 and D9 are for high energy e^-p scattering with positive helicity as is important for electroweak NC physics. These variations of data taking are subsequently studied for their effect on PDF determinations.

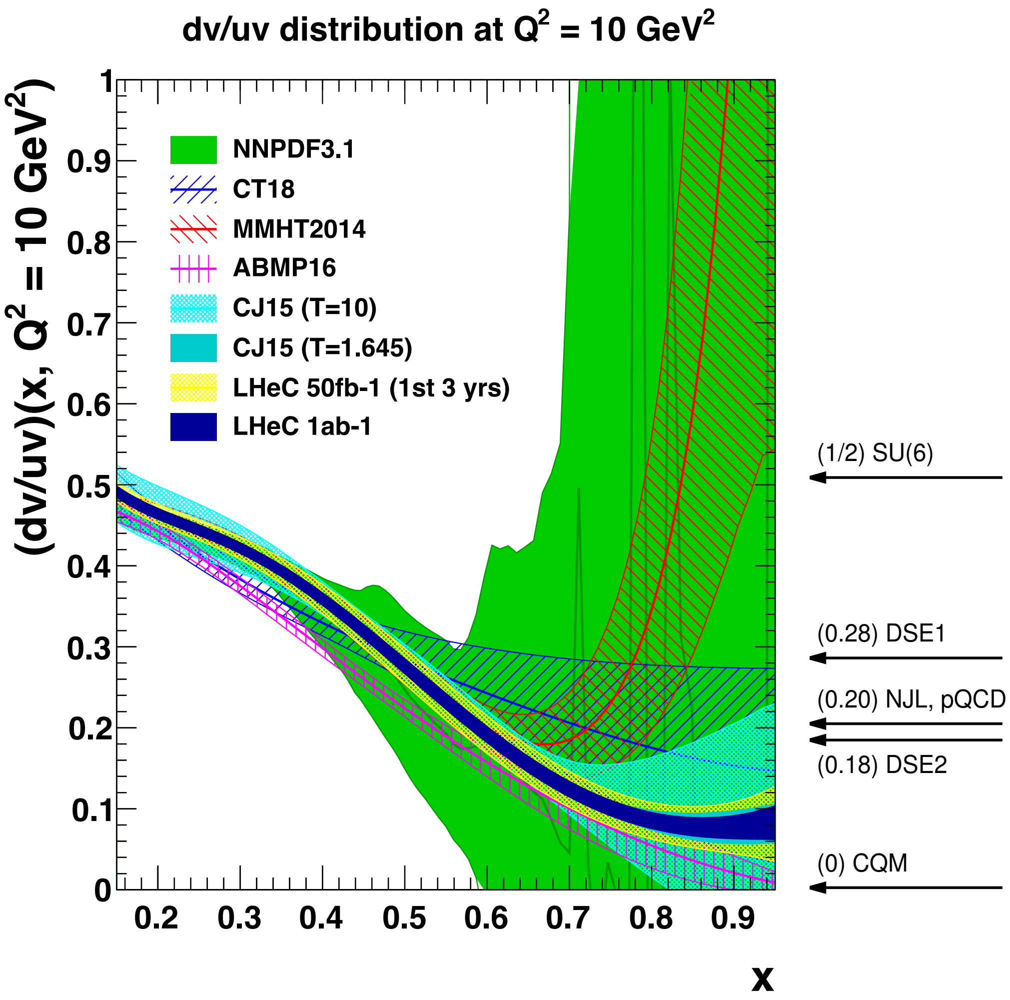
LHeC pdf parameterisation

- QCD fit ansatz based on HERAPDF2.0, with following differences:
- no requirement that ubar=dbar at small x
- no negative gluon term (only 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, **17 free parameters**

d/u at large x

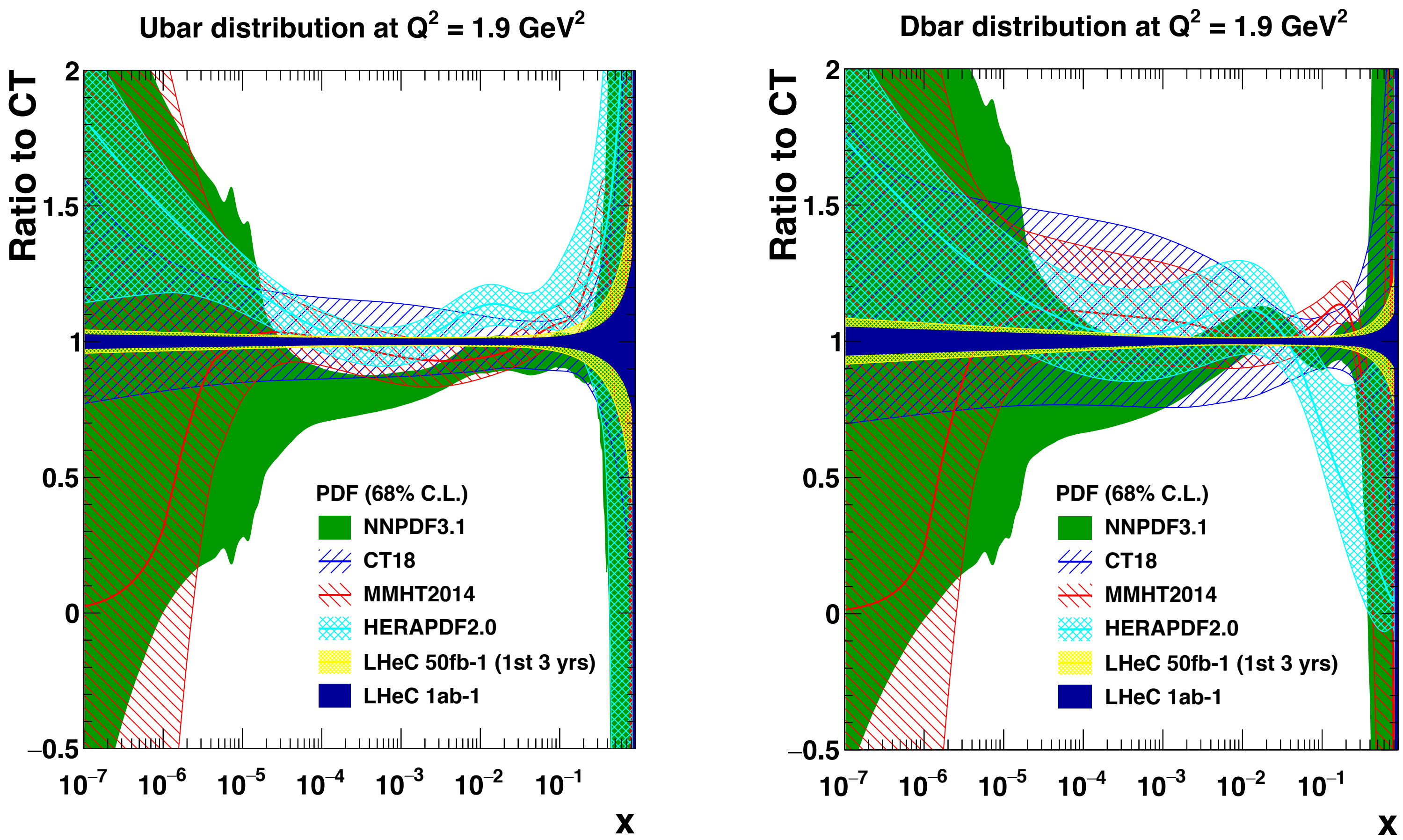


d/u essentially unknown at large x

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

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.)
NNPDF3.1
CT18
MMHT2014
HERAPDF2.0
LHeC 50fb-1 (1st 3 yrs)
LHeC 1ab-1
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.)
NNPDF3.1
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LHeC 50fb-1 (1st 3 yrs)
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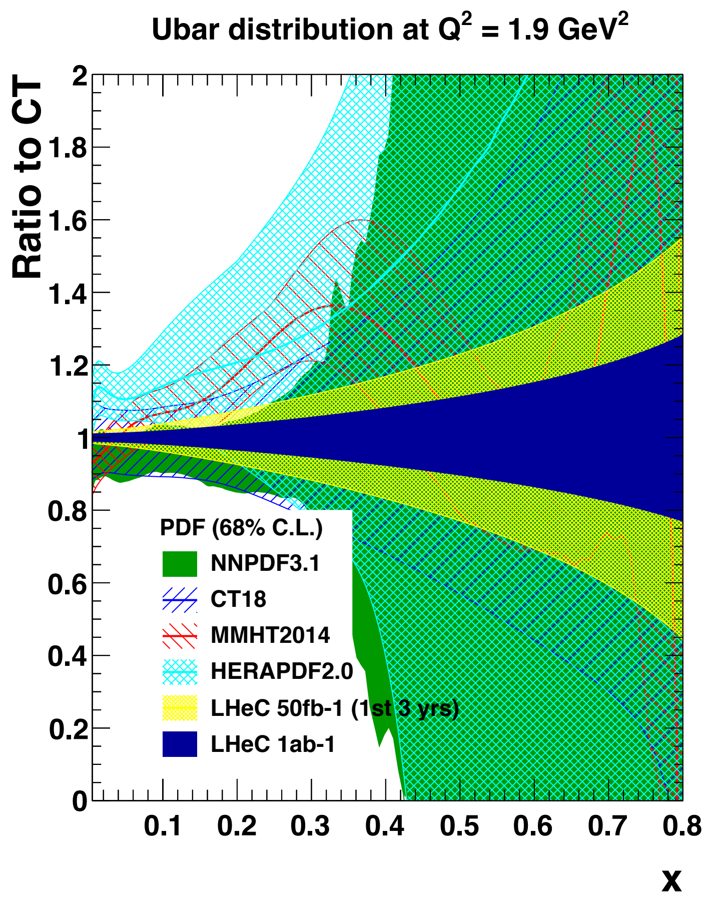
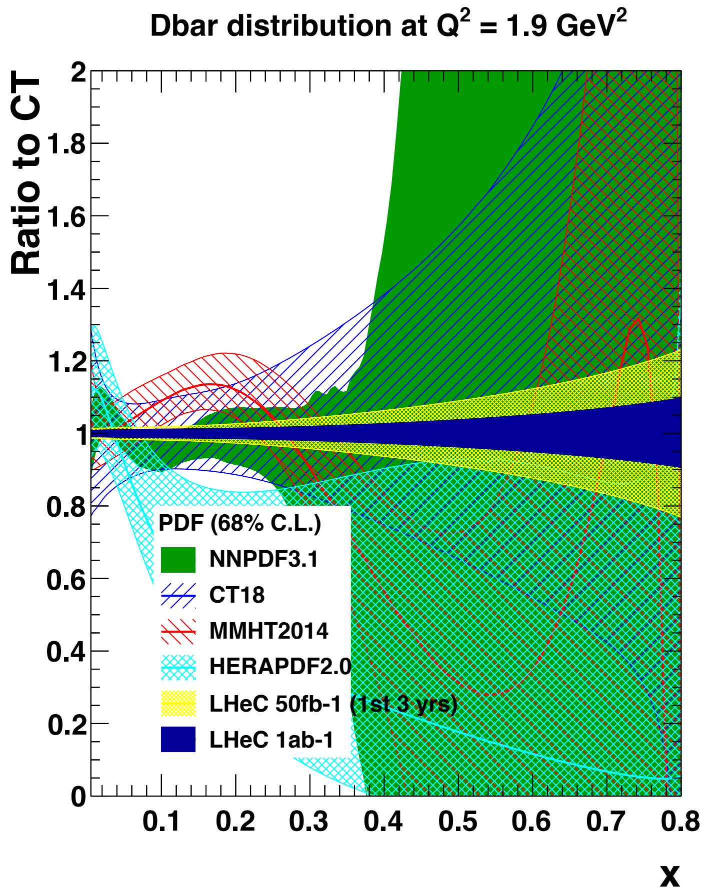
sea quarks



Ubar distribution at Q^2 = 1.9 GeV^2
Ratio to CT
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
x
PDF (68% C.L.)
NNPDF3.1
CT18
MMHT2014
HERAPDF2.0
LHeC 50fb-1 (1st 3 yrs)
LHeC 1ab-1



Dbar distribution at Q^2 = 1.9 GeV^2
Ratio to CT
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
x
PDF (68% C.L.)
NNPDF3.1
CT18
MMHT2014
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LHeC 50fb-1 (1st 3 yrs)
LHeC 1ab-1

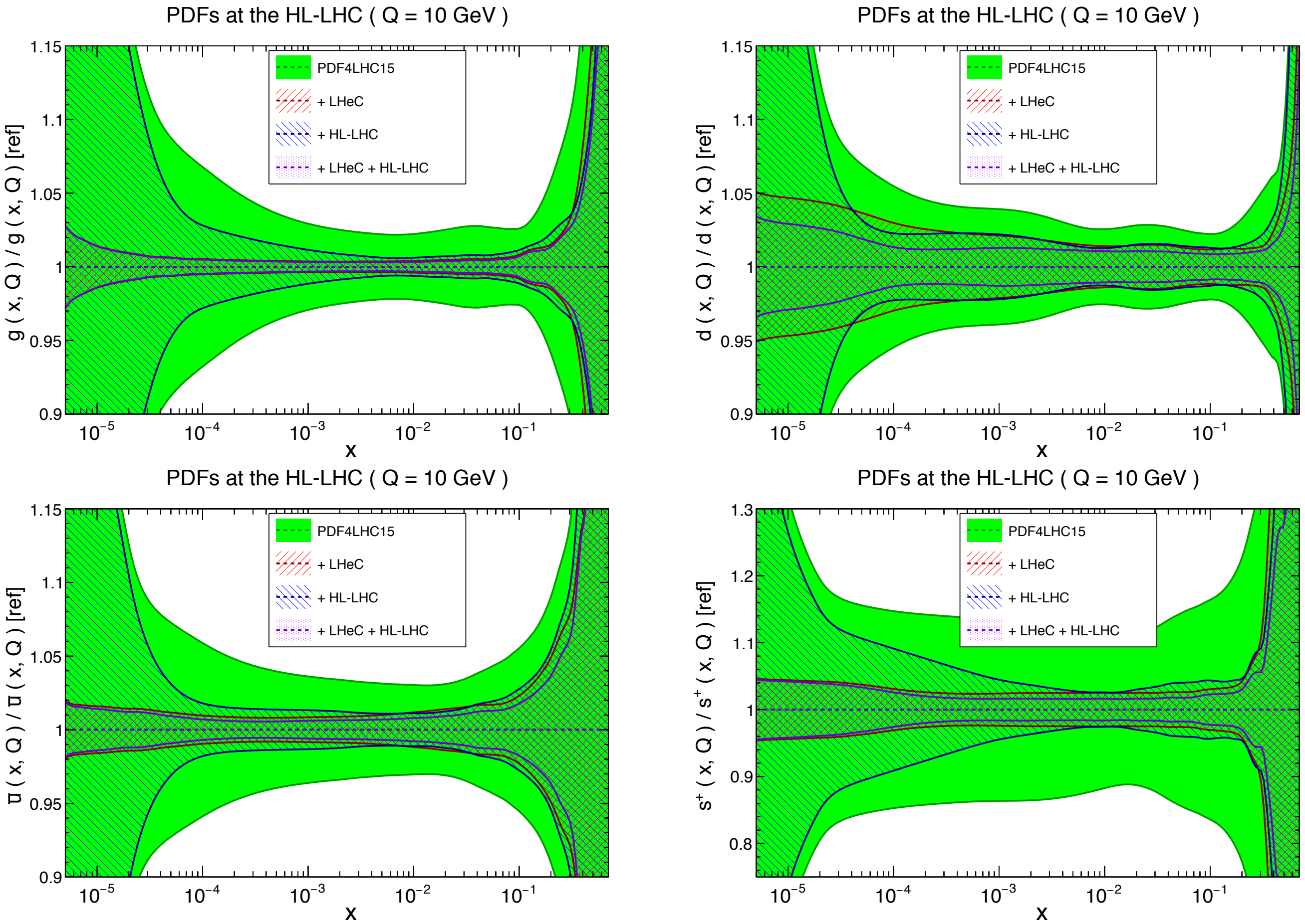


Figure 9.9: Impact of LHeC on the 1-σ relative PDF uncertainties of the gluon, down quark, anti–up quark and strangeness distributions, with respect to the PDF4LHC15 baseline set (green band). Results for the LHeC (red), the HL-LHC (blue) and their combination (violet) are shown.

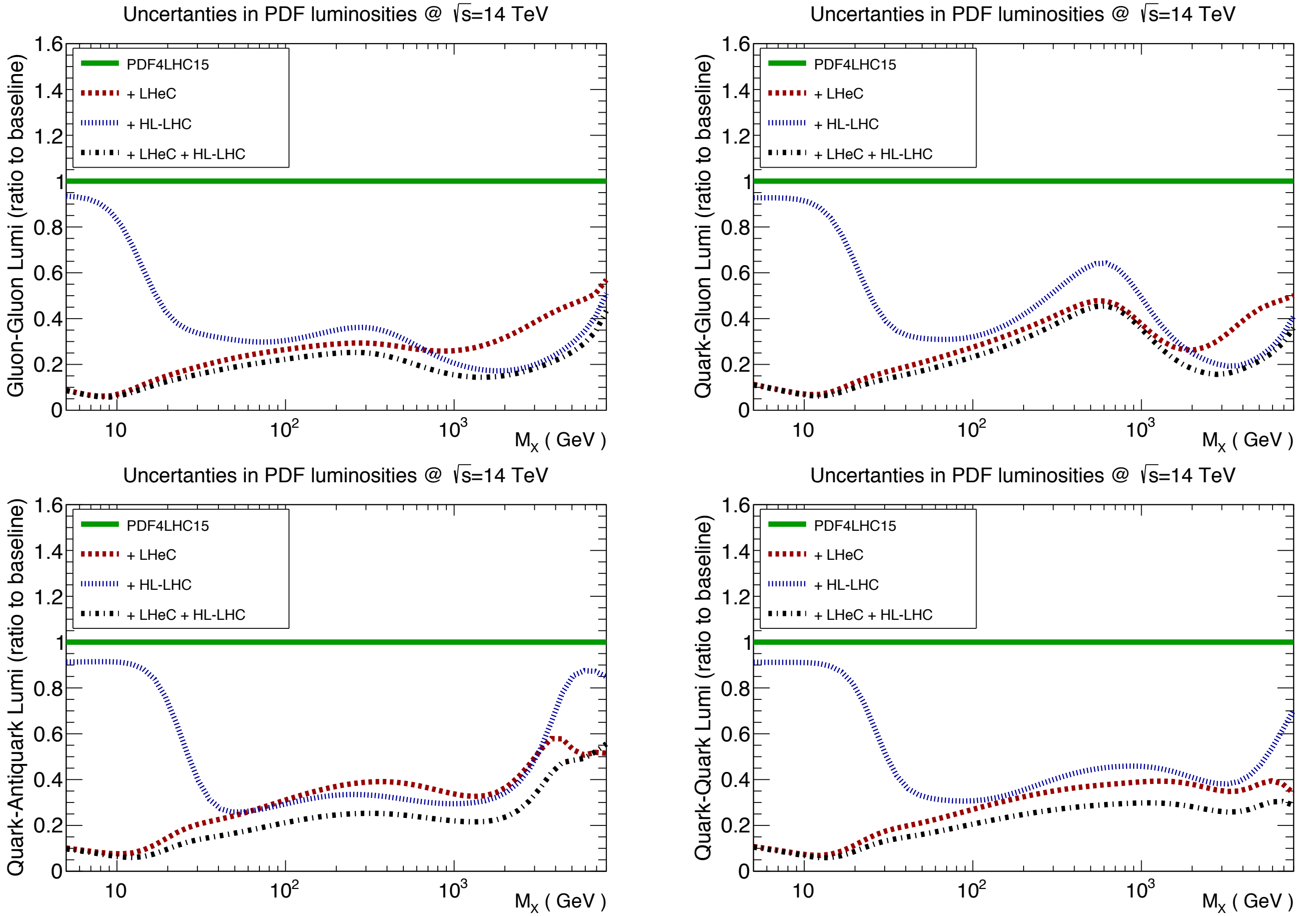


Figure 9.10: Impact of LHeC, HL-LHC and combined LHeC + HL-LHC pseudodata on the uncertainties of the gluon-gluon, quark-gluon, quark-antiquark and quark-quark luminosities, with respect to the PDF4LHC15 baseline set. In this comparison we display the relative reduction of the PDF uncertainty in the luminosities compared to the baseline.

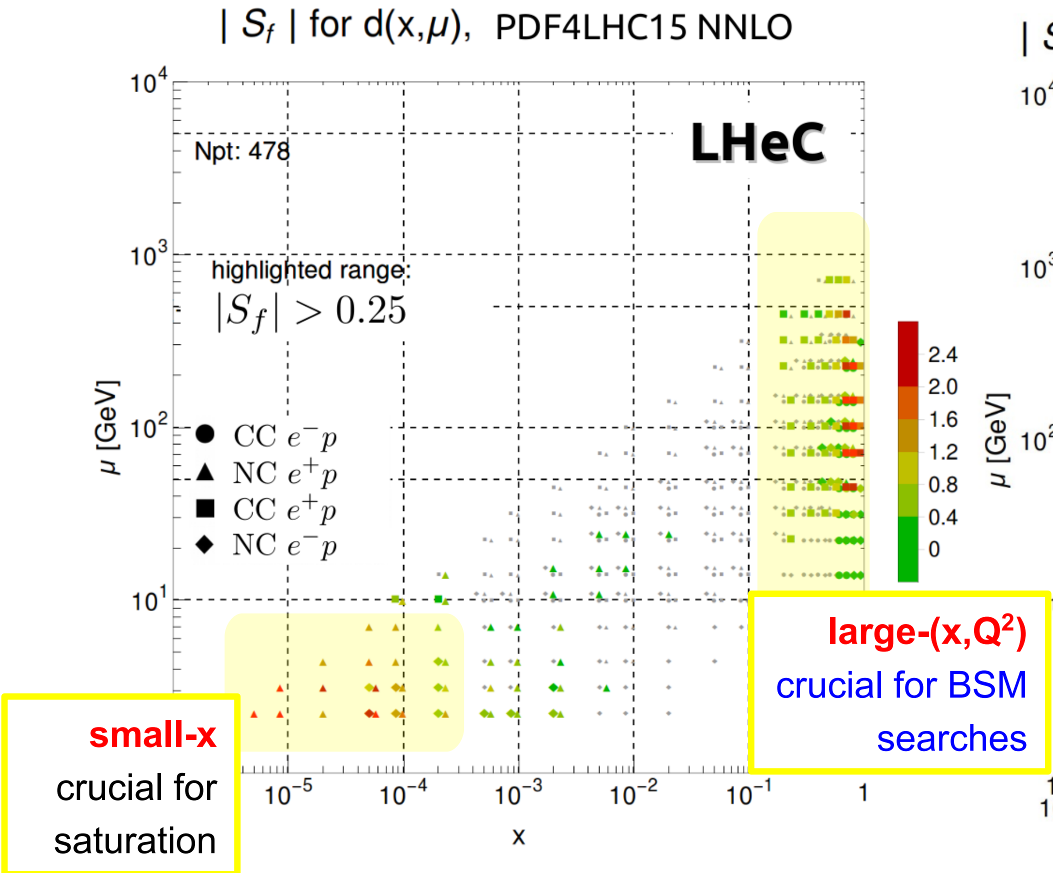
"sensitivity" Sf

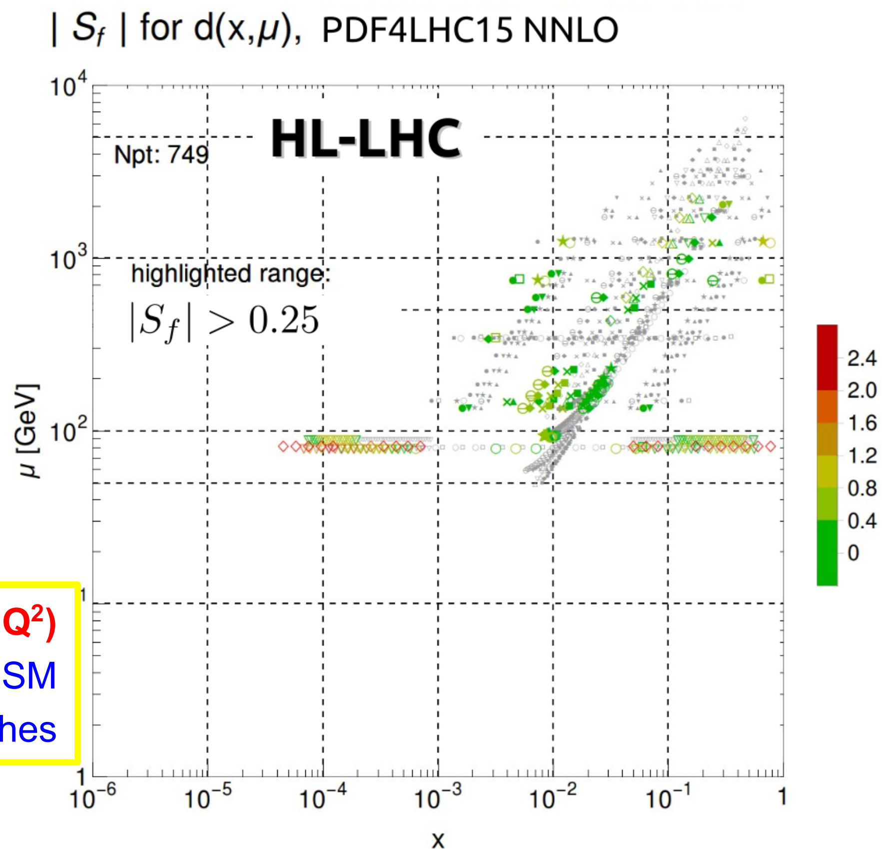
= **C**orrelation ×

scaled **r**esidual

pdf sensitivity

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





enormous sensitivity in regions currently poorly constrained

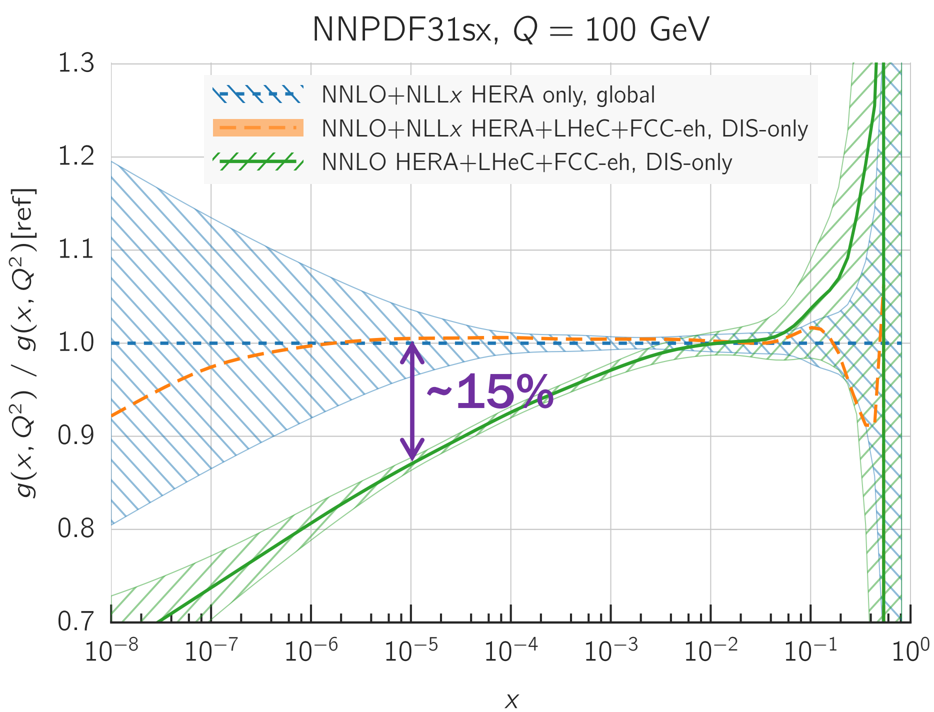
PDFSENSE: tool for quickly quantifying potential impact of experimental pseduodata

small x resummation

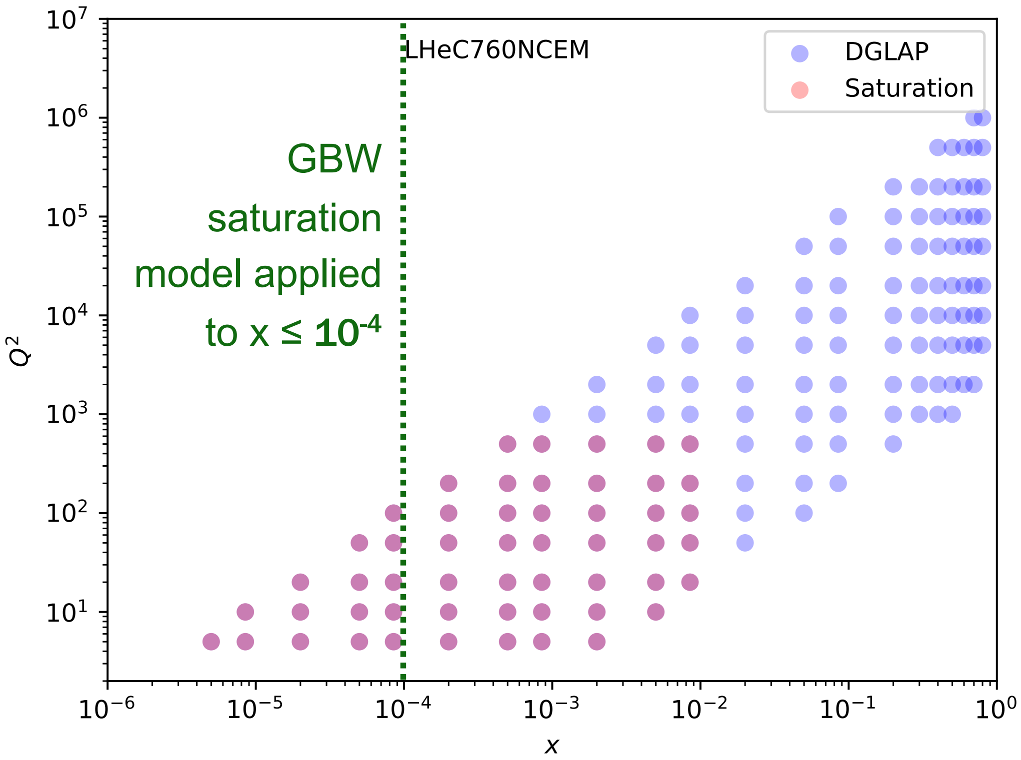
- NNLO+NLLx resummed calculation used to produce **LHeC** and **FCC-eh** simulated inclusive NC and CC pseudo-data
- then, fitted using **NNLO (DGLAP only)** vs. **NNLO+NLLx**

χ^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



non-linear QCD dynamics



non-linear QCD dynamics

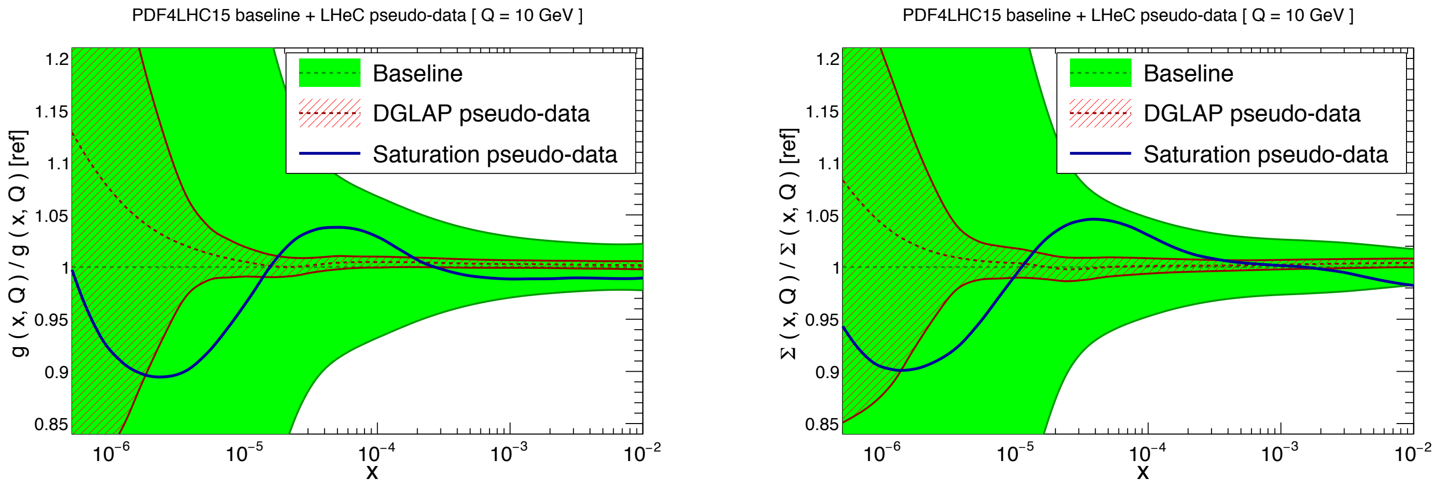


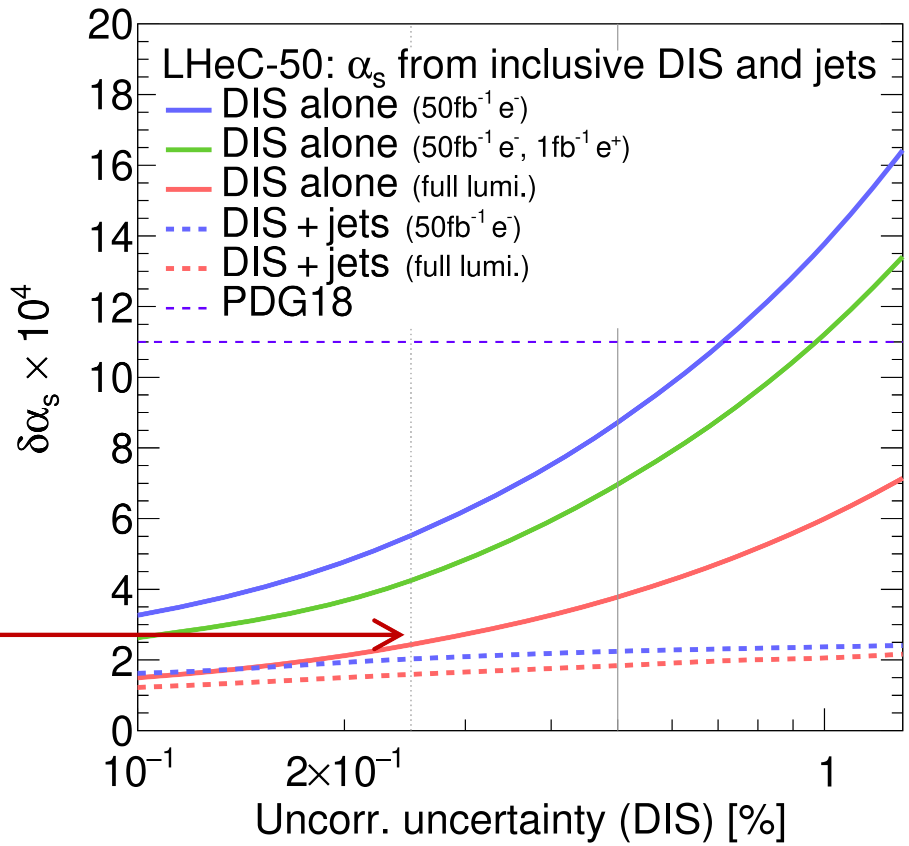
Figure 4.12: Comparison between the PDF4LHC15 baseline (green band) with the results of the profiling of the LHeC pseudodata for the gluon (left) and quark singlet (right) for $Q = 10\,\mathrm{GeV}$. We show the cases where the pseudodata is generated using DGLAP calculations (red hatched band) and where it is partially based on the GBW saturation model (blue curve).

αs from LHeC inclusive NC/CC DIS

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

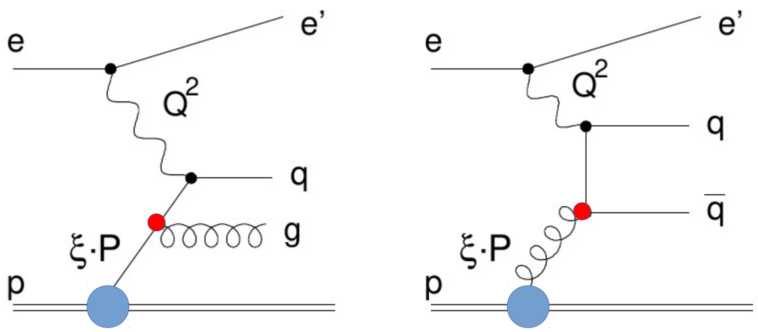
- **3** LHeC scenarios:
- LHeC **1**st Run (**50** fb^{-1} e-p)
- plus **1** fb^{-1} positron data
- full inclusive LHeC dataset (**1** ab^{-1})

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



- **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

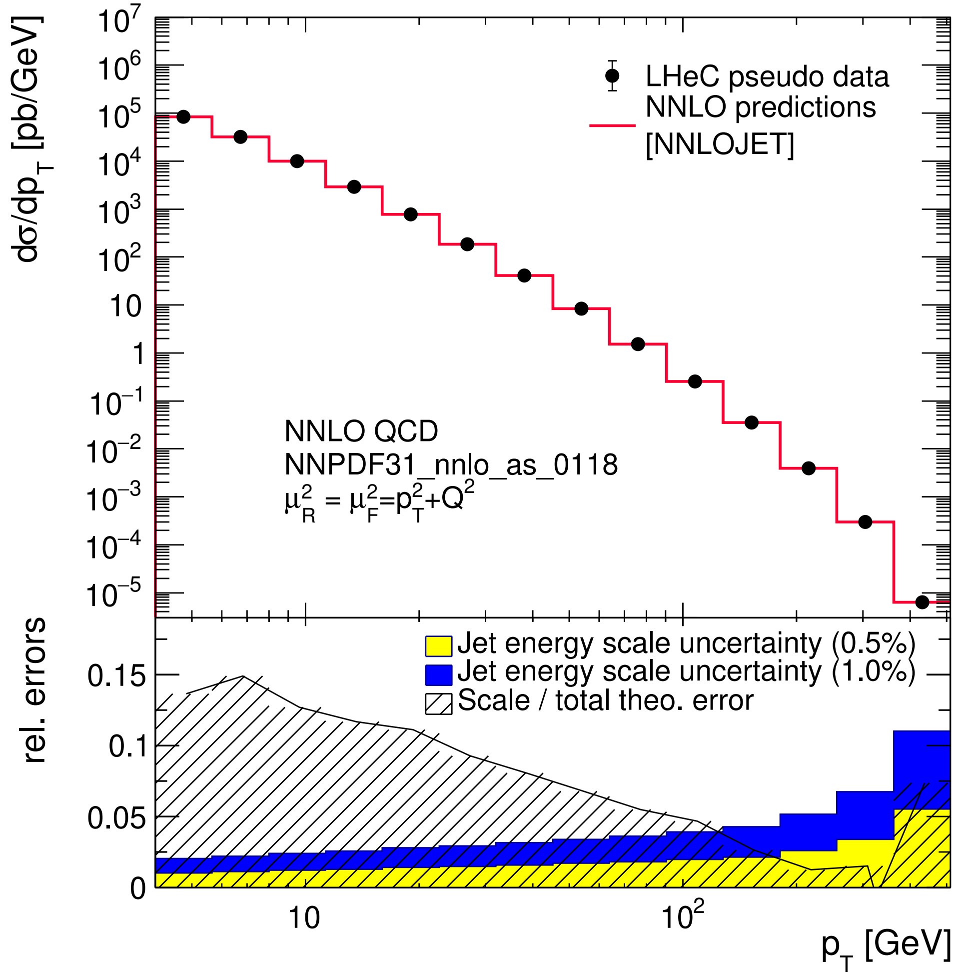


- sensitive to αs at lowest order

- 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 uncerts. considered; benchmarked with H1, ZEUS, ATLAS, CMS

Exp. uncertainty	Shift	Size on σ [%]
Statistics with $1\,\text{ab}^{-1}$	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 jets

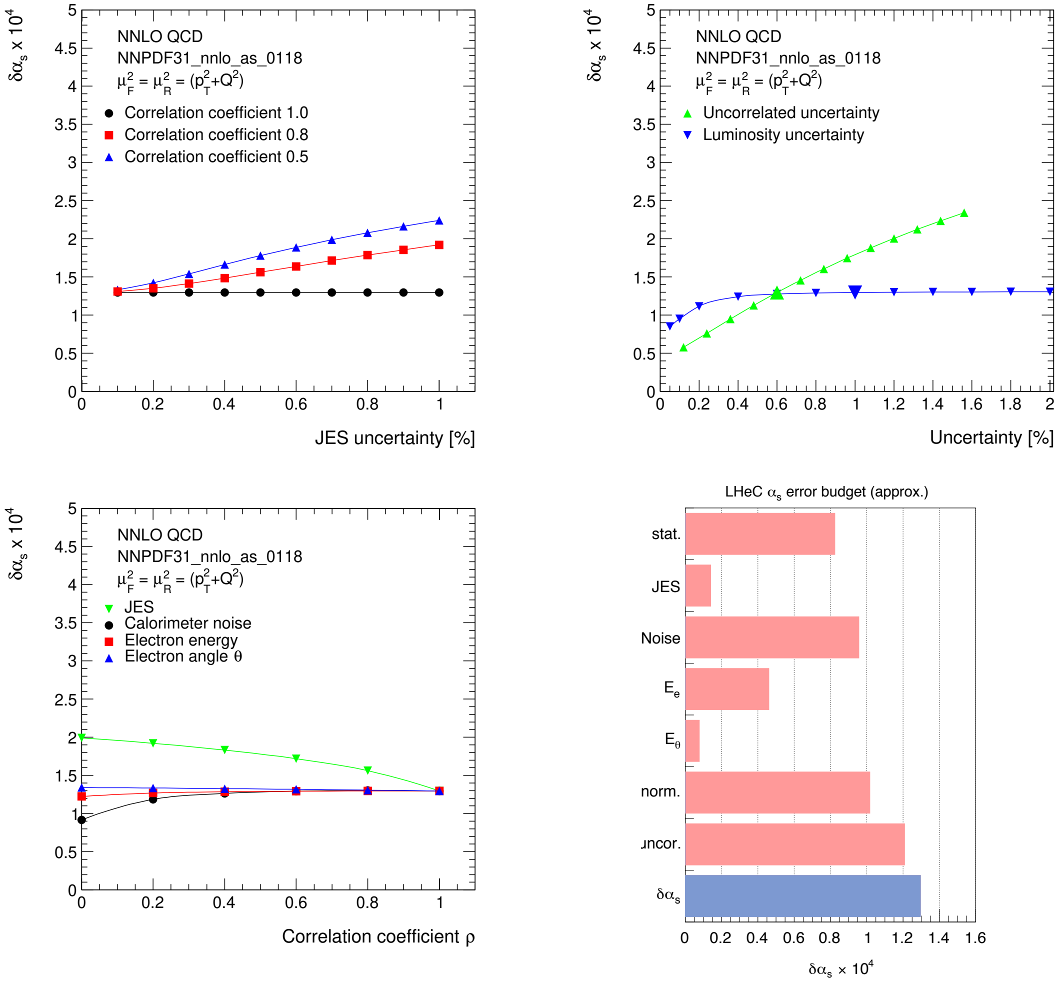
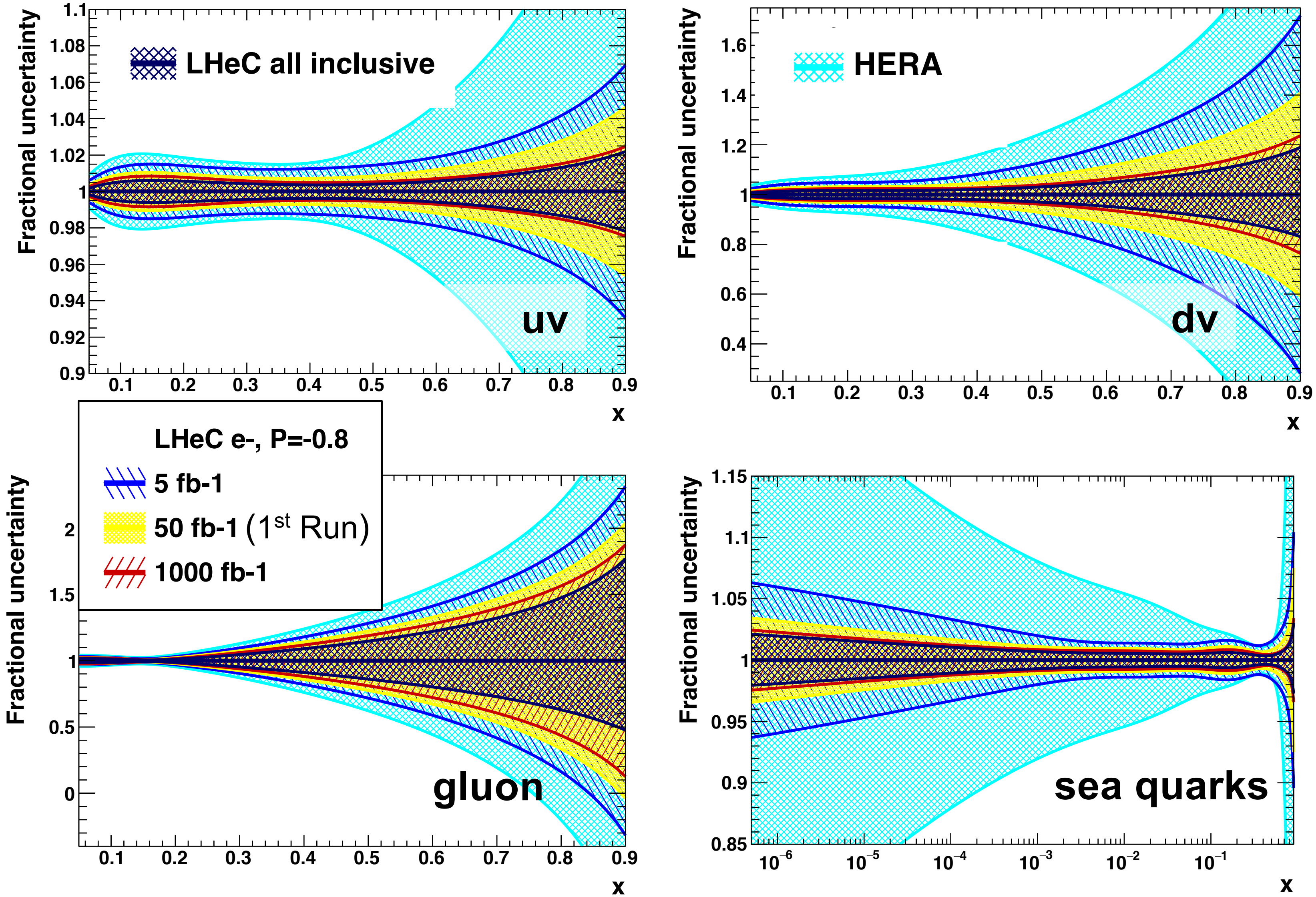


Figure 4.3: Studies of the size and correlations of experimental uncertainties impacting the uncertainty of $\alpha_s(M_Z)$. Top left: Study of the value of the correlation coefficient ρ for different systematic uncertainties. Common systematic uncertainties are considered as fully correlated, $\rho = 1$. Top right: Size of the JES uncertainty for three different values of $\rho_{\rm JES}$. Bottom left: Impact of the uncorrelated and normalisation uncertainties on $\Delta\alpha_{\rm s}(M_{\rm Z})$. Bottom right: Contribution of individual sources of experimental uncertainty to the total experimental uncertainty of $\alpha_{\rm s}(M_{\rm Z})$.

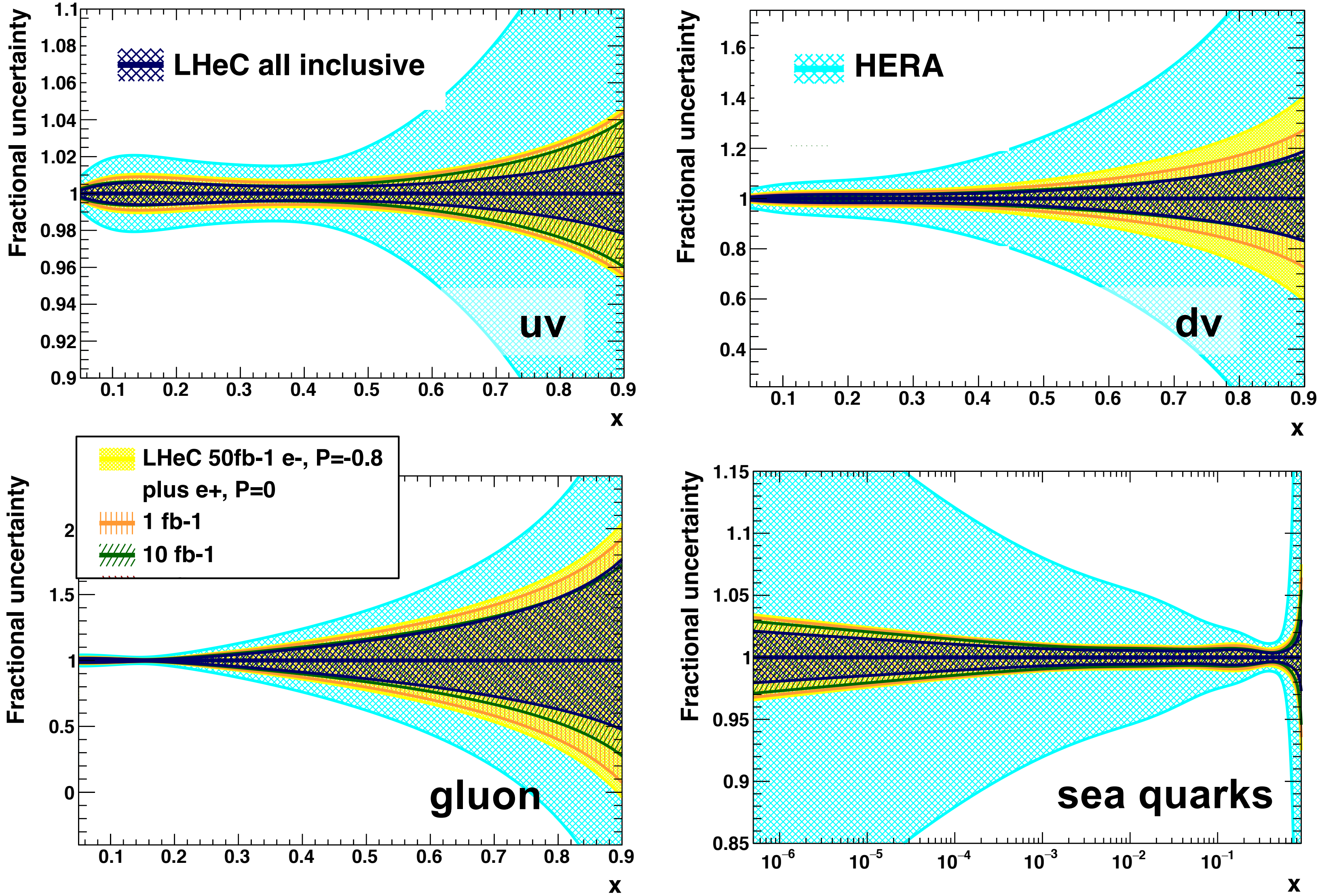
impact of luminosity



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

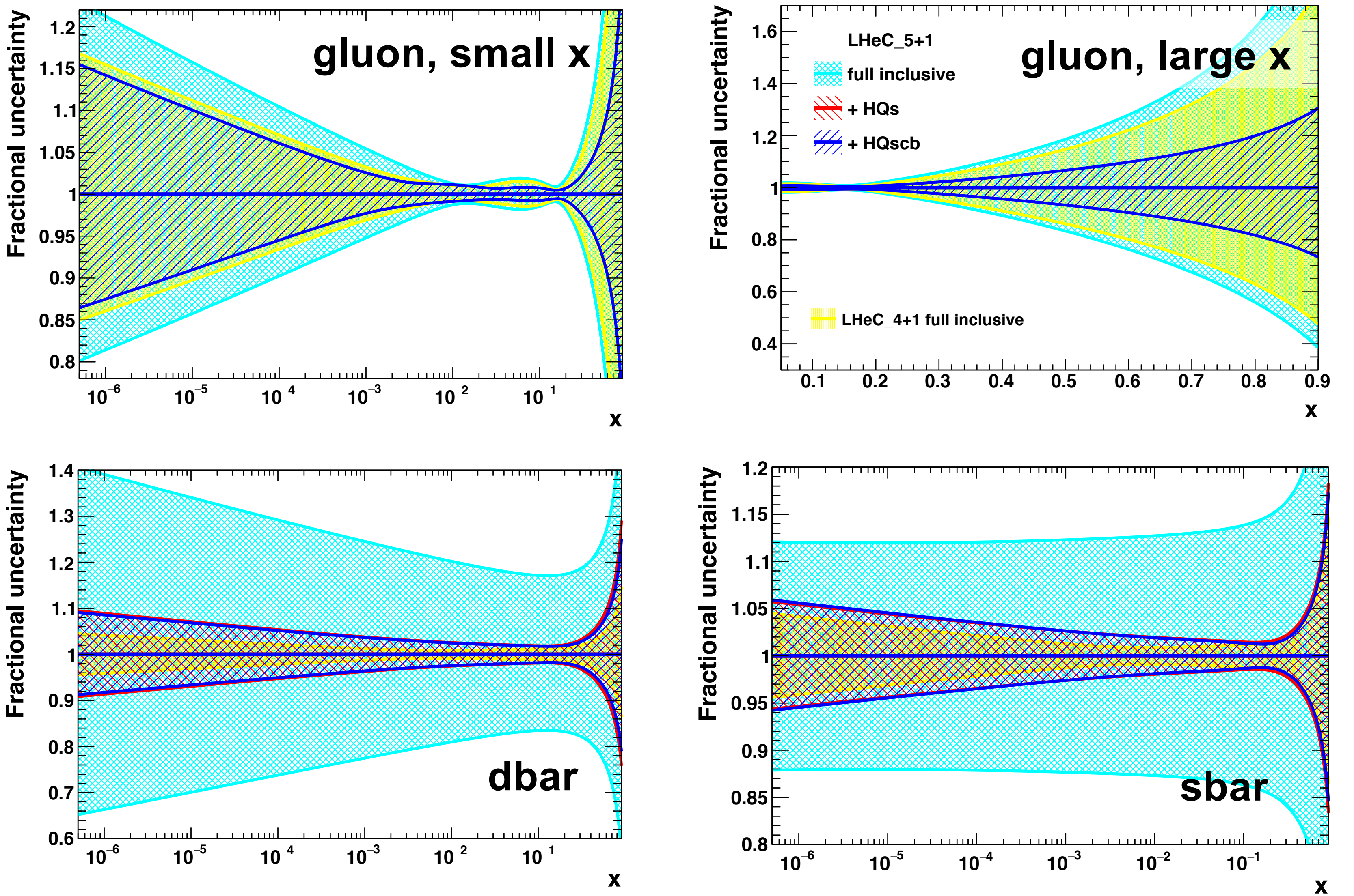
large x (≡ large Q^2), gain from increased Lint

impact of positrons



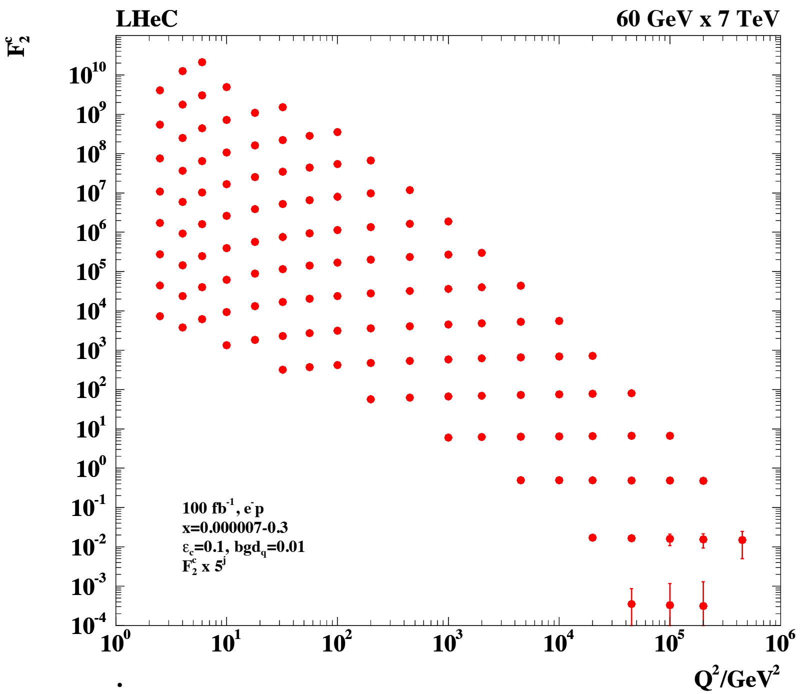
CC: e+ sensitive to d; **NC**: e± asymmetry gives $xF3^{\gamma Z}$, sensitive to valence

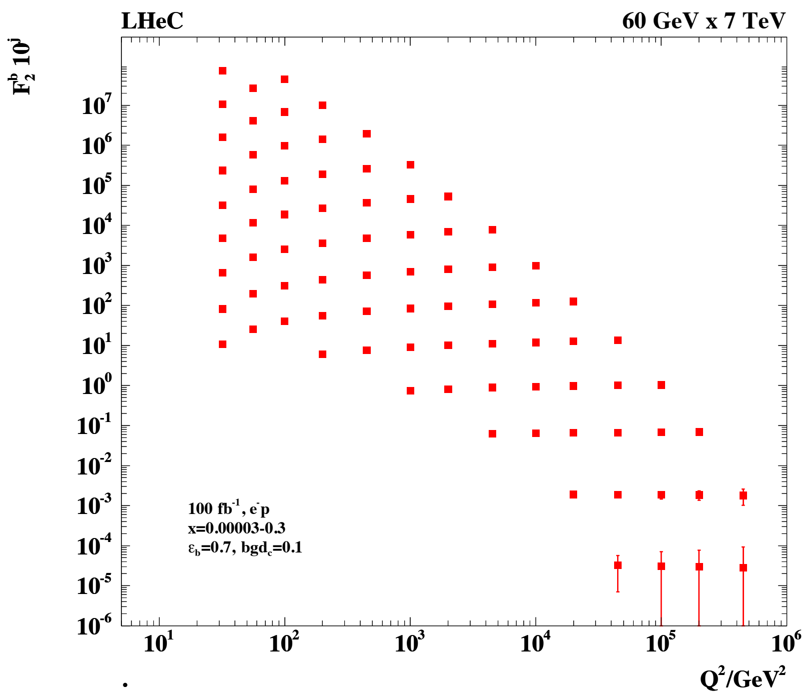
impact of s, c, b



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

c, b quarks



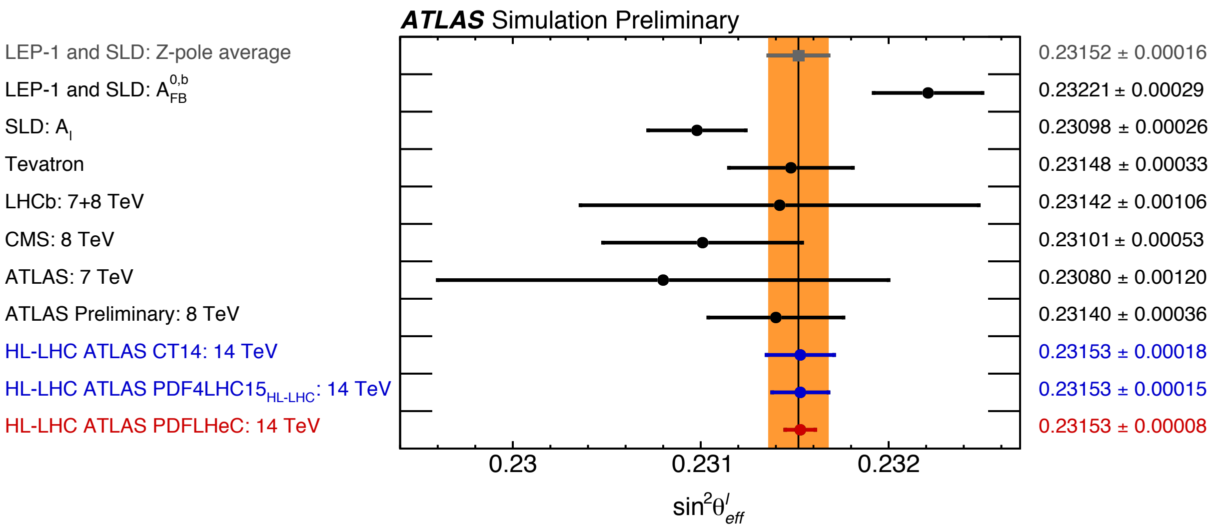


LHeC: enormously extended range and much improved precision c.f. HERA

- **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 $b\bar{b} \rightarrow A$

empowering the LHC: $\sin^2\vartheta W$

Parameter	Unit	ATLAS (Ref. [433])	HL-LHC projection		
		MMHT2014	CT14	HL-LHC PDF	LHeC PDF
Centre-of-mass energy, $\sqrt{s}$	TeV	8	14	14	14
Int. luminosity, $\mathcal{L}$	fb^{-1}	20	3000	3000	3000
Experimental uncert.	10^{-5}	$\pm$ 23	$\pm$ 9	$\pm$ 7	$\pm$ 7
PDF uncert.	10^{-5}	$\pm$ 24	$\pm$ 16	$\pm$ 13	$\pm$ 3
Other syst. uncert.	10^{-5}	$\pm$ 13	–	–	–
Total uncert., $\Delta \sin^2\theta_W$	10^{-5}	$\pm$ 36	$\pm$ 18	$\pm$ 15	$\pm$ 8



empowering the LHC: MW

Parameter	Unit	ATLAS (Ref. [424])	HL-LHC projection			
		CT10	CT14	HL-LHC	LHeC	LHeC
Centre-of-mass energy, $\sqrt{s}$	TeV	7	14	14	14	14
Int. luminosity, $\mathcal{L}$	fb^{-1}	5	1	1	1	1
Acceptance		$\lvert\eta\rvert < 2.4$	$\lvert\eta\rvert < 2.4$	$\lvert\eta\rvert < 2.4$	$\lvert\eta\rvert < 2.4$	$\lvert\eta\rvert < 4$
Statistical uncert.	MeV	$\pm$ 7	$\pm$ 5	$\pm$ 4.5	$\pm$ 4.5	$\pm$ 3.7
PDF uncert.	MeV	$\pm$ 9	$\pm$ 12	$\pm$ 5.8	$\pm$ 2.2	$\pm$ 1.6
Other syst. uncert.	MeV	$\pm$ 13	-	-	-	
Total uncert. Δm_W	MeV	$\pm$ 19	13	7.3	5.0	4.1