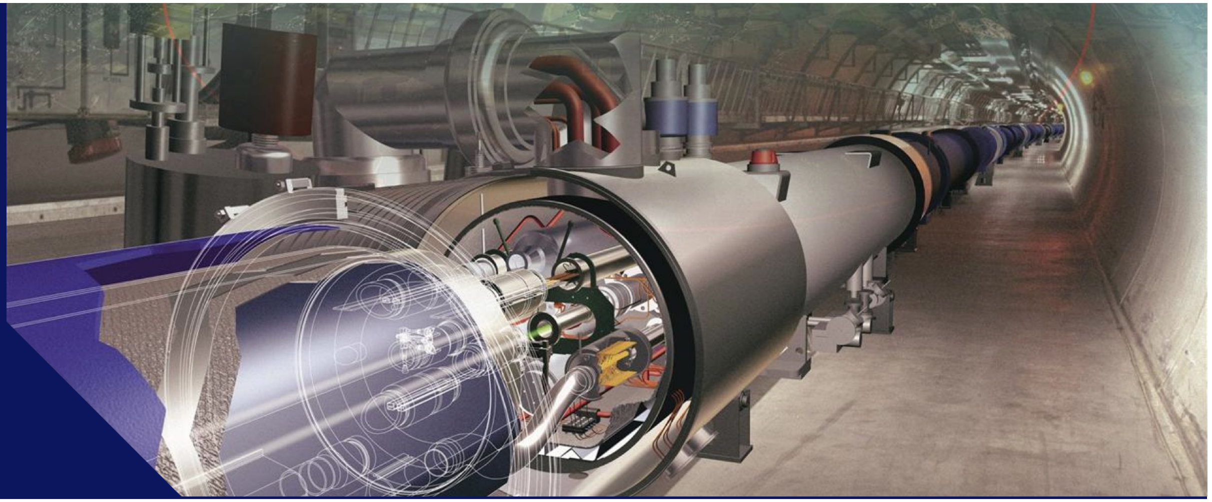
ECFA-UK 2024

Durham

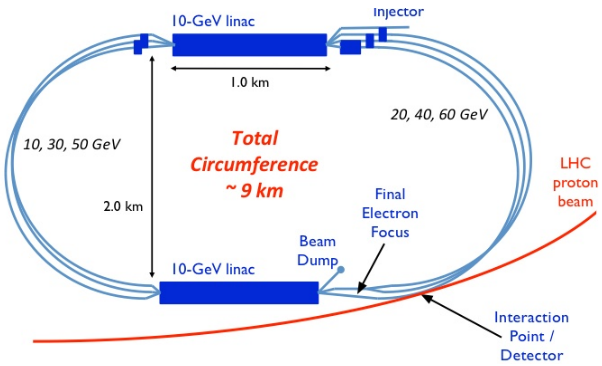
23 – 26 Sept 2024

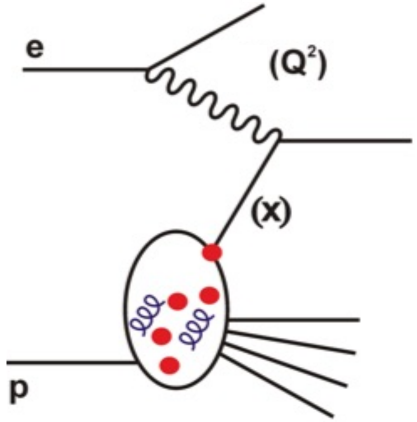


PDFs and QCD at the LHeC and other future ep colliders

Claire Gwenlan, Oxford

ep/eA@CERN study group for the LHeC and FCC-eh : *https://indico.cern.ch/e/LHeCFCCeh*

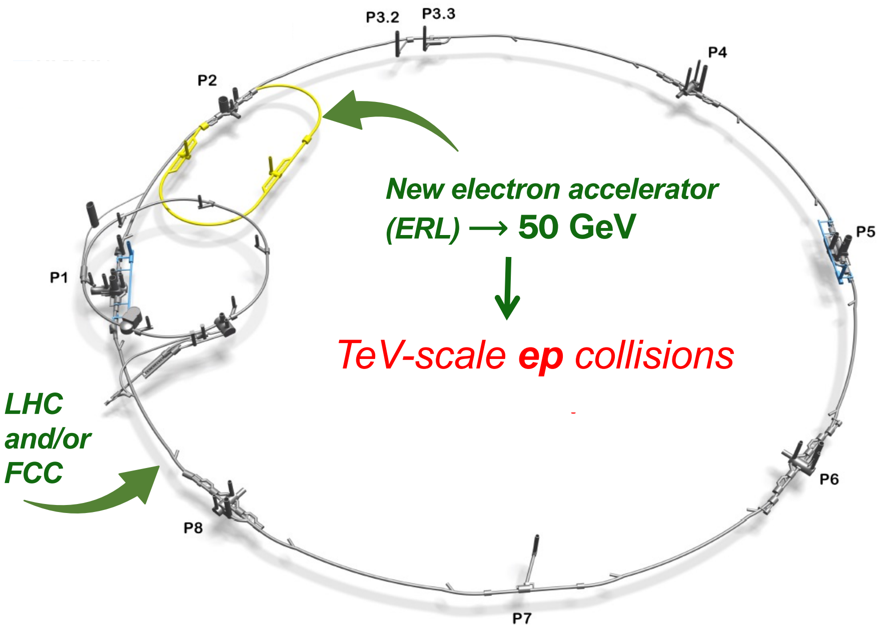


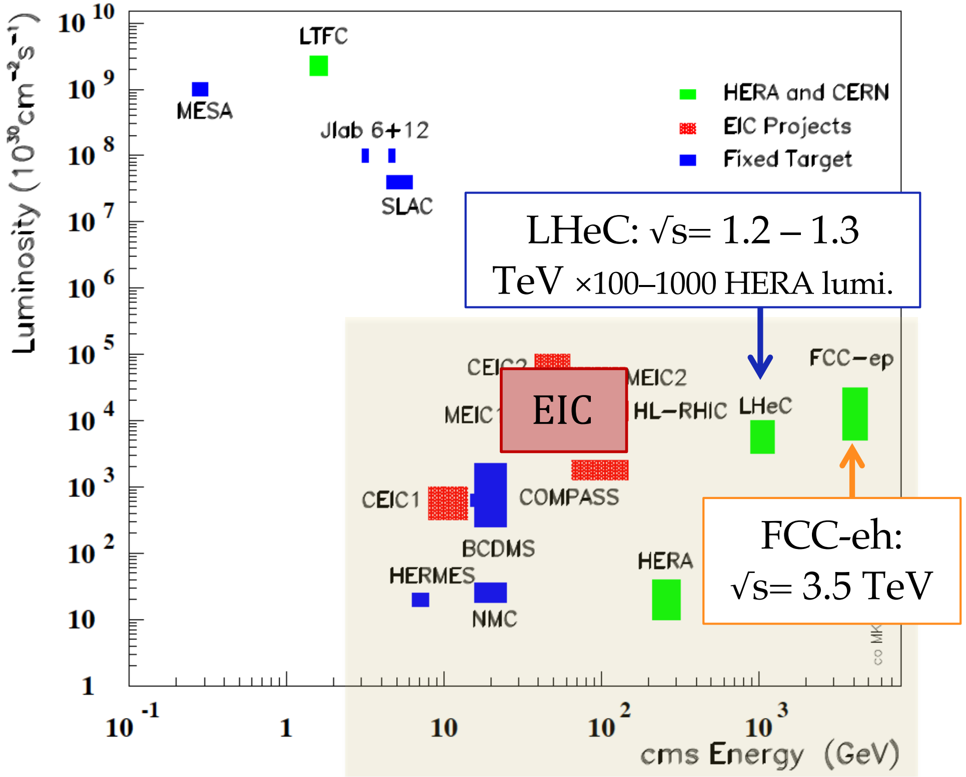


UNIVERSITY OF OXFORD

LHeC and FCC-eh

CERN future colliders: arXiv:[1810.13022](1810.13022)

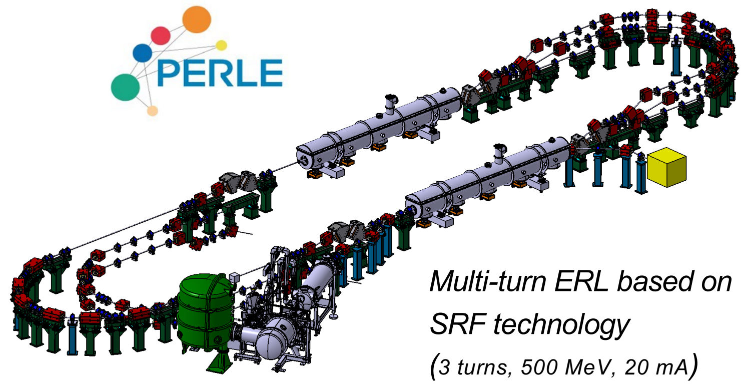




- **e: energy recovery LINAC** (ERL)
- attached to HL-LHC (or FCC)
- e beam: ⟶ **50** GeV
- e pol.: P= **±0.8**
- Lint ⟶ **1–2** ab^{-1} (1000× HERA!)

- **PERLE @ IJCLab (Orsay)** ⟶

under construction to demonstrate all ERL aspects for LHeC/FCC-eh



Multi-turn ERL based on SRF technology
(3 turns, 500 MeV, 20 mA)

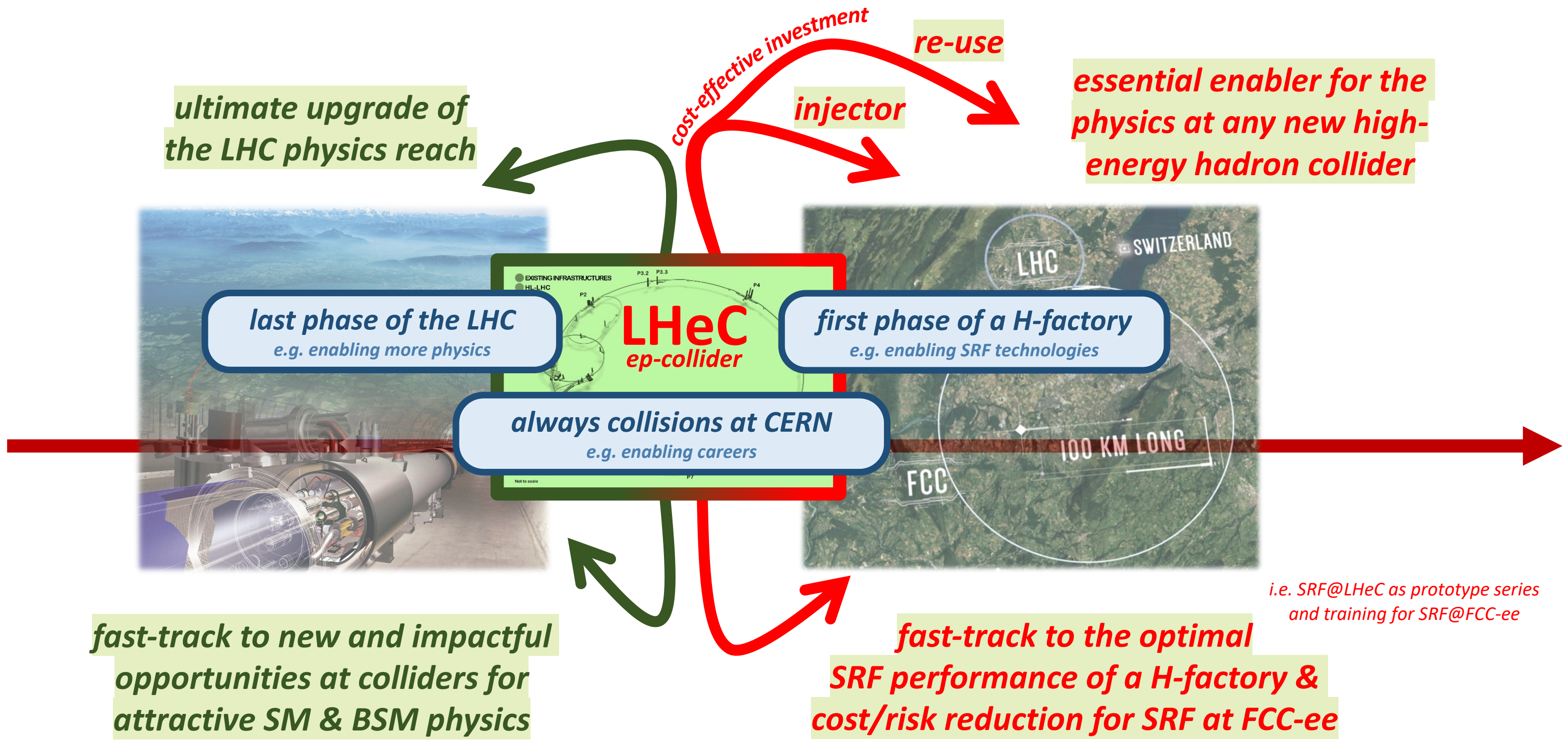
CDR: *J.Phys.G* 45 (2018) 6, 065003

LHeC timescale

ep-option with HL-LHC: LHeC
CDR update: [JPhys G48 (2021) 11, 110501]

10 yrs@1.2 TeV (1 ab^{-1}) = Run 6 + 5yrs ***ep-only***
6yrs ***ep-only*** *@ LHC (> 1 ab^{-1})*

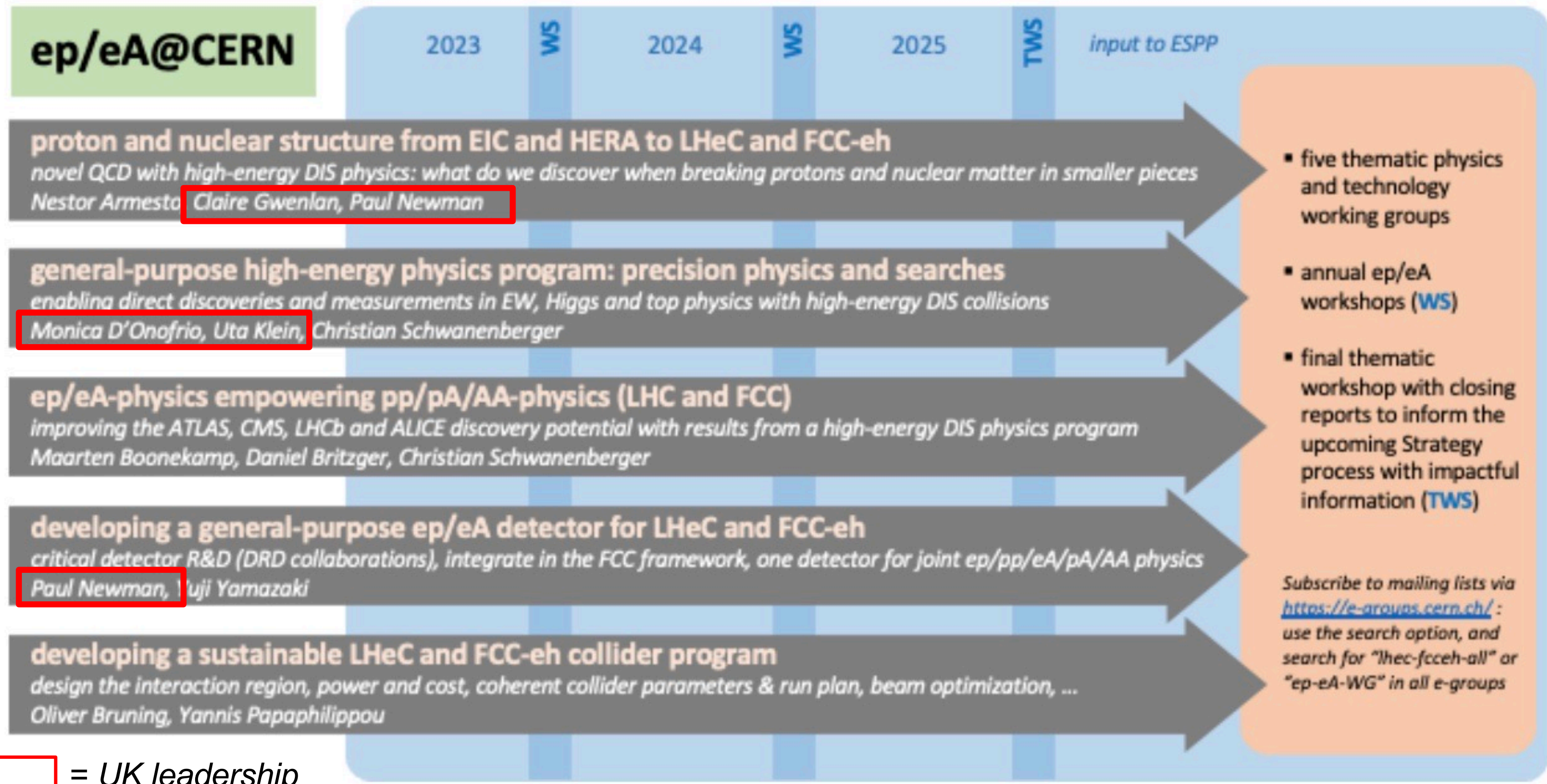
An impactful "*bridge*" between major colliders @ CERN



CERN-mandated LHeC/FCC-eh study towards ESPP

https://indico.cern.ch/e/LHeCFCCeh

ep/eA white paper in preparation for ESPP

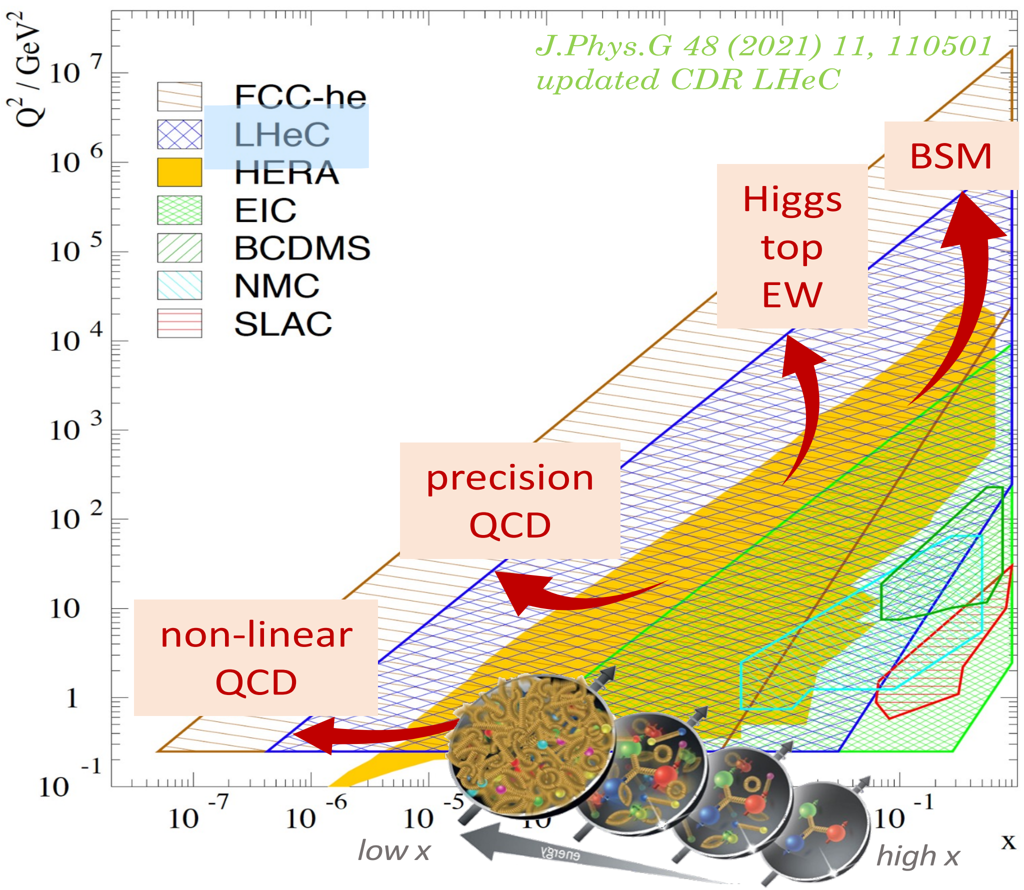


= *UK leadership*

= *themes of this talk*

(see also, **LHeC CDR**, arXiv:1206.2913 and update: J. Phys. G 48 (2021) 11, 110501
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



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

DIS: cleanest high-resolution microscope

opportunity for **unprecedented increase in kinematic reach from single DIS experiment**;

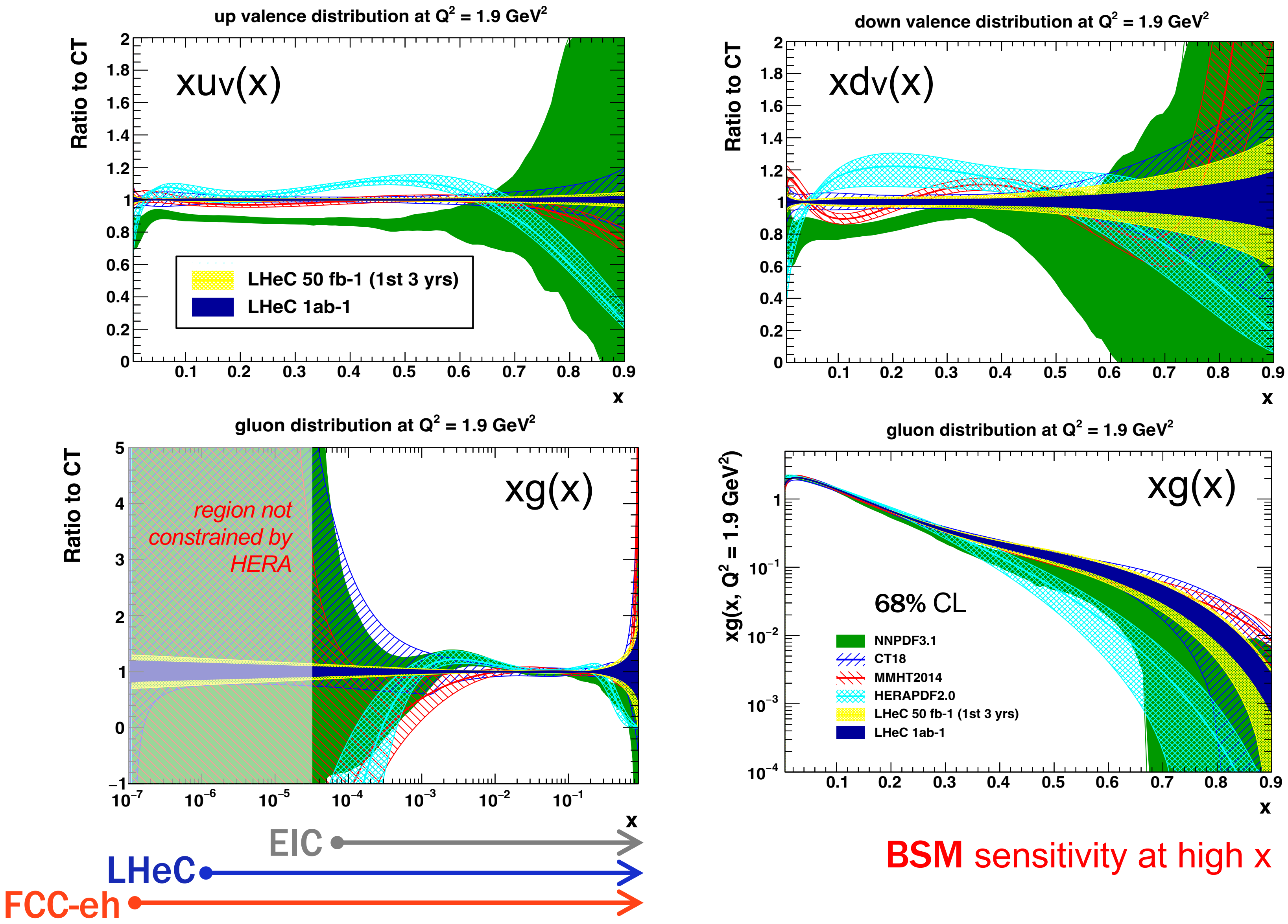
- **×1000** increase in lumi. cf. HERA, and much broader kinematic coverage cf. EIC
- **well understood correlated systematics** from single, consistent dataset – precedent @ HERA
- **theoretically clean** and **less subject to BSM contamination** at high scales cf. LHC

- **QCD precision physics** and **discovery**, empowering the HL-LHC and FCC-hh
  - unprecedented access to **small x**
  - unique **nuclear physics** facility

PLUS powerful **Higgs**, **EW**, **top**, **BSM** programmes in its own right

arXiv:2007.14491

Quark and Gluon PDFs



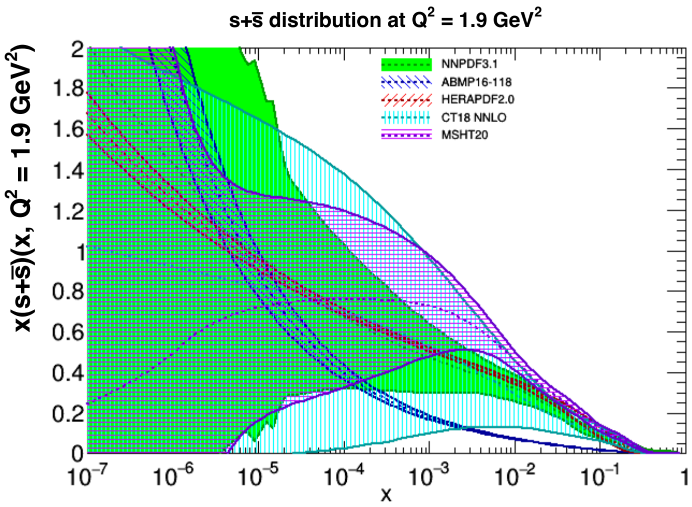
BSM sensitivity at high x

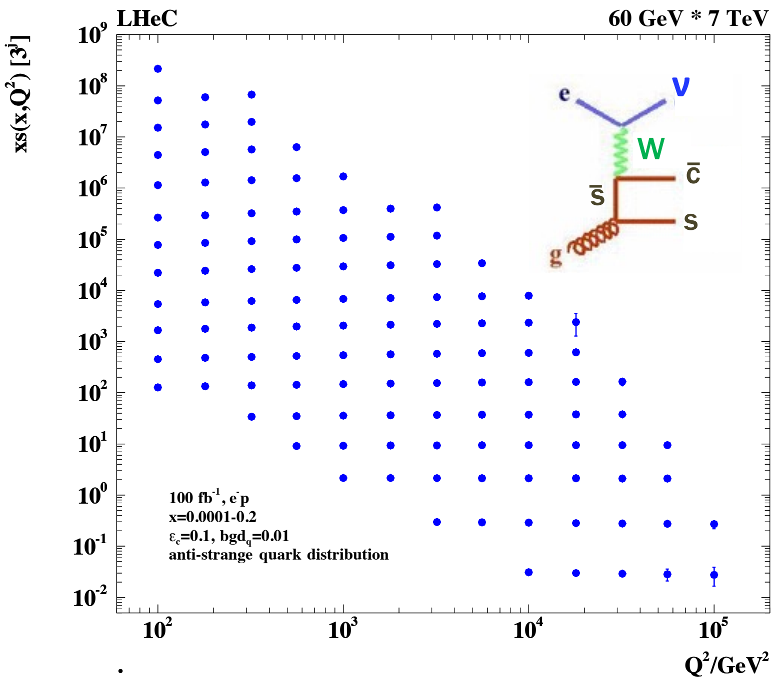
(***EIC*** *impacts at high x, see* EG. *arXiv:2309.11269*)

Strange, c, b

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

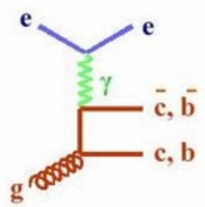
➜ **LHeC:** direct sensitivity via charm tagging in Ws→c
(x,Q^2) mapping of strange density for first time





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

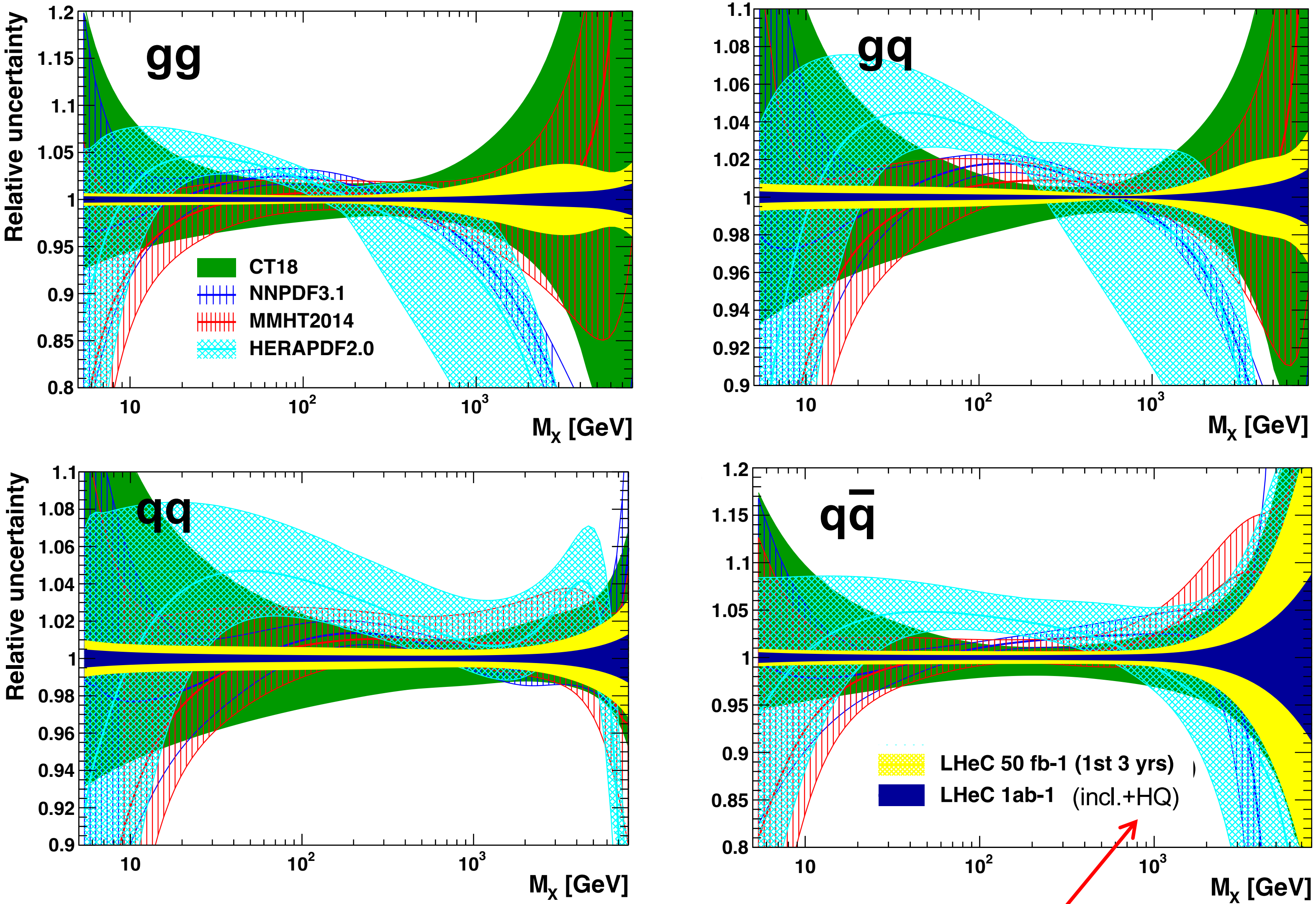
- **δMc = 50 (HERA)** to **3 MeV**: impacts on **α**s, regulates ratio of charm to light, crucial for precision t, H
- **δMb** to **10 MeV**; MSSM: Higgs produced dominantly via $b\bar{b} \rightarrow A$



- **t pdf** also accessible (EG. G.R. Boroun, PLB 744 (2015) 142; 741 (2015) 197)

- completely resolve all proton **pdfs** (**ubar, uv, dbar, dv, s, c, b, t, xg**)

PDF luminosities @ 14 TeV



(s,c,b) also included

arXiv:2007.14491
featured in Snowmass **αs** White Paper,
arXiv:2203.08271

Strong Coupling

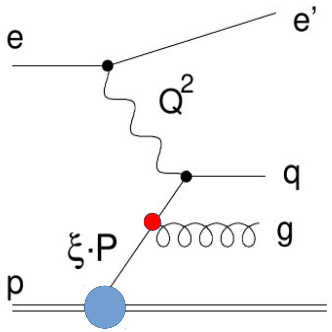
- **αs**: least known coupling constant
- current state-of-the-art: $\delta\alpha_s/\alpha_s = \mathcal{O}(1\%)$

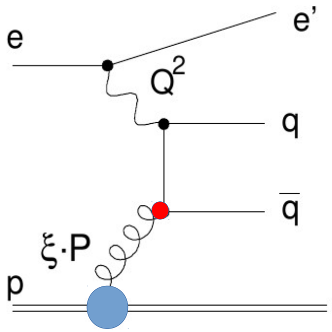
- simultaneous **PDF+αs** fits:
- **EIC** (arXiv:2307.01183): $\mathcal{O}$**(0.4%)** (exp+PDF)
- **LHeC**:
- $\Delta\alpha_s(M_Z)$[incl. DIS] = **±0.00022** (exp+PDF)
- $\Delta\alpha_s(M_Z)$= ± **0.00018** for incl. DIS together with **ep jets**
- achievable precision: $\mathcal{O}$**(0.1–0.2%)**

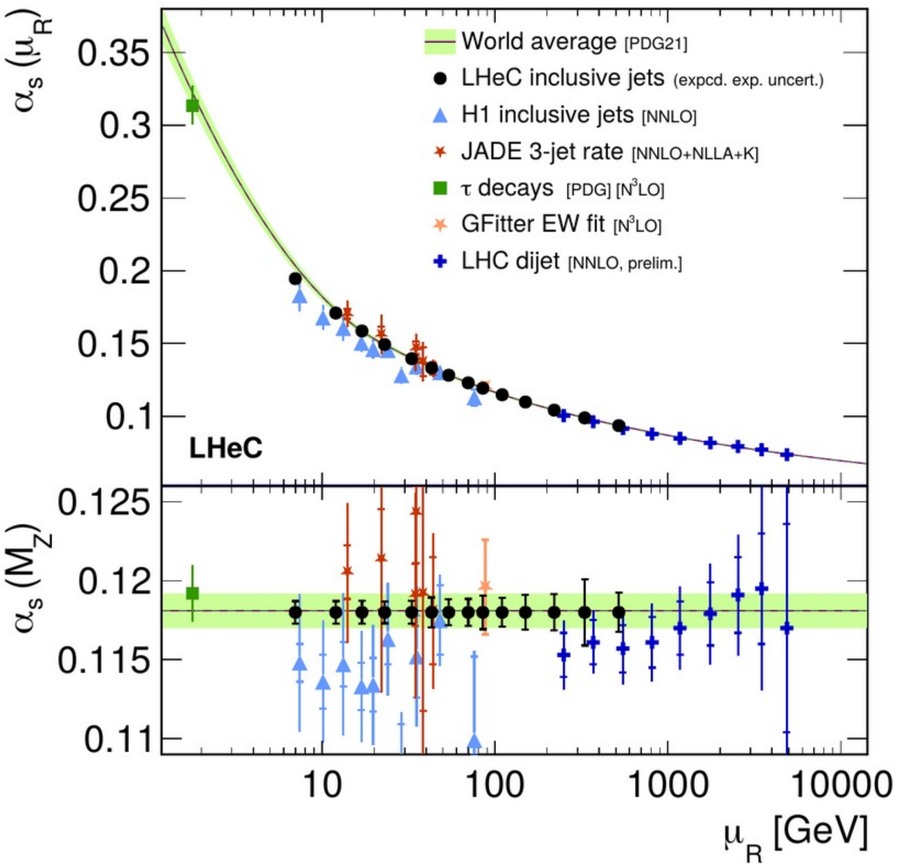
  ×5–10 better than today

  comparable precision to FCC-ee

ep jets:





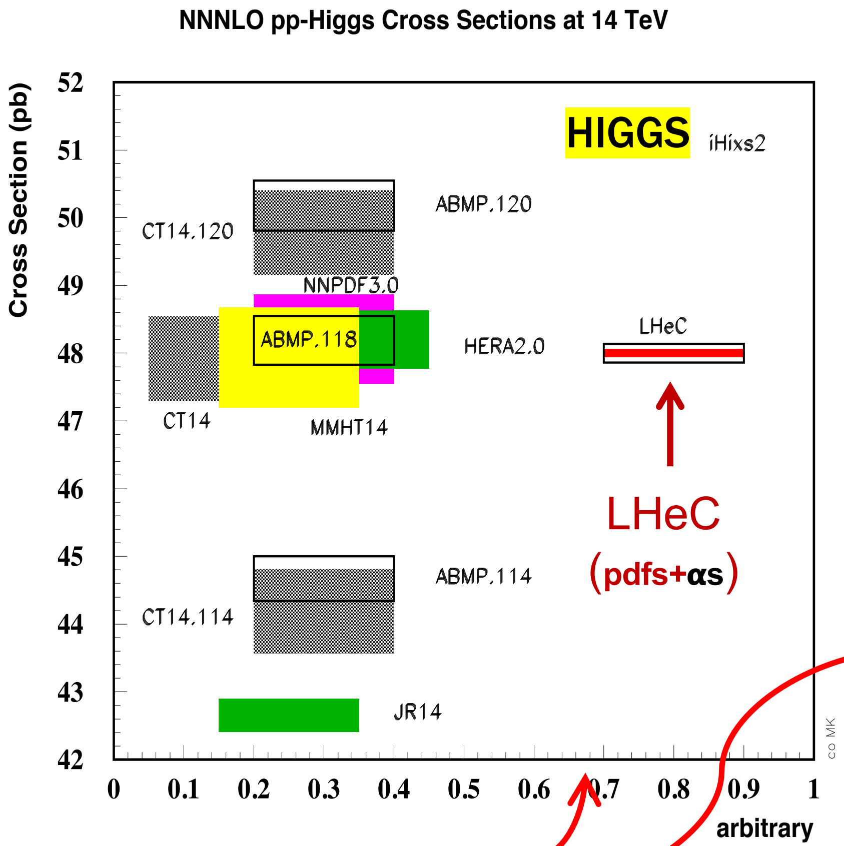


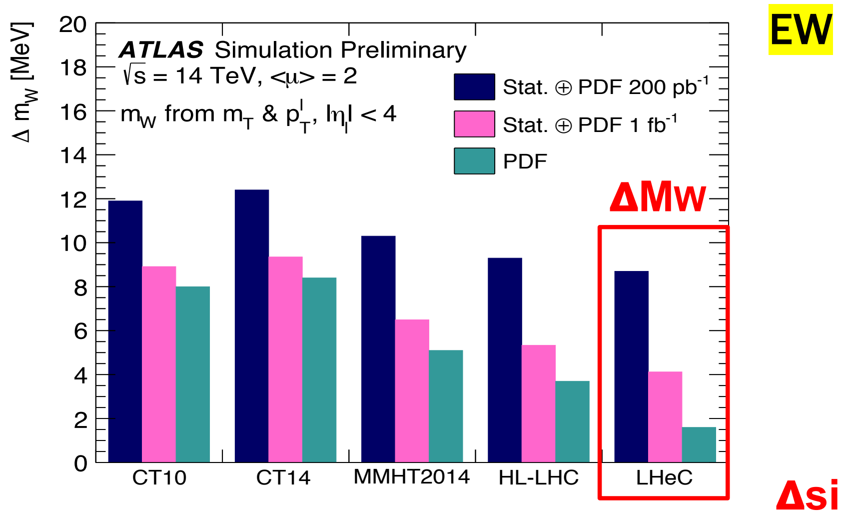
$= \sqrt{(Q^2 + p_T^2)}$

- **αs** from fits to **ep** jet production (**LHeC**)
- connects **τ**-decays to Z-pole and beyond
- **FCC-eh** further increases precision and range

arXiv:2007.14491
arXiv:1902.04070

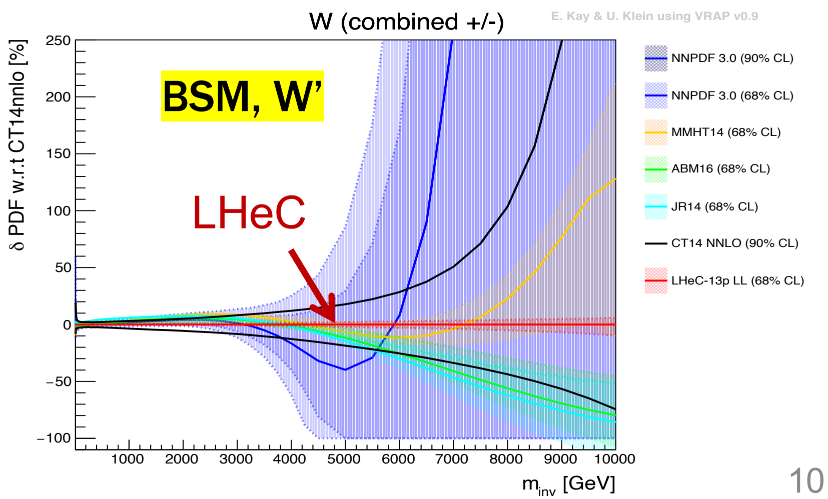
empowering the LHC





Δsin²θW

CMS 13 TeV *Preliminary*	± 0.00020 (exp+th) ± **0.00027** (pdf)
HL-LHC ATLAS PDF4LHC15$_{HL-LHC}$: 14 TeV	± 0.00007 (exp) ± **0.00013** (pdf)
HL-LHC ATLAS PDFLHeC: 14 TeV	± 0.00007 (exp) ± **0.00003** (pdf)

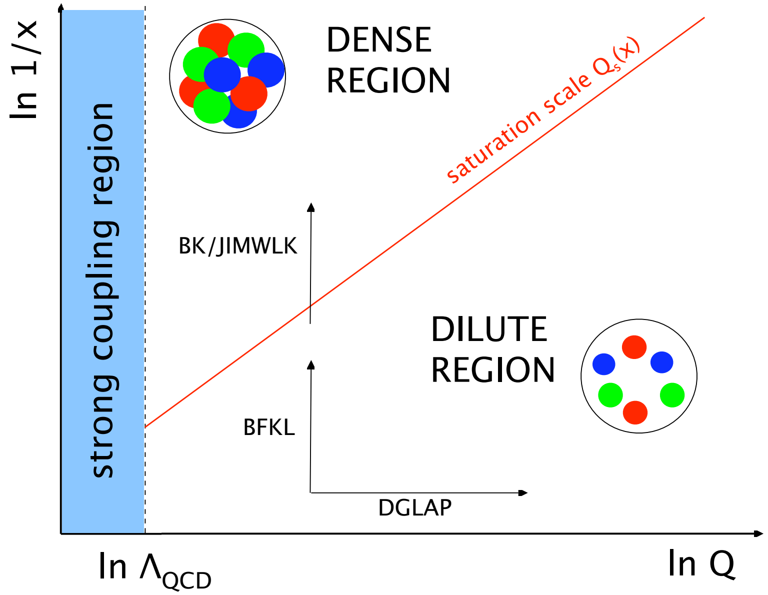


- **transformation** in precision with **LHeC** input (**pp+ep**)

PLUS powerful and complementary **ep**-only **HIGGS**, **EW**, **BSM** , **TOP**

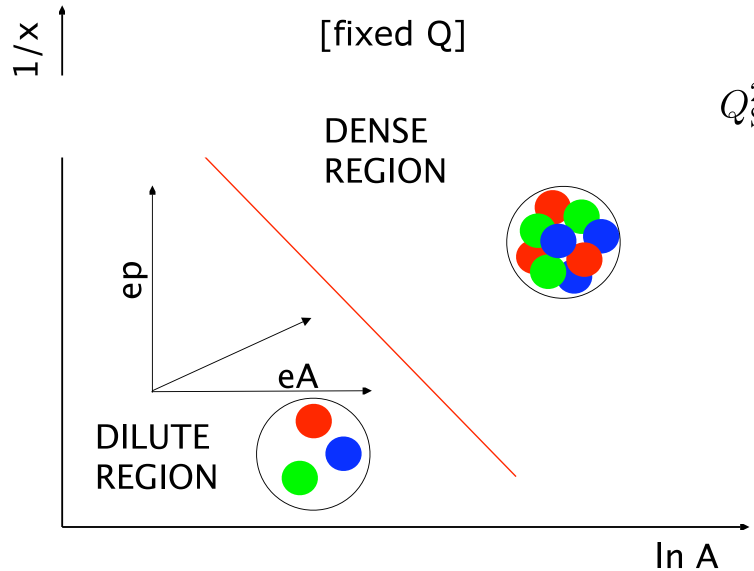
(***see Monica's talk***)

Novel QCD dynamics



- **small x** – various phenomena may occur which go beyond standard DGLAP QCD evolution:
- BFKL, connected to small-x resummation of $\log \frac{1}{x}$ terms
- gluon recombination

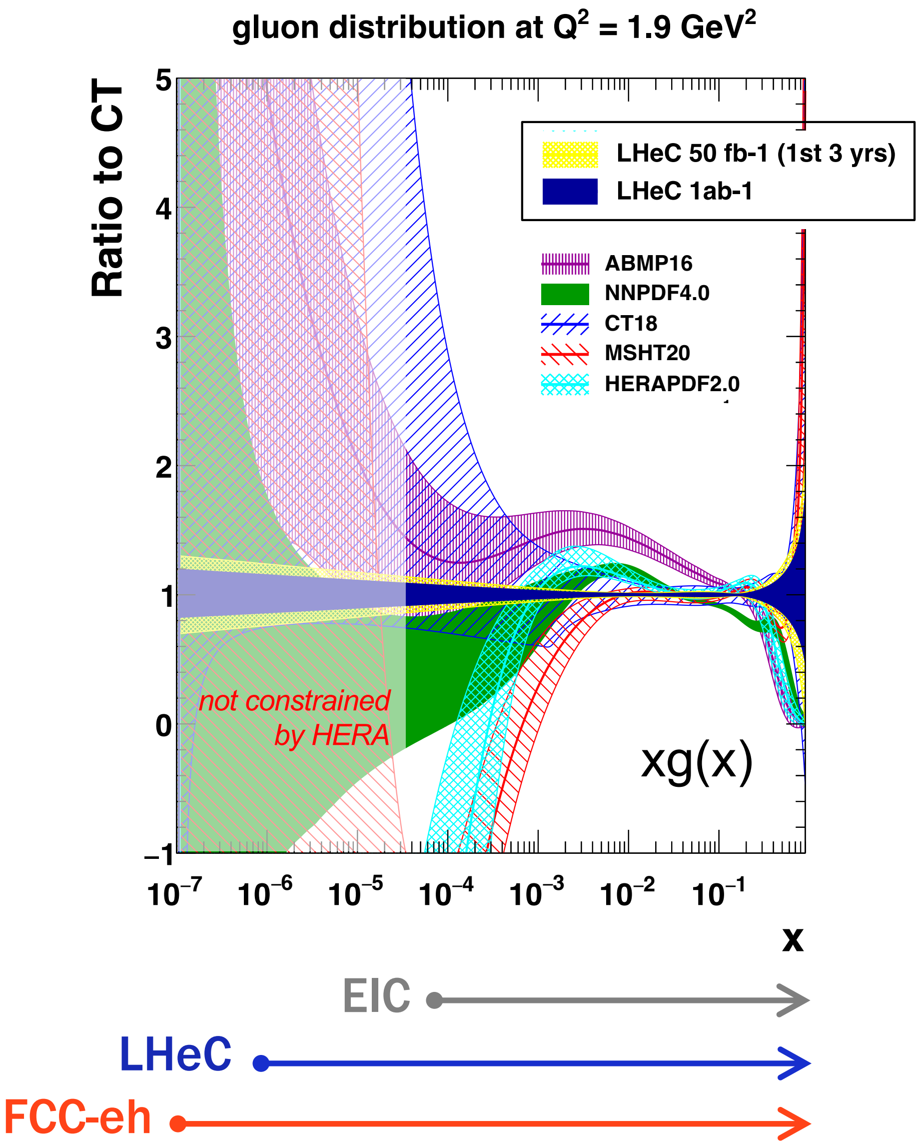
  → modification of parton evolution by including non-linear / saturation effects



$$Q_S^2 \sim \frac{A\, xg(x, Q_S^2)}{\pi R_A^2} \sim \frac{A\, xg(x, Q_S^2)}{A^{2/3}} \sim \boxed{A^{1/3}} x^{-\lambda}$$

ep and **eA** at **LHeC/FCC-eh** allows discovery and tests of **novel QCD dynamics** via two-prong approach: **small x** and **large A**

Gluon PDF in proton at small x

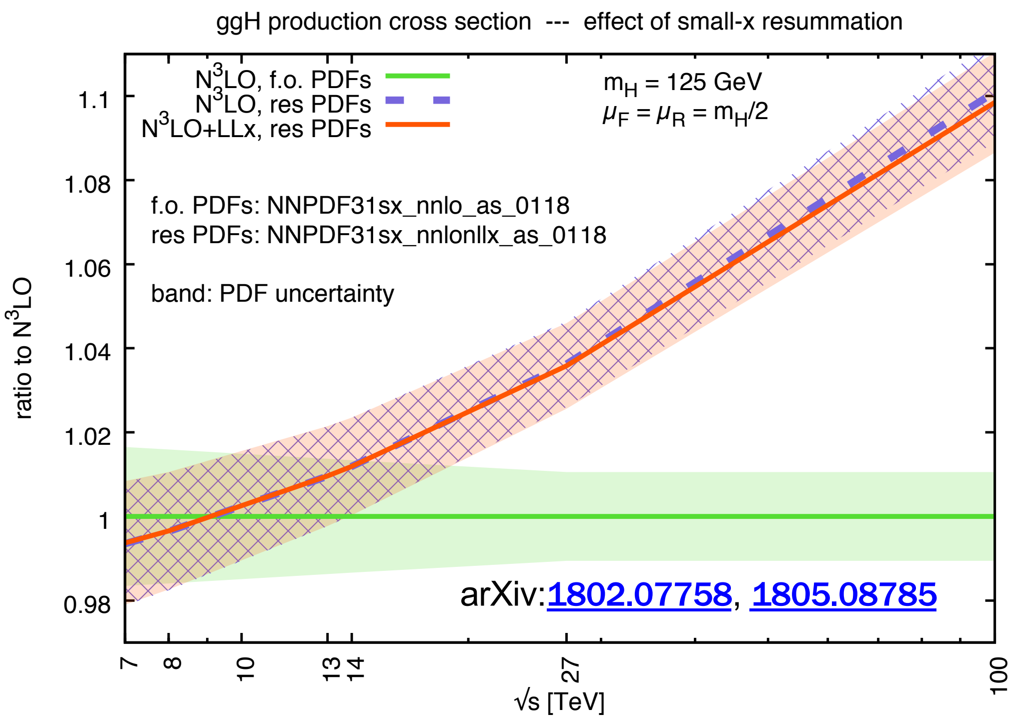


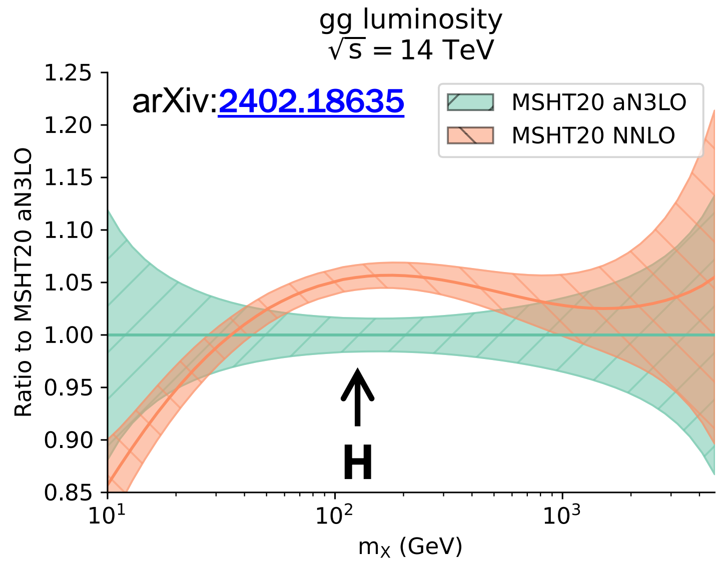
HERA sensitivity stops x ≃ 5.10^{-5}

LHeC and FCC-eh offer unprecedented access to explore **small x** QCD regime:

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

small x treatment matters





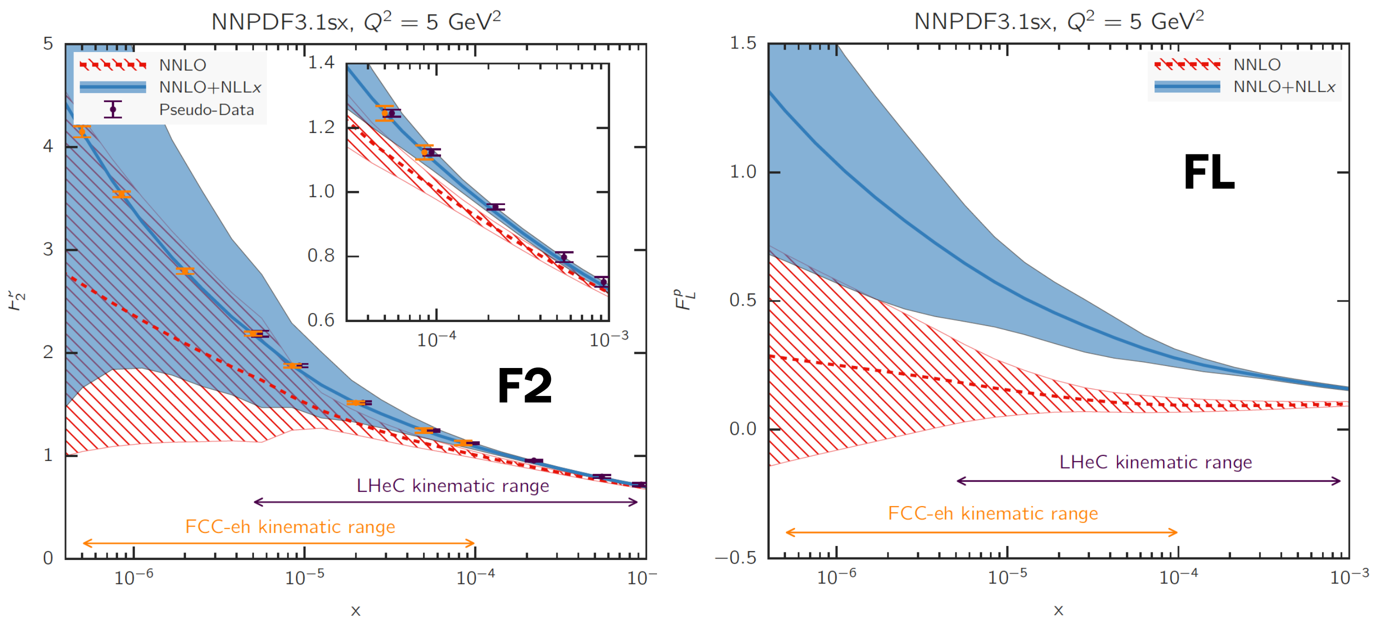
- effect of small x resummation – needed to stabilise BKFL expansion :
- EG. **gg→H** cross section for LHC, HE-LHC, FCC
- significant impact, especially at ultra low x values probed at FCC

(see also work on forward H production (arXiv:2011.03193) and HQ (arXiv:2211.10142); other processes in progress)

- (approximate) **N^{3}LO pdfs** also now available (MSHT, NNPDF)
- significant impact on small x gluon, affecting small MX in gg lumi, with knock-on effects in H region (MX=125 GeV)

- **BEWARE small x effects!**

LHeC and FCC−eh sensitivity to small x effects

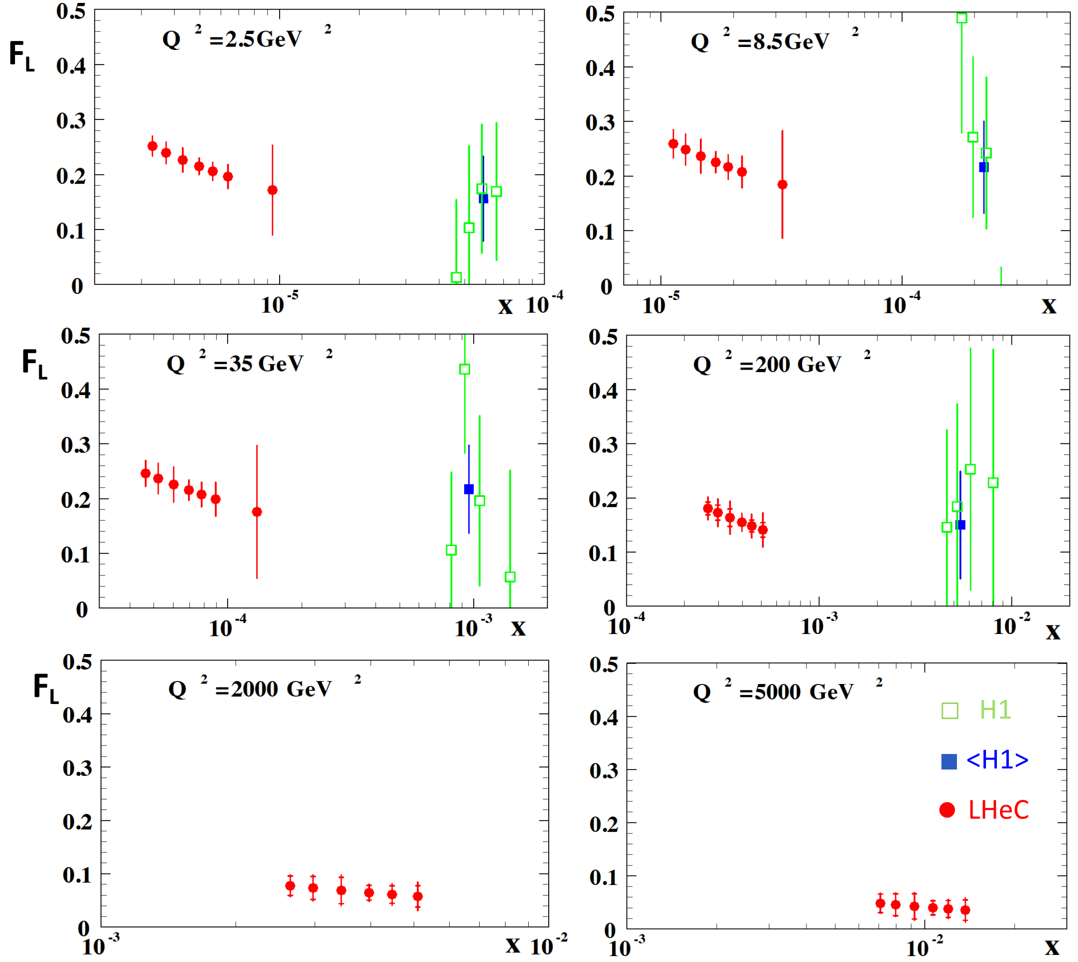


(arXiv:[1710.05935](1710.05935))

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** (further detailed studies in arXiv:2007.14491)
- measurement of FL has a significant role to play, arXiv:1802.04317

Longitudinal Structure Function



simulated for:

Ep = 7 TeV and

Ee = 60, 30, 20 GeV

integrated luminosity:

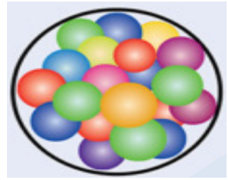
10, 1, 1 fb^{-1}

measurement dominated by systematics

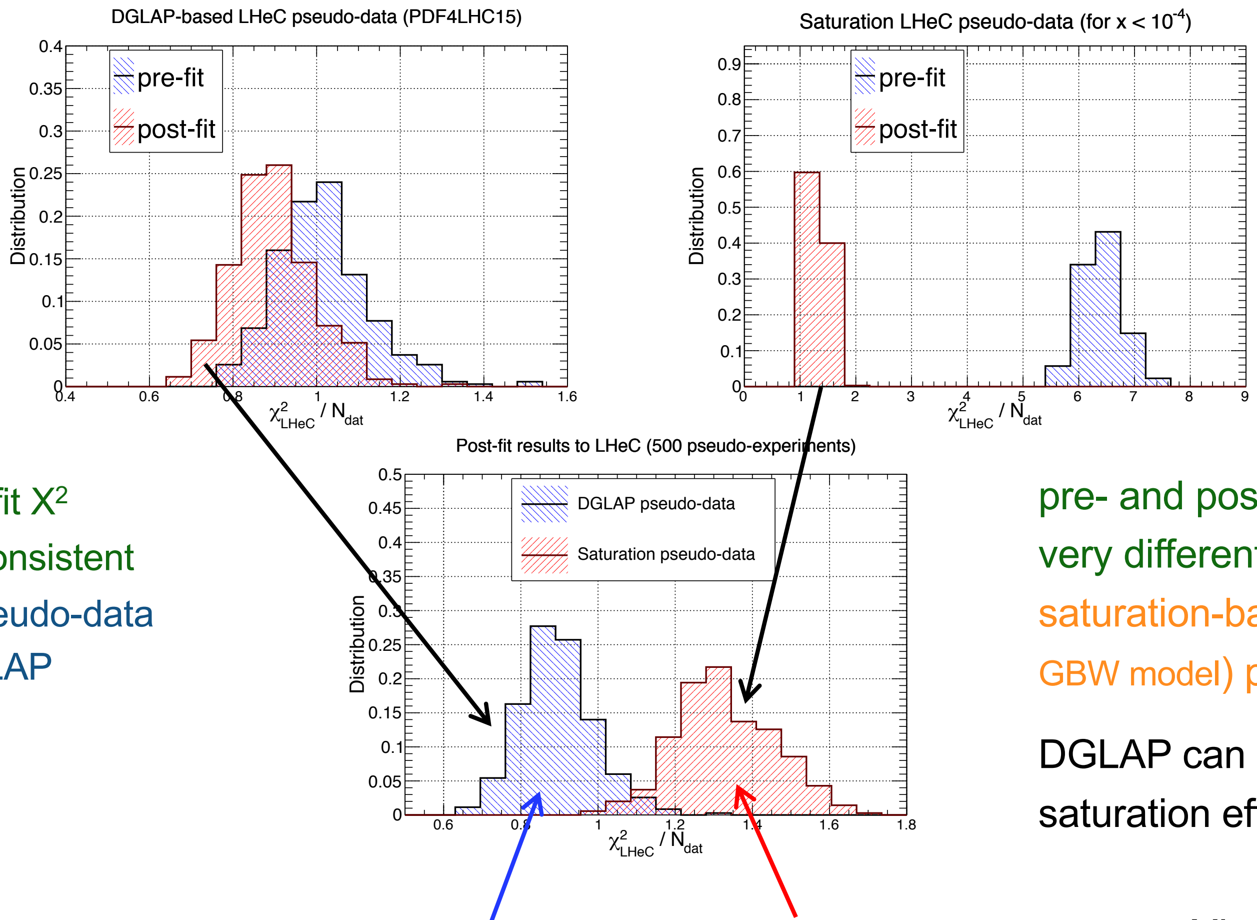
(arXiv:1802.04317)

- **simultaneous measurement of F2 and FL is clean way to pin down dynamics at small x**
- vary also nuclear size to definitively disentangle small-x resummation from non-linear dynamics

Novel dynamics at small x: saturation



- studies show linear evolution **cannot accommodate saturation**, even at NNLO or NNLO+NLLx
- EG, **DGLAP-** vs **saturation-** based simulated data fitted with NNLO DGLAP



pre- and post-fit X^2 distributions consistent for DGLAP pseudo-data fitted with DGLAP

pre- and post-fit distributions very different for DGLAP fit to saturation-based ($x \leq 10^{-4}$, GBW model) pseudo-data

DGLAP can not absorb <u>all</u> saturation effects

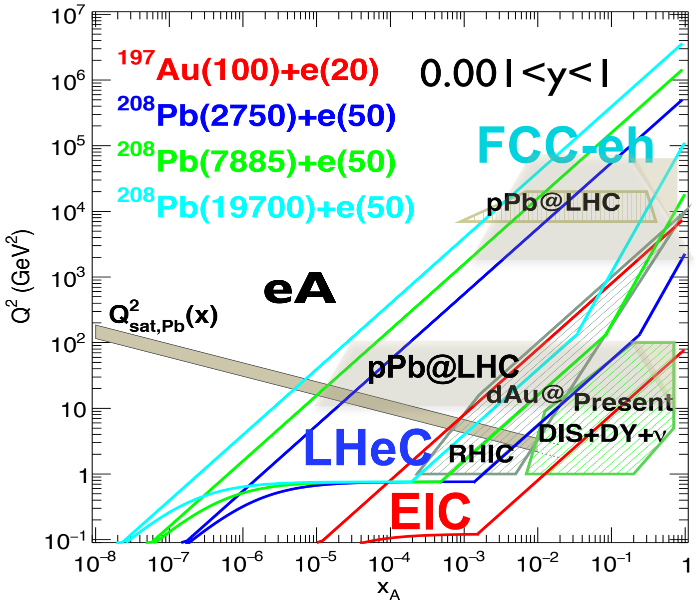
LHeC can distinguish between **DGLAP** and **saturation**

arXiv:[2007.14491](2007.14491)

(NB, **large lever arm in Q^2 crucial**, see also arXiv:[1702.00839](1702.00839))

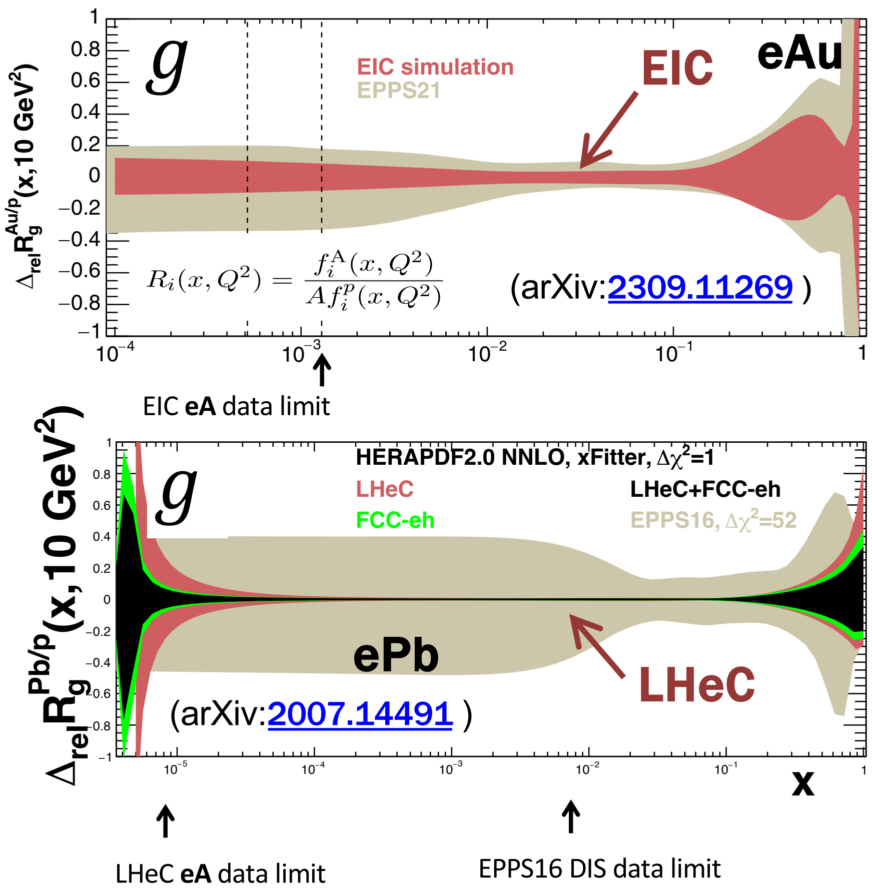
Impact on Nuclear pdfs

- **saturation effects** will show up most strongly in heavy nuclei
- **EIC** and **LHeC/FCC-eh** also operate with **eA**
- **LHeC/FCC-eh: 4–5 orders of magnitude** extension in Q^2, 1/x vs existing DIS, and **~ 2–3 vs EIC**

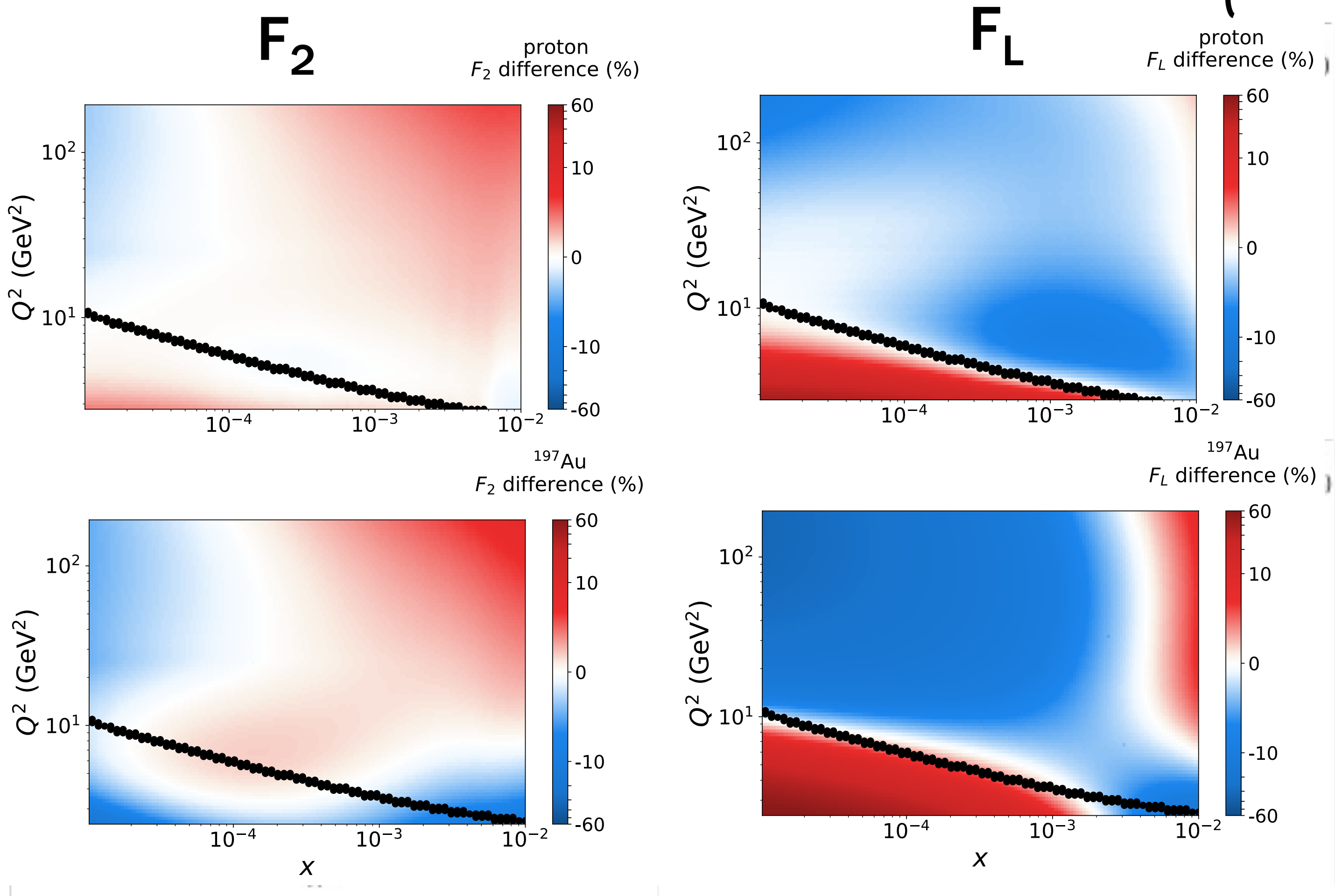


- **nuclear pdfs** on **single nucleus** for the first time (only experimental uncertainties shown (**ΔX**^{2}=1))

gluon nuclear modification factor



Novel small x dynamics: saturation



$$\frac{F_{2,L}^{\mathrm{BK}} - F_{2,L}^{\mathrm{DGLAP}}}{F_{2,L}^{\mathrm{BK}}}$$

ep

up to 40% for F_L @ LHeC

eAu

up to 10% effect for F_2 and 60% for F_L @ LHeC

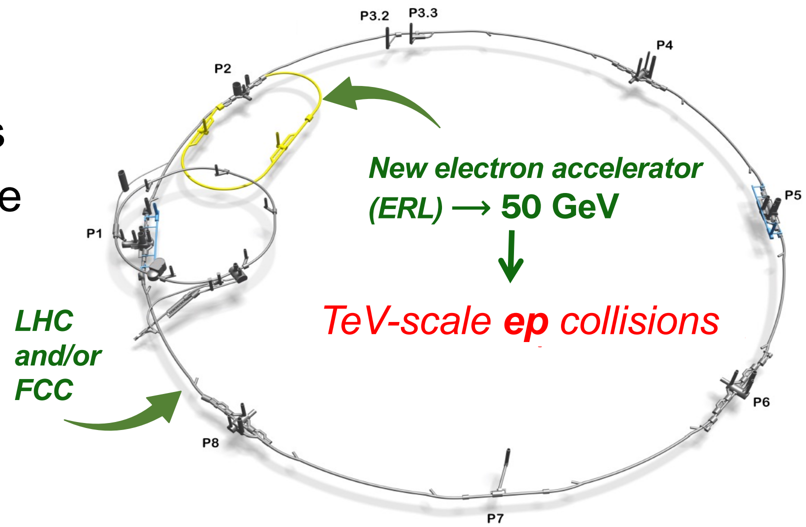
(cf. 10 – 15% in EIC range)

(arXiv:2203.05846)

- complementary study of **linear DGLAP** vs **non-linear evolution with saturation (BK)**
- match the two approaches in specific regions where effects from saturation small
- quantify differences away from matching region: **sensitive to differences in evolution dynamics**

Summary

- a new highly luminous, energy frontier **ep/eA** collider **@CERN** is a **QCD precision** and **discovery machine**; enables full exploitation of current and future hadron colliders
  - precise determination of **proton** and **nuclear pdfs** across vast kinematic range that cannot be matched at other colliders, including precise HQ measurements
  - **α_s** to approaching **per mille** level
  - **ep** together with **eA** allows discovery and tests of non-linear / saturation effects at small x and with different A dependence



- **UK** has significant involvement and leadership in **ep/eA@CERN** studies
- ↪ **White Paper** in preparation for **ESPP**

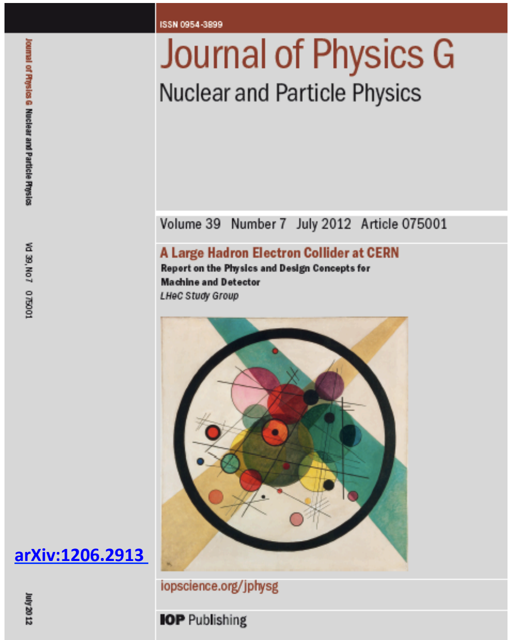
in remembrance of Max Klein, the "father" of these projects:
https://home.cern/news/obituary/physics/max-klein-1951-2024

Extras

LHeC Conceptual Design Report and Beyond

CDR 2012: commissioned by CERN, ECFA, NuPECC

200 authors, 69 institutions



arXiv:[1206.2913]

<u>Further selected references</u>:

On the relation of the LHeC and the LHC
arXiv:1211.5102

The Large Hadron Electron Collider
arXiv:1305.2090

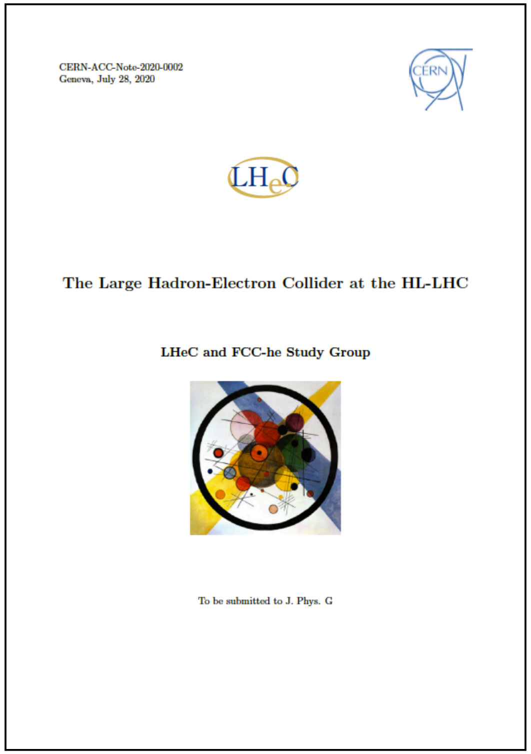
Dig Deeper
Nature Physics 9 (2013) 448

Future Deep Inelastic Scattering with the LHeC
arXiv:1802.04317

An Experiment for Electron-Hadron Scattering at the LHC
arXiv:2201.02436

CDR update

400 pages, 300 authors, 156 institutions



J. Phys. G 48 (2021) 11, 110501

(arXiv:2007.14491)

see also, FCC CDR, vols 1 and 3:

physics, EPJ C79 (2019), 6, 474

FCC with eh integrated, EPJ ST 228 (2019), 4, 755

5 page summary: ECFA newsletter No. 5, August 2020

https://cds.cern.ch/record/2729018/files/ECFA-Newsletter-5-Summer2020.pdf

Statement of the IAC

Members of the Committee

Sergio Bertolucci (Bologna)
Nichola Bianchi (INFN, now Singapore)
Frederick Bordy (CERN)
Stan Brodsky (SLAC)
Oliver Brüning (CERN, coordinator)
Hesheng Chen (Beijing)
Eckhard Elsen (CERN)
Stefano Forte (Milano)
Andrew Hutton (Jefferson Lab)
Young-Kee Kim (Chicago)
Max Klein (Liverpool, coordinator)
Shin-Ichi Kurokawa (KEK)
Victor Matveev (JINR Dubna)
Aleandro Nisati (Rome I)
Leonid Rivkin (PSI Villigen)
Herwig Schopper (CERN, em.DG, Chair)
Jürgen Schukraft (CERN)
Achille Stocchi (Orsay)
John Womersley (ESS Lund)

In conclusion it may be stated

- The installation and operation of the LHeC has been demonstrated to be commensurate with the currently projected HL-LHC program, while the FCC-eh has been integrated into the FCC vision;
- The feasibility of the project as far as accelerator issues and detectors are concerned has been shown. It can only be realised at CERN and would fully exploit the massive LHC and HL-LHC investments;
- The sensitivity for discoveries of new physics is comparable, and in some cases superior, to the other projects envisaged;
- The addition of an ep/A experiment to the LHC substantially reinforces the physics program of the facility, especially in the areas of QCD, precision Higgs and electroweak as well as heavy ion physics;
- The operation of LHeC and FCC-eh is compatible with simultaneous pp operation; for LHeC the interaction point 2 would be the appropriate choice, which is currently used by ALICE;
- The development of the ERL technology needs to be intensified in Europe, in national laboratories but with the collaboration of CERN;
- A preparatory phase is still necessary to work out some time-sensitive key elements, especially the high power ERL technology (PERLE) and the prototyping of Intersection Region magnets.

Recommendations

i) It is recommended to further develop the ERL based ep/A scattering plans, both at LHC and FCC, as attractive options for the mid and long term programme of CERN, resp. Before a decision on such a project can be taken, further development work is necessary, and should be supported, possibly within existing CERN frameworks (e.g. development of SC cavities and high field IR magnets).

ii) The development of the promising high-power beam-recovery technology ERL should be intensified in Europe. This could be done mainly in national laboratories, in particular with the PERLE project at Orsay. To facilitate such a collaboration, CERN should express its interest and continue to take part.

iii) It is recommended to keep the LHeC option open until further decisions have been taken. An investigation should be started on the compatibility between the LHeC and a new heavy ion experiment in Interaction Point 2, which is currently under discussion.

After the final results of the European Strategy Process will be made known, the IAC considers its task to be completed. A new decision will then have to be taken for how to continue these activities.

Herwig Schopper, Chair of the Committee, Geneva, November 4, 2019

(published in LHeC CDR update, J. Phys. G 48 (2021) 11, 110501)

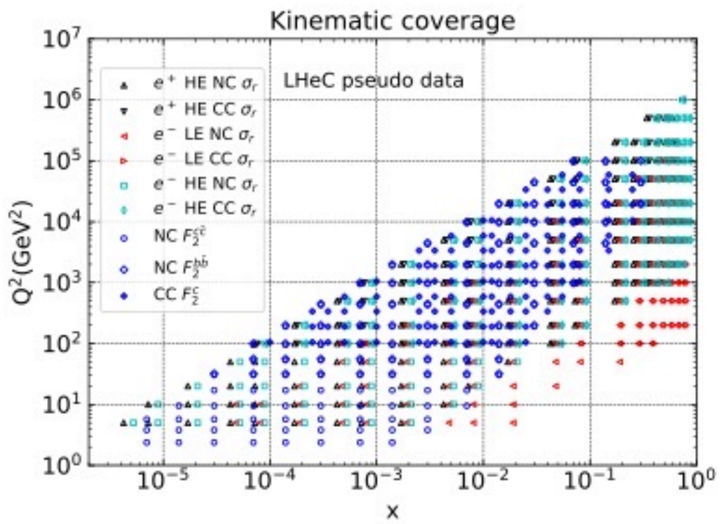
LHeC simulated data

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

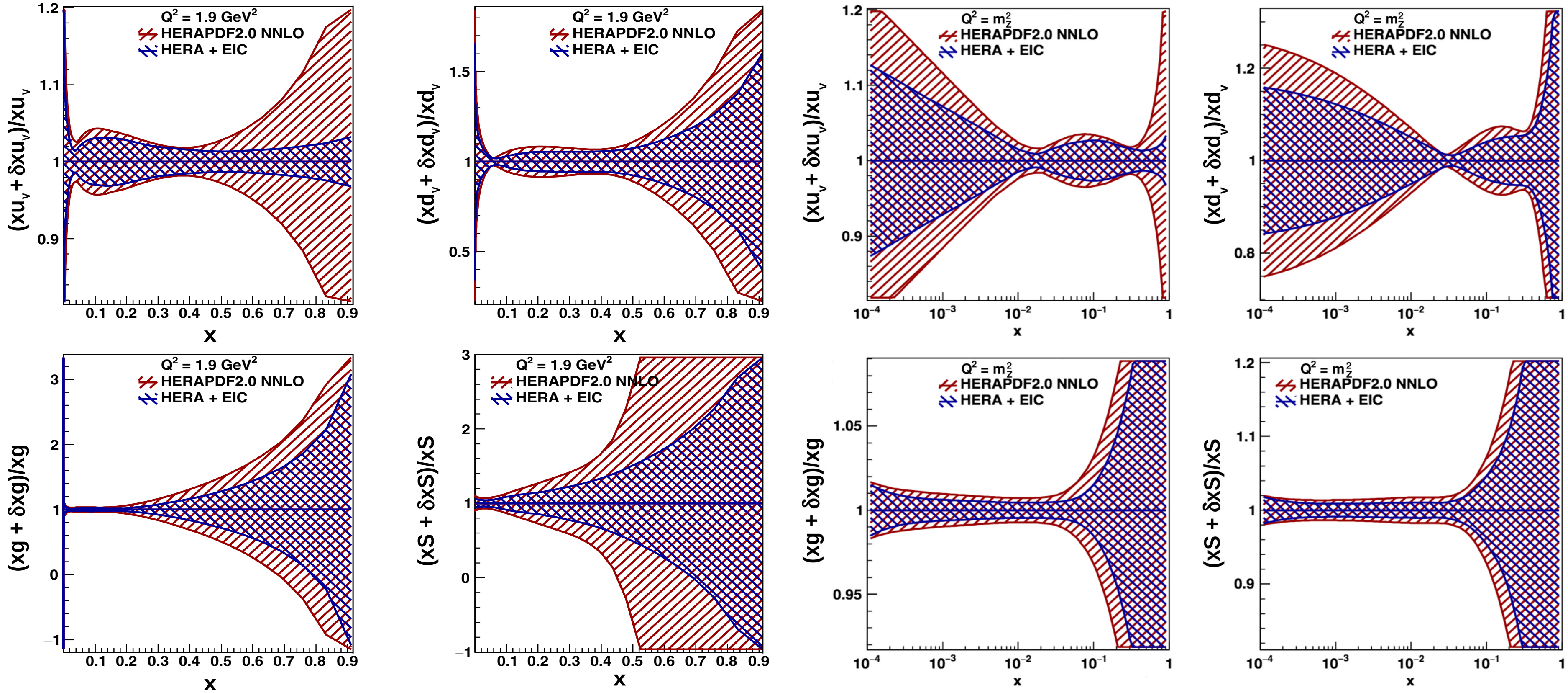
- QCD fit ansatz based on HERAPDF2.0, with following differences:
- no requirement that ubar=dbar at small x
- no negative gluon term (only for the aesthetics of ratio plots – it has been checked that this does not impact size of projected uncertainties)

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

- **4+1** pdf fit (above) has **14 free parameters**
- **5+1** pdf fit for HQ studies parameterises dbar and sbar separately, **17 free parameters**

Impact of EIC on proton pdfs

(arXiv:2309.11269)



$$
\begin{aligned}
xg(x) &= A_g x^{B_g}(1-x)^{C_g} - A_g' x^{B_g'}(1-x)^{25}; \\
xu_v(x) &= A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}\left(1+E_{u_v}x^2\right); \\
xd_v(x) &= A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}; \\
x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}\left(1+D_{\bar{U}}x\right); \\
x\bar{D}(x) &= A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}.
\end{aligned}
$$

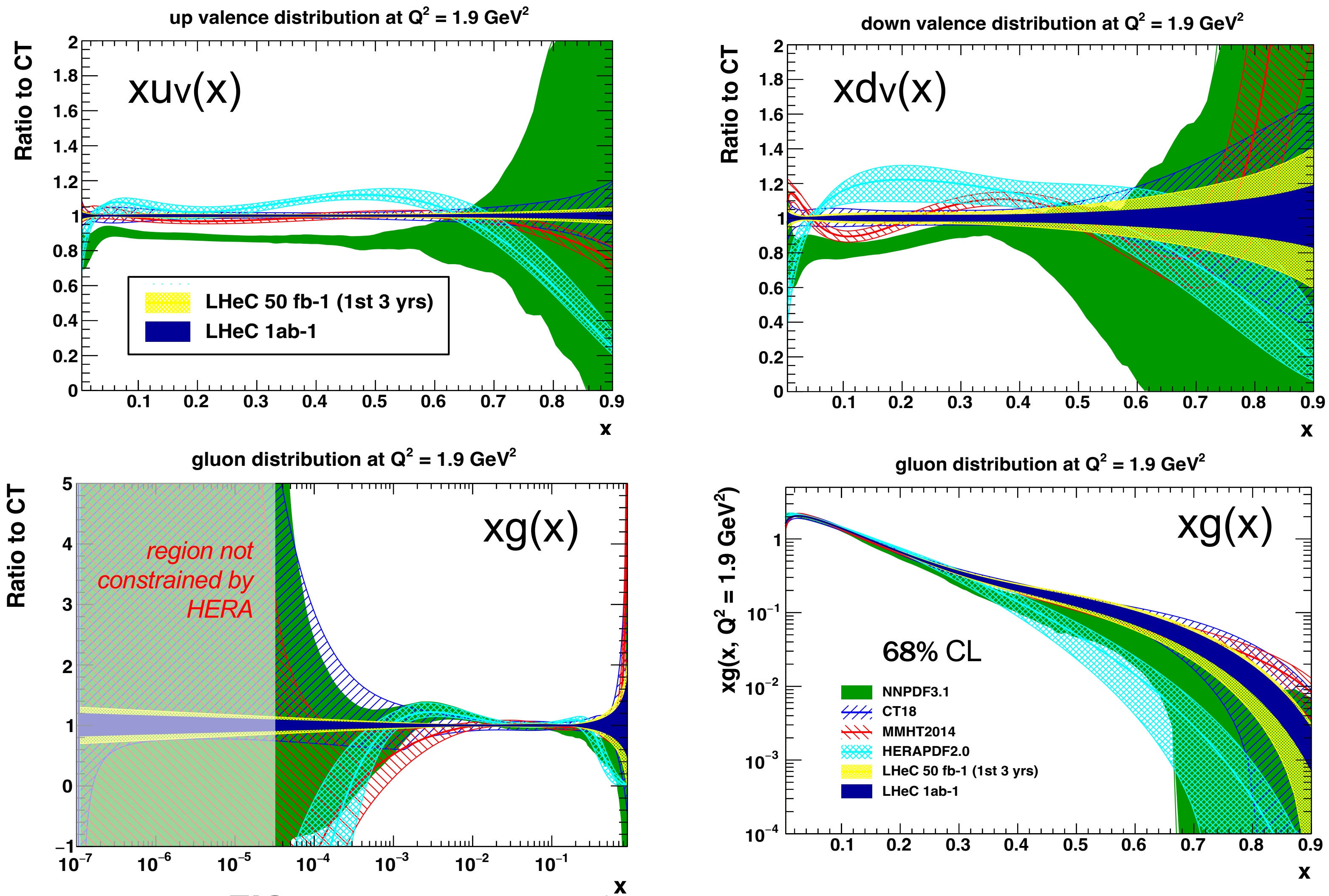
e-beam energy (GeV)	p-beam energy (GeV)	$\sqrt{s}$ (GeV)	Integrated lumi (fb^{-1})
18	275	141	15.4
10	275	105	100
10	100	63	79.0
5	100	45	61.0
5	41	29	4.4

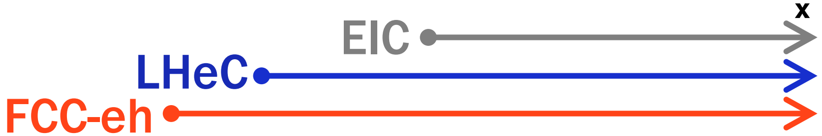
$x\bar{u} = xd$ is imposed as $x \to 0$

$f_s = 0.4$ whereby $x\bar{s} = f_s x\bar{D}$ for all x

NB, slightly less flexible parameterisation than used for LHeC/FCC-eh studies arXiv:[2007.14491](https://arxiv.org/abs/2007.14491)

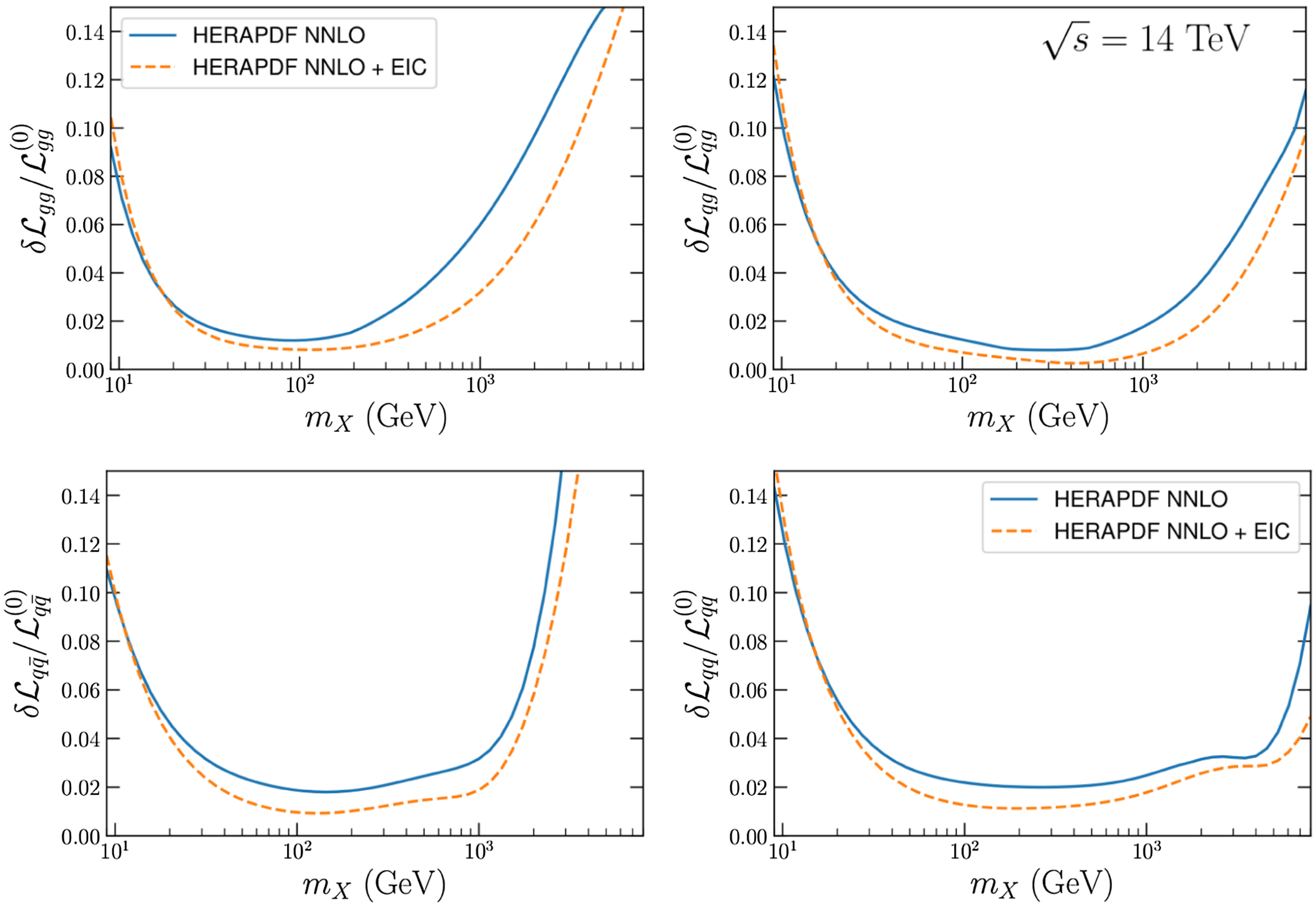
Quark and Gluon PDFs





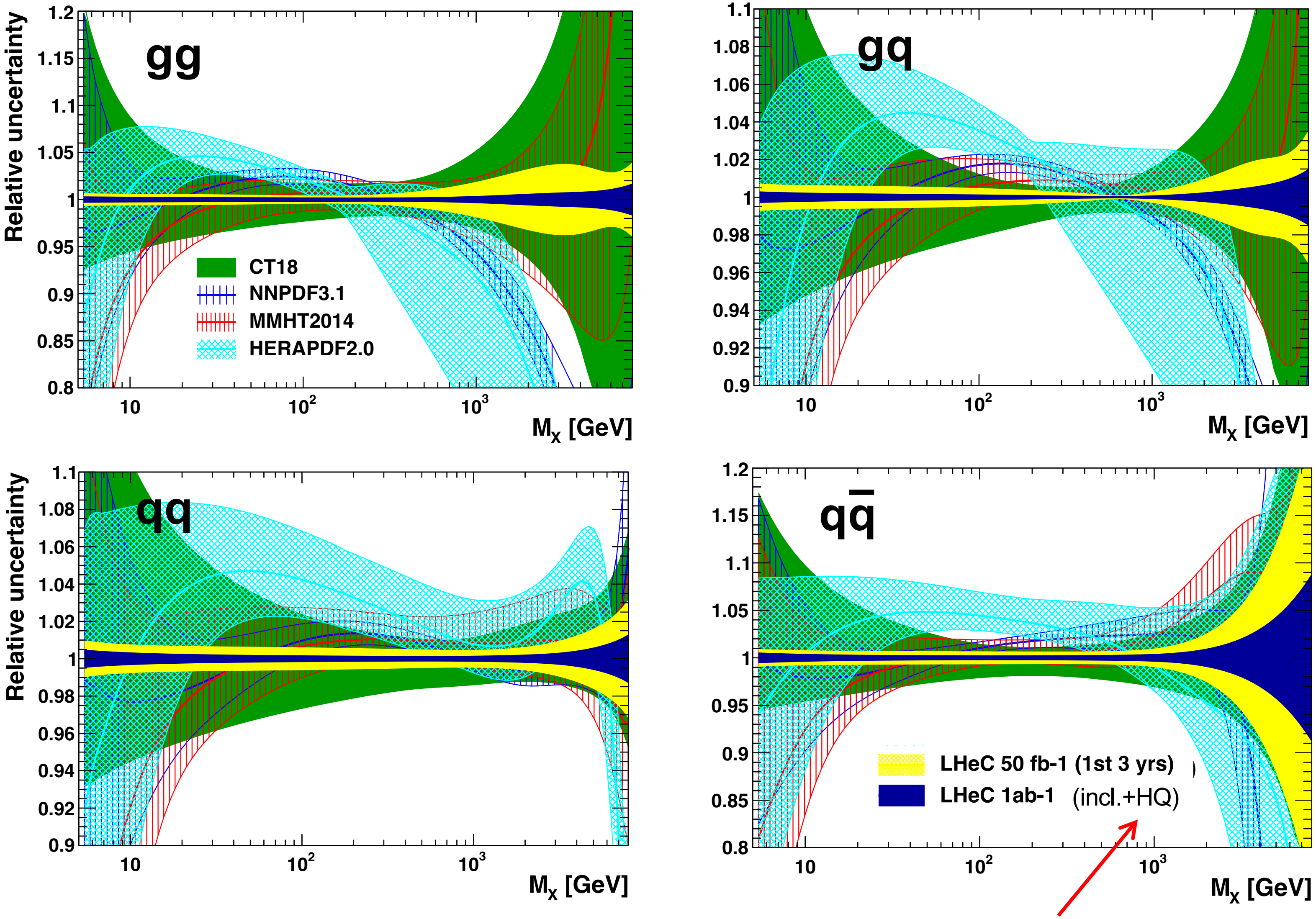
BSM sensitivity at high x

PDF luminosities @ 14 TeV – EIC



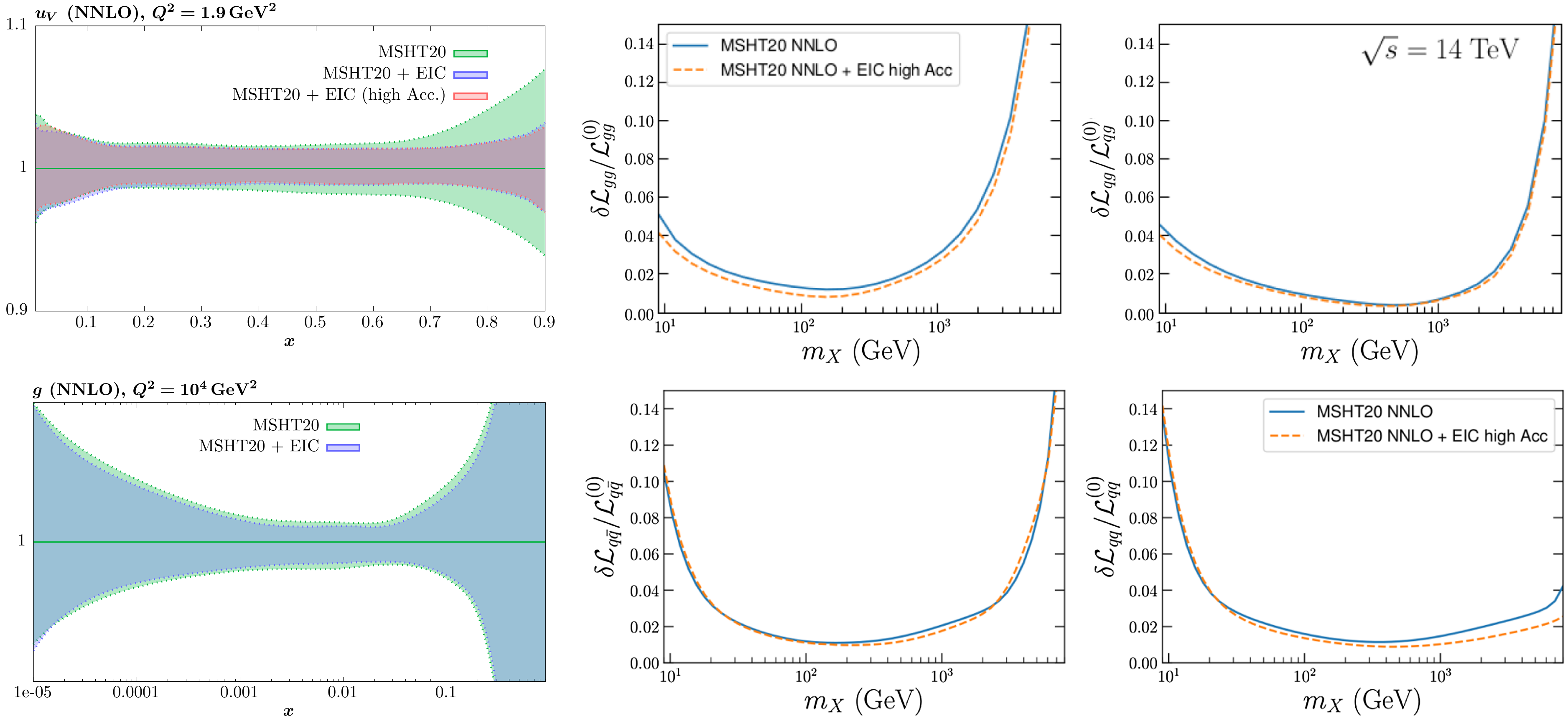
(arXiv:2309.11269)

c.f. PDF luminosities @ 14 TeV – LHeC



(s,c,b) also included

Impact of EIC on proton pdfs (MSHT20)



Less impact in context of a global PDF fit, but still providing some valuable information at high x

(arXiv:2309.11269)

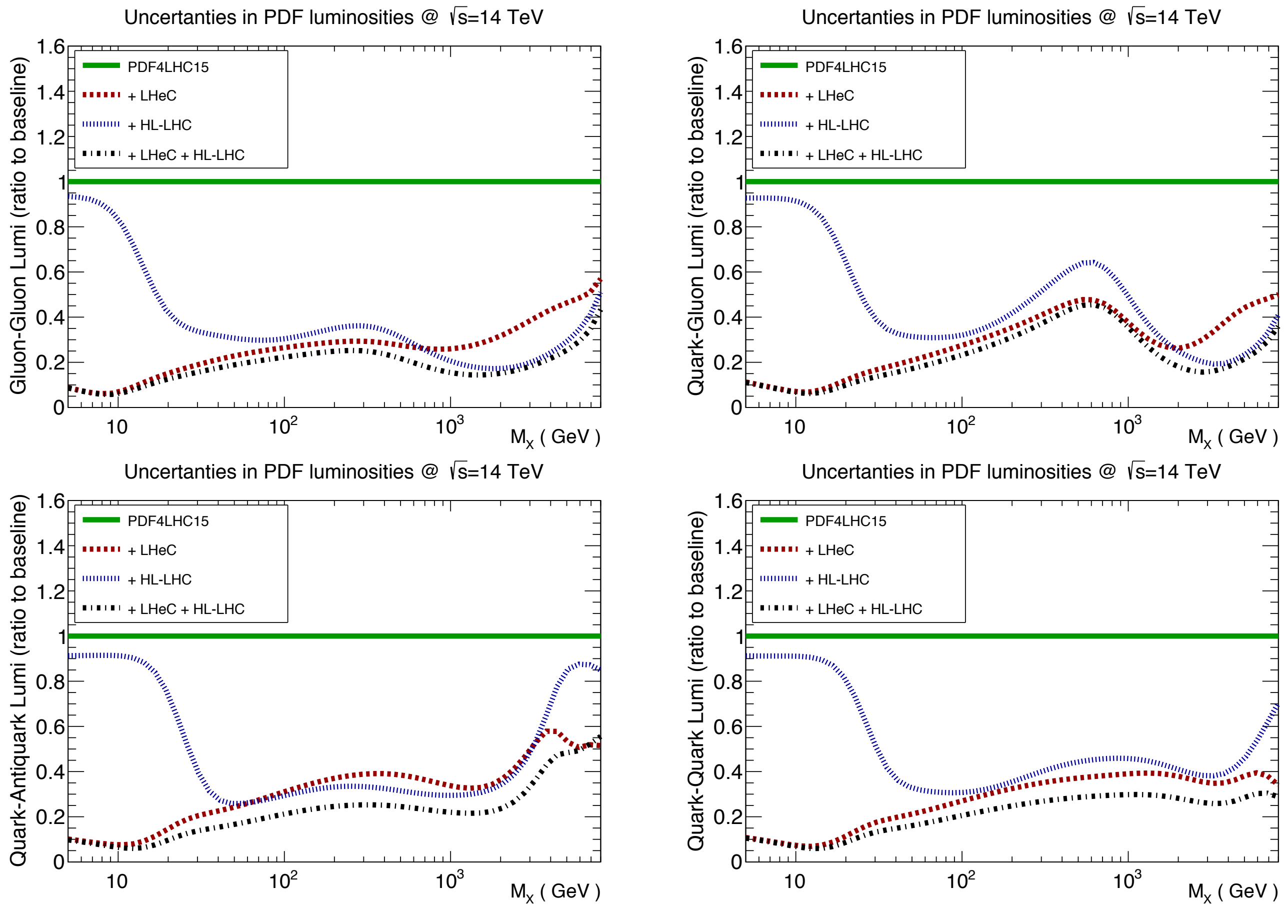
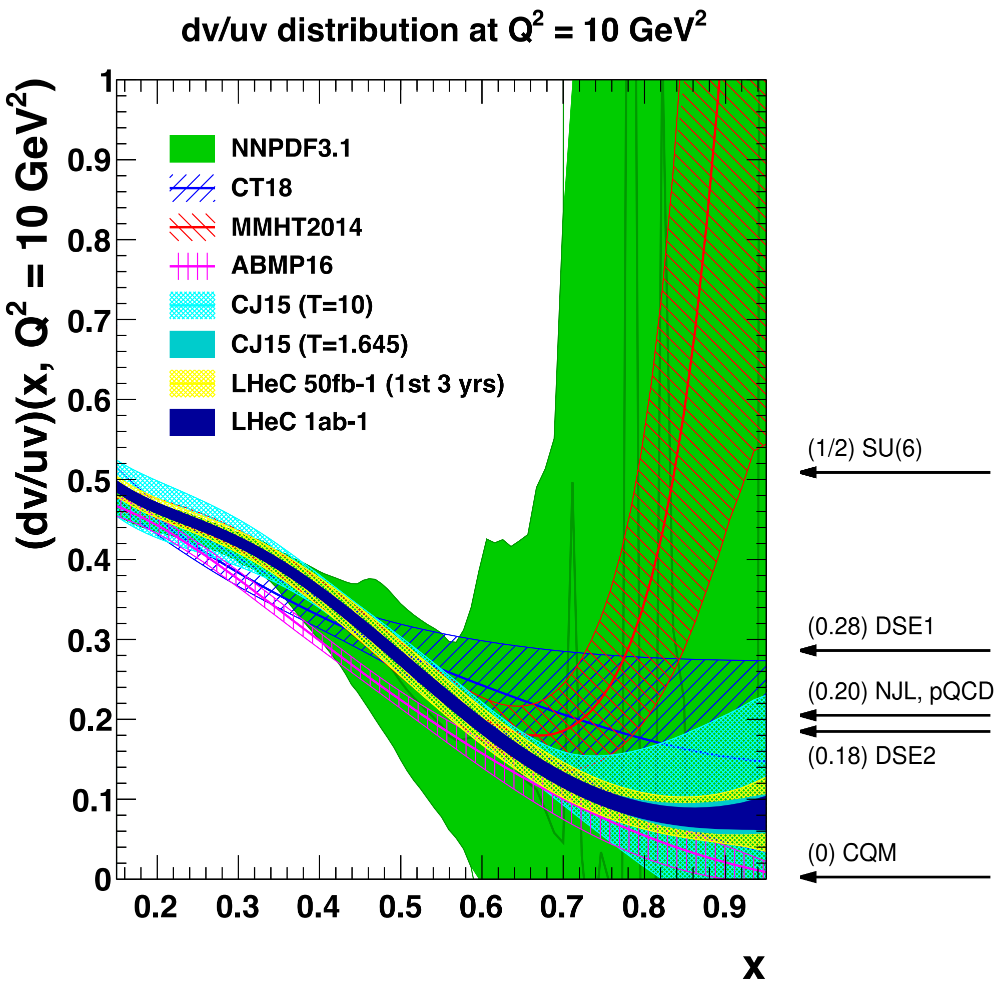


Figure 9.10: Impact of LHeC, HL-LHC and combined LHeC + HL-LHC pseudodata on the uncertainties of the gluon-gluon, quark-gluon, quark-antiquark and quark-quark luminosities, with respect to the PDF4LHC15 baseline set. In this comparison we display the relative reduction of the PDF uncertainty in the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

arXiv:2007.14491

d/u at large x

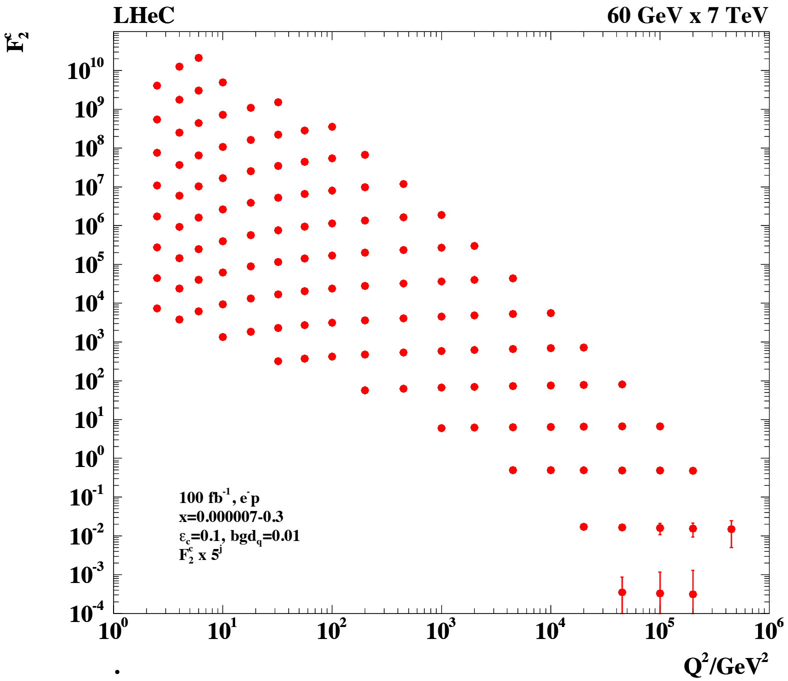


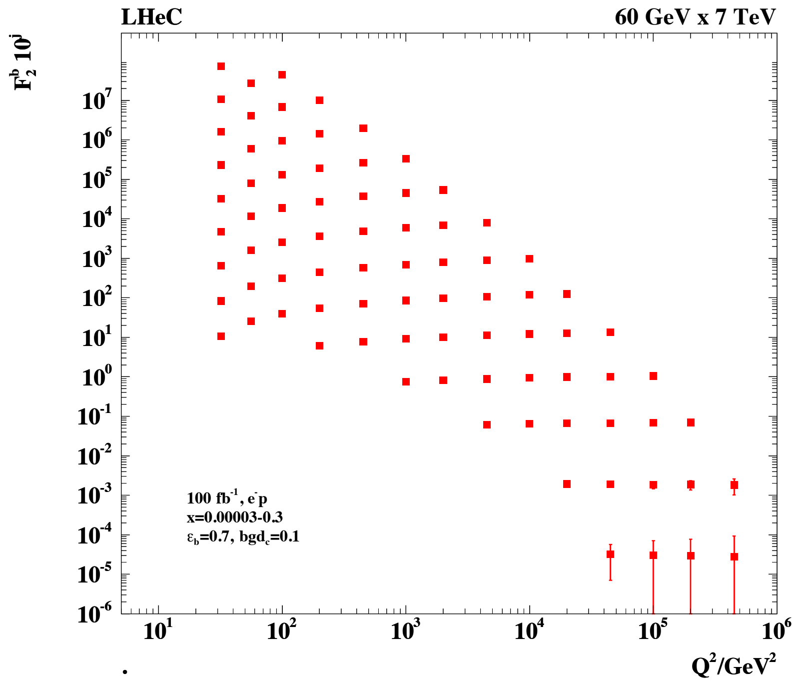
d/u essentially unknown at large x

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

c, b quarks

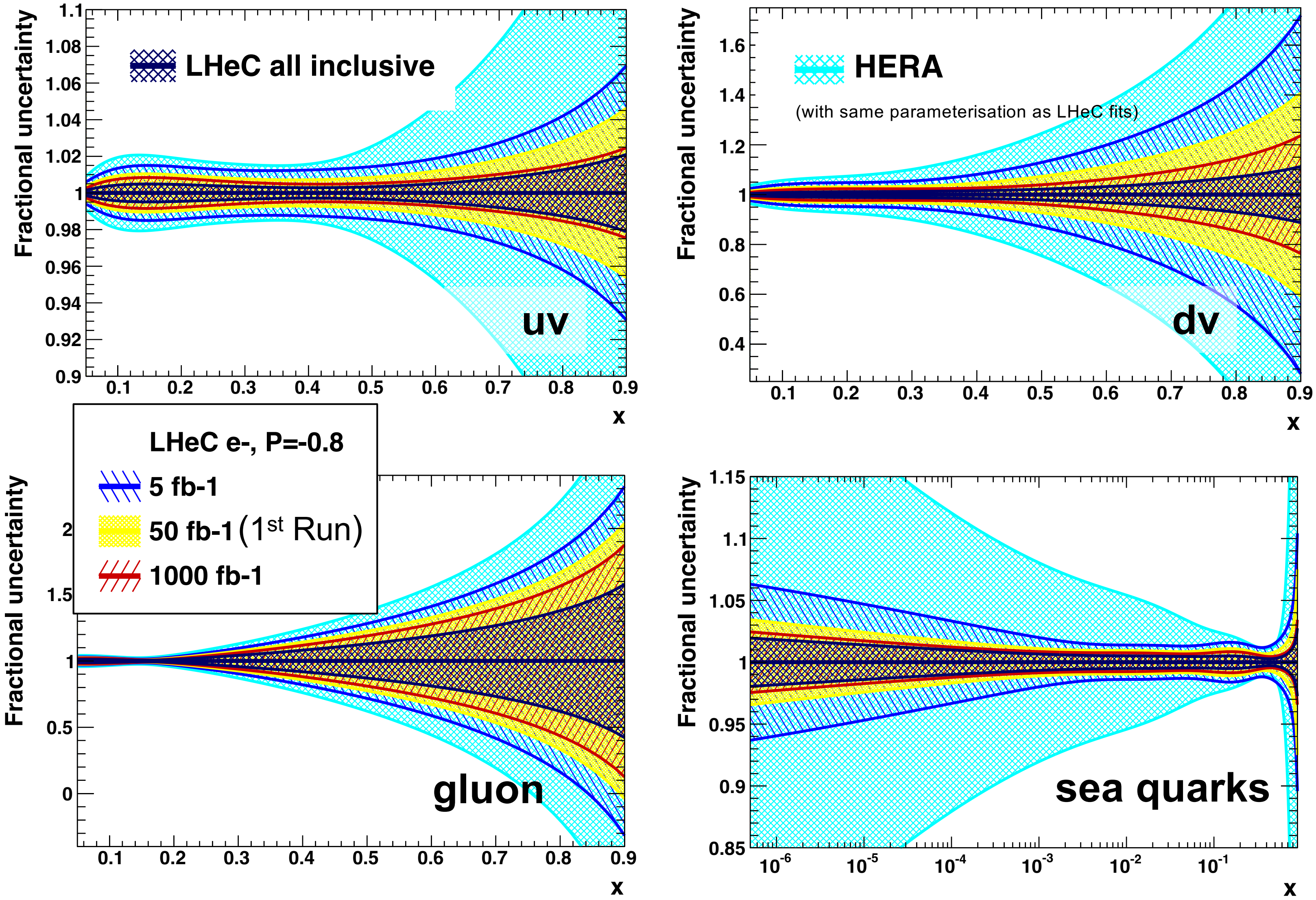




LHeC: enormously extended range and much improved precision c.f. HERA

- **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 bb → A

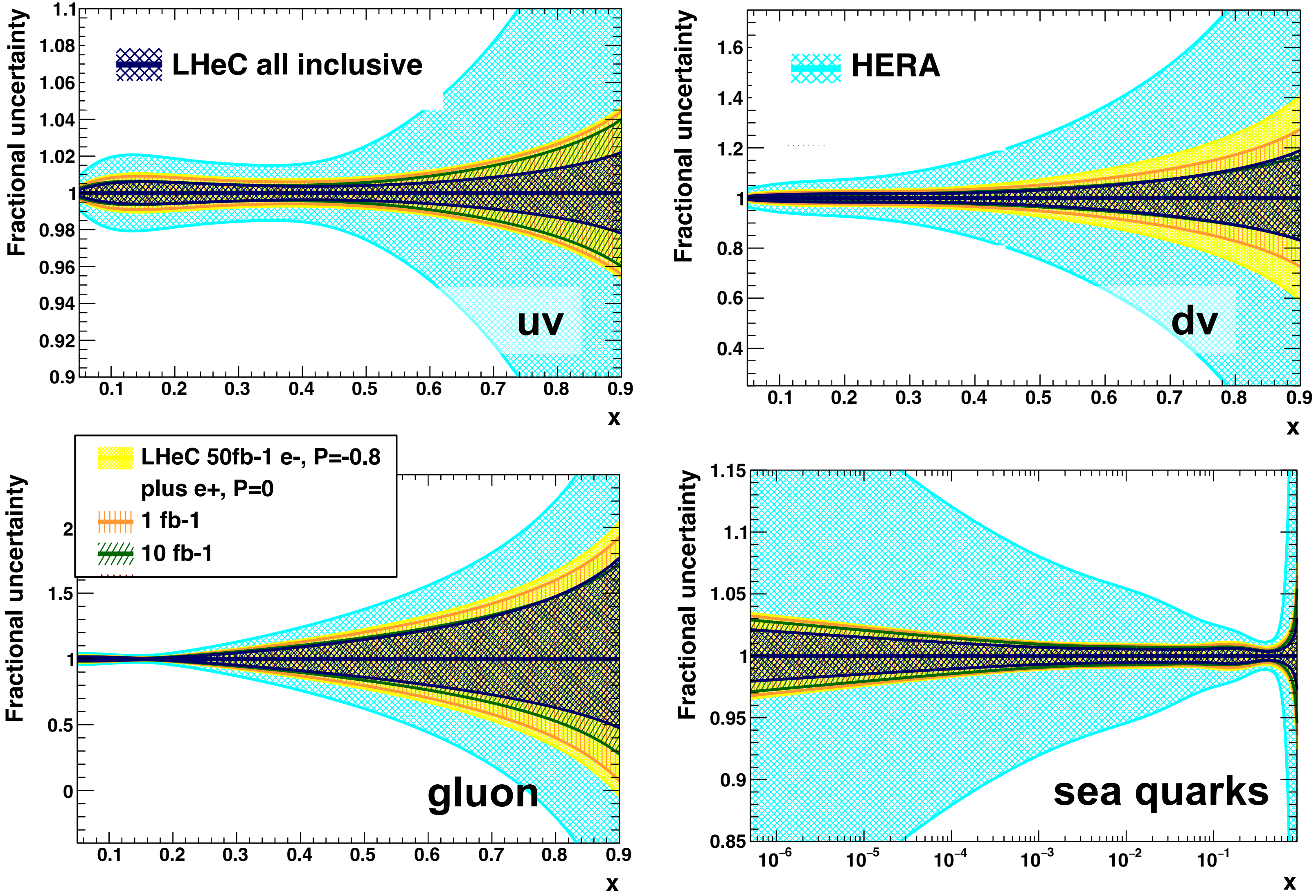
impact of luminosity on PDFs



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

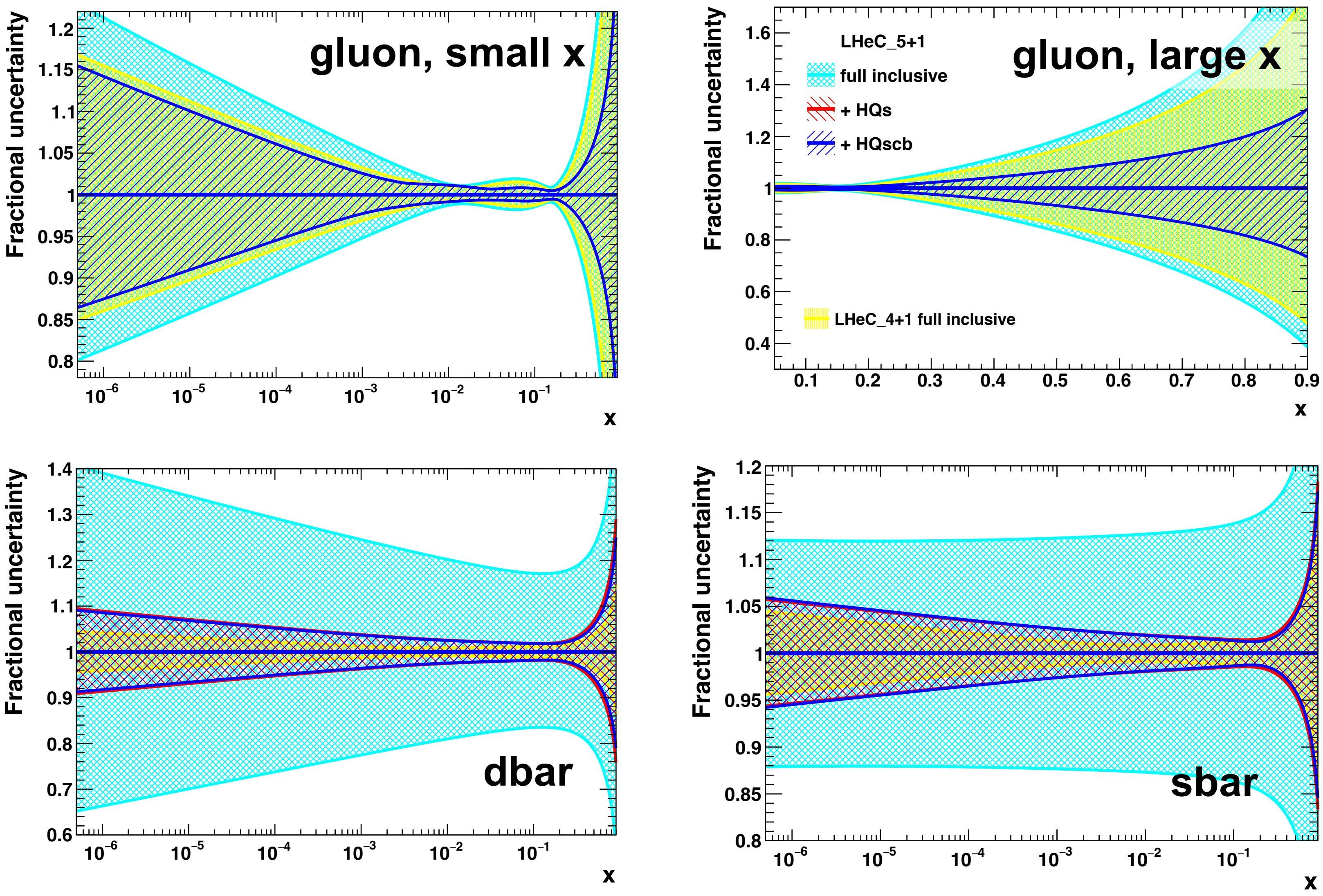
large x (≡ large Q2), gain from increased Lint; still, early massive improvement cf. today

Impact of positrons



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

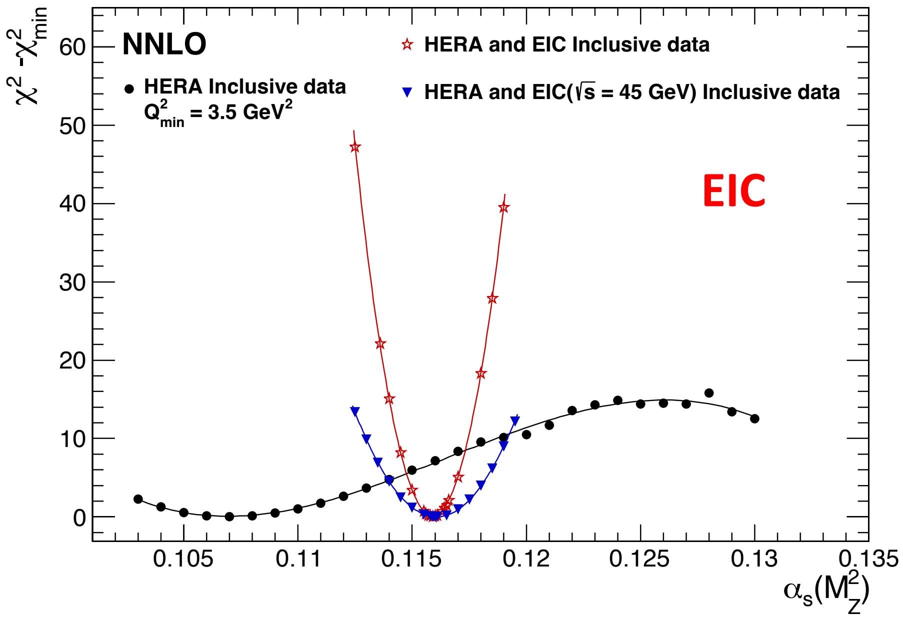
Impact of s, c, b

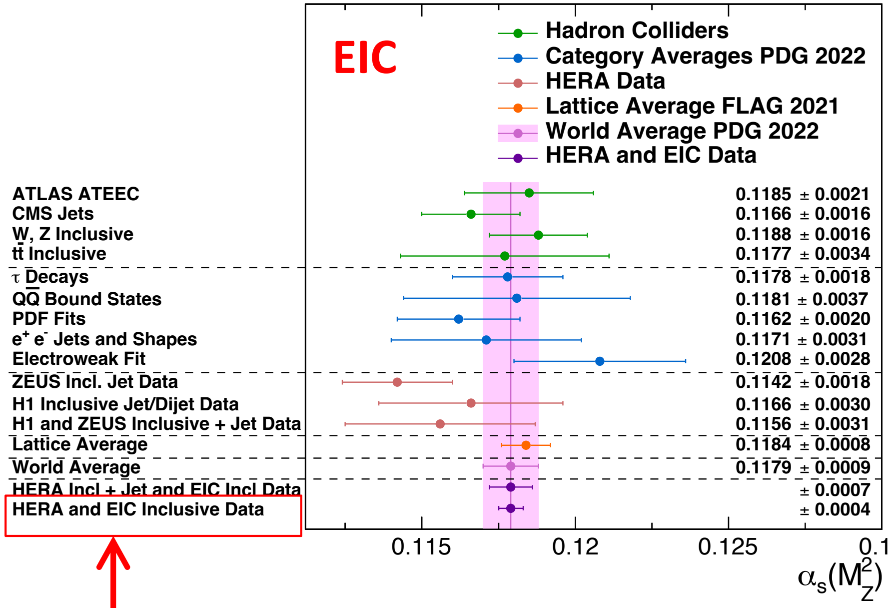


- **4+1** xuv, xdv, xUbar, xDbar + xg **(14)**
- **5+1** xuv, xdv, xUbar, xdbar, xsbar + xg **(17)**

strong coupling at EIC and LHeC

arXiv:2307.01183





e-beam energy (GeV)	p-beam energy (GeV)	$\sqrt{s}$ (GeV)	Integrated lumi (fb^{-1})
18	275	141	15.4
10	275	105	100
10	100	63	79.0
5	100	45	61.0
5	41	29	4.4

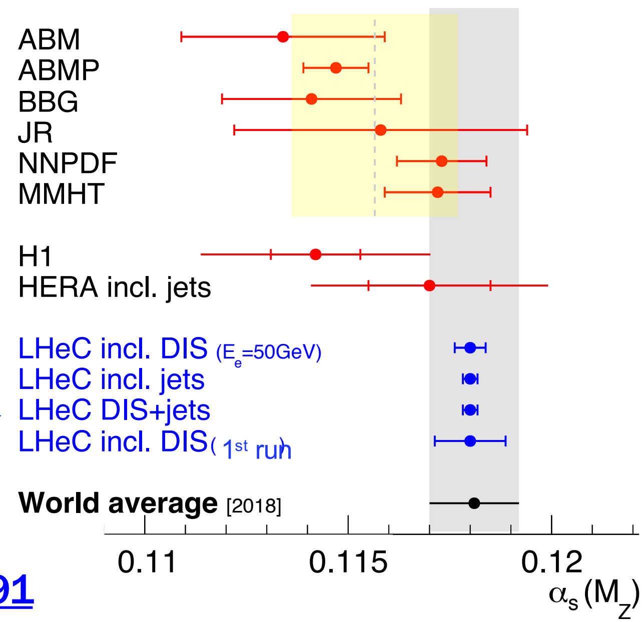
EIC $\mathcal{O}$(0.4%)

$$\alpha_s(M_Z^2) = 0.1159 \pm 0.0004\ (\text{exp})\ {}^{+0.0002}_{-0.0001}\ (\text{model} + \text{parameterisation}).$$

LHeC $\mathcal{O}$(0.2%)

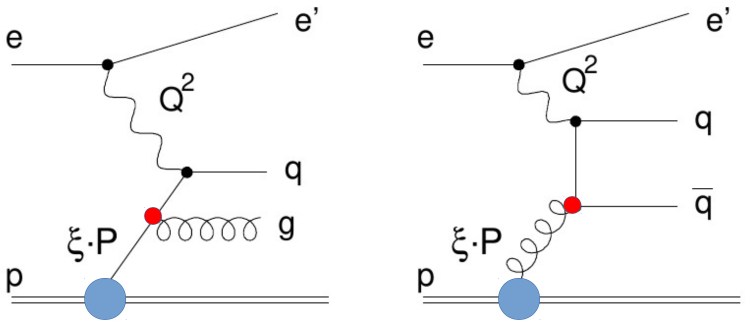
$$\Delta\alpha_s(M_Z)(\text{incl. DIS}) = \pm 0.00022_{(\text{exp+PDF})}$$

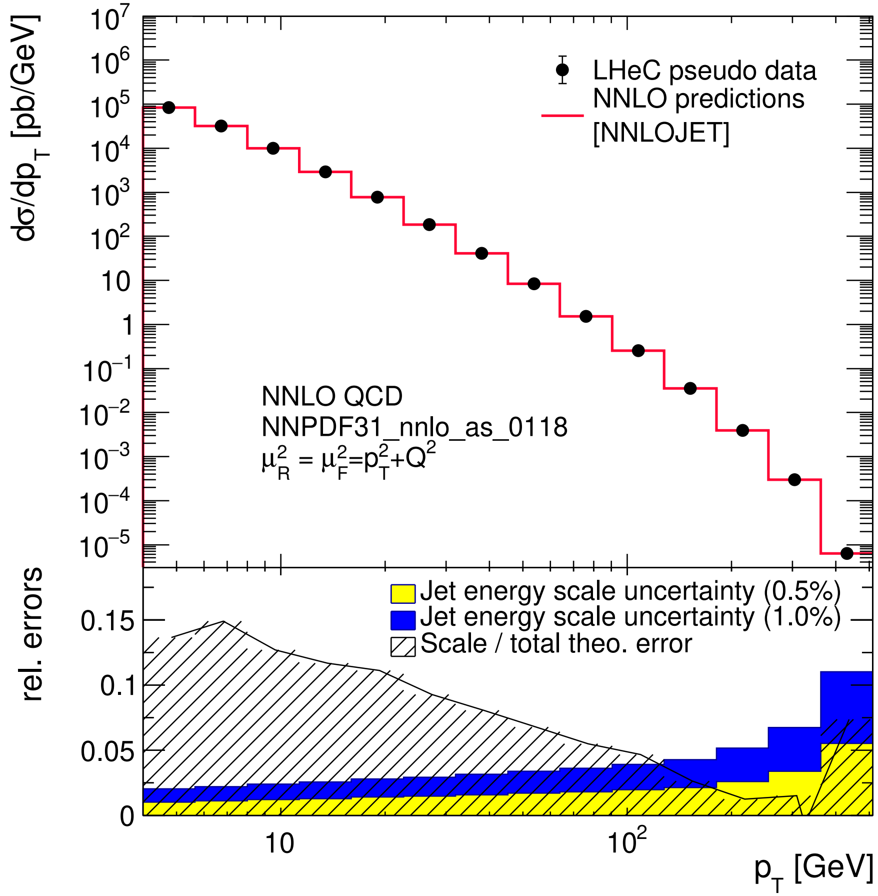
$$\Delta\alpha_s(M_Z)(\text{incl. DIS \& jets}) = \pm 0.00018_{(\text{exp+PDF})}$$



arXiv:2007.14491

NC DIS jet production at the LHeC





sensitive to αs at lowest order

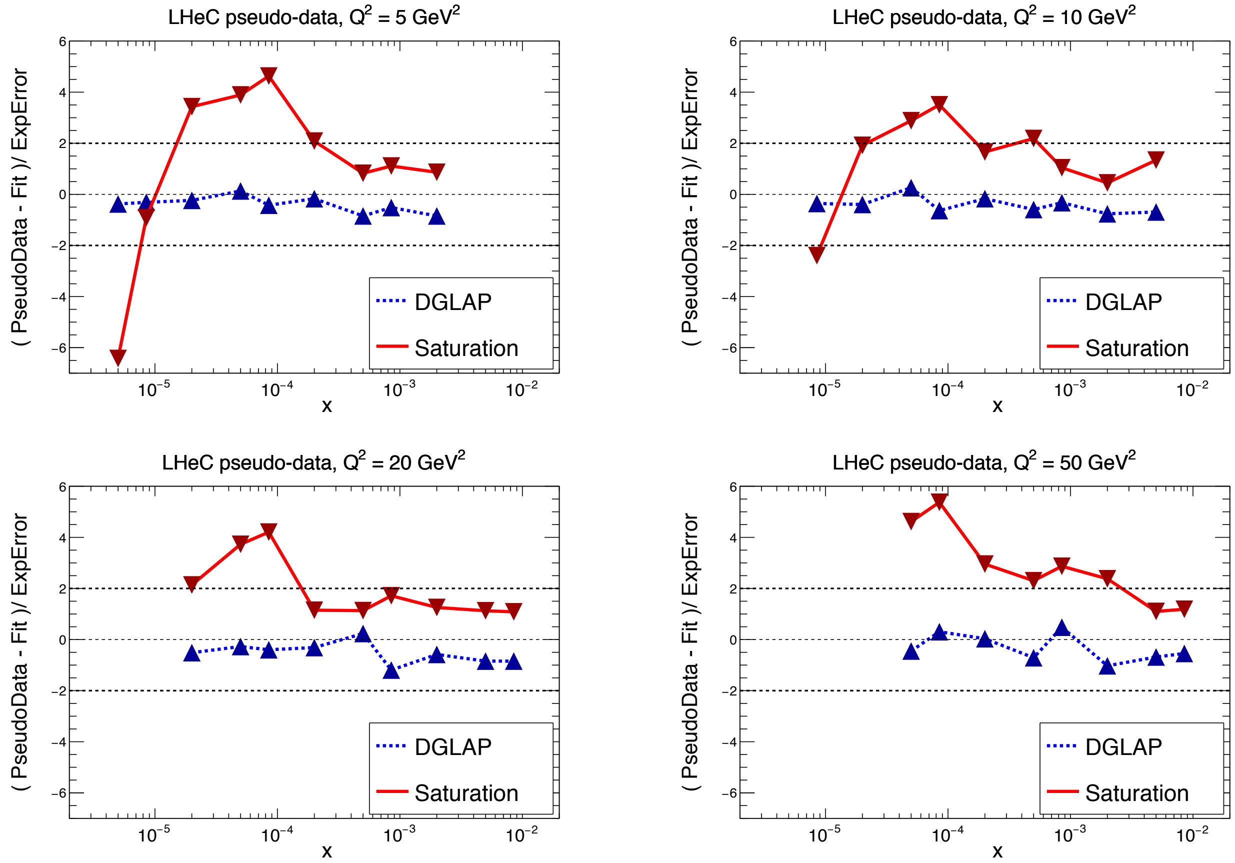
different dependencies on **xg(x)** and **αs** c.f. inclusive DIS; gives improved constraints on both, when used in simultaneous **pdf+αs** fit

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

Novel dynamics at small x: saturation



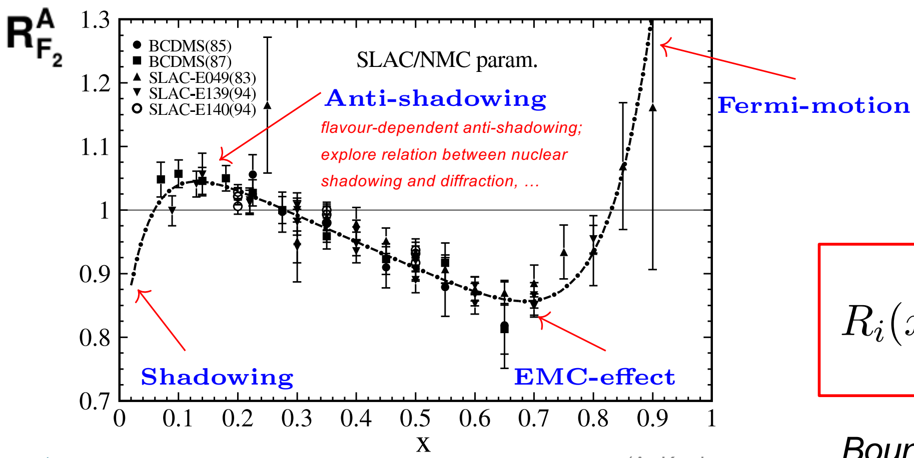
- **PULLS** highlight origin of worse agreement: in **saturation case** (fitted with **DGLAP**), theory overshoots data at smallest x, and undershoots at higher x
- while a different x dependence might be absorbed into PDFs at scale Q_0, this is not possible with a Q^2 dependence – ***large Q^2 lever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

(see also arXiv:1702.00839)

High energy QCD and eA at the LHeC/FCC-eh

$$F_2^A(x) \neq ZF_2^p(x) + NF_2^n(x)$$

- **nuclear pdfs** for **single nuclei**; flavour unfolding; same method of extraction in **ep** and **eA**
- studies of 3D structure



HIGH ENERGY

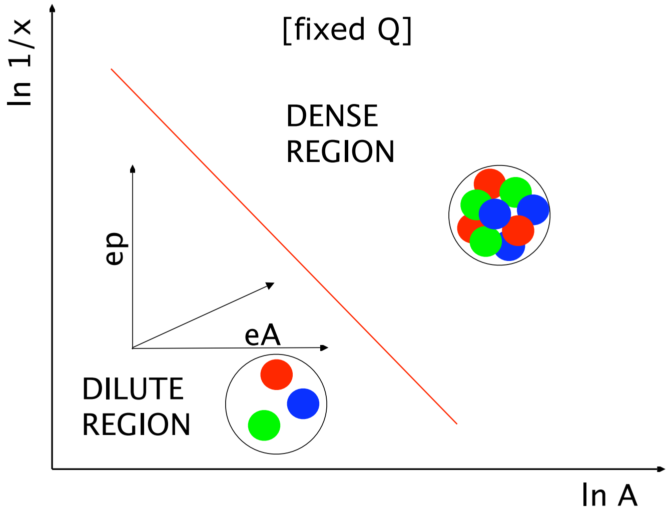
(A. Kusina, HonexComb 2023)

How does structure of a hadron change when immersed in a nuclear medium?

$$R_i(x,Q^2) = \frac{f_i^A(x,Q^2)}{Af_i^p(x,Q^2)}$$

Bound nucleon ≠ Free nucleon

Where is the novel non-linear regime of QCD that leads to saturation of parton densities, and what are its properties?



- **QCD high energy regime** characterised by large parton densities **↓x / ↑A**
- **ep** and **eA** + **range** in **1/x** and **Q²**: physics beyond **standard collinear factorisation** tested in single setup; size effects disentangled from energy effects; large lever arm in **x** at perturbative **Q²**

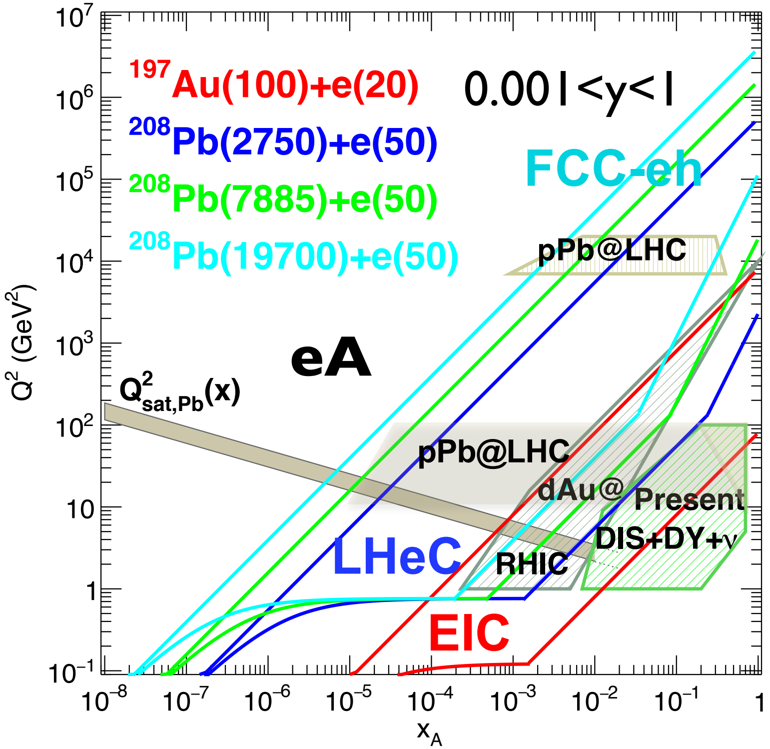
- strong implications for **pp/pA/AA** at the **HL-LHC** and **FCC**

(adapted from N Armesto, ICHEP 2022)

eA at the LHeC and FCC-eh

- **ep:** ×**15**/**120** extension in Q^2, 1/x vs HERA
- **eA**: **4–5 orders of magnitude →** extension in Q^2, 1/x vs existing DIS data, and **∼ 2–3 vs EIC**

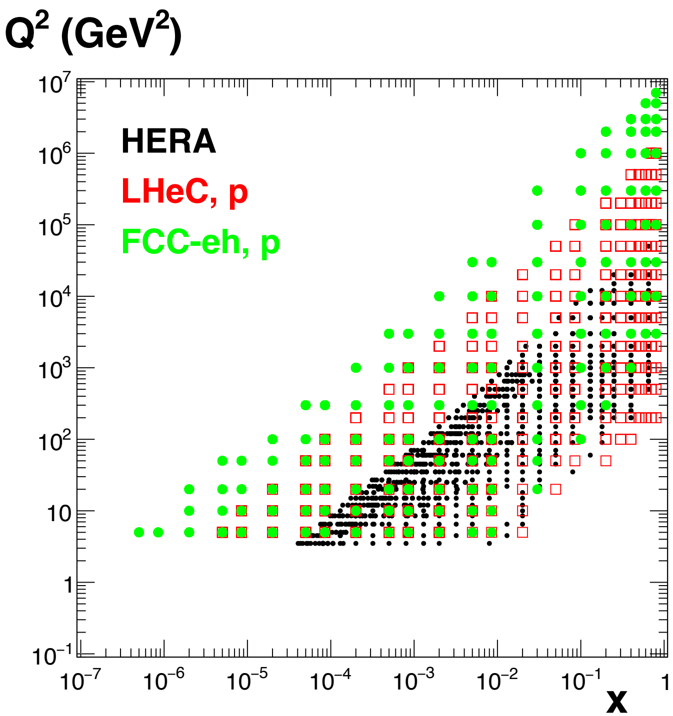
- **DIS offers:**
- complementarity to **pA** and **UPC**
- **clean experimental environment**: low multiplicity; no pileup; fully constrained kinematics
- **sophisticated theoretical calculations** both in collinear and non-collinear frameworks

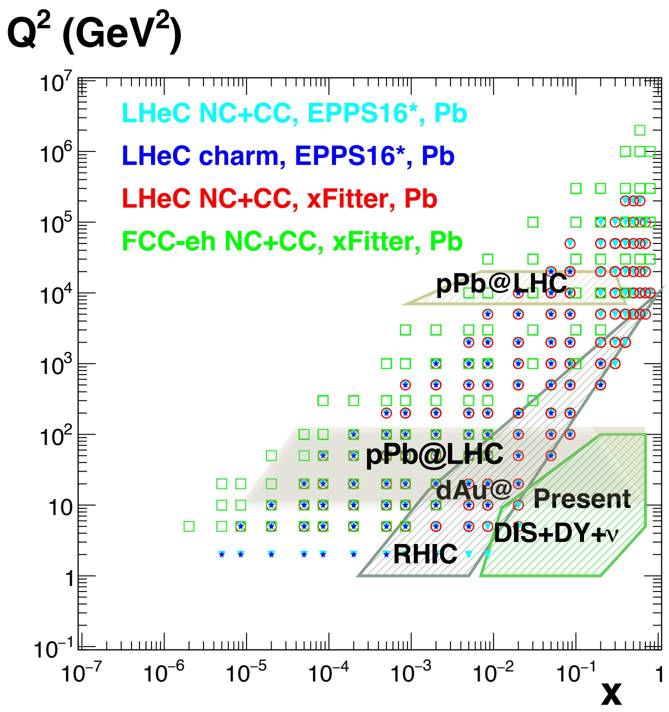


Parameter	Unit	LHeC	FCC-eh (E_p=20 TeV)	FCC-eh (E_p=50 TeV)
Ion energy E_{Pb}	PeV	0.574	1.64	4.1
Ion energy/nucleon E_{Pb}/A	TeV	2.76	7.88	19.7
Electron beam energy E_e	GeV	50	60	60
Electron-nucleon CMS $\sqrt{s_{eN}}$	TeV	0.74	1.4	2.2
Bunch spacing	ns	50	100	100
Number of bunches		1200	2072	2072
Ions per bunch	10^8	1.8	1.8	1.8
Normalised emittance ϵ_n	μm	1.5	1.5	1.5
Electrons per bunch	10^9	6.2	6.2	6.2
Electron current	mA	20	20	20
IP beta function β_A^*	cm	10	10	15
e-N Luminosity	10^{32}cm^{-2}s^{-1}	7	14	35

ep and eA coverage and simulated data

- **ep** and **eA** simulated NC and CC generated using code (M. Klein) validated against H1 MC

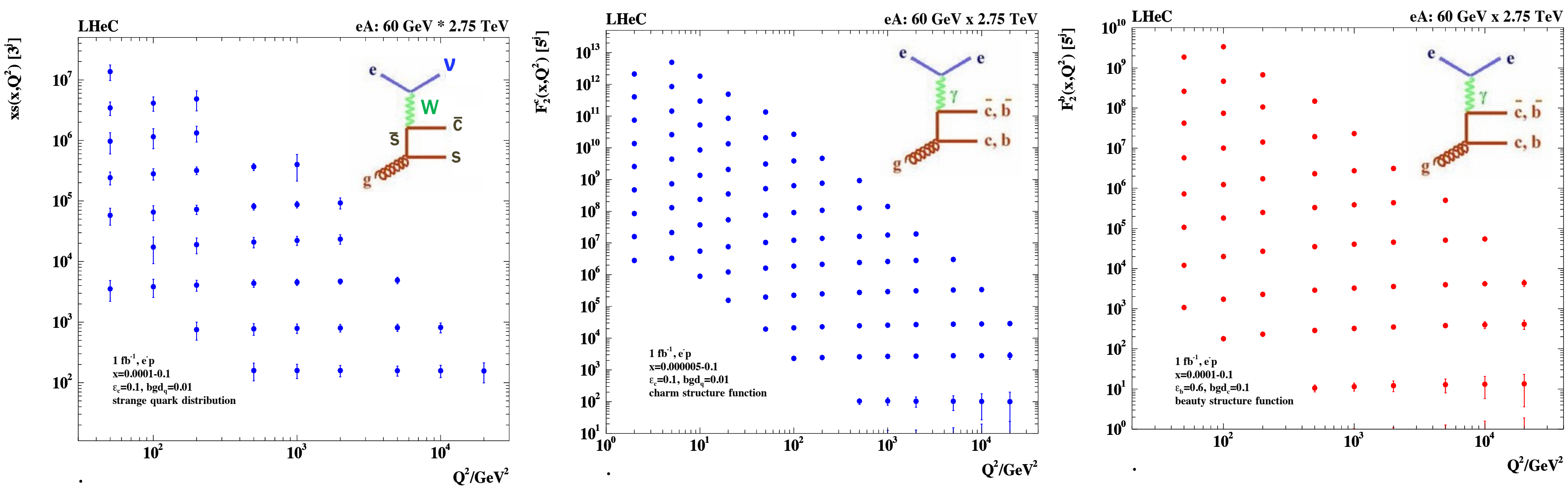




Source of uncertainty	Error on the source or cross section
Scattered electron energy scale	0.1 %
Scattered electron polar angle	0.1 mrad
Hadronic energy scale	0.5 %
Calorimeter noise ($y < 0.01$)	1–3 %
Radiative corrections	1–2 %
Photoproduction background	1 %
Global efficiency error	0.7 %

- cuts: $|\eta_{max}|$=5, 0.001 < y < 0.95
- uncertainty assumptions: ∼ ×2 smaller than HERA (excepting luminosity)

ep and eA coverage and simulated data

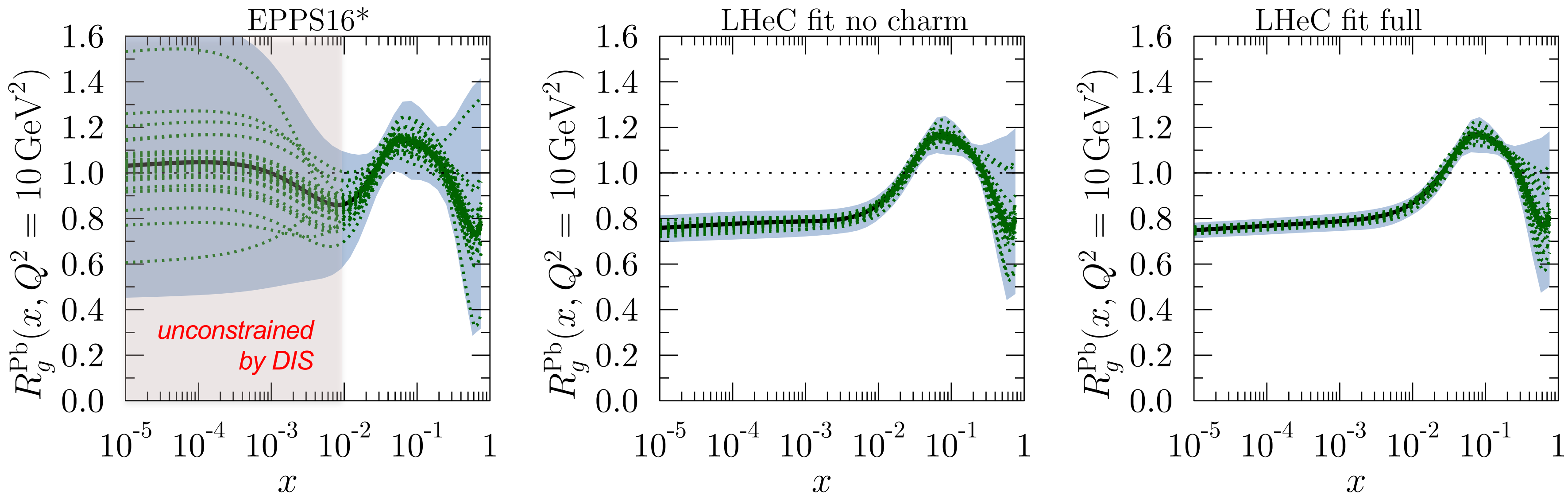


- semi-inclusive measurements of strange, charm and beauty in DIS at the LHeC (**eA** shown here)

Source of uncertainty	Error on the source or cross section
Scattered electron energy scale	0.1 %
Scattered electron polar angle	0.1 mrad
Hadronic energy scale	0.5 %
Calorimeter noise ($y < 0.01$)	1–3 %
Radiative corrections	1–2 %
Photoproduction background	1 %
Global efficiency error	0.7 %

- cuts: $|\eta_{max}|$=5, **0.001** < y < **0.95**
- uncertainty assumptions: ∼ ×2 smaller than HERA (excepting luminosity)
- s, c, b include additional uncertainties for tagging, acceptance and BG

nPDFs from LHeC in global fit context



$$R_i(x, Q^2) \equiv \frac{f_i^{\mathrm{p}/Pb}(x, Q^2)}{f_i^{\mathrm{p}}(x, Q^2)}$$

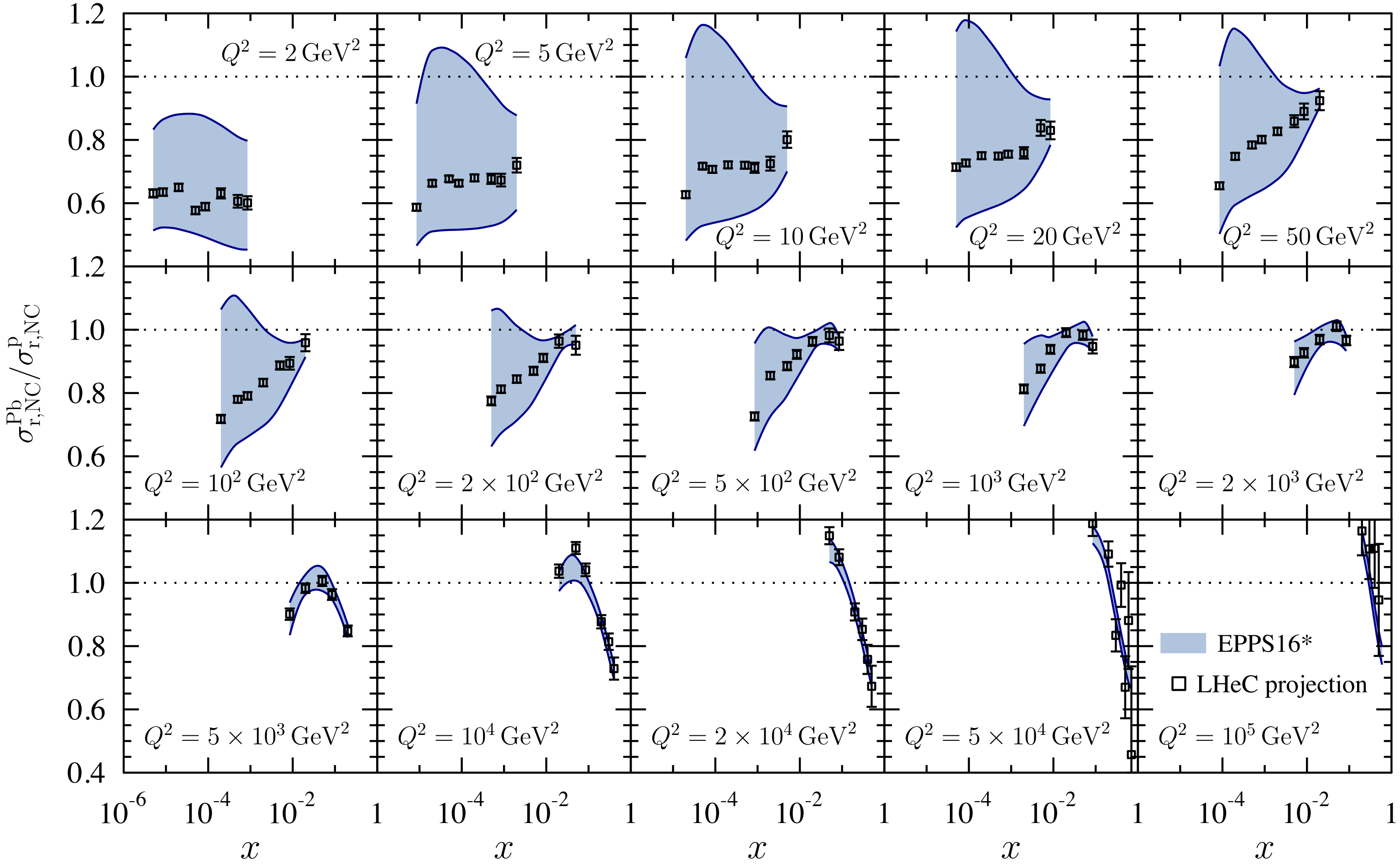
Nuclear Modification Factor *(for parton i)*

shown above for the ***gluon***

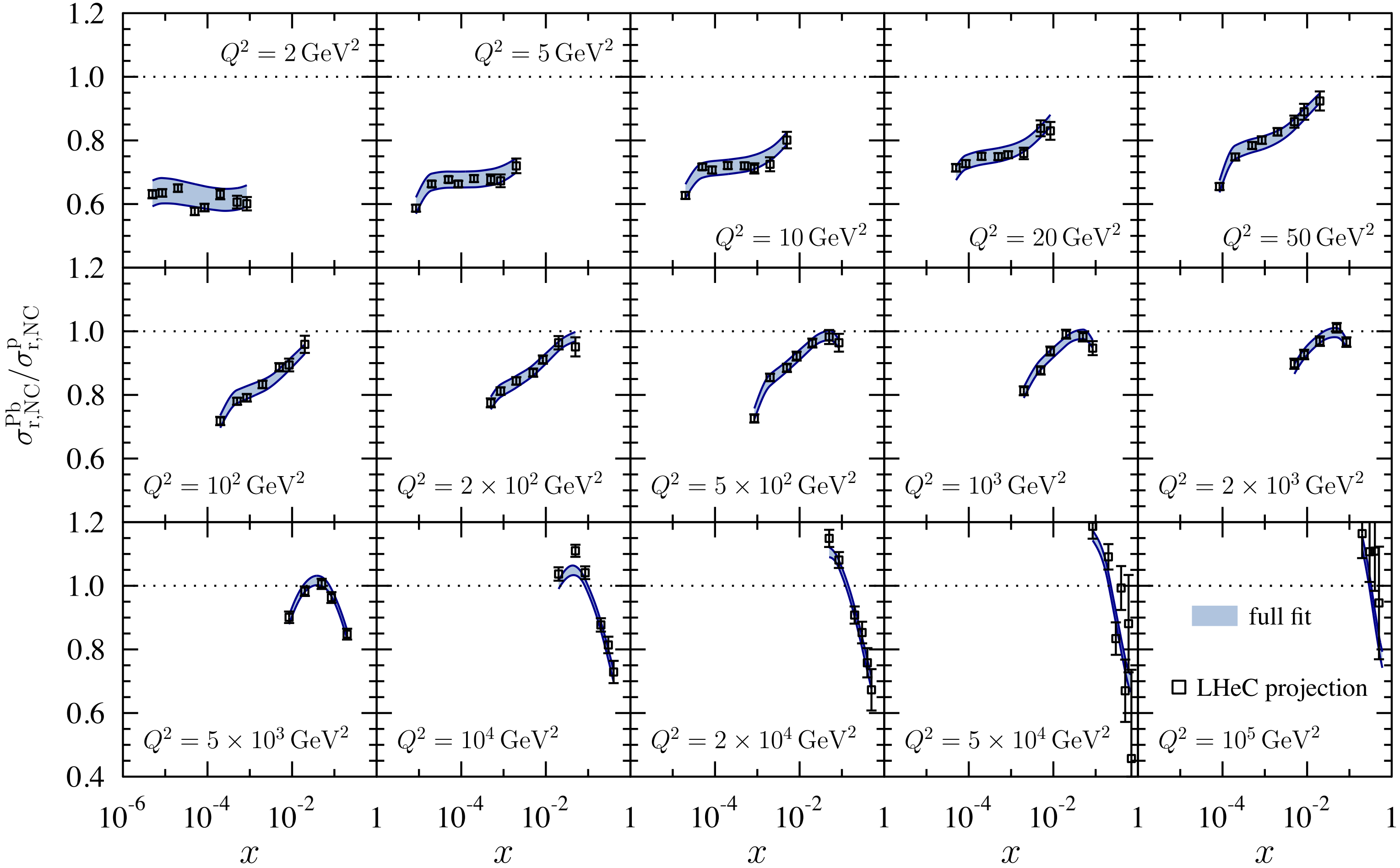
- **EPPS16***: EPPS16-like global analysis of **nuclear pdfs** (arXiv:1612.05741)
- same data sets, method, and tolerance (**Δχ^2**=52), BUT with added flexibility in functional form at small x
- **ADD** LHeC **NC**, **CC** and **charm** reduced cross sections

→ with LHeC, **nuclear gluon pdf** precisely determined down to x values of at least 10^{-5}

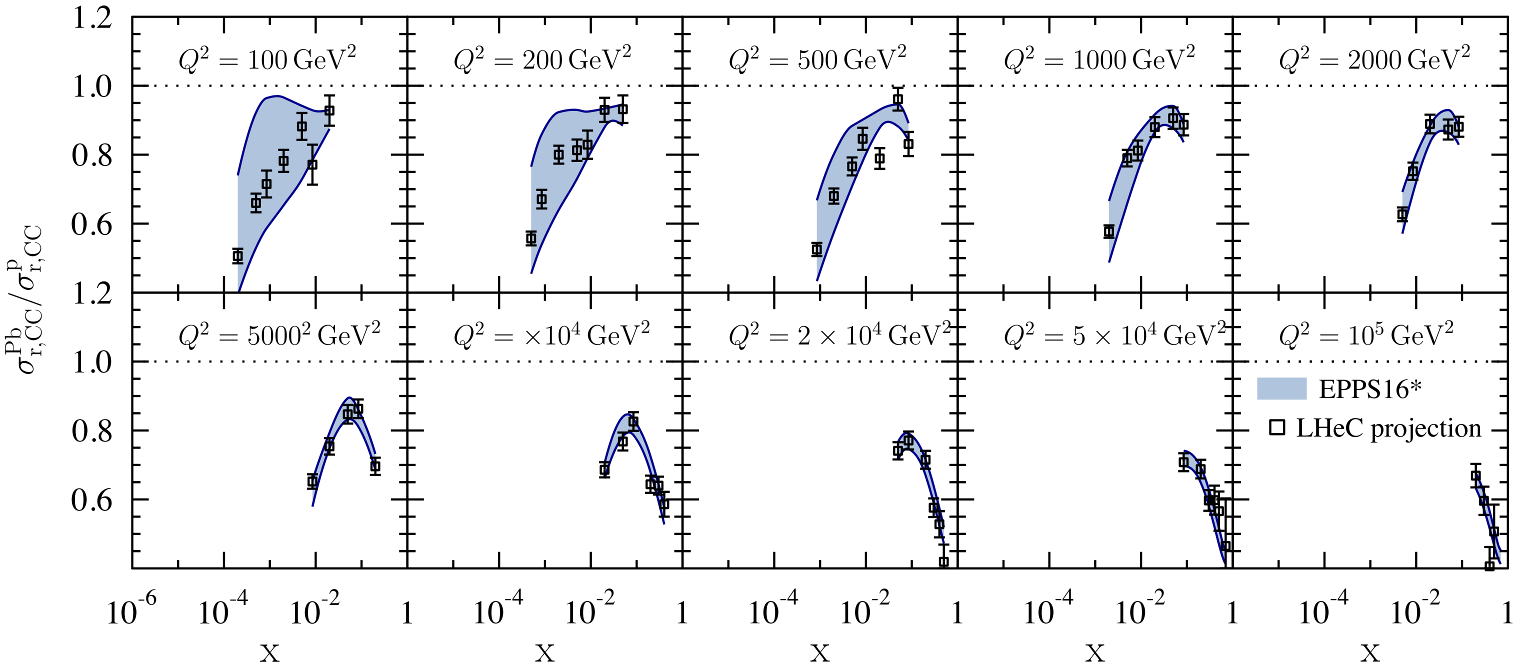
nPDFs from LHeC in global fit context



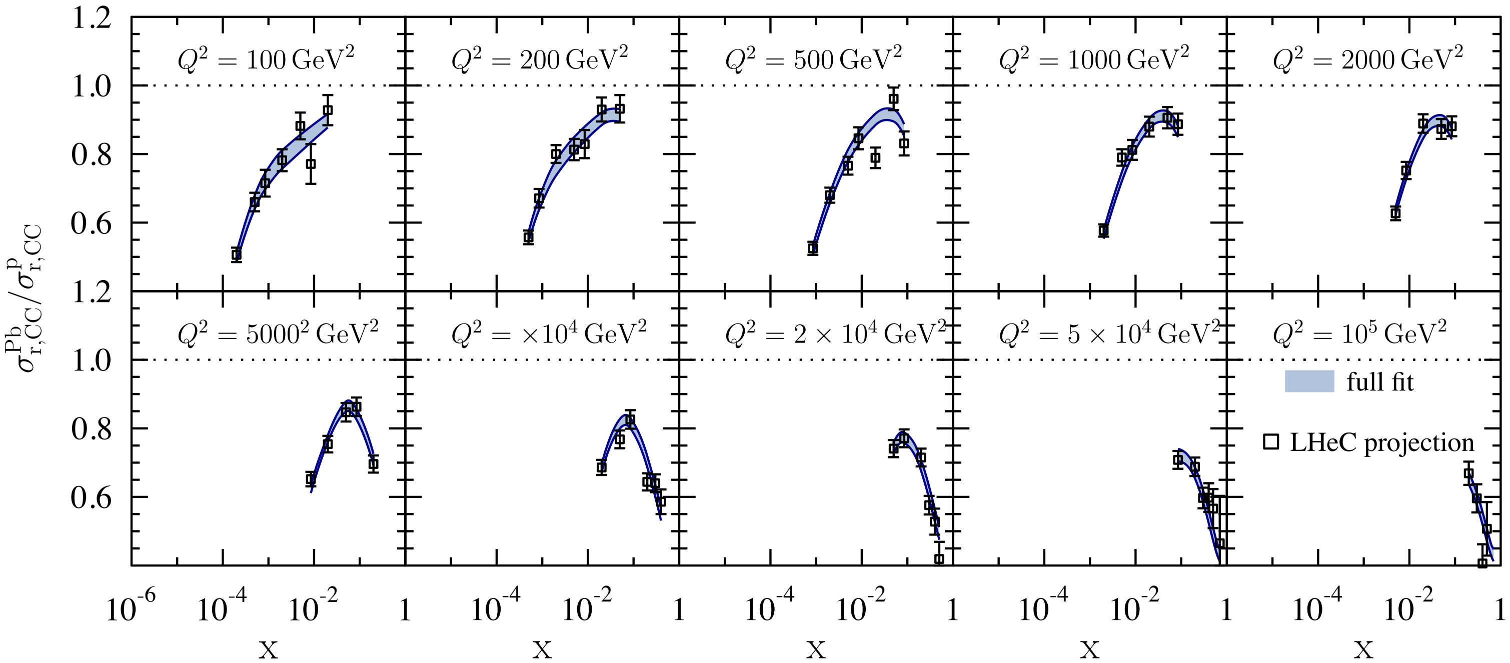
nPDFs from LHeC in global fit context



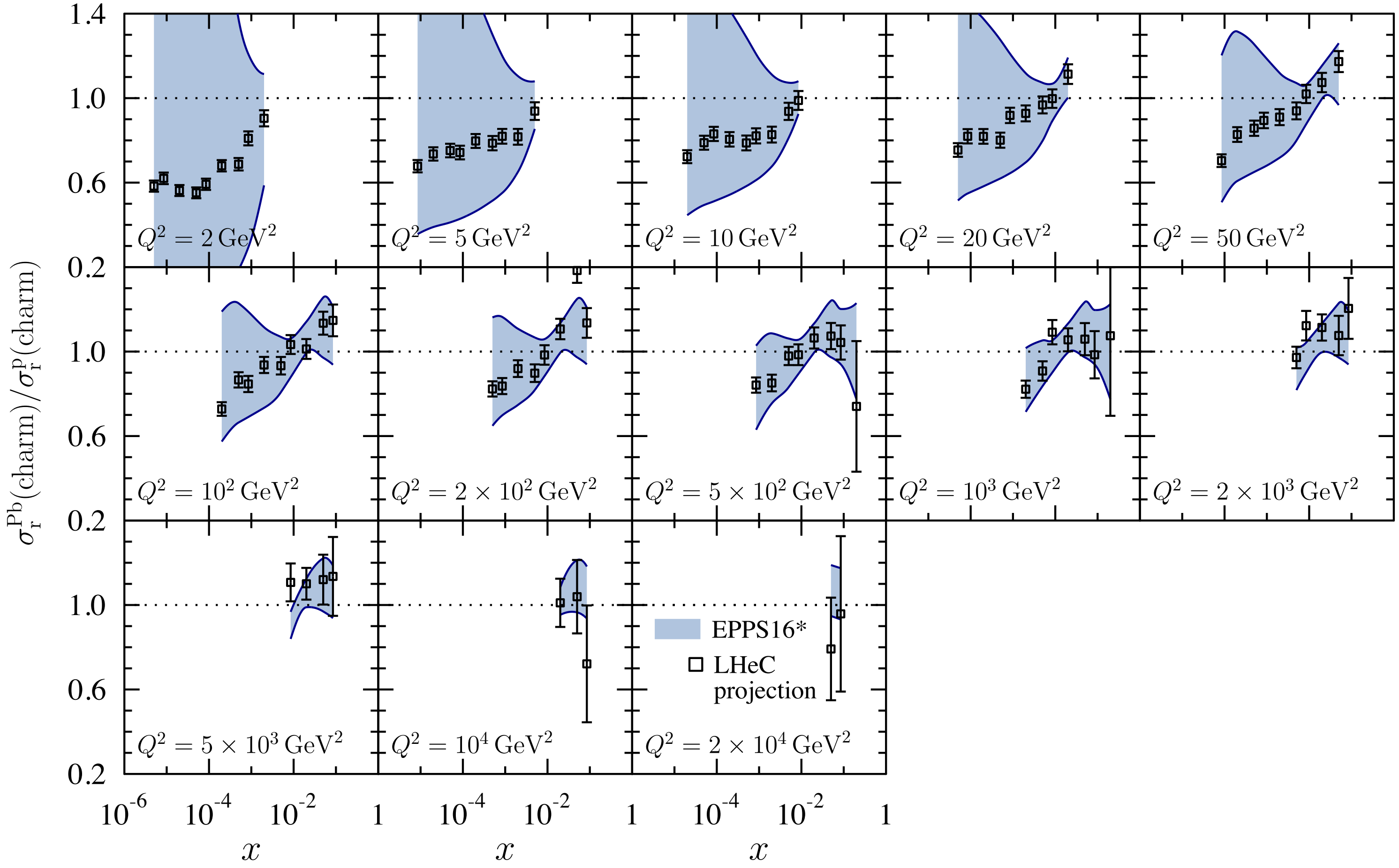
nPDFs from LHeC in global fit context



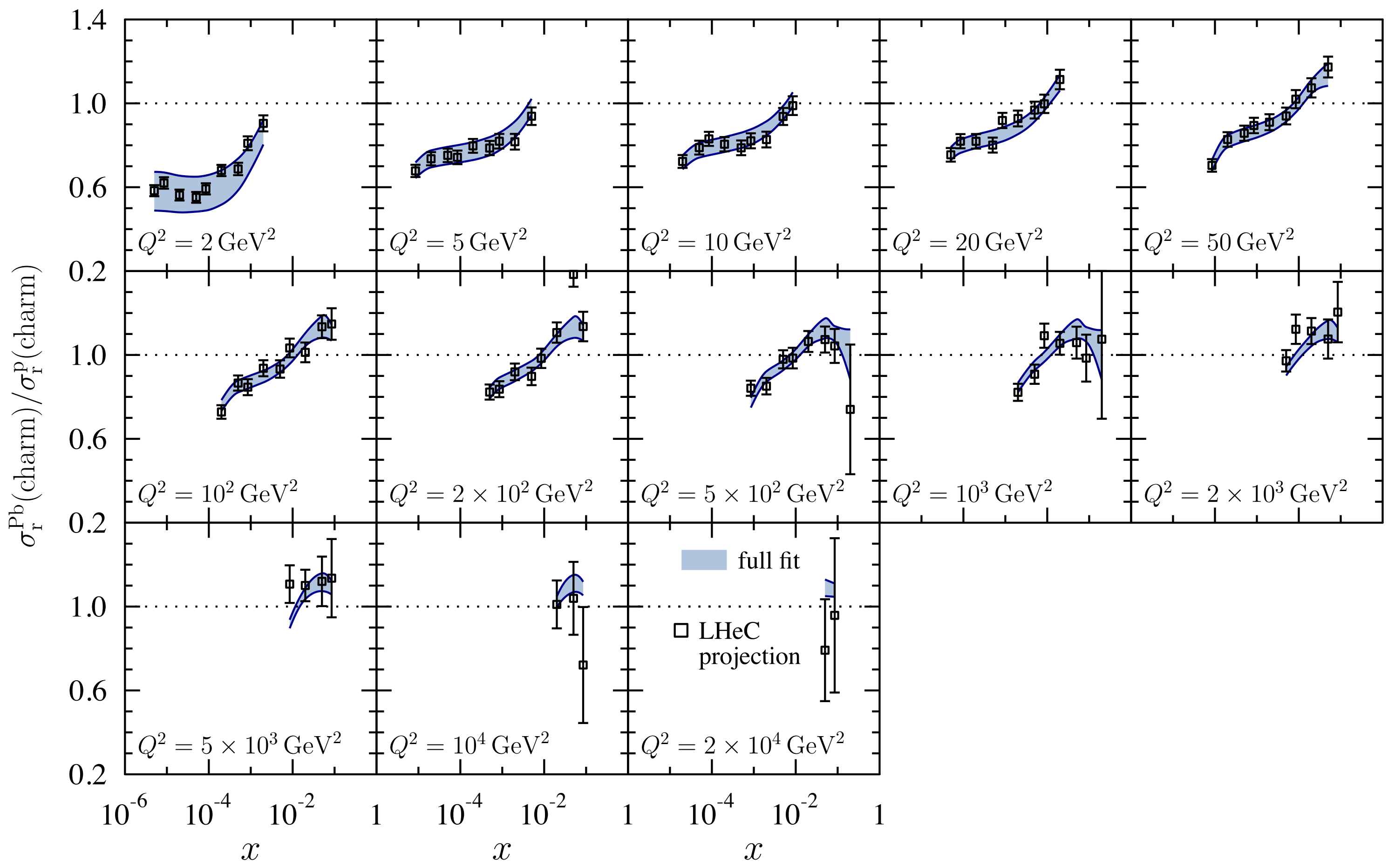
nPDFs from LHeC in global fit context



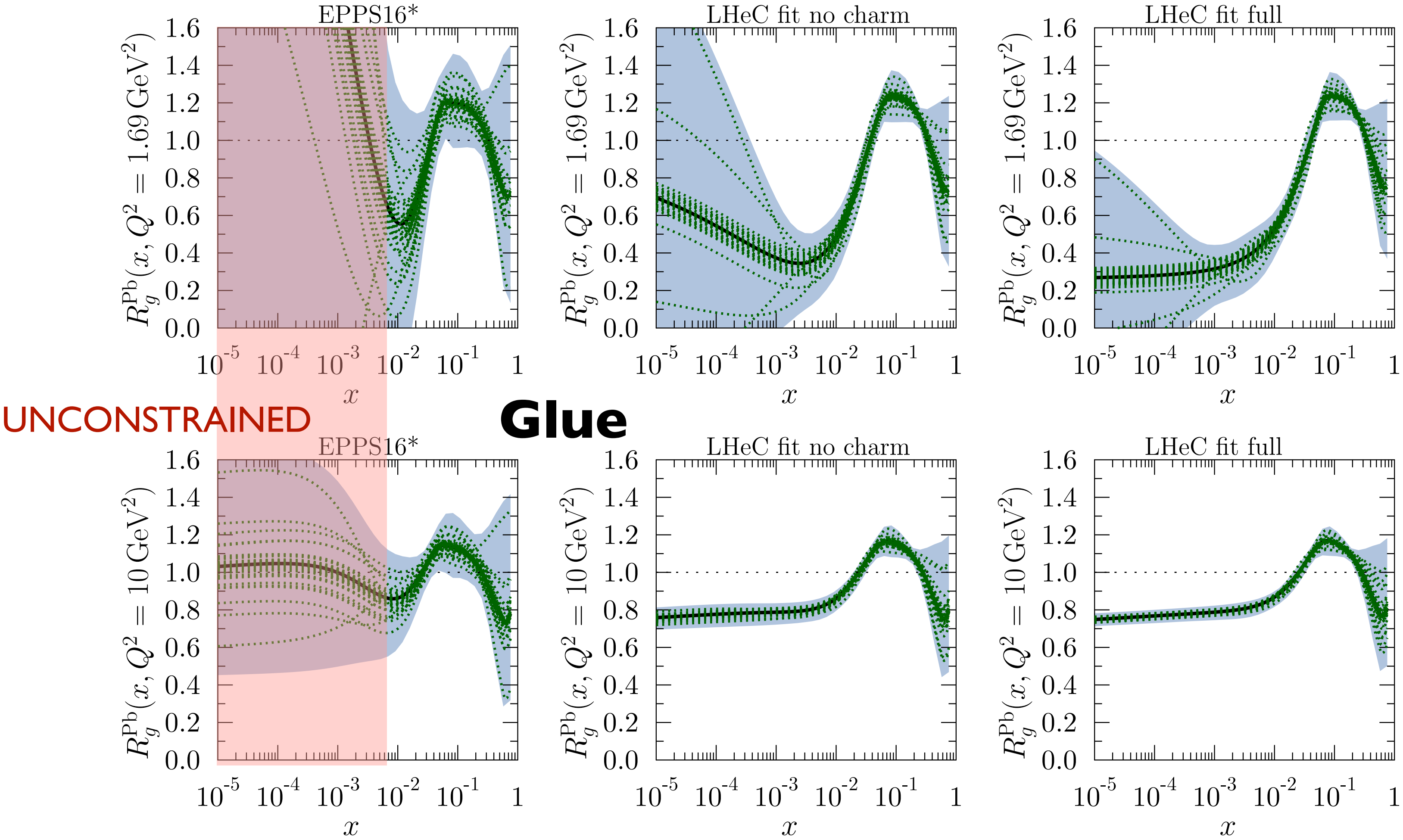
nPDFs from LHeC in global fit context



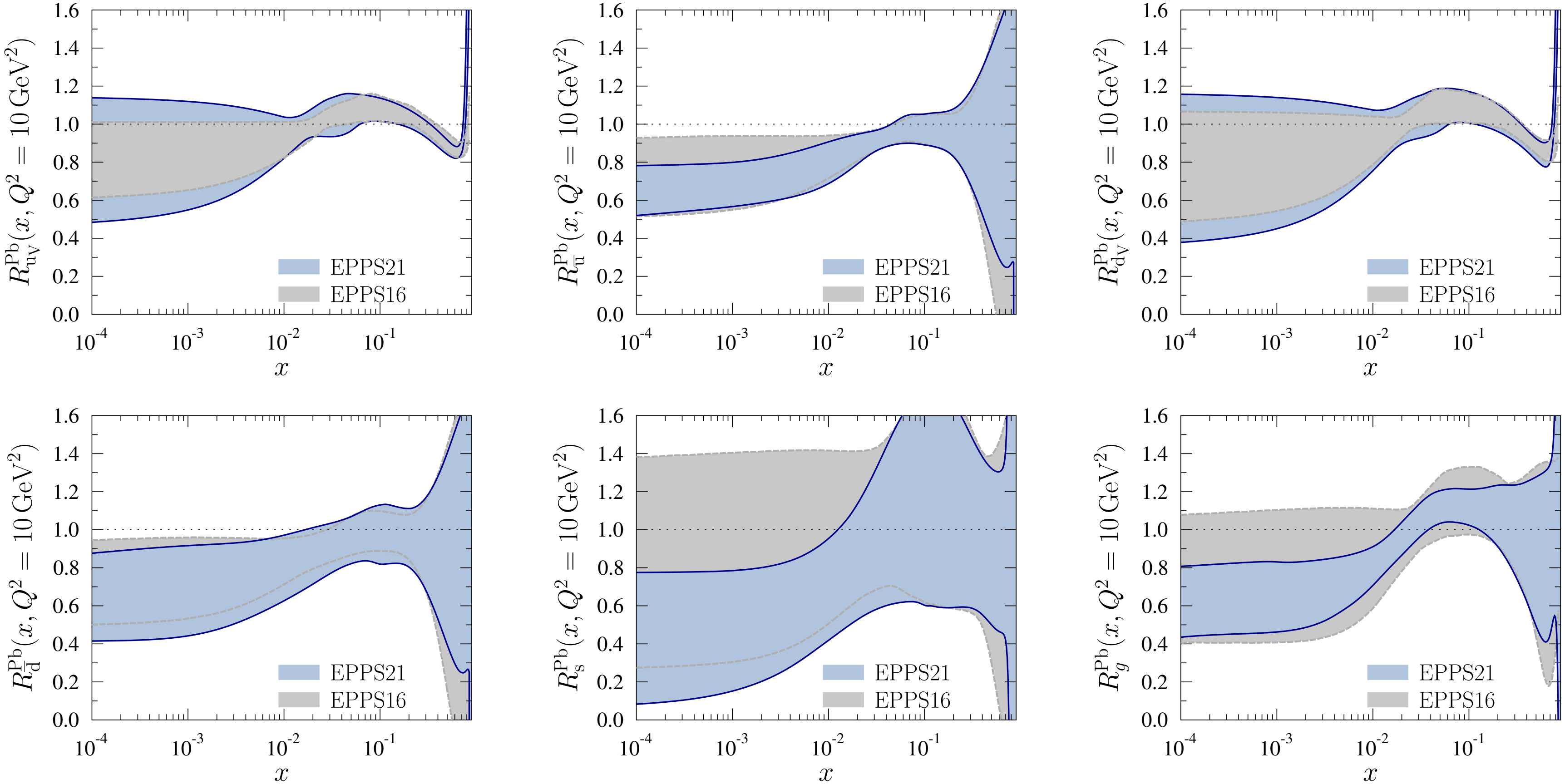
nPDFs from LHeC in global fit context



nPDFs from LHeC in global fit context



EPPS21



arXiv:2112.12462

nPDFs from DIS on single nucleus

- **extraction of Pb-only nuclear PDFs from NC+CC LHeC/FCC-eh simulated data:**
- estimate uncertainties coming solely from achievable experimental precision
- HERAPDF2.0-style parameterisation (arXiv:1506.06042), 14 free parameters, NNLO DGLAP evolution, RTOPT mass scheme, **α**s(MZ)=0.118

$$xU = xu + xc\,, \qquad x\bar{U} = x\bar{u} + x\bar{c}\,, \qquad xD = xd + xs\,, \qquad x\bar{D} = x\bar{d} + x\bar{s}$$

$$\begin{aligned}
xg(x) &= A_g x^{B_g}(1-x)^{C_g} - A'_g x^{B'_g}(1-x)^{C'_g}, \\
xu_v(x) &= A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}\left(1 + E_{u_v}x^2\right), \\
xd_v(x) &= A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}, \\
x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}\left(1 + D_{\bar{U}}x\right), \\
x\bar{D}(x) &= A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}.
\end{aligned}$$

- central values of simulated data from HERAPDF2.0: neither parameterisation bias nor theory uncertainties included
- standard xFitter/HERAPDF treatment of correlated/uncorrelated systematics; tolerance **Δ**X^2=1 (NB, **Δ** X^2=52 in EPPS16*)
- only data with Q^2 ≥3.5 GeV2, initial evolution scale 1.9 GeV^2
- proton PDFs extracted in same set up for consistency

(analysis performed with xFitter, arXiv:1410.4412)

nPDFs from DIS on single nucleus