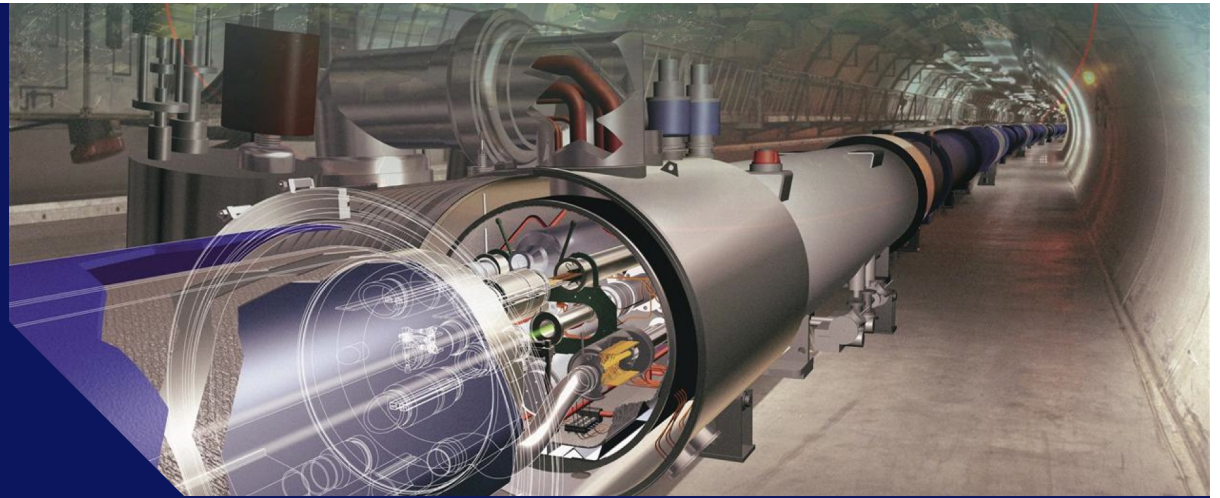


# POETIC XI

Miami

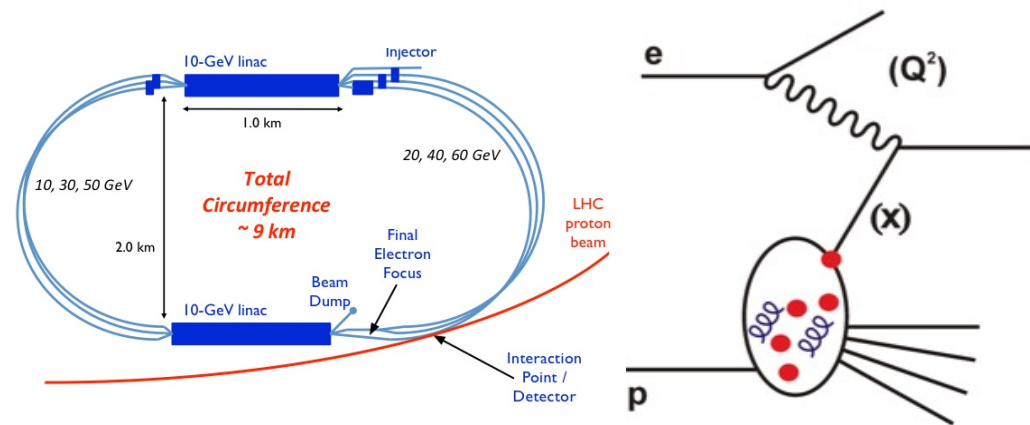
24 – 28 February 2025



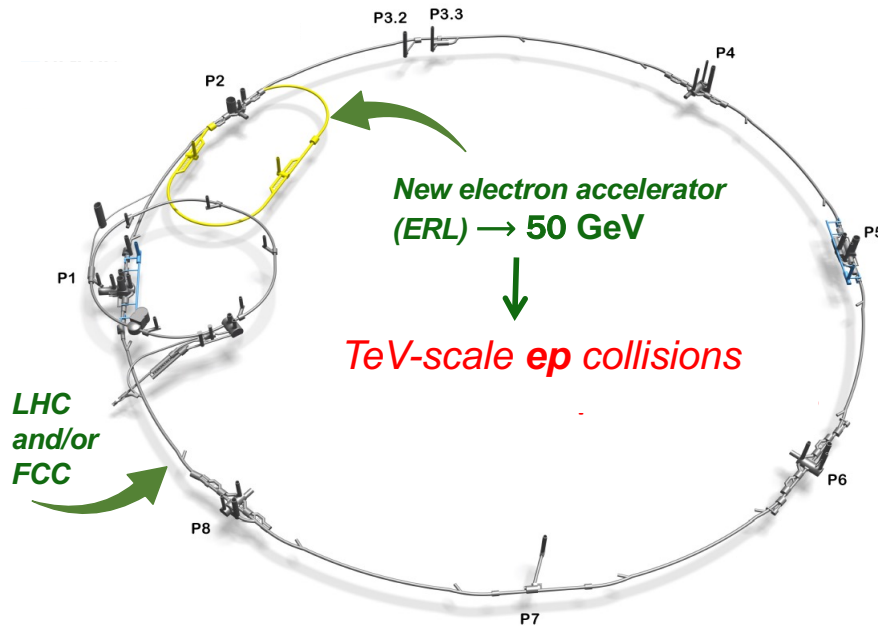
## Proton and nuclear structure at the LHeC and FCC-eh

Claire Gwenlan,  
Oxford

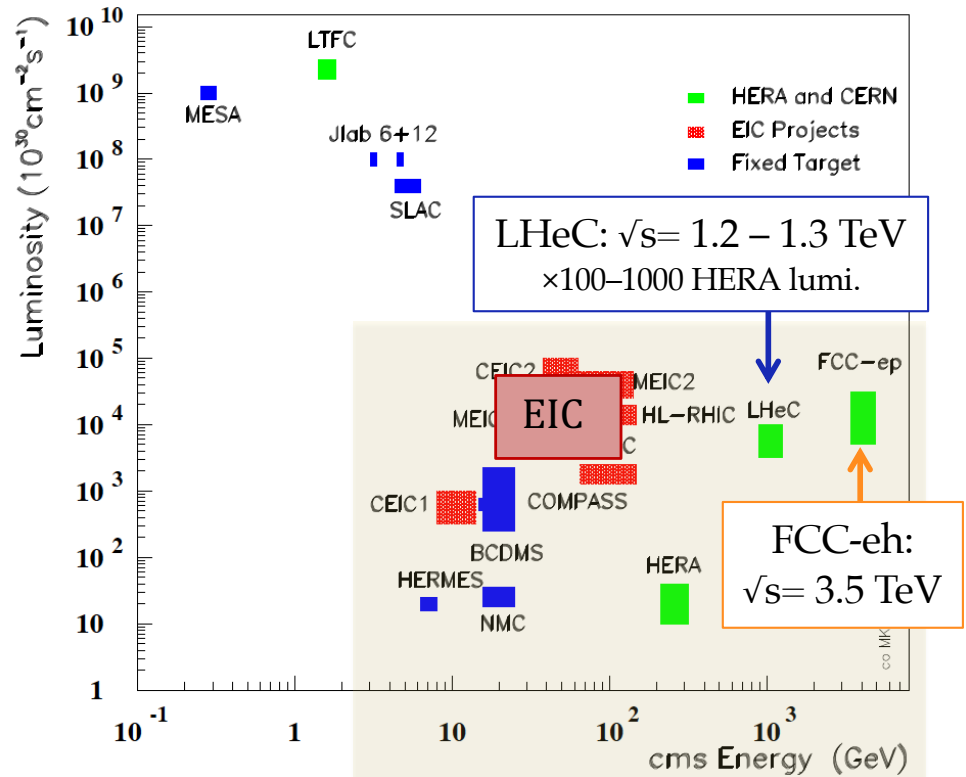
*on behalf of the ep/eA@CERN study  
group for the LHeC and FCC-eh*  
<https://indico.cern.ch/e/LHeCFCCeh>



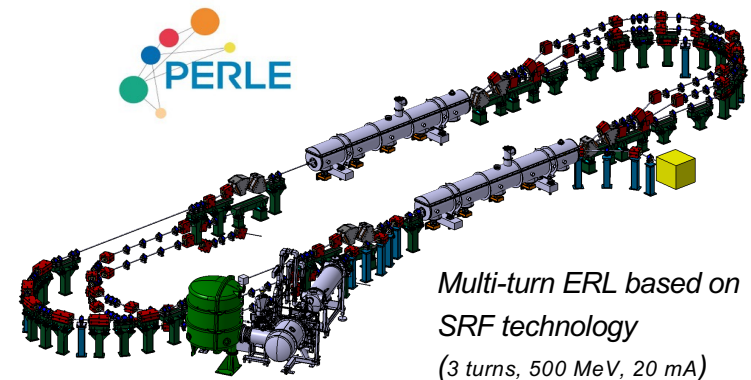
# LHeC and FCC-eh



CERN future colliders: arXiv:[1810.13022](https://arxiv.org/abs/1810.13022)



- **e:** new energy recovery LINAC (ERL)
- attached to HL-LHC (or FCC)
- e beam:  $\rightarrow 50 \text{ GeV}$
- e pol.:  $P = \pm 0.8$
- Lint  $\rightarrow 1-2 \text{ ab}^{-1}$  (**1000× HERA!**)
- **PERLE @ IJCLab (Orsay)**  $\longrightarrow$   
under construction to demonstrate all ERL aspects for LHeC/FCC-eh



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

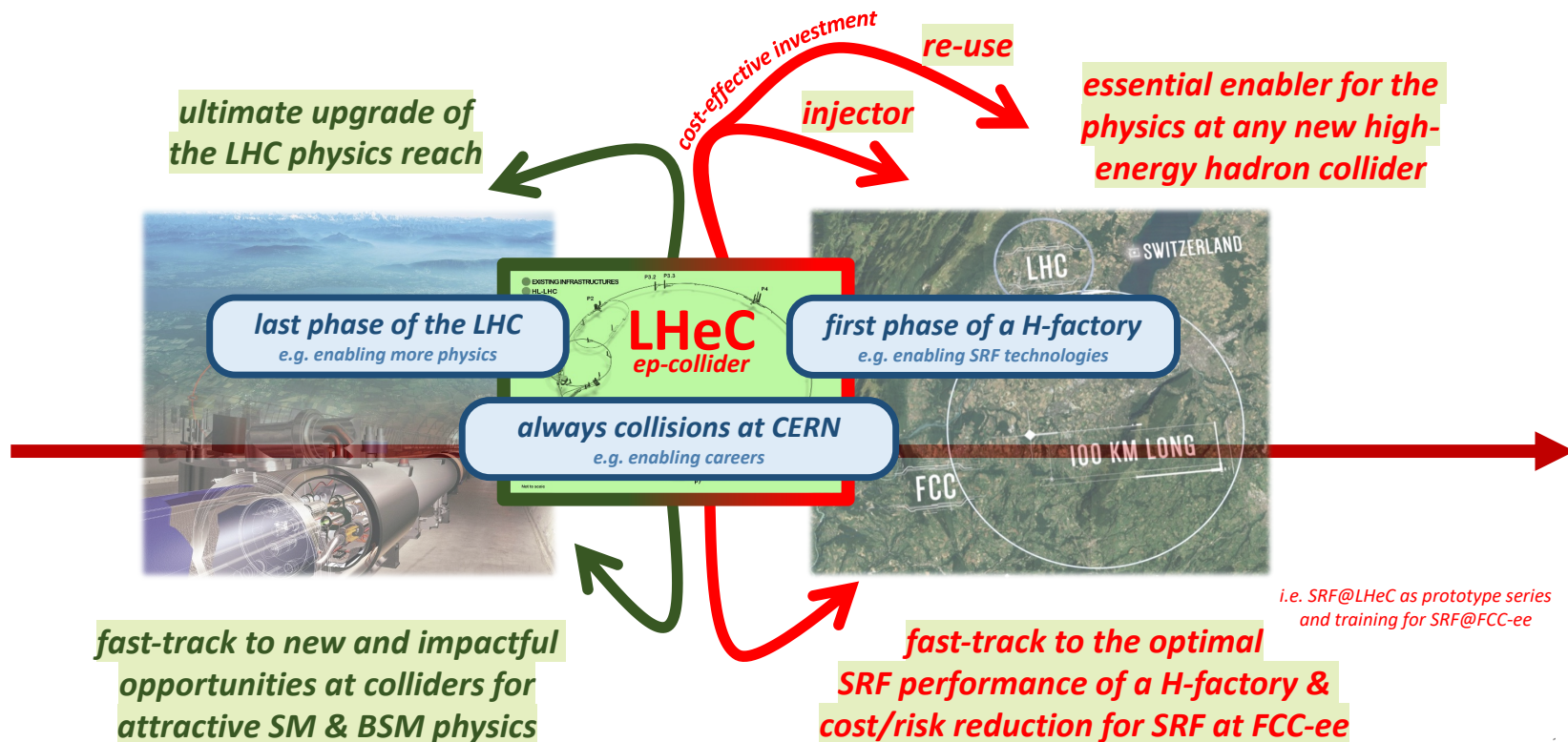


# LHeC timescale

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

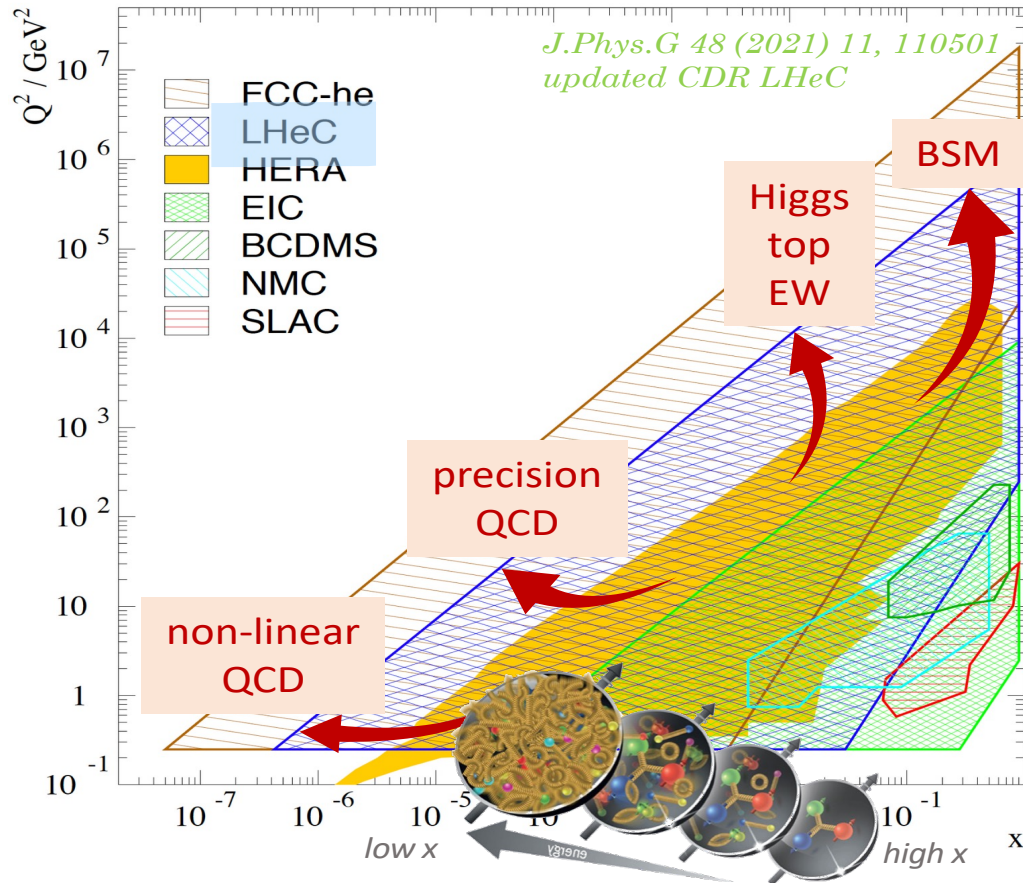
10 yrs@1.2 TeV ( $1 \text{ ab}^{-1}$ ) = Run 6 + 5yrs **ep-only**  
 6yrs **ep-only** @ LHC ( $> 1 \text{ ab}^{-1}$ )

## An impactful “bridge” between major colliders @ CERN



**The Large Hadron electron Collider as a bridge project for CERN;** contribution to be submitted to European Strategy for Particle Physics update, <https://europeanstrategy.cern/european-strategy-for-particle-physics>

# Physics with Energy Frontier DIS

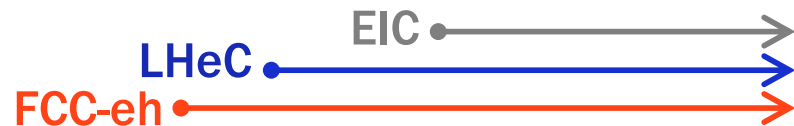
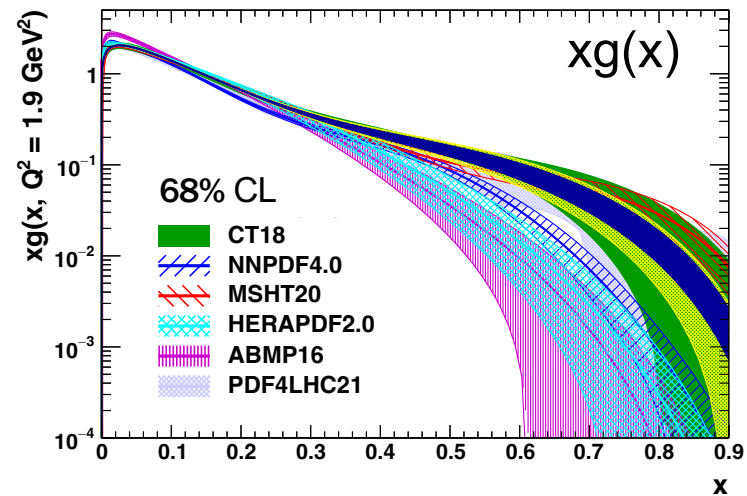
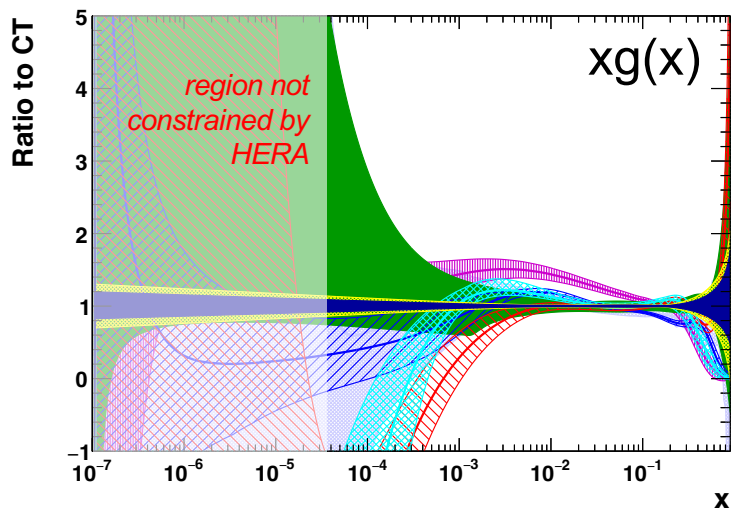
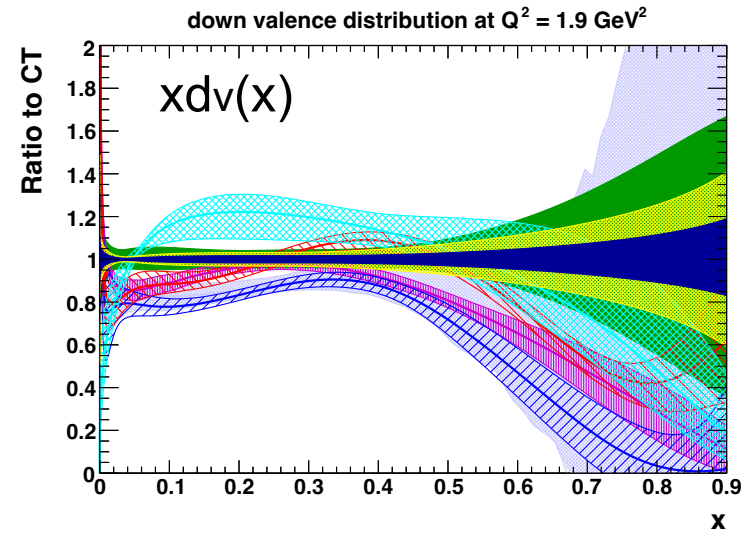
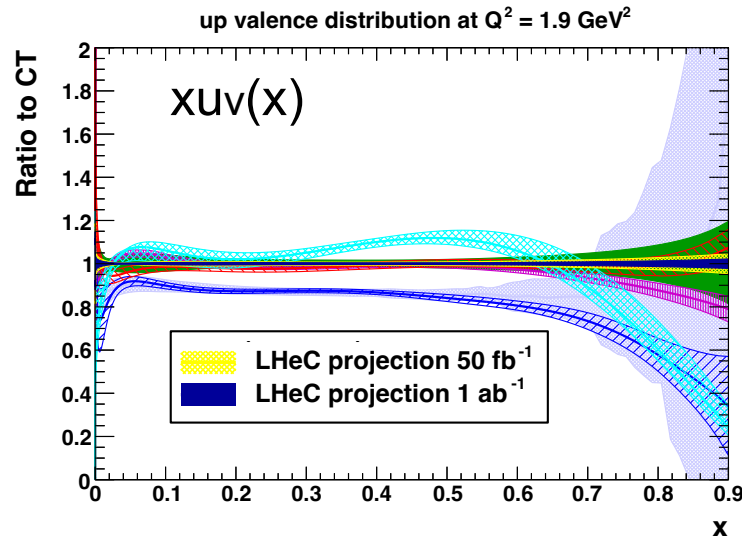


- DIS**: cleanest high-resolution microscope
- opportunity for **unprecedented increase in kinematic reach from single DIS experiment**;
- ×1000 increase in lumi. cf. HERA
- **QCD precision physics and discovery**, empowering the HL-LHC and FCC-hh
    - unprecedented access to **small x**
    - unique **nuclear physics** facility

PLUS powerful **Higgs, EW, top, BSM** programmes

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

# Quark and Gluon PDFs



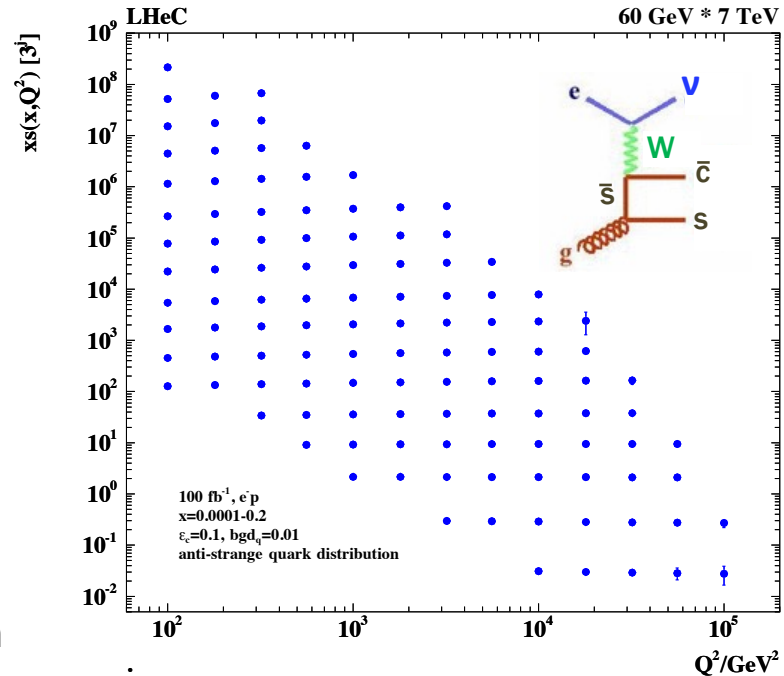
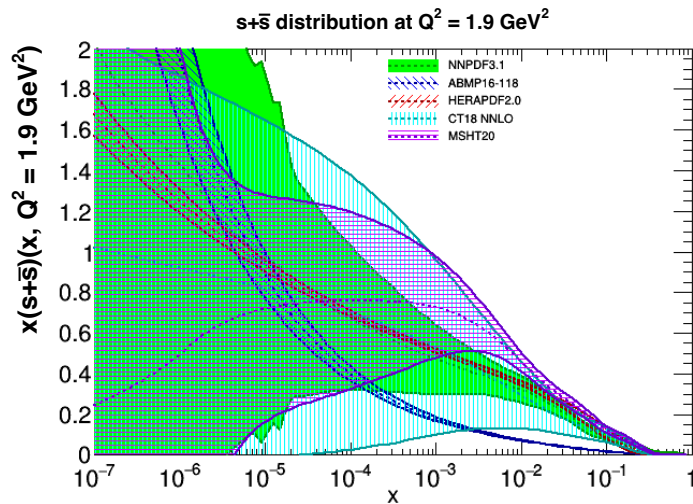
**BSM sensitivity at high x**

(**EIC** pdf studies, see EG. arXiv:[2309.11269](https://arxiv.org/abs/2309.11269))

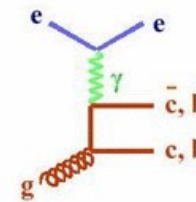
# Strange, c, b

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

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



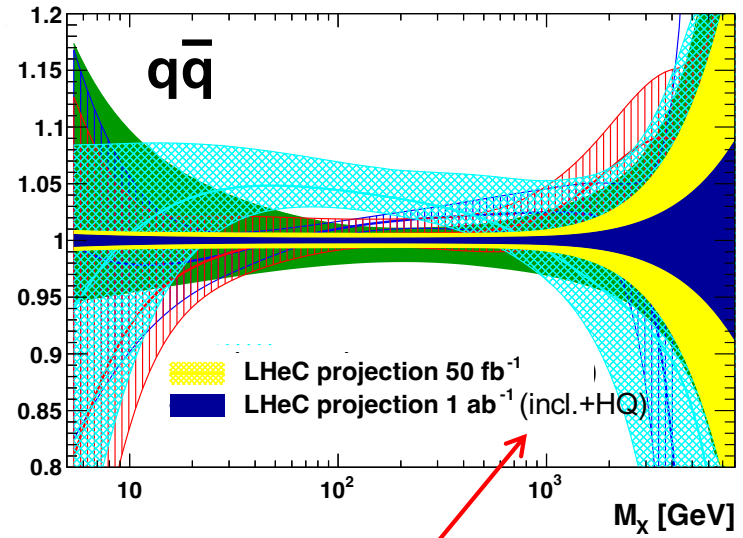
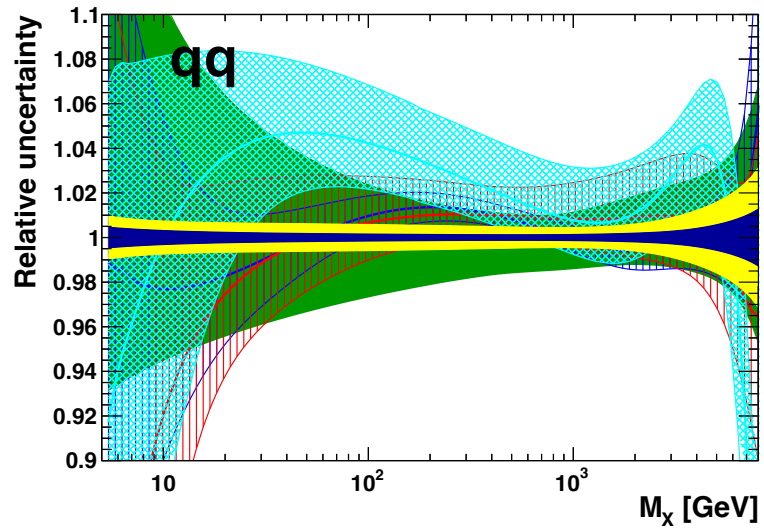
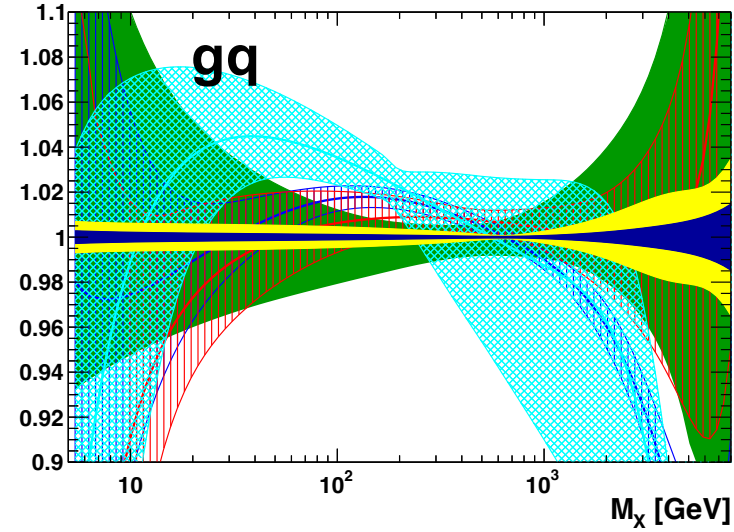
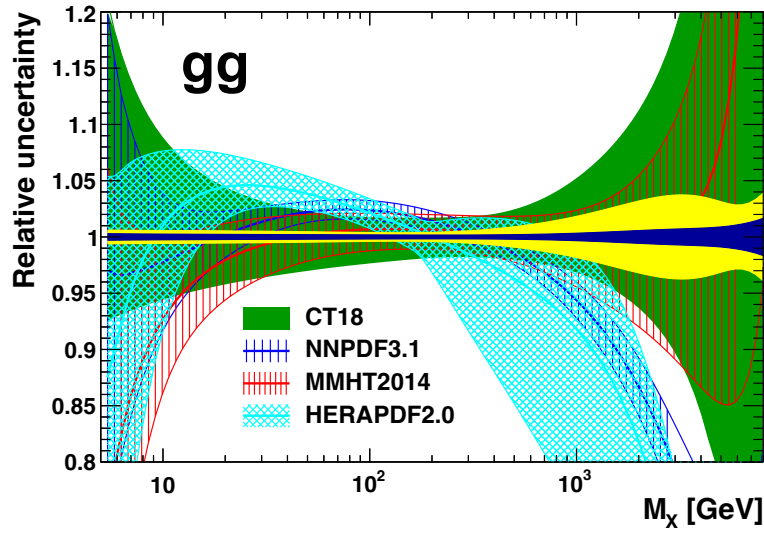
- **c, b**: enormously extended range and much improved precision c.f. HERA
- $\delta M_c = 50$  (HERA) to **3 MeV**: impacts on  $\alpha_s$ , regulates ratio of charm to light, crucial for precision t, H
- $\delta M_b$  to **10 MeV**; MSSM: Higgs produced dominantly via  $b\bar{b} \rightarrow A$
- **t pdf** also accessible (EG. G.R. Boroun, [PLB 744 \(2015\) 142](#); [741 \(2015\) 197](#))



- completely resolve all proton **pdfs** ( $u$ ,  $\bar{u}$ ,  $d$ ,  $\bar{d}$ ,  $s$ ,  $c$ ,  $b$ ,  $t$ ,  $xg$ )



# PDF luminosities @ 14 TeV



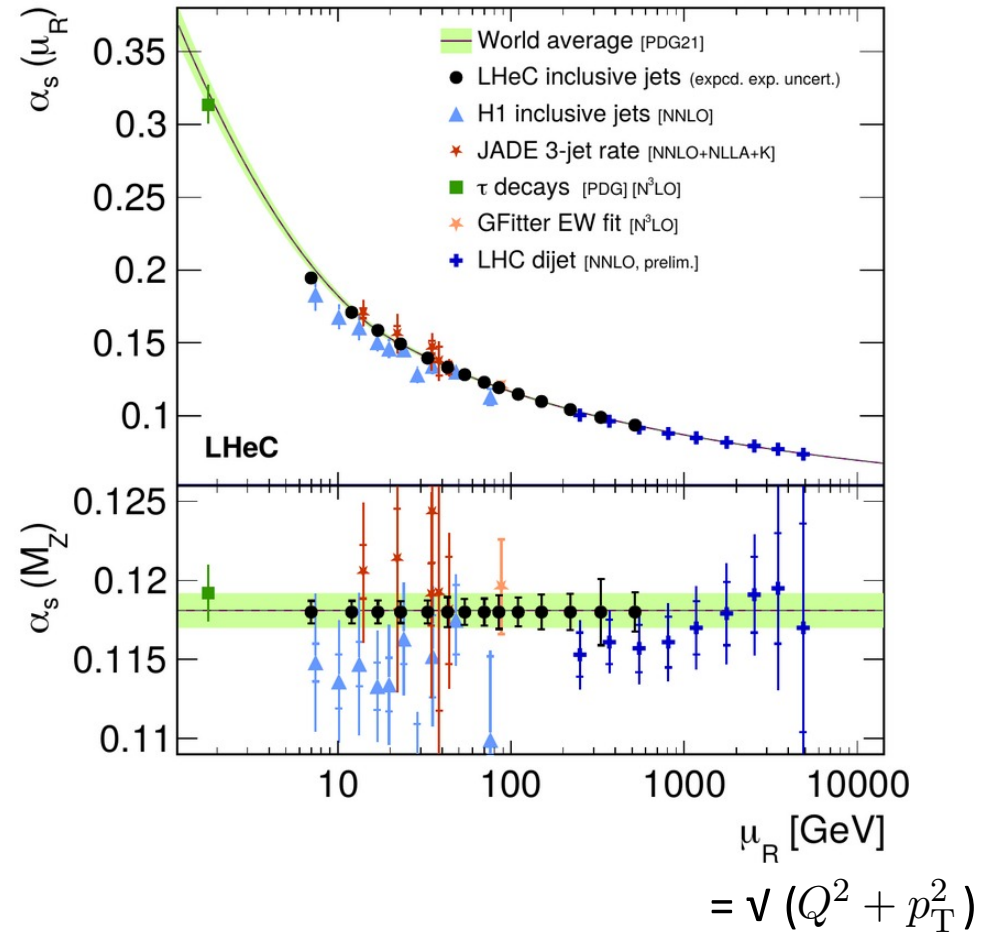
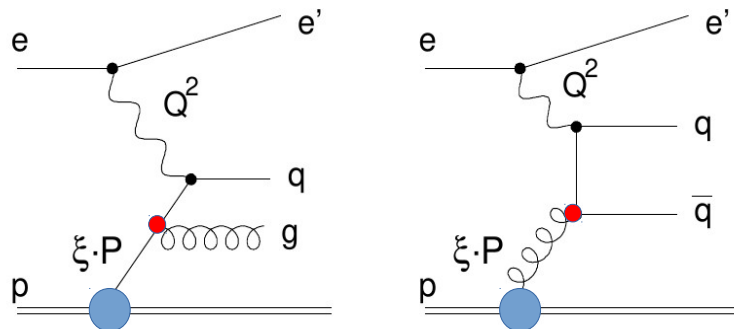
(s,c,b) also included

# Strong Coupling

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

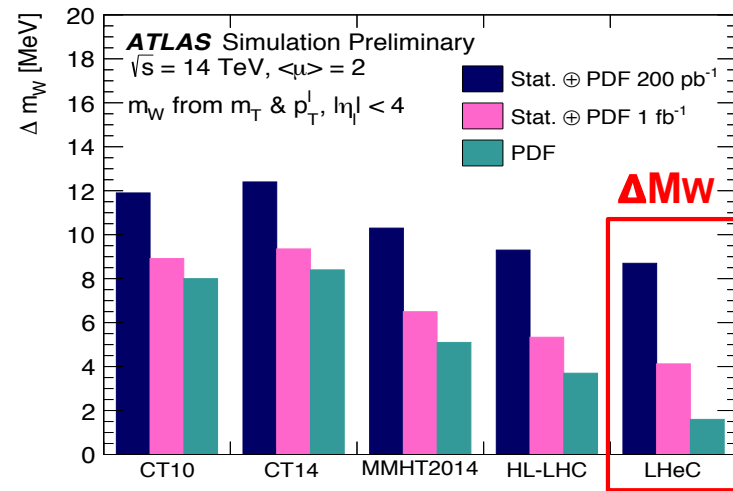
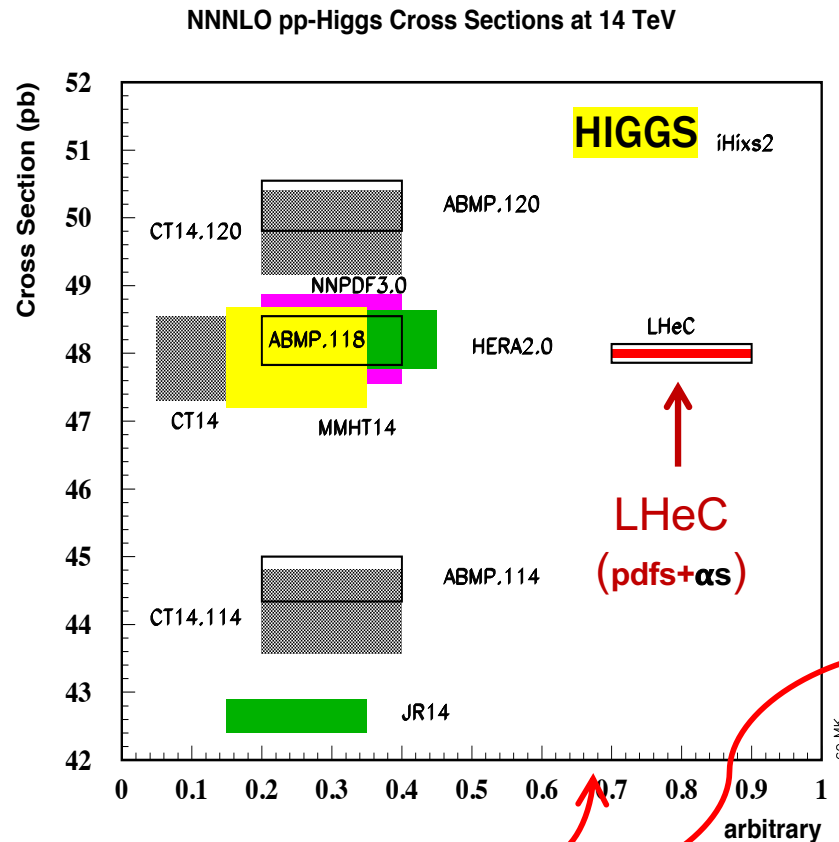
- simultaneous PDF+ $\alpha_s$  fits:
- EIC (arXiv:[2307.01183](https://arxiv.org/abs/2307.01183)):  $\mathcal{O}(0.4\%)$  (exp+PDF)
- LHeC:
- $\Delta\alpha_s(M_Z)[\text{incl. DIS}] = \pm 0.00022$  (exp+PDF)
- $\Delta\alpha_s(M_Z) = \pm 0.00018$  for incl. DIS together with ep jets
- achievable precision:  $\mathcal{O}(0.1-0.2\%)$   
×5–10 better than today

ep jets:



- $\alpha_s$  from fits to ep jet production (LHeC)
- connects  $\tau$ -decays to Z-pole and beyond
- FCC-eh further increases precision and range

# empowering the LHC



**EW**

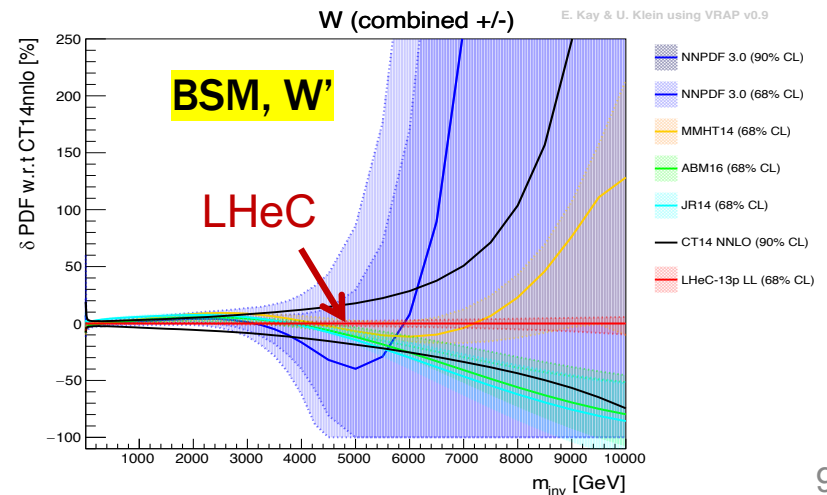
**$\Delta \sin^2 \theta_W$**

CMS 13 TeV Preliminary  
 HL-LHC ATLAS PDF4LHC15<sub>HL-LHC</sub>: 14 TeV  
 HL-LHC ATLAS PDFLHeC: 14 TeV

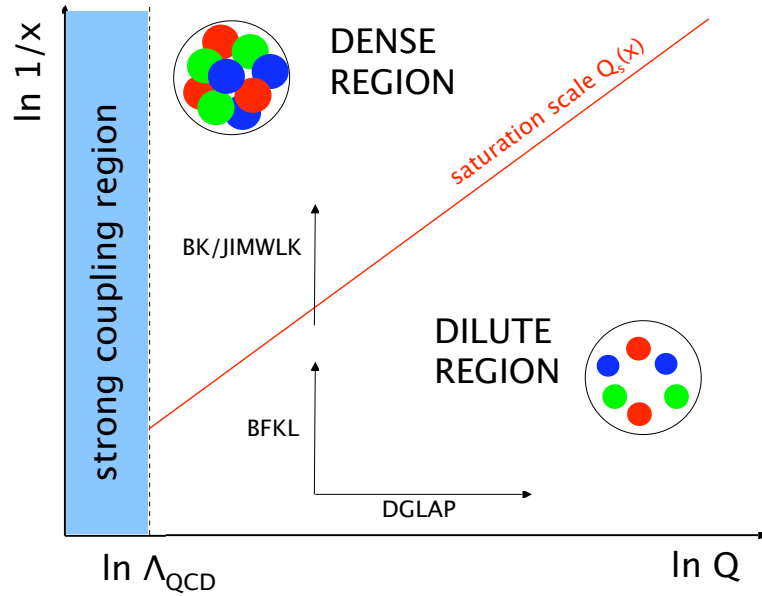
$\pm 0.00020$  (exp+th)  $\pm 0.00027$  (pdf)  
 $\pm 0.00007$  (exp)  $\pm 0.00013$  (pdf)  
 $\pm 0.00007$  (exp)  $\pm 0.00003$  (pdf)

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

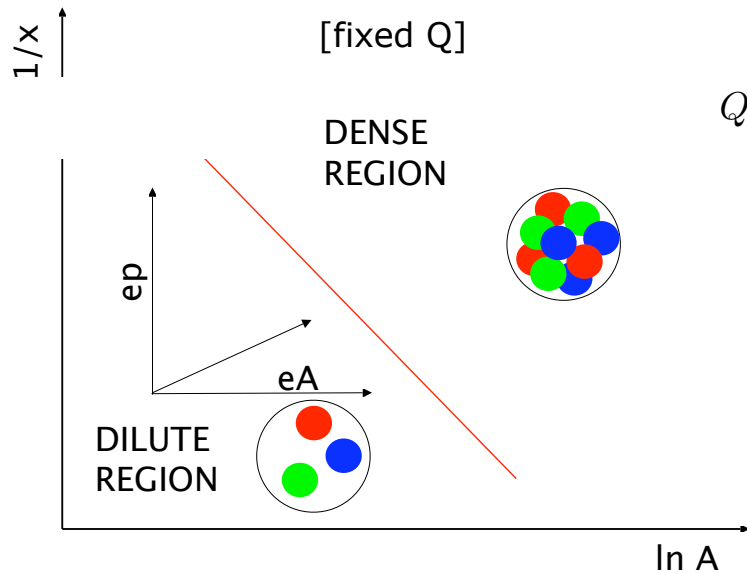
PLUS powerful and complementary **ep-only** Higgs, EW, top, BSM



# 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

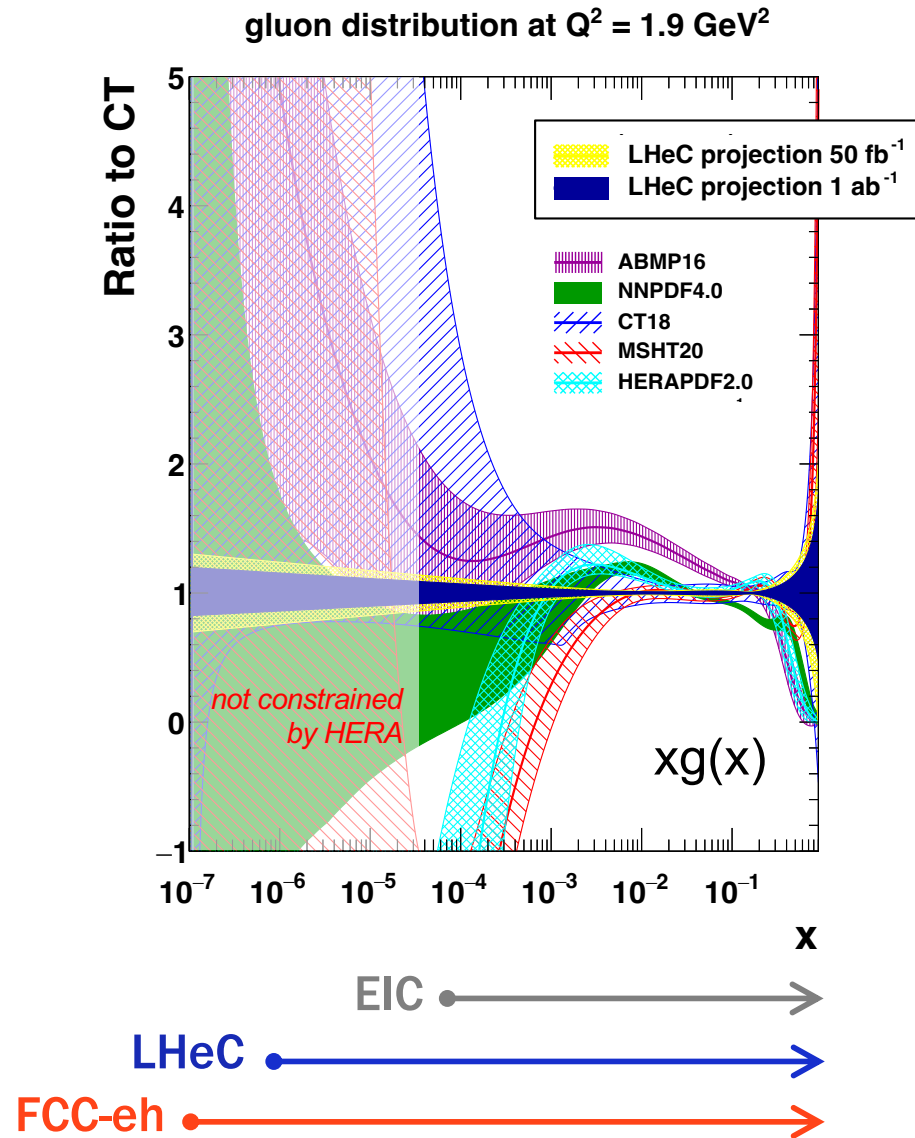


$$Q_S^2 \sim \frac{A x g(x, Q_S^2)}{\pi R_A^2} \sim \frac{A x g(x, Q_S^2)}{A^{2/3}} \sim A^{1/3} x^{-\lambda}$$

**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

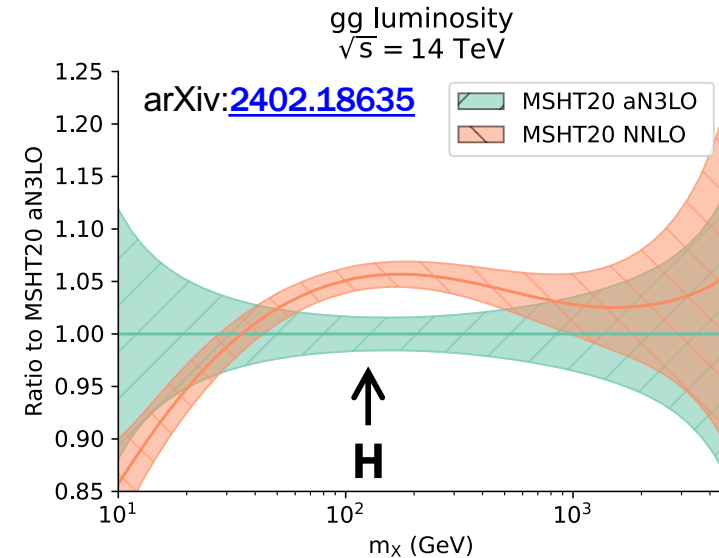
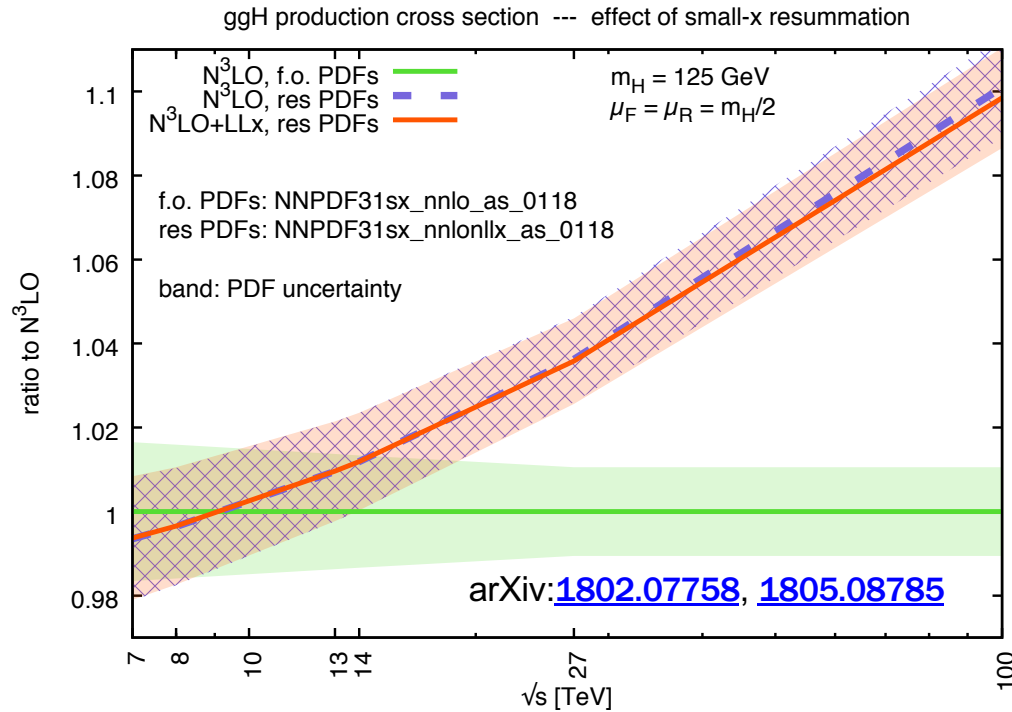


HERA sensitivity stops  $x \simeq 5 \cdot 10^{-5}$

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



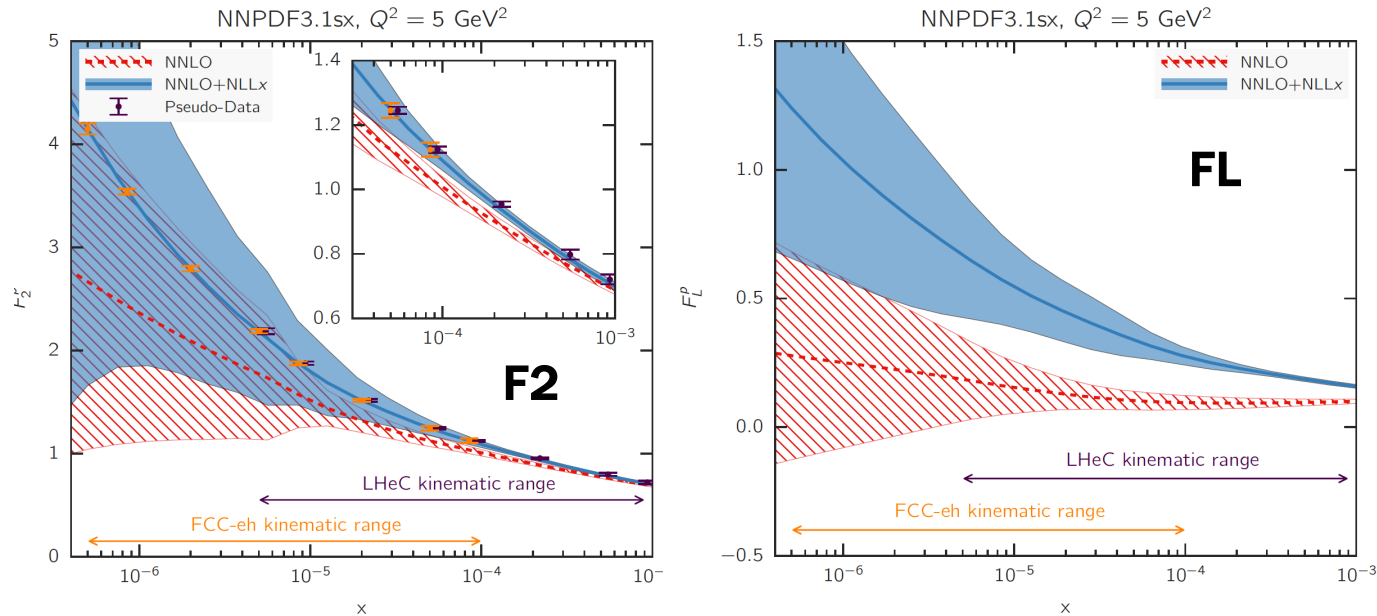
- effect of small x resummation (needed to stabilise BKFL expansion) :
- EG.  $gg \rightarrow H$  cross section for LHC, HE-LHC, FCC
- **significant impact, especially at ultra low x values probed at FCC**

(see also work on forward H production (arXiv:[2011.03193](https://arxiv.org/abs/2011.03193)) and HQ (arXiv:[2211.10142](https://arxiv.org/abs/2211.10142)); other processes in progress)

- (approximate) **N<sup>3</sup>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

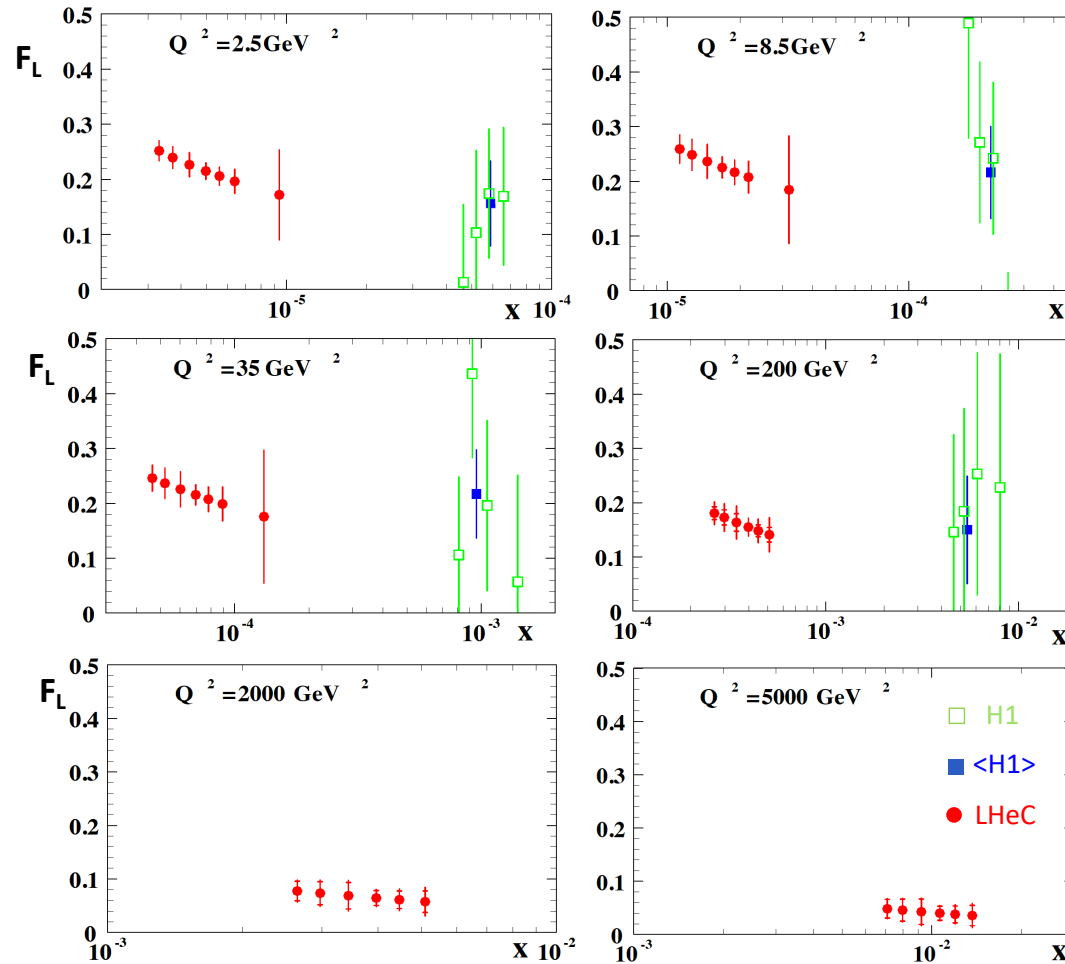


(arXiv:[1710.05935](https://arxiv.org/abs/1710.05935))

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

- 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** (further detailed studies in arXiv:[2007.14491](https://arxiv.org/abs/2007.14491))
- measurement of FL has a significant role to play, arXiv:[1802.04317](https://arxiv.org/abs/1802.04317)

# Longitudinal Structure Function



simulated for:

$E_p = 7 \text{ TeV}$  and

$E_e = 60, 30, 20 \text{ GeV}$

integrated luminosity:

10, 1, 1  $\text{fb}^{-1}$

measurement

dominated by

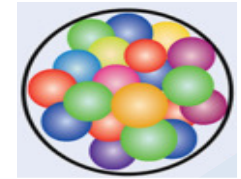
systematics

(arXiv:[1802.04317](https://arxiv.org/abs/1802.04317))

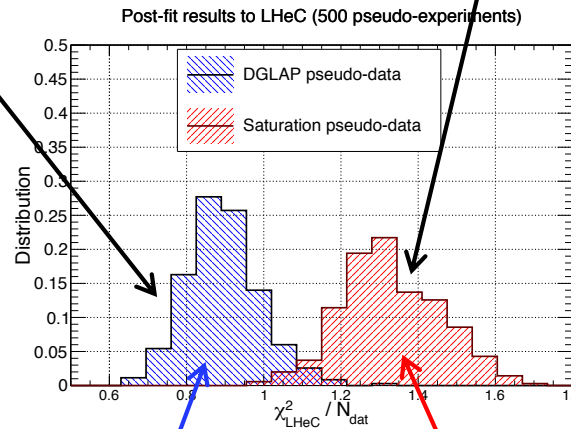
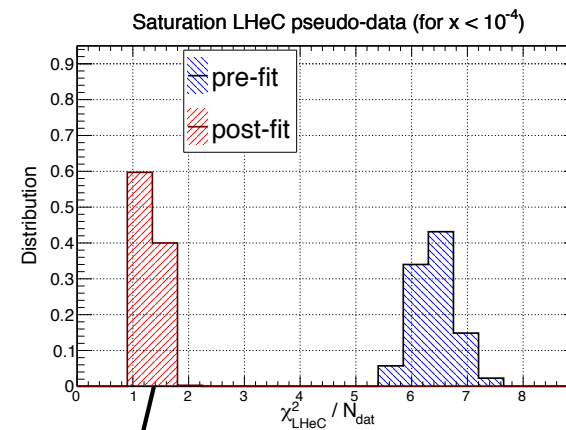
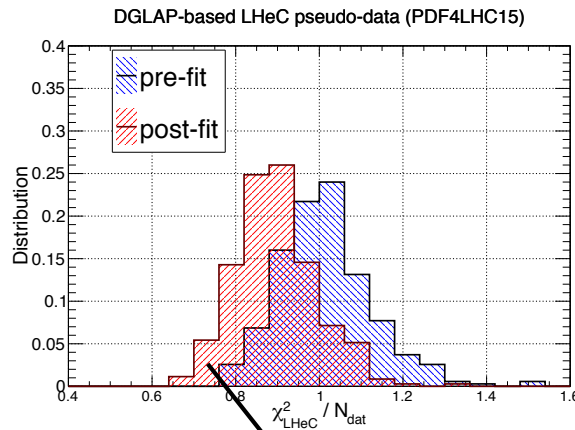
- simultaneous measurement of  $F_2$  and  $F_L$  is clean way to pin down dynamics at small  $x$
- vary also nuclear size to definitively disentangle small- $x$  resummation from non-linear dynamics



# 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  $\chi^2$  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 all saturation effects

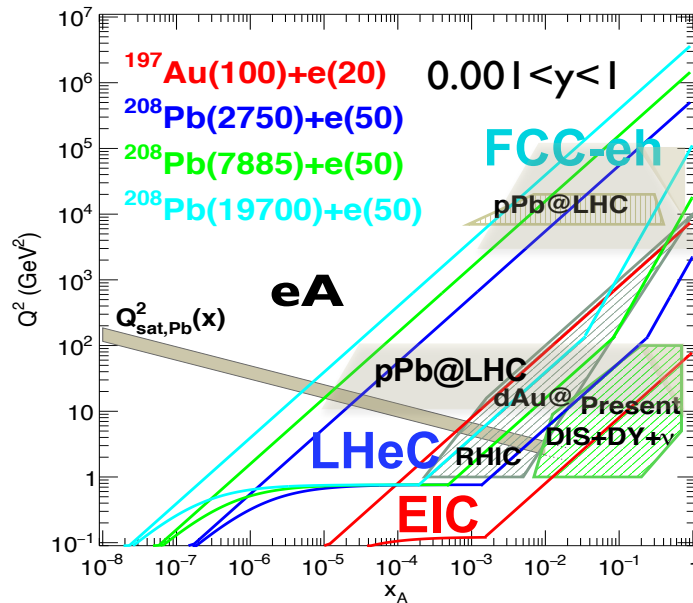
LHeC can distinguish between **DGLAP** and **saturation**

arXiv:[2007.14491](https://arxiv.org/abs/2007.14491)

(NB, large lever arm in  $Q^2$  crucial, see also arXiv:[1702.00839](https://arxiv.org/abs/1702.00839) )

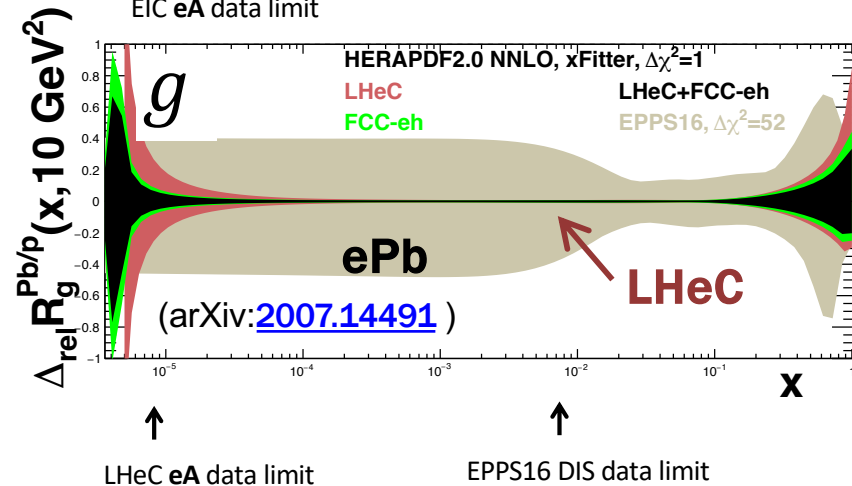
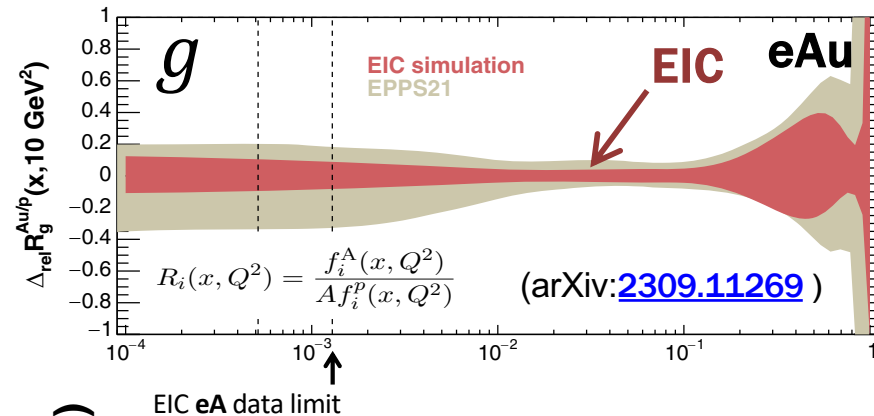
# Impact on Nuclear pdfs

- **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  $\sim 2–3$  vs **EIC**

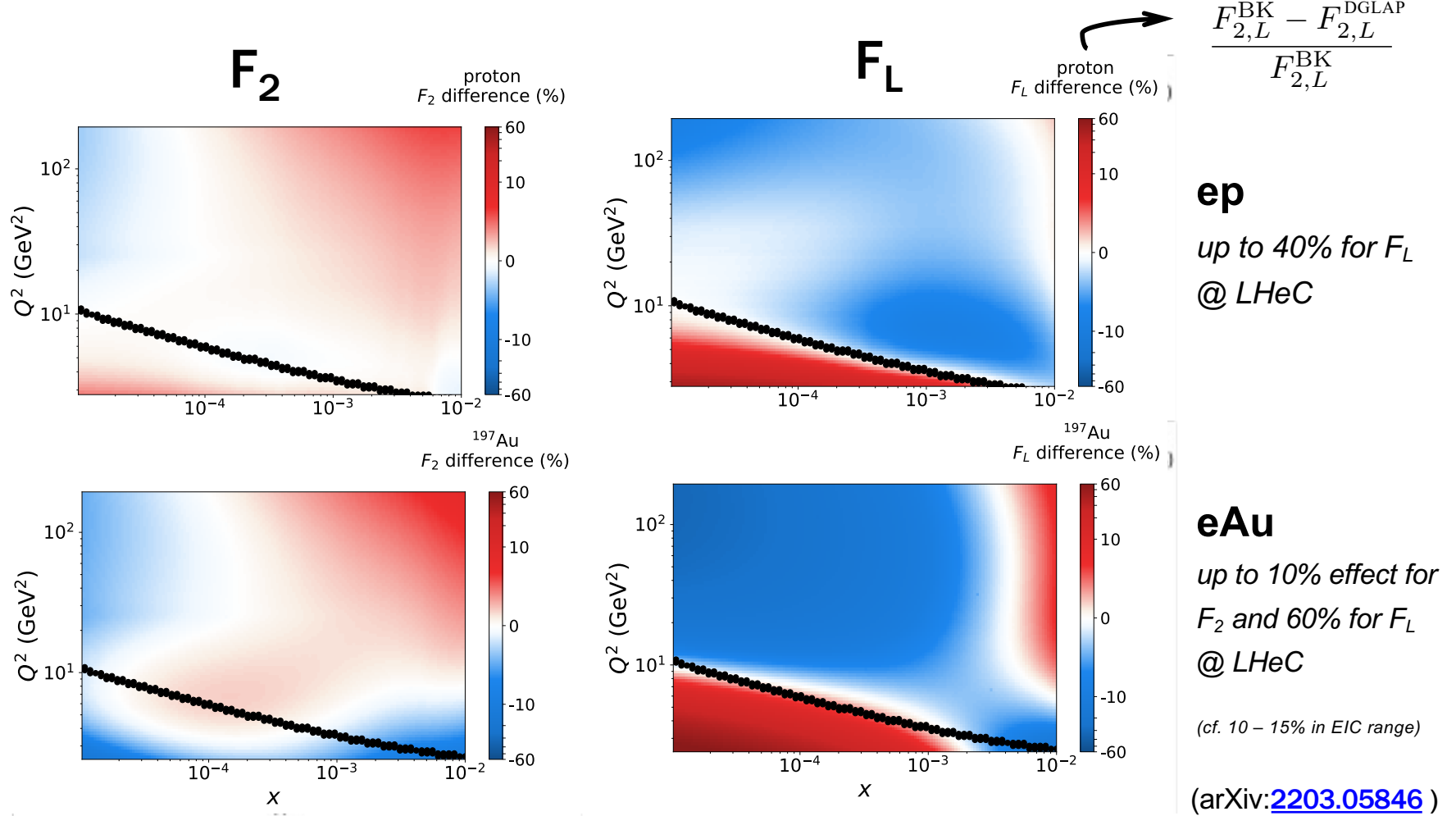


- **nuclear pdfs** on **single nucleus** for the first time (only experimental uncertainties shown ( $\Delta\chi^2=1$ ))

## gluon nuclear modification factor



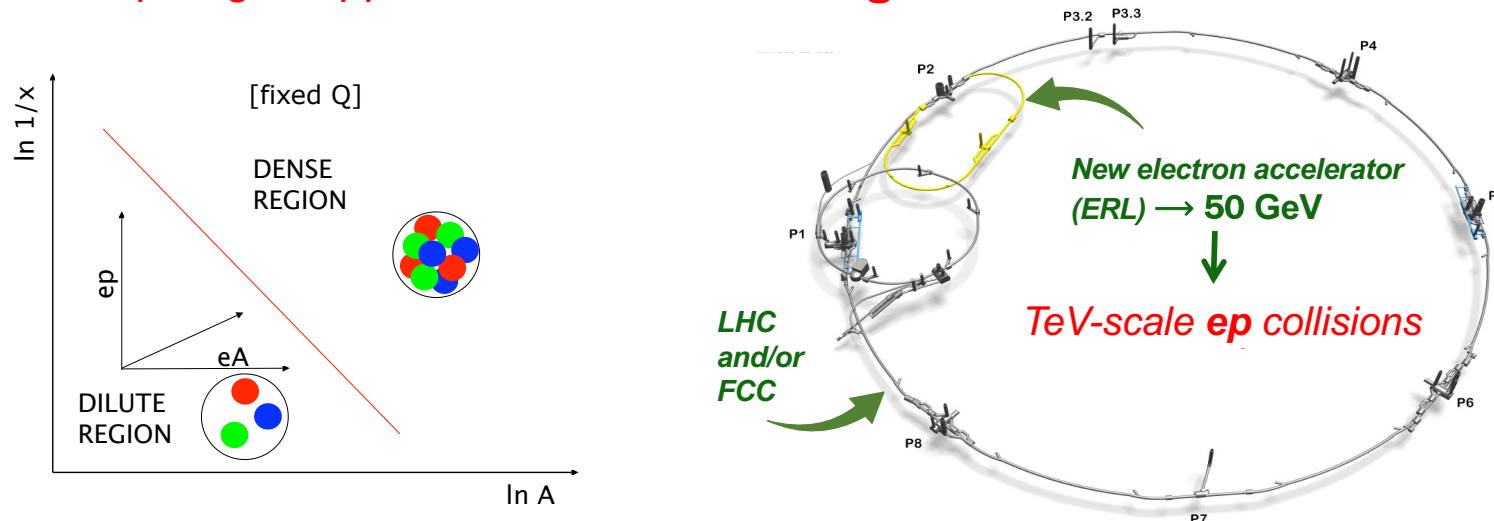
# Novel small x dynamics: saturation



- study differences in evolution between **linear DGLAP** and **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

- **LHeC** and **FCC-eh**: new highly luminous energy frontier **ep/eA** colliders @ **CERN**  
→ **QCD precision** and **discovery machines**
- physics programme both **complementary to** and **unique from EIC**
- precise determination of **proton** and **nuclear pdfs** across vast kinematic range that cannot be matched at other colliders, including precise measurements of heavy quarks, and  **$\alpha_s$**  to **per mille** level  
→ **enabling full exploitation of current and future hadron colliders**
- **ep** together with **eA** allows discovery and tests of non-linear / saturation effects at small  $x$  and with different  $A$  dependence  
→ **two-pronged approach : small  $x$  and large  $A$**

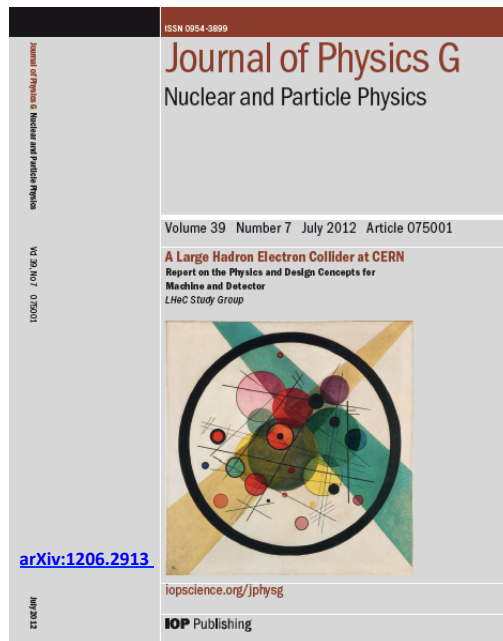




# Extras

# LHeC Conceptual Design Report and Beyond

CDR 2012: commissioned by  
CERN, ECFA, NuPECC  
200 authors, 69 institutions



arXiv:[1206.2913](https://arxiv.org/abs/1206.2913)

see also, **FCC CDR**, vols 1 and 3:  
physics, [EPJ C79 \(2019\), 6, 474](https://arxiv.org/abs/1907.04847)  
FCC with eh integrated, [EPJ ST 228 \(2019\), 4, 755](https://arxiv.org/abs/1907.04847)

Further selected references:

*On the relation of the LHeC and the LHC*  
arXiv:[1211.5102](https://arxiv.org/abs/1211.5102)

*The Large Hadron Electron Collider*  
arXiv:[1305.2090](https://arxiv.org/abs/1305.2090)

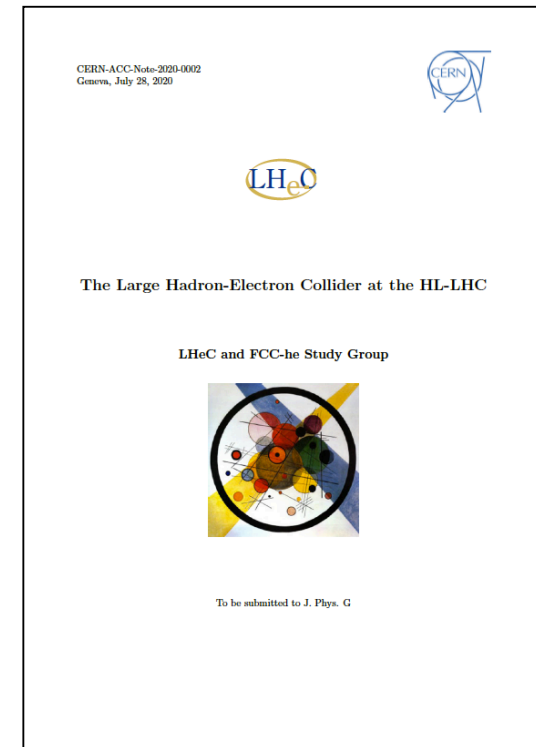
*Dig Deeper*  
*Nature Physics* 9 (2013) 448

*Future Deep Inelastic Scattering with the LHeC*  
arXiv:[1802.04317](https://arxiv.org/abs/1802.04317)

*An Experiment for Electron-Hadron Scattering at the LHC*  
arXiv:[2201.02436](https://arxiv.org/abs/2201.02436)

CDR update

400 pages, 300 authors, 156 institutions



[J. Phys. G 48 \(2021\) 11, 110501](https://arxiv.org/abs/2007.14491)  
(arXiv:[2007.14491](https://arxiv.org/abs/2007.14491))

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

## 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](#) )

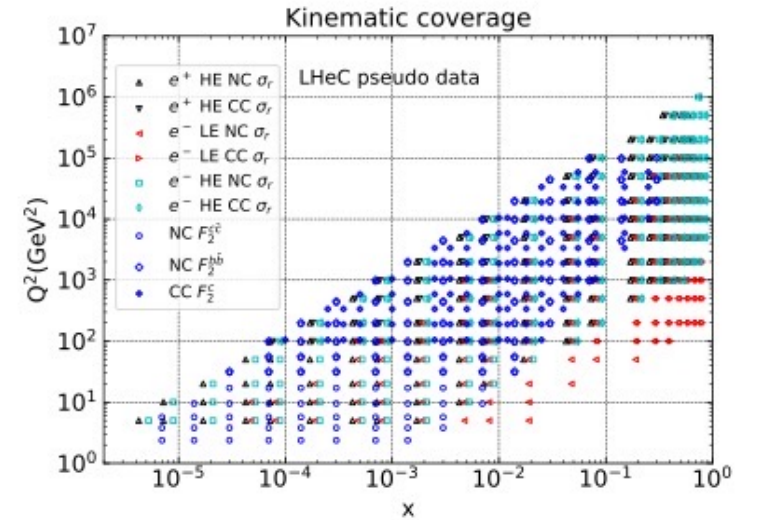
# LHeC simulated data

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 <sup>-1</sup>	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  $E_e = 50$  GeV. Sets D1-D4 are for  $E_p = 7$  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  $E_p$  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

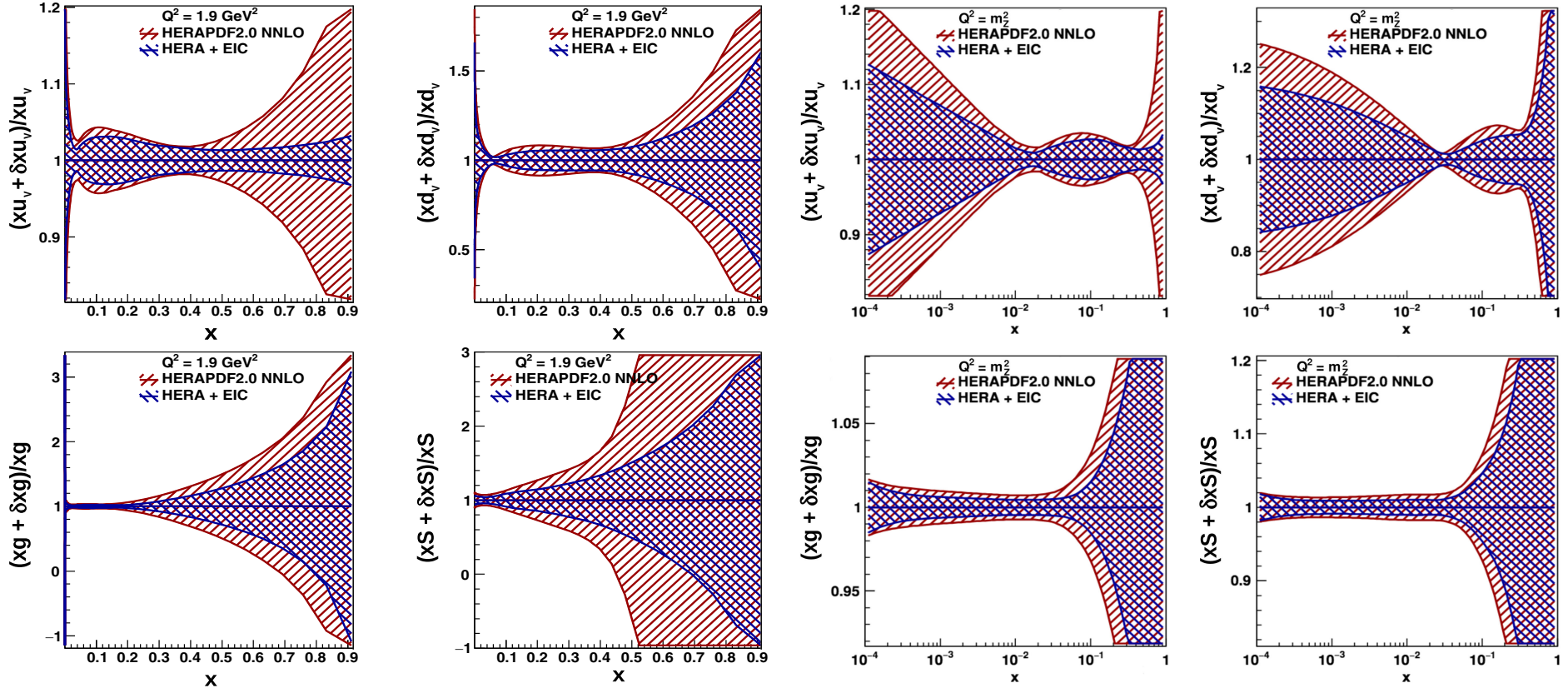
- QCD fit ansatz based on HERAPDF2.0, with following differences:
- no requirement that  $\bar{u}=\bar{d}$  at small  $x$
- no negative gluon term (only for the aesthetics of ratio plots – it has been checked that this does not impact size of projected uncertainties)

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

- **4+1** pdf fit (above) has **14 free parameters**
- **5+1** pdf fit for HQ studies parameterises  $\bar{d}$  and  $\bar{s}$  separately, **17 free parameters**

# Impact of EIC on proton pdfs

(arXiv:[2309.11269](https://arxiv.org/abs/2309.11269))



$$xg(x) = A_g x^{B_g} (1-x)^{C_g} - A'_g x^{B'_g} (1-x)^{25};$$

$$xu_v(x) = A_{u_v} x^{B_{u_v}} (1-x)^{C_{u_v}} (1 + E_{u_v} x^2);$$

$$xd_v(x) = A_{d_v} x^{B_{d_v}} (1-x)^{C_{d_v}};$$

$$x\bar{U}(x) = A_{\bar{U}} x^{B_{\bar{U}}} (1-x)^{C_{\bar{U}}} (1 + D_{\bar{U}} x);$$

$$x\bar{D}(x) = A_{\bar{D}} x^{B_{\bar{D}}} (1-x)^{C_{\bar{D}}}.$$

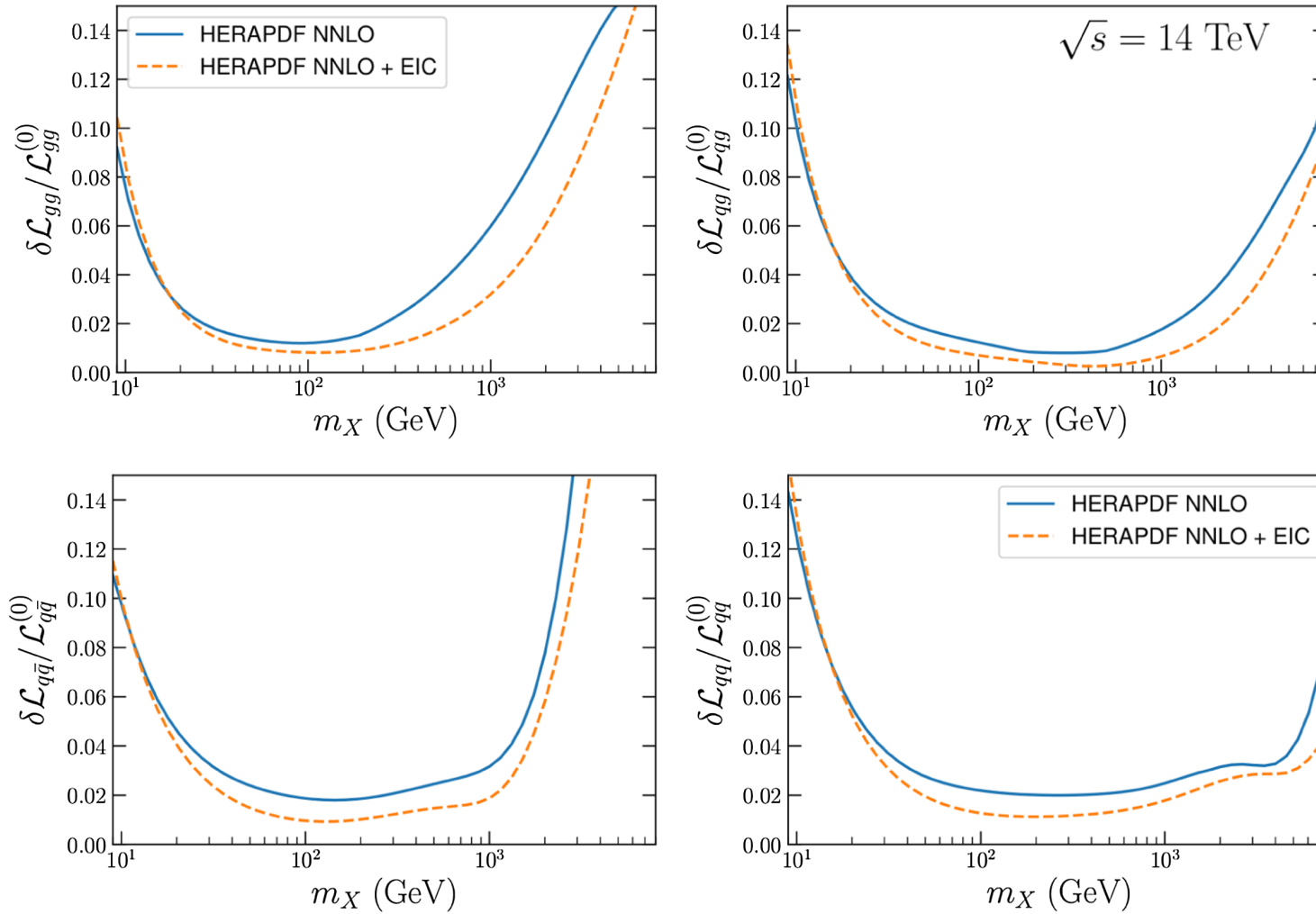
$x\bar{u} = xd$  is imposed as  $x \rightarrow 0$   
 $f_s = 0.4$  whereby  $x\bar{s} = f_s x\bar{D}$  for all  $x$

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

*NB, slightly less flexible parameterisation than used for LHeC/FCC-eh studies*

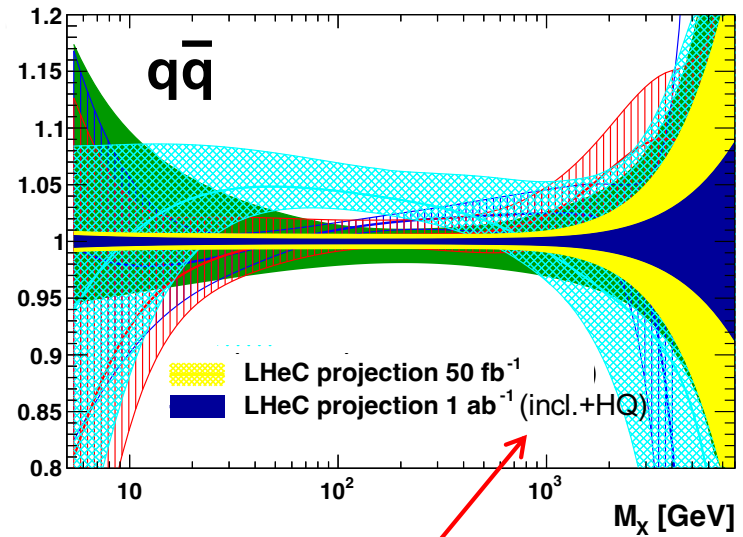
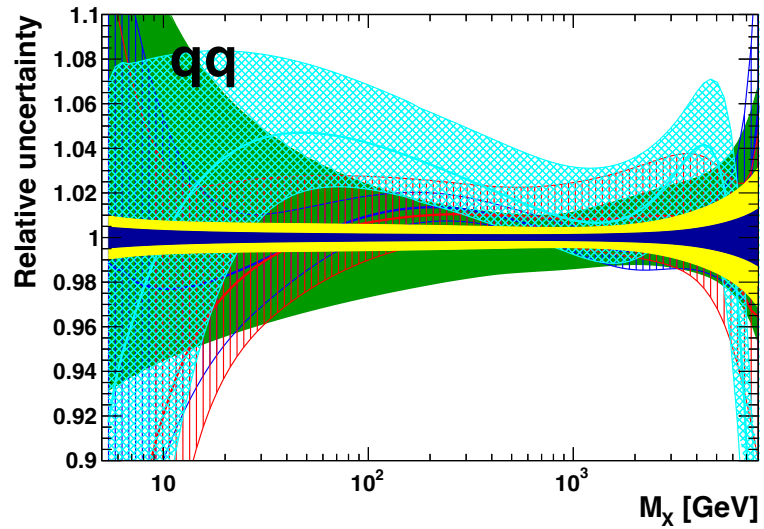
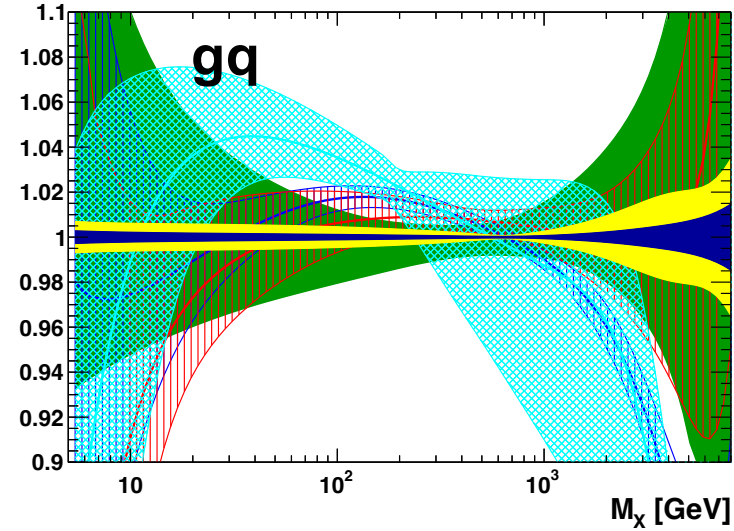
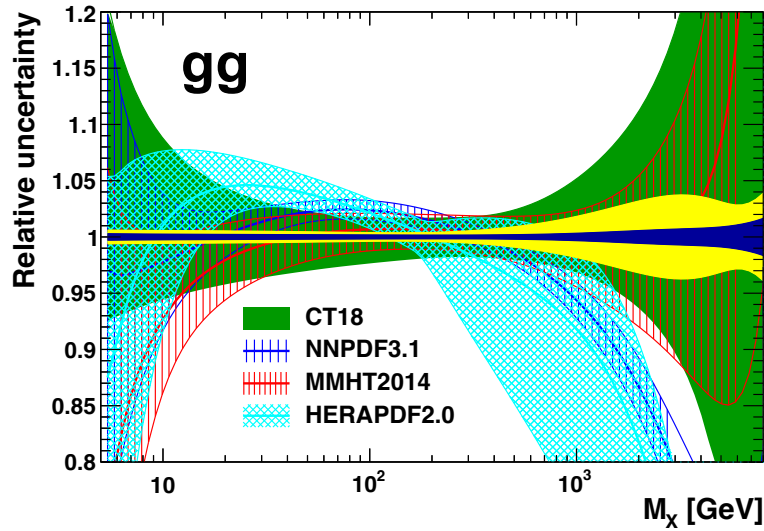


# PDF luminosities @ 14 TeV – EIC



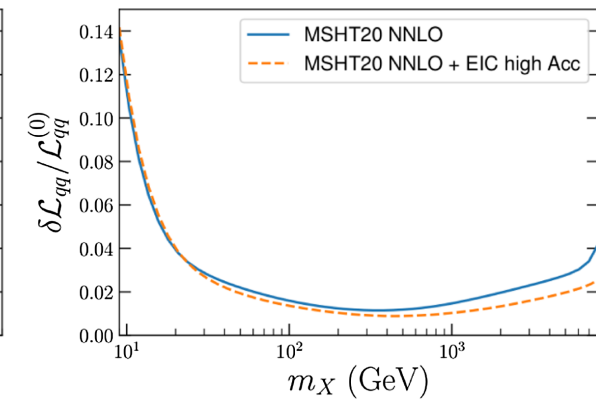
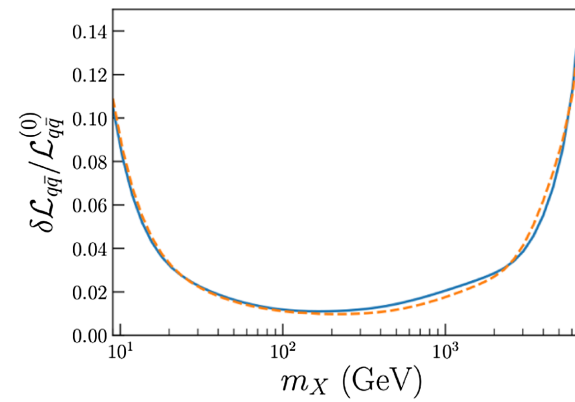
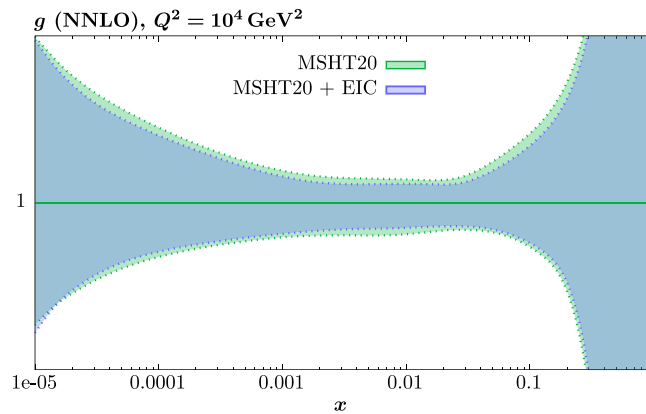
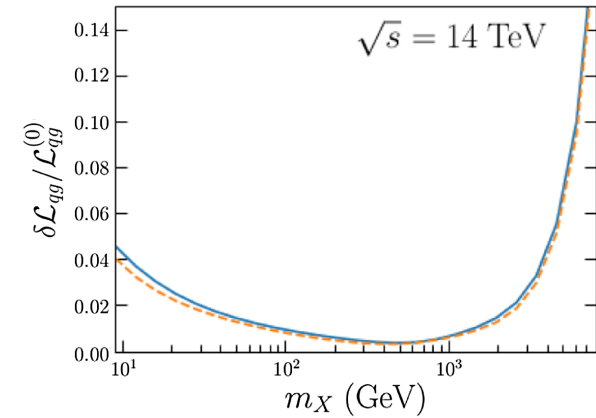
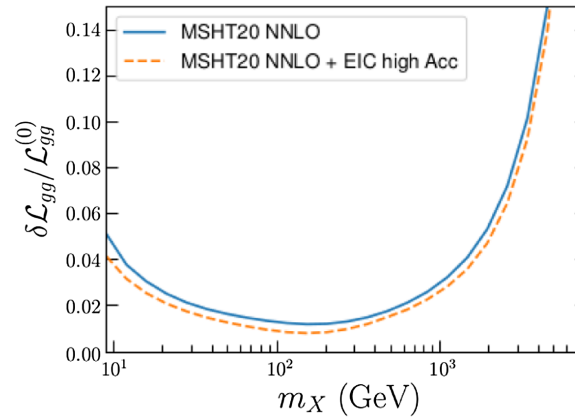
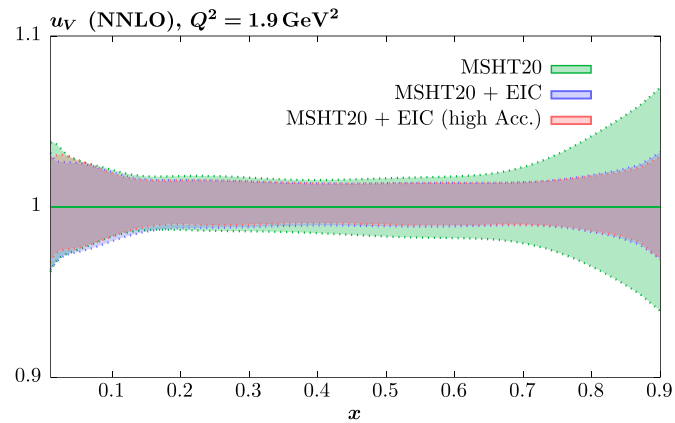
(arXiv:[2309.11269](https://arxiv.org/abs/2309.11269))

# c.f. PDF luminosities @ 14 TeV – LHeC

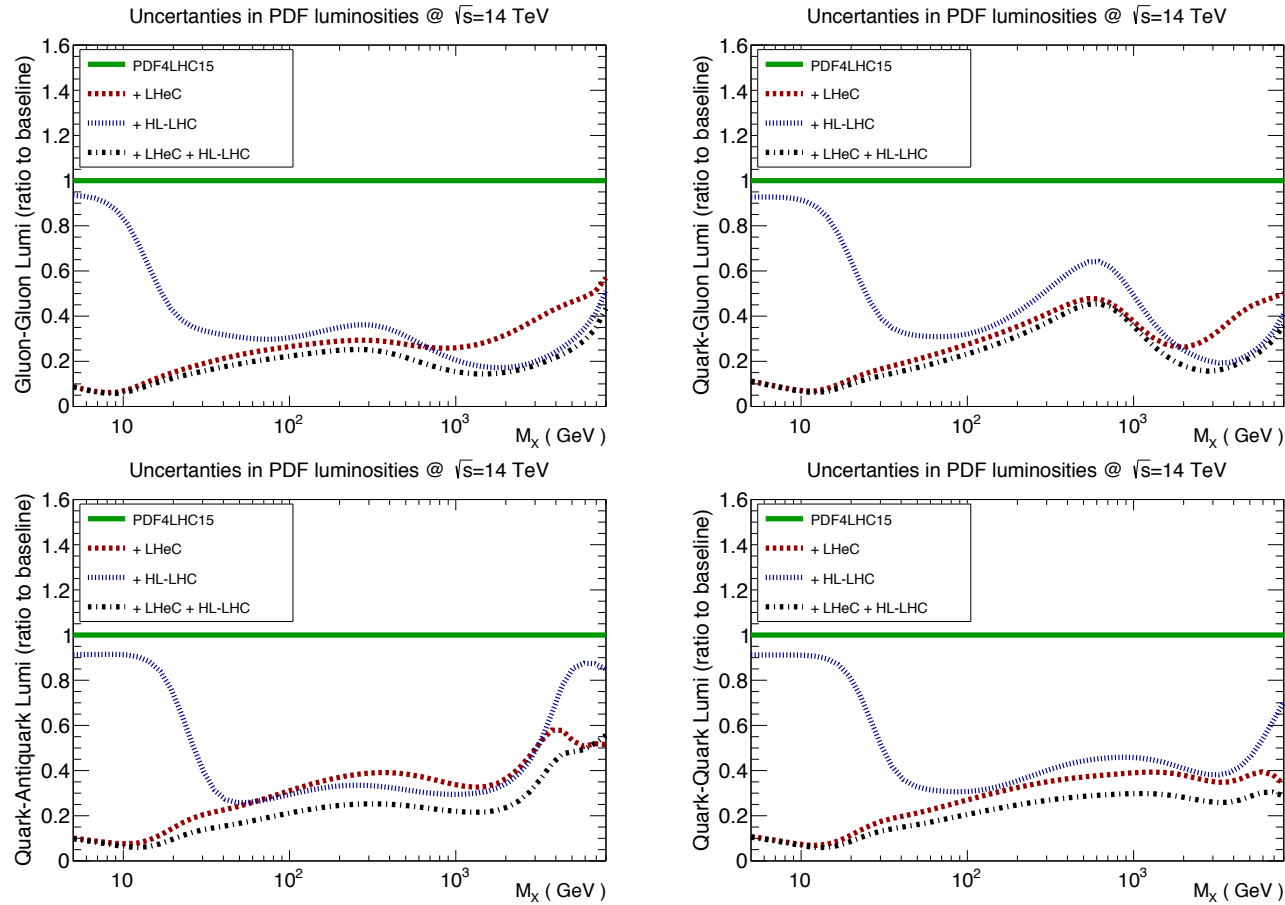


(s,c,b) also included

# Impact of EIC on proton pdfs (MSHT20)

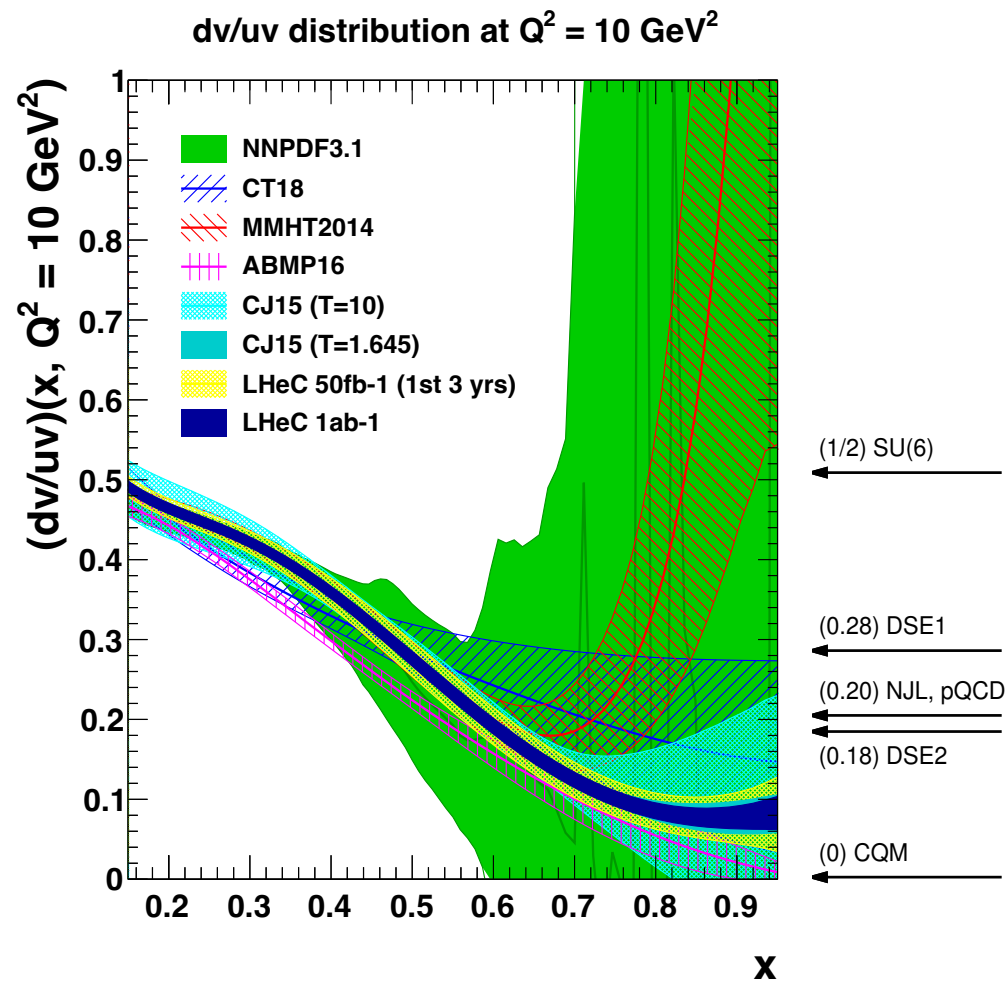


*Less impact in context of a global PDF fit, but still providing some valuable information at high  $x$*



**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.

# d/u at large x

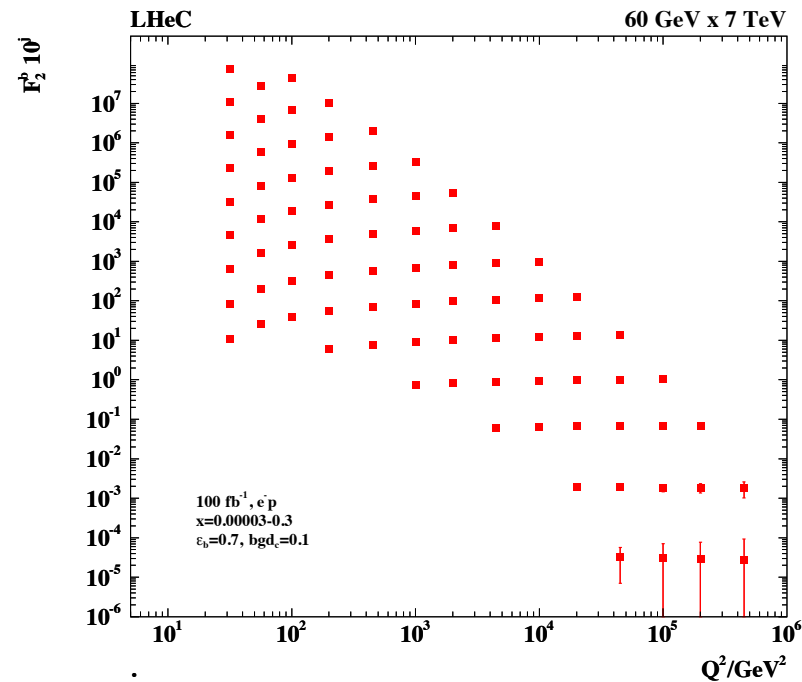
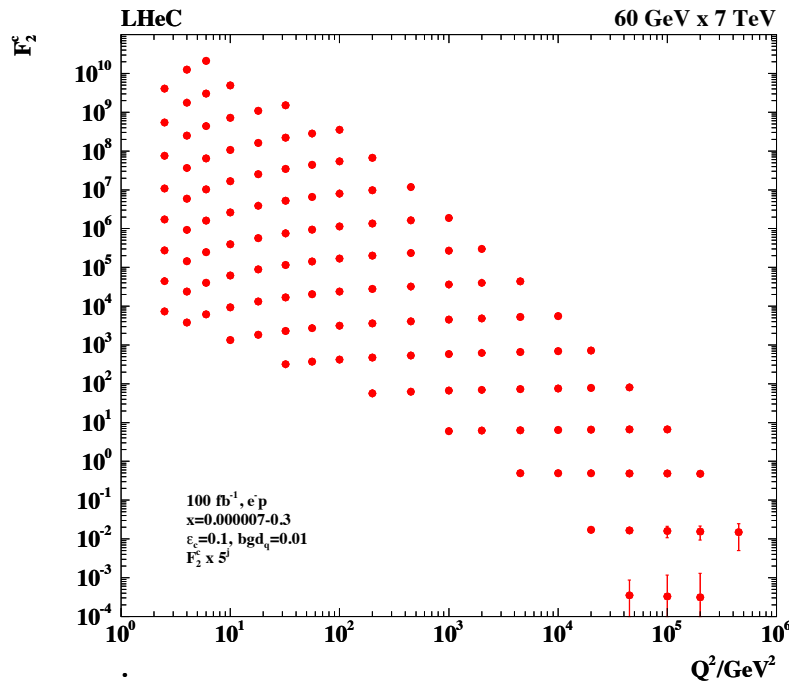


## d/u essentially unknown at large x

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

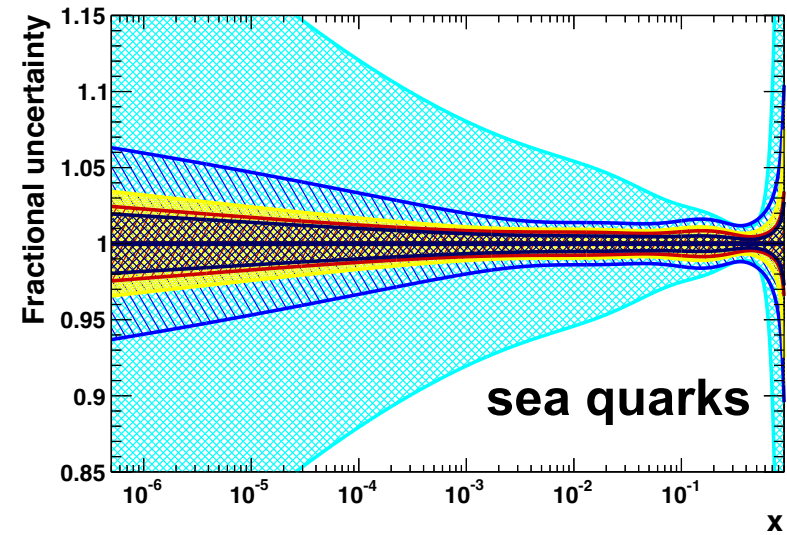
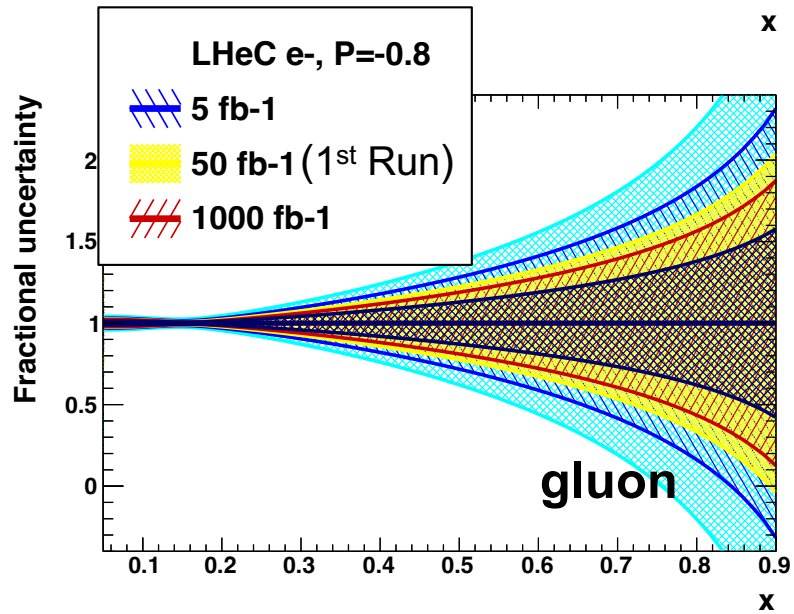
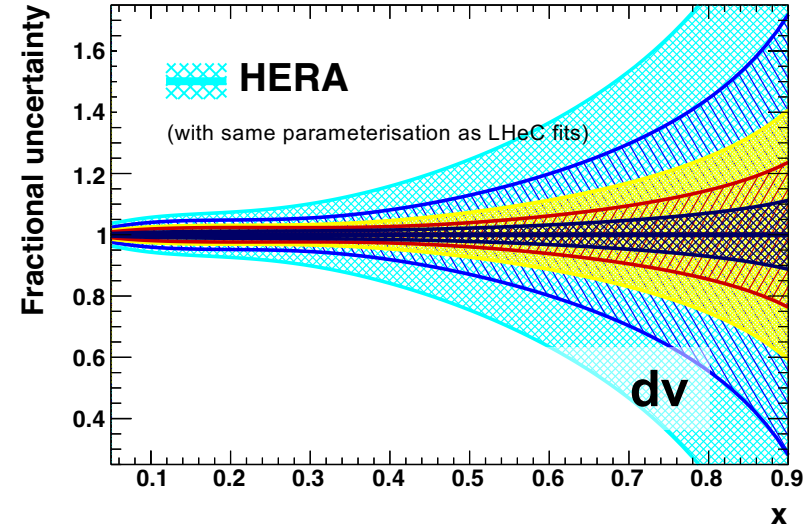
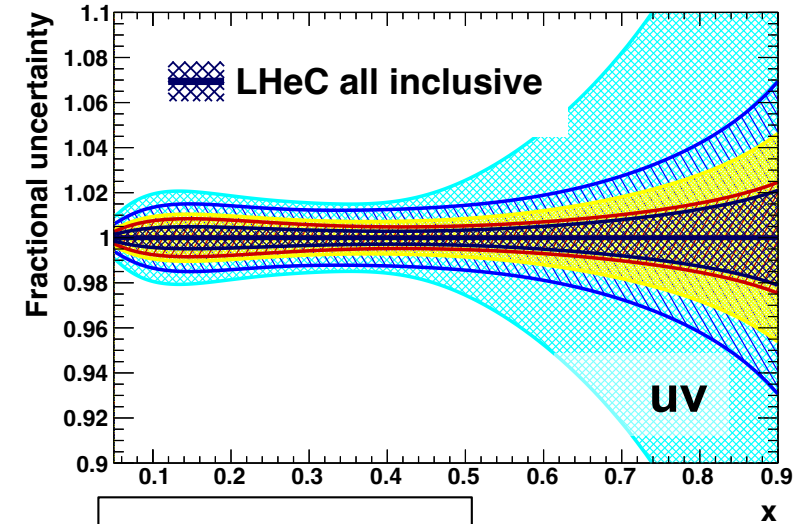


**LHeC: enormously extended range and much improved precision c.f. HERA**

- **$\delta M_c = 50$  (HERA) to  $3$  MeV**: impacts on  $\alpha_s$ , regulates ratio of charm to light, crucial for precision t, H
- **$\delta M_b$  to  $10$  MeV**; MSSM: Higgs produced dominantly via  $bb \rightarrow A$



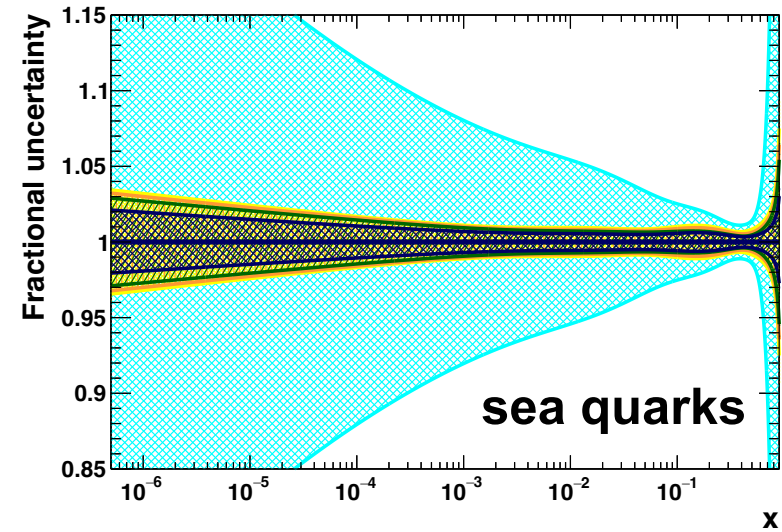
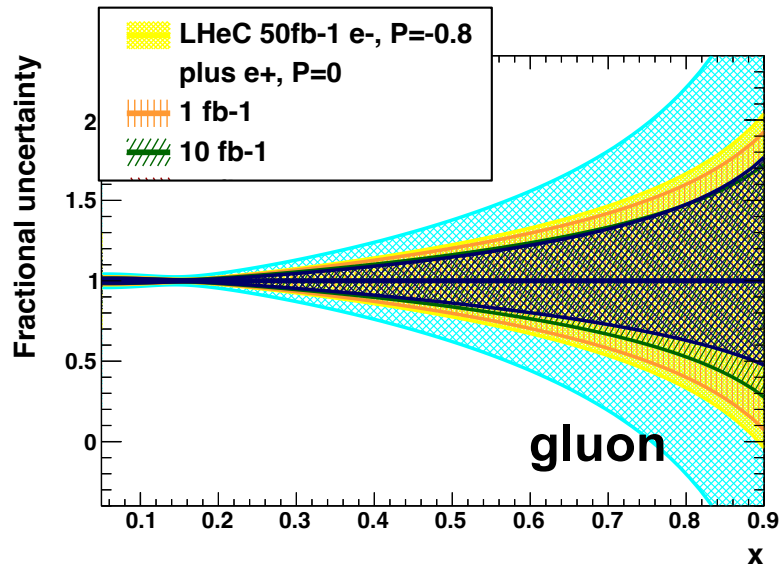
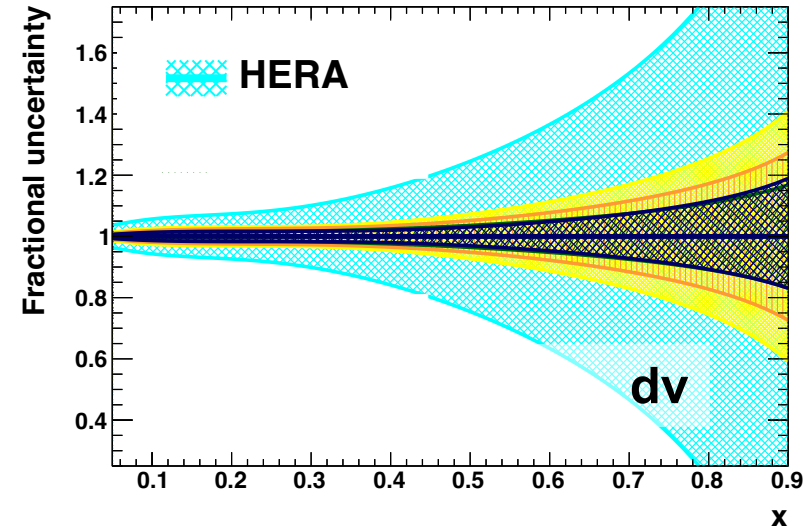
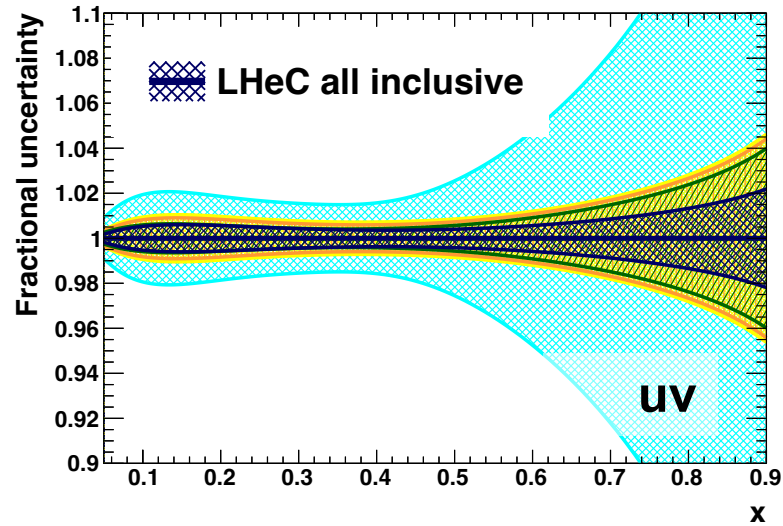
# impact of luminosity on PDFs



**small and medium  $x$**  quickly constrained (5 fb<sup>-1</sup>  $\equiv$   $\times 5$  HERA  $\equiv$  1 year LHeC)

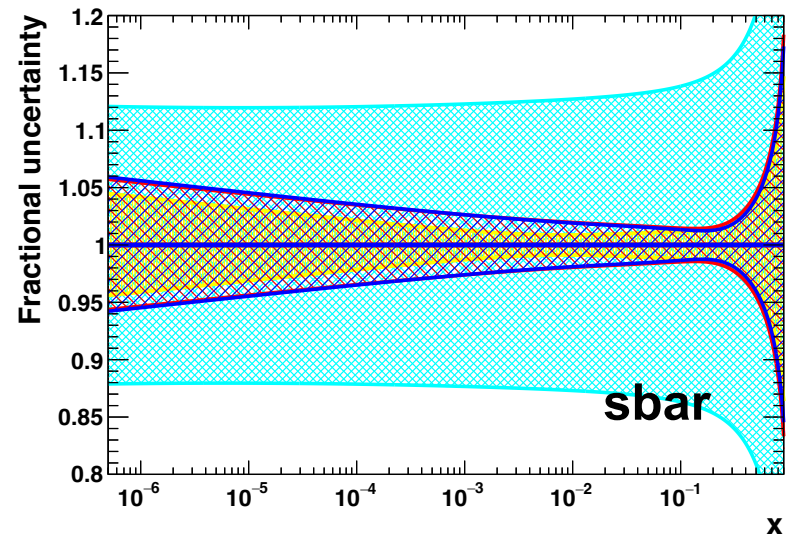
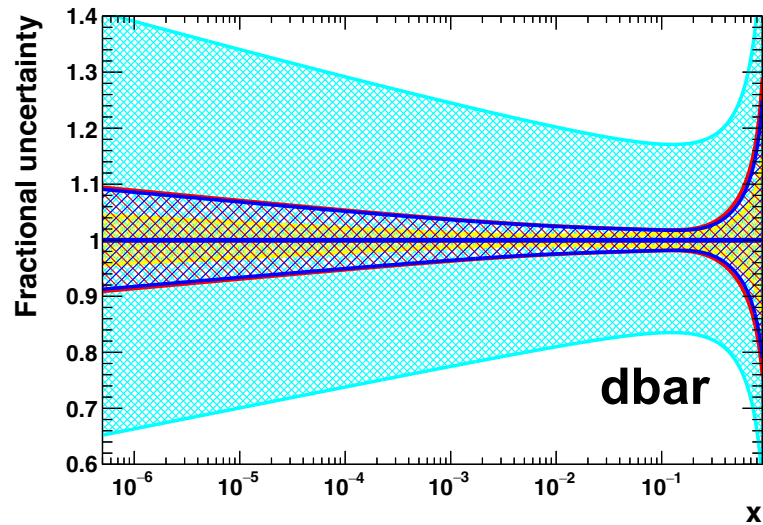
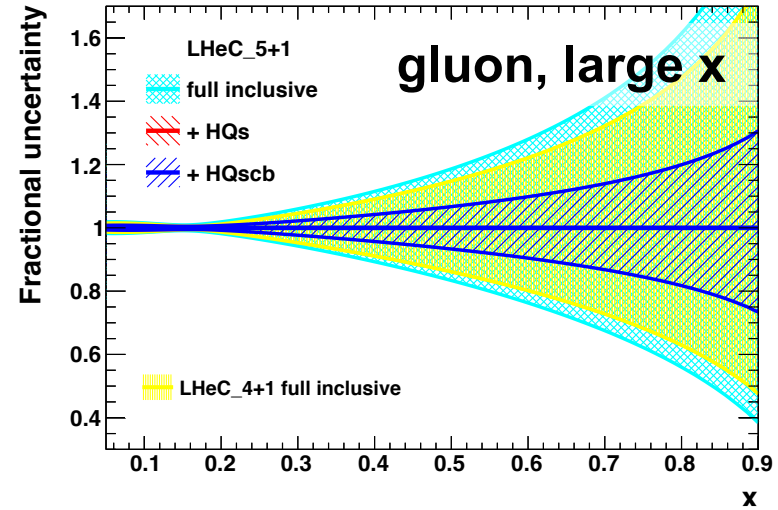
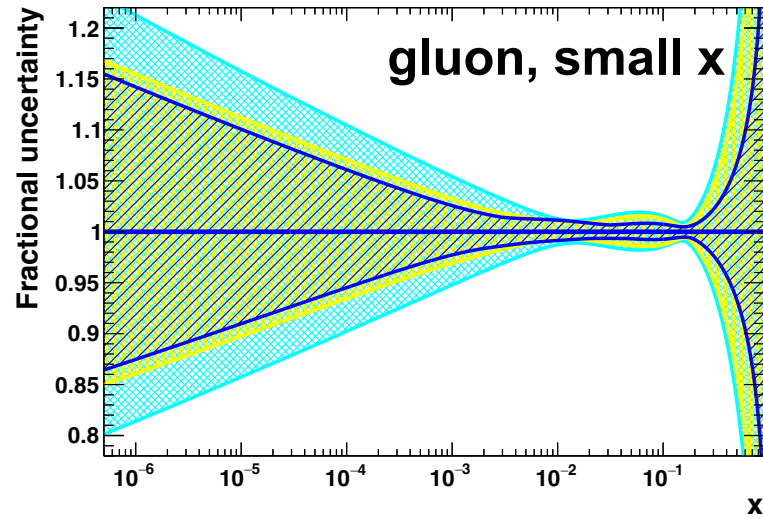
**large  $x$**  ( $\equiv$  large  $Q^2$ ), gain from increased  $L_{int}$ ; still, early massive improvement cf. today <sup>31</sup>

# Impact of positrons



**CC:** e<sup>+</sup> sensitive to d; **NC:** e<sup>±</sup> asymmetry gives xF<sub>3</sub><sup>νZ</sup>, sensitive to valence

# Impact of s, c, b

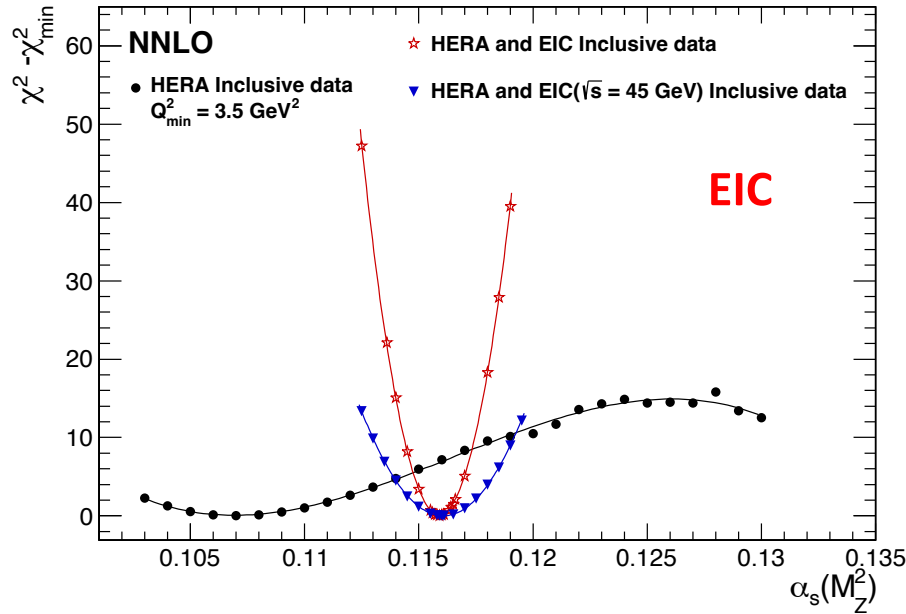


- **4+1**  $x_{uv}$ ,  $x_{dv}$ ,  $x_{Ubar}$ ,  $x_{Dbar}$  +  $x_g$  (14)

- **5+1**  $x_{uv}$ ,  $x_{dv}$ ,  $x_{Ubar}$ ,  $x_{dbar}$ ,  $x_{sbar}$  +  $x_g$  (17)

# strong coupling at EIC and LHeC

arXiv:2307.01183



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

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

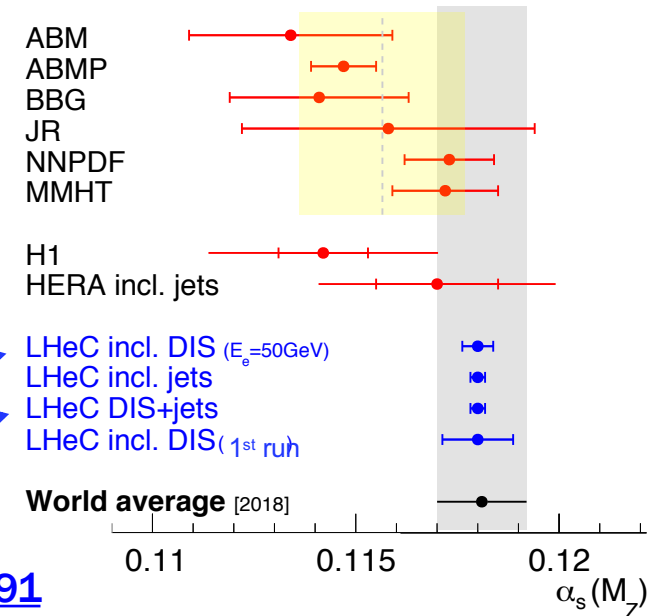
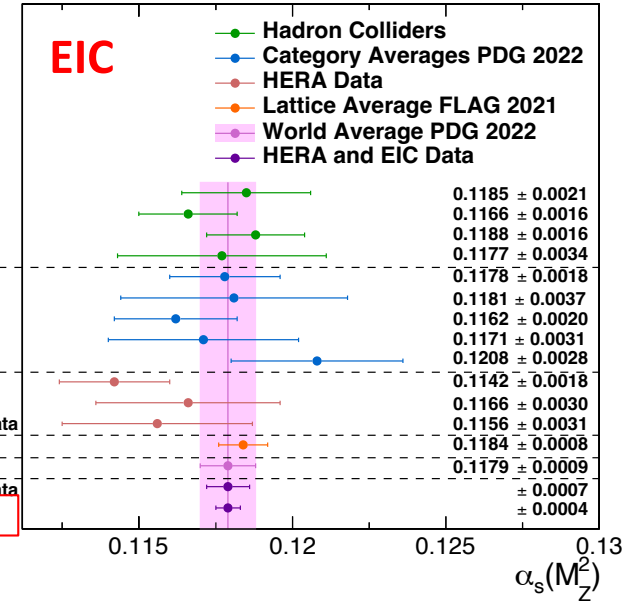
**LHeC  $\mathcal{O}(0.2\%)$**

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

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

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

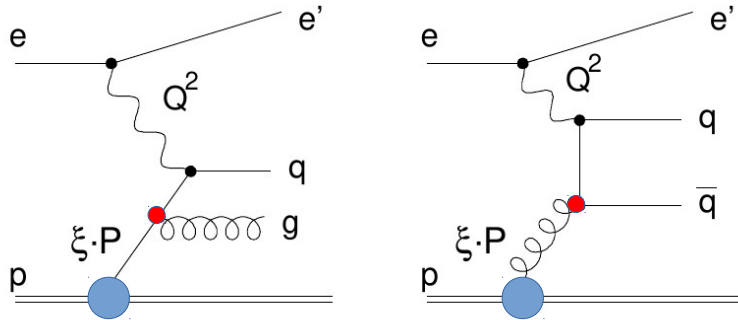
- ATLAS ATEEC
- CMS Jets
- W, Z Inclusive
- tt Inclusive
- $\tau$  Decays
- QQ Bound States
- PDF Fits
- $e^+e^-$  Jets and Shapes
- Electroweak Fit
- ZEUS incl. Jet Data
- H1 Inclusive Jet/Dijet Data
- H1 and ZEUS Inclusive + Jet Data
- Lattice Average
- World Average
- HERA Incl + Jet and EIC Incl Data
- HERA and EIC Inclusive Data



arXiv:2007.14491



# NC DIS jet production at the LHeC



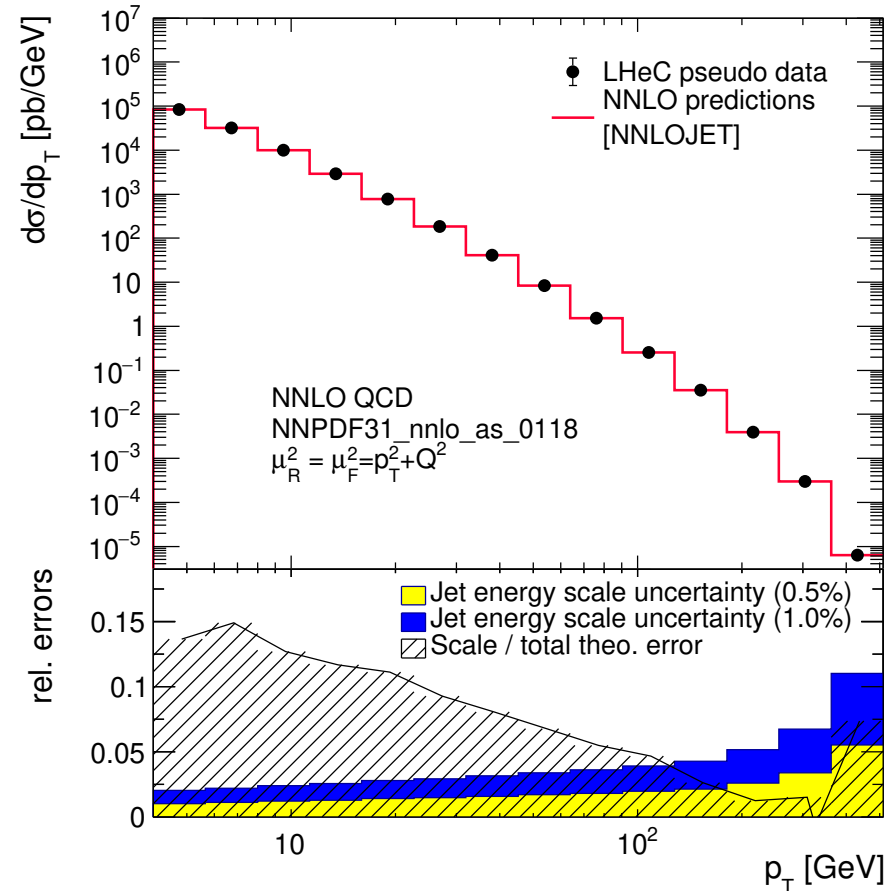
sensitive to  $\alpha_s$  at lowest order

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

NNLO QCD calculations for DIS jets available in NNLOJet (arXiv:[1606.03991](https://arxiv.org/abs/1606.03991), [1703.05977](https://arxiv.org/abs/1703.05977)), and implemented in APPLfast (arXiv:[1906.05303](https://arxiv.org/abs/1906.05303))

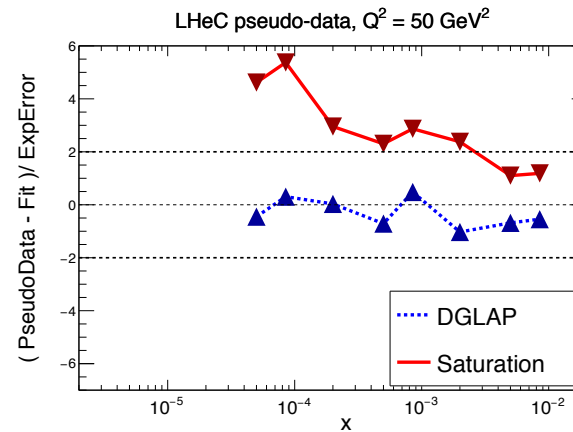
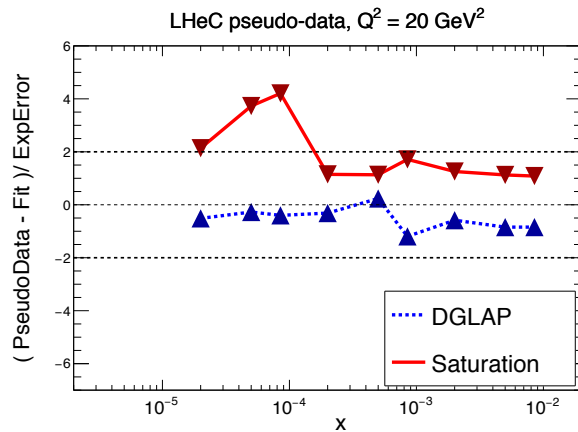
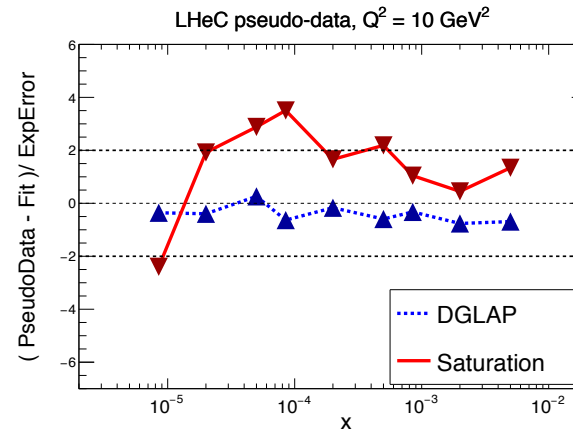
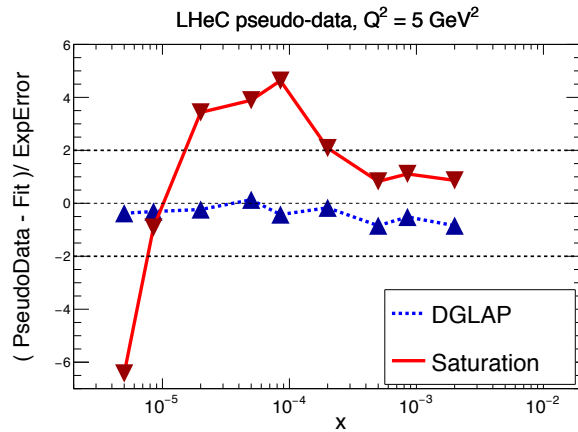
full set of systematic uncertainties considered

– benchmarked with H1, ZEUS, ATLAS, CMS



Exp. uncertainty	Shift	Size on $\sigma$ [%]
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	$\pm 20 \text{ MeV}$	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 small x dynamics: saturation



- 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**