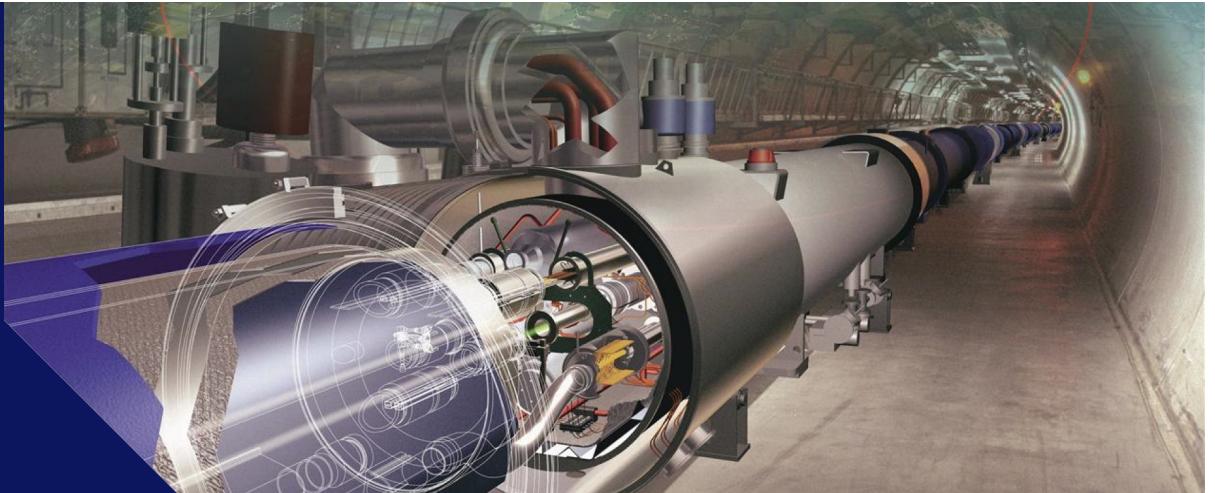


# DIS2022

Santiago de Compostela  
2 – 6 May 2022

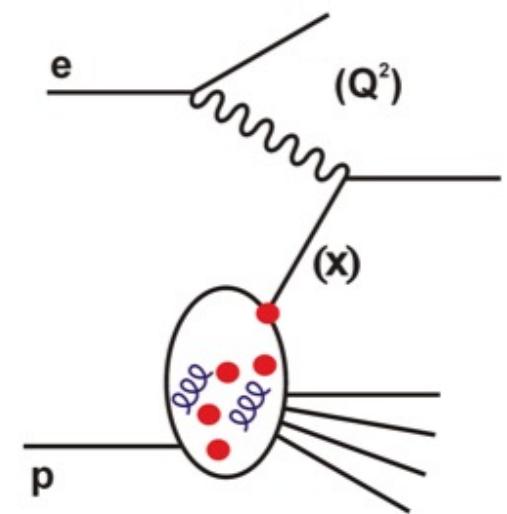


## Precision QCD at the LHeC and FCC-eh

Claire Gwenlan, Oxford

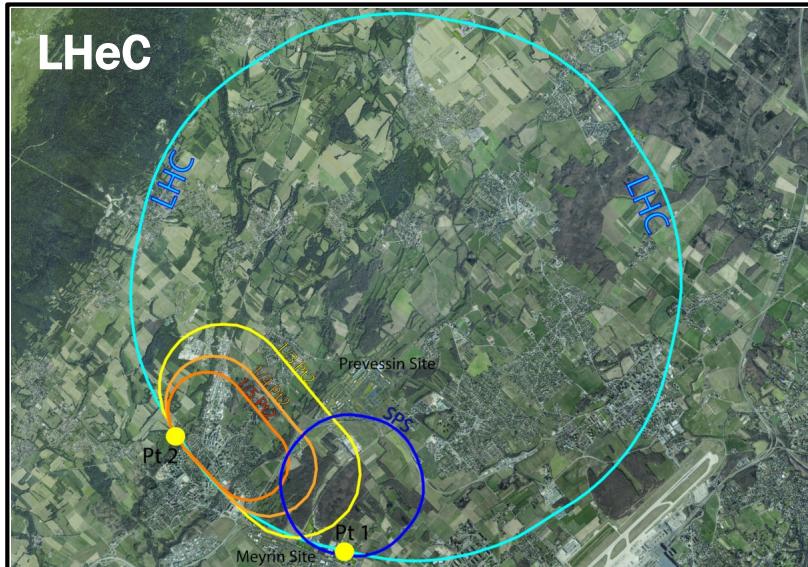
on behalf of the LHeC and FCC-eh study groups

with focus on results from [J. Phys. G 48 \(2021\) 11, 110501](#)



# LHeC, FCC-eh and PERLE

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



## energy recovery LINAC (ERL)

attached to HL-LHC (or FCC)

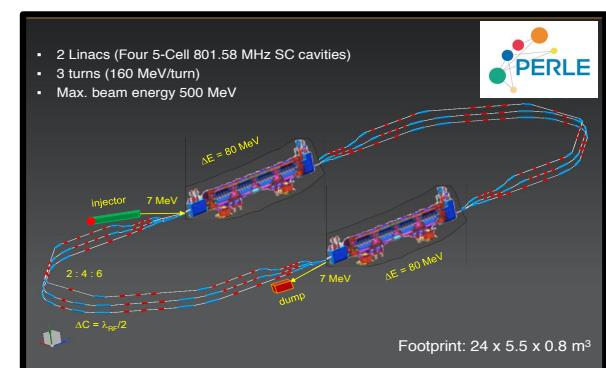
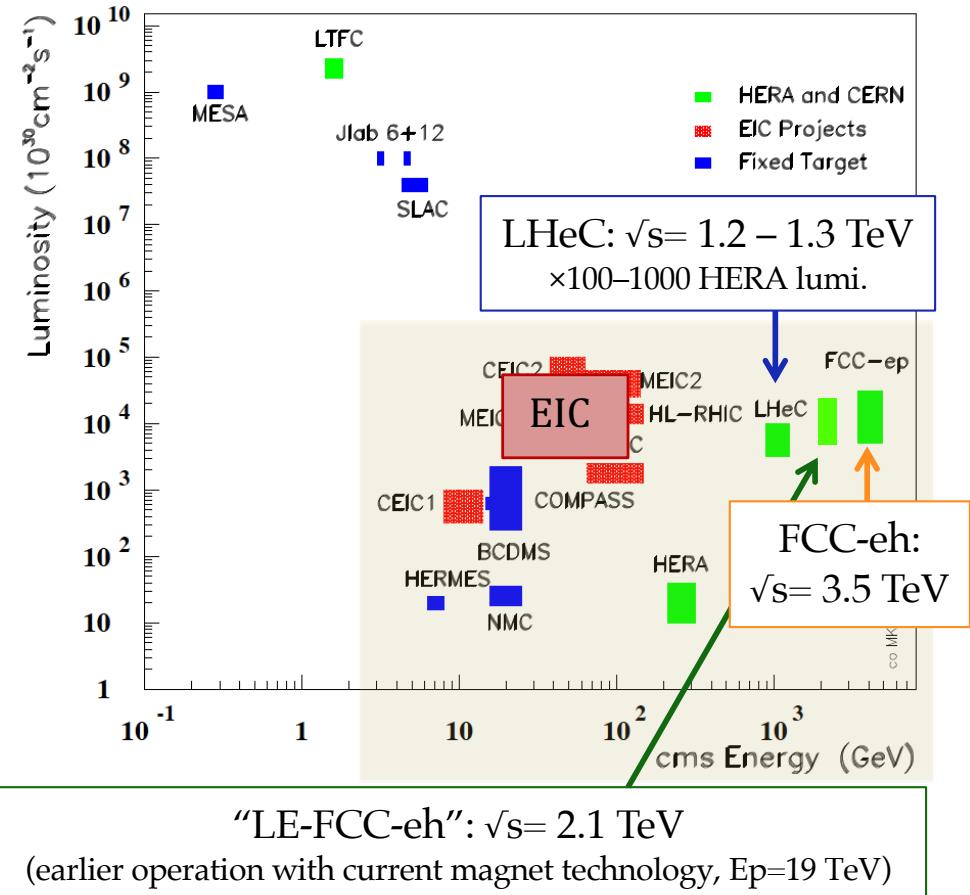
e beam:  $\rightarrow$  50 or 60 GeV

e pol.:  $P = \pm 0.8$

$L_{int} \rightarrow 1-2 \text{ ab}^{-1}$  (**1000 $\times$  HERA!**)

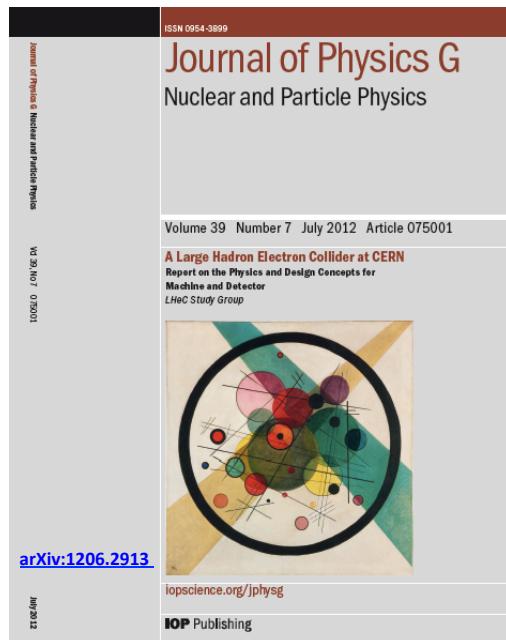
**PERLE** (see talk by A. Stocchi): international collaboration built to realise 500 MeV facility at Orsay, **for development of ERL with LHeC conditions**

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



# 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://doi.org/10.1088/1361-6471/ab3e0d)

FCC with eh integrated, [EPJ ST 228 \(2019\), 4, 755](https://doi.org/10.1088/1361-6471/ab3e0d)

## 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)

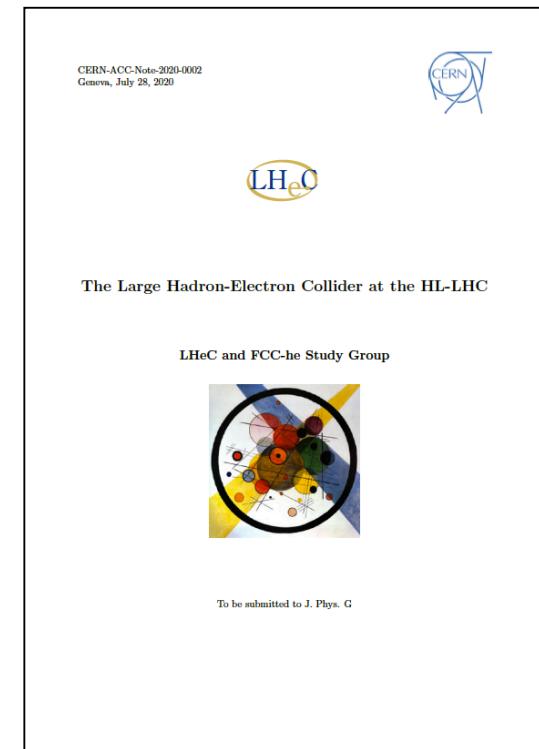
*Dig Deeper*  
*Nature Physics* 9 (2013) 448

*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://doi.org/10.1088/1361-6471/ac3f3c)  
(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>

# Physics with Energy Frontier DIS

see also, other **LHeC / FCC-eh** contributions to this conference:

LHeC and FCC-eh Overview,  
C. Schwanenberger

A Common eh/hh LHC  
Interaction Region, K. Andre

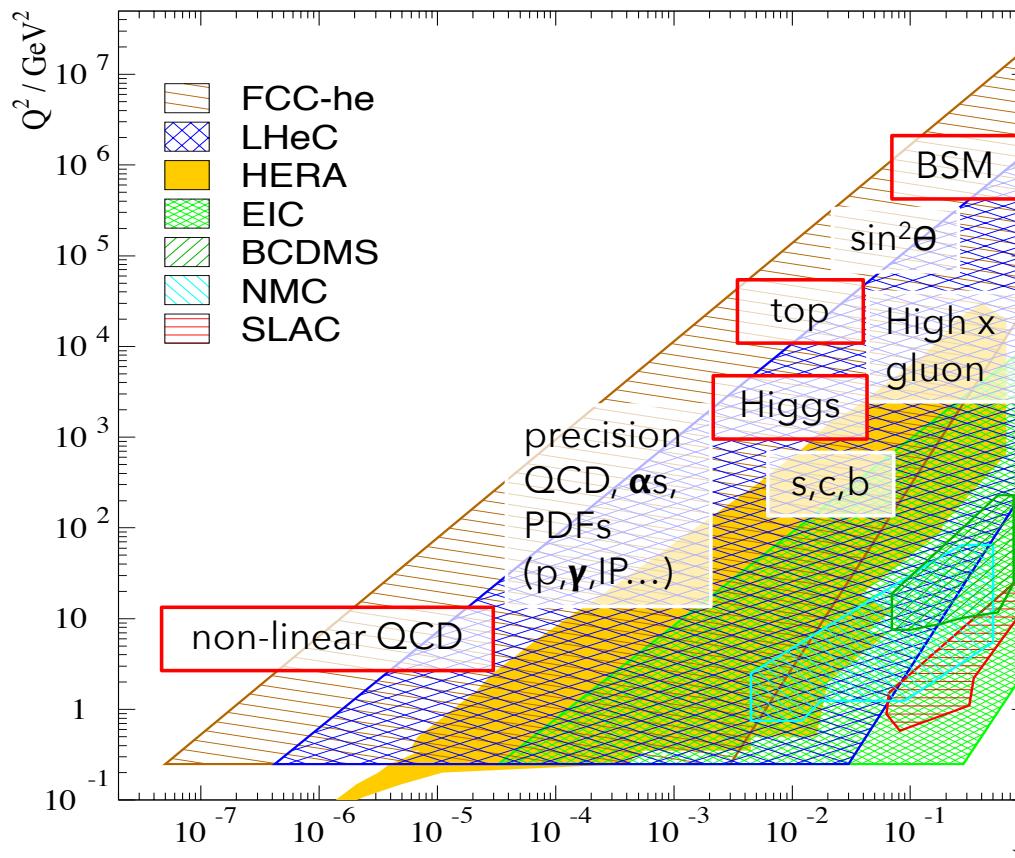
PERLE, A. Stocchi

Impact on Future Hadron  
Collider Physics (HL-LHC and  
FCC-hh), D. Britzger

BSM and Top, O. Fischer

Small- $x$ , A. Stasto

Higgs & EW, C. Schwanenberger



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

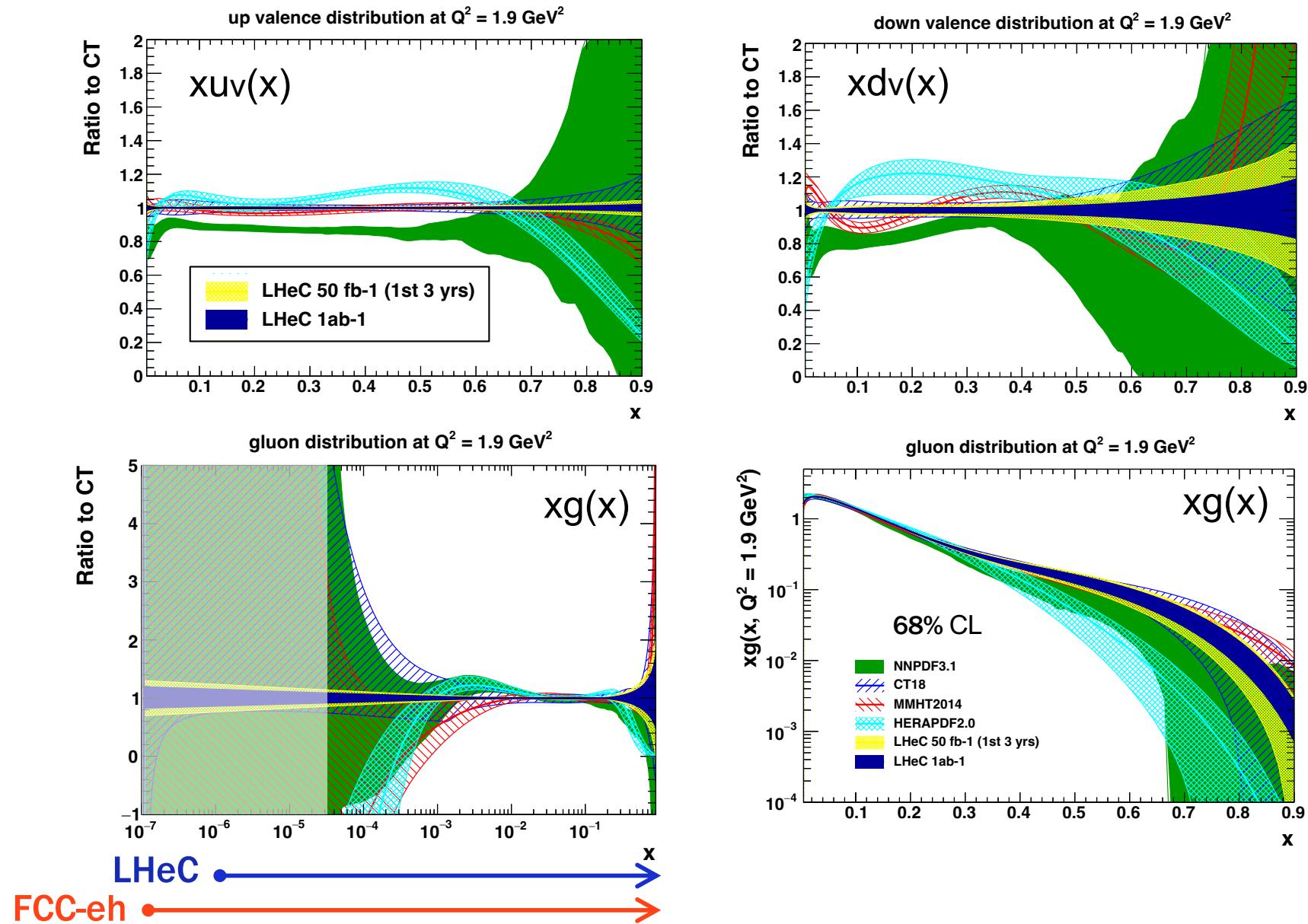
no higher twist,  
no nuclear corrections,  
free of symmetry  
assumptions,  
N3LO theory, ...

completely resolve  
**all proton pdfs**,  
sensitivity to  $x \rightarrow 1$ ,  
and exploration of  
**small x regime**;  
 **$\alpha_s$  to permille precision**

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

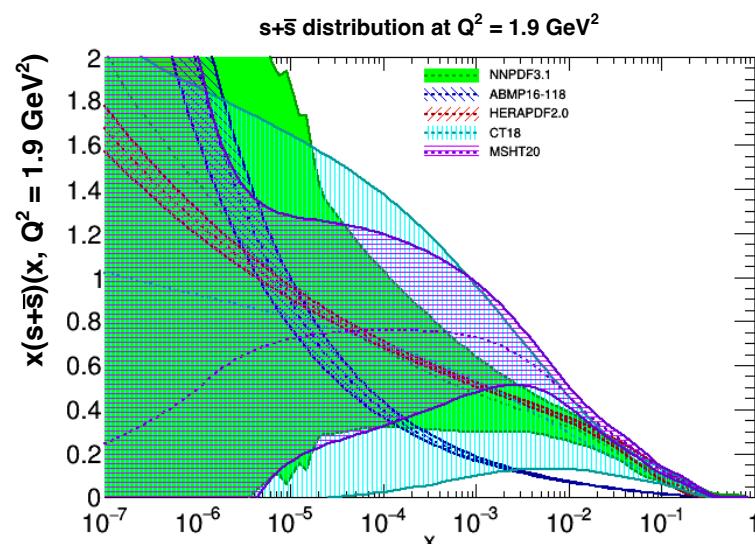
(LHeC projected timeline, several years concurrent HL-LHC operation, plus dedicated run, arXiv:[1810.13022](https://arxiv.org/abs/1810.13022) )

# Quark and Gluon PDFs

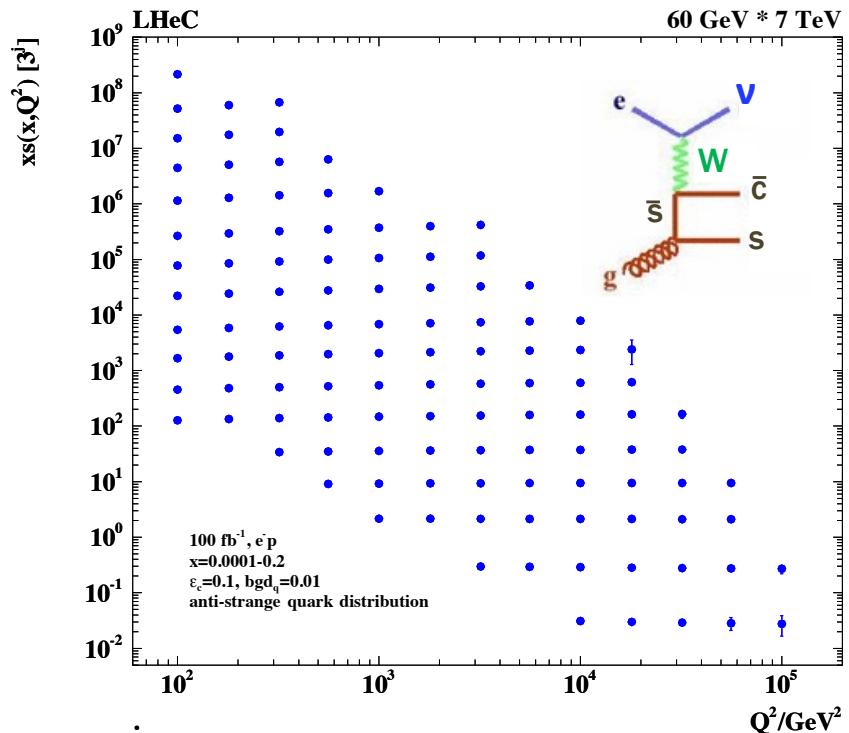


# Strange, c, b

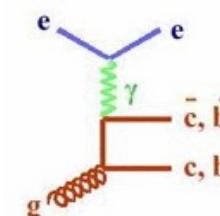
- **strange pdf poorly known**
- suppressed cf. other light quarks?  
strange valence?



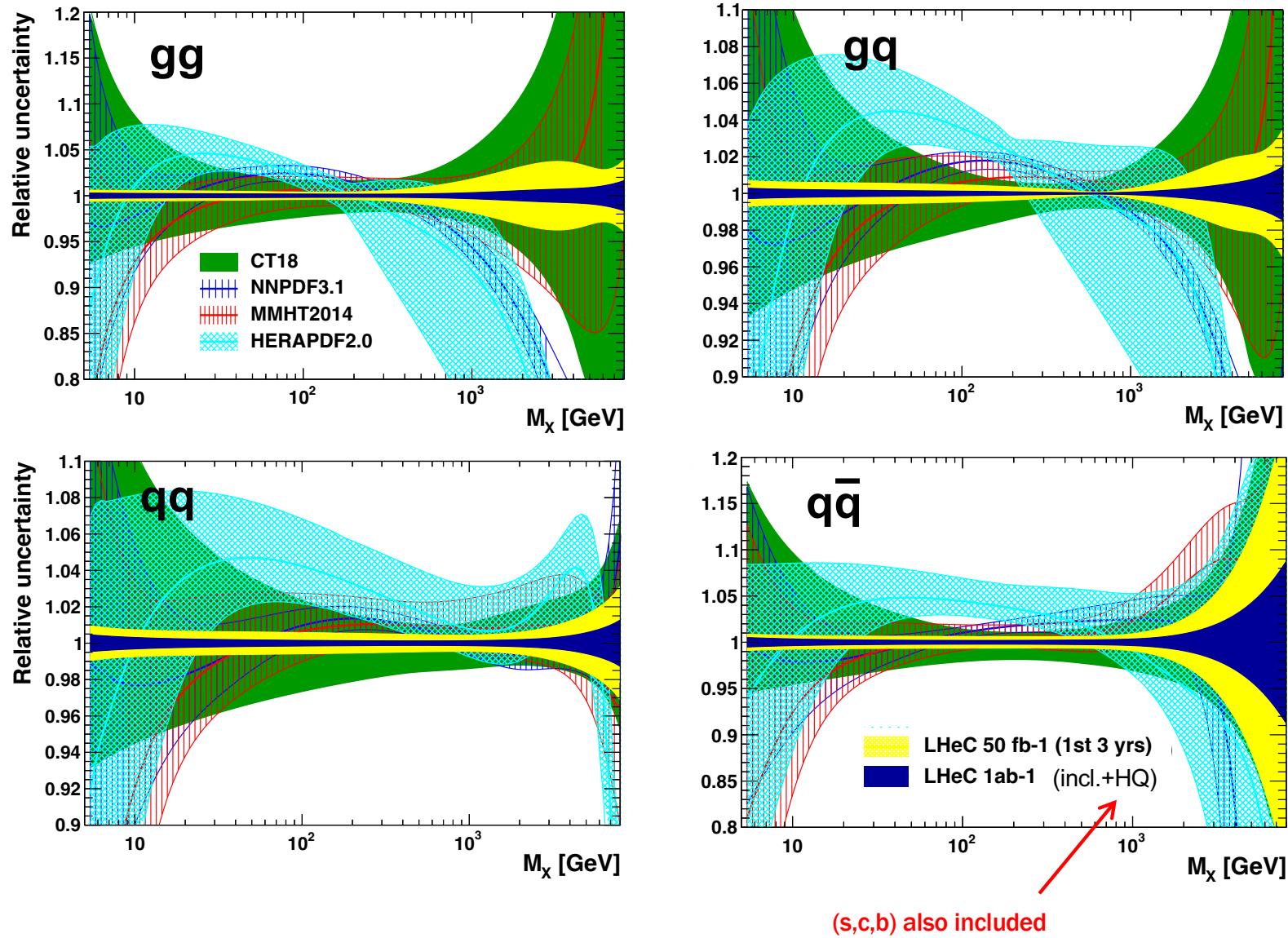
→ LHeC: direct sensitivity via charm tagging in  $W s \rightarrow c$   
( $x, Q^2$ ) mapping of strange density for first time



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

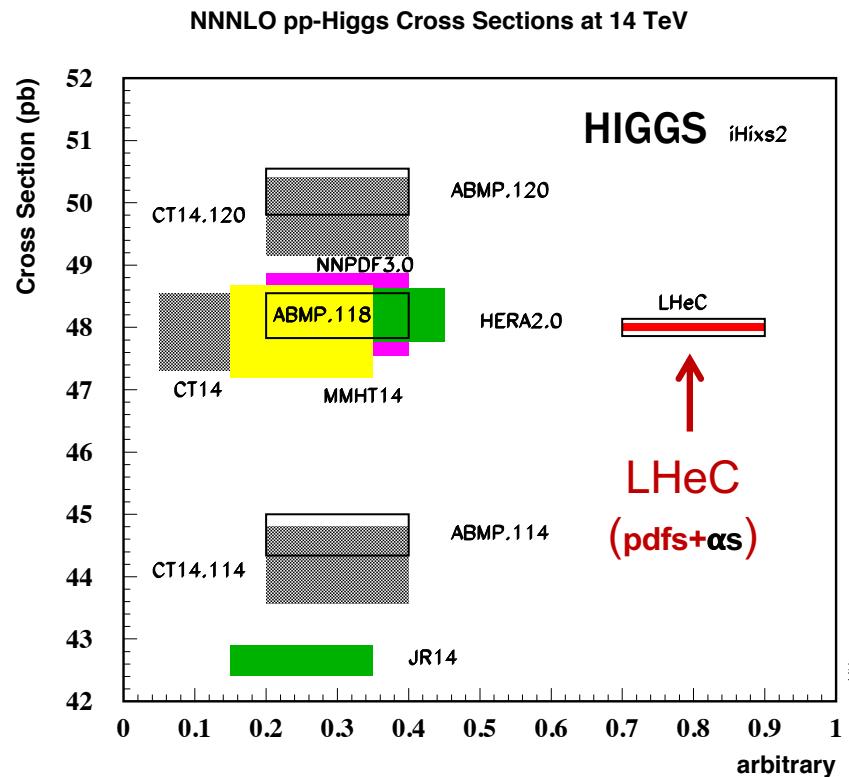
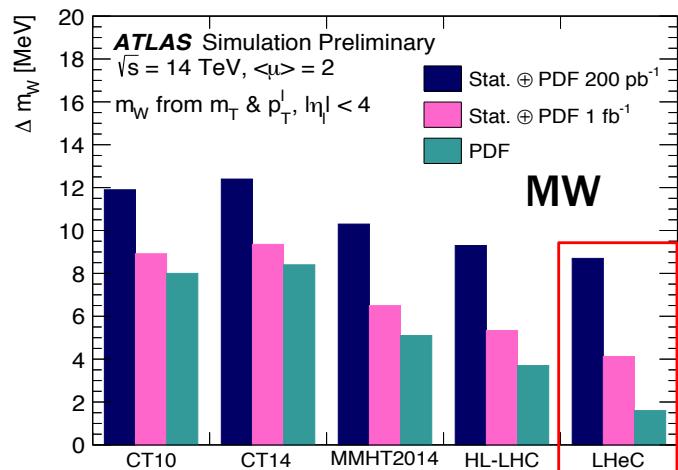
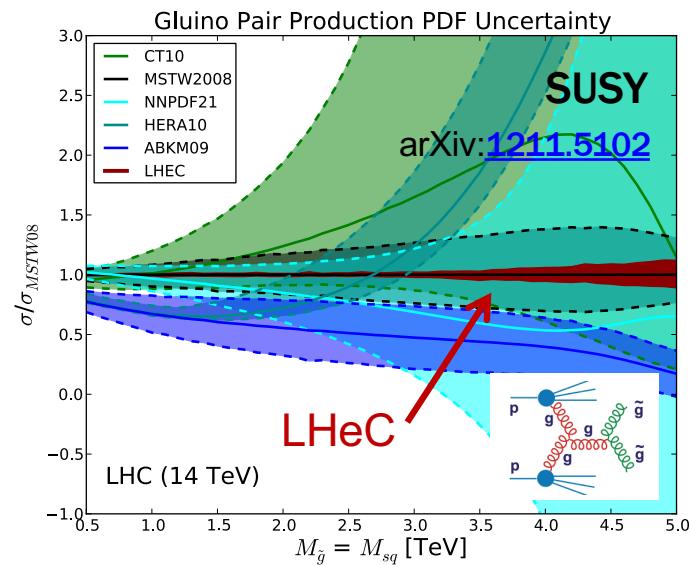


# PDF luminosities @ 14 TeV



# Empowering the LHC

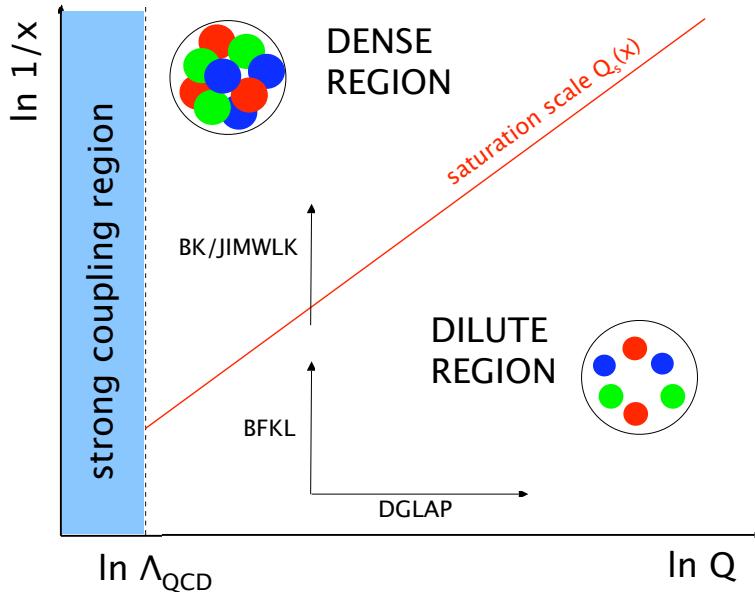
external, reliable, precise **pdfs** needed for  
range extension and interpretation



**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

# Novel small $x$ 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** → non-linear evolution, parton saturation

unprecedented opportunity to explore  
**small  $x$**  with **LHeC/FCC-eh**  
×15/120 extension in  $1/x$  cf. HERA

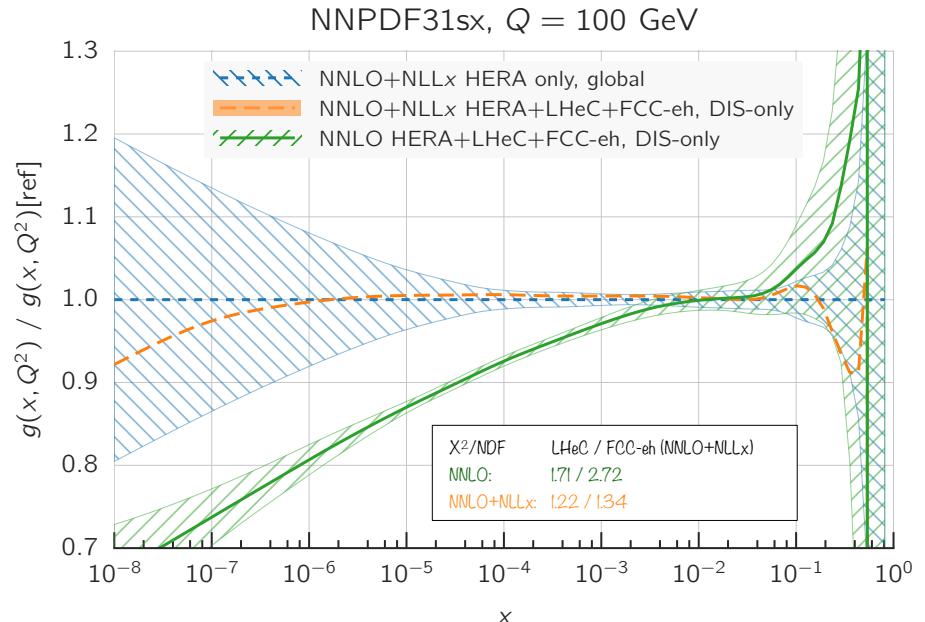
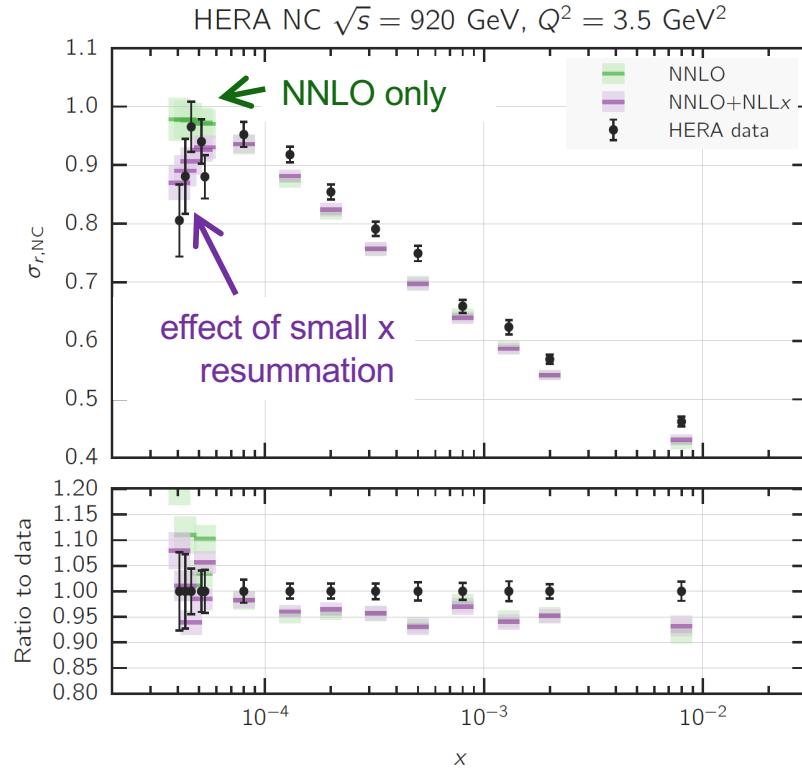
$\tau = \frac{Q^2}{s}$	Higgs	$Z, W$	low mass DY	$c\bar{c}$
LHC (13 TeV)	$10^{-4}$	$5 \times 10^{-5}$	$\sim 10^{-6}$	$\sim 10^{-7}$
FCC-hh (100 TeV)	$1.5 \times 10^{-6}$	$8 \times 10^{-7}$	$\sim 10^{-8}$	$\sim 10^{-9}$

(note: typical values  $x_1, x_2 \sim \sqrt{\tau}$ )

central rapidity ↑

M. Bonvini, 4<sup>th</sup> FCC workshop, CERN, November 2020

# Novel small $x$ dynamics: resummation

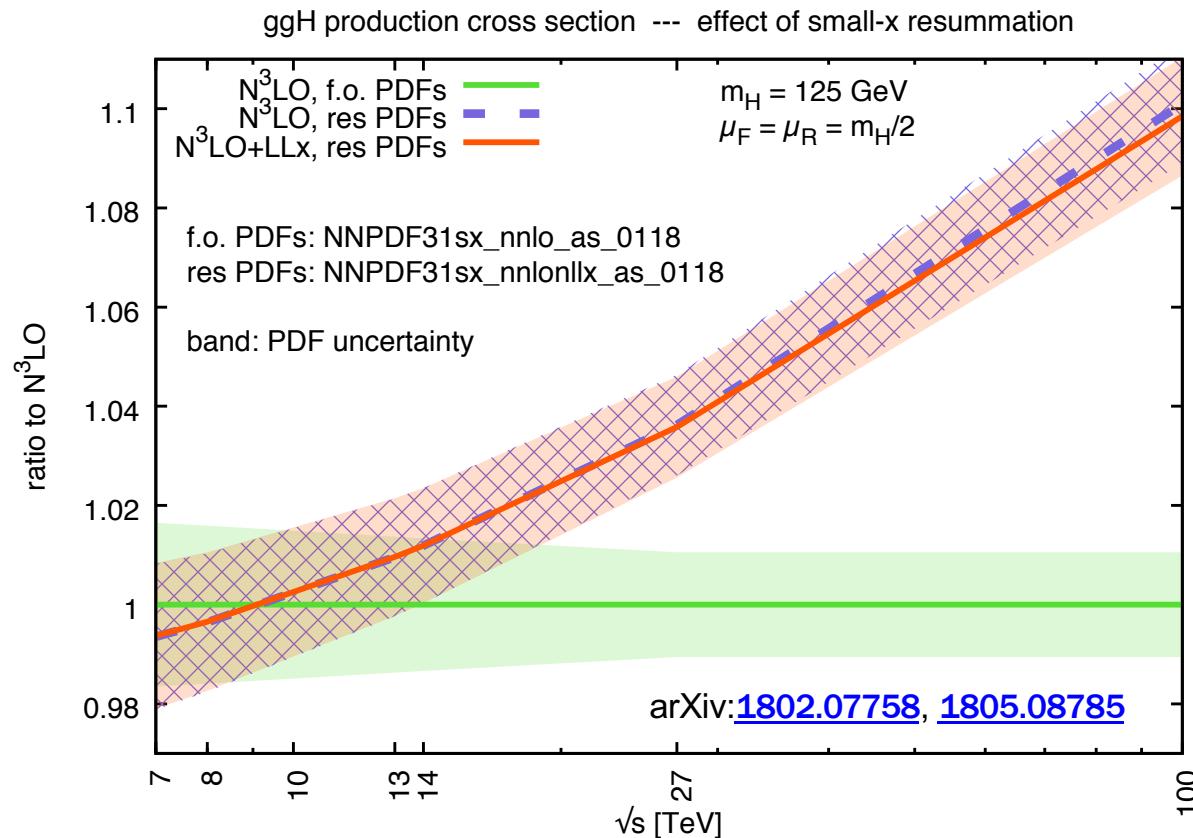


- recent evidence for onset of BFKL dynamics in HERA inclusive data,
- arXiv:[1710.05935](https://arxiv.org/abs/1710.05935); [1802.00064](https://arxiv.org/abs/1802.00064)

(see also, arXiv:[1604.02299](https://arxiv.org/abs/1604.02299))

- small  $x$  resummation mainly affects **gluon pdf** – dramatic effect for  $x \leq 10^{-3}$
- essential for LHeC and FCC-eh
- NB, gluon pdf obtained with small  $x$  resummation grows more quickly – **saturation** at some point!

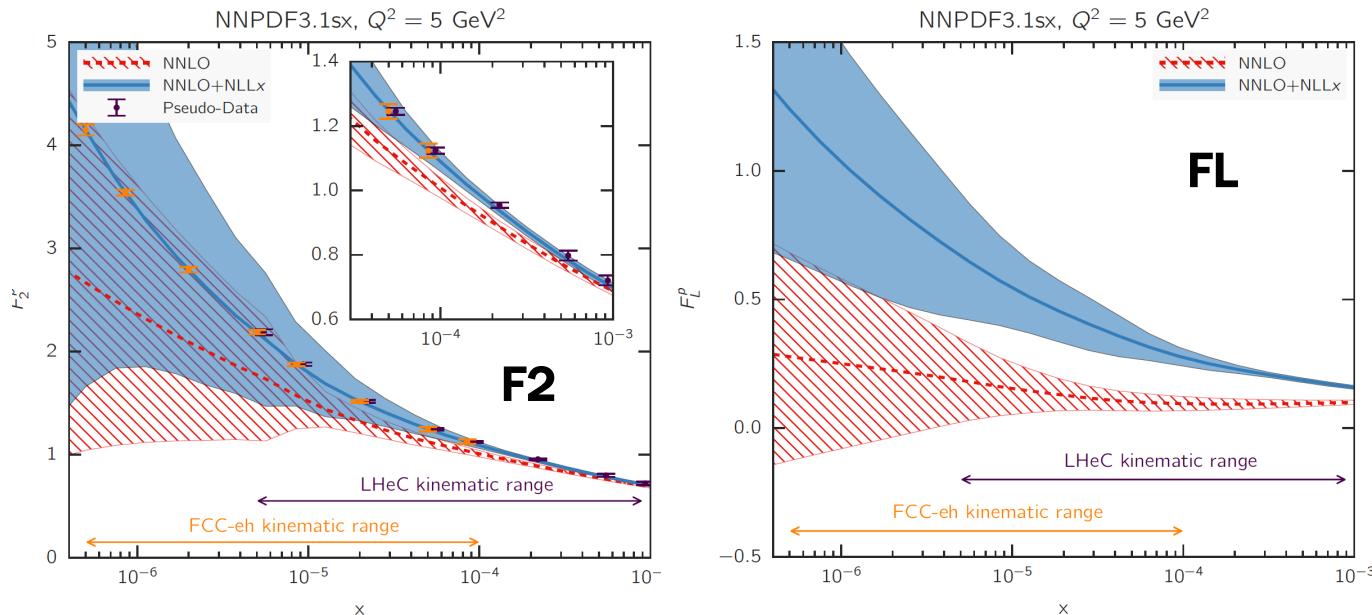
# Impact on pp phenomenology



- effect of small  $x$  resummation on  $gg \rightarrow H$  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](https://arxiv.org/abs/2011.03193); other processes in progress)

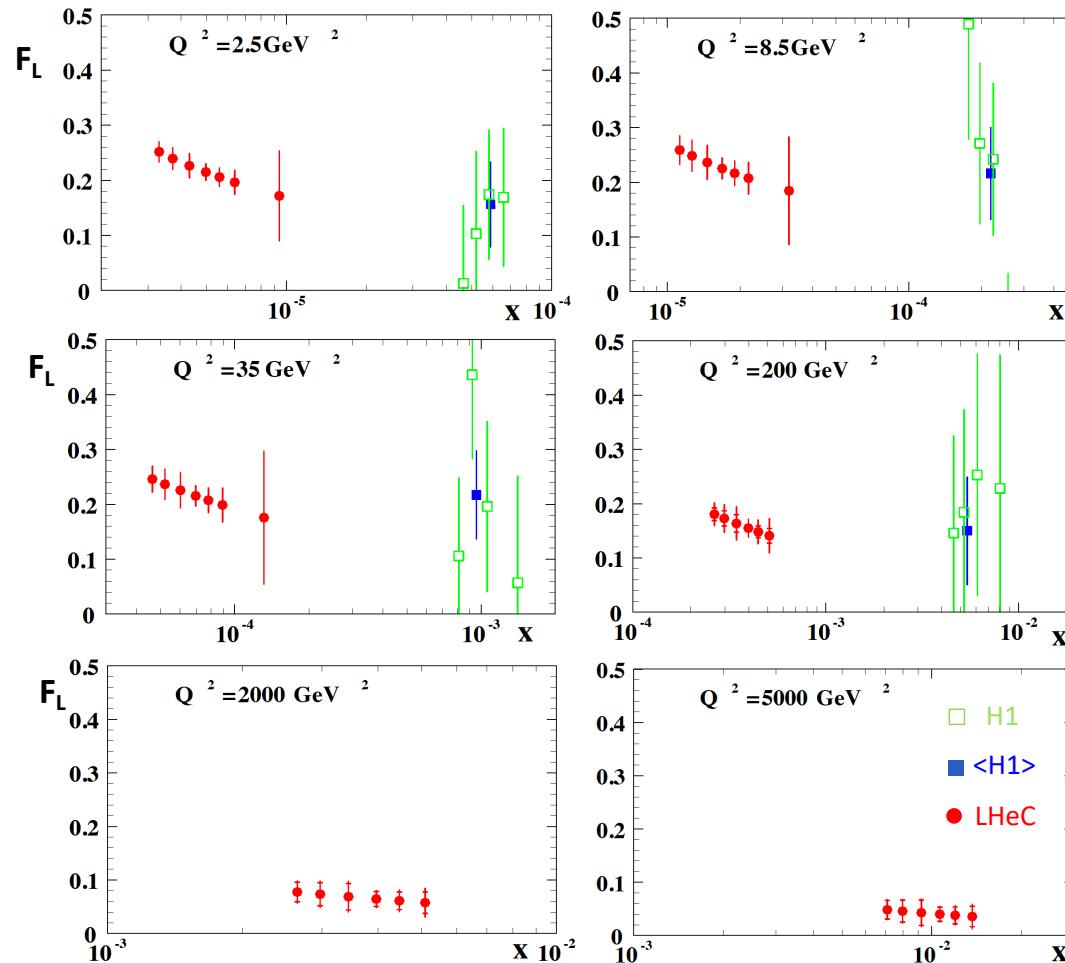
# LHeC and FCC-eh sensitivity to small $x$



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

- 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  $F_L$  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:

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

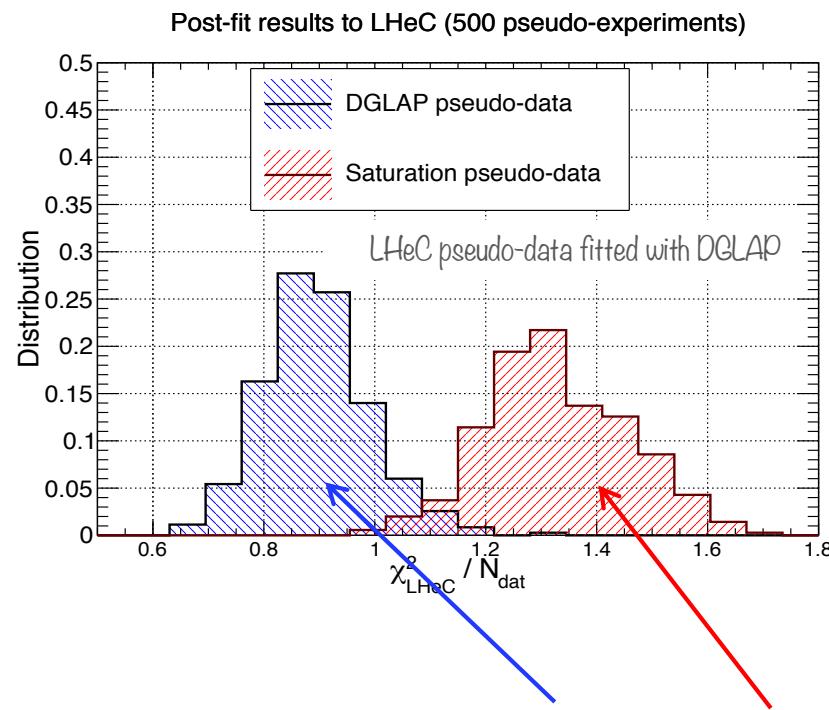
measurement  
dominated by  
systematics

- simultaneous measurement of  $F_2$  and  $F_L$  is clean way to pin down dynamics at small  $x$

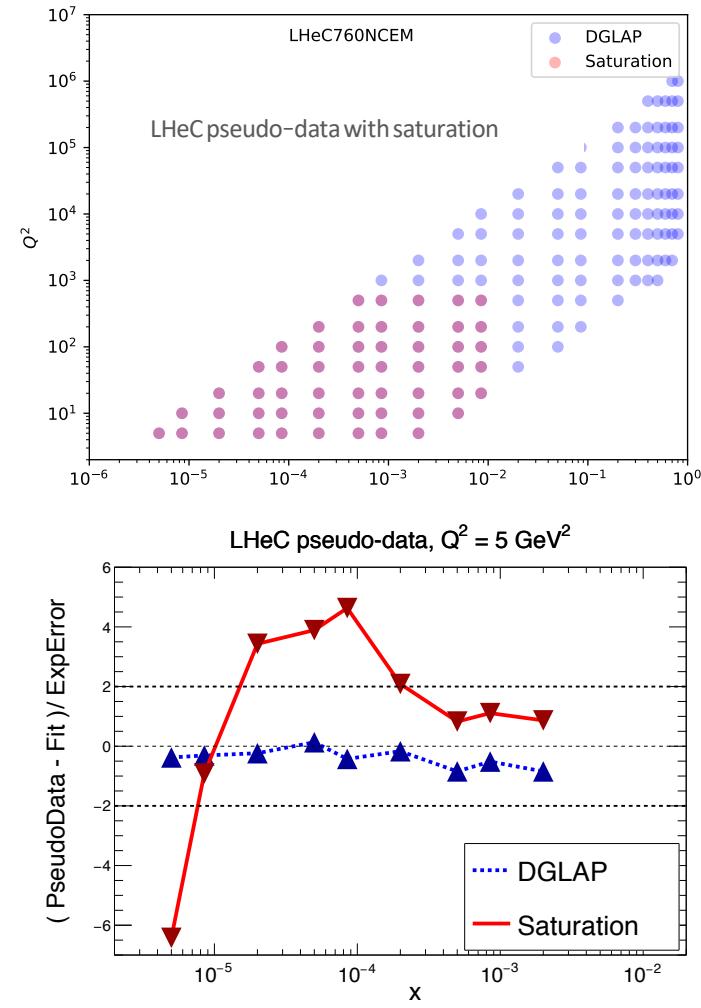
# Novel dynamics at small $x$ : saturation



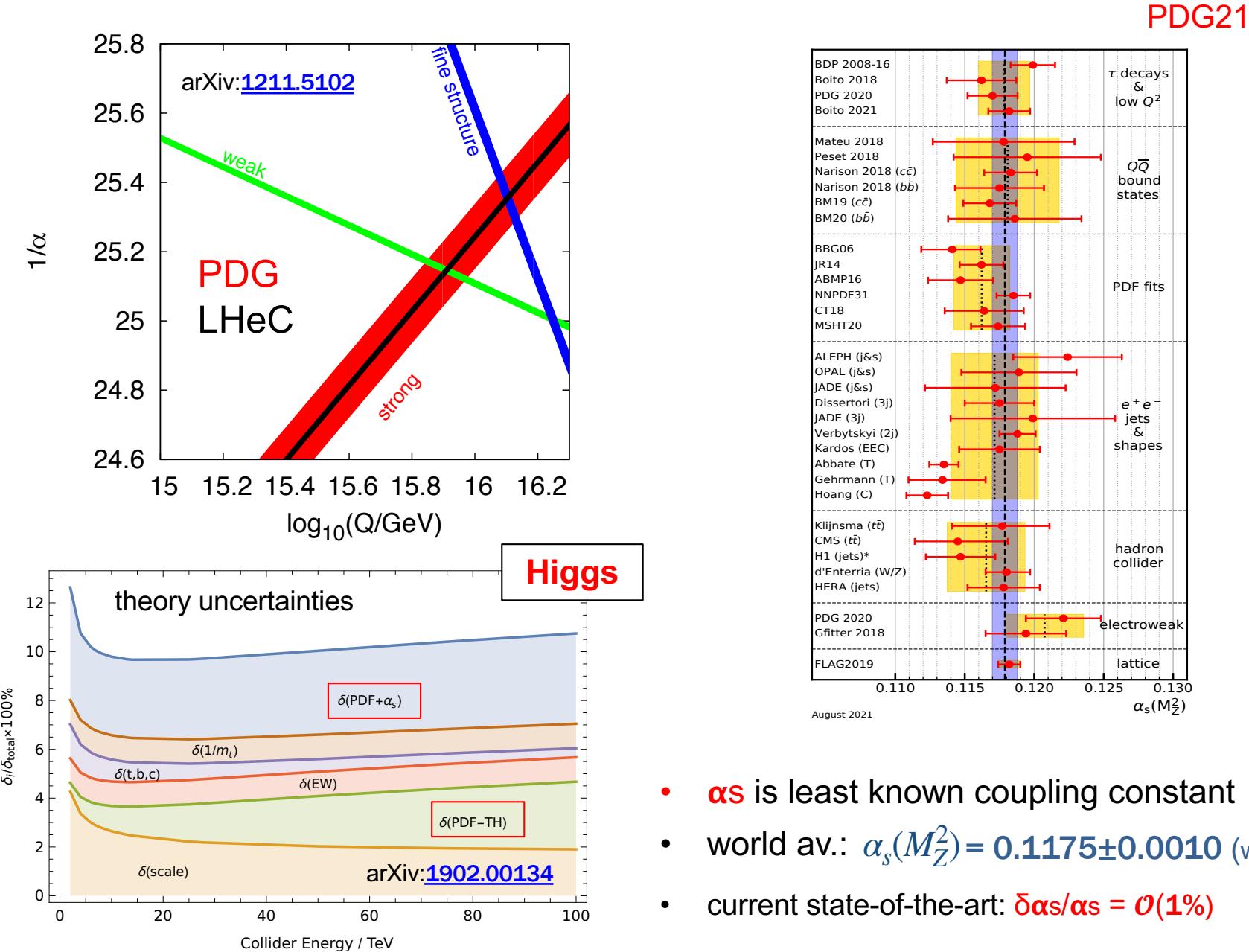
- with the unprecedented small- $x$  reach, **gluon recombination / parton saturation may also be expected**, manifesting as deviation from linear DGLAP



- LHeC can distinguish between **DGLAP** and **saturation**
- possible to identify saturation by distortions in pulls** →
- large lever arm in  $Q^2$  is crucial; fit cannot absorb a non-DGLAP  $Q^2$  dependence

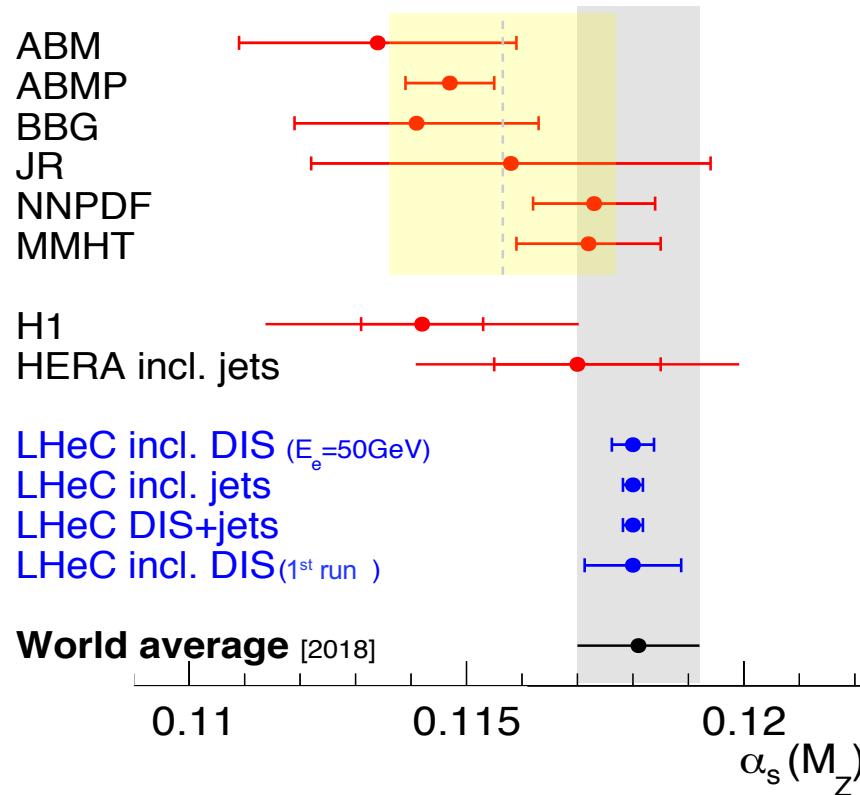


# Strong Coupling

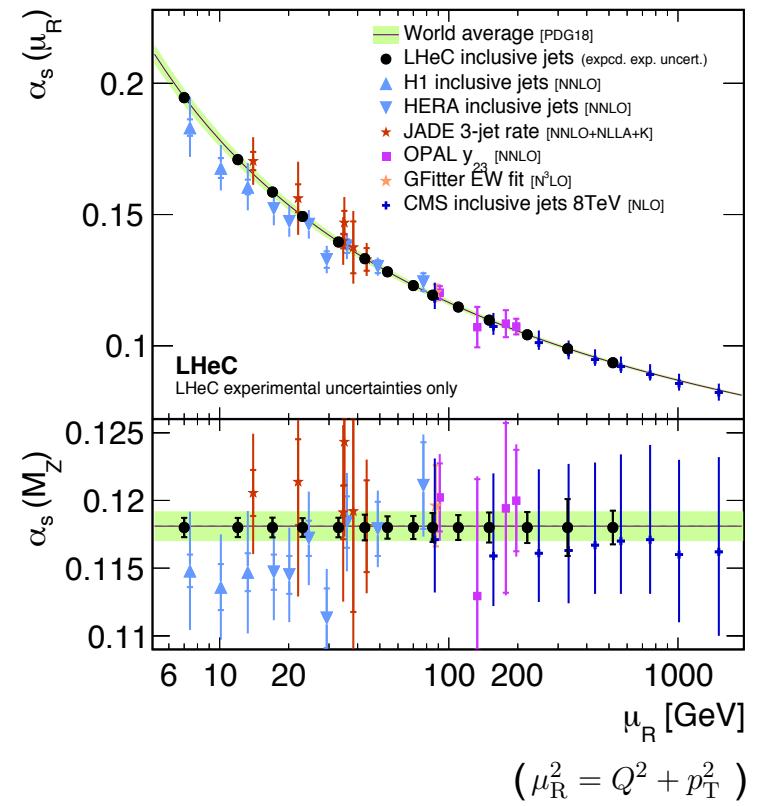


# Strong Coupling

$\alpha_s$  determinations at NNLO QCD:



fit to subsets of ep jet data:



- **LHeC** simultaneous **PDF+ $\alpha_s$**  fit
- achievable precision at **LHeC**:  **$\mathcal{O}(0.1\%)$**
- $\alpha_s$  running testable over two orders of magnitude in scale
- **QCD theory uncerts.** will be limiting factor

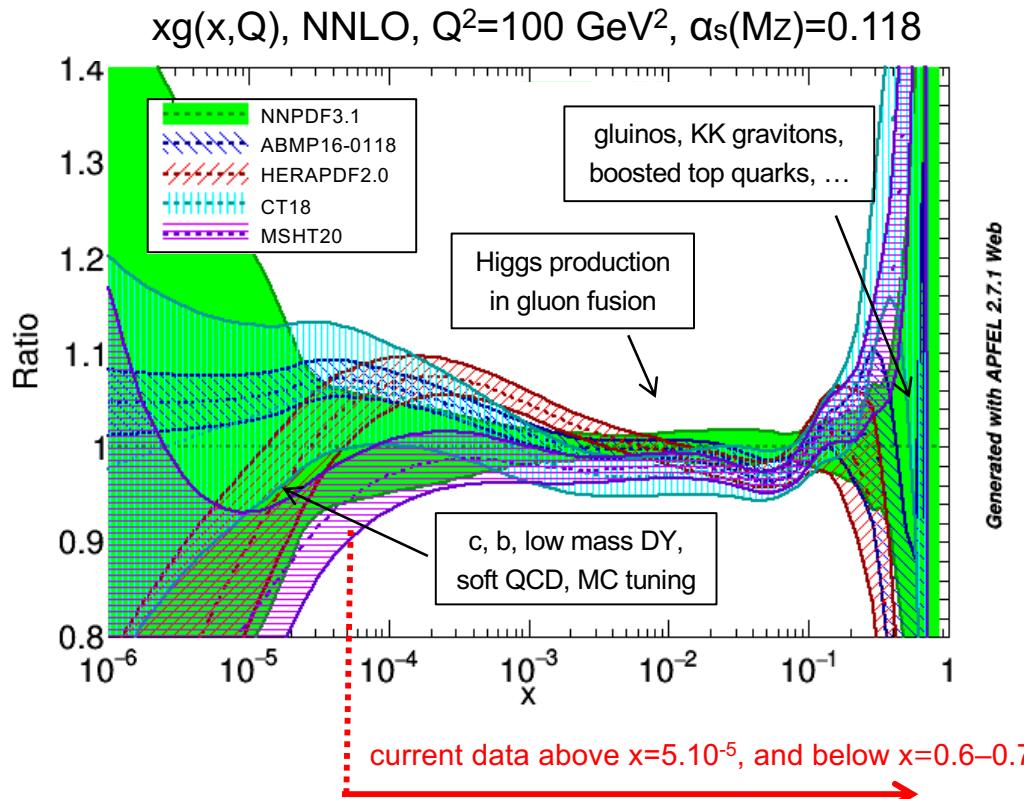
# Summary

- 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  $x \rightarrow 1, s, c, b, (t)$ ; N3LO; small  $x$ ; strong coupling to permille precision; ...
- **LHeC CDR update** ([J. Phys. G 48 \(2021\) 11, 110501](#)) 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** ( $\sim 50 \text{ fb}^{-1} \equiv \times 50 \text{ HERA}$ ), in parallel with HL-LHC operation
- unprecedented access to novel kinematic regime, with **unique potential to explore small  $x$  phenomena**
- **as to permille experimental precision** achievable early, with use of inclusive DIS and/or jets

... and much more in realm of **QCD** and **small  $x$**  physics (see also talk by A. Stasto); no time today to cover EG. **diffractive, vector meson,  $\gamma p$ , ... physics**

# Extras

# pdfs: the situation today

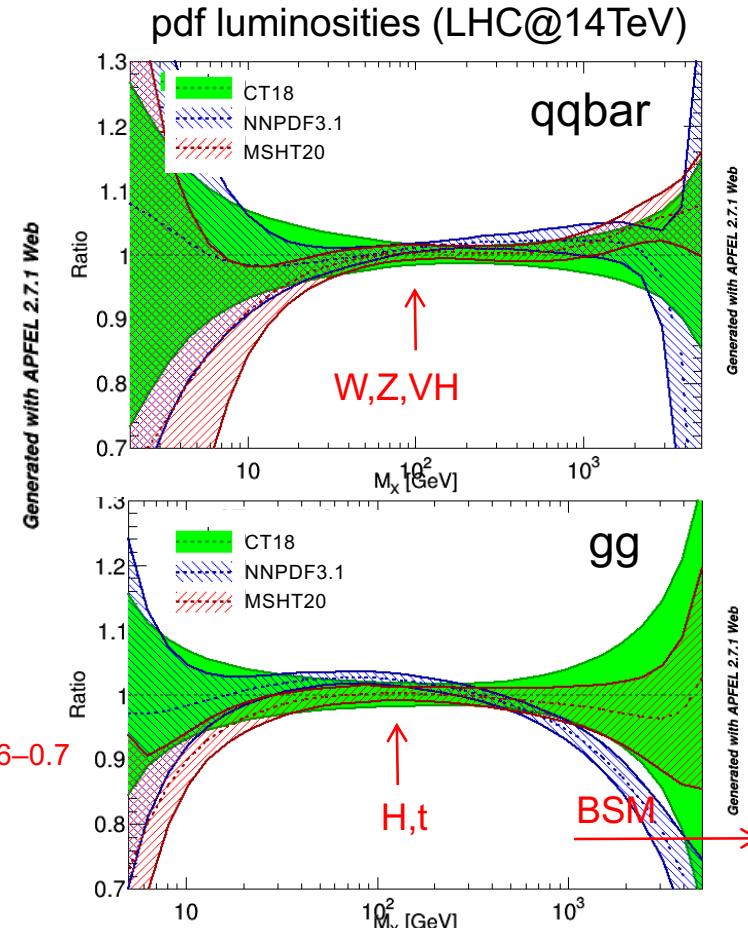


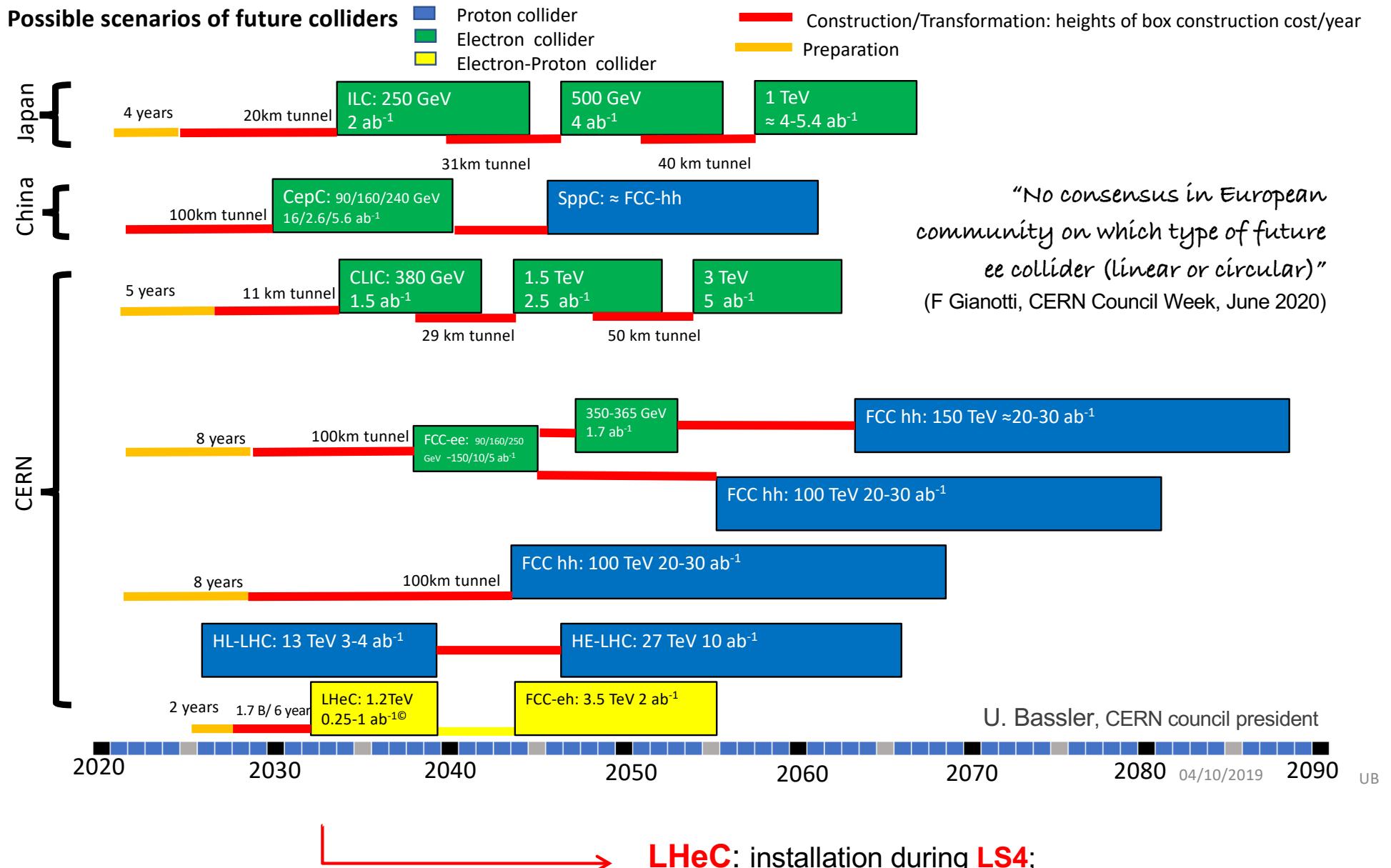
pdfs poorly known at **large and small  $x$**

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

... plus precision **MW**,  $\sin^2\theta_W$  (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](https://arxiv.org/abs/2104.02723), [1905.05215](https://arxiv.org/abs/1905.05215)





# 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

# 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	$\text{fb}^{-1}$	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  $E_p$  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.

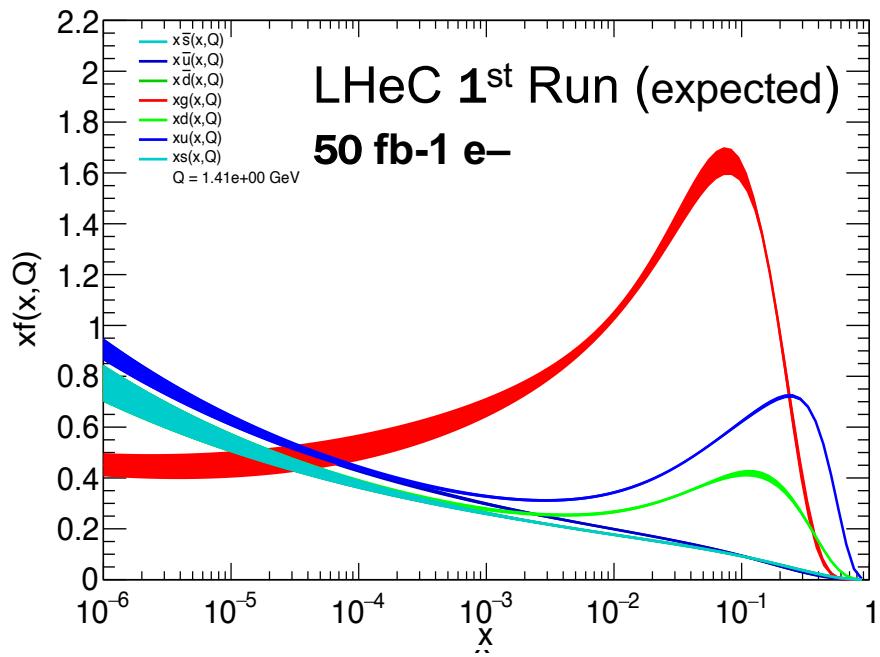
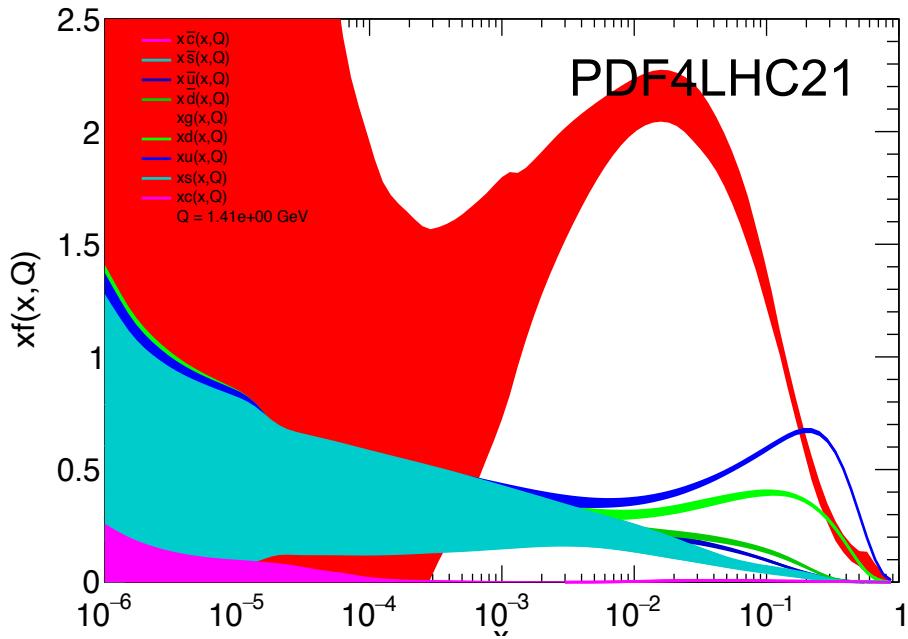
# LHeC pdf parameterisation

- QCD fit ansatz based on HERAPDF2.0, with following differences:
  - no requirement that  $u\bar{u}=d\bar{d}$  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  $d\bar{d}$  and  $s\bar{s}$  separately,  
**17 free parameters**

# Summary of LHeC pdfs



Generated with APFEL 2.7.1 Web

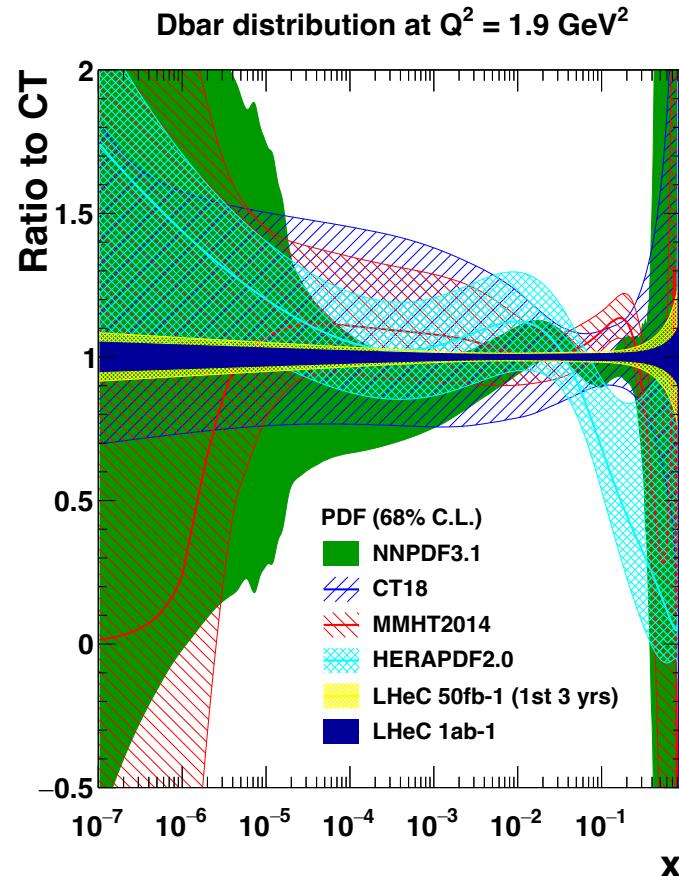
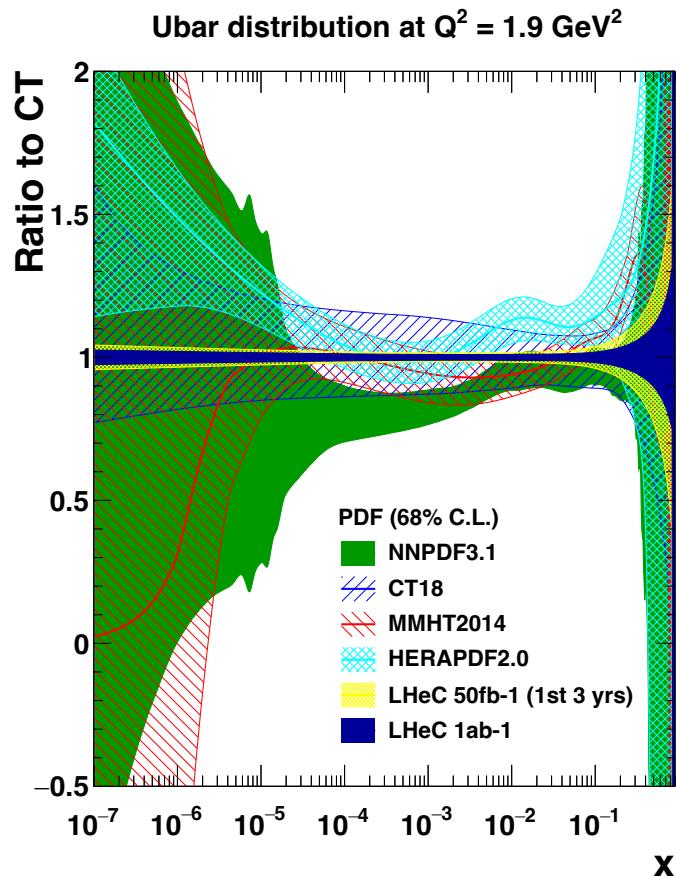
situation today



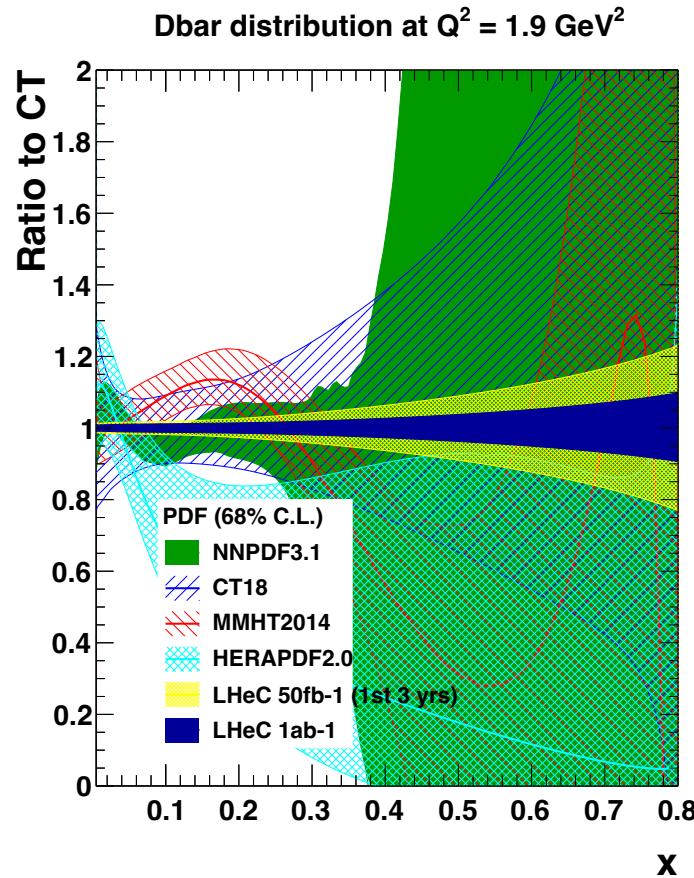
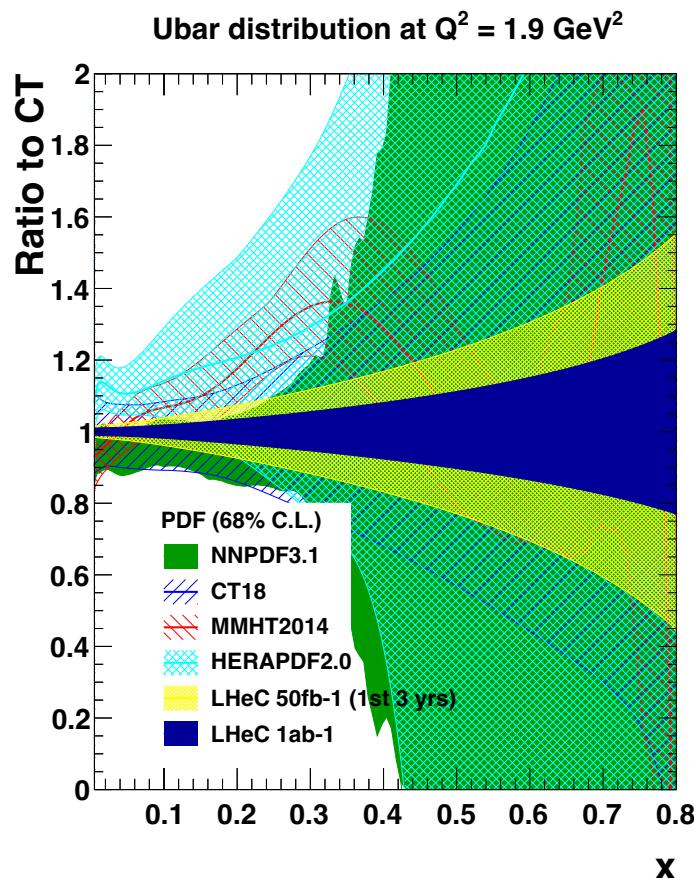
after 1<sup>st</sup> LHeC Run

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

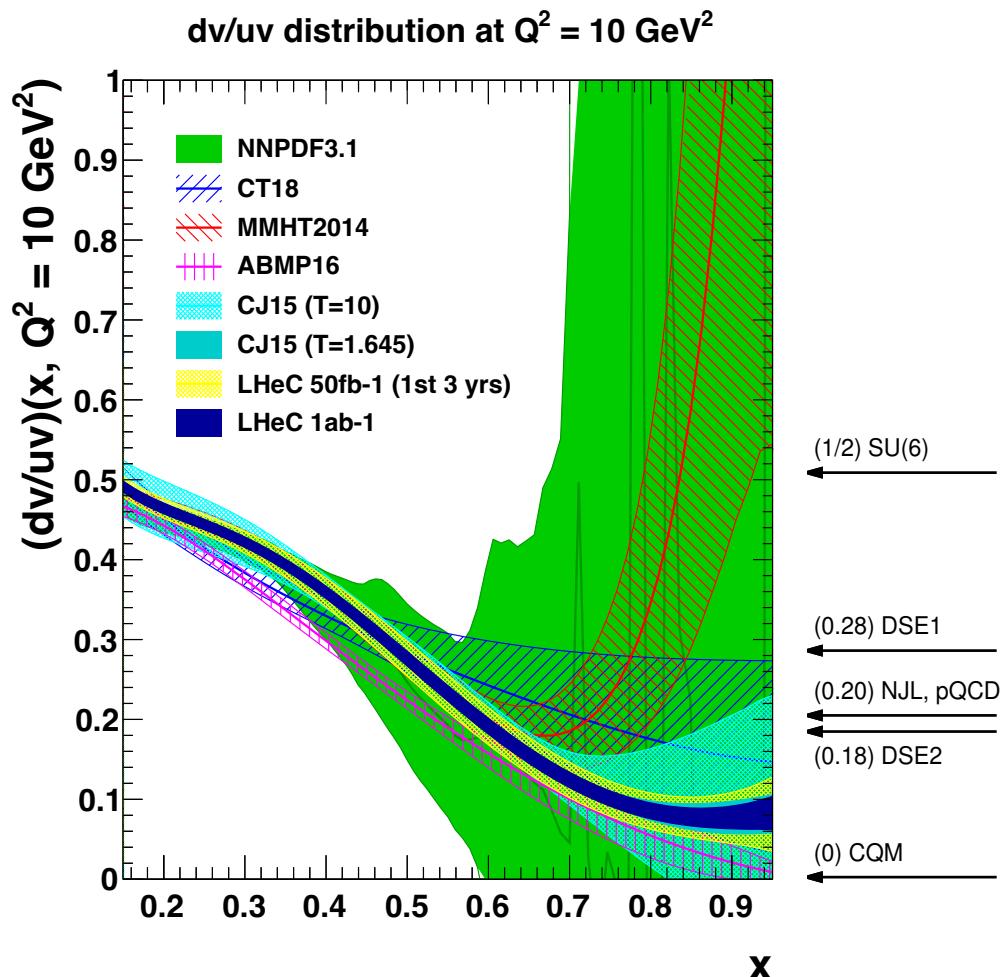
# Sea quarks



# Sea quarks



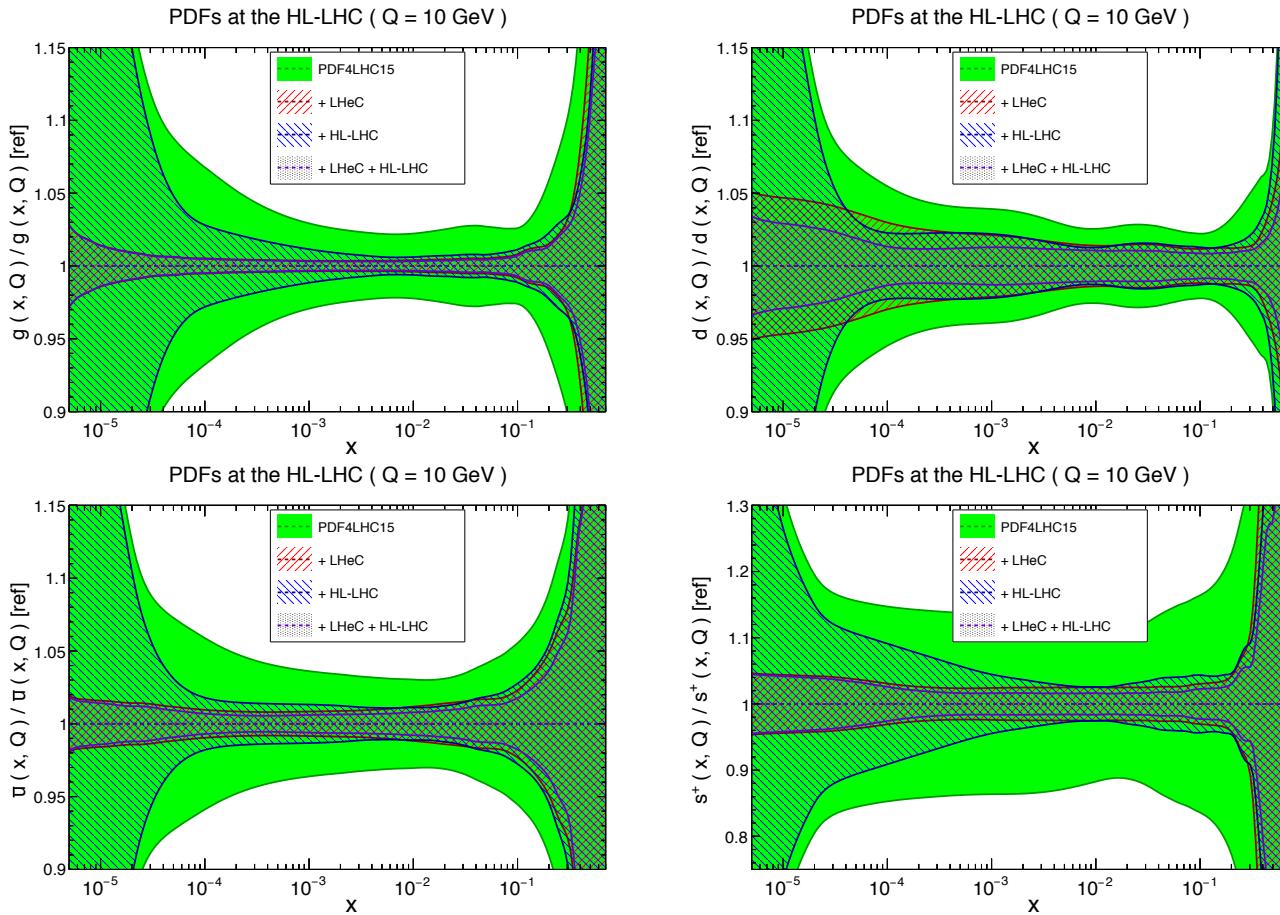
# d/u at large x



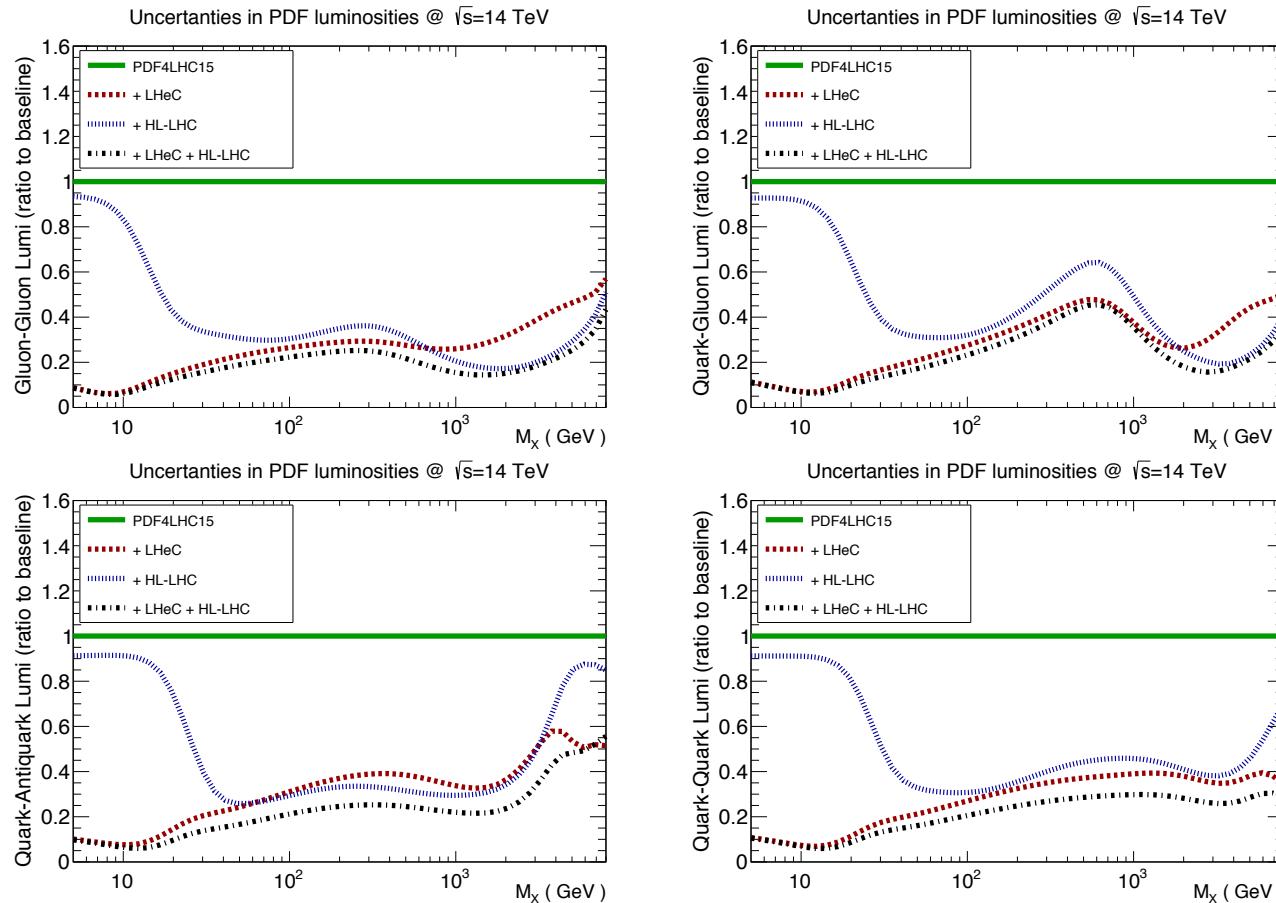
**d/u essentially unknown  
at large x**

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

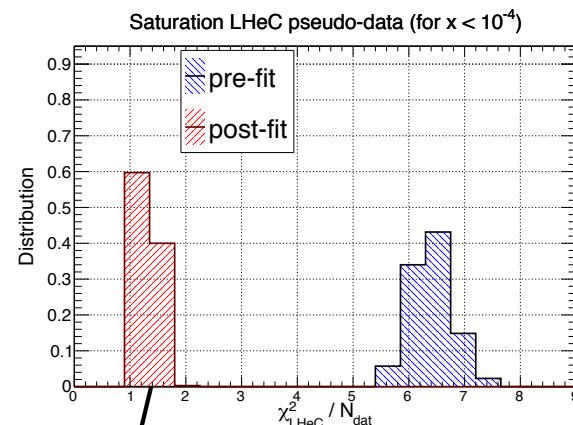
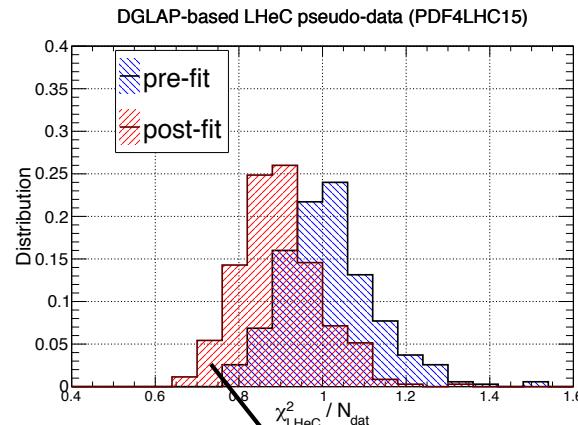


**Figure 9.9:** Impact of LHeC on the  $1-\sigma$  relative PDF uncertainties of the gluon, down quark, anti-up quark and strangeness distributions, with respect to the PDF4LHC15 baseline set (green band). Results for the LHeC (red), the HL-LHC (blue) and their combination (violet) are shown.

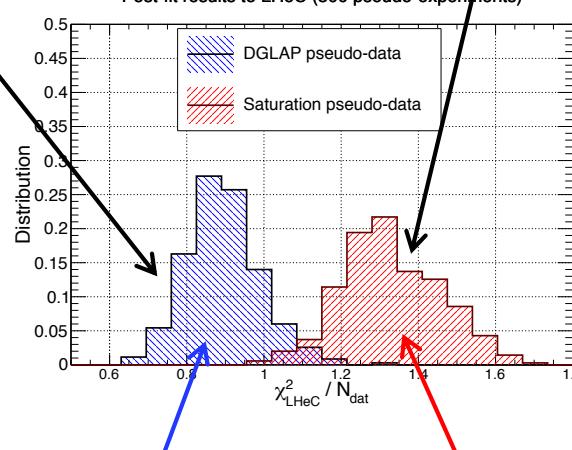


**Figure 9.10:** Impact of LHeC, HL-LHC and combined LHeC + HL-LHC pseudodata on the uncertainties of the gluon-gluon, quark-gluon, quark-antiquark and quark-quark luminosities, with respect to the PDF4LHC15 baseline set. In this comparison we display the relative reduction of the PDF uncertainty in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

# Novel dynamics at small $x$ : saturation



pre- and post-fit  $\chi^2$   
distributions consistent  
for DGLAP pseudo-data  
fitted with DGLAP

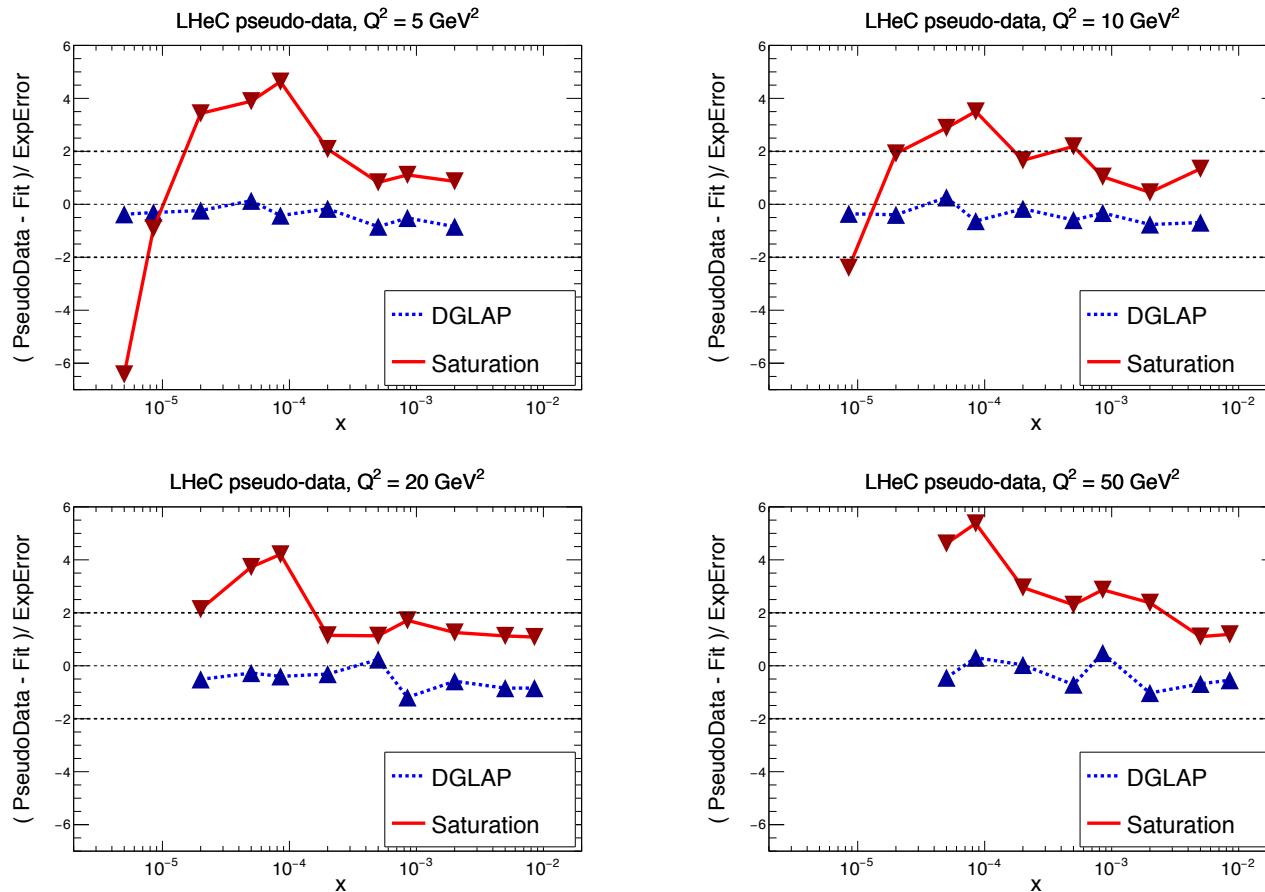


pre- and post-fit distributions  
very different for DGLAP fit to  
saturation-based ( $x \leq 10^{-4}$ , GBW  
model) pseudo-data

DGLAP can not absorb all  
saturation effects

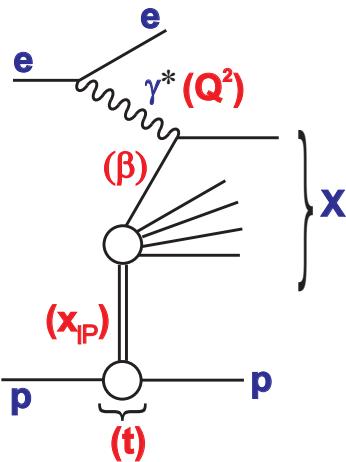
LHeC can distinguish between **DGLAP** and **saturation**

# 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**

# Diffraction



Longitudinal momentum fraction  
of the Pomeron w.r.t hadron

$$\xi \equiv x_{IP} = \frac{Q^2 + M_X^2 - t}{Q^2 + W^2}$$

Longitudinal momentum fraction  
of the parton w.r.t Pomeron

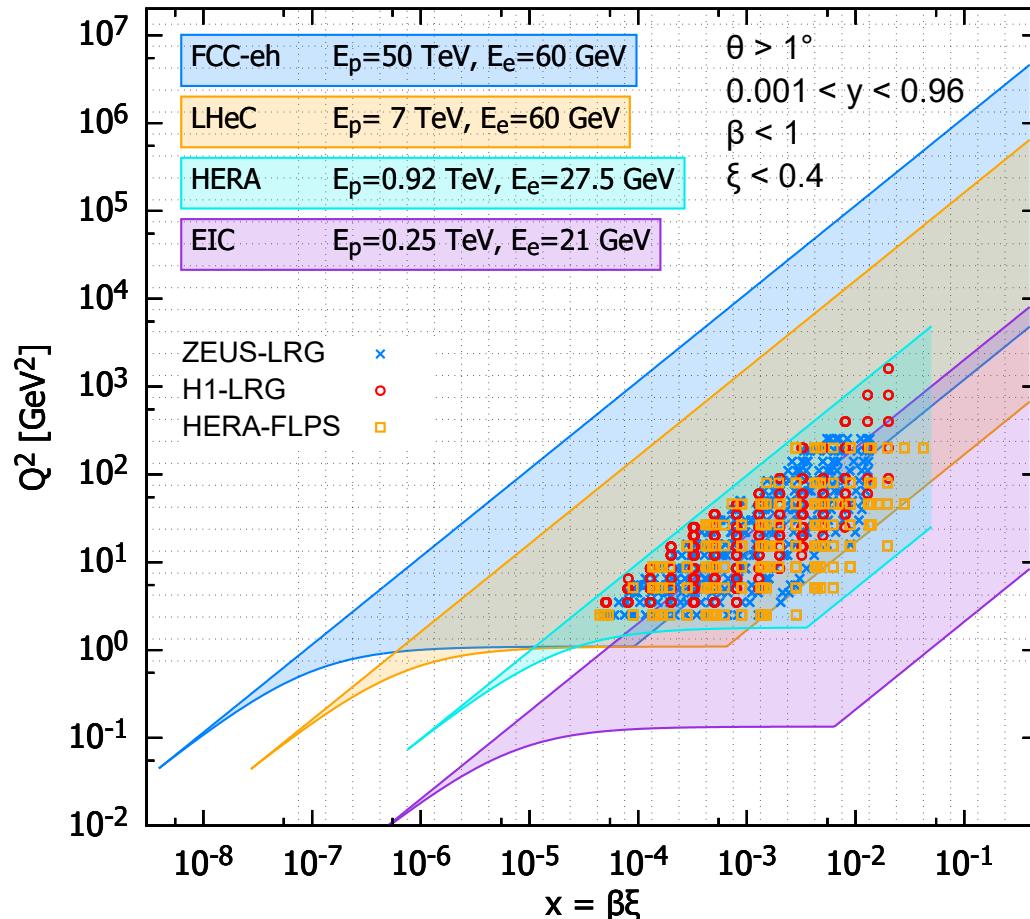
$$\beta = \frac{Q^2}{Q^2 + M_X^2 - t}$$

4-momentum transfer squared

$$t = (p - p')^2$$

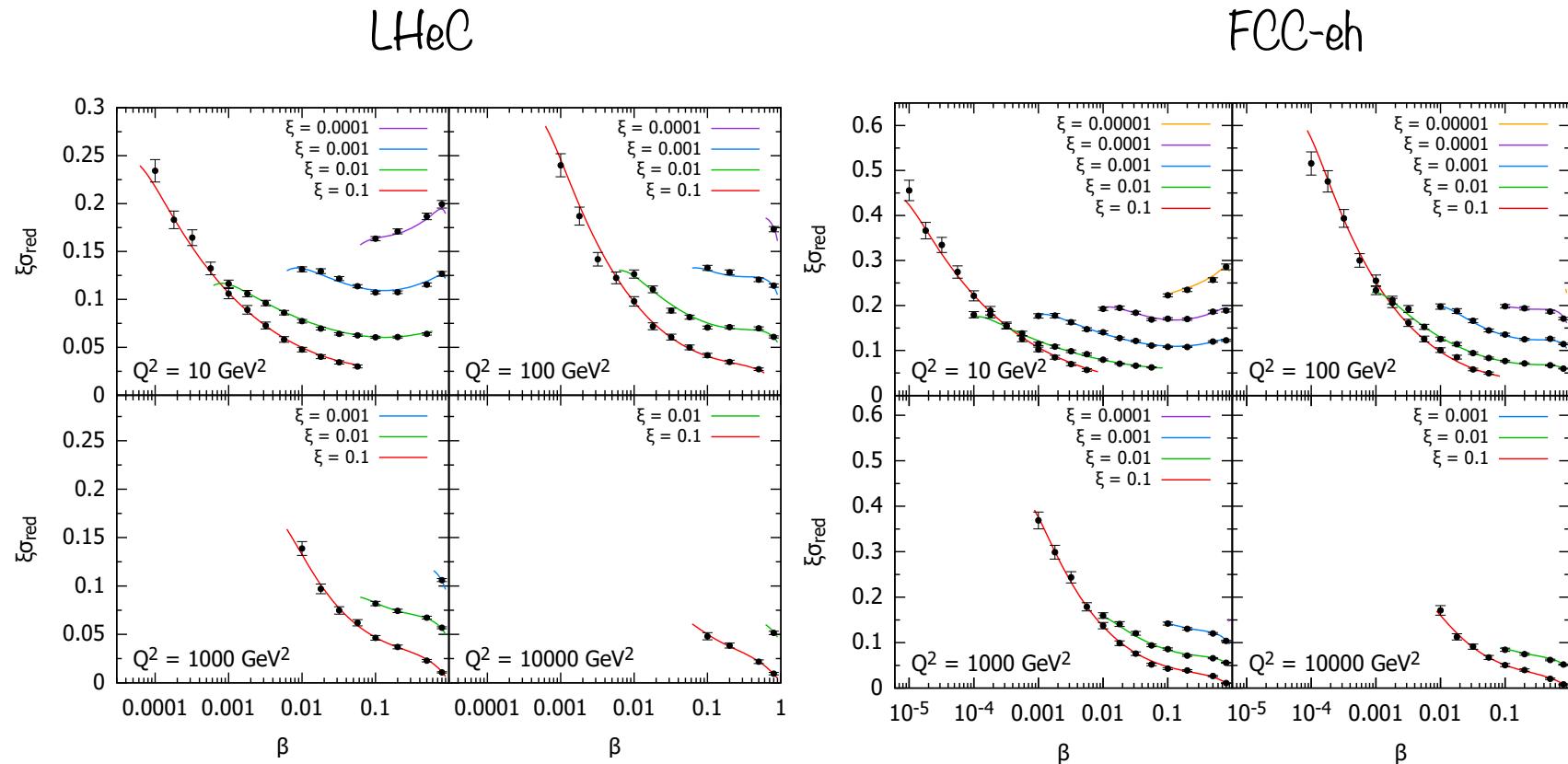
Bjorken  $x$  relation

$$x_{Bj} = x_{IP}\beta$$



- inclusive diffraction, constraints on diffractive pdfs, new final states in diffraction, also EW exchange

# Diffractive $\sigma_{\text{red}}$ pseudo-data

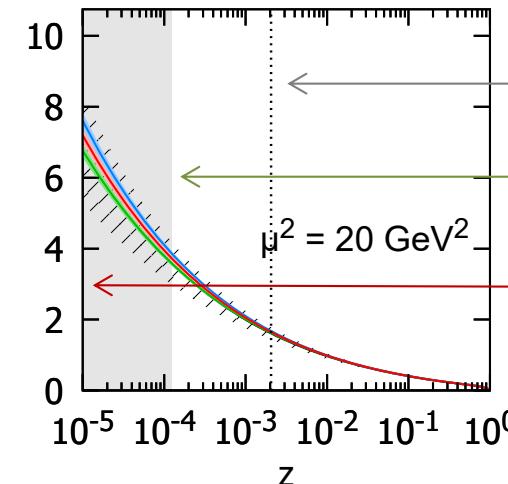
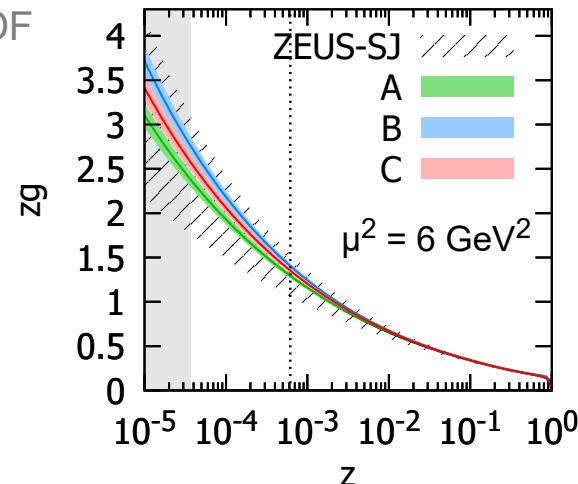


- potential for high quality data for inclusive diffraction at **LHeC/FCC-eh** (only small subset of simulated data shown)
- prospects for precise extraction of **diffractive pdfs, tests of factorisation breaking** (soft and collinear)

# Diffractive PDFs

Gluon diffractive PDF  
from LHeC:

(A,B,C : independent sets of  
LHeC pseudodata)

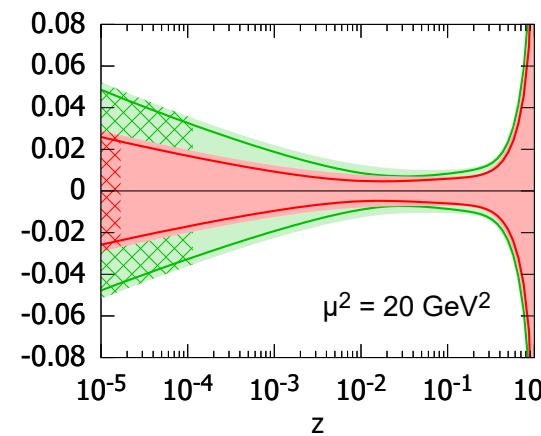
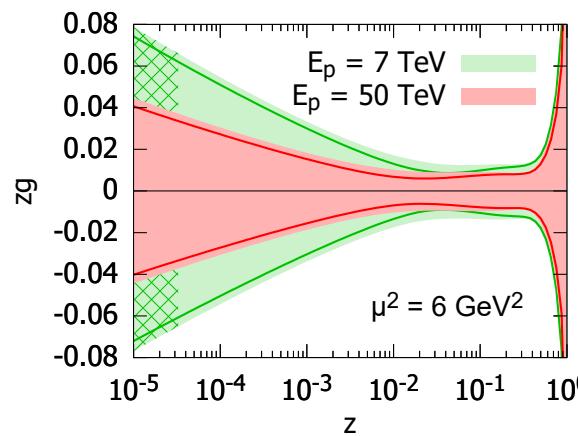


HERA

LHeC

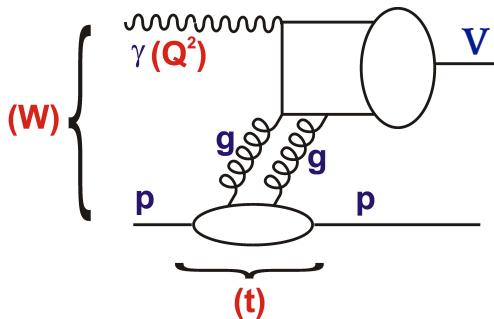
FCC-eh

Relative uncertainty,  
LHeC and FCC-eh:

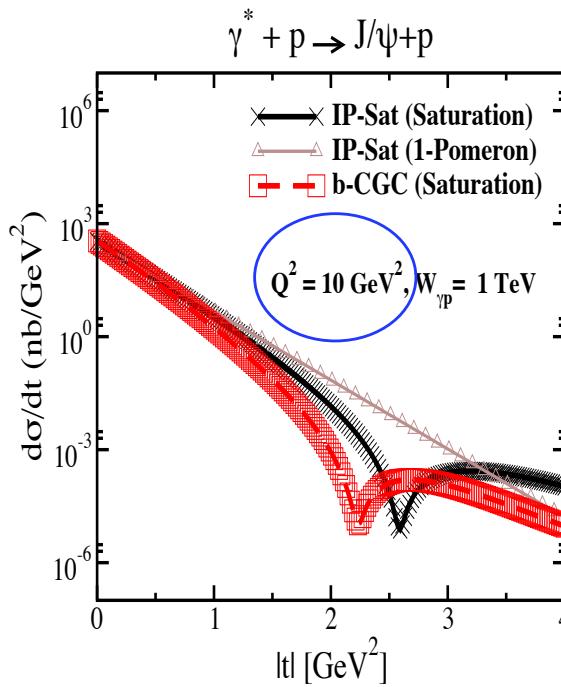
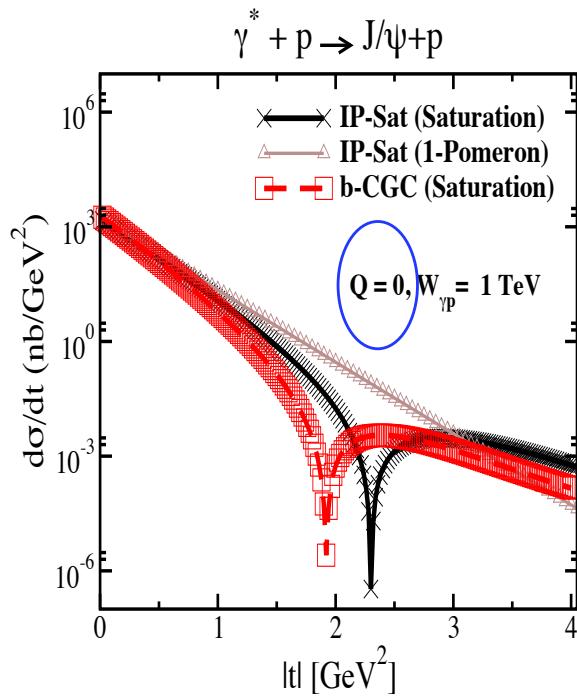
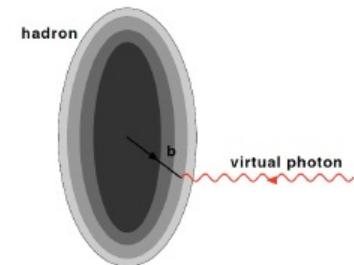


DPDF uncertainties reduced by factor 5 – 7 at LHeC and 10 – 15 at FCC-eh with inclusive data alone  
**prospects for precise extraction of diffractive PDFs, tests of factorisation breaking (collinear and soft)**

# Elastic diffraction of vector mesons

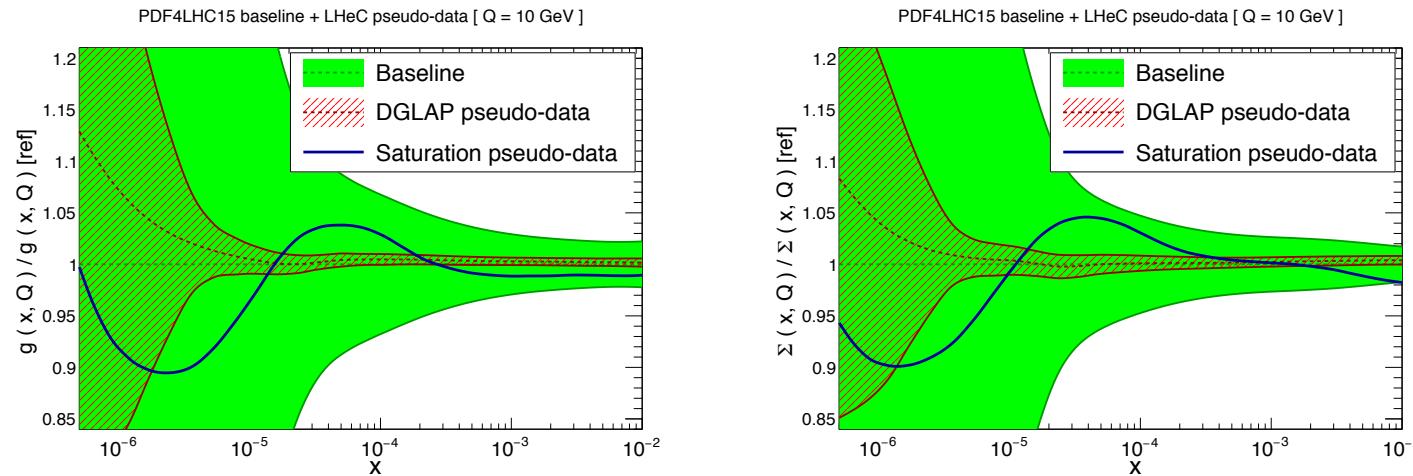


- access to GPDs, encoding 3d structure of nucleon
- $t$ -dependence gives information on spatial distribution  
≡ Fourier Transform of impact parameter profile
- sensitivity to non-linear evolution and saturation



- one of the best processes to test for novel small  $x$  dynamics
- characteristic dips a feature of saturation models – positions depend on exact model,  $Q$ ,  $W_{\gamma p}$ ,  $M_V$

# Non-linear QCD dynamics

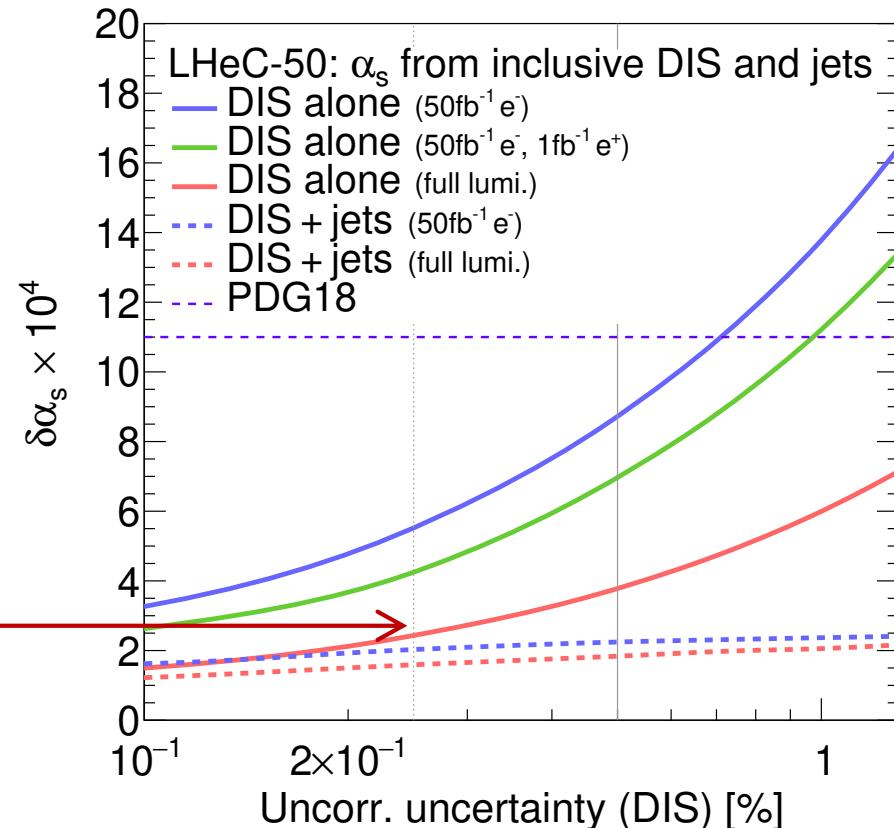


**Figure 4.12:** Comparison between the PDF4LHC15 baseline (green band) with the results of the profiling of the LHeC pseudodata for the gluon (left) and quark singlet (right) for  $Q = 10$  GeV. We show the cases where the pseudodata is generated using DGLAP calculations (red hatched band) and where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

# $\alpha_s$ from LHeC inclusive NC/CC DIS

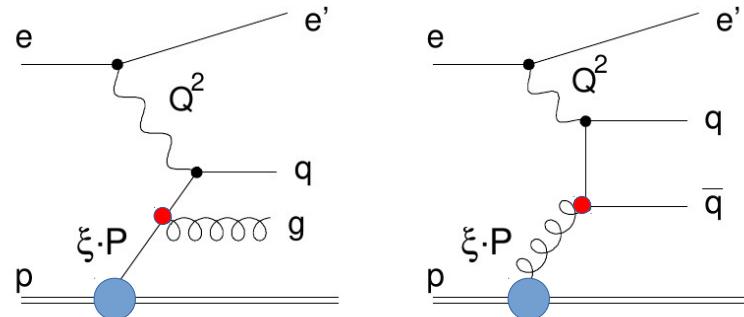
- $\alpha_s$  from inclusive NC/CC DIS:
- simultaneous determination of **pdfs** and  $\alpha_s$  in **NNLO QCD fit**
- 3 LHeC scenarios:
  - LHeC 1<sup>st</sup> Run ( $50 \text{ fb}^{-1}$  e-p)
  - plus  $1 \text{ fb}^{-1}$  positron data
  - full inclusive LHeC dataset ( $1 \text{ ab}^{-1}$ )

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



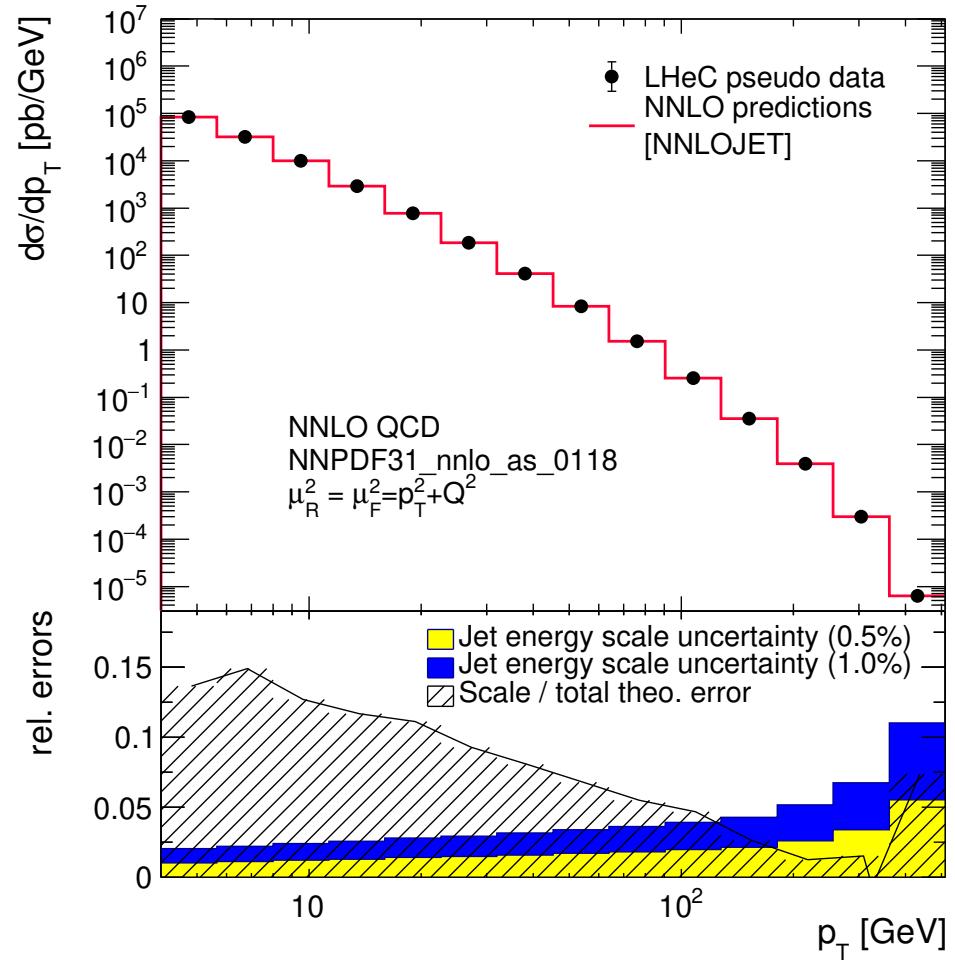
- $\alpha_s$  to better than 2 permille experimental uncertainty!
- inclusion of jet cross sections yields further improvement, and stabilises against uncorrelated uncertainty scenario →

# NC DIS jet production at the LHeC

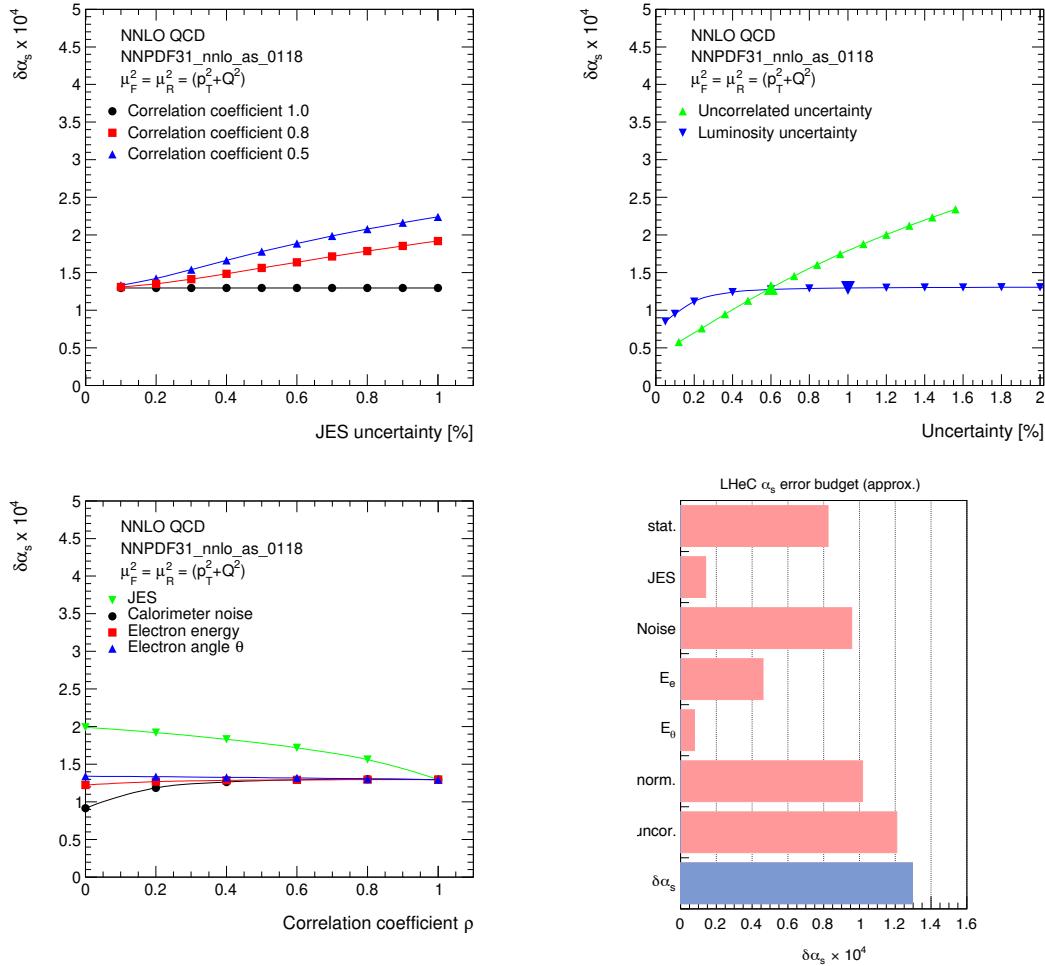


- sensitive to  $\alpha s$  at lowest order
- NNLO QCD calculations for DIS jets available in NNLOJet (arXiv:[1606.03991](https://arxiv.org/abs/1606.03991), [1703.05977](https://arxiv.org/abs/1703.05977)), and implemented in APPLfast (arXiv:[1906.05303](https://arxiv.org/abs/1906.05303))
- full set of systematic uncert. 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

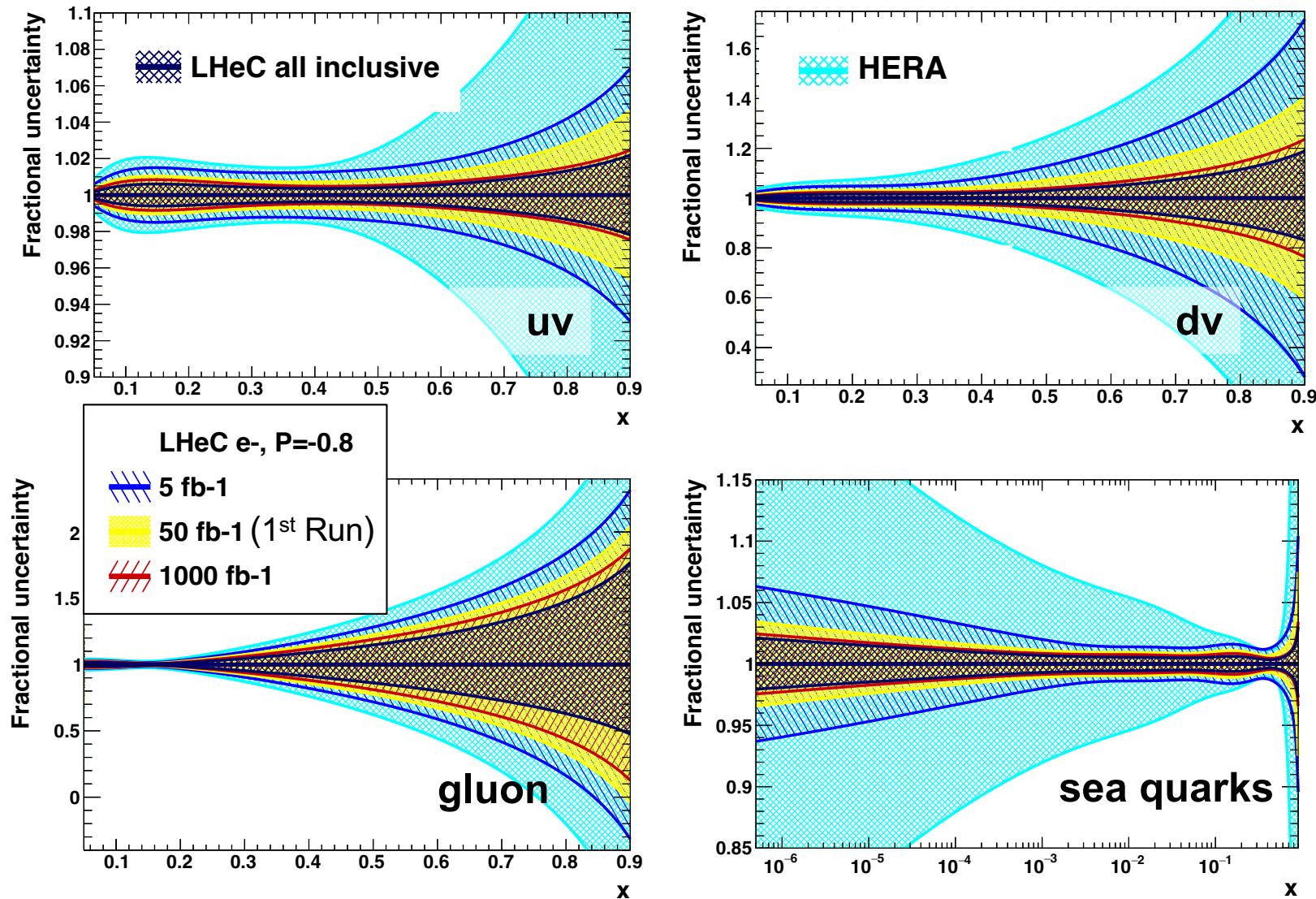


# $\alpha_s$ from LHeC NC DIS jets



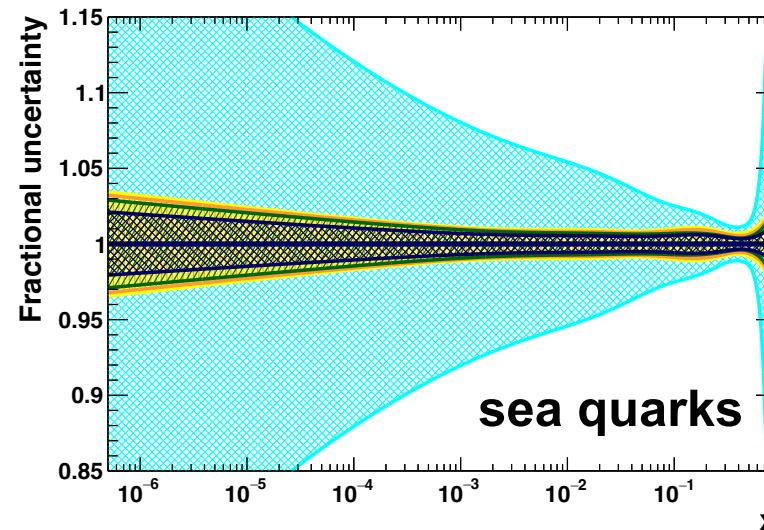
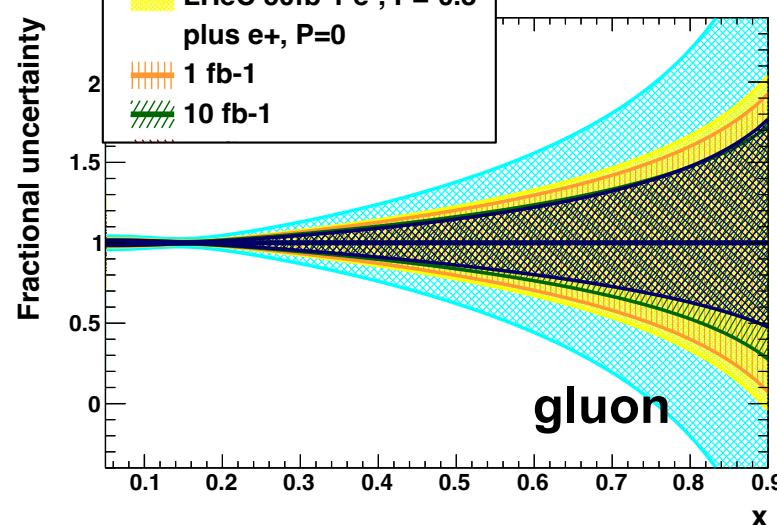
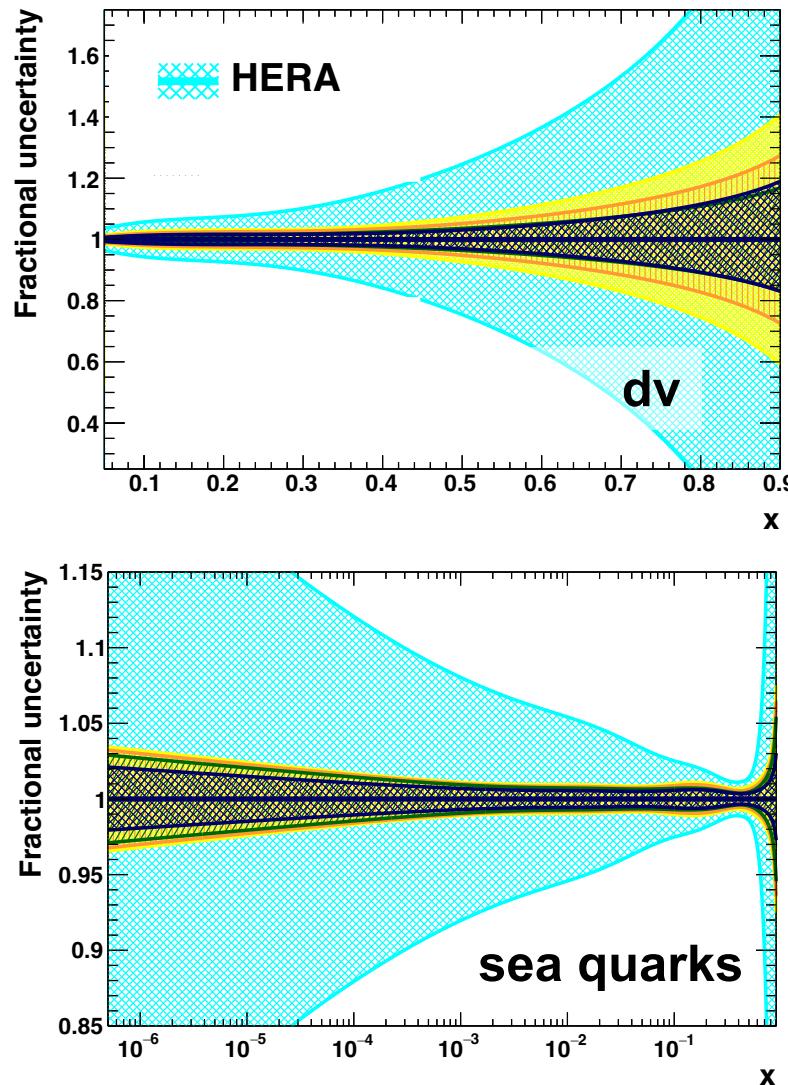
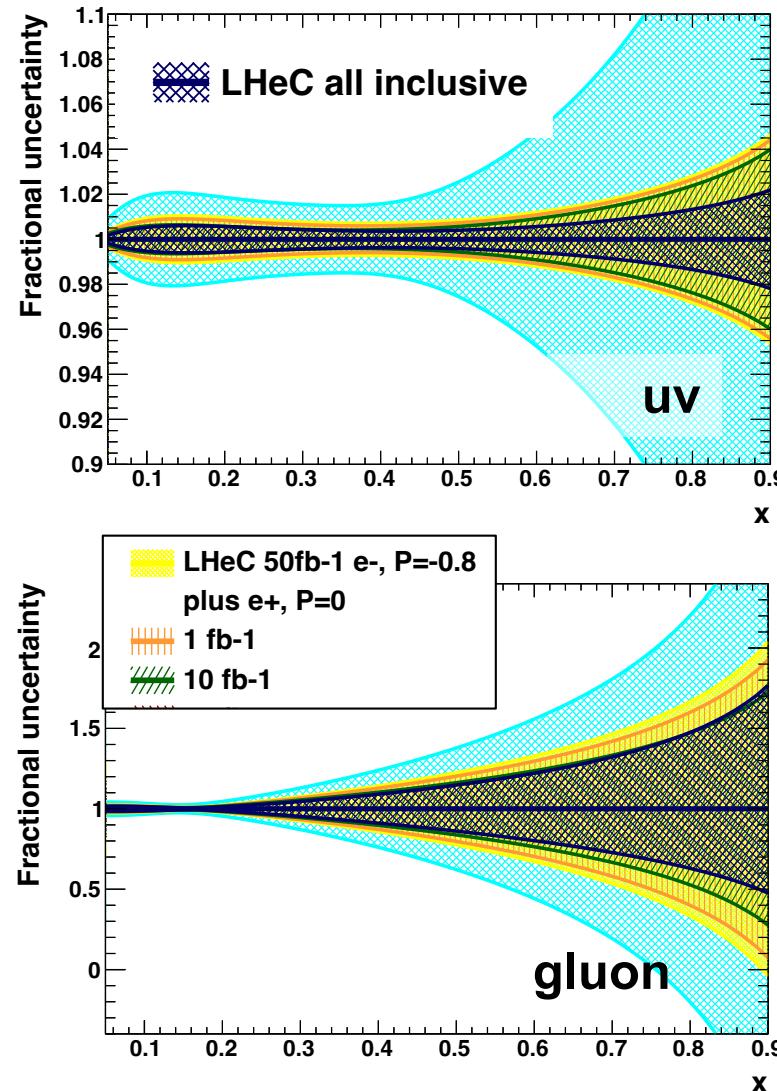
**Figure 4.3:** Studies of the size and correlations of experimental uncertainties impacting the uncertainty of  $\alpha_s(M_Z)$ . Top left: Study of the value of the correlation coefficient  $\rho$  for different systematic uncertainties. Common systematic uncertainties are considered as fully correlated,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

# Impact of luminosity



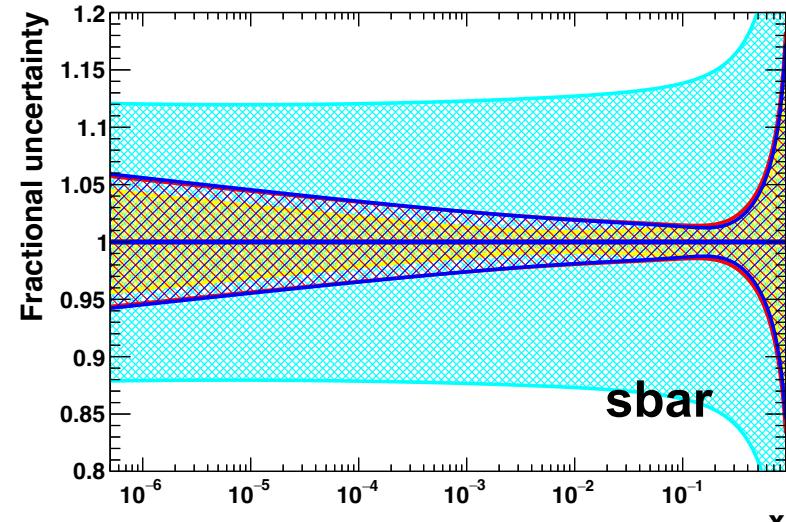
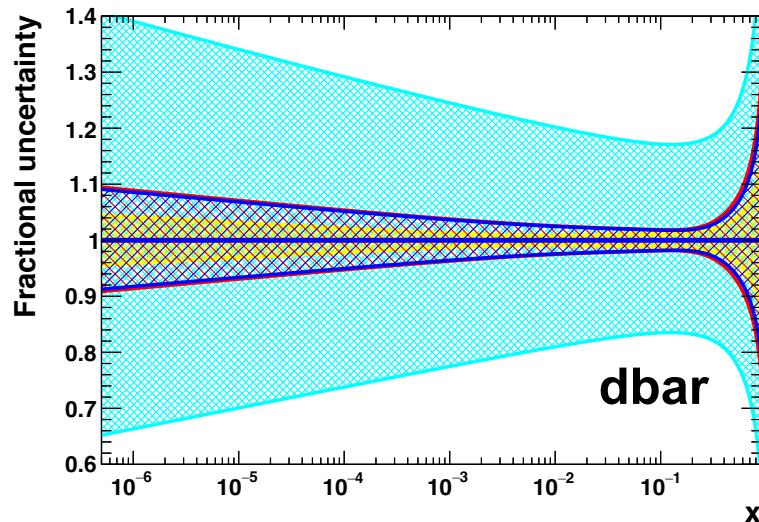
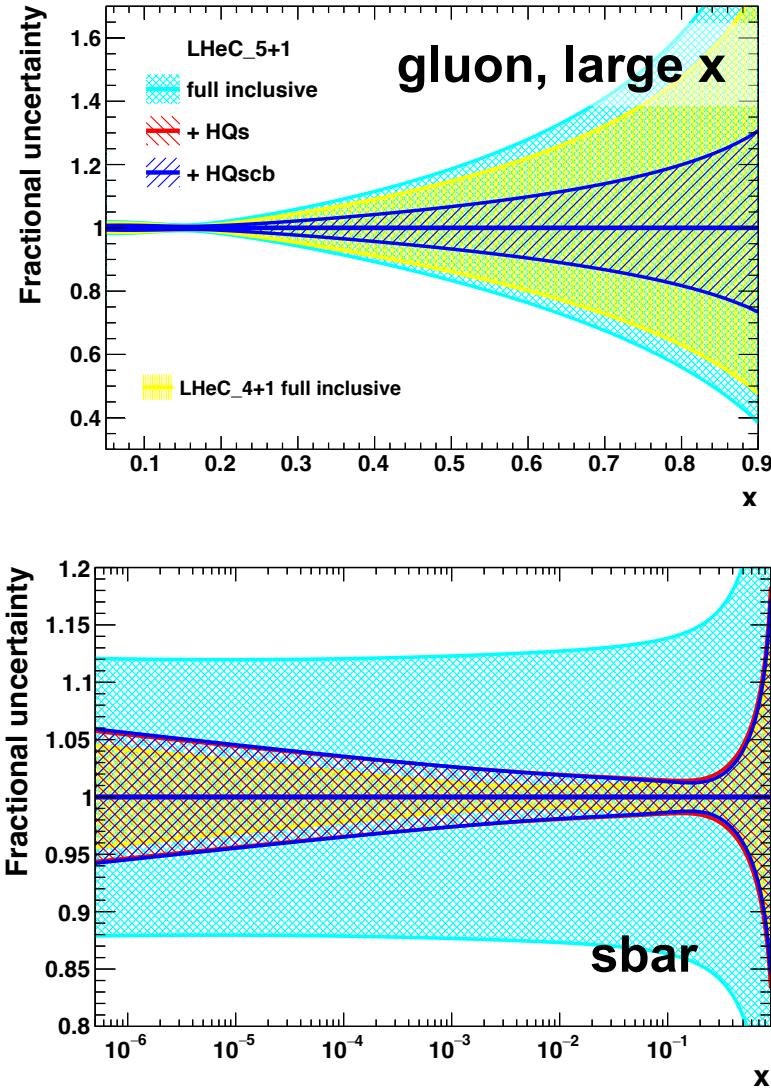
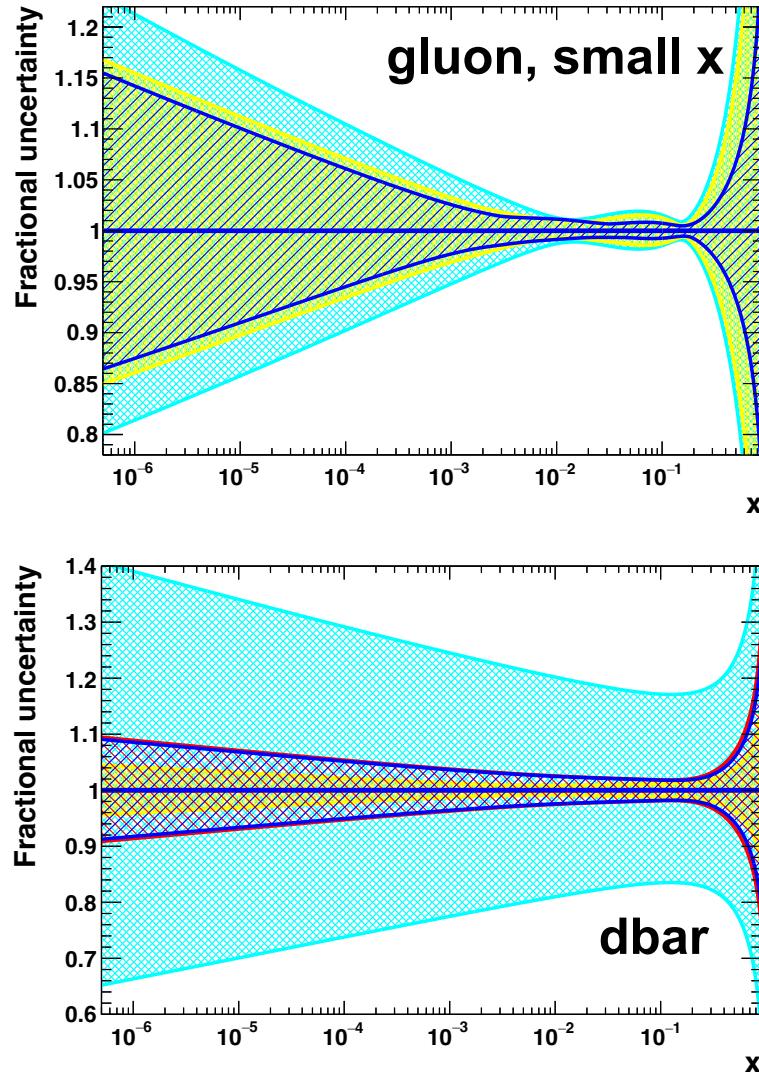
**small and medium  $x$**  quickly constrained ( $5 \text{ fb}^{-1} \equiv \times 5 \text{ HERA} \equiv 1\text{st year LHeC}$ )  
**large  $x$**  ( $\equiv$  large  $Q^2$ ), gain from increased Lint

# Impact of positrons



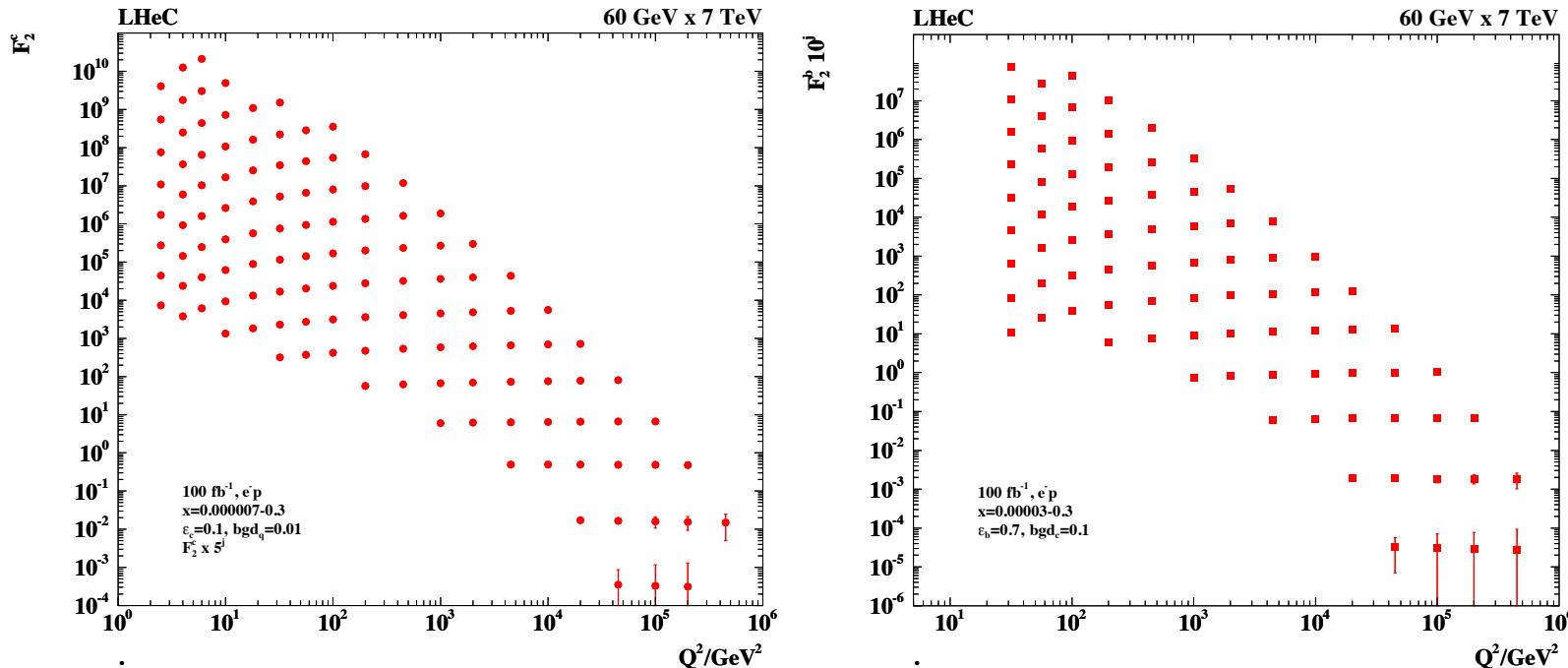
**CC:**  $e^+$  sensitive to  $d$ ; **NC:**  $e^\pm$  asymmetry gives  $xF3^{YZ}$ , sensitive to valence

# 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

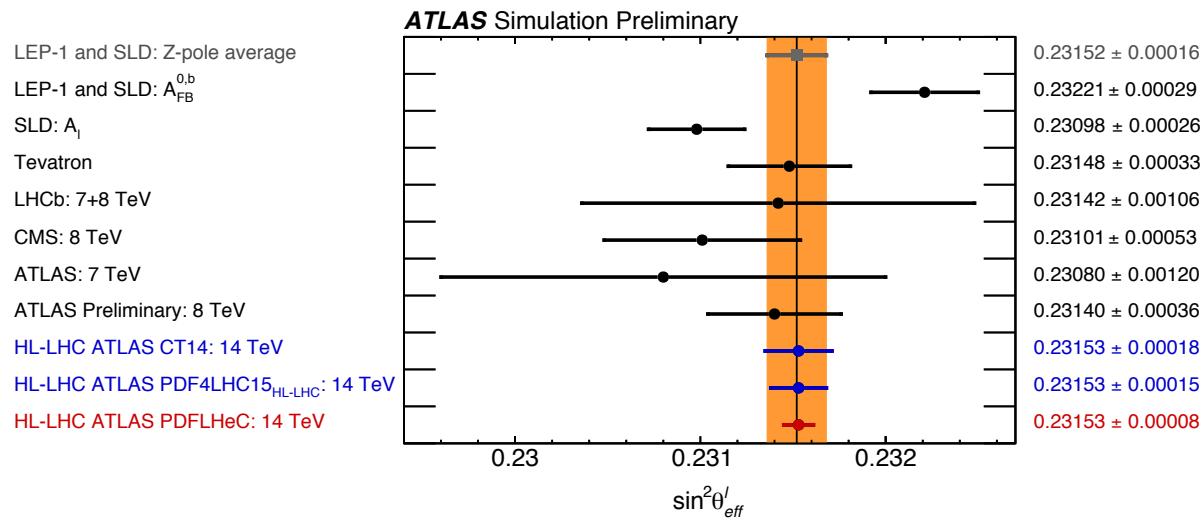


**LHeC:** enormously extended range and much improved precision c.f. HERA

- **$\delta M_c = 50$  (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  $bb \rightarrow A$

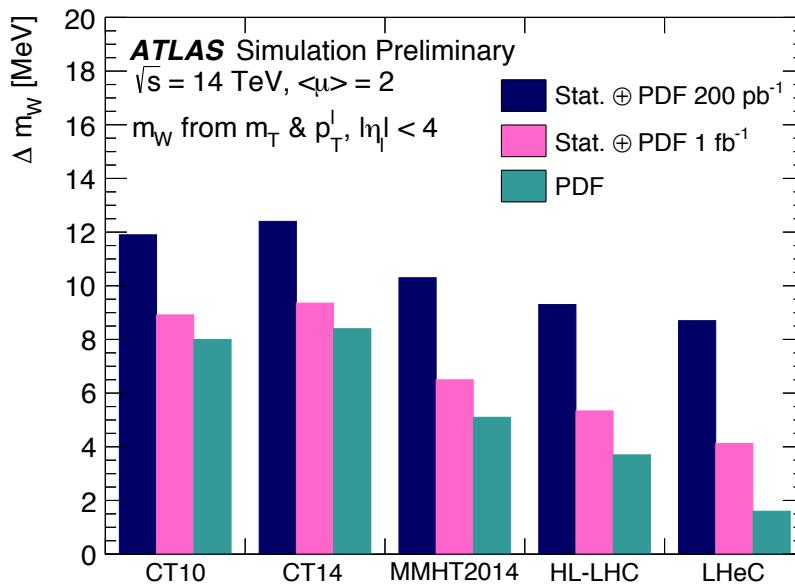
# Empowering the LHC: $\sin^2\theta_W$

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, $\mathcal{L}$	$\text{fb}^{-1}$	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., $\Delta \sin^2\theta_W$	$10^{-5}$	$\pm 36$		$\pm 18$	$\pm 15$	$\pm 8$



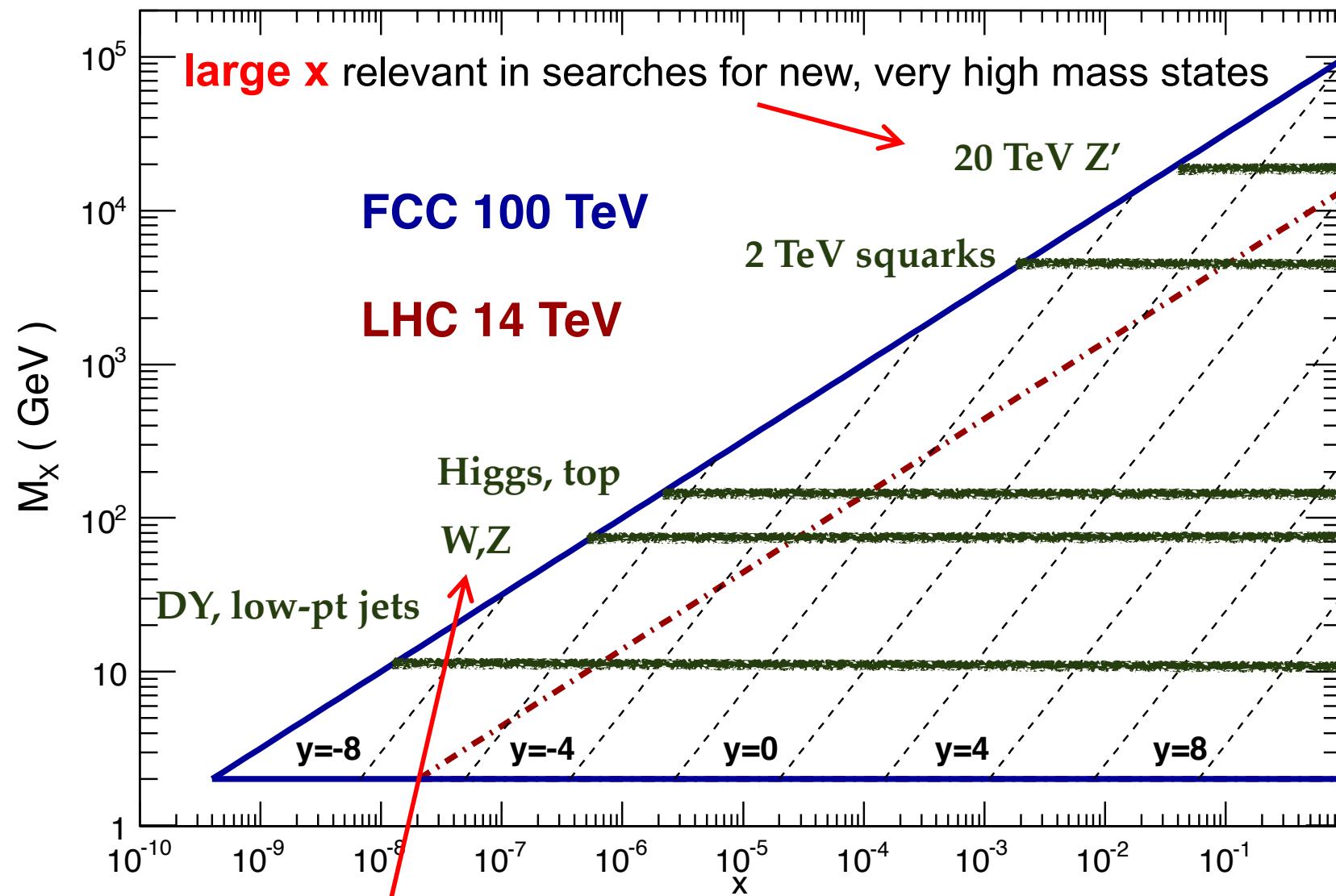
# Empowering the LHC: MW

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



# Kinematics of a 100 TeV FCC

Plot by J. Rojo, Dec 2013



**small  $x$**  becomes relevant even for “common” physics (EG. W, Z, H, t)