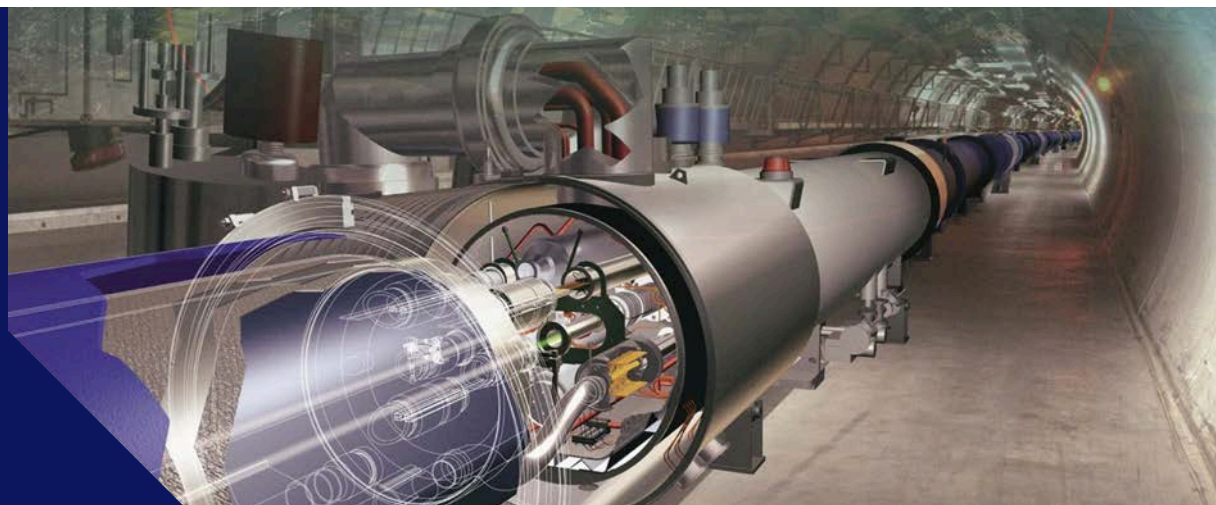


# PDF4LHC meeting

2<sup>nd</sup> October 2020



## Precision QCD at the LHeC and FCC-eh

Claire Gwenlan, Oxford

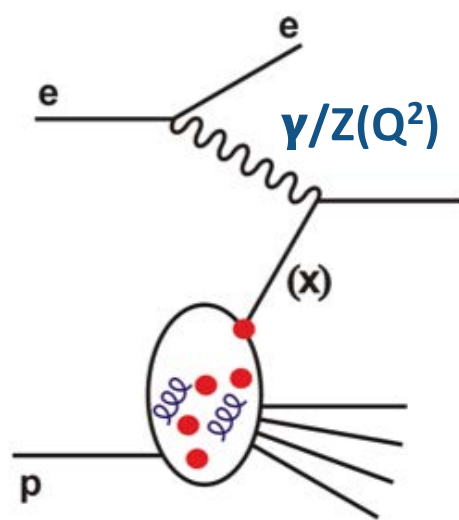
on behalf of the LHeC and FCC-eh study groups



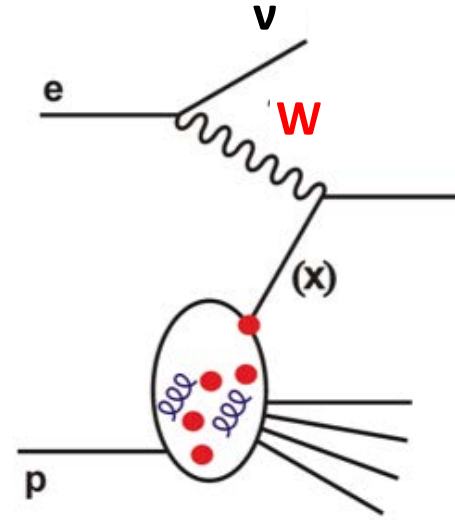
focus on results from new LHeC white paper, [arXiv:2007.14491](https://arxiv.org/abs/2007.14491)



# ep collider – a precision microscope



Neutral Current:  $ep \rightarrow e'X$

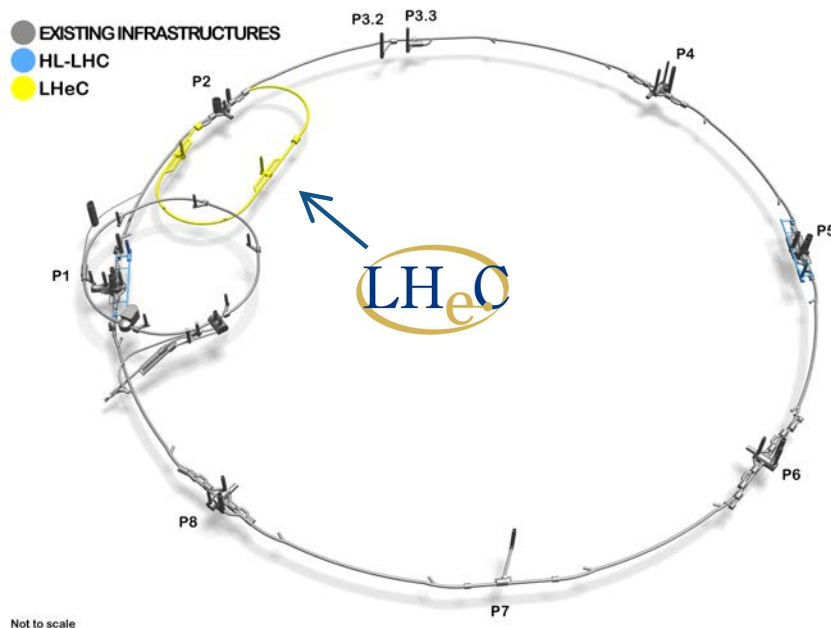


Charged Current:  $ep \rightarrow \nu_e X$

“The point-like electron “probes” the interior of the proton via the **electroweak force**, while acting as a neutral observer with regard to the **strong force**”, R-D Heuer

cleanest high resolution microscope for probing proton structure and ideal QCD laboratory

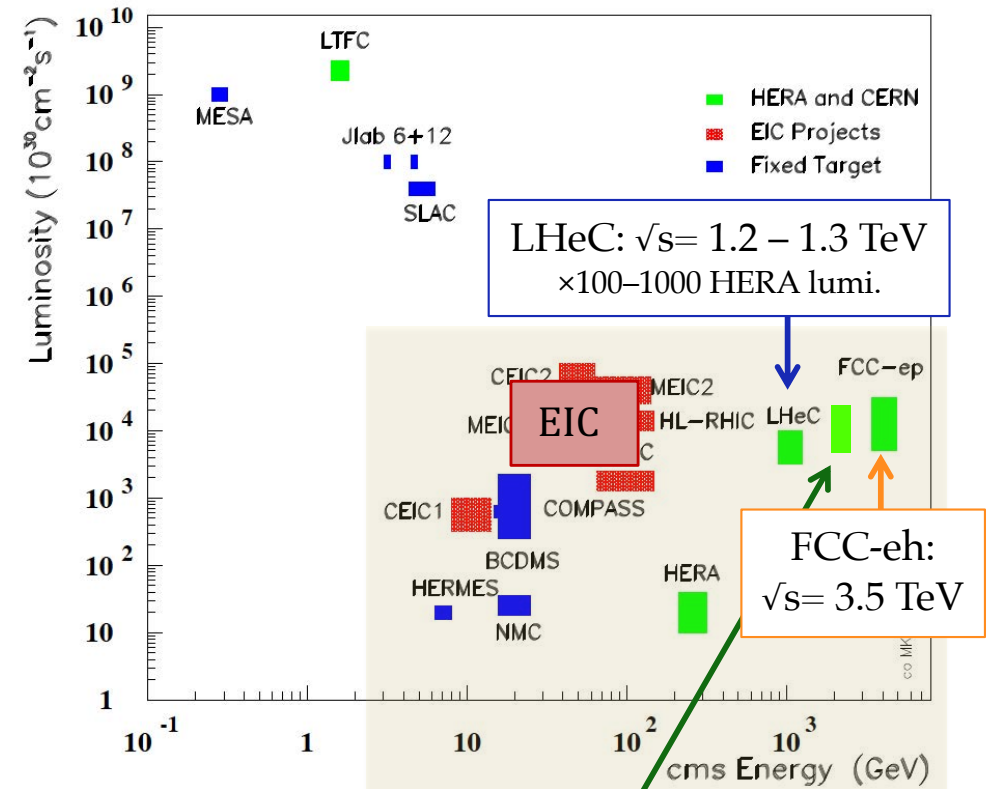
# LHeC and FCC-eh



**energy recovery LINAC (ERL)**  
 attached to HL-LHC (or FCC)  
 e beam: → 50 or 60 GeV  
 Lint → 1 ab<sup>-1</sup> (1000× HERA ; per 10 yrs)

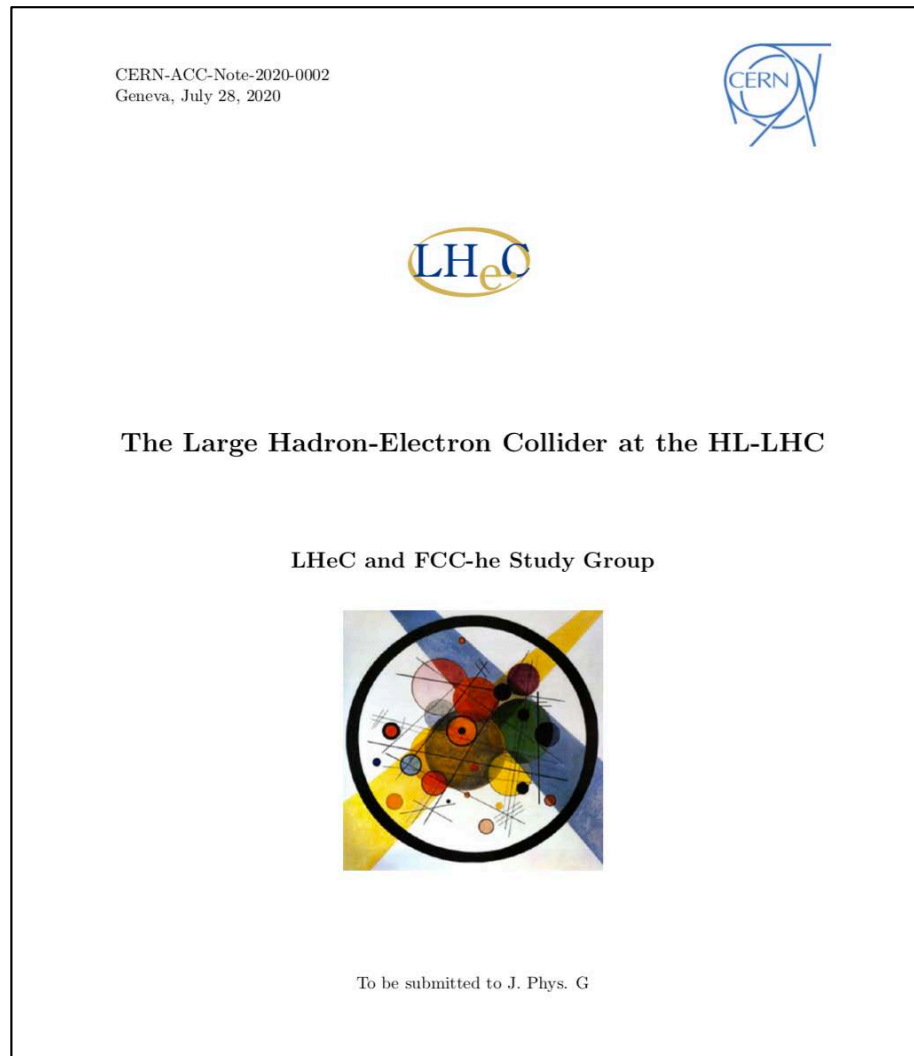
**ESPPU: ERL is a “high-priority future initiative” for CERN**

Lepton-Proton Scattering Facilities



“FCC-eh (A)”:  $\sqrt{s}= 2.2$  TeV  
 (earlier operation with current magnet technology,  $E_p=20$  TeV)

# LHeC white paper



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

update to LHeC CDR, arXiv:[1206.2913](https://arxiv.org/abs/1206.2913)

compilation of new and updated studies over the past two years, from > 330 authors

this talk:

**QCD and proton structure – Ch. 3, 4**

very wide-ranging additional physics programme:

**BSM**

**EW and top quark**

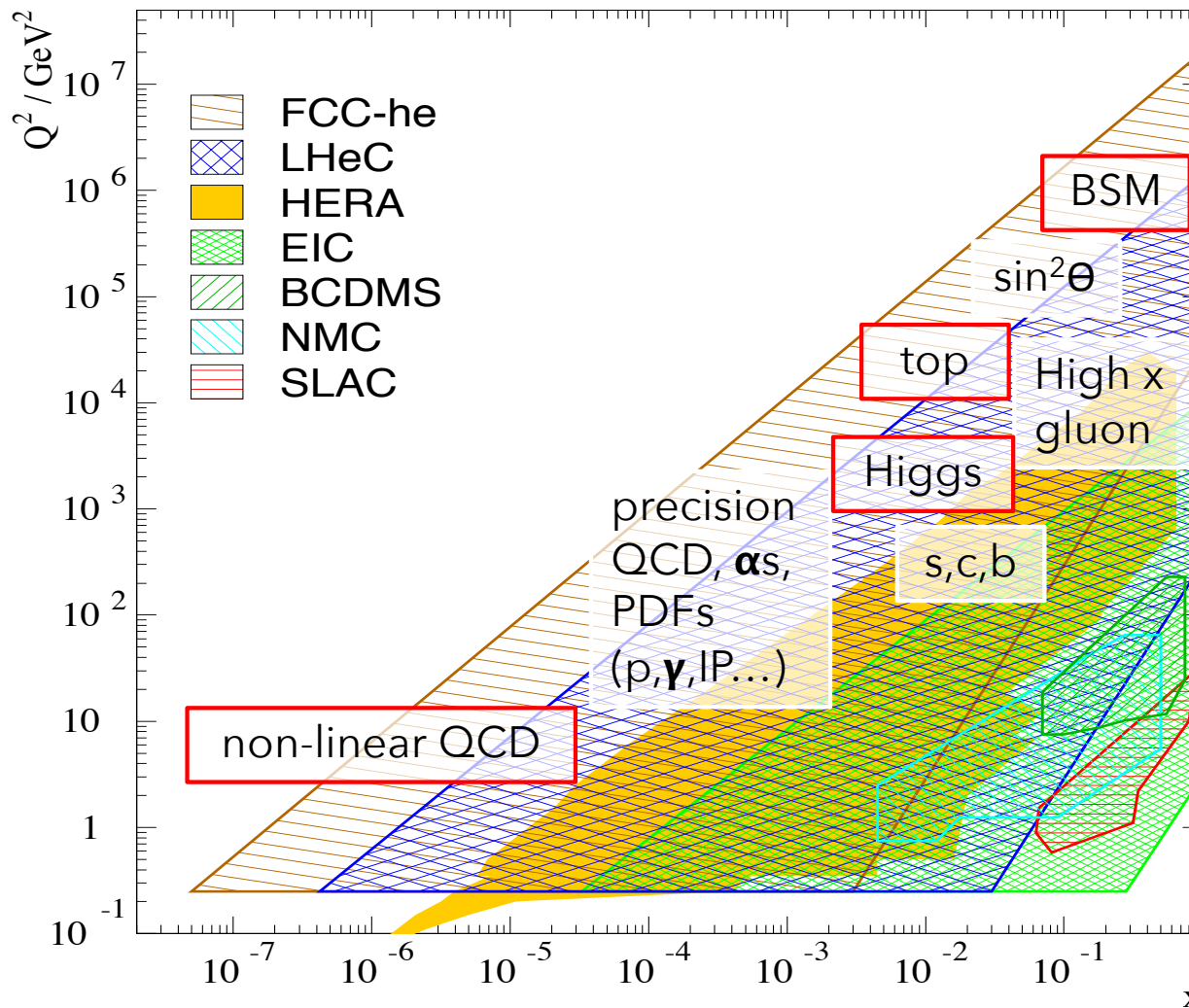
**Heavy ions**

**Higgs**

see also FCC CDR, volume 1, [EPJ C79 \(2019\), no.6, 474](https://arxiv.org/abs/1903.01217)



# kinematic coverage



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

no higher twist,  
 no nuclear corrections,  
 free of symmetry  
 assumptions,  
 N<sup>3</sup>LO theory possible,  
 ...

**precision pdfs up  
 to  $x \rightarrow 1$ ,**  
**and exploration of  
 small  $x$  regime;**  
 plus extensive  
 additional physics  
 programme

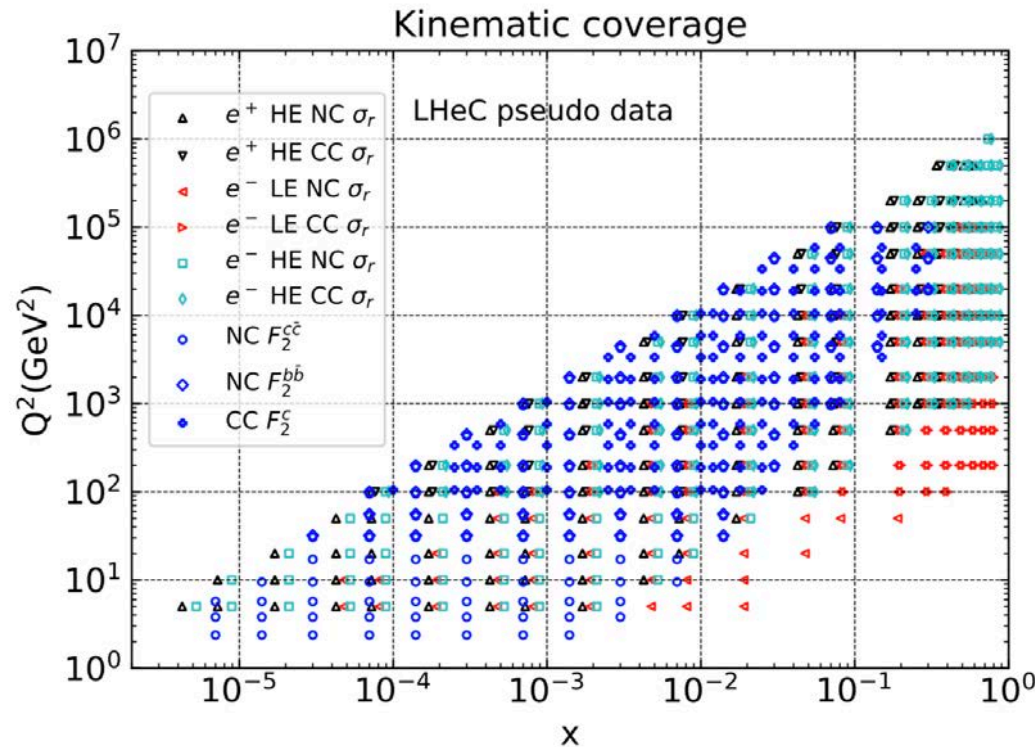
×15/120 extension in  $Q^2$ ,  $1/x$  reach vs HERA

# LHeC simulated data and QCD fits

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

**LHeC 1<sup>st</sup> Run**  
 50 fb<sup>-1</sup> e<sup>-</sup> only; 3 yrs;  
 concurrent with HL-LHC

**LHeC full incl.**  
 1000 fb<sup>-1</sup> e<sup>-</sup> (P<sub>e</sub>=-0.8)  
 50 fb<sup>-1</sup> e<sup>-</sup> (P<sub>e</sub>=+0.8)  
 1 fb<sup>-1</sup> e<sup>+</sup>  
 1 fb<sup>-1</sup> e<sup>-</sup> (E<sub>p</sub>=1 TeV)

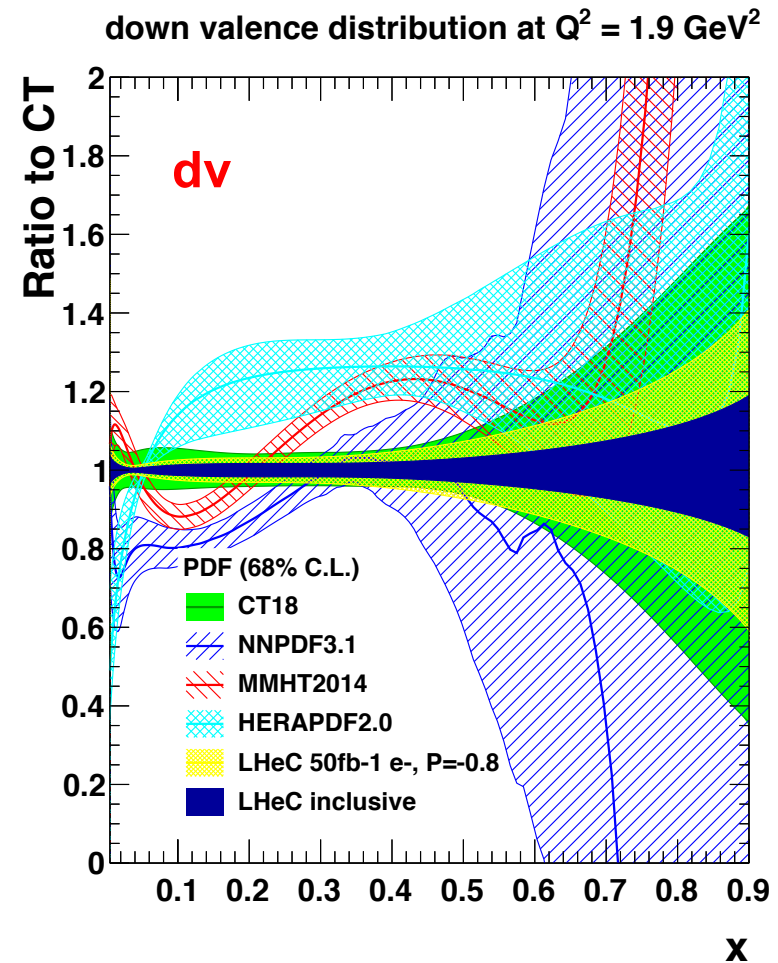
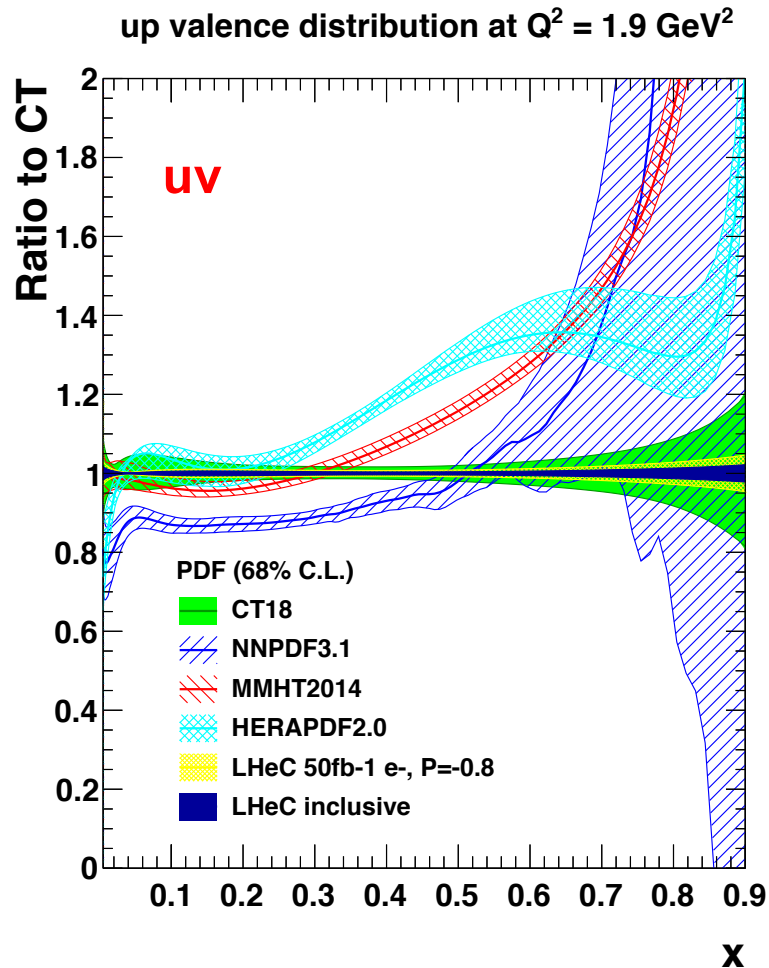


E<sub>e</sub>: 50 GeV  
 HE: E<sub>p</sub>=7 TeV  
 LE: E<sub>p</sub>=1 TeV

**full set of systematic uncertainties considered:**  
 elec. energy scale: 0.1%  
 hadr. energy scale 0.5%  
 radiative corr.: 0.3%  
 $\gamma p$  at high y: 1%  
 uncorrelated uncert.: 0.5%  
 CC syst.: 1.5%  
 luminosity: 0.5%

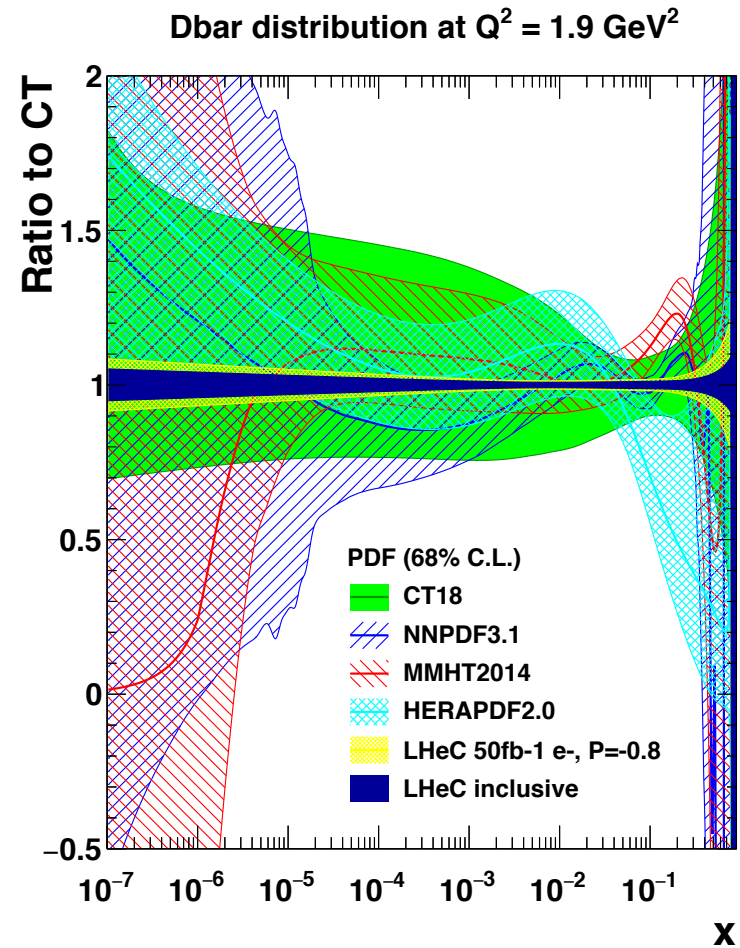
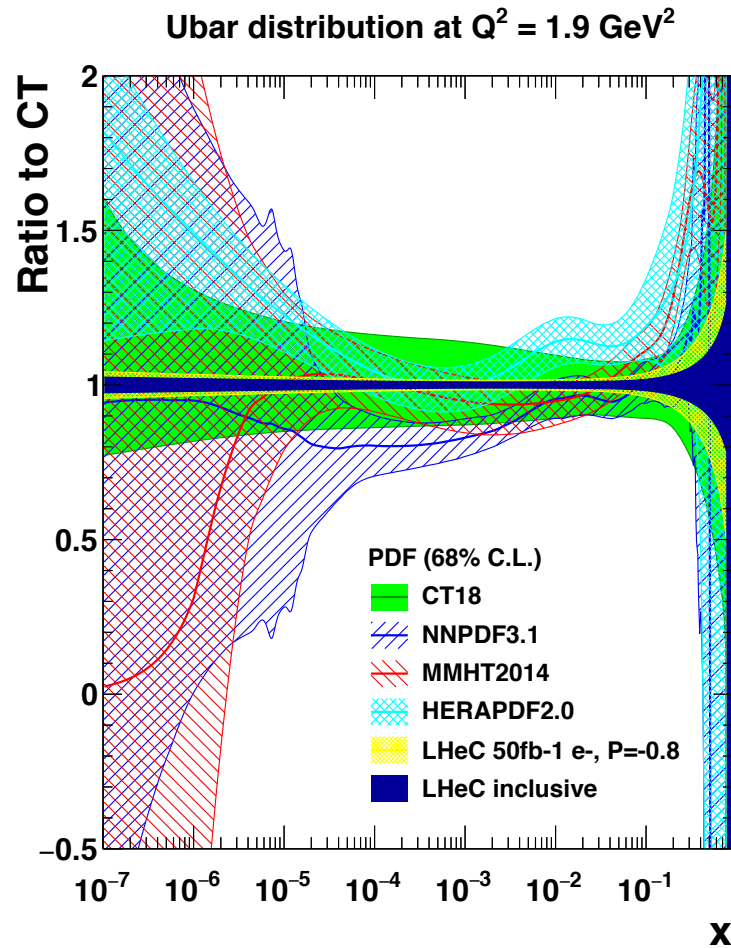
- QCD analysis a la HERAPDF2.0**, except **more flexible**, notably in **NO constraint** requiring dbar=ubar at small x;
- 4+1** xuv, xdv, xUbar, xDbar and xg (**14 free parameters**, cf. 10 by default in CDR)
- 5+1** xuv, xdv, xUbar, xdbar, xsbar and xg (if strange and HQ included; **17 free parameters**)

# valence quarks

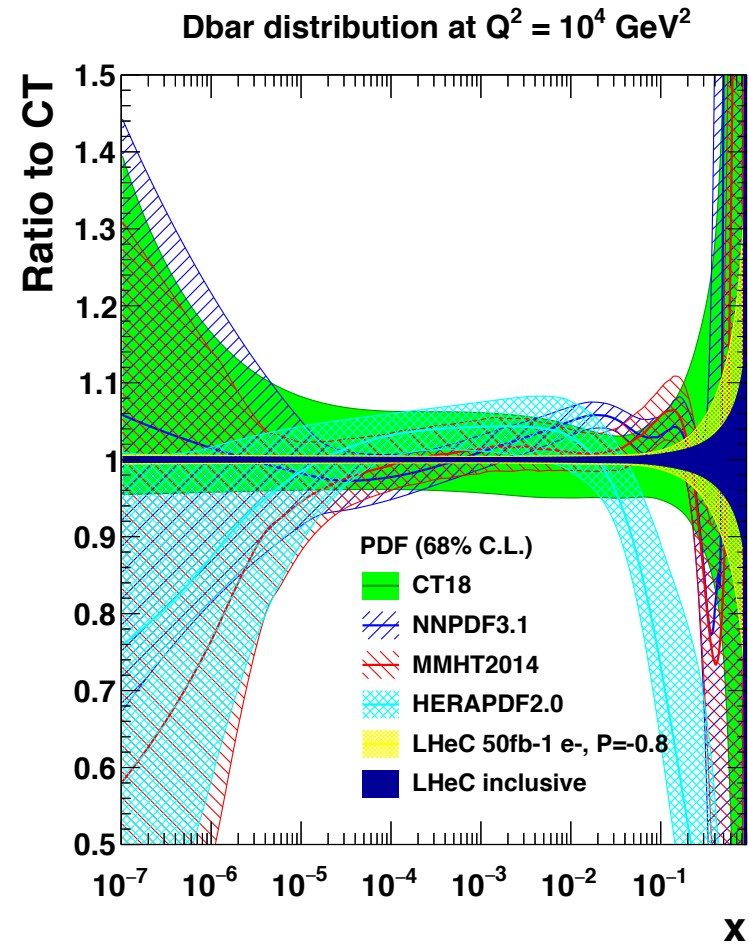
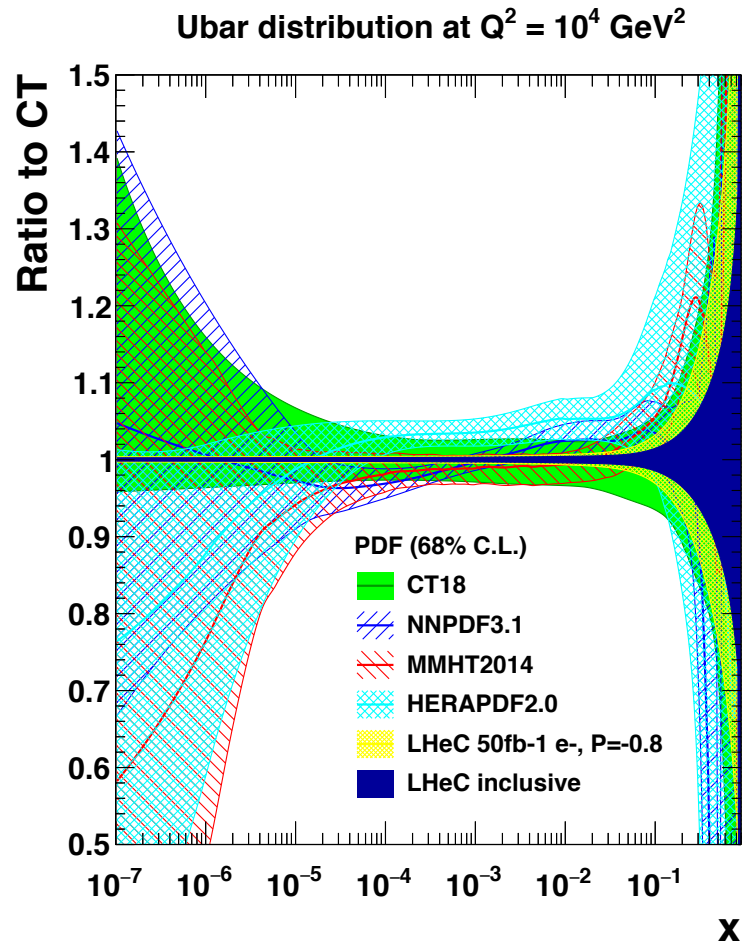


- precision determination, free from higher twist corrections and nuclear uncertainties
- **large x crucial for HL/HE-LHC and FCC searches;** also relevant for DY, MW etc.;
- can also resolve long-standing mystery of d/u ratio at large x

# sea quarks



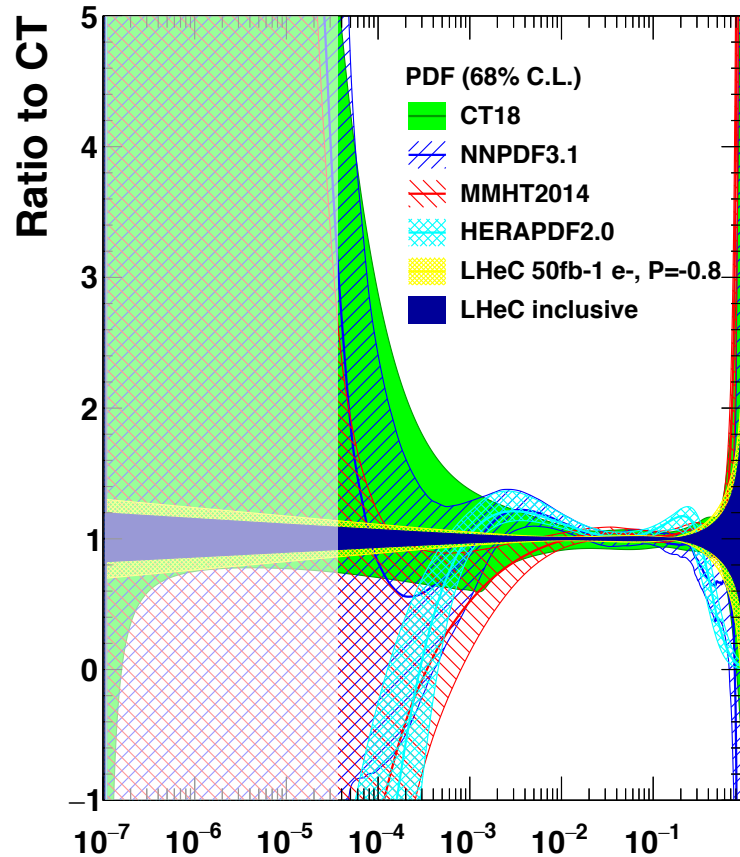
# sea quarks @ $Q^2=10^4 \text{ GeV}^2$





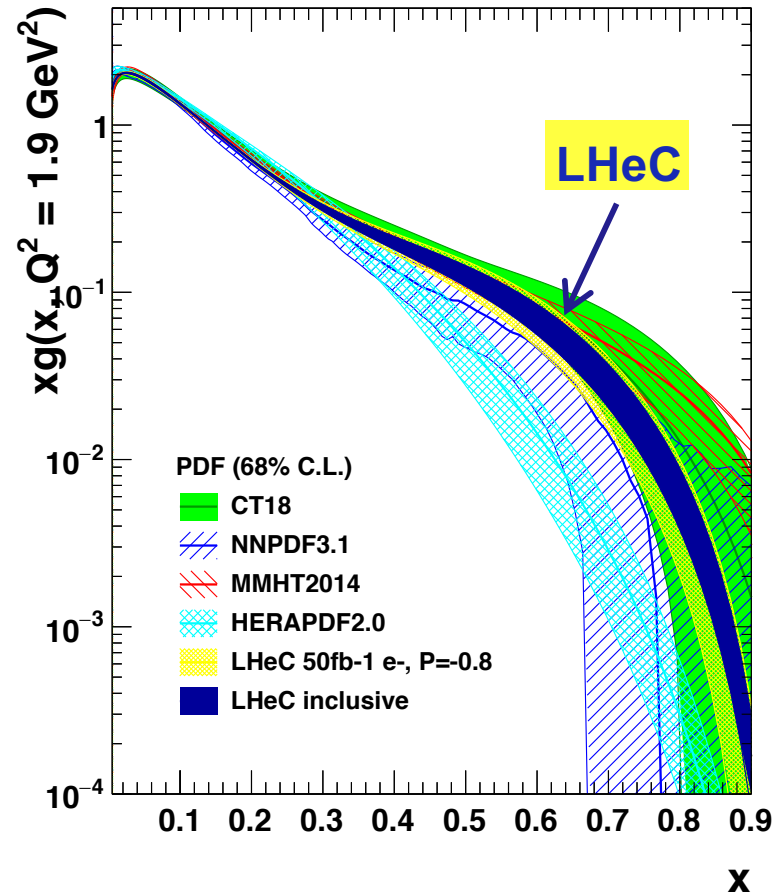
# gluon

gluon distribution at  $Q^2 = 1.9 \text{ GeV}^2$



**exploration of small x QCD:** DGLAP vs BFKL; non-linear evolution; gluon saturation; implications for ultra high energy neutrinos

gluon distribution at  $Q^2 = 1.9 \text{ GeV}^2$



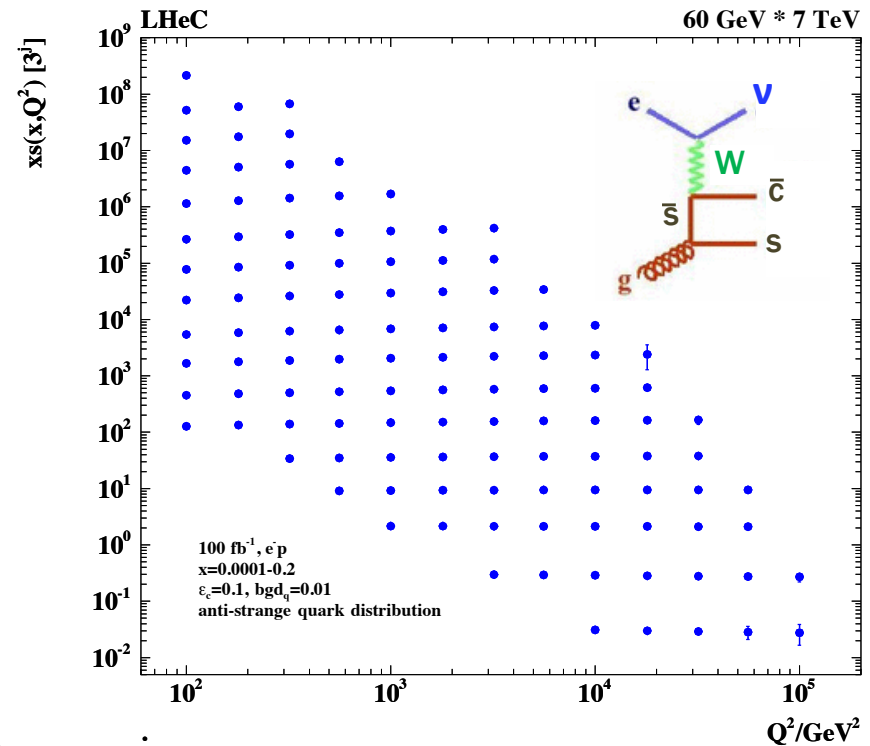
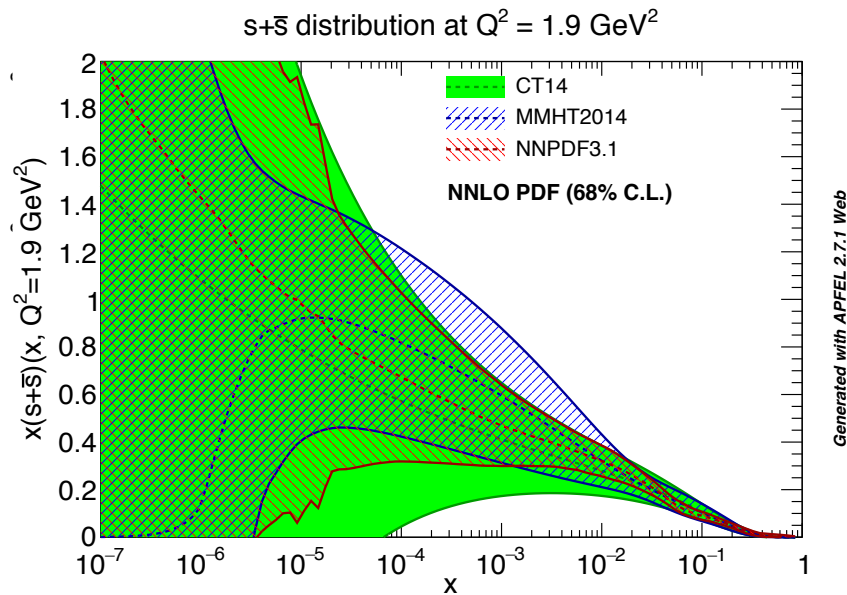
gluon at large x is small and currently poorly known; **crucial for BSM searches**



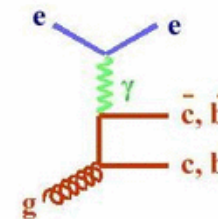
# strange, c, b

- **strange pdf** poorly known
- suppressed c.f. 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

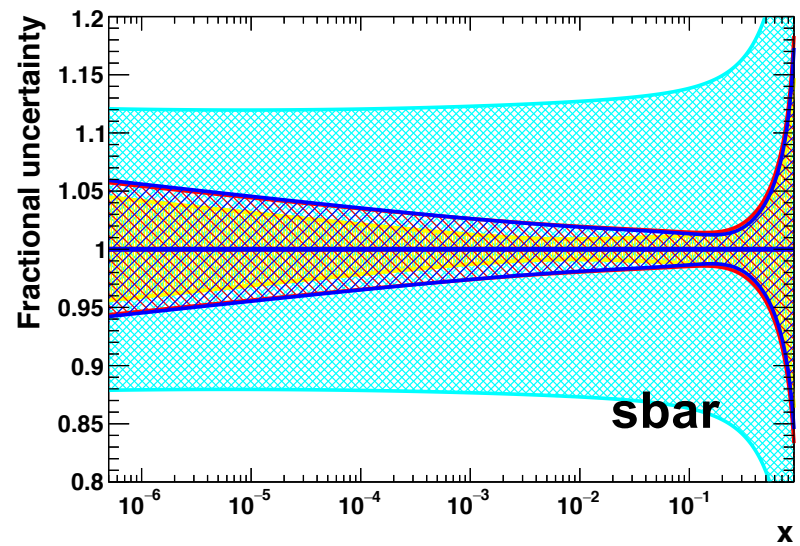
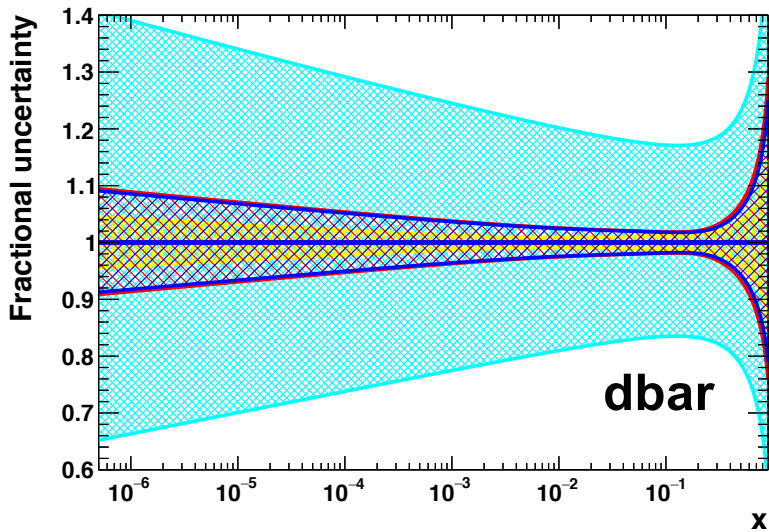
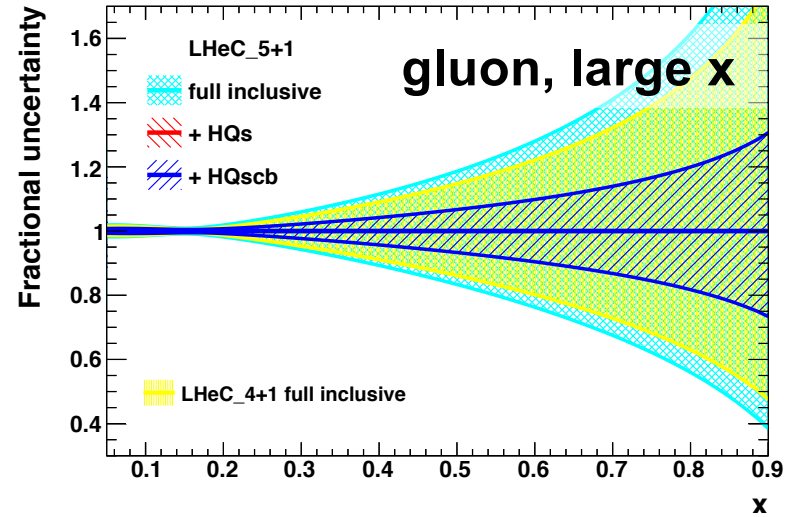
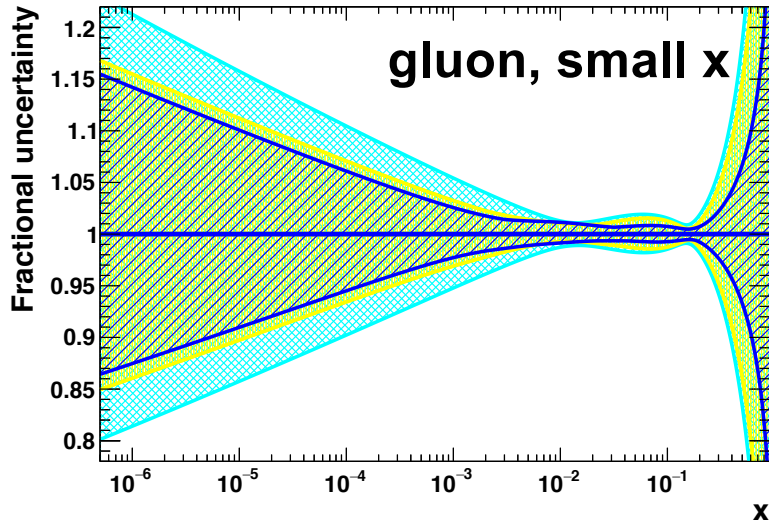


- **c, b**: enormously extended range and much improved precision c.f. HERA
- $\delta M_c = 50 \text{ (HERA) to } 3 \text{ MeV}$ : impacts on  $\alpha_s$ , regulates ratio of charm to light, crucial for precision t, H
- $\delta M_b$  to 10 MeV; MSSM: Higgs produced dominantly via  $b\bar{b} \rightarrow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



# impact of s, c, b

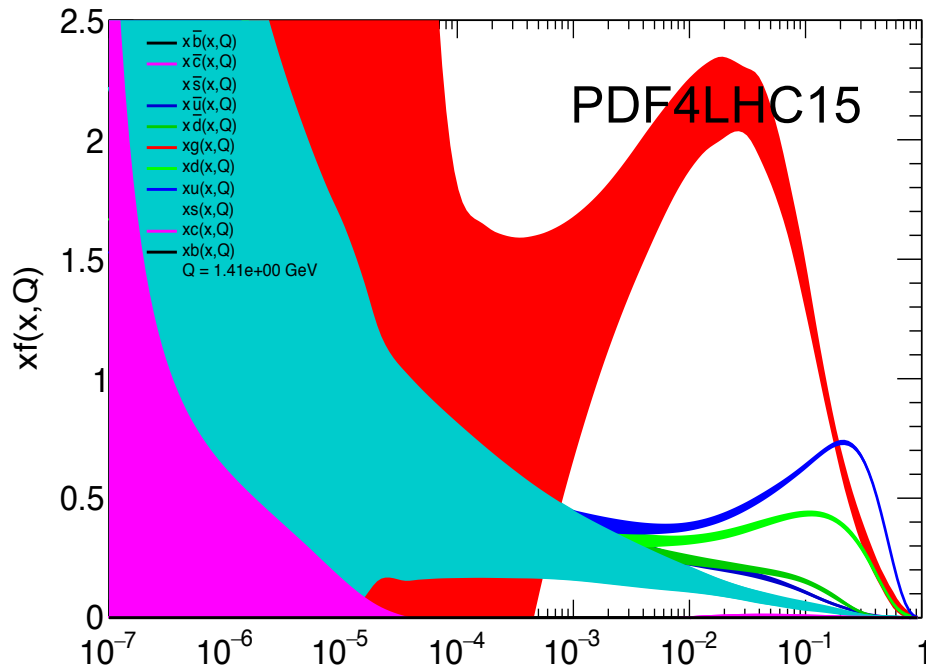
see also,  
[arXiv:1907.01014](https://arxiv.org/abs/1907.01014)



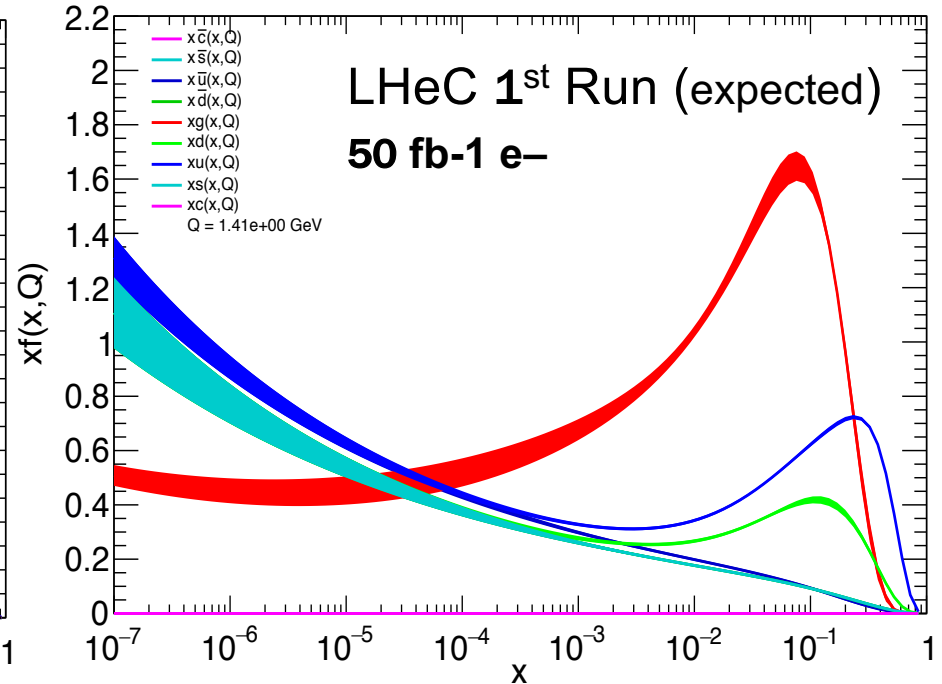
- **4+1** xuv, xdv, xUbar, xDbar + xg (14)

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

# summary of LHeC pdfs



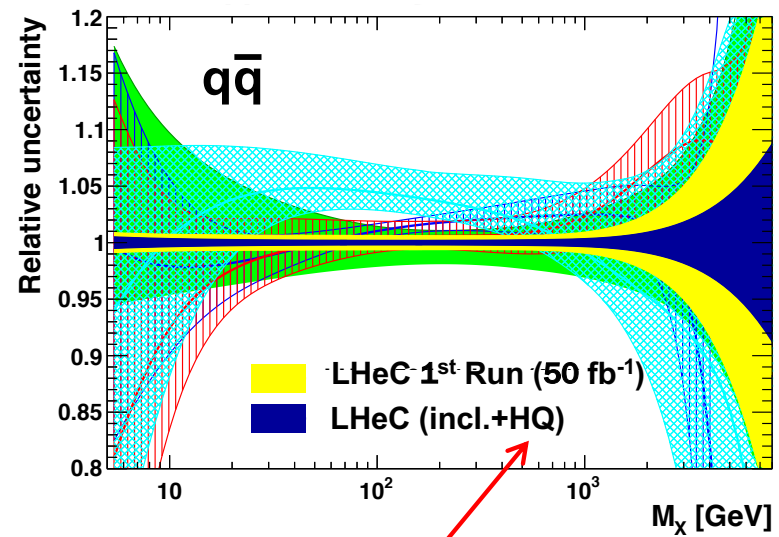
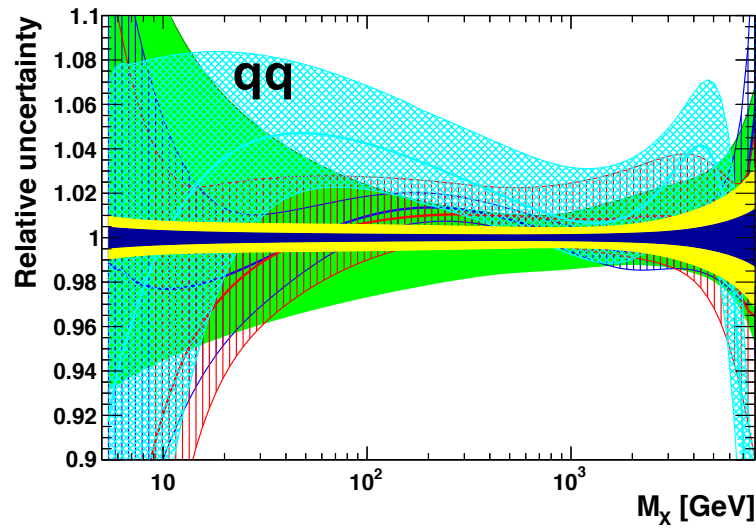
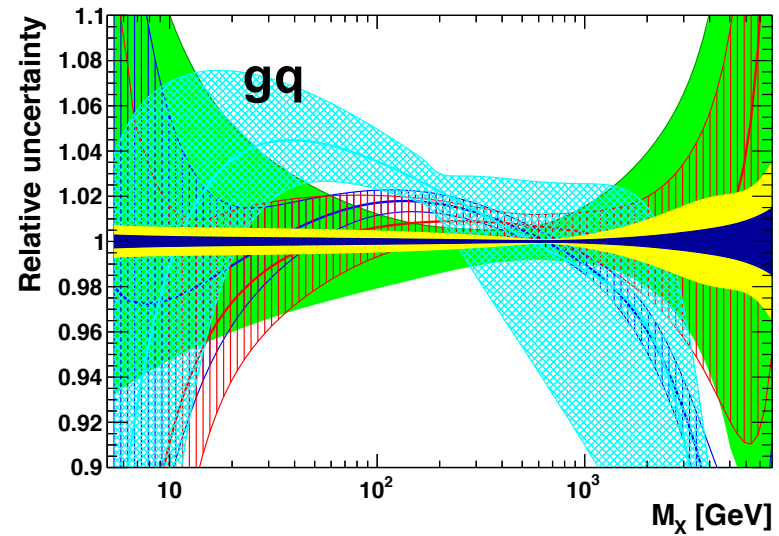
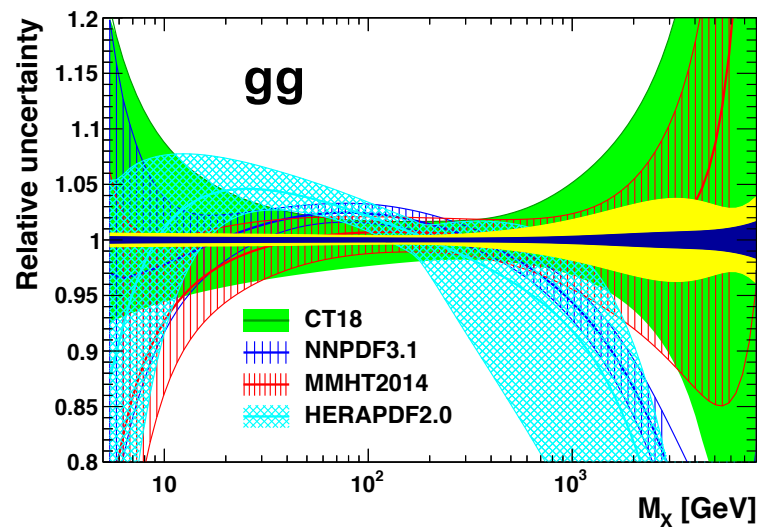
situation today



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

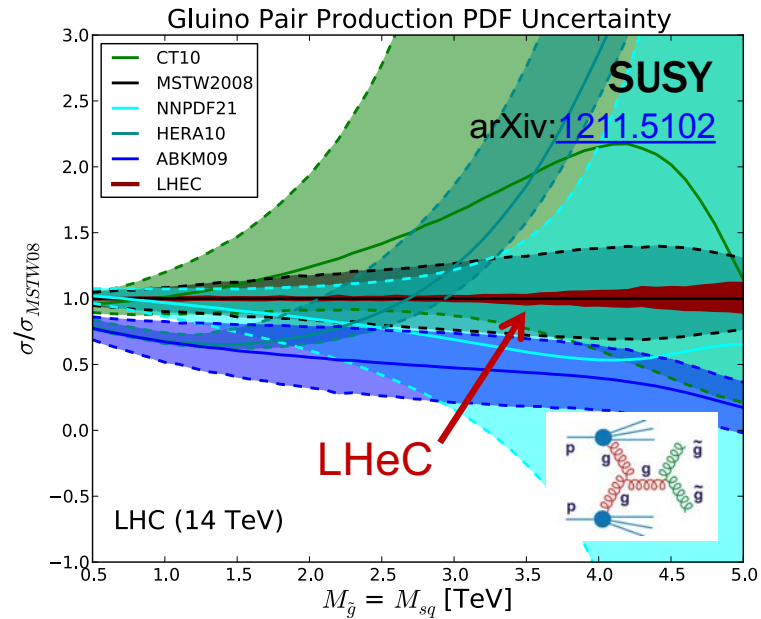
with further improvements after full running period, plus HQs, (DIS jets, ... )

# pdf luminosities @ 14TeV

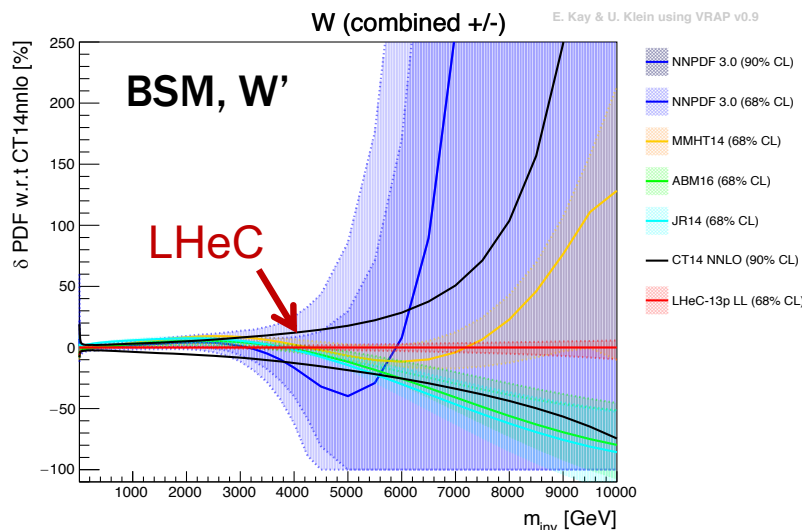
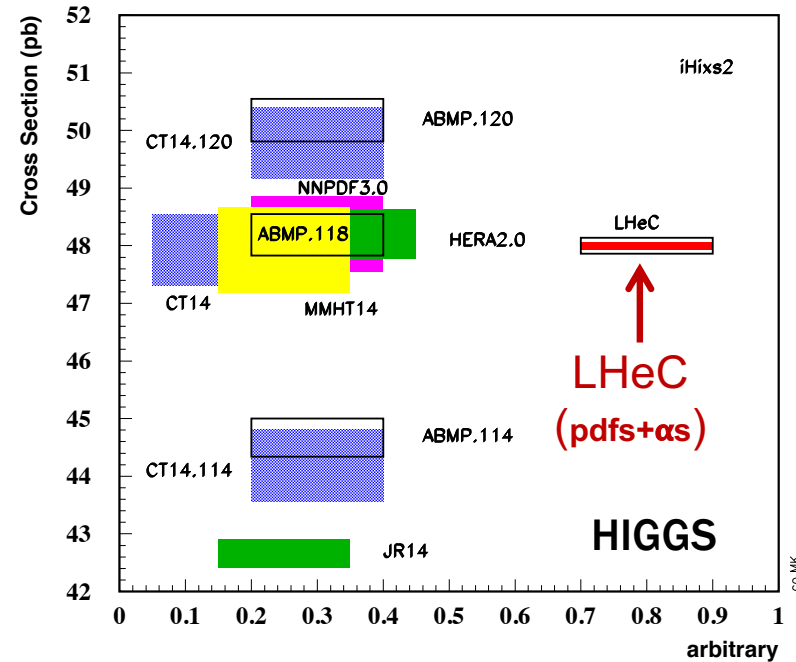


(s,c,b) also included, with more flexible (5+1) fit

# empowering the LHC

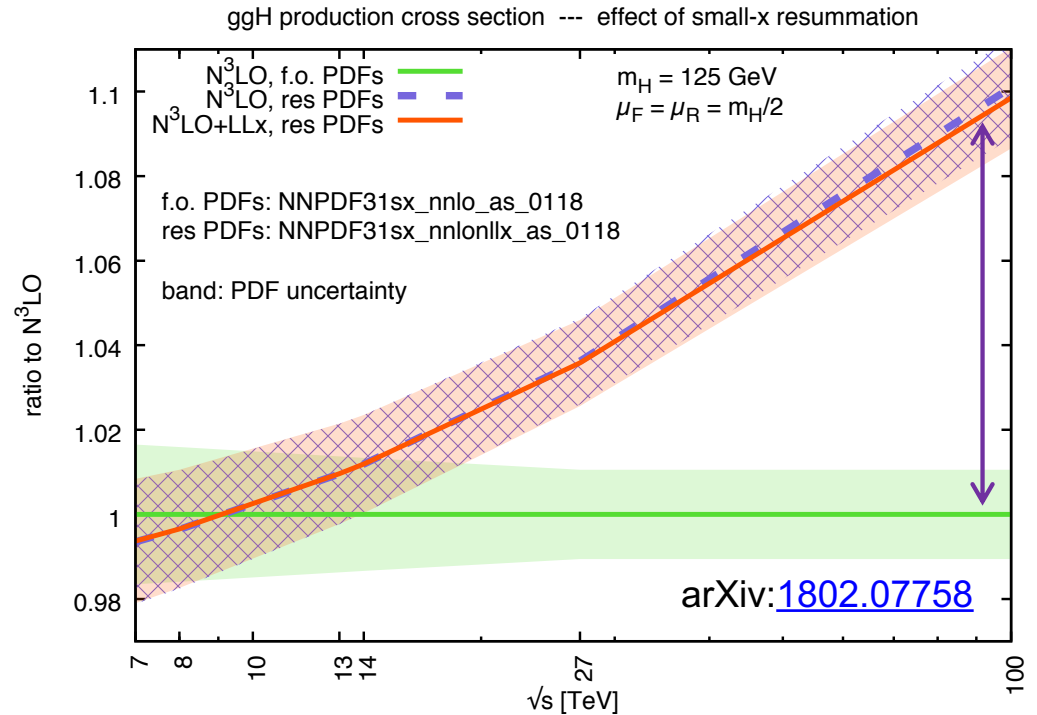
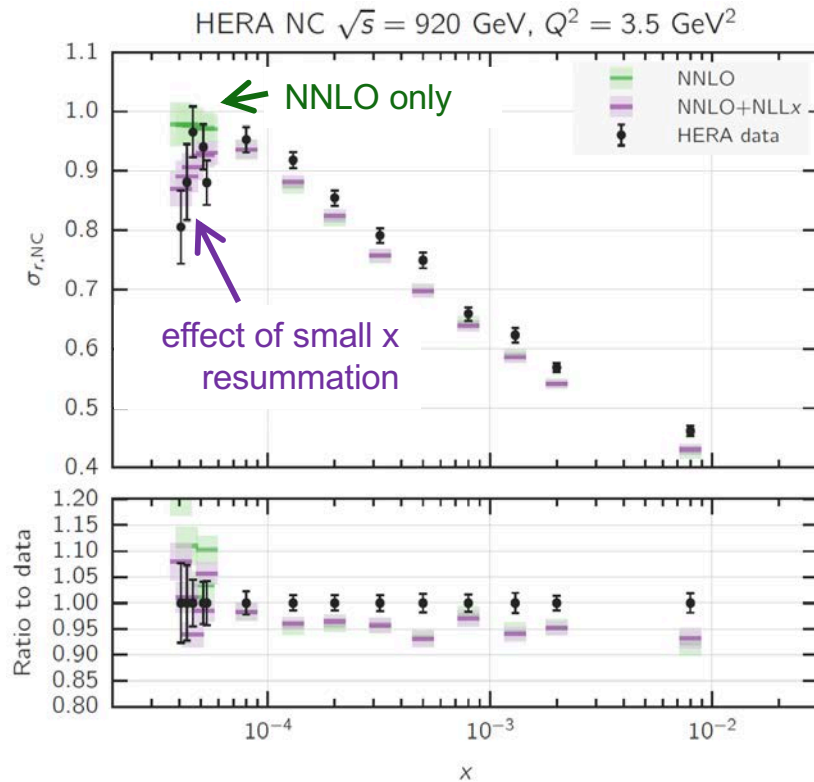


NNLO pp-Higgs Cross Sections at 14 TeV



- external, reliable, precise pdfs needed for range extension and interpretation
- BSM, gluons and quarks at large x (SUSY, LQs, additional high mass bosons, ...)
- Higgs, theory uncert. dominated by pdfs+ $\alpha_s$
- SM parameters, EG. MW, sin<sup>2</sup> $\theta_W$  (see white paper)

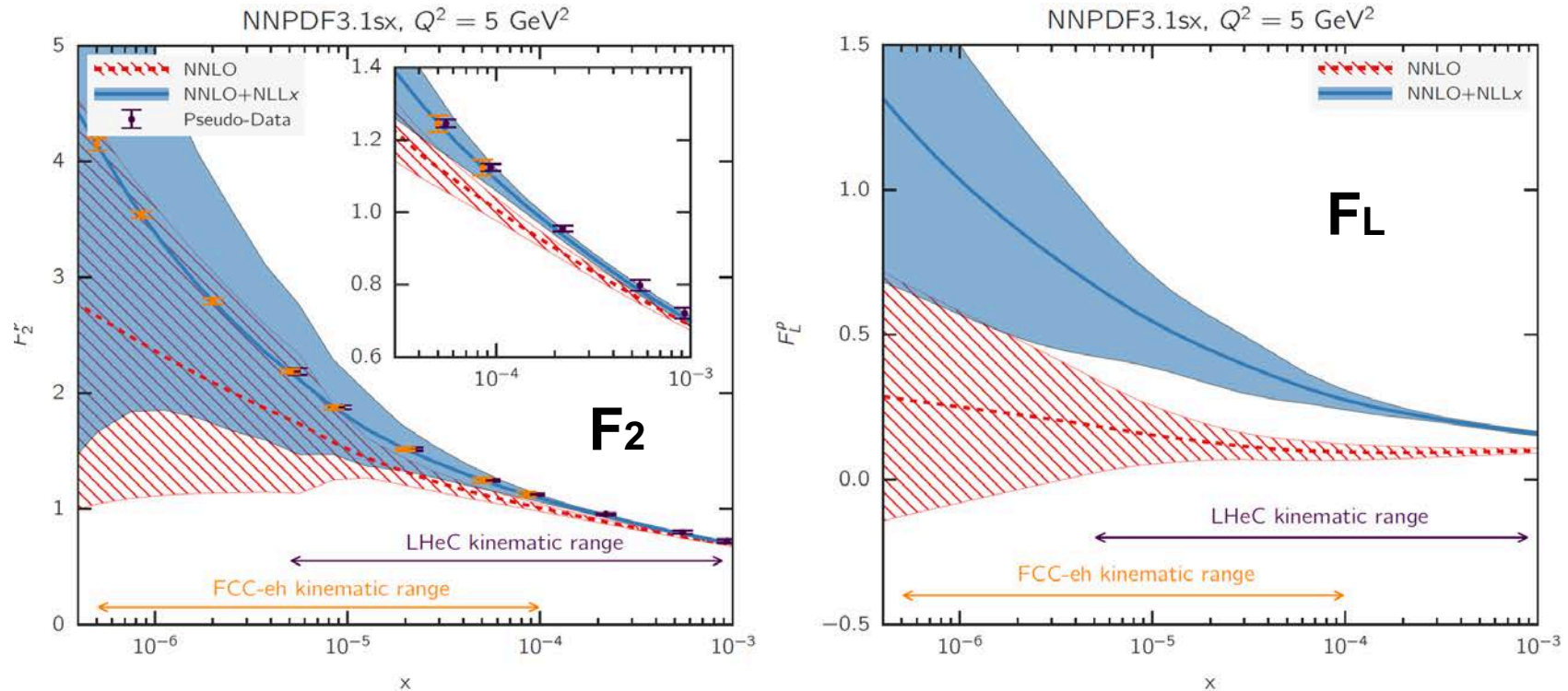
# more on small x QCD



- evidence for onset of BFKL dynamics in HERA inclusive data,
- arXiv:[1710.05935](https://arxiv.org/abs/1710.05935); confirmed in xFitter study, arXiv:[1802.00064](https://arxiv.org/abs/1802.00064)
- LHeC and FCC-eh have unprecedented kinematic reach to **explore small x** phenomena
- effect of small x resummation on ggH cross section for LHC, HE-LHC, FCC
- impact for LHC, and most certainly at ultra low x values probed at FCC**



# LHeC sensitivity to small x phenomena



$F_2$  and  $F_L$  predictions for simulated kinematics of **LHeC** and **FCC-eh**

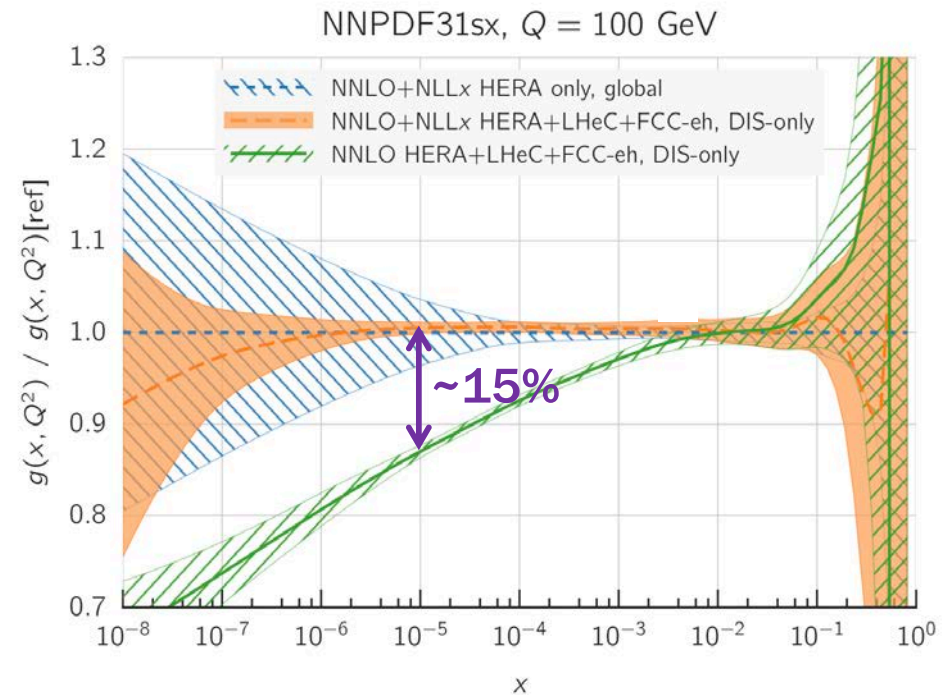
- **ep simulated data very precise** – significant constraining power to discriminate between theoretical scenarios of small  $x$  dynamics, arXiv:[1710.05935](https://arxiv.org/abs/1710.05935)
- **measurement of  $F_L$  has a critical role to play**  
see, EG. arXiv:[1802.04317](https://arxiv.org/abs/1802.04317)

# small x resummation

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

- **X<sup>2</sup> per DOF**      LHeC / FCC-eh
- **NNLO:**              **1.71 / 2.72**
- **NNLO+NLLx**      **1.22 / 1.34**

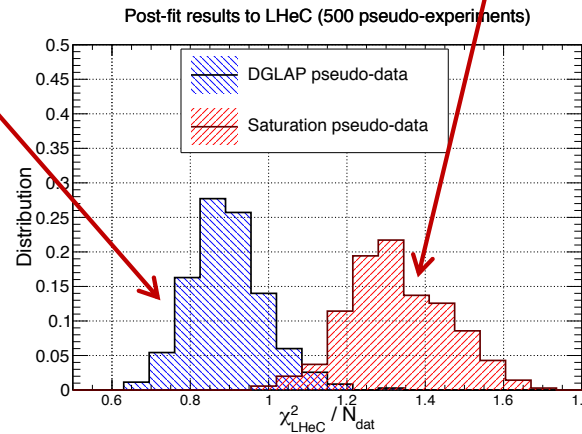
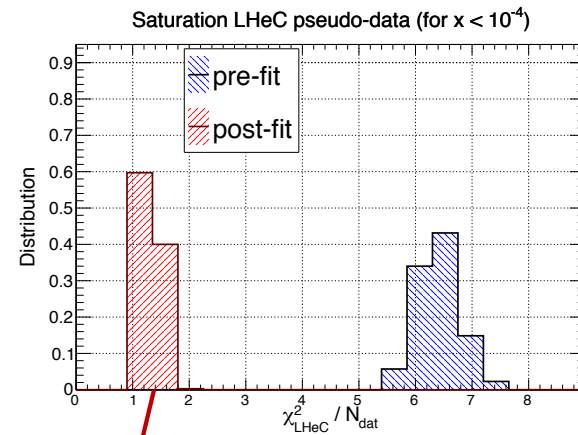
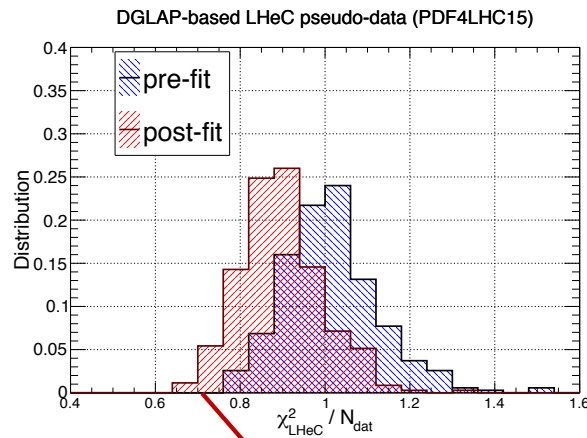
- substantial difference in extracted gluon ( **10 (15)%** at  $x=10^{-4}$  ( $10^{-5}$ ) )
- much larger than precision with which gluon can be determined using LHeC or FCC-eh DIS data



- **large sensitivity and discriminatory power to pin down details of small x QCD dynamics**

# non-linear QCD dynamics

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

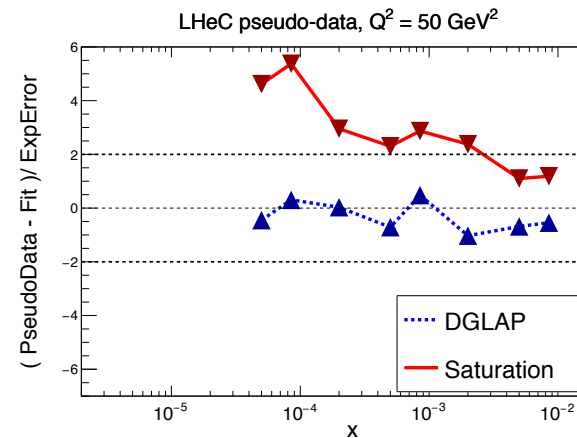
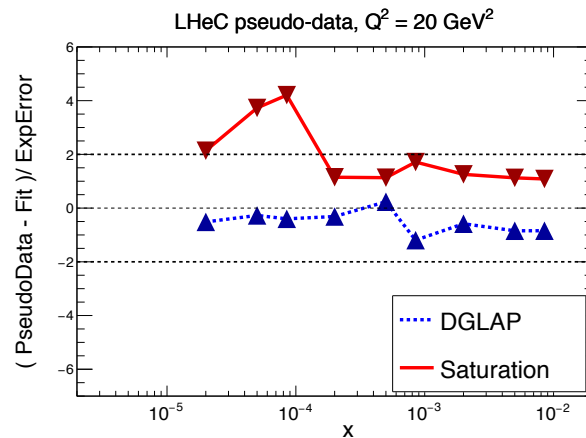
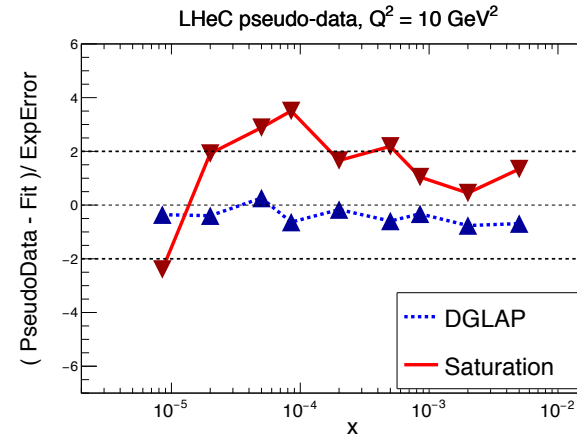
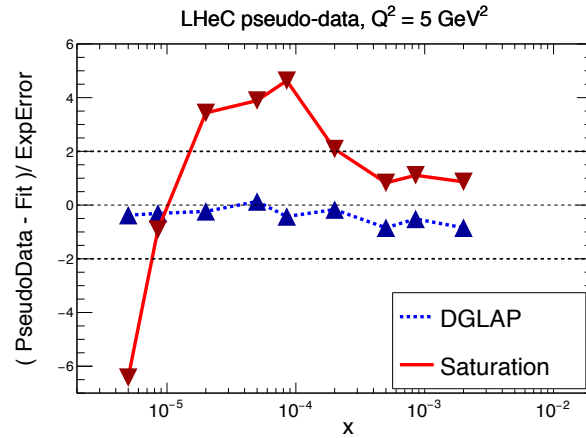


LHeC inclusive NC pseudo-data produced using **DGLAP**, and fitted with **DGLAP**

LHeC inclusive NC pseudo-data produced using (GBW) **saturation model for  $x \leq 10^{-4}$** , and fitted with **DGLAP**

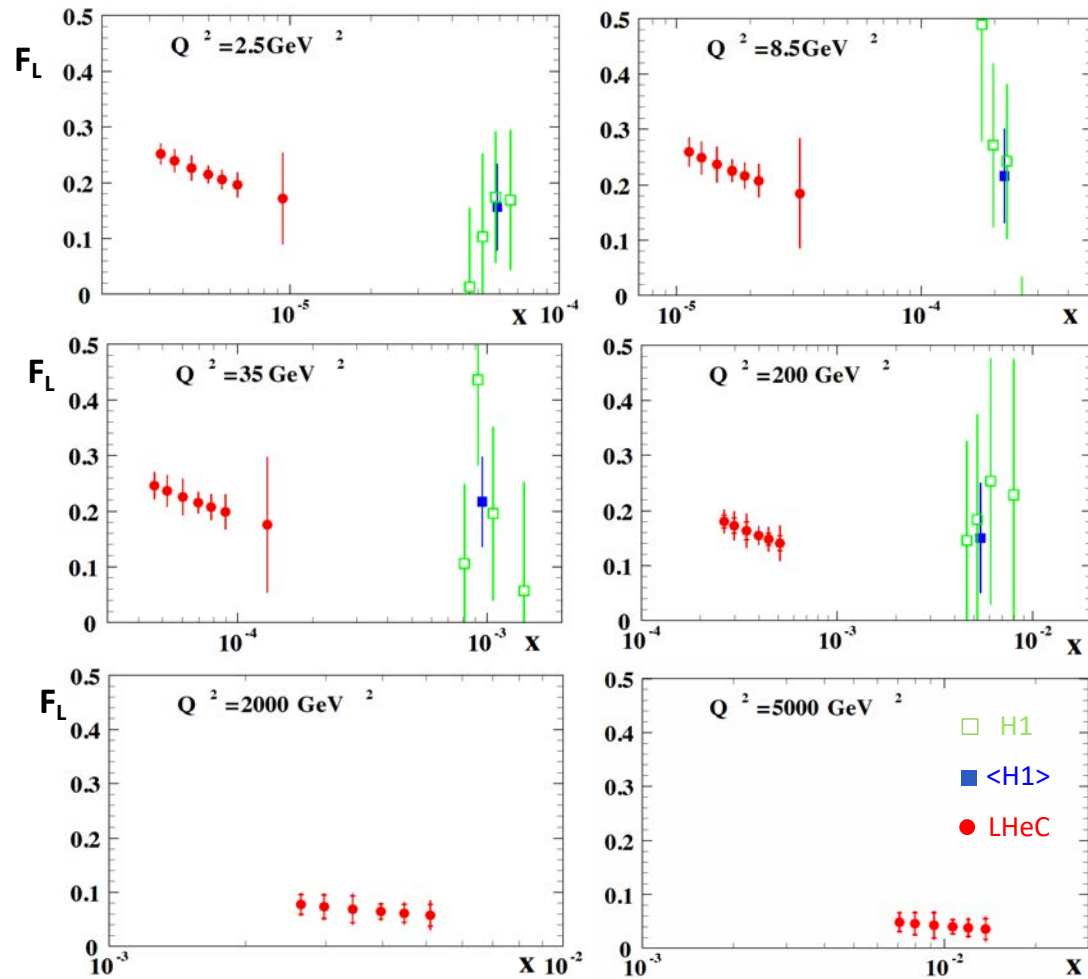
LHeC HE and LE incl. NC e-p;  
( $N_{\text{exp}}=500$  independent sets of LHeC pseudodata, each characterised by different random fluctuations)

# non-linear QCD dynamics



- 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**

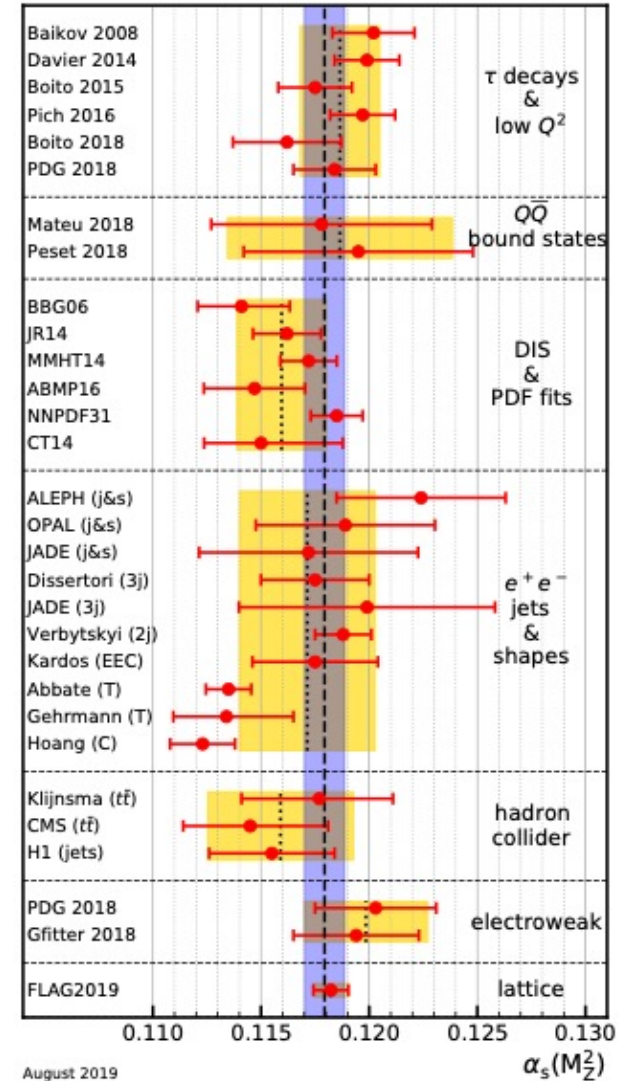
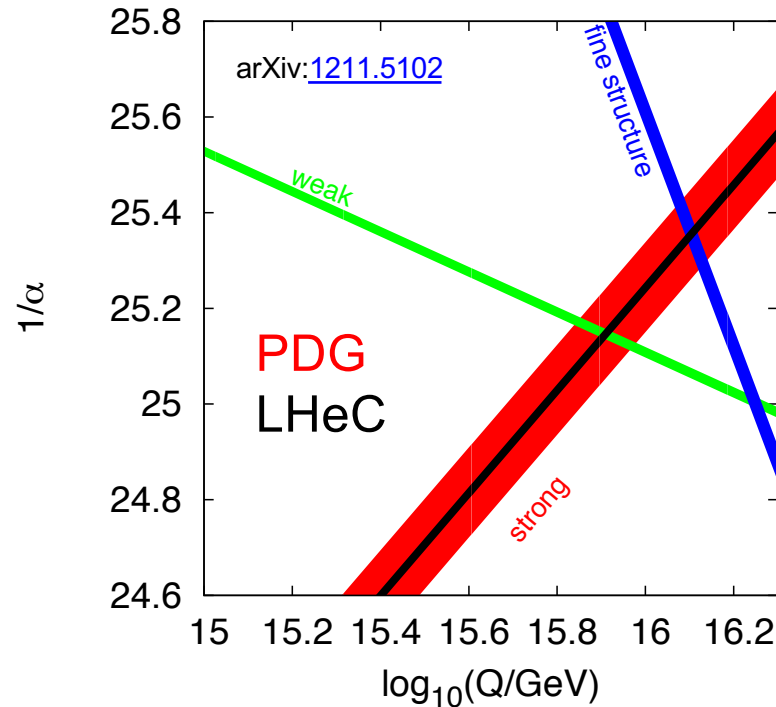
# FL from the LHeC



- **expect significant additional discrimination from dedicated precision measurement of  $F_L$**  (not yet included in shown studies); **incorrect small  $x$  treatment unlikely to accommodate both  $F_2$  and  $F_L$**

# strong coupling, $\alpha_s$

PDG19



- $\alpha_s$  is the least known coupling
- needed: for cross section predictions, including Higgs; to constrain GUT scenarios, etc.
- measurements not all consistent:– what is true central value, uncertainty? is  $\alpha_s(\text{DIS})$  lower than world average? role of lattice QCD?

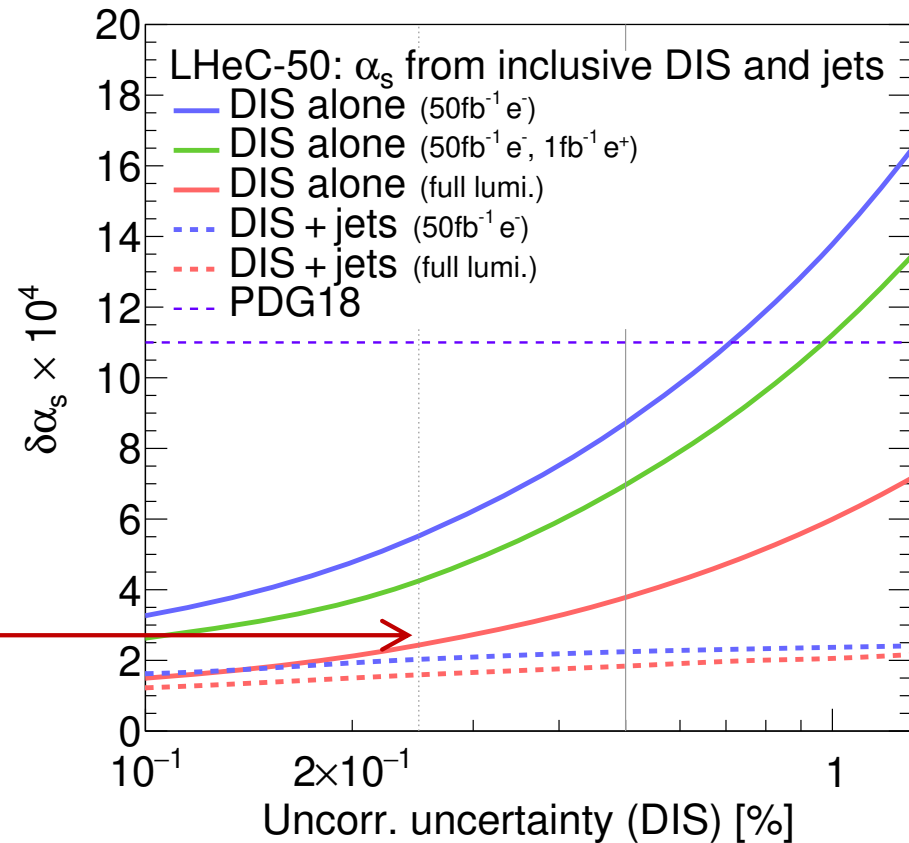
world ave.  $\alpha_s(M_Z^2) = 0.1179 \pm 0.0010$



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

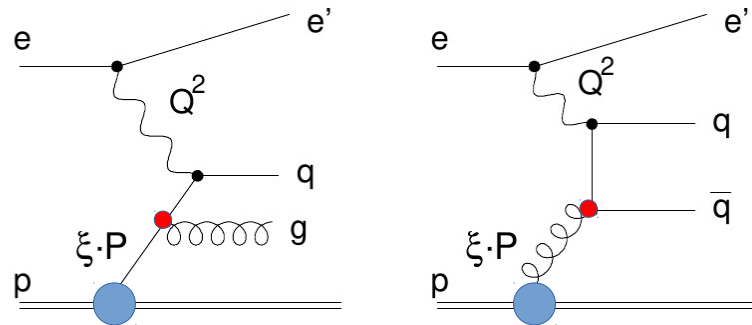
- $\alpha_s$  from inclusive NC/CC DIS:
- simultaneous determination of **pdfs** and  $\alpha_s$  in **NNLO QCD** fit
- 3 LHeC scenarios:
  - LHeC 1<sup>st</sup> Run (50 fb<sup>-1</sup> e-p)
  - plus 1 fb<sup>-1</sup> positron data
  - full inclusive LHeC dataset (1 ab<sup>-1</sup>)

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

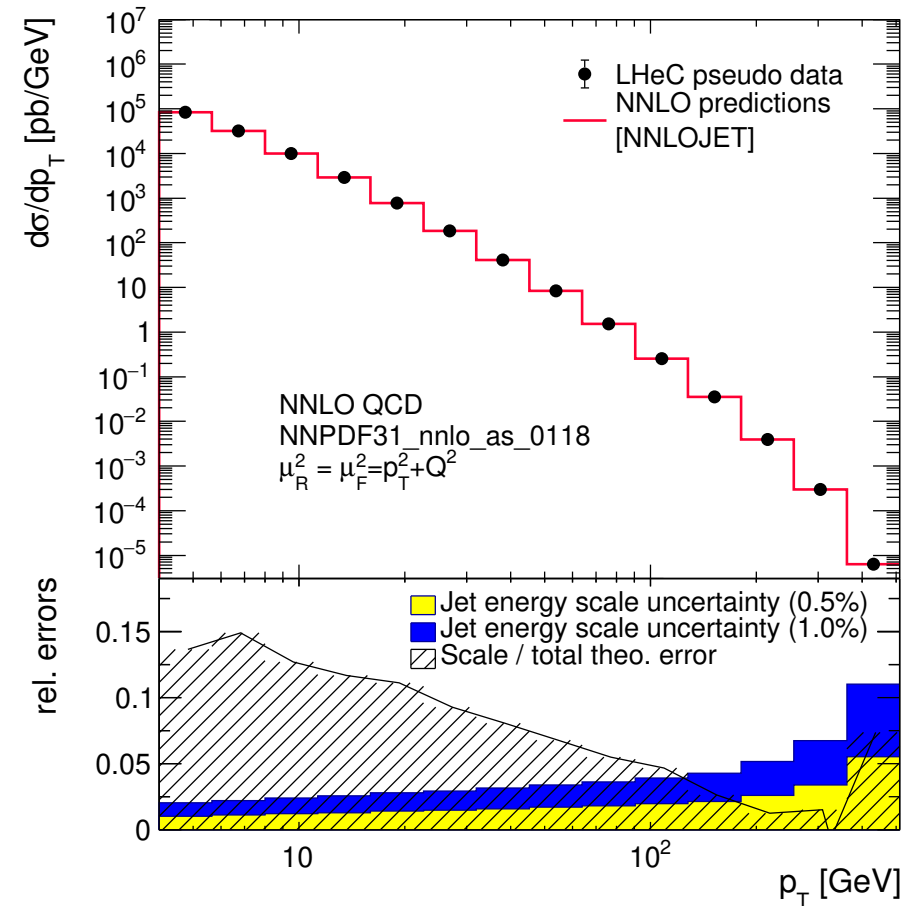


- $\alpha_s$  to better than 2 permille experimental uncertainty!
- inclusion of jet cross sections yields further improvement, and stabilises against uncorrelated uncertainty scenario →

# NC DIS jet production at the LHeC



- **sensitive to  $\alpha_s$  at lowest order**
- different dependencies on  **$xg(x)$**  and  **$\alpha_s$**  c.f. inclusive DIS; 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

# $\alpha_s$ from LHeC NC DIS jet production

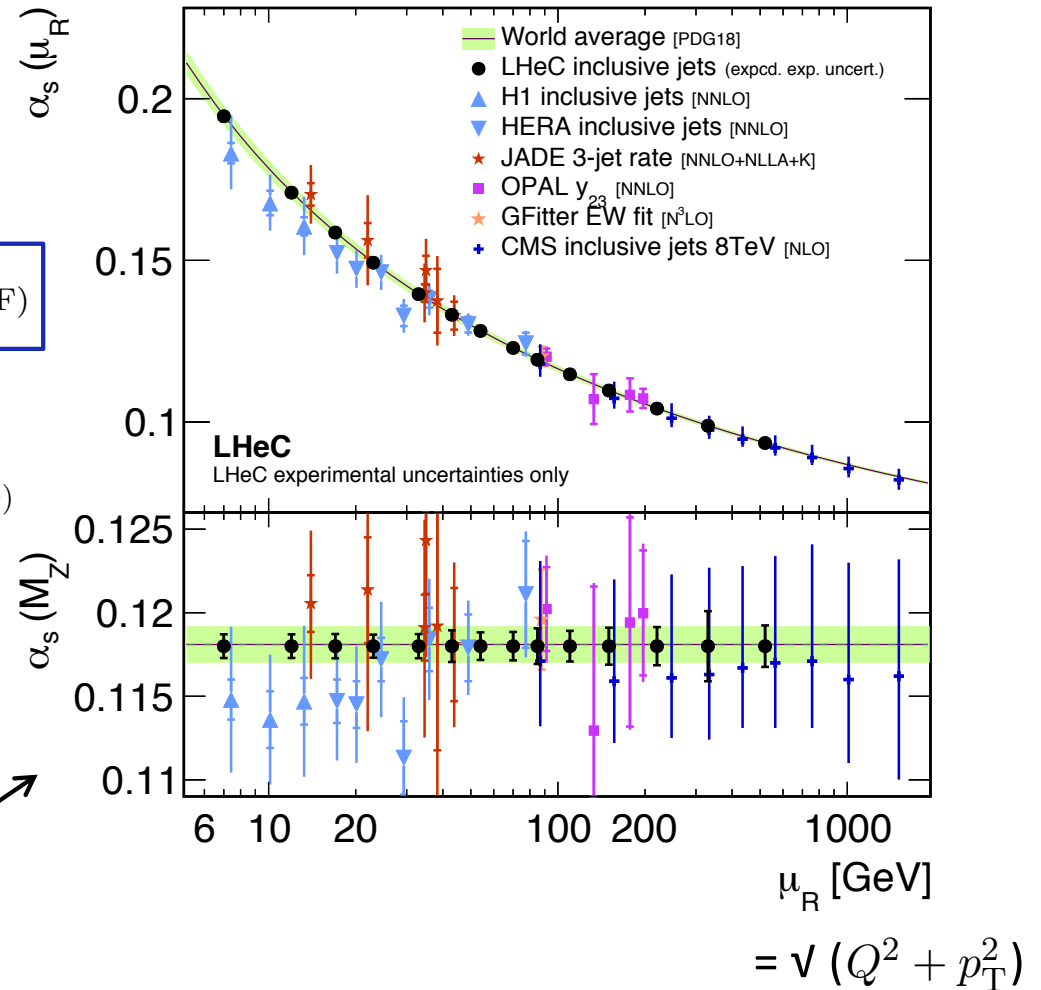
- $\alpha_s$  extracted in **NNLO QCD** fit to LHeC simulated jet data only
- methodology as for arXiv:[1709.07251](https://arxiv.org/abs/1709.07251), [1906.05303](https://arxiv.org/abs/1906.05303)

$$\Delta\alpha_s(M_Z)(\text{jets}) = \pm 0.00013_{(\text{exp})} \pm 0.00010_{(\text{PDF})}$$

- **extraordinary experimental precision**
- scale uncertainty dominates  $\Delta\alpha_s(M_Z) = 0.0035$  (NNLO)  
**restricting to higher  $p_T$  or  $Q^2$  can reduce to**  
 $\Delta\alpha_s(M_Z) \approx 0.0010$   
**trade off with increased experimental uncertainties**  
 (N<sup>3</sup>LO by 2030s ?)

- $\alpha_s$  running tested over two orders of magnitude in  $\mu_R$

- enormous improvement over other jet-based measurements
- LHeC uniquely connects low  $\mu(\text{GeV})$  scales with high  $\mu(\text{MZ})$  scales



# LHeC $\alpha_s$ summary

- LHeC is an ideal QCD laboratory
- connects low-scale to Z-pole and beyond with high experimental precision

- inclusive NC/CC DIS only:**

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

- inclusive jet cross sections only:**

$$\Delta\alpha_s(M_Z)(\text{jets}) = \pm 0.00013_{(\text{exp})} \pm 0.00010_{(\text{PDF})}$$

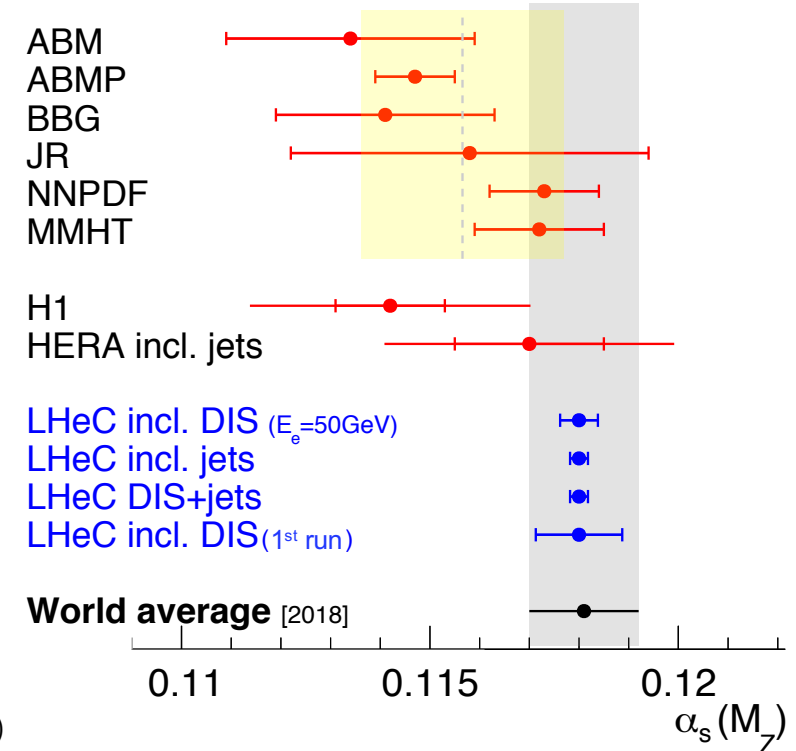
- inclusive DIS and jet cross sections:**

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

- achievable precision on same level as  $\alpha_s$  determination from FCC-ee
- QCD theory uncertainties will be limiting factor for ultimate precision

- other sensitive processes/measurements:** dijets, multijets, HQs, jets in  $\gamma p$ , event shapes, ...

## $\alpha_s$ determinations at NNLO:



# summary

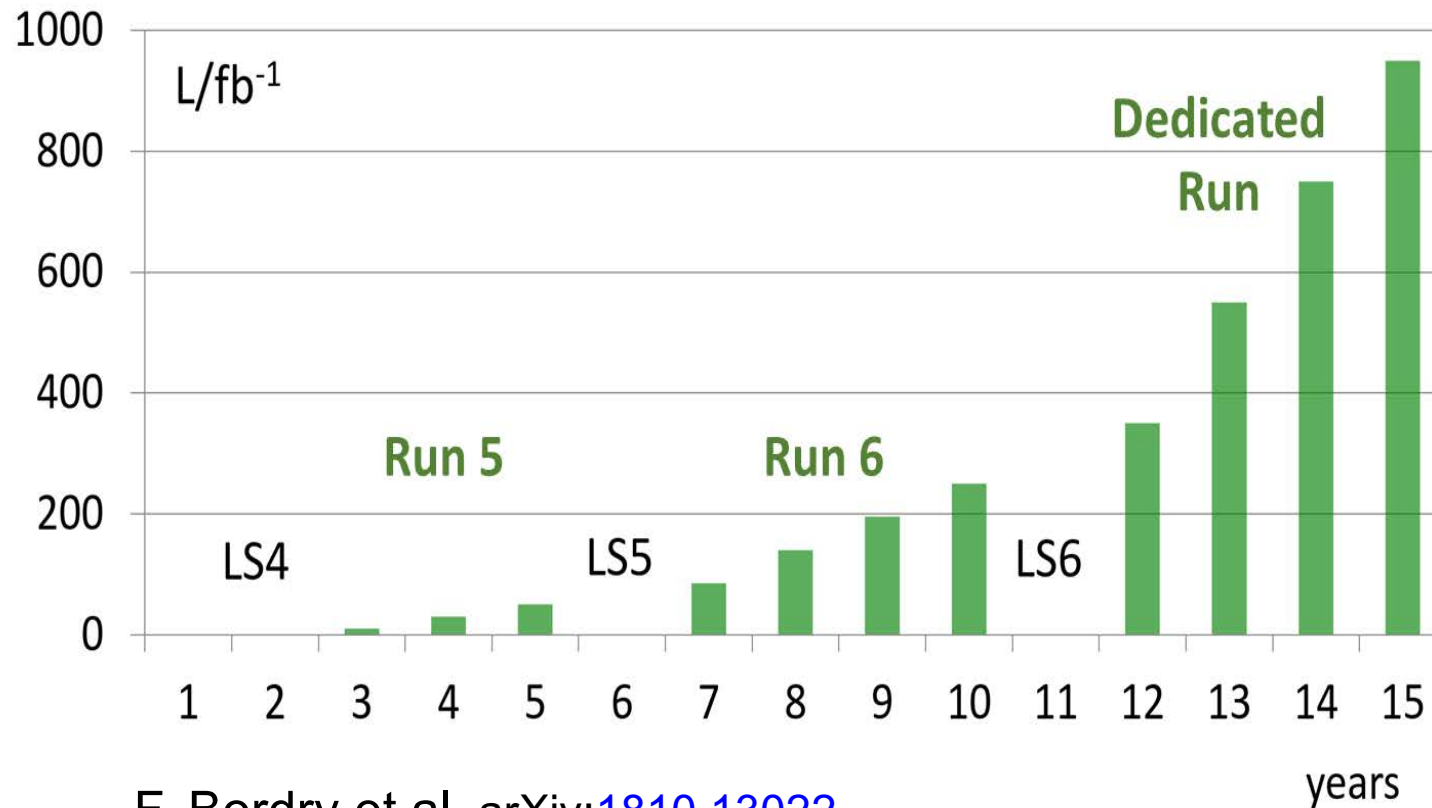
- energy frontier **electron-proton colliders** essential for full exploitation of current and future hadron colliders (Higgs, BSM, electroweak, ...)
- **external precision pdf input**; complete  $q, g$  unfolding, high luminosity  $x \rightarrow 1$ , s, c, b, (t); N3LO; small  $x$ ; strong coupling to permille precision; ...
- NEW LHeC white paper summarises wealth of new and updated studies, [arXiv:2007.14491](https://arxiv.org/abs/2007.14491)
- 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
- **$\alpha_s$  to permille exp. precision also achievable early**, with use of NC DIS jets
- unprecedented access to novel kinematic regime, with **unique potential to explore novel small  $x$  phenomena**

extras



# LHeC timescale

**LHeC** projected Integrated Luminosity:



F. Bordry et al. arXiv:[1810.13022](https://arxiv.org/abs/1810.13022)

# LHeC simulated data

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

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

Parameter	Unit	Data set								
		D1	D2	D3	D4	D5	D6	D7	D8	D9
Proton beam energy	TeV	7	7	7	7	1	7	7	7	7
Lepton charge		-1	-1	-1	-1	-1	+1	+1	-1	-1
Longitudinal lepton polarisation		-0.8	-0.8	0	-0.8	0	0	0	+0.8	+0.8
Integrated luminosity	fb <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  $Ep$  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.

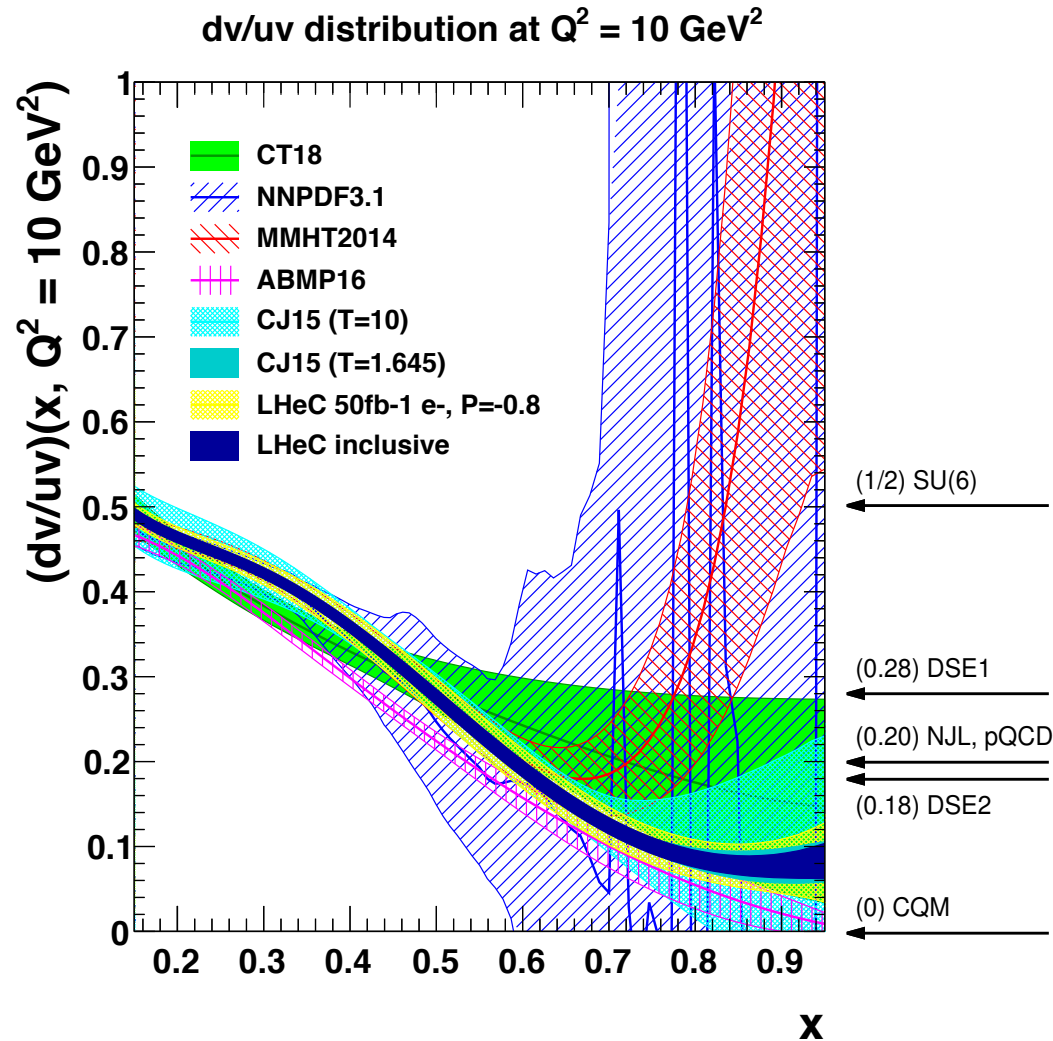
# LHeC pdf parameterisation

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

# d/u at large x

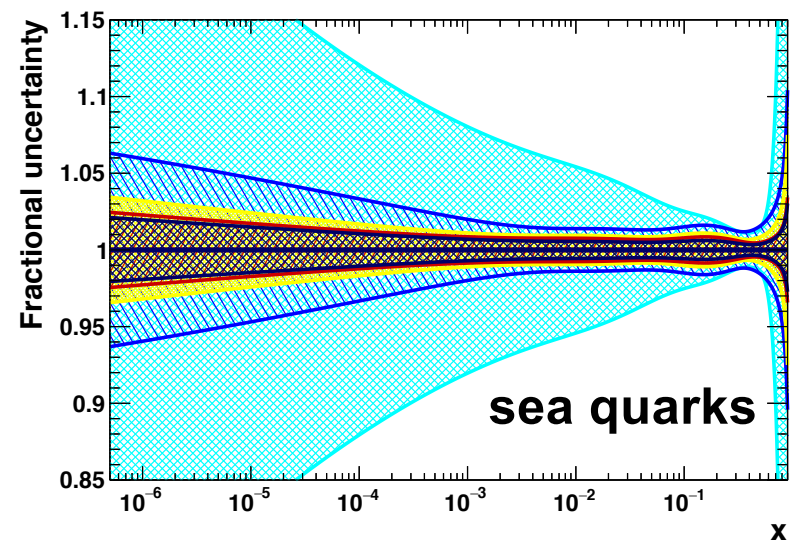
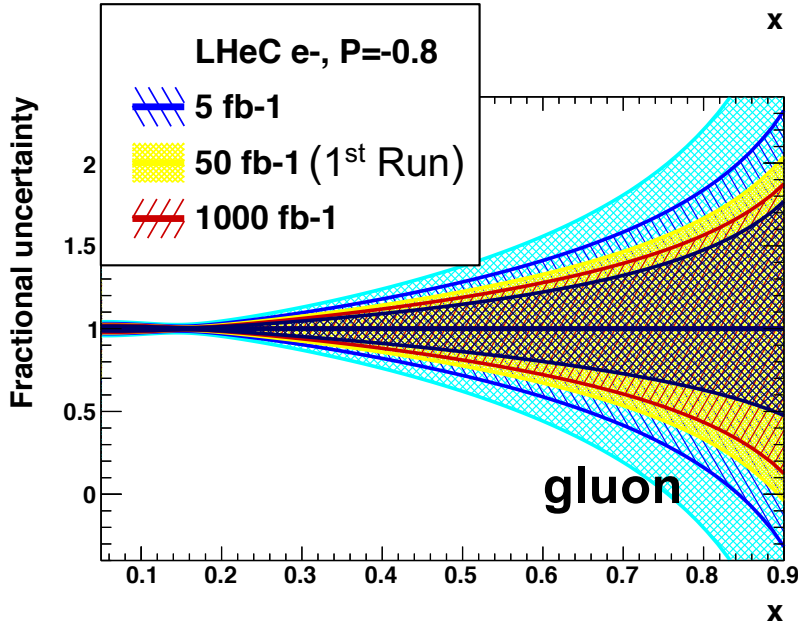
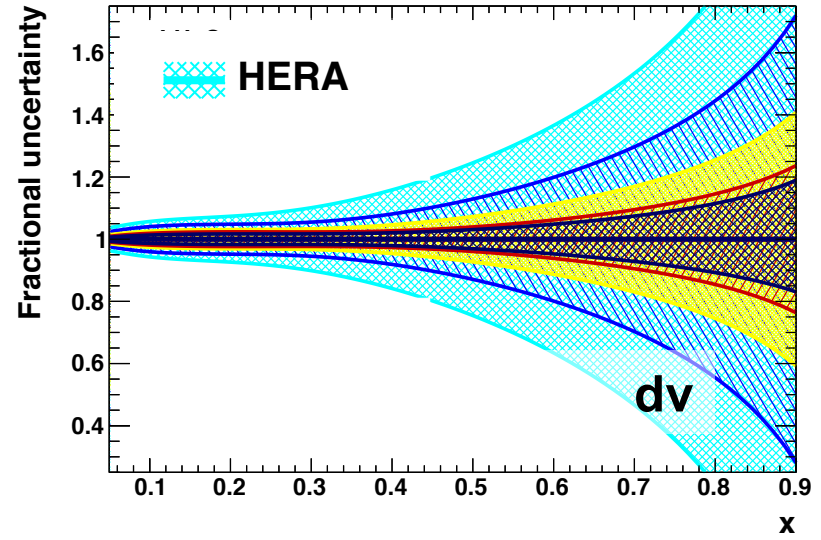
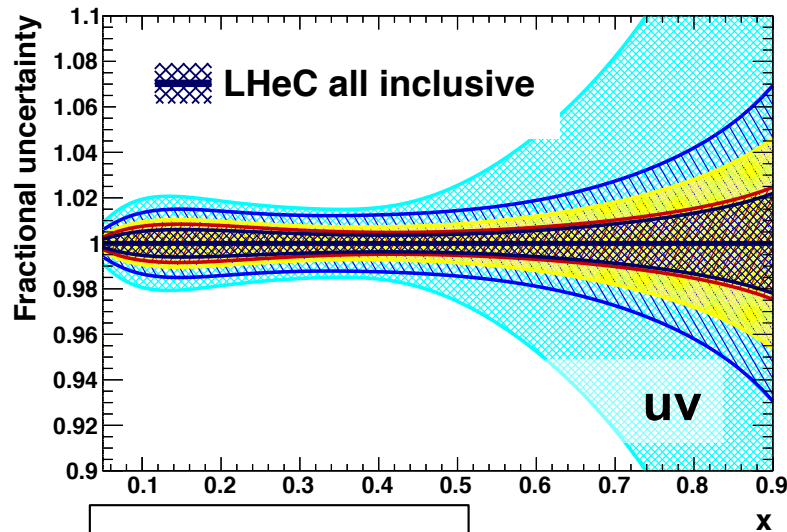


**d/u essentially unknown at large x**

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

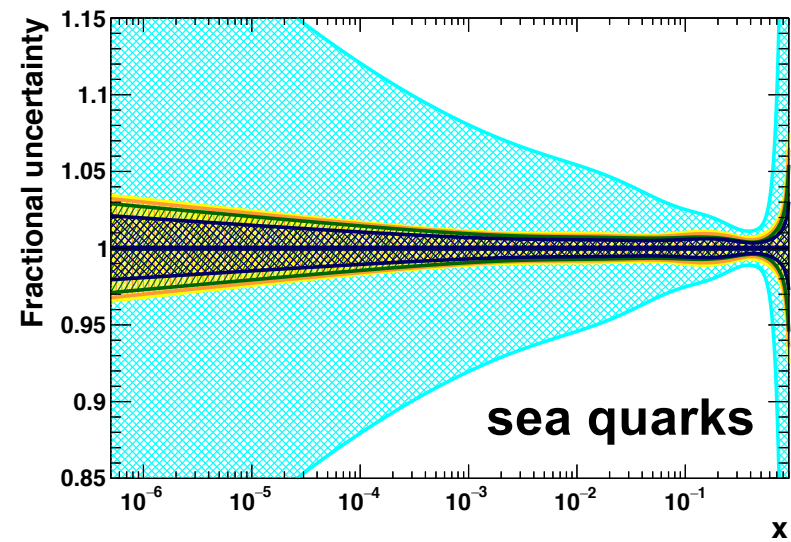
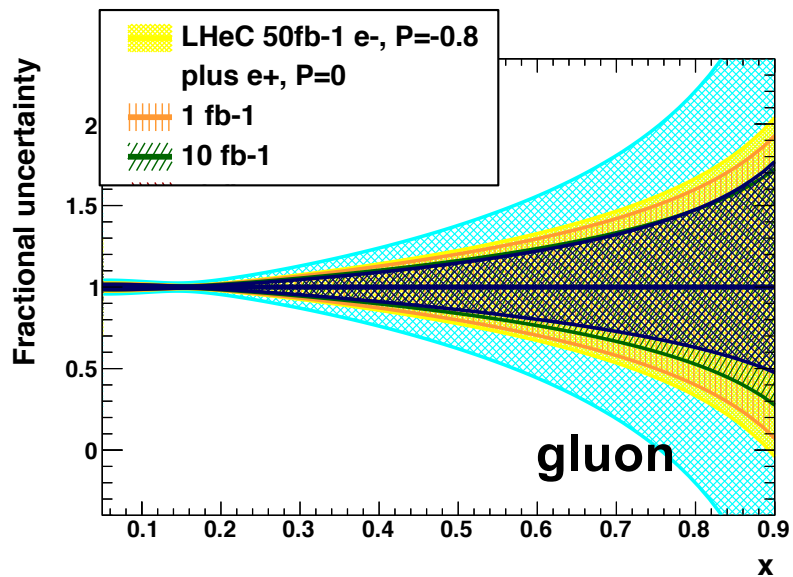
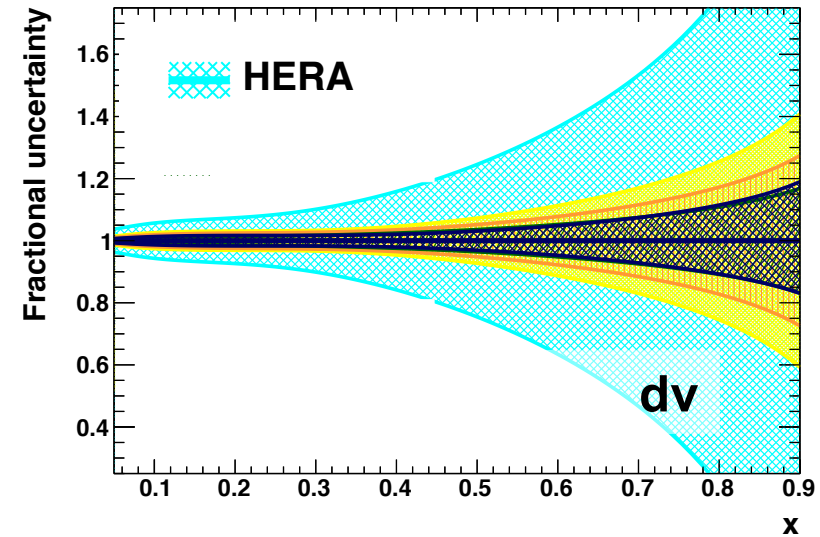
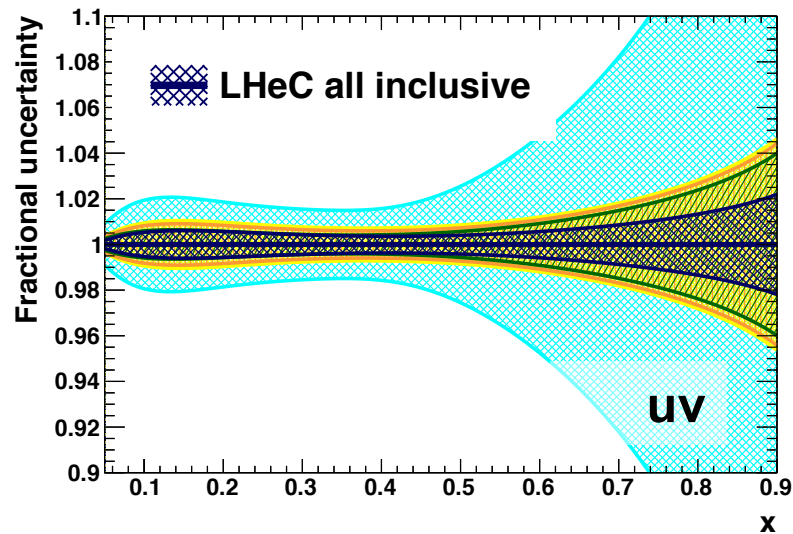
can resolve long-standing  
mystery of d/u ratio at large x

# impact of luminosity



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

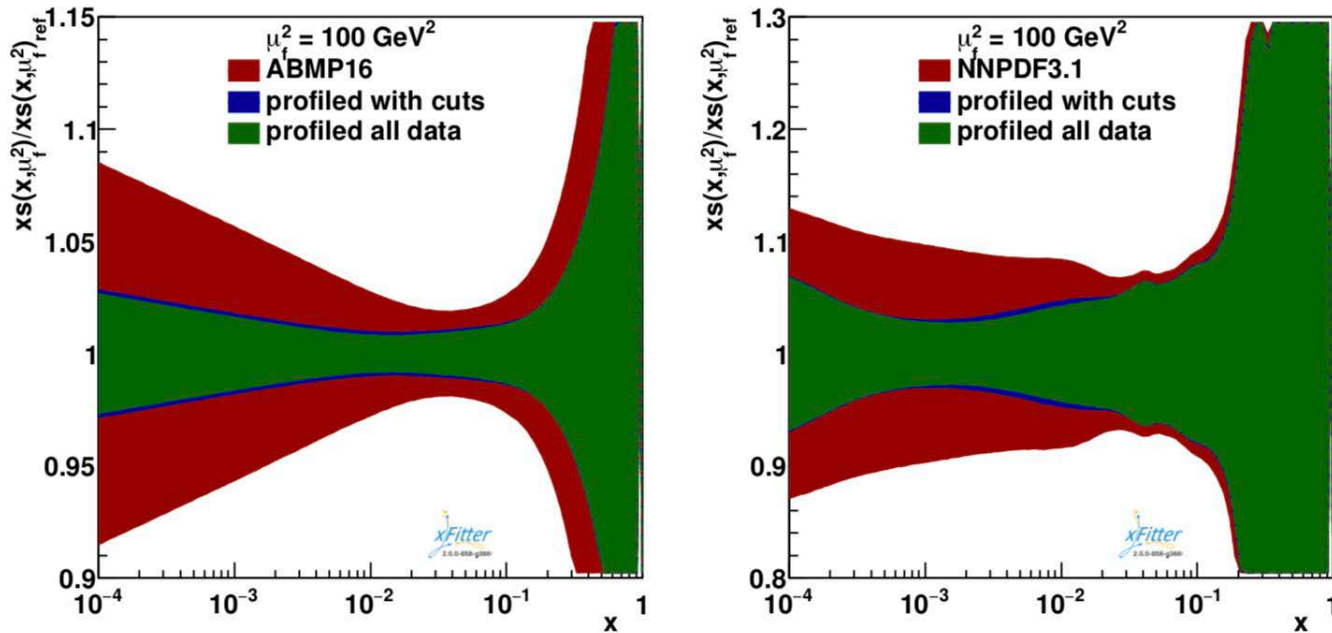
# impact of positrons



**CC:**  $e^+$  sensitive to  $d$ ; **NC:**  $e^\pm$  asymmetry gives  $x F_3^{Y,Z}$ , sensitive to valence

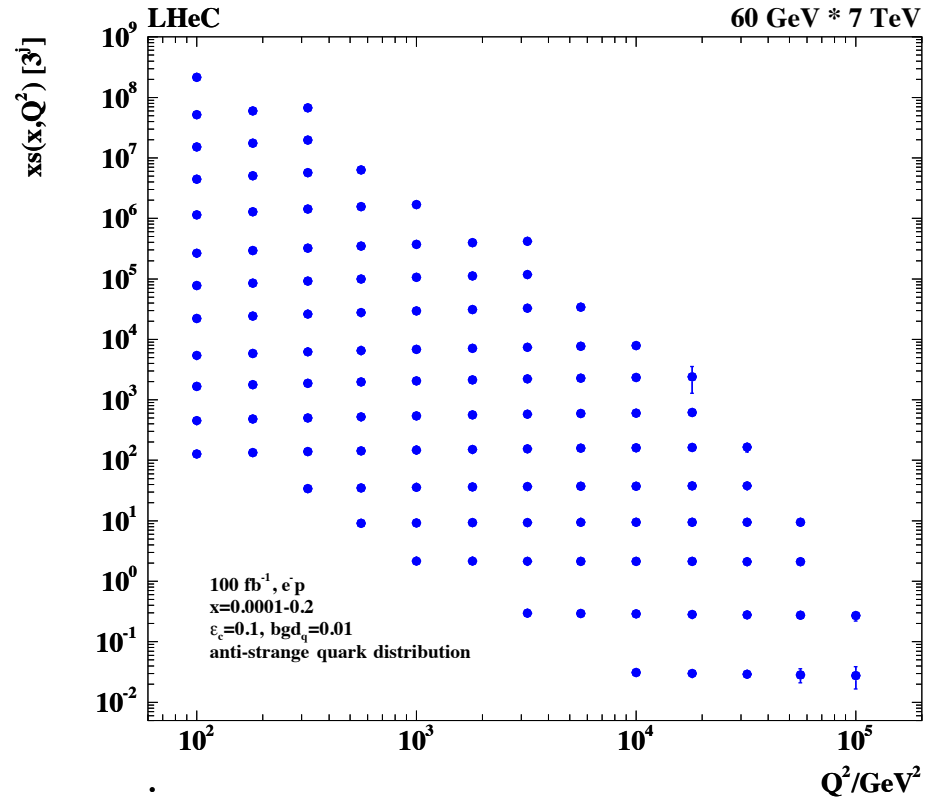


# impact of strange



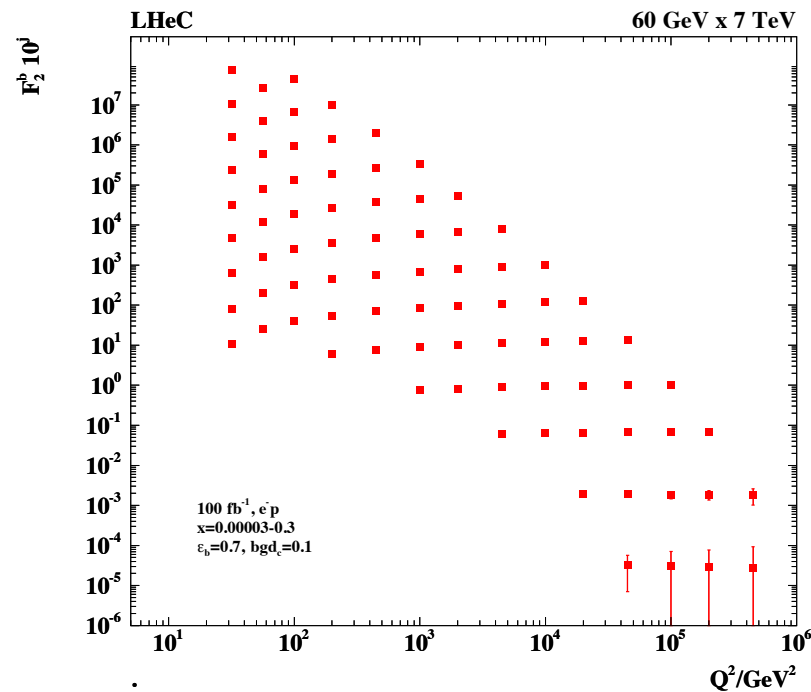
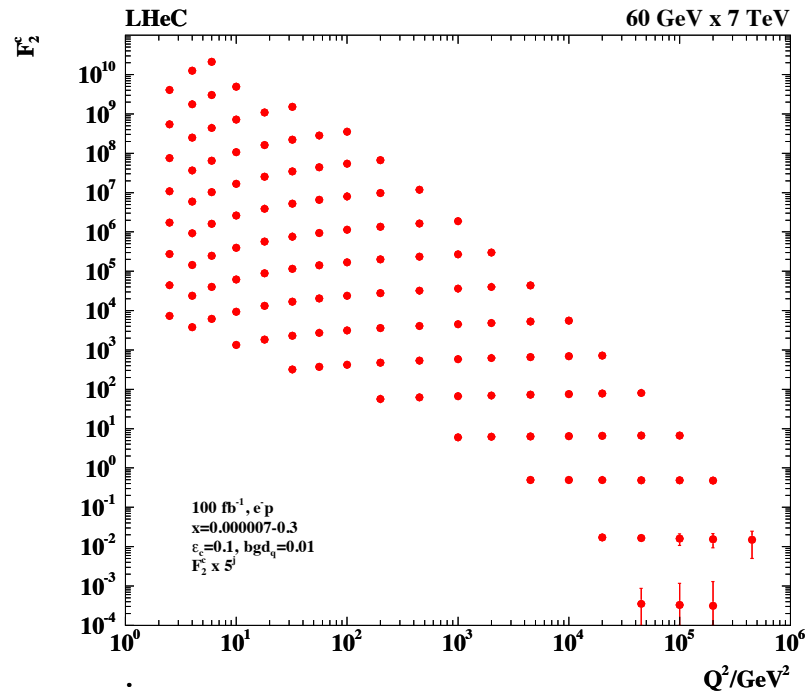
**Figure 3.13:** Constraints on the strange quark PDF  $xS$  using simulated data for charged-current production of charm quarks at the LHeC, from a profiling study [79] using the ABMP16 (left) and the NNPDF3.1 (right) PDF sets. The red band displays the nominal PDF uncertainties, and the green and blue bands the improved uncertainties due to the LHeC strange quark data.





**Figure 3.5:** Simulation of the measurement of the (anti)-strange quark distribution,  $x\bar{s}(x, Q^2)$ , in charged current  $e^-p$  scattering through the t-channel reaction  $W^- \bar{s} \rightarrow c$ . The data are plotted with full systematic and statistical errors added in quadrature, mostly non-visible. The covered  $x$  range extends from  $10^{-4}$  (top left bin), determined by the CC trigger threshold conservatively assumed to be at  $Q^2 = 100 \text{ GeV}^2$ , to  $x \simeq 0.2$  (bottom right) determined by the forward tagging acceptance limits, which could be further extended by lowering  $E_p$ .

# c, b quarks



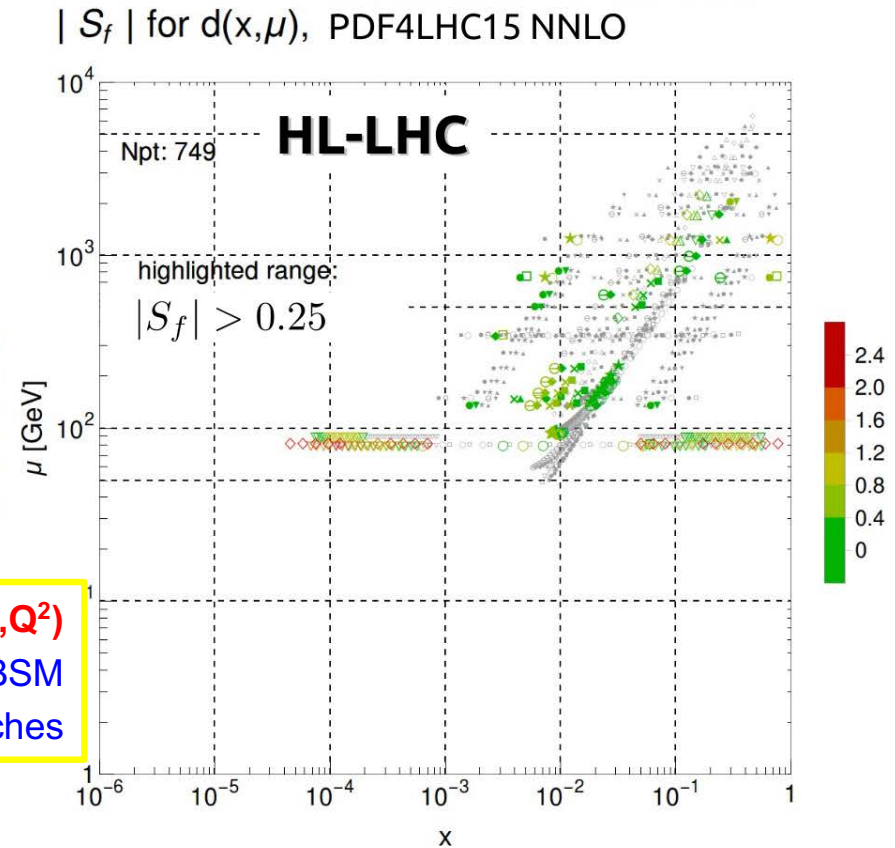
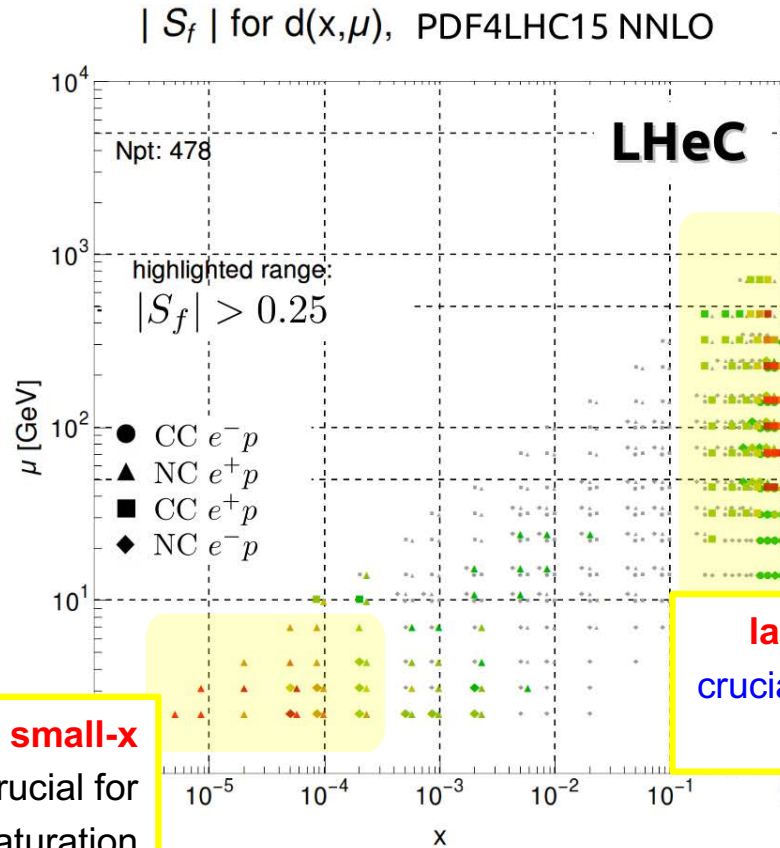
**LHeC: enormously extended range and much improved precision c.f. HERA**

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

“sensitivity”  $S_f$   
 = Correlation  $\times$   
 scaled residual

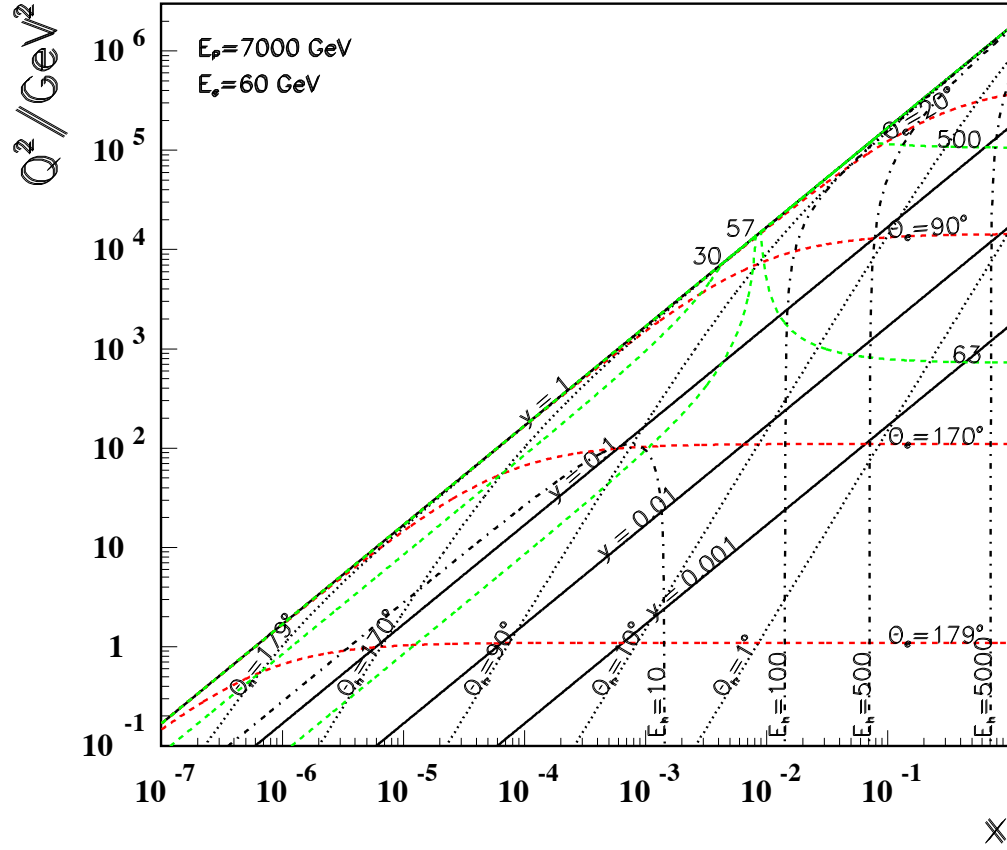
# pdf sensitivity

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



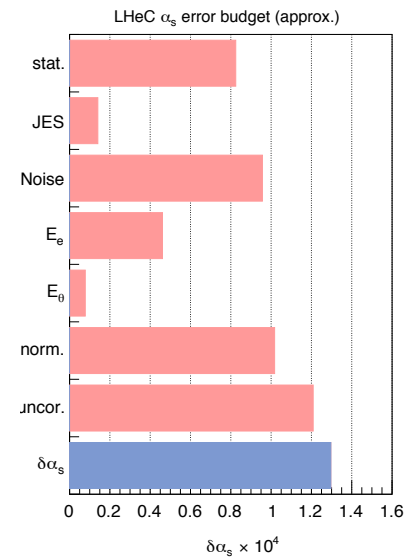
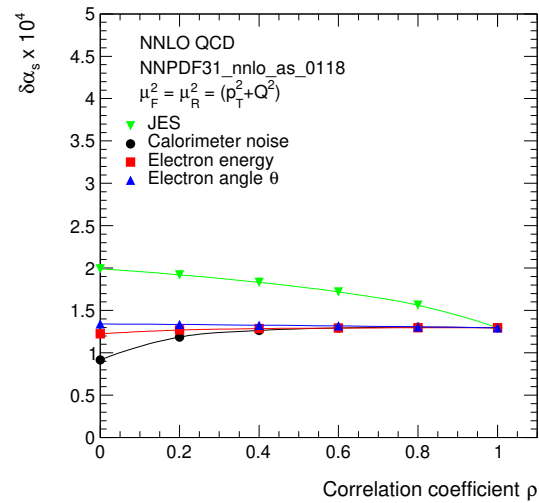
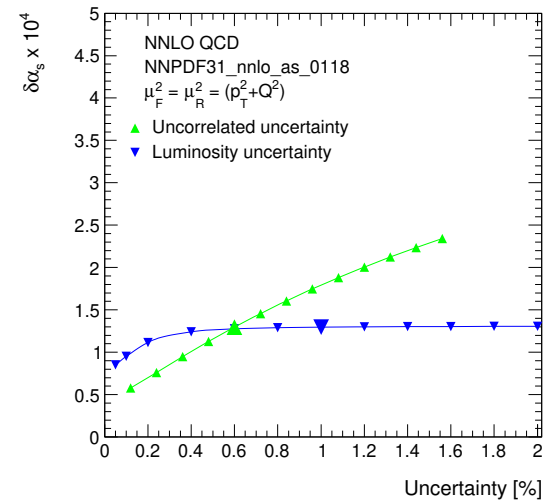
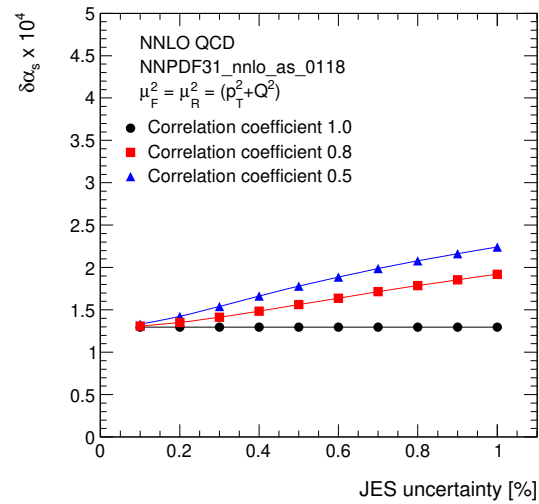
enormous sensitivity in regions currently poorly constrained

PDFSENSE: tool for quickly quantifying potential impact of experimental pseudodata



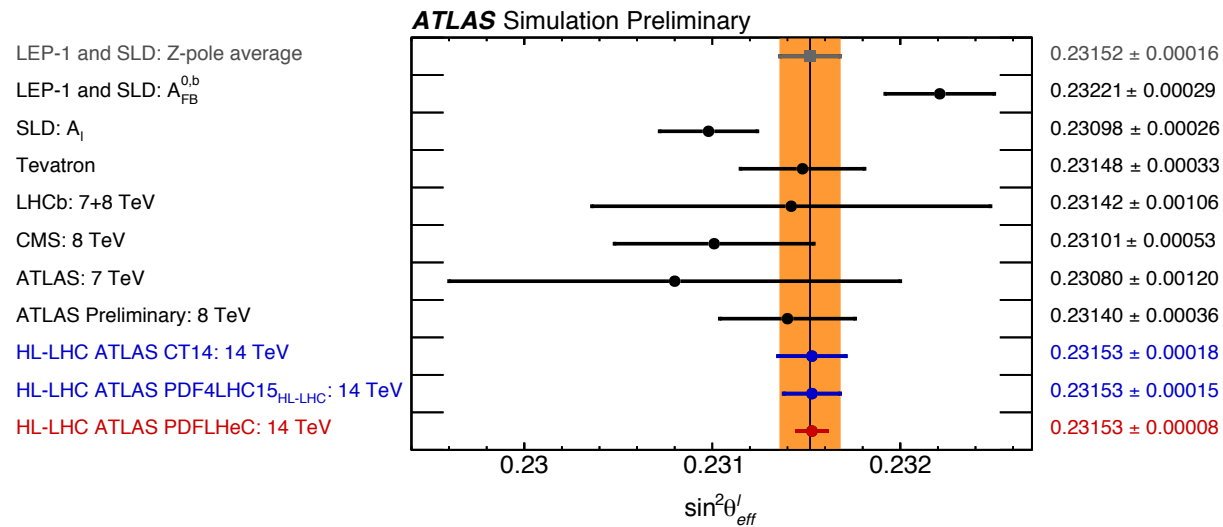
**Figure 3.2:** Kinematic plane covered with the maximum beam energies at the LHeC. Red dashed: Lines of constant scattered electron polar angle. Note that low  $Q^2$  is measured with electrons scattered into the backward region, highest  $Q^2$  is reached with Rutherford backscattering; Black dotted: lines of constant angle of the hadronic final state; Black solid: Lines of constant inelasticity  $y = Q^2/sx$ ; Green dashed: Lines of constant scattered electron energy  $E'_e$ . Most of the central region is covered by what is termed the kinematic peak, where  $E'_e \simeq E_e$ . The small  $x$  region is accessed with small energies  $E'_e$  below  $E_e$  while the very forward, high  $Q^2$  electrons carry TeV energies; Black dashed-dotted: lines of constant hadronic final state energy  $E_h$ . Note that the very forward, large  $x$  region sees very high hadronic energy deposits too.

# $\alpha_s$ from LHeC NC DIS jets



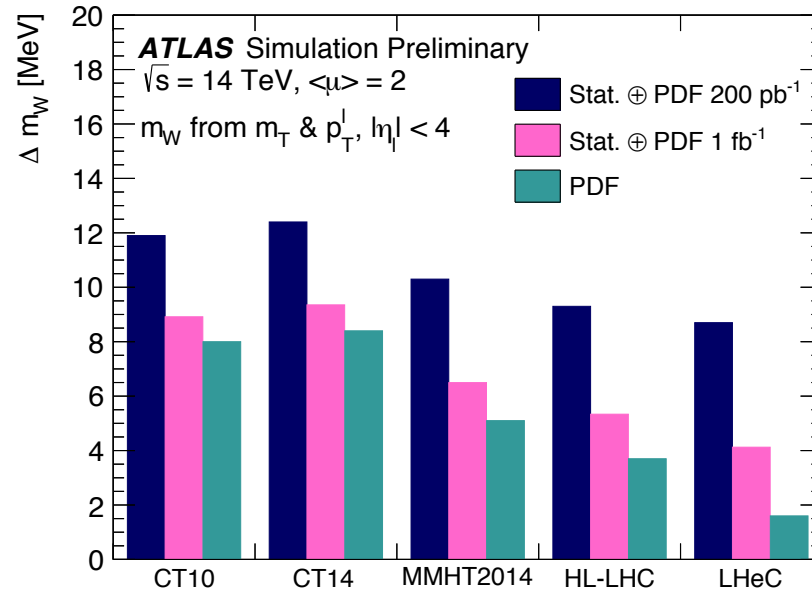
# empowering the LHC: $\sin^2\theta_W$

Parameter	Unit	HL-LHC projection			
		ATLAS (Ref. [433]) 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

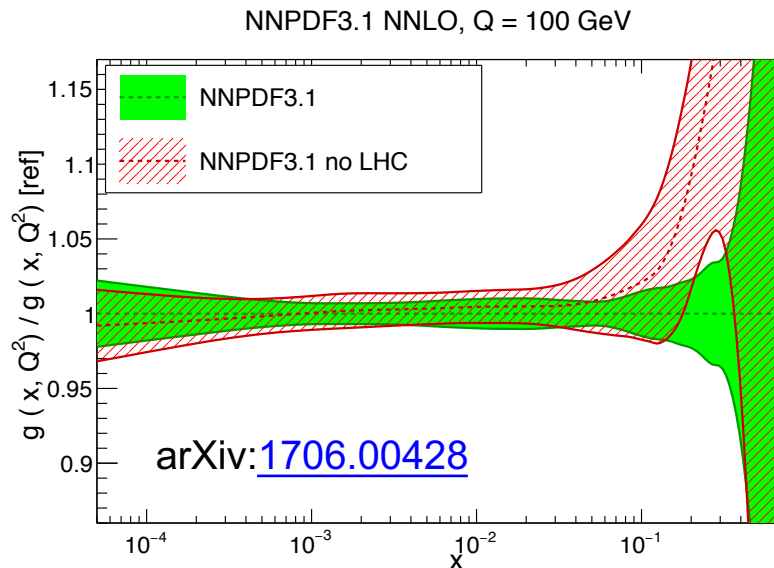
Parameter	Unit	ATLAS (Ref. [424])				
		CT10	CT14	HL-LHC	LHeC	LHeC
Centre-of-mass energy, $\sqrt{s}$	TeV	7	14	14	14	14
Int. luminosity, $\mathcal{L}$	$\text{fb}^{-1}$	5	1	1	1	1
Acceptance		$ \eta  < 2.4$	$ \eta  < 2.4$	$ \eta  < 2.4$	$ \eta  < 2.4$	$ \eta  < 4$
Statistical uncert.	MeV	$\pm 7$	$\pm 5$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





# pp vs ep ?

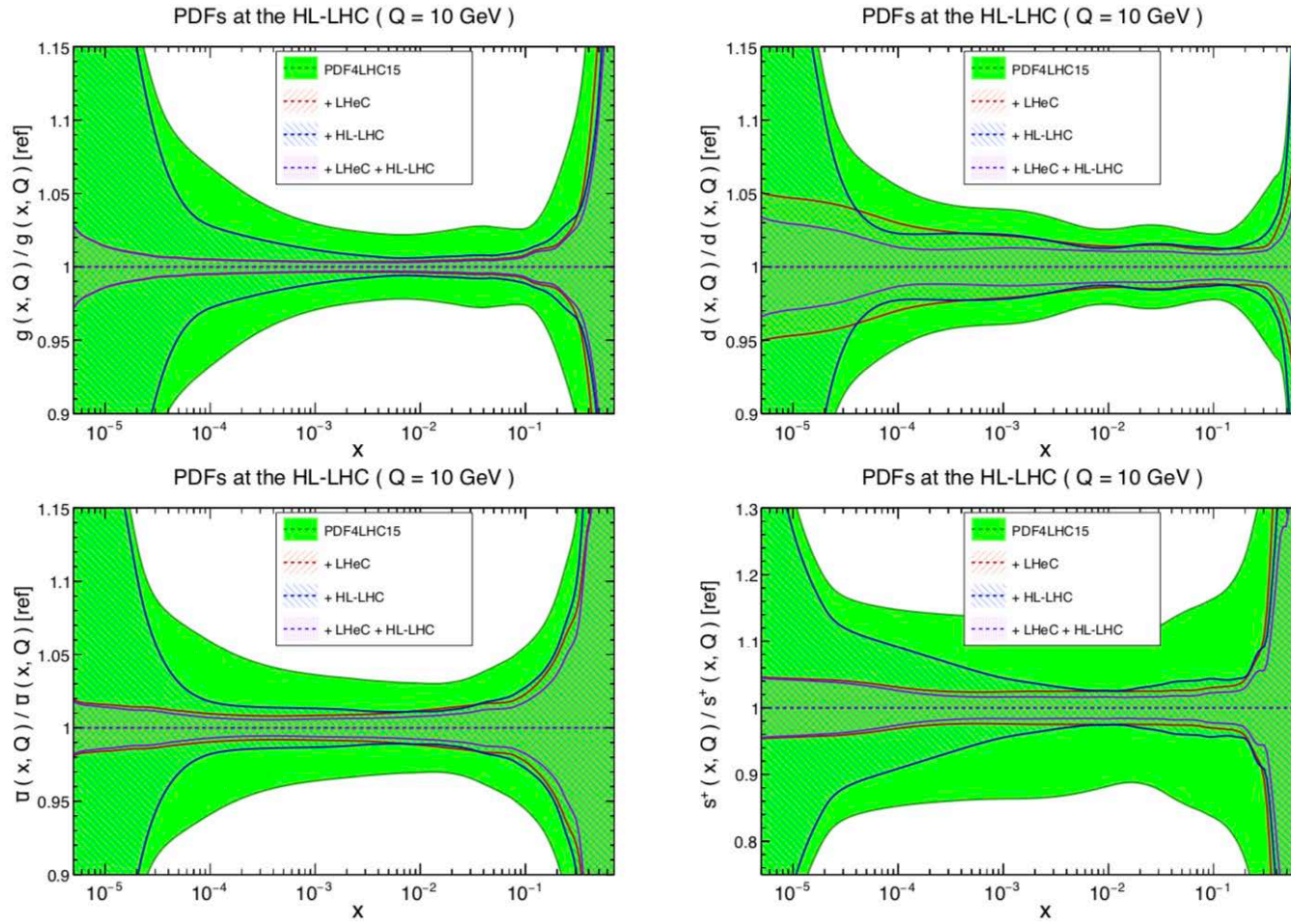
**LHC** data constrain **pdfs**, BUT  
do not precisely **determine** them



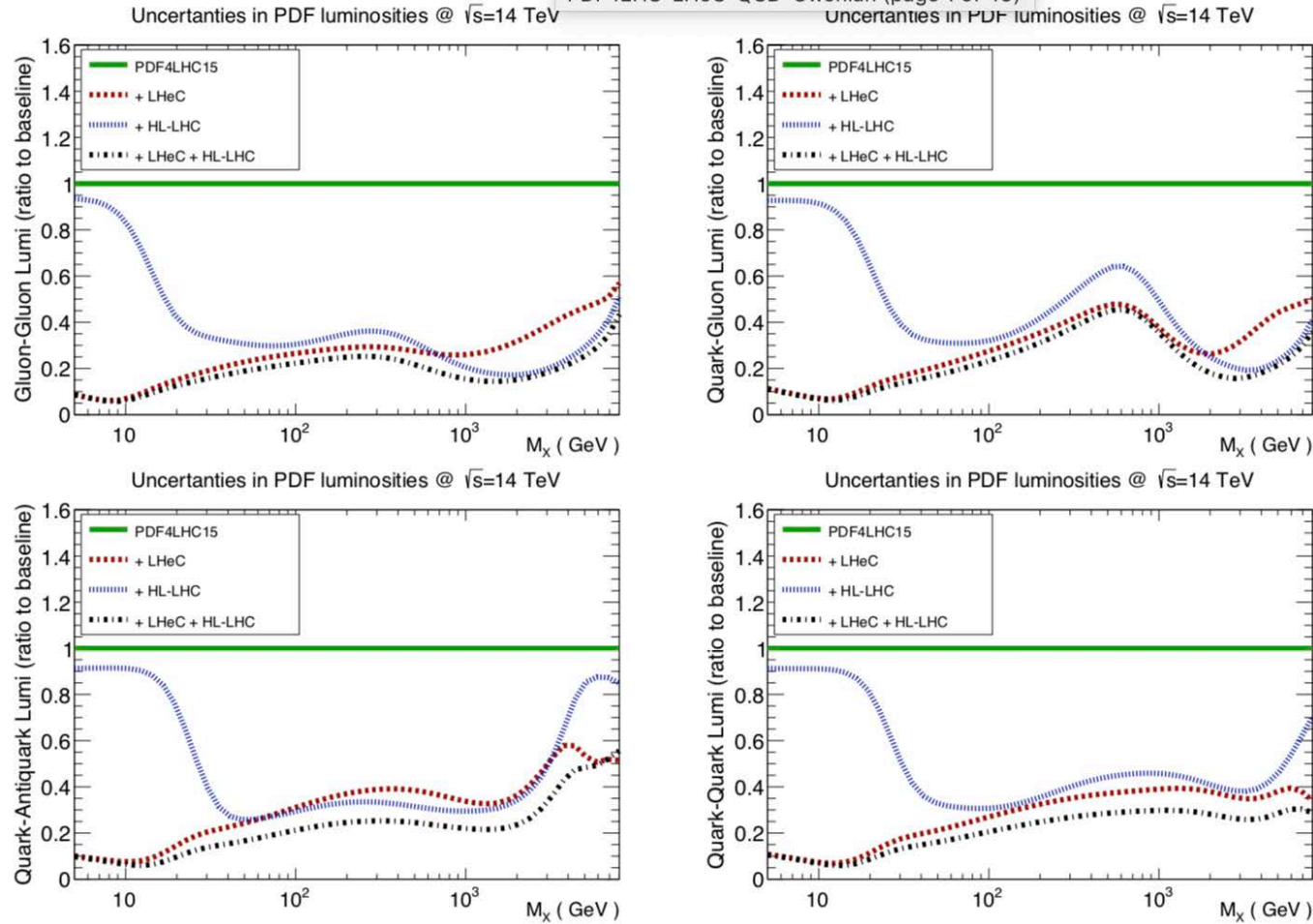
**pp**: providing useful constraints in global fits and also interesting results (EG. non-suppressed strange at  $x \sim 0.01$  from ATLAS); **must nevertheless be aware that it is not ep ...**

**cf. ep**

- complete  $q, g$  unfolding at all  $x$
- $\alpha_s$  to order permille precision (not in pp)
- clear theory (EG. N3LO, scale choice, hadronisation)
- strong effects from  $Q^2$  variation (which cannot come from EG. W, Z at  $Q^2=10^4 \text{ GeV}^2$ )
- HQ separation:  $s, c, b, (t)$
- understanding of small  $x$  dynamics, EG. BFKL, saturation, ... (comes from F2 and FL)
- gives external precision input for QCD subtleties (EG. factorisation, resummation), and for subtle discoveries
- single DIS dataset a tried and tested reliable way to achieve precision ( $\Delta X^2=1$ ; cf. current LHC measurements; issues understanding systematics, correlations, data inconsistencies, ...)



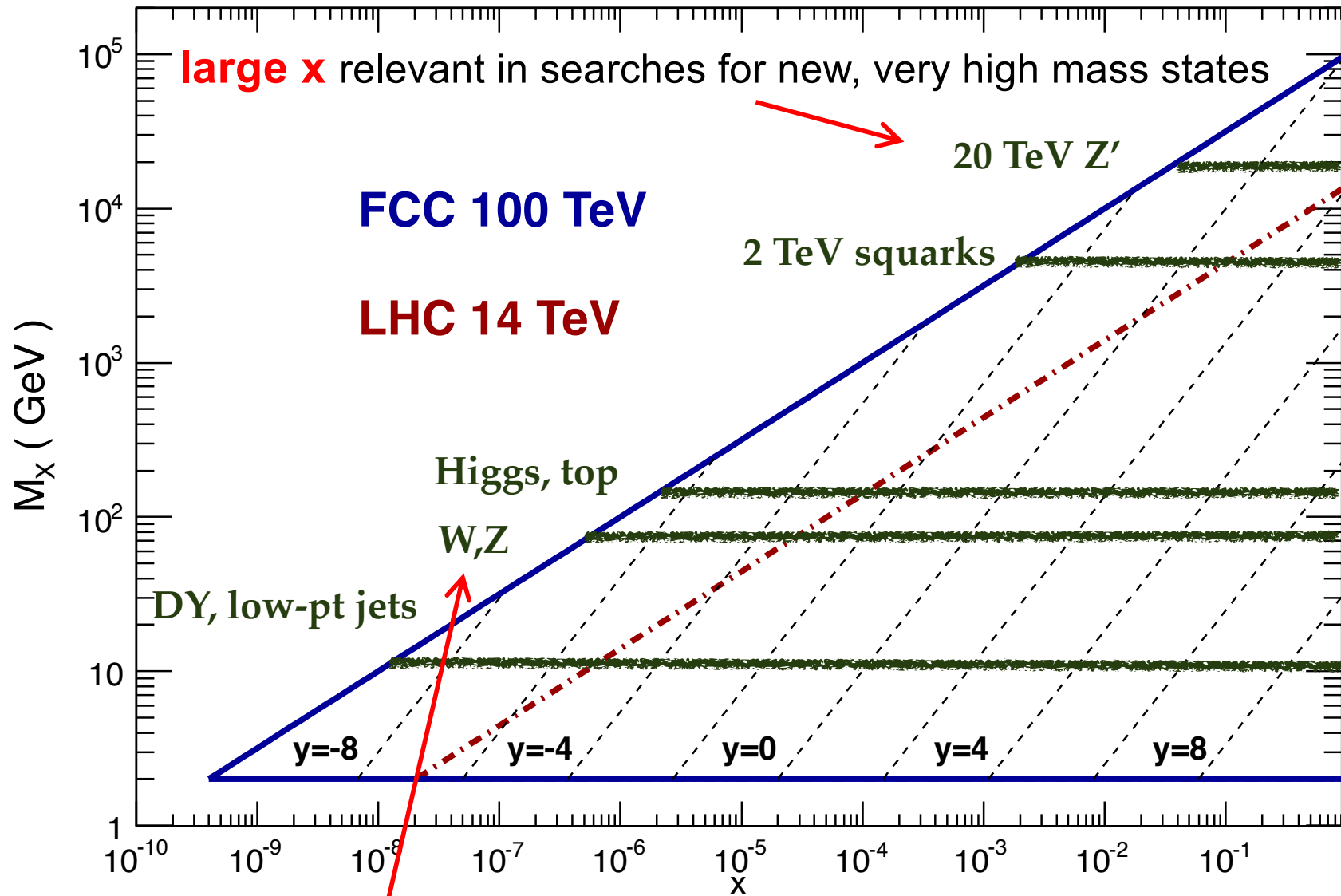
**Figure 9.10:** Impact of LHeC on the  $1\text{-}\sigma$  relative PDF uncertainties of the gluon, down quark, anti-up quark and strangeness distributions, with respect to the PDF4LHC15 baseline set (green band). Results for the LHeC (red), the HL-LHC (blue) and their combination (violet) are shown.



**Figure 9.11:** 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.

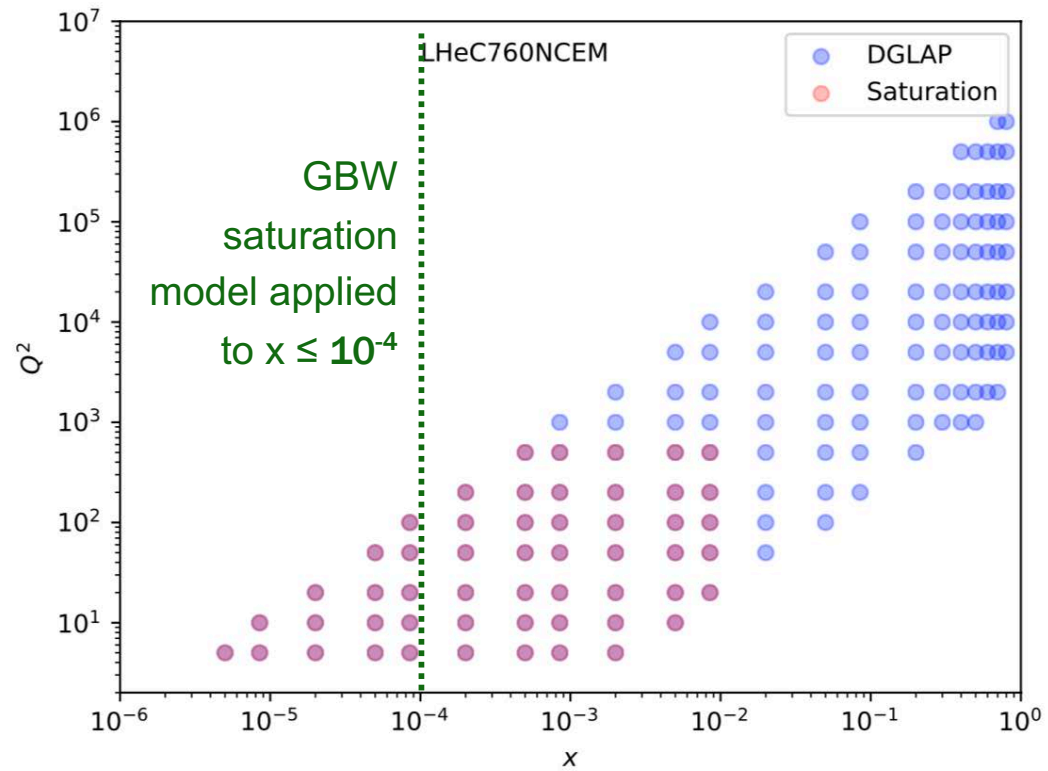
# Kinematics of a 100 TeV FCC

Plot by J. Rojo, Dec 2013

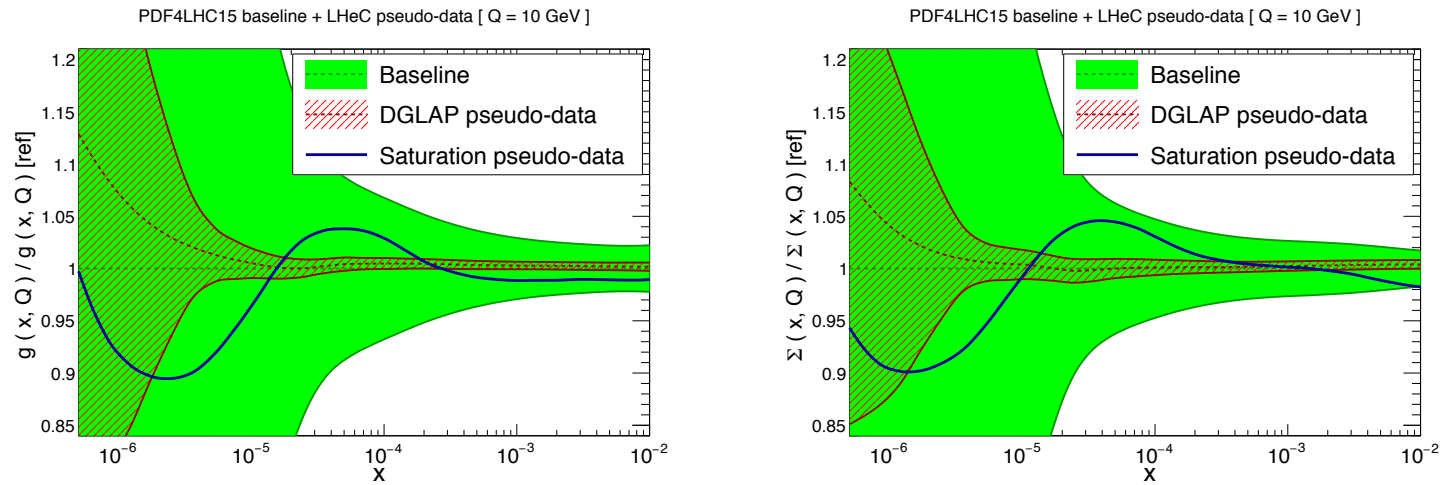


**small x** becomes relevant even for “common” physics (EG. W, Z, H, t)

# non-linear QCD dynamics



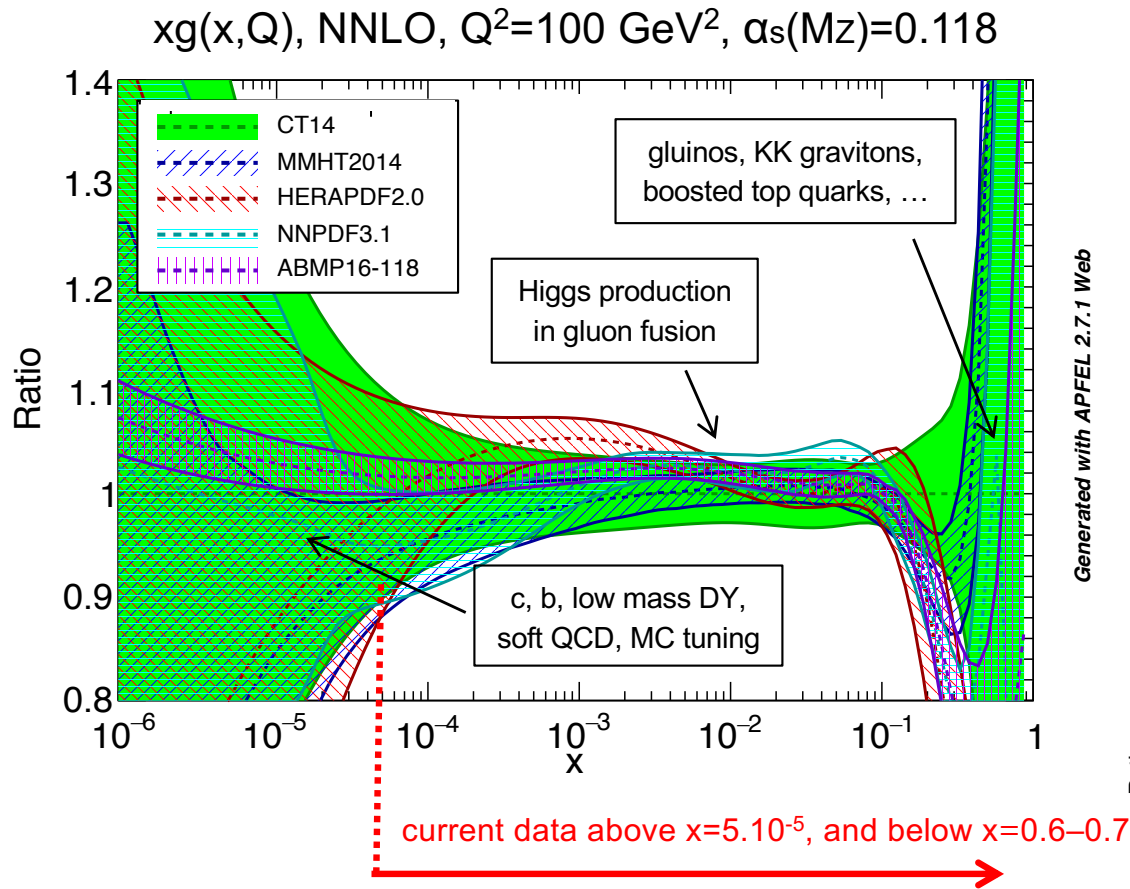
# non-linear QCD dynamics



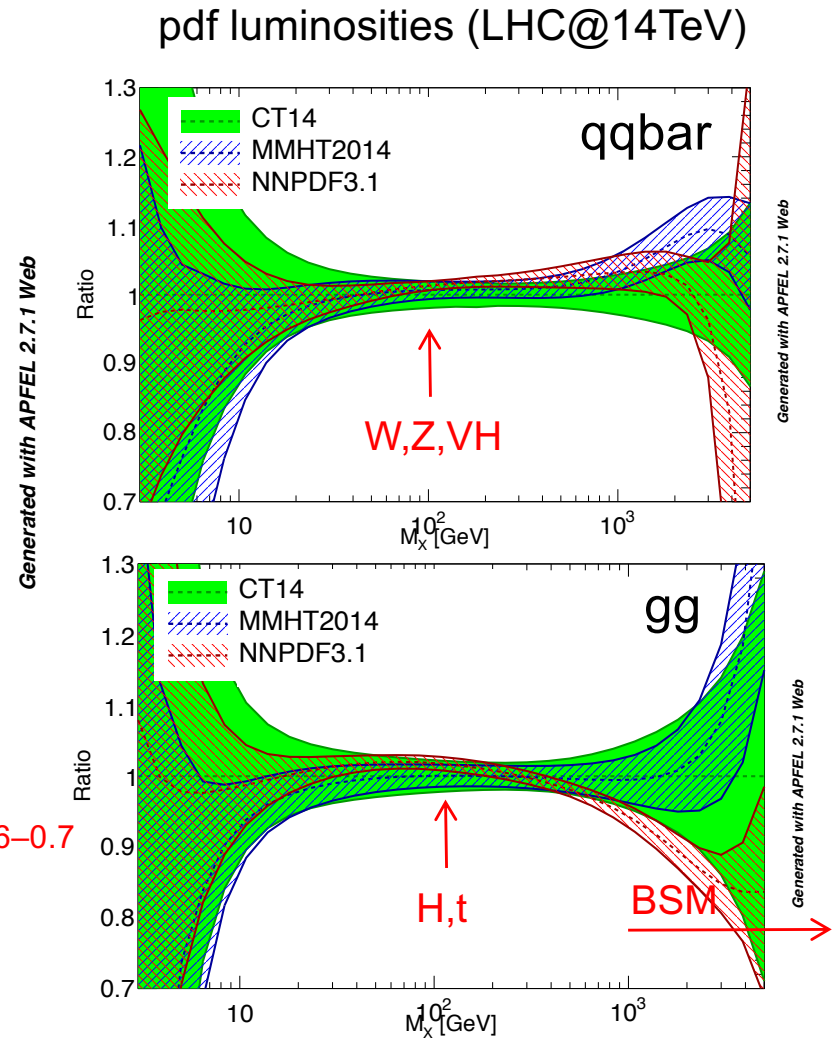
**Figure 4.12:** Comparison between the PDF4LHC15 baseline (green band) with the results of the profiling of the LHeC pseudodata for the gluon (left) and quark singlet (right) for  $Q = 10$  GeV. We show the cases where the pseudodata is generated using DGLAP calculations (red hatched band) and where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



# pdfs: the situation today



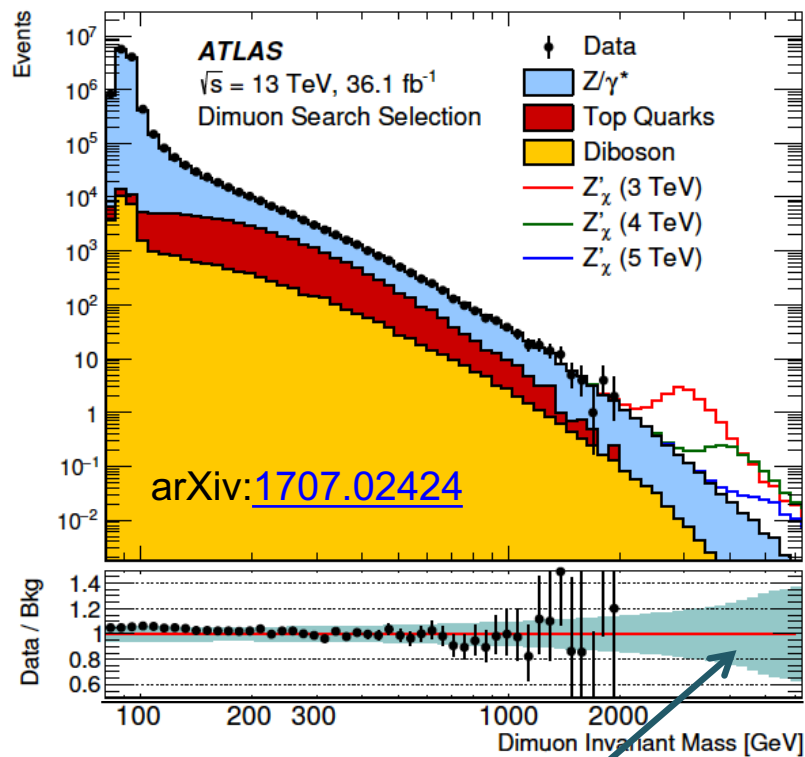
pdfs poorly known at **large** and **small x**  
 higher precision needed also for H, W, t





# why pdfs matter

- **BSM searches** and other processes at high scales limited by (lack of) knowledge of **large x gluon** and **quark pdfs** (EG. top, SUSY, LQs, extra heavy bosons, ...)
- ... plus precision **MW**,  **$\sin^2\theta_W$**  (where small discrepancies may indicate BSM physics) and **Higgs**, are also limited by **pdf uncertainties** at medium x, where we know pdfs best!



pdf uncertainty dominates

ATLAS Mw, arXiv: [1701.07240](https://arxiv.org/abs/1701.07240)

Channel	$m_{W^+ - W^-}$ [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bkg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.
$W \rightarrow e\nu$	-29.7	17.5	0.0	4.9	0.9	5.4	0.5	0.0	24.1	30.7
$W \rightarrow \mu\nu$	-28.6	16.3	11.7	0.0	1.1	5.0	0.4	0.0	26.0	33.2
Combined	-29.2	12.8	3.3	4.1	1.0	4.5	0.4	0.0	23.9	28.0

