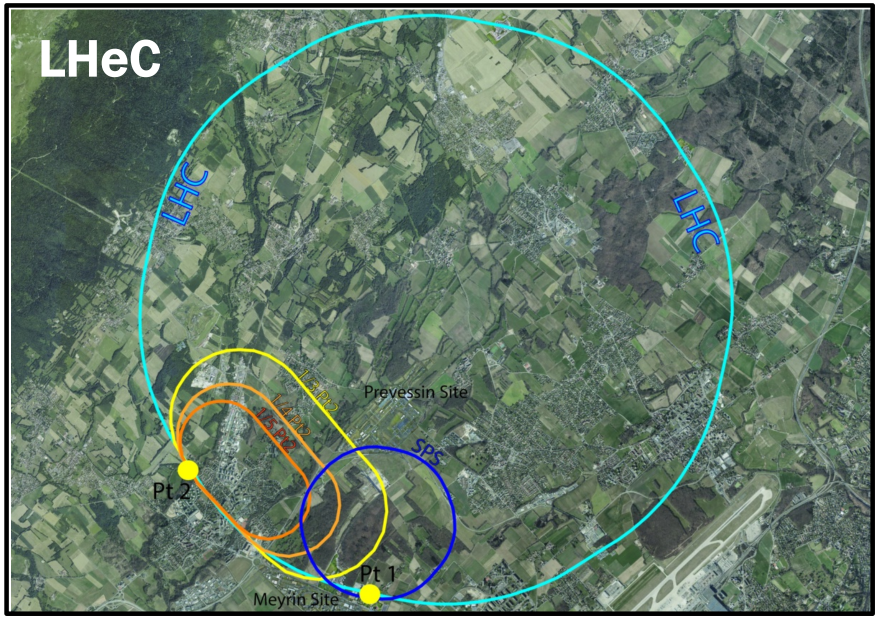
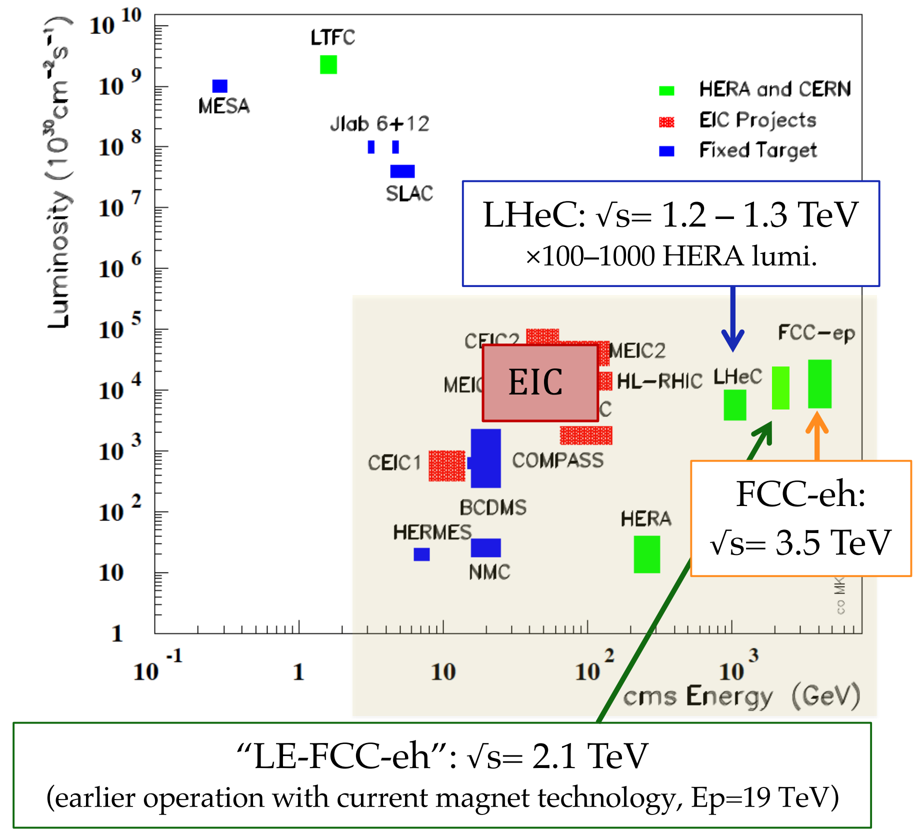
PDFs from LHeC and FCC-eh

Francesco Giuli (on behalf of the LHeC and FCC-eh study groups)

XXIX Cracov EPIPHANY Conference
19/01/2023

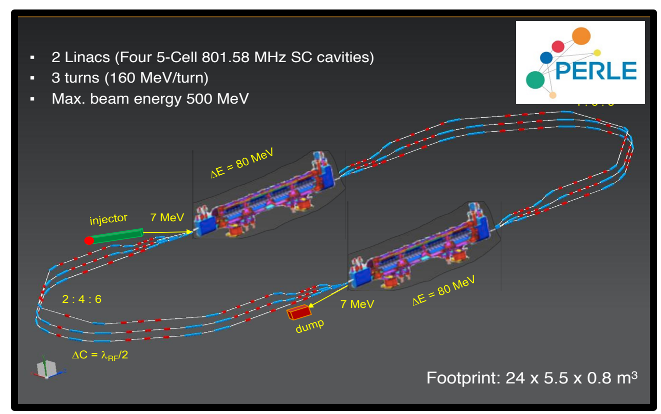
LHeC, FCC-eh and PERLE





- **Energy Recovery LINAC** (ERL) <u>attached to HL-LHC (or FCC)</u>
  - e beam → 50/60 GeV
  - e polarisation → ± 0.8
  - $\int \mathcal{L}$ = 1-2 ab^{-1} (x100-1000 HERA!)

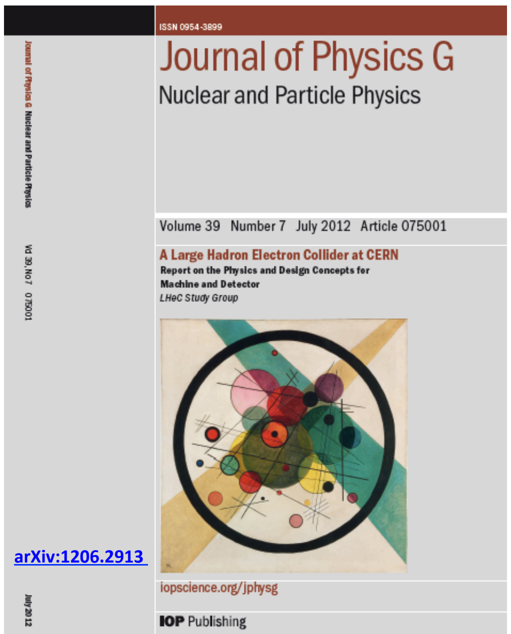
- PERLE: international collaboration built to realise 500 MeV facility at Orsay, for development of ERL with LHeC conditions



LHeC Conceptual Design Report

CDR 2012: commissioned by CERN, ECFA, NuPECC

200 authors, 69 institutions



arXiv:1206.2913

1206.2913

Further selected references:

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

The Large Hadron Electron Collider
arXiv:1305.2090

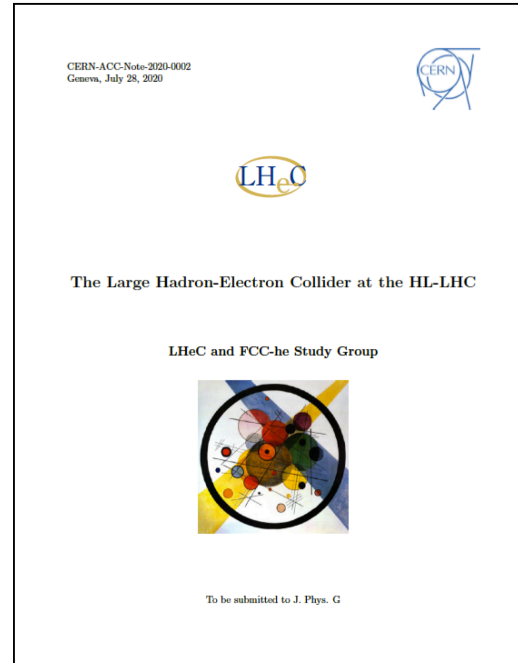
Dig Deeper
Nature Physics 9 (2013) 448

Future Deep Inelastic Scattering with the LHeC
arXiv:1802.04317

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

CDR update

400 pages, 300 authors, 156 institutions



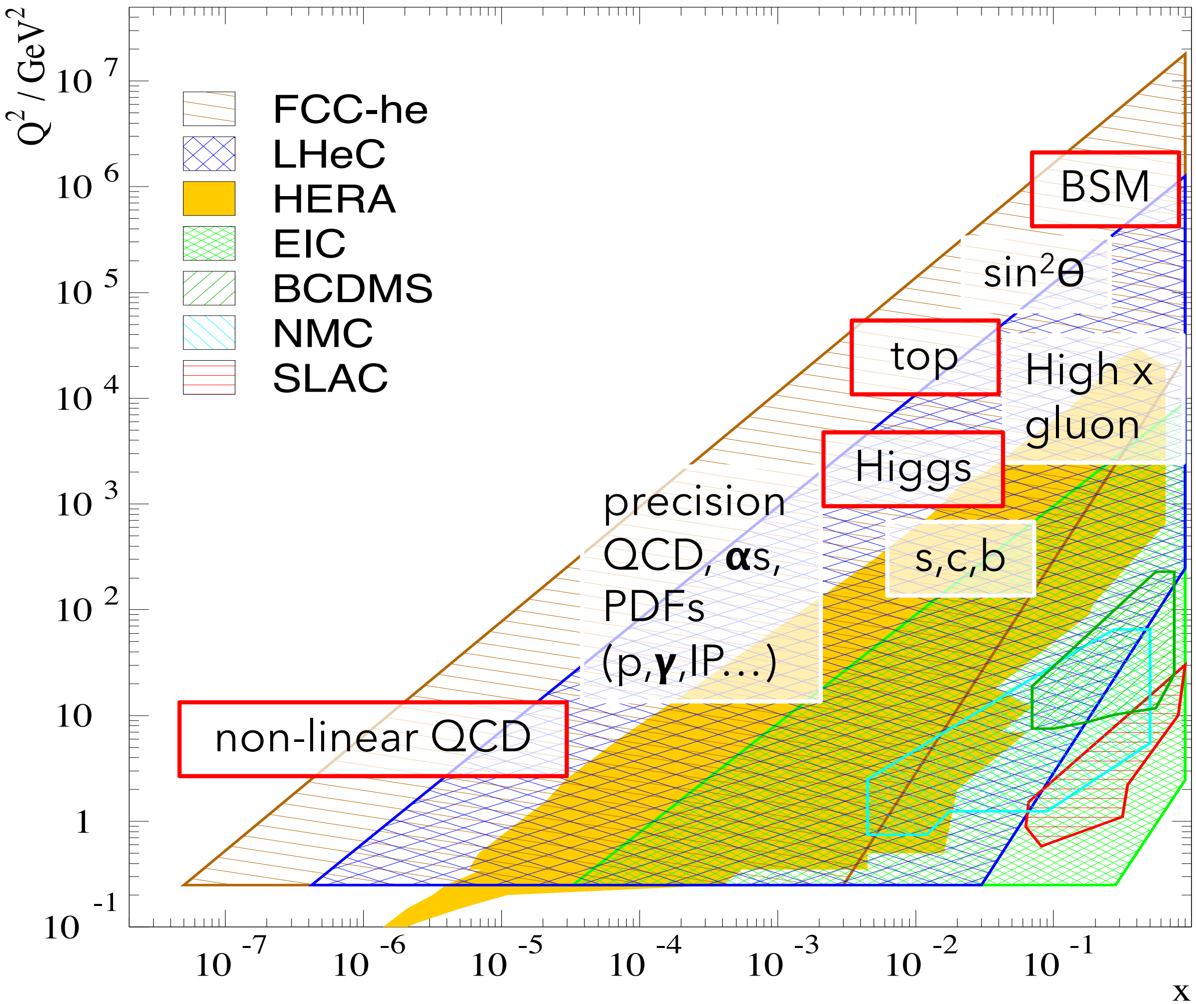
2007.14491

Last LHeC workshop

ICHEP talk

- See also FCC CDR:
  - Physics (volume 1) and with eh integrated (volume 3)
- 5 pages summary: ECFA newsletter No. 5, August 2020

Physics with energy frontier DIS



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

- DIS: cleanest high-resolution microscope
- **Opportunity for unprecedented increase in DIS kinematic reach**
- x10^3 luminosity increase wrt HERA
- QCD precision physics and discovery
- …+ Higgs, top EW, BSM
- Completely resolve all proton PDFs, sensitivity to x → 1, exploration of small-x regime, and α_S at per-mille level
- Empowering the HL-LHC and FCC-hh

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 %

A factor 2 better than at HERA, except for lumi

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.

e^- e^+

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

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

LHeC PDF parametrisation

- QCD fit based on HERAPDF2.0, with following differences:
  - No requirement that $x\bar{u} = x\bar{d}$ when $x \to 0$
  - No negative term for the gluon PDF

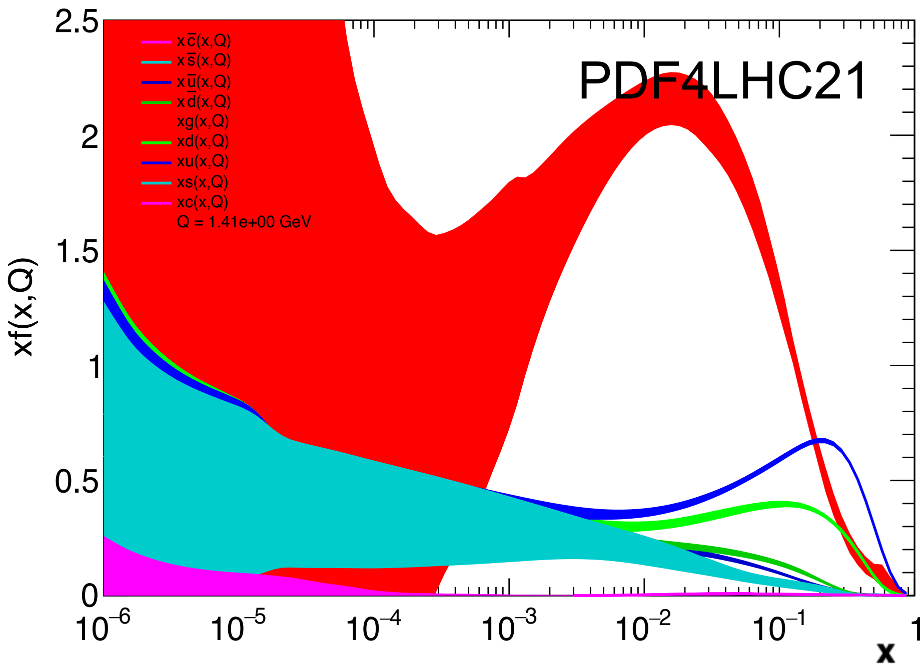
$$
\begin{aligned}
xg(x) &= A_g x^{B_g} (1-x)^{C_g} (1 + D_g x) \\
xu_v(x) &= A_{u_v} x^{B_{u_v}} (1-x)^{C_{u_v}} (1 + E_{u_v} x^2) \\
xd_v(x) &= A_{d_v} x^{B_{d_v}} (1-x)^{C_{d_v}} \\
x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}} (1-x)^{C_{\bar{U}}} \\
x\bar{D}(x) &= A_{\bar{D}} x^{B_{\bar{D}}} (1-x)^{C_{\bar{D}}}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

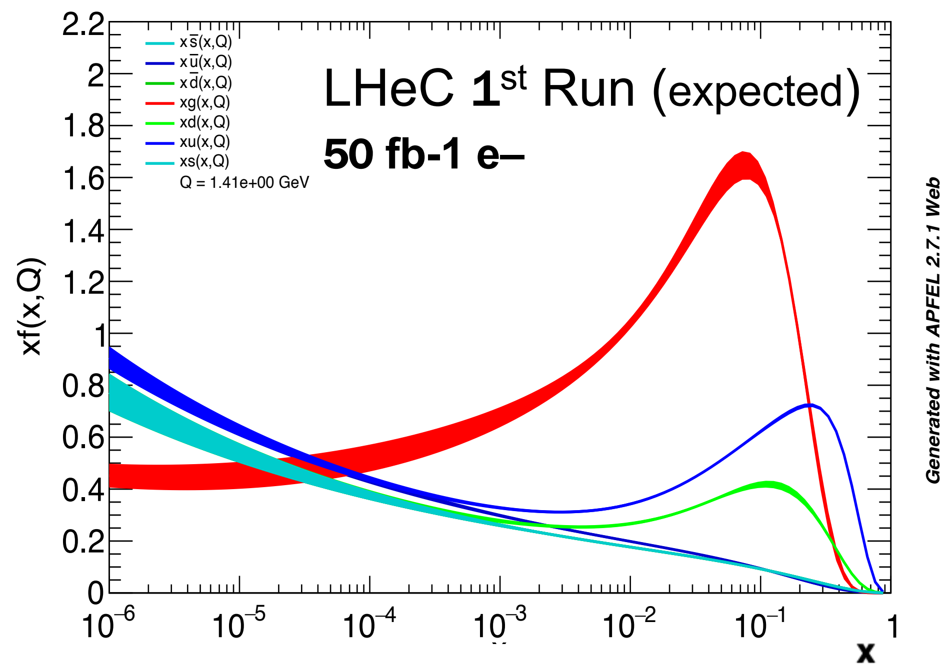
- 4 + 1 PDF fit (above) has 14 free parameters

- 5 + 1 PDF fit for Heavy Quark (HQ) studies - $x\bar{d}$ and $x\bar{s}$ PDFs parametrised separately, 17 free parameters

- All the fits were performed using xFitter

Summary of LHeC PDFs



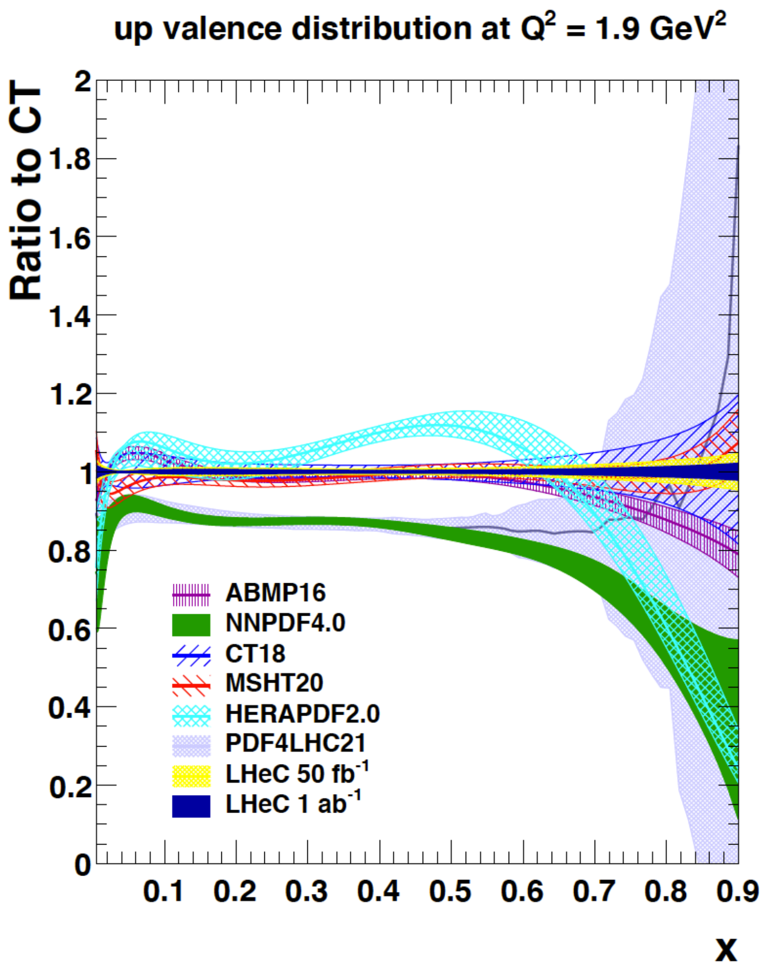


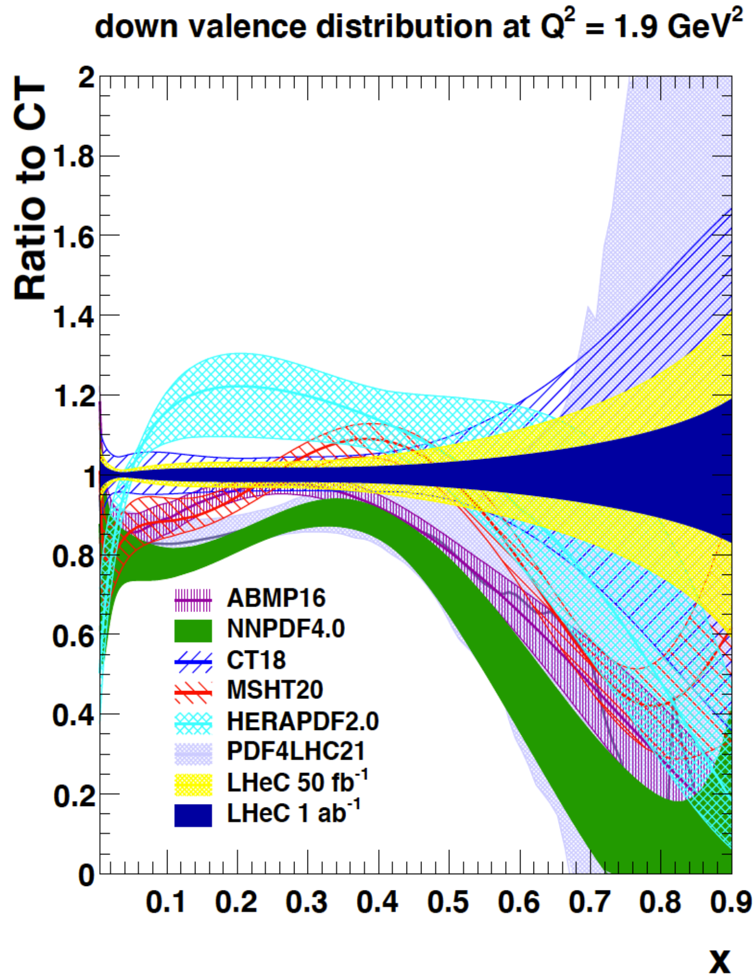
Situation today → After 1st LHeC Run

$\Delta\chi^2$ = 1 criterium used (only experimental uncertainties)

(with improvements after full running period – plus HQ, DIS jets, etc.)

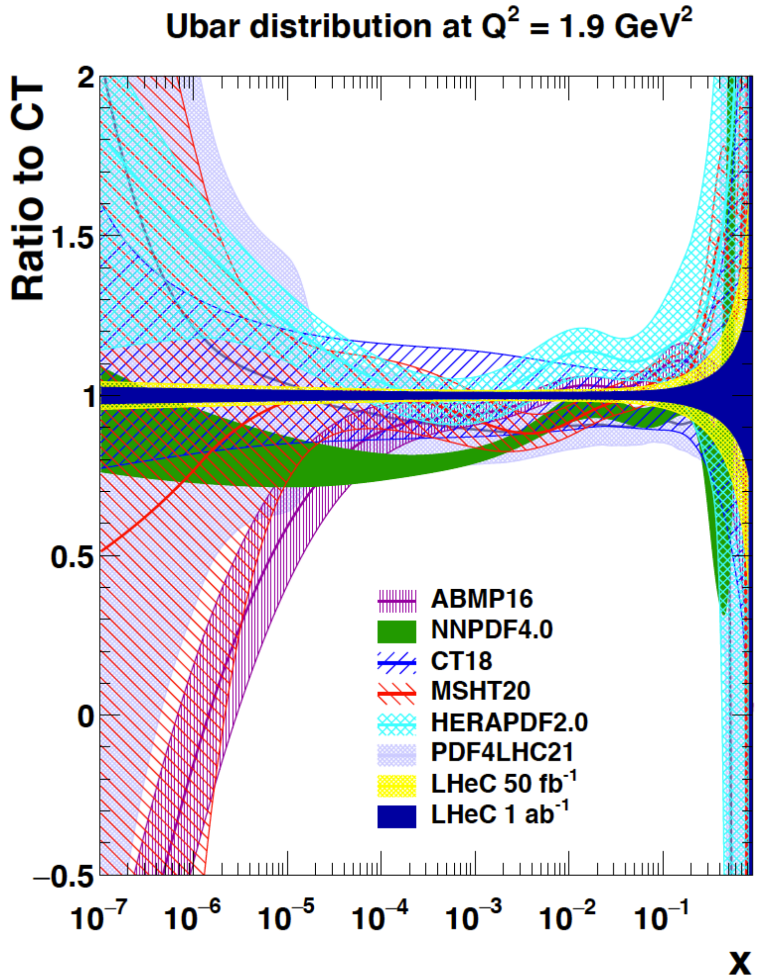
Valence quarks PDFs

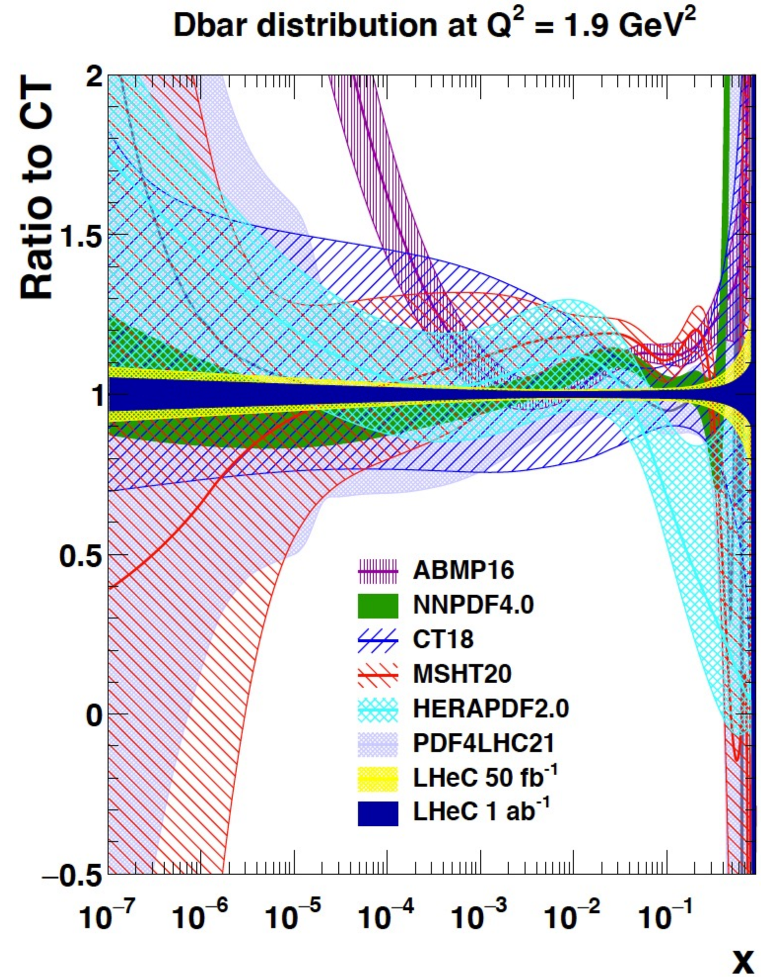




- Large differences of 20-30%
- Note that the fit only considers NC and CC data, unlike LHC fits which include “everything”

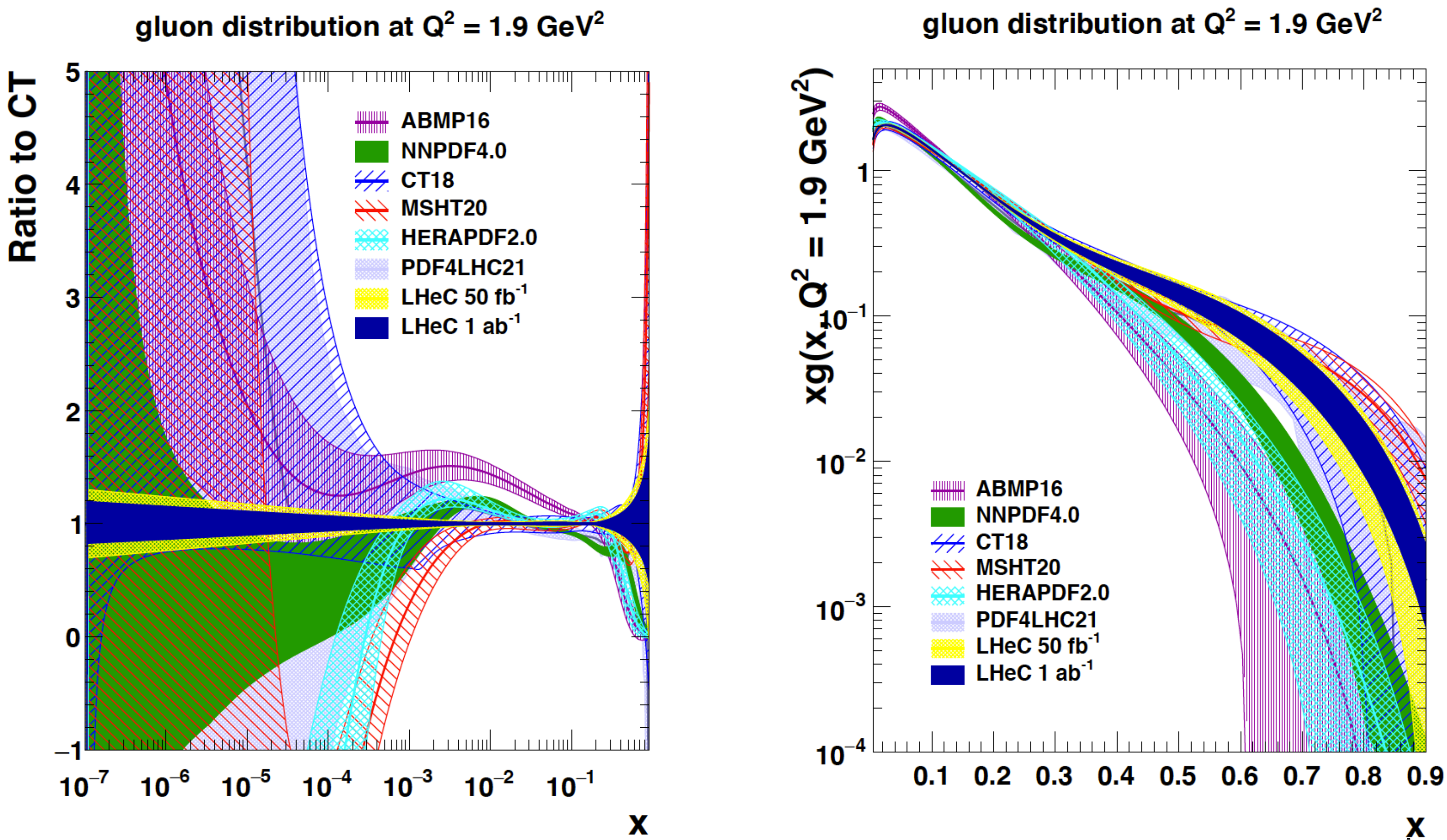
Sea quarks PDFs





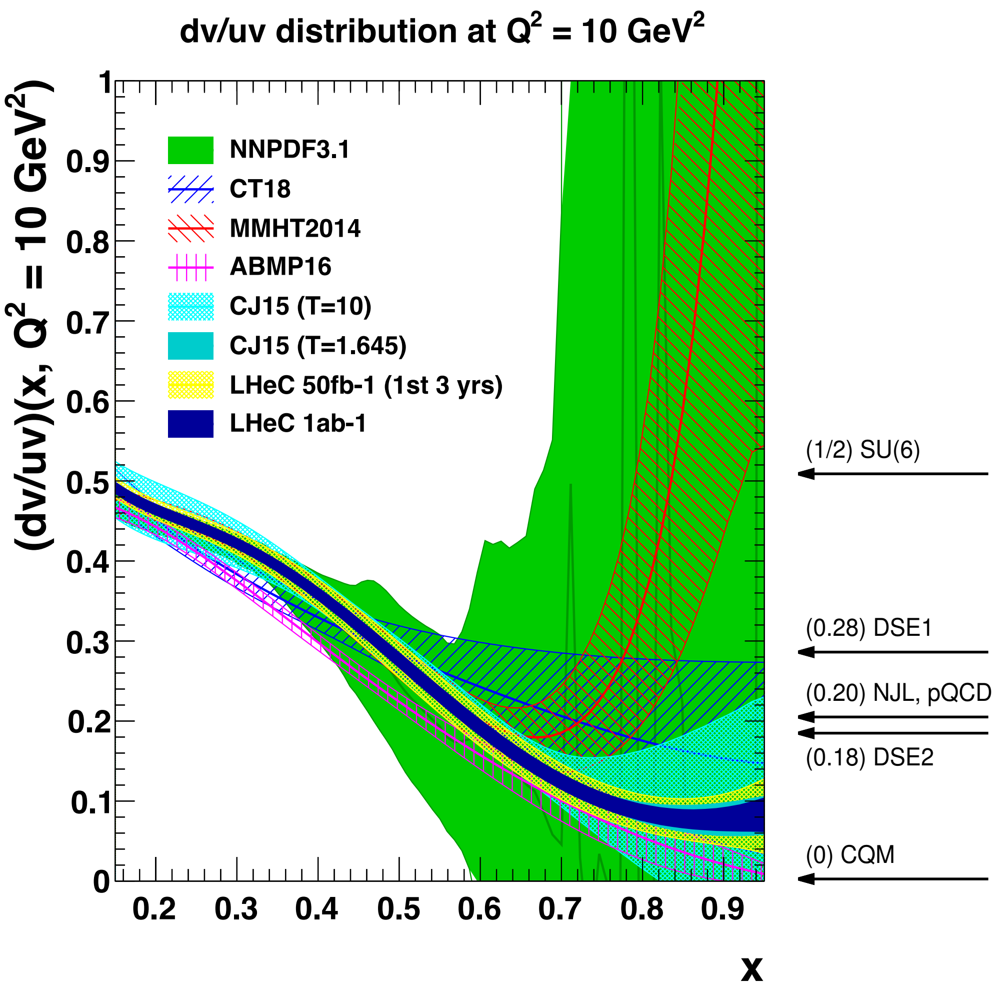
- Here, the **reduction of the PDF error in the low-x region is visible** – particularly remarkable

Gluon PDF



- **Uncertainties on the high-x gluon PDF reduced drastically!**
- DIS data have even a better effect when jets are involved (not here)

d_V/u_V at large-x

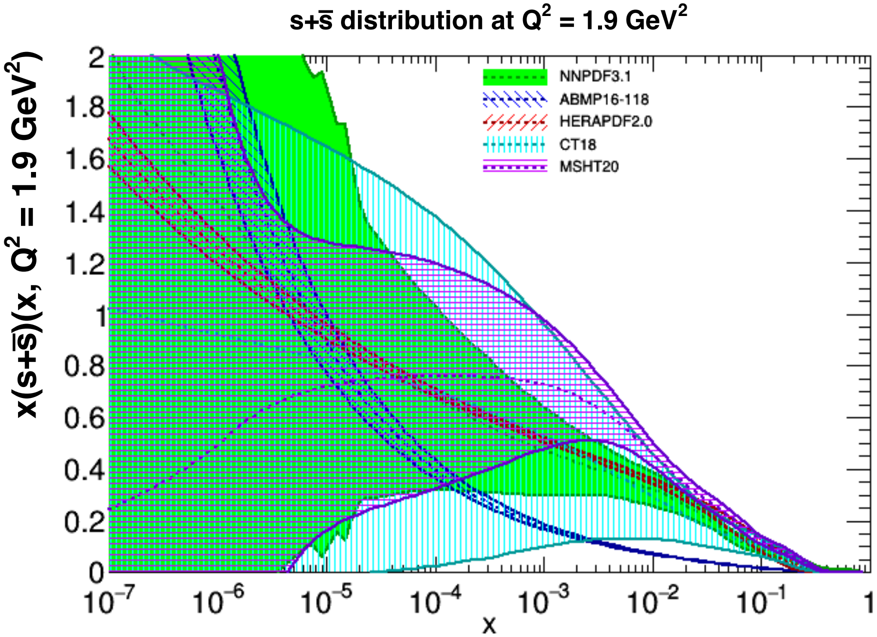


- **d_V/u_V essentially unknown at large-x**
- No predictive power from current PDFs
- Conflicting theory pictures
- Data inconclusive
- Large nuclear uncertainties

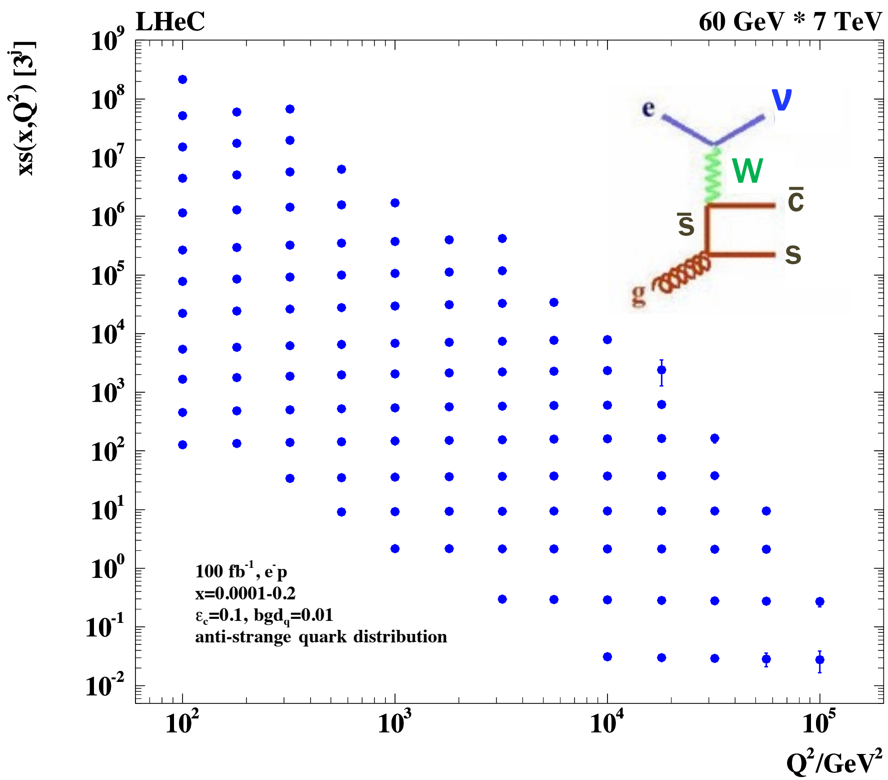
LHeC/FCC-eh data can resolve this long-standing mistery

Strange, c- and b-quarks

- Strange PDF poorly known – suppressed wrt other light quarks? Strange valence?

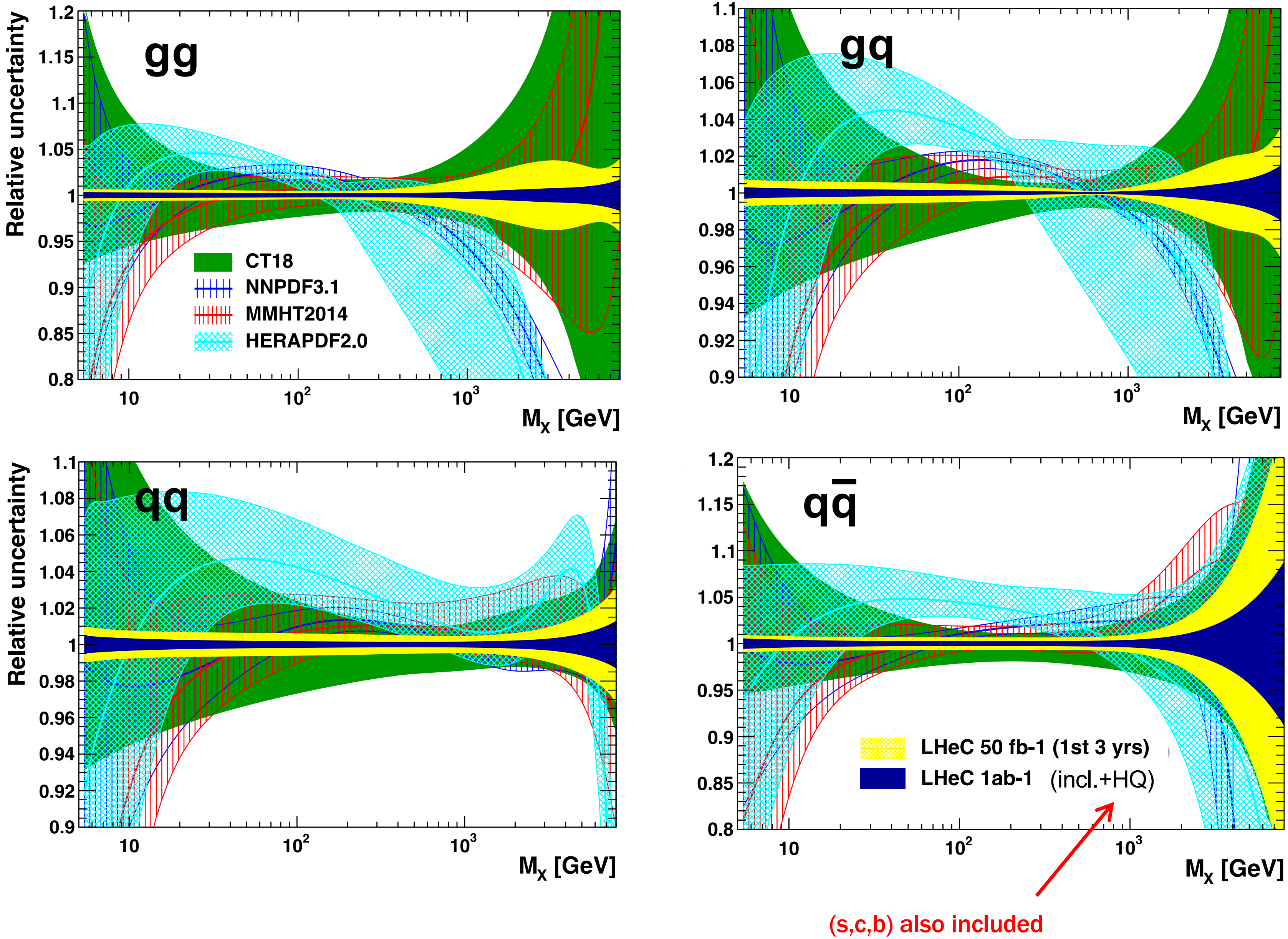


Direct sensitivity to Ws → c via charm tagging – First (x,Q^2) mapping of the strange density

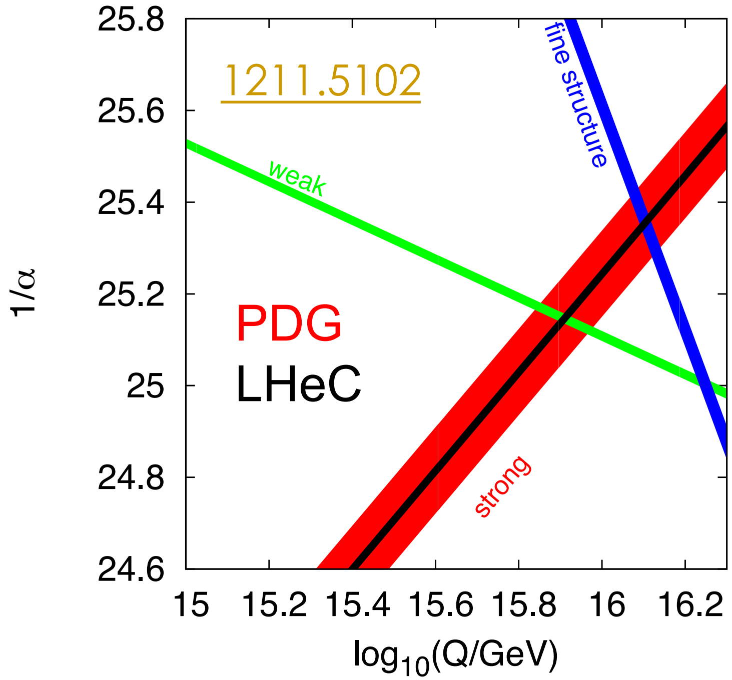


- c,b: enormously extended range and much higher precision wrt HERA
- $\boldsymbol{\delta m_c}$ = 50 (HERA) to **3 MeV**: impact of α_S, regulated ratio of charm to light, crucial for precision top and Higgs physics
- $\boldsymbol{\delta m_b}$ to **10 MeV**: MSSM, Higgs produced dominantly via $b\bar{b}$ → A
- top-quark PDF also accessible - 1411.6492, 1503.01590

PDF luminosities @14 TeV

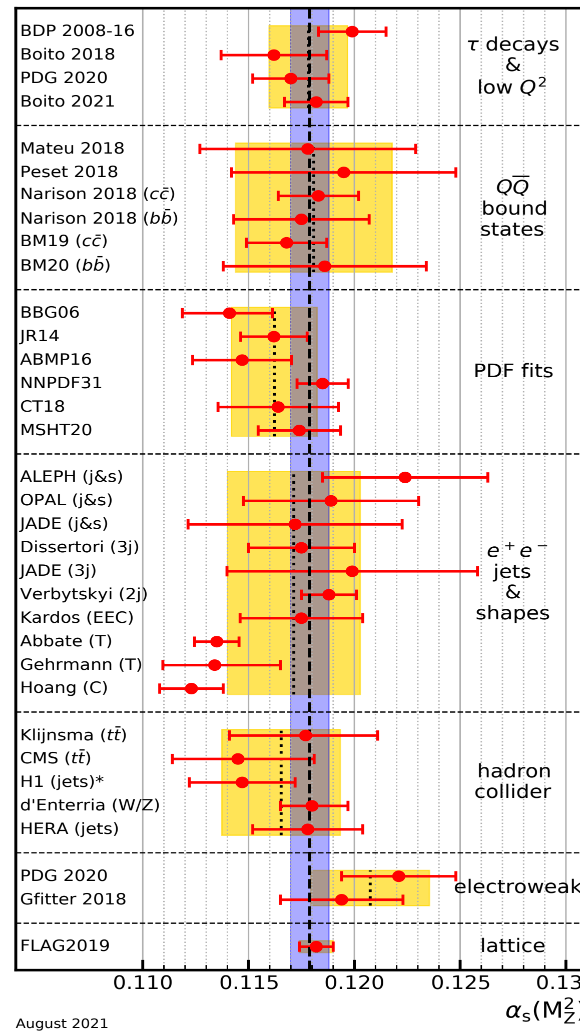


The strong coupling constant

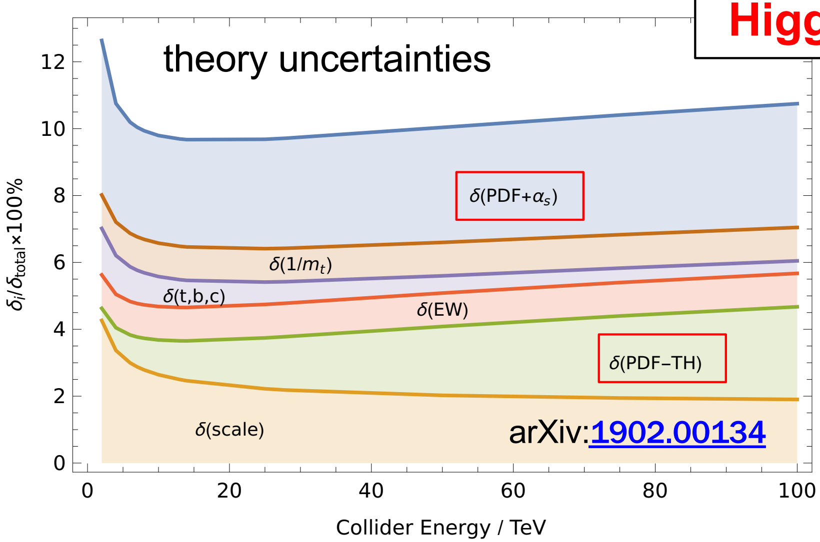


PDG21

FG's talk



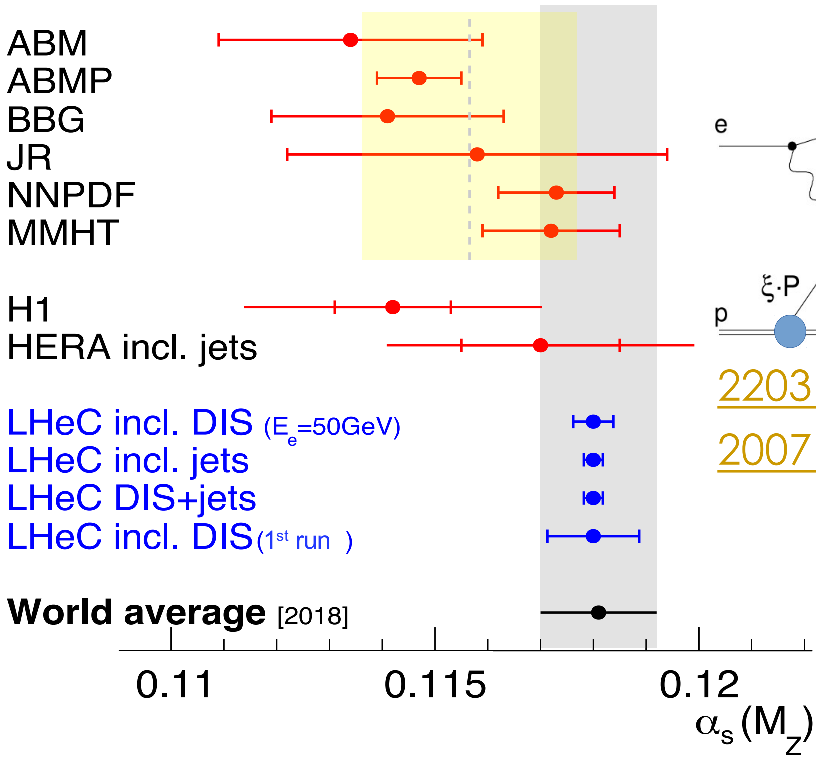
Higgs

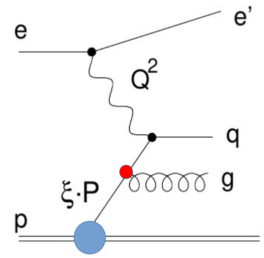


- α_S → least known coupling constant
- Current state-of-the-art: $\delta\alpha_S/\alpha_S = \mathcal{O}(1\%)$

The strong coupling constant

αs determinations at NNLO QCD:





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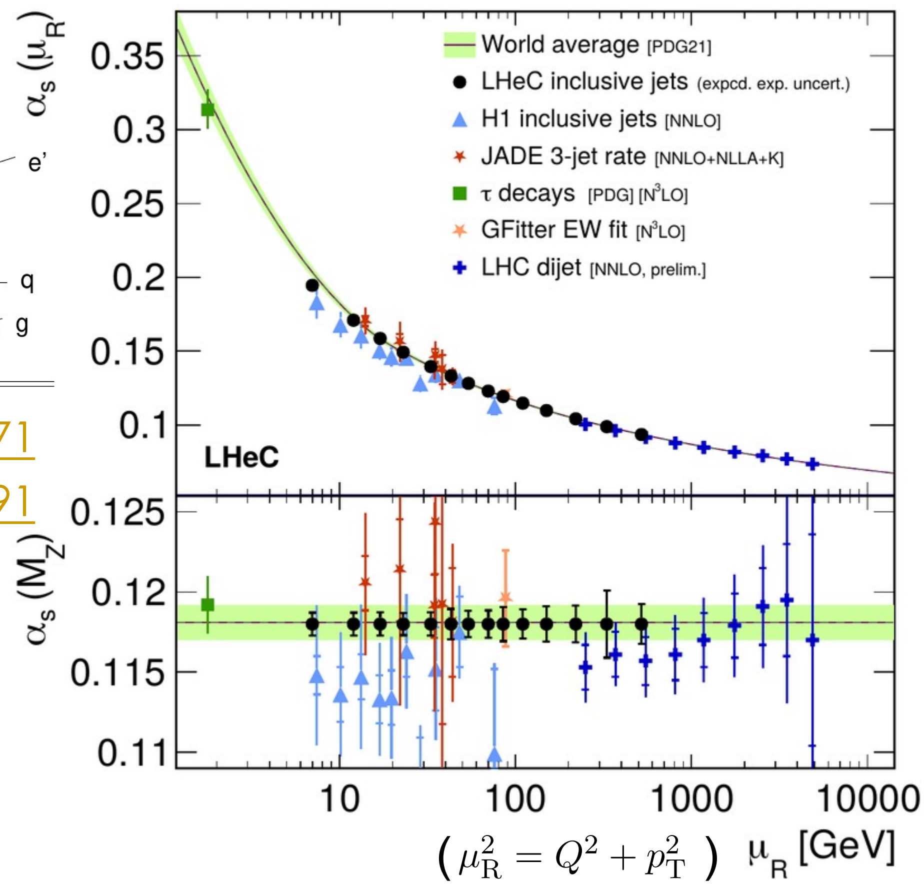
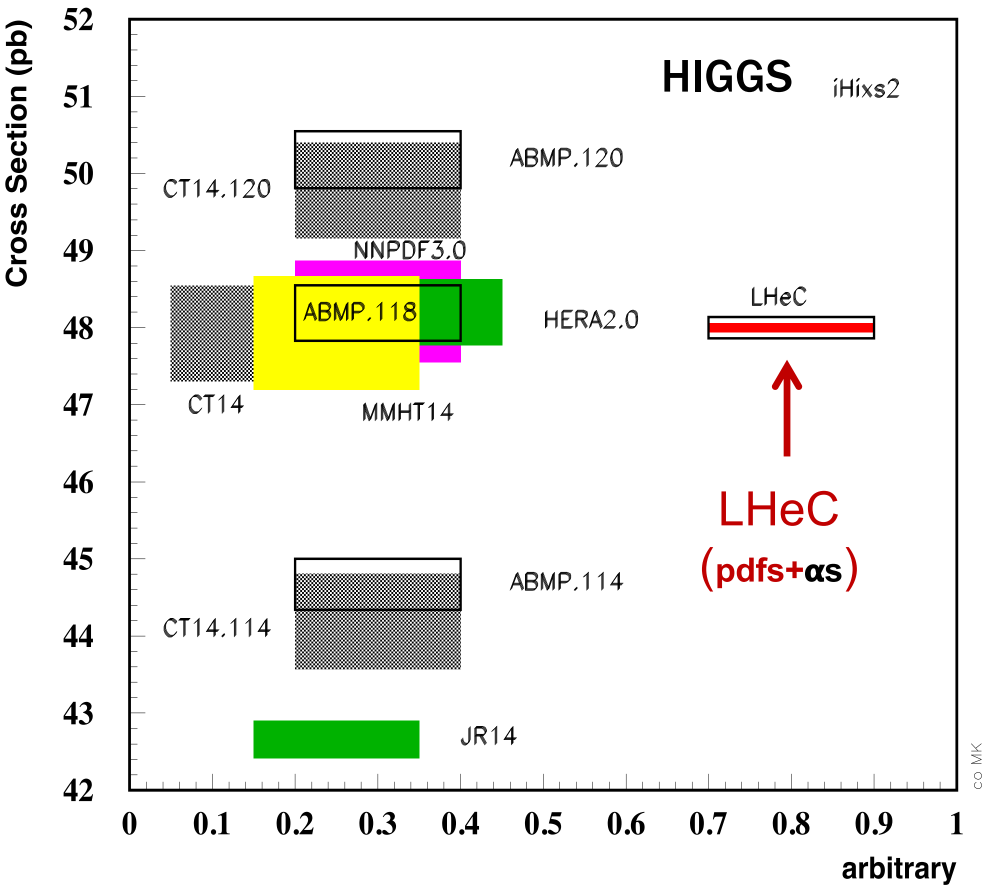


- LHeC simultaneous PDF+α_S fit:
  - $\Delta\alpha_S(m_Z) = \pm 0.00022$ (exp.+PDF)
  - $\Delta\alpha_S(m_Z) = \pm 0.00018$ (with ep jets)
- Achievable precision: ***$\mathcal{O}$(0.1%)*** - **x5-10** better than today
- α_S from fits to ep jet production (**LHeC**)
- FCC-eh further increases precision and range

Empowering the LHC: Higgs

NNNLO pp-Higgs Cross Sections at 14 TeV

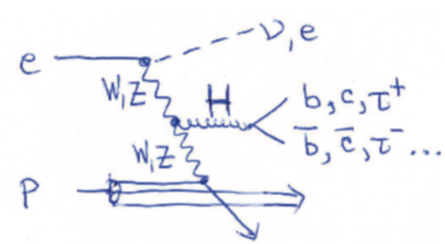


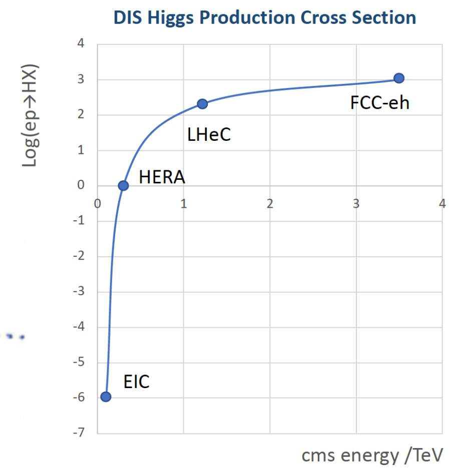
Transformed precision for Higgs @HL-LHC, due to PDF+α_s

Wide and comprehensive Higgs programme – complementarity between pp and ep

2201.02436

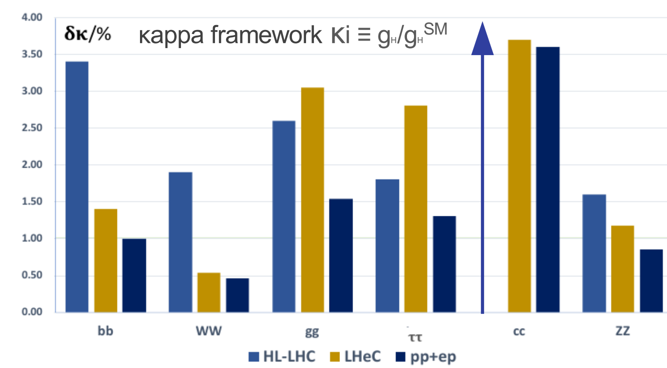
2007.14491





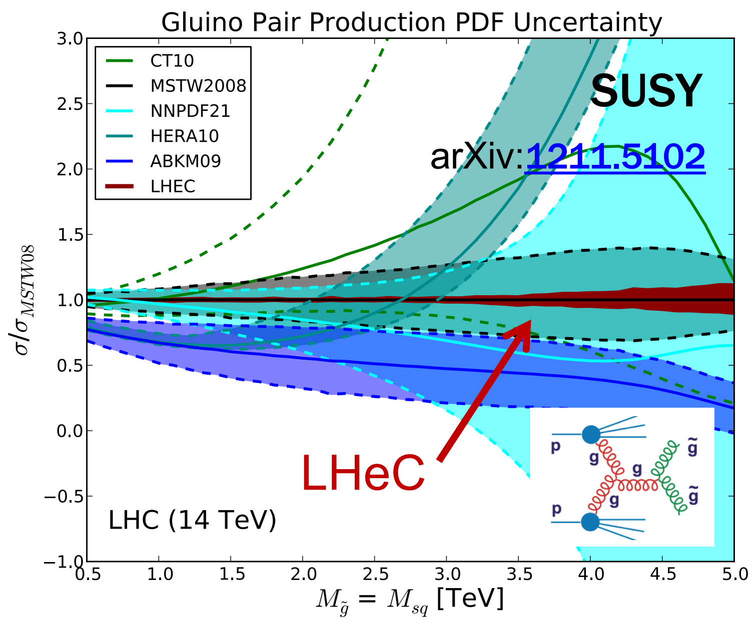
Interplay between *pp* and *ep*
(shown here: LHeC & HL-LHC)

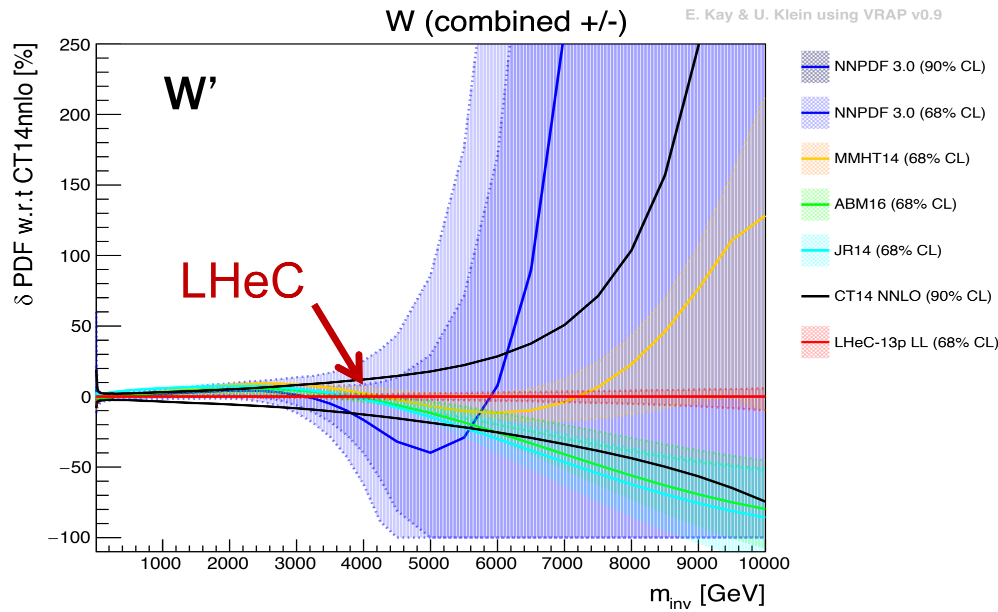
HL=LHC prospects - 1902.00134



Empowering the LHC: BSM

- **BSM**: external, reliable and precise PDFs needed for **range extension** and **interpretation** - 1902.04070, 2007.14491



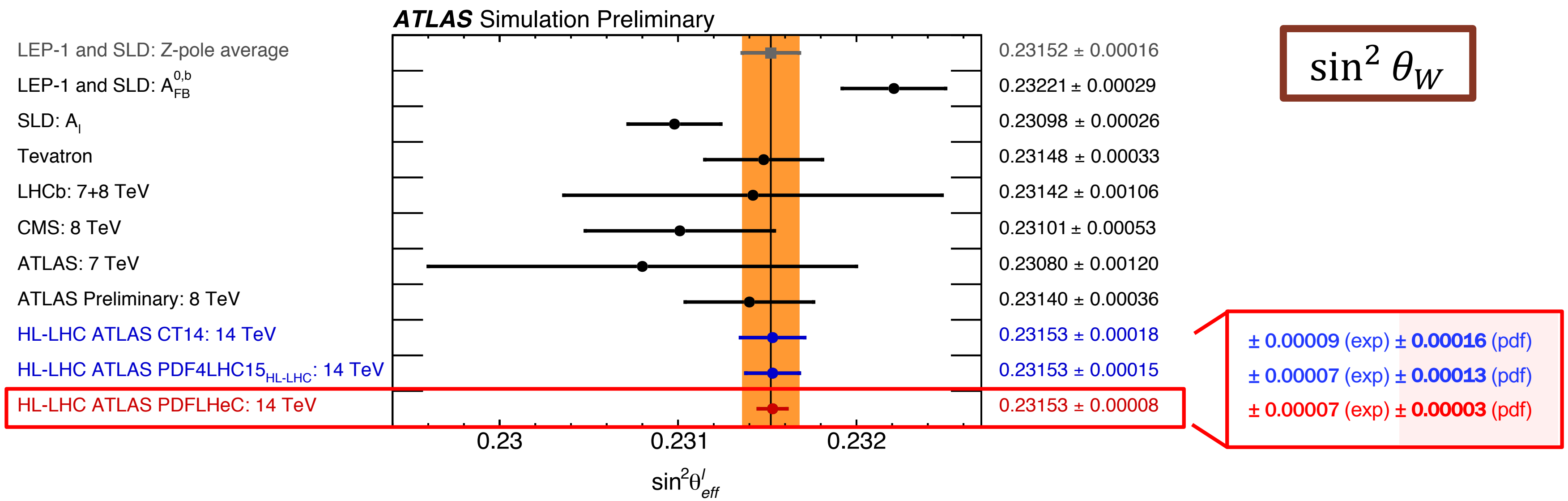


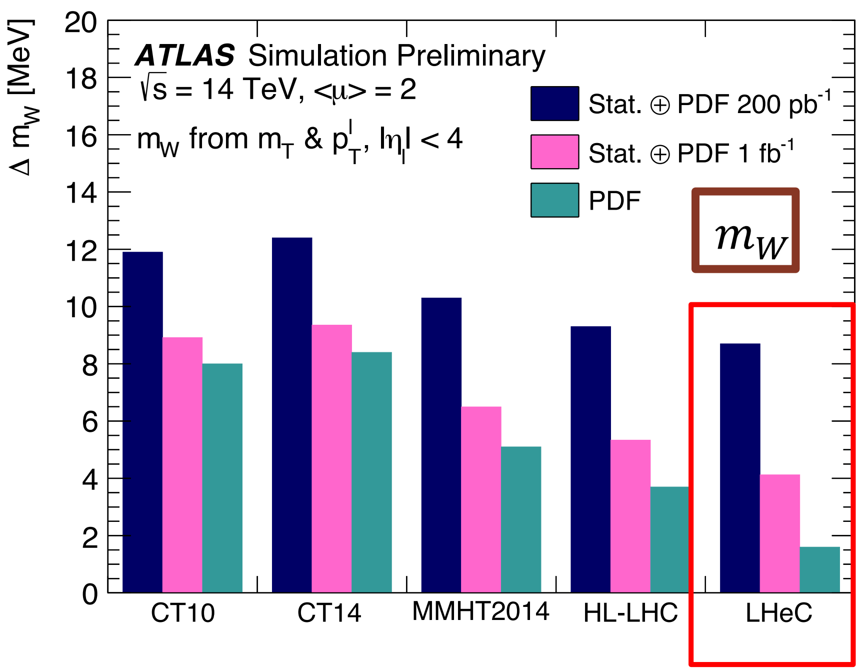
CONTACT INTERACTIONS: $\mathcal{L}_{CI} = \frac{g^2}{\Lambda^2}\eta_{ij}(\bar{q}_i\gamma_\mu q_i)(\bar{\ell}_i\gamma^\mu \ell_i)$

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

- **Unique sensitivity to search in regions not accessible in pp**
- Long-lived Particles (LLP), Lepton Flavour Violation (LFV), R-parity violating (RPV) and compressed SUSY, sterile ν, …

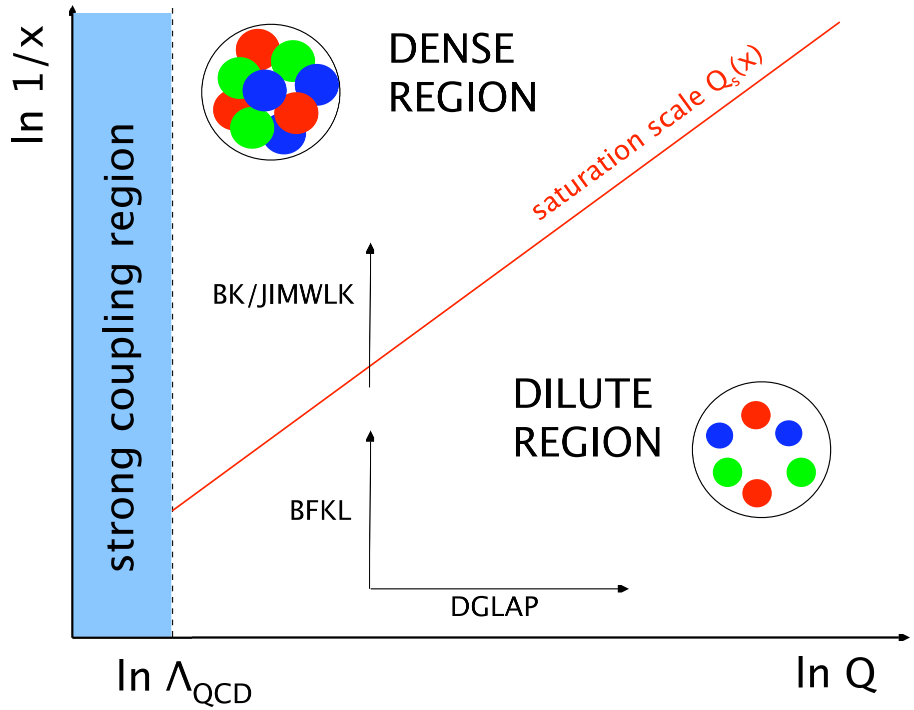
Empowering the LHC: precision EW





- m_W, $\sin^2\theta_W$ precision measurement sensitive to BSM physics
- **PDF uncertainties become sub-dominant when using LHeC PDFs**
- Complementary ep DIS EW programme i.e. m_W, $\sin^2\theta_W$ from simultaneous PDF+EW fits and more

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

$x_1, x_2, \frac{\tau}{x_1 x_2}$ can get as small as $\tau = \frac{Q^2}{s}$ (note: typical values $x_1, x_2 \sim \sqrt{\tau}$)

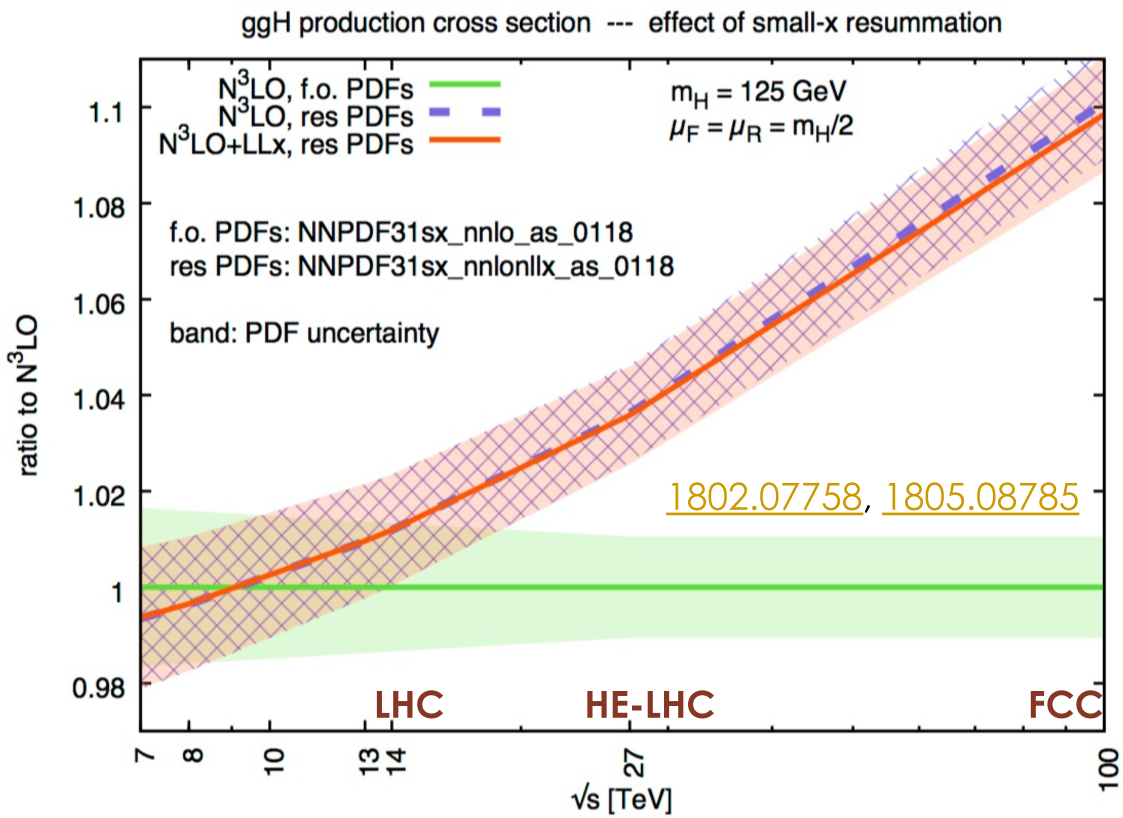
τ	Higgs	Z, W	low mass DY	$c\bar{c}$
LHC (13 TeV)	10^{-4}	5×10^{-5}	$\sim 10^{-6}$	$\sim 10^{-7}$
FCC-hh (100 TeV)	1.5×10^{-6}	8×10^{-7}	$\sim 10^{-8}$	$\sim 10^{-9}$

Unprecedented opportunity to explore small-x with LHeC/FCC-eh

M. Bonvini, LFC 2022 Workshop

Resummed pp phenomenology

- Inclusive **gluon-fusion Higgs** production process

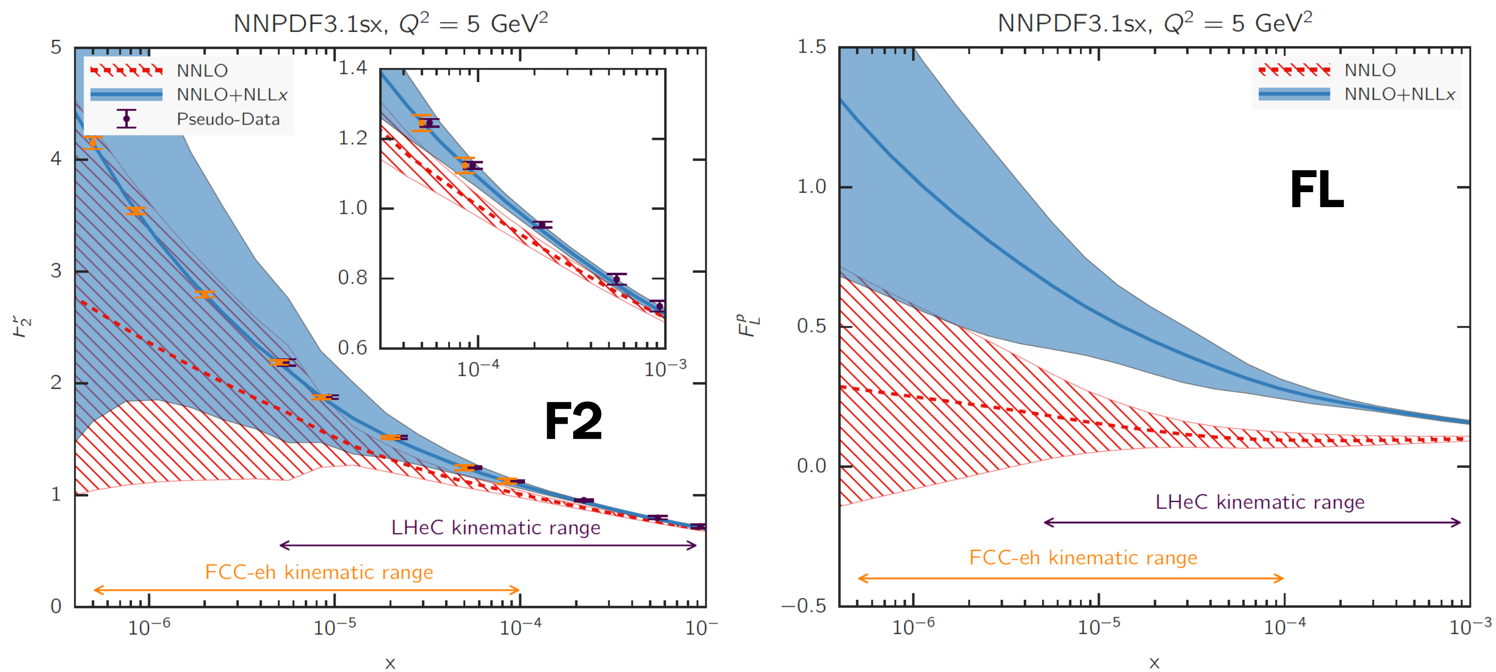


- Resummed calculation matched to N^{3}LO FO calculations
- Small-x resummation has a modest impact at current LHC energies
- Its impact grows substantially with the energy, reaching **10% at 100 TeV**
- **Bulk of the effect:** the resummed PDFs and their resummed evolution

Work on forward Higgs production; other processes in progress i.e. HQ

- Here inclusive cross sections BUT a more prominent effect is expected in exclusive/differential cross section (especially in e.g. large-rapidity regions)

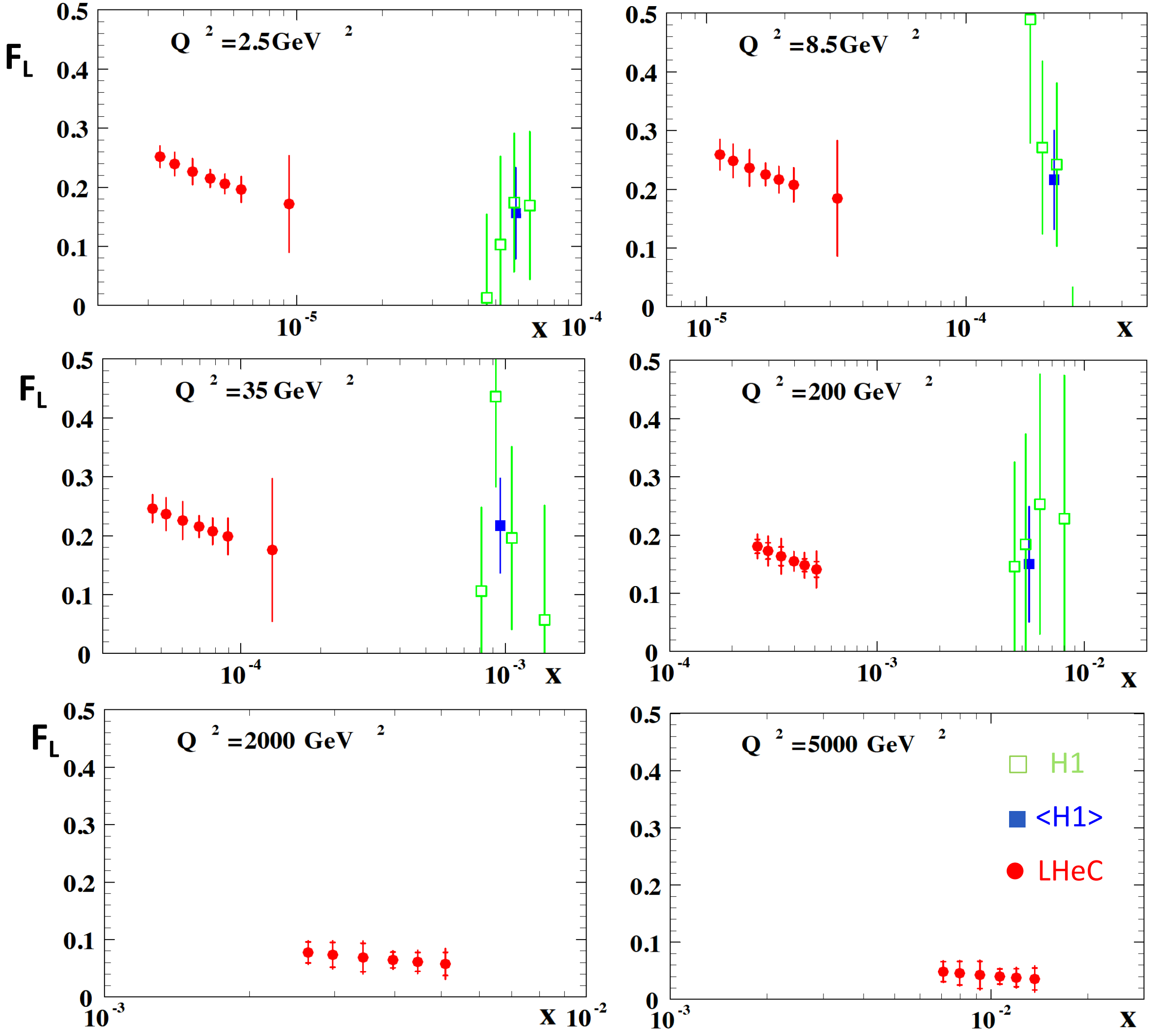
LHeC/FCC-eh sensitivity to small-x



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

- **LHeC and FCC-eh have unprecedented kinematic reach to small-x**
- Very large sensitivity and discriminatory power to pin down details of small-x QCD dynamics - 2007.14491
- Measurement of F_L plays a significant role - 1802.04317

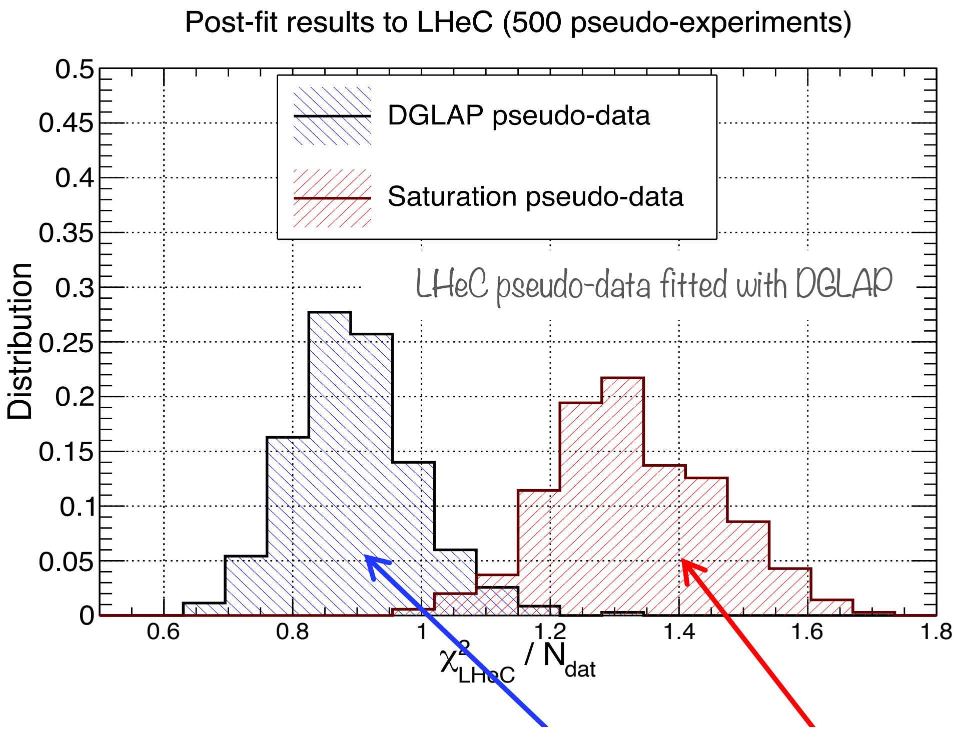
Longitudinal structure functions

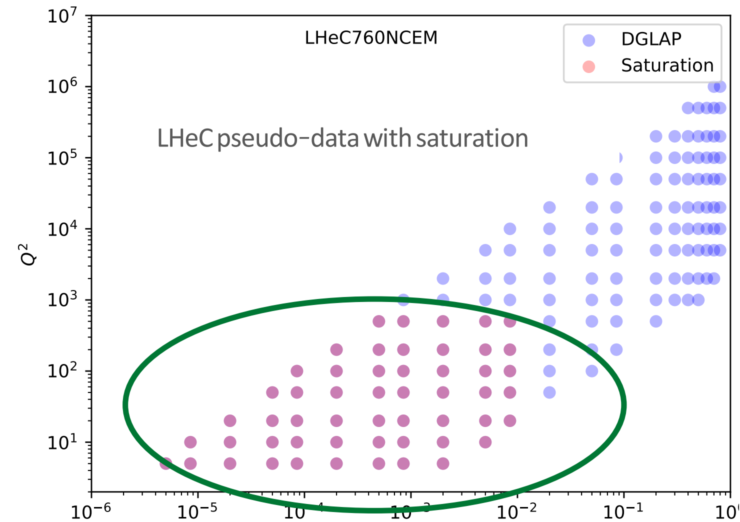


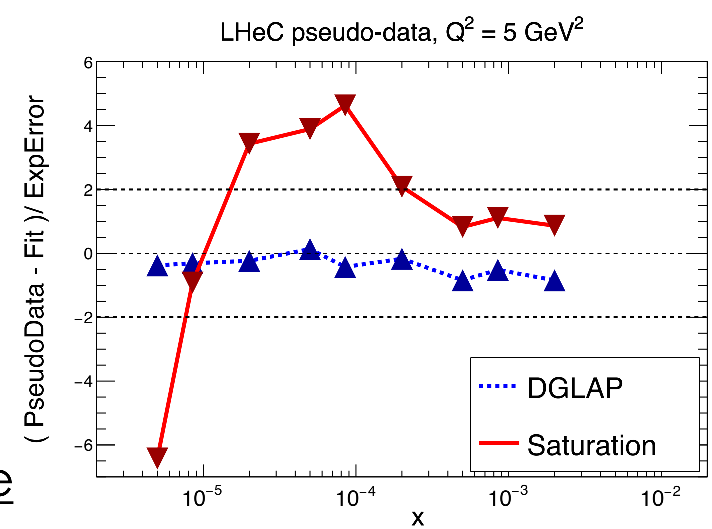
- Simulated for E_p = 7 TeV and E_e = 20, 30, 60 GeV
- $\int \mathcal{L}$ = 1, 10, 50 fb^{-1}
- Current measurements dominated by systematics
- **Simultaneous measurement of F_2 and F_L** is a clean way to pin down dynamics at small-x

Parton saturation

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







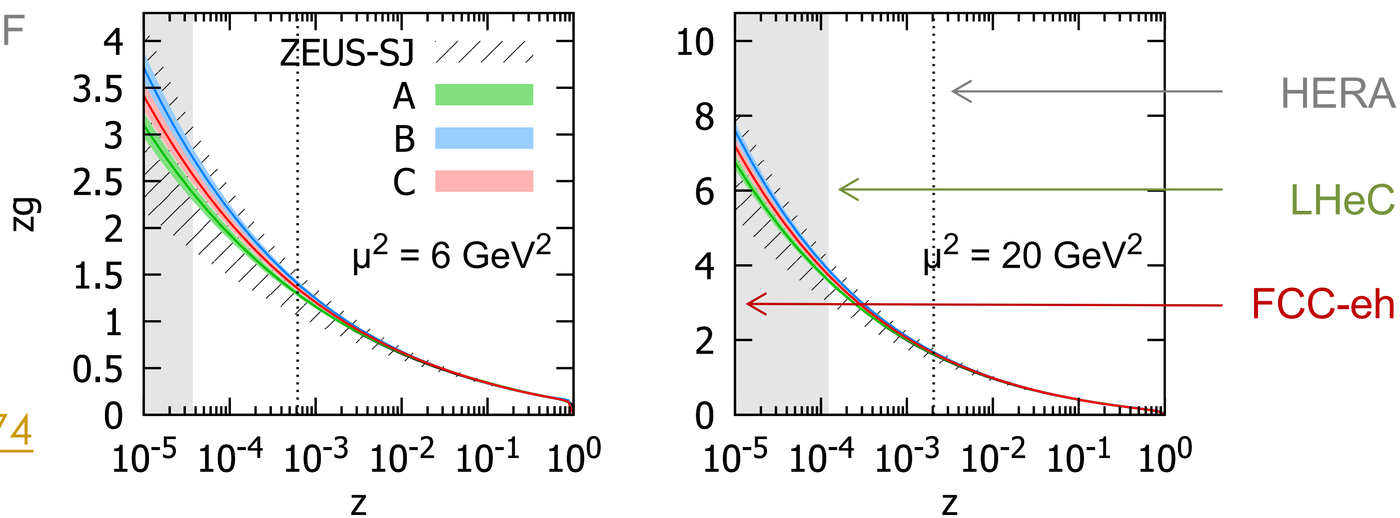
- LHeC can distinguish **DGLAP** and **saturation**
- Possible to identify saturation by distortions in pulls
- Fit cannot absorb a non-DGLAP Q^2 dependence

Diffractive PDFs

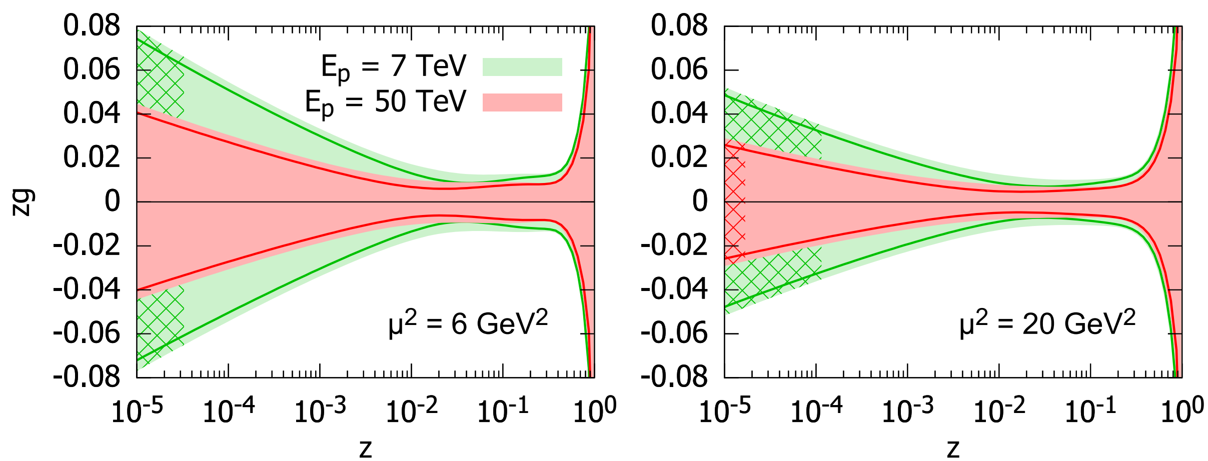
Gluon diffractive PDF from LHeC:

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

EPJ C79 (2019), 6, 474



Relative uncertainty, LHeC and FCC-eh:



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

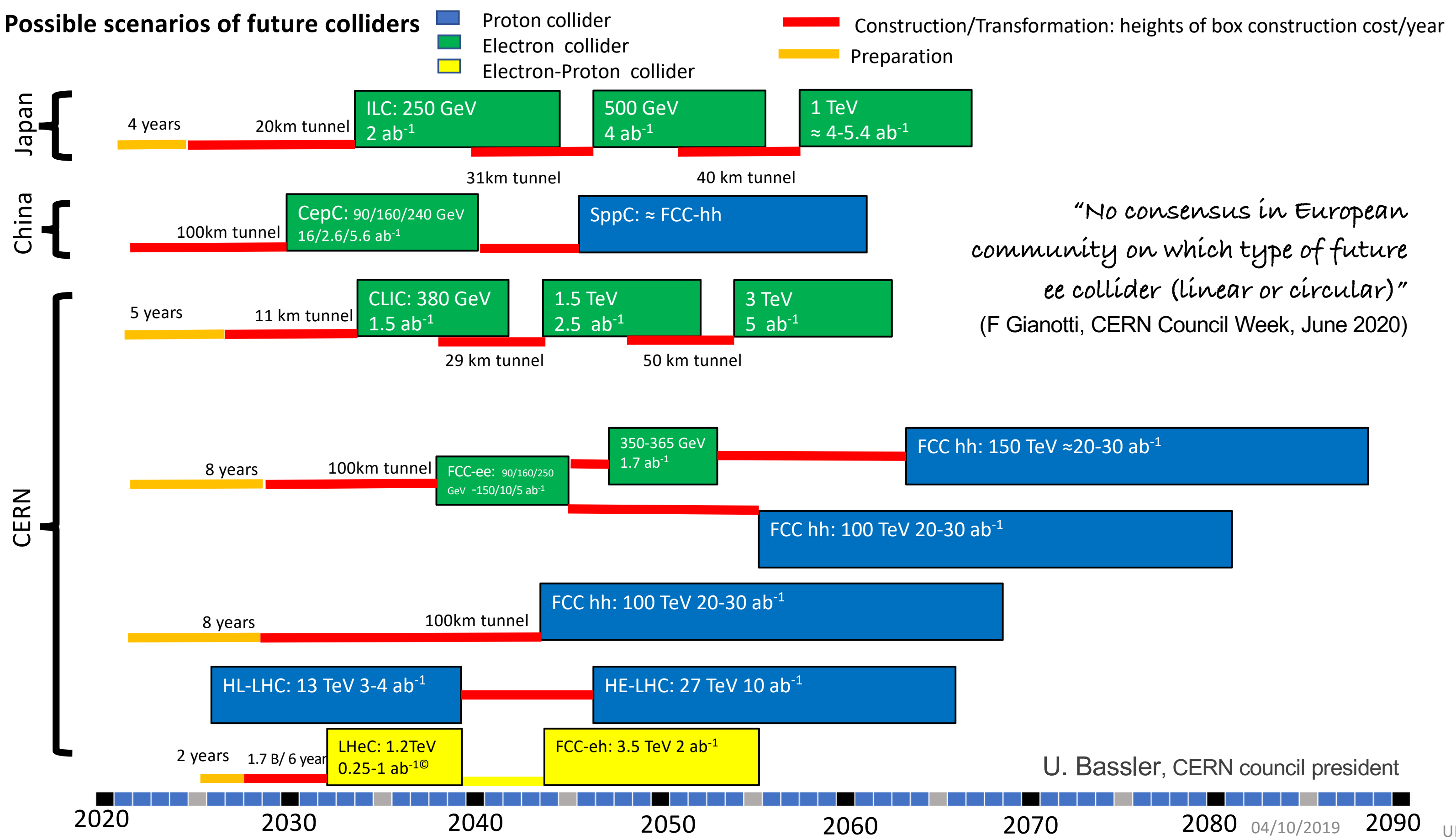
Summary

- Energy frontier electron-proton colliders essential for full exploitation of current and future hadron colliders (Higgs, BSM, EW, …)
- Wealth of new and updated studies from LHeC/FCC-eh
- Enormously rich physics programs in their own right, and for transformation of pp machines into precision facilities
- **All critical PDF information can be obtained with early data** (~50 fb^{-1} = x50 HERA), in parallel with HL-LHC operation
- **Unprecedented access to novel kinematic regime, with unique potential to explore small-x phenomena**
- α_S to per-mille experimental precision achievable, with use of inclusive DIS and/or jets
- … and much more in realm of Higgs, top EW and BSM physics (see talk by N. Armesto Perez)

Backup Slides

LHeC timeline

CERN/ESG/05



LHeC: installation during **LS4**;

- Concurrent operation through **LHC Run 5/6**, and **period of dedicated running**

Statement of the IAC

Members of the Committee

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Nichola Bianchi (INFN, now Singapore)
Frederick Bordy (CERN)
Stan Brodsky (SLAC)
Oliver Brüning (CERN, coordinator)
Hesheng Chen (Beijing)
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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.

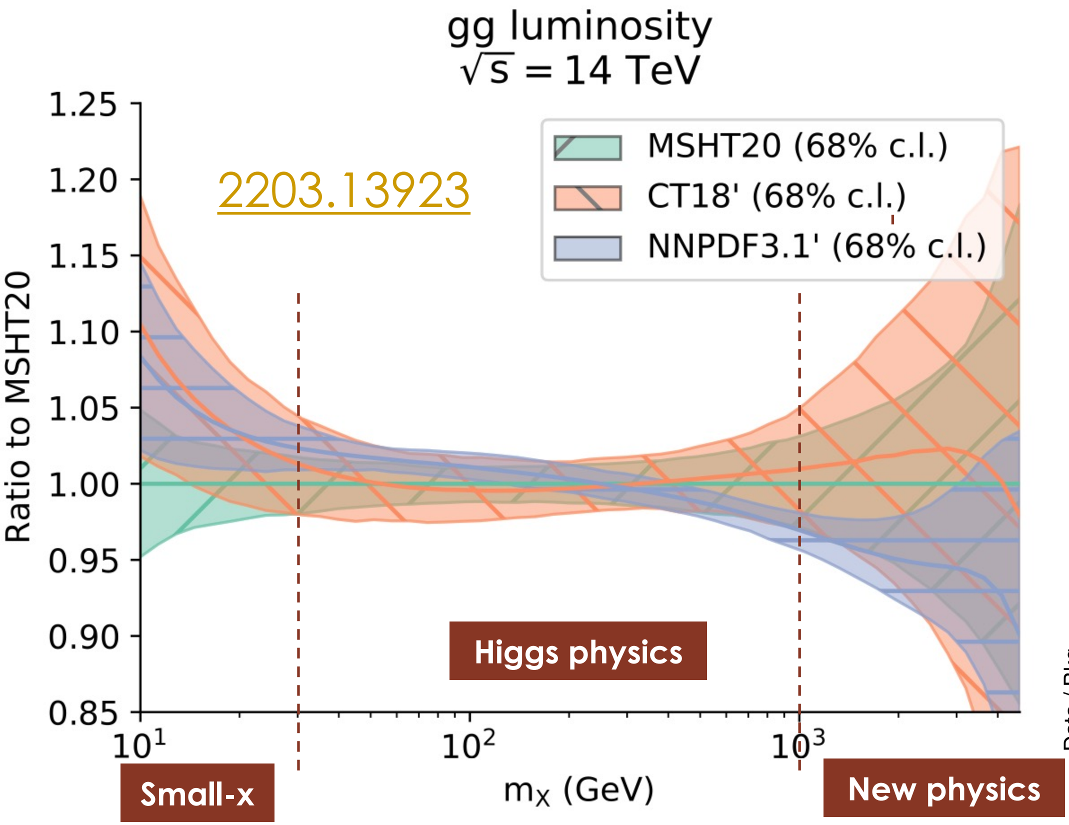
After the final results of the European Strategy Process will be made known, the IAC considers its task to be completed. A new decision will then have to be taken for how to continue these activities.

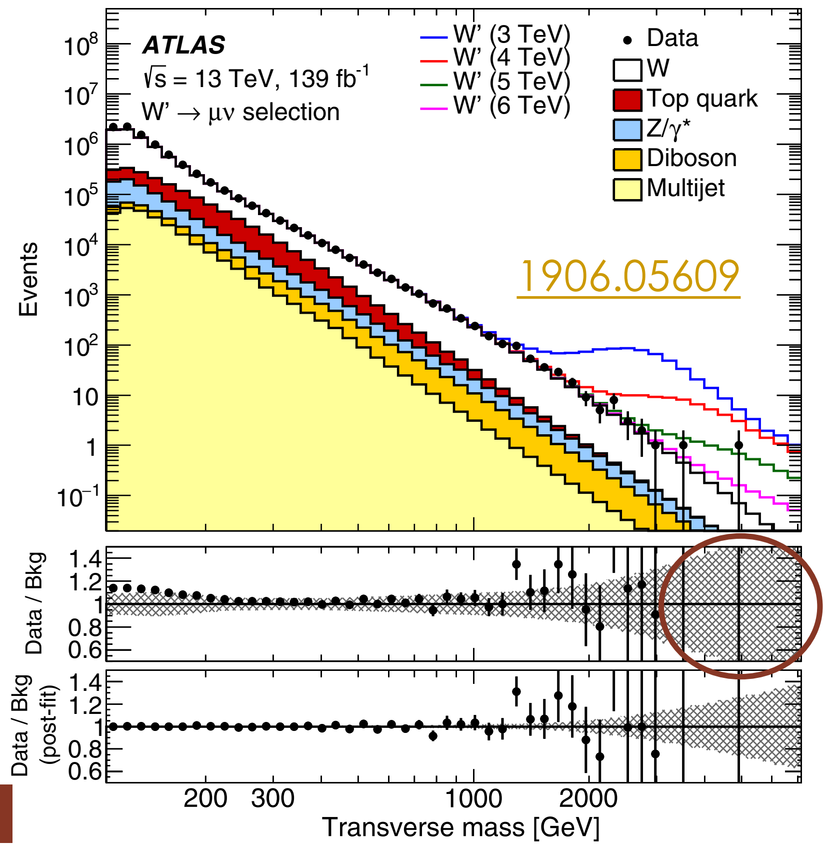
Herwig Schopper, Chair of the Committee, Geneva, November 4, 2019

- Published in LHeC CDR update - 2007.14491

Why proton PDFs matter

- Precise knowledge of Parton Distribution Functions (PDFs) is essential
- PDFs have large uncertainties in the LHC kinematics regions
  - Significant source of uncertainty for Higgs and top production
  - Limits precision on fundamental parameters (m_W, α_S, etc.)
  - Limits searches for new massive particles





PDFs at HL-LHC

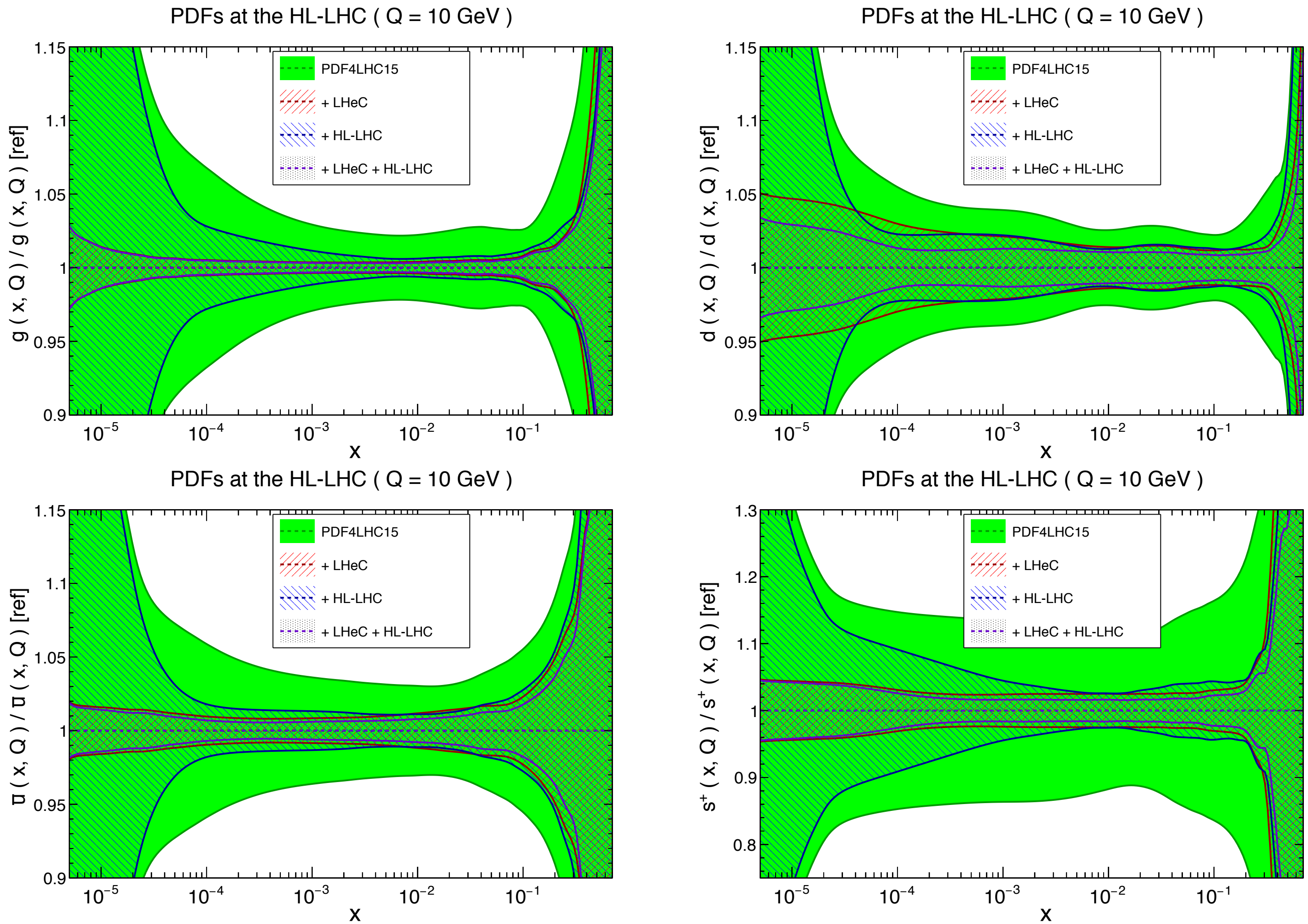


Figure 9.9: Impact of LHeC on the 1-σ relative PDF uncertainties of the gluon, down quark, anti–up quark and strangeness distributions, with respect to the PDF4LHC15 baseline set (green band). Results for the LHeC (red), the HL-LHC (blue) and their combination (violet) are shown.

Parton luminosities at HL-LHC

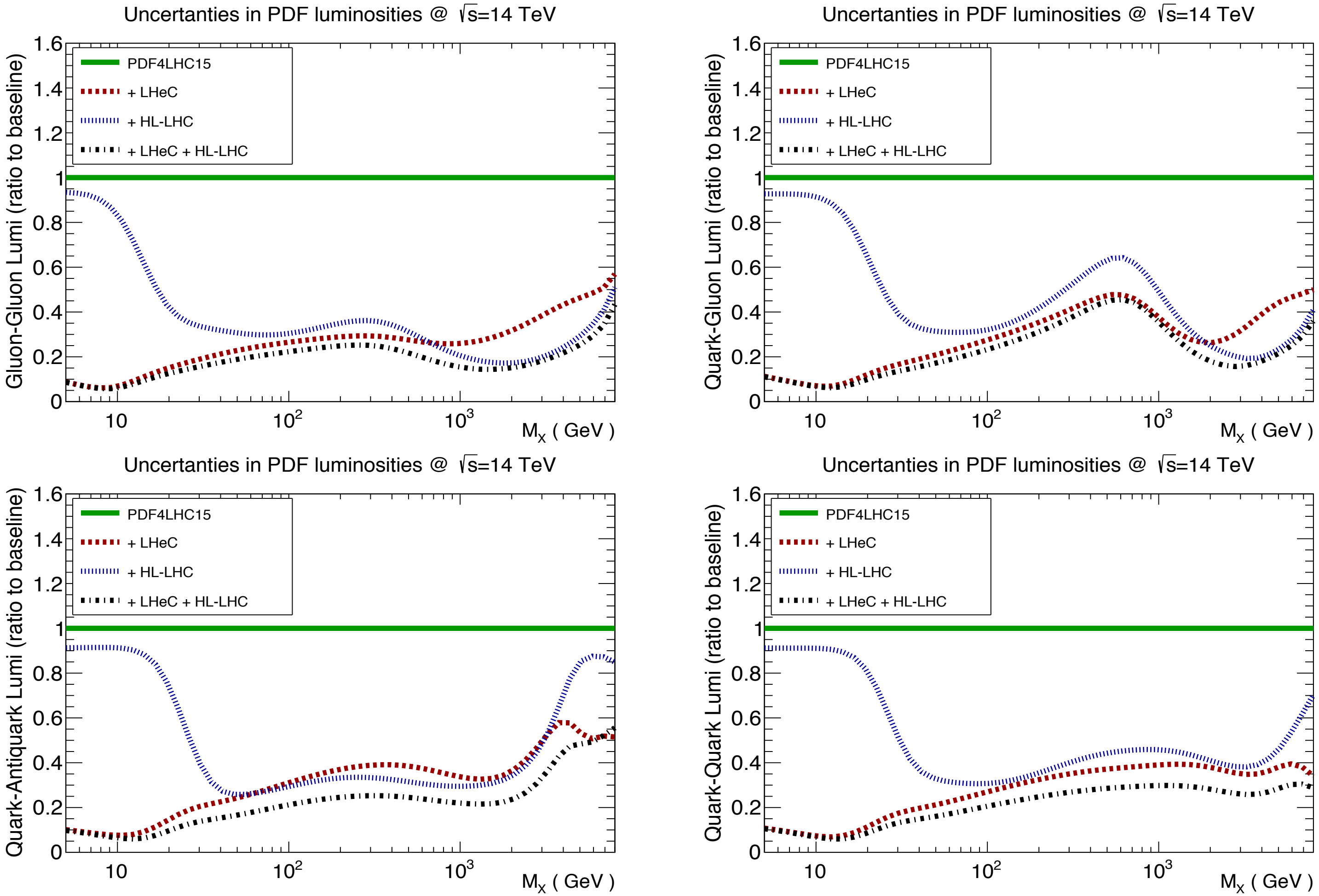
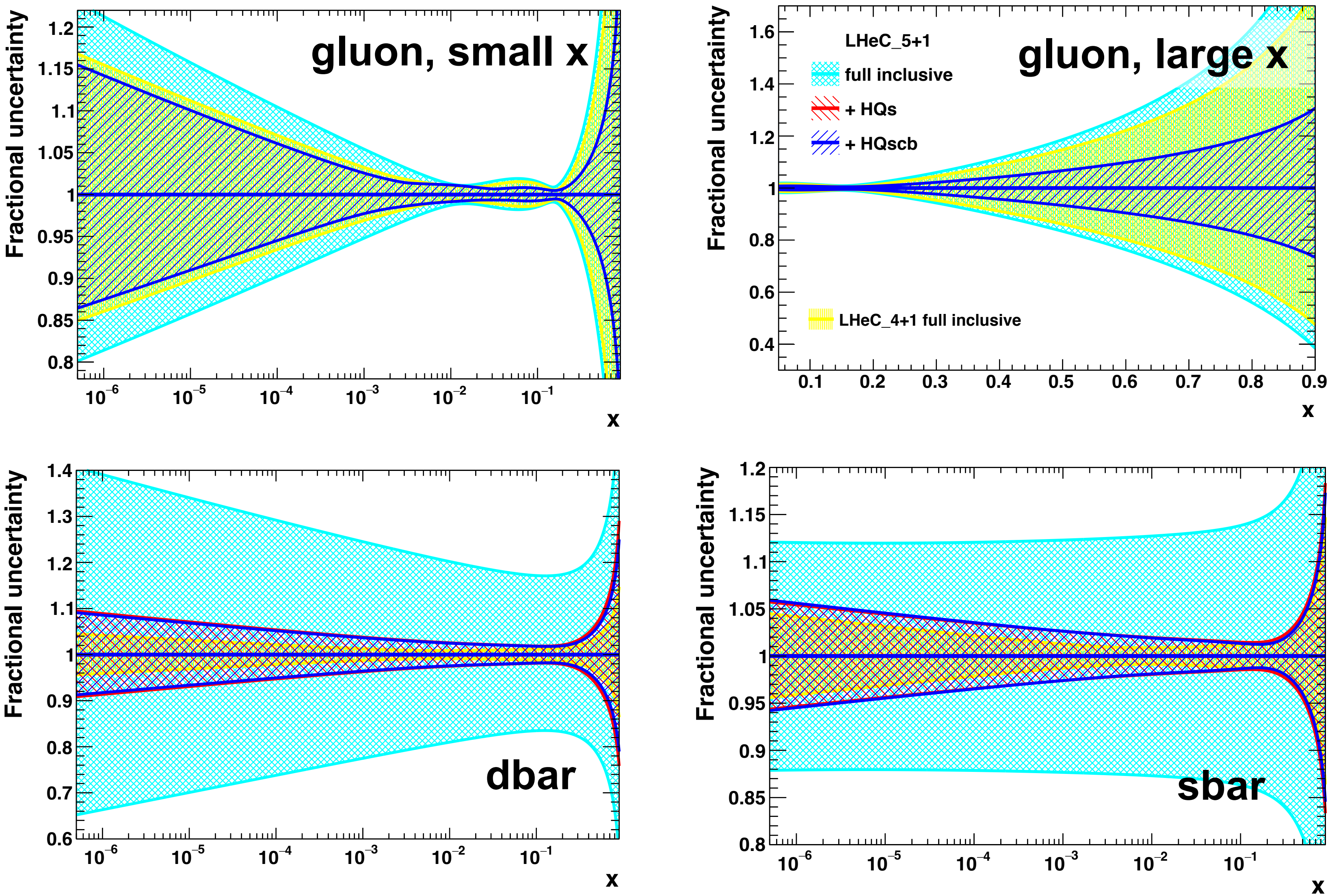


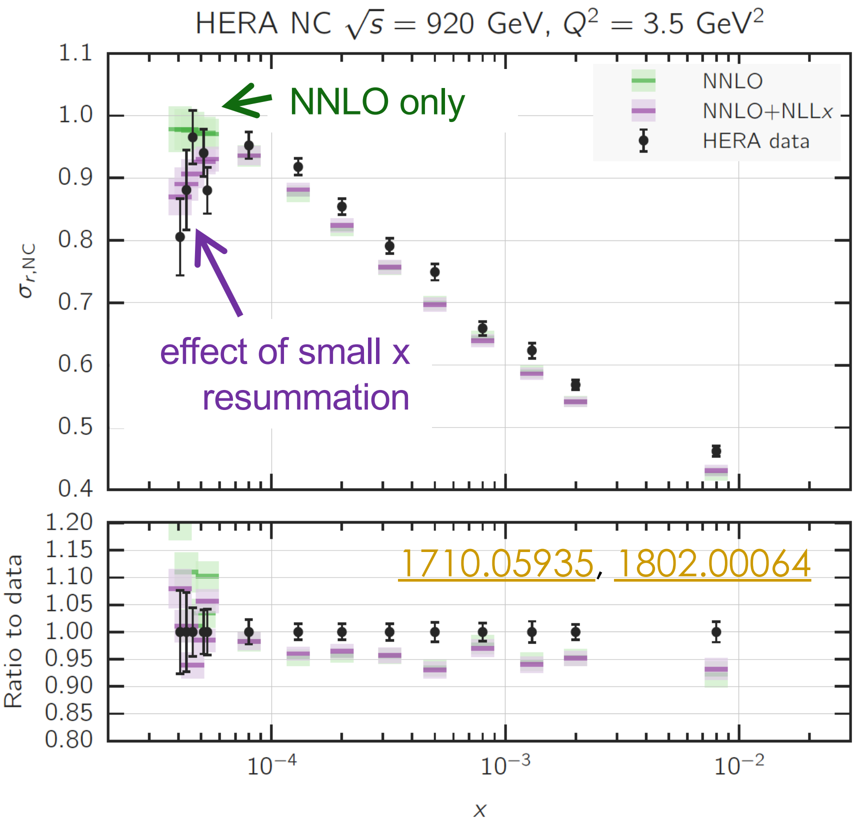
Figure 9.10: Impact of LHeC, HL-LHC and combined LHeC + HL-LHC pseudodata on the uncertainties of the gluon-gluon, quark-gluon, quark-antiquark and quark-quark luminosities, with respect to the PDF4LHC15 baseline set. In this comparison we display the relative reduction of the PDF uncertainty in the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

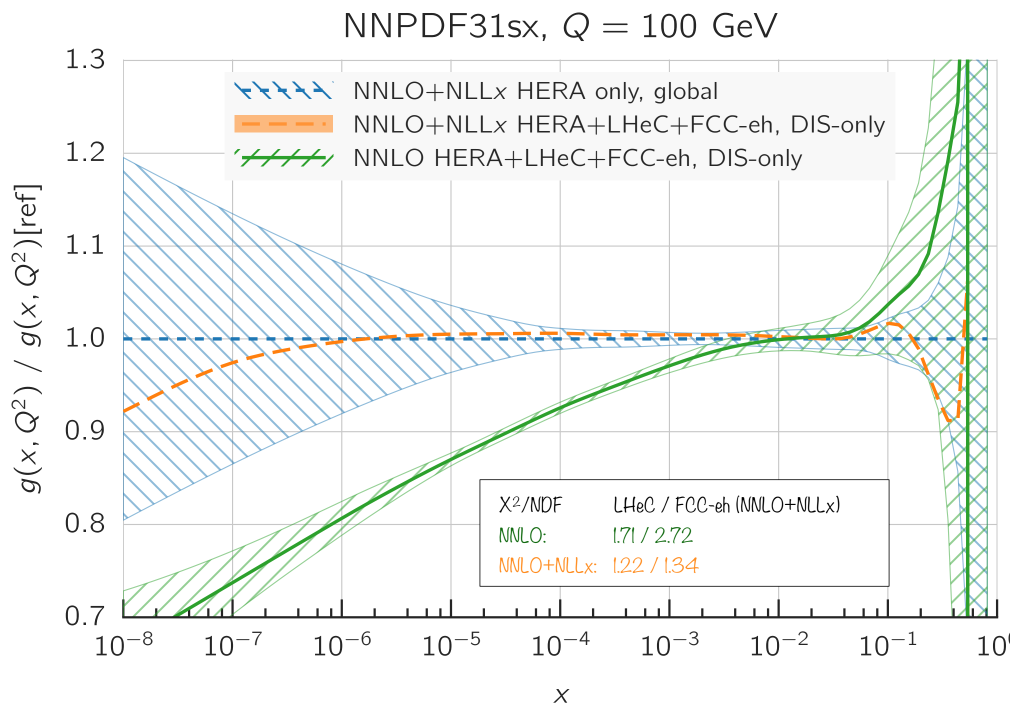
Impact of strange, c- and b-quarks



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

Small-x resummation

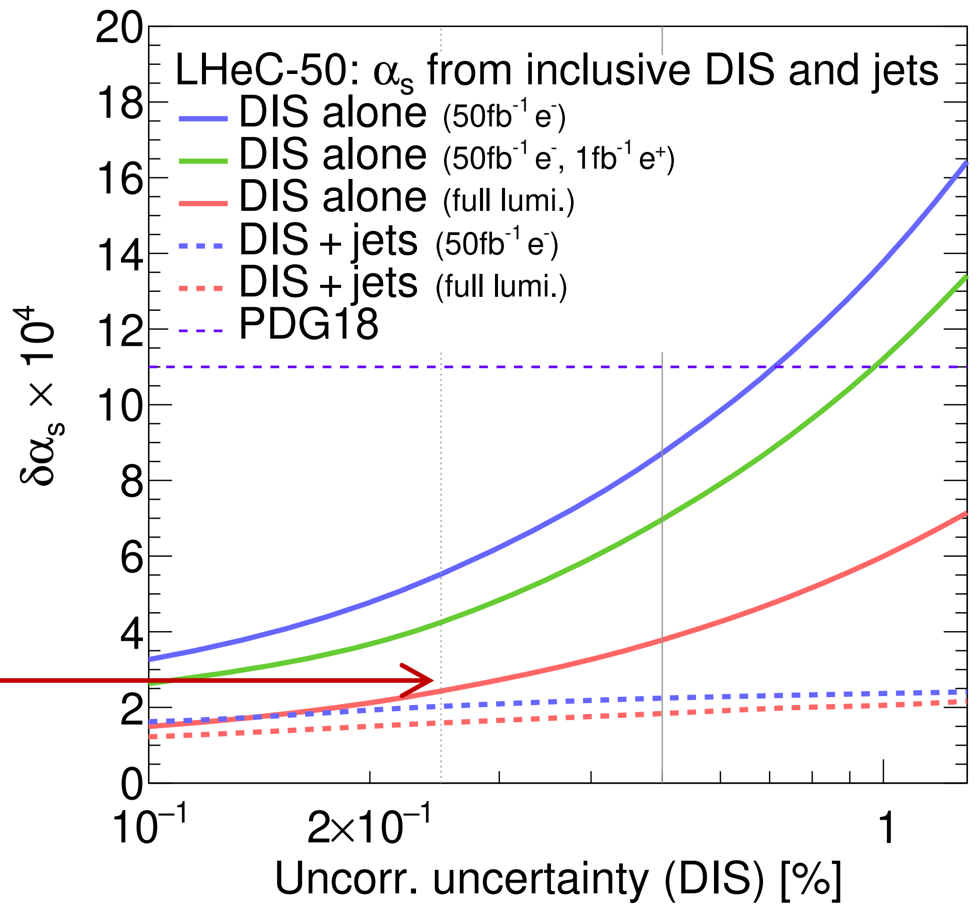




- Recent evidence of onset of NFKL dynamics in HERA inclusive data
- Small-x resummation mainly effects gluon PDF – **dramatic effect for x ≤ 10^{-3}**
- Essential for LHeC and FCC-eh!
- Gluon PDF with small-x rersummation grows more quickly → saturation at some point!

α_s from LHeC inclusive NC/CC DIS

- α_s from inclusive NC/CC DIS
- Simultaneous determination of PDFs and α_s in a NNLO QCD fit
- 3 LHeC scenarios:
  - LHeC 1st Run (50 fb^{-1} e-p)
  - Plus 1 fb^{-1} positron data
  - Full inclsuive LHeC (1 ab^{-1})



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

- α_s to **better than 2 per-mille** experimental uncertainty!
- Inclusion of jet cross sections yields further improvement, and stabilises against uncorrelated uncertainty scenario