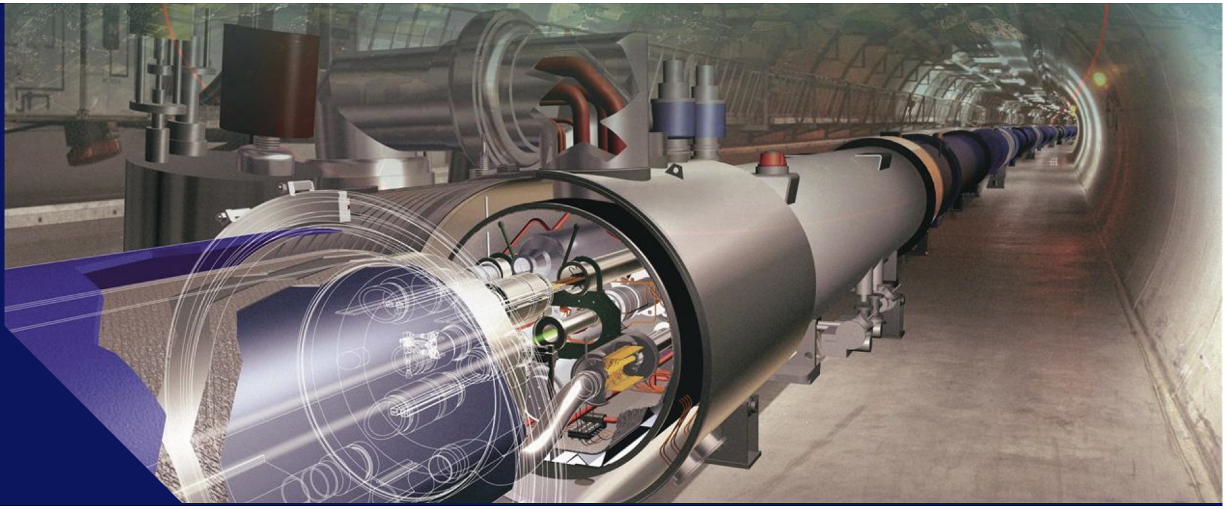
ICHEP2022

Bologna, Italy

6 – 13 July 2022

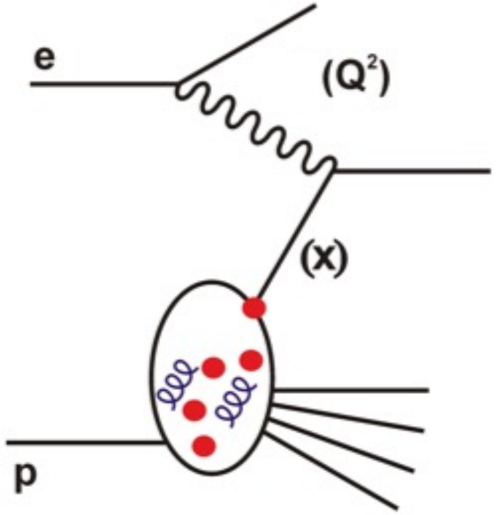


Proton Structure at the LHeC and FCC−eh

Claire Gwenlan, Oxford

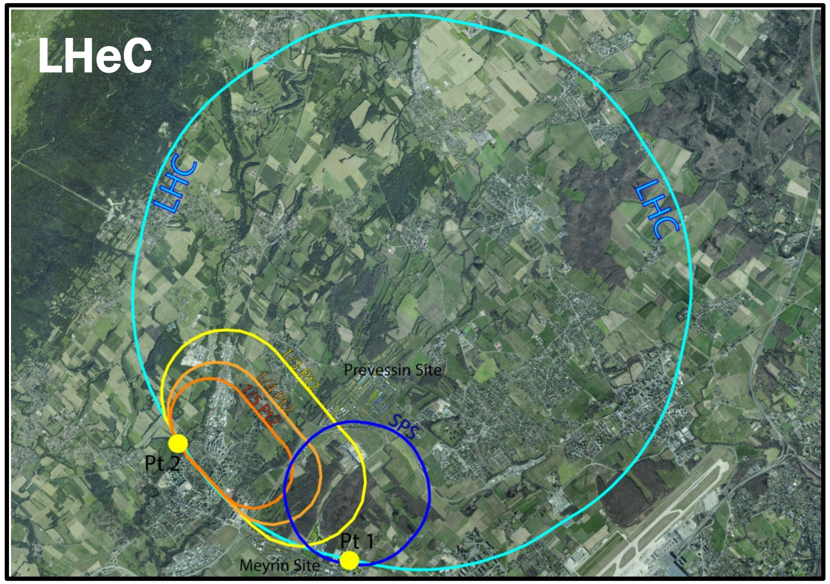
on behalf of the LHeC and FCC-eh study groups

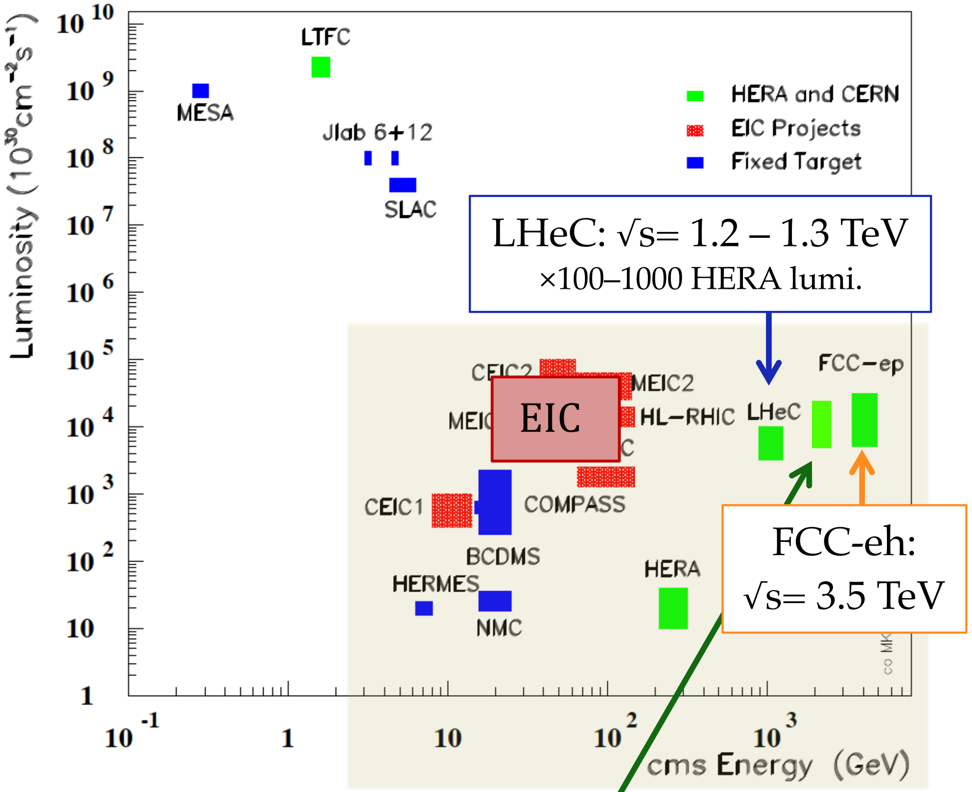
with focus on results from J. Phys. G 48 (2021) 11, 110501



CERN future colliders: arXiv:1810.13022

LHeC, FCC−eh and PERLE





LHeC: √s= 1.2 – 1.3 TeV
×100–1000 HERA lumi.

FCC-eh:
√s= 3.5 TeV

"LE-FCC-eh": √s= 2.1 TeV
(earlier operation with current magnet technology, Ep=19 TeV)

energy recovery LINAC (ERL)

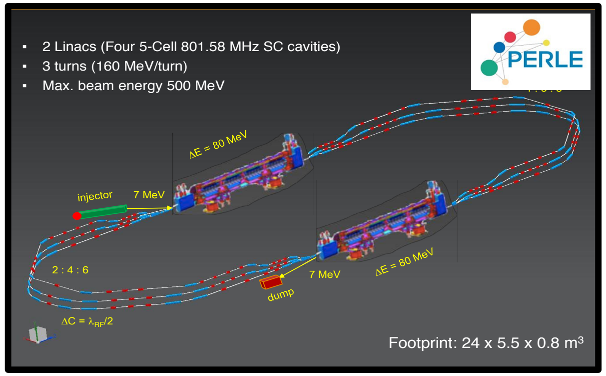
attached to HL-LHC (or FCC)

e beam: ⟶ **50 or 60** GeV

e pol.: P= **±0.8**

Lint ⟶ **1–2** ab^{-1} (1000× HERA!)

PERLE: international collaboration built to realise **500** MeV facility at Orsay, for development of ERL with LHeC conditions (arXiv:1705.08783)



- 2 Linacs (Four 5-Cell 801.58 MHz SC cavities)
- 3 turns (160 MeV/turn)
- Max. beam energy 500 MeV

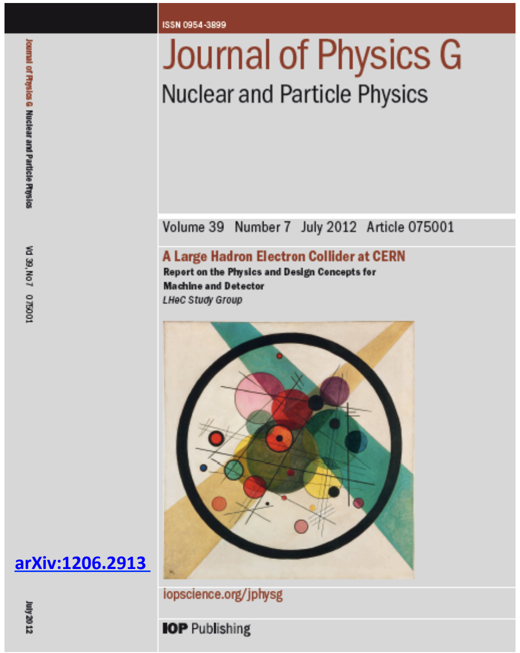
Footprint: 24 x 5.5 x 0.8 m^3

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



ISSN 0954-3899

Journal of Physics G

Nuclear and Particle Physics

Volume 39 Number 7 July 2012 Article 075001

A Large Hadron Electron Collider at CERN

Report on the Physics and Design Concepts for Machine and Detector

LHeC Study Group

iopscience.org/jphysg

IOP Publishing

arXiv: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

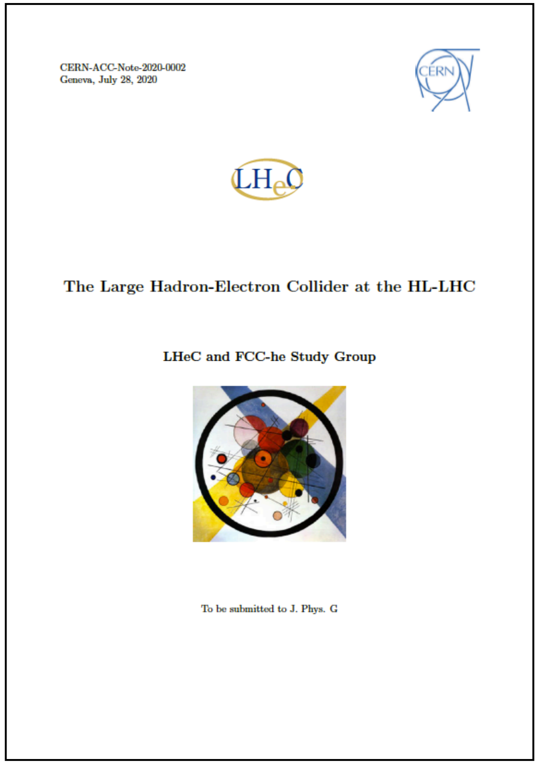
Dig Deeper
Nature Physics 9 (2013) 448

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



CERN-ACC-Note-2020-0002
Geneva, July 28, 2020

The Large Hadron-Electron Collider at the HL-LHC

LHeC and FCC-he Study Group

To be submitted to J. Phys. G

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

(arXiv:2007.14491)

see also, FCC CDR, vols 1 and 3:

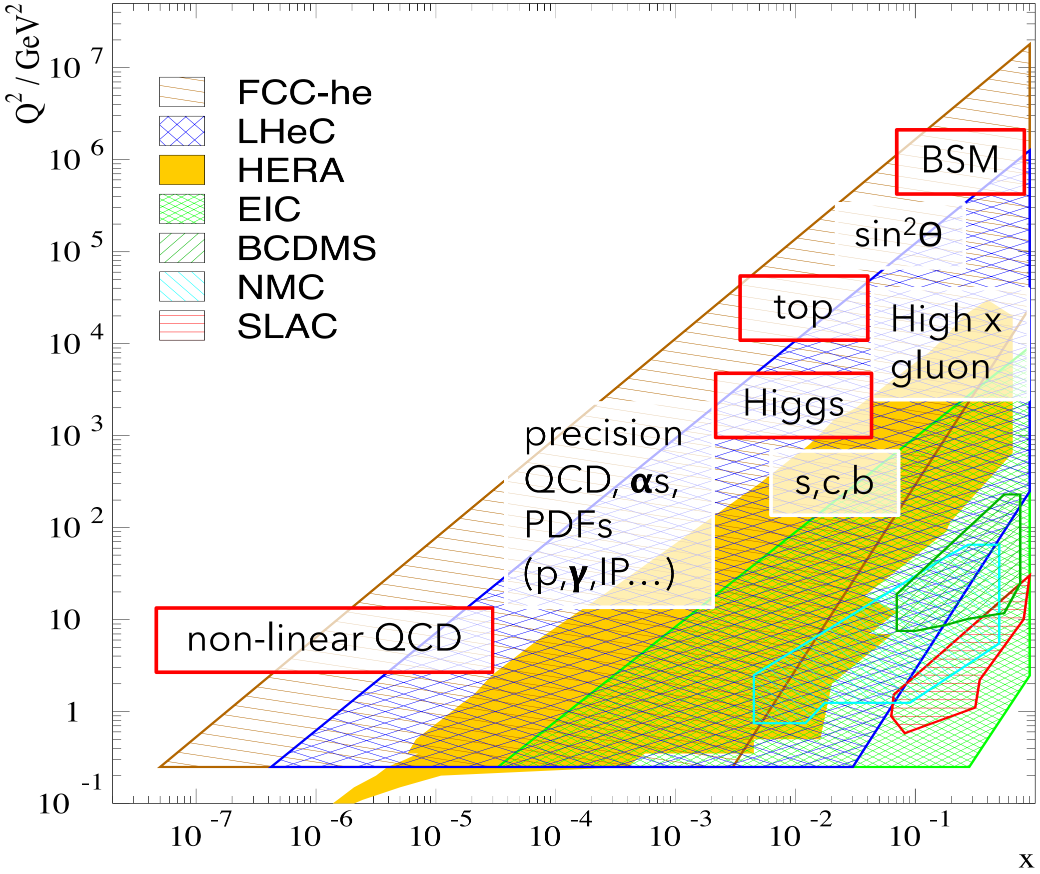
physics, EPJ C79 (2019), 6, 474

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

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

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

Physics with Energy Frontier DIS



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

DIS: cleanest high-resolution microscope

opportunity for unprecedented increase in DIS kinematic reach;

×1000 increase in lumi. cf. HERA

- QCD precision physics and discovery
- empowering the HL-LHC and FCC-hh

unique nuclear physics facility

(N. Armesto, HI, Thurs 12:25)

complementary Higgs programme

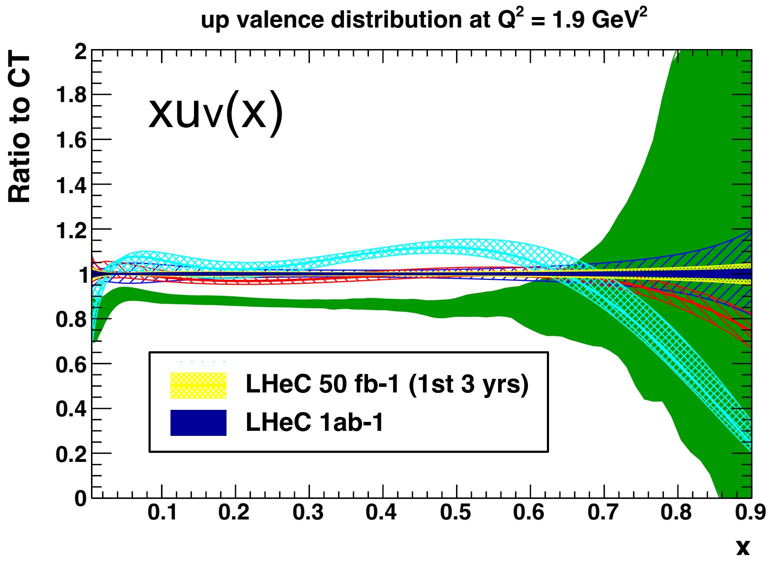
(U. Klein, HIGGS, Fri 15:00)

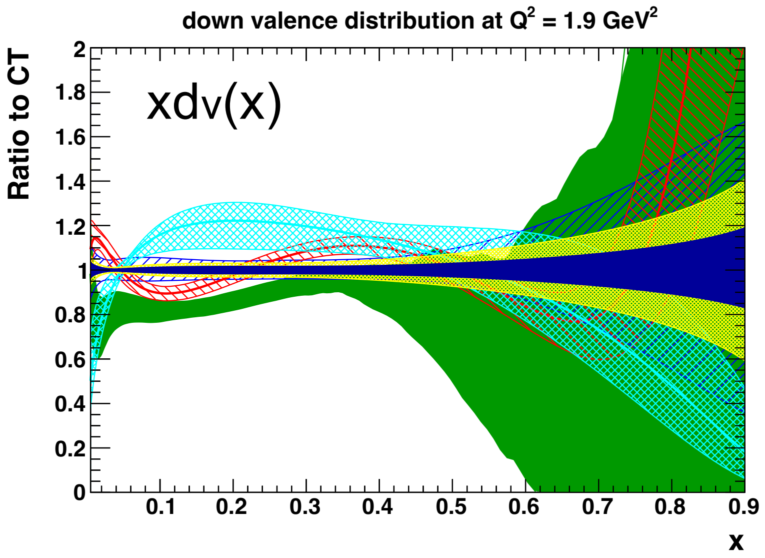
electroweak and top

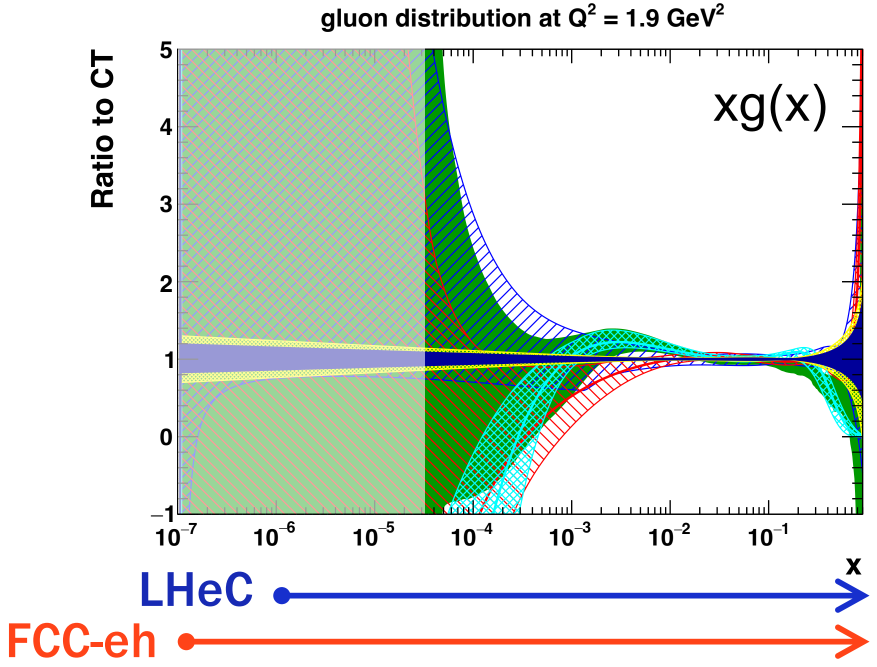
(D. Britzger, TOP&EW, Fri 18:30)

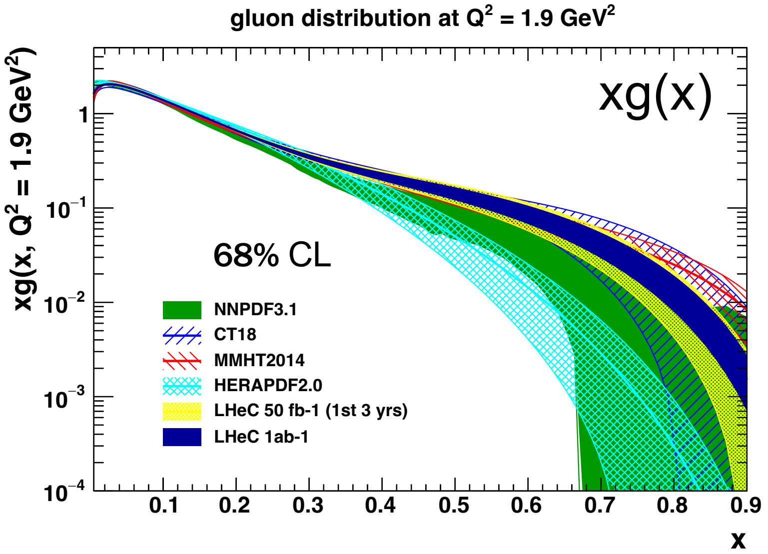
(**LHeC**: **ep** in **2030s**, several years concurrent HL-LHC operation, plus dedicated run, arXiv:1810.13022)

Quark and Gluon PDFs







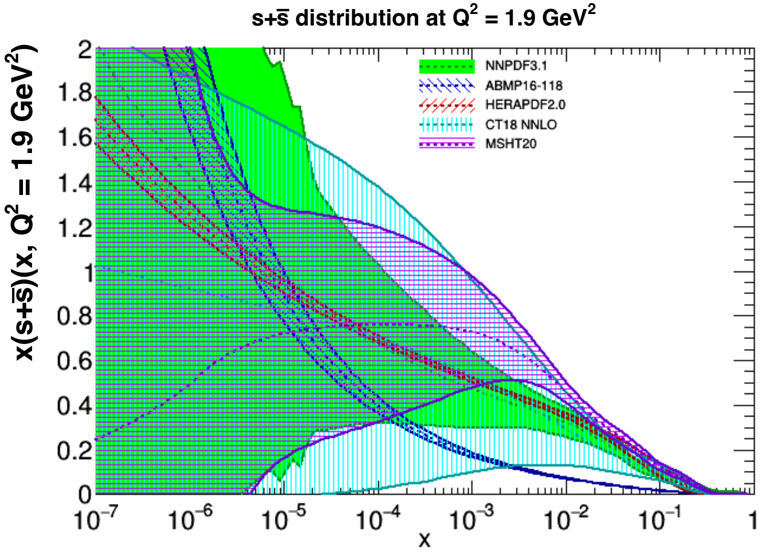


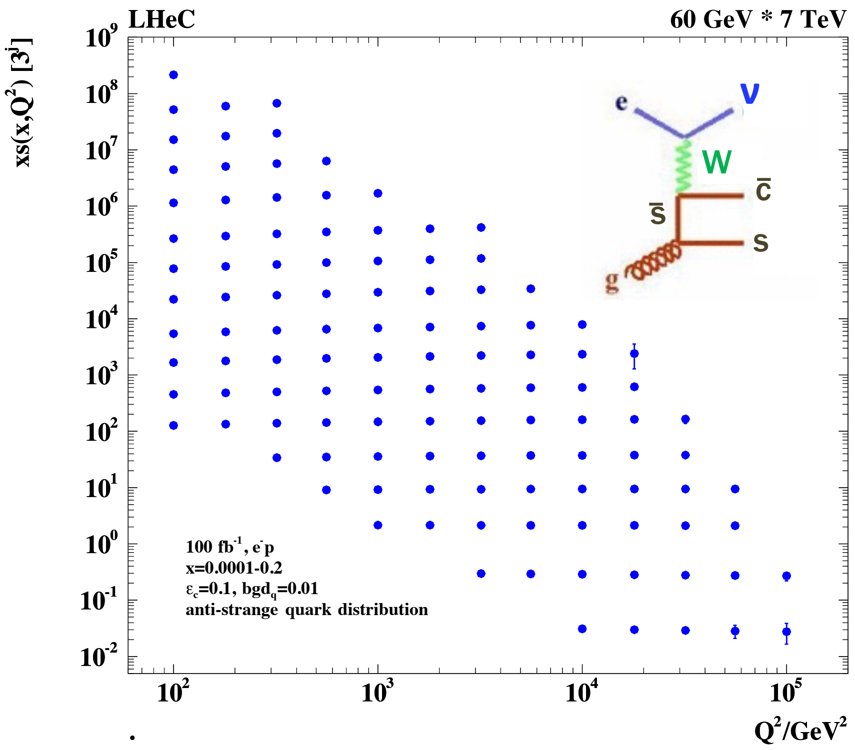
Strange, c, b

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

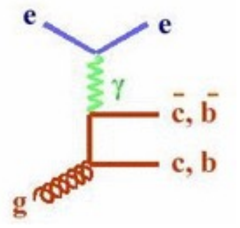
→ **LHeC:** direct sensitivity via charm tagging in Ws→c

(x,Q^2) mapping of strange density for first time



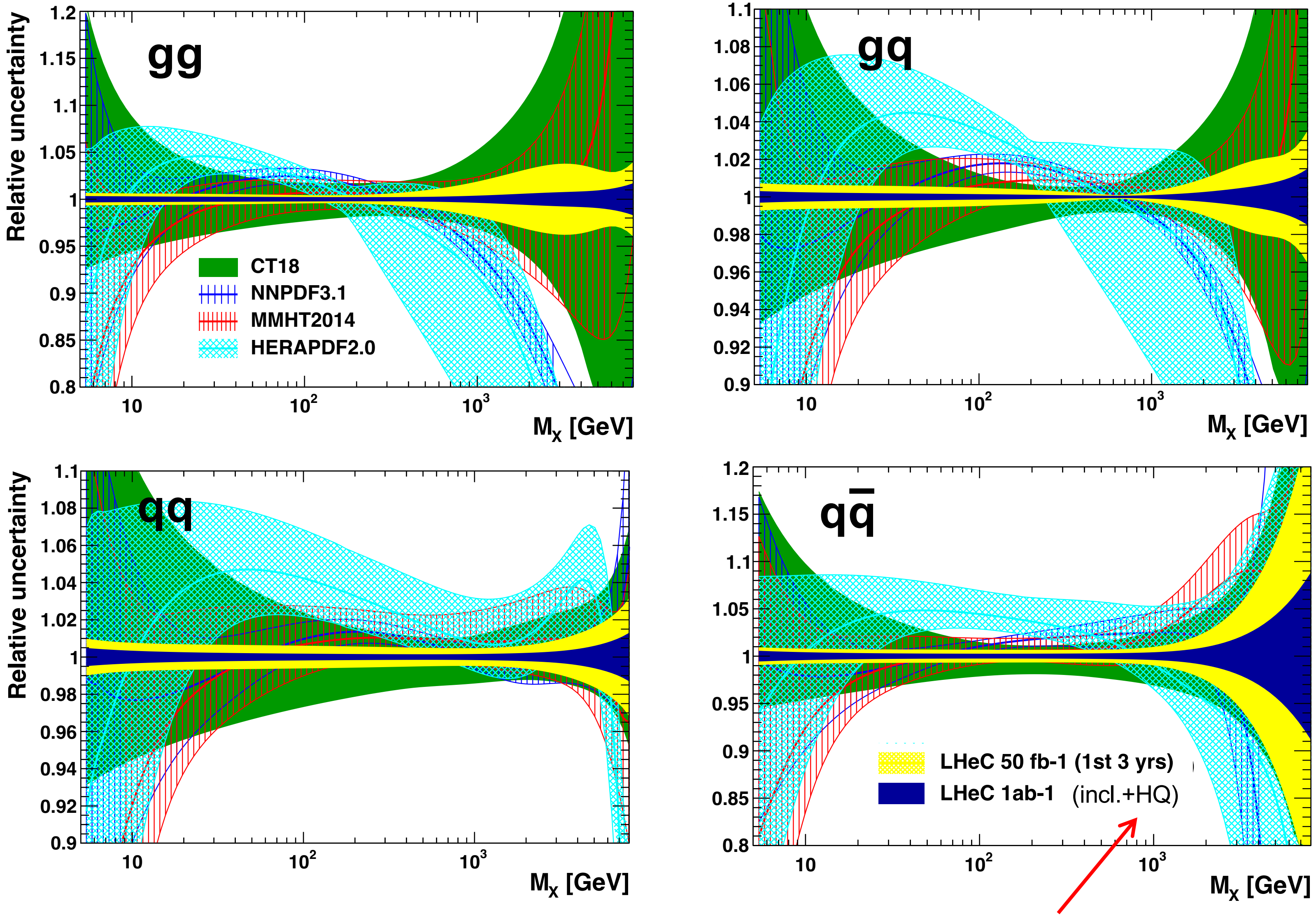


- **c, b:** enormously extended range and much improved precision c.f. HERA
- **δMc = 50 (HERA)** to **3 MeV**: impacts on **α**s, regulates ratio of charm to light, crucial for precision t, H
- **δMb** to **10 MeV**; MSSM: Higgs produced dominantly via $b\bar{b} \rightarrow A$



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

PDF luminosities @ 14 TeV



(s,c,b) also included

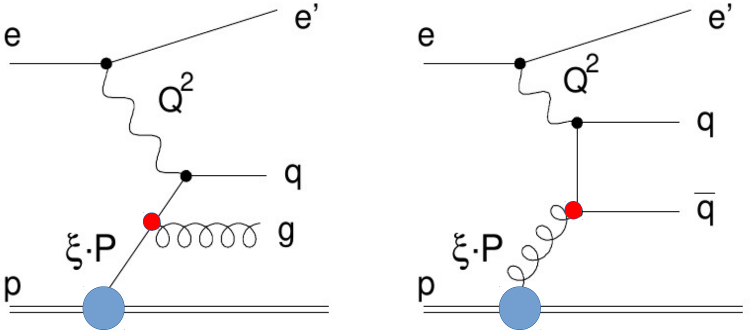
arXiv:2007.14491
featured in Snowmass **αs** White Paper,
arXiv:2203.08271

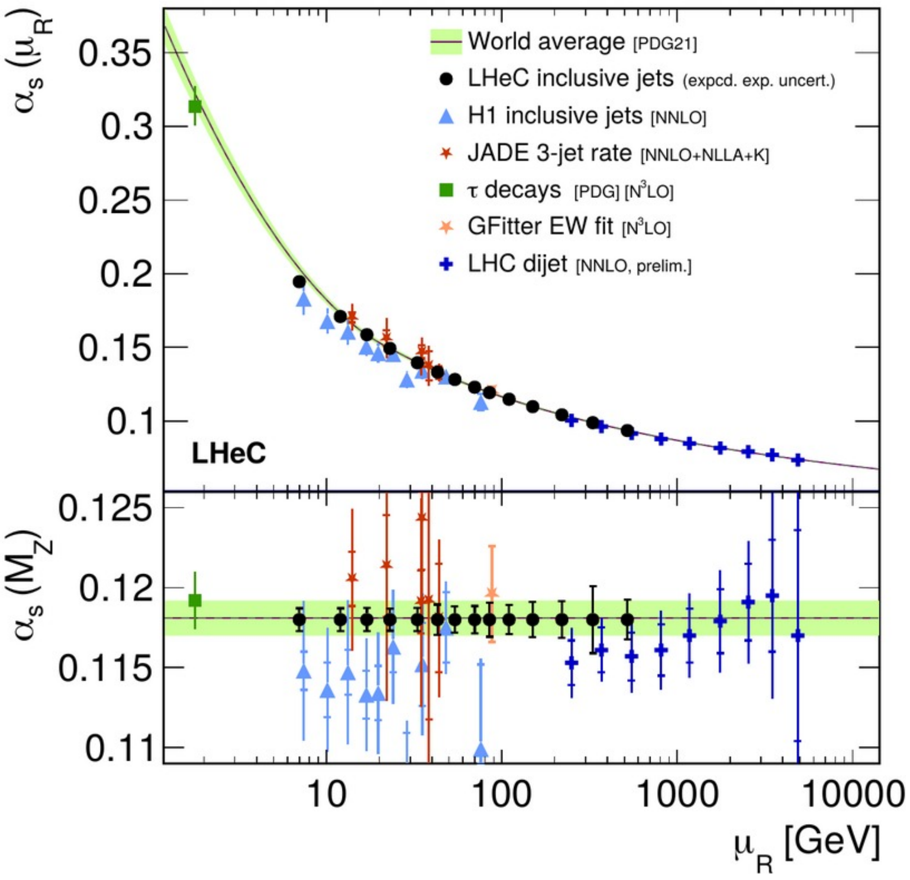
Strong Coupling

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

- **LHeC** simultaneous **PDF+αs** fit:
- **Δαs(M_Z)[incl. DIS] = ±0.00022**$_{(exp+PDF)}$
- Δαs(M_Z)= ± **0.00018** for incl. DIS together with **ep jets**
- achievable precision: ***$\mathcal{O}$*(0.1%)**
  ×5–10 better than today

ep jets:

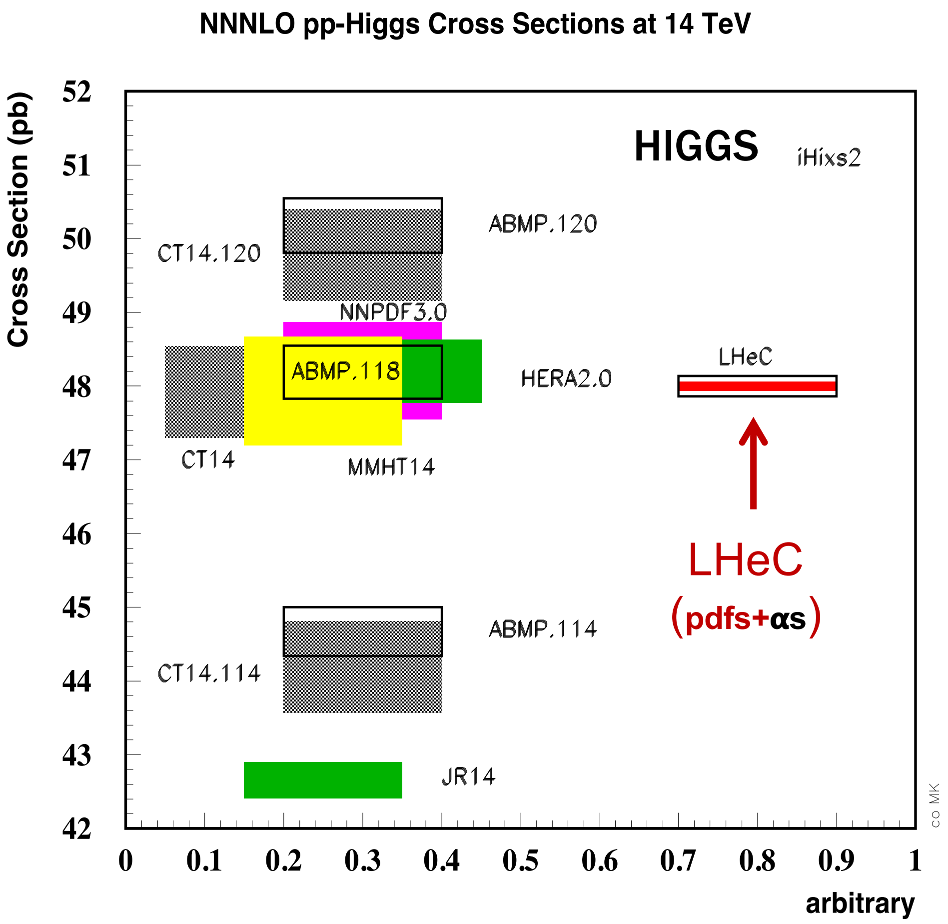


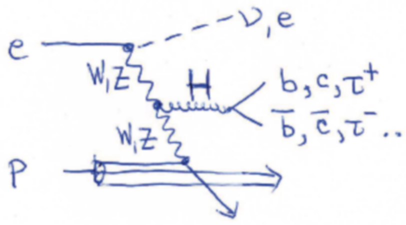


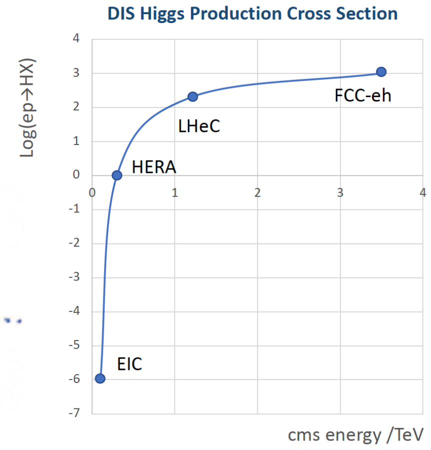
- **αs** from fits to **ep** jet production (**LHeC**)
- connects **τ**-decays to Z-pole and beyond
- **FCC-eh** further increases precision and range

arXiv:2201.02436
arXiv:2007.14491

Empowering the LHC: Higgs



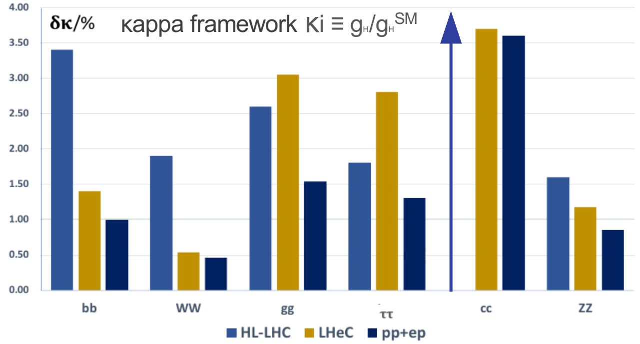




Interplay between *pp* and *ep*

(shown here: LHeC & HL-LHC)

HL-LHC prospects, arXiv:1902.00134



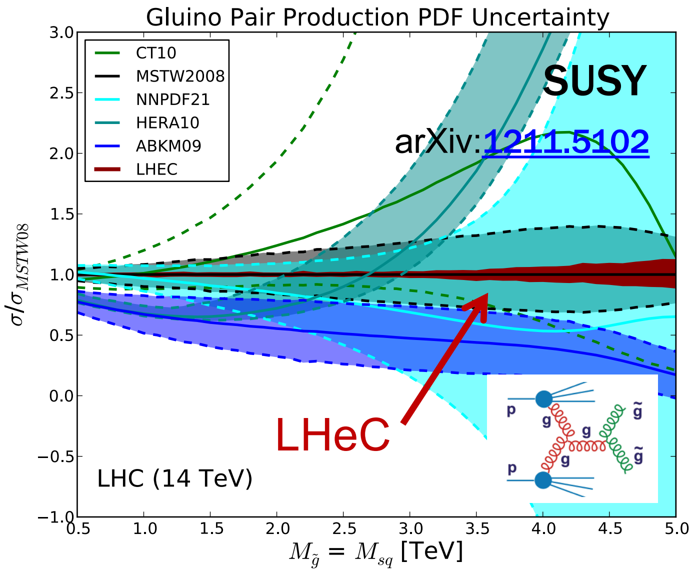
- transformed precision for Higgs @HL-LHC, due to **LHeC pdfs+αs**

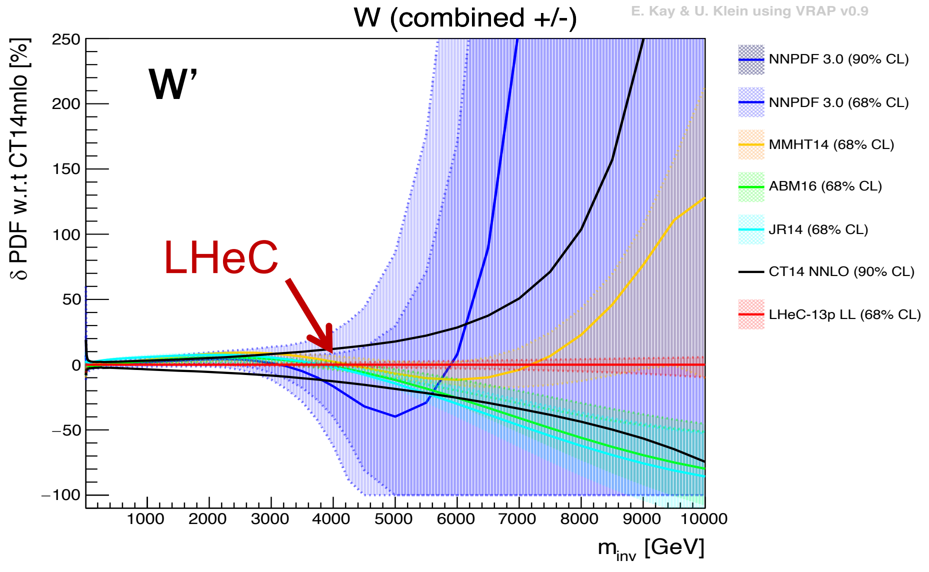
- … plus own comprehensive Higgs programme
- complementarity between **pp** and **ep**
  (see talk by U. Klein, HIGGS, Fri 15:00)

arXiv:2007.14491
arXiv:1902.04070

Empowering the LHC: BSM

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





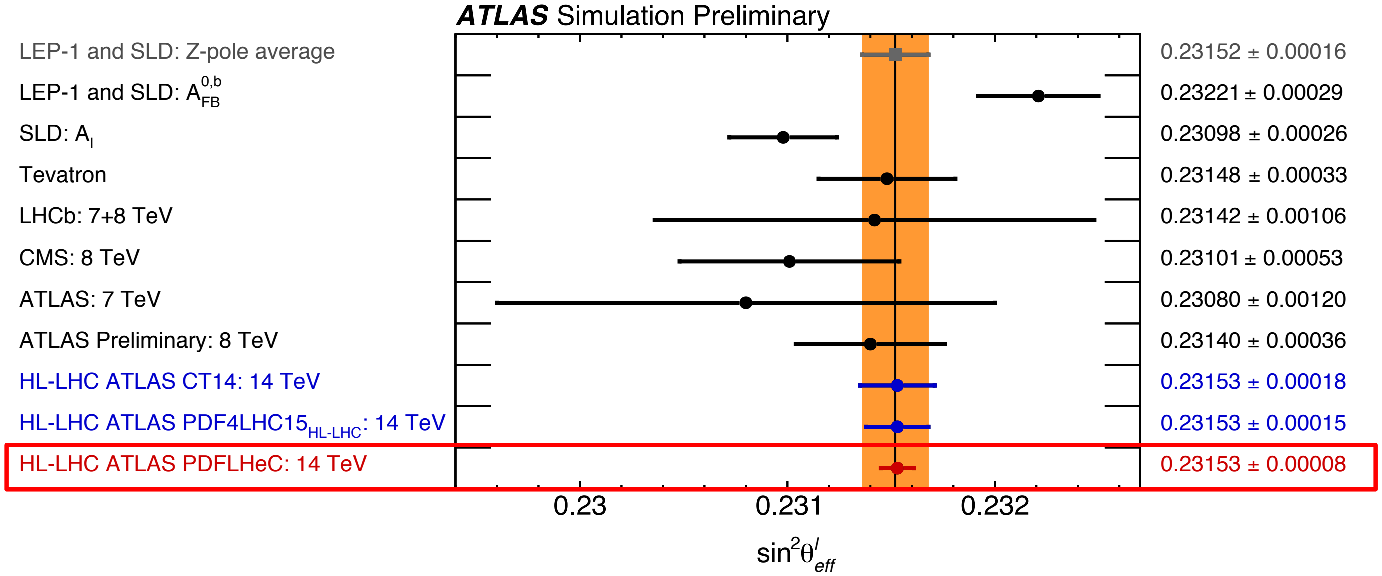
CONTACT INTERACTIONS: $\mathcal{L}_{\mathrm{CI}} = \frac{g^2}{\Lambda^2}\eta_{ij}(\bar{q}_i\gamma_\mu q_i)(\bar{\ell}_i\gamma^\mu\ell_i)$

Model	ATLAS (Ref. [702])	HL-LHC	
	$\mathcal{L} = 36\,\mathrm{fb}^{-1}$ (CT14nnlo)	$\mathcal{L} = 3\,\mathrm{ab}^{-1}$ (CT14nnlo)	$\mathcal{L} = 3\,\mathrm{ab}^{-1}$ (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

- … plus unique sensitivity to search regions **not accessible in pp**
- EG. LLP, LFV, RPV and compressed SUSY, sterile ν, … scenarios

arXiv:2007.14491
arXiv:1902.04070

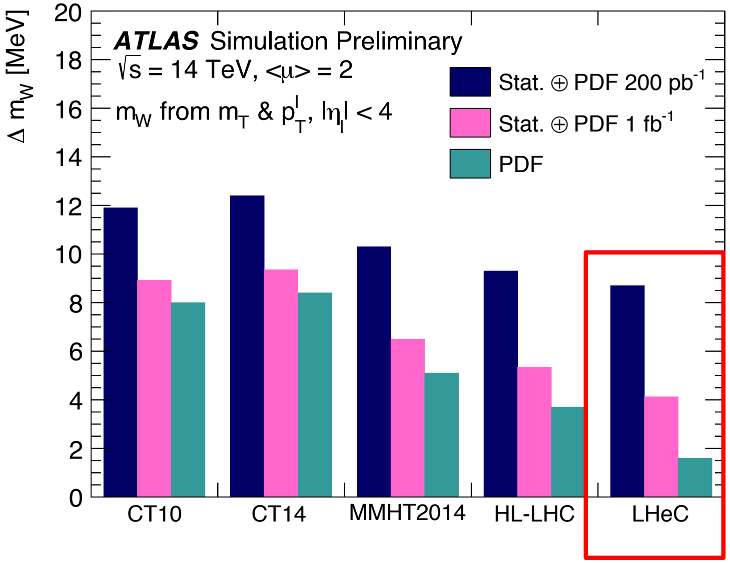
Empowering the LHC: precision EW



$\sin^2\vartheta W$

± 0.00009 (exp) ± **0.00016** (pdf)
± 0.00007 (exp) ± **0.00013** (pdf)
± 0.00007 (exp) ± **0.00003** (pdf)

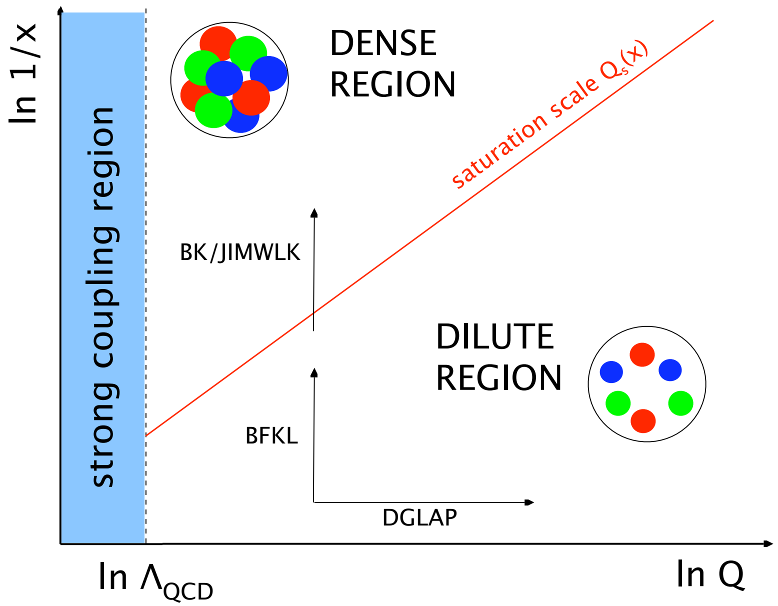
MW



- **MW**, **$\sin^2\vartheta W$** precision measurements sensitive to BSM physics
- **pdf** uncerts. become sub-dominant with **LHeC pdfs**!

- … plus complementary ep DIS electroweak programme
- EG. **MW**, **$\sin^2\vartheta W$** from simultaneous **pdf+EW** fits, and more (see talk by D. Britzger, TOP&EW, Fri 18:30)

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

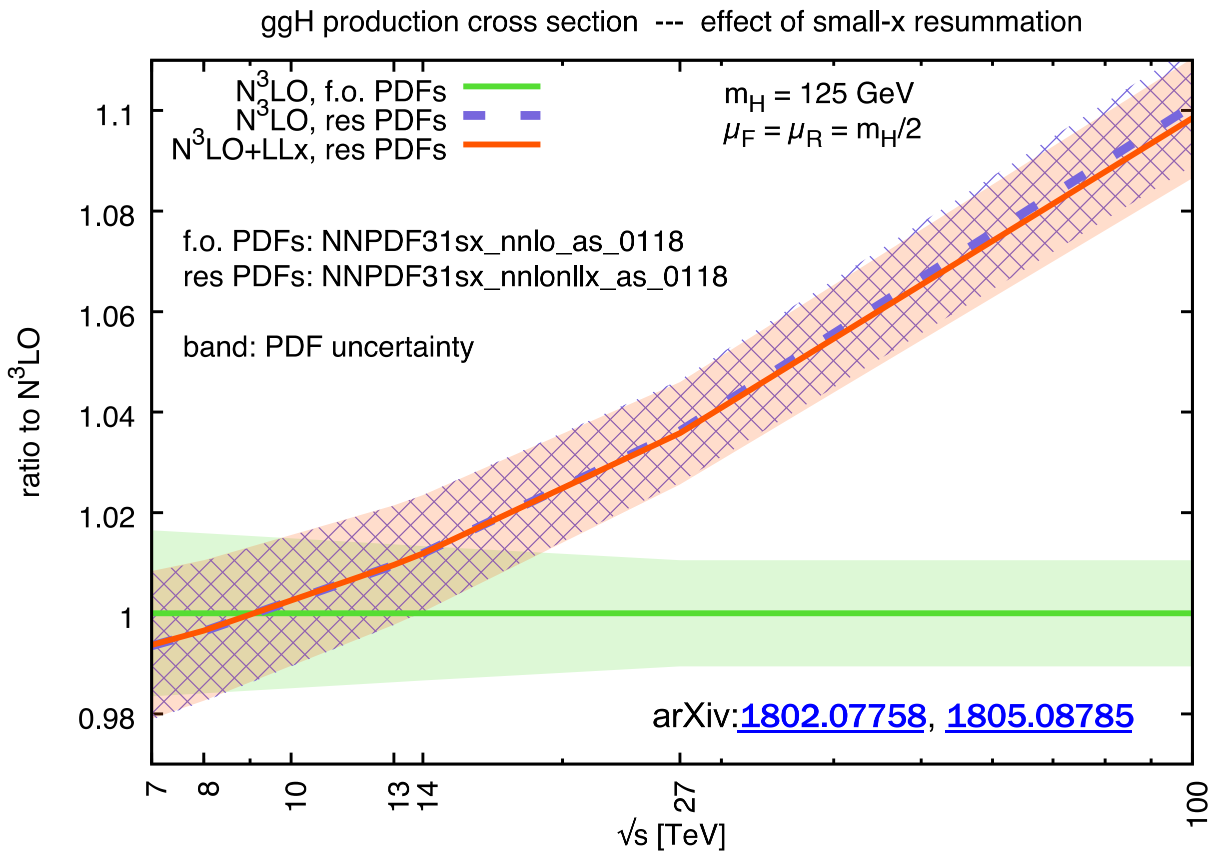
$\tau = \frac{Q^2}{s}$	Higgs	Z, W	low mass DY	$c\bar{c}$
LHC (13 TeV)	10^{-4}	5×10^{-5}	$\sim 10^{-6}$	$\sim 10^{-7}$
FCC-hh (100 TeV)	1.5×10^{-6}	8×10^{-7}	$\sim 10^{-8}$	$\sim 10^{-9}$

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

central rapidity ↑

M. Bonvini, 4th FCC workshop, CERN, November 2020

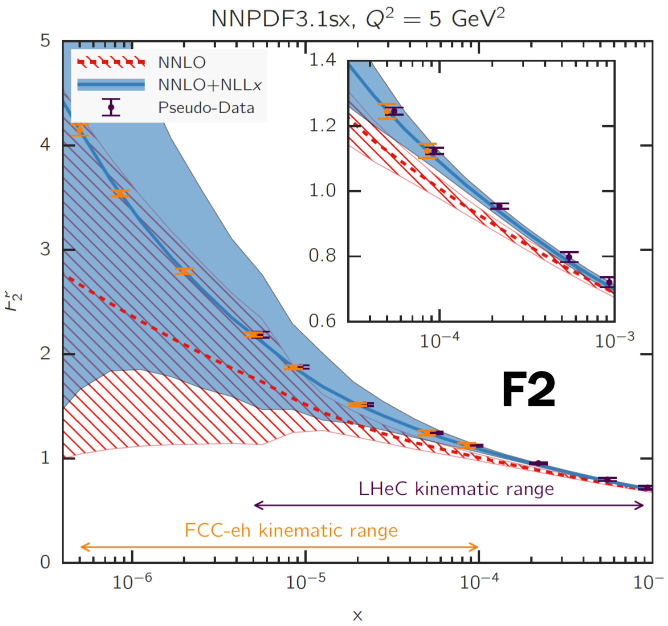
Impact on pp phenomenlogy

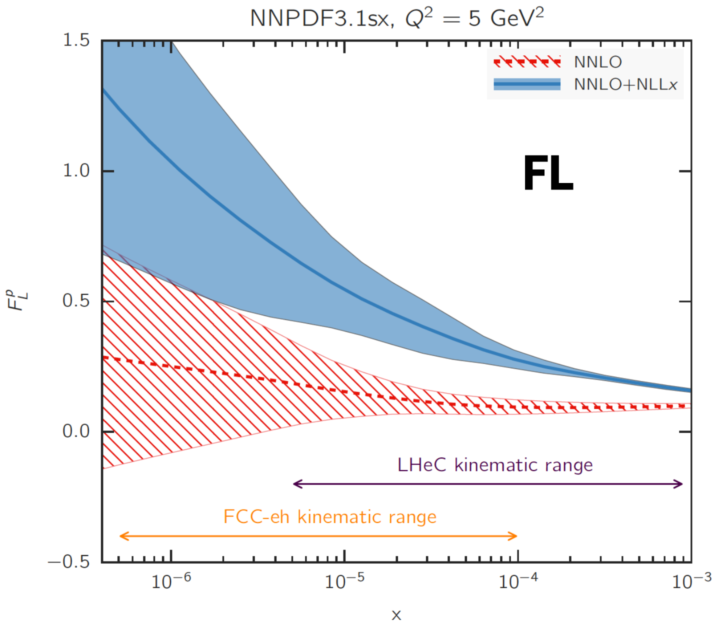


- effect of small x resummation on gg→H cross section for LHC, HE-LHC, FCC
- significant impact, especially at ultra low x values probed at FCC

(see also recent work on forward Higgs production, arXiv:2011.03193; other processes in progress) arXiv:[1710.05935](1710.05935)

LHeC and 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** (further detailed studies in arXiv:2007.14491 ; see also talk by N. Armesto, HI, Thur 12:25)
- measurement of FL has a significant role to play, arXiv:1802.04317

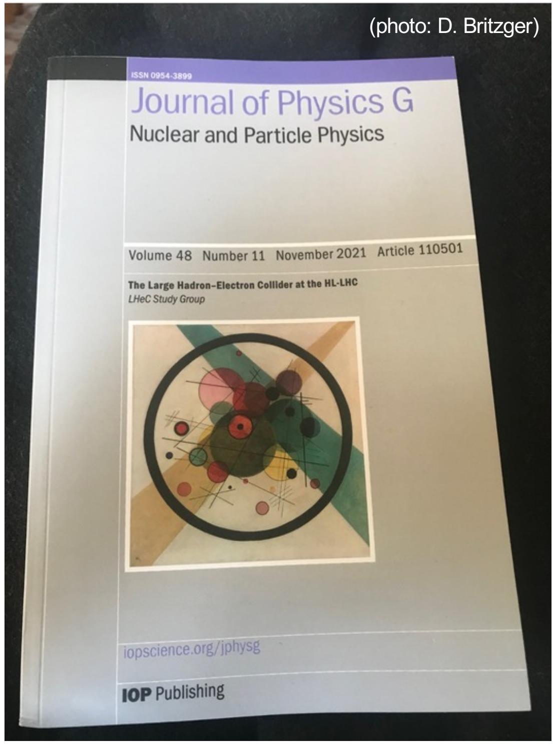
Summary

- a new highly luminous, energy frontier **ep collider** would enable the **full exploitation** of current and future hadron colliders (Higgs, BSM, EW, …)

- wealth of new and updated studies from LHeC / FCC-eh
- enormously rich physics programmes in their **own right**, and for **transformation of pp machines** into precision facilities

- **all critical pdf information can be obtained early**
- unprecedented access to novel kinematic regime, with **unique potential to explore small x phenomena**
- **αs** to **permille experimental precision**

- … and much more in realm of **QCD** and **small x** physics;
  no time today to cover EG. **diffractive**, **vector meson**, **γp**, … **physics**



(photo: D. Britzger)

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Journal of Physics G
Nuclear and Particle Physics

Volume 48 Number 11 November 2021 Article 110501

The Large Hadron-Electron Collider at the HL-LHC
LHeC Study Group

iopscience.org/jphysg

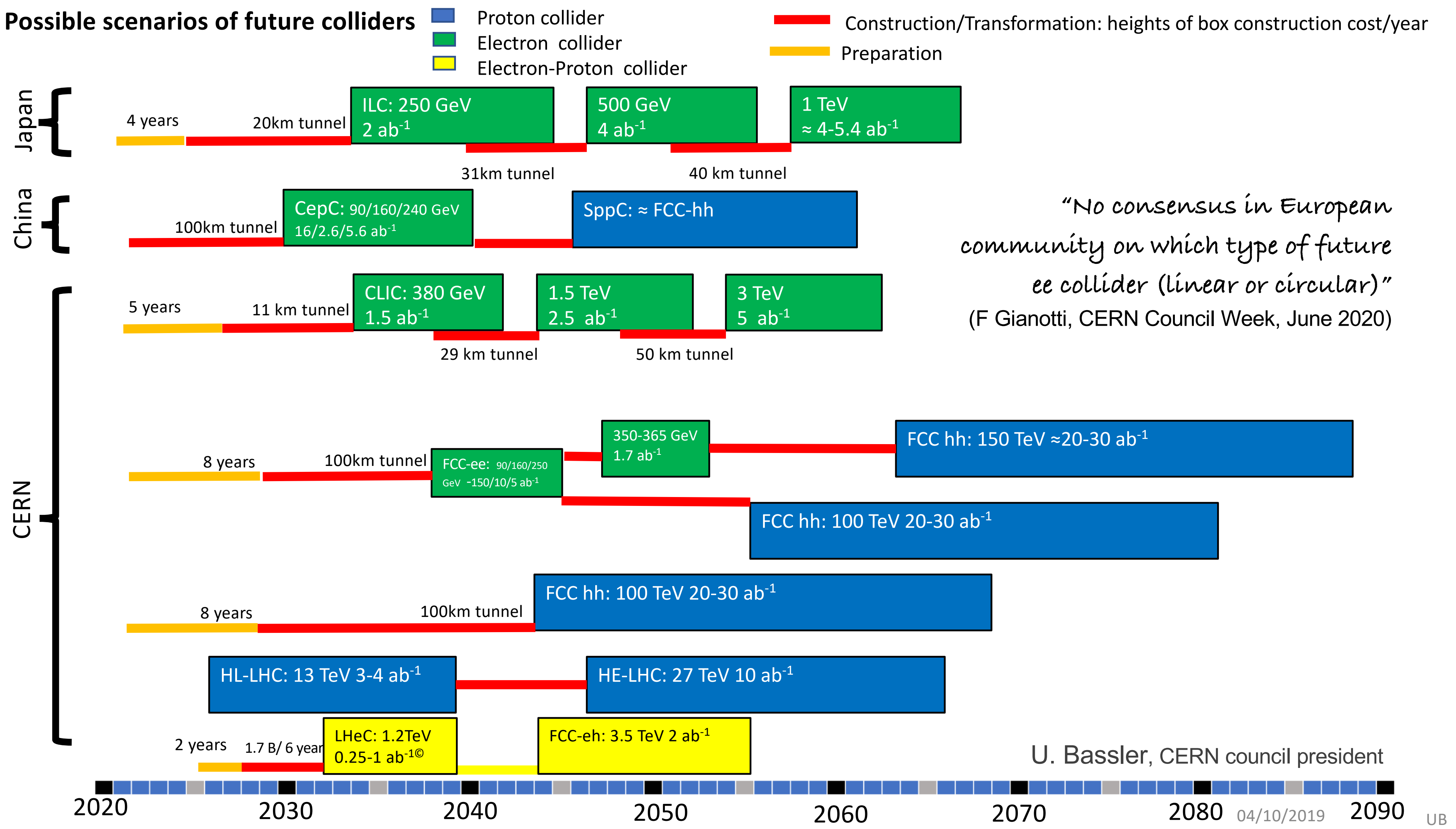
IOP Publishing

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

> statement from the IAC:
>
> 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;

Extras

CERN/ESG/05



"No consensus in European community on which type of future ee collider (linear or circular)"
(F Gianotti, CERN Council Week, June 2020)

U. Bassler, CERN council president

LHeC: installation during **LS4**;

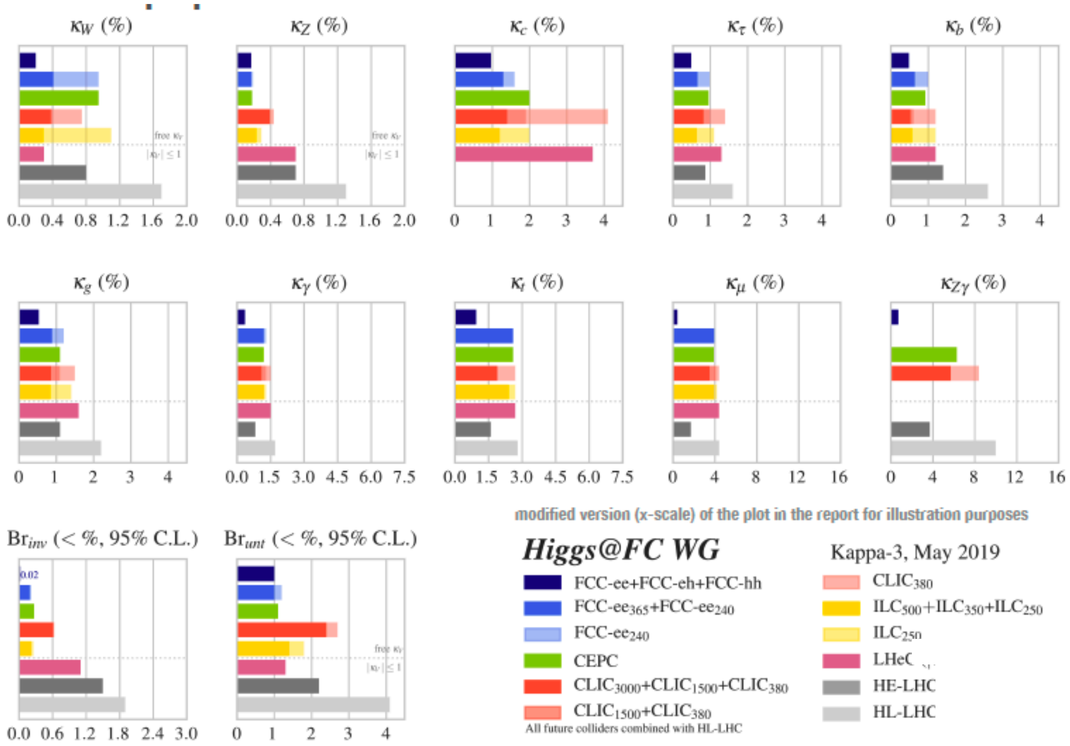
concurrent operation through LHC **Runs 5/6**; and period of **dedicated running**, arXiv:1810.13022

Higgs prospects: collider comparison

Some observations:

- **HL-LHC** achieves precision of ~1-3% in most cases
  - In some cases model-dependent
- Proposed e^+e^- and ep colliders improve w.r.t. HL-LHC by factors of ~2 to 10
- **Initial stages of e^+e^- colliders** have comparable sensitivities (within factors of 2)
- **ee** colliders constrain $BR \rightarrow untagged$ w/o assumptions
- **Access to κ_c** at ee and eh

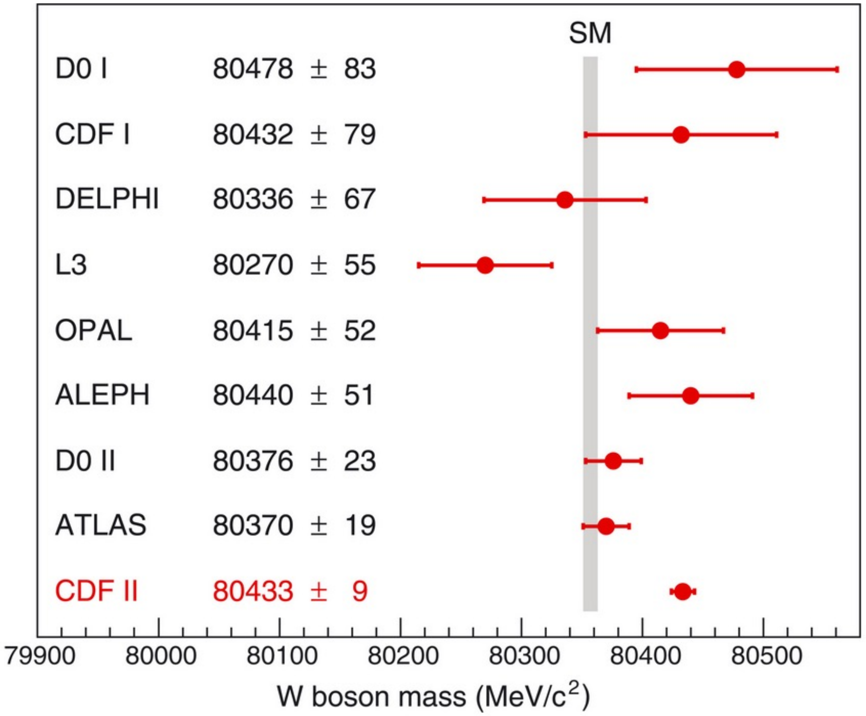
arXiv:[1905.03764](https://arxiv.org/abs/1905.03764)



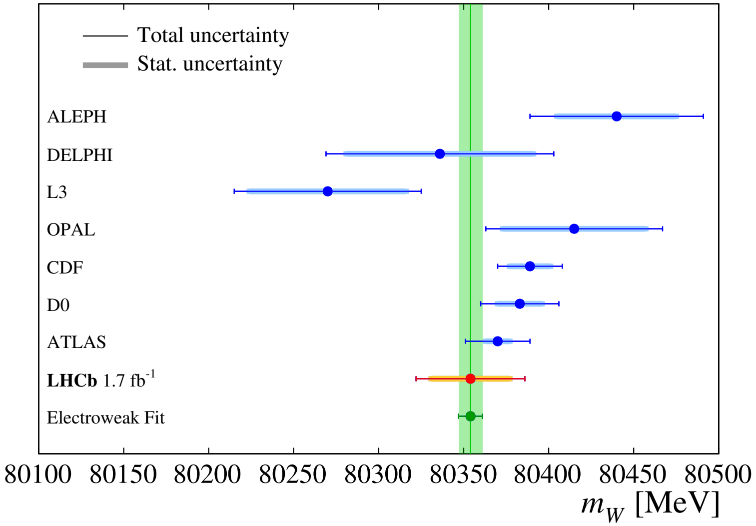
modified version (x-scale) of the plot in the report for illustration purposes

Beate Heinemann, ESU, Granada, 2019

MW today



(science 376 (2022) no. 6589, 170–176)



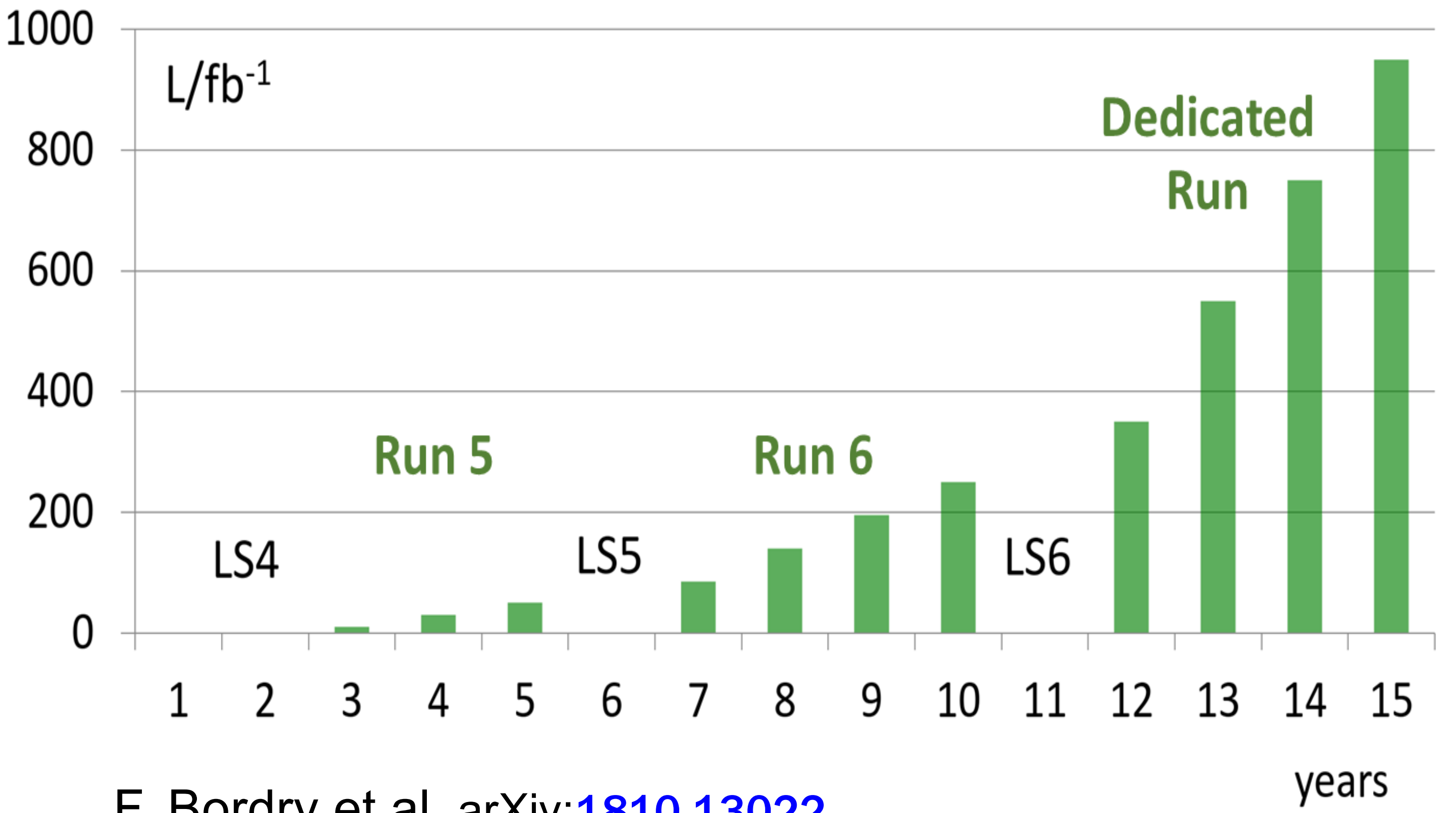
(JHEP01 (2022) 036)

CDFII: $M_W = 80,433.5 \pm 9.4\ \mathrm{MeV}$

LHCb: $m_W = 80354 \pm 23_{\mathrm{stat}} \pm 10_{\mathrm{exp}} \pm 17_{\mathrm{theory}} \pm 9_{\mathrm{PDF}}\ \mathrm{MeV}$

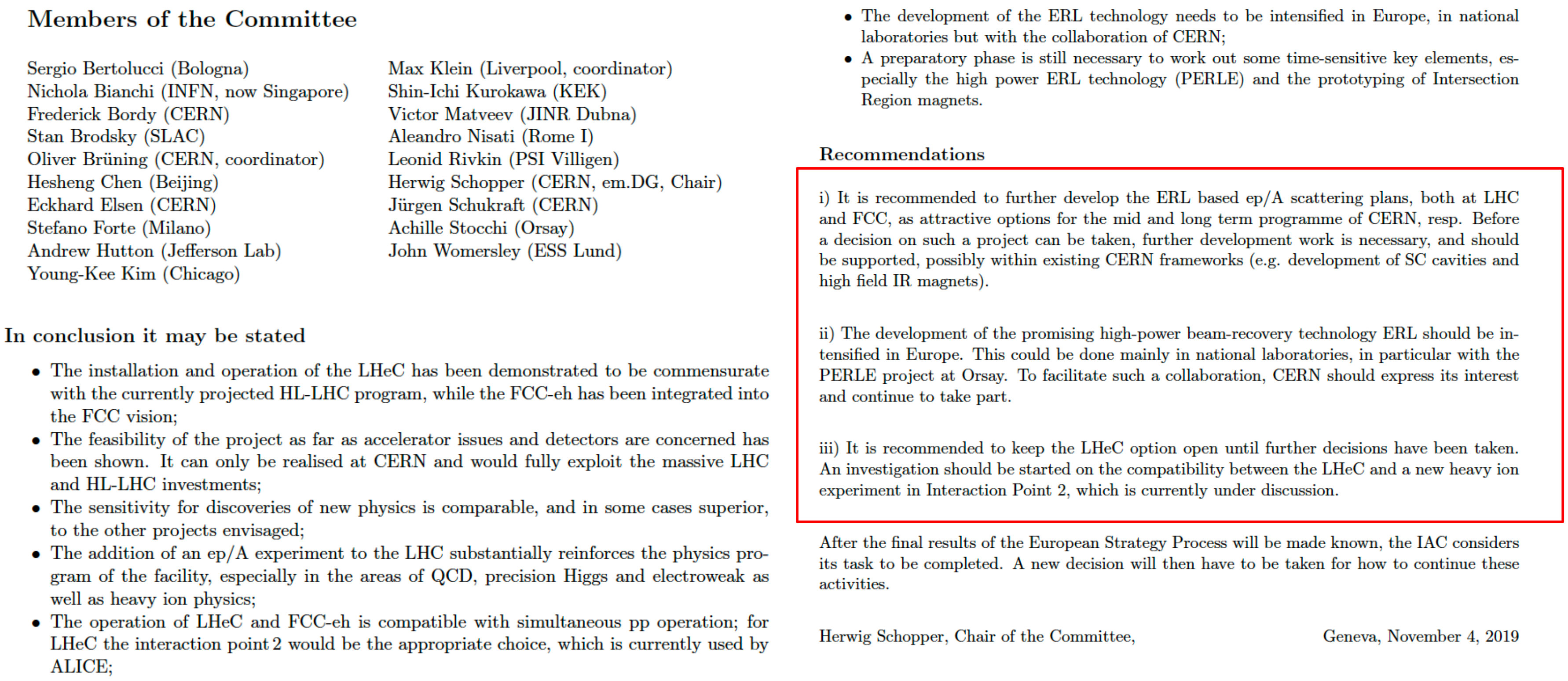
LHeC timescale

LHeC projected **Integrated Luminosity:**



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

Statement of the IAC



Members of the Committee

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

In conclusion it may be stated

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

Recommendations

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

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

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

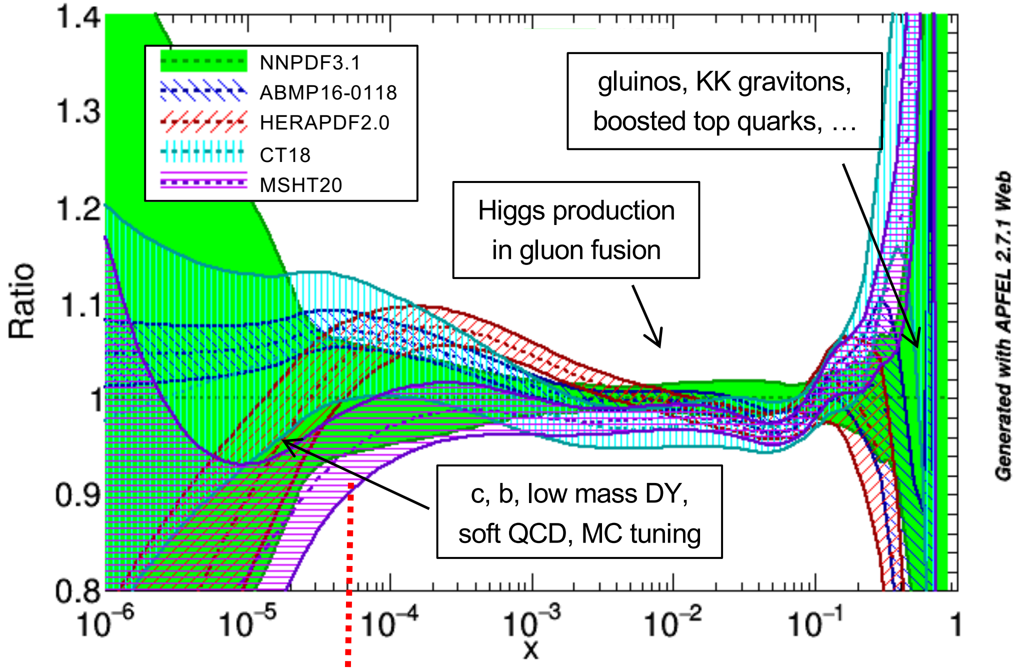
After the final results of the European Strategy Process will be made known, the IAC considers its task to be completed. A new decision will then have to be taken for how to continue these activities.

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

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

pdfs: the situation today

$xg(x,Q)$, NNLO, Q^2=100 GeV^2, $\alpha_s(M_Z)$=0.118



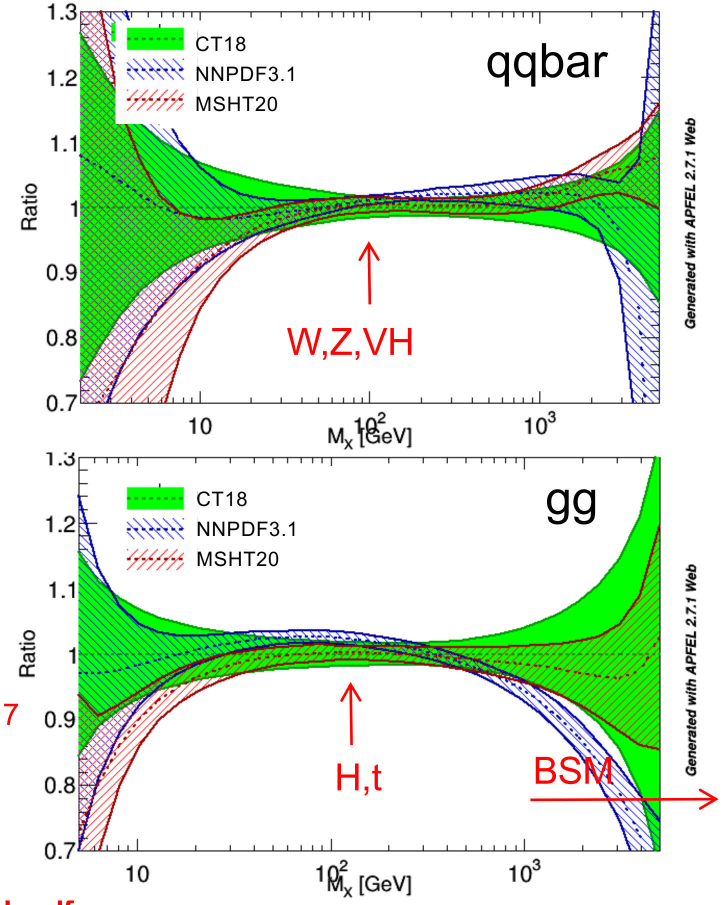
gluinos, KK gravitons, boosted top quarks, …

Higgs production in gluon fusion

c, b, low mass DY, soft QCD, MC tuning

current data above x=5.10^{-5}, and below x=0.6–0.7

pdf luminosities (LHC@14TeV)



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**, **sin²θW** (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 , 1905.05215

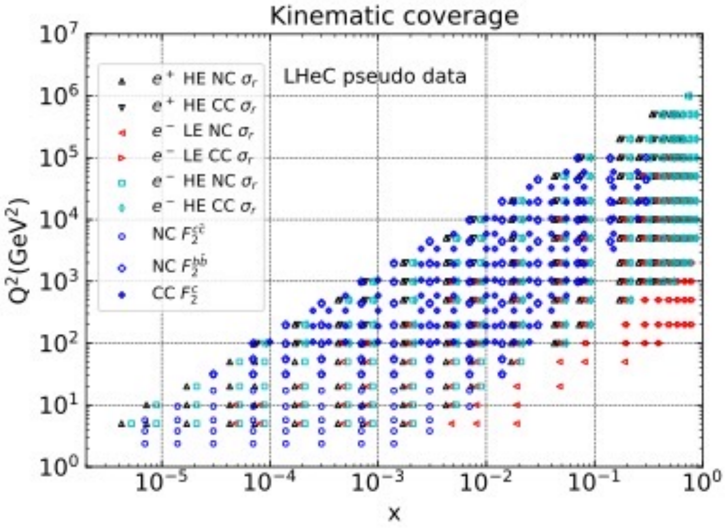
LHeC simulated data

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

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

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

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



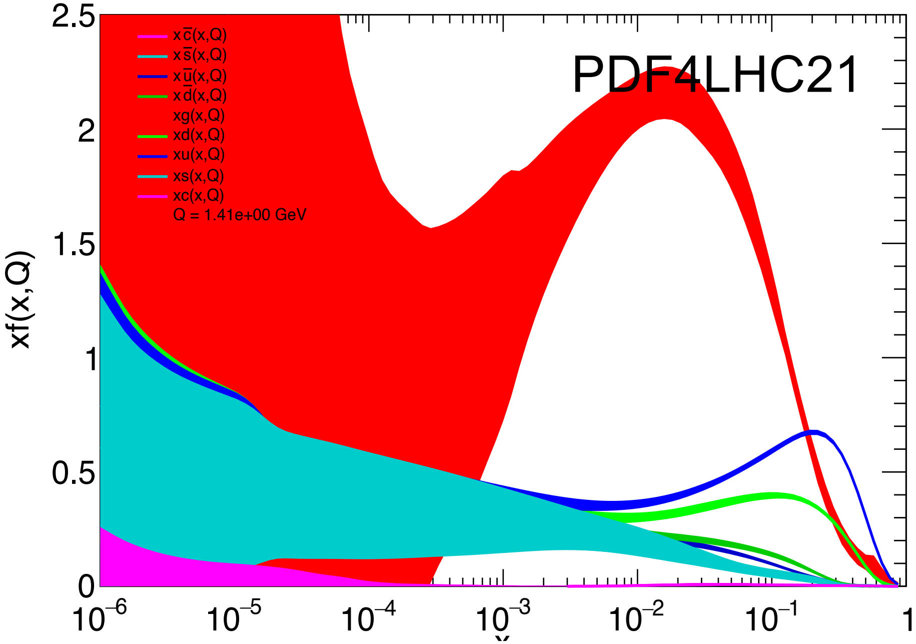
LHeC pdf parameterisation

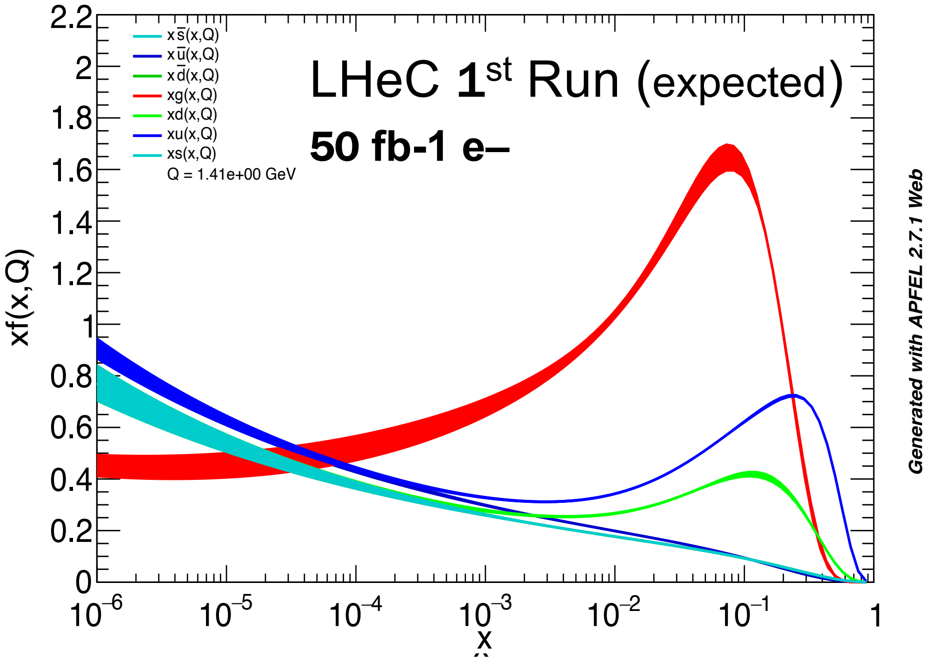
- QCD fit ansatz based on HERAPDF2.0, with following differences:
- no requirement that ubar=dbar at small x
- no negative gluon term (only for the aesthetics of ratio plots – it has been checked that this does not impact size of projected uncertainties)

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

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

Summary of LHeC pdfs

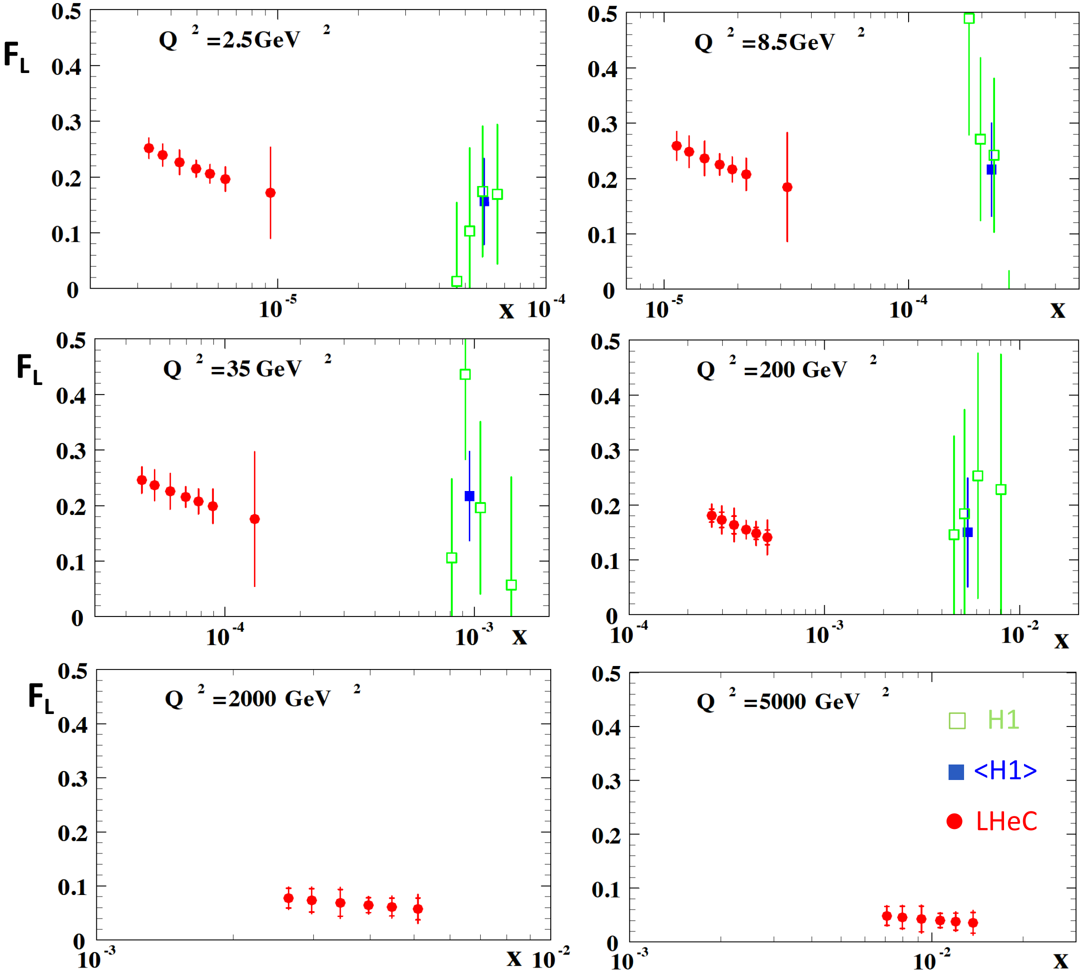




situation today → after 1st LHeC Run

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

Longitudinal Structure Function

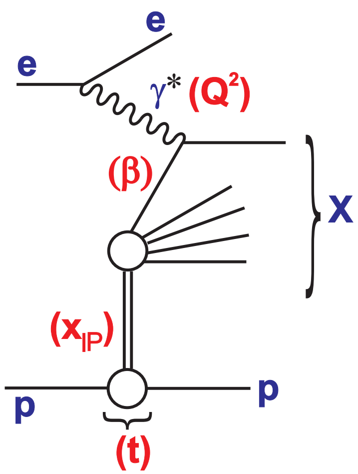


simulated for:
Ep = 7 TeV and
Ee = 60, 30, 20 GeV

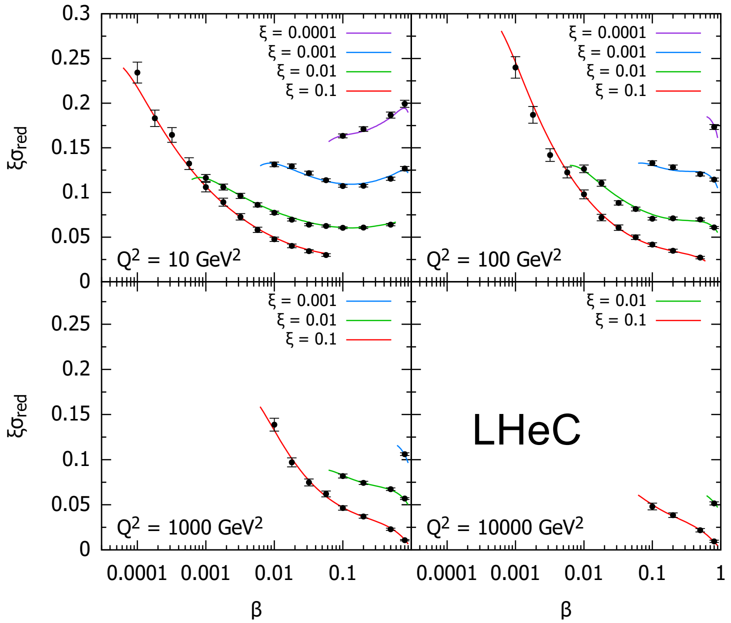
integrated luminosity:
10, 1, 1 fb^{-1}

measurement dominated by systematics

- **simultaneous measurement of F2 and FL is clean way to pin down dynamics at small x**

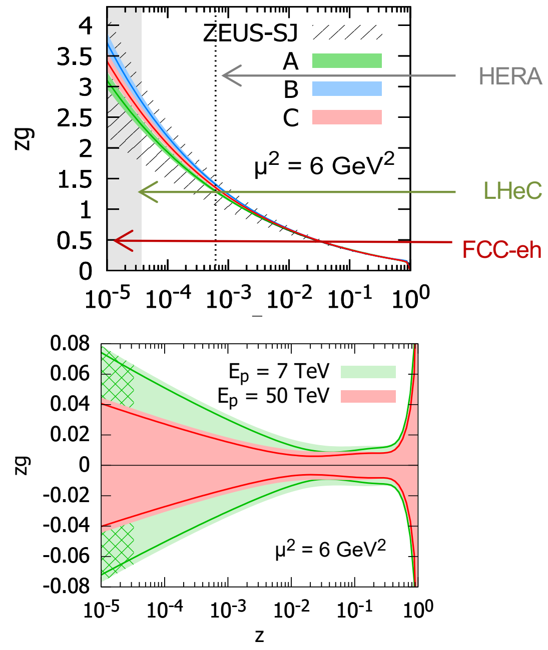


Diffractive Physics

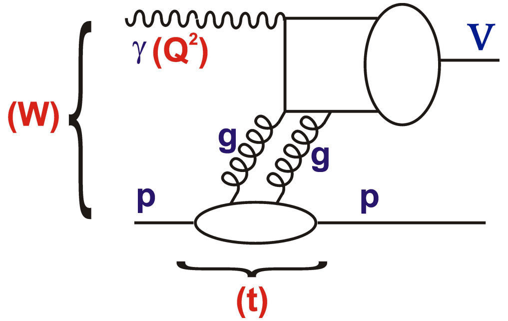


arXiv:[2007.14491](https://arxiv.org/abs/2007.14491) , [EPJ C79 (2019), 6, 474]()

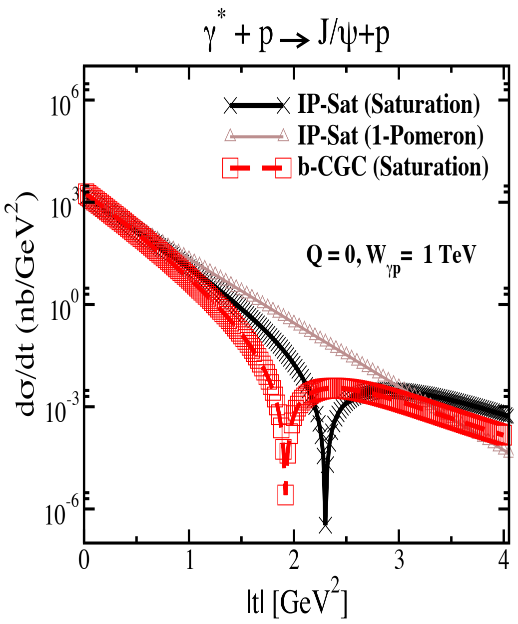
gluon dpdf (A,B,C = LHeC)



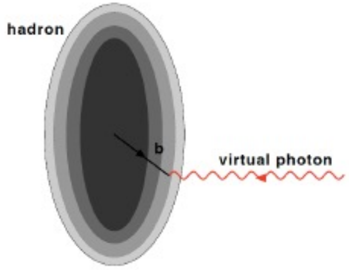
- inclusive diffraction
- constraints on diffractive pdfs, new final states in diffraction, EW exchange, …



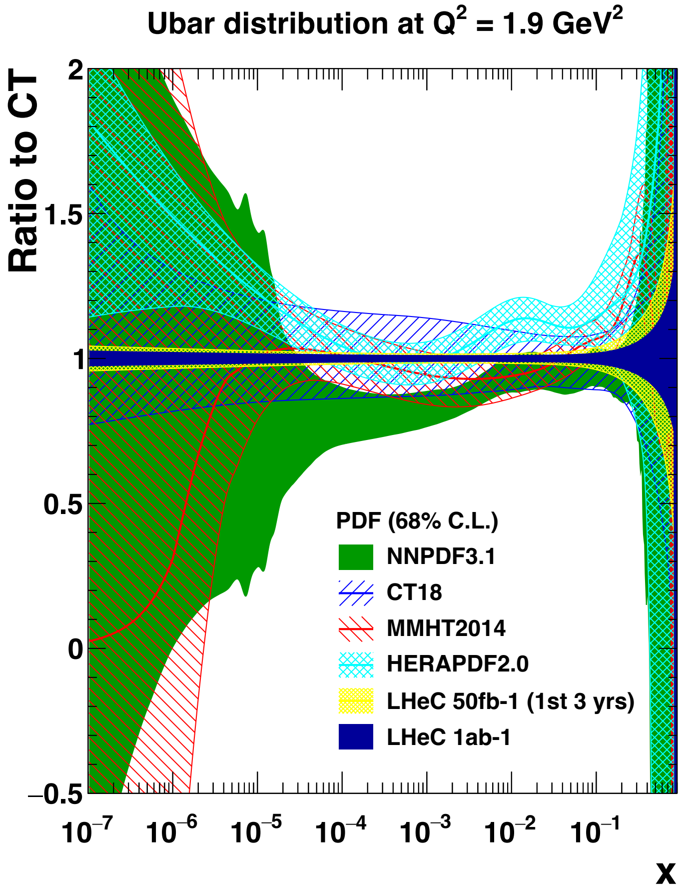
- elastic diffraction of vector mesons
- sensitive to novel small x dynamics
- characteristic dips a feature of saturation models ➔

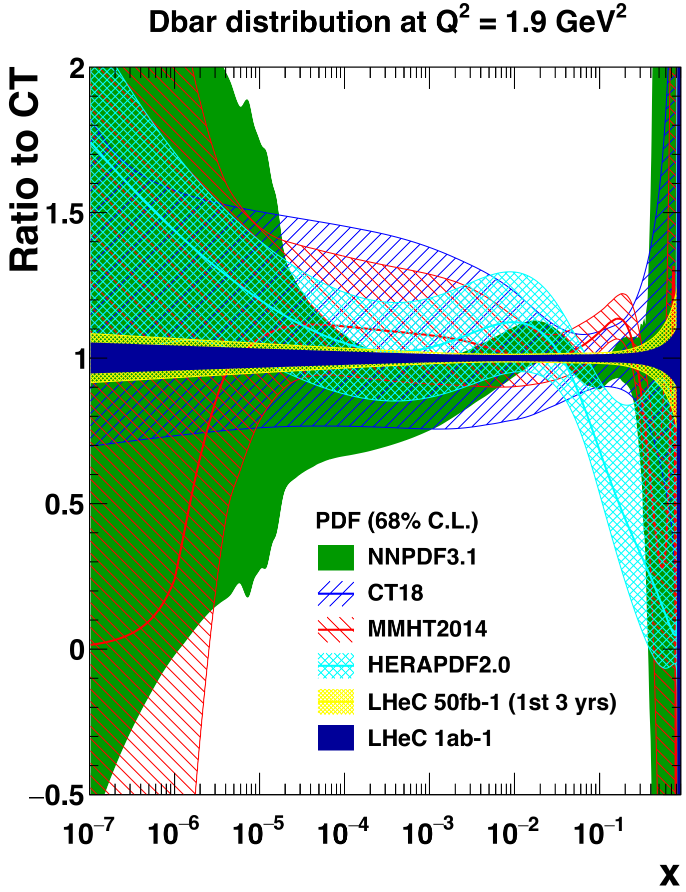


- access to GPDs, encoding 3D structure of nucleon
- t-dependence gives information on spatial distribution
  ≡ Fourier Transform of impact parameter profile
- sensitivity to non-linear evolution and saturation



Sea quarks


Ubar distribution at $Q^2 = 1.9$ GeV^2
Ratio to CT
2
1.5
1
0.5
0
−0.5
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
x
PDF (68% C.L.)
NNPDF3.1
CT18
MMHT2014
HERAPDF2.0
LHeC 50fb-1 (1st 3 yrs)
LHeC 1ab-1


Dbar distribution at $Q^2 = 1.9$ GeV^2
Ratio to CT
2
1.5
1
0.5
0
−0.5
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
x
PDF (68% C.L.)
NNPDF3.1
CT18
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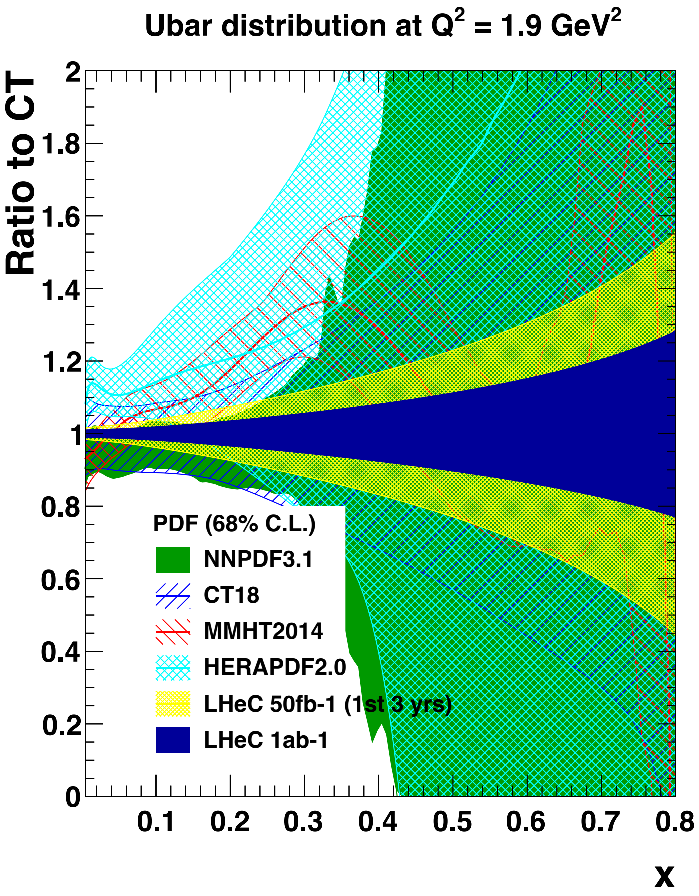
Sea quarks


Ubar distribution at $Q^2 = 1.9$ GeV^2
Ratio to CT
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
x
PDF (68% C.L.)
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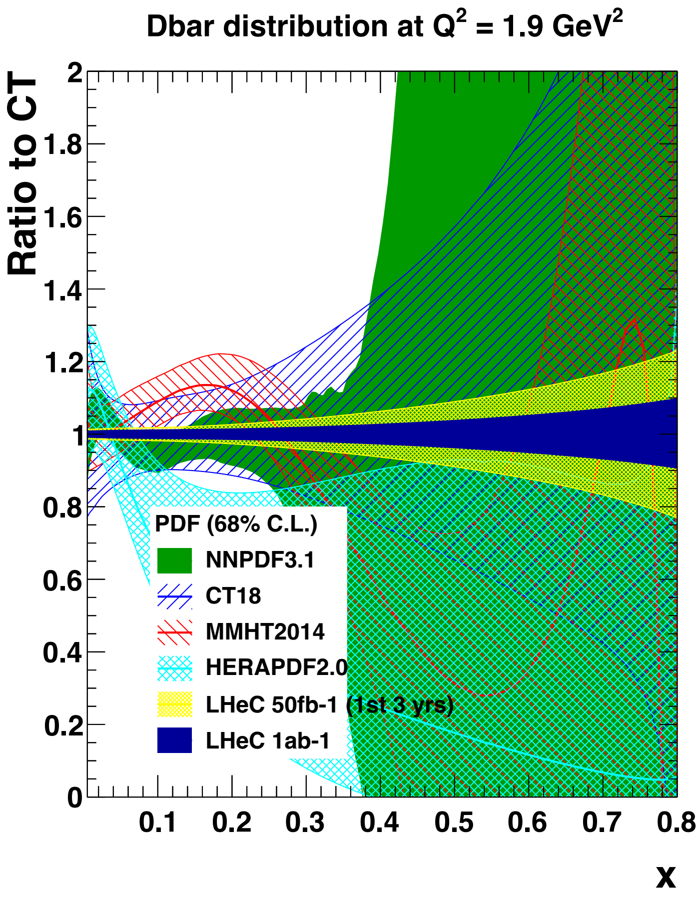
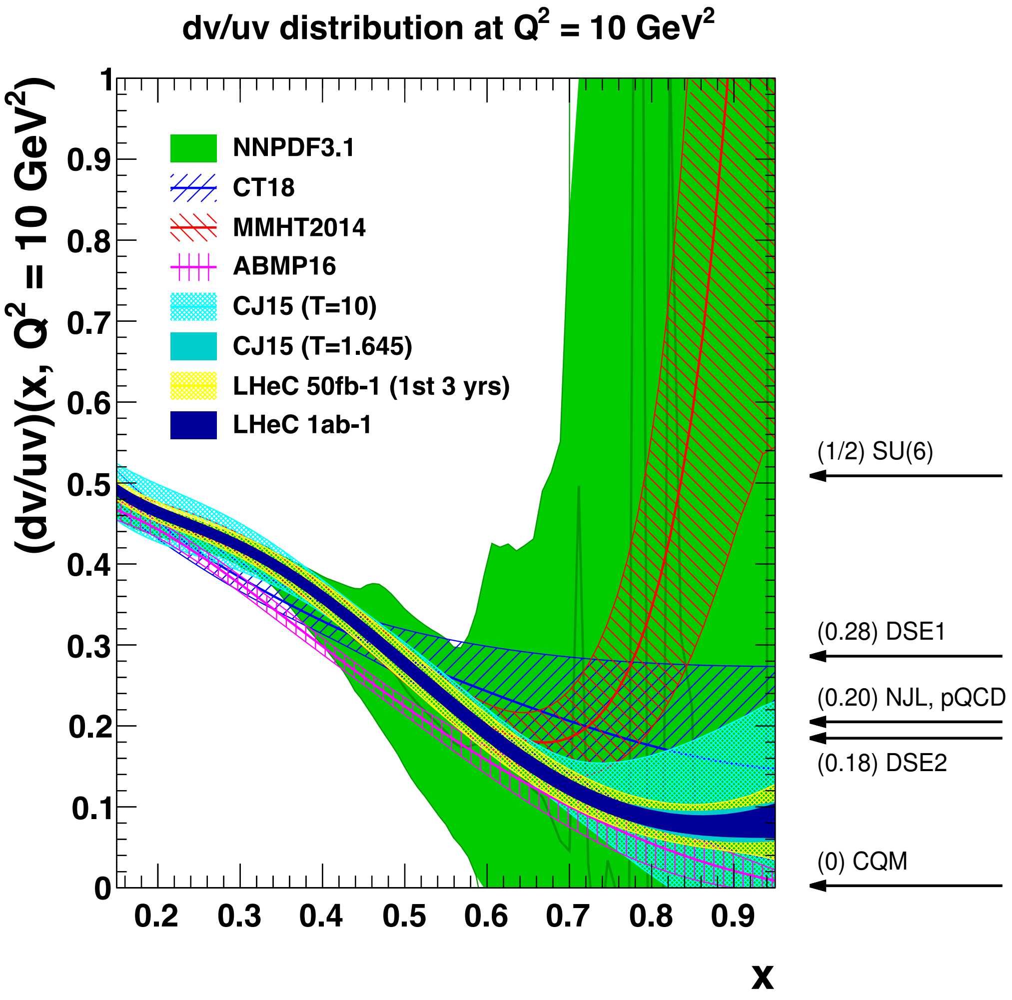

Dbar distribution at $Q^2 = 1.9$ GeV^2
Ratio to CT
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
x
PDF (68% C.L.)
NNPDF3.1
CT18
MMHT2014
HERAPDF2.0
LHeC 50fb-1 (1st 3 yrs)
LHeC 1ab-1

d/u at large x

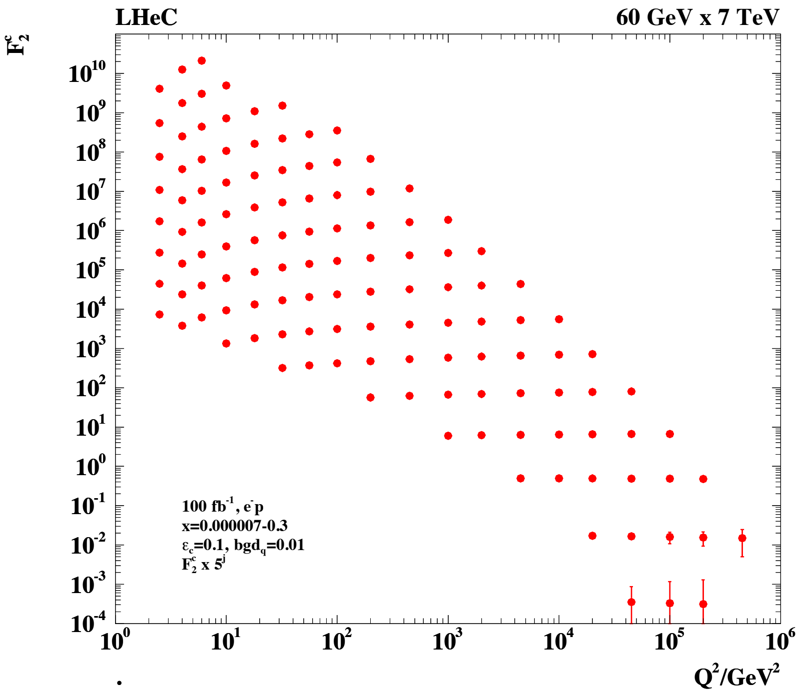


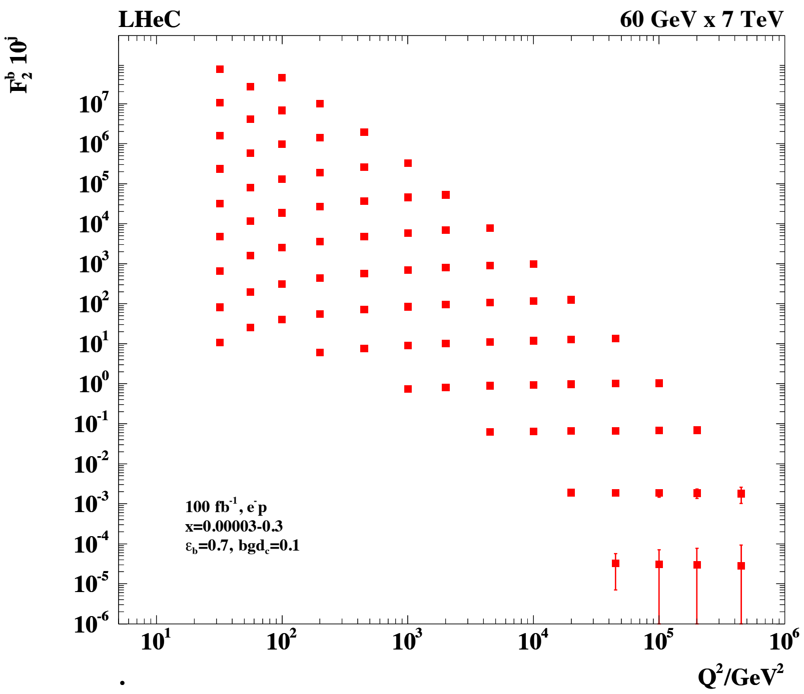
d/u essentially unknown at large x

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

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

c, b quarks





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

- **δMc = 50 (HERA)** to **3 MeV**: impacts on αs, regulates ratio of charm to light, crucial for precision t, H
- **δMb** to **10 MeV**; MSSM: Higgs produced dominantly via bb → A

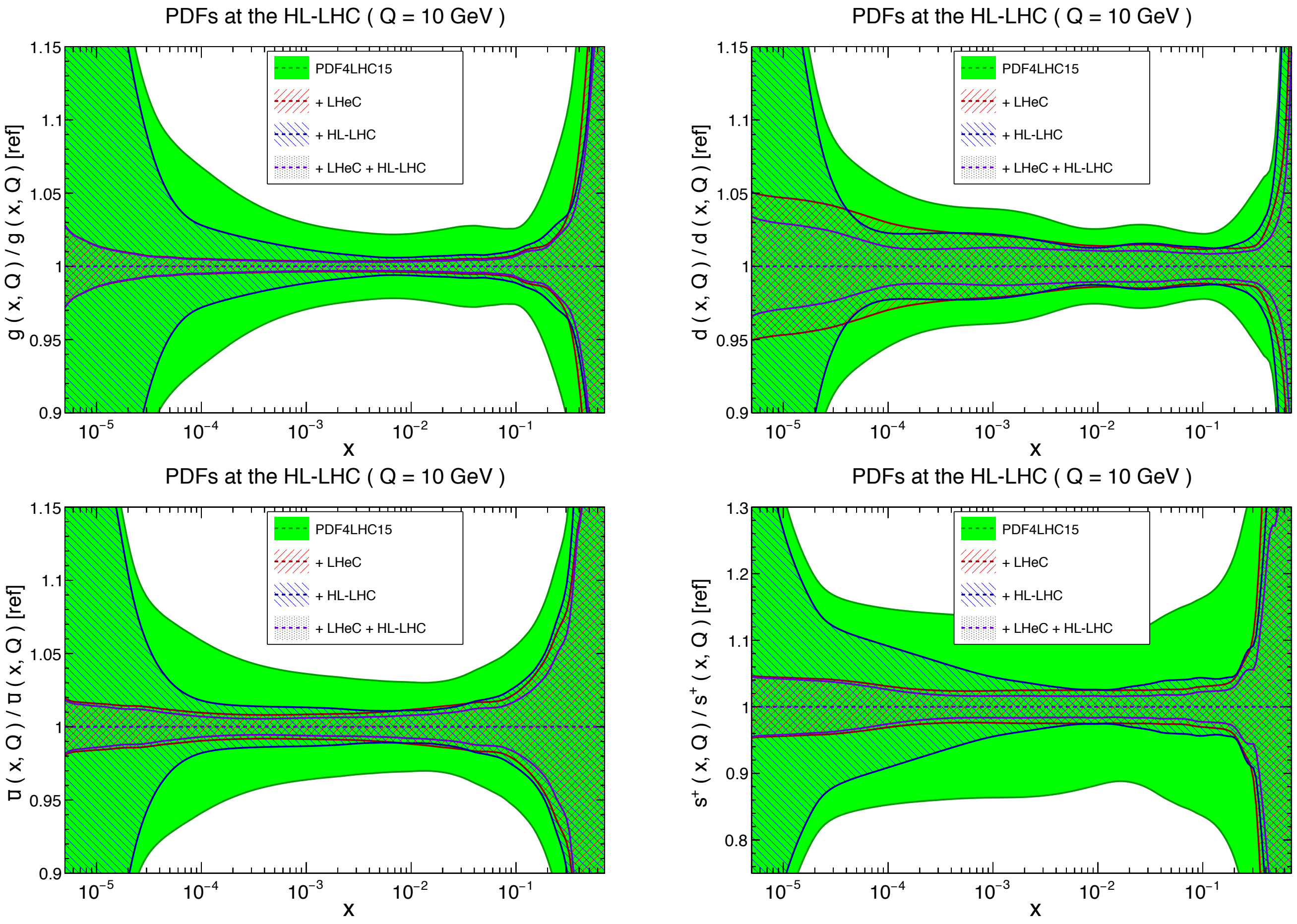


Figure 9.9: Impact of LHeC on the 1-σ relative PDF uncertainties of the gluon, down quark, anti–up quark and strangeness distributions, with respect to the PDF4LHC15 baseline set (green band). Results for the LHeC (red), the HL-LHC (blue) and their combination (violet) are shown.

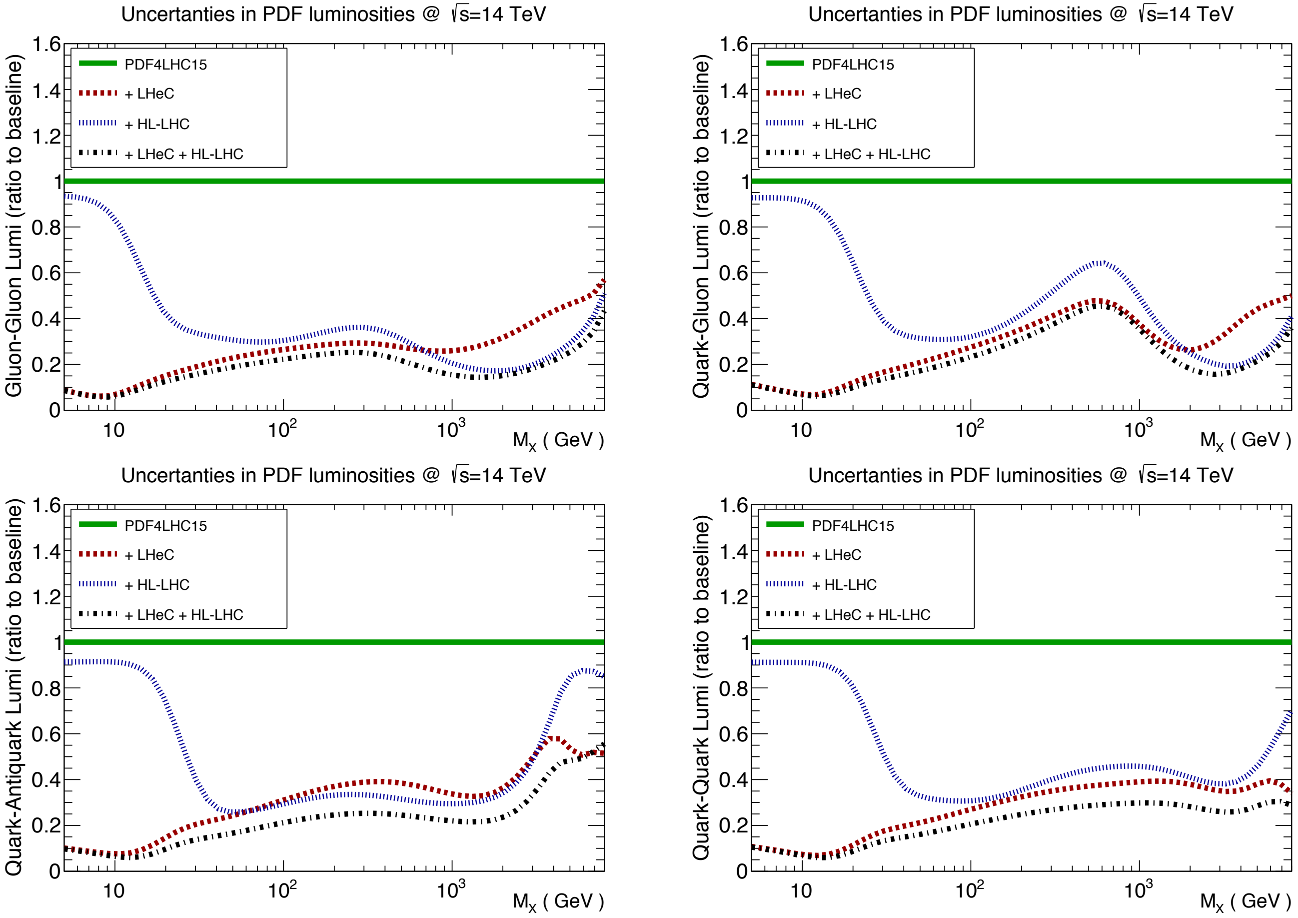
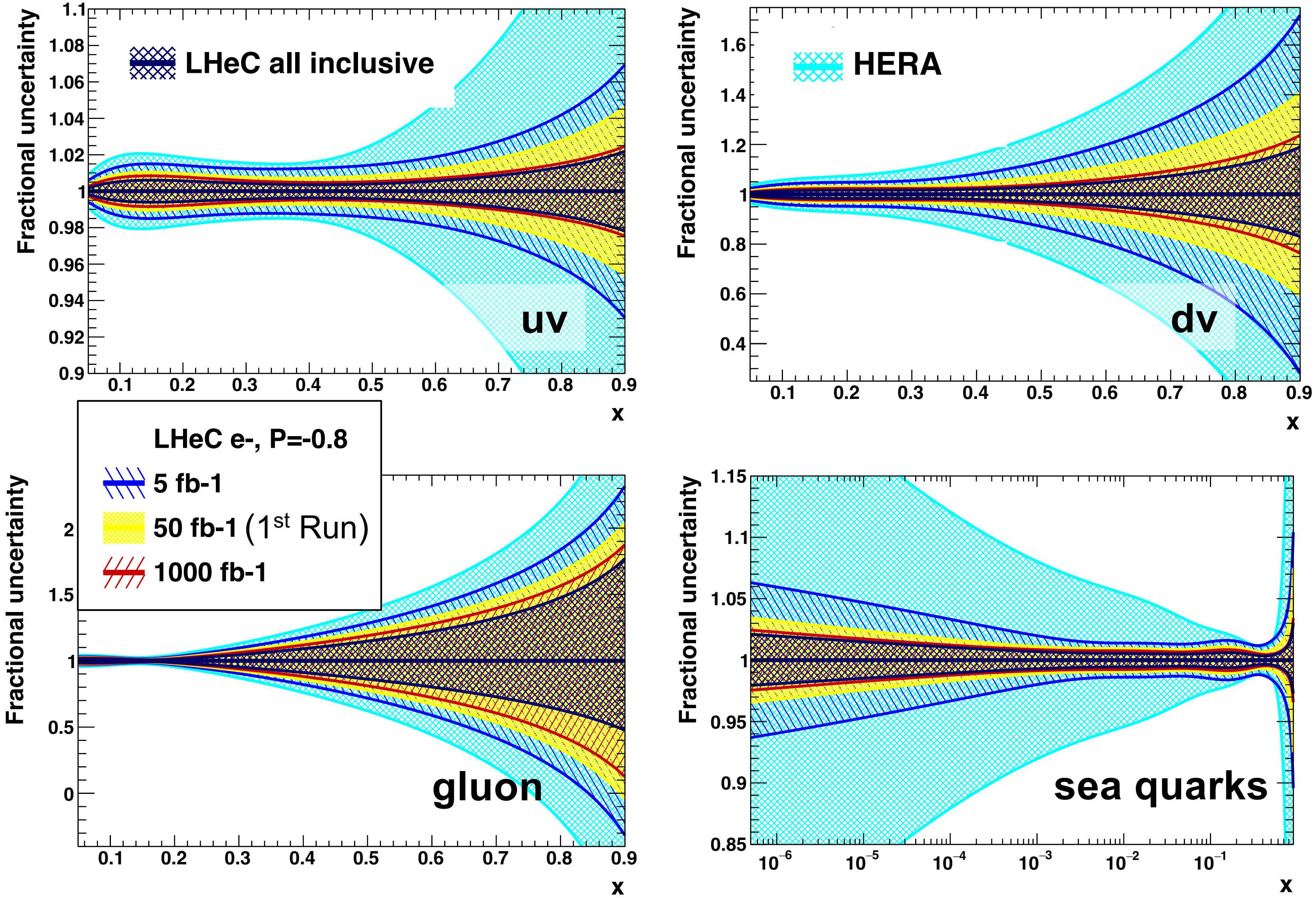


Figure 9.10: Impact of LHeC, HL-LHC and combined LHeC + HL-LHC pseudodata on the uncertainties of the gluon-gluon, quark-gluon, quark-antiquark and quark-quark luminosities, with respect to the PDF4LHC15 baseline set. In this comparison we display the relative reduction of the PDF uncertainty in the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

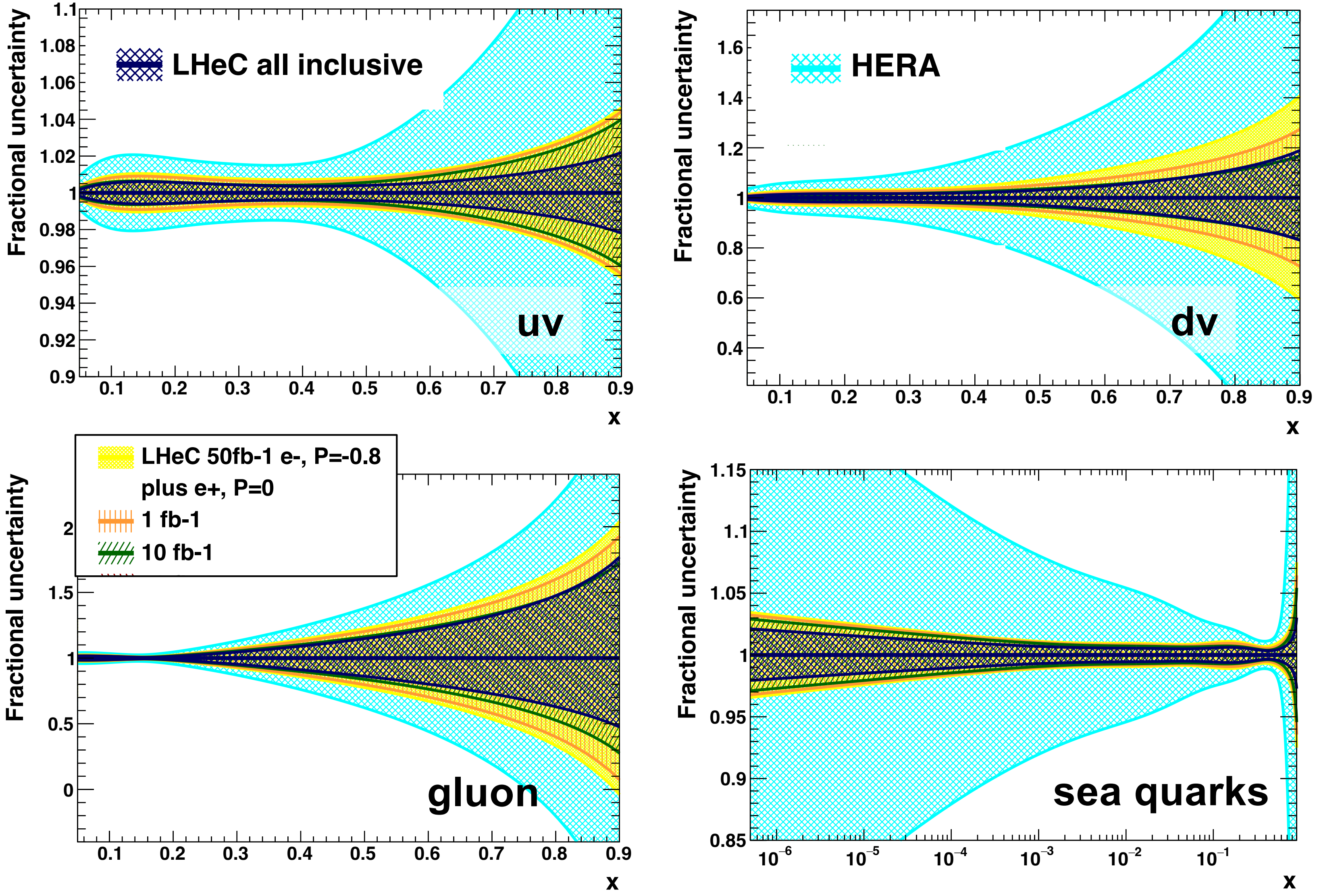
Impact of luminosity



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

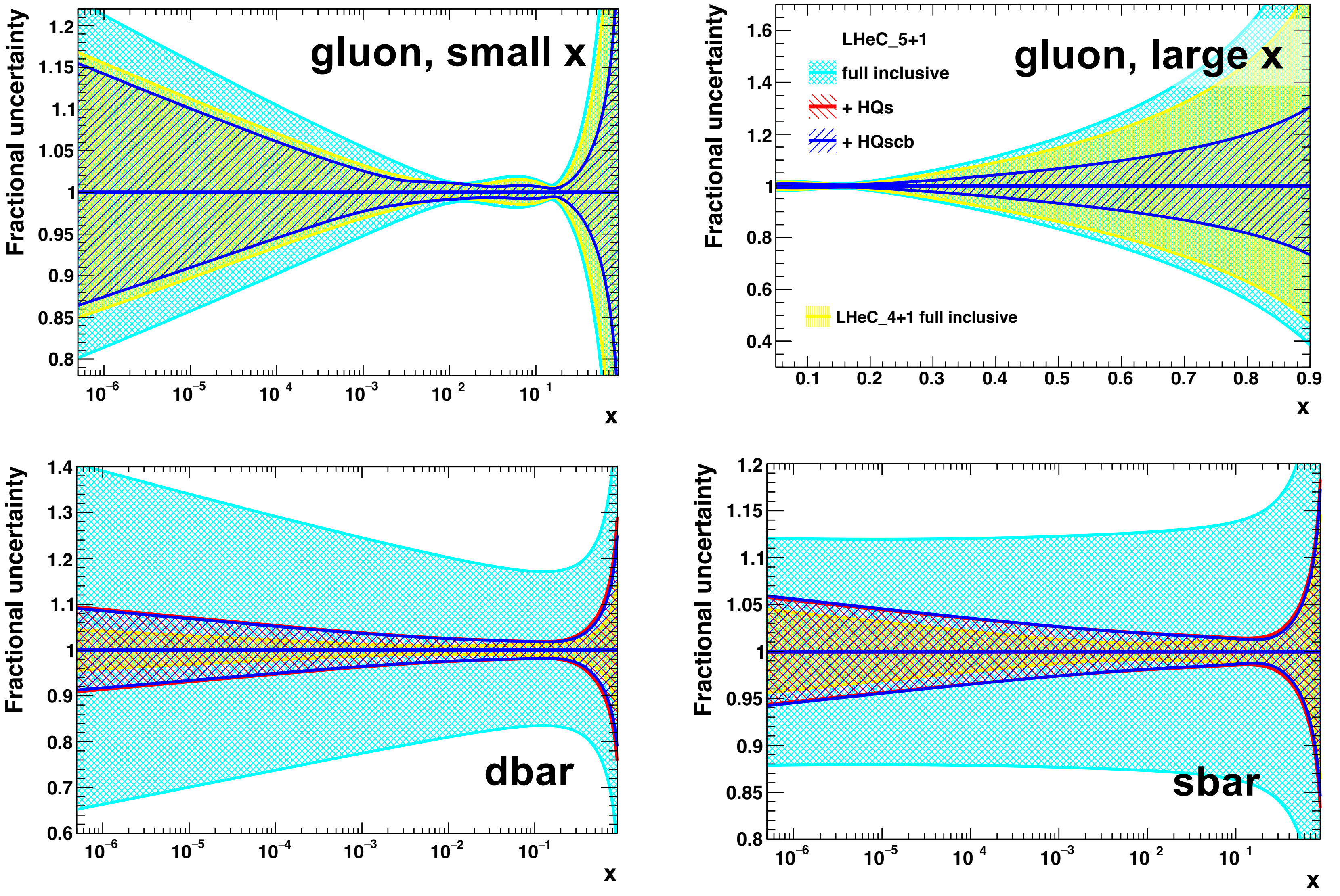
large x (≡ large Q^2), gain from increased Lint

Impact of positrons

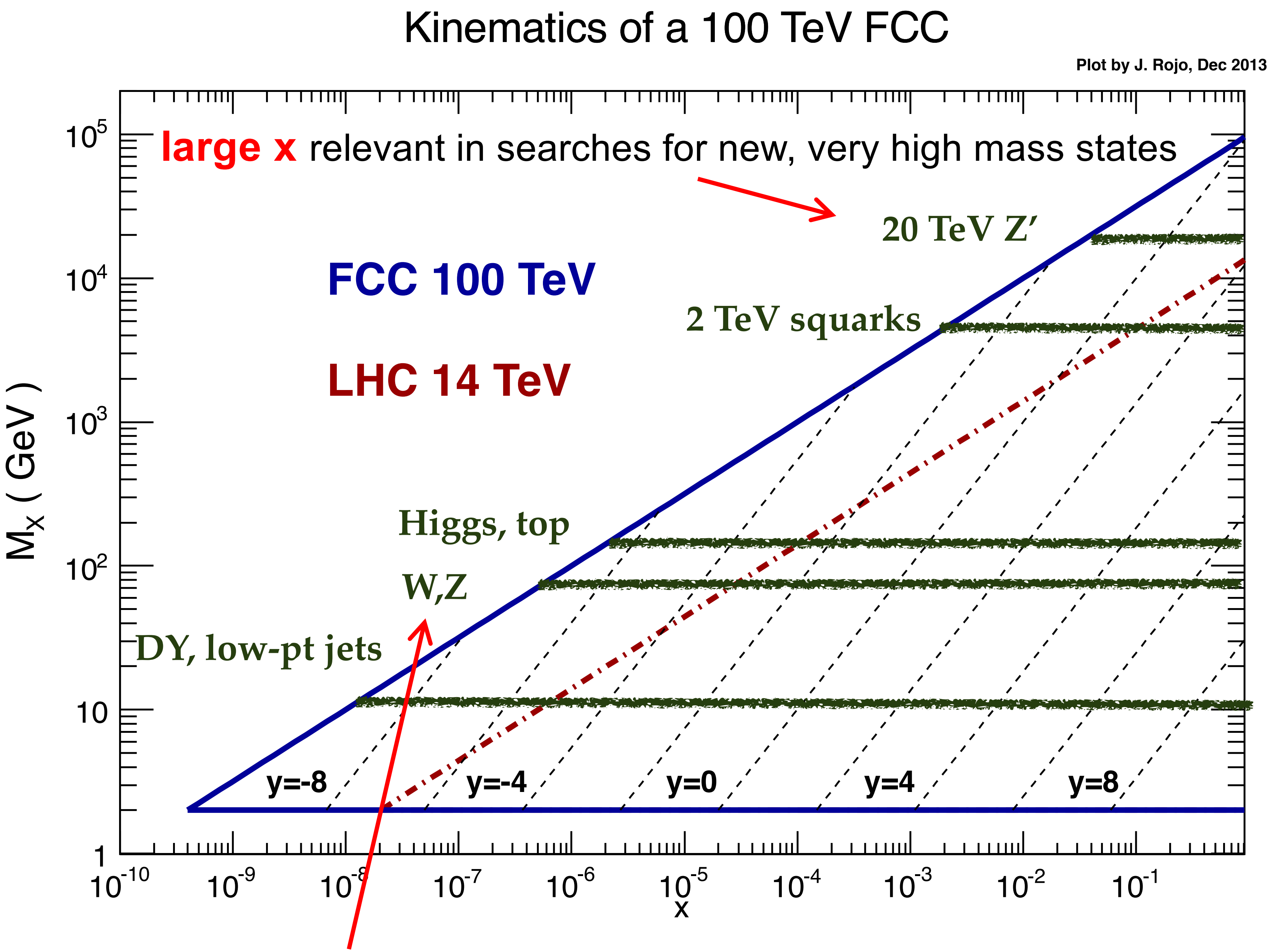


CC: e+ sensitive to d; **NC**: e± asymmetry gives xF3$^{\gamma Z}$, sensitive to valence

Impact of s, c, b



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



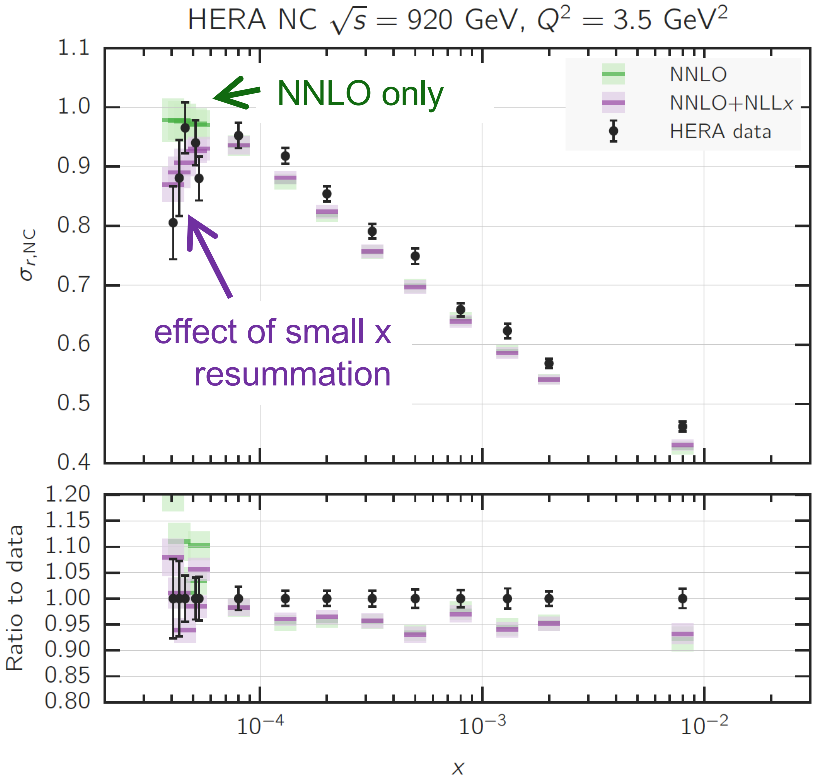
Kinematics of a 100 TeV FCC

Plot by J. Rojo, Dec 2013

large x relevant in searches for new, very high mass states

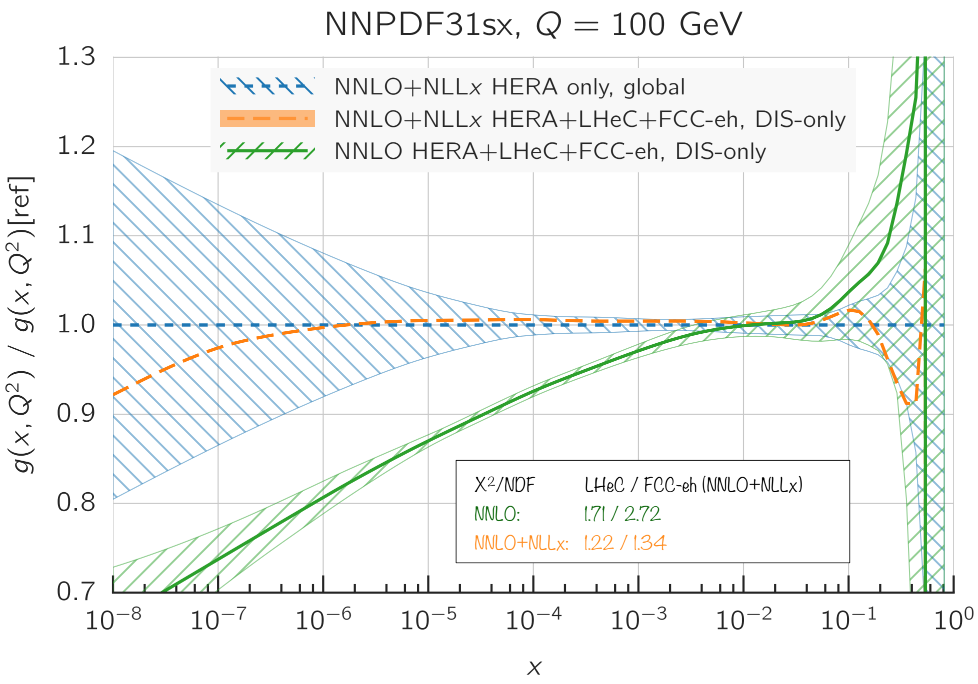
small x becomes relevant even for “common” physics (EG. W, Z, H, t)

Novel small x dynamics



- recent evidence for onset of BFKL dynamics in HERA inclusive data,
- arXiv:1710.05935; 1802.00064

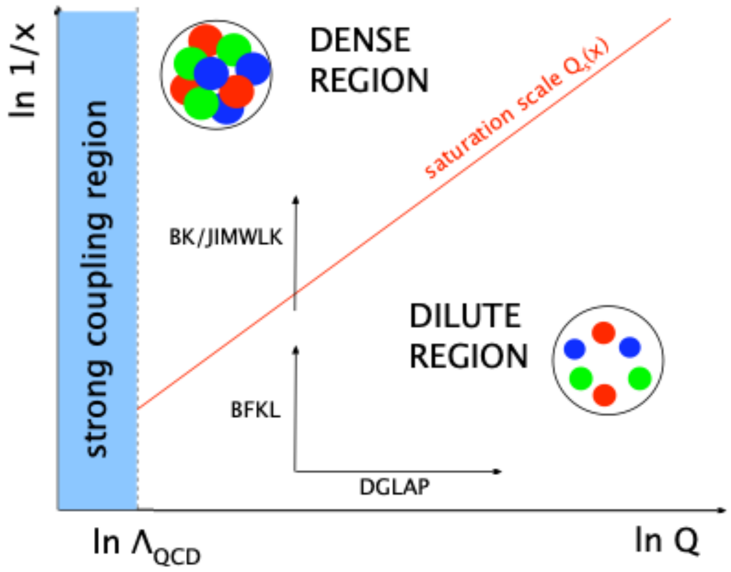
(see also, arXiv:1604.02299)

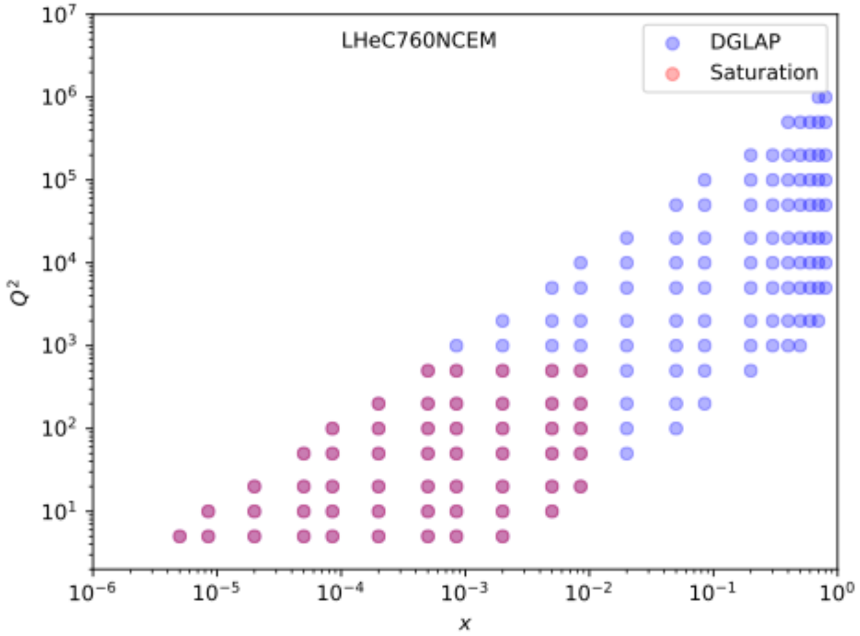


- small x resummation mainly affects **gluon pdf** – dramatic effect for x ≤ **10^{-3}**
- essential for LHeC and FCC-eh

- NB, gluon pdf obtained with small x resummation grows more quickly – **saturation** at some point!

Novel small x dynamics: saturation





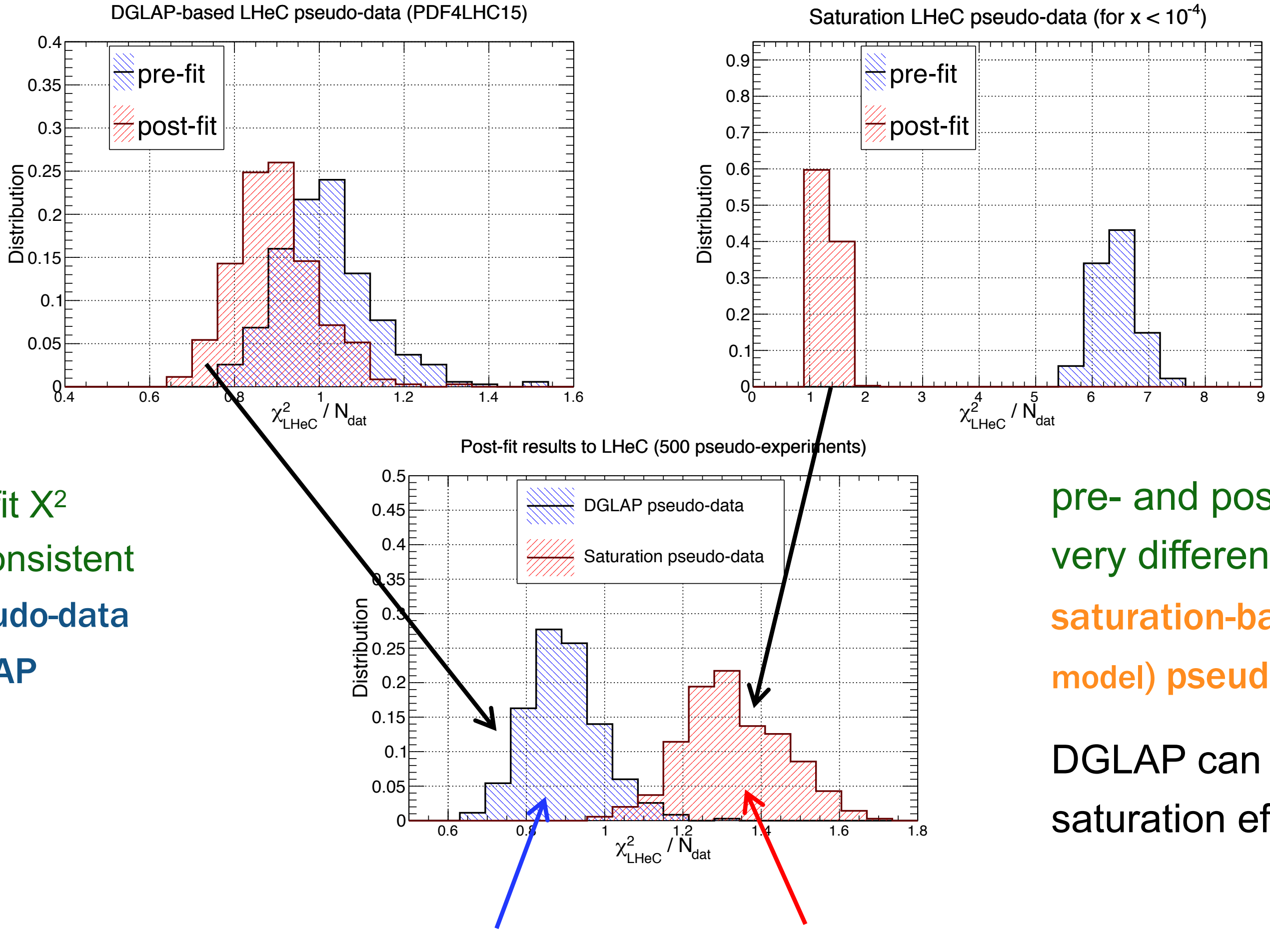
Test for saturation potential at LHeC:

Simulated pseudodata with saturation at low x

In the rest of kinematic range use DGLAP to simulate the data

Perform the fits of DGLAP to these data and check the tension/agreement

Novel dynamics at small x: saturation



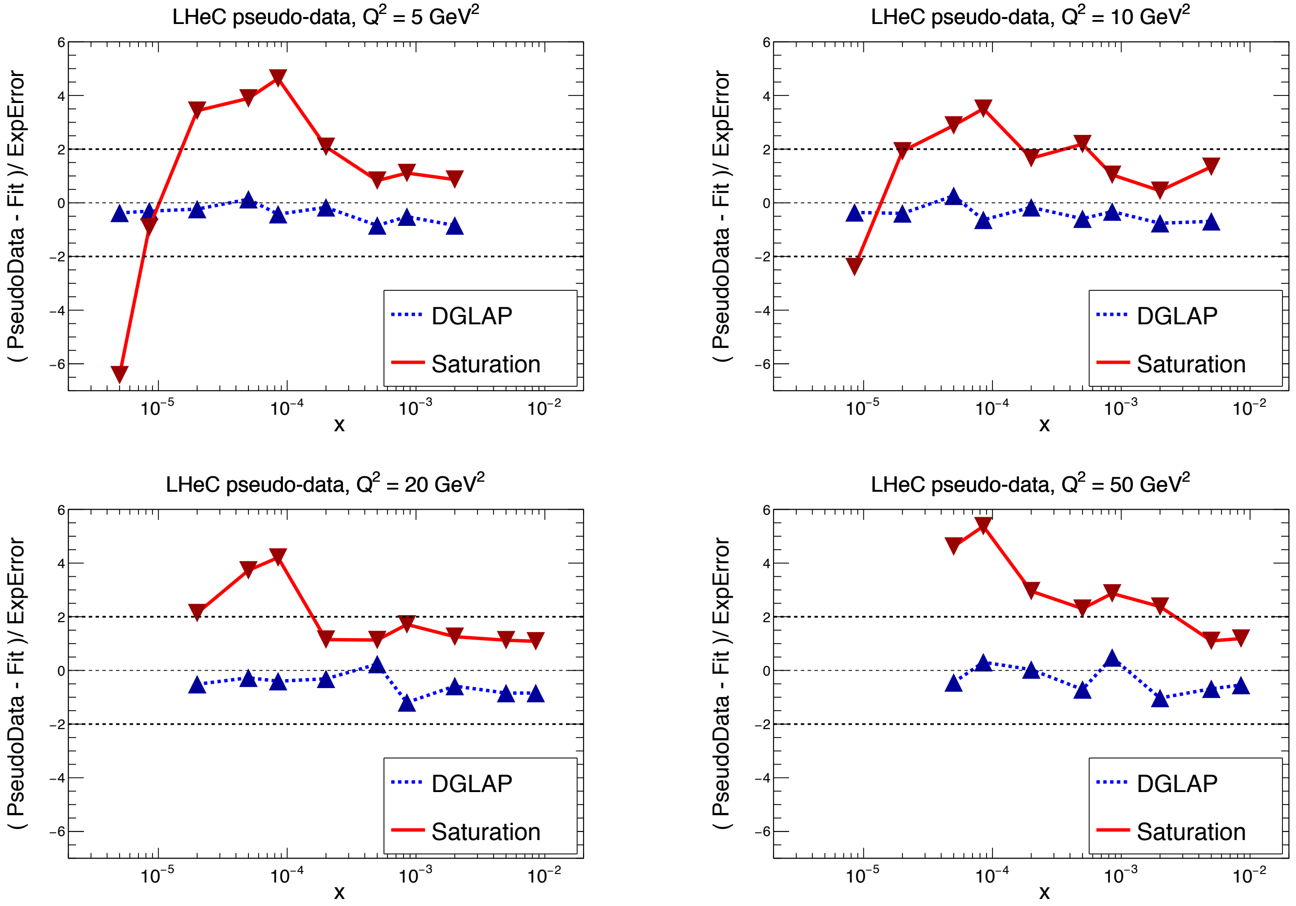
pre- and post-fit X^2 distributions consistent for **DGLAP pseudo-data** fitted with **DGLAP**

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

DGLAP can not absorb all saturation effects

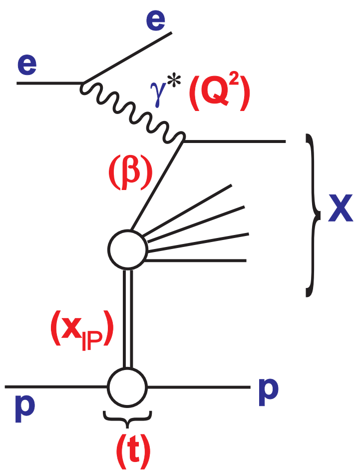
LHeC can distinguish between **DGLAP** and **saturation**

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

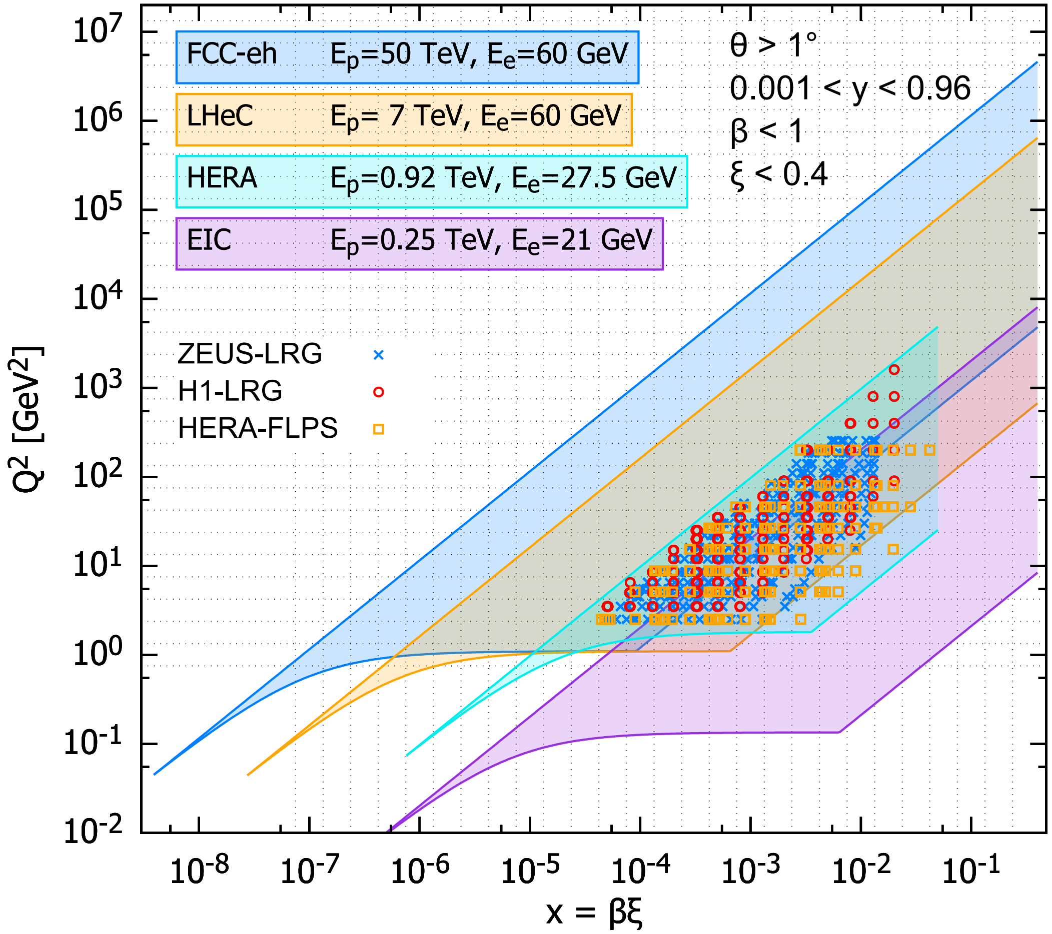
$$\beta = \frac{Q^2}{Q^2 + M_X^2 - t}$$

4-momentum transfer squared

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

Bjorken x relation

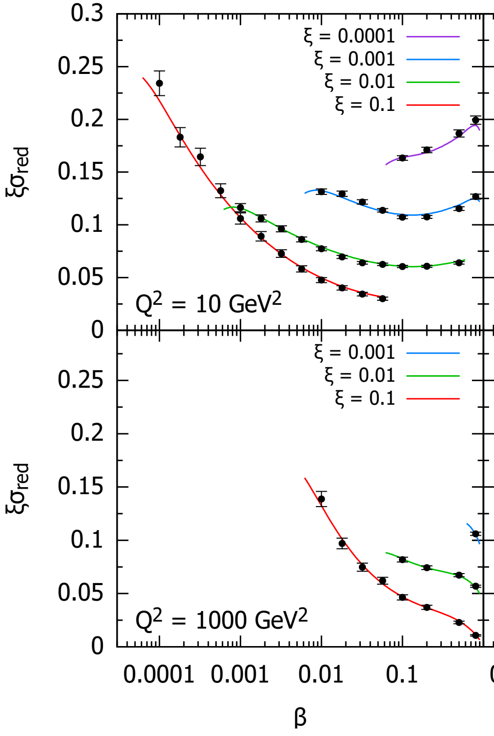
$$x_{Bj} = x_{IP}\beta$$



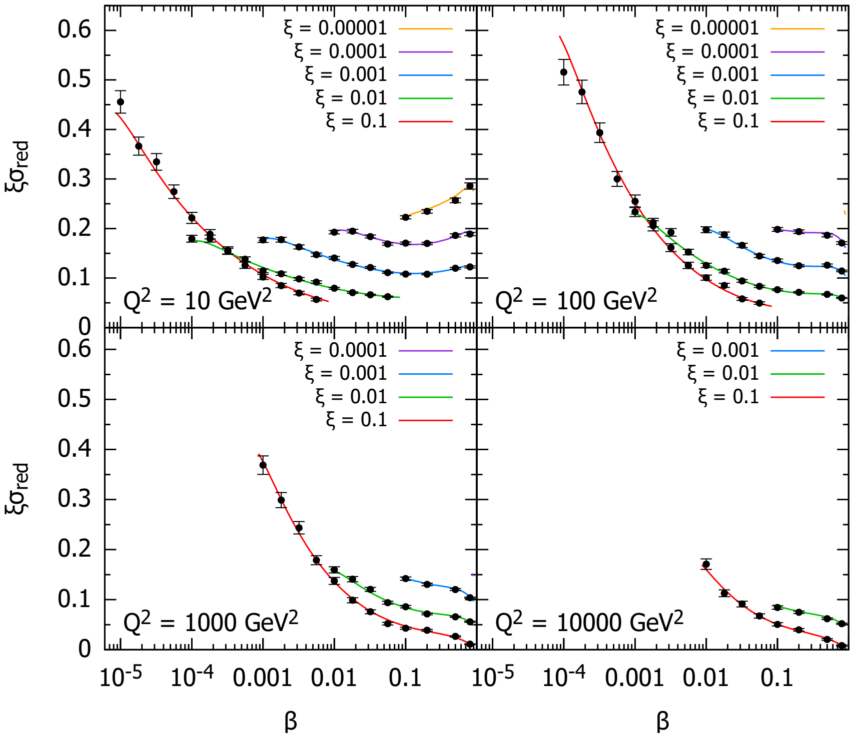
- inclusive diffraction, constraints on diffractive pdfs, new final states in diffraction, also EW exchange

Diffractive σ_{red} pseudo−data

LHeC



FCC-eh



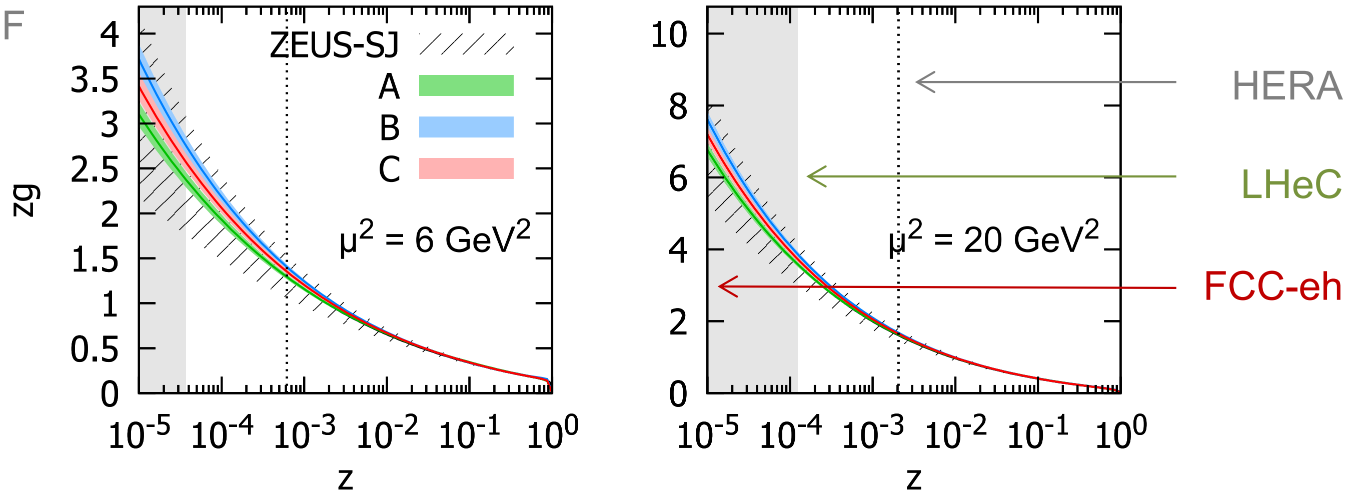
- potential for high quality data for inclusive diffraction at **LHeC/FCC-eh** (only small subset of simulated data shown)
- prospects for precise extraction of **diffractive pdfs**, **tests of factorisation breaking** (soft and collinear)

arXiv:2007.14491
EPJ C79 (2019), 6, 474
(thanks also to A. Stasto)

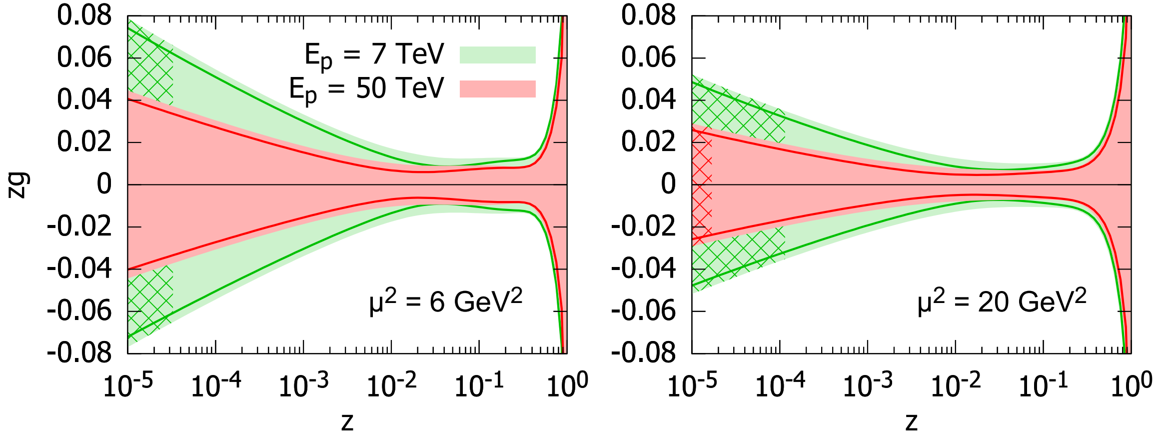
Diffractive PDFs

Gluon diffractive PDF from LHeC:

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



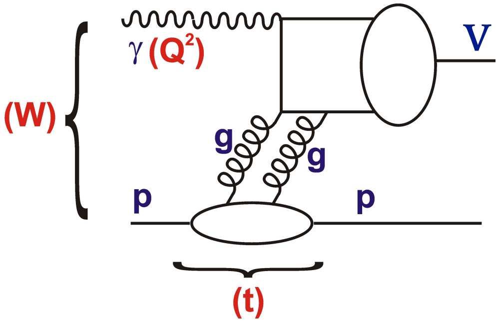
Relative uncertainty, LHeC and FCC-eh:



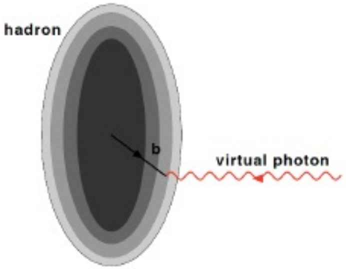
DPDF uncertainties reduced by factor 5 – 7 at LHeC and 10 – 15 at FCC-eh with inclusive data alone

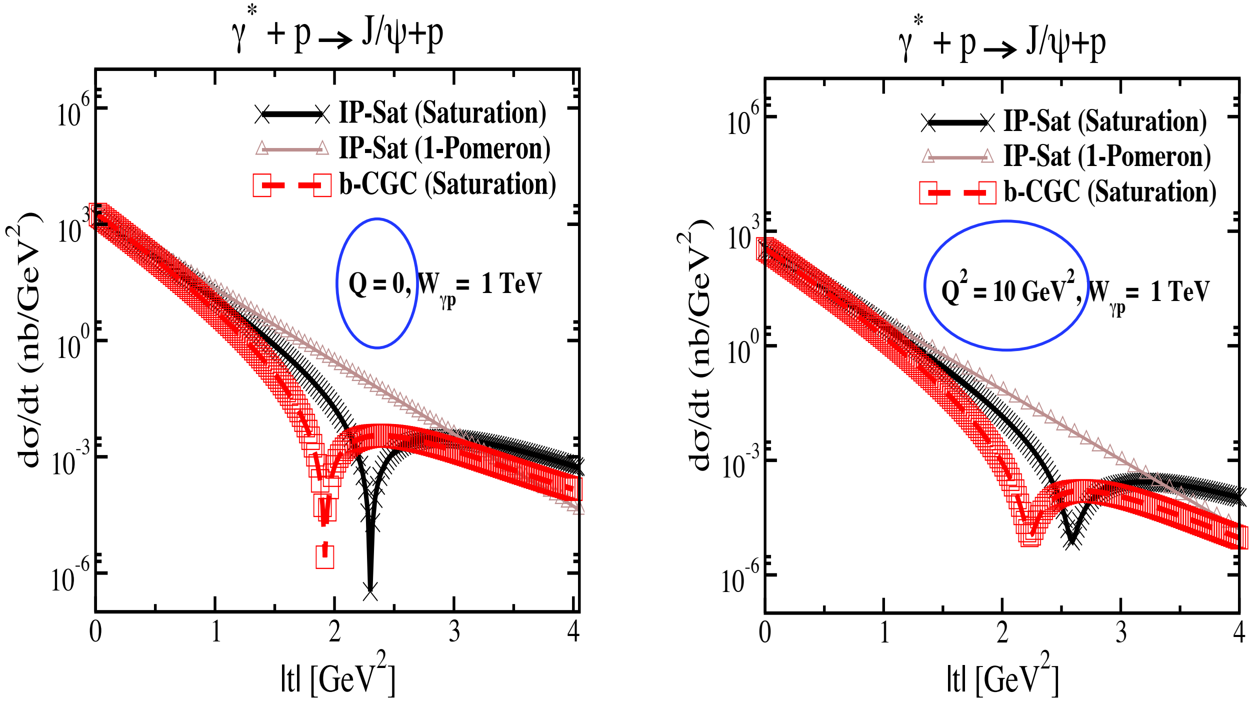
prospects for precise extraction of diffractive PDFs, tests of factorisation breaking (collinear and soft)

small x: elastic diffraction of vector mesons



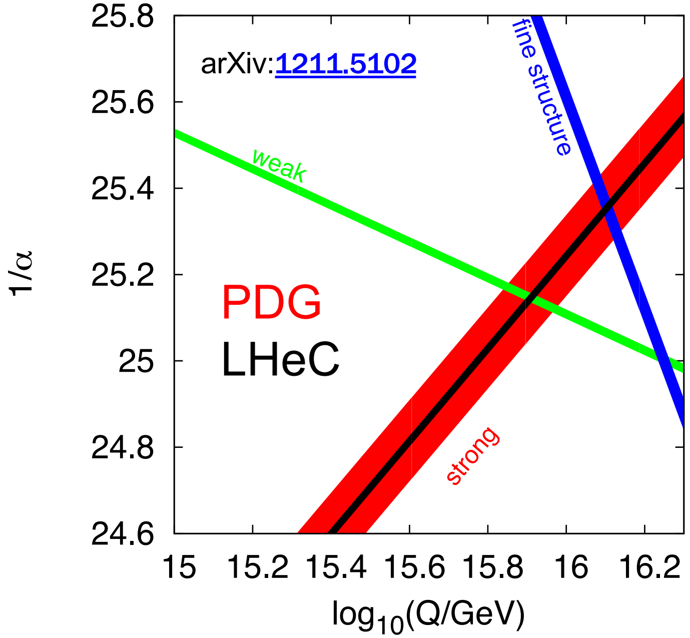
- access to GPDs, encoding 3d structure of nucleon
- t-dependence gives information on spatial distribution
  ≡ Fourier Transform of impact parameter profile
- sensitivity to non-linear evolution and saturation

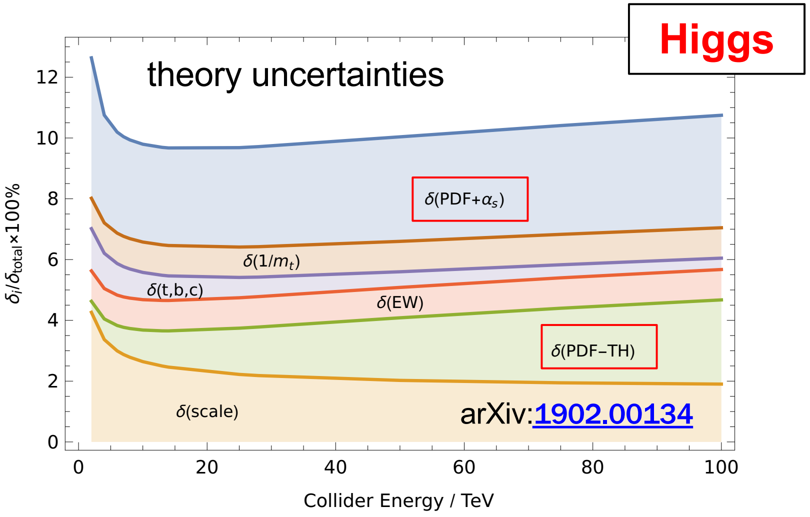




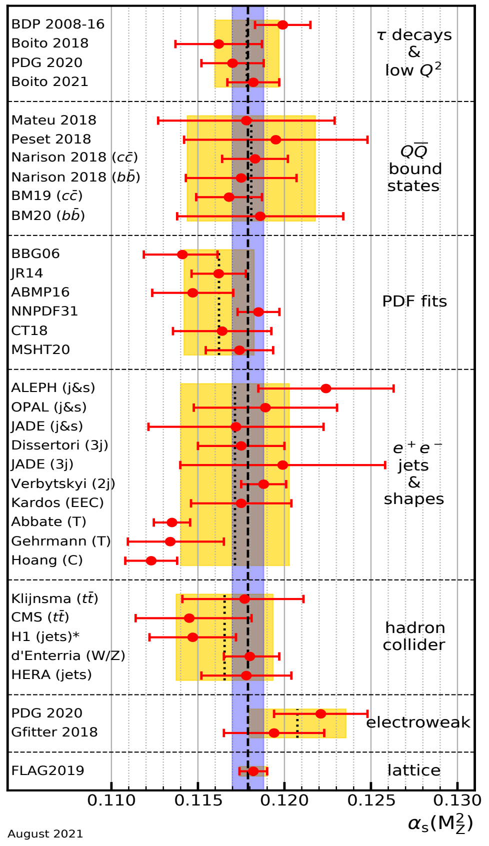
- **one of the best processes to test for novel small x dynamics**
- characteristic **dips** a feature of saturation models – positions depend on exact model, Q, $W_{\gamma p}$, M_V

Strong Coupling





PDG21

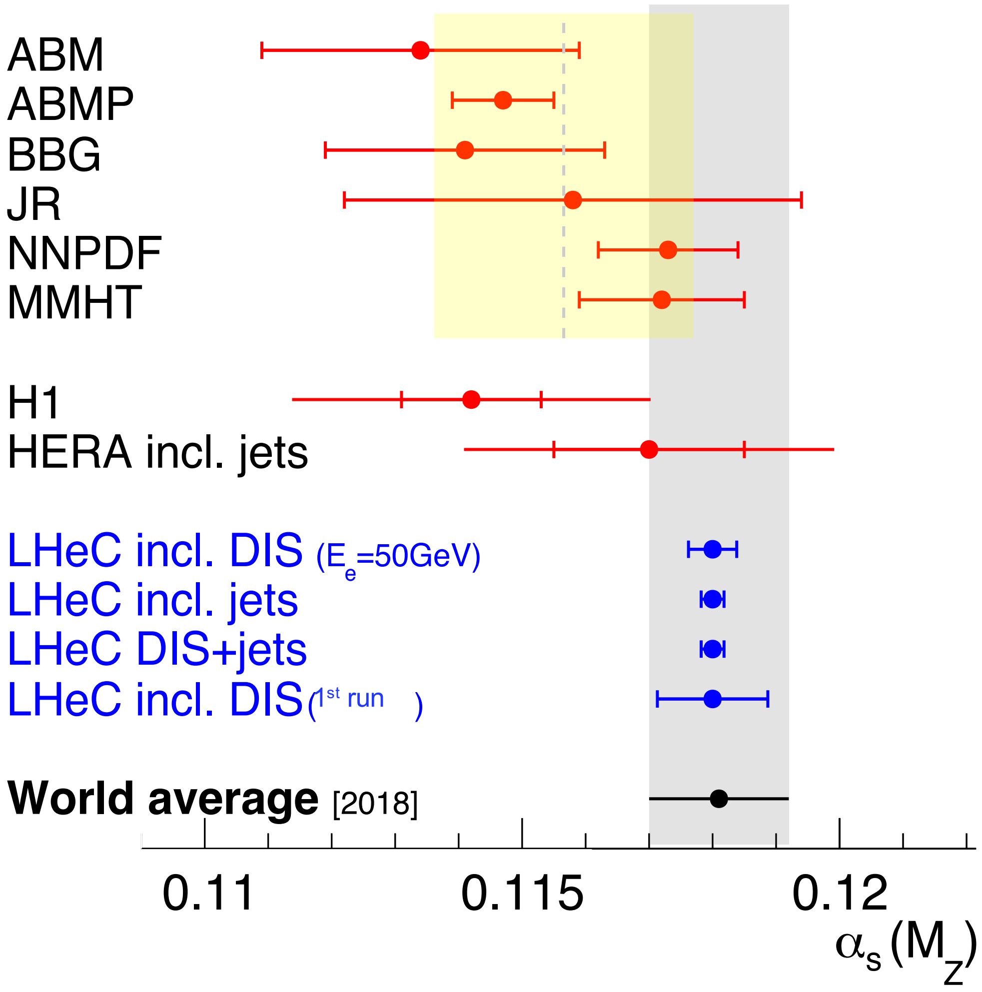


- **αs** is least known coupling constant
- world av.: $\alpha_s(M_Z^2)$ = **0.1175±0.0010** (w/o lattice)
- current state-of-the-art: **δαs/αs = $\mathcal{O}$(1%)**

Strong Coupling

arXiv:2007.14491
Featured also in Snowmass **αs** White Paper,
arXiv:2203.0827

αs determinations at NNLO QCD:

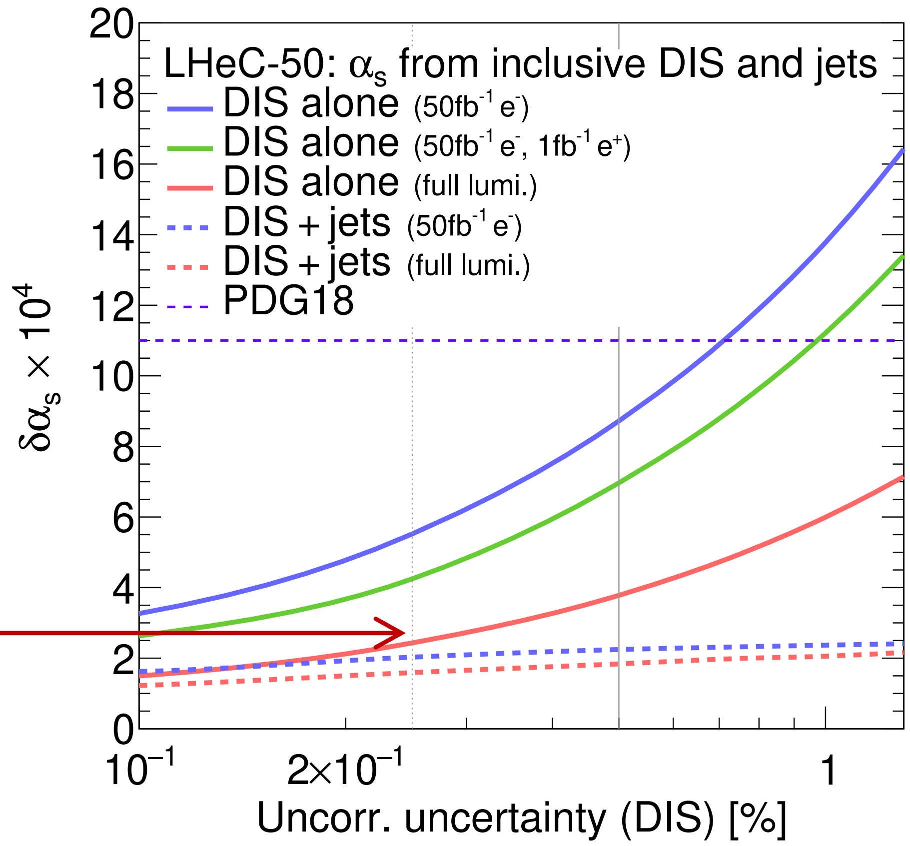


αs from LHeC inclusive NC/CC DIS

- **αs** from inclusive NC/CC DIS:
- simultaneous determination of **pdfs** and **αs** in **NNLO QCD** fit

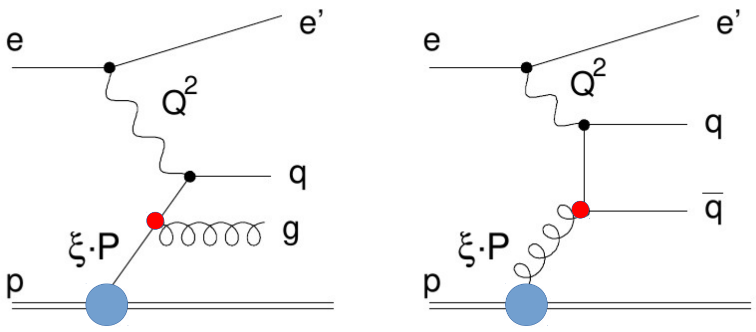
- **3** LHeC scenarios:
- LHeC **1**st Run (**50** fb^{-1} e-p)
- plus **1** fb^{-1} positron data
- full inclusive LHeC dataset (**1** ab^{-1})

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



- **αs** 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

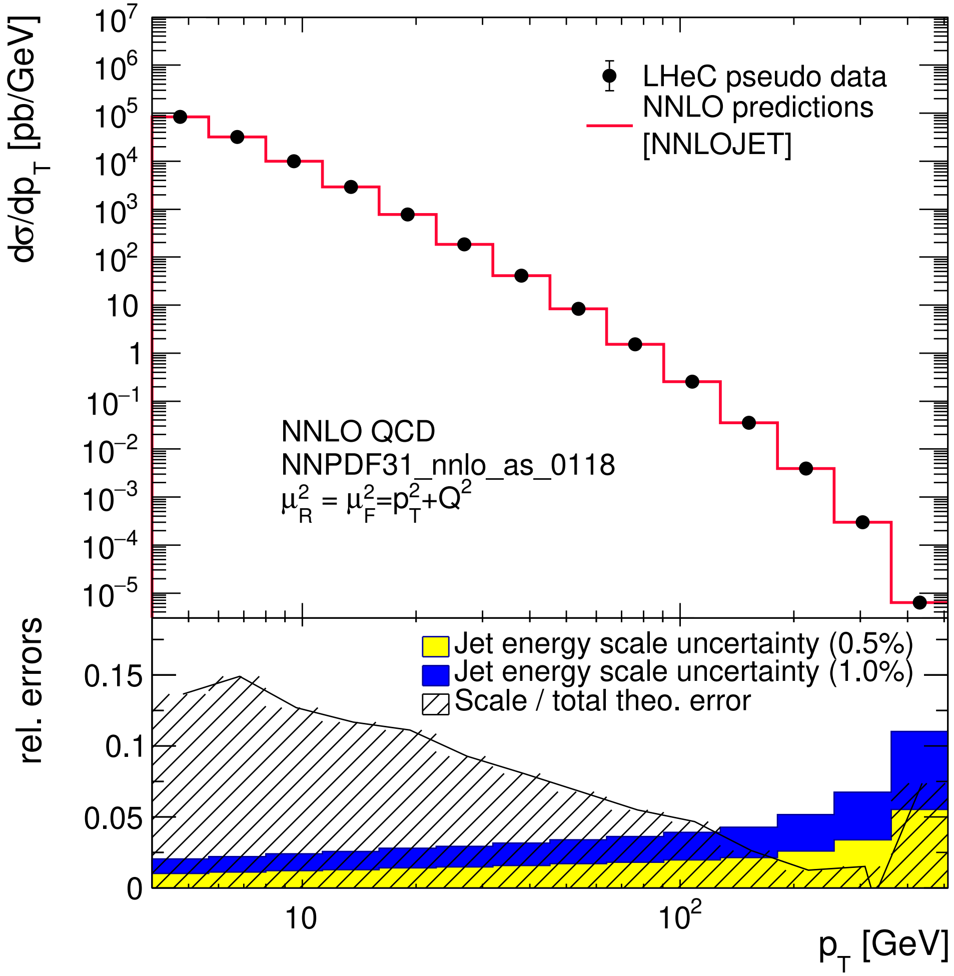


- sensitive to **αs** at lowest order

- NNLO QCD calculations for DIS jets available in NNLOJet (arXiv:1606.03991, 1703.05977), and implemented in APPLfast (arXiv:1906.05303)

- full set of systematic uncerts. considered; benchmarked with H1, ZEUS, ATLAS, CMS

Exp. uncertainty	Shift	Size on σ [%]
Statistics with $1\,\mathrm{ab}^{-1}$	min. 0.15 %	0.15 – 5
Electron energy	0.1 %	0.02 – 0.62
Polar angle	2 mrad	0.02 – 0.48
Calorimeter noise	±20 MeV	0.01 – 0.74
Jet energy scale (JES)	0.5 %	0.2 – 4.4
Uncorrelated uncert.	0.6 %	0.6
Normalisation uncert.	1.0 %	1.0



αs from LHeC NC DIS jets

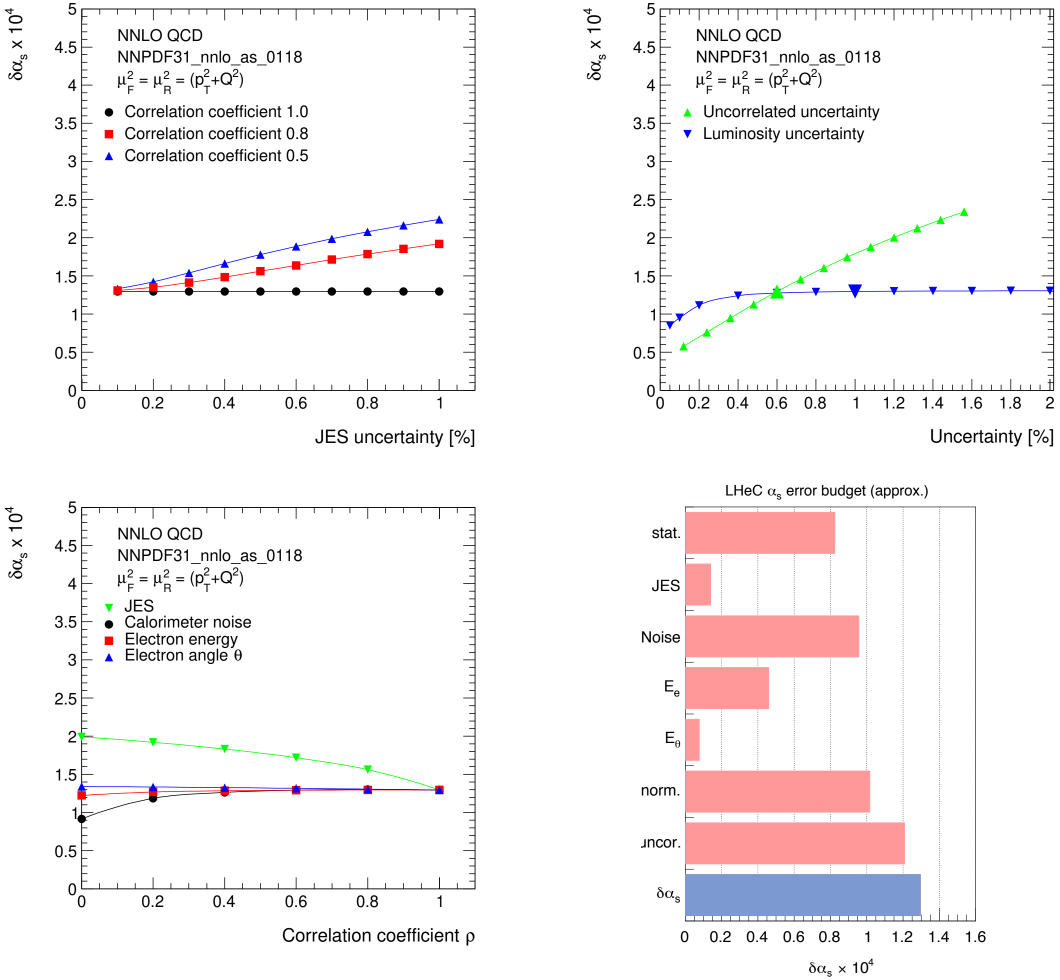
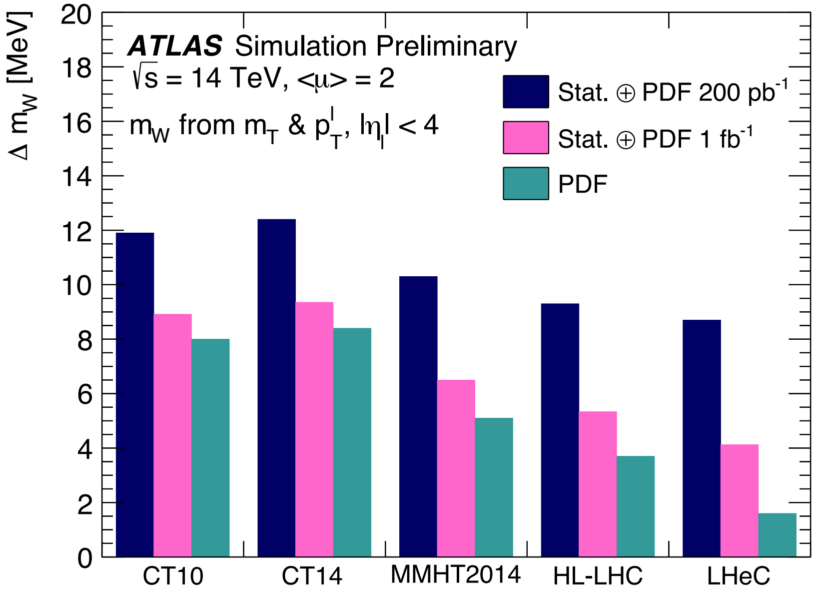


Figure 4.3: Studies of the size and correlations of experimental uncertainties impacting the uncertainty of $\alpha_s(M_Z)$. Top left: Study of the value of the correlation coefficient ρ for different systematic uncertainties. Common systematic uncertainties are considered as fully correlated, $\rho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

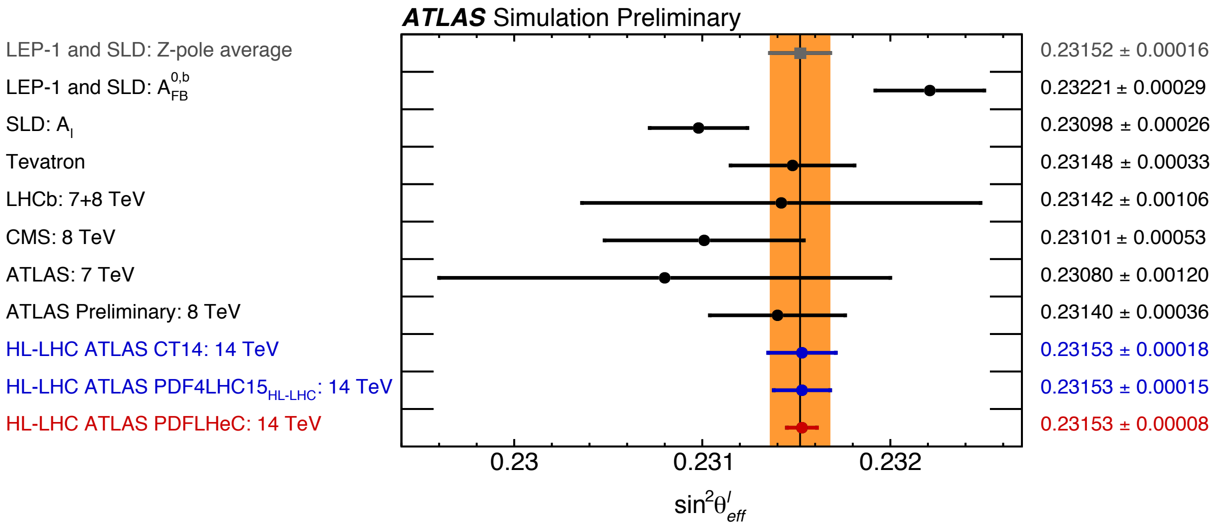
Empowering the LHC: MW

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



Empowering the LHC: sin$^2\vartheta$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, $\mathcal{L}$	fb^{-1}	20	3000	3000	3000
Experimental uncert.	10^{-5}	± 23	± 9	± 7	± 7
PDF uncert.	10^{-5}	± 24	± 16	± 13	± 3
Other syst. uncert.	10^{-5}	± 13	–	–	–
Total uncert., $\Delta\sin^2\theta_W$	10^{-5}	± 36	± 18	± 15	± 8

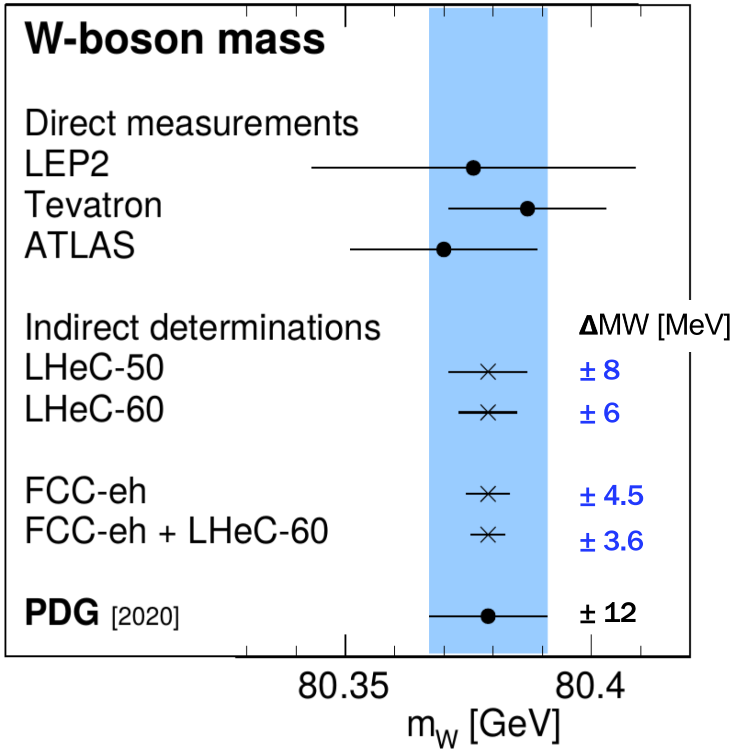


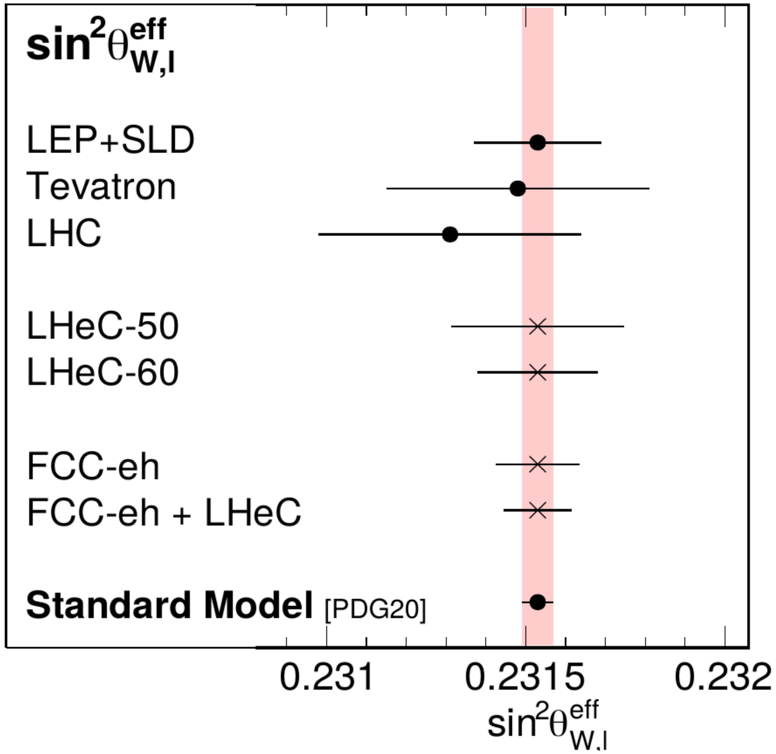
MW and $\sin^2\theta W$

FCC WS Nov 2020

arXiv:2007.11799

pdf+EW fits





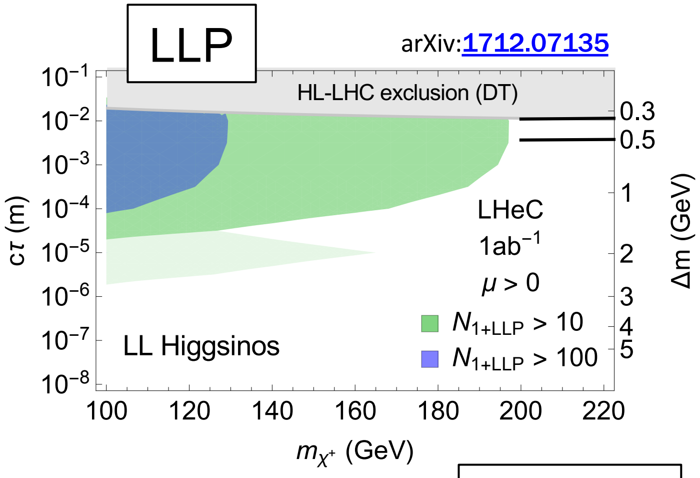
- Mw: most precise determination from a single experiment
- complementary to direct measurements

- $\sin^2\theta W$: potential for most precise measurement from single experiment
- can also test SM-prediction of scale dependence across wide range of scale to $\mathcal{O}(0.1\%)$ precision

arXiv:2007.14491

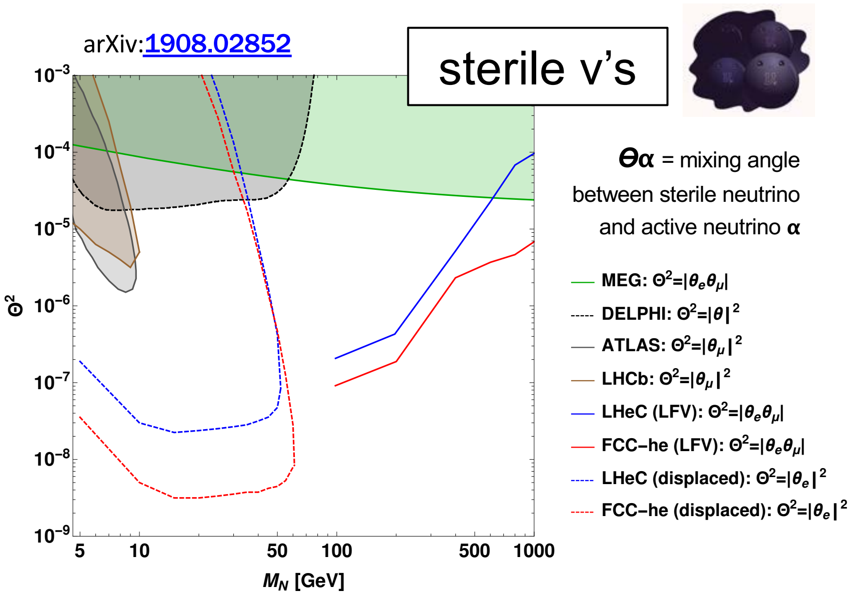
BSM

- selected examples:



LLP

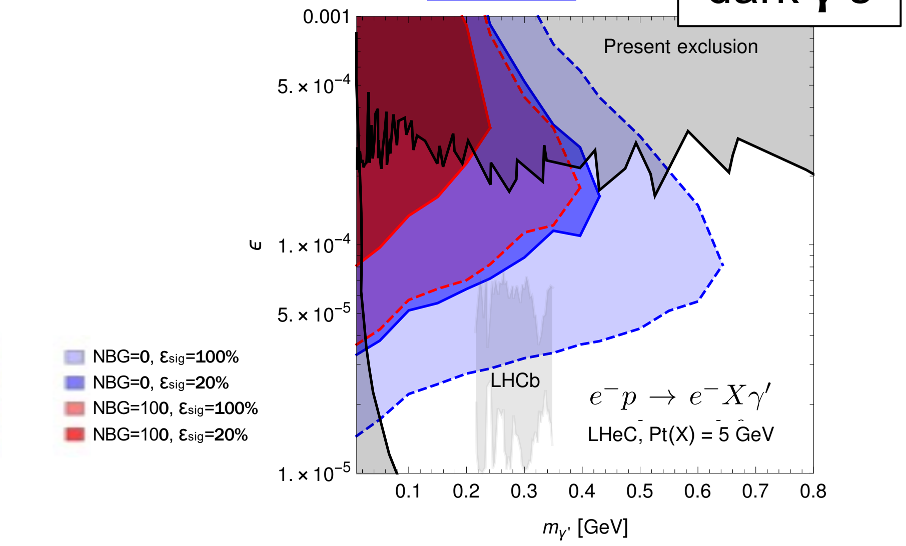
arXiv:1712.07135



arXiv:1908.02852

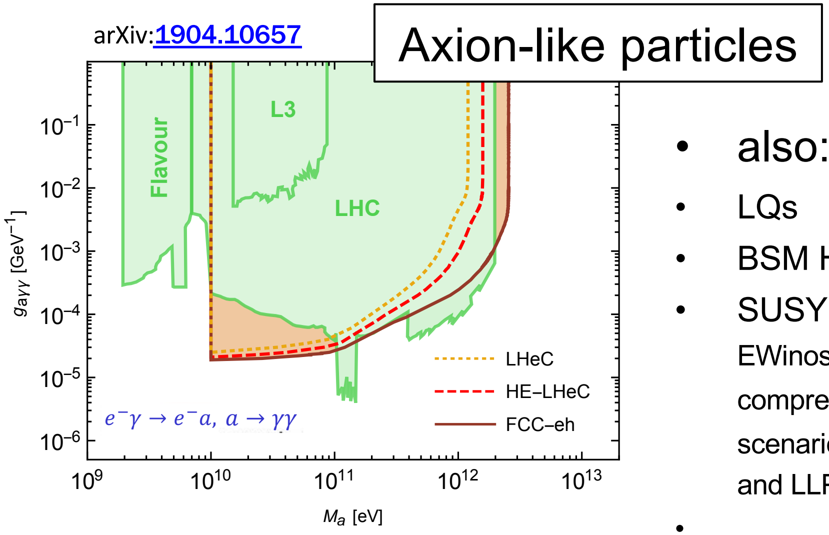
sterile ν's

Θα = mixing angle between sterile neutrino and active neutrino **α**



arXiv:1909.02312

dark γ's



arXiv:1904.10657

Axion-like particles

- also:
- LQs
- BSM Higgs
- SUSY (RPV; EWinos in compressed scenarios, prompt and LLP, …)
- …