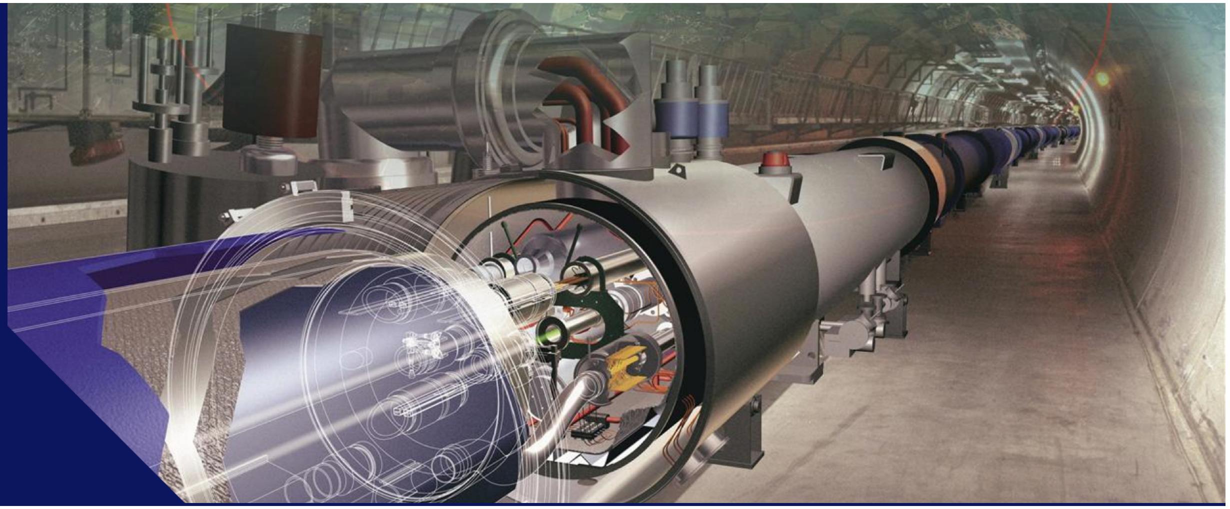
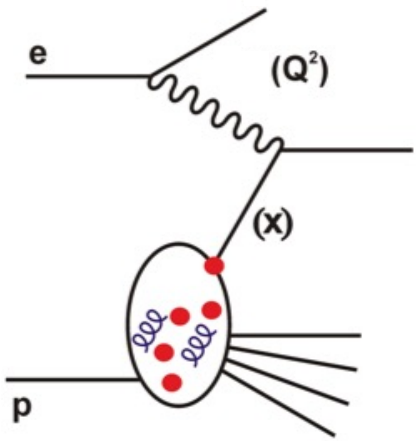
online conference

26 – 30 July 2021



Precision QCD and Small x Physics at the LHeC and FCC-eh



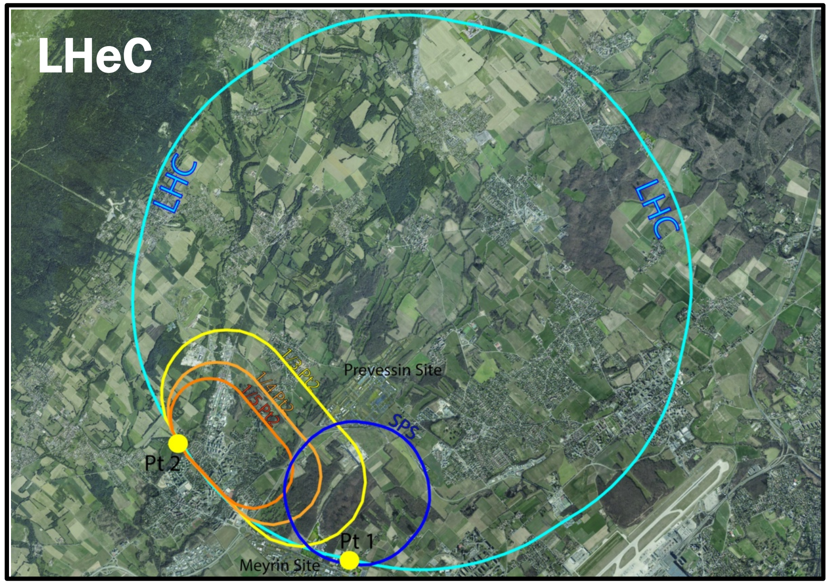
Claire Gwenlan, Oxford

on behalf of the LHeC and FCC-eh study groups

with focus on results from LHeC CDR update, arXiv:2007.14491

LHeC, FCC-eh and PERLE

CERN future colliders: arXiv:[1810.13022]



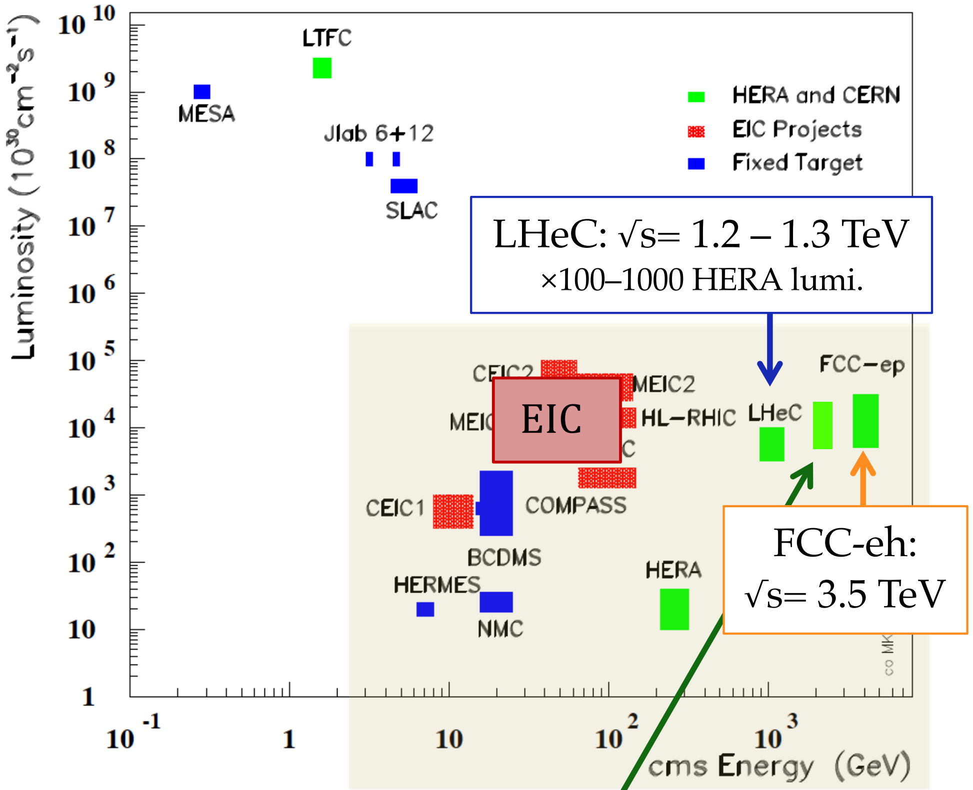
energy recovery LINAC (ERL)

attached to HL-LHC (or FCC)

e beam: ⟶ **50** or **60** GeV

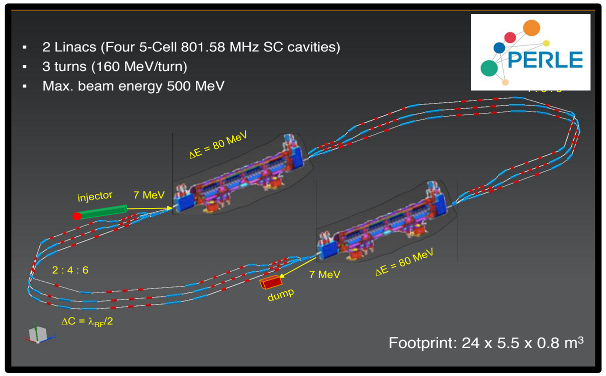
e pol.: P= **±0.8**

Lint ⟶ **1–2** ab^{-1} (1000× HERA!)



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

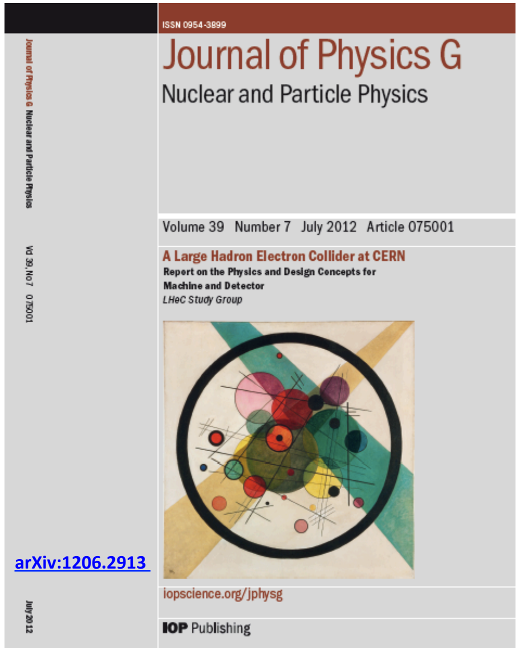
PERLE: international collaboration built to realise **500** MeV energy facility at Orsay, for development of ERL with LHeC conditions



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

LHeC Conceptual Design Report and Beyond

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



arXiv:[1206.2913]

Further selected references:

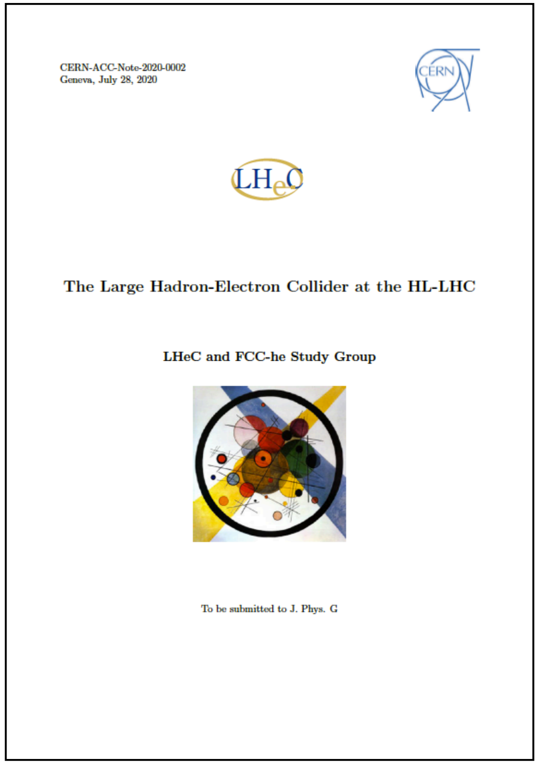
On the relation of the LHeC and the LHC
arXiv:1211.5102

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

CDR update 2020
400 pages, 300 authors, 156 institutions



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

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

BSM, O. Fischer

eA, G. Milhano

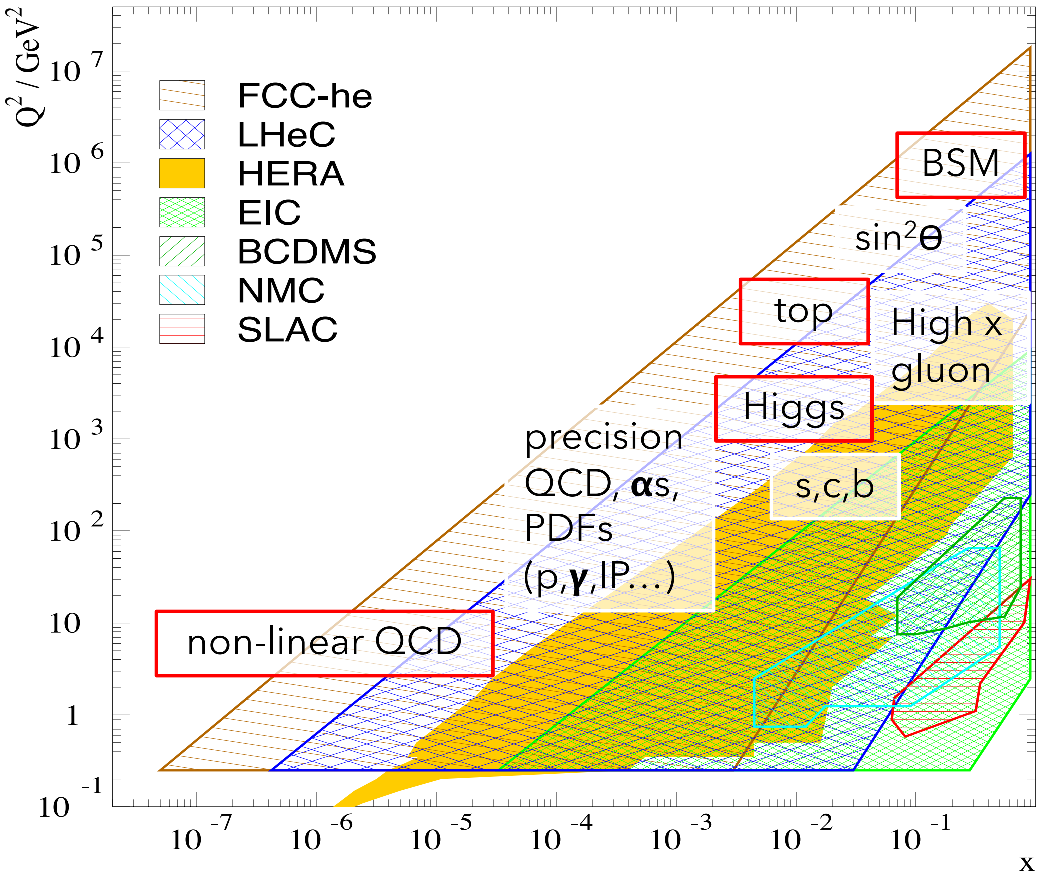
Higgs, U. Klein

EW, and LHeC as part of HL-LHC, D. Britzger

Top, S. Behera

LHeC status and plans, K. Andre (poster)

PERLE, B. Hounsell (poster)



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

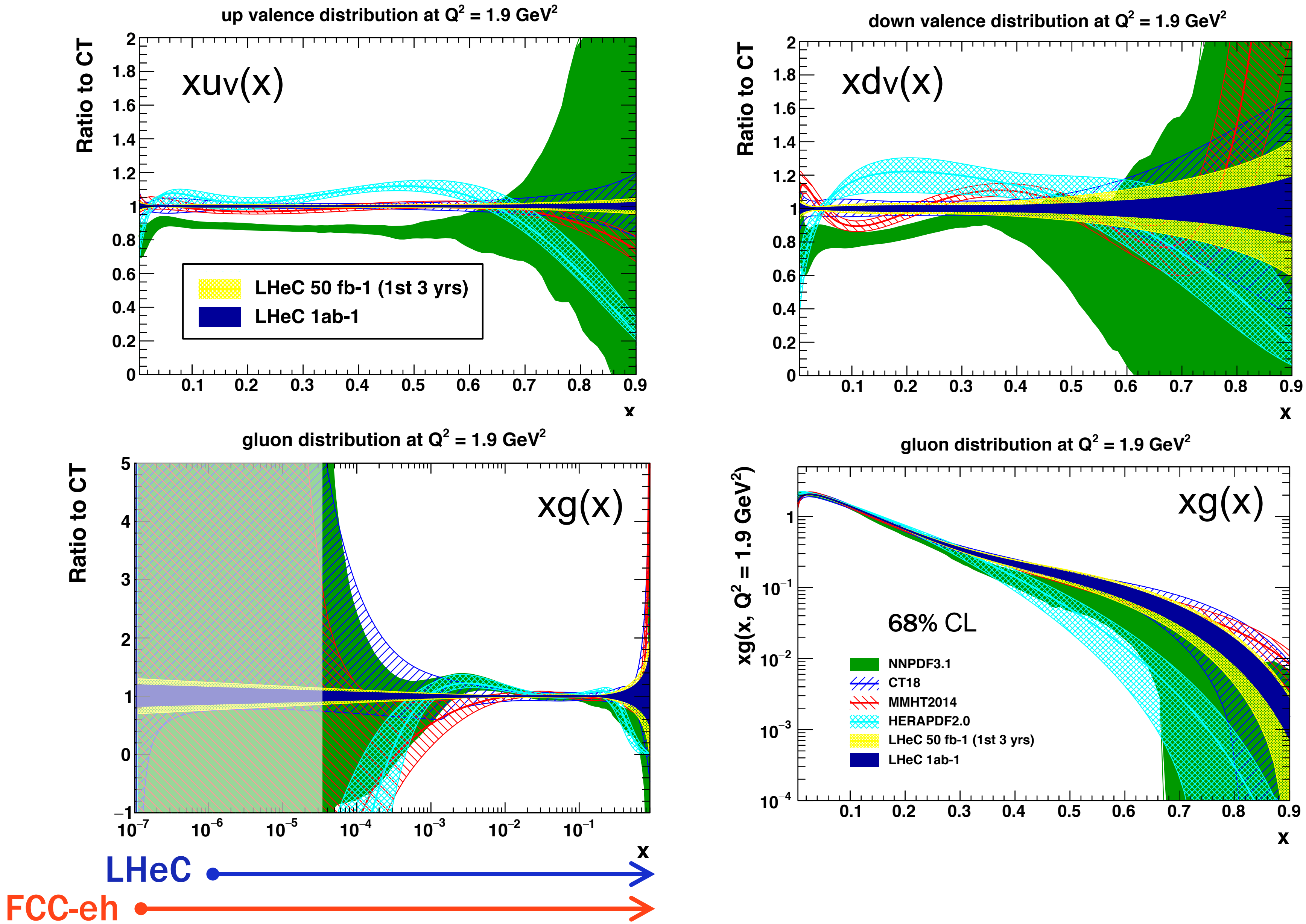
no higher twist, no nuclear corrections, free of symmetry assumptions, N3LO theory, …

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

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

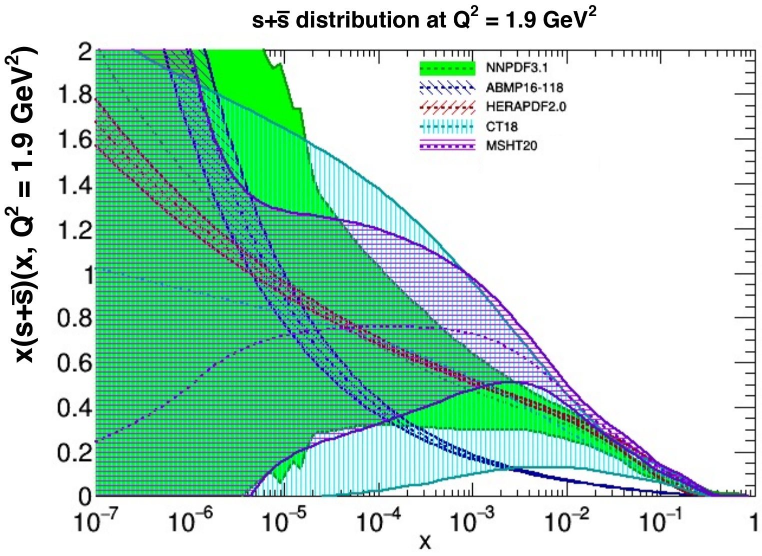
(LHeC projected timeline, several years concurrent HL-LHC operation, plus dedicated run, arXiv:1810.13022) arXiv:2007.14491

Quark and Gluon PDFs



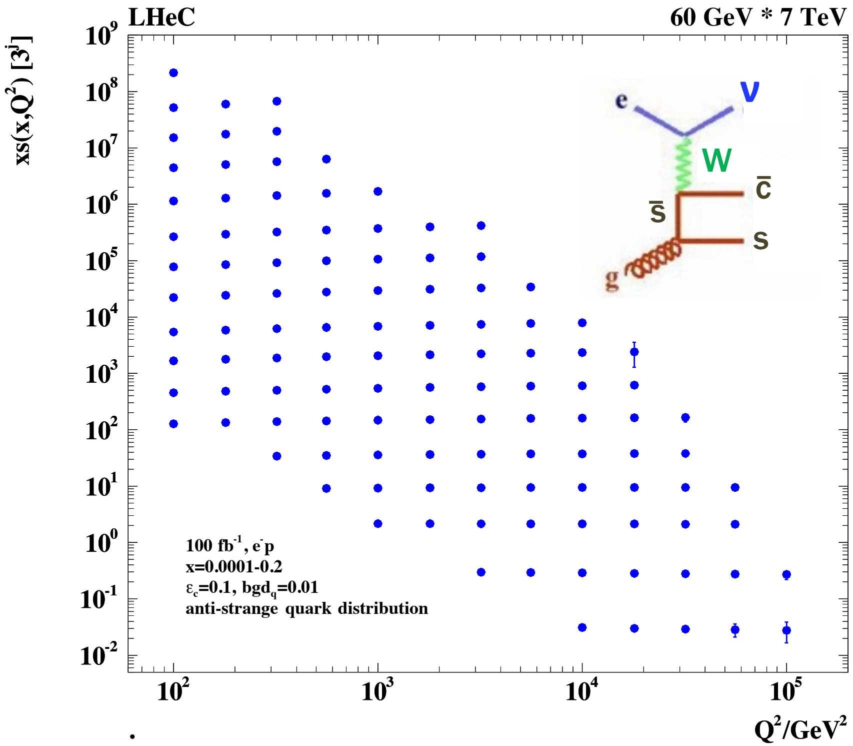
Strange, c, b

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

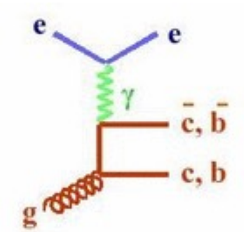


➜ **LHeC:** direct sensitivity via charm tagging in Ws→c

(x,Q²) mapping of strange density for first time

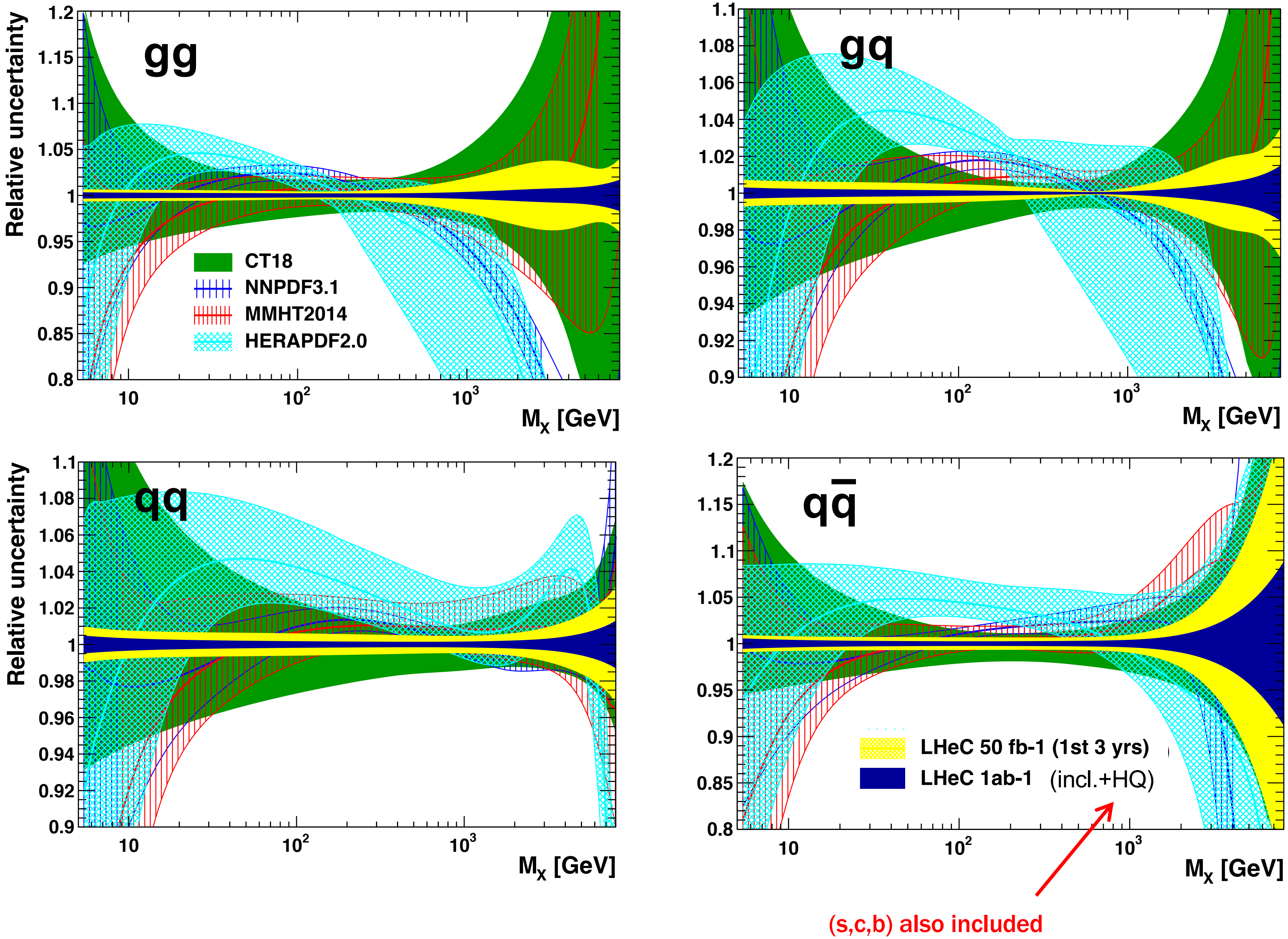


- **c, b:** enormously extended range and much improved precision c.f. HERA



- **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 bb̄ → A

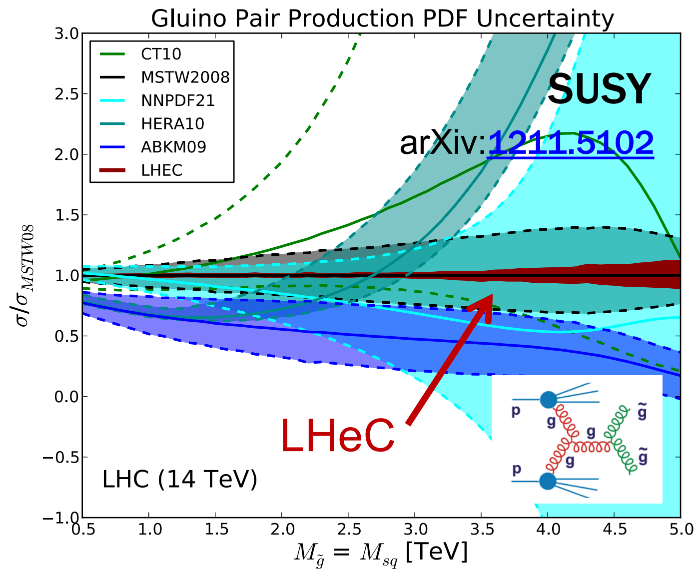
PDF luminosities @ 14 TeV

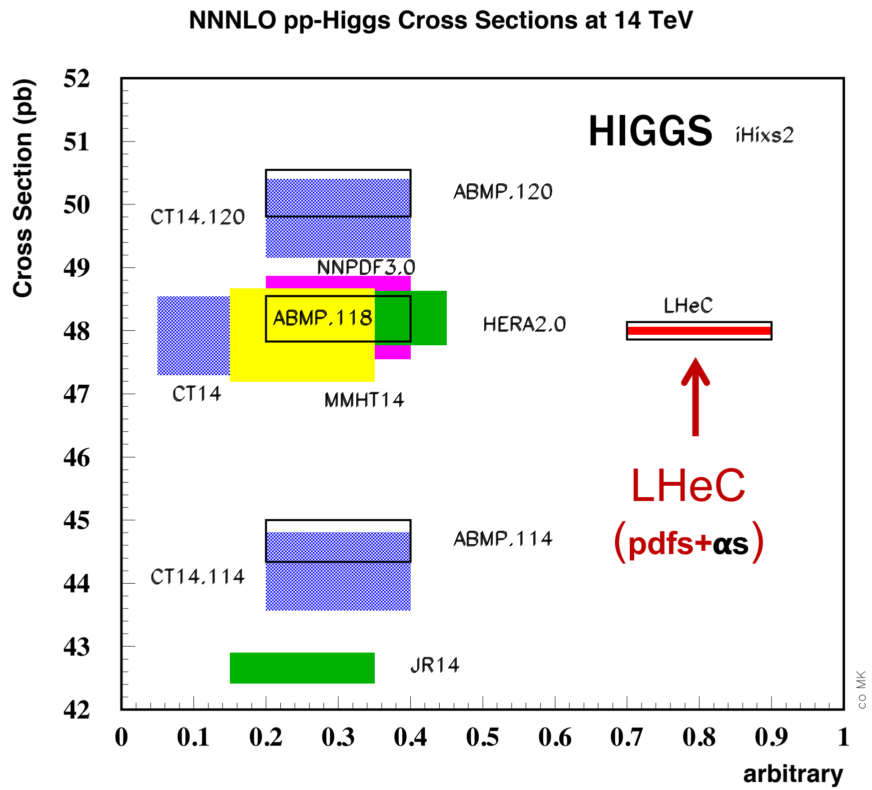


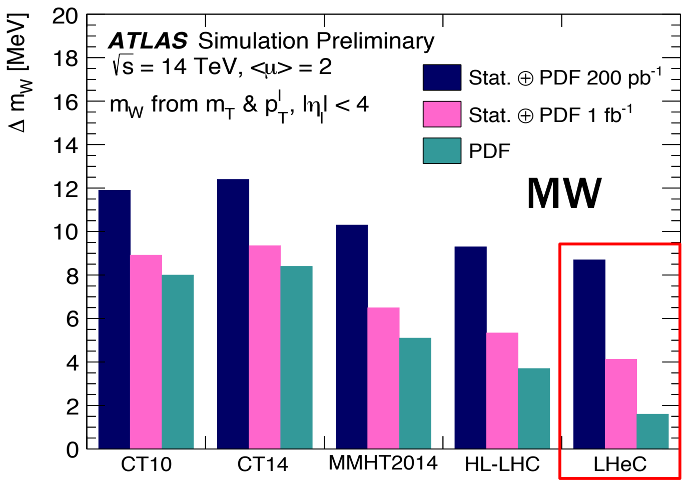
Empowering the LHC

arXiv:2007.14491
arXiv:1902.04070

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



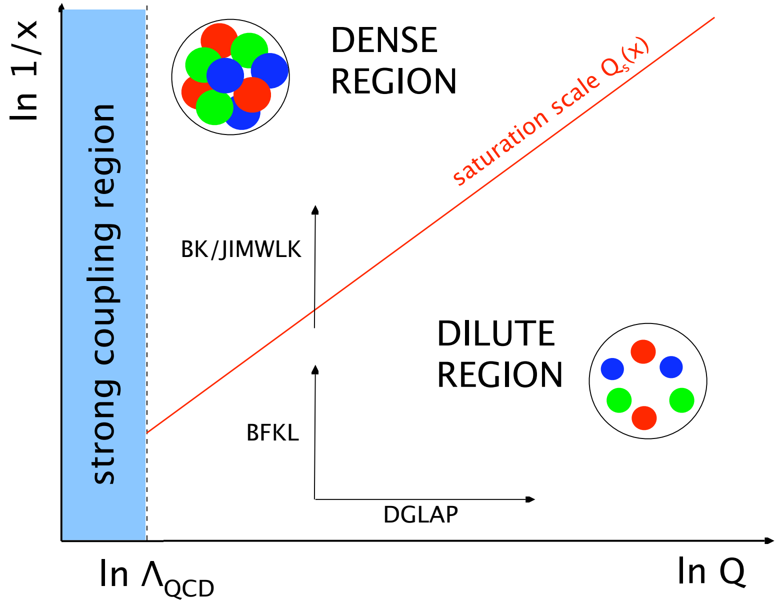




CONTACT INTERACTIONS: $\mathcal{L}_{\rm CI} = \frac{g^2}{\Lambda^2}\eta_{ij}(\bar{q}_i\gamma_\mu q_i)(\bar{\ell}_i\gamma^\mu\ell_i)$

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

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

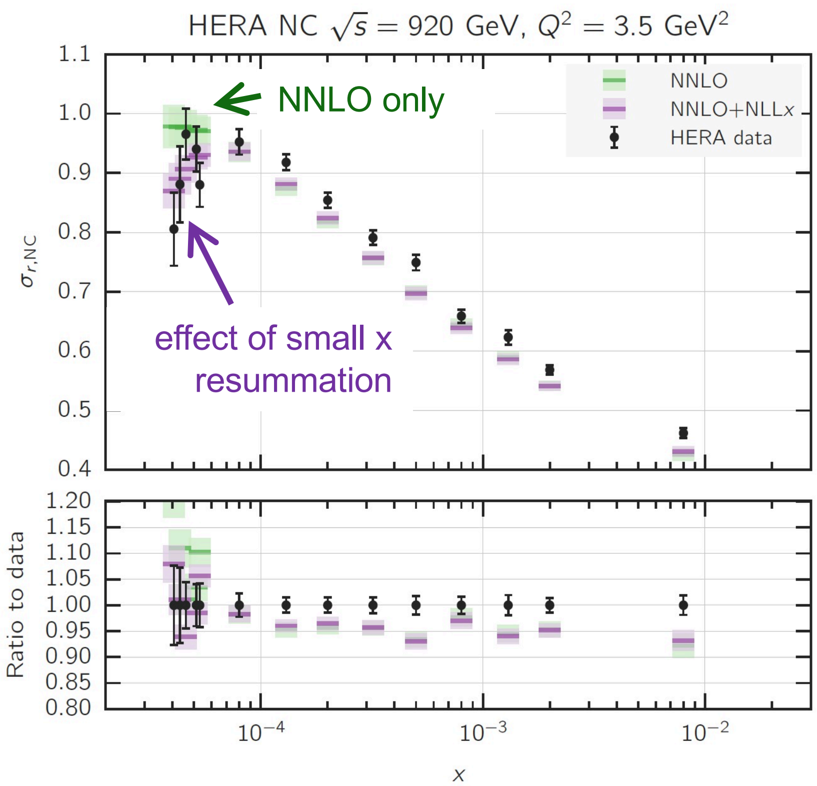
$\tau = \frac{Q^2}{s}$	Higgs	Z, W	low mass DY	$c\bar{c}$
LHC (13 TeV)	10^{-4}	5×10^{-5}	$\sim 10^{-6}$	$\sim 10^{-7}$
FCC-hh (100 TeV)	1.5×10^{-6}	8×10^{-7}	$\sim 10^{-8}$	$\sim 10^{-9}$

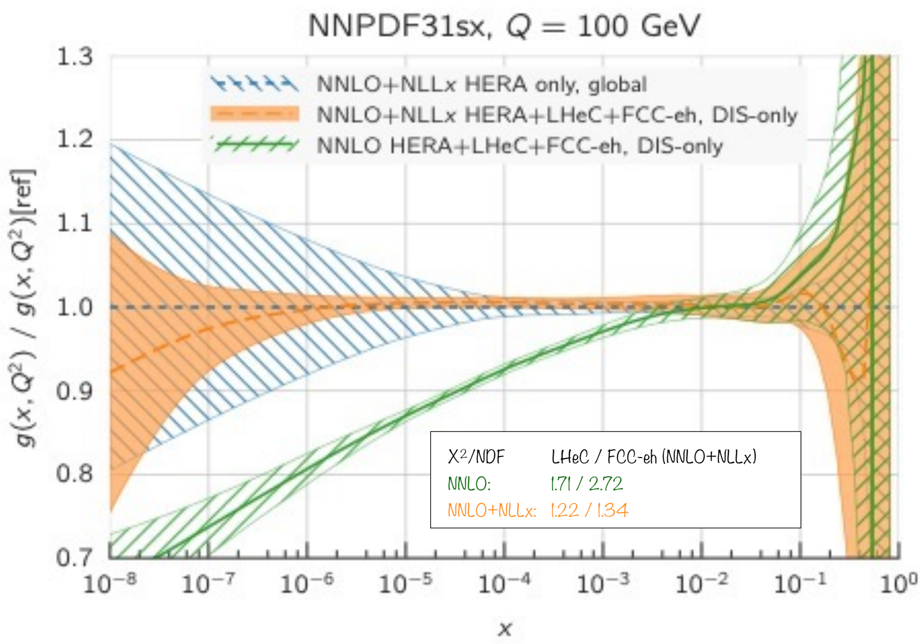
(note: typical values $x_1, x_2 \sim \sqrt{\tau}$)

central rapidity ↑

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

Novel small x dynamics: resummation





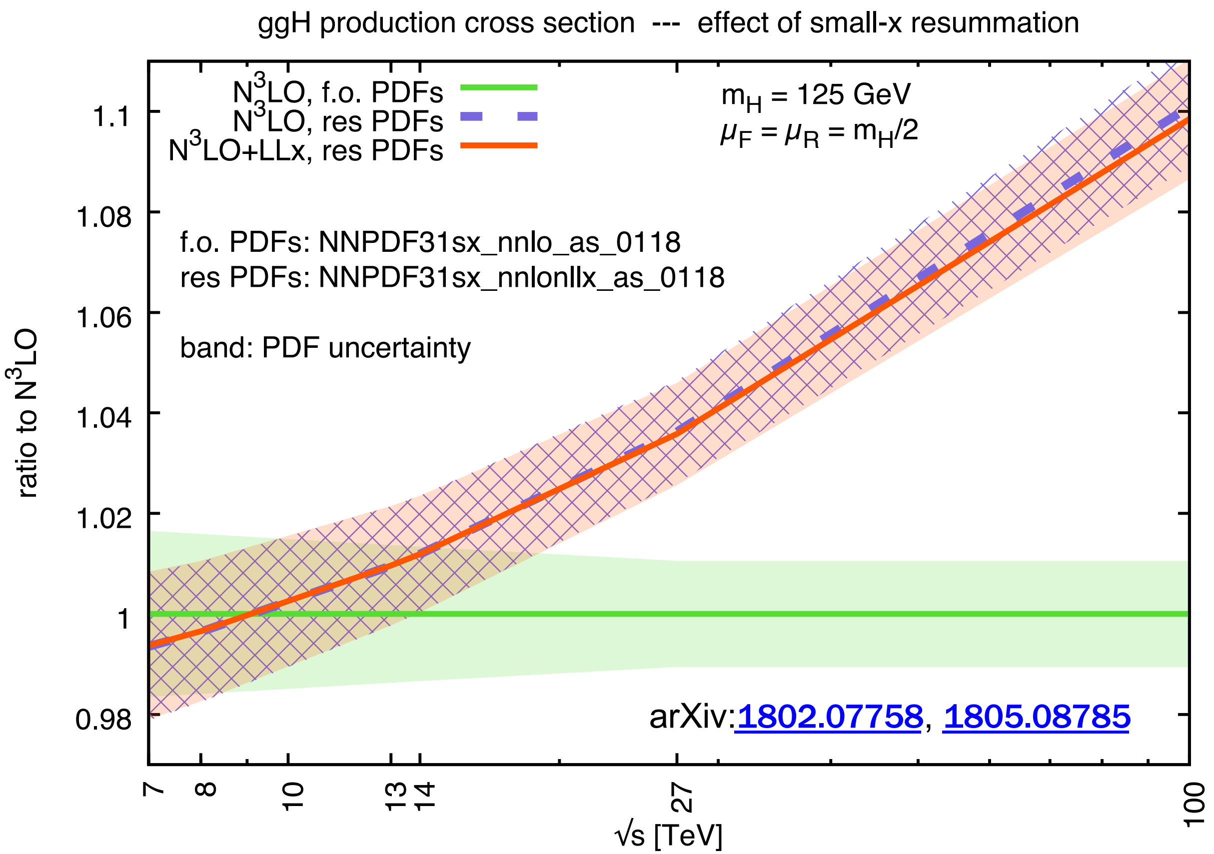
- recent evidence for onset of BFKL dynamics in HERA inclusive data,
- arXiv:1710.05935; 1802.00064

(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!

Impact on pp phenomenlogy

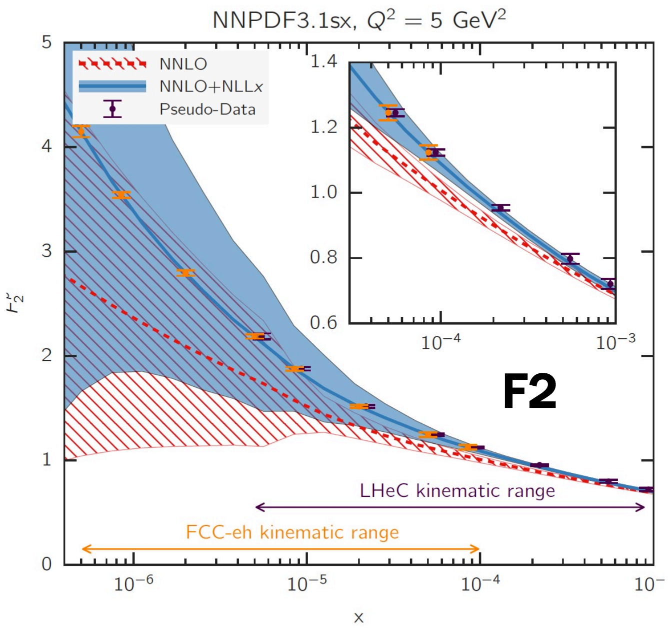


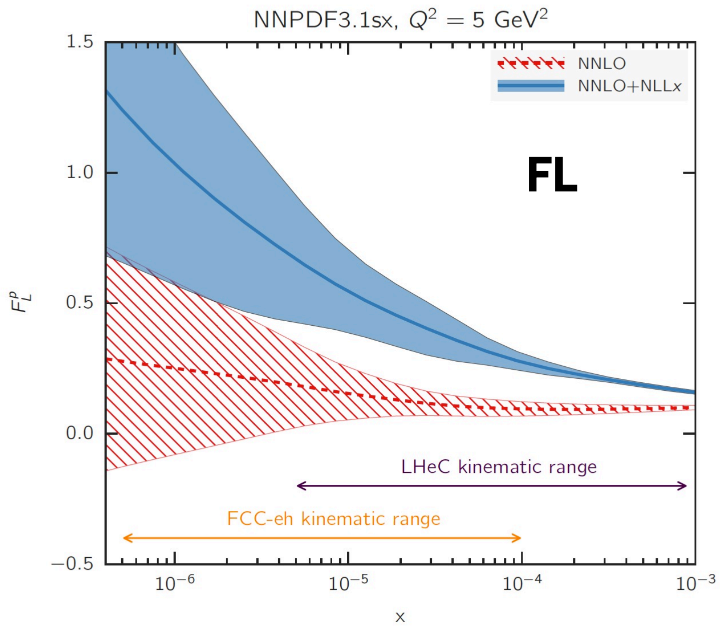
- effect of small x resummation on gg→H cross section for LHC, HE-LHC, FCC
- significant impact, especially at ultra low x values probed at FCC

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

arXiv:1710.05935

LHeC and FCC-eh sensitivity to small x



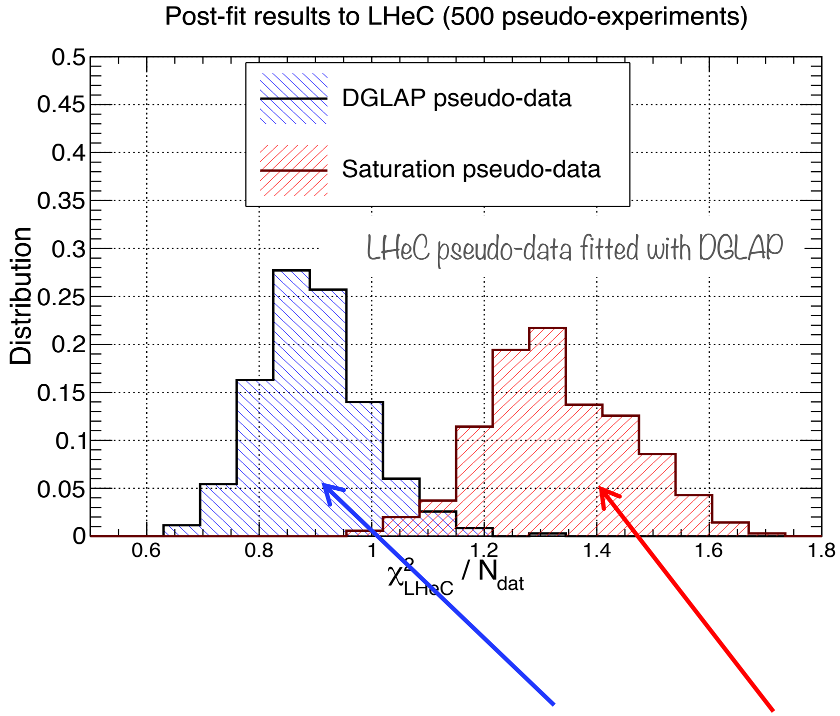


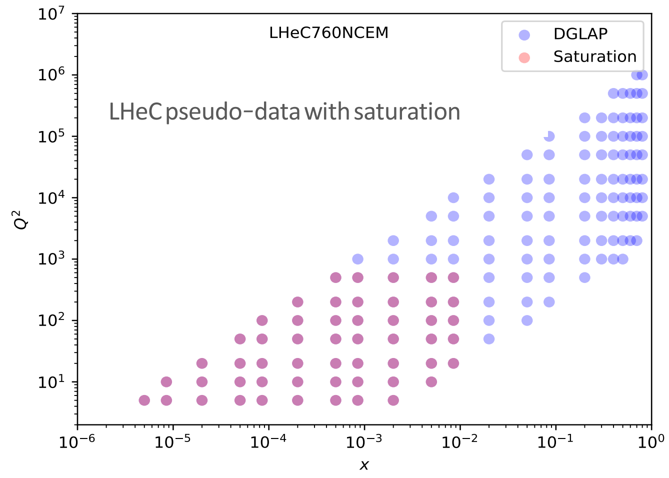
NC cross section: $\sigma_{r,\mathrm{NC}} = F_2(x,Q^2) - \frac{y^2}{1+(1-y)^2} F_L(x,Q^2)$ $\quad y = \frac{Q^2}{x\,s}$

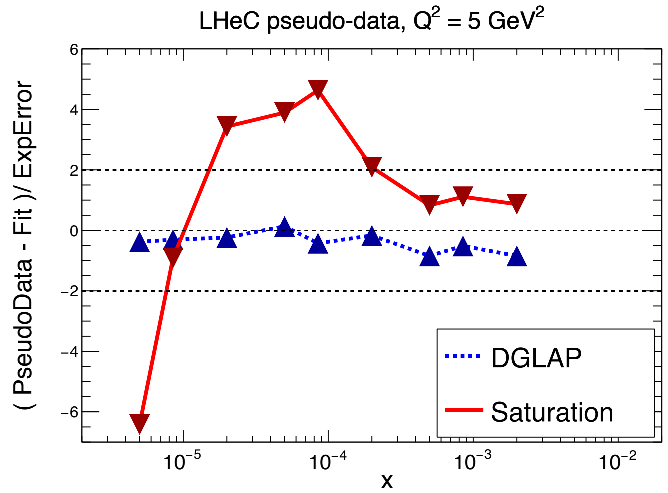
- LHeC and FCC-eh have unprecedented kinematic reach to **small x**; very large sensitivity and discriminatory power to pin down details of **small x QCD dynamics**
- measurement of FL has a significant role to play, arXiv:1802.04317

Novel dynamics at small x: saturation

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

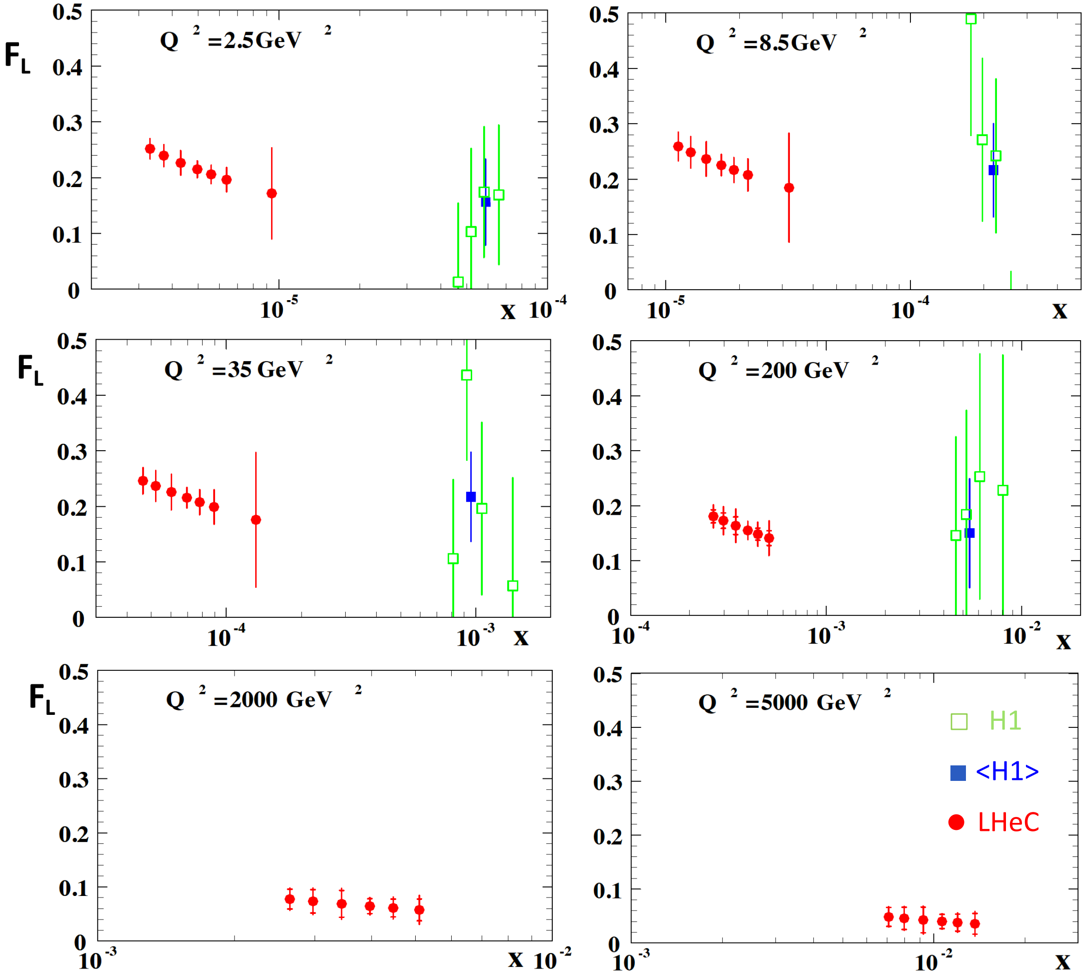






- LHeC can distinguish between **DGLAP** and **saturation**
- **possible to identify saturation by distortions in pulls ➔**
- large lever arm in Q2 is crucial; fit cannot absorb a non-DGLAP Q2 dependence

Longitudinal Structure Function



simulated for:

Ep = 7 TeV and

Ee = 60, 30, 20 GeV

integrated luminosity:

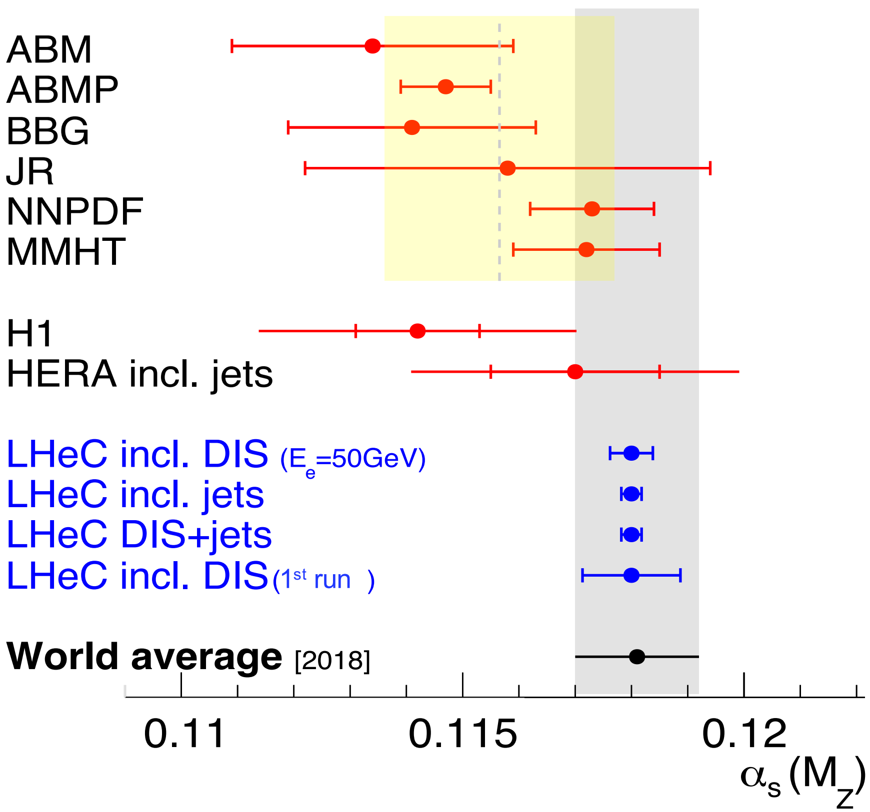
10, 1, 1 fb^{-1}

measurement dominated by systematics

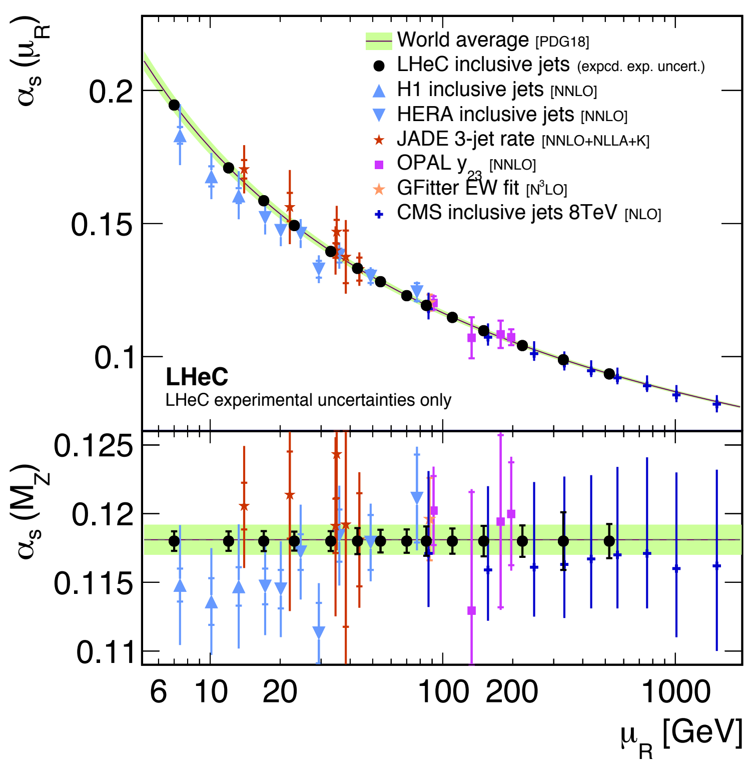
- **simultaneous measurement of F2 and FL is clean way to pin down dynamics at small x**

Strong Coupling

αs determinations at NNLO QCD:



fit to subsets of ep jet data:



- αs is least known coupling constant
- current state-of-the-art: $\delta\alpha_s/\alpha_s = \mathcal{O}(1\%)$
- achievable precision at **LHeC**: $\mathcal{O}(0.1\%)$

- αs running testable over two orders of magnitude in scale
- QCD theory uncerts. will be limiting factor

Summary

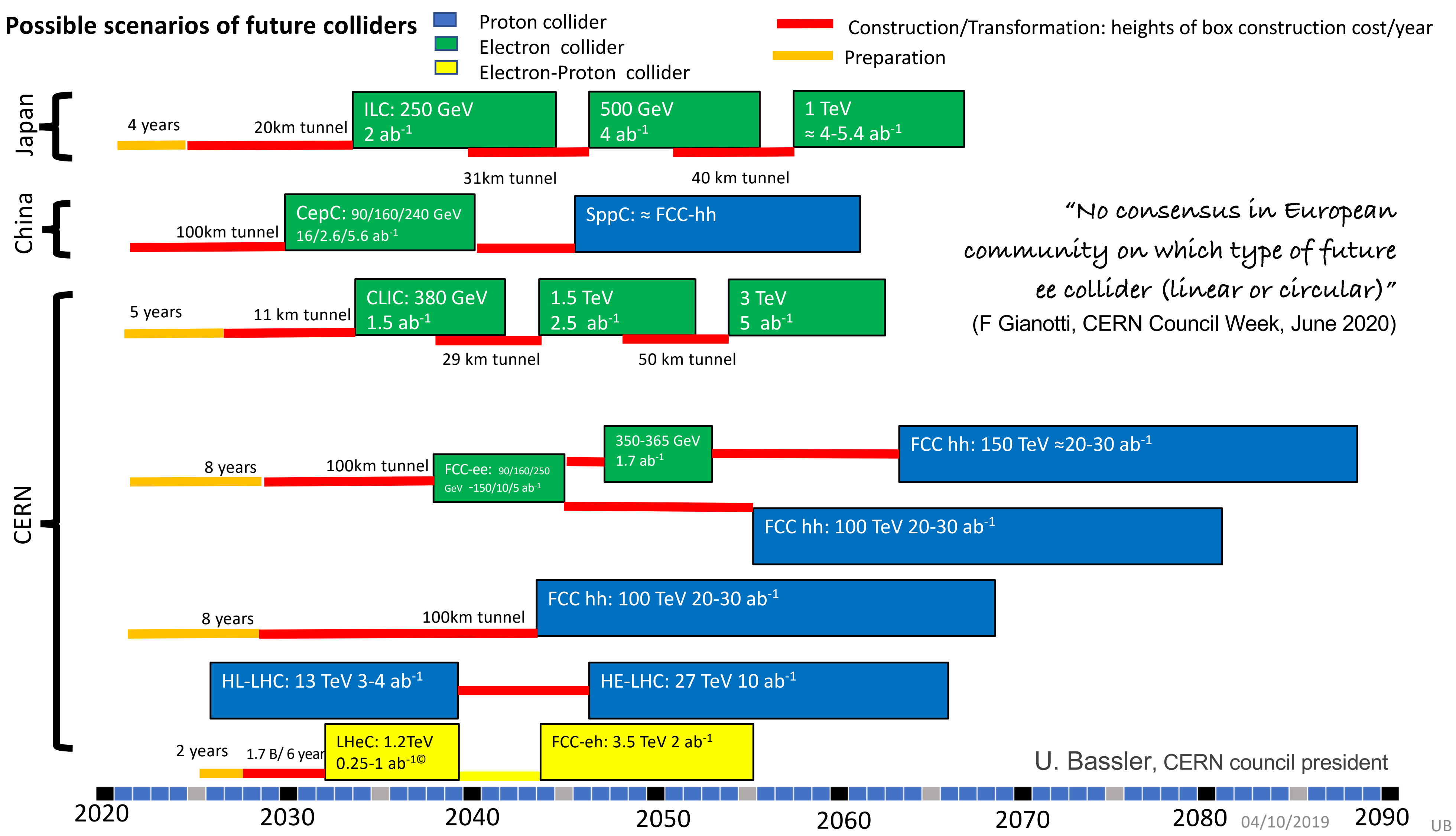
- energy frontier **electron-proton colliders** essential for full exploitation of current and future hadron colliders (Higgs, BSM, electroweak, …)
- **external precision pdf input**; complete q,g unfolding, high luminosity x ⟶ 1, s, c, b, (t); N3LO; small x; strong coupling to permille precision; …

- LHeC CDR update (arXiv:**2007.14491**) summarises wealth of new and updated studies
- enormously rich physics programme both in **own right**, and for **transformation of proton-proton machines** into precision facilities

- **all critical pdf information can be obtained early** (~ **50** fb^{-1} ≡ ×**50** HERA), in parallel with HL-LHC operation
- unprecedented access to novel kinematic regime, with **unique potential to explore small x phenomena**
- **αs** to **permille experimental precision** also achievable early, with use of inclusive DIS and/or jets

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

Extras



"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

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.

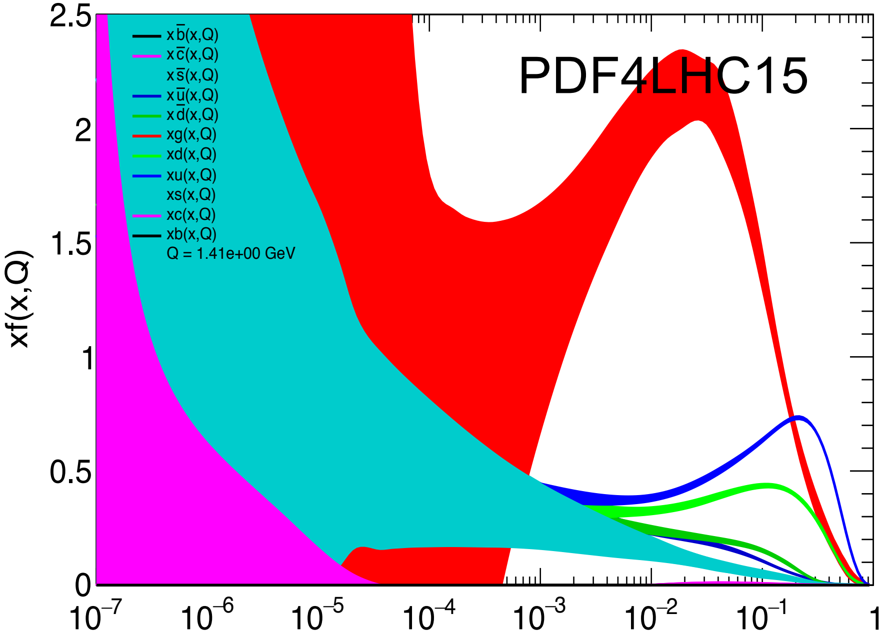
LHeC pdf parameterisation

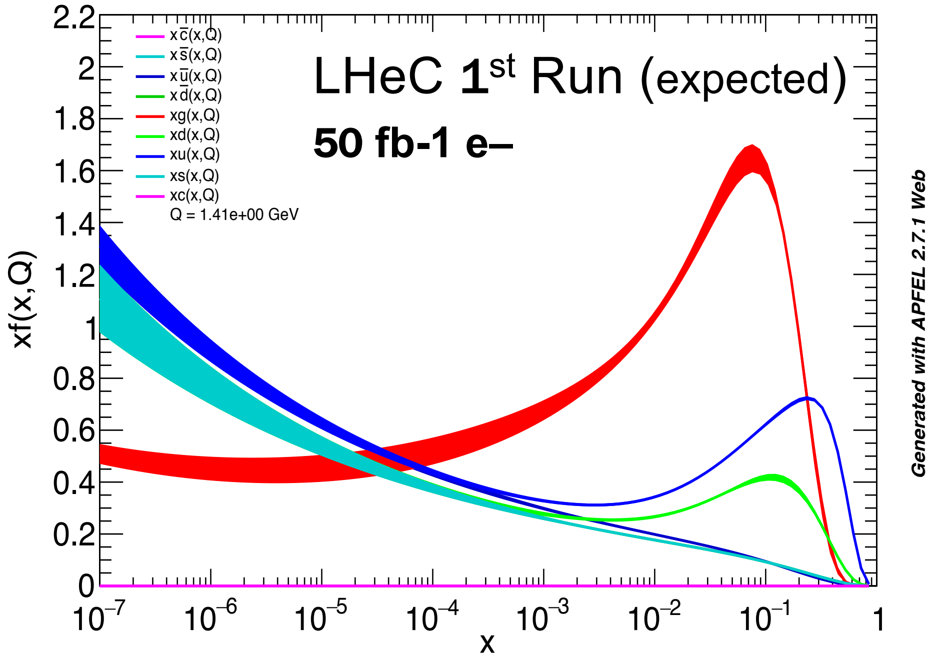
- QCD fit ansatz based on HERAPDF2.0, with following differences:
- no requirement that ubar=dbar at small x
- no negative gluon term (only for the aesthetics of ratio plots – it has been checked that this does not impact size of projected uncertainties)

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

- **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

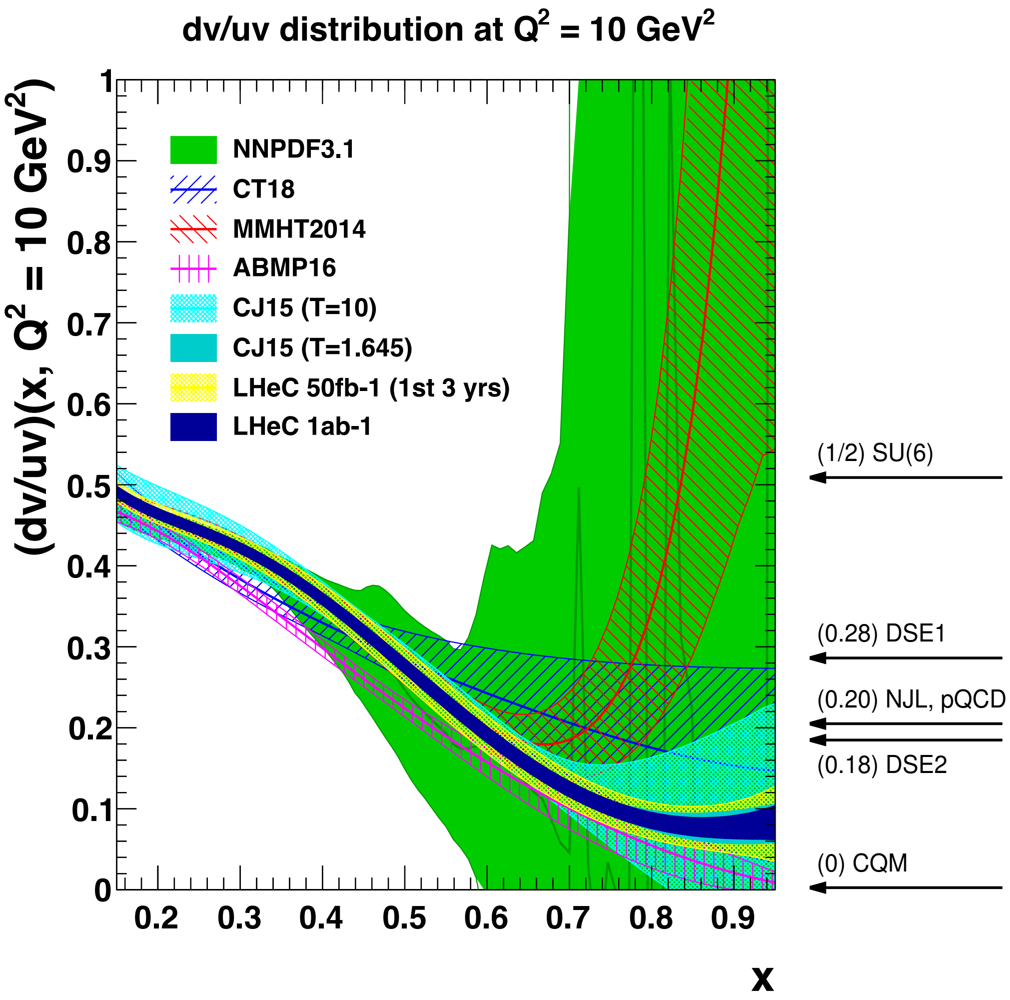




situation today → after 1st LHeC Run

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

d/u at large x

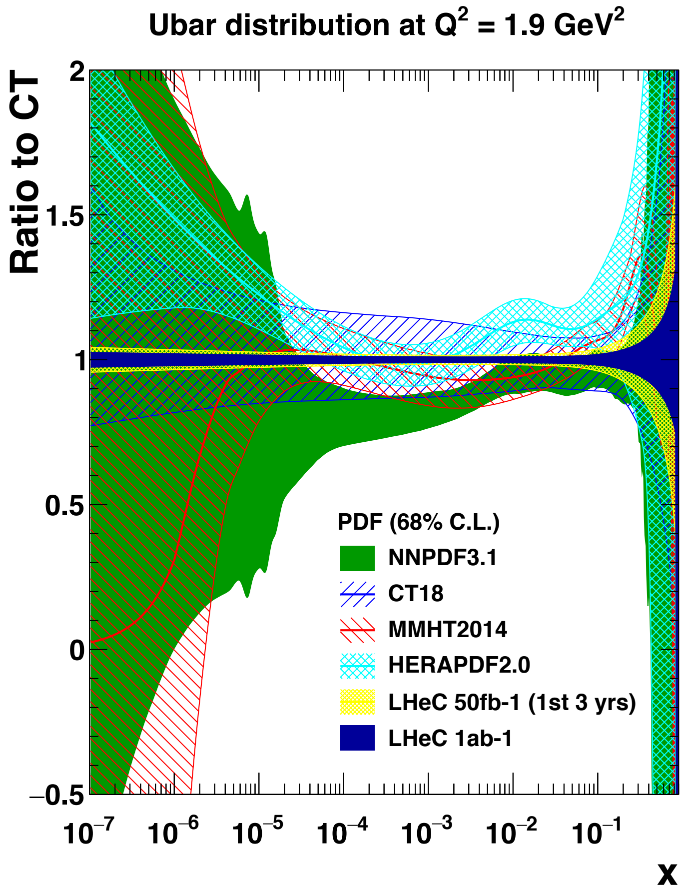


d/u essentially unknown at large x

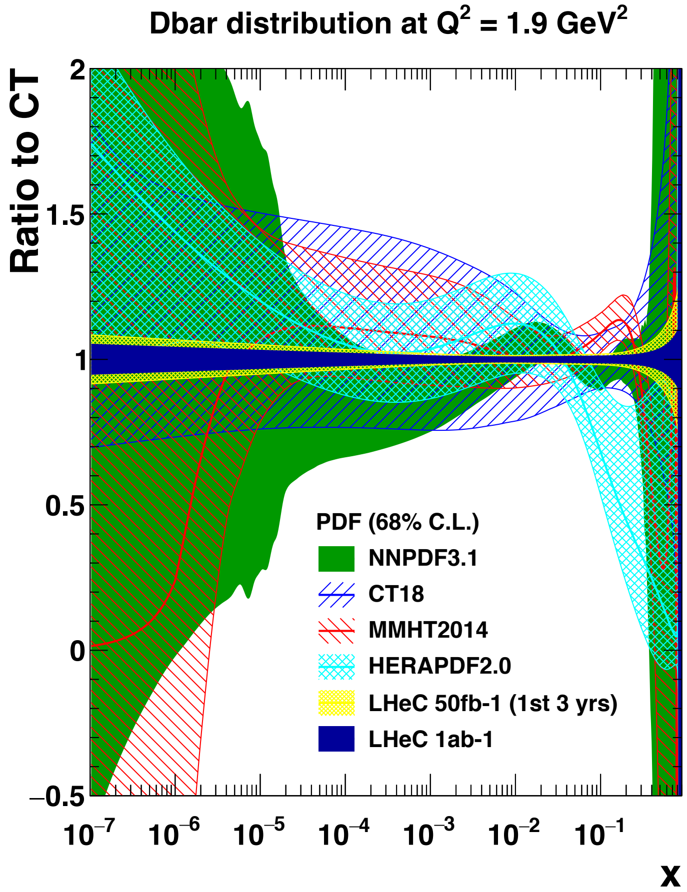
no predictive power from current pdfs;
conflicting theory pictures;
data inconclusive, large nuclear uncertainties

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

Sea quarks

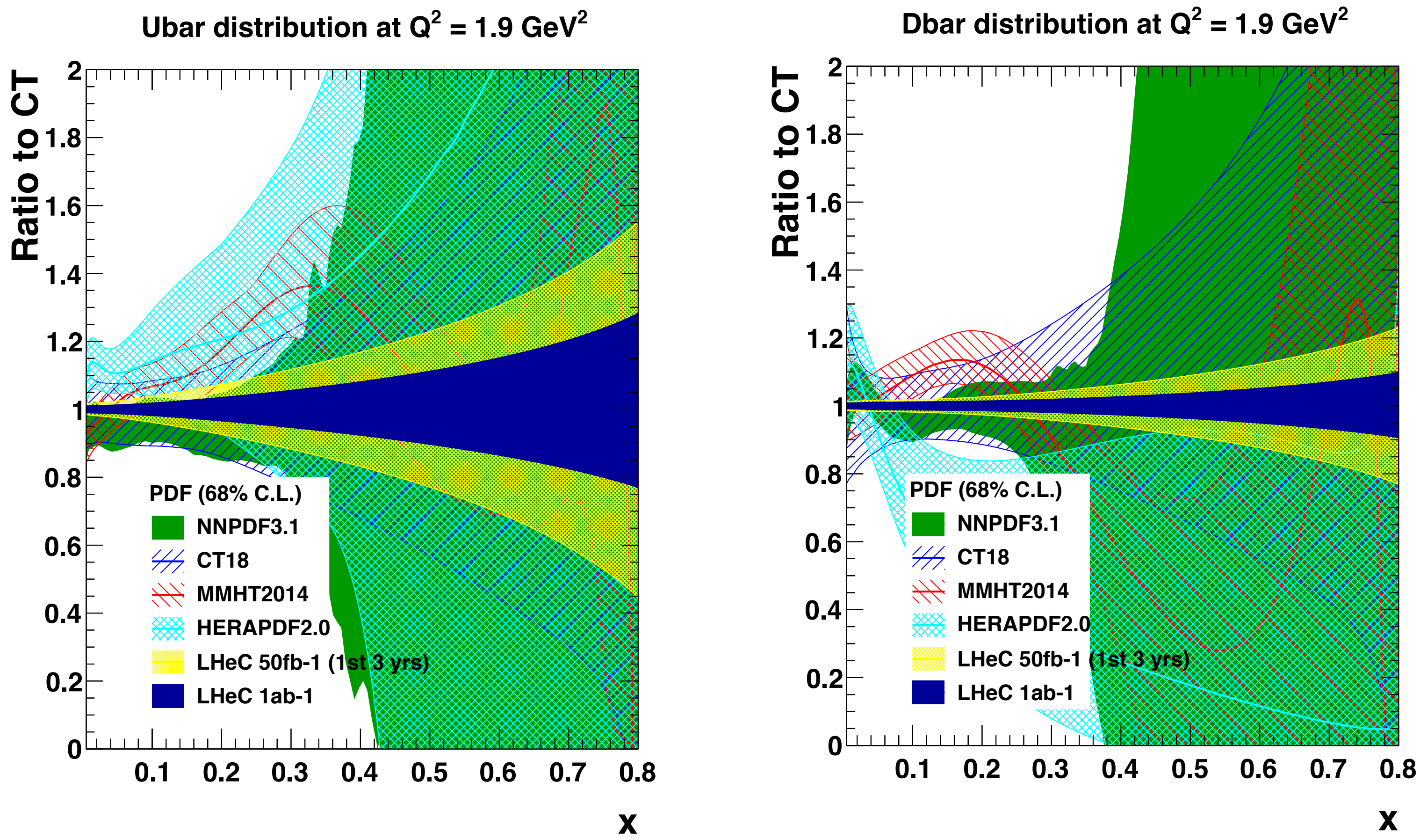


Ubar distribution at Q^2 = 1.9 GeV^2
Ratio to CT
2
1.5
1
0.5
0
−0.5
10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1}
x
PDF (68% C.L.)
NNPDF3.1
CT18
MMHT2014
HERAPDF2.0
LHeC 50fb-1 (1st 3 yrs)
LHeC 1ab-1



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
MMHT2014
HERAPDF2.0
LHeC 50fb-1 (1st 3 yrs)
LHeC 1ab-1

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.)
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
1.8
1.6
1.4
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0.8
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0.2
0
0.1
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0.5
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x
PDF (68% C.L.)
NNPDF3.1
CT18
MMHT2014
HERAPDF2.0
LHeC 50fb-1 (1st 3 yrs)
LHeC 1ab-1

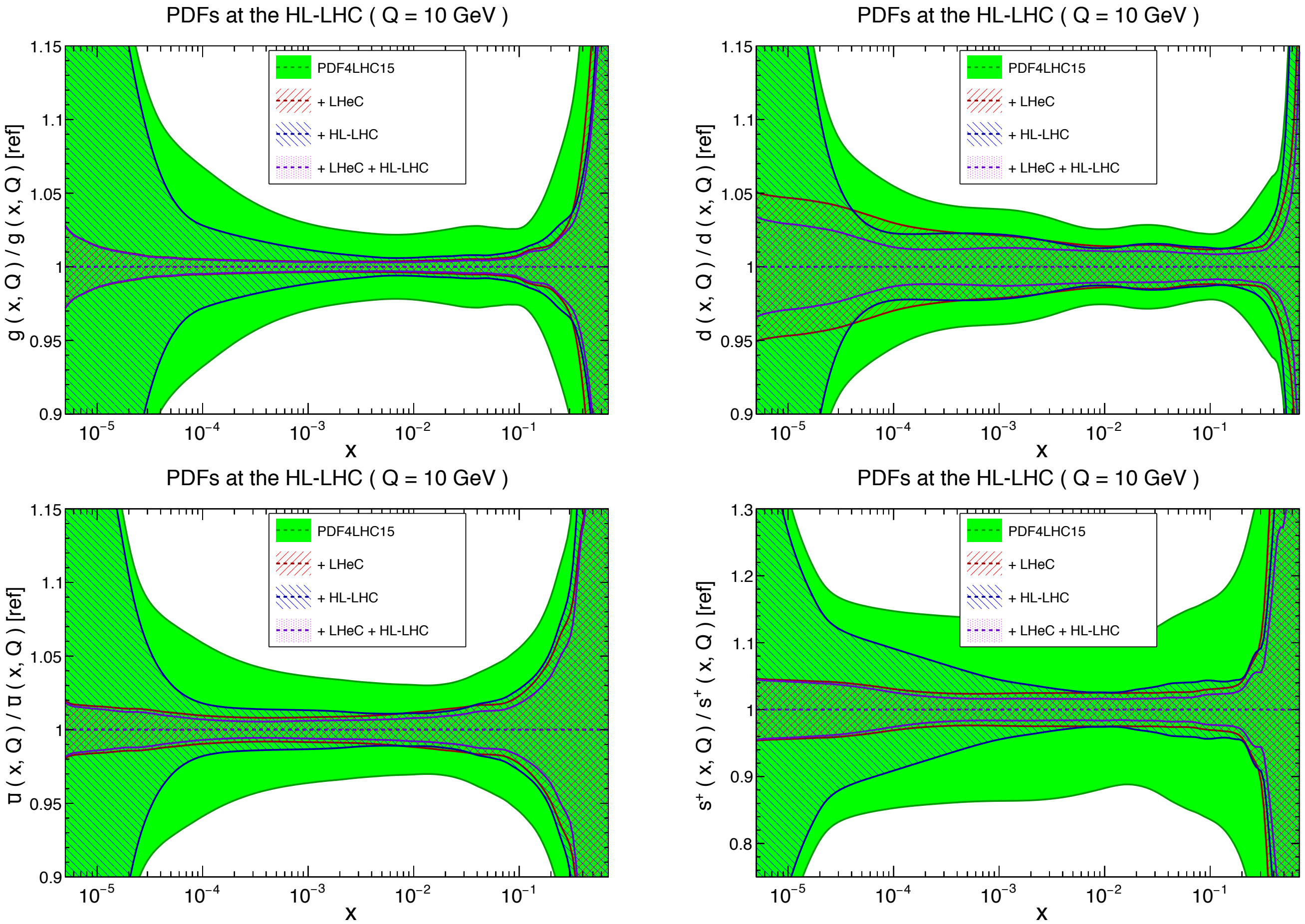


Figure 9.9: Impact of LHeC on the 1-σ relative PDF uncertainties of the gluon, down quark, anti–up quark and strangeness distributions, with respect to the PDF4LHC15 baseline set (green band). Results for the LHeC (red), the HL-LHC (blue) and their combination (violet) are shown.

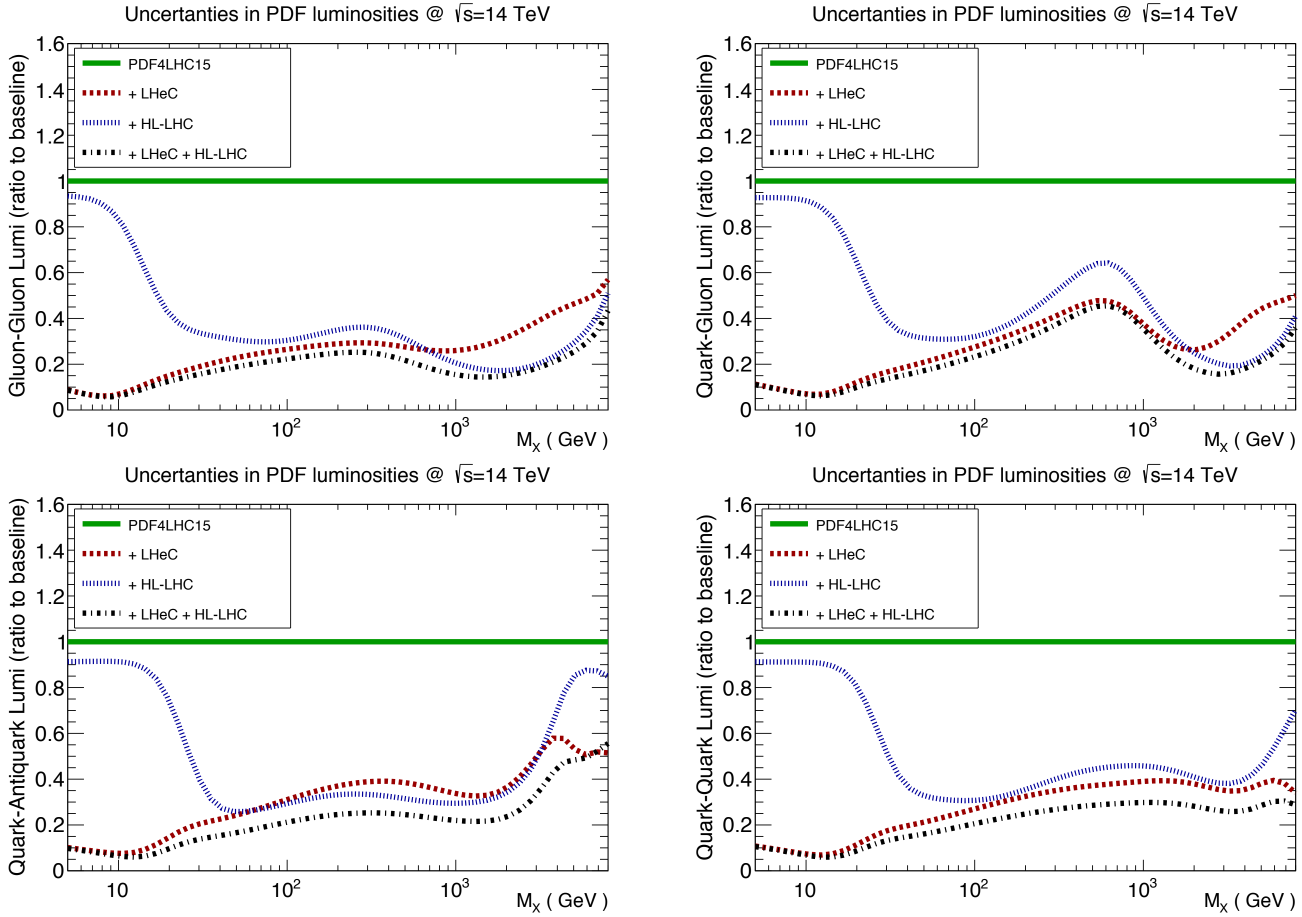
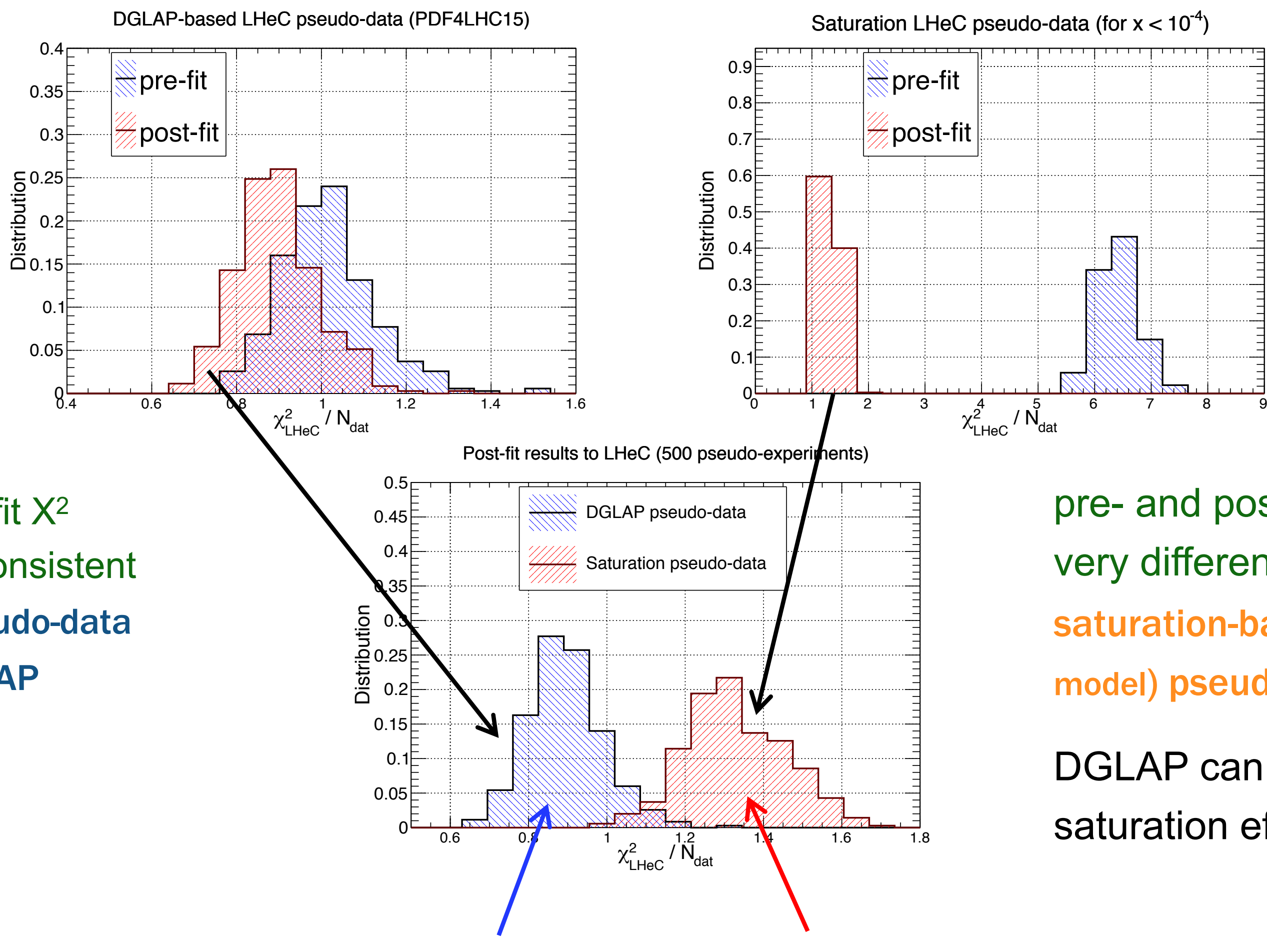


Figure 9.10: Impact of LHeC, HL-LHC and combined LHeC + HL-LHC pseudodata on the uncertainties of the gluon-gluon, quark-gluon, quark-antiquark and quark-quark luminosities, with respect to the PDF4LHC15 baseline set. In this comparison we display the relative reduction of the PDF uncertainty in the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

Novel dynamics at small x: saturation



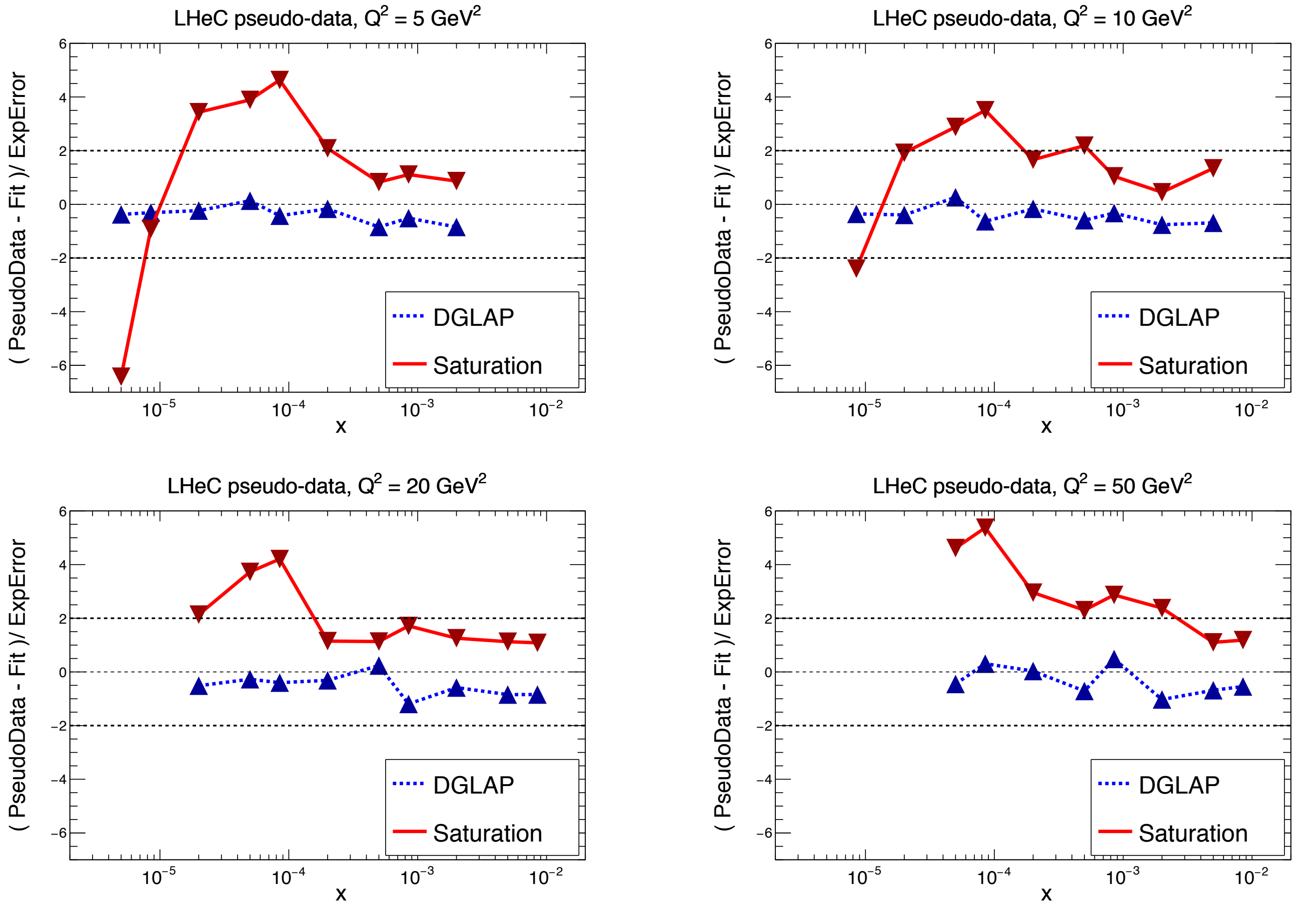
pre- and post-fit X^2 distributions consistent for **DGLAP pseudo-data** fitted with **DGLAP**

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

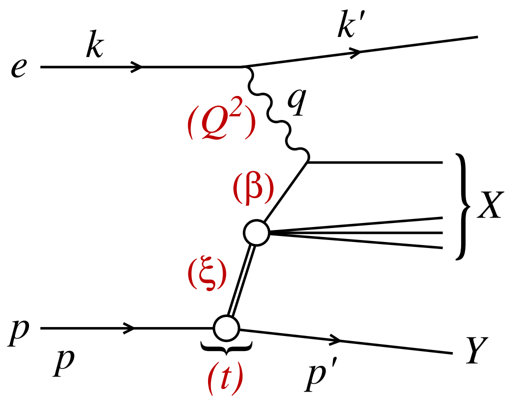
LHeC can distinguish between **DGLAP** and **saturation**

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

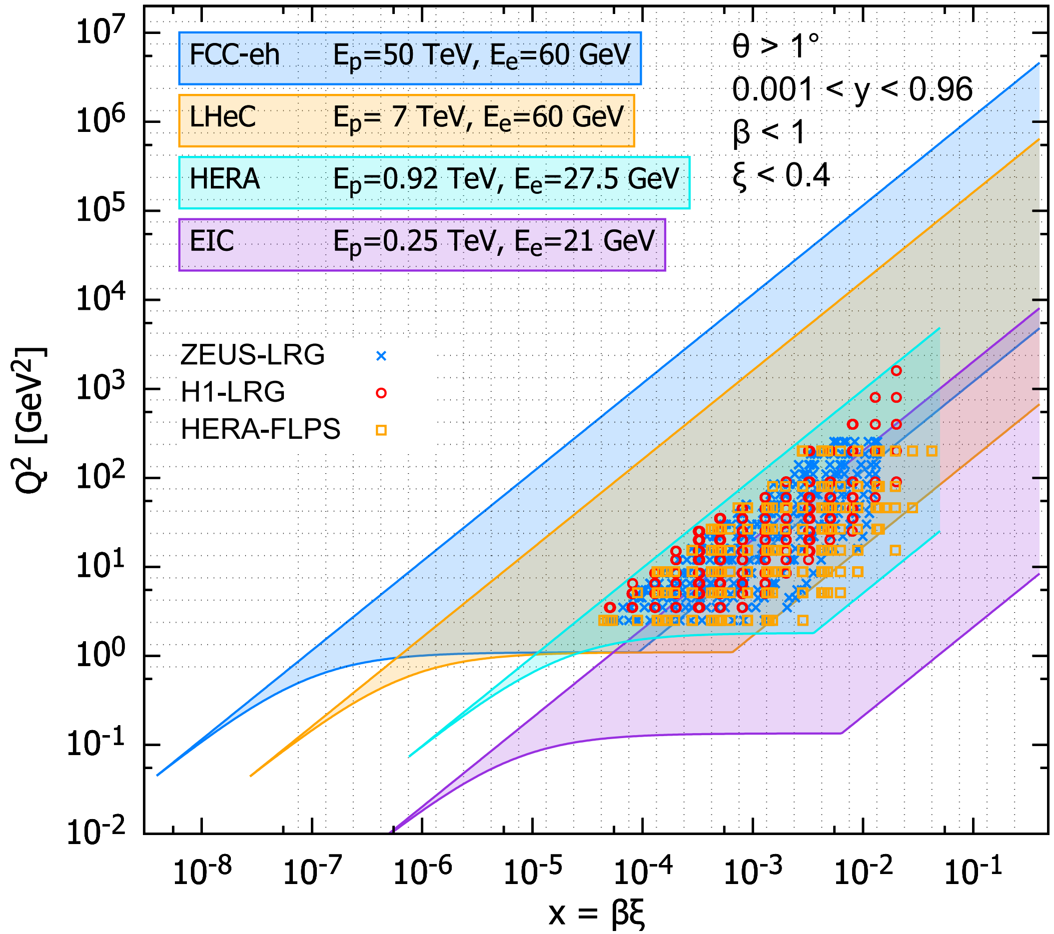
$$\beta = \frac{Q^2}{Q^2 + M_X^2 - t}$$

4-momentum transfer squared

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

Bjorken x relation

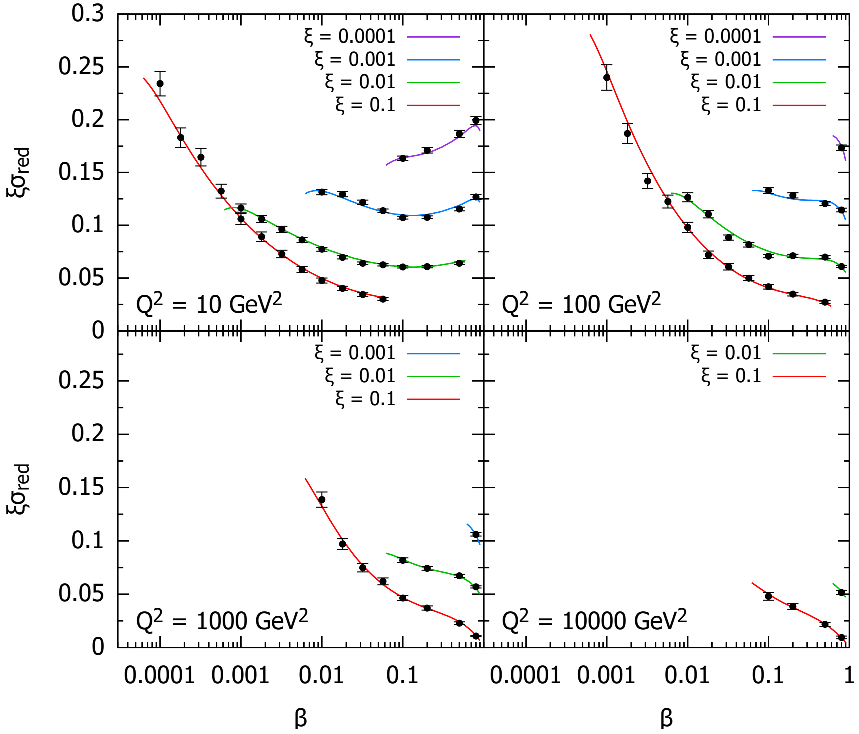
$$x_{Bj} = x_{IP}\beta$$



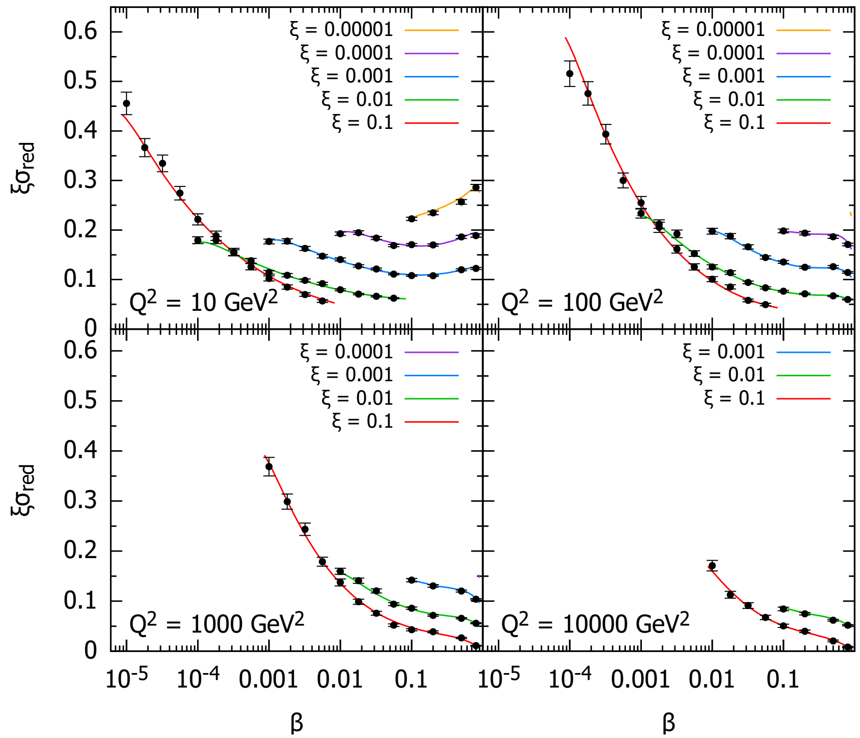
- inclusive diffraction, constraints on diffractive pdfs, new final states in diffraction, also EW exchange

Diffractive σ_{red} pseudo-data

LHeC



FCC-eh

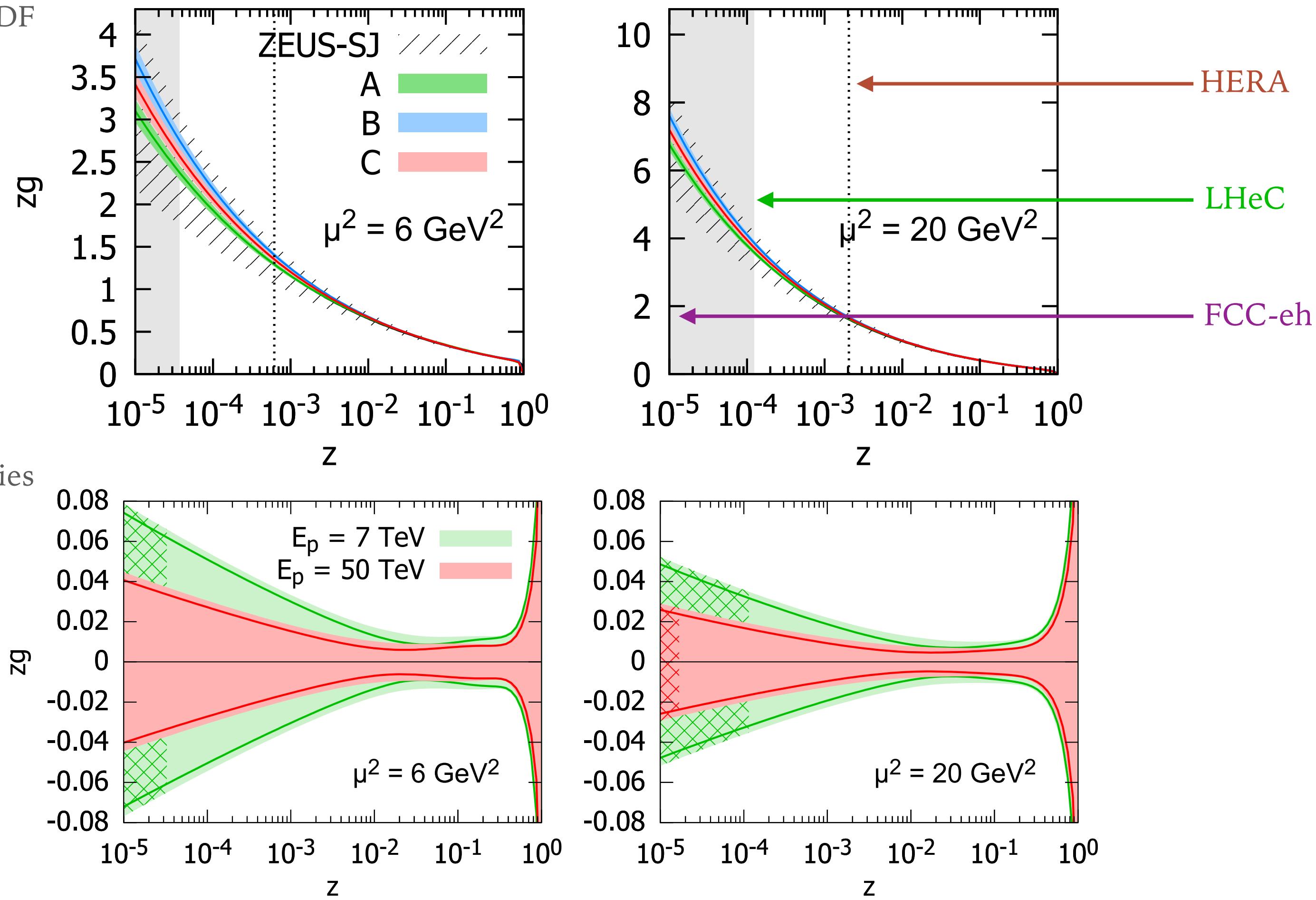


- potential for high quality data for inclusive diffraction at **LHeC/FCC-eh** (only small subset of simulated data shown)
- prospects for precise extraction of **diffractive pdfs**, **tests of factorisation breaking** (soft and collinear)

Diffractive PDFs from simulation

Diffractive gluon PDF

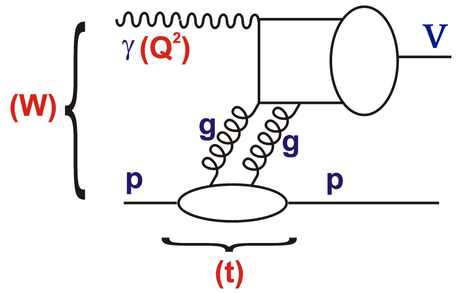
Relative uncertainties

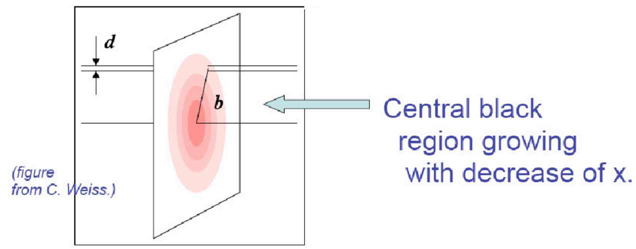


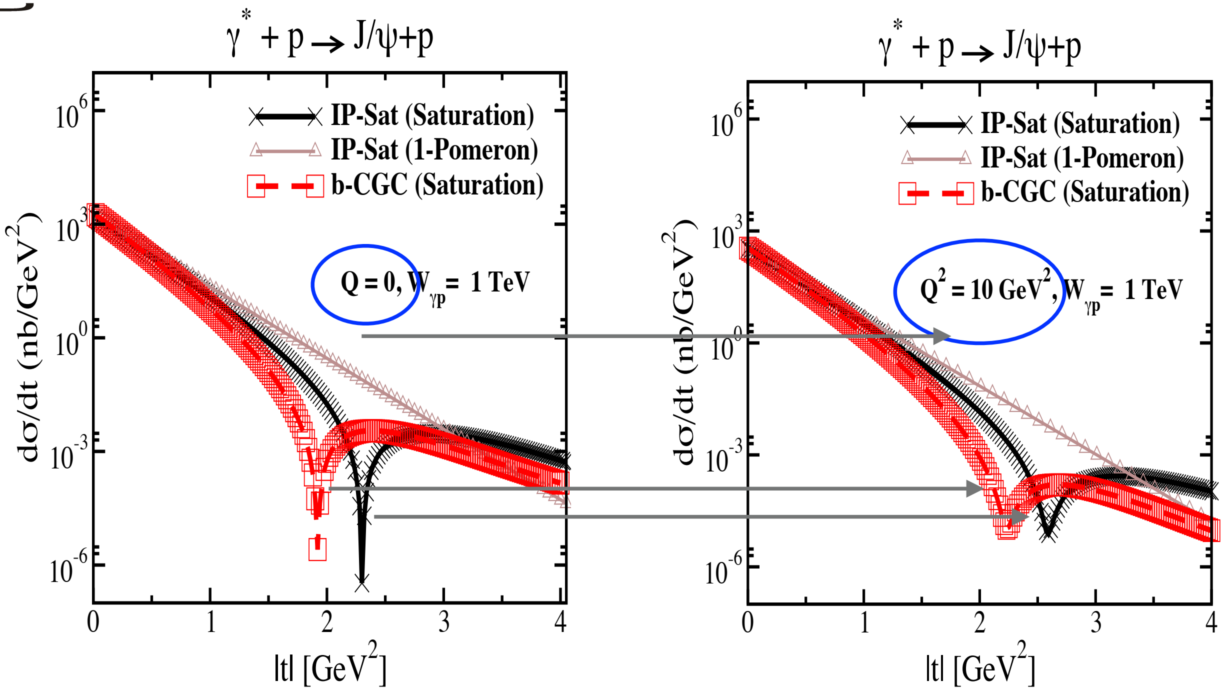
Reduction of DPDF uncertainty by factor 5 — 7 at LHeC and 10 — 15 at FCC-eh with inclusive data alone

Prospects for precise extraction of diffractive PDFs, tests of factorization breaking (collinear and soft)

Elastic diffraction of vector mesons







Advantage over UPC:

Q^2 dependence

- **one of the best processes to test for novel small x dynamics**

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