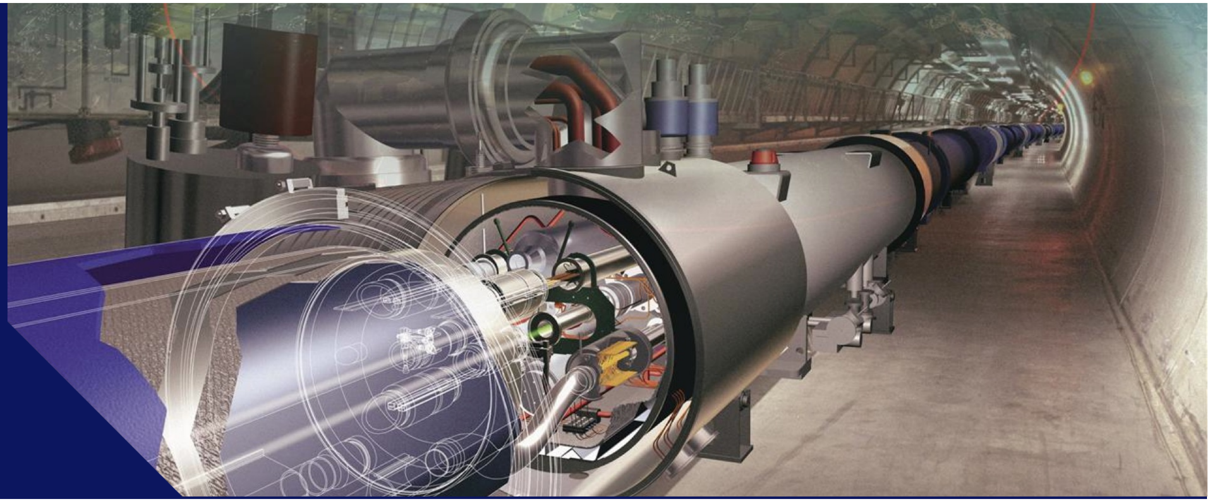
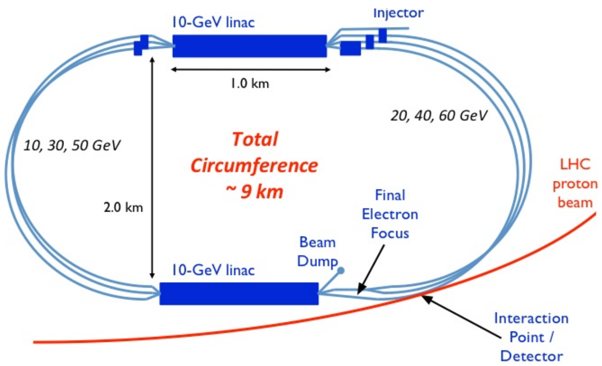
DIS 2023

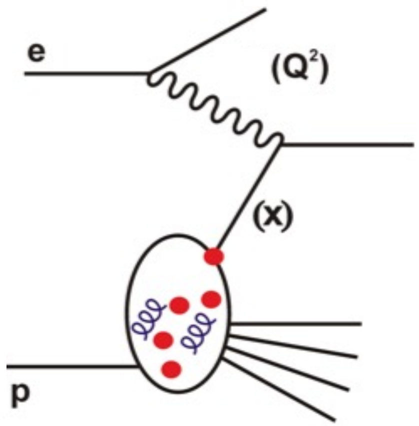
Michigan State University

27 – 31 March 2023



High energy QCD and eA collisions at the LHeC and FCC−eh





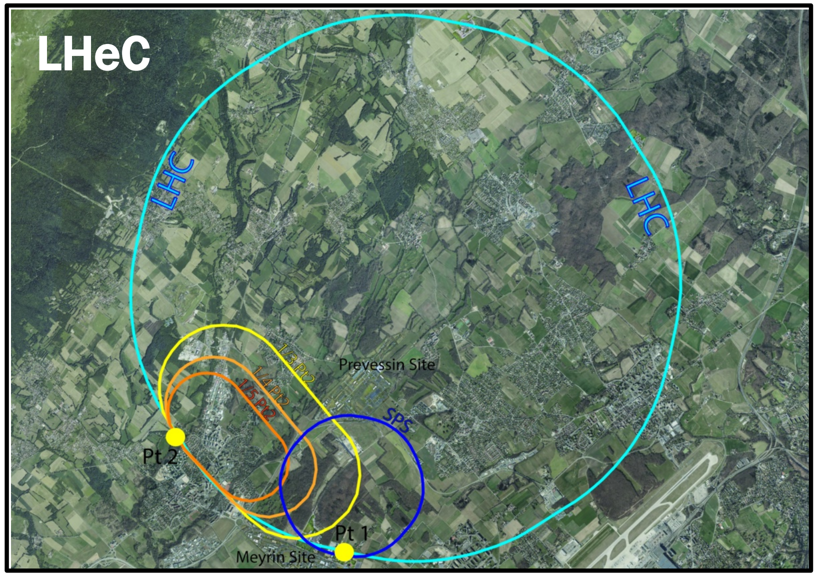
Claire Gwenlan,
Oxford

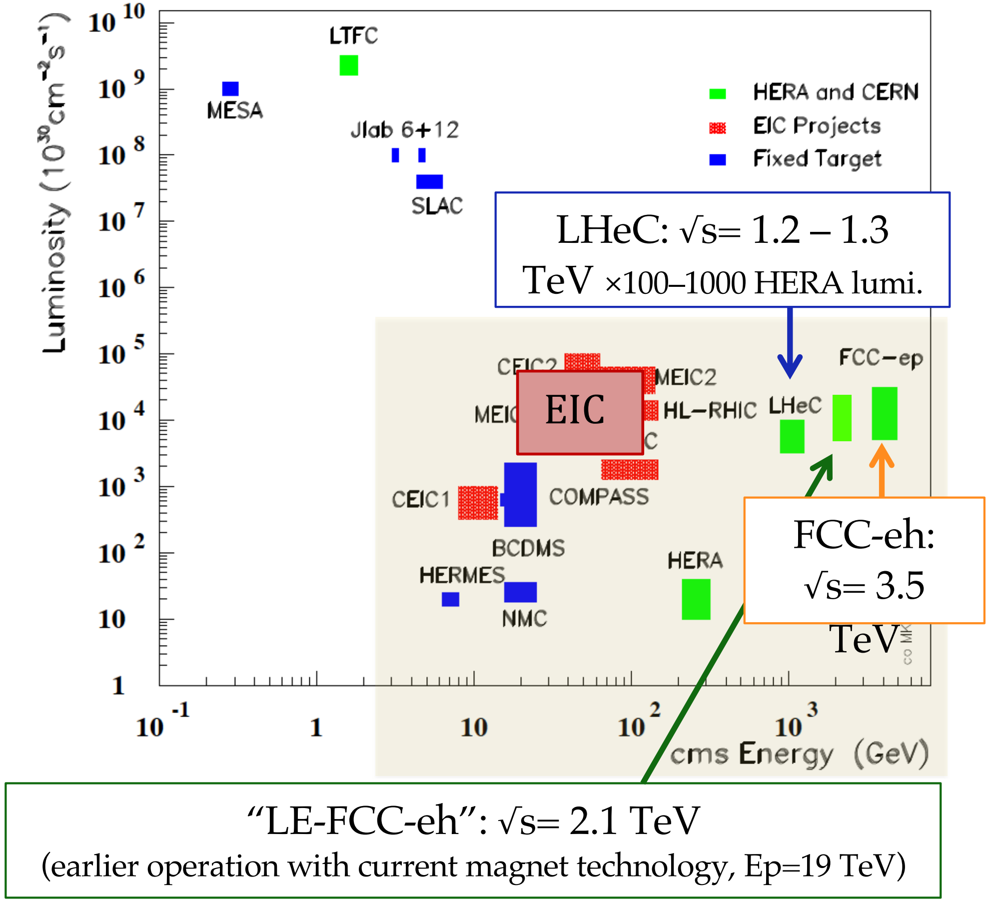
on behalf of the LHeC and FCC-eh study groups

LHeC PERLE FCC hh ee he CERN UNIVERSITY OF OXFORD

LHeC, FCC-eh and PERLE

CERN future colliders: arXiv:1810.13022





energy recovery LINAC (ERL)

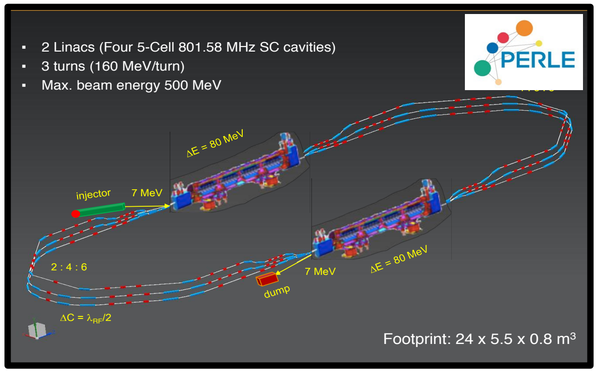
attached to HL-LHC (or FCC)

e beam: ⟶ **50** or **60** GeV

e pol.: P= **±0.8**

Lint ⟶ **1–2** ab^{-1} (1000× HERA!)

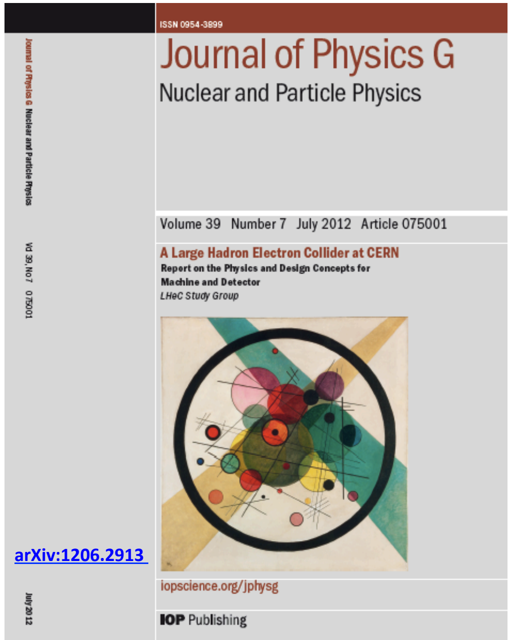
PERLE: international collaboration built to realise **500** MeV facility at Orsay, for development of ERL with LHeC conditions (arXiv:1705.08783)



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
arXiv:1206.2913
iopscience.org/jphysg
IOP Publishing

arXiv:[1206.2913]

Further selected references:

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

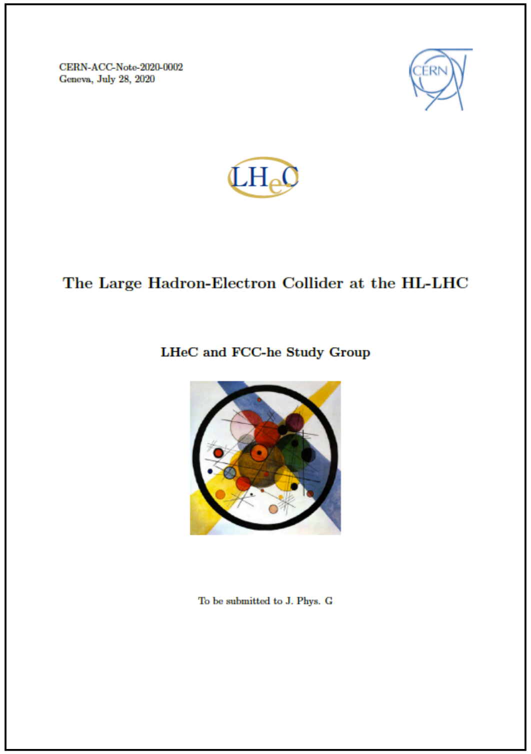
The Large Hadron Electron Collider
arXiv:1305.2090

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

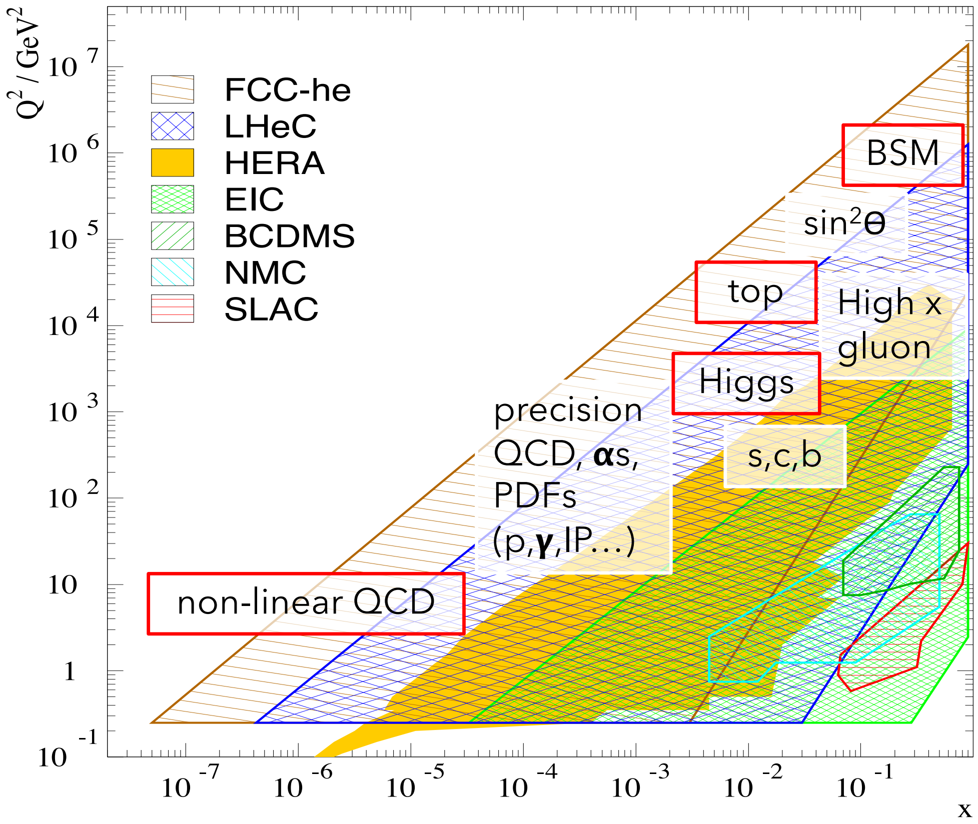

CERN-ACC-Note-2020-0002
Geneva, July 28, 2020
LHeC
The Large Hadron-Electron Collider at the HL-LHC
LHeC and FCC-he Study Group
To be submitted to J. Phys. G

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



- **DIS**: cleanest high-resolution microscope

opportunity for extraordinary increase in DIS kinematic reach

×**1000** increase in luminosity cf. HERA

clean experimental environment, fully constrained kinematics

sophisticated theoretical calculations

- **QCD precision physics and discovery**

empowering the HL-LHC and FCC

and with unprecedented access to **small x**

- **unique nuclear physics facility**

PLUS much more:

electroweak, t quark, Higgs, BSM, …

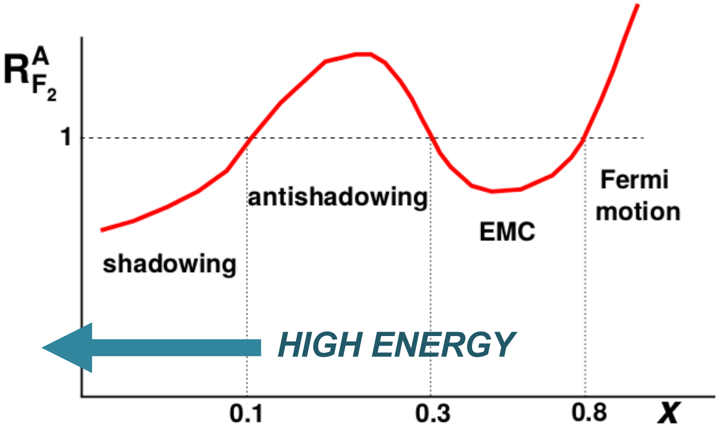
- other LHeC/FCC-eh talks in this conference (WG6):
- *P. Newman, **DETECTOR***, TUES 11:20
- *N. Armesto, **STATUS** and **CHALLENGES***, THUR 12:10
- *F. Giuli, **PDFs** and **αs***, THUR 16:50
- *A. Stasto, **DIFFRACTION***, THUR 17:10
- *S. H. Lee, **TOP** and **EW***, THUR 11:10

- ***contents of this talk:***

1. *introduction*
2. *nuclear pdfs*
3. *small x and saturation*
4. *summary*

High energy QCD and eA at the LHeC/FCC-eh

- **nuclear pdfs** for **single nuclei**, with flavour unfolding; same method of extraction in **ep** and **eA**
- studies of transverse structure

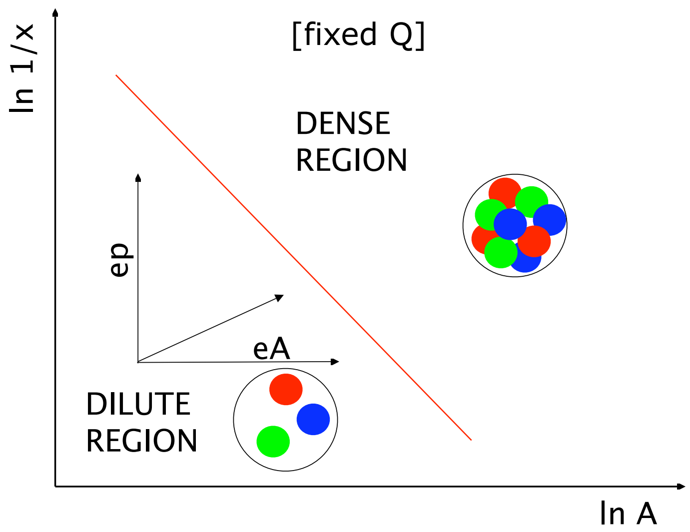


How does structure of a hadron change when immersed in a nuclear medium?

$$R_i(x,Q^2) = \frac{f_i^A(x,Q^2)}{A f_i^p(x,Q^2)}$$

Bound nucleon ≠ Free nucleon

Where is the novel non-linear regime of QCD that leads to saturation of parton densities?



- **QCD high energy regime** characterised by large parton densities ↓**x**/↑**A**
- physics beyond **standard collinear factorisation** can be tested in a single setup, with size effects disentangled from energy effects and large lever arm in x at perturbative Q^2

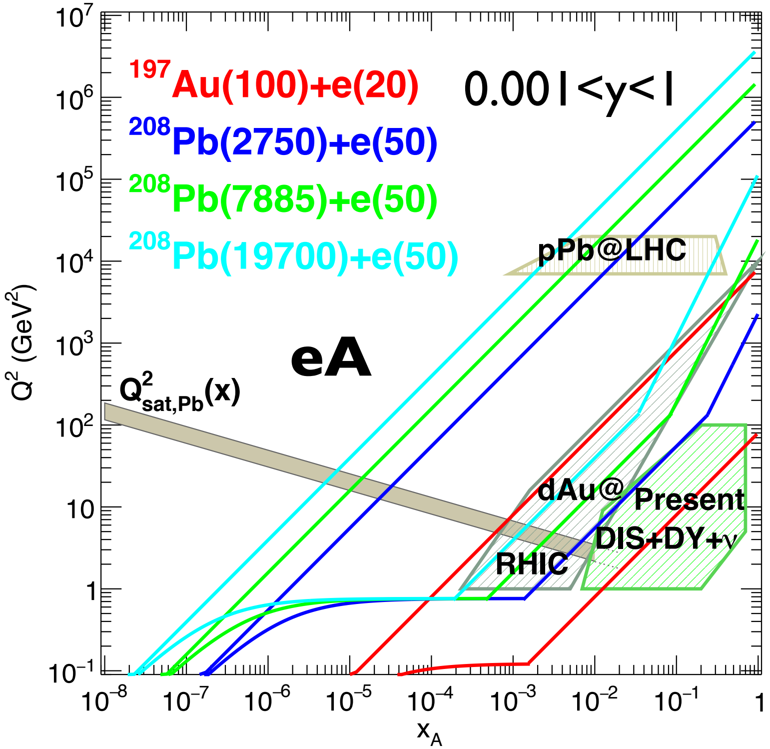
- strong implications for **pp/pA/AA** at the **HL-LHC** and **FCC**

eA at the LHeC and FCC-eh

- **eA** : **4–5 orders of magnitude** extension in Q^2, 1/x vs existing DIS data, and **∼ 2–3 vs EIC**

- (**ep:** ×15/120 extension in Q^2, 1/x vs HERA)

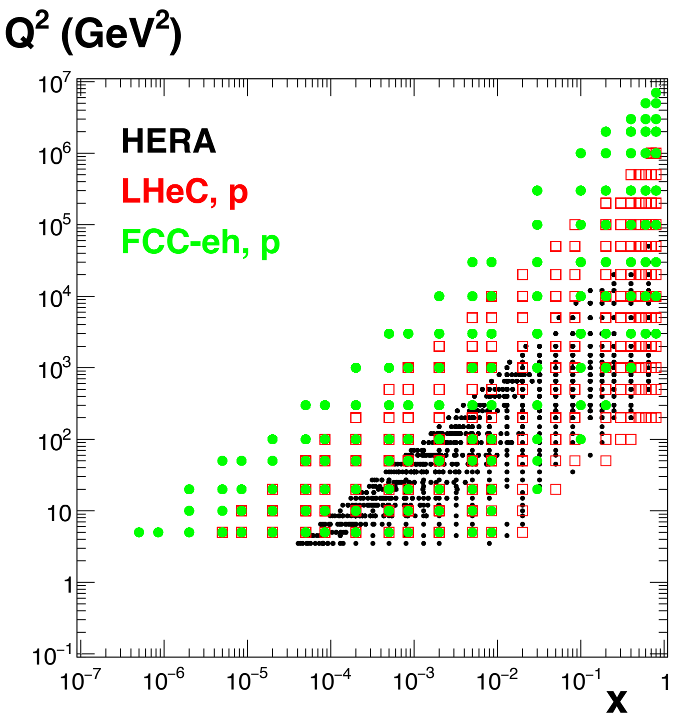
- DIS offers:
- clean experimental environment with fully constrained kinematics
- sophisticated theoretical calculations in collinear and non-collinear frameworks

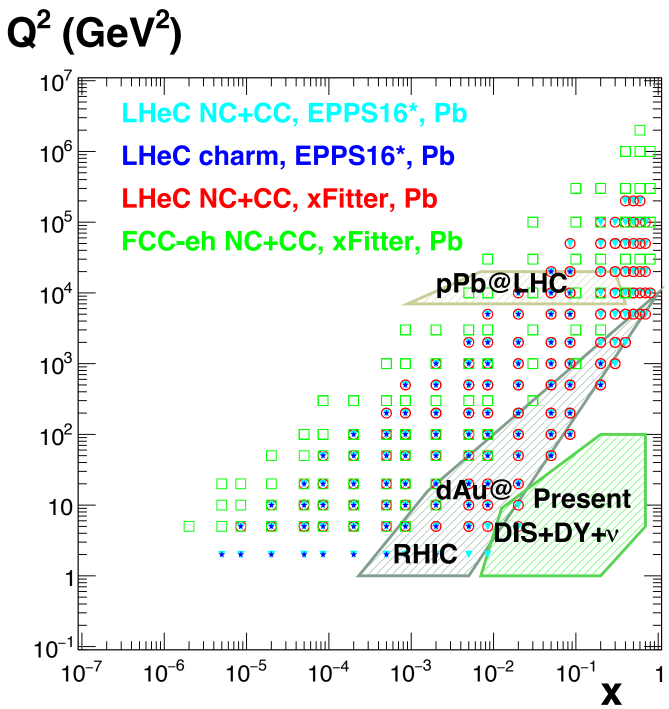


Parameter	Unit	LHeC	FCC-eh (E_p=20 TeV)	FCC-eh (E_p=50 TeV)
Ion energy E_{Pb}	PeV	0.574	1.64	4.1
Ion energy/nucleon E_{Pb}/A	TeV	2.76	7.88	19.7
Electron beam energy E_e	GeV	50	60	60
Electron-nucleon CMS $\sqrt{s_{eN}}$	TeV	0.74	1.4	2.2
Bunch spacing	ns	50	100	100
Number of bunches		1200	2072	2072
Ions per bunch	10^8	1.8	1.8	1.8
Normalised emittance ϵ_n	μm	1.5	1.5	1.5
Electrons per bunch	10^9	6.2	6.2	6.2
Electron current	mA	20	20	20
IP beta function β_A^*	cm	10	10	15
e-N Luminosity	10^{32}cm^{-2}s^{-1}	7	14	35

ep and eA coverage and simulated data

- **ep** and **eA** simulated NC and CC generated using code (M. Klein) validated against H1 MC

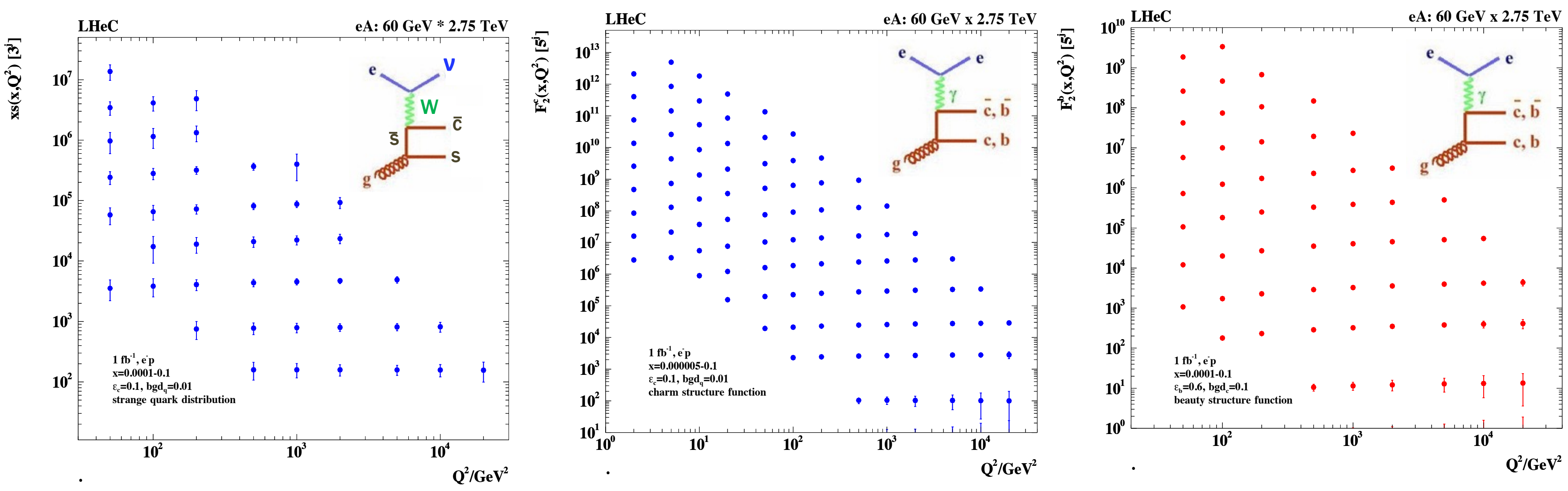




Source of uncertainty	Error on the source or cross section
Scattered electron energy scale	0.1 %
Scattered electron polar angle	0.1 mrad
Hadronic energy scale	0.5 %
Calorimeter noise ($y < 0.01$)	1–3 %
Radiative corrections	1–2 %
Photoproduction background	1 %
Global efficiency error	0.7 %

- cuts: $|\eta_{max}|$=5, 0.001 < y < 0.95
- uncertainty assumptions: ∼ ×2 smaller than HERA (excepting luminosity)

ep and eA coverage and simulated data

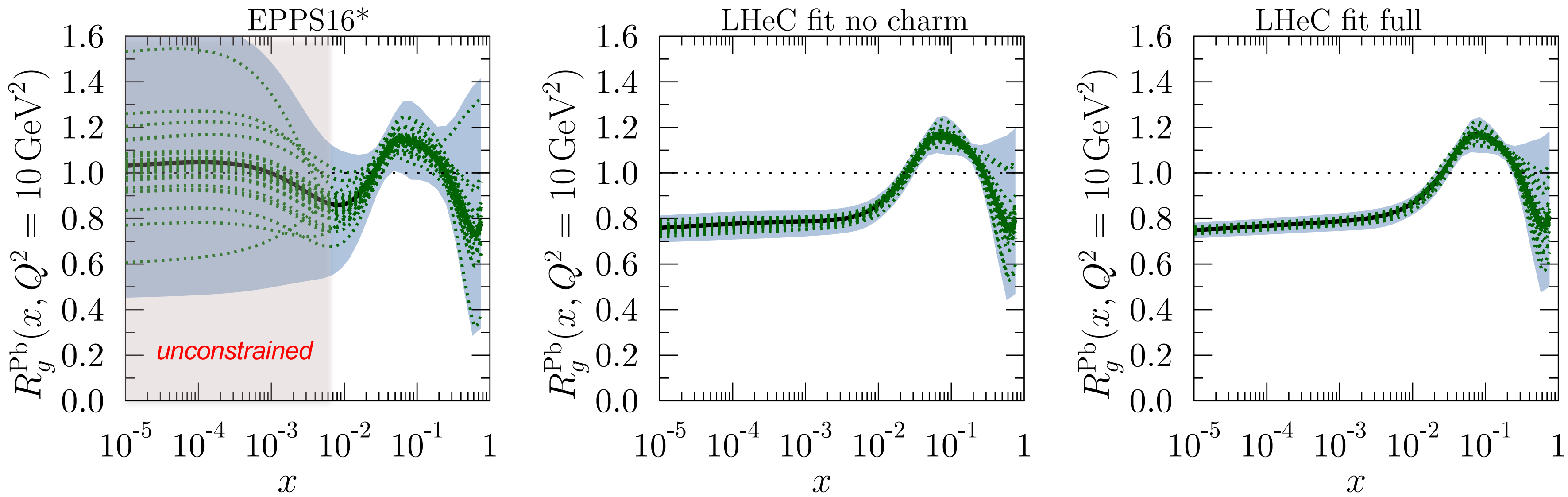


- semi-inclusive measurements of strange, charm and beauty in DIS at the LHeC (**eA** shown here)

Source of uncertainty	Error on the source or cross section
Scattered electron energy scale	0.1 %
Scattered electron polar angle	0.1 mrad
Hadronic energy scale	0.5 %
Calorimeter noise ($y < 0.01$)	1–3 %
Radiative corrections	1–2 %
Photoproduction background	1 %
Global efficiency error	0.7 %

- cuts: $|\eta_{max}|$=5, **0.001** < y < **0.95**
- uncertainty assumptions: ∼ ×2 smaller than HERA (excepting luminosity)
- s, c, b include additional uncertainties for tagging, acceptance and BG

nPDFs from LHeC in global fit context



$$R_i(x, Q^2) \equiv \frac{f_i^{p/Pb}(x, Q^2)}{f_i^{p}(x, Q^2)}$$

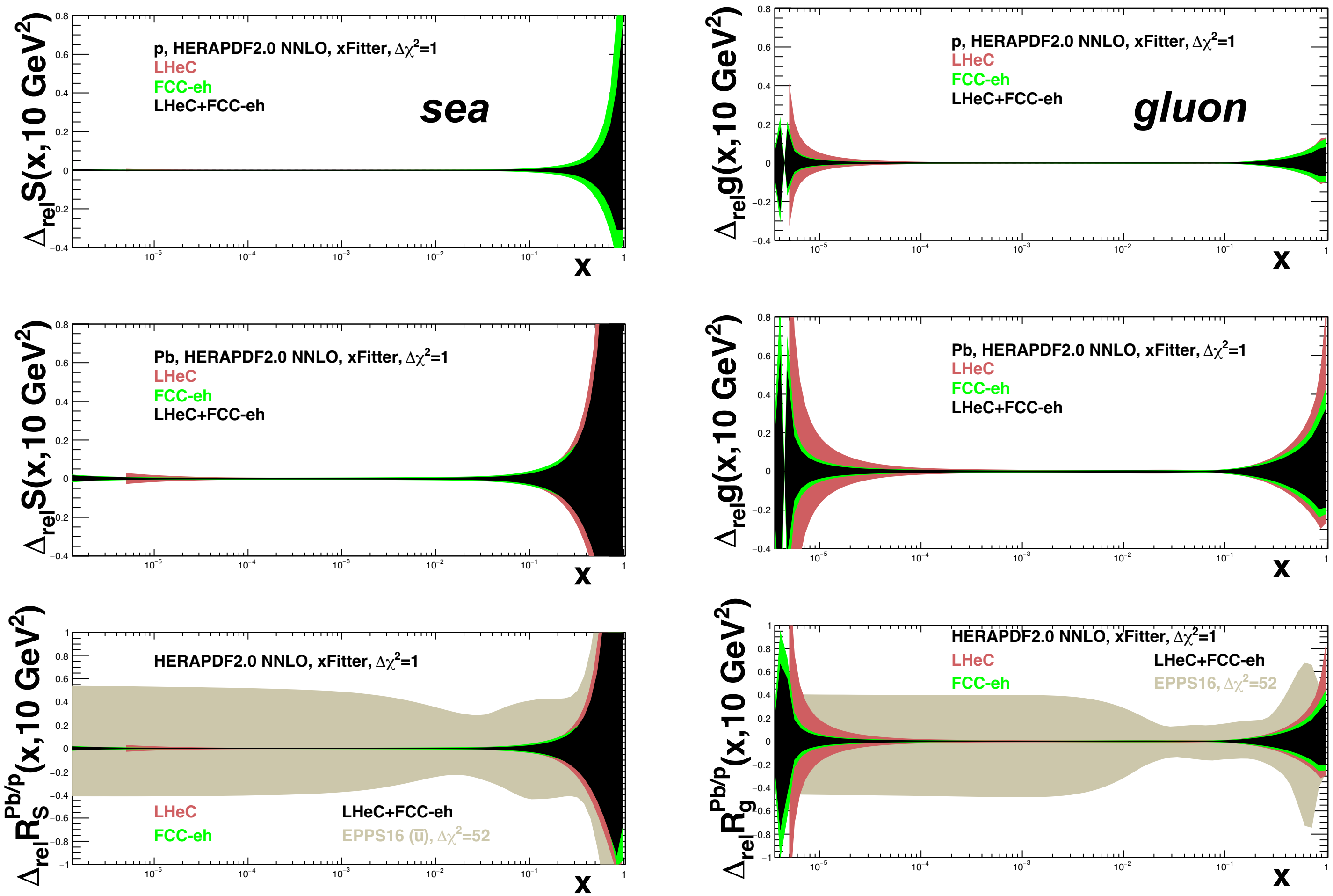
Nuclear Modification Factor *(for parton i)*

shown above for the ***gluon***

- **EPPS16***: EPPS16-like global analysis of **nuclear pdfs** (arXiv:1612.05741)
- same data sets, method, and tolerance (**Δ**χ^2=52), BUT with added flexibility in functional form at small x
- **ADD** LHeC **NC**, **CC** and **charm** reduced cross sections

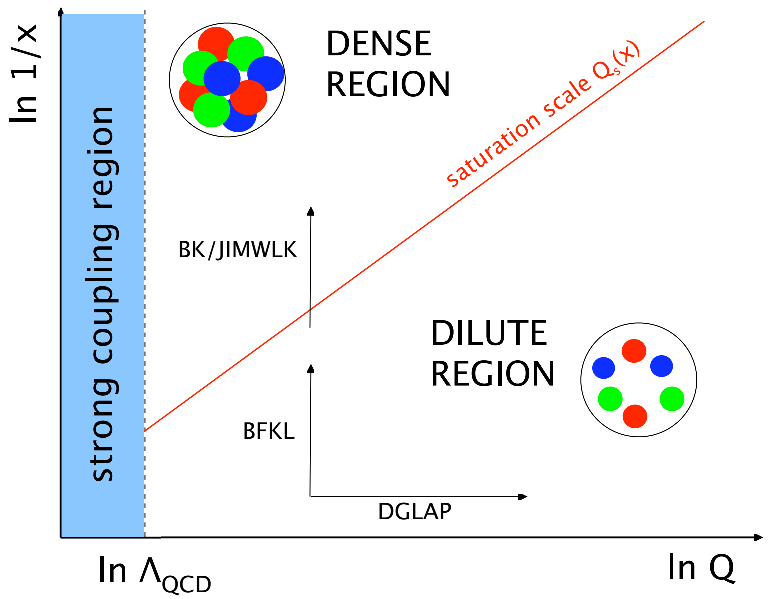
→ with LHeC, **nuclear gluon pdf** precisely determined down to x values of at least 10^{-5}

nPDFs from DIS on single nucleus



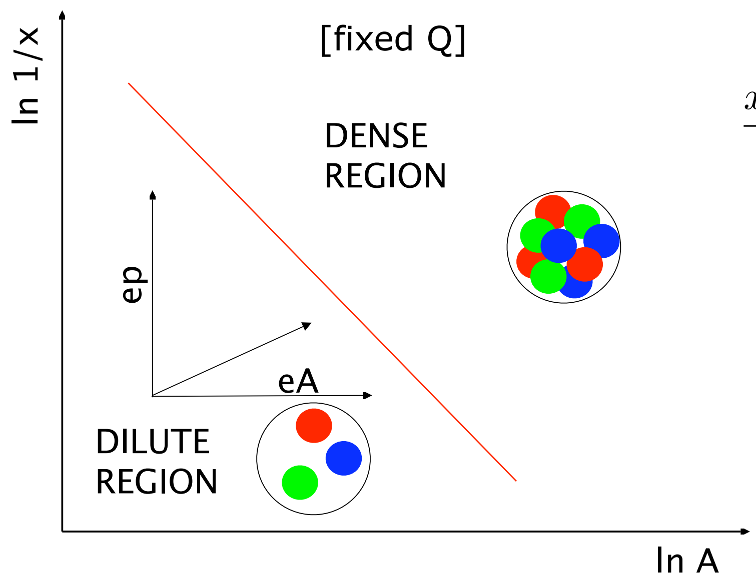
- **nuclear pdfs** using NC and CC DIS only on **single nucleus** – only experimental uncerts. (**Δχ^2**=1)
- **significant uncertainty reduction at all x; stringent tests of collinear factorisation in pA**
- expect further improvements from : charm, beauty, strange from CC with tagged charm

Novel QCD dynamics



- **High energy regime** characterised by **large parton densities ↓x/↑A**
- 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

→ modification of parton evolution by including non-linear / saturation effects

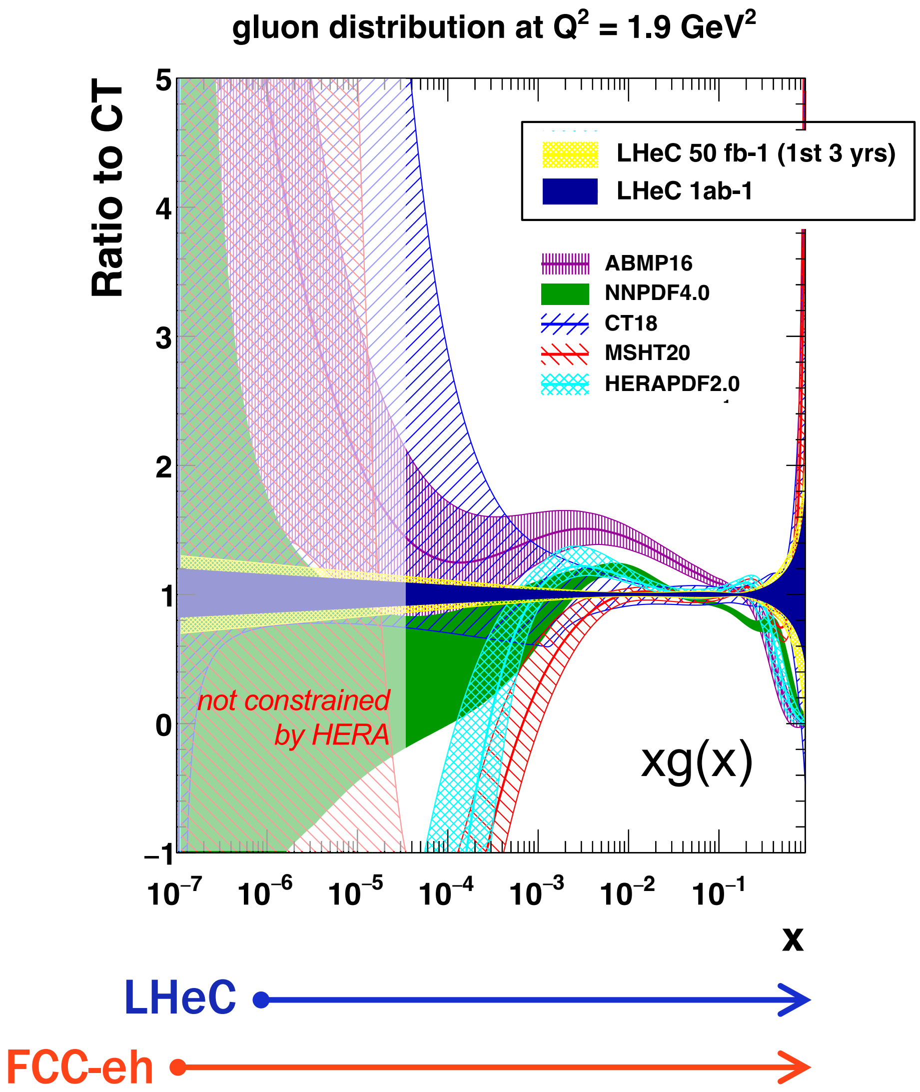


$$\frac{xG_A(x,Q_s^2)}{\pi R_A^2 Q_s^2} \sim 1 \longrightarrow Q_s^2 \sim \boxed{A^{1/3}} x^{-\lambda}$$

ep/eA at **LHeC/FCC-eh** allows discovery and tests of **novel QCD dynamics** via two-prong approach: **small x** and **large A**

(NB, diffraction also plays special role, A. Stasto, THUR 17:10)

Gluon PDF in proton at small x



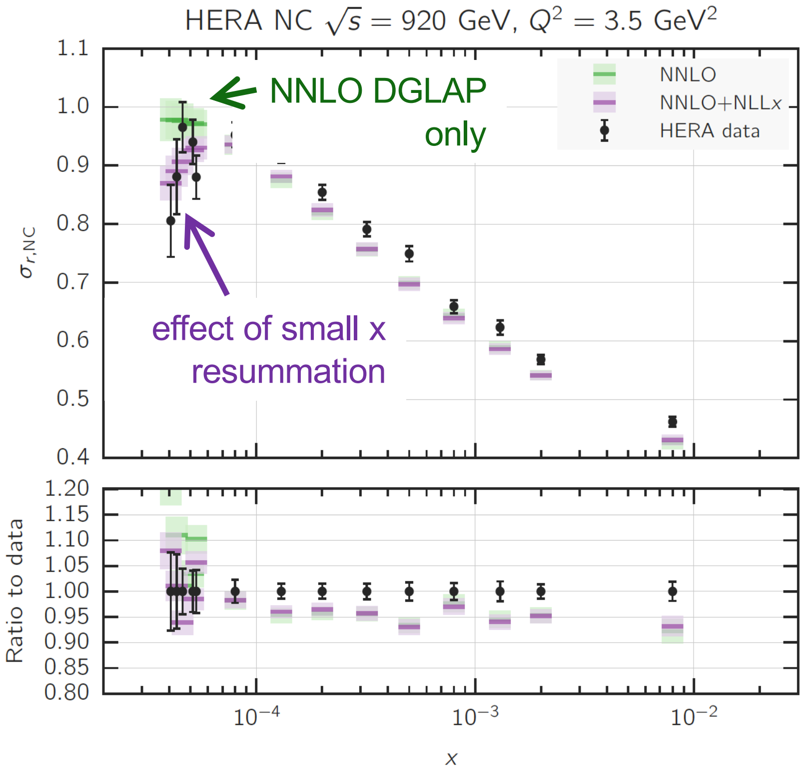
HERA sensitivity stops $x \simeq 5.10^{-5}$

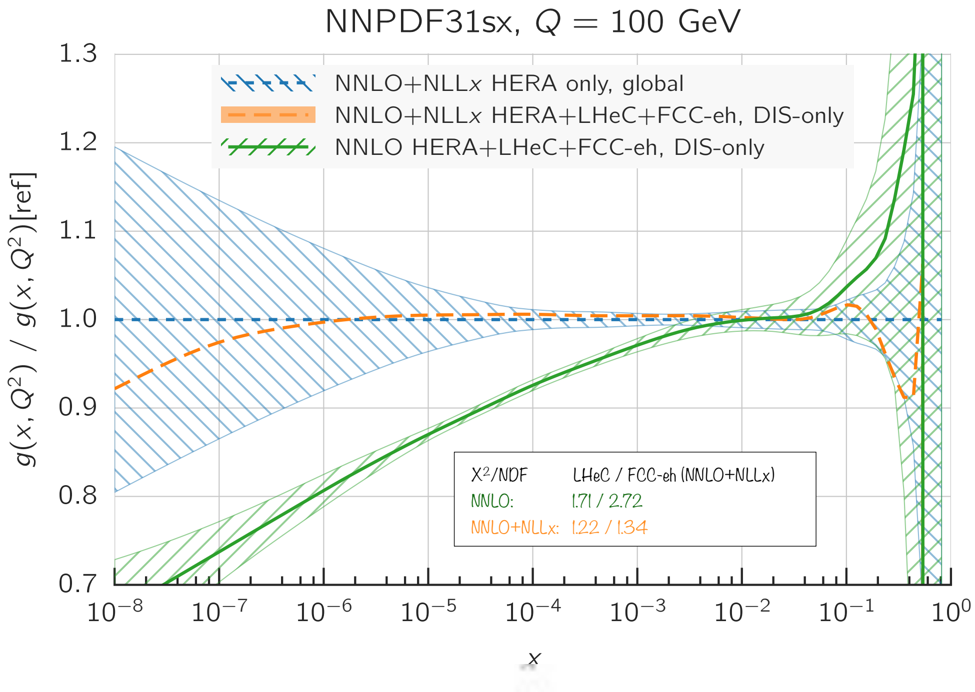
LHeC and FCC-eh offer unprecedented access to explore **small x** QCD regime:

DGLAP vs BFKL
non-linear evolution / gluon saturation
with implications for ultra high energy neutrino cross sections

(see more on **pdfs** in talk by F. Giuli, WG6, THUR 16:50)

Novel small x dynamics: resummation





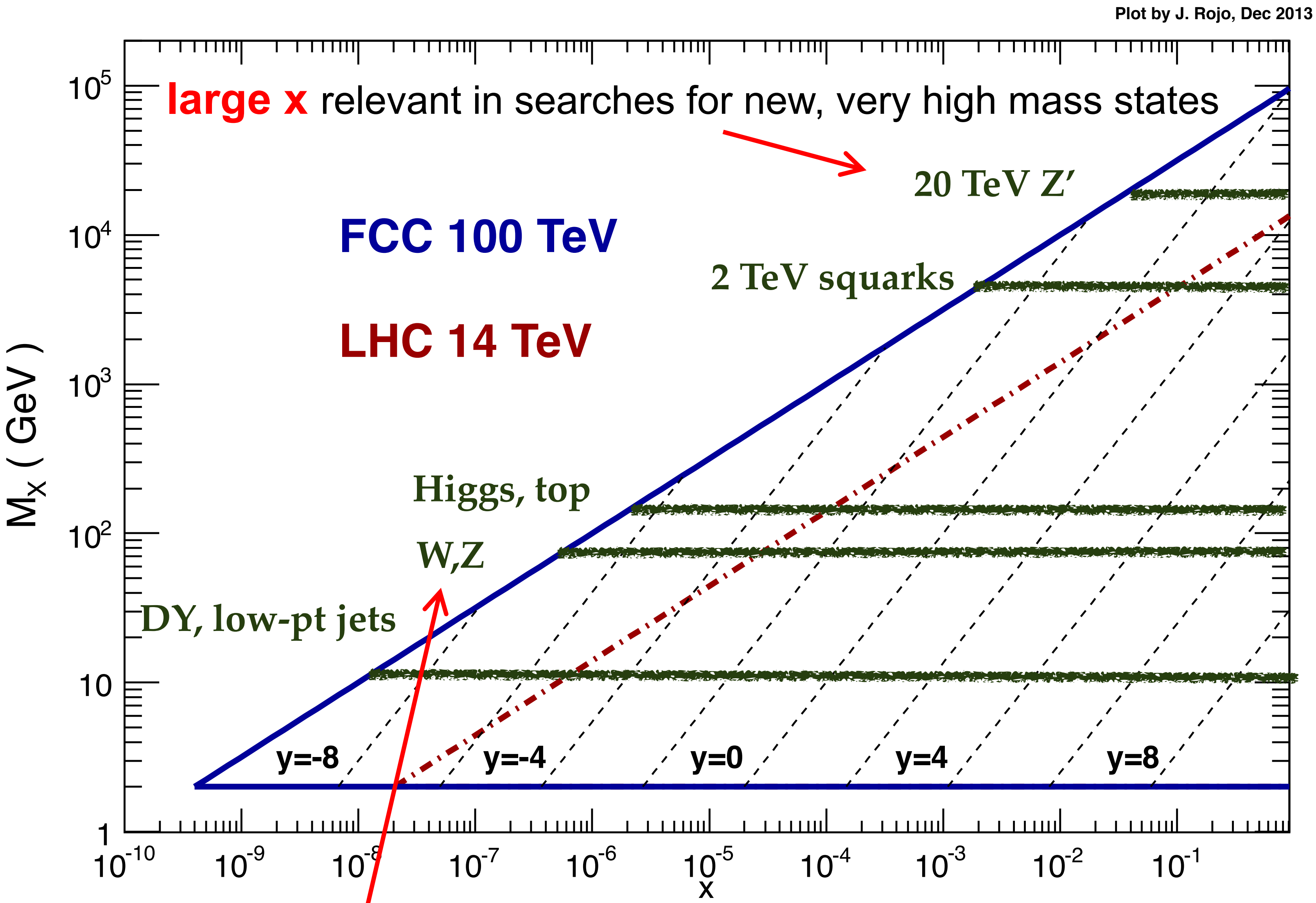
- small x resummation needed to stabilise BFKL expansion
- **DGLAP+resummation** substantially improves description of HERA inclusive data at small x arXiv:1710.05935; 1802.00064

(see also, arXiv:1604.02299)

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

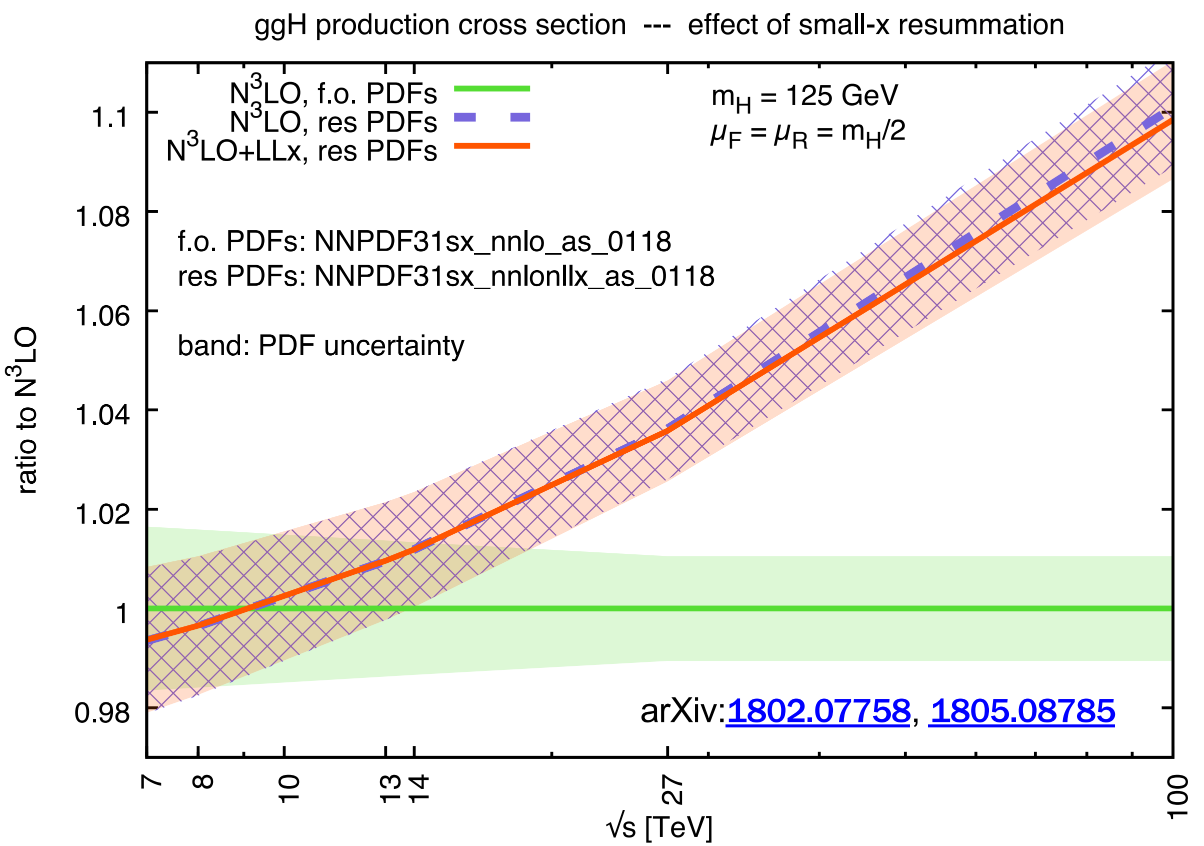
- NB, gluon pdf obtained with small x resummation grows more quickly – **saturation** at some point!

Kinematics of a 100 TeV FCC



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

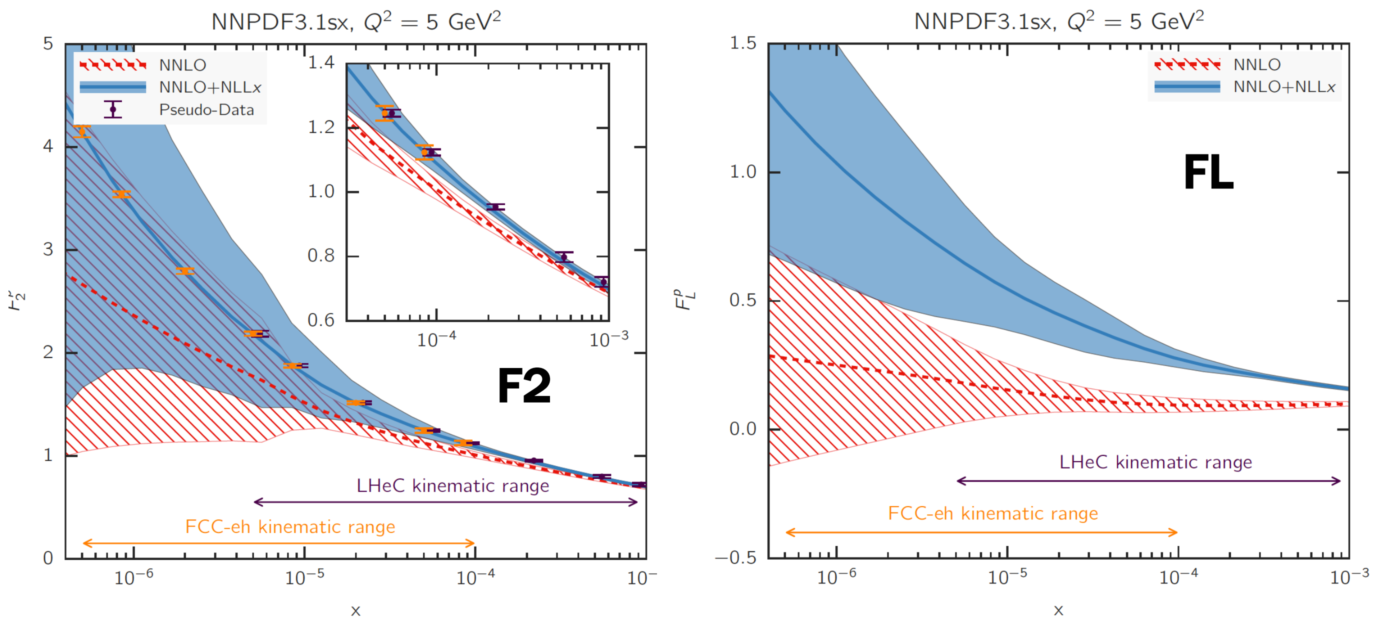
small x treatment matters



- 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 work on forward Higgs production (arXiv:2011.03193) and HQ (arXiv:2211.10142); other processes in progress)

LHeC and FCC−eh sensitivity to small x resummation

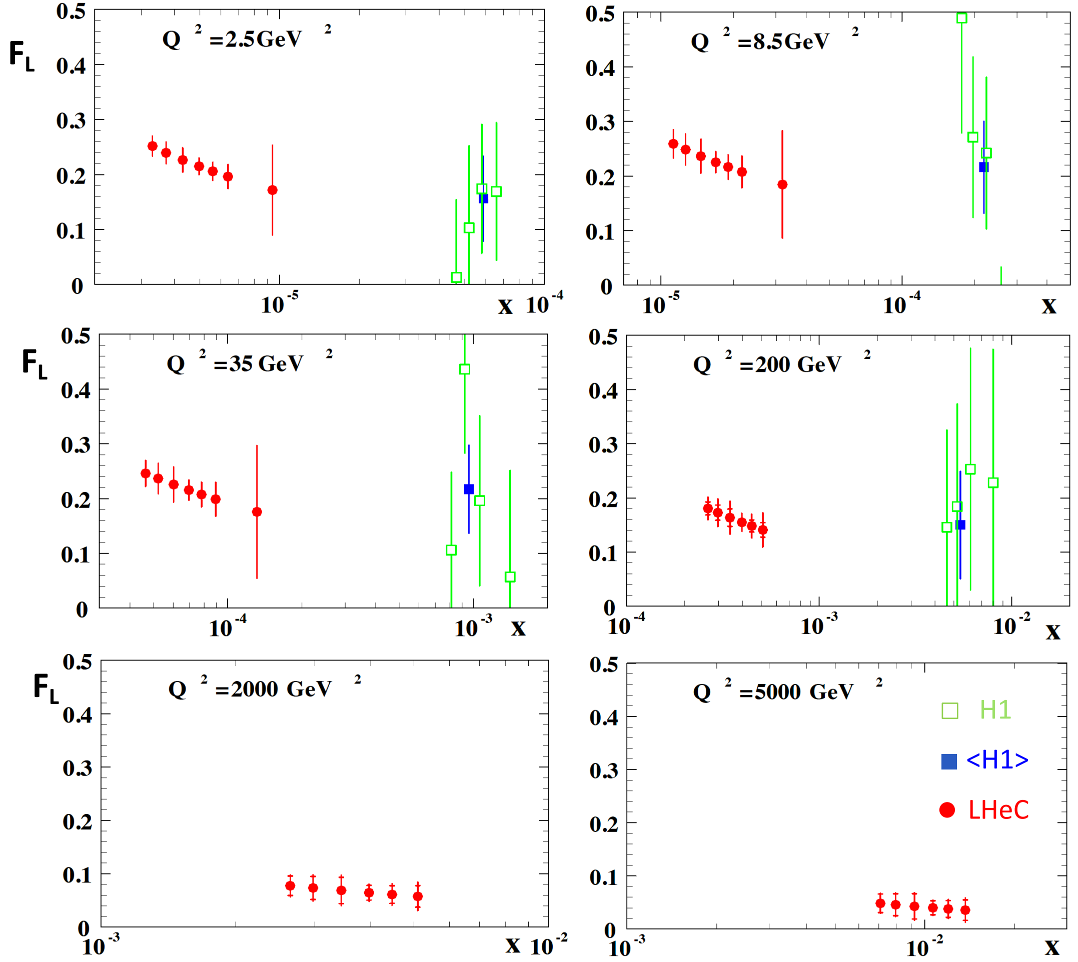


(arXiv:1710.05935)

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

- 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)
- measurement of FL has a significant role to play, arXiv:1802.04317

Longitudinal Structure Function



simulated for:

Ep = 7 TeV and

Ee = 60, 30, 20 GeV

integrated luminosity:

10, 1, 1 fb^{-1}

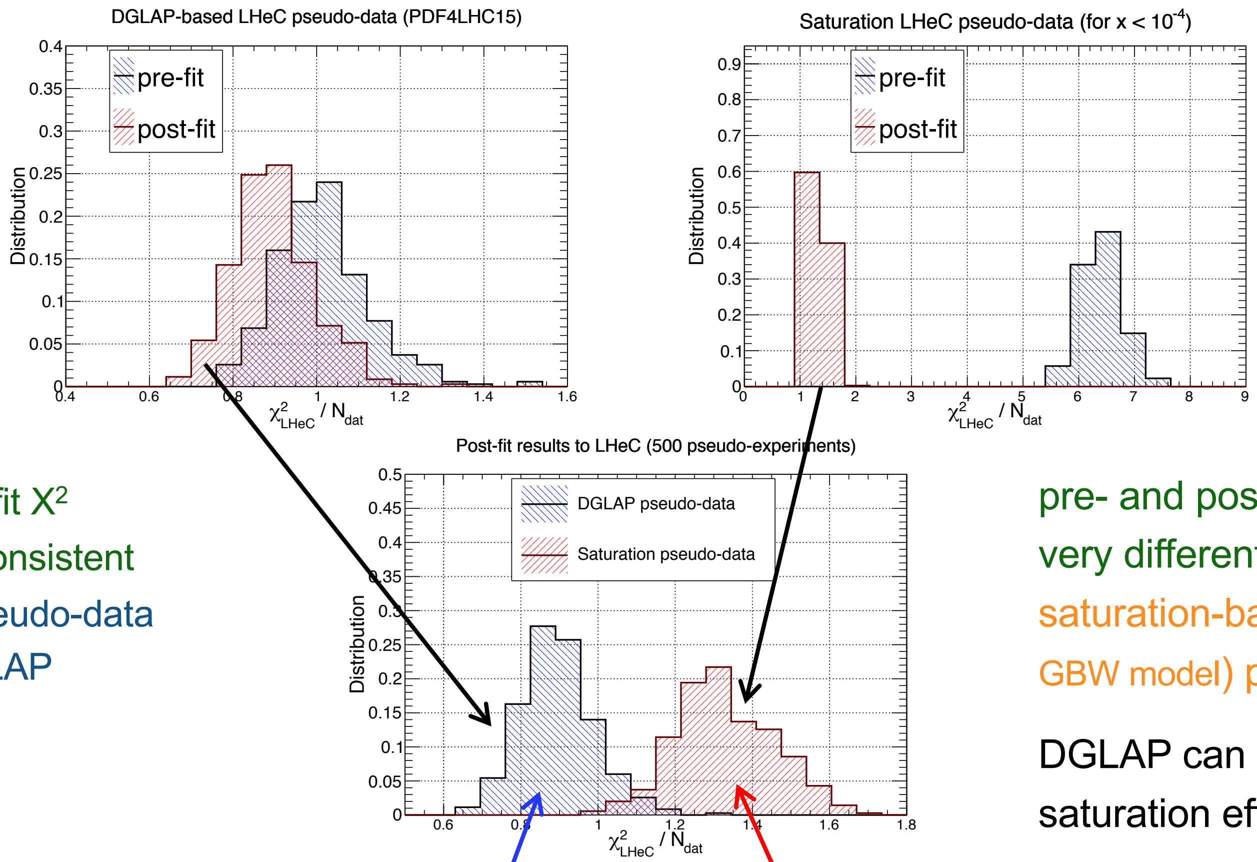
measurement dominated by systematics

(arXiv:1802.04317)

- **simultaneous measurement of F2 and FL is clean way to pin down dynamics at small x**
- vary also nuclear size to definitively disentangle small-x resummation from non-linear dynamics

Novel dynamics at small x: saturation

- studies show linear evolution **cannot accommodate saturation**, even at NNLO or NNLO+NLLx
- EG, **DGLAP-** vs **saturation-** based simulated data fitted with NNLO DGLAP



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

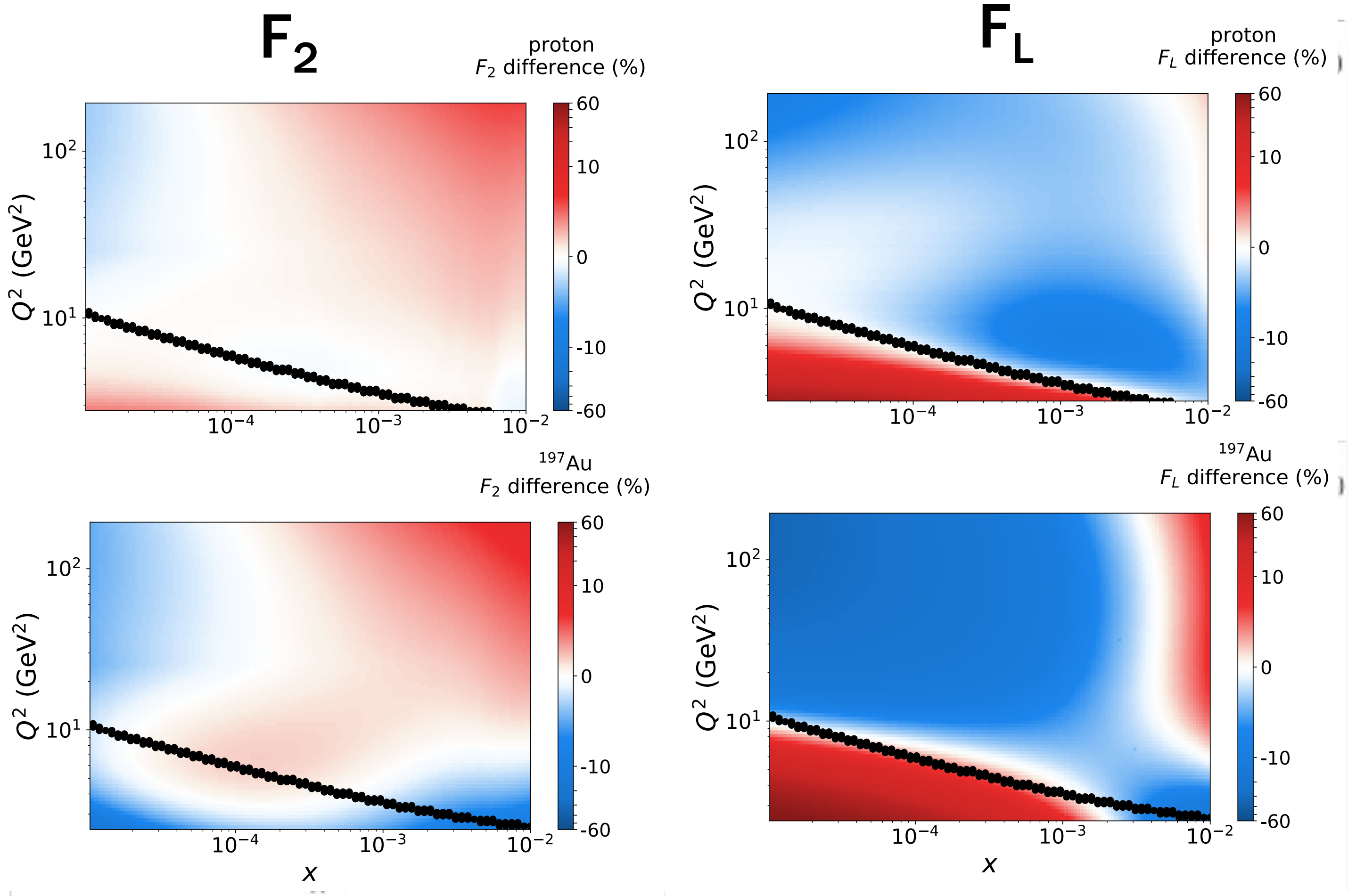
LHeC can distinguish between **DGLAP** and **saturation**

(NB, large lever arm in Q^2 crucial, see also arXiv:1702.00839)

arXiv:2007.14491

(more detail in EXTRAS)

Novel small x dynamics: saturation



ep

up to 40% for F_L

eAu

up to 10% effect for F_2 and 60% for F_L

(cf. 10 – 15% in EIC range)

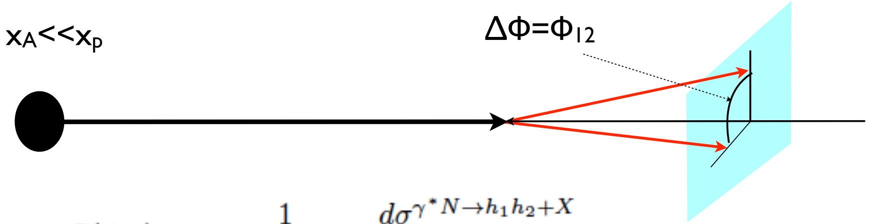
(arXiv:2203.05846)

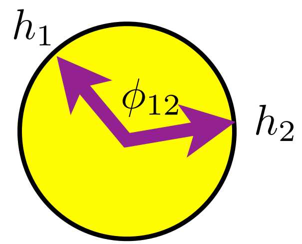
- recent, complementary study of **linear DGLAP vs non-linear evolution with saturation**
- match the two approaches in specific regions where effects from saturation small
- quantify differences away from matching region: sensitive to differences in evolution dynamics

Novel small x dynamics: exclusive observables

other key probes of saturation:

- **dihadron azimuthal decorrelation**
- currently discussed at RHIC as suggestive of saturation

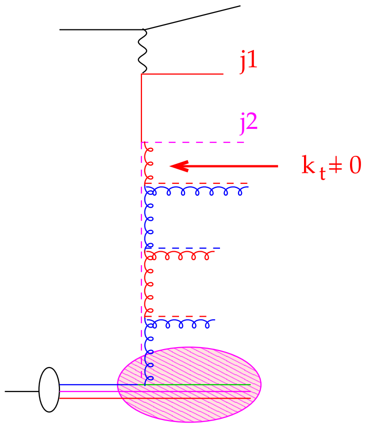


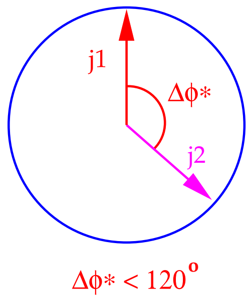


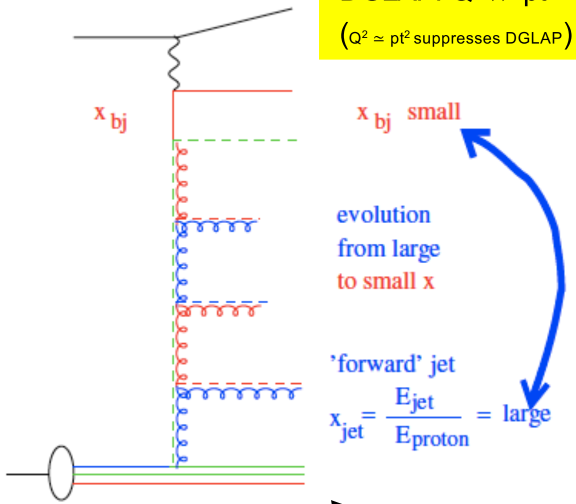
$$C(\phi_{12}) = \frac{1}{\frac{d\sigma(\gamma^* N \to h_1 X)}{dz_{h1}}} \frac{d\sigma^{\gamma^* N \to h_1 h_2 + X}}{dz_{h1} dz_{h2} d\phi_{12}}$$

- **nuclear** and **saturation effects** on usual BFKL signals, EG. dijet azimuthal decorrelation, Mueller-Navelet jets
- **A** dependence?

DGLAP: $Q^2 \gg pt^2$
($Q^2 \simeq pt^2$ suppresses DGLAP)







if incoming gluon has sizeable kt, jets no longer back-to-back; must balance kt of incoming virtual gluon

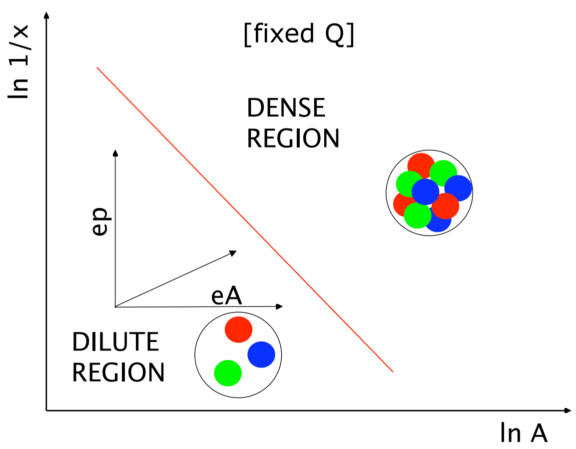
measurements with large rapidity separations and different (Q,pt) combinations to systematically test parton dynamics

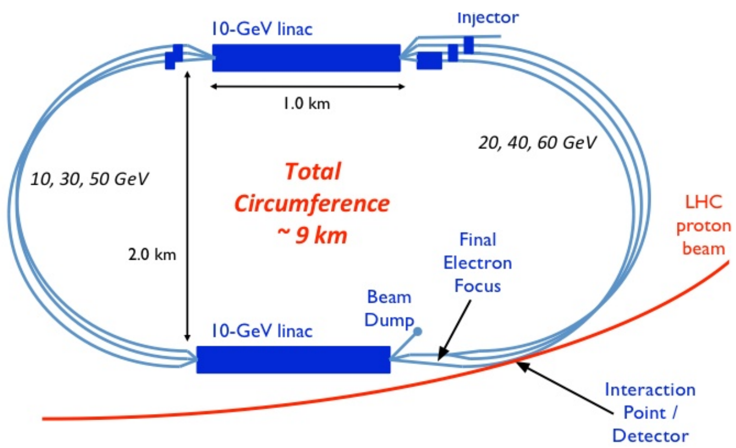
Summary

- a new highly luminous, energy frontier **ep/eA** collider is a **QCD precision** and **discovery machine**; enables full exploitation of current and future hadron colliders

- precise determination of **nuclear pdfs** that cannot be matched at hadron colliders, including precise measurements of heavy quarks in **eA**
- stringent tests of collinear factorisation in **pA**
- critical input for understanding phenomena in **HI** collisions

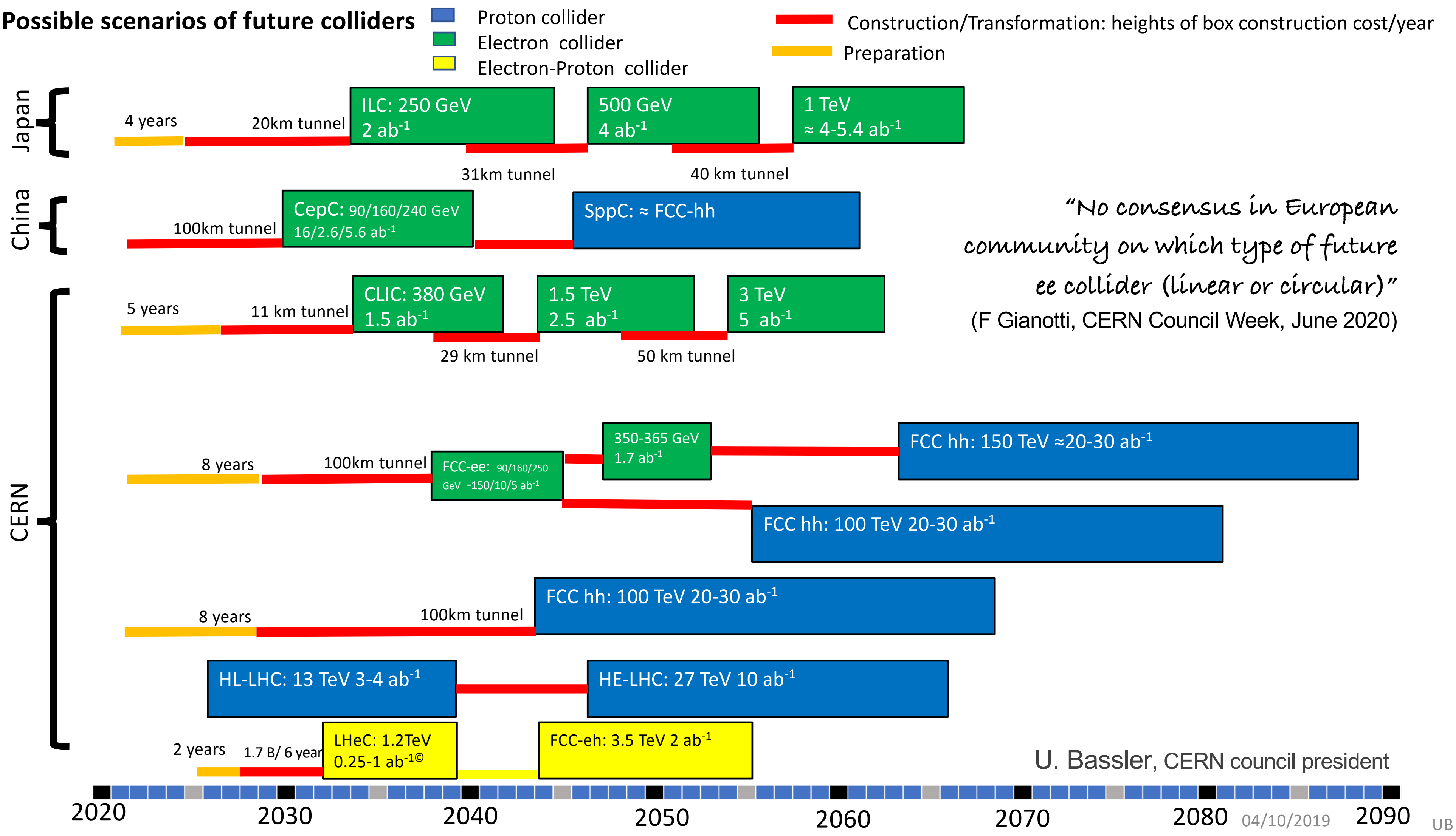
- **eA** together with **ep**, allows discovery and tests of saturation at small x and with different A dependence → two-pronged approach : **small x** and **large A**





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)

LHeC: installation during **LS4**;

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

Statement of the IAC

Members of the Committee

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Nichola Bianchi (INFN, now Singapore)
Frederick Bordy (CERN)
Stan Brodsky (SLAC)
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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.

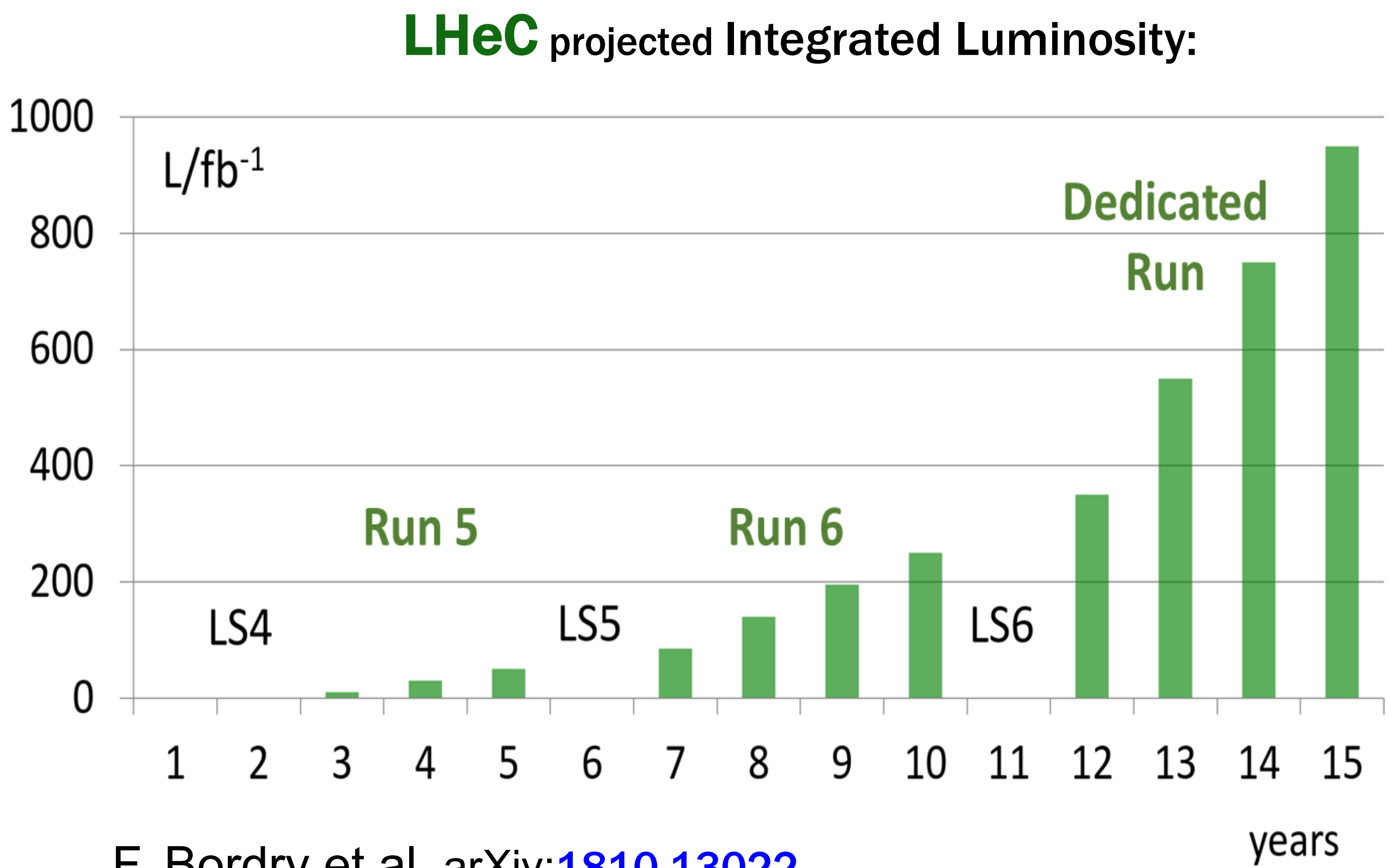
iii) It is recommended to keep the LHeC option open until further decisions have been taken. An investigation should be started on the compatibility between the LHeC and a new heavy ion experiment in Interaction Point 2, which is currently under discussion.

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)

LHeC timescale



F. Bordry et al. arXiv:[1810.13022]

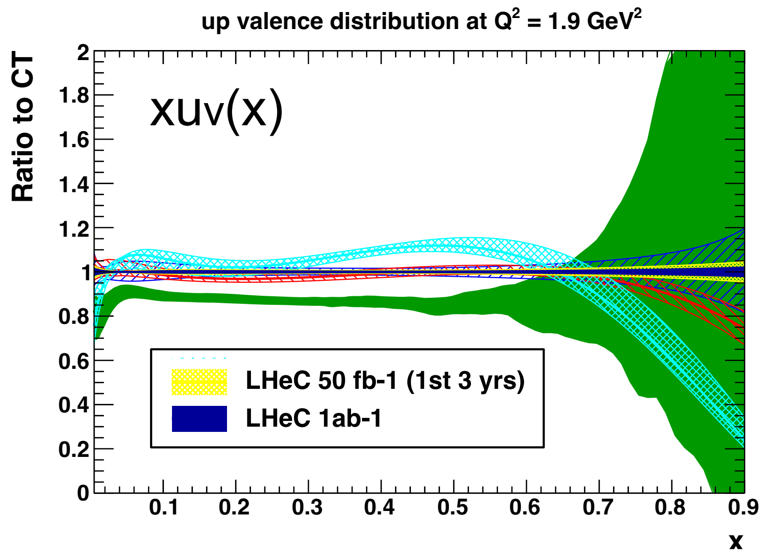
ep and eA simulated data

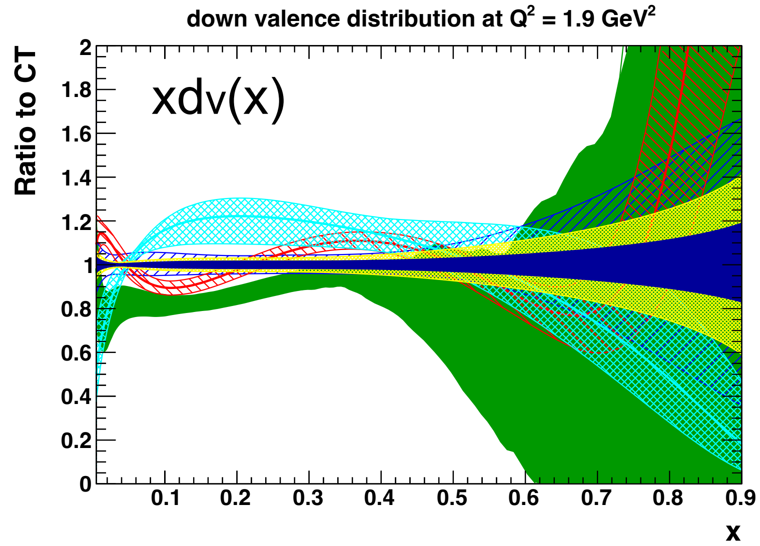
	E_e (GeV)	E_h (TeV/nucleon)	Polarisation	Luminosity (fb^{-1})	NC/CC	# data
ep@LHeC, 1005 data points for $Q^2 \geq 3.5$ GeV^2	60 (e^-)	1 (p)	0	100	CC	93
	60 (e^-)	1 (p)	0	100	NC	136
	60 (e^-)	7 (p)	-0.8	1000	CC	114
	60 (e^-)	7 (p)	0.8	300	CC	113
	60 (e^+)	7 (p)	0	100	CC	109
	60 (e^-)	7 (p)	-0.8	1000	NC	159
	60 (e^-)	7 (p)	0.8	300	NC	159
	60 (e^+)	7 (p)	0	100	NC	157
ePb@LHeC, 484 data points for $Q^2 \geq 3.5$ GeV^2	20 (e^-)	2.75 (Pb)	-0.8	0.03	CC	51
	20 (e^-)	2.75 (Pb)	-0.8	0.03	NC	93
	26.9 (e^-)	2.75 (Pb)	-0.8	0.02	CC	55
	26.9 (e^-)	2.75 (Pb)	-0.8	0.02	NC	98
	60 (e^-)	2.75 (Pb)	-0.8	1	CC	85
	60 (e^-)	2.75 (Pb)	-0.8	1	NC	129
ep@FCC-he, 619 data points for $Q^2 \geq 3.5$ GeV^2	20 (e^-)	7 (p)	0	100	CC	46
	20 (e^-)	7 (p)	0	100	NC	89
	60 (e^-)	50 (p)	-0.8	1000	CC	67
	60 (e^-)	50 (p)	0.8	300	CC	65
	60 (e^+)	50 (p)	0	100	CC	60
	60 (e^-)	50 (p)	-0.8	1000	NC	111
	60 (e^-)	50 (p)	0.8	300	NC	110
	60 (e^+)	50 (p)	0	100	NC	107
ePb@FCC-he, 150 data points for $Q^2 \geq 3.5$ GeV^2	60 (e^-)	20 (Pb)	-0.8	10	CC	58
	60 (e^-)	20 (Pb)	-0.8	10	NC	101

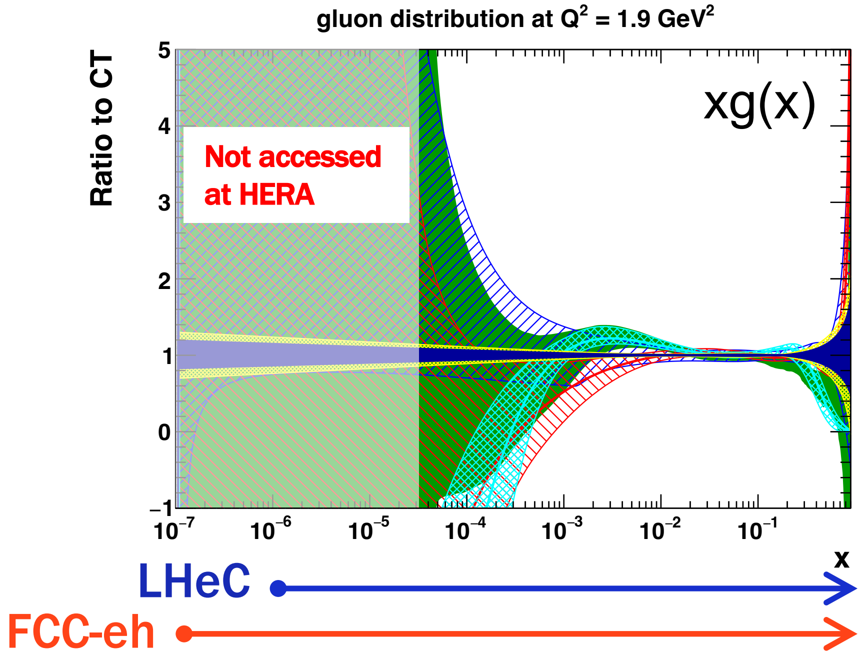
(taken from N Armesto, ICHEP 2022)

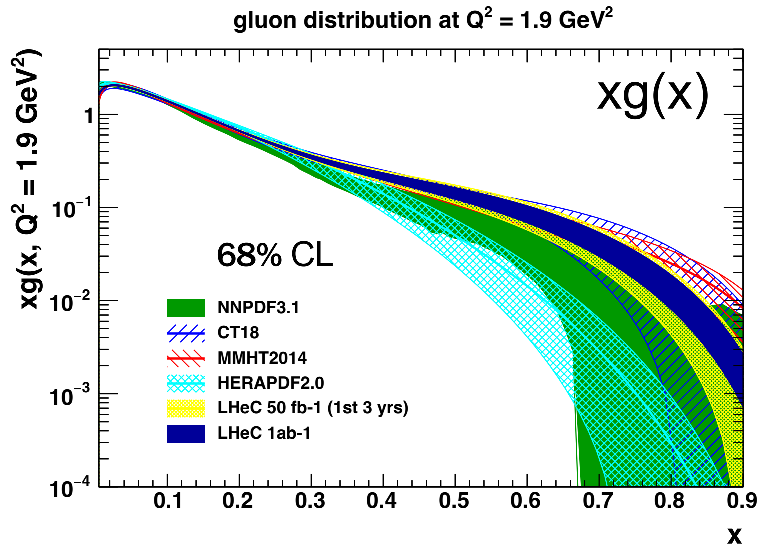
Quark and Gluon proton PDFs

(see more in talk on ***pdfs***
F. Giuli, WG6, THUR 16:50)





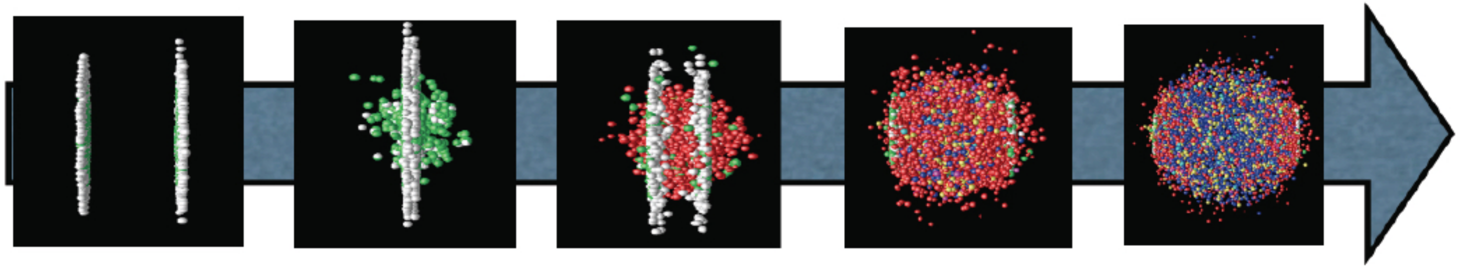




↰ probing unprecedented small values of x

eA: complementarity to pA, AA at LHC

Heavy Ions



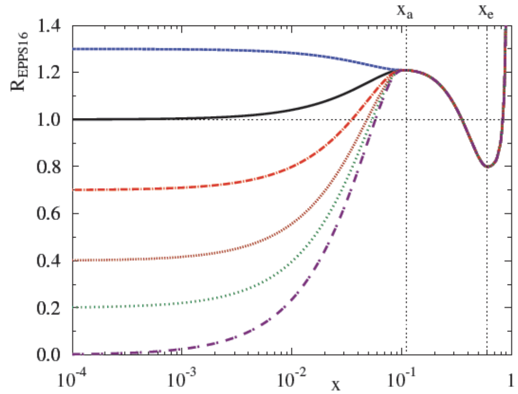
- **strong implications on pA/AA at the HL-LHC and FCC-hh**

- precision measurement of initial state
- nuclear structure functions
- particle production in early stages
- factorisation eA/pA/AA
- modification of QCD radiation and hadronisation in nuclear medium

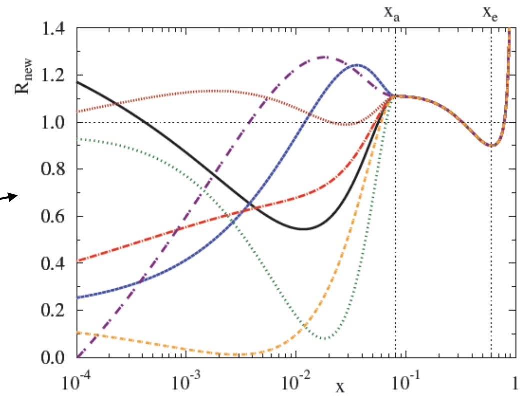
EPPS16* setup

- **EPPS16-like analysis updated**, with the same datasets plus LHeC NC, CC and charm reduced cross sections
- central values generated usimg EPS09
- same methods and tolerance (**ΔX**^{2}=52) as EPPS16, but more flexible functional form

$$R_{\mathrm{EPPS16}}(x) = \begin{cases} a_0 + a_1(x-x_a)^2 & x \le x_a \\ b_0 + b_1 x^{\alpha} + b_2 x^{2\alpha} + b_3 x^{3\alpha} & x_a \le x \le x_e \\ c_0 + (c_1 - c_2 x)(1-x)^{-\beta} & x_e \le x \le 1. \end{cases}$$

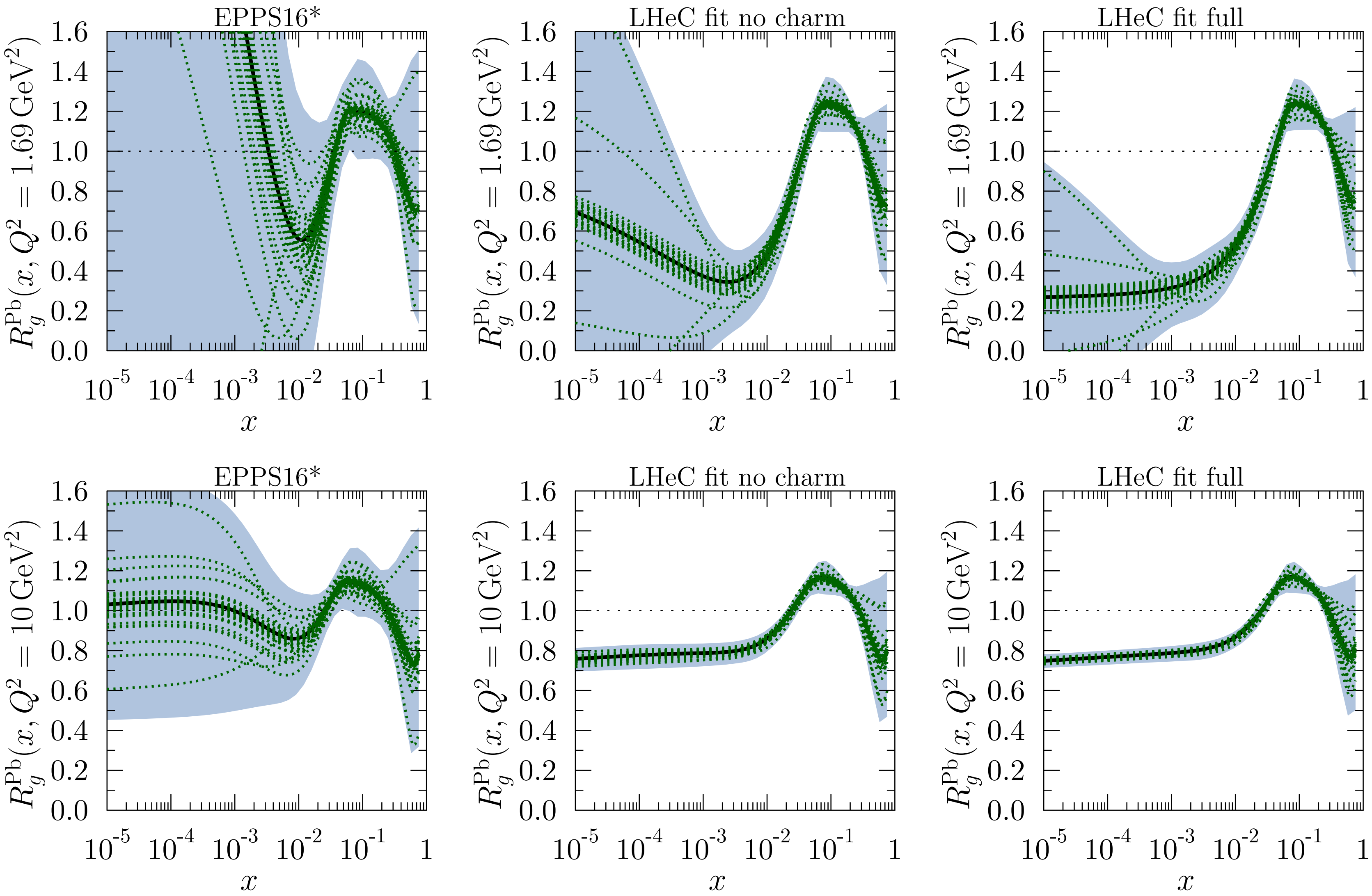


$$R_{\mathrm{new}}(x \le x_a) = a_0 + (x - x_a)^2 \left[a_1 + \sum_{k=1}^{2} a_{k+2} x^{k/4} \right]$$

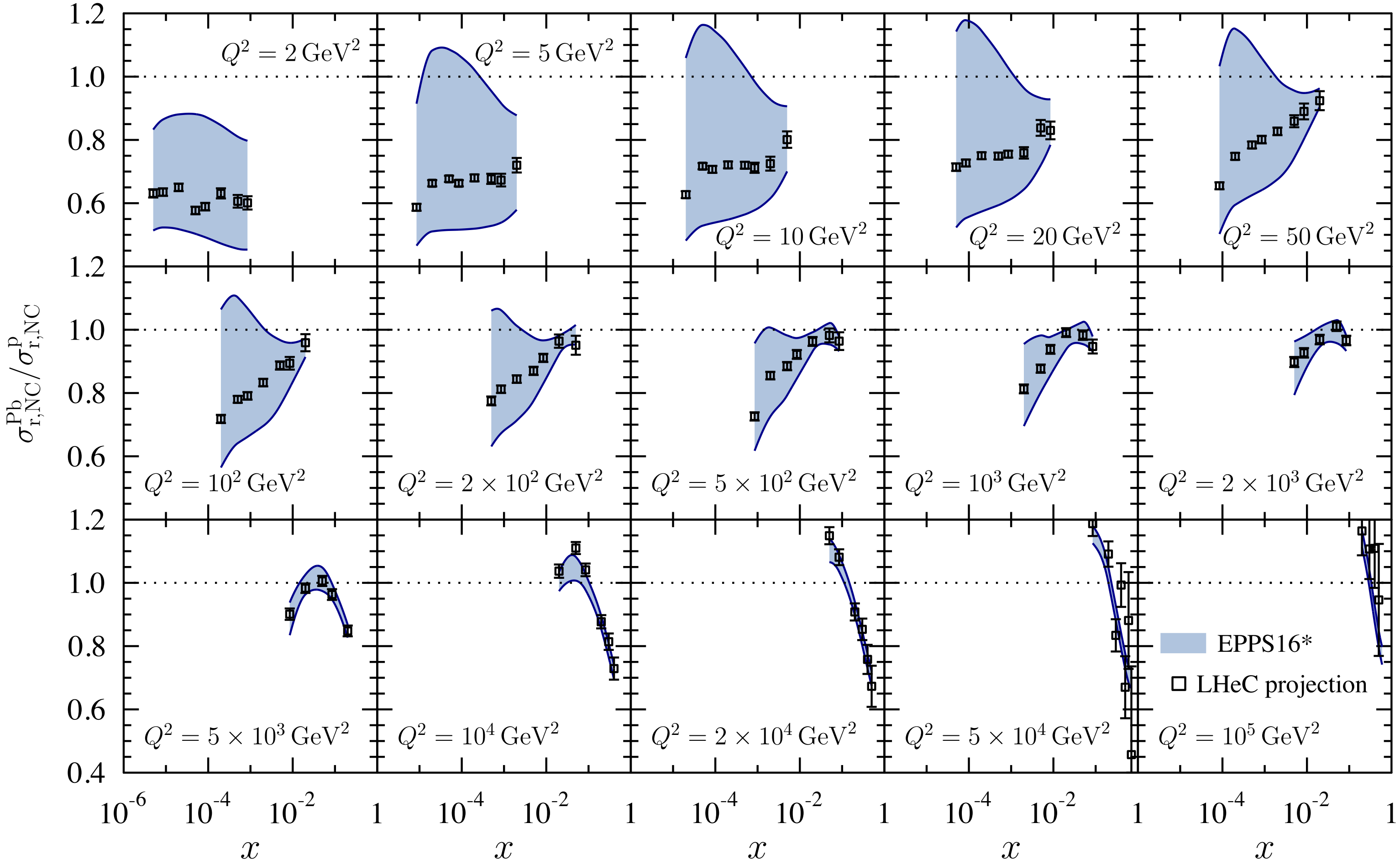


(taken from N Armesto, ICHEP 2022)

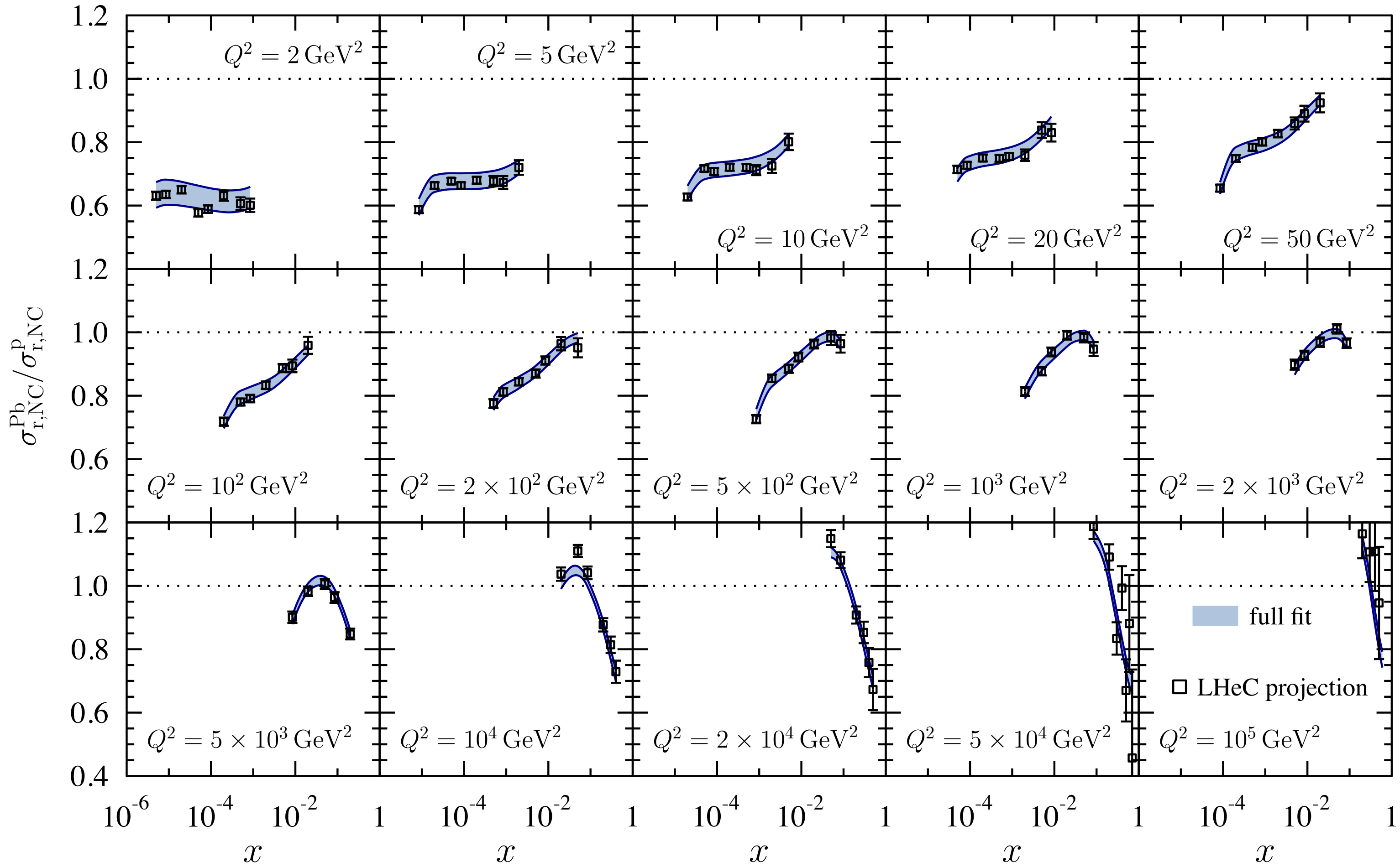
nPDFs from LHeC in global fit context



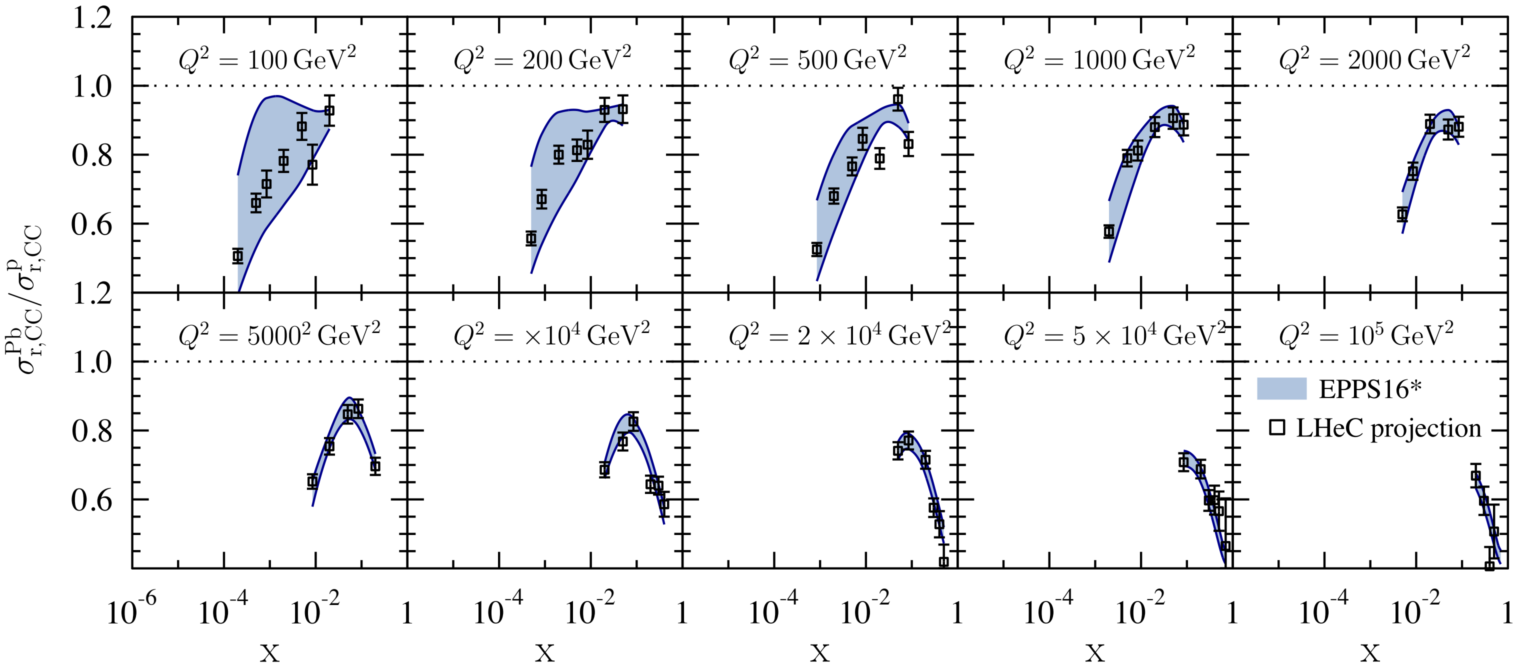
nPDFs from LHeC in global fit context



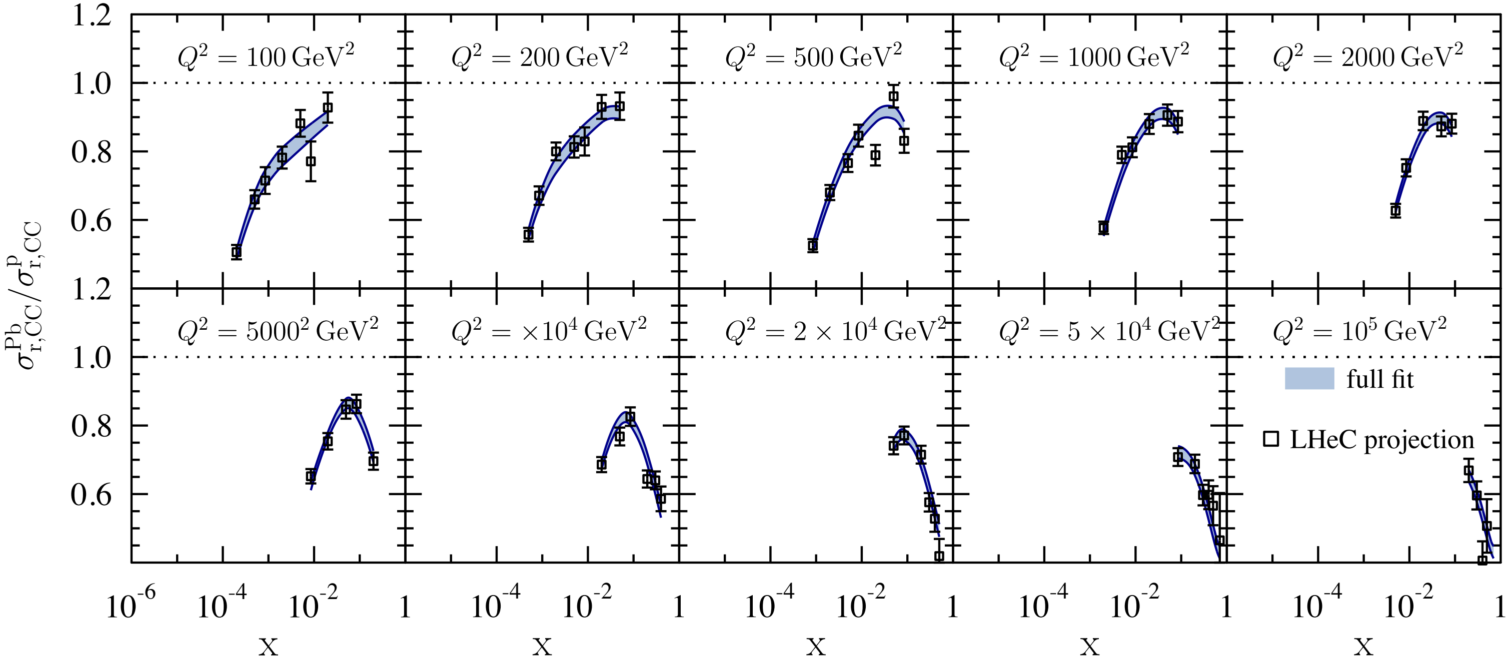
nPDFs from LHeC in global fit context



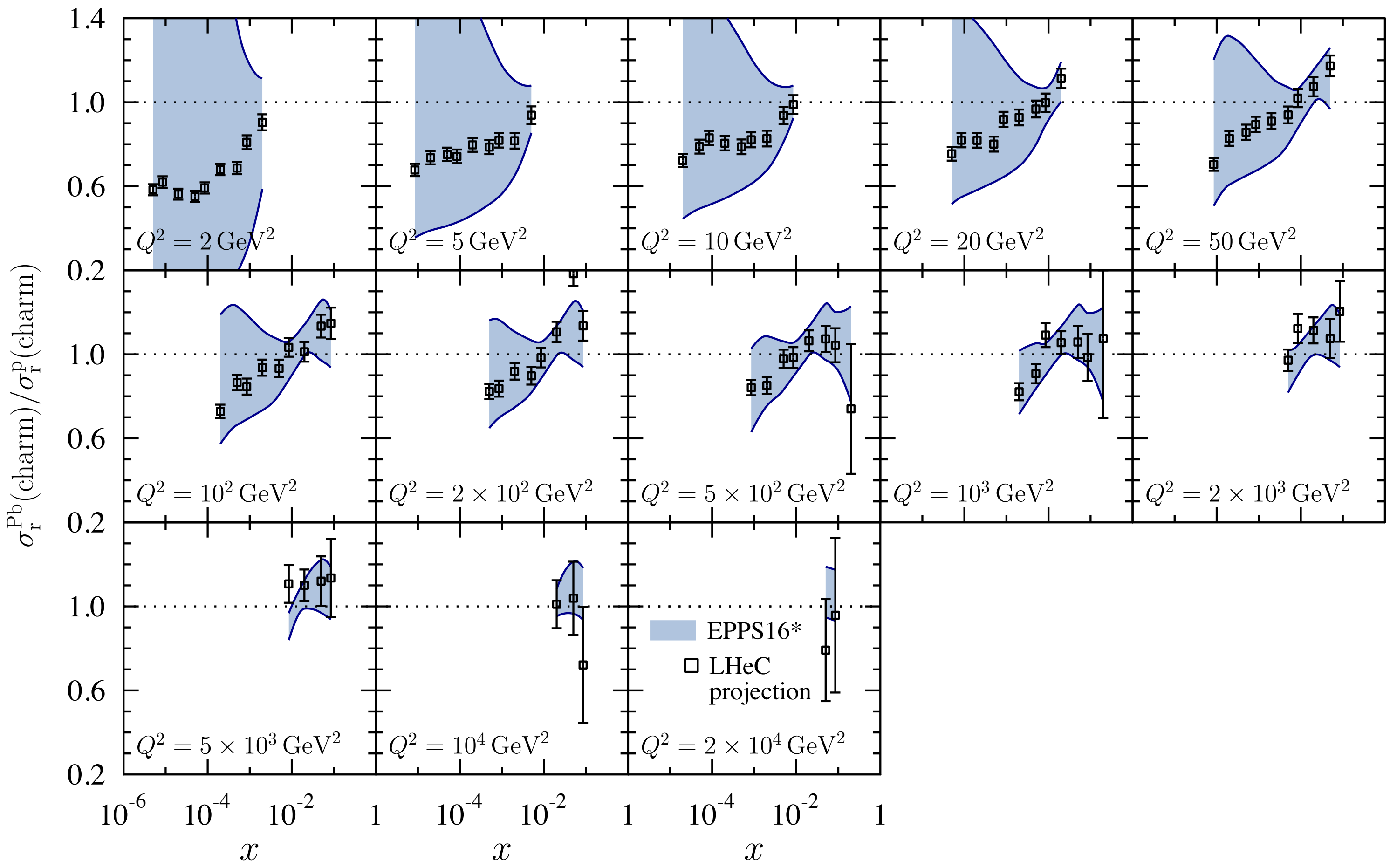
nPDFs from LHeC in global fit context



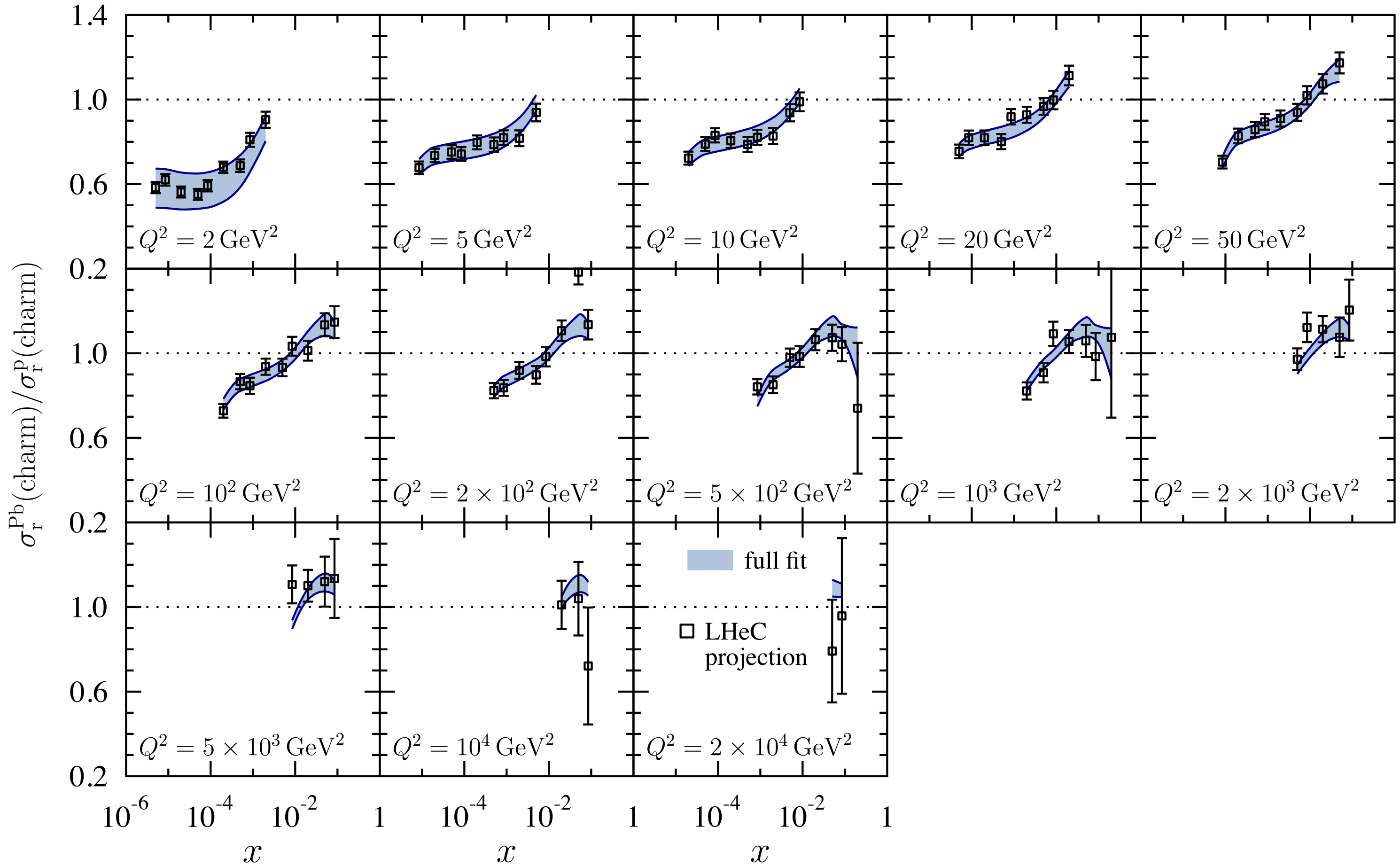
nPDFs from LHeC in global fit context



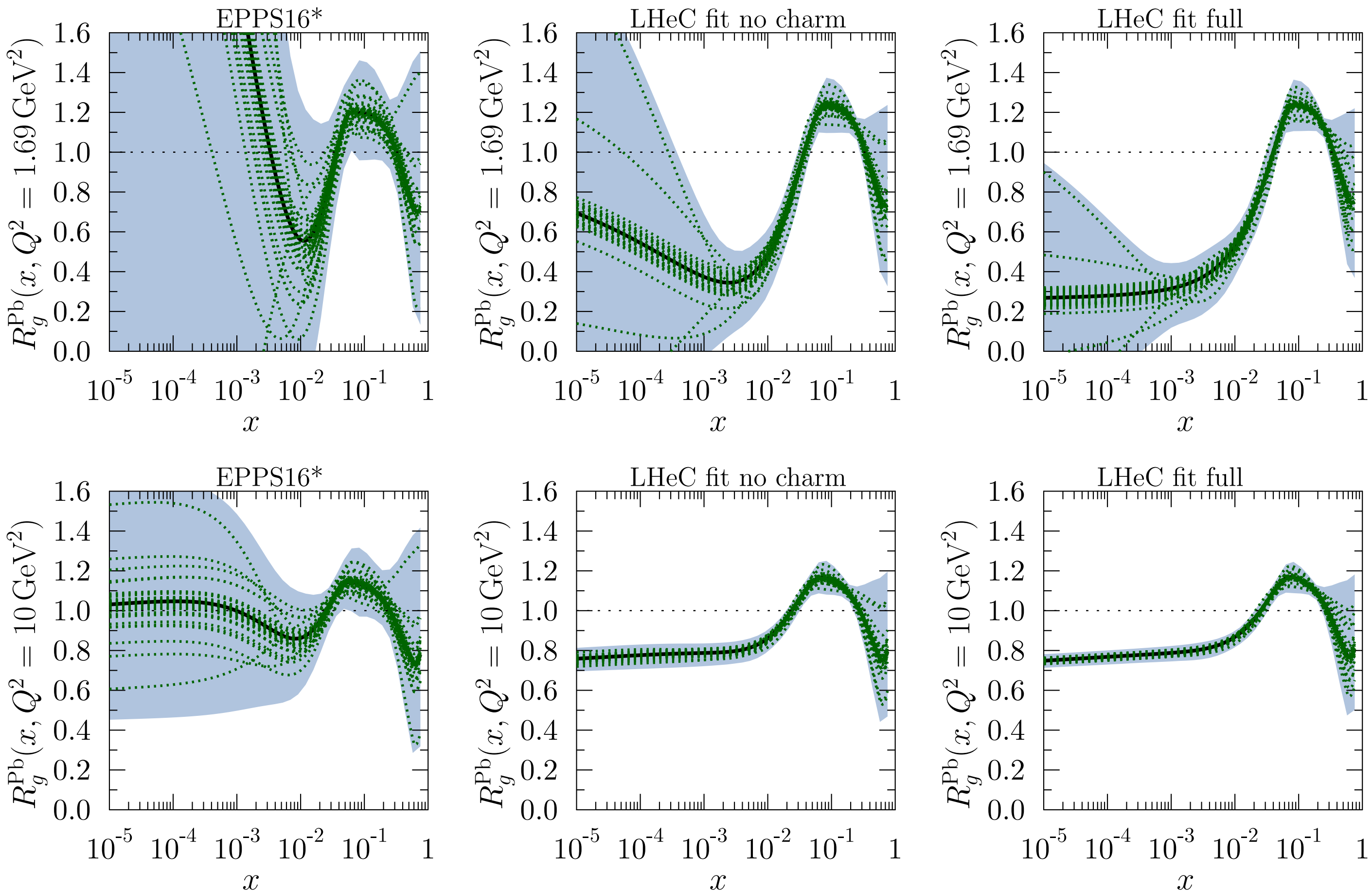
nPDFs from LHeC in global fit context



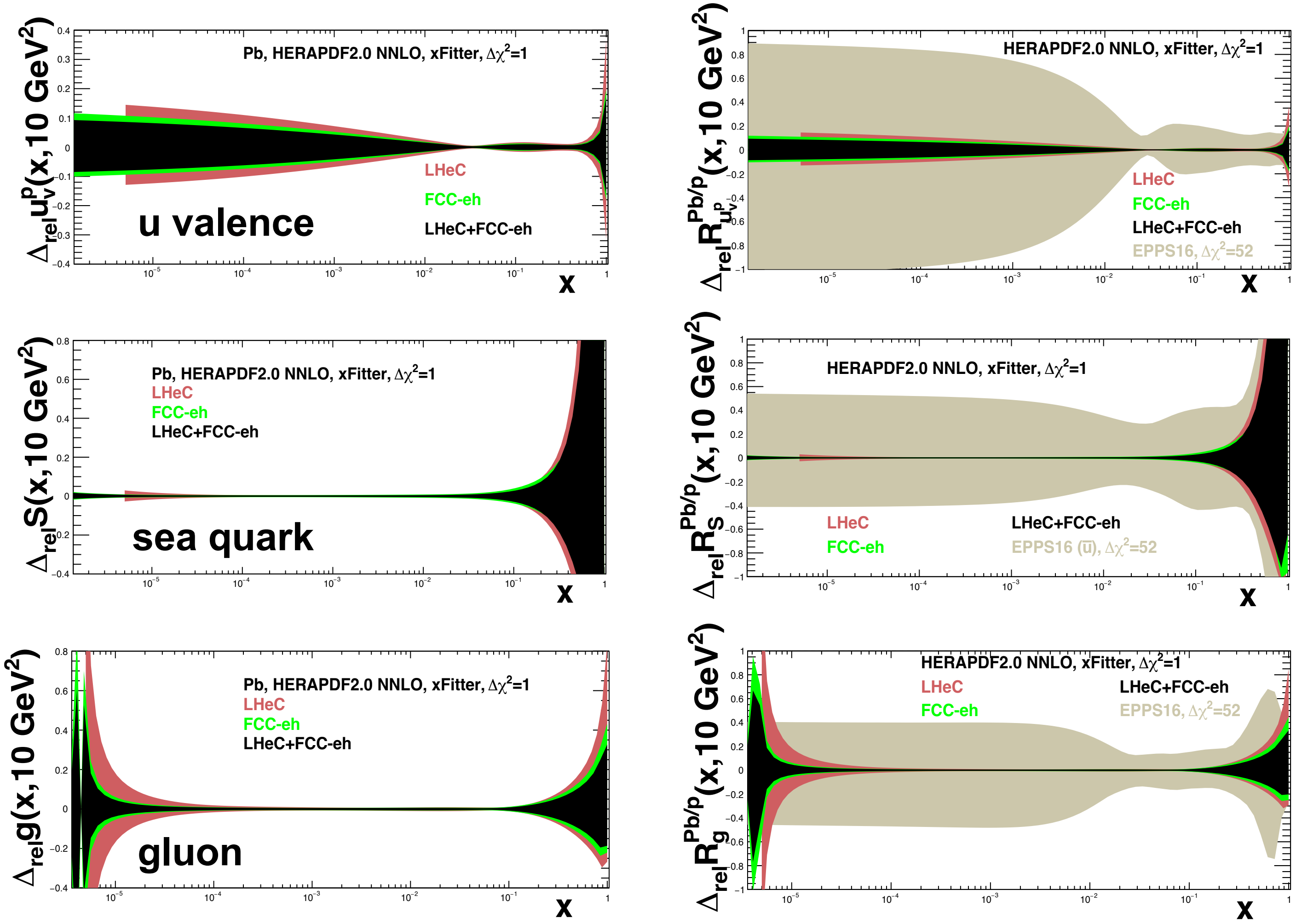
nPDFs from LHeC in global fit context



nPDFs from LHeC in global fit context

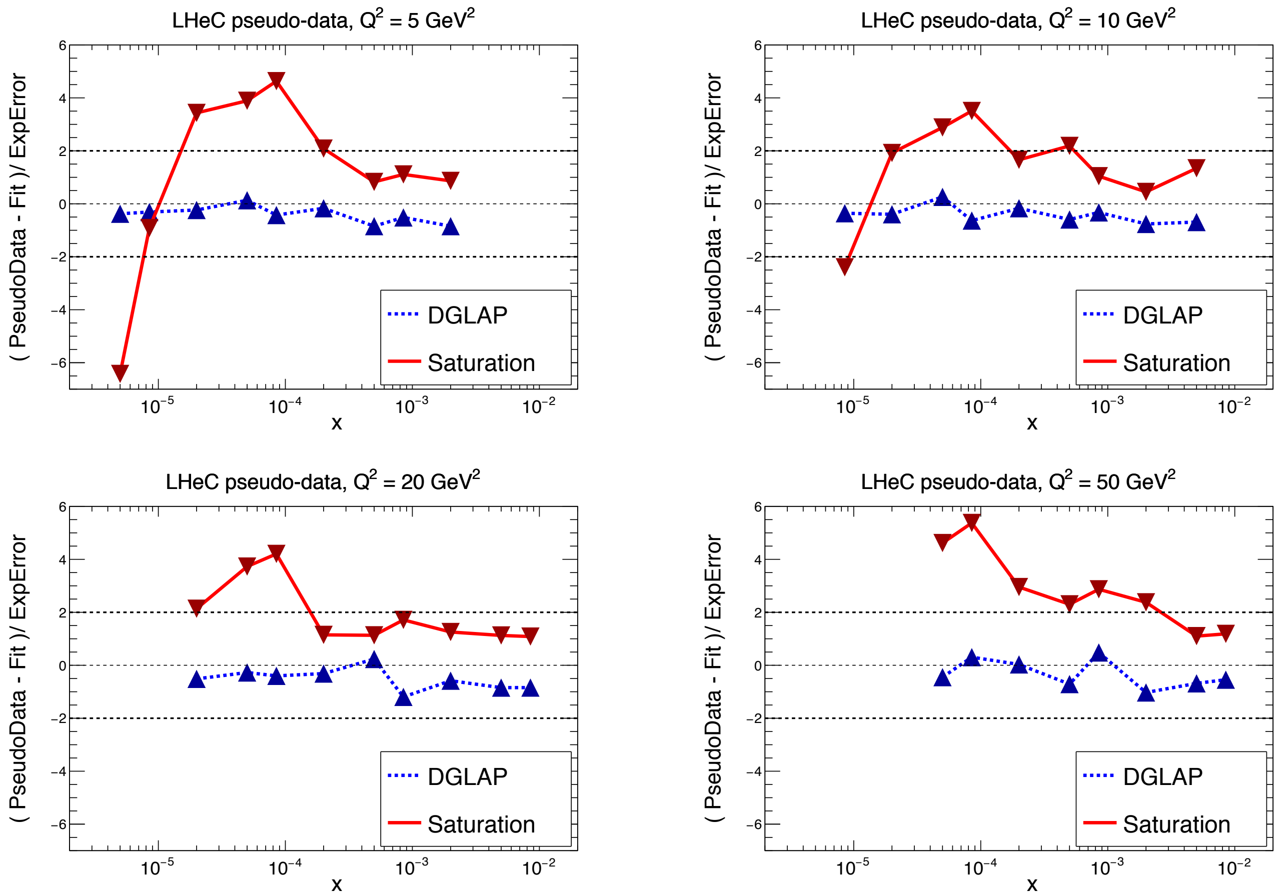


nPDFs from DIS on single nucleus



- **nuclear pdfs** using NC and CC DIS alone on **single nucleus** – only experimental uncertainties (**ΔX^2**=1)
- **significant uncertainty reduction at all x ; also allows stringent tests of collinear factorization in pA**
- expect further improvements from : charm, beauty, strange from CC with tagged charm

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**

small x treatment matters

(arXiv:2211.10142)

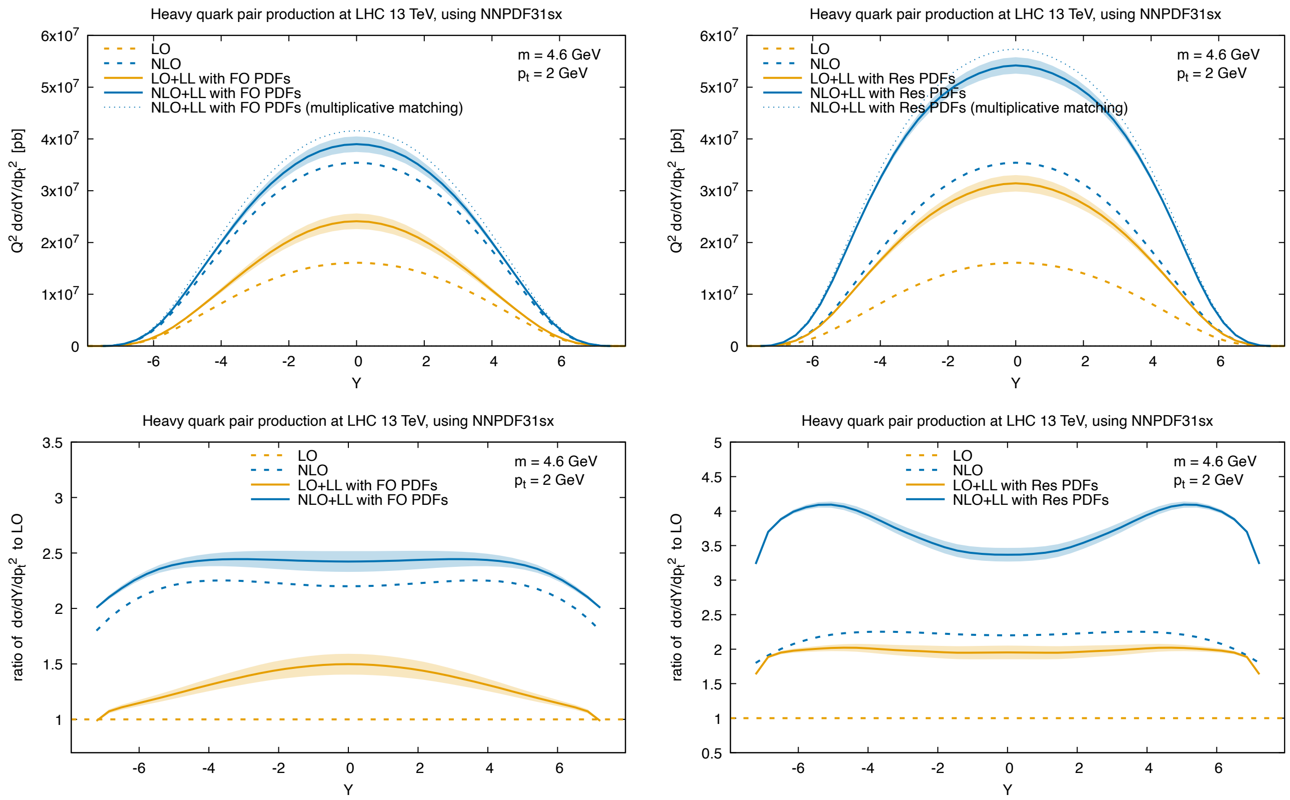


Figure 2. The double differential distribution in rapidity and transverse momentum of the bottom quark, plotted as a function of the rapidity for $p_t = 2$ GeV, for bottom pair production at LHC 13 TeV. The left plots are obtained using NNPDF31sx at fixed order, while in the right plot the resummed result is computed with the resummed PDFs from the same family. The uncertainty band represents an estimate of NLL corrections.