



Unravelling non-linear parton dynamics at small x through high energy ep and eA scattering.....

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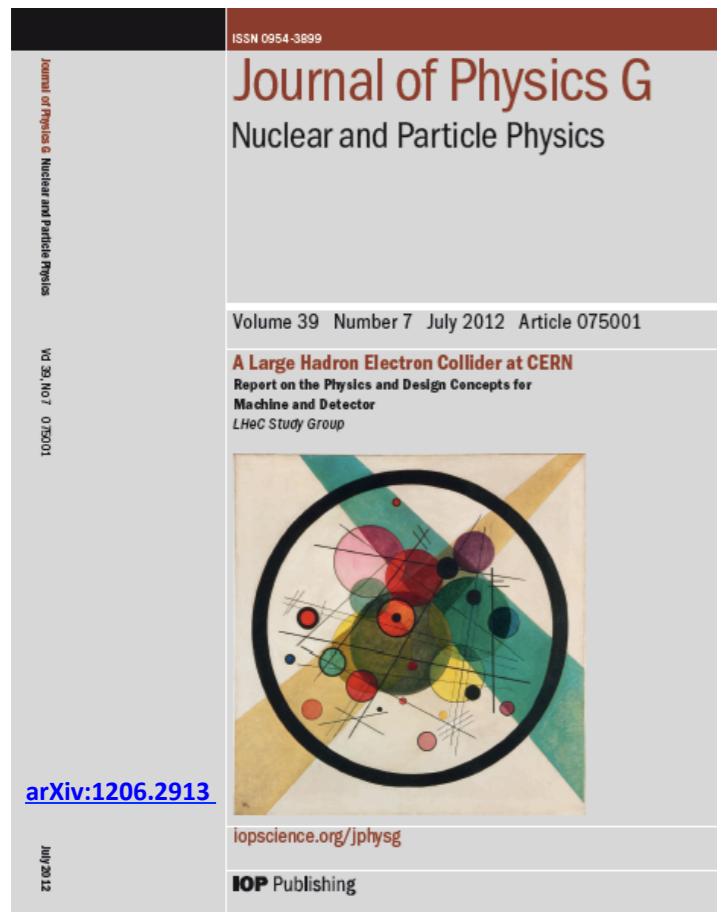
DIS2022, May 5, 2022

Outline

- Introduction: LHeC and FCC-eh parameters and kinematics
- Parton distributions at small x
- Potential for testing resummation and saturation
- Longitudinal structure function
- Diffractive phenomena

LHeC Conceptual Design Report and beyond

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



arXiv:1206.2913

Further selected references:

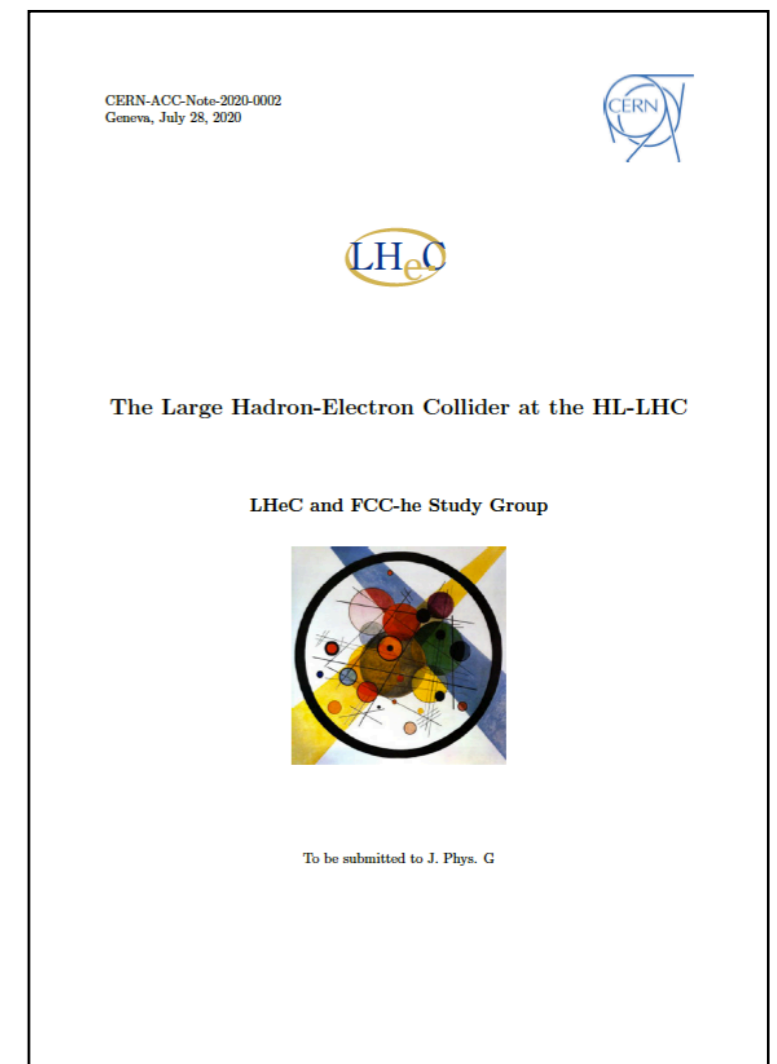
On the relation of the LHeC and the LHC
arXiv:1211.5102

The Large Hadron Electron Collider
arXiv:1305.2090

Dig Deeper
Nature Physics 9 (2013) 448

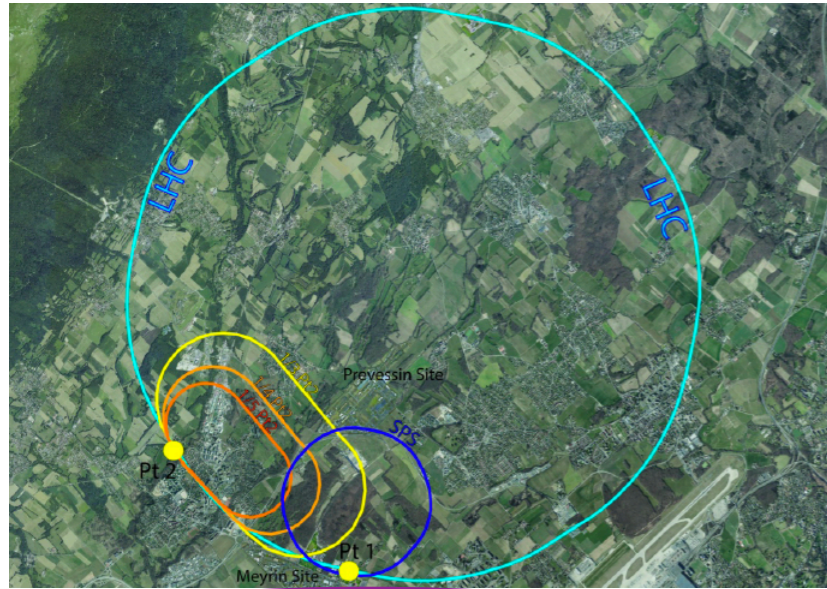
Future Deep Inelastic Scattering with the LHeC
arXiv:1802.04317

CDR update 2020
300 authors, 156 institutions



arXiv:2007.14491

Accelerator concepts for electron-proton collisions



50 x 7000 GeV²: 1.2 TeV ep collider

Operation: 2035+, Cost: O(1) BCHF

CDR: 1206.2913 J.Phys.G (550 citations)

Upgrade to 10³⁴ cm⁻²s⁻¹, for Higgs, BSM

CERN-ACC-Note-2018-0084 (ESSP)

arXiv:2007.14491, subm J.Phys.G

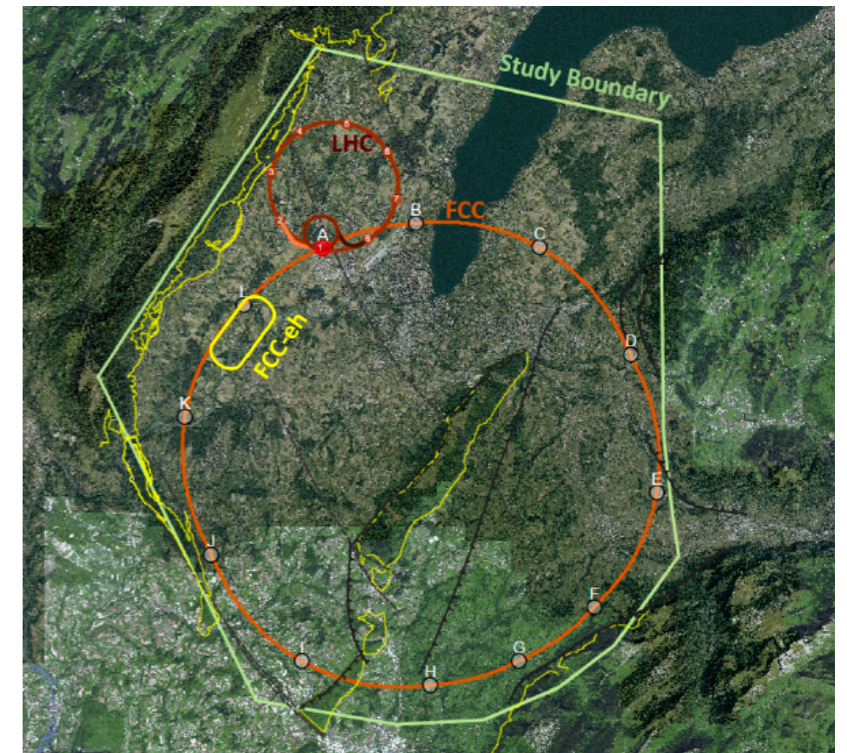
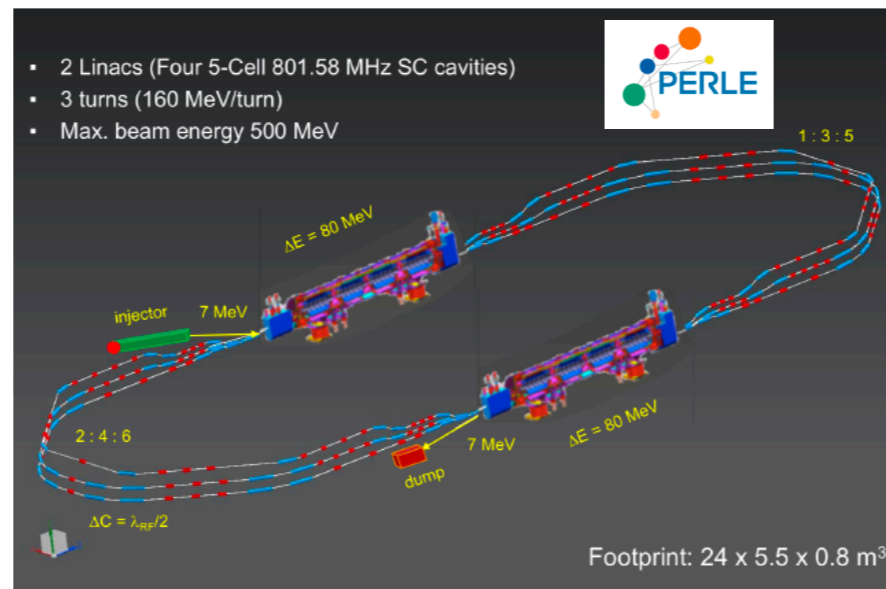
LHeC, PERLE and FCC-eh

Powerful ERL for Experiments @ Orsay
CDR: 1705.08783 J.Phys.G
CERN-ACC-Note-2018-0086 (ESSP)

Operation: 2025+, Cost: O(20) MEuro

LHeC ERL Parameters and Configuration
 $I_e=20\text{mA}$, 802 MHz SRF, 3 turns \rightarrow
 $E_e=500\text{ MeV} \rightarrow$ first 10 MW ERL facility

BINP, CERN, Daresbury, Jlab, Liverpool, Orsay (IJC), +



60 x 50000 GeV²: 3.5 TeV ep collider

Operation: 2050+, Cost (of ep) O(1-2) BCHF

Concurrent Operation with FCC-hh

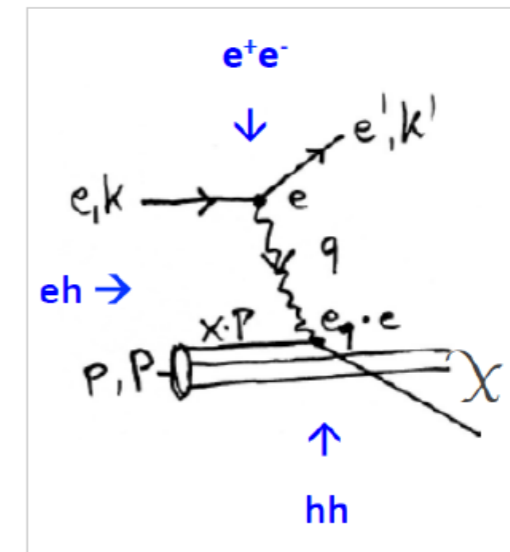
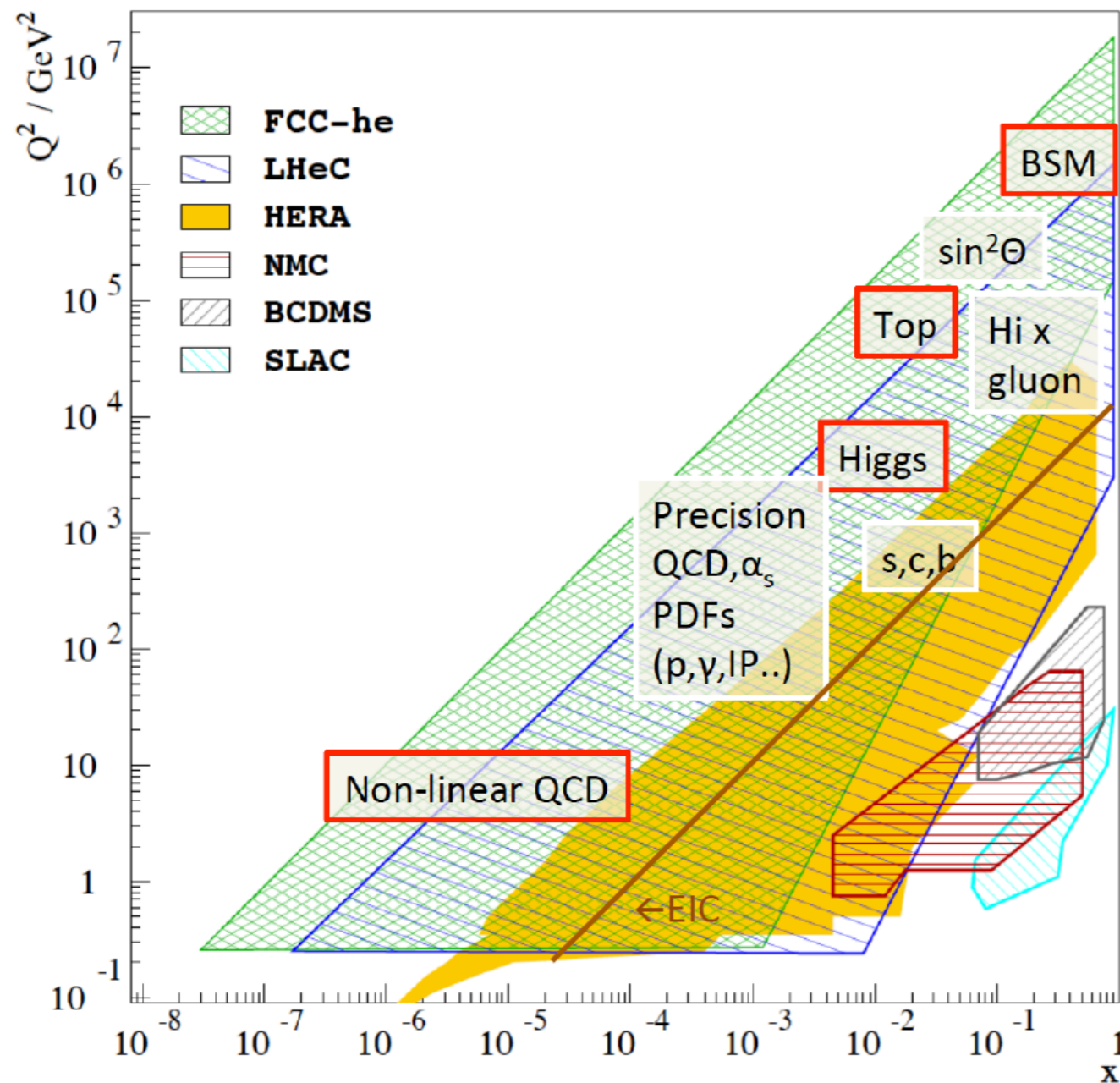
FCC CDR:

Eur.Phys.J.ST 228 (2019) 6, 474 Physics

Eur.Phys.J.ST 228 (2019) 4, 755 FCC-hh/eh

Future CERN Colliders: 1810.13022 Bordry+

Physics with Energy Frontier DIS



ep/eA collider: cleanest high resolution microscope

Precision and discovery in QCD

Study of EW physics, multi-jet final states

Transform the LHC/FCC into a high precision Higgs facility

Unique and complementary potential for the BSM studies

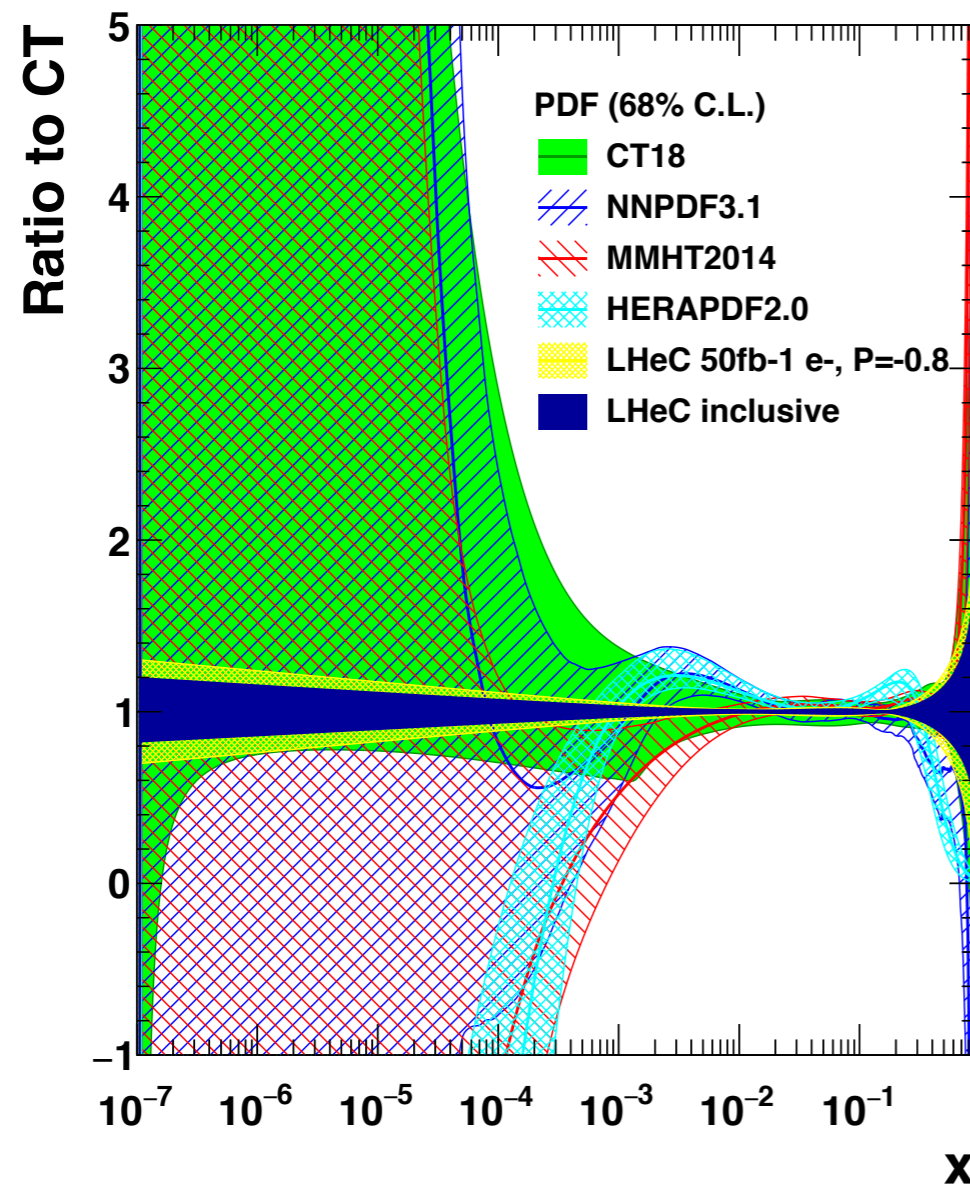
Empower the LHC/FCC search programme

Overall: a unique Particle and Nuclear Physics Facility

Parton distributions at small x

Complete unfolding of parton contents in
unprecedented kinematic range: u,d,s,c,b,t,g

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

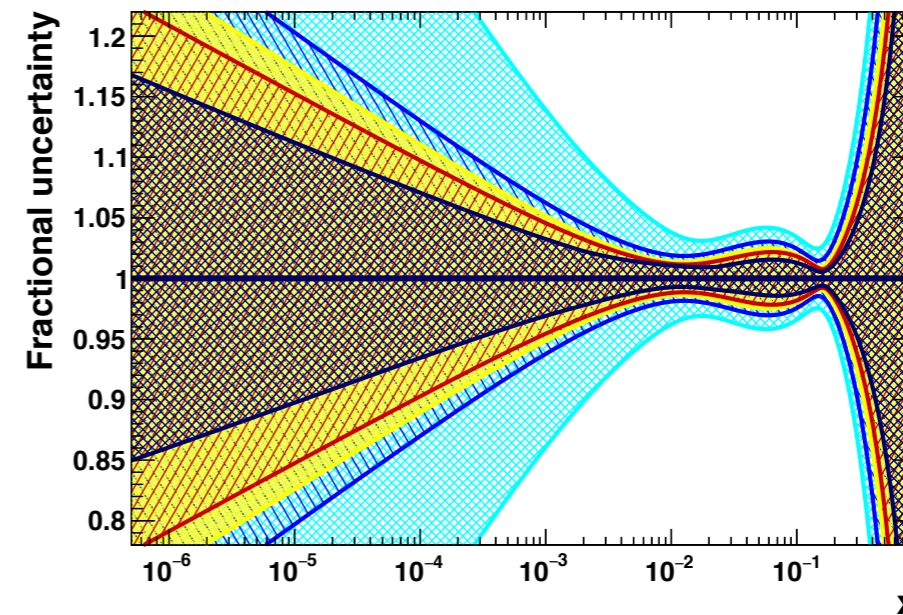


HERA kinematic limitations to $x \sim 5 \cdot 10^{-4}$

LHeC can constrain gluon down to $x \sim 10^{-5}$

Few percent precision on the gluon

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



Sensitivity to different integrated luminosities:

(Blue, yellow, red, dark blue) 5,50,1000 fb^{-1} and inclusive

Compared with HERA

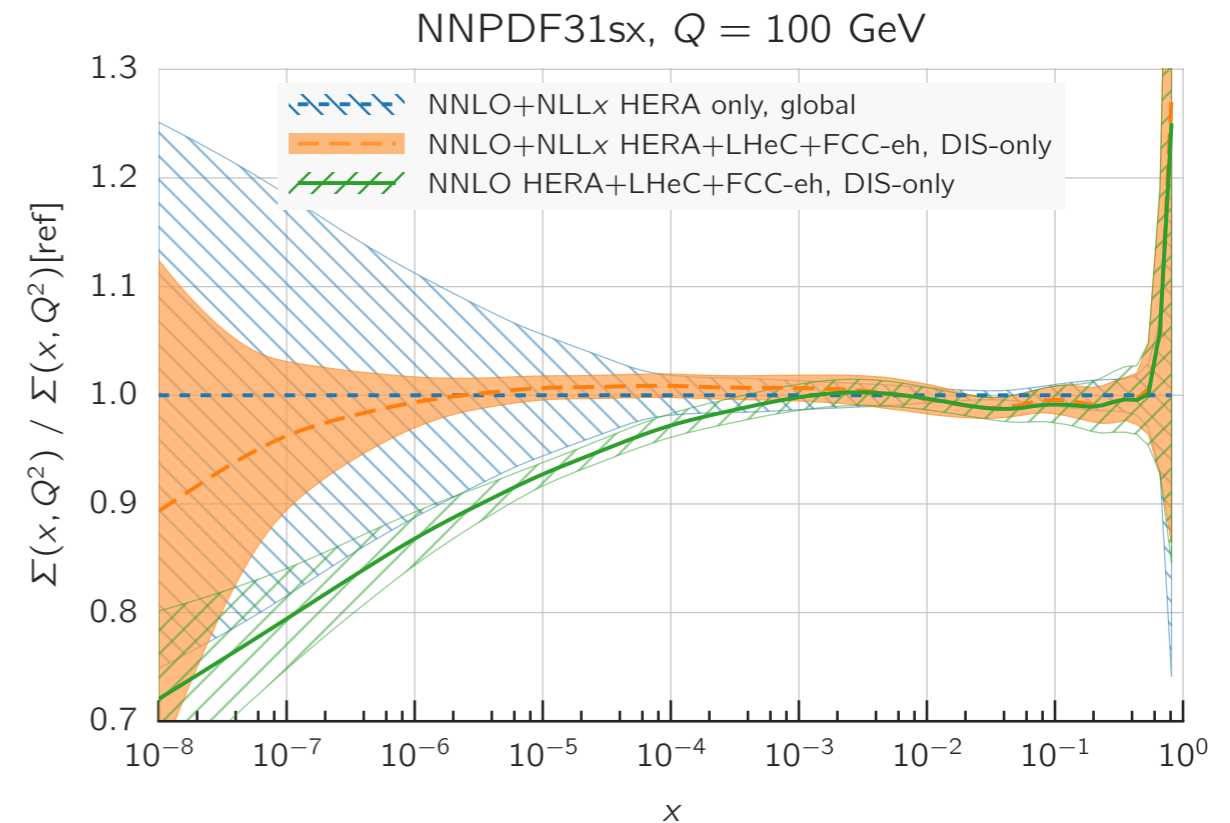
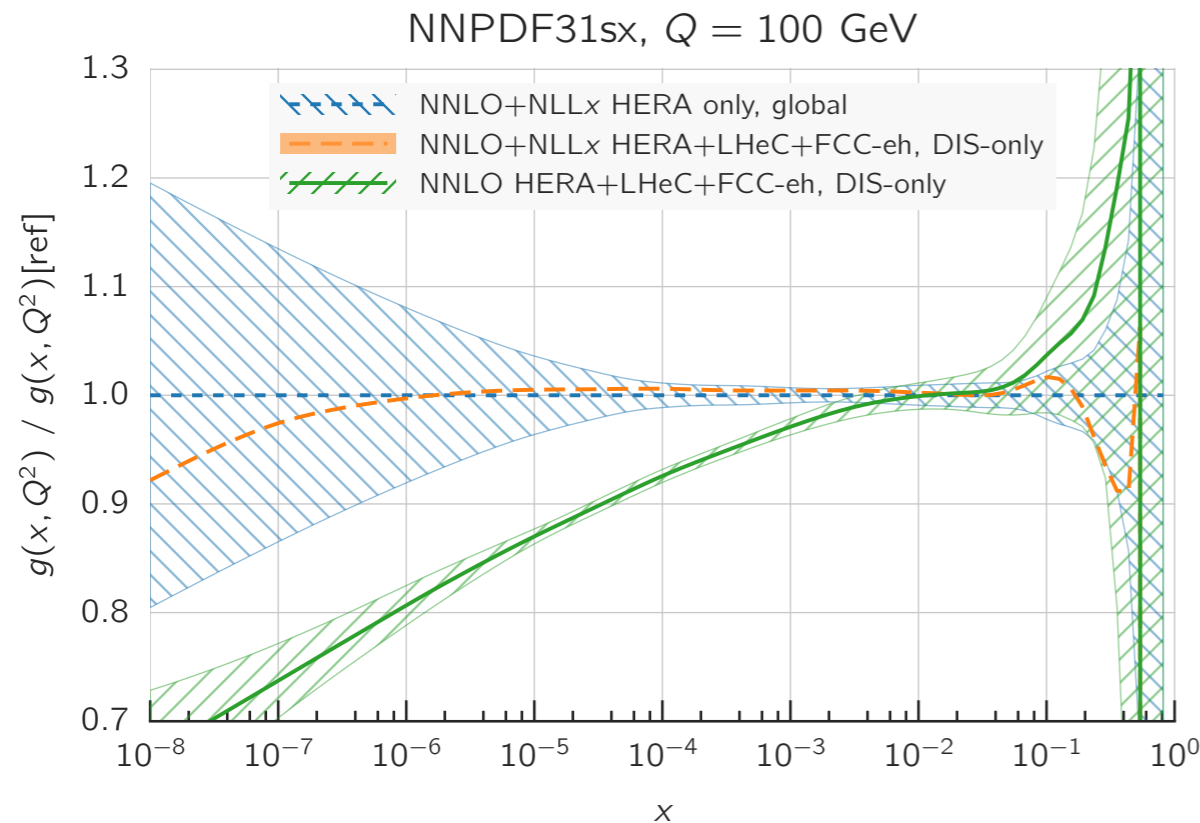
See more on PDFs at LHeC: Talk by Claire Gwenlan

Novel dynamics at small x : resummation

Resummation at low x needed to stabilize BFKL expansion

Fits to HERA data: DGLAP + resummation, improve the description at low x

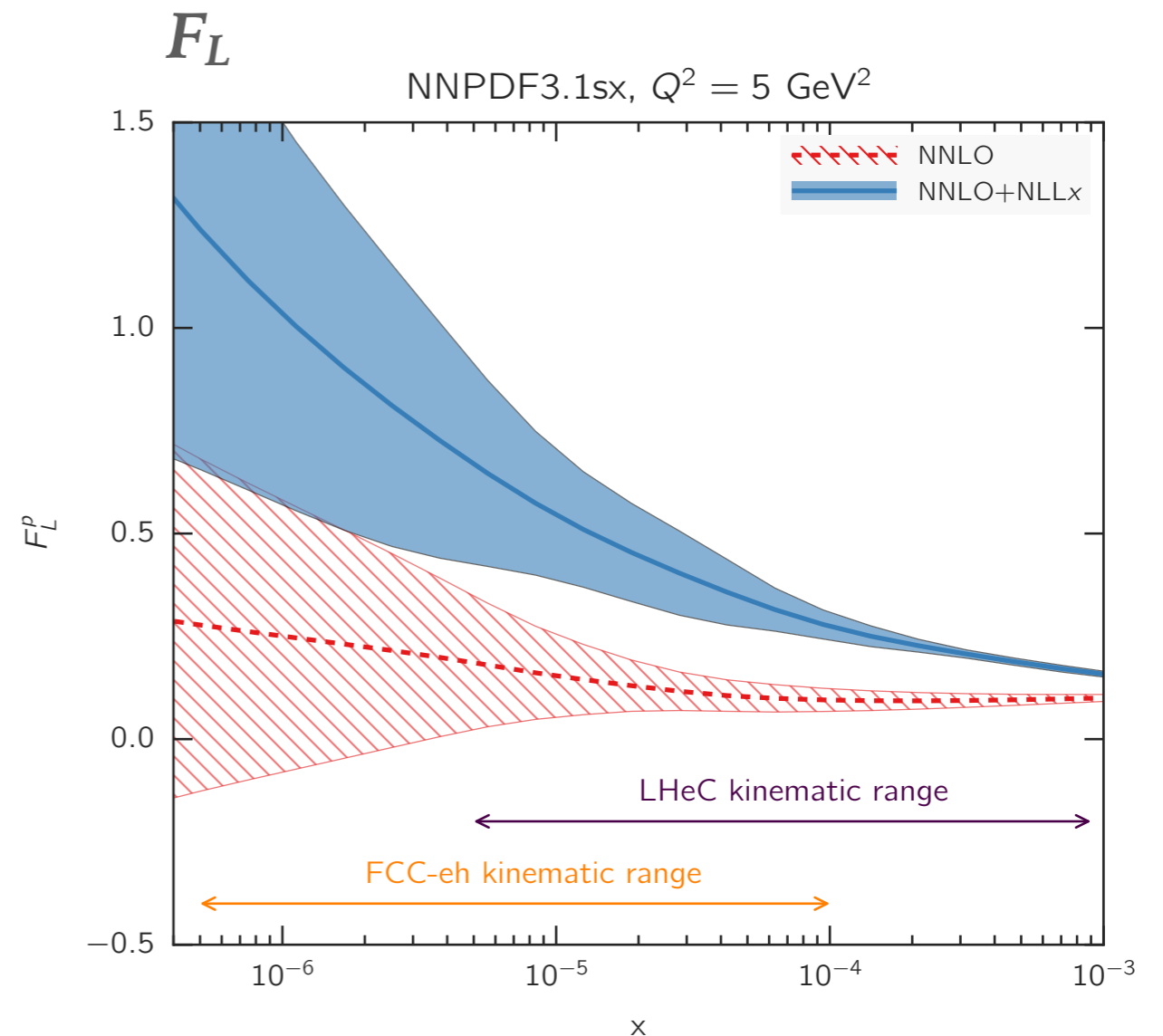
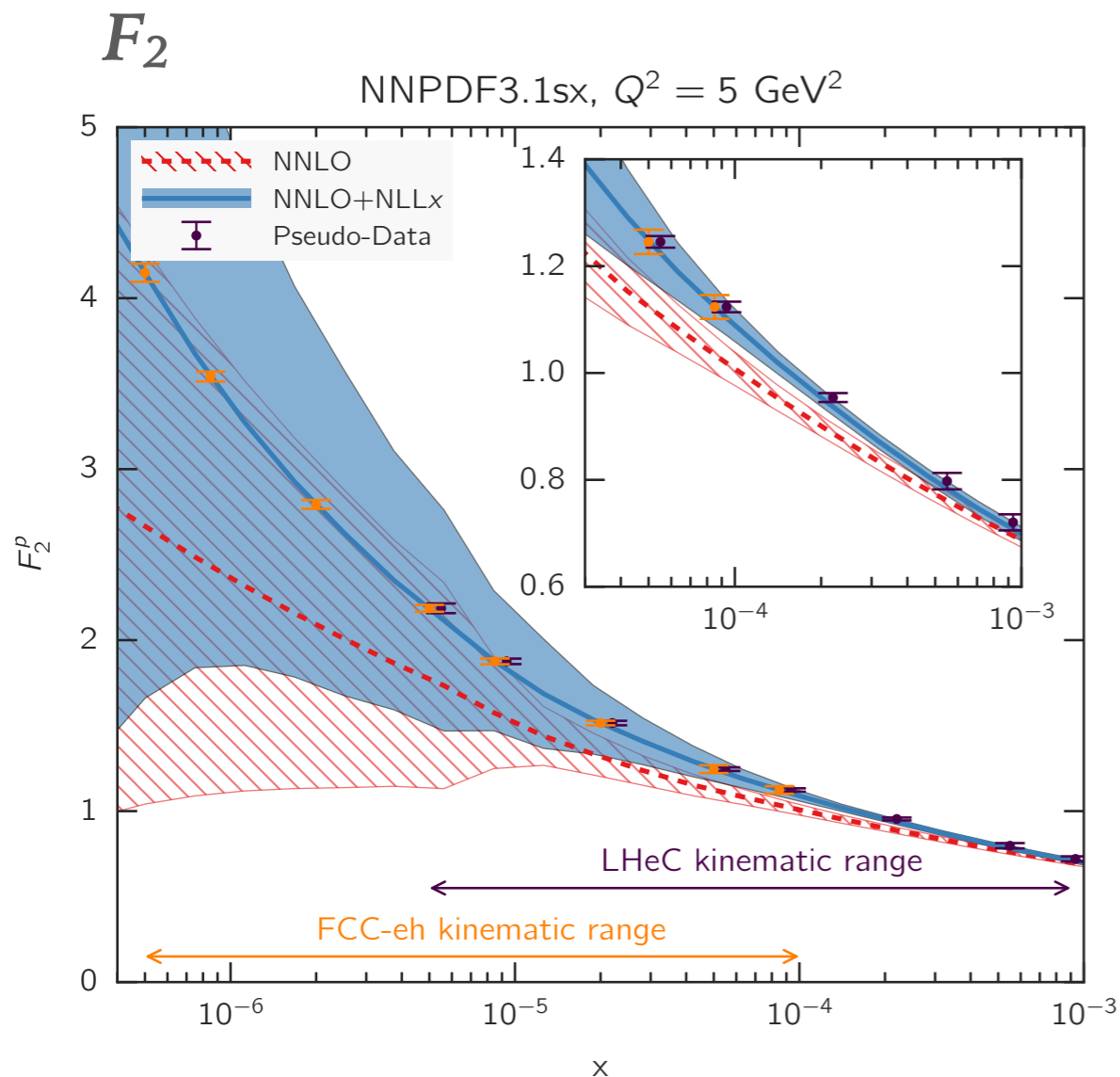
Ball, Bertone, Bonvini, Marzani, Rojo, Rottoli



Large differences in the parton density at low x .

Essential for LHeC and FCC-eh

Novel dynamics at small x : resummation



Important consequences for LHeC and FCC-eh

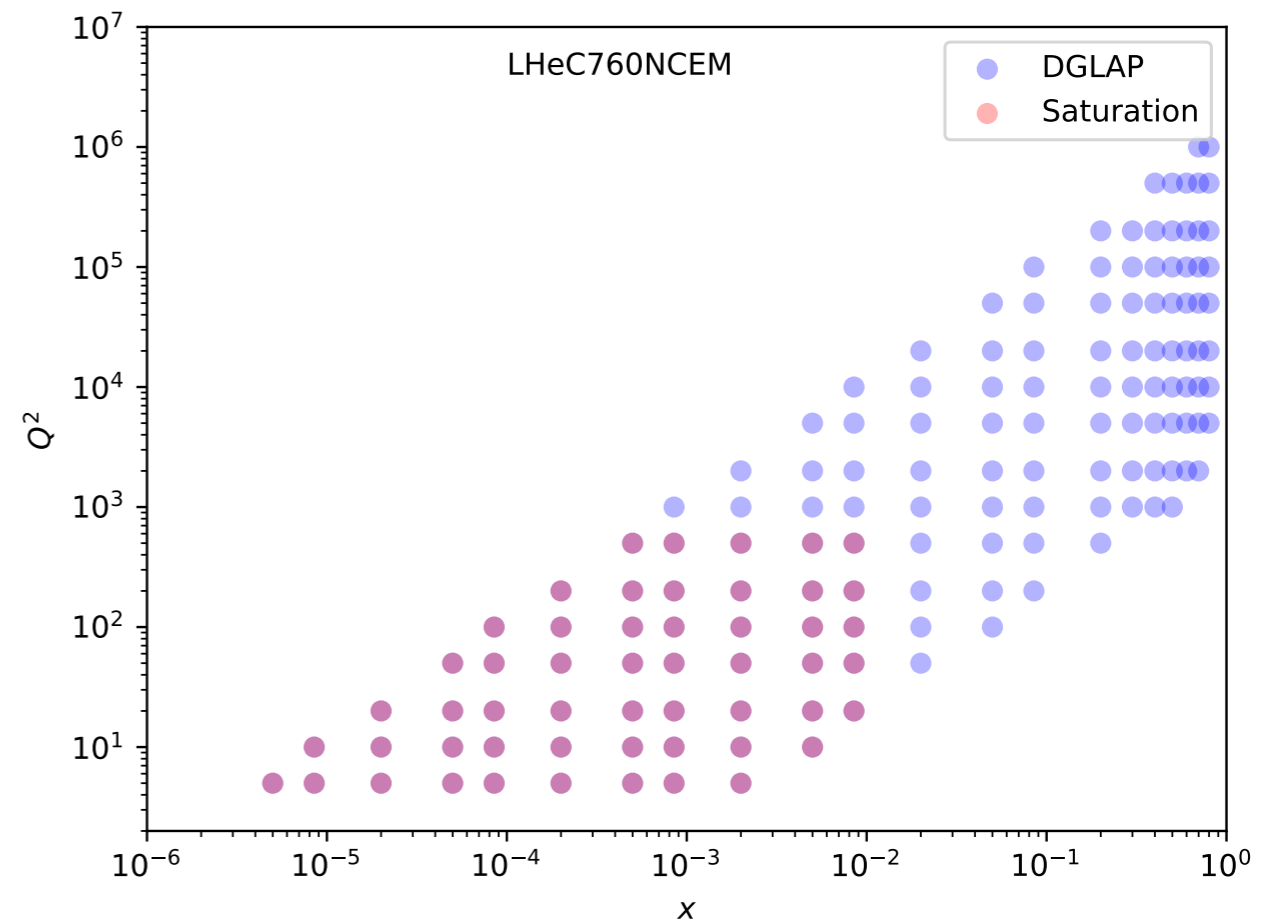
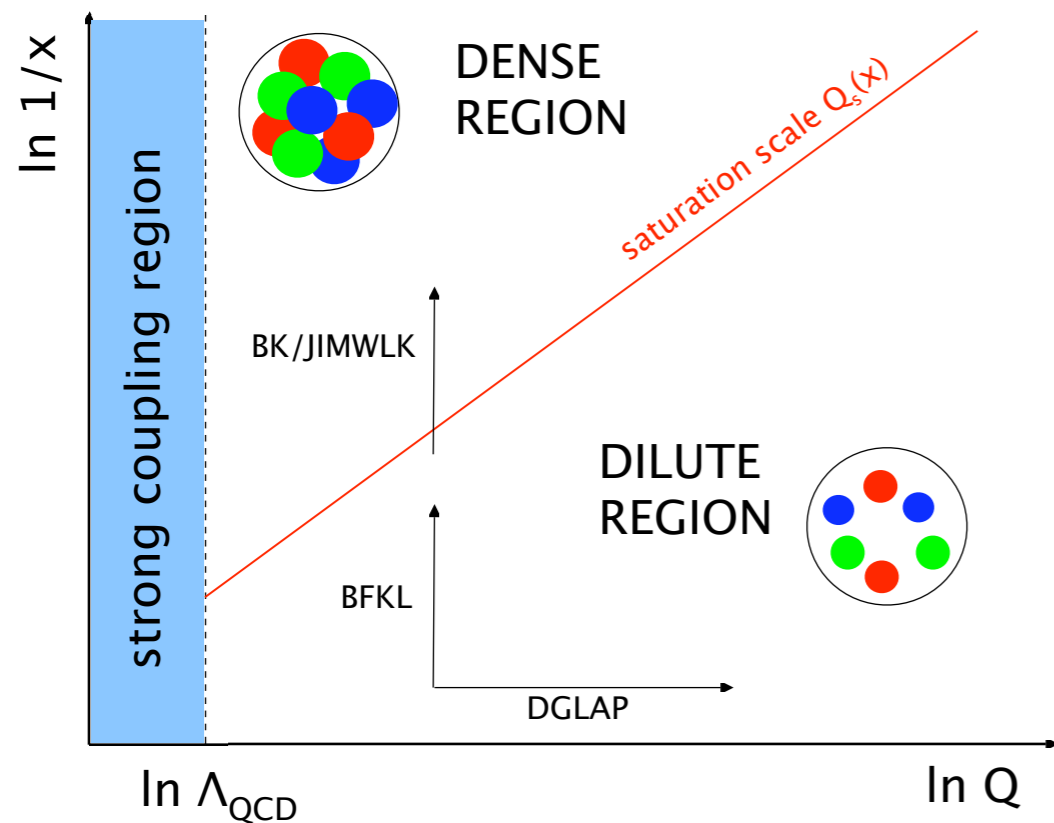
20-40% difference of central values for F_2

Factor 2 to 4 for F_L

DGLAP fit will likely fail at the LHeC range

Resummation mandatory for LHeC and FCC-eh

Novel dynamics at small x: saturation



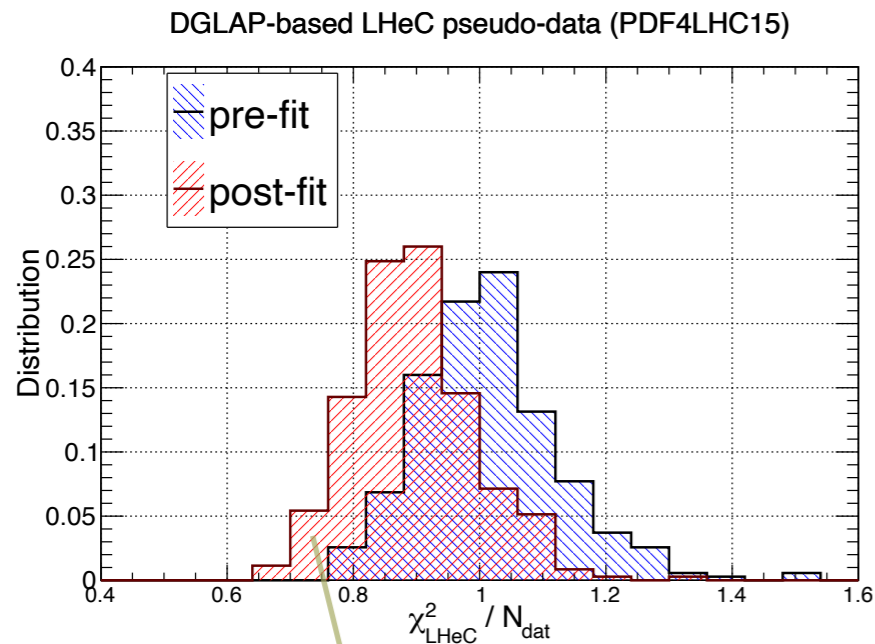
Test for saturation potential at LHeC:

Simulated pseudodata with saturation at low x

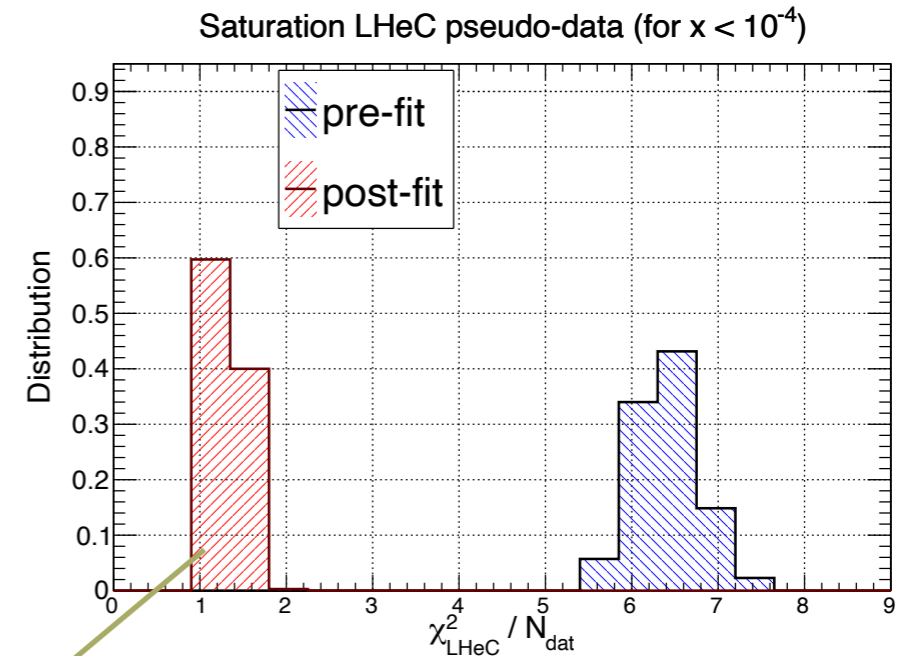
In the rest of kinematic range use DGLAP to simulate the data

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

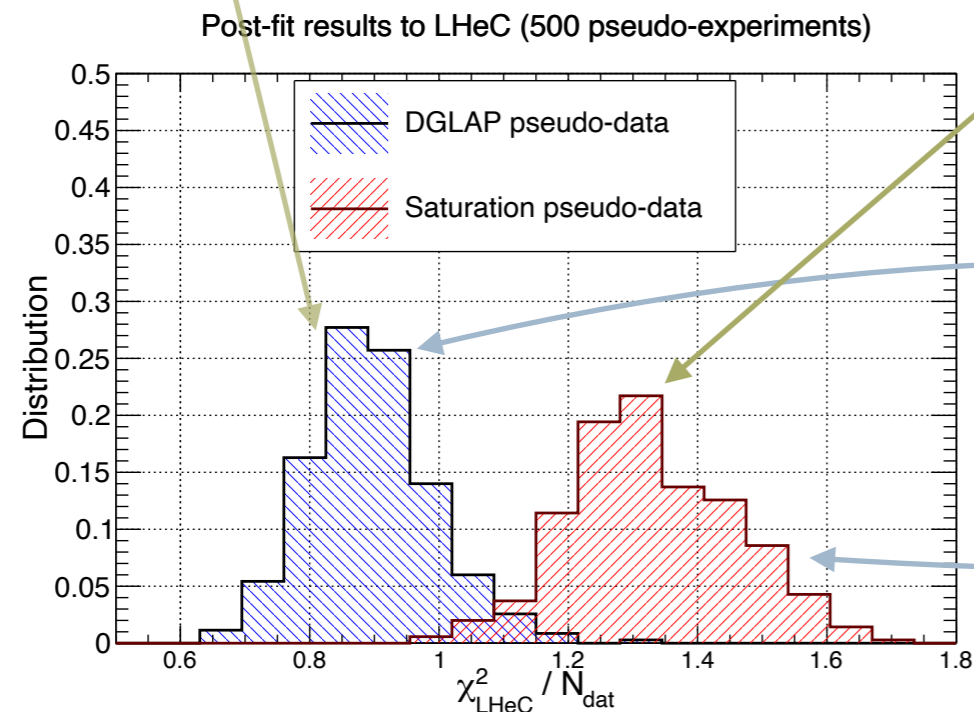
Testing for saturation at the LHeC



Pre-fit and post-fit distribution consistent for DGLAP based LHeC pseudodata



Pre-fit and post-fit distribution very different for DGLAP fit to pseudodata with saturation



DGLAP can accommodate some effects from saturation, but not all

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

Longitudinal structure function

Simultaneous measurement of F_2 and F_L is a cleanest way to pin down dynamics at low x

Independent constraint on the gluon density

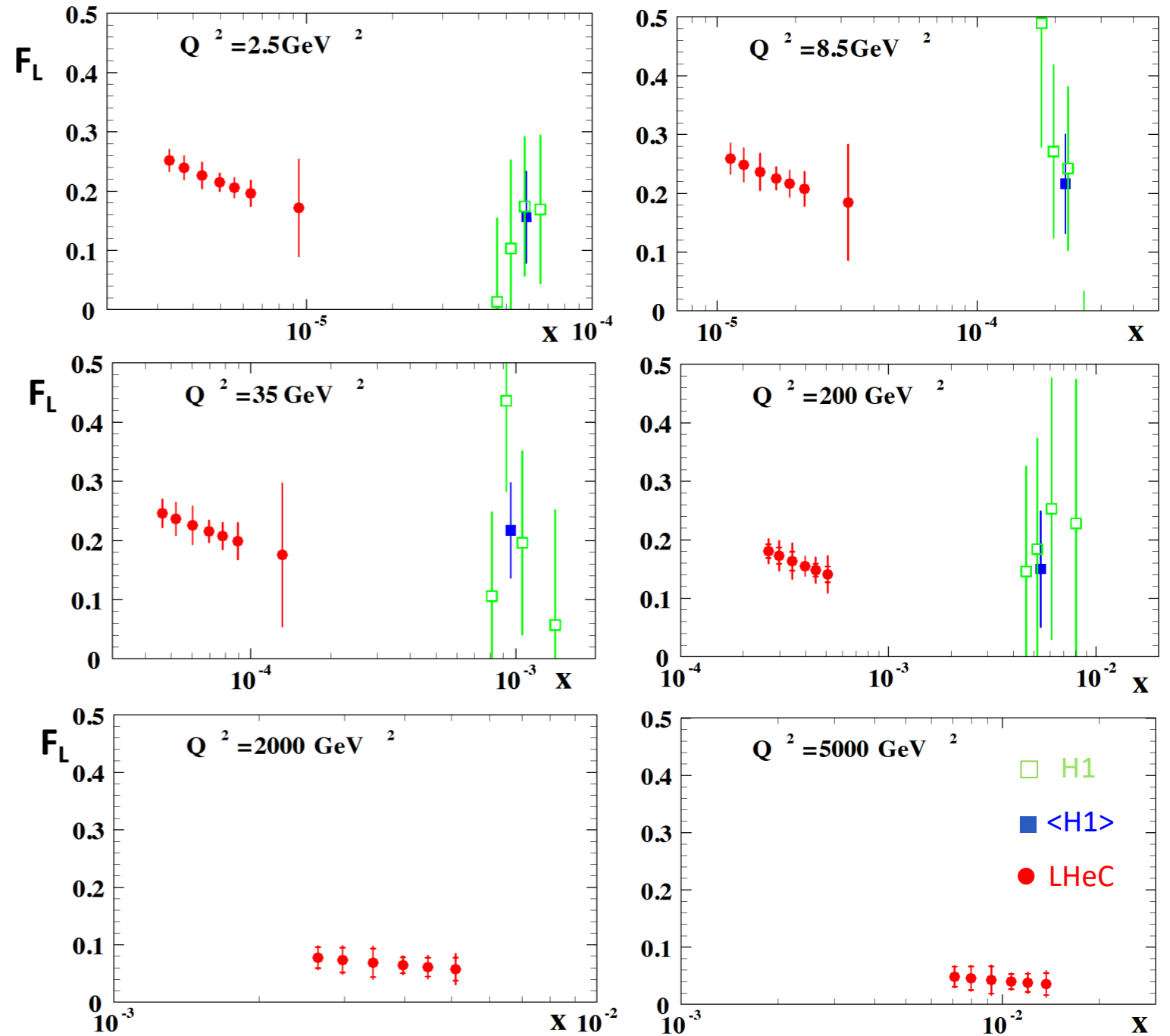
Pseudodata simulated for $E_p=7$ TeV and $E_e=60, 30, 20$ GeV

Integrated luminosity: 10,1,1 fb⁻¹

Uncertainties: E_e' scale uncertainty from 0.5% to 1.2%, θ_e to 0.2 mrad, background contamination from photo-production 0.5%, radiative corrections to 1%. Uncorrelated systematic error 0.2-0.5%

F_L obtained from the slope of the fit to $\sigma_r = F_2 - f(y)F_L$

Measurement dominated by systematics

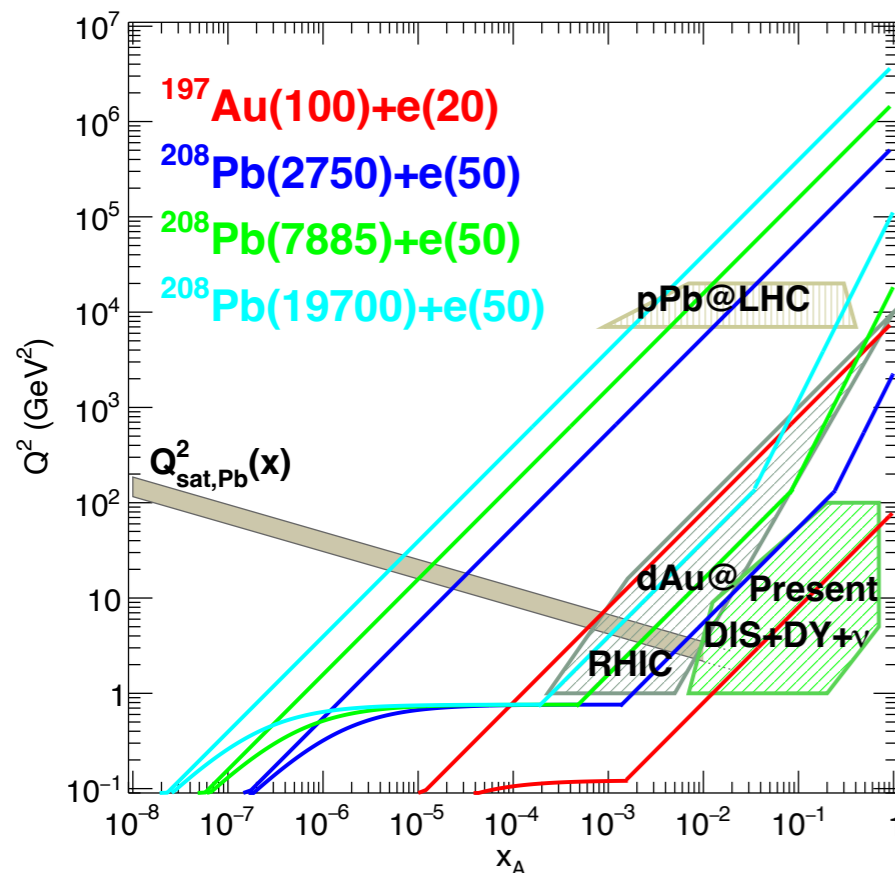


Prospect for much higher quality of F_L which would allow to discover departures from DGLAP

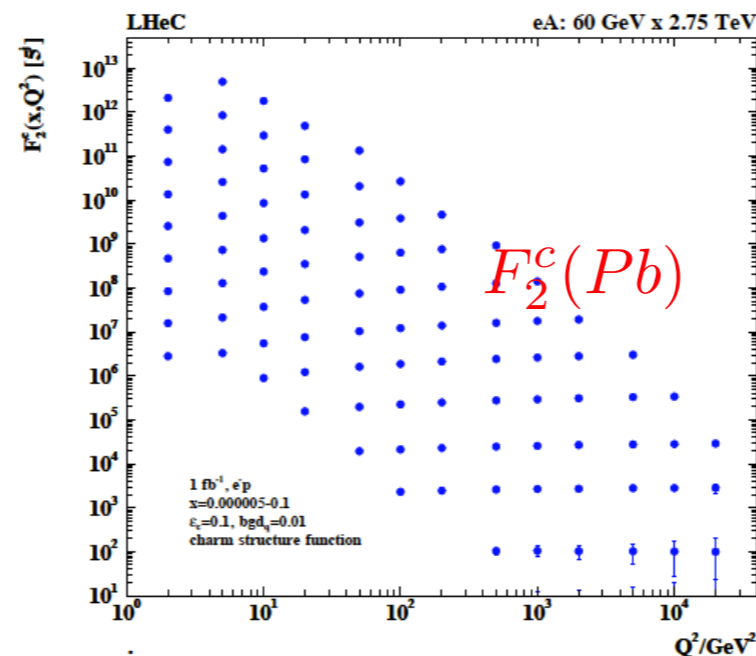
LHeC as eA collider

- eA at LHeC/FCC-eh: x and Q^2 extended by 4 decades
- Determination of inclusive and diffractive **nuclear parton densities**
- Studies of transverse structure: 3D picture
- **Saturation** (ep & eA, nuclear enhancement)
- Flavour dependent anti shadowing, Gribov relation with diffraction,...
- Strong impact on the **pA/AA** programmes at the HL-LHC and FCC-hh

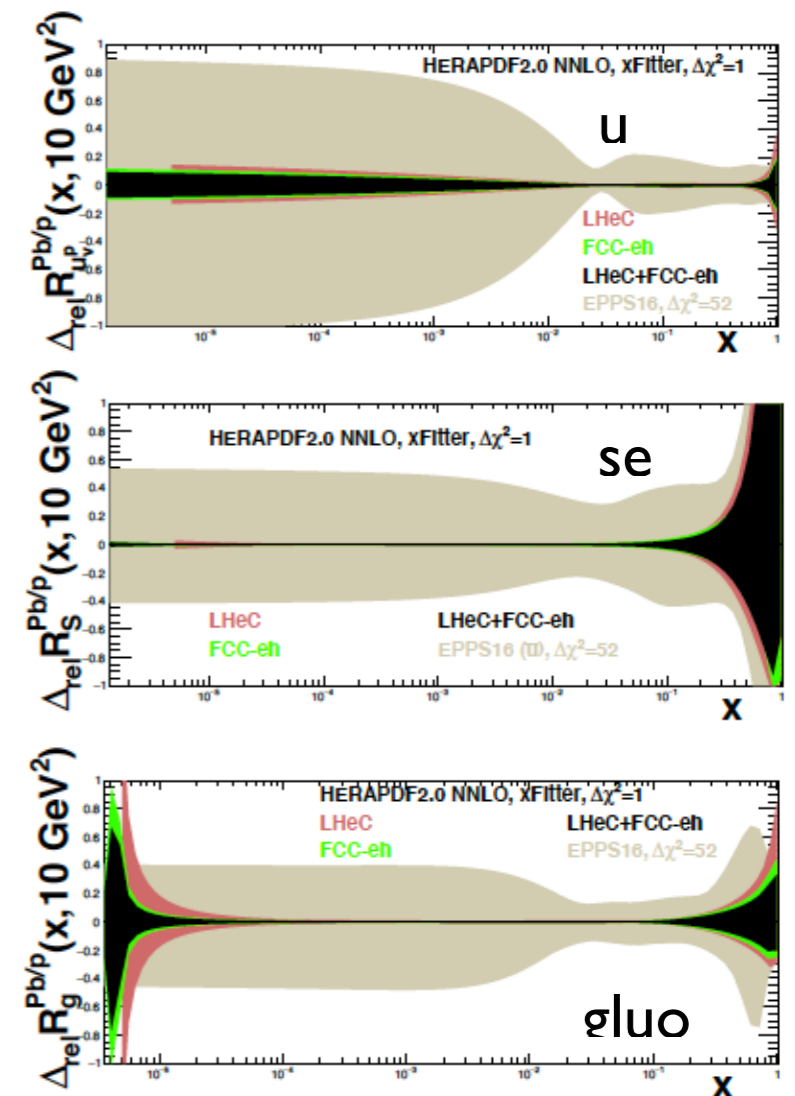
Kinematic plane for eA



Precision structure functions, also for heavy flavors



Relative uncertainties for nuclear modification factor



Unconstrained for x below 0.01

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

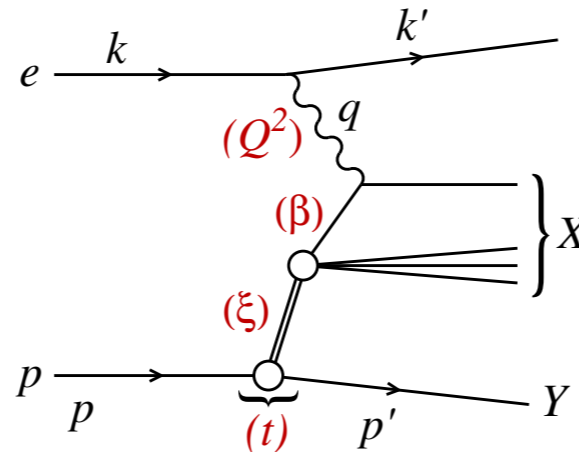
$$\beta = \frac{Q^2}{Q^2 + M_X^2 - t}$$

4-momentum transfer squared

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

Bjorken x relation

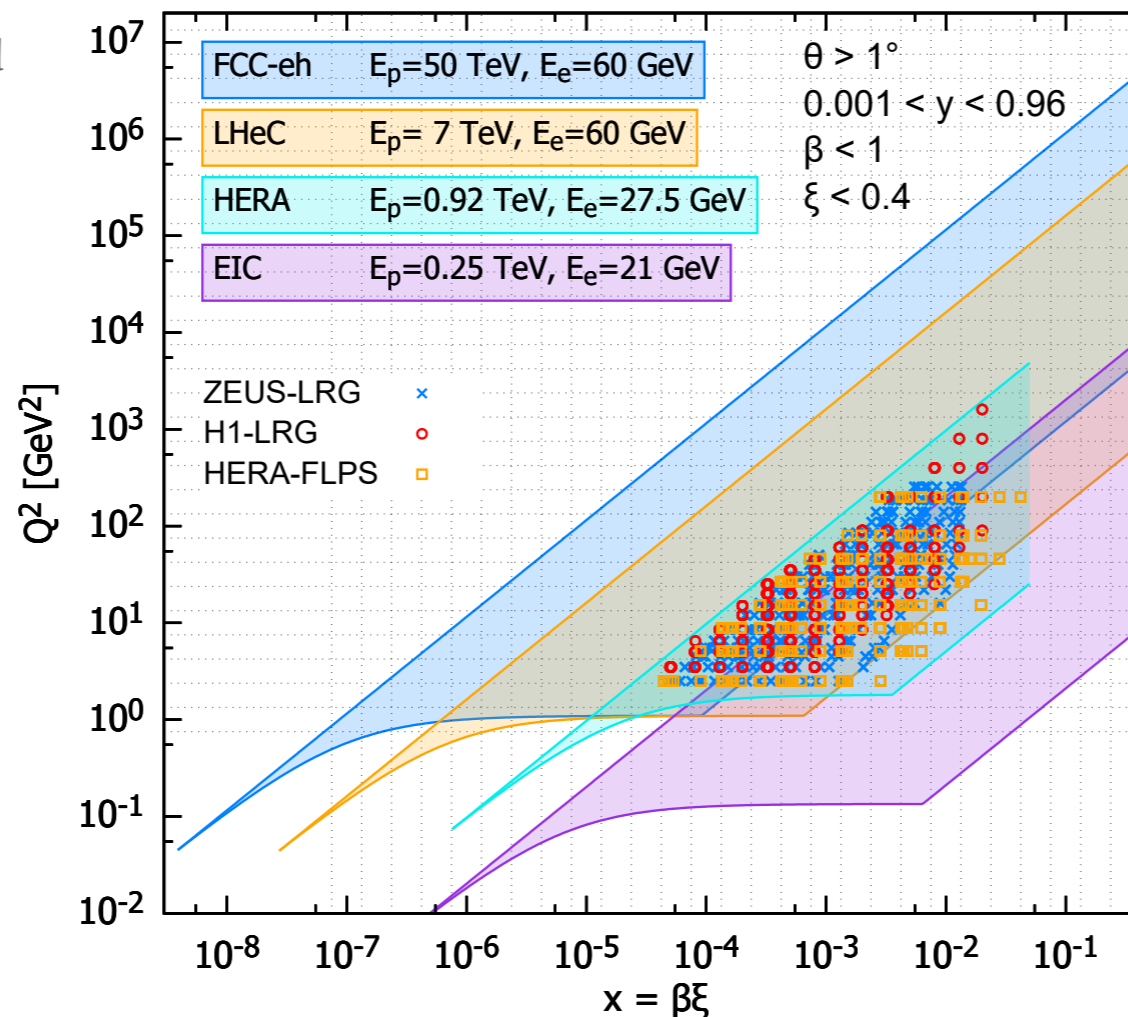
$$x_{Bj} = x_{IP}\beta$$



HERA: 10% events diffractive: **rapidity gap**

Rapidity gap events interpreted as exchange of vacuum quantum numbers **Pomeron**

Importance of diffraction for understanding of small x dynamics, shadowing, confinement, soft and collinear factorization



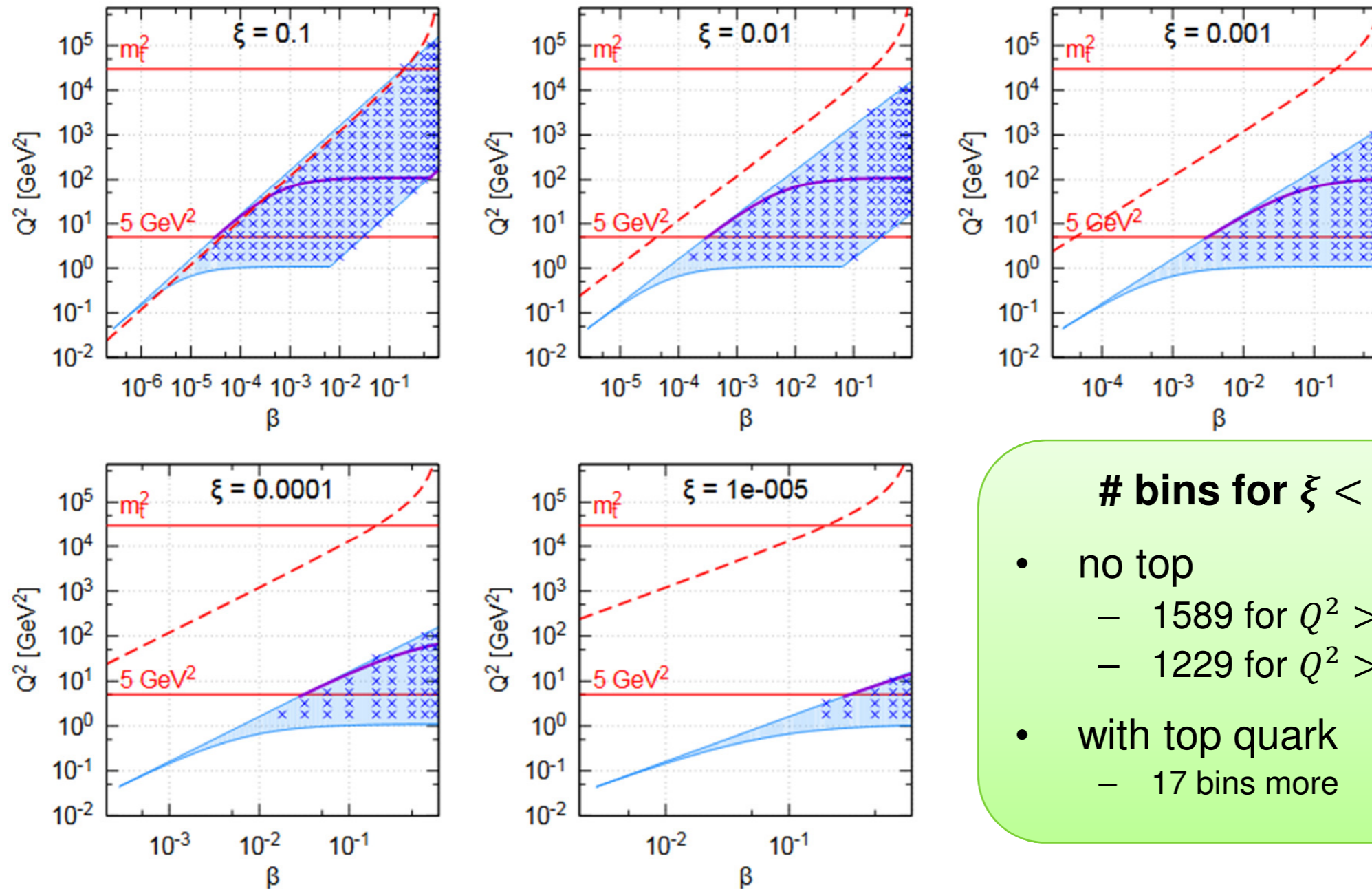
$E_e = 60 \text{ GeV}$

- **$E_p = 7 \text{ TeV}$ vs. HERA**
 - x_{\min} down by factor ~ 20
 - Q_{\max}^2 up by factor ~ 100
- **$E_p = 50 \text{ TeV}$ vs. 7 TeV**
 - x_{\min} down by factor ~ 10
 - Q_{\max}^2 up by factor ~ 10

LHeC phase space: (β, Q^2) fixed ξ

$$E_p = 7 \text{ TeV}, E_e = 60 \text{ GeV}, y_{\min} = 0.001, y_{\max} = 0.96$$

$\theta > 1^\circ$ ■ $\theta = 10^\circ$ — bins \times $M_X = 2 m_t$ - - -



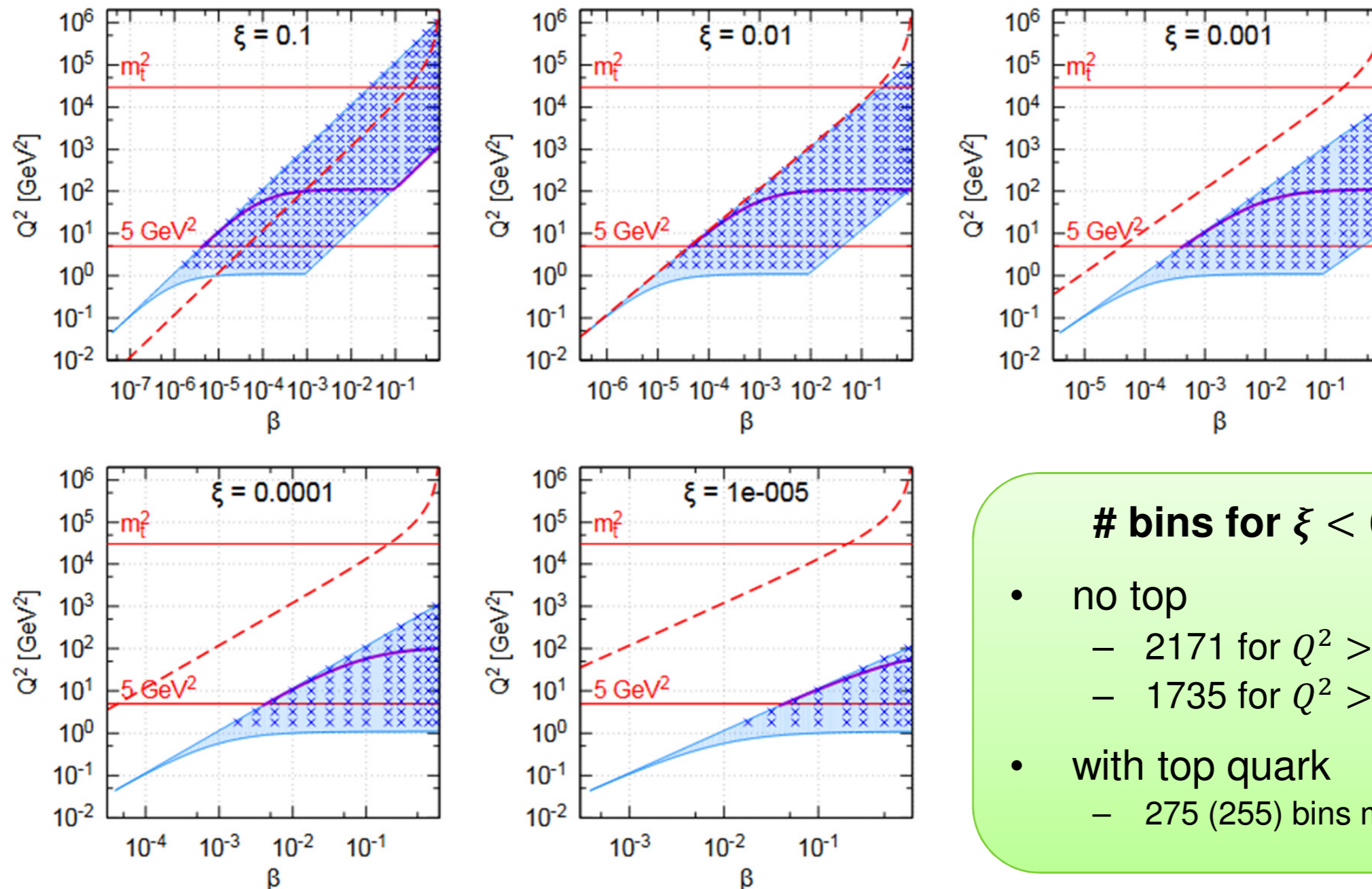
bins for $\xi < 0.15$

- no top
 - 1589 for $Q^2 > 1.3 \text{ GeV}^2$
 - 1229 for $Q^2 > 5 \text{ GeV}^2$
- with top quark
 - 17 bins more

FCC-eh phase space: (β, Q^2) fixed ξ

$$E_p = 50 \text{ TeV}, E_e = 60 \text{ GeV}, y_{\min} = 0.001, y_{\max} = 0.96$$

$\theta > 1^\circ$ ■ $\theta = 10^\circ$ — bins \times $M_X = 2 m_t$ - - -



bins for $\xi < 0.15$

- no top
 - 2171 for $Q^2 > 1.3 \text{ GeV}^2$
 - 1735 for $Q^2 > 5 \text{ GeV}^2$
- with top quark
 - 275 (255) bins more

Pseudodata for σ_{red}

Simulations based on extrapolation of ZEUS-SJ DPDFs

Variable Flavor Number scheme without top

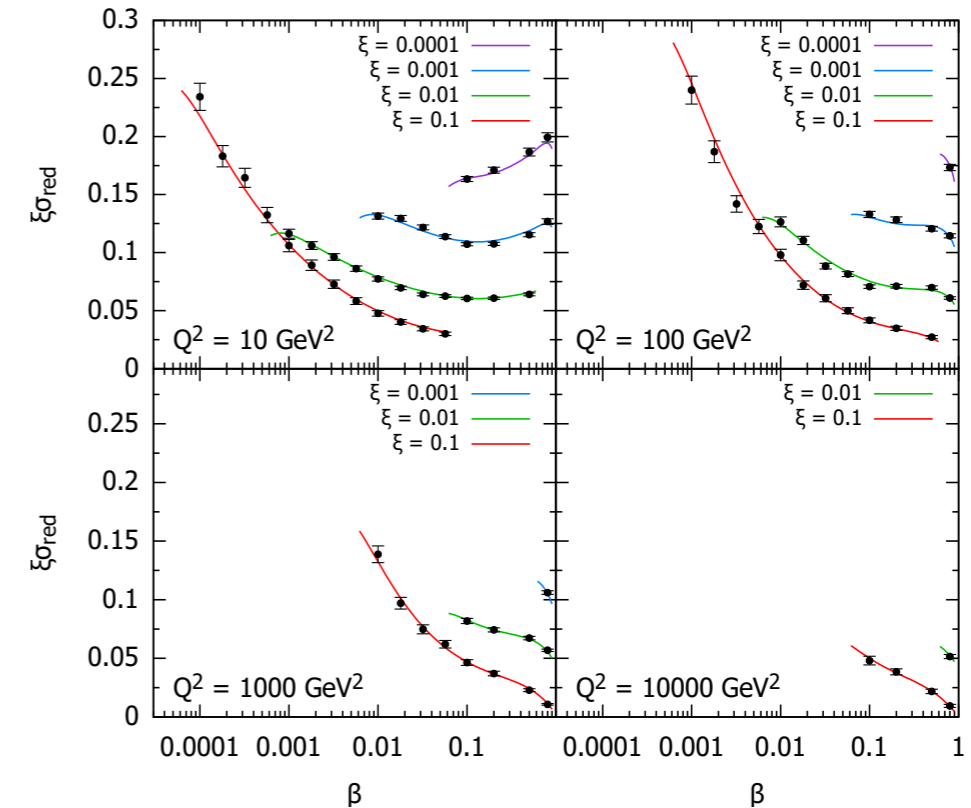
Binning to assume negligible statistical errors

5% systematic error, dominates the total error

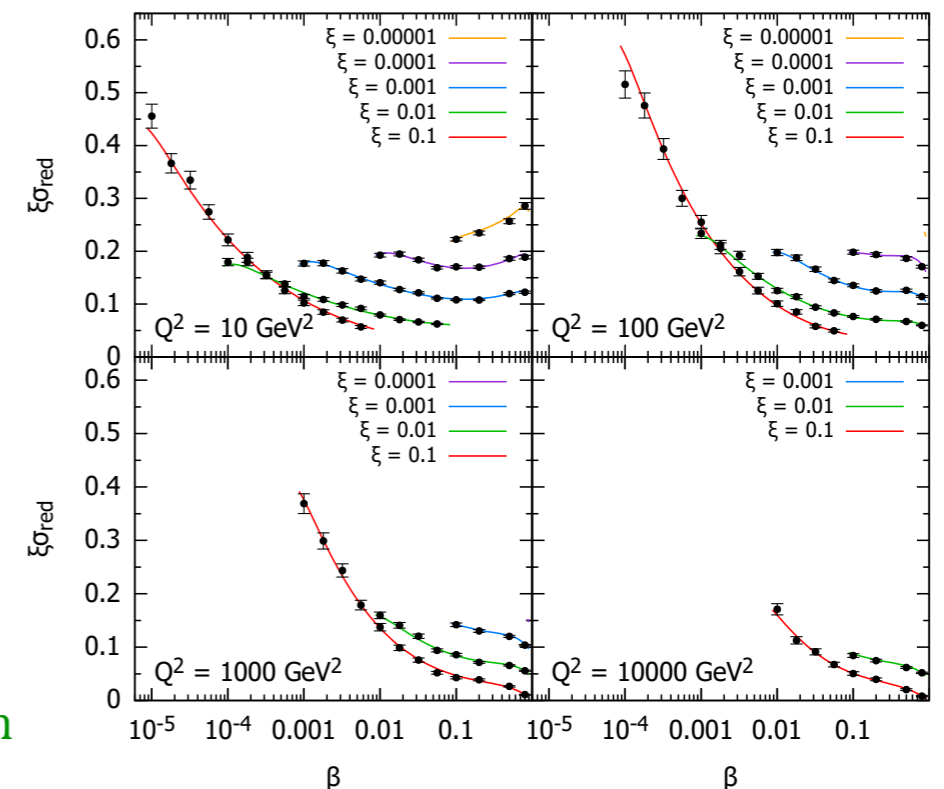
Potential for high quality data for inclusive diffraction at LHeC/FCC-eh

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

Only small subset of simulated data is shown



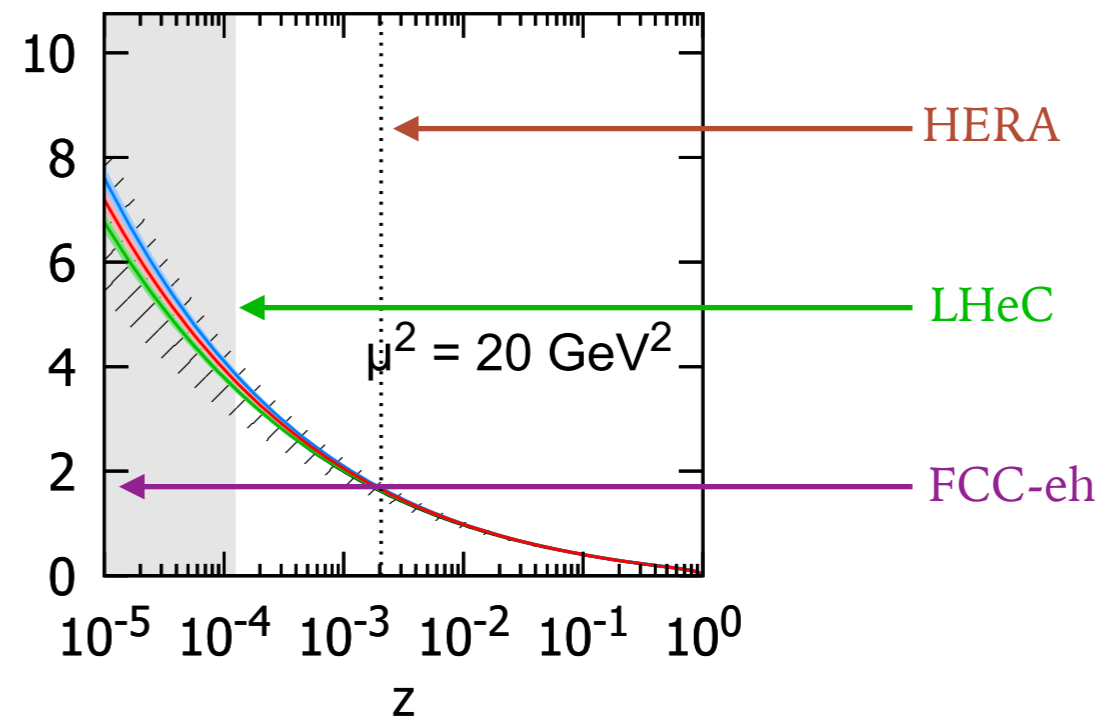
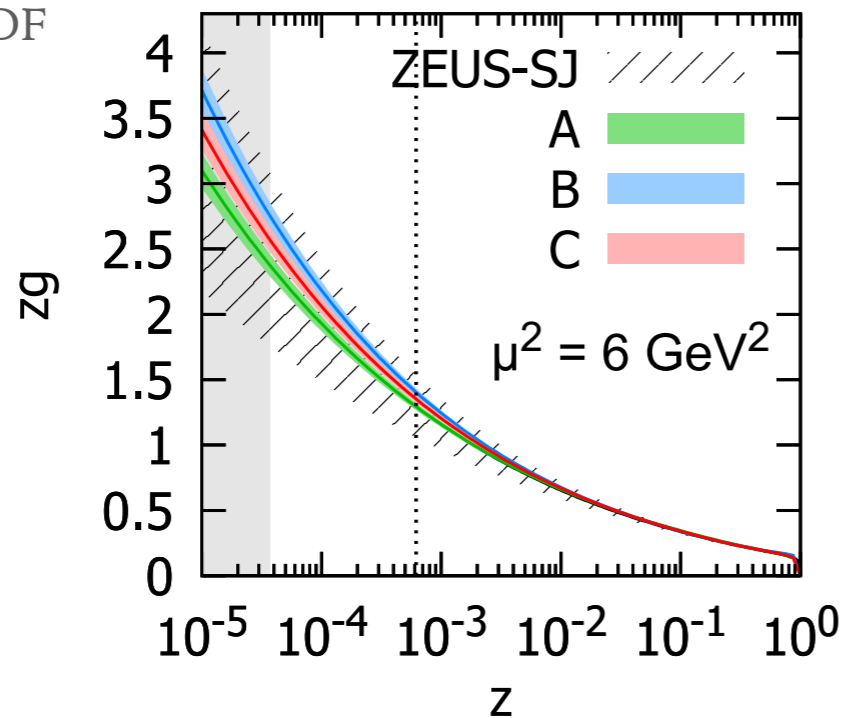
LHeC



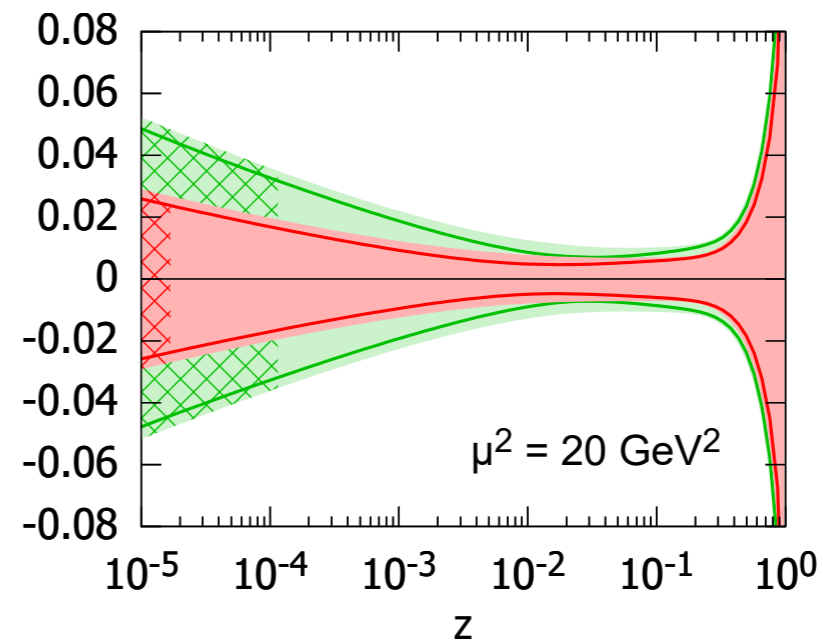
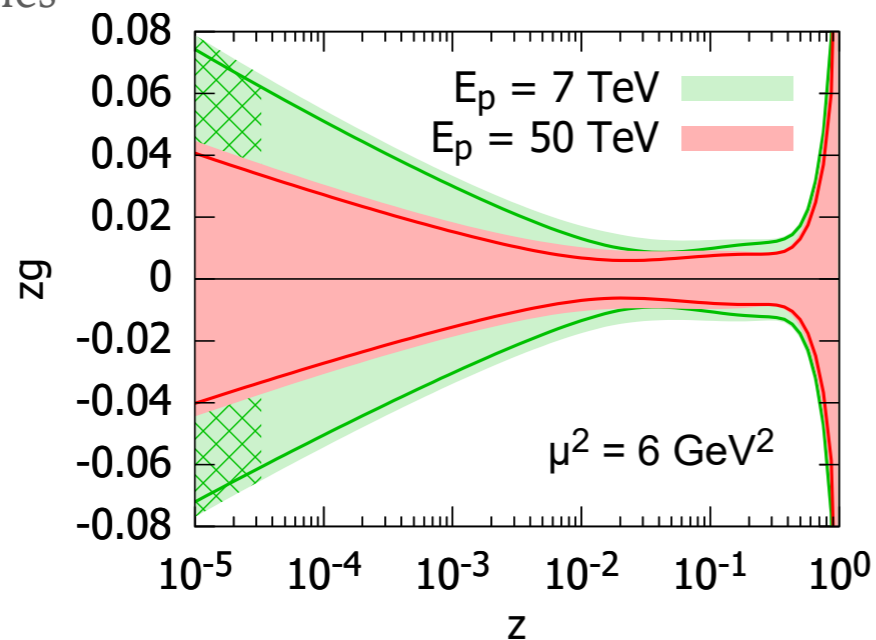
FCC-eh

Diffractive PDFs from simulations

Diffractive gluon PDF



Relative uncertainties



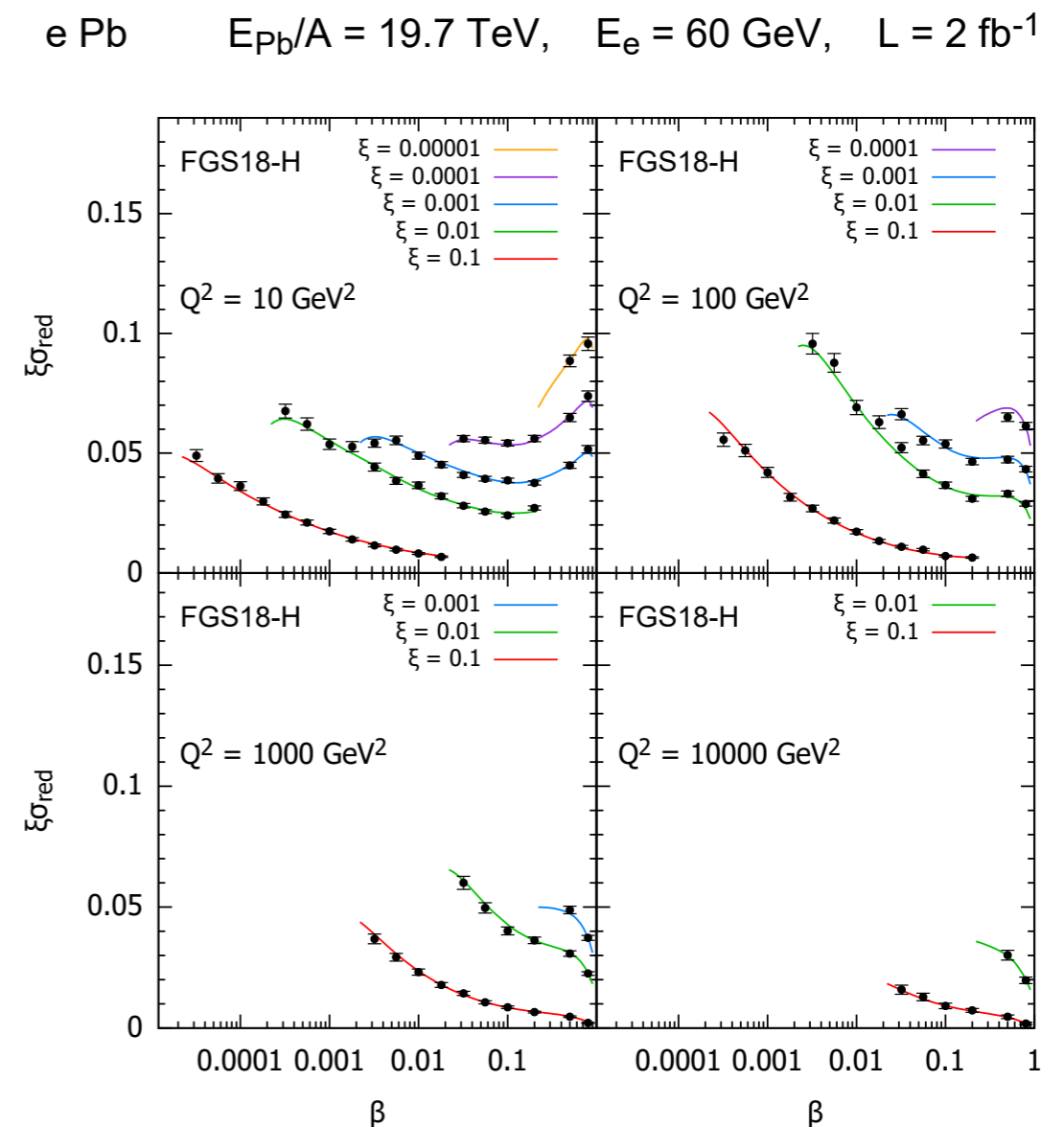
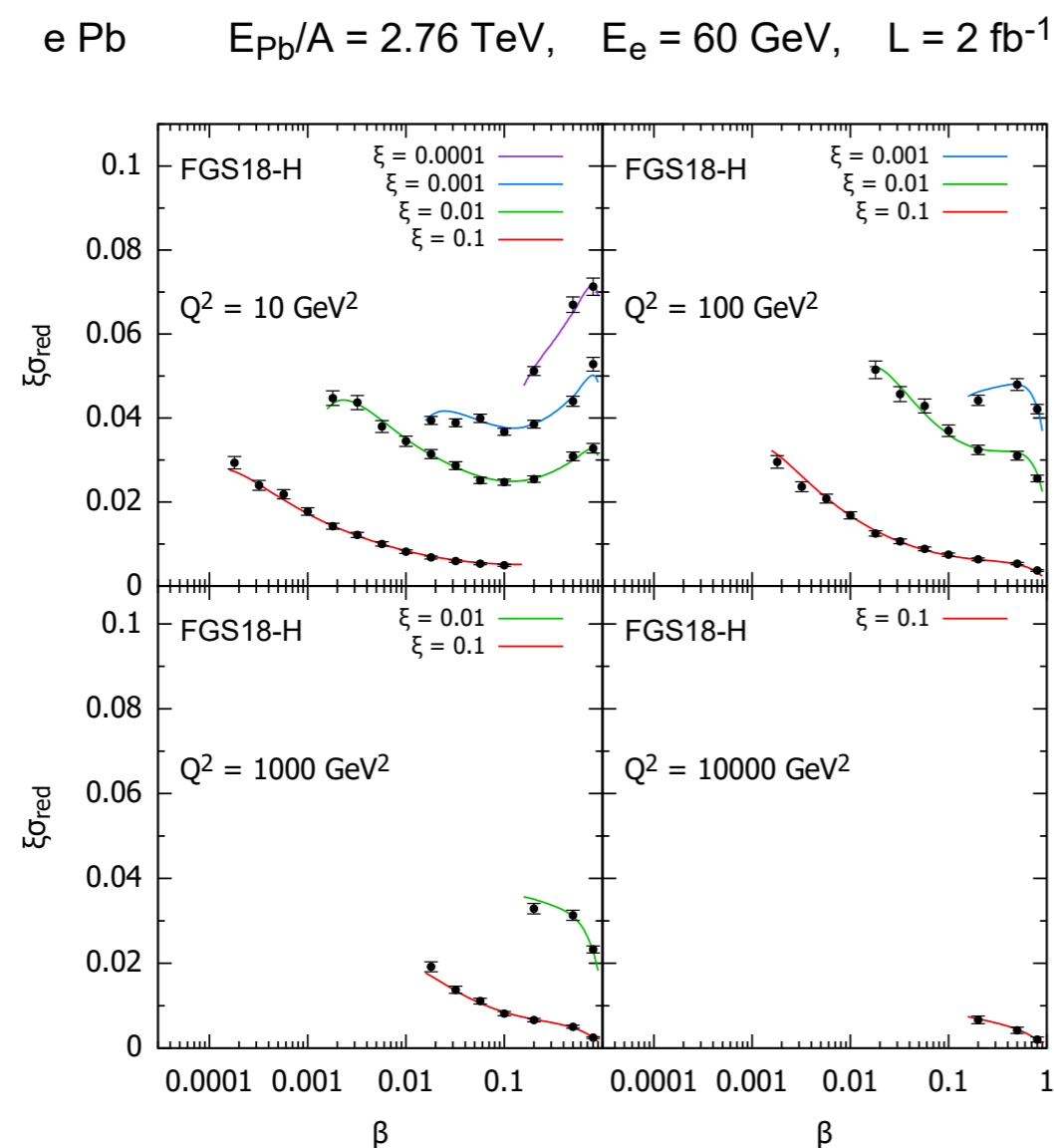
Reduction of DPDF uncertainty by factor 5 — 7 at LHeC and 10 — 15 at FCC-eh with inclusive data alone

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

Inclusive diffraction on nuclei

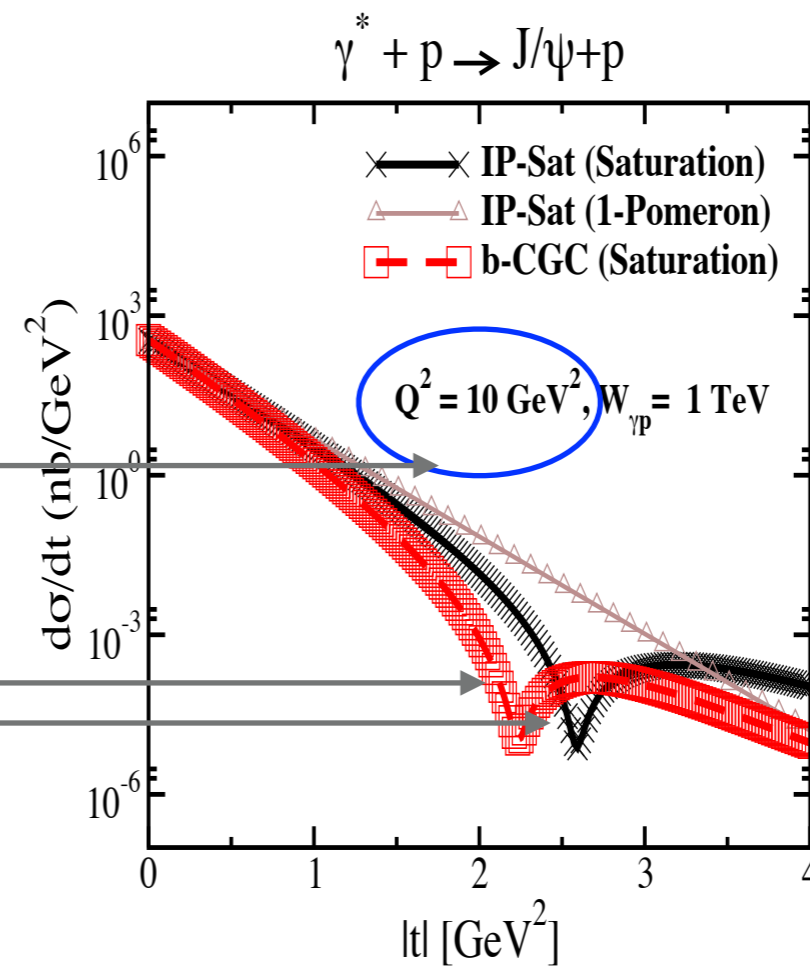
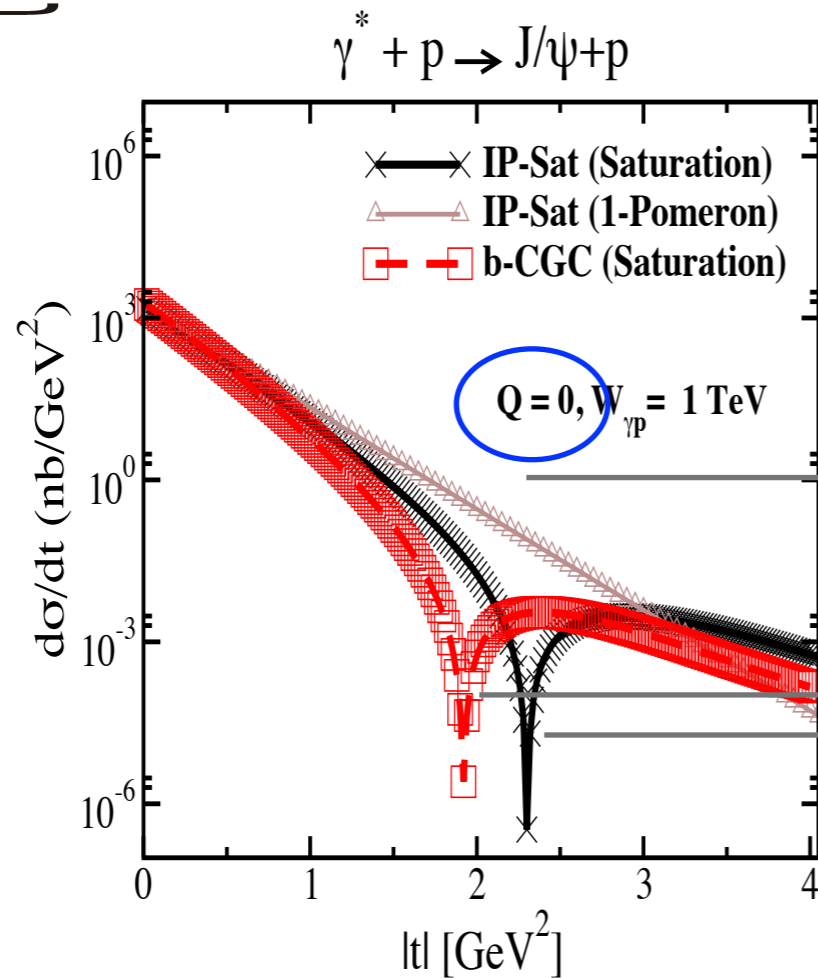
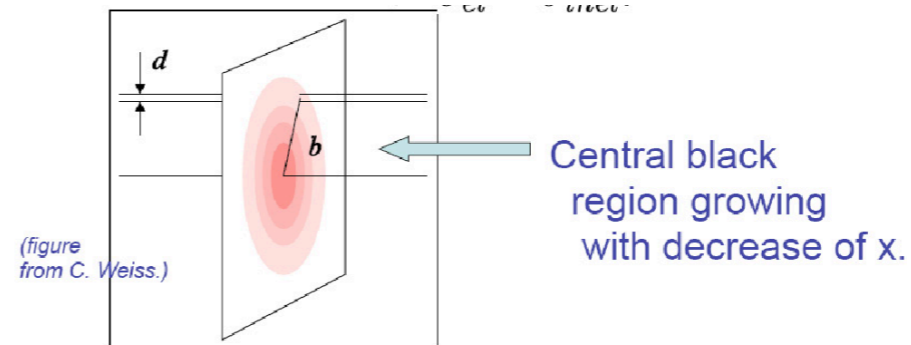
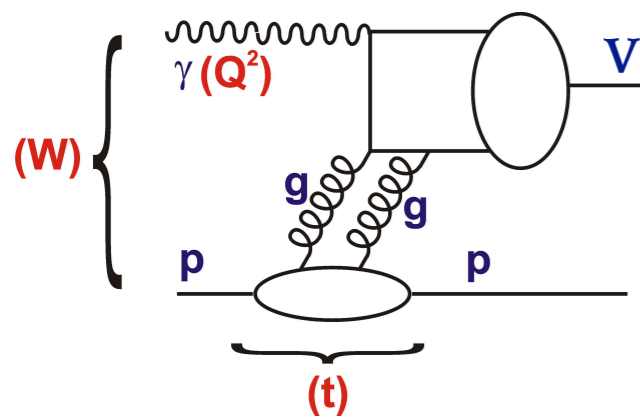
Reduced cross section from Frankfurt, Guzey, Strikman model

Pseudodata simulated under the same assumptions: 5% systematics, conservative luminosity 2 fb^{-1}



High precision data would allow to extract the nuclear DPDFs with similar accuracy to the proton case

Elastic diffraction of vector mesons



Advantage over UPC:

Q^2 dependence

Precision t , W and Q^2 dependence of vector mesons
Example : tests of saturation from the slope in t

One of the best processes to
test for novel small x dynamics

Summary

- LHeC and FCC-eh are electron-proton facilities which represent seminal opportunity to advance particle physics
- Broad physics potential: QCD studies, both precision and discovery, precision Higgs and EW, expand prospects for BSM, physics with nuclei
- Ultimate precision small x machines in ep/eA:
 - Precision PDFs at low x . Potential for testing resummation and saturation
 - Inclusive diffraction, constraints on diffractive PDFs, new final states in diffraction, also EW exchange. Relation between diffraction and shadowing
 - Exclusive diffraction, vector meson production, DVCS
 - Small x and nuclear effects can be tested in one facility. Test of universality of saturation
 - ...and much more...!