Small x physics at the LHeC and FCC-eh

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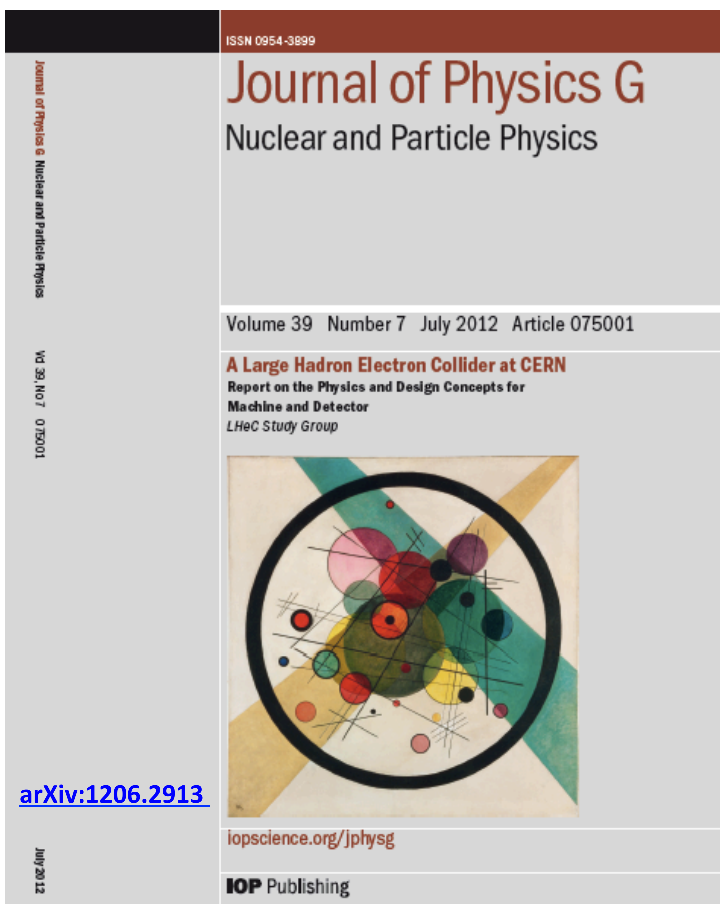
Outline

- 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:

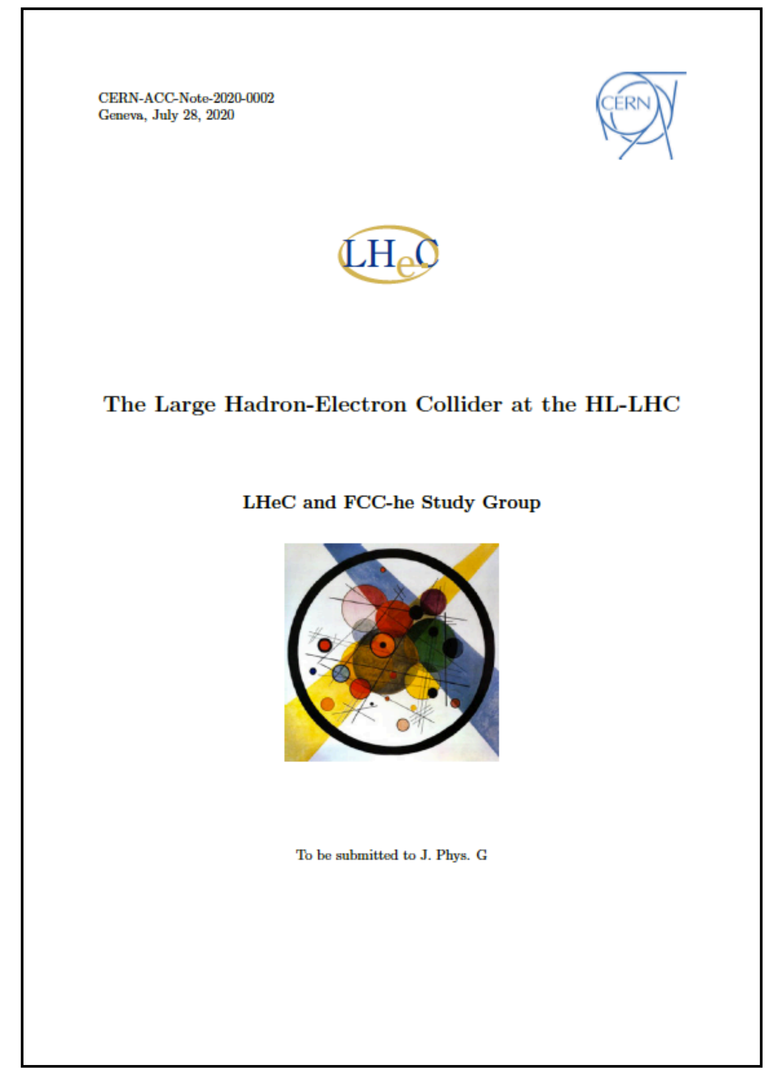
On the relation of the LHeC and the LHC
arXiv:1211.5102

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

LHeC, PERLE and FCC-eh

50 x 7000 GeV^2: 1.2 TeV ep collider

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

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

Upgrade to 10^{34} cm^{-2}s^{-1}, for Higgs, BSM

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

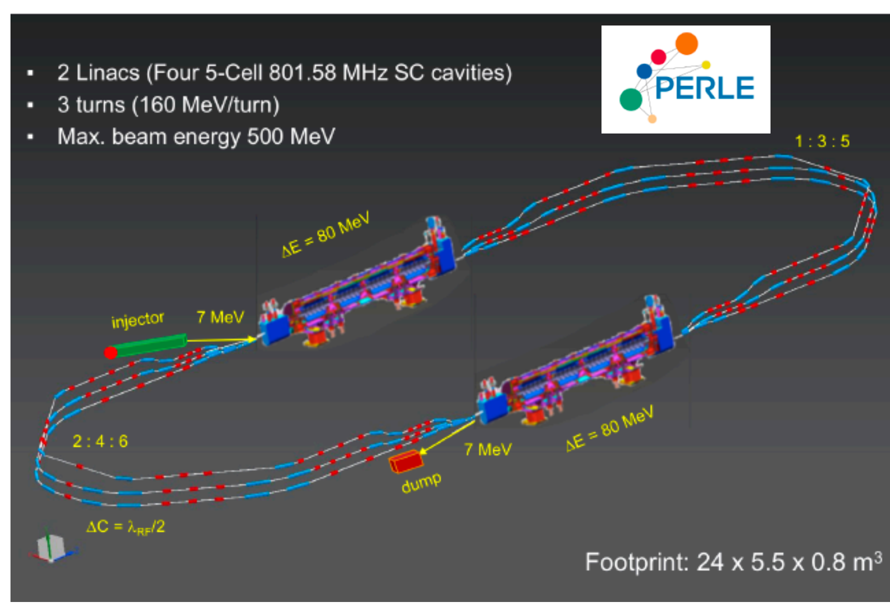
arXiv:2007.14491, subm J.Phys.G

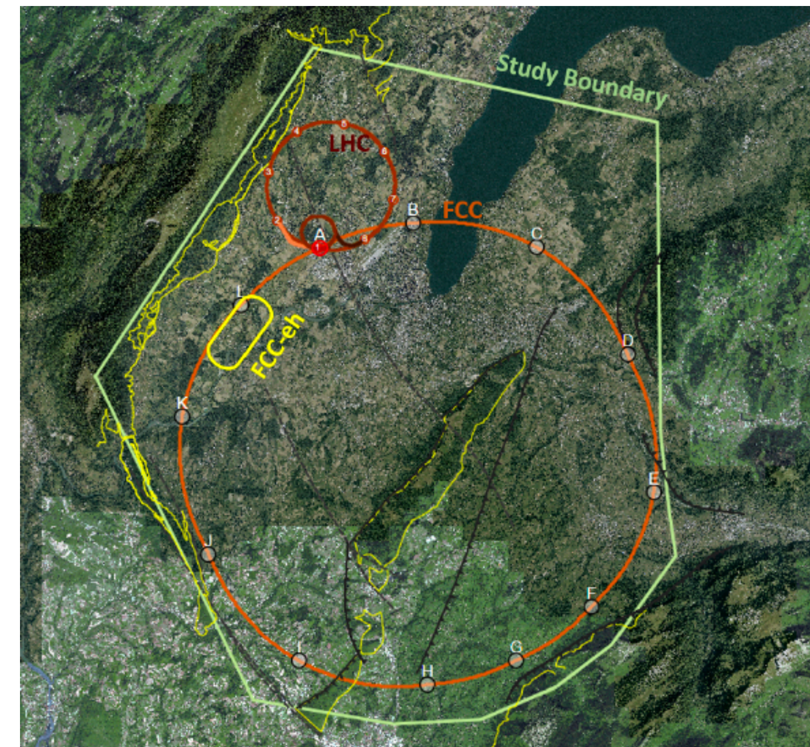
Powerful ERL for Experiments @ Orsay
CDR: 1705.08783 J.Phys.G
CERN-ACC-Note-2018-0086 (ESSP)

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

LHeC ERL Parameters and Configuration
I_e=20mA, 802 MHz SRF, 3 turns →
E_e=500 MeV → first 10 MW ERL facility

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





60 x 50000 GeV^2: 3.5 TeV ep collider

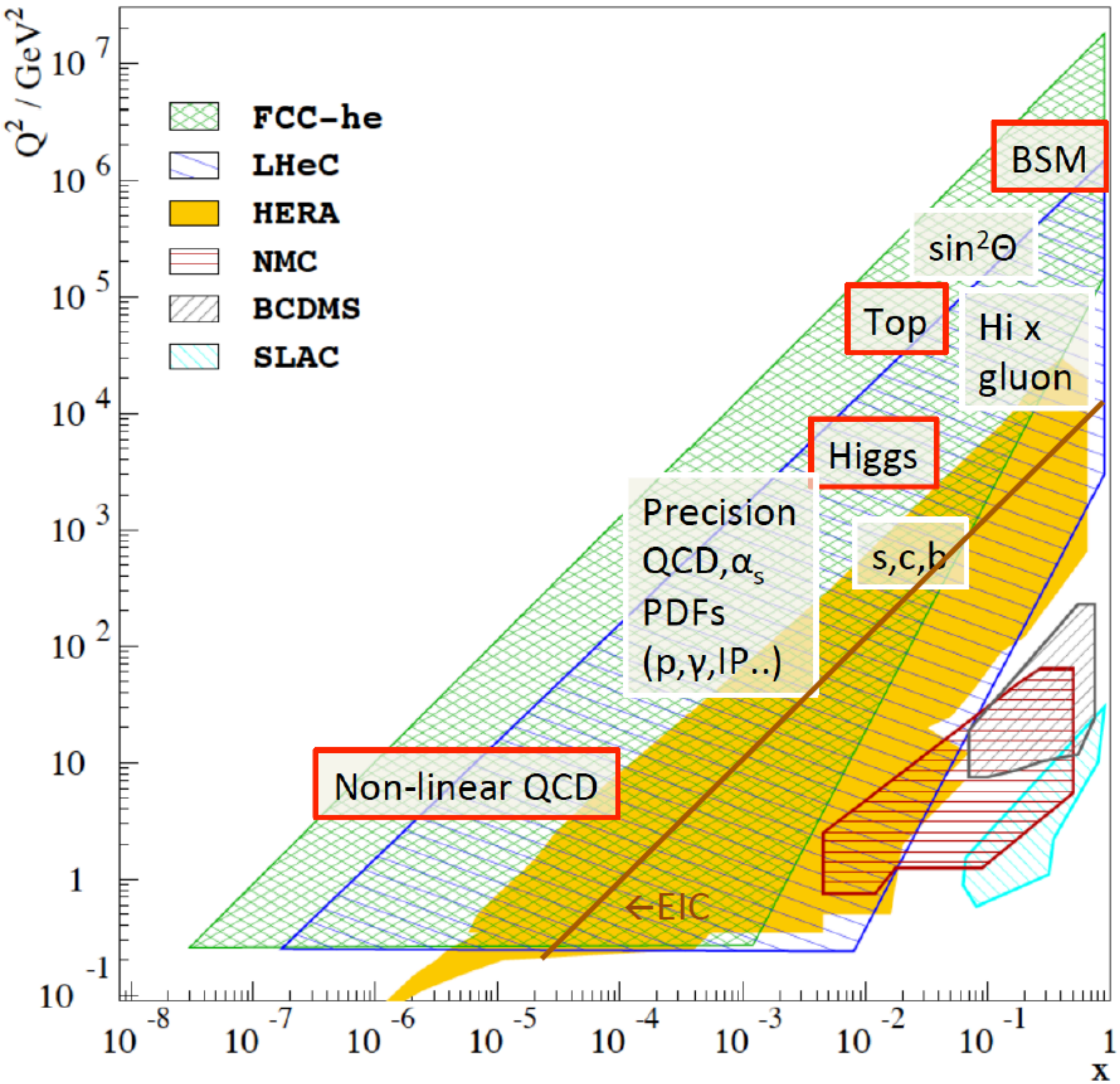
Operation: 2050+, Cost (of ep) O(1-2) BCHF

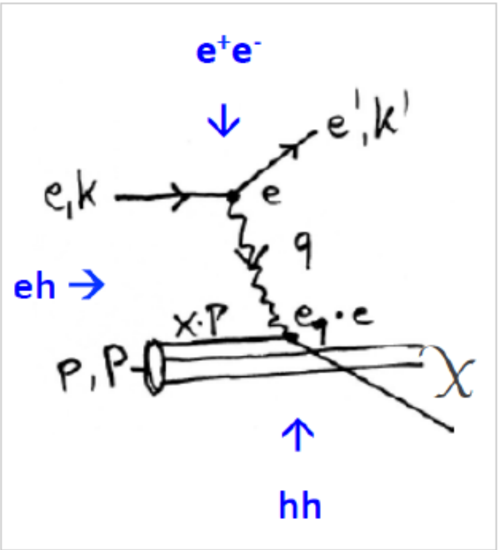
Concurrent Operation with FCC-hh

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

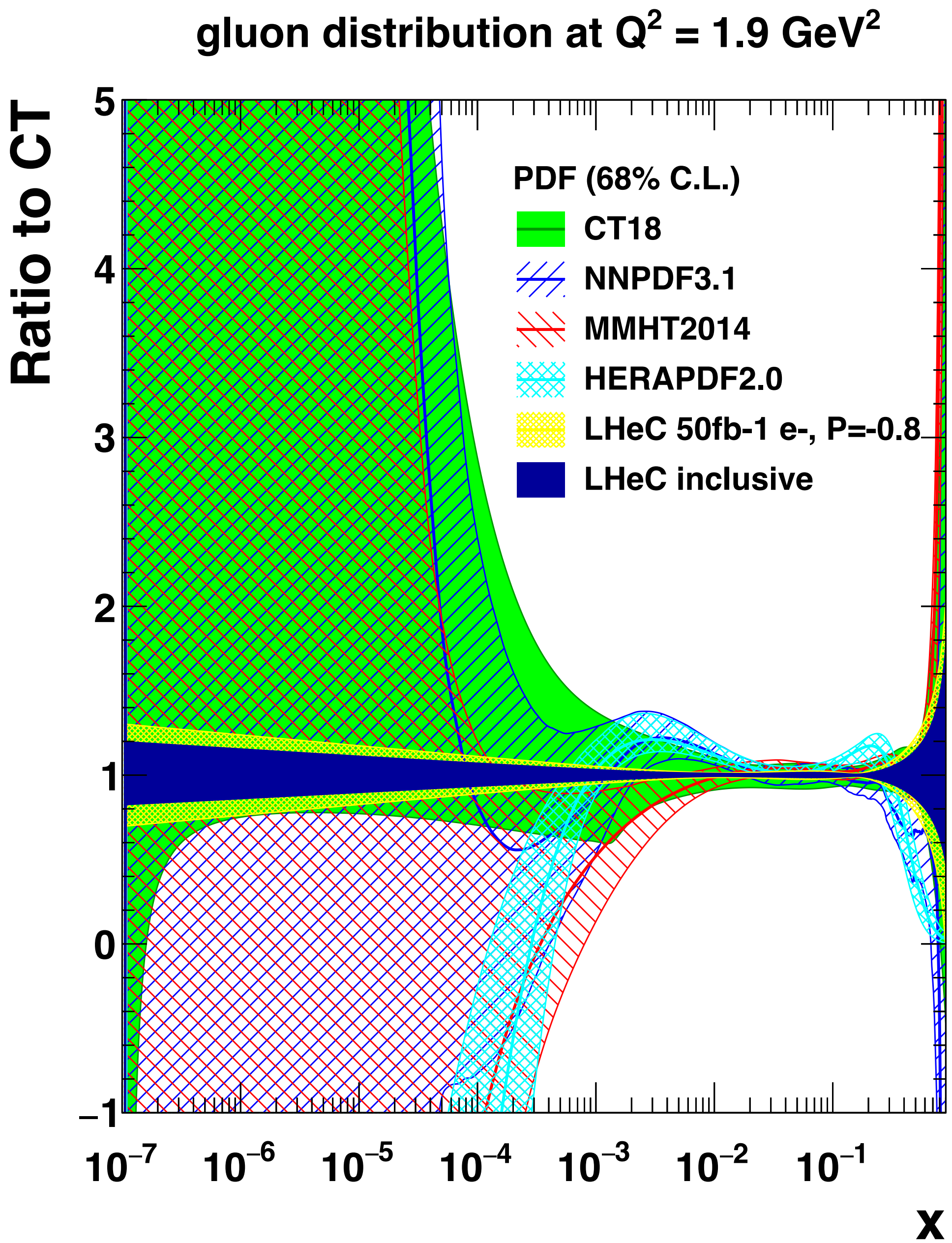
Unique and complementary potential for the BSM particles

Empower the LHC/FCC search programme

Overall: a unique Particle and Nuclear Physics Facility

Parton distributions at small x

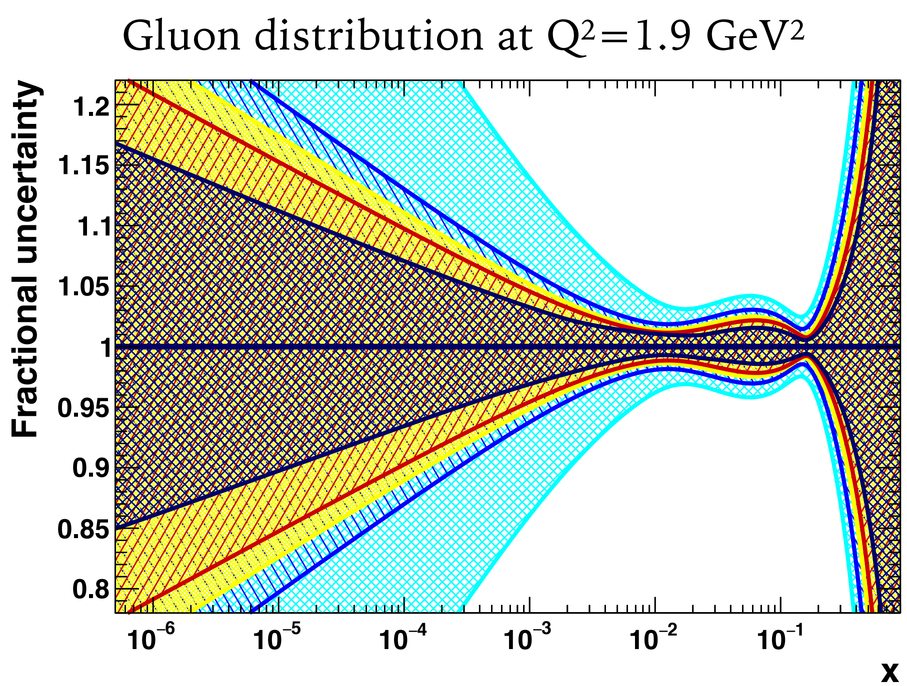
Complete unfolding of parton contents in unprecedented kinematic range: u,d,s,c,b,t,g



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

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

Few percent precision on the gluon



Sensitivity to different integrated luminosities:

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

Compared with HERA

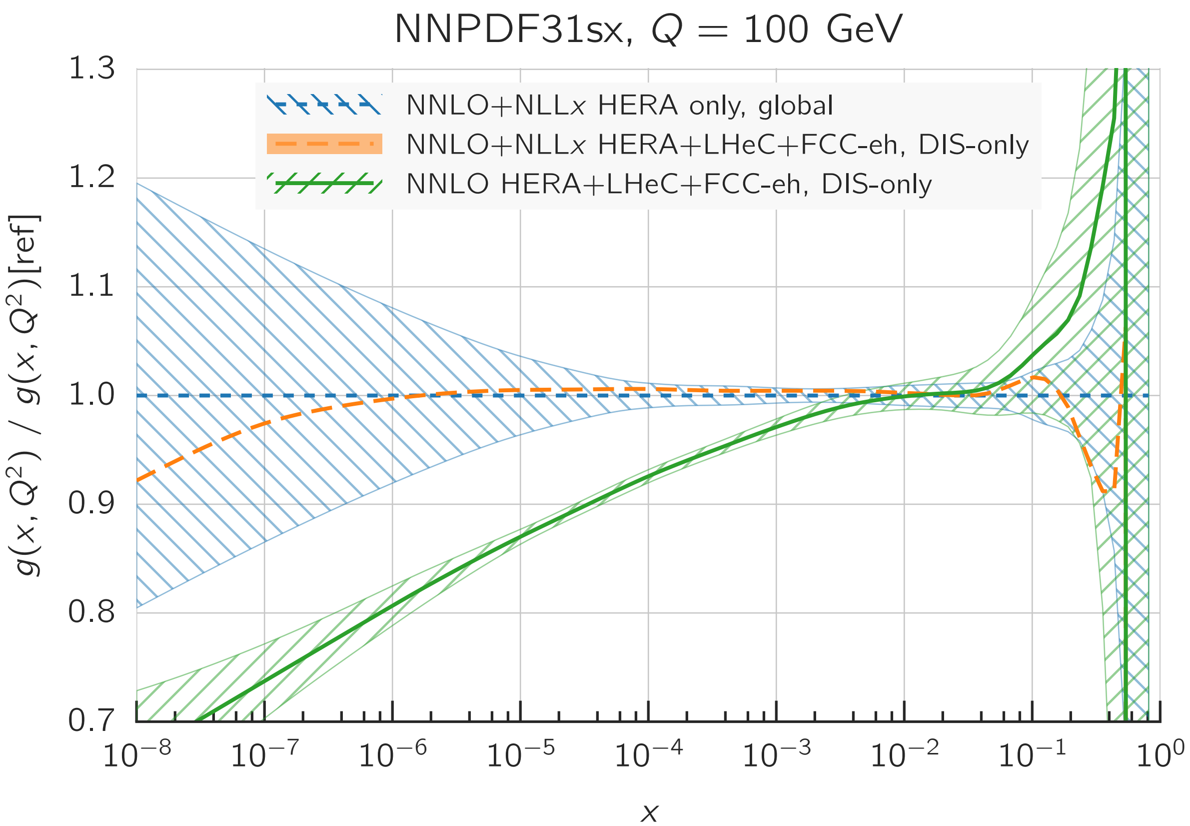
See more on PDFs at LHeC: Talk by Claire Gwenlan

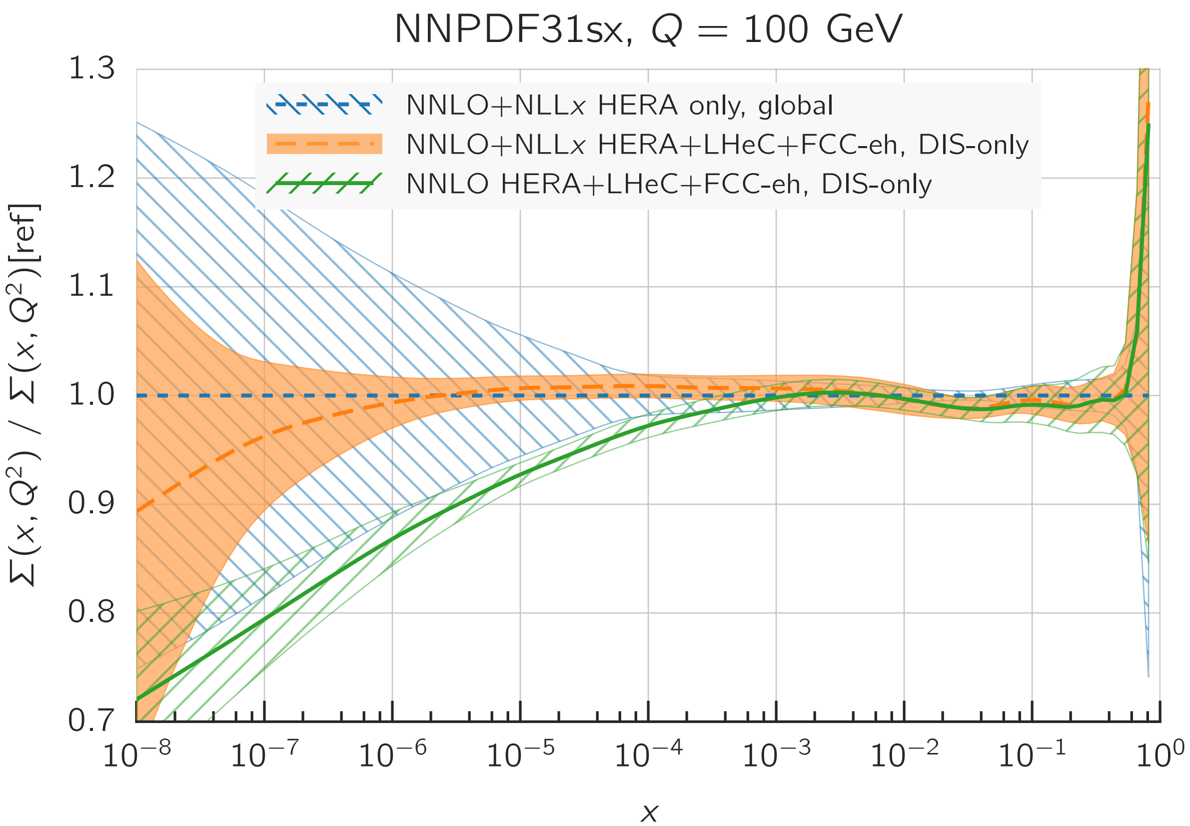
Novel dynamics at small x : resummation

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



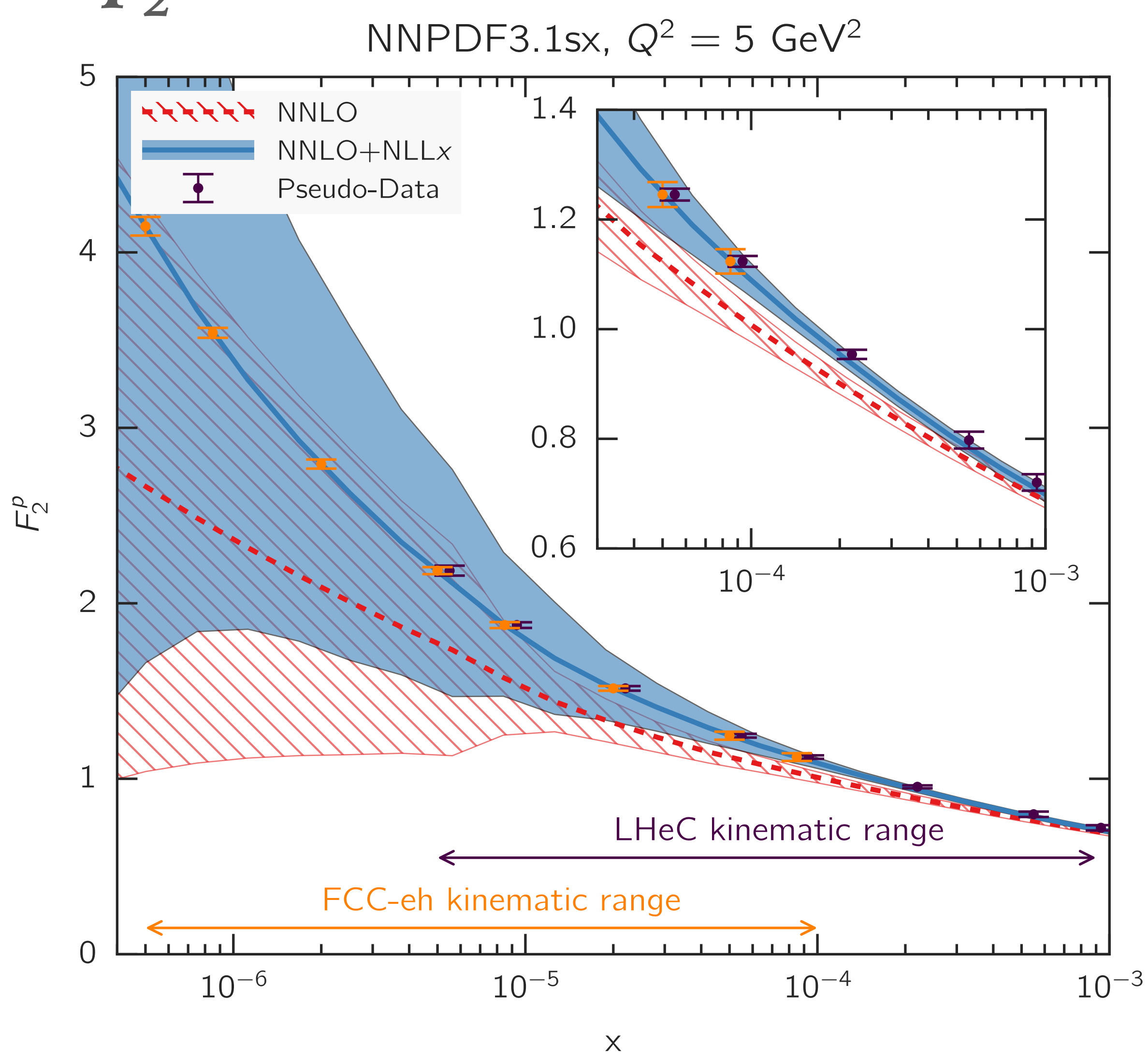


Large differences in the parton density at low x.

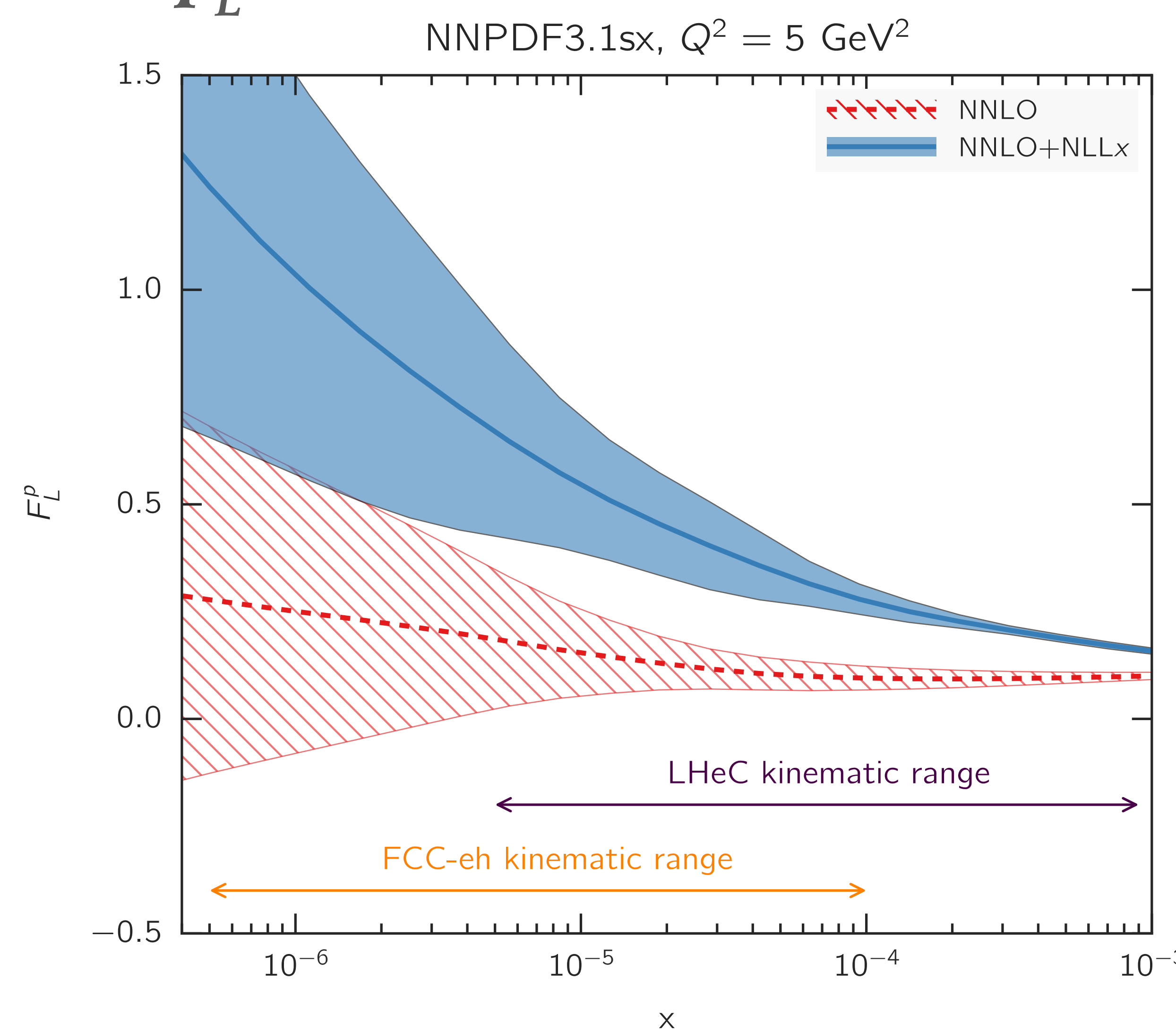
Essential for LHeC and FCC-eh

Novel dynamics at small x : resummation

F_2



F_L



Important consequences for LHeC and FCC-eh

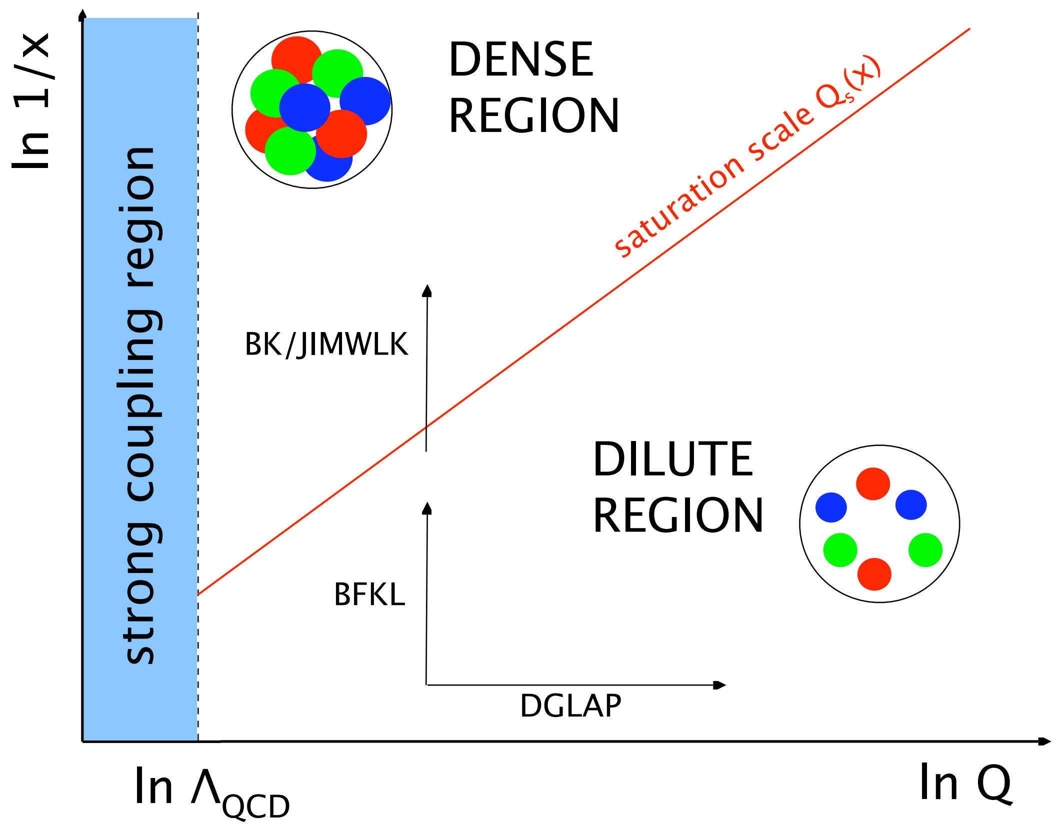
20-40% difference of central values for F_2

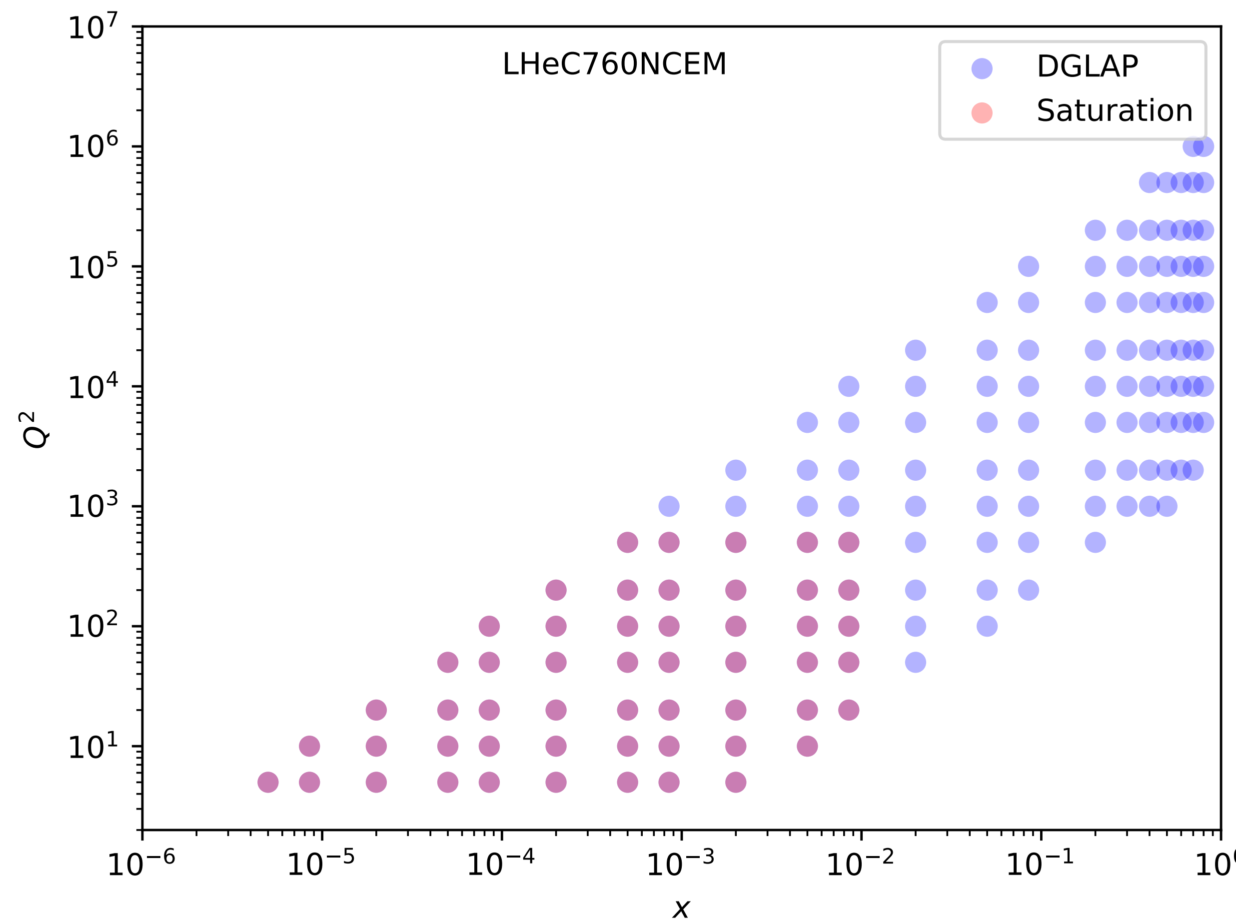
Factor 2 to 4 for F_L

DGLAP fit will likely fail at the LHeC range

Resummation mandatory for LHeC and FCC-eh

Novel dynamics at small x: saturation





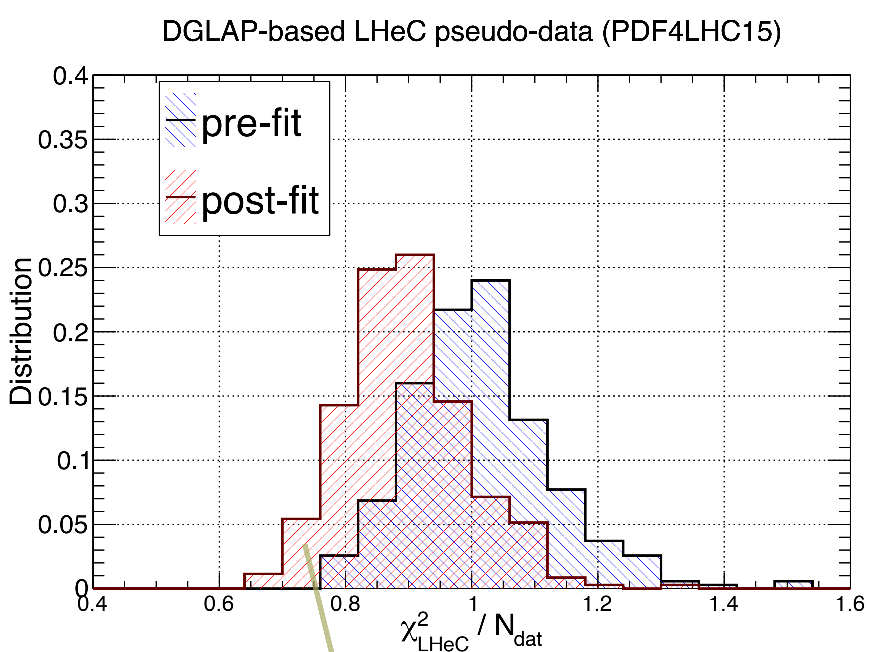
Test for saturation potential at LHeC:

Simulated pseudodata with saturation at low x

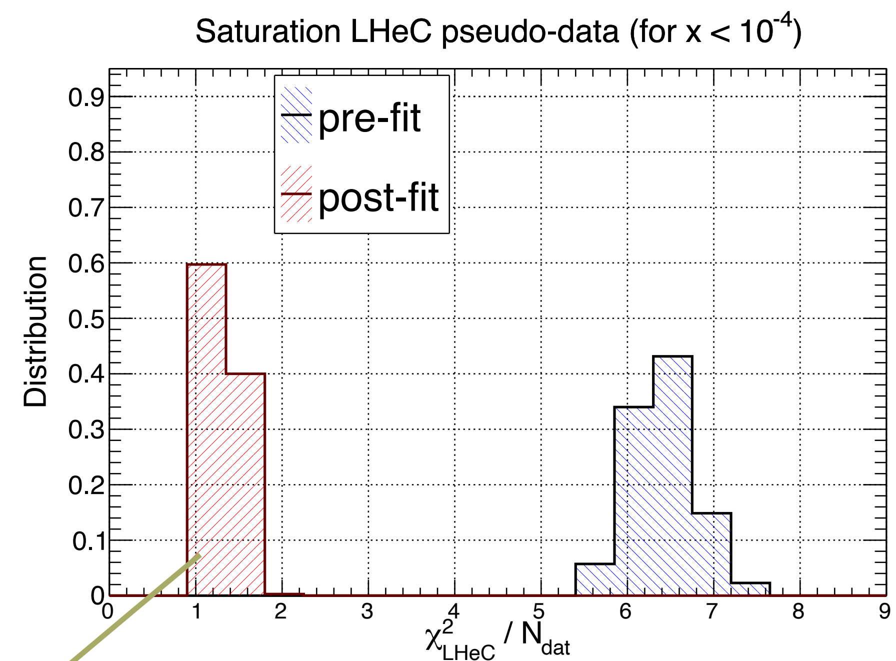
In the rest of kinematic range use DGLAP to simulate the data

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

Testing for saturation at the LHeC

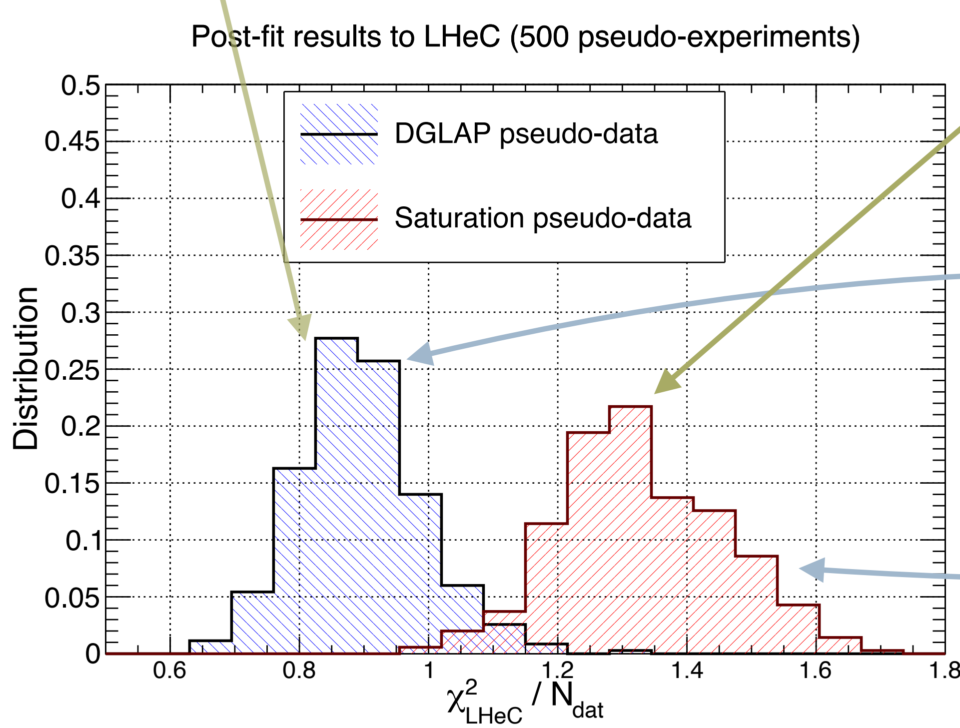


Pre-fit and post-fit distribution consistent for DGLAP based LHeC pseudodata



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

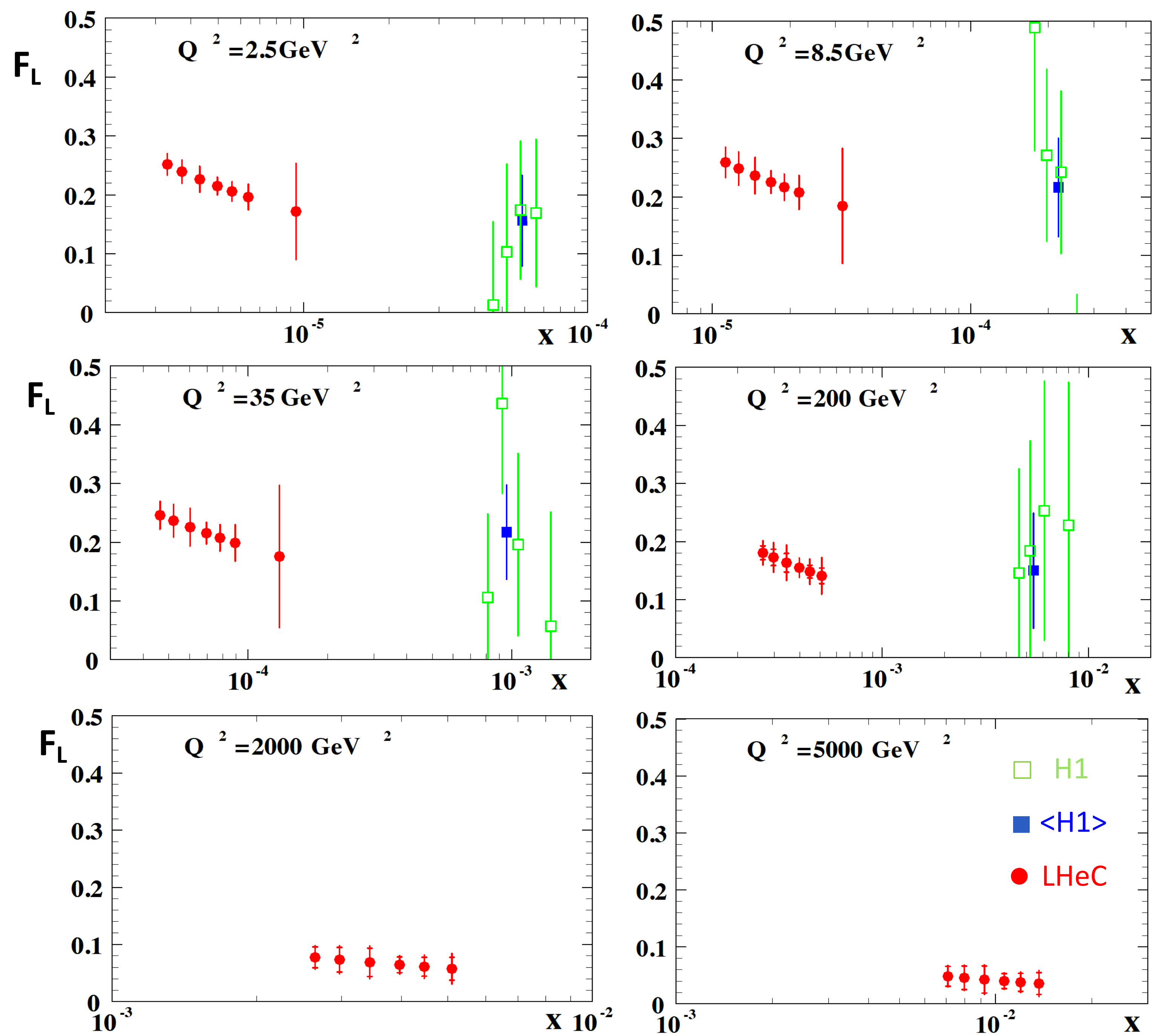
Pseudodata simulated for E_p=7 TeV and E_e=60, 30, 20 GeV

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

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

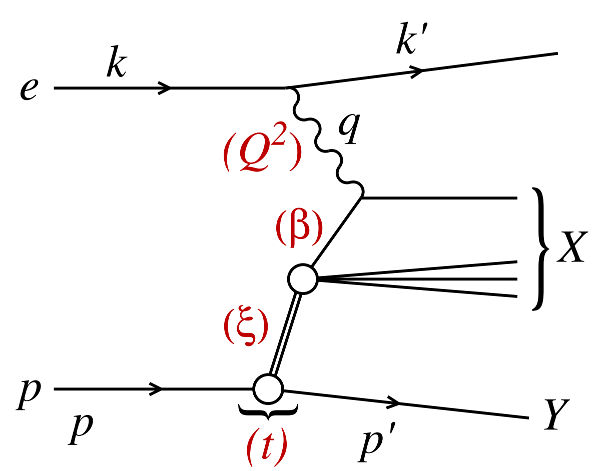
$$\beta = \frac{Q^2}{Q^2 + M_X^2 - t}$$

4-momentum transfer squared

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

Bjorken x relation

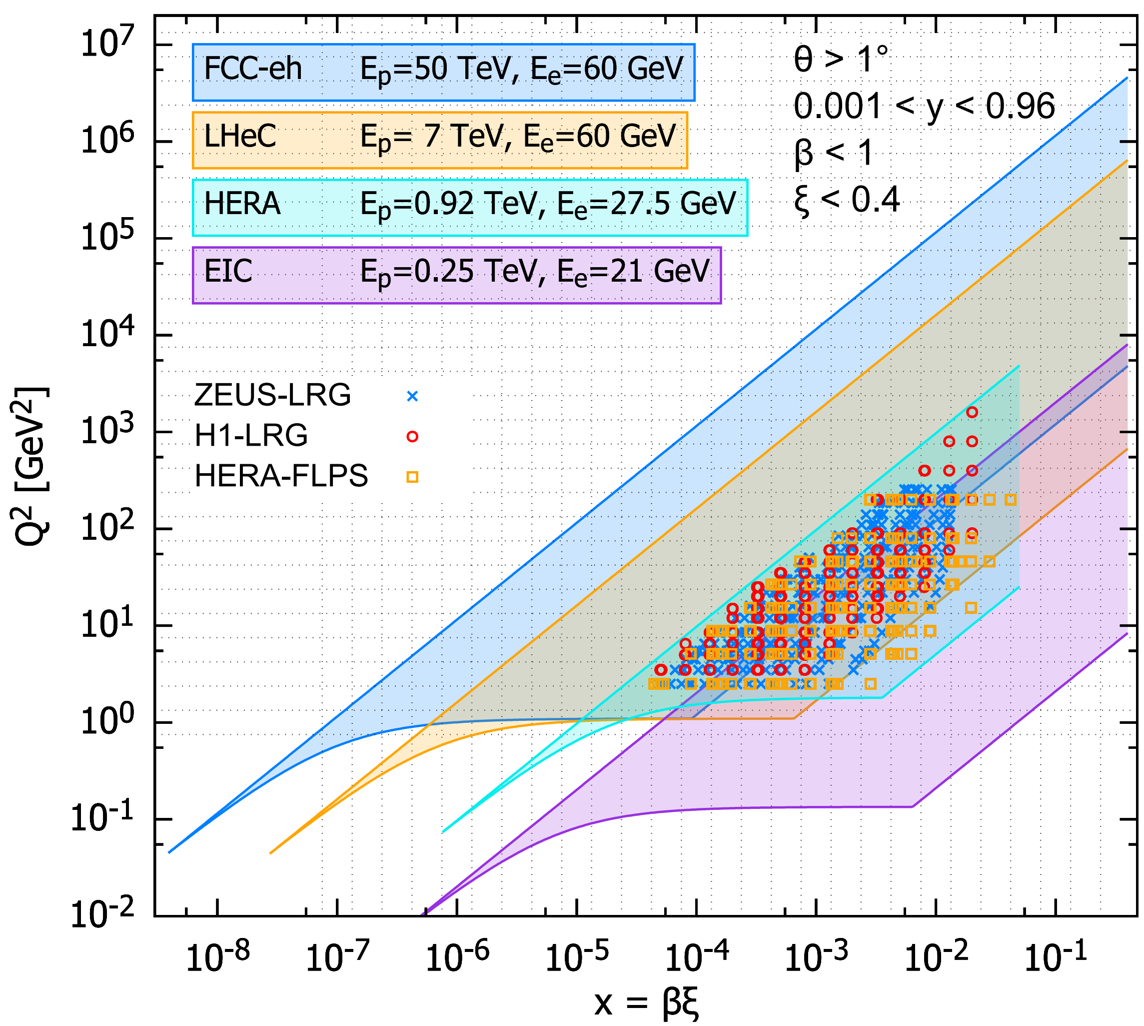
$$x_{Bj} = x_{IP}\beta$$



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

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

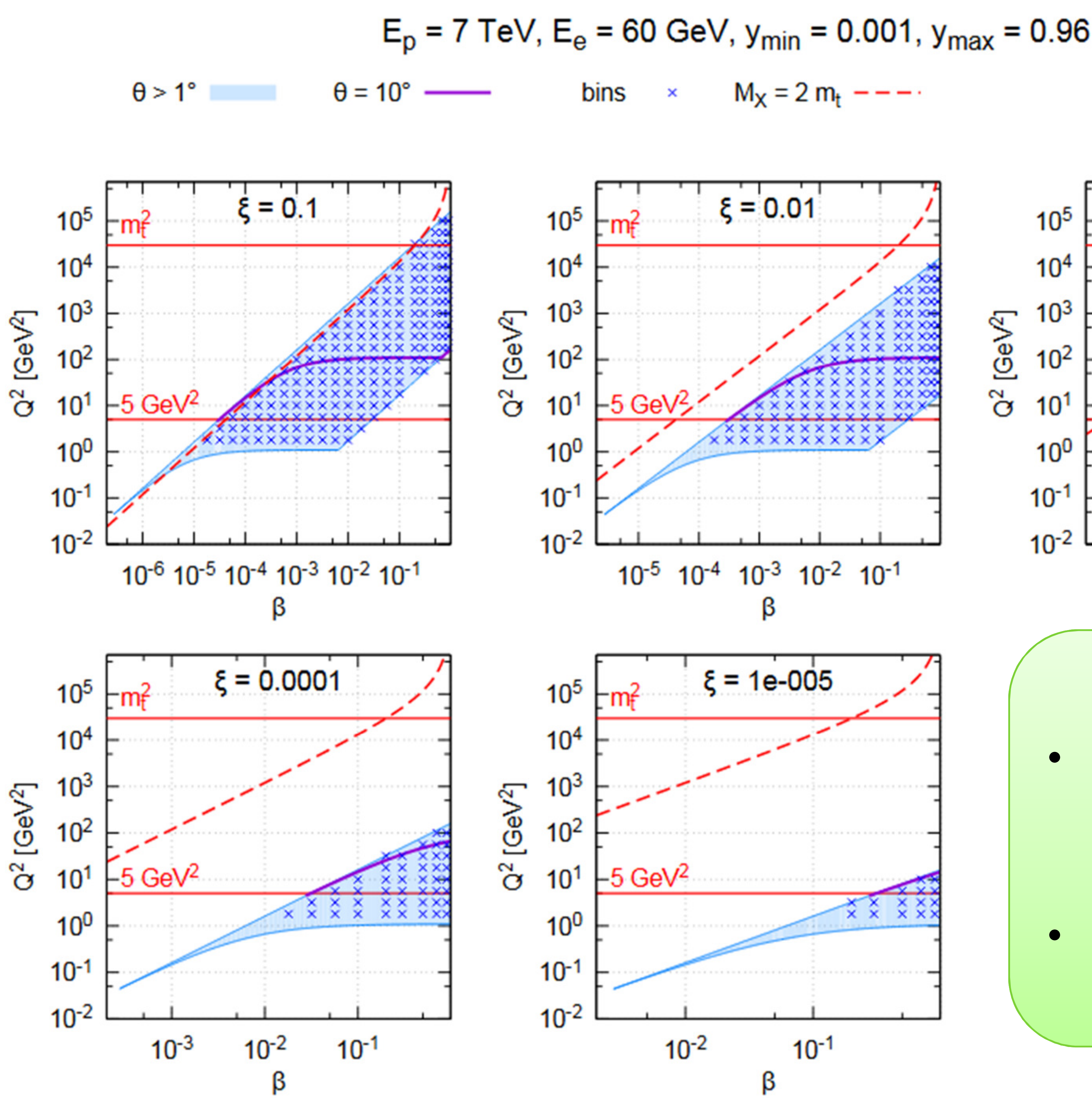
Importance of diffraction for understanding of small x dynamics, shadowing, confinement, soft and collinear factorization



$E_e = 60$ GeV

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

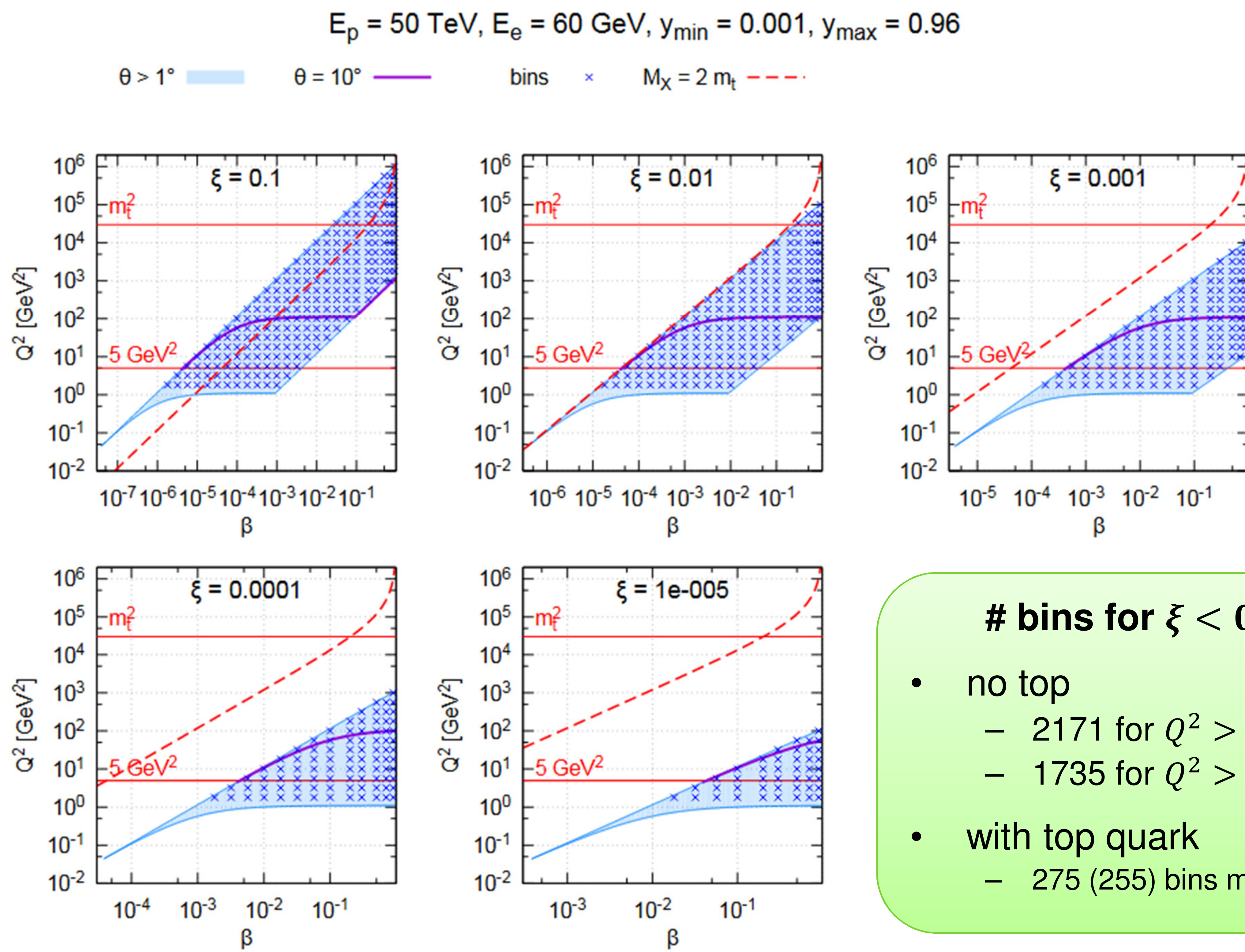
LHeC phase space: (β,Q²) fixed ξ



 # bins for $\xi < 0.15$

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

FCC-eh phase space: (β,Q^2) fixed ξ



 # bins for $\xi < 0.15$

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

Pseudodata for σ_{red}

Simulations based on extrapolation of ZEUS-SJ DPDFs

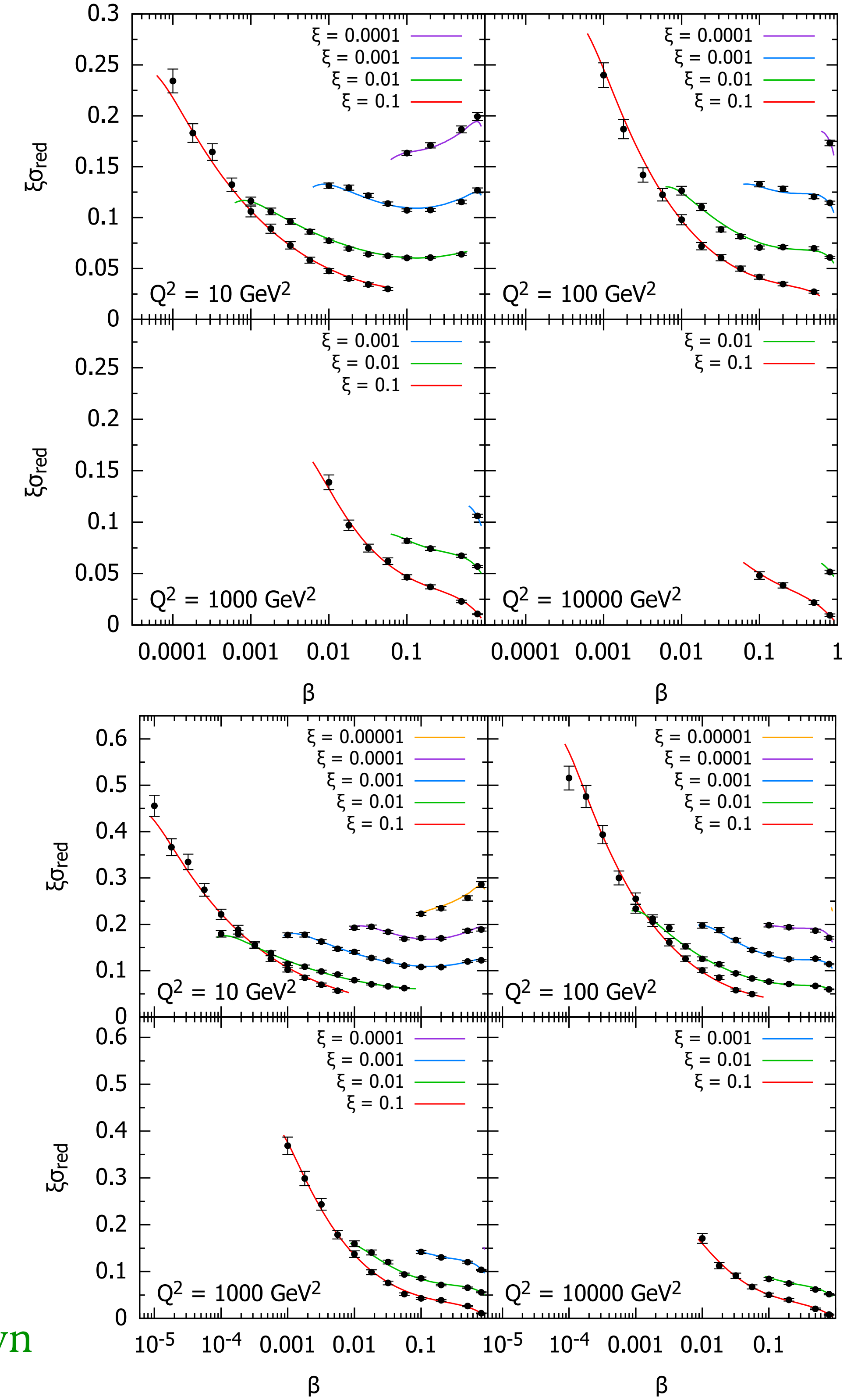
Variable Flavor Number scheme without top

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)



LHeC

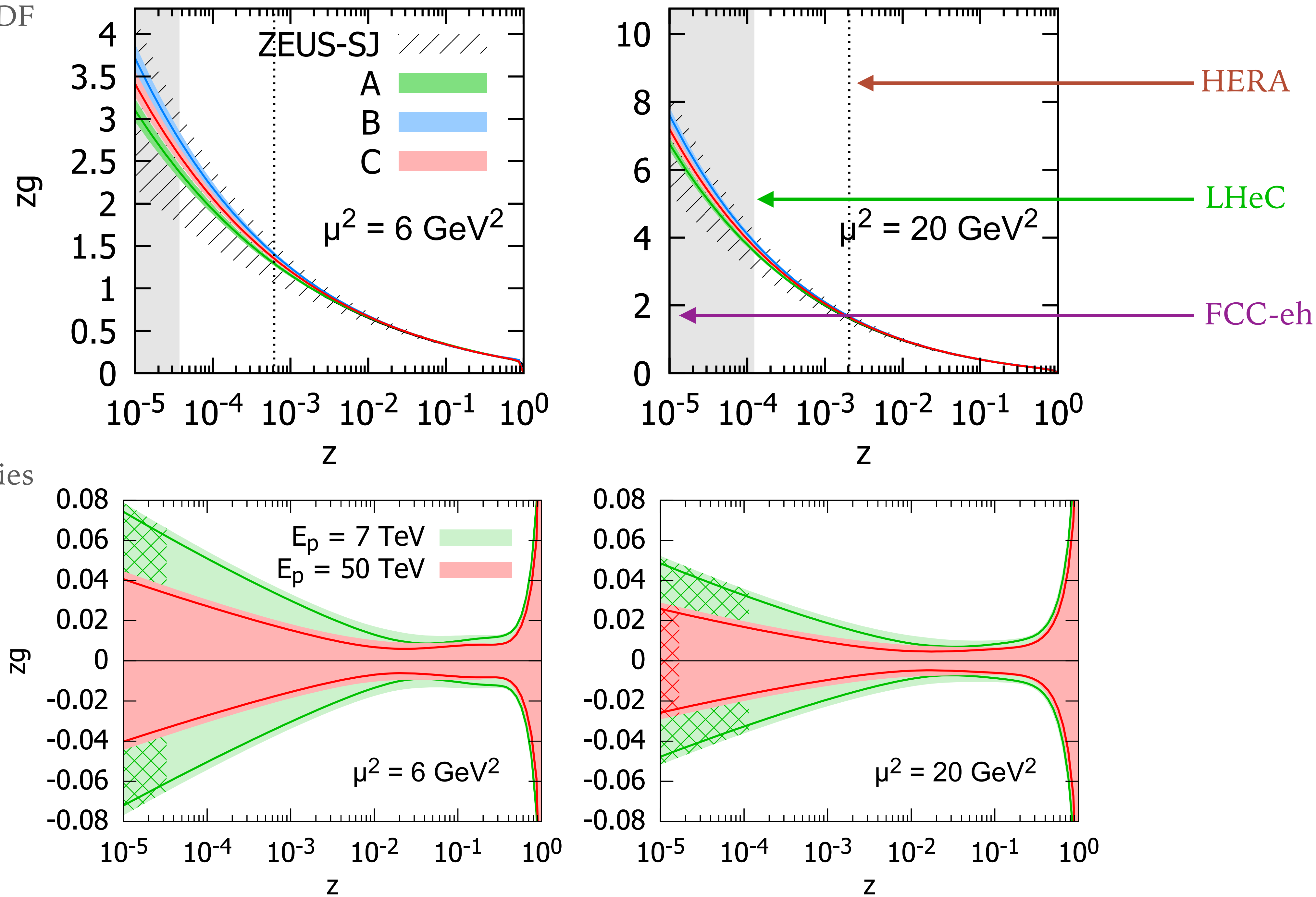
FCC-eh

Only small subset of simulated data is shown

Diffractive PDFs from simulations

Diffractive gluon PDF

Relative uncertainties



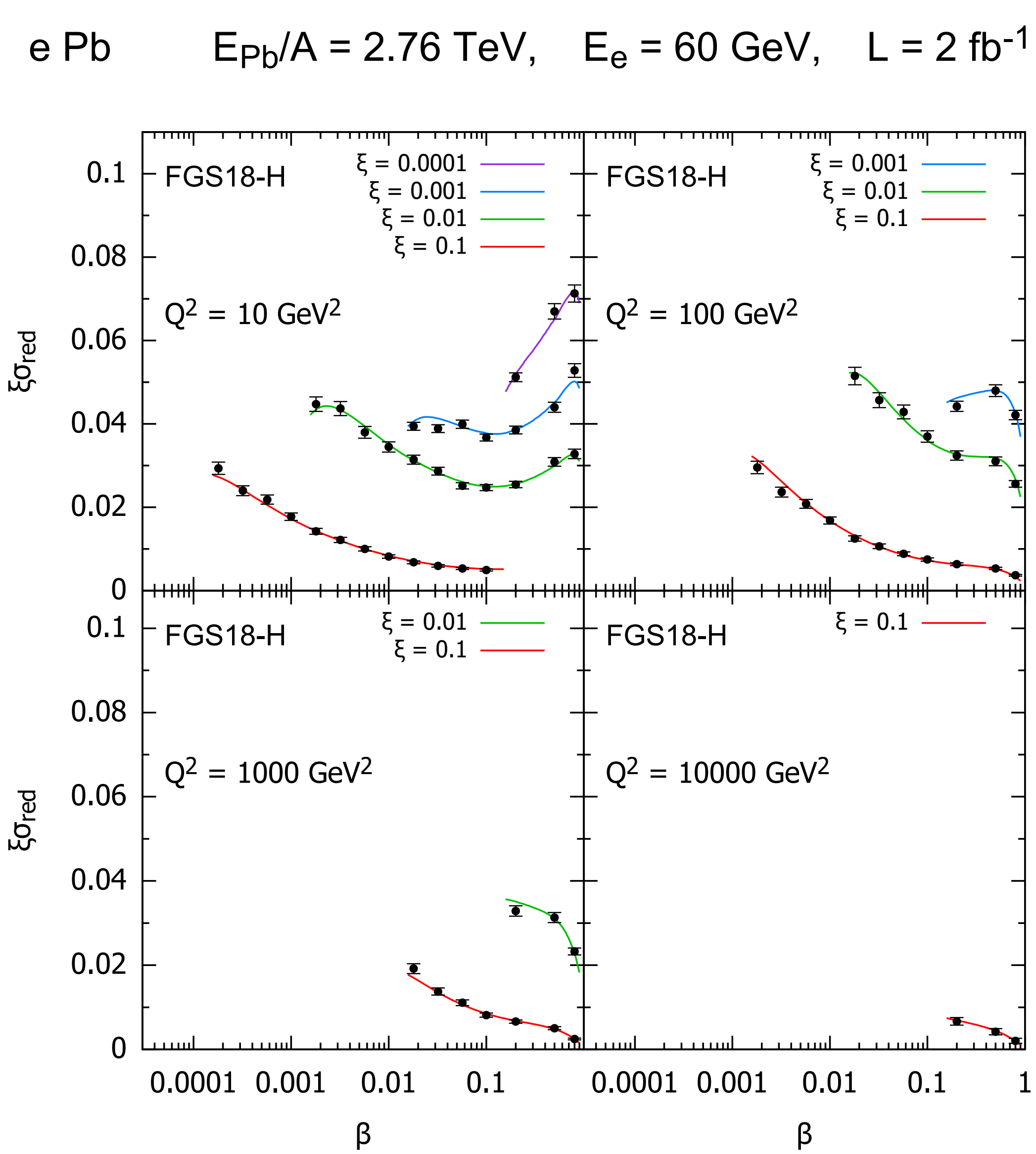
Reduction of DPDF uncertainty by factor 5 — 7 at LHeC and 10 — 15 at FCC-eh with inclusive data alone

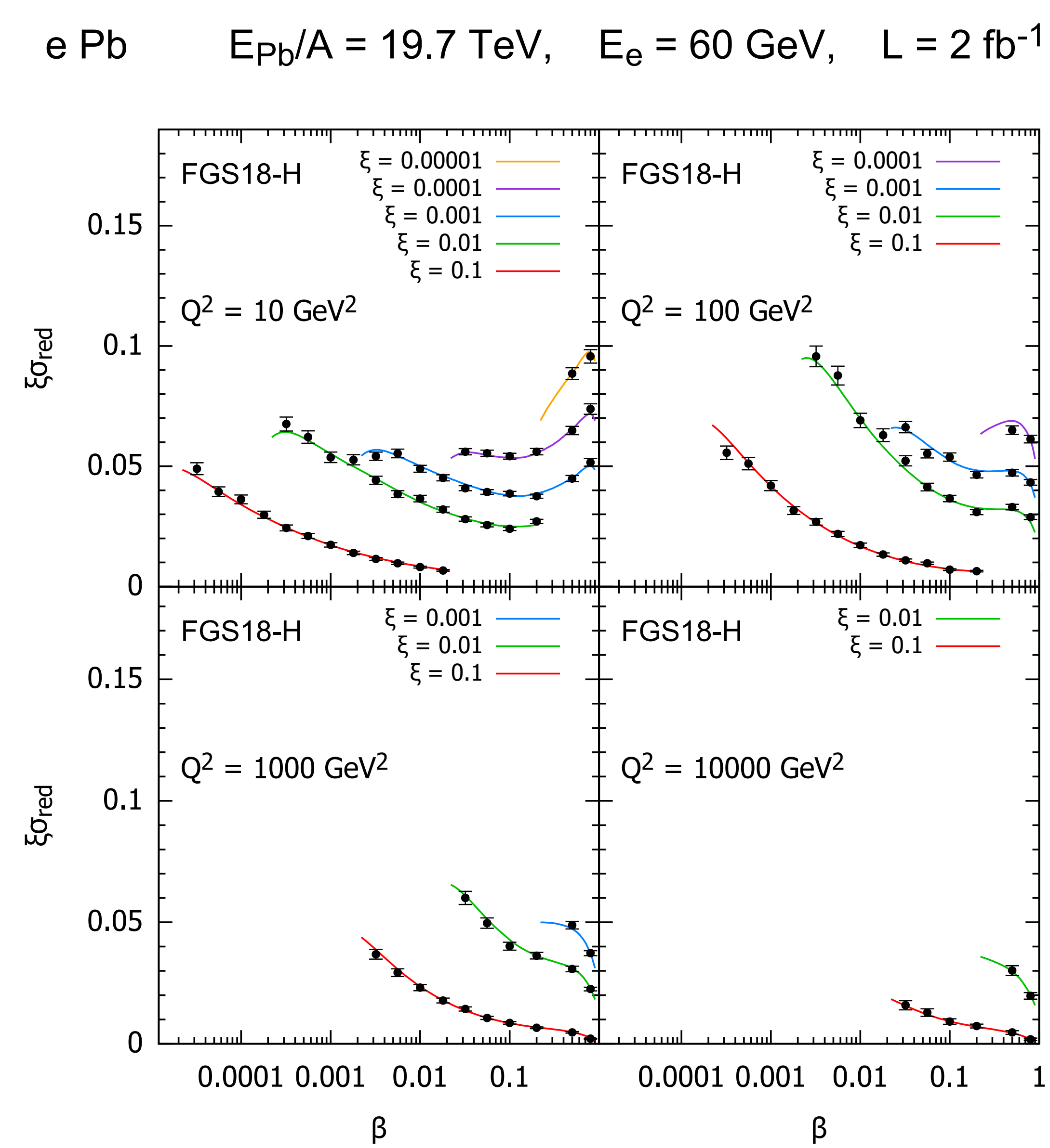
Prospects for precise extraction of diffractive PDFs, tests of factorization breaking (collinear and soft)

Inclusive diffraction on nuclei

Reduced cross section from Frankfurt, Guzey, Strikman model

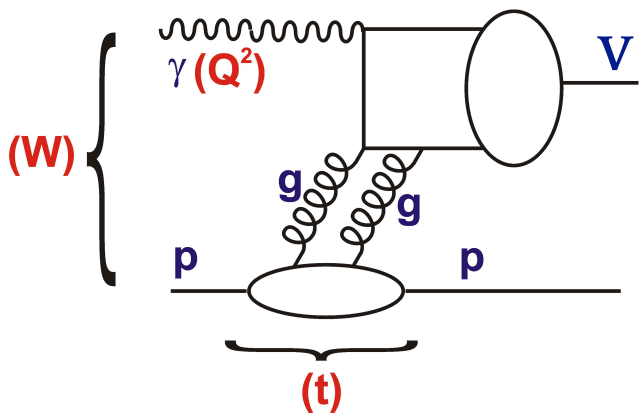
Pseudodata simulated under the same assumptions: 5% systematics, conservative luminosity 2 fb^{-1}

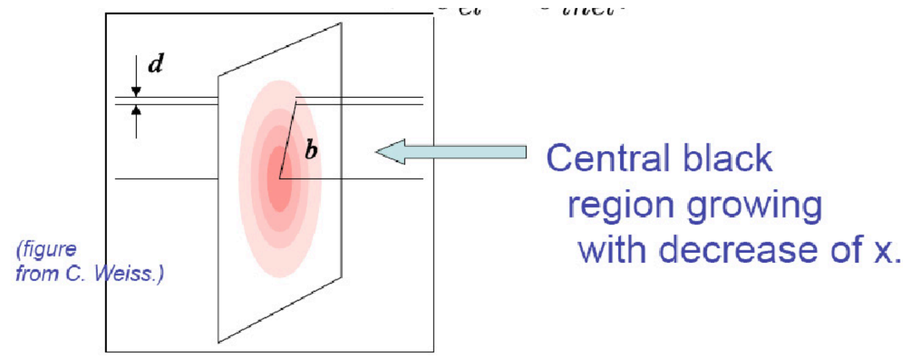


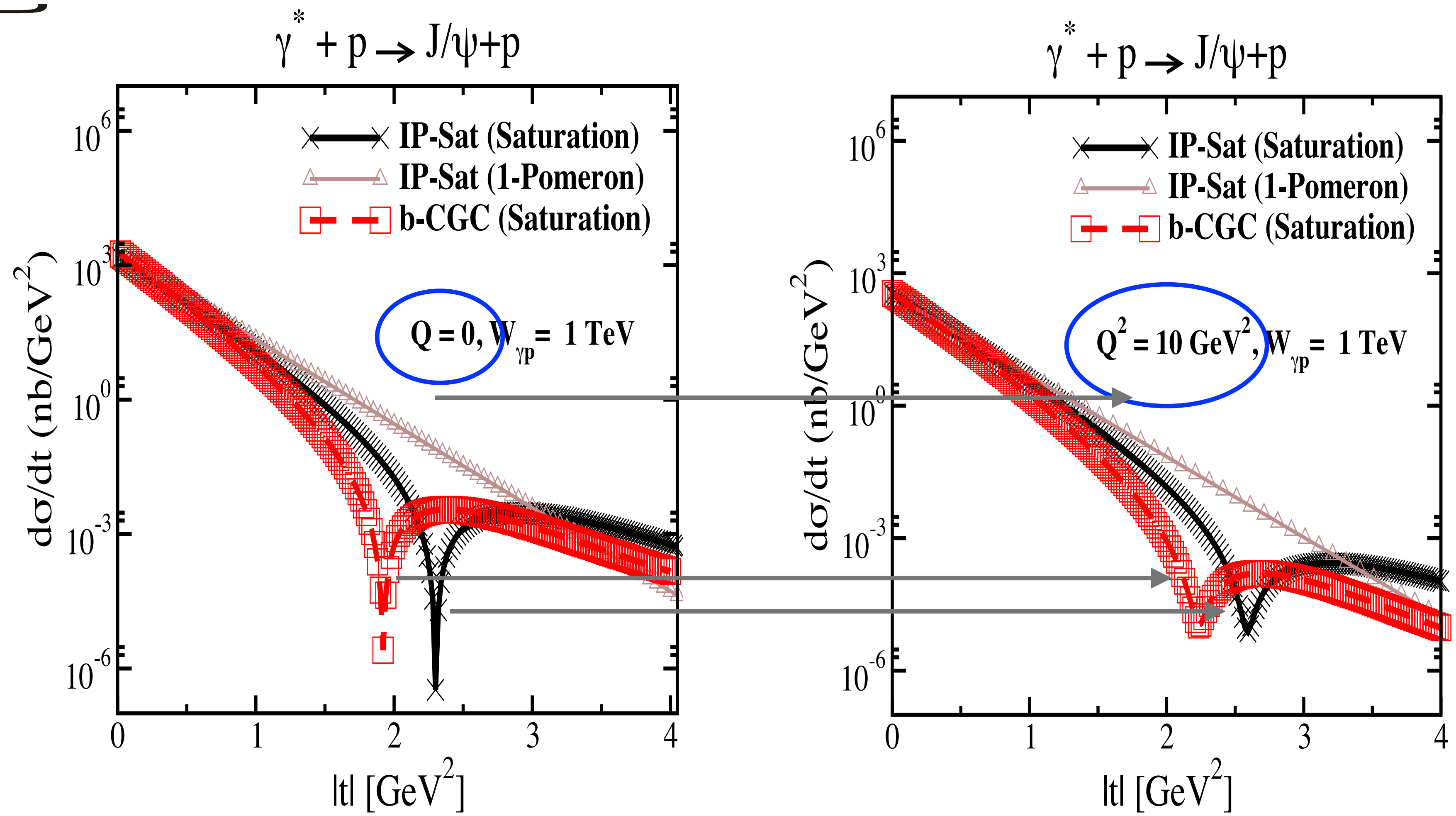


High precision data would allow to extract the nuclear DPDFs with similar accuracy to the proton case

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:
    - 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
    - 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…!

LHeC/FCC-eh/PERLE at DIS2021

For more information about LHeC/FCC-eh see talks at DIS:

Session: Future Experiments

Alex Bogacz, *The ERL Facility PERLE at Orsay*

Oliver Fischer, *BSM Physics at the LHeC and the FCC-eh*

Heikki Mantysaari, *Electron-Ion Collisions at the LHeC and FCC-eh*

Claire Gwenlan, *Determination of the Parton Densities in the Proton at the LHeC*

Christian Schwanenberger, *The Large Hadron-electron Collider at CERN: Status and Plans*

Ludovica Aperio Bella, *The LHeC as Part of the HL-LHC Programme*

Session: EW Physics and BSM

Mukesh Kumar, *Top Physics at the LHeC and the FCC-eh*

Uta Klein, *Higgs physics at the LHeC and the FCC-eh*

Daniel Britzger, *Precision electroweak measurements at the LHeC and the FCC-eh*

Plenary Session:

Tim Hobbs, *DIS (EIC & LHeC) physics and connections to LHC*