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

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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

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

arXiv:1206.2913


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Accelerator concepts for electron–proton collisions

**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

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

50 x 7000 GeV\(^2\): 1.2 TeV ep collider
Operation: 2035+, Cost: O(1) BCHF
Upgrade to \( 10^{34} \text{ cm}^{-2} \text{s}^{-1} \), for Higgs, BSM
CERN-ACC-Note-2018-0084 (ESSP)

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:

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 $Q^2 = 1.9$ 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

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

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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 $x$

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%, $\theta_e$ 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

Relative uncertainties for nuclear modification factor

Kinematic plane for eA

Precision structure functions, also for heavy flavors

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 GeV**

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

- \( E_p = 50 \text{ TeV} \) vs. 7 TeV
  - \( x_{min} \) down by factor ~10
  - \( Q^2_{max} \) up by factor ~10
LHeC phase space: $(\beta, Q^2)$ fixed $\xi$

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

$\theta > 1^\circ$  $\theta = 10^\circ$  bins  $M_X = 2m_t$

# bins for $\xi < 0.15$
- no top
  - 1589 for $Q^2 > 1.3$ GeV$^2$
  - 1229 for $Q^2 > 5$ GeV$^2$
- with top quark
  - 17 bins more
FCC–eh phase space: $(\beta, Q^2)$ fixed $\xi$

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

\[ \theta > 1^\circ \quad \theta = 10^\circ \quad \text{bins} \times \quad M_X = 2 m_t \quad \text{--- dashed} \]

# 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 $\sigma_{\text{red}}$

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
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)
 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

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

Advantage over UPC:
- $Q^2$ dependence

Central black region growing with decrease of $x$. 
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...!