Electron-Ion Physics with the LHeC

DIS2015

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Outline

- Large Hadron Electron Collider
  - Kinematics
- Nuclear PDFs
  - Recent analyses
  - Current data constraints
  - Impact of LHeC data
- Other $e+\Lambda$ physics
  - Small-$x$ physics
  - Jet production and hadronization
- Summary & Outlook

Thanks to

- Nestor Armesto (Univ. of Santiago de Compostela)
- Hannu Paukkunen (Univ. of Jyväskylä)
# Large Hadron Electron Collider (LHeC)

LHC proton/ion beam + new $e^\pm$ accelerator

- $E_p = 7$ TeV (corresponds to $E_{Pb} = 2.76$ TeV), $E_e = 60$ GeV
- Synchronous $p+p$ and $e+p (A+A$ and $e+A)$ operation
- Luminosity:
  - $e+p$: $16 \cdot 10^{33}$ cm$^{-2}$s$^{-1}$ (post-CDR)
  - $e+A$(per nucleon): $5 \cdot 10^{31}$ cm$^{-2}$s$^{-1}$ (updated: few $\cdot 10^{32}$ cm$^{-2}$s$^{-1}$)

Further in the future: FCC-he ($E_p = 50$ TeV, $E_e = 175$ GeV)

[from N. Armesto]
Kinematics

Deep inelastic scattering (DIS):

\[ q = k - k' \]

\[ p \]

\[ M \]

\[ k' \]

\[ M_x \]

Invariant variables

\[ Q^2 = -q^2 \]

\[ x = \frac{Q^2}{2 p \cdot q} \]

\[ y = \frac{p \cdot q}{p \cdot k} \]

Cross section

\[
\frac{d\sigma^{\text{DIS}}}{dx dQ^2} = \frac{4\pi \alpha_{\text{EM}}^2}{Q^4} \frac{1}{x} \left[ xy^2 F_1(x, Q^2) + (1 - y) F_2(x, Q^2) \right]
\]

Measured structure functions \( F_i(x, Q^2) \) can be directly related to parton distribution functions (PDFs)

Also other interesting (non-inclusive) measurements in \( e + p/A \)!
Structure functions modified in nuclear collisions:

Modifications absorbed into process independent nuclear PDFs:

\[ f_i^A(x, Q^2) = R_i^A(x, Q^2) f_i(x, Q^2) \]

Global DGLAP analyses

- Provide the nuclear modifications \( R_i^A(x, Q^2) \)
- Test factorization of nuclear effects
Recent nPDF analyses

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<th>Ref.</th>
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<th>EPS09</th>
<th>DSSZ</th>
<th>nCTEQ prelim.</th>
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[from H. Paukkunen]
Kinematic coverage of data in current nPDF fits

- DIS, DY and inc. hadrons:
  - Brahms data not included to fits
  - Lower $Q^2$ cut varies between analyses (EPS09 cut shown)

- Neutrino DIS:
  - Included only to DSSZ so far
  - Provides flavor separation
Kinematic coverage of data in current nPDF fits

- DIS, DY and inc. hadrons:
  - Lower $Q^2$ cut varies between analyses (EPS09 cut shown)
  - Brahms data not included to fits

- Comparison to proton PDF fits:
  - Much broader reach due to HERA and LHC data
  - $p+Pb$ data will improve kinematic reach of nPDF analyses
Kinematic coverage of data in current nPDF fits

- DIS, DY and inc. hadrons:
- Brahms data not included to fits
- Lower $Q^2$ cut varies between analyses (EPS09 cut shown)

The expected coverage of LHeC:

- LHeC data would provide a huge improve for the kinematic reach!
- $e+A$ much cleaner measurement than $p+A$
Kinematic coverage of data in current nPDF fits

- DIS, DY and inc. hadrons:
  - Lower $Q^2$ cut varies between analyses (EPS09 cut shown)
  - Brahms data not included to fits

The expected coverage of FCC-eA:

- Further extension of kinematics
- Large electron energy requires large acceptance
Uncertainties in the current nPDF fits

Comparison between different fits:

- nCTEQ analysis provides somewhat larger uncertainties
  [Talk by A. Kusina at 14.00 (WG1)]

- Recent p+Pb data from LHC constrains nPDFs mostly at $x > 0.01$
  [Talk by I.H. at 14.25 (WG1)]

- Uncertainties remain large at small-$x$ regions
  $\Rightarrow$ No accurate baseline for heavy-ion physics at LHC

- Impact of the LHeC?
# Impact of LHeC data

## How to study impact of new data

1. Generate "pseudodata" corresponding the expected measurement
2. Add the pseudodata to global analysis on top of existing data
3. Perform a re-analysis and compare the results

## For the LHeC

- Samples of neutral current DIS reduced cross section

\[
\sigma_{\text{reduced}} = \frac{xQ^4}{2\pi\alpha^2_{\text{EM}}Y_+} \frac{d^2\sigma^{\text{DIS}}}{dx dQ^2}
\]

where \( Y_+ = 1 + (1 - y)^2 \)

were generated in the kinematic window

- \( 10^{-5} < x < 1 \)
- \( 2 < Q^2 < 10^5 \text{ GeV}^2 \)

- Nuclear modifications from EPS09
Impact of LHeC data

- Low-$Q^2$ pseudodata and prediction before the inclusion:

**60 GeV lepton beam**

Pseudodata

Standard Fit

\( Q^2 = 2 \text{ GeV}^2 \)

\( Q^2 = 5 \text{ GeV}^2 \)

\( Q^2 = 10 \text{ GeV}^2 \)

\( Q^2 = 20 \text{ GeV}^2 \)

\( Q^2 = 50 \text{ GeV}^2 \)

\( Q^2 = 100 \text{ GeV}^2 \)

\( Q^2 = 200 \text{ GeV}^2 \)

\( Q^2 = 500 \text{ GeV}^2 \)

[H. Paukkonen, preliminary]
Impact of LHeC data

- Low-$Q^2$ pseudodata and prediction after the inclusion:

![Graph showing impact of pseudodata and standard fit at different $Q^2$ values (2 GeV^2 to 500 GeV^2)]

- Significant reduction of nPDF-originating uncertainties (blue bands)

---

[H. Paukkunen, preliminary]
Impact of LHeC data

- Impact to the nPDF uncertainties

- Huge reduction of the small-$x$ uncertainties for gluons and sea quarks
- Results still preliminary: the form of the fit function at low $x$ might have impact also to size of the uncertainties
- Charged current ($c$ and $b$) data should constrain flavor dependence (Currently unconstrained, some constraints from $W^\pm$ in $p+Pb$)
Small-x physics

- Linear QCD-evolution leads to large number of gluons at small $x$
- Breakdown at high densities $\Rightarrow$ saturation?

$Q_s^2 \propto A^{1/3} x^{-0.3} \Rightarrow$ saturation more pronounced at large $A$

$\Rightarrow$ LHeC should be sensitive to saturation physics especially with $e + A$

Inclusive hadrons in $p + Pb$ (NLO):

In $p + Pb$, $\sqrt{s} = 5.0$ TeV, $p_T = 5$ GeV

d$(\sigma_{\pi^0} / dp_T dy d(\log(x^2)))$ [pb]

$y = 0$
$y = 2$
$y = 4$
Jets in $e+A$

- Photoproduction of jets: direct and resolved ($\gamma$ PDFs) processes

$\frac{d\sigma^\gamma_{Q^2=0}}{dE_{T\text{jet}}} (\mu b/GeV \text{ per nucleon})$

$\frac{d\sigma^\gamma_{Q^2=0}}{d\eta_{\text{jet}}} (\mu b \text{ per nucleon})$

- Large $E_T$ jets also in $e+A$
- Useful to study parton dynamics and photon structure
- Not all theoretical uncertainties considered yet
Hadronization in nuclear medium

- LHeC provides clean environment to study hadron production with nuclear target ("cold nuclear matter")
  - Low energy:
    - hadronization happens inside the nuclear medium
    - pre-hadronic absorption?
  - High energy:
    - hadronization happens outside the nuclear medium
    - partonic evolution inside the medium

- Benchmark for hadron production in $A+A$ and $p+A$
- See *Phys. Rev. D81 (2010) 054001* for medium modified FF analysis
Summary

Nuclear PDFs

- Data constraining current nPDF fits quite limited in kinematics
- $p+Pb$ data from LHC will improve fits at $x \gtrsim 0.01$
- LHeC would provide very precise data down to $x \sim 10^{-5}$
  ⇒ Drastic reduction of the nPDF uncertainties!
  ⇒ Flavor decomposition from charged current and heavy quark data

Other $e+A$ physics

- Clean environment to study small-$x$ phenomena such as saturation
- Photoproduction of jets can be used to study photon (nuclear) PDFs
- Cold nuclear matter effects to hadron production
+ Topics not covered here (Diffraction, Vector Mesons, ...)
Outlook

Theoretical improvements

- Finalize the nPDF re-analysis with pseudodata
  - Include charged current data
    ⇒ Relax the assumption of flavor symmetry
  - Chart the uncertainty due to the initial parametrization
- Details of jet production and reconstruction
- Monte Carlo generators for $e+p/A$

TDR during this year
Backup
Impact of LHeC data

- High-$Q^2$ pseudodata and prediction before the inclusion:

- The nPDF-originating uncertainties (blue bands) already rather small at high-$Q^2$.
Impact of LHeC data

- High-$Q^2$ pseudodata and prediction after the inclusion:

- the nPDF-originating uncertainties (blue bands) already rather small at high-$Q^2$
Vector Meson (VM) production

- The $t$-differential cross-section of exclusive diffractive VM production can be related to impact parameter
  $\Rightarrow$ Transverse profile of hadron/nucleus can be extracted

- Also sizable saturation effects expected

\[ \gamma^* A \rightarrow J/\Psi A \quad Q^2 = 0 \]

\[ d\sigma/dt \ (nb/GeV^2) \]

\[ 10^{-5} \quad 10^{-4} \quad 10^{-3} \quad 10^{-2} \quad 10^{-1} \]

\[ 0 \quad 0.02 \quad 0.04 \quad 0.06 \quad 0.08 \quad 0.1 \quad 0.12 \quad 0.14 \quad 0.16 \quad 0.18 \]

\[ t \ (GeV^2) \]

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Elastic VM production

- Coherent VM production:
  \[ \gamma (Q^2) \rightarrow VM (W) \]

  Predictions available showing large saturation \( \Rightarrow \)

- Incoherent VM production:
  \[ \gamma (Q^2) \rightarrow VM (W) \]

Energy dependence of coherent VM

\[ \gamma^* A \rightarrow J/\Psi A \]

\[ b - \text{Sat} \]

\( t = 0, \; Q^2 = 0 \)

\[ \frac{1}{A^2} \frac{d\sigma}{dt} \text{ (\( \mu b/GeV^2 \))} \]

- nosat
- proton
- Calcium
- Lead

W (GeV)

0 200 400 600 800 1000
Charged hadron production

- Nuclear modification factor at forward rapidities for charged hadrons

Data induces tension in global analysis

- NLO calculation agree with the d+Au spectra but not with the p+p baseline