Constraining Nuclear PDFs at an EIC

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Spatial and Momentum Tomography of Hadrons and Nuclei

INT-17-3 Program (2017) - Seattle
Proton PDFs from HERA

**What we Know:**
- Extensive program carried at HERA
- $F_2$ precisely measured in a large-$x$ range
- At low-$x$ gluons dominate

Differential cross section:

$$ \frac{d^2 \sigma_{e^+p}}{dx dQ^2} = \frac{2}{xQ^4} Y_+^2 r(x, Q^2) $$

Reduced cross section:

$$ r(x, Q^2) = F_2(x, Q^2) \frac{Y^2}{Y^+} F_L(x, Q^2) $$
Nuclear Structure Functions

Inclusive DIS on e+\(A\) analog to e+\(p\):

\[
\frac{d^2\sigma^{eA\rightarrow eX}}{dx\,dQ^2} = \frac{4\pi\alpha^2}{xQ^4} \left[ \left( 1 - y + \frac{y^2}{2} \right) F_2(x, Q^2) - \frac{y^2}{2} F_L(x, Q^2) \right]
\]

Theory/models have to be able to describe the structure functions and their evolution.

DGLAP:

predicts \(Q^2\) but not A-dependence and x-dependence

Saturation models:

predict A-dependence and x-dependence but not \(Q^2\)

\(\rightarrow\) Need: large \(Q^2\) lever-arm for fixed x, A-scan

Aim at extending our knowledge on structure functions into the realm where gluon saturation effects emerge ∘ different evolution

\(\text{Ratio: } \frac{F_2(x,Q^2)_{\text{Pb}}}{F_2(x,Q^2)_{\text{p}}}\)
An EIC at its highest extends kinematic coverage for e+A data by a decade in $x$ at a fixed $Q^2$ by a decade in $Q^2$ at a fixed $x$. 
Nuclear Modifications – Present Knowledge

Measure different structure functions in e+A \rightarrow \text{constrain nPDF}

Latest state-of-the-art nPDF is EPPS16


- Replacing EPS09. Quark flavors are now separated
- includes latest LHC data
- EPPS16* \rightarrow \text{functional form} with less constraints (for gluons) in extrapolating for x < x_{data}
- Critical to study the impact of the high precision EIC data!
- What is the possible impact of an Electron-Ion Collider?

Ratio: \frac{g(x,Q^2)_{Pb}}{g(x,Q^2)_p}
Reduced Cross Section & Structure Functions

\[ r = F_2(x, Q^2) \frac{y^2}{1 + (1 - y)^2} F_L(x, Q^2) \]

\[ \frac{y^2}{1 + (1 - y)^2} = Y^+ \]

- Structure functions can be extracted from the reduced cross section
- Pseudo-data are generated using PYTHIA and according to EPS09 central values
- In order to extract \( F_2 \) from the reduced cross section, we adopted the same method used at HERA [e.g. see HERMES paper on arXiv:1103.5704]
- \( F_L \) extracted from the reduced cross section by fitting the slopes in \( Y^+ \) for different \( \sqrt{s} \)s at fixed \( x, Q^2 \) requires running at (at least) three different c-o-m energies

**Simulation:**
e+Au sample simulated using PYTHIA
5(20) GeV electrons X 50 GeV Au [\( \sqrt{s} = 32(63) \) GeV] \( \rightarrow \) \( L = 2 \text{ fb}^{-1}/A \)
5(20) GeV electrons X 75 GeV Au [\( \sqrt{s} = 39(78) \) GeV] \( \rightarrow \) \( L = 4 \text{ fb}^{-1}/A \)
5(20) GeV electrons X 100 GeV Au [\( \sqrt{s} = 45(89) \) GeV] \( \rightarrow \) \( L = 4 \text{ fb}^{-1}/A \)

**Total simulated event sample** (for each electron energy) \( L = 10 \text{ fb}^{-1}/A \)
Reduced Cross Section & $F_2 (e+Au)$

\[ r = F_2(x, Q^2) \frac{y^2}{1 + (1/y)^2} F_L(x, Q^2) \]

- **Systematics = 3%**
- Stat. and Sys. error summed in quadrature (Sys. dominate!)
- Gluon extraction via scaling violation \( \rightarrow d\sigma(x, Q^2)/d\ln Q^2 \) (requires \( \sim > 1 \) decade in \( Q^2 \) at a fixed \( x \))
- Comparison of linear with non-linear evolution in \( x \) will signal saturation

Large expected impact on current theory uncertainty, especially at low-\( x \) and low-\( Q^2 \)

An EIC at its highest energy provides a factor 10 larger reach in \( Q^2 \) and low-\( x \) compared to available data
Radiated photons

We use **Django simulator** including $O(\alpha)$ radiative effects

*We look at photons radiated from the electron before or after the interaction*

**Radiated photons are**
- Low energy (most of them $< 1$ GeV)
- uniformly distributed in the azimuthal angle
- collinear to the scattered electron ($\theta_\gamma > 3$ rad)

**Correction factor:**
\[
Rc = \frac{\text{red}(O(\cdots))}{\text{red}(\text{Born})} \cdot 1
\]

**Radiative corrections - 20 GeV x 100 GeV**

[Graph showing radiative corrections with different $Q^2$ values]
Extracting $F_L (e+Au)$

**Higher energy EIC: $\sqrt{s} = 63, 78, 89$ GeV**

Enough Lever Arm required (three points, $Y^+ > 0.2$)

Errors still dominated by systematics

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**Fraction of statistical uncertainty over total uncertainty in measuring $\sigma_r$**

- total error = stat. + sys. summed in quadrature
- assumed sys. = 3%
- Star error dominates only at large-$x$ and very large $Q^2$
Errors dominated by the systematics in the cross section measurement
→ Not luminosity hungry!
Study: $10 \text{ fb}^{-1} \rightarrow 100 \text{ fb}^{-1}$
has negligible impact
(see backup slide)
Charm production: a unique tool!

- Direct access to gluons at medium to high $x$ by tagging photon-gluon
- Helps determining heavy quarks mass scheme

Novel probe!

Selection of charm-production events

We select kaons in the final state of the $D$ meson decay, looking for:
- a displaced vertex: $0.01 \text{ cm} < |\text{Vertex}| < 3 \text{ cm}$
- Momentum within the acceptance of an EIC model detector (BeAST @ eRHIC)

<table>
<thead>
<tr>
<th>Region</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CENTRAL DETECTOR (-1 &lt; $\eta$ &lt; 1)</strong></td>
<td>$dE/dx \rightarrow 0.2 \text{ GeV} &lt; P &lt; 0.8 \text{ GeV}$</td>
</tr>
<tr>
<td></td>
<td>RICH -&gt; $2 \text{ GeV} &lt; P &lt; 5 \text{ GeV}$</td>
</tr>
<tr>
<td><strong>FORWARD (1 &lt; $\eta$ &lt; 3.5)</strong></td>
<td>$RICH \rightarrow 2 \text{ GeV} &lt; P &lt; 40 \text{ GeV}$</td>
</tr>
<tr>
<td><strong>REAR (-3.5 &lt; $\eta$ &lt; -1)</strong></td>
<td>$RICH \rightarrow 2 \text{ GeV} &lt; P &lt; 15 \text{ GeV}$</td>
</tr>
</tbody>
</table>

S. Fazio (BNL)
Charm - reduced Cross Section & $F_2$ (e+Au)

Systematics = 7%
Stat. and Sys. error summed in quadrature (Sys. dominate!)
No world data exist!

Large expected impact on current theory uncertainty, especially at low-$x$ and low-$Q^2$
Charm - $F_L (e+Au)$

Errors dominated by the systematics in the cross section measurement

- Not luminosity hungry!

- Study: $10 \text{ fb}^{-1} \to 100 \text{ fb}^{-1}$ has negligible impact (see backup slide)

- High energy EIC: huge impact on current predictions
Background study
We look at background from DIS events with kaons that pass the whole selection but are not coming from a charm decay.
The fraction of background over signal events is:
\[
\frac{\text{(selected bkg events)}}{\text{(selected Charm Events)}}
\]
Conclusion:
The B/S fraction is expected in the order of \(~1\%\) with a very light energy dependence

Efficiency study
We look at the efficiency of selection charm production events. The efficiency is defined as:
\[
\frac{\text{(selected Charm Events)}}{\text{(charm Events in Acceptance)}}
\]
Conclusion:
The charm selection efficiency is expected in the order of \(~28\%\) with no significant energy dependence
The EIC impact

Fits to the EIC simulated data

EPPS16* → EPPS16 using a flexible function with a couple of extra free parameters at small x for gluon (not for the quarks)

EIC: \( \sqrt{s} = 32, 39, 45 \) GeV

low-energy scenario

EIC: \( \sqrt{s} = 63, 78, 89 \) GeV

high-energy scenario

EPPS16* → EPPS16 using a flexible function with a couple of extra free parameters at small x for gluon (not for the quarks)
The EIC impact – sea quarks

Fits to the EIC simulated data

EIC: √s = 32, 39, 45 GeV
low-energy scenario

EIC: √s = 63, 78, 89 GeV
high-energy scenario

\[ R_{Pb}^{P}(x, Q^2) = 1.69 \text{GeV}^2 \]

\[ R_{g}^{P}(x, Q^2) = 1.69 \text{GeV}^2 \]

\( x \) range from \( 10^{-4} \) to 1

**u-bar**

**d-bar**
The EIC impact – gluons

low-energy scenario

\[
\begin{array}{c}
\text{Red. factor} \\
10^{-3} \quad 10^{-2} \quad 10^{-1} \quad X
\end{array}
\]

\[
\begin{array}{c}
\text{R}_{\text{gg}}^{\text{Pb}} \nend{array}
\]

\[Q^2 = 10 \text{ GeV}^2\]

\[\sqrt{s} = 31.6 - 44.7 \text{ GeV}\]

high-energy scenario

\[
\begin{array}{c}
\text{Red. factor} \\
10^{-3} \quad 10^{-2} \quad 10^{-1} \quad X
\end{array}
\]

\[
\begin{array}{c}
\text{R}_{\text{gg}}^{\text{Pb}} \nend{array}
\]

\[Q^2 = 10 \text{ GeV}^2\]

\[\sqrt{s} = 31.6 - 89.4 \text{ GeV}\]

Inclusive DIS alone has a huge effect at low-\(x\)

Charm has a dramatic effect at high-\(x\)
**Proton SFs**

**e+Au $F_L$ - EIC**

**Proton $F_L$ - HERA**

Not only for nuclei!

Comparable precision for proton Structure Functions in e+p scattering, to even higher $Q^2$ at high $x$.

→ Beyond what HERA achieved: precise measurement of proton $F_L$
Proton PDFs

Therefore EIC can have large impact on proton PDFs too!

- **e+Deutrium data** are sensitive to u/d quark flavor separation (need to correct for nuclear modifications)
- **Electroweak data** allow to constrain s quark PDFs as well as **SIDIS +FF**
Conclusions

e+A physics program at a future Electron-Ion Collider provides an unprecedented opportunity to study quarks and gluons in nuclei

✧ Precise measurements of nuclear structure functions in a large phase-space
✧ Constrain gluon nPDFs at large-x by tagging photon-gluon fusion through precise measurements of charm production
✧ Large impact in constraining gluon nPDFs at low-x
✧ Same or better precision expected for proton SFs too, Plus constraining large x gluons and separate u/d/s flavors

This is day 1 high impact physics!

Recent publication:

E.C. Aschenauer, S. F., M.A.C. Lamont, H. Paukkunen, P. Zurita
[arXiv:1708.05654]
Fraction of Statistical Uncertainty

\( e+Au \)
\( \bar{s} = 31.6 \text{ GeV} \)
\( Ldt = 2 \text{ fb}^{-1}/A \)
Sys. unc. = 1.6 %

\( e+Au \)
\( \bar{s} = 44.7 \text{ GeV} \)
\( Ldt = 4 \text{ fb}^{-1}/A \)
Sys. unc. = 1.6 %

\( e+Au \)
\( \bar{s} = 89.4 \text{ GeV} \)
\( Ldt = 4 \text{ fb}^{-1}/A \)
Sys. unc. = 1.6 %
Impact from and on p+A and A+A physics

- nPDFs required as input to physics in A+A
- p+A @ LHC has so far only moderate impact (see arXiv:1612.05741) on constraining nPDFs

Higher energy configurations of an EIC constrain nPDFs in an x-range critical for the A+A program at the LHC