Nuclear PDFs and electron-ion colliders

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Probing Nucleons and Nuclei in High Energy Collisions
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Why do nPDFs matter?

PDFs

\[ e + p \]
\[ p + p \]

FFs

\[ e^+ + e^- \]
Why do nPDFs matter?

PDFs

\[ e + p \]
\[ p + p \]

FFs

\[ e^+ + e^- \]
\[ e + p \]
\[ p + p \]
Why do nPDFs matter?

PDFs

$e + p$
$p + p$
$e + A$
$\nu + A$

FFs

$e^+ + e^-$
$e + p$
$p + p$

nPDFs

$\nu + A$
$e + A$
$p + A$
Why do nPDFs matter?

PDFs

\[ e^+ + e^- \]
\[ e + p \]
\[ p + p \]
\[ e + A \]
\[ \nu + A \]

FFs

\[ e^+ + e^- \]
\[ e + p \]
\[ p + p \]

nPdfs

\[ \nu + A \]
\[ e + A \]
\[ p + A \]

nFFs

\[ e + A \]
\[ p + A \]

and I’m not including A+A!
Outline

- The things we all know
- What’s up with the data?
- I’m free!
- Comparing nPDFs
- What can we do with an EIC?
The things we all know


The things we all know

**if we maintain the partonic description**

it is a fact that partons in nuclei do not behave as in the free proton

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**FIG. 1.** (a) $\sigma_{Al}/\sigma_D$ and (b) $\sigma_{Fe}/\sigma_D$ vs $x$. Only random errors are shown. Point-to-point systematic errors have been added linearly (outer bars) where applicable. The normalization errors of $\pm 2.3\%$ and $\pm 1.1\%$ for $\sigma_{Al}/\sigma_D$ (E49B) and $\sigma_{Fe}/\sigma_D$ (E87), respectively, are not included. All data for $W \geq 1.8$ GeV are included. The data have been corrected for the small neutron excess and have not been corrected for Fermi-motion effects. The curve indicates the expected ratio if Fermi-motion effects were the only effects present (Ref. 11). High-$Q^2$ $\sigma_{Fe}/\sigma_D$ data from EMC (Ref. 2), low-$Q^2$ $\sigma_{Al}/\sigma_D$ and $\sigma_{Cu}/\sigma_D$ data from Ref. 9, and photoproduction $\sigma_{Al}/\sigma_D$ and $\sigma_{Fe}/\sigma_D$ data from Ref. 13 are shown for comparison. The systematic error in the EMC data is $\pm 1.5\%$ at $x = 0.35$ and increases to $\pm 6\%$ for the points at $x = 0.05$ and $x = 0.65$.

The things we all know

we have the factorisation theorems

+ we know about proton PDFs

so we use the same ideas

and perform global fits to the world data

\[
f_i^A(x, Q_0^2) = \frac{Zf_i^{p/A}(x, Q_0^2) + (A - Z)f_i^{n/A}(x, Q_0^2)}{A}
\]
The things we all know

we have the factorisation theorems

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\[ f_i^A(x, Q_0^2) = \frac{Zf_i^{p/A}(x, Q_0^2) + (A - Z)f_i^{n/A}(x, Q_0^2)}{A} \]

Are nuclear PDFs a done deal?
The things we all know

we have the factorisation theorems +
we know about proton PDFs

so we use the same ideas
and perform global fits to the world data

\[ f_i^A(x, Q_0^2) = \frac{Z f_i^{p/A}(x, Q_0^2) + (A - Z) f_i^{n/A}(x, Q_0^2)}{A} \]

Are nuclear PDFs a done deal?

ABSOLUTELY NOT!
Steps for a global fit:

1. Select the data

2. Write the (n)PDFs at some initial scale ($Q_0$) in terms of free parameters

3. Give values to the parameters

4. Determine the distributions at the experimental scales ($Q$) using the DGLAP evolution equations

5. Write theoretical predictions using (4)

6. Use (1)+(5) to estimate the “goodness” of the description

7. Repeat (6) until the description is “good enough”

8. Determine how much one can move the parameters without spoiling (6)

9. Take the parameters of (7)+(8) and generate grids for public use
What’s up with the data?
What’s up with the data?

NNPDF3.0 NLO dataset

<table>
<thead>
<tr>
<th>Points</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>NC DIS</td>
<td>51.8 %</td>
</tr>
<tr>
<td>CC DIS</td>
<td>4.6 %</td>
</tr>
<tr>
<td>CC DIS</td>
<td>22 %</td>
</tr>
<tr>
<td>DY &amp; EW</td>
<td>15 %</td>
</tr>
<tr>
<td>Jets</td>
<td>6.6 %</td>
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</tbody>
</table>

Ball et al., JHEP 1504 (2015) 040

for the proton
What's up with the data?

**Figure:**

- **Data Points:**
  - Total Points: 1811
  - Points for nuclei: 869

**Legend:**
- Fixed target DIS and DY
- LHC dijets
- LHC W & Z
- CHORUS neutrino data
- PHENIX $\pi^0$

**Nuclear Data:**

<table>
<thead>
<tr>
<th>Element</th>
<th># Points</th>
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<tbody>
<tr>
<td>He</td>
<td>37</td>
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<tr>
<td>Li</td>
<td>168</td>
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<td>Be</td>
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<td>Au</td>
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<td>Pb</td>
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</table>
What’s up with the data?

The graph shows the distribution of data points in the $(Q^2, x)$ plane, with various processes contributing to the data:

- **fixed target DIS and DY**
- **LHC dijets**
- **LHC W & Z**
- **CHORUS neutrino data**
- **PHENIX $\pi^0$**

The figure includes a legend with different colors indicating the processes.

### Table: Number of Points for Nuclei

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Not only issues with the amount of data and the coverage...
What's up with the data? NC DIS

\[ \frac{F_2^A}{F_2^A'} \]

What’s up with the data? NC DIS

- little sensitivity to gluons
- $F_2$ extraction based on parameterisations of $R = \sigma_L/\sigma_T$
- some are actually $\sigma^A/\sigma^{A'}$
- are there any $R$ data? YES!
- are there any non-ratio data? YES!

Doing some archeology, for $Q^2 > 1\ GeV^2$

<table>
<thead>
<tr>
<th></th>
<th># points</th>
</tr>
</thead>
<tbody>
<tr>
<td>F$_2$ ratio</td>
<td>1061</td>
</tr>
<tr>
<td>$\sigma$ ratio</td>
<td>730</td>
</tr>
<tr>
<td>F$_2$</td>
<td>927</td>
</tr>
<tr>
<td>R</td>
<td>79</td>
</tr>
</tbody>
</table>

corrections for non-isoscalarity
What's up with the data? Drell-Yan


NLO: EPJ C77 (2017) no.3, 163

some constraint on the sea

92-120 points

LO/NLO very similar
What’s up with the data? Drell-Yan


![Graph 1](image1)

![Graph 2](image2)

*EPJ C77 (2017) no.3, 163*
What’s up with the data? $\pi$ production at RHIC

PRD93 (2016) no.8, 085037

- sensitive to the gluon density
- large uncertainties
- depends on the fragmentation functions
What’s up with the data? π production at RHIC

-final state effects?

\[
R_A^h(\nu, Q^2, z, p_T^2) = \left( \frac{N_A^h(\nu, Q^2, z, p_T^2)}{N_e(\nu, Q^2)} \right)_A \left( \frac{N_e(\nu, Q^2)}{N_e(\nu, Q^2)} \right)_D
\]

Airapetian et al., Nucl. Phys. B780 (2007) 1
What’s up with the data? CC DIS

<table>
<thead>
<tr>
<th>Exp.</th>
<th>Ref.</th>
<th>A</th>
<th>Comments</th>
</tr>
</thead>
</table>

Also: CCFR, IHEP-JINR, CHARM, Gargamelle, NOMAD, Minerva

![Diagram](image)
What’s up with the data? CC DIS

- the ratio is different
- no proton reference for these experiments
- the problem seems to be NuTev data, only for the $\sigma$

- normalisation uncertainties in some energy bins
- only when considering the covariance matrix

EPJ C77 (2017) no.3, 163

**OPEN ISSUE**
I’m free!

(all I can do and how it impacts the results)
I’m free!

I get to pick!

- the data
  - ratios, $F_2$, cross-sections?
  - DIS, DY, jets, hadrons?
  - non-isoscalar corrections?
  - kinematical cuts
  - etc.

- the theory
  - FFs, final state effects?
  - scales?
  - nuclear effects for deuteron?
  - proton PDF reference?
  - etc.
choose a proton PDF as reference and (try to!) be consistent

- select $Q_0$ accordingly (see (4))
- treat the heavy quarks accordingly
- kinematical cuts not always accordingly

- somehow include the nuclear dependence (limit for $A=1$?)

- HKM, HKN, EPS09, DSSZ, KA15, EPPS16

\[
f_{i/A}(x, Q_0^2) \equiv f_{i/p}(x, Q_0^2) R_i^A(x, Q_0^2)
\]

- nDS

\[
f_{i/A}(x, Q_0^2) \equiv \int_x^A \frac{dy}{y} W_i^A(y, Q_0^2) f_{i/p}\left(\frac{x}{y}, Q_0^2\right)
\]

- nCTEQ

directly parameterise the nPDF
choose perturbative order: LO, NLO, NNLO, …
understand clearly what it means in terms of $\alpha_s$
how do we treat the heavy-quarks?

GM-VFNS: TR’, ACOT, SACOT, FONLL, …?
FFNS
ZM-VFNS

xFitter manual: https://www.xfitter.org/
nuclear effects in the deuteron?

in HKN07 (and CTEQ15?)

final state effects for hadrons?

only in DSSZ

25% variation in RHIC $\chi^2$

< 2% variation on the fit $\chi^2$
I'm free! The $\chi^2$ minimisation

(6) $\chi^2$

$$\chi^2(a) = \sum_{i,j} \left[ T_i(a) - E_i \right] C_{i,j}^{-1} \left[ T_j(a) - E_j \right]$$

- $a$ : parameters
- $T_i(a)$ : theoretical value of datapoint “$i$”
- $E_i$ : experimental value of datapoint “$i$”
- $C_{i,j}$ : covariance matrix

if not know

$$\chi^2(a) = \sum_i \left[ \frac{T_i(a) - f_N E_i}{\delta_i^{\text{uncorr.}}} \right]^2 + \left( \frac{1 - f_N}{\delta_{\text{norm}}} \right)^2$$
I'm free! The fit

(7) the fit

- average number of parameters: ~ 20
- multiple local minima, very hard to find the absolute minimum
- poor sensitivity to some flavours
- can give relevance to some data sets by adding weights

\[
\begin{align*}
Q^2 &= 10 \text{ GeV}^2 \\
\Delta \chi^2 &= 30
\end{align*}
\]

This fit EPS 09 nDS Q \( \sqrt{2} \) = 10 GeV

\[
\begin{align*}
R_i^A &= \frac{1}{100} \\
R_i^A &= \frac{1}{100}
\end{align*}
\]

\[
\begin{align*}
\Delta \chi^2 &= 1 \\
\Delta \chi^2 &= 30
\end{align*}
\]

\[
\begin{align*}
\text{this fit} \\
\text{EPS 09} \\
nDS
\end{align*}
\]

PRD85 (2012) 074028
The uncertainties

\( \chi^2(a) \approx \chi^2_0 + \sum_{i,j} \delta a_i H_{ij} \delta a_j \)

\( \delta a_i \equiv a_j - a_j^0 \) deviation from best fit value of the parameter

Diagonalise the Hessian matrix:

\( D_{kj} \equiv \sqrt{\varepsilon_k} v^{(k)}_j \)

Define new parameters:

\( z_k \equiv \sum_j D_{kj} \delta a_j \)

More information in:
I’m free! The uncertainties

- in the new parameter space
  \[ \chi^2(a) \approx \chi_0^2 + \sum_i z_i^2 \]

- for any PDF dependent quantity the uncertainty can be obtained by
  \[ \Delta \mathcal{O} = \sqrt{\sum_i (\Delta z_i)^2 \left( \frac{\partial \mathcal{O}}{\partial z_i} \right)^2} \]

- defining the PDFs error sets \( S_i^{\pm} \)

\[ z(S_i^{\pm}) = \pm t_i^{\pm} (0, \ldots, i, \ldots 0) \quad i = 1, \ldots, N_{\text{param}} \]

More information in:
Comparing nPDFs
Comparing nPDFs: the valence

\[ \frac{4}{9} u + \frac{1}{9} d \rightarrow \left( \frac{A + 3Z}{9A} \right) u + \left( \frac{4A - 3Z}{9A} \right) d \]
Comparing nPDFs: the sea

Extrapolation!
Comparing nPDFs: the gluon extrapolation!

$Q^2 = 1 \text{ GeV}^2$

$R_A^g$

EPJ C77 (2017) no.3, 163

extrapolation!

extrapolation!
Comparing nPDFs: magic!

All give nice descriptions of the data.
What can we do with an EIC?
What can we do with an EIC?

- extend the kinematic coverage!
- more, high precision, “non-modified” data
- get all data (not only structure functions!)
- lever arm in $A$ (doable at the LHeC?)
- publish covariance matrices

**Generalities**

**Measurements with $A \geq 56$ (Fe):**

- eA/μA DIS (E-139, E-665, EMC, NMC)
- JLAB-12
- vA DIS (CCFR, CDHSW, CHORUS, NuTeV)
- DY (E772, E866)

**EIC**

- $\sqrt{s} = 32 - 90$ GeV, $0.01 \leq y \leq 0.95$
- $\sqrt{s} = 15 - 40$ GeV, $0.01 \leq y \leq 0.95$
- $\sqrt{s} = 22 - 63$ GeV, $0.01 \leq y \leq 0.95$
- $\sqrt{s} = 45 - 141$ GeV, $0.01 \leq y \leq 0.95$

**Current polarized DIS ep data:**

- CERN, DESY, JLab-6, SLAC

**Current polarized RHIC pp data:**

- PHENIX, π, STAR 1-jet, W bosons

**arXiv:1708.01527**
What can we do with an EIC?

The things we know and have been doing

- study the neutron
- study inclusive cross-sections

![Graph](image)

Aschenauer, Fazio, Lamont, Paukkunen, PZ, PRD96 (2017) no.11, 114005
The things we know and have not done

determine $F_L$

(try to) achieve full flavour decomposition using CC

explore heavy flavour schemes and intrinsic charm

check for final state nuclear effects in SIDIS, determine them if existing

study the link between centrality and collision geometry, reach high density effective nuclei?

What can we do with an EIC?

study heavy-quark cross-sections

Aschenauer, Fazio, Lamont, Paukkunen, PZ, PRD96 (2017) no.11, 114005

See also C. Weiss talk at “Santa Fe Jets and Heavy Flavor Workshop, 30-Jan-18”

https://indico.fnal.gov/event/15328/session/4/contribution/15/material/slides/0.pdf
What can we do with an EIC?

include jet data

Klasen, Kovarik, Potthoff, PRD95 (2017) no.9, 094013

Klasen and Kovarik, PRD97 (2018) no.11, 114013
What can we do with an EIC?

The things we do not know

- validity of the factorisation?
- validity of isospin symmetry?
- new phenomena (saturation?)
- nuclear GPDs and TMDs

🤔 ????
Why do nPDFs matter?

PDFs

\[ e + p \]
\[ p + p \]
\[ e + A \]

EIC: the first chance to make everything the right way from the beginning

nPDFs

\[ e + A \]
\[ p + A \]

FFs

\[ e^+ + e^- \]
\[ e + p \]
\[ p + p \]

nFFs

\[ e + A \]
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