SEMI-INCLUSIVE DIS, PDFs AND FFs AT A FUTURE EIC

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PDFs Selected Highlights

How well do we know the sea quarks?
PDFs Selected Highlights
How well do we know the sea quarks?

Semi-Inclusive processes in Global Fits
New insights from SIDIS
Combined extraction of PDFs & FFs

IB, R. Sassot, M. Stratmann
PDFs Selected Highlights
How well do we know the sea quarks?

Semi-Inclusive processes in Global Fits
New insights from SIDIS
Combined extraction of PDFs & FFs

Parton Distributions @ EIC
A case of study

IB, R. Sassot, M. Stratmann

E. Aschenauer, IB, R. Sassot, C. Van Hulse
Remarkable progress in the last decades:

- NNLO extractions
- High precision LHC measurements now included in fits (ATLAS/CMS W,Z production)
- Uncertainties reduction to a few percent points (and expected to be further constrained by the HL-LHC).
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We have a pretty clear image of how the quarks and gluons are distributed inside the proton.
Remarkable progress in the last decades:

- NNLO extractions
- High precision LHC measurements now included in fits (ATLAS/CMS W,Z production)
- Uncertainties reduction to a few percent points (and expected to be further constrained by the HL-LHC).
The strangeness puzzle

\[ R_s(x, Q^2) = \frac{[s(x, Q^2) + \bar{s}(x, Q^2)]}{[u(x, Q^2) + \bar{d}(x, Q^2)]} \]

- Strange content of the proton not so well constrained.
- Tension in strangeness driven by disagreement between collider data and neutrino DIS
The strangeness puzzle

\[ R_s(x, Q^2) = \frac{[s(x, Q^2) + \bar{s}(x, Q^2)]}{[\bar{u}(x, Q^2) + \bar{d}(x, Q^2)]} \]

NNLO, Q=100 GeV

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Strange content of the proton not so well constrained.

Tension in strangeness driven by disagreement between collider data and neutrino DIS

There is still a lot of room for PDFs improvement
HOW WELL DETERMINED ARE THESE PARTON DISTRIBUTIONS?

The strangeness puzzle

How can we improve our knowledge of the PDFs?
What can we learn from a future Electron-Ion Collider?
HOW CAN WE IMPROVE OUR KNOWLEDGE OF THE PDFS?

Which are the experiments constraining the strangeness in the proton?

Traditional approach: completely inclusive DIS data

\[ [f_q^P(x) + f_{\bar{q}}^P(x)] \]

Deuterium + Flavor symmetries for flavor separation

- DIS with electroweak currents
- W/Z production in p-p
HOW CAN WE IMPROVE OUR KNOWLEDGE OF THE PDFS?

Which are the experiments constraining the strangeness in the proton?

Traditional approach: completely inclusive DIS data

\[ [f_q^P(x) + f_{\bar{q}}^P(x)] \]

Deuterium + Flavor symmetries for flavor separation

For strange distributions

Indirect sensitivity to the strange content of the proton
IDENTIFIED FINAL STATE PARTICLES OBSERVABLES

SIDIS as a tool to probe the sea quark distributions

\[ \sum_q e_q^2 D_q^H(x, Q^2) \otimes f_q(x, Q^2) \]
IDENTIFIED FINAL STATE PARTICLES OBSERVABLES

SIDIS as a tool to probe the sea quark distributions

\[ \sum_q e_q^2 D_q^H(x, Q^2) \otimes f_q(x, Q^2) \]

FFs acting as an effective charges, allowing for flavor a separation
IDENTIFIED FINAL STATE PARTICLES OBSERVABLES

SIDIS as a tool to probe the sea quark distributions

\[ \sum_{q} e_q^2 D_q^H(x, Q^2) \otimes f_q(x, Q^2) \]
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SIDIS as a tool to probe the sea quark distributions

\[ |K^+\rangle = |u\bar{s}\rangle \quad |K^-\rangle = |\bar{u}s\rangle \]

\[ \sum \quad e_q^2 \, D_q^H(x, Q^2) \otimes f_q(x, Q^2) \]

Kaon production as a tool to pin down the strangeness in the proton
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SIDIS as a tool to probe the sea quark distributions

\[ |K^+\rangle = |u\bar{s}\rangle \quad |K^-\rangle = |\bar{u}s\rangle \]

\[ \sum_q e_q^2 D_q^H(x, Q^2) \otimes f_q(x, Q^2) \]

Semi-inclusive observables as a tool to probe the sea quark of the proton

PDFs & FFs global fit?
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PDFs & FFs Combined Global Extraction: Cross-Talk between non perturbative quantities

Big number of parameters to fit
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PDFs & FFs Combined Global Extraction: Cross-Talk between non perturbative quantities

Big number of parameters to fit

Factorial-like increase in the number of iterations needed
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PDFs & FFs Combined Global Extraction: Cross-Talk between non perturbative quantities

- Big number of parameters to fit
- Factorial-like increase in the number of iterations needed
- Different Phase Space/Precision
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PDFs & FFs Combined Global Extraction: Cross-Talk between non perturbative quantities

Big number of parameters to fit

Factorial-like increase in the number of iterations needed

Different Phase Space/Precision
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PDFs & FFs Combined Global Extraction: Cross-Talk between non perturbative quantities

Some effort made in this direction:

- JAM Collaboration PDFs+FFs
  arXiv:1905.03788

- JAM Collaboration polPDFs+FFs
A different approach: Bayesian Inference

Based on the previous generation of replicas of the PDFs/FFs

$fi(x)$
A different approach: Bayesian Inference

Based on the previous generation of replicas of the PDFs/FFs

\[ f_i(x) \]
A different approach: Bayesian Inference

Based on the previous generation of replicas of the PDFs/FFs

Statistically sound uncertainties

Allows for the inclusion of new data without a refit

\[
\langle \mathcal{O} \rangle = \frac{1}{N_{\text{rep}}} \sum_{k=1}^{N} \mathcal{O}[f(k)]
\]

\[
\Delta \mathcal{O}^2 = \frac{1}{(N_{\text{rep}} - 1)} \sum_{k=1}^{N} (\mathcal{O}[f(k)] - \langle \mathcal{O} \rangle)^2
\]
A different approach: Bayesian Inference

Based on the previous generation of replicas of the PDFs/FFs

We can include new information in the fit:

\[
\chi^2(y, f) = \sum_i \frac{(y_i - y_i[f])^2}{\sigma_i^2}
\]

\[
w(k) \propto e^{-\frac{1}{2} \chi^2(f_k)}
\]

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w(k) \propto e^{-\frac{1}{2} \chi^2(f_k)}
\]

\[
\langle \mathcal{O} \rangle_{\text{new}} = \frac{1}{N_{\text{rep}}} \sum_{k=1}^{N} \mathcal{O}[f(k)] \cdot w(k)
\]

\[
\Delta \mathcal{O}_{\text{new}}^2 = \frac{1}{(N_{\text{rep}} - 1)} \sum_{k=1}^{N} (\mathcal{O}[f(k)] - \langle \mathcal{O} \rangle_{\text{new}})^2 \cdot w(k)
\]
ITERATIVE PDF & FF EXTRACTION

ITERATIVE PDF & FF EXTRACTION


PDFs & FFs

Reweighting using SIDIS data

Modified PDFs

FFs extraction using new PDFs

FFs
ITERATIVE PDF & FF EXTRACTION

ITERATIVE PDF & FF EXTRACTION

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PDFs & FFs

Reweighting using SIDIS data

Modified PDFs

FFs extraction using new PDFs

FFs

Combined PDFs & FFs extraction including COMPASS & HERMES \( \pi \) and K SIDIS data

Robust

Fast convergence

Independent of the PDFs set used
What can we learn from SIDIS @ EIC?

Reweighting with EIC $\pi^\pm$ & $K^\pm$ SIDIS pseudo-data

$10^3$ NNPDF3.0 replicas
$10^5$ DSS14 & DSS17 replicas
What can we learn from SIDIS @ EIC?

Wide coverage in \( \{x, Q^2\} \)

5 GeV x 100 GeV \( \sqrt{s} = 45 \) GeV

20 GeV x 250 GeV \( \sqrt{s} = 140 \) GeV
What can we learn from SIDIS @ EIC?

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- \( 5 \text{ GeV} \times 100 \text{ GeV} \) \( \sqrt{s} = 45 \text{ GeV} \)
- \( 20 \text{ GeV} \times 250 \text{ GeV} \) \( \sqrt{s} = 140 \text{ GeV} \)

Pseudodata generation:

- \( Q^2 > 1 \text{ GeV}^2 \)
- \( 0.01 < y < 0.95 \) \( \text{PYTHIA6} \)
- \( W^2 > 10 \text{ GeV}^2 \) \( 10 \text{ fb}^{-1} \)
- \( -3.5 < \eta < 3.5 \)
COMBINED PDFS & FFS EXTRACTION FROM EIC


What can we learn from SIDIS @ EIC?
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COMBINED PDFS & FFS EXTRACTION FROM EIC

What can we learn from SIDIS @ EIC?

- 30% uncertainty reduction for $u$
- 20% uncertainty reduction for $d$

COMBINED PDFS & FFS EXTRACTION FROM EIC

What can we learn from SIDIS @ EIC?

What can we learn from SIDIS @ EIC?


Growing $Q^2$

Growing $z$

Combining PDFs & FFS Extraction from EIC

$\pi^+ \sqrt{s}=140$ GeV
What can we learn from SIDIS @ EIC?

Dominated by PDFs uncertainty

Dominated by FFs uncertainty

\[ \chi^2(y, f) = \sum_i \frac{(y_i - y_i[f])^2}{\sigma_i^2} \]
What can we learn from SIDIS @ EIC?

Dominated by PDFs uncertainty

Dominated by FFs uncertainty

\[ \chi^2(y, f) = \sum_i \frac{(y_i - y_i[f])^2}{\sigma_i^2} \]

Must include FF's uncertainty

EIC pseudodata

\( \pi^+ \sqrt{s}=140 \text{ GeV} \)
What can we learn from SIDIS @ EIC?

**Dominated by PDFs uncertainty**

**Dominated by FFs uncertainty**

Higher impact for the region of low $Q^2$ & $x_B$, where the PDFs are comparatively less constrained.

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COMBINED PDFS & FFS EXTRACTION FROM EIC


What can we learn from SIDIS @ EIC?

30% uncertainty reduction for u
20% uncertainty reduction for d
What can we learn from SIDIS @ EIC?

E. Aschenauer, IB, R. Sassot, C. Van Hulse.  
Phys.Rev. D99 (2019) no.9, 094004

\begin{align*}
\frac{s}{s_{\text{NNPDF}}} & = 1.1 \pm 0.1 \\
\frac{(s+\bar{s})}{(u+\bar{u})} & = 0.9 \pm 0.05
\end{align*}
COMBINED PDFS & FFS EXTRACTION FROM EIC


What can we learn from SIDIS @ EIC?

- Figure showing NNPDF3.0 and NNPDFrew PDFs for different xB values at √s = 45 GeV and √s = 140 GeV.

\[
\frac{s}{s_{\text{NNPDF}}} \quad \frac{(s+\bar{s})}{(\bar{u}+\bar{d})} \quad \frac{(s-s)}{(s+s)} \quad \frac{(u-d)}{(u+d)}
\]

- Expressions for different PDF combinations.

- Graphs illustrating the comparison of NNPDF3.0 and NNPDFrew for the PDF ratios and their uncertainties.
What can we learn from SIDIS @ EIC?

Remarkable reduction on the strangeness uncertainty driven by kaon SIDIS data

SIDIS can look into the proton’s strange content

What can we learn from SIDIS @ EIC?

Effect on Fragmentations

COMBINED PDFS & FFS EXTRACTION FROM EIC

SUMMARY

• There is still a lot of room for PDFs improvement

• **Semi-inclusive DIS** offers a great tool to probe the sea quark of the parton, as well as the confinement process into hadrons
  
  • The same analysis could be translated to nPDFs!

• **EIC semi-inclusive data** expected to provide important constrains on both PDFs & FFs, with new insights on the:

  • Proton’s strange content
  
  • Charge (& isospin) symmetry breaking
  
  • Nuclear effects on PDFs & FFs
THANK YOU
BACKUP SLIDES
What can we learn from SIDIS @ EIC?

\[ \rho_w[A, B] = \frac{\langle A - \langle A \rangle \rangle \langle B - \langle B \rangle \rangle}{\sigma^w_A \sigma^w_B} \]

\[ \sqrt{s} = 140 \text{ GeV} \]

\[ \rho[u(x), d^3 \sigma/dx \, dQ^2 \, dz] \]

\[ \rho[d(x), d^3 \sigma/dx \, dQ^2 \, dz] \]

\[ \rho[s(x), d^3 \sigma/dx \, dQ^2 \, dz] \]

\[ \rho[\bar{s}(x), d^3 \sigma/dx \, dQ^2 \, dz] \]

\[ K^+ \quad - \quad K^- \quad - \quad . \]

COMBINED PDFS & FFS EXTRACTION FROM EIC

What can we learn from SIDIS @ EIC?

\[ \rho_{w}[A, B] = \frac{\langle A - \langle A \rangle \rangle \langle B - \langle B \rangle \rangle}{\sigma_{A}^{th} \sigma_{B}^{th}} \]

\begin{align*}
\rho[u(x), K^+] = \rho[u(x), K^-] \\
\rho[\bar{u}(x), K^+] = \rho[\bar{u}(x), K^-] \\
\rho[d(x), K^+] = \rho[d(x), K^-] \\
\rho[\bar{d}(x), K^+] = \rho[\bar{d}(x), K^-] \\
\rho[s(x), K^+] = \rho[s(x), K^-] \\
\rho[\bar{s}(x), K^+] = \rho[\bar{s}(x), K^-]
\end{align*}

\( \sqrt{s} = 140 \text{ GeV} \)

\( Q^2 [\text{GeV}^2] \)

\( x_B \)
What can we learn from SIDIS @ EIC?

\[ S[A, B] = \frac{\langle A - \langle A \rangle \rangle \langle B - \langle B \rangle \rangle}{\xi \sigma_A^{th} \sigma_B^{th}} \]

\[ \xi = \frac{\sigma_{exp}}{\sigma_B^{th}} \]

\( \sqrt{s} = 140 \text{ GeV} \)

\( \sigma \)
What can we learn from SIDIS @ EIC?

\[ \rho_w[A, B] = \frac{\langle A - \langle A \rangle \rangle \langle B - \langle B \rangle \rangle}{\sigma_A^{th} \sigma_B^{th}} \]

\[ \rho[u(x), d^3\sigma/dx dQ^2 dz] \]

\[ \rho[\bar{u}(x), d^3\sigma/dx dQ^2 dz] \]

\[ \rho[d(x), d^3\sigma/dx dQ^2 dz] \]

\[ \rho[\bar{d}(x), d^3\sigma/dx dQ^2 dz] \]

\[ \rho[s(x), d^3\sigma/dx dQ^2 dz] \]

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What can we learn from SIDIS @ EIC? 

\[ \rho_w[A,B] = \frac{\langle A - \langle A \rangle \rangle \langle B - \langle B \rangle \rangle}{\sigma_A^{th} \sigma_B^{th}} \]

COMBINED PDFS & FFS EXTRACTION FROM EIC


What can we learn from SIDIS @ EIC?  

$$S[A, B] = \frac{\langle A - \langle A \rangle \rangle \langle B - \langle B \rangle \rangle}{\xi \sigma_A^{th} \sigma_B^{th}}$$

$$\xi = \frac{\sigma_{exp}^B}{\sigma_B^{th}}$$

$$\sqrt{s} = 140 \text{ GeV}$$
\( \chi^2_{FF_s} = 1271 \)
\[ \chi^2_{FFs} = 1271 \]
\[ \chi^2_{FFs} = 1041 \]

**REWIGHTING IN ACTION: STRANGE QUARK DISTRIBUTION**
REWEIGHTING IN ACTION: STRANGE QUARK DISTRIBUTION

$\chi^2_{FFs} = 1271$

$\chi^2_{FFs} = 1041$

$\chi^2_{FFs} = 1002$
\[ \chi^2_{FFs} = 1271 \]
\[ \chi^2_{FFs} = 1041 \]
\[ \chi^2_{FFs} = 1002 \]

- Fast convergence
- Uncertainties reduction of order 10%

REWEIGHTING IN ACTION: STRANGE QUARK DISTRIBUTION

![Graph showing reweighting in action for strange quark distribution with chi-squared values and convergence remarks.](image-url)
Starting from DSS based MMHT14

Starting from DSS based NNPDF3.0

Independency from the starting set of PDFs
Using NNPDF3.0 Replicas

Using CT14 Replicas

Independency from the set of replicas used