EIC impact on collinear PDFs

Filippo Delcarro

in collaboration with C. Cocuzza and Y. Zhou
• EIC impact on unpolarized PDFs
• on polarized PDFs
  • Double longitudinal asymmetry $A_{LL}$
  • Parity violating DIS asymmetry $A_{PV}$
EIC predictions: unpolarized PDFs

Current knowledge of unpolarized collinear PDFs has been driven by:

- inclusive neutral current (NC) and
- charged current DIS cross sections
- \( p\bar{p} \) collisions at the Tevatron
- \( pp \) collisions at LHC

Range: \( x \) down to \( 10^{-5} \) and \( Q^2 \) up to \( 10^4 \) GeV\(^2\). Complementary in accessing the small-\( x \) and large-\( x \) longitudinal hadron structure.

EIC: overlapping kinematic range between HERA and the fixed-target experiments, instantaneous luminosity 3 orders larger

Simulated statistical and systematic uncertainties for \( eP \) NC DIS at \( \sqrt{s} = 18 \) TeV.
PDFs at EIC: unpolarized reduced $\sigma$

To assess the impact of EIC data on the unpolarized PDF we study the reduced cross section for different configurations.

**Different scenarios**

**DIS Neutral Current**

$$\sigma_r = \frac{d\sigma^c}{dx dQ^2 \frac{xQ^4}{2\pi\alpha^2[1 + (1 - y)^2]}} = F_2^c(x, Q^2) - \frac{y^2}{1 + (1 - y)^2} F_L^c(x, Q^2)$$

**DIS Charged Current**

with electron and positron beam

For the neutral current

$$\left[F_2^\gamma, F_2^{\gamma Z}, F_2^Z\right] = x \sum_q \left[ e_q^2, 2e_q g_q^q, g_q^q + g_A^{q2}\right] (q + \bar{q})$$

$$\left[F_3^\gamma, F_3^{\gamma Z}, F_3^Z\right] = \sum_q \left[ 0, 2e_q g_A^q, 2g_q^q g_A^q\right] (q - \bar{q})$$

For the charged current

$F_{2W}^- = 2x(u + \bar{d} + \bar{s} + c\ldots)$

$F_{3W}^- = 2(u - \bar{d} - \bar{s} + c\ldots)$

For $W^+$: $d \leftrightarrow u$, $s \leftrightarrow c$

for neutron: $d \leftrightarrow u$
unpolarized EIC pseudodata

Multistep Monte Carlo procedure with Bayesian inference

For spin-averaged PDFs

- fixed target DIS
- HERA collider DIS
- JLab F2 data
- Drell-Yan
- SSA W production
- W decay charge asymmetry
- W production
- W production

Compare the uncertainties of these two last steps
EIC impact: unpolar. PDFs uncertainties

Comparison of relative uncertainties for unpolarized PDFs $xf(x)$ for multiple flavors, before and after the inclusion of EIC data for electron beam
EIC predictions: unpol. PDFs comparison

Comparison of relative uncertainties for unpolarized PDFs $x f(x)$ for multiple flavors, before and after the inclusion of EIC data for electron beam for different collaborations.
Comparison of relative uncertainties for unpolarized PDFs $xf(x)$ for multiple flavors, before and after the inclusion of EIC data for electron and positron beam
EIC predictions: impact on $\Delta g$ uncertainties

A precise determination of the helicity gluon distribution function $\Delta g$ is one of the golden measurements of nucleon spin structure at the EIC

EIC White Paper [1212.1701]

Proton Spin Puzzle: Open problem since EMC experiment

$$\frac{1}{2} = S_q + L_q + S_g + L_g$$

In particular for gluons

$$S_g(Q^2) = \int_0^1 \Delta_g(x, Q^2) dx$$

$$\Delta f (x, Q^2) \equiv f^+ (x, Q^2) - f^- (x, Q^2)$$

with $f^+$ ($f^-$) denoting the number density of partons with the same (opposite) helicity as the nucleons

$$g_1^h(x, Q^2, z) = \frac{1}{2} \sum_q e_q^2 \left[ \Delta q(x, Q^2) D_q^h(z, Q^2) + \Delta \bar{q}(x, Q^2) D_{\bar{q}}^h(z, Q^2) \right]$$
Impact on polarized PDFs

DOUBLE LONGITUDINAL SPIN ASYMMETRY

\[ A_{LL} = \frac{\sigma_{\uparrow\uparrow} - \sigma_{\downarrow\uparrow}}{\sigma_{\downarrow\uparrow} + \sigma_{\uparrow\uparrow}} \]

longitudinally polarized e− off longit. polarized hadrons

PARITY VIOLATING ASYMMETRY

\[ A_{PV} = \frac{\sigma_{\uparrow} - \sigma_{\downarrow}}{\sigma_{\uparrow} + \sigma_{\downarrow}} \]

unpolarized leptons off longit. polarized hadrons

impact of future EIC data on quark and gluon helicity distributions in the proton
**EIC impact on helicity PDFs**

- EIC will cover a wider range of \((x, Q^2)\)
- How much this will improve our determination of \(\Delta g\)?

Pseudodata for double-spin asymmetry

\[
A_{LL} = \frac{\sigma^{\uparrow\uparrow} - \sigma^{\downarrow\uparrow}}{\sigma^{\downarrow\uparrow} + \sigma^{\uparrow\uparrow}} = D (A_1 + \eta A_2).
\]

\[
A_1 = \frac{(g_1 - \gamma^2 g_2)}{F_1}, \quad A_2 = \gamma \frac{(g_1 + g_2)}{F_1}
\]

\[
A_{LL} = \frac{y (2 - y)}{y^2 + 2(1 - y)(1 + R)} \frac{g_1}{F_1}
\]

\[
g_1(x, Q^2) = \frac{1}{2} \sum_q e_q^2 \left( [\Delta C_{1q} \otimes \Delta q^+](x, Q^2) + [\Delta C_{1g} \otimes \Delta q](x, Q^2) \right)
\]

**Flavor separation**  
\(p, d, ^3\text{He}\)
Parity violating asymmetry

\[ A_{PV} = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} \]

scattering of unpolarized leptons
from longitudinally polarized hadrons

\[ A_{PV} = \frac{G_F x Q^2}{2\sqrt{2}\pi\alpha} \left( \frac{g_1^e Y^{-} Y^{\gamma Z} + g_V^e Y^{+} Y^{\gamma Z}}{x y^2 F_1 + (1 - y) F_2} \right) \]

\[ g_{1}^{\gamma Z}(x, Q^2) = \sum_{q} e_q g^{q}_{V} \left( [\Delta C_{1q} \otimes \Delta q^{+}](x, Q^2) + 2[\Delta C_{1g} \otimes \Delta g](x, Q^2) \right) \]

\[ g_{5}^{\gamma Z}(x, Q^2) = \sum_{q} e_q g^{q}_{A} \left[ \Delta C_{5q} \otimes \Delta q^{-} \right](x, Q^2) \]

Independent linear combination of helicity PDFs
together with \( g_{1} \) allow cleaner flavor separation
Polarized pseudodata

Multistep Monte Carlo with Bayesian inference

For spin-averaged PDFs

fixed target DIS
BCDMS SLAC NMC

HERA collider DIS
H1 ZEUS HERA

Drell-Yan
E866

Jet production
D0 CDF STAR

parameters of the spin-averaged PDFs are fixed

For spin-dependent PDFs

polarized DIS
EMC, SMC COMPASS SLAC HERMES

RHIC jet data Polarized pp
STAR PHENIX

EIC pseudodata
Baseline PDFs for EIC pseudodata

$A_{LL}^p$  $A_{LL}^d$

$A_{LL}^{3\text{He}}$  $A_{PV}^p$

6 scenarios

absolute statistical uncertainties for the asymmetries

$$\delta A \approx \frac{1}{\sqrt{L \sigma_{\text{unp}}}},$$

low  mid  high

Imposing or not $\text{SU}(3)$ flavor symmetry

$$\int_0^1 dx \left[ \Delta u^+(x, Q^2) - \Delta d^+(x, Q^2) \right] = g_A$$

$$\int_0^1 dx \left[ \Delta u^+(x, Q^2) + \Delta d^+(x, Q^2) - 2\Delta s^+(x, Q^2) \right] = a_8$$
EIC impact on $g_1$ uncertainties

Impact of projected e-p $A_{LL}$ data on the proton $g_1^p$ structure function
EIC impact on $g_1$ uncertainties

Impact of projected e-p $A_{LL}$ data on the neutron $g_1^n$ structure function
EIC impact on truncated moments

\[ \Delta G_{\text{trunc}}(Q^2) = \int_{10^{-4}}^{1} dx \left[ \Delta q(x, Q^2) + \Delta \overline{q}(x, Q^2) \right] \]

\[ \Delta G_{\text{trunc}}(Q^2) = \int_{10^{-4}}^{1} dx \Delta g(x, Q^2) \]
PDFs constraints from $A_{PV}$ pseudo data

Ratio of uncertainties on the PDFs as functions of $x$, including EIC data on the PVDIS asymmetry $A_{PV}$ to those without EIC data.

$Q^2 = 10 \text{ GeV}^2$

$\delta_{EIC}/\delta$

$\Delta G_{\text{trunc}}$

$\Delta \Sigma_{\text{trunc}}$

$A_{PV}^p$

$\delta_{EIC}/\delta$

0.2 0.4 0.6 0.8 1 1.2 1.4
Conclusions

We performed a dedicated impact study of future EIC data on unpolarized cross section and polarization asymmetries, based on a global fit with a Monte Carlo approach.

There is a significant impact in the unpolarized PDFs, mostly in the valence case.

The study of polarized asymmetries can greatly improve the determination of the helicity PDFs at low-x. ALL and APV acts in an almost complementary way on the quark singlet and gluon moment.

The EIC facility will provide unprecedented access to the flavor and spin structure of the nucleon in previously unexplored regions of kinematics at low x values.