Diffractive longitudinal structure function at the Electron Ion Collider

Anna Stańto
Penn State University
Outline

• Motivation: why is $F^{D(3)}_L$ interesting?
• H1 measurement
• Proton tagging as a method for diffraction at EIC
• Pseudodata simulation, energy beam scenarios
• Extraction by linear fit. Kinematic range and precision
• Prospects for $F^{D(3)}_L$ and $R$ ratio of longitudinal to transverse cross section
• Outlook

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Diffractive kinematics in DIS

Standard DIS variables:

- **Electron-proton**
  - cms energy squared:
    \[ s = (k + p)^2 \]
- **Photon-proton**
  - cms energy squared:
    \[ W^2 = (q + p)^2 \]
  - inelasticity
    \[ y = \frac{p \cdot q}{p \cdot k} \]
  - Bjorken x
    \[ x = \frac{-q^2}{2p \cdot q} \]
  - (minus) photon virtuality
    \[ Q^2 = -q^2 \]

Diffractive DIS variables:

- \[ \xi \equiv x_{IP} = \frac{Q^2 + M_X^2 - t}{Q^2 + W^2} \]
  - momentum fraction of the Pomeron w.r.t hadron
- \[ \beta = \frac{Q^2}{Q^2 + M_X^2 - t} \]
  - momentum fraction of parton w.r.t Pomeron
- \[ t = (p - p')^2 \]
  - 4-momentum transfer squared

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Diffractive cross section, structure functions

Diffractive cross section depends on 4 variables \((\xi, \beta, Q^2, t)\):

\[
\frac{d^4 \sigma^D}{d\xi d\beta dQ^2 dt} = \frac{2\pi \alpha^2_{em}}{\beta Q^4} Y + \sigma_r^{D(4)}(\xi, \beta, Q^2, t)
\]

\[Y_+ = 1 + (1 - y)^2\]

Reduced cross section depends on two structure functions:

\[
\sigma_r^{D(4)}(\xi, \beta, Q^2, t) = F_2^{D(4)}(\xi, \beta, Q^2, t) - \frac{y^2}{Y_+} F_L^{D(4)}(\xi, \beta, Q^2, t)
\]

Upon integration over \(t\):

\[
F_{2,L}^{D(3)}(\xi, \beta, Q^2) = \int_{-\infty}^{0} dt F_{2,L}^{D(4)}(\xi, \beta, Q^2, t)
\]

Dimensions:

\[
[\sigma_r^{D(4)}] = \text{GeV}^{-2}
\]

\[
\sigma_r^{D(3)} \quad \text{Dimensionless}
\]
Why $F_L^{D(3)}$ is interesting? $F_L^{D(3)}$ at HERA

Why $F_L^D$ is interesting?

$F_L^D$ vanishes in the parton model

Gets non-vanishing contributions in QCD

As in inclusive case, particularly sensitive to the diffractive gluon density

Expected large higher twists, provides test of the non-linear, saturation phenomena

Experimentally challenging…

Measurement requires several beam energies

H1 measurement: 4 energies, $E_p=920, 820, 575, 460$ GeV, electron beam $E_e=27.6$ GeV

Large errors, limited by statistics at HERA

Careful evaluation of systematics. Best precision 4%, with uncorrelated sources as low as 2%
EIC can operate at various energy combinations

Can cover wide range of x

Large instantaneous luminosity

Statistics should not be a limiting factor

Only selected energy scenarios at EIC shown
Far forward detectors at EIC

![Diagram of far forward detectors at EIC]

| Detector                | Angle                      | Position [m] |
|-------------------------|----------------------------|--------------|
| ZDC                     | $\theta<5.5$ mrad          | 37.5         |
| Roman Pots              | $0.5<\theta<5.0$ mrad      | 26.0, 28.0   |
| Off-momentum detectors  | $\theta<5.0$ mrad          | 22.5, 25.5   |
| B0                      | $6.0<\theta<20.0$ mrad     | 5.4<$z<$6.4  |
Final proton tagging

Small angle acceptance i.e. Roman pots

\[(x_L, p_\perp, \theta)\] measured in LAB, collinear (e,p) frame

Much better than at HERA

Best way to select diffractive events through proton tagging

\[
t = \frac{p_\perp^2}{x_L} - \frac{(1 - x_L)^2}{x_L} m_p^2
\]
Pseudodata generation: energy choice

\[ \sigma_{\text{red}}^{D(3)} = F_2^{D(3)}(\beta, \xi, Q^2) - Y_L F_L^{D(3)}(\beta, \xi, Q^2) \]

Integrated over t-momentum transfer

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

Can disentangle \( F_2^{D(3)} \) from \( F_L^{D(3)} \) by varying energy and performing the linear fit.

\[ y = \frac{Q^2}{xS} = \frac{Q^2}{\beta \xi S} \]

Need to vary the energy \( \sqrt{s} \) to change \( y \) for fixed \( (\beta, \xi, Q^2) \)

| EIC energies for electron and proton: |
|--------------------------------------|
| \( E_e = 5, 10, 18 \text{ GeV} \) |

| \( E_p \) [GeV] |
|-----------------|
| 41 100 120 165 180 275 |
| 5 29 45 49 57 60 74 |
| 10 40 63 69 81 85 105 |
| 18 54 85 93 109 114 141 |

S-17 all 17 combinations
S-9 9 - bold red
S-5 5 - green (EIC preferred)
Pseudodata generation

**Binning and cuts**

Uniform logarithmic binning, 4 bins per order of magnitude in each $\beta, Q^2, \xi$

Bins in $(\xi, \beta, Q^2)$, common to at least four beam setups

$Q^2 > 3 \text{ GeV}^2$ both H1 and ZEUS fits indicate deterioration of fits for low $Q^2$

$0.96 > y > 0.005$ expected coverage of the experiment

**Simulations**

Cross section generation from ZEUS-SJ diffractive PDFs evolved with DGLAP

Assumed $\delta_{\text{sys}} = 1-2\%$, extrapolated from HERA 2\% uncorrelated systematics; normalization/correlated systematics negligible effect on extraction of $F_{L^D}$

$\delta_{\text{stat}}$ from 10 fb$^{-1}$ integrated luminosity

Several random samples are generated
The S-17 set of beam energies contains the most points in each bin. Only cases with a number of counts greater than 4 are taken for $F_L$ extraction.

Set-17: 364, set-9: 285, set-5: 160 values of $F_L$
\( F_{L}^{D(3)} \) extraction

\[
\sigma_{T} = F_{2}(\xi, \beta, Q^{2}) - Y_{L}F_{L}(\xi, \beta, Q^{2}) \quad \text{as a function of } Y_{L}
\]

Bins in \((\xi, \beta, Q^{2})\)

Uncorrelated systematics 1%
Differences between S-17 and S-9, S-5 small
Increase in error bar on the extraction when smaller number of energy points
Largest errors for bins with shortest range of \(Y_{L}\)
Simulated measurement of $F_L^{D(3)}$ vs β in bins of $(\xi, Q^2)$

Systematic error 1%, 5 MC samples to illustrate fluctuations

Small differences between S-17 and S-9, small reduction to range and increase in uncertainties.

More pronounced reduction in range and higher uncertainties in S-5.

An extraction of $F_L^D$ possible with EIC-favored set of energy combinations
Simulated measurement of $F_L^{D(3)}$ vs $\beta$ in bins of $(\xi, Q^2)$

$\delta_{\text{sys}} = 1\%$

$\delta_{\text{sys}} = 2\%$

Change from 1% to 2% results in roughly twice large error bars

Statistical errors negligible
**$F_L^{D(3)}$ fit accuracy**

Estimate the accuracy of extraction for $F_L^{D(3)}$

Generate several MC samples of pseudodata and perform fits

Use direct arithmetic averaging neglecting the uncertainties from the fits

$$
\bar{v} = \frac{S_1}{N}
$$

$$
(\Delta v)^2 = \frac{S_2 - S_1^2/N}{N - 1}
$$

$$
S_n = \sum_{i=1}^{N} v_i^n
$$

Where $v_i$ is the value of $F_L^D$
in Monte Carlo sample $i$

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**R_D = F_L^D / F_T^D** ratio of longitudinal to transverse

Ratio of cross section for longitudinally polarized photons to cross sections for transverse polarized photons

\[ R_{D}^{D(3)} = \frac{F_{L}^{D(3)}}{F_{T}^{D(3)}} \]

\[ F_{T}^{D(3)} = F_{2}^{D(3)} - F_{L}^{D(3)} \]

\[ \sigma_{\text{red}}^{D(3)} = [1 + (1 - Y_{L}) R_{D}^{D(3)}] F_{T}^{D(3)} \]

Different form of reduced cross section

Alternative fit has different sensitivities to the uncertainties

Systematics 1%

Averaged over 10 MC samples: reduced fluctuations
Summary and outlook

- Investigated potential of EIC for the longitudinal structure function in diffraction: \( F_L^D \)
- Important quantity, sensitive to diffractive gluon density (saturation, higher twists...). Only one extraction at HERA by H1, large errors. Challenging measurement.
- Three scenarios: 17, 9, 5 energy combinations. Pseudodata from DGLAP, assumed 1-2% systematics, 10 fb\(^{-1}\) integrated luminosity. Extraction via linear fit to reduced cross section.
- Scenarios S-17 and S-9 do not differ much, S-5 reduced kinematic range.
- Precision in a given bin of \((Q^2, \xi, \beta)\) correlates strongly with range in inelasticity \(y\).
- Still, precision comparable in all scenarios, dominated by systematics. Extracted R ratio too.
- **Overall: very good prospects for this quantity and EIC even with 5 energy combinations**

Possible directions:

- 4-dimensional structure function
- Sensitivity to different models (dipole model, saturation...)

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