Large-x Structure Function Data from JLab

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Introduction

- Physics Motivation
- Using JLab data from 6 GeV experiments
- Application for theory
- JLab at 12 GeV
Electron-Nucleon Scattering

- Inclusive cross section for $eN \rightarrow eX$
- Can be expressed in terms of absorption of transverse and longitudinal photons.

\[
\frac{d^2\sigma}{d\Omega dE'} = \Gamma \left( \sigma_T(x, Q^2) + \varepsilon \sigma_L(x, Q^2) \right)
\]

- Nucleon structure information encoded in $F_1, F_2$

\[
F_1(x, Q^2) = \frac{K}{4\pi^2 \alpha} M \sigma_T(x, Q^2)
\]
\[
F_2(x, Q^2) = \frac{K}{4\pi^2 \alpha} \frac{\nu}{(1 + \nu^2/Q^2)} \left[ \sigma_T(x, Q^2) + \sigma_L(x, Q^2) \right]
\]
Gluon Distributions

- Gluon distribution sensitive to $F_2$ through logarithmic evolution in $Q^2$.
- Large uncertainties in gluon distribution for $x > 0.3$.
- Use $F_L$ instead to access the glue.

$$G(x) \approx \frac{d}{d \log Q^2} F_2(x, Q^2)$$
Longitudinal Structure Function, $F_L$

- Next-to-Leading Order (NLO) gluons contribute to both $F_1, F_2$
- Obtain a gluon sum rule.

$$F_L(x) = \frac{\alpha_s}{\pi} \int_{x}^{1} \frac{dy}{y} \left( \frac{x}{y} \right)^2 \left\{ \frac{4}{3} F_2(y) + 2c(n_f) \left( 1 - \frac{x}{y} \right) yG(y) \right\}$$

- At leading twist, $F_L$ is directly sensitive to the gluons.
Strong coupling constant, $\alpha_s$ expansion

- In QCD is dependent on $Q^2$ and mass scale $\Lambda$

$$\alpha_s(Q^2) = \frac{4\pi}{\beta_0 \ln(Q^2/\Lambda^2)} \left\{ 1 - \frac{\beta_1}{\beta_0^2} \frac{\ln[\ln(Q^2/\Lambda^2)]}{\ln(Q^2/\Lambda^2)} + (\cdots) \right\}$$

- Leading order (LO)
- Next-to-Leading order (NLO)
- Next-to-Next-to-Leading order (NNLO)
Moments Expansion and Twist

- In the Operator Product Expansion (OPE), moments can be expanded in powers of $1/Q^2$

$$M_L^{(n)}(Q^2) = \sum_\tau \frac{A_\tau^{(n)}(\alpha_s(Q^2))}{Q^{\tau-2}}$$

$$= A_2^{(n)} + \frac{A_4^{(n)}}{Q^2} + \frac{A_6^{(n)}}{Q^4} + \cdots$$

Matrix elements of operators with a specific "twist" $\tau$

$\tau = \text{dimension} - \text{spin}$

$\tau = 2$

$\tau > 2$
Measuring $F_L$

\[
\sigma_R = \frac{1}{\Gamma} \frac{d^2 \sigma}{d\Omega dE'} = \sigma_T(x, Q^2) + \epsilon \sigma_L(x, Q^2)
\]

\[
\sigma_T \propto F_1 \quad \sigma_L \propto F_L
\]

\[
F_L = \left(1 + \frac{Q^2}{\nu^2}\right) F_2 - 2x F_1
\]

- Determine $F_L$ through a Rosenbluth separation of the cross-section
- Require data measured at fixed $Q^2$ and $x$, at multiple $\epsilon$ points
  ⇒ need multiple beam energies and spectrometer settings
- $F_L \sim 25\%$ of cross-section for JLab kinematics $\sigma_T$ and $\sigma_L$
  ⇒ require $< 2\%$ uncertainty (pt-to-pt) in $\epsilon$ to extract $F_L$ to $\sim 15\%$
Moments of Structure Functions

- Determination of structure function moments allows the transition of QCD from asymptotic to confinement scales to be studied

\[ M_{2,L}^{(n)}(Q^2) = \int_0^1 dx \ x^{n-2} \ F_{2,L}(x, Q^2) \]

- Moments of structure functions are their x-weighted integrals ⇒ allow \( Q^2 \) dependence to be studied

- Higher moments are weighted towards higher x-values ⇒ poorly determined

- At large x, cross sections are small, so resulting extraction of gluon density becomes increasingly difficult ⇒ large uncertainties in gluon density
Analysis of Longitudinal Moments

- $F_L$ sensitive to gluon distribution at Next-to-Leading Order
- $F_L$ also sensitive to power corrections in $Q^2$
- Previous study by Ricco, Simula and Battaglieri (Nucl. Phys. B555, 306-334, 1999)
  - ⇒ little data at low $Q^2$ and high $x$
  - ⇒ “… transverse data with better quality at $x > 0.6$ and $Q^2 < 10 \text{ (GeV}/c)^2$ and more
- Precise, systematic determinations of the L/T cross-section ratios are still required ....”
- New cross section data available from JLab (at high $x$ and low $Q^2$) and HERA (low $x$)
  - ⇒ high precision measurements, from dedicated experiments
  - DATA driven analysis
Nachtmann Moments

- Nachtmann moments, defined in terms of $\xi$, removes target mass corrections $\sim M^2/Q^2$

$$\xi = \frac{2x}{1 + \sqrt{1 + 4M^2x^2/Q^2}}$$

$$M_L^{N(n)}(Q^2) = \int_0^1 dx \frac{\xi^{n+1}}{x^3} \left\{ F_L(x, Q^2) + \frac{4M^2x^2}{Q^2} \frac{(n+1)\xi/x - 2(n+2)}{(n+2)(n+3)} F_2(x, Q^2) \right\}$$

- Nachtmann moments from experiment are compared to Cornwall-Norton moments
- from (leading twist, $M=0$) pQCD calculations
  ⇒ are higher twist components important?
  ⇒ is the gluon contribution in the leading twist calculation sufficient?
Data Coverage in $x$ and $Q^2$

- L/T separated data → cross section data
- Proton data only
- JLab data over region with higher $x$ and lower $Q^2$

for $Q^2 < 4$, JLab data covers ~50% of $x$ range
Bin-center $F_L$ Data in $Q^2$

$Q^2 = 0.75$ (GeV/c)$^2$

$Q^2 = 1.75$ (GeV/c)$^2$

$Q^2 = 2.5$ (GeV/c)$^2$

$Q^2 = 3.75$ (GeV/c)$^2$

$Q^2 = 5.0$ (GeV/c)$^2$

$Q^2 = 6.5$ (GeV/c)$^2$

$Q^2 = 8.0$ (GeV/c)$^2$

$Q^2 = 10.0$ (GeV/c)$^2$

$Q^2 = 15.0$ (GeV/c)$^2$

$Q^2 = 20.0$ (GeV/c)$^2$

$Q^2 = 45.0$ (GeV/c)$^2$
Bin-center $F_2$ Data in $Q^2$
Filling Gaps in the Data

- Use model to calculate empty bins
  DIS: \( W^2 > 3.9 \text{ GeV}^2 \)
  Resonance: \( W^2 < 3.9 \text{ GeV}^2 \)
  \( \Rightarrow \) apply rescale factor based on the error weighted average of adjacent data points

- for \( x < 0.4 \), use all data points to determine the rescale factor

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Error Estimation

- Use Monte Carlo method to estimate uncorrelated errors in data
- Generate pseudo-data via Gaussian → randomisation of data within error bars
  ⇒ distribution of moment contributions
  ⇒ derive statistical error from standard deviation of moment distributions
- Model dependent error estimated via analysis using different models ⇒ small
Nachtmann $M_L$ Moments

- Comparing data to global PDF fits
- Higher twist appears to improve the fit
- Observe missing strength in highest moment – largest weighting by high $x$
  $\Rightarrow$ require larger gluon contribution at large $x$?
  $\Rightarrow$ higher twist effects?

- MSTW excludes high $x$ data
- CJ includes high $x$ data, but not $F_L$ data directly (HT not available)
- ABKM includes higher twist terms but fits to a subset of the data
Nachtmann $M_L$ Moments

- Comparing different orders of only the MSTW calculation to data
- Higher order calculations in better agreement with data – NNLO best
  ⇒ perhaps no HT contributions needed
- Highest moment curves all undershoot the data
  ⇒ perhaps a larger gluon contribution at high $x$
- Need improved global fits to disentangle different effects
CJ15 at a Glance

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Deuterium data and nuclear corrections important for accuracy and precision of d/u determination for x>0.6
JLab at 12 GeV

- Double $Q^2$ range
- Similar precision to JLab at 6 GeV
- E12-10-002 – $F_2$ at large $x$

CJ cut: $W^2 > 3 \text{ GeV}^2$

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BoNuS-12 Experiment

*JLab E12-06-113*

**CJ11**
- PDF uncertainty
- nuclear uncertainty
- BONUS12 projected

**BONUS 12**

**SU(6)**
- helicity conserv
- scalar diquark

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Marathon Experiment

JLab E12-10-103

CJ11

PDF uncertainty
nuclear uncertainty

JLab (MARATHON) projected

MARATHON

\[
\frac{d}{u}
\]

x

\[
0 \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1
\]

\[0 \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1\]

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Summary

- JLab experiments produced high precision structure function data at large-$x$
- Combine with global datasets and use in PDF fits
  - Add further improvements to theory
  - Reduction in error bars
- Moments analysis indicated importance of higher twist and/or gluon contributions
- JLab at 12 GeV will provide more large-$x$ data, at higher $Q^2$