Upcoming Hall C Measurements of $F_2$ Structure Functions at Large Bjorken $x$ from $H(e,e')$ and $D(e,e')$ Inelastic Scattering

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Carnegie Mellon University
Outline

➢ Physics motivation

➢ Experiment setup

➢ Run plan
E12-10-002 Schedule

<table>
<thead>
<tr>
<th>Week</th>
<th>Date</th>
<th>Day</th>
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<td>148</td>
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E12-10-002 2-day run on Dec. 12, 13 at 6.4 GeV for R measurement

E12-10-002/008 starts on Jan. 30, 2017 and runs for 25 days
Inelastic Scattering

➢ Initial state nucleon target is excited or blown apart and ends up with many hadrons in final state

\[ Q^2 = -q^2 = 4E_0E'\sin^2\frac{\theta}{2} \]

\[ E' = \frac{E_0 - \frac{W^2-M^2}{2M}}{1 + \frac{2E_0\sin^2\frac{\theta}{2}}{M}} \]

\[ \nu = E_0 - E' \quad y = \frac{\nu}{E_0} \]

\[ x = \frac{Q^2}{2M\nu} = \frac{Q^2}{W^2 + Q^2 - M^2} \]

\[ W^2 = (P + q)^2 = M^2 + 2M\nu - Q^2 \]
Inelastic Scattering

- Initial state nucleon target is excited or blown apart and ends up with many hadrons in final state

Elastic scattering
- e.g. e+p→e+p, \( W=M_p \)

Resonance region
- e.g. e+p→e+Δ, \( W=M_{\Delta} \)

Deep inelastic scattering
- e.g. e+p→e+(\( X=\text{many hadrons} \)), \( W^2>M_p^2 \)

Expression for differential cross section:

\[
\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2}{4E_0 sin^4 \frac{\theta}{2}} \left[ \frac{1}{\nu} F_2(x, Q^2) cos^2 \theta \frac{\theta}{2} + \frac{2}{M} F_1(x, Q^2) sin^2 \theta \frac{\theta}{2} \right]
\]
Parton Distribution Functions

➢ Parton distribution functions keep track of the dynamics of quarks and gluons inside nucleons

Three non-interacting quarks

Three interacting quarks

Three interacting quarks with sea of quarks, anti-quarks and gluons

➢ Parton distribution functions are extracted from global fits to measurements of cross sections from DIS and other processes

\[
\sigma^{DIS} \sim \sum_q \int dx f_q(x, \mu^2) \sigma^{hard}(x/\Lambda^2, Q^2/\mu^2)
\]

Perturbative QCD calculations from fits to a large set of data
Constrain PDFs at Large $x$

➢ Typical PDFs extraction still lacking in the required precision at low $x$ and large $x$
Why It’s Important to Know PDFs at Large $x$?

➢ Relevant for studies of the non-perturbative dynamics of nucleons: $d/u$ ratio at $x=1$ can give hints of how quarks are confined

➢ Poor knowledge of PDFs at large $x$ propagates to low $x$
  • Perturbative QCD evolution moves strength from large $x$, low $Q^2$ to low $x$, high $Q^2$
  • The $x$-dependence of PDFs is parametrized at low $Q^2$ where most of their strength is at large $x$

➢ Partons need large energy to create a particle with large mass at the LHC

$$x = \frac{M}{\sqrt{S}} e^y$$
Experiments at JLab Focused on Large $x$

- Several approved experiments at Jefferson Lab and a theory-experiment Collaboration, CTEQ-JLab, to constrain valence PDFs at large $x$. 
Experiments at JLab Focused on Large x

- Several approved experiments at Jefferson Lab and a theory-experiment Collaboration, CTEQ-JLab, to constrain valence PDFs at large x

Experiments:

- CLAS12 BONuS: accesses $F_2^n$ via spectator tagging in deuterium protons with low momentum and backward angles to minimize nuclear effects and target fragmentation effects - VIP

- $F_2^n$ is extracted from ratio of tagged and inclusive events
Several approved experiments at Jefferson Lab and a theory-experiment Collaboration, CTEQ-JLab, to constrain valence PDFs at large $x$.

Experiments:

\(-\rightarrow\) Hall A MARATHON (2017): accesses $F_2^n/F_2^p$ via DIS off mirror nuclei, $^3\text{H}$ and $^3\text{He}$

\[ \frac{F_2^n}{F_2^p} = \frac{4d + u}{4u + d} \]

\[ F_2^n = 2\mathcal{R} - \frac{F_2^3\text{He}}{F_2^3\text{H}} \]

\[ F_2^p = \frac{2F_2^3\text{He}}{F_2^3\text{H}} - \mathcal{R} \]

\[ \mathcal{R} = \frac{R^{(3\text{He})}}{R^{(3\text{H})}} \]

\[ R^{(3\text{He})} = \frac{F_2^3\text{He}}{2F_2^p + F_2^n} \]

\[ R^{(3\text{H})} = \frac{F_2^3\text{H}}{F_2^p + 2F_2^n} \]
Experiments at JLab Focused on Large $x$

- Several approved experiments at Jefferson Lab and a theory-experiment Collaboration, CTEQ-JLab, to constrain valence PDFs at large $x$

Experiments:

- Hall A MARATHON (2017): accesses $F_2^n/F_2^p$ via DIS off mirror nuclei, $^3\text{H}$ and $^3\text{He}$

\[
\frac{F_2^n}{F_2^p} = \frac{4d + u}{4u + d}
\]

- Hall A SoLID PVDIS: accesses d/u via measurements of parity violating asymmetries in H
Experiments at JLab Focused on Large $x$

- Several approved experiments at Jefferson Lab and a theory-experiment Collaboration, CTEQ-JLab, to constrain valence PDFs at large $x$

Experiments:

- Hall C E12-10-002 (2017): accesses $F_2^p$ and $F_2^d$ via IS off proton and deuteron

- DIS: constrain nucleon’s PDFs within CTEQ-JLab framework
Experiments at JLab Focused on Large $x$

- Several approved experiments at Jefferson Lab and a theory-experiment Collaboration, CTEQ-JLab, to constrain valence PDFs at large $x$

Experiments:

- Hall C E12-10-002 (2017): accesses $F_2^p$ and $F_2^d$ via IS off proton and deuteron

- Resonance region: study confinement and transition from confinement to asymptotic freedom, quark-hadron duality

- Resonance region: possibly include averaged resonance region data in the CJ fits
CTEQ-JLab Global PDF Fits

➢ Relax kinematic cuts to include large $x$, low $Q^2$ data in PDF fits

$W^2 > 12.25 \text{ GeV}^2$

Kinematic cut of almost all other PDF analysis before CJ

$W^2 > 3 \text{ GeV}^2$

CTEQ-JLab cut includes more data at large $x$

Include non-perturbative corrections: data with low $W$ are used

Include nuclear corrections: use of deuterium data requires careful treatment of nuclear corrections
Results from CTEQ-JLab Fits

➢ Compare to previous analyses:

greatly reduced experimental errors, up to 80% on the d quark PDF at large x

Results from CTEQ-JLab Fits

➢ Highlights: regarding the universality of PDFs

Non-perturbative $1/Q^2$ corrections: dynamical and kinematical higher-twist

\[ F_2(x, Q^2) = F_{2LT}(x, Q^2)(1 + \frac{C(x)}{Q^2}) \]

1) The dynamical HT extraction depends on the kinematical HT (TMC) prescription used

2) Almost identical results for the d-quark distribution when different prescriptions of TMCs are used in conjunction with the dynamical HT

Results from CTEQ-JLab Fits

➢ Highlights: regarding nuclear corrections

Nuclear effects in deuterium: binding, Fermi motion (well known), off-shellness (less well known)

- Global fits without deuterium data show:
  modest increase in the error band for $u$ for $x>0.7$
  significant increase in the error band for $d$

- Smaller error band for $d$ if deuteron hence nuclear correction included
Results from CTEQ-JLab Fits

➢ Highlights: regarding $d/u$ at large $x$

Improvement in uncertainty of $d/u$ extraction

How do we practically run E12-10-002?
Inclusive Cross Section Measurements

➢ $F_2$ structure function obtained from cross section measurements

$$\frac{d^2\sigma}{d\Omega dE'} = (N_{\text{measured}} - BG) \frac{1}{N_e N_t} \frac{1}{d\Omega dE'} \frac{1}{A \varepsilon}$$

absolute cross section with radiative effects
Inclusive Cross Section Measurements

➢ F2 structure function obtained from cross section measurements

\[ \frac{d^2\sigma}{d\Omega dE'} = (N_{\text{measured}} - BG) \frac{1}{N_e N_t} \frac{1}{d\Omega dE'} \frac{1}{A \varepsilon} \]

absolute cross section with radiative effects
Inclusive Cross Section Measurements

- F2 structure function obtained from cross section measurements

\[
\frac{d^2\sigma}{d\Omega dE'} = (N_{\text{measured}} - BG) \frac{1}{N_e N_t} \frac{1}{d\Omega dE'} A \varepsilon
\]

- absolute cross section with radiative effects

Background
- cryogenic target endcaps
- e- from decay of \( \pi^0 \) produced in the target
- contamination from pion response in PID
Inclusive Cross Section Measurements

➢ F2 structure function obtained from cross section measurements

\[ \frac{d^2\sigma}{d\Omega dE'} = (N_{measured} - BG) \frac{1}{N_e N_t} \frac{1}{d\Omega dE'} \frac{1}{A \varepsilon} \]

absolute cross section with radiative effects
Inclusive Cross Section Measurements

➢ F2 structure function obtained from cross section measurements

\[
\frac{d^2\sigma}{d\Omega dE'} = (N_{\text{measured}} - BG) \frac{1}{N_e N_t} \frac{1}{d\Omega} \frac{1}{dE'} \frac{1}{A \varepsilon}
\]

absolute cross section with radiative effects

experimental efficiencies
detectors
front-end electronics
DAQ

Background
• cryogenic target endcaps
• e- from decay of π⁰ produced in the target
• contamination from pion response in PID

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• cryogenic target endcaps
• e- from decay of π⁰ produced in the target
• contamination from pion response in PID
Hall C Setup

Super High Momentum Spectrometer (SHMS)

SHMS is new, built during the upgrade

8.5°

5.5°

Beamline

electron beam

target chamber:
cryogenic hydrogen and deuterium for E12-10-002 production

used during the 6 GeV program
SHMS Magnets

- Horizontal bender provides a 3 deg initial bend to allow small angle detection
- Q1(v), Q2(h), Q3(v) focus in horizontal and vertical directions
- Dipole defocuses in the vertical direction

Central Momentum: 2-11 GeV/c

Scattering Angle: 5.5 to 40 degrees

Solid Angle Acceptance: 4.0 msr

Momentum Acceptance: -10%<δ<22%

Momentum Resolution: 0.03%-0.08%
SHMS Detector Hut

- **Particle identification**
  - Noble gas Cherenkov
  - Heavy gas Cherenkov
  - Lead Glass Calorimeter

- **Trigger**
  - Hodoscope + PID

- **Tracking**
  - Drift chamber

Diagram showing various detector elements:
- Drift chambers
- Noble gas Cherenkov (University of Virginia)
- Heavy gas Cherenkov (University of Regina)
- Lead Glass Calorimeter (Yerevan/Jlab)
- Trigger hodoscopes (James Madison University and North Carolina A&T)

Shower indicated on the right side of the diagram.
E12-10-002 Running Conditions

➢ Unpolarized Beam

   energy: 10.6 and 6.4 for R measurement
   current: 30 µA or larger

➢ Targets

   10 cm hydrogen - production
   10 cm Deuterium - production
   Al foils - background measurement

➢ SHMS is used to take most of the production data

➢ HMS is used to measure highest $Q^2$ point and for cross-calibration with SHMS
E12-10-002 Run Plan

➢ SHMS is used to take most of the production data

SHMS kinematic settings with 10.5732 GeV beam

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<th>Angle</th>
<th>Momentum (GeV/c)</th>
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<tr>
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<td>2.7, 3.3, 4.0, 5.1</td>
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<td>25</td>
<td>2.5, 3.0, 3.5, 4.4</td>
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<td>29</td>
<td>2.0, 2.4, 3.0, 3.7</td>
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<tr>
<td>33</td>
<td>1.7, 2.1, 2.6, 3.2</td>
</tr>
<tr>
<td>39</td>
<td>1.3, 1.6, 2.0, 2.5</td>
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➢ 6 angle changes
➢ 25 momentum changes

different colors for different central momentum settings
cover a wide kinematic range because of large momentum acceptance
HMS is used to measure highest $Q^2$ point and for cross-calibration with SHMS.

### HMS Kinematic Settings with 10.5732 GeV Beam

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<th>Angle</th>
<th>Momentum (GeV/c)</th>
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<tr>
<td>18</td>
<td>4.1, 4.6, 5.1, 5.6, 6.4</td>
</tr>
<tr>
<td>59</td>
<td>1.05, 1.18, 1.35, 1.50</td>
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</tbody>
</table>

- **59 deg**: Production to push to highest $x$, $Q^2$
- **18 deg**: Commissioning data to cross-calibrate HMS and SHMS

- 2 angle changes
- 9 momentum changes

Covered range is smaller than SHMS because of smaller momentum acceptance.

During the SHMS production running at 21, 25, 29, 33, 39 deg the HMS will take production data at 59 deg.
Production Rate, SHMS

\[ N_{measured} = \text{cross section} \times N_{beam} \times N_{target} \]

\[ \text{rate} = \frac{d\sigma}{d\Omega dE'} \times d\Omega \times dE' \times \frac{I}{Q_e} \times \frac{N_A \times \rho \times t}{A} \]

- **Input parameters:**
  - target length: 10 cm
  - beam current: 30 µA
  - bin size: \( W^2 \) bin of 0.1 GeV²

- **Shape due to**
  - detector acceptance effect
Production Rates on H target, SHMS

➢ Rate plots for all kinematics
Production Rates on D target, SHMS

➤ Rate plots for all kinematics

➢ Rate plots for 200 Hz
Production Time Estimation, SHMS

- Input parameters:
  - Target length: 10 cm
  - Beam current: 30 µA
  - bin size: $W^2$ bin of 0.1 GeV$^2$

- Shape due to detector acceptance effect

- Shown are times corresponding to different statistical precisions

\[ \theta = 18^\circ \]

$1.5\% \text{ statistics}, W^2 > 1.4, \text{time} = 1.47$

$\text{time} = 0.12$

$4\% \text{ statistics}$
H Production Time Estimation, SHMS

➤ Time estimations for all kinematics
D Production Time Estimation, SHMS

➢ Time estimations for all kinematics

Time=0.41
1.5% stat. for W2>1.9, time=5.85

Time=1.00
1.5% stat. for W2>1.4, time=1.00

Time=2.32
1.5% stat. for W2>2.7, time=14.38

Time=1.50
1.5% stat. for W2>1.6, time=2.92

Time=3.50
1.5% stat. for W2>2.4, time=1.00
Production Time Estimation: Preliminary

- 1.5% statistics in $W^2$ bin of 0.1 GeV$^2$

<table>
<thead>
<tr>
<th>Angle(deg)</th>
<th>Time(h) H target</th>
<th>Time(h) D target</th>
<th>1.5% stat. for $W^2$?</th>
</tr>
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<td>2</td>
<td>1.4</td>
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statistical precision will be less than 1.5% below the $W^2$ cuts

- Total time for H running: 153 h
- Total time for D running: 82 h
- Dummy run time: 15% of D target
- May still be changed to compromise between time and statistics
➢ Rate at large angle is low

➢ HMS will stay at 59 deg after taking data at 18 deg
π⁻/e⁻ Ratios for H

➢ Target length: 10 cm
➢ Beam current: 40 μA
➢ Pion cross section: Wiser’s fit to π⁺ and π⁻ production on H

estimating π/e PID
SHMS Running Parameters: Cherenkov

➢ For momenta between 1.4 and 4 GeV, $\pi/e < 250$

Cherenkov rejection: HGC - 25:1 & LGC (Ar) - 25:1

➢ For momenta > 4 GeV, $\pi/e < 2.5$

Cherenkov rejection: LGC (Ar) - 25:1

Pertaining to SHMS

Heavy Gas Cherenkov (HGC)

$C_4F_8O$ at 0.45 atm gives a 4 GeV momentum threshold for $\pi$

HGC can separate $\pi/e$ when momentum is smaller than 4 GeV/c
SHMS Running Parameters: Calorimeter

- For momenta between 1.4 and 4 GeV, $\pi/e < 250$
  - Cherenkov rejection: HGC - 25:1 & LGC (Ar) - 25:1
  - Calorimeter rejection: 150-200 (99.5 efficient)
- For momenta > 4 GeV, $\pi/e < 2.5$
  - Cherenkov rejection: LGC (Ar) - 25:1
  - Calorimeter rejection: 200 (99.5 efficient)
HMS Running Equipments

➢ For momenta between 1.4 and 4 GeV, \( \pi/e < 150 \)
  
  Cherenkov rejection: 100:1
  
  Calorimeter rejection: 100-180
  \[ \rightarrow 1.5\% \pi \text{ contamination} \]

➢ For momenta > 4 GeV, \( \pi/e < 2.5 \)
  
  Calorimeter rejection: 150
  \[ \rightarrow 1.6\% \pi \text{ contamination} \]

Momenta between 1.4 and 7 GeV: calorimeter \( \pi \) rejection factor between 100 and 200 can be achieved while keeping the \( e \) efficiency larger than 98% (for calorimeter cut of 0.9)

\[ C_4F_8O \text{ at 0.45 atm gives a 4 GeV momentum threshold for } \pi \]
The Charge Symmetric Background

- Neutral pions decay into photon-electron-positron $\pi^0 \rightarrow \gamma + e^- + e^+$

- Secondary electrons will pass PID cuts and be detected $e^-_{\text{total}} = e^-_{\text{DIS}} + e^-_{\text{bg}}$

- Number of positrons is the same as number of background electrons

- Subtract background electrons to get electrons from actual scattering

- Need more time to get statistics
e^+/e^- Ratios for H

➢ Target length: 10 cm

➢ e^+ cross section: P. Bosted’s code based on Wiser’s fit to π+ and π- production on H

We will measure charge symmetric background with the same spectrometer that detects the scattered electrons.
Going from Cross sections to $F_2$: Determination of R

> Cannot claim a precise extraction of $F_2$ from cross section without a precise knowledge of $R$

$$\frac{d\sigma}{d\Omega dE'} = \Gamma(\sigma_T(x, Q^2) + \varepsilon \sigma_L(x, Q^2)) = \Gamma \sigma_T(1 + \varepsilon R)$$

ratio of longitudinal and transverse photo absorption cross section

$$\varepsilon = \frac{1}{1 + 2\frac{\nu^2 + Q^2}{Q^2} \tan^2 \frac{\theta}{2}}$$

$$F_1(x, Q^2) = \frac{\kappa M}{4\pi^2 \alpha} \sigma_T(x, Q^2)$$

$$F_2(x, Q^2) = \frac{\kappa}{4\pi^2 \alpha} \frac{\nu}{1 + \nu^2/Q^2} [\sigma_T(x, Q^2) + \sigma_L(x, Q^2)]$$

> Measurements at different beam energies than 10.6 GeV to extract $R$, especially in the region of large $x$ and large $Q^2$
Determination of R

R from R1990 parametrization (SLAC)

Measure R at large x low \(Q^2\), where data are scarce or none.

\[ x = 0.748, \quad Q^2 = 6.299 \]

\[ x = 0.855, \quad Q^2 = 6.655 \]
Summary

- Measurements of $F_2$ at large $x$ help us to better constrain the valence content of the nucleon

- E12-10-002 is scheduled in Hall C in few months from now

- We are in the process of finalizing the run plan

Groups involved in preparation for running:

- E12-10-002
  - Students: Abel Sun (CMU), Deb Biswas (HU)
  - Spokespeople: Eric Christy, Thia Keppel, Simona Malace (contact), Ioana Niculescu

- E12-10-008
  - Students: Kayla Craycraft (UT), Abishek Karki (MSU)
  - Spokespeople: John Arrington, Aji Daniel, Dave Gaskell (contact), Nadia Fomin

Some slides have been modified from talks by S. Malace
Thank you.