$d_2^n$: PROBING QUARK-GLUON CORRELATIONS IN THE NEUTRON

On Behalf of $d_2^n$ Collaboration

Junhao Chen

The College of William & Mary
POLARIZED STRUCTURE FUNCTION

Target Spin Longitudinal to Electron Spin

\[
\frac{d^2\sigma^{\uparrow\uparrow}}{d\Omega dE'} - \frac{d^2\sigma^{\uparrow\uparrow}}{d\Omega dE'} = 4 \frac{\alpha^2 E'}{Q^2 E} \left[ \frac{(E + E' \cos \theta)}{Mv} g_1(x, Q^2) \right.
- \left. \frac{Q^2}{Mv^2} g_2(x, Q^2) \right]
\]

Target Spin Transverse to Electron Spin

\[
\frac{d^2\sigma^{\uparrow\rightarrow}}{d\Omega dE'} - \frac{d^2\sigma^{\uparrow\rightarrow}}{d\Omega dE'} = 4 \frac{\alpha^2 E'}{Q^2 E} \sin \theta \cos \phi \left[ \frac{g_1(x, Q^2)}{Mv} + \frac{2E g_2(x, Q^2)}{Mv^2} \right]
\]
\( g_2 \) AND QUARK-GLUON CORRELATION

- \( g_2 \) could not be understood through simple quark gluon model, but rather be interpreted as a higher twist structure function.
- \( g_2 \) is the imaginary part of the spin-dependent Compton amplitude for the process

\[
\gamma^* (+1) + N(1/2) \rightarrow \gamma^* (0) + N(-1/2)
\]

\[
g_2 = g_2^{WW} (x, Q^2) + \overline{g_2}
\]

- A direct probe of the quark-gluon correlation

\( \overline{g_2}(x, Q^2) = -\int_x^1 \frac{dy}{y} \left[ \frac{m}{M} h_T(y, Q^2) + \xi(y, Q^2) \right] \) 

(Cortes, Pire & Ralston)

\( h_T(x, Q^2) \): transverse polarization density function (Transversity)
\( \xi \): twist-3 term from quark-gluon correlations

Helicity exchange occur in two ways

\[
\gamma^* (+1) + N(1/2) \rightarrow \gamma^* (0) + N(-1/2)
\]

Plot reproduced by Murchhana Roy

Twist 2 Wandzura - Wilczek term

\[
g_2^{WW} (x, Q^2) = -g_1 (x, Q^2) + \int_x^1 \frac{g_1(y, Q^2)}{y} dy
\]
**WHAT IS $d_2$**

$d_2$: second moment in $x$ of a linear combination of $g_1$ and $g_2$

$$d_2(Q^2) = \int_0^1 x^2 [2g_1(x, Q^2) + 3g_2(x, Q^2)] dx$$

$$= 3 \int_0^1 x^2 [g_2(x, Q^2) - g_2^{WW}(x, Q^2)] dx$$

$$= 3 \int_0^1 x^2 \overline{g_2}(x, Q^2) dx$$

- Clean probe to higher twist effects
- Been thoroughly studied in Lattice QCD
- Reflects the response of color electric and magnetic fields to the polarization of the nucleon

$$x_E = \frac{(4d_2 + 2f_2)}{3} \quad x_B = \frac{(4d_2 - f_2)}{3}$$

$f_2$: twist-4 reduced matrix element which contains non-trivial quark-gluon interactions
HALL C SETUP

**Electron Beam:**
- Beam energy: 10.38 GeV
- Beam current: 30 μA
- Beam polarization ~ 85% (~3% uncertainty)

Used for the first time for extended target (40cm)
Polarized $^3\text{He}$ target:
Target polarization: 45% to 50% (~5% uncertainty).
About 10 atm $^3\text{He}$ in beam.
reference target: $N_2$, $H_2$, un-polarized $^3\text{He}$. 
EXPERIMENT COVERAGE

- 25% reduction in coverage relative to Proposal to accommodate Accelerator schedule. Accelerator performance difficulties during run limited final data collected to:
  - Completed: Kin A, C, X, Z
  - Partial: Kin Y, B
Extract $g_1, g_2, d_2$ through measured unpolarized cross section($\sigma_0$) and asymmetries($A_\parallel, A_\perp$)

$$g_1 = \frac{MQ^2}{4\alpha^2} \frac{2y}{(1-y)(2-y)} \sigma_0 \left[ A_\parallel + \tan\frac{\theta}{2}A_\perp \right]$$

$$g_2 = \frac{MQ^2}{4\alpha^2} \frac{2y}{(1-y)(2-y)} \sigma_0 \left[-A_\parallel + \frac{1 + (1-y) \cos \theta}{(1-y) \sin \theta} A_\perp \right]$$

$$d_2 = \int_0^1 \frac{MQ^2}{4\alpha^2} \frac{x^2y^2}{(1-y)(2-y)} \sigma_0 \left[ 3 \frac{1 + (1-y) \cos \theta}{(1-y) \sin \theta} + \frac{4y}{y} \tan\frac{\theta}{2} \right] A_\parallel + A_\parallel \frac{4}{y} \right] dx$$

$A_\parallel = \frac{1}{P_t P_b D_{N_2}} \frac{1}{(\cos \phi) \left[ N_\parallel \Rightarrow - N_\parallel \Rightarrow \right]} N_\parallel \Rightarrow + N_\parallel \Rightarrow$

$P_t$: target polarization
$P_b$: beam polarization
$D_{N_2}$: $N_2$ Dilution
$N_\parallel \Rightarrow$: count when target polarization is longitudinal(transverse to election polarization)

$\sigma_{\text{raw}}(E', \theta) = \frac{\text{Yield}_{\text{cor}}(E', \theta)}{L A \Delta\Omega \Delta E'}$

$L = n_{\text{tar}} * l_{\text{tar}} * Q_{\text{tar}} / |e| \ (\text{integrated luminosity})$

$\Delta\Omega = \text{solid angle generated per (E',}\theta) \ bin$

$\Delta E' = \text{momentum acceptance per (E',}\theta) \ bin$

$A(E', \theta) = N_{\text{detected}}(E', \theta) / N_{\text{threshold}}(E', \theta) \ (\text{section 7.4.7})$

Credit to Murchhana Roy
TARGET POLARIZATION

Target polarization for each run

Polarimetry Uncertainties

<table>
<thead>
<tr>
<th>Uncertainty contributors</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density Model</td>
<td>0.9%</td>
</tr>
<tr>
<td>$\kappa_{39K}$ Parameterization</td>
<td>0.9%</td>
</tr>
<tr>
<td>$\sigma(\kappa(T_{pc})n_{pc}(T_{tc},T_{pc}))$ due to Pumping Chamber Temperature</td>
<td>0.3%/5°C</td>
</tr>
<tr>
<td>Target Chamber Temperature</td>
<td>0.7%/5°C</td>
</tr>
<tr>
<td>$V_{pc}, V_{tc}, V_{tt}$ (uncorrelated)</td>
<td>0.13%, 0.10%, 0.02%</td>
</tr>
<tr>
<td>$n^{3He}$</td>
<td>Undetermined expecting to be 5%</td>
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</table>

Less than 3% (combined)
# Beam Polarization

<table>
<thead>
<tr>
<th>Period</th>
<th>Double WIEN</th>
<th>IHWP IN</th>
<th>IHWP OUT</th>
<th>Beam Polarization</th>
</tr>
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<tbody>
<tr>
<td>1 pass Dec 2019</td>
<td>FLIP RIGHT</td>
<td>UPSTREAM</td>
<td>DOWNSTREAM</td>
<td>84.5%</td>
</tr>
<tr>
<td>5 pass before Feb 17th, 2020</td>
<td>FLIP RIGHT</td>
<td>DOWNSTREAM</td>
<td>UPSTREAM</td>
<td>85.4%</td>
</tr>
<tr>
<td>5 pass Feb 17th to MEDCON6</td>
<td>FLIP LEFT</td>
<td>UPSTREAM</td>
<td>DOWNSTREAM</td>
<td>85.4%</td>
</tr>
<tr>
<td>5 pass D2n</td>
<td>FLIP RIGHT</td>
<td>DOWNSTREAM</td>
<td>UPSTREAM</td>
<td>85.6%</td>
</tr>
<tr>
<td>1 pass (end of run)</td>
<td>FLIP RIGHT</td>
<td>UPSTREAM</td>
<td>DOWNSTREAM</td>
<td>81.7%</td>
</tr>
</tbody>
</table>

Credit to William Henry
\[ D_{N_2} = 1 - \frac{\Sigma (N_2) \cdot t_{ps}(N_2) \cdot Q^{(3}\text{He}) \cdot t_{LT}^{(3}\text{He}) \cdot n_{N_2}(^{3}\text{He})}{\Sigma \text{total}^{(3}\text{He}) \cdot t_{ps}(^{3}\text{He}) \cdot Q(N_2) \cdot t_{LT}(N_2) \cdot n_{N_2}(N_2)}. \]

\[ \frac{\text{Yield}_{N_2}(N_2)}{\text{Yield}_{Total}(^{3}\text{He})} \times \frac{n_{N_2}(^{3}\text{He})}{n_{N_2}(N_2)} \]

- \( \text{Yield}_{N_2} = \frac{\Sigma t_{ps}}{Q \cdot t_{LT}} \)
- (N2 or 3He): N2 target or Pol-3He target
- \( \Sigma\): good events from root file
- \( t_{ps}\): pre-scaler factor
- \( t_{LT}\): live time
- \( n\): density

\(~9%\ for \( d_2^n \) targets\)
\[ A_{phys} = \frac{N^+}{Q^{+CLT}P_tP_b} - \frac{N^-}{Q^{-CLT}} \times \frac{N^+}{Q^{+CLT}P_tP_b} + \frac{N^-}{Q^{-CLT}} \]

\(D_{N_2}\): Nitrogen dilution factor
\(P_b\): Beam polarization
\(P_t\): Target polarization
\(\bar{A}_{phys}\): Averaged physics asymmetry with same run condition
Raw Cross-section Extraction: *(Section 7.5)*

\[
\sigma_{raw}(E', \theta) = \frac{\text{Yield}_{cor}(E', \theta)}{L \cdot A \cdot \Delta \Omega \cdot \Delta E'}
\]

\[
\text{Yield}_{cor}(E', \theta) = \frac{\text{Yield}(E', \theta)}{\epsilon_{cal} \cdot \epsilon_{chern} \cdot \epsilon_{tr} \cdot \epsilon_{trig} \cdot \text{livetime}}
\]

\[L = \eta_{tar} \cdot l_{tar} \cdot Q_{tot} / |e| \text{ (integrated luminosity)}\]
\[\Delta \Omega = \text{solid angle generated per (E', } \theta \text{) bin}\]
\[\Delta E' = \text{momentum acceptance per (E', } \theta \text{) bin}\]
\[A(E', \theta) = N_{\text{detected}}(E', \theta) / N_{\text{thrown}}(E', \theta) \text{ (section 7.4.7)}\]

Cuts used:
- \(-9 < z < 9 \text{ (cm)}\)
- \(-8 < \delta < 8 \text{ (cm)}\)
- \(-0.04 < xp < 0.04 \text{ (rad)}\)
- \(-0.02 < yp < 0.02 \text{ (rad)}\)
- PID Cuts: \(0.2 < E/P < 2\)
  (calorimeter), \(npe > 1\) (Cherenkov)
Cross-section Extraction: Radiative Correction

$$\sigma_{\text{Born}} = (\sigma_{\text{rad}} - \sigma_{\text{rad, elastic model}} - \sigma_{\text{rad, quasieelastic model}}) \times \frac{\sigma_{\text{Born, model}}}{\sigma_{\text{rad, inelastic, model}}}$$
### $^3$He DENSITY EXTRACTION: PRESSURE CURVE

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<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Briana</td>
<td>6.938/0.1177</td>
<td>240/30</td>
<td>PC: 289.5 TC: 99.88 TT: 26.97</td>
<td>He3: 161.9 N2: 2.75</td>
<td>160.6 ± 1.5</td>
<td>1645 ± 1.5</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>142.2 ± 0.7 158.5 ± 0.6</td>
</tr>
<tr>
<td>Dutch</td>
<td>7.759/0.1102</td>
<td>240/30</td>
<td>PC: 297.15 TC: 111.87 TT: 32.52</td>
<td>He3: 179.3 N2: 2.55</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>191.1 ± 2.0 209.4 ± 2.1</td>
</tr>
<tr>
<td>Big Brother</td>
<td>7.093/0.1120</td>
<td>240/30</td>
<td>PC: 293.82 TC: 100.76 TT: 32.6</td>
<td>He3: 165.5 N2: 2.59</td>
<td>NA</td>
<td>NA</td>
<td>174.1 ± 1.0</td>
<td>192.0 ± 1.0</td>
<td>178.5 ± 1.6</td>
<td>NA</td>
</tr>
<tr>
<td>Austin</td>
<td>7.498/0.1145</td>
<td>240/30</td>
<td>PC: 305.9 TC: 106.5 TT: 37.92</td>
<td>He3: 174.6 N2: 2.70</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Tommy</td>
<td>7.760/0.13</td>
<td>240/30</td>
<td>PC: 284 TC: 110 TT: 33</td>
<td>He3: 178.8 N2: 3.0</td>
<td>NA</td>
<td>184.1 ± 1.4</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>157.0 ± 0.6 173.3 ± 0.5</td>
</tr>
</tbody>
</table>

**Extracted target chamber pressure in run condition**

- **Filling Pressure**: 161.9 psia
- **He3 Pressure, N2 Corrected**: 142.2 ± 0.7 psia
- **He3 Pressure, N2 Uncorrected**: 158.5 ± 0.6 psia
SUMMARY

- E12-06-121 experiment was successfully completed in September 2020
- Physical value extractions are still going on
  - Asymmetry: doing radiative correction
  - Cross section: several uncertainties still need to be finalized
BACKUP SLIDES
DRIFT CHAMBER CALIBRATION

Assumptions for calibration:
- The minimum drift time is 0
- Charged particles pass through single drift cell uniformly

What to calibrate:
The drift distance for each wire calibrated from drift time

Pictures credit to Carlos Yero
DRIFT CHAMBER CALIBRATION

- Add a new time offset per wire fitting method
  - Fit the integrated drift time with step function to increase the fitting stability

- Have finished first round calibration
- Hodoscope params was updated this week, is doing a 2\textsuperscript{nd} round calibration
- Expecting finish 2\textsuperscript{nd} round this week
HODOSCOPE CALIBRATION

\[ t_{\text{Corr}} = t_{\text{RAW}} - t_{\text{TW}} - t_{\text{Cable}} - t_{\text{propagation}} - t_{\lambda} \]

- TW : Time-walk Corrections
- tcable: Cable Time Corrections
- tprop: Propagation Time Corrections
- t\(\lambda\): Hodoscope Planes Time Difference Corrections

- HMS 3994: \( ^3\)He DIS, \( d_2^n \) experiment
- Longitudinal 180 deg
- Kin-B: \( E_p = 6.4 \text{ GeV}, 14.5^\circ \)
- Trigger: 3/4 (hTRIG1)

Graph Source: E. Pooser

\[ f_{TW}(a) = c_1 + \frac{(a / TDC_{\text{thr}})}{c_2} \]

- \( a \) is ADC amplitude; \( TDC_{\text{thr}} = 120 \text{ mV} \)

Paddle 2y: Time-Walk Corr. TimeDiff. vs. Hod Track Position

\[ F_{fit}(x) = \frac{x}{V_p} + b_0 \]

- \( V_p = 15.42 \text{ cm/ns} \)
- \( b_0 = -0.0054 \text{ ns} \)
HODOSCOPE CALIBRATION

\[ t_{\text{corr}} = t_{\text{raw}} - t_{\text{TW}} - t_{\text{cable}} - t_{\text{propagation}} - t_\lambda \]

\[ t_{\text{corr}}^{(+)} = t_{\text{corr}}^{(+)} - (L_+ - \text{hit}) \frac{1}{v_p}, \quad \text{where} \quad t_{\text{prop}}^{(+)} \equiv (L_+ - \text{hit}) \frac{1}{v_p} \]

\[ t_{\text{corr}}^{(-)} = t_{\text{corr}}^{(-)} - (\text{hit} - L_-) \frac{1}{v_p}, \quad \text{where} \quad t_{\text{prop}}^{(-)} \equiv (\text{hit} - L_-) \frac{1}{v_p} \]

\[ t_{\text{avgcorr}} = \frac{1}{2} (t_{\text{corr}}^{(+)} + t_{\text{corr}}^{(-)}) = \frac{1}{2} (t_{TW\text{corr}}^{(+)} + t_{TW\text{corr}}^{(-)}) \]

This correction is done in hcana.

-HMS 3994: \(^3\)He DIS, \(d^2\) experiment
-Longitudinal 180 deg
-Kin-B: \(E_p = 6.4\) GeV, 14.5°
-Trigger: 3/4 (hTRIG1)

-All possible time difference combinations considered; solve the system of six linear equations.

HMS Beta after Hodoscope calibration

HMS Beta before Hodoscope calibration

Graph Source: E.Pooser