Medium Modification of Separated Longitudinal and Transverse Structure Functions in the Resonance Region

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Talk Structure

- Experiment Motivation (E02-109 & E04-001)
- HallC LT Program at JLab
- Physics Overview
- Experimental Setup
- Analysis Steps and Preliminary Results
- Future work
Experiment Motivation
(E02-109, E04-001)

- Measure the separated longitudinal and transverse structure functions $F_L$ and $F_1$ from nuclei in the resonance region.

- Investigate quark-hadron duality in nuclei

- Neutrino cross section model development in collaboration with the neutrino community. Measurement of neutrino oscillation parameters require precise knowledge of structure functions. The vector part of $F_1$ and $F_2$ in neutrino scattering can be modeled using electron scattering data.
- Provide information of medium modifications of separated $F_1$ and $F_L$. Non-zero $R_D - R_A$ requires that the medium modifications are different for $F_1$, $F_L$, and $F_2$.

- look for nuclear pions (G. A Miller, Phys. ReV. C 64, 022201 (2001))
- look at EMC effect ratios for $F_L$, $F1$ (L/T) separately
- check observed SRC correlation for L/T components separately
### 6 GeV L/T Separation Program in HallC

<table>
<thead>
<tr>
<th>Experiment</th>
<th>target(s)</th>
<th>W range</th>
<th>Q&lt;sup&gt;2&lt;/sup&gt; range</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>E94-110</td>
<td>p</td>
<td>RR</td>
<td>0.3 - 4.5</td>
<td>nucl-ex/041002</td>
</tr>
<tr>
<td>E99-118</td>
<td>p,d</td>
<td>DIS+RR</td>
<td>0.1 - 1.7</td>
<td>PRL98:14301</td>
</tr>
<tr>
<td>E00-002</td>
<td>p,d</td>
<td>DIS+RR</td>
<td>0.25 - 1.5</td>
<td>Analysis finalized/Published Phys.Rev. C97 (2018) no.4, 045204</td>
</tr>
<tr>
<td>E02-109</td>
<td>d</td>
<td>RR+QE</td>
<td>0.2 - 2.5</td>
<td>Finalizing dσ analysis</td>
</tr>
<tr>
<td>E06-009</td>
<td>d</td>
<td>RR+QE</td>
<td>2.0 - 4.0</td>
<td>Cross section, F&lt;sub&gt;L&lt;/sub&gt; finalized Non-singlet moments paper in collaboration review</td>
</tr>
<tr>
<td>E04-001 - I</td>
<td>C,Al,Fe</td>
<td>RR+QE</td>
<td>0.2 - 2.5</td>
<td>Finalizing dσ analysis</td>
</tr>
<tr>
<td>E04-001 - II</td>
<td>C,Al,Fe</td>
<td>RR+QE</td>
<td>2.0 - 4.0</td>
<td>Cross section, RA-Rd finalized for most targets</td>
</tr>
</tbody>
</table>

First to see some nuclear dependence
Greatly expanding of $W^2$ and $Q^2$
### Phase II achieved uncertainties

Total < 2.\% point-to-point

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Uncertainty</th>
<th>$\delta \sigma$%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy, $E$</td>
<td>0.05%</td>
<td>0.25 %</td>
</tr>
<tr>
<td>Scattered electron energy, $E'$</td>
<td>0.06%</td>
<td>0.025 %</td>
</tr>
<tr>
<td>Scattered electron angle, $\theta$</td>
<td>0.2 mrad</td>
<td>0.3 %</td>
</tr>
<tr>
<td>Beam Current</td>
<td>0.3 $\mu$A</td>
<td>0.3 %</td>
</tr>
<tr>
<td>Electronic Live Time</td>
<td>0.008%</td>
<td>0.008 %</td>
</tr>
<tr>
<td>Computer Live Time</td>
<td>0.2%</td>
<td>0.2 %</td>
</tr>
<tr>
<td>Trigger Efficiency</td>
<td>0.007%</td>
<td>0.007 %</td>
</tr>
<tr>
<td>Tracking Efficiency</td>
<td>0.15%</td>
<td>0.15 %</td>
</tr>
<tr>
<td>Cerenkov Efficiency</td>
<td>0.15%</td>
<td>0.15 %</td>
</tr>
<tr>
<td>Calorimeter Efficiency</td>
<td>0.05-0.2%</td>
<td>0.05-0.2 %</td>
</tr>
<tr>
<td>Charge Symmetric Background Correction</td>
<td>0.1-0.4%</td>
<td>0.1-0.4 %</td>
</tr>
<tr>
<td>Acceptance</td>
<td>0.7%</td>
<td>0.7 %</td>
</tr>
<tr>
<td>Radiative Corrections</td>
<td></td>
<td>$\leq 1.0$ %</td>
</tr>
</tbody>
</table>
Previous results from HallC LT program

Proton: E94-110 + SLAC

Deuteron

Phase I (E02-109) **deuteron** will:

→ add more precision points at low $Q^2$ and $W^2$
→ improve precision at intermediate $Q^2$ when combined with Phase II (E06-009)
Nuclear study dependence study at larger $Q^2$

$^{12}$C: Phase-II

Modeling suggests that the enhancement is due to different Fermi smearing for different nuclei.
Hall C top view (6 GeV era). High Momentum Spectrometer (HMS) was used to detect scattered electrons, whereas the Short Orbit Spectrometer (SOS) was used largely for charge symmetric background rejection.
Experimental Setup

HMS Detector Stack (view from above)

HMS Properties

<table>
<thead>
<tr>
<th>Kinematic Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Momentum:</td>
</tr>
<tr>
<td>0.5-7.5 GeV/c</td>
</tr>
<tr>
<td>Angular:</td>
</tr>
<tr>
<td>10.5°-80°</td>
</tr>
</tbody>
</table>

Acceptance

<table>
<thead>
<tr>
<th>$\Delta \Omega$</th>
<th>~6.5 msr</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta p/p$</td>
<td>+/-10%</td>
</tr>
</tbody>
</table>

Resolution

<table>
<thead>
<tr>
<th>$\Delta p/p$</th>
<th>&lt;0.1 %</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta$</td>
<td>~ 1 mrad</td>
</tr>
</tbody>
</table>
1. For each kinematic, generate MC events with $\sigma$ "model" weighting including the radiative contributions. The "model" is a global fit including preliminary data from this experiment **Model: Global fit to existing data by M.E. Christy, A Bodek, T. Gautam (in preparation), based on Bosted-Mamyan**

2. The efficiency corrected electron yield after subtraction of BG events is:

   \[ Y_{Data} = L_{Data} \cdot \sigma_{Data} \cdot (\Delta E' \cdot \Delta \Omega) \cdot A \]

   \[ Y_{MC} = L_{MC} \cdot \sigma_{MC} \cdot (\Delta E' \cdot \Delta \Omega) \cdot A_{MC} \]

3. Assuming that the acceptance $A = A_{MC}$, the ratio of the Data to the model Yield leads to:

   \[ \frac{Y_{Data}}{Y_{MC}} = \frac{L_{Data} \cdot \sigma_{Data} \cdot A}{L_{MC} \cdot \sigma_{MC} \cdot A} \]

4. After Scaling the MC luminosity by a factor of $L_{Data} / L_{MC}$ so that $L_{Data} = L_{MC}$, the cross section is calculated for each $W^2$ bin and integrated over $\theta$ using:

   \[ \sigma_{Data} = \sigma_{MC} \times \frac{Y_{Data}}{Y_{MC}} \]
MC includes all the physics, and well modeled spectrometer-> allows precision in extracting cross section

(C) Run # 53345, $E = 2.348$ GeV, $E' = 0.442$ GeV, $\theta = 45.01^\circ$, SF = 1.030

Iterated to with 1-2% precision
Cross Section Extraction

E = 2.3466 GeV, θ = 45.00°

C

do/dΩ dE (nb/sr.GeV)

W^2 (GeV^2)

Model

Data

E = 3.4889 GeV, θ = 20.00°

Fe

do/dΩ dE (nb/sr.GeV)

W^2 (GeV^2)

Model

Data

(C) E = 2.347 GeV , θ = 45.00°

σ_{Data}/σ_{Model}

0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5

W^2 (GeV^2)

(Fe) E = 3.489 GeV , θ = 20.00°

σ_{Data}/σ_{Model}

0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5

W^2 (GeV^2)
Evidence some $\epsilon$ dependence, and nuclear longitudinal dependence. Validation requires final evaluation of full systematics.
The reduced cross section $\sigma_R$ is linear in $\varepsilon$:

$$\sigma_R = \sigma_T + \varepsilon \sigma_L$$

Hence, one can plot $\sigma_R$ versus $\varepsilon$ for fixed $W^2$ and $Q^2$ and extract $\sigma_L$ (slope) and $\sigma_T$ (intercept). This method is called *Rosenbluth separation technique*.

The Rosenbluth separation points are chosen for each target, where the points have the same $W^2$ and in a $Q^2$ range of 15% about a central $Q^2_c$ (got almost 188 LT sets, will be increased when combined with phase II data).

The difference $R_D - R_A$ and $F_{2D}/F_{2A}$ are extracted from the linear fits to the ratio of differential cross section

$$\frac{\sigma_D}{\sigma_A} = \frac{\sigma_D^T}{\sigma_A^T} \left[ 1 + \varepsilon' (R_D - R_A) \right]$$

where:

$$\varepsilon' = \frac{\varepsilon}{1 + \varepsilon R_A}$$
Rosenbluth Separation

\[
\sigma_R^C (\sigma/\Gamma) \quad \chi^2 / \text{ndf} \quad 1.817 / 2
\]

\[ Q^2 = 1.291 \text{ GeV}^2, \quad W^2 = 0.580 \text{ GeV}^2 \]

\[
\begin{align*}
p_0 & = 2.343 \times 10^4 \pm 1575 \\
p_1 & = 1.109 \times 10^4 \pm 2019
\end{align*}
\]

\[
\sigma_R^C (\sigma/\Gamma) \quad \chi^2 / \text{ndf} \quad 0.3397 / 2
\]

\[ Q^2 = 0.619 \text{ GeV}^2, \quad W^2 = 1.060 \text{ GeV}^2 \]

\[
\begin{align*}
p_0 & = 4.654 \times 10^5 \pm 2.203 \times 10^4 \\
p_1 & = 1.284 \times 10^5 \pm 2.841 \times 10^4
\end{align*}
\]

\[
\sigma_R^C (\sigma/\Gamma) \quad \chi^2 / \text{ndf} \quad 1.341 / 3
\]

\[ Q^2 = 0.671 \text{ GeV}^2, \quad W^2 = 1.100 \text{ GeV}^2 \]

\[
\begin{align*}
p_0 & = 3.058 \times 10^5 \pm 8722 \\
p_1 & = 1.242 \times 10^5 \pm 1.382 \times 10^4
\end{align*}
\]

\[
\sigma_R^C (\sigma/\Gamma) \quad \chi^2 / \text{ndf} \quad 0.4146 / 1
\]

\[ Q^2 = 1.438 \text{ GeV}^2, \quad W^2 = 2.820 \text{ GeV}^2 \]

\[
\begin{align*}
p_0 & = 3.374 \times 10^4 \pm 1387 \\
p_1 & = 9199 \pm 2182
\end{align*}
\]
Rosenbluth Separation

\[ \sigma_{R}^{Fe} (\sigma/\Gamma) \]

\[ Q^2 = 2.800 \text{ GeV}^2, W^2 = 0.500 \text{ GeV}^2 \]

- \[ \chi^2 / \text{ndf} = 1.425 / 1 \]
- \[ p0 = 3293 \pm 563.4 \]
- \[ p1 = 1040 \pm 753.3 \]

\[ Q^2 = 0.653 \text{ GeV}^2, W^2 = 0.860 \text{ GeV}^2 \]

\[ \sigma_{R}^{Fe} (\sigma/\Gamma) \]

- \[ \chi^2 / \text{ndf} = 1.551 / 2 \]
- \[ p0 = 2.688e+06 \pm 1.698e+05 \]
- \[ p1 = 1.537e+06 \pm 2.336e+05 \]

\[ Q^2 = 0.404 \text{ GeV}^2, W^2 = 3.740 \text{ GeV}^2 \]

\[ \sigma_{R}^{Fe} (\sigma/\Gamma) \]

- \[ \chi^2 / \text{ndf} = 1.452 / 3 \]
- \[ p0 = 8.682e+04 \pm 3651 \]
- \[ p1 = 1.992e+04 \pm 5298 \]

\[ Q^2 = 1.394 \text{ GeV}^2, W^2 = 4.100 \text{ GeV}^2 \]

\[ \sigma_{R}^{Fe} (\sigma/\Gamma) \]

- \[ \chi^2 / \text{ndf} = 0.001629 / 1 \]
- \[ p0 = 3.302e+04 \pm 2061 \]
- \[ p1 = 7071 \pm 3977 \]
Study of the inelastic $Q^2$ dependence requires subtraction of the QE contribution.

Fit: M.E. Christy, A Bodek, T. Gautam (in preparation)
What’s Next?

- Finalize extracting FL, F1, F2 for all targets (d, Al, C and Fe) (Check EMC)
- Check the pion enhancement at low $Q^2$ region.
- Final results -> by end of summer 2018
Great thanks to all the spokespeople of E02-109/E04-001.

Special Thanks for Eric Christy
Thanks!
(c)