Nuclear Hadronization Studies at JLab: Present and Future

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Schematic diagram describing semi-inclusive Deep Inelastic Scattering of a lepton off a nucleon

One photon exchange reaction

Proton in “A” nucleus

Quarks, gluons

Hadron cascades

$Q^2 > 1$ & Large invariant mass $W$

$X = (\pi^+, \pi^-, K^0, ...)$
To conduct a thorough investigation into how the nuclear medium influences quark hadronization, it is essential to perform a multidimensional cinemactical analysis on a range of different hadrons. This approach not only uncovers the color properties inherent to the nuclear medium but also provides a comprehensive understanding of the phenomenon.
Illustration of a parton moving through nuclear media. At the top the prehadron is formed outside the nuclei and at the bottom it is formed inside.
Experimental observables

Transverse momentum broadening:

$$\Delta p_T^2 = p_T^2(A) - p_T^2(^2H)$$

(DIS kinematics)

Hadronic multiplicity ratio:

$$R_M^h(z, \nu, p_T^2, Q^2, \phi) = \frac{\left\{ \frac{N_h^{DIS}(z, \nu, p_T^2, Q^2, \phi)}{N_e^{DIS}(\nu, Q^2)} \right\} A}{\left\{ \frac{N_h^{DIS}(z, \nu, p_T^2, Q^2, \phi)}{N_e^{DIS}(\nu, Q^2)} \right\} D}$$
Studies with HERMES on He, Ne, Kr, Xe
Studies with HERMES on He, Ne, Kr, Xe
Past CLAS Spectrometer at JLab
Eg2 Double-Target

<table>
<thead>
<tr>
<th>Target</th>
<th>Thickness (cm)</th>
<th>$\rho_A/\rho_D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0.17</td>
<td>0.894</td>
</tr>
<tr>
<td>Fe</td>
<td>0.04</td>
<td>0.949</td>
</tr>
<tr>
<td>Pb</td>
<td>0.014</td>
<td>0.478</td>
</tr>
</tbody>
</table>

Studies performed with EG2 data

- Hadronization studies in nuclear medium
- Color transparency
- Short-Range Nuclear correlations
- Two-pion BEC correlations
- Dihadron supresión
- Etc.
DIS cinematics on CLAS6
Charged pions - multiplicity ratio

Charged pions - multiplicity ratio - multidimensional

Charged pions - ‘Cronin Effect’ - positive pions

Transverse momentum broadening $Zh$ dependence for positive pions - integrated (CLAS PRELIMINARY)

Esteban Molina et al.
Transverse momentum broadening Zh dependence for positive pions- differential (CLAS PRELIMINARY)
Schematic representation of the momentum vector sum in an event with multiple-pions in the final state.

Transverse momentum broadening in function of $A^{1/3}$, with all the other variables integrated. The circles are single-pion events, and the squares are two-pion events.
Transverse momentum broadening is shown as a function of the sum of $Z_h$ (with all other variables integrated), with each box representing a different target. Single-pion events are depicted in red, and two-pion events are depicted in blue.
Neutral Pions

Tayisia Mineeva et al. approved CLAS analysis note.
Etas and Omegas

Andres Borquez, Orlando Soto et al. (CLAS PRELIMINARY).
Multihadron events studies: Two-hadron azimuthal correlations

Multihadron events studies: Two-pion BEC correlations

C double ratio Fixed-Random mix

<table>
<thead>
<tr>
<th>dr_mix_rot_fixed</th>
<th>Entries</th>
<th>3112</th>
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</thead>
<tbody>
<tr>
<td>Mean</td>
<td>0.4473</td>
<td></td>
</tr>
<tr>
<td>Std Dev</td>
<td>0.2983</td>
<td></td>
</tr>
<tr>
<td>$\chi^2 / ndf$</td>
<td>70.78 / 41</td>
<td></td>
</tr>
<tr>
<td>gamma2</td>
<td>1.188 ± 0.010</td>
<td></td>
</tr>
<tr>
<td>lambda2</td>
<td>0.4186 ± 0.0578</td>
<td></td>
</tr>
<tr>
<td>rg2</td>
<td>2.284 ± 0.181</td>
<td></td>
</tr>
<tr>
<td>delta2</td>
<td>−0.3408 ± 0.0211</td>
<td></td>
</tr>
</tbody>
</table>

Antonio Radic et al. (CLAS PRELIMINARY)
CLAS12 Spectrometer at JLab
12 GeV cinematics

Data from RGF experiment
Hadrons in CLAS12
Experiment Context: CLAS12 Conditions

1. Reduced Space in Beamline, 85mm
2. High Vacuum, 10-6 mbar
3. Strong Magnetic Field, 5 Tesla
4. Cryogenic Temperatures, 22 Kelvin cryo-cell
5. 11 GeV Beam energy

- Interchangeable solid targets system in high vacuum
- Remote control system
- Resistant to high radiation
- Non-magnetic materials
- High vacuum resistant materials (no out-gassing)
- Fit in a 85mm diameter, cylindrical room
- Estimation of temperature in targets and devices
RGE Experiment Double Target System
Double Target for RG-E
## Target configuration with 70 nA beam current

<table>
<thead>
<tr>
<th>Target configuration</th>
<th>Solid target thickness in mm</th>
<th>Liquid target Luminosity</th>
<th>Solid target Luminosity</th>
<th>Total Luminosity</th>
<th>Number of Days to Run</th>
<th>Days: inbending/outbending</th>
</tr>
</thead>
<tbody>
<tr>
<td>2cm LD2 + C</td>
<td>1.48</td>
<td>8.56E+34</td>
<td>8.79E+34</td>
<td>1.74E+35</td>
<td>9</td>
<td>8/1</td>
</tr>
<tr>
<td>2cm LD2 + Al</td>
<td>1.20</td>
<td>&quot;&quot;</td>
<td>8.53E+34</td>
<td>1.71E+35</td>
<td>9</td>
<td>8/1</td>
</tr>
<tr>
<td>2cm LD2 + Cu</td>
<td>0.36</td>
<td>&quot;&quot;</td>
<td>8.50E+34</td>
<td>1.71E+35</td>
<td>9</td>
<td>8/1</td>
</tr>
<tr>
<td>2cm LD2 + Sn</td>
<td>0.30</td>
<td>&quot;&quot;</td>
<td>5.78E+34</td>
<td>1.43E+35</td>
<td>14</td>
<td>12/2</td>
</tr>
<tr>
<td>2cm LD2 + Pb</td>
<td>0.14</td>
<td>&quot;&quot;</td>
<td>4.18E+34</td>
<td>1.27E+35</td>
<td>19</td>
<td>17/2</td>
</tr>
</tbody>
</table>

Integrated luminosity for each solid target is: 6.81E+40
### Run Plan

<table>
<thead>
<tr>
<th></th>
<th>Inbending</th>
<th>Number of PAC Days to Run</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>2cm LD2 + C</td>
<td>4</td>
</tr>
<tr>
<td>2.</td>
<td>2cm LD2 + Pb</td>
<td>8.5</td>
</tr>
<tr>
<td>3.</td>
<td>2cm LD2 + Cu</td>
<td>4</td>
</tr>
<tr>
<td>4.</td>
<td>2cm LD2 + Sn</td>
<td>6</td>
</tr>
<tr>
<td>5.</td>
<td>2cm LD2 + Al</td>
<td>4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Outbending</th>
<th>Number of PAC Days to Run</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.</td>
<td>2cm LD2 + C</td>
<td>0.5</td>
</tr>
<tr>
<td>7.</td>
<td>2cm LD2 + Pb</td>
<td>1</td>
</tr>
<tr>
<td>8.</td>
<td>2cm LD2 + Cu</td>
<td>0.5</td>
</tr>
<tr>
<td>9.</td>
<td>2cm LD2 + Sn</td>
<td>1</td>
</tr>
<tr>
<td>10.</td>
<td>2cm LD2 + Al</td>
<td>0.5</td>
</tr>
</tbody>
</table>
Solid targets characterization measurements

<table>
<thead>
<tr>
<th>Target</th>
<th>thickness (cm)</th>
<th>width (cm)</th>
<th>length (cm)</th>
<th>V (cm³)</th>
<th>weight (min) (g)</th>
<th>weight (max)</th>
<th>Density (min)</th>
<th>Density (max)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>0.151</td>
<td>0.524</td>
<td>0.524</td>
<td>0.04146098</td>
<td>0.07</td>
<td>0.071</td>
<td>1.688</td>
<td>1.712</td>
</tr>
<tr>
<td>Aluminium*</td>
<td>0.121</td>
<td>0.525</td>
<td>0.525</td>
<td>0.03335063</td>
<td>0.086</td>
<td>0.088</td>
<td>2.579</td>
<td>2.639</td>
</tr>
<tr>
<td>Copper*</td>
<td>0.0335</td>
<td>0.524</td>
<td>0.525</td>
<td>0.00921585</td>
<td>0.076</td>
<td>0.077</td>
<td>8.247</td>
<td>8.355</td>
</tr>
<tr>
<td>Tin*</td>
<td>0.0289</td>
<td>0.525</td>
<td>0.525</td>
<td>0.00796556</td>
<td>0.056</td>
<td>0.058</td>
<td>7.030</td>
<td>7.281</td>
</tr>
<tr>
<td>Lead*</td>
<td>0.0143</td>
<td>0.525</td>
<td>0.525</td>
<td>0.00394144</td>
<td>0.041</td>
<td>0.043</td>
<td>10.402</td>
<td>10.910</td>
</tr>
</tbody>
</table>

Luminosities from calculations for 50 nA:
Lead: 2.99E34
Carbon: 4.64
Deuterium: 6.11E34

Ratios from the calculations:
Deuterium/Lead: 2.05
Deuterium/Carbon: 1.32

Ratios from RG-E experimental data (50 nA):
Deuterium/Lead: 2.17
Deuterium/Carbon: 1.40
First Preliminary RG-E measurements

Quick analysis performed by Ryan Milton, Antonio Radic, Milan Ungerer, Sebouh Paul, Sebastian Moran
Run 20046, LD2 + Pb
positive particles, p<10 GeV
0 < β < 1.2

Quick analysis performed by Ryan Milton, Antonio Radic, Milan Ungerer, Sebouh Paul, Sebastian Moran
First Preliminary RG-E measurements
Multiplicity Ratio vs Z for LD2+Pb with DIS cuts

Quick analysis performed by Ryan Milton, Antonio Radic, Milan Ungerer, Sebouh Paul, Sebastian Moran
Conclusions:

• The CLAS-EG2 experiment, conducted on various types of nuclear targets, has provided a unique opportunity to measure a wide range of nuclear medium variables, such as hadronic multiplicity ratios, transverse momentum broadening, and correlation functions. These measurements offer a valuable opportunity to gain a comprehensive understanding of the hadronization phenomena within the nuclear medium.

• A new CLAS12-RGE experiment, scheduled for 2024 and 2025, aims to build upon the previous results by extending the study to a wider kinematic range and increasing the range of hadron species with higher statistical significance.

Remark:

• The program will benefit significantly from the future EIC and also from the potential JLab upgrade to 20 GeV.