IN MATTER AND IN THE VACUUM

USING ATOMIC NUCLEI AS SPATIAL ANALYZERS

WILL BROOKS
UNIVERSIDAD TÉCNICA FEDERICO SANTA MARÍA, VALPARAÍSO, CHILE

Spatial and Momentum Tomography of Hadrons and Nuclei
INT Program INT-17-3 Week 3
September 2017
OUTLINE

WHY COLOR PROPAGATION IS INTERESTING

SPACE-TIME PROPERTIES OF SIDIS

THE BROOKS-LOPEZ GEOMETRICAL MODEL OF SIDIS ON NUCLEI

MEASUREMENTS: HERMES, JLAB, LHC

FUTURE PROSPECTS: JLAB, LHC, EIC
COLOR PROPAGATION: WHY IS IT INTERESTING?

RESTORATION OF COLOR NEUTRALITY IN HIGH ENERGY INTERACTIONS IS DYNAMICAL ENFORCEMENT OF CONFINEMENT

PRECISION PQCD RELIES ON THE CONCEPT OF FACTORIZATION

FUNDAMENTAL STRONG INTERACTION THERMODYNAMICS

NON-ADIABATIC COLOR DYNAMICS: QUANTUM COLOR FLUCTUATIONS
Terminology!

*Production length and production time:* The time or distance required for a colored system to evolve into a color singlet system. Historical term; can be estimated in models. A “colored system” can be a quark, a gluon, a color dipole, etc.

*Color lifetime, lifetime of highly virtual quark:* Means the same thing as “production time”
HIGHLIGHTS OF RESULTS I WILL SHOW

COLOR LIFETIME (COLD MATTER AND VACUUM)

CONSTRAINTS ON FUNCTIONAL FORM OF COLOR LIFETIME

TIME DILATION OF COLOR LIFETIME

CONFIRMATION OF LUND STRING CONSTANT

PREDICTION: COLOR LIFETIME AT EIC ENERGIES

QUARK ENERGY LOSS IN COLD MATTER
Aims

Quark-Hadron Transition
Discover new fundamental features of hadronization
• Characteristic time distributions
• Mechanisms of color neutralization

Quark-Nucleus Interaction
Understand how color interacts within nuclei
• Partonic interactions with medium ("tomography")
  • energy loss in-medium: $\hat{e}$
  • transverse momentum broadening: $\hat{q}$

Method: struck quark from DIS probes nuclei of different sizes
Connection to Confinement

$V=0$ at $\sim 0.4$ fm
Connection to Confinement

$V(r)$

$V=0$ at $\sim 0.4$ fm

quenched QCD

full QCD

Coulomb part
Beyond $\sim 1$ fm the potential is irrelevant but confinement is still enforced.
FUNDAMENTAL QCD PROCESSES
(DIS, pQCD picture)

The production length is shown in yellow
FUNDAMENTAL QCD PROCESSES
(DIS, pQCD picture)

Partonic elastic scattering in medium

The production length is shown in yellow
FUNDAMENTAL QCD PROCESSES
(DIS, pQCD picture)

Partonic elastic scattering in medium

Gluon bremsstrahlung in vacuum and in medium

The production length is shown in yellow
FUNDAMENTAL QCD PROCESSES
(DIS, pQCD picture)

Partonic elastic scattering in medium

Gluon bremsstrahlung in vacuum and in medium

Color neutralization

The production length is shown in yellow
FUNDAMENTAL QCD PROCESSES
(DIS, pQCD picture)

Partonic elastic scattering in medium

Gluon bremsstrahlung in vacuum and in medium

Color neutralization

Hadron formation

The production length is shown in yellow
Comparison of Color Propagation in Three Processes

DIS

D-Y

RHI Collisions

cold QCD matter

hot QCD matter
Comparison of Color Propagation in Three Processes

- DIS
- D-Y
- RHI Collisions
By comparing $p_T$ broadening and hadron attenuation in nuclei of different sizes, one can measure the *length* of the color propagation process (fm scale)
Observable: $p_T$ broadening

$$\Delta p_T^2 \equiv \langle p_T^2 \rangle_A - \langle p_T^2 \rangle_D$$

$p_T$ broadening is a tool: sample the gluon field using a colored probe:

$$\Delta p_T^2 \propto G(x, Q^2) \rho L$$

and radiative energy loss:

$$- \frac{dE}{dx} = \frac{\alpha_s N_c}{4} \Delta p_T^2$$
**pt broadening data - Drell-Yan and SIDIS**

\[ \Delta p_T^2 = \langle p_T^2 \rangle_A - \langle p_T^2 \rangle_D \]

- New, precision data with identified hadrons!
- **CLAS** $\pi^+$: 81 four-dimensional bins in $Q^2$, $\nu$, $z_h$, and $A$
- Intriguing *saturation*: production length or something else?
**p_T broadening data - Drell-Yan and SIDIS**

\[ \Delta p_T^2 = \langle p_T^2 \rangle_A - \langle p_T^2 \rangle_D \]

- New, precision data with identified hadrons!
- CLAS \( \pi^+ \): 81 four-dimensional bins in \( Q^2, \nu, z_h, \) and \( A \)
- Intriguing *saturation*: production length or something else?

---

Observe saturation of \( p_T \) broadening with system size at low energies.
Production Time Extraction - Geometrical Effects

Quark Path Length * Nuclear Density vs. $A^{1/3}$

- $L_p = 20$ fm
- $L_p = 5$ fm
- $L_p = 3$ fm
- $L_p = 2$ fm
- $L_p = 1$ fm
- $L_p = 0.5$ fm

Mass number to the 1/3 power ($A^{1/3}$) vs. Quark Path Length * Nuclear Density
Production Time Extraction - Geometrical Effects

Quark Path Length * Nuclear Density vs. $A^{1/3}$

- $L_p = 20$ fm
- $L_p = 5$ fm
- $L_p = 3$ fm
- $L_p = 2$ fm
- $L_p = 1$ fm
- $L_p = 0.5$ fm

Graph shows the relationship between Quark Path Length * Nuclear Density and Mass number to the $1/3$ power ($A^{1/3}$).
Production Time Extraction - Geometrical Effects

Quark Path Length * Nuclear Density vs. $A^{1/3}$

- $L_p = 20$ fm
- $L_p = 5$ fm
- $L_p = 3$ fm
- $L_p = 2$ fm
- $L_p = 1$ fm
- $L_p = 0.5$ fm
Production Time Extraction - Geometrical Effects

Quark Path Length * Nuclear Density vs. $A^{1/3}$

- $L_p = 20$ fm
- $L_p = 5$ fm
- $L_p = 3$ fm
- $L_p = 2$ fm
- $L_p = 1$ fm
- $L_p = 0.5$ fm

Mass number to the $1/3$ power ($A^{1/3}$)
Production Time Extraction - Geometrical Effects

Quark Path Length * Nuclear Density vs. $A^{1/3}$

Fits of Z-Scaled Broadening vs. $A^{1/3}$

JLab/CLAS preliminary
Data from CLAS6 and CLAS12 will provide the ultimate low-$\nu$ studies in up to 4-fold differential multiplicity ratios. EIC will have overlap and will provide the crucial high-$\nu$ studies.

CLAS6: $\pi^+$ ($K^0$, $\pi^0$, $\pi^-$)
Lund String Model (~1983)

Remarkably successful model, foundational tool in HEP

- Alternative physical picture to pQCD: emission of many gluons in vacuum, string as an average; quantitative
- Successful, but few connections to fundamental QCD
- We can compare some of our results to the Lund String Model, and other results to pQCD
Richard P. Feynman - Nobel Lecture
Nobel Lecture, December 11, 1965

The Development of the Space-Time View of Quantum Electrodynamics


A Future Nobel Prize to a theorist for Space-Time View of QCD?
Space-time characteristics of the struck quark

Assume: Single-photon exchange, no quark-pair production

“JLab” example: $Q^2 = 3 \text{ GeV}^2$, $\nu = 3 \text{ GeV}$. ($x_{Bj} \sim 0.5$)

Struck quark absorbs virtual photon energy $\nu$ and momentum $p_{\gamma^*} = |\vec{p}_{\gamma^*}| = \sqrt{\nu^2 - Q^2}$.

- Neglect any initial momentum/mass of quark
- Immediately after the interaction, quark mass $m_q = Q = \sqrt{Q^2}$.
- Gamma factor is therefore $\gamma = \nu/Q$, beta is $\beta = p_{\gamma^*}/\nu$.

JLab example: $\gamma = 1.73$, $\beta = 0.82$

Rigorous? $\gamma$, $\beta$ allow:
1. extrapolations to EIC kinematics,
2. test of time dilation in CLAS fits, and
3. direct comparison between JLab and HERMES fits
Space-time characteristics of the struck quark, cont’d

Comments on terminology and conceptual consequences in space-time physics

In momentum space, the LHC has typical energies that are \(4000\) times greater than at JLab. It appears totally different.

In \(time\) space the LHC has \(<20\%\) faster times (e.g. of interacting parton) than at JLab. Almost the same.

We loosely use expressions like “frozen during the interaction” and “fast quarks”. These ideas are only approximations, with limited validity. The interaction time, even for hard interactions, is finite, and not always small compared to the system size of 1 fm/c.

Space-time view of factorization
Extracting characteristic times from HERMES and CLAS $\pi^+$ data using the Brooks-Lopez Geometric Model
HERMES Study - Observables

Multiplicity ratio

\[ R_M^{h}(Q^2, \nu, z, p_T) \equiv \frac{1}{N_e(Q^2, \nu)} \cdot \frac{N_h(Q^2, \nu, z, p_T)|_A}{N_h(Q^2, \nu, z, p_T)|_p} \]

\( p_T \) broadening

\[ \Delta p_T^2(Q^2, \nu, z) \equiv \langle p_T^2(Q^2, \nu, z)\rangle |_A - \langle p_T^2(Q^2, \nu, z)\rangle |_p \]

We fit both observables simultaneously
B-L Geometric model description I

- Propagating quark causes $p_T$ broadening of final hadron
- Propagating (pre-)hadron “disappears” when it undergoes an inelastic interaction with cross section $\sigma$
- Implemented as Monte Carlo calculation in $x, y, z, L_p$
- Simultaneous fit of $p_T$ broadening and multiplicity ratio
- Realistic nuclear density, integrated along path

Path of quark is divided into “partonic phase” and “hadronic phase”
Baseline Model ("BL") implemented with 3 parameters:

1. **q-hat** parameter (transport coefficient) that sets the scale of $p_T$ broadening

2. Production length $\langle L_p \rangle$: distance over which $p_T$ broadening and energy loss occur. Assumed exponential form.

3. **Cross section** for prehadron to interact with nucleus.
B-L Geometric model description III

\[ \langle \Delta p_T^2 \rangle = \langle \hat{q}_0 \int_{z=z_0}^{z=z_0+L_p^*} \rho(x_0, y_0, z) \, dz \rangle_{x_0, y_0, z_0, L_p} \]

L_p is distributed as exponential

x_0, y_0, z_0 thrown uniformly in sphere, weighted by \( \rho(x, y, z) \)

\( L_p^* = L_p \) except where truncated by integration sphere

\[ \langle R_M \rangle = \langle \exp(-\sigma \int_{z=z_0+L_p}^{z=z_{\text{max}}} \rho(x, y, z) \, dx \, dy \, dz) \rangle_{x_0, y_0, z_0, L_p} \]

The above are computed sequentially (same \( x_0, y_0, z_0, L_p \))

Data in \((x, Q^2, z)\) bin: fitted to model, 3 parameters: \( \hat{q}_0, \langle L_p \rangle, \sigma \)

No dynamical information is assumed; it emerges from fit

Systematic errors: 3% for multiplicity ratio, 4% for \( p_T \) broadening
Comment on the B-L model

I believe that studies of this kind can be carried out at the same level of validity as the estimation of centrality in heavy ion collisions.

This model has the same foundation as the well-known “Glauber Model” used to estimate centrality in heavy ion collisions: the spatial mass distribution of protons and neutrons in the nucleus.

1. Plot showing $\Delta <P^2> (\text{GeV}^2)$ with data points and error bars.
2. Plot showing $\chi^2/\text{DOF}$ with different data sets.
3. Plot showing $R_m$ with data points and error bars.
4. Plot showing $L_p$ with data points and error bars.

Graphs with legend indicating data points for different fits and subtractions.


Graphs with legend indicating data points for different fits and subtractions.
Fit of HERMES $L_p$ results to Lund Model form

A fit of our HERMES results to the Lund model form

This is a strong validation of our model

We recover the known value of the string constant completely independently!

Light cone Lund String Model form for lab frame:

$$l_p = \frac{1}{2\mathcal{K}} \cdot \left( M_p + \nu + \sqrt{\nu^2 + Q^2 - 2 \cdot \nu \cdot z'} \right)$$
HERMES data analysis: exploring potential nuclear dependence of production time, and extrapolation to the vacuum

\[ L_p(A) = L_{p0} + c_1 A^{1/3} + c_2 A^{2/3} \]
The case with **free** $L_{p0}$, $c_1$ and $c_2$

We see a strong fit correlation between $L_p$ and $c_1$.

Therefore, in the next slide we fix $c_1 = 0$

(BL30 model variant)
The case with free $L_{p0}$ and $c_2$, and fixed $c_1=0$

Extrapolation to vacuum: $A=0$

Suggests vacuum $L_p$ is smaller for low $z$, ~unchanged at high $z$

Uncertainties are large in this study (HERMES data). A future JLab study may be better constrained.
Conclusion: good evidence for the following functional form. The vacuum term \( L_{p0} \) is determined, but with large uncertainties. There are hints that may help us to understand color propagation mechanisms at lower and higher \( z_h \). The JLab data should allow a more precise study.

\[
L_p(A) = L_{p0} + c_2 A^{2/3}
\]
HERMES data analysis: comparison of two possible functional forms of the production length distributions: \textit{exponential} and \textit{fixed}(delta function)
The fit has some sensitivity to the functional form of the production length. More comments in upcoming slides.
Color lifetime extraction: B-L model applied to CLAS 5 GeV data
Color lifetime extraction: B-L model applied to CLAS 5 GeV data

\( \chi^2/\text{dof} \) vs. \( z \)

Model with 3 parameters describes data in range 0.2<z<0.9 rather well.

Suggests that its validity can extend beyond the struck quark to include secondary quarks.

With reasonable requirements, more than 100 bins in \( Q^2, \nu, z \) with \( \chi^2/\text{dof} < 3 \)
Example of fit (one of 150 bins in x, \(Q^2\), and z)

\[
<x>=0.166, \quad <Q^2>=1.17 \text{ GeV}^2, \quad (<\nu>=3.76 \text{ GeV}), \quad <z>=0.445
\]

\[L_p=1.8\pm0.4 \text{ fm}\]

\[\chi^2/\text{dof} = 0.5\]

Simultaneous fit *couples* \(p_T\) broadening to multiplicity ratio
Three possible distributions of production time
Three possible distributions of production time

Time distribution of the hard interaction

Production time (fm/c)
Three possible distributions of production time

- Non-fluctuating “fixed” production time
- Well-separated from the hard interaction
  “Hadronization happens much later”
Three possible distributions of production time

Exponential production time
Intuitively plausible
Partially inconsistent with QCD factorization
Three possible distributions of production time

- Modified-exponential production time distribution
- More consistent with QCD factorization
Three possible distributions of production time

This can be studied experimentally!
Effect of production length distribution on $p_T$ broadening

- **Fixed production time**
- **Exponential production time distribution**
- **QCD factorization**
  - Relevance at high energy
  - Relevance to EIC!
Tests of exponential distribution hypothesis for quark lifetime

CLAS Exploratory Study with 5 GeV Data

Exponential distribution of quark lifetime

103 points, chisquared=69.2, chisq/dof = 0.685  MEDIUM event selection.

<table>
<thead>
<tr>
<th>NO.</th>
<th>NAME</th>
<th>VALUE</th>
<th>ERROR</th>
<th>SIZE</th>
<th>DERIVATIVE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>p0</td>
<td>1.07864e+00</td>
<td>4.83476e-01</td>
<td>-0.00000e+00</td>
<td>6.52690e-07</td>
</tr>
<tr>
<td>2</td>
<td>p1</td>
<td>9.33423e-01</td>
<td>2.45714e-01</td>
<td>2.45714e-01</td>
<td>7.34350e-11</td>
</tr>
</tbody>
</table>

Single value of quark lifetime

88 points, chisquared=289.5, chisq/dof = 3.36  MEDIUM event selection.

<table>
<thead>
<tr>
<th>NO.</th>
<th>NAME</th>
<th>VALUE</th>
<th>ERROR</th>
<th>SIZE</th>
<th>DERIVATIVE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>p0</td>
<td>1.95920e+00</td>
<td>2.75776e-01</td>
<td>-0.00000e+00</td>
<td>8.75252e-07</td>
</tr>
<tr>
<td>2</td>
<td>p1</td>
<td>3.95062e-01</td>
<td>1.37012e-01</td>
<td>1.37012e-01</td>
<td>-3.09899e-10</td>
</tr>
</tbody>
</table>

The data clearly prefer an exponential distribution
CLAS Exploratory Analysis ≈ Lund String Model
CLAS Exploratory Analysis $\approx$ Lund String Model

\[
\frac{L_p(Q^2, v, z_h)}{L_p(\text{LSM})}
\]

$L_p(Q^2, v, z_h)$ from CLAS analysis similar to values from the Lund String Model for $z_h > 0.4$
CLAS Exploratory Analysis \( \approx \) Lund String Model

\[
\frac{L_p(Q^2, \nu, z_h)}{L_p(\text{LSM})}
\]

100 bins in \( Q^2, \nu, z_h \) CLAS exploratory analysis

\( L_p (Q^2, \nu, z_h) \) from CLAS analysis similar to values from the Lund String Model for \( z_h > 0.4 \)
Time dilation test of the results

production time demonstrates time dilation

average slope of $L_p$ vs $\gamma$ is $1 \pm 0.1$!
Extrapolation from HERMES to EIC and CLAS

Using the prescription $\gamma = \nu/Q$, $\beta = p_{\gamma^*}/\nu$, we can extrapolate:

<table>
<thead>
<tr>
<th>$Q^2$</th>
<th>$\nu$</th>
<th>$\beta^*\gamma$</th>
<th>$l_p, \ z=0.32$</th>
<th>$l_p, \ z=0.53$</th>
<th>$l_p, \ z=0.75$</th>
<th>$l_p, \ z=0.94$</th>
<th>Experiment</th>
<th>$x$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.40</td>
<td>14.50</td>
<td>9.31</td>
<td>8.57</td>
<td></td>
<td></td>
<td></td>
<td>HERMES</td>
<td>0.09</td>
</tr>
<tr>
<td>2.40</td>
<td>13.10</td>
<td>8.40</td>
<td>6.39</td>
<td></td>
<td></td>
<td></td>
<td>HERMES</td>
<td>0.10</td>
</tr>
<tr>
<td>2.40</td>
<td>12.40</td>
<td>7.94</td>
<td></td>
<td>4.63</td>
<td></td>
<td></td>
<td>HERMES</td>
<td>0.10</td>
</tr>
<tr>
<td>2.30</td>
<td>10.80</td>
<td>7.05</td>
<td></td>
<td></td>
<td>2.40</td>
<td></td>
<td>HERMES</td>
<td>0.11</td>
</tr>
<tr>
<td>3.00</td>
<td>4.00</td>
<td>2.08</td>
<td>1.92</td>
<td>1.58</td>
<td>1.21</td>
<td>0.71</td>
<td>CLAS</td>
<td>0.40</td>
</tr>
<tr>
<td>7.00</td>
<td>7.00</td>
<td>2.45</td>
<td>2.26</td>
<td>1.86</td>
<td>1.43</td>
<td>0.83</td>
<td>CLAS12</td>
<td>0.53</td>
</tr>
<tr>
<td>1.00</td>
<td>4.00</td>
<td>3.87</td>
<td>3.57</td>
<td>2.95</td>
<td>2.26</td>
<td>1.32</td>
<td>CLAS</td>
<td>0.13</td>
</tr>
<tr>
<td>2.00</td>
<td>9.00</td>
<td>6.28</td>
<td>5.79</td>
<td>4.78</td>
<td>3.66</td>
<td>2.14</td>
<td>CLAS12</td>
<td>0.12</td>
</tr>
<tr>
<td>12.00</td>
<td>32.50</td>
<td>9.33</td>
<td>8.59</td>
<td>7.10</td>
<td>5.44</td>
<td>3.18</td>
<td>EIC</td>
<td>0.20</td>
</tr>
<tr>
<td>8.00</td>
<td>37.50</td>
<td>13.22</td>
<td>12.17</td>
<td>10.06</td>
<td>7.71</td>
<td>4.50</td>
<td>EIC</td>
<td>0.11</td>
</tr>
<tr>
<td>45.00</td>
<td>140.00</td>
<td>20.85</td>
<td>19.20</td>
<td>15.86</td>
<td>12.15</td>
<td>7.10</td>
<td>EIC</td>
<td>0.17</td>
</tr>
<tr>
<td>27.00</td>
<td>150.00</td>
<td>28.85</td>
<td>26.57</td>
<td>21.96</td>
<td>16.82</td>
<td>9.82</td>
<td>EIC</td>
<td>0.10</td>
</tr>
</tbody>
</table>

At EIC we can study a wide range of production lengths!
Extrapolation of HERMES fits to EIC kinematics - two different methods

Fair agreement for several kinematic bins

Largest divergence at low z and high \( \nu \) - target fragmentation region

Wide range of production lengths shows that an interesting program of measurements will be feasible at EIC
The Breakthrough Potential of EIC
The Breakthrough Potential of EIC

• Solving the heavy quark puzzle via heavy meson production (see following slides)
The Breakthrough Potential of EIC

• Solving the heavy quark puzzle via heavy meson production (see following slides)

• Precision time dilation tests over a wide range in ν
The Breakthrough Potential of EIC

- Solving the heavy quark puzzle via heavy meson production (see following slides)
- Precision time dilation tests over a wide range in $\nu$
- pQCD enhanced non-linear broadening (see following)
The Breakthrough Potential of EIC

- Solving the heavy quark puzzle via heavy meson production (see following slides)
- Precision time dilation tests over a wide range in $\nu$
- pQCD enhanced non-linear broadening (see following)
- Flavor dependencies of formed hadrons
The Breakthrough Potential of EIC

• Solving the heavy quark puzzle via heavy meson production (see following slides)
• Precision time dilation tests over a wide range in $\nu$
• pQCD enhanced non-linear broadening (see following)
• Flavor dependencies of formed hadrons
• $L_p$ distribution determination
In addition, the EIC could for the first time reliably quantify the nuclear gluon distribution with a wider kinematic reach in both functions, following a non-trivial function of Bjorken $x$.

The dramatic difference in light quark and heavy quark production at all energies due to very different photon energies indicates that the hadron was formed inside the nucleus, like in the bottom sketch of Fig. zs. The mesons are formed outside of the nucleus, as shown in the top sketch of Fig. zs, by the virtual photon taken by the observed meson. The calculation of red lines and blue symbols assumes the mesons are formed outside of the nucleus, as shown in the top sketch of Fig. zs, and the solid line is an immediate consequence of the difference in the suppression between the square symbols and solid lines.

The enhancement of the ratio is due to the virtual photon. The enhancement of the ratio is due to the virtual photon. The enhancement of the ratio is due to the virtual photon. The enhancement of the ratio is due to the virtual photon. The enhancement of the ratio is due to the virtual photon.

This figure shows the multiplicity ratio of pions compared to heavy mesons. The multiplicity ratio is integrated over different photon energies. The ratio of semi-inclusive cross sections for producing a pion (red), composed of light quarks, and a single D meson (blue) is shown. The multiplicity ratio is compared to s and c quark energy loss in D mesons. The comparison shows the suppression of pion production in electron-lead collisions compared to electron-deuteron collisions.

Access to very strong, unique light quark energy loss signature via D$^0$ heavy meson. Compare to s and c quark energy loss in D$s^+$.
NEW THEORY DEVELOPMENT


- **Old**: multiple scattering $\rightarrow$ gluon emission, $\equiv$ energy loss

\[-\frac{dE}{dx} = \frac{\alpha_s N_c}{4} \Delta p_T^2 \propto \hat{q} L\]

- **New**: this energy loss creates *more* $p_T$ broadening

\[\Delta p_T^2 = \frac{\alpha_s N_c}{8\pi} \hat{q} L \left(\ln^2 \frac{L}{l_0^2}\right) + \ldots\]

$\rightarrow$ predicts a non-linear relationship between $p_T$ broadening and $L$. We can look for this at EIC!
pQCD description of quark energy loss on $p_T$ broadening

![Graph showing $p_T$ broadening as a function of nuclear size](image)
**DIS channels:** *stable* hadrons, accessible with 11 GeV JLab future experiment PR12-06-117

<table>
<thead>
<tr>
<th>meson</th>
<th>c(T)</th>
<th>mass</th>
<th>flavor content</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\pi^0)</td>
<td>25 nm</td>
<td>0.13</td>
<td>ud</td>
</tr>
<tr>
<td>(\pi^+, \pi^-)</td>
<td>7.8 m</td>
<td>0.14</td>
<td>ud</td>
</tr>
<tr>
<td>(\eta)</td>
<td>170 pm</td>
<td>0.55</td>
<td>uds</td>
</tr>
<tr>
<td>(\omega)</td>
<td>23 fm</td>
<td>0.78</td>
<td>uds</td>
</tr>
<tr>
<td>(\eta')</td>
<td>0.98 pm</td>
<td>0.96</td>
<td>uds</td>
</tr>
<tr>
<td>(\varphi)</td>
<td>44 fm</td>
<td>1</td>
<td>uds</td>
</tr>
<tr>
<td>f1</td>
<td>8 fm</td>
<td>1.3</td>
<td>uds</td>
</tr>
<tr>
<td>(K^0)</td>
<td>27 mm</td>
<td>0.5</td>
<td>ds</td>
</tr>
<tr>
<td>(K^+, K^-)</td>
<td>3.7 m</td>
<td>0.49</td>
<td>us</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>baryon</th>
<th>c(T)</th>
<th>mass</th>
<th>flavor content</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>stable</td>
<td>0.94</td>
<td>ud</td>
</tr>
<tr>
<td>(\bar{p})</td>
<td>stable</td>
<td>0.94</td>
<td>ud</td>
</tr>
<tr>
<td>(\Lambda)</td>
<td>79 mm</td>
<td>1.1</td>
<td>uds</td>
</tr>
<tr>
<td>(\Lambda(1520))</td>
<td>13 fm</td>
<td>1.5</td>
<td>uds</td>
</tr>
<tr>
<td>(\Sigma^+)</td>
<td>24 mm</td>
<td>1.2</td>
<td>us</td>
</tr>
<tr>
<td>(\Sigma^-)</td>
<td>44 mm</td>
<td>1.2</td>
<td>ds</td>
</tr>
<tr>
<td>(\Sigma^0)</td>
<td>22 pm</td>
<td>1.2</td>
<td>uds</td>
</tr>
<tr>
<td>(\Xi^0)</td>
<td>87 mm</td>
<td>1.3</td>
<td>us</td>
</tr>
<tr>
<td>(\Xi^-)</td>
<td>49 mm</td>
<td>1.3</td>
<td>ds</td>
</tr>
</tbody>
</table>
**HERMES**

<table>
<thead>
<tr>
<th>meson</th>
<th>$cT$</th>
<th>mass</th>
<th>flavor content</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^0$</td>
<td>25 nm</td>
<td>0.13</td>
<td>ud</td>
</tr>
<tr>
<td>$\pi^+$, $\pi^-$</td>
<td>7.8 m</td>
<td>0.14</td>
<td>ud</td>
</tr>
<tr>
<td>$\eta$</td>
<td>170 pm</td>
<td>0.55</td>
<td>uds</td>
</tr>
<tr>
<td>$\omega$</td>
<td>23 fm</td>
<td>0.78</td>
<td>uds</td>
</tr>
<tr>
<td>$\eta'$</td>
<td>0.98 pm</td>
<td>0.96</td>
<td>uds</td>
</tr>
<tr>
<td>$\varphi$</td>
<td>44 fm</td>
<td>1</td>
<td>uds</td>
</tr>
<tr>
<td>$f_1$</td>
<td>8 fm</td>
<td>1.3</td>
<td>uds</td>
</tr>
<tr>
<td>$K^0$</td>
<td>27 mm</td>
<td>0.5</td>
<td>ds</td>
</tr>
<tr>
<td>$K^+$, $K^-$</td>
<td>3.7 m</td>
<td>0.49</td>
<td>us</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>baryon</th>
<th>$cT$</th>
<th>mass</th>
<th>flavor content</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$</td>
<td>stable</td>
<td>0.94</td>
<td>ud</td>
</tr>
<tr>
<td>$\bar{p}$</td>
<td>stable</td>
<td>0.94</td>
<td>ud</td>
</tr>
<tr>
<td>$\Lambda$</td>
<td>79 mm</td>
<td>1.1</td>
<td>uds</td>
</tr>
<tr>
<td>$\Lambda(1520)$</td>
<td>13 fm</td>
<td>1.5</td>
<td>uds</td>
</tr>
<tr>
<td>$\Sigma^+$</td>
<td>24 mm</td>
<td>1.2</td>
<td>us</td>
</tr>
<tr>
<td>$\Sigma^-$</td>
<td>44 mm</td>
<td>1.2</td>
<td>ds</td>
</tr>
<tr>
<td>$\Sigma^0$</td>
<td>22 pm</td>
<td>1.2</td>
<td>uds</td>
</tr>
<tr>
<td>$\Xi^0$</td>
<td>87 mm</td>
<td>1.3</td>
<td>us</td>
</tr>
<tr>
<td>$\Xi^-$</td>
<td>49 mm</td>
<td>1.3</td>
<td>ds</td>
</tr>
</tbody>
</table>

DIS channels: *stable* hadrons, accessible with 11 GeV JLab future experiment PR12-06-117
DIS channels: *stable* hadrons, accessible with 11 GeV
JLab future experiment PR12-06-117

Actively underway with existing 5 GeV data

**HERMES**

<table>
<thead>
<tr>
<th>meson</th>
<th>cτ</th>
<th>mass</th>
<th>flavor content</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^0$</td>
<td>25 nm</td>
<td>0.13</td>
<td>ud</td>
</tr>
<tr>
<td>$\pi^+, \pi^-$</td>
<td>7.8 m</td>
<td>0.14</td>
<td>ud</td>
</tr>
<tr>
<td>$\eta$</td>
<td>170 pm</td>
<td>0.55</td>
<td>uds</td>
</tr>
<tr>
<td>$\omega$</td>
<td>23 fm</td>
<td>0.78</td>
<td>uds</td>
</tr>
<tr>
<td>$\eta'$</td>
<td>0.98 pm</td>
<td>0.96</td>
<td>uds</td>
</tr>
<tr>
<td>$\varphi$</td>
<td>44 fm</td>
<td>1</td>
<td>uds</td>
</tr>
<tr>
<td>f1</td>
<td>8 fm</td>
<td>1.3</td>
<td>uds</td>
</tr>
<tr>
<td>$K^0$</td>
<td>27 mm</td>
<td>0.5</td>
<td>ds</td>
</tr>
<tr>
<td>$K^+, K^-$</td>
<td>3.7 m</td>
<td>0.49</td>
<td>us</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>baryon</th>
<th>cτ</th>
<th>mass</th>
<th>flavor content</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$</td>
<td>stable</td>
<td>0.94</td>
<td>ud</td>
</tr>
<tr>
<td>$\bar{p}$</td>
<td>stable</td>
<td>0.94</td>
<td>ud</td>
</tr>
<tr>
<td>$\Lambda$</td>
<td>79 mm</td>
<td>1.1</td>
<td>uds</td>
</tr>
<tr>
<td>$\Lambda(1520)$</td>
<td>13 fm</td>
<td>1.5</td>
<td>uds</td>
</tr>
<tr>
<td>$\Sigma^+$</td>
<td>24 mm</td>
<td>1.2</td>
<td>us</td>
</tr>
<tr>
<td>$\Sigma^-$</td>
<td>44 mm</td>
<td>1.2</td>
<td>ds</td>
</tr>
<tr>
<td>$\Sigma^0$</td>
<td>22 pm</td>
<td>1.2</td>
<td>uds</td>
</tr>
<tr>
<td>$\Xi^0$</td>
<td>87 mm</td>
<td>1.3</td>
<td>us</td>
</tr>
<tr>
<td>$\Xi^-$</td>
<td>49 mm</td>
<td>1.3</td>
<td>ds</td>
</tr>
</tbody>
</table>
### DIS channels: stable hadrons, accessible with 11 GeV JLab future experiment PR12-06-117

Actively underway with existing 5 GeV data

**HERMES**

<table>
<thead>
<tr>
<th>meson</th>
<th>$c\tau$</th>
<th>mass</th>
<th>flavor content</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^0$</td>
<td>25 nm</td>
<td>0.13</td>
<td>ud</td>
</tr>
<tr>
<td>$\pi^+$, $\pi^-$</td>
<td>7.8 m</td>
<td>0.14</td>
<td>ud</td>
</tr>
<tr>
<td>$\eta$</td>
<td>170 pm</td>
<td>0.55</td>
<td>uds</td>
</tr>
<tr>
<td>$\omega$</td>
<td>23 fm</td>
<td>0.76</td>
<td>uds</td>
</tr>
<tr>
<td>$\eta'$</td>
<td>0.98 pm</td>
<td>0.96</td>
<td>uds</td>
</tr>
<tr>
<td>$\phi$</td>
<td>44 fm</td>
<td>1</td>
<td>uds</td>
</tr>
<tr>
<td>$f_1$</td>
<td>8 fm</td>
<td>1.3</td>
<td>uds</td>
</tr>
<tr>
<td>$K^0$</td>
<td>27 mm</td>
<td>0.5</td>
<td>ds</td>
</tr>
<tr>
<td>$K^+$, $K^-$</td>
<td>3.7 m</td>
<td>0.49</td>
<td>us</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>baryon</th>
<th>$c\tau$</th>
<th>mass</th>
<th>flavor content</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$</td>
<td>stable</td>
<td>0.94</td>
<td>ud</td>
</tr>
<tr>
<td>$\Sigma^+$</td>
<td>24 mm</td>
<td>1.2</td>
<td>us</td>
</tr>
<tr>
<td>$\Sigma^-$</td>
<td>44 mm</td>
<td>1.2</td>
<td>ds</td>
</tr>
<tr>
<td>$\Xi^0$</td>
<td>22 pm</td>
<td>1.2</td>
<td>uds</td>
</tr>
<tr>
<td>$\Xi^+$, $\Xi^-$</td>
<td>87 mm</td>
<td>1.3</td>
<td>us</td>
</tr>
<tr>
<td>$\Lambda$</td>
<td>87 mm</td>
<td>1.3</td>
<td>ds</td>
</tr>
</tbody>
</table>

**EIC: heavy mesons and baryons; wide kinematic range!**
Study of $J/\psi \rightarrow \mu^+\mu^-$ and $\psi(2S) \rightarrow \mu^+\mu^-$ production with 2015 Pb+Pb data at $\sqrt{s_{_{NN}}} = 5.02$ TeV and pp data at $\sqrt{s} = 5.02$ TeV with the ATLAS detector.


Heavy quarks and fragile mesons similarly suppressed with centrality!
Direct measurement of quark energy loss

Collaboration: Miguel Arratia, Cristian Peña, Hayk Hakobyan, Sebastian Tapia, Oscar Aravena, René Rios, Gabriela Hamilton, WB
Parton energy loss in pQCD (BDMPS-Z) exhibits a critical system length $L_c$ and a critical energy $E_c$

\[ L < L_{\text{Critical}} \]
\[ \frac{dE}{dx} \propto L \hat{q} \]

\[ L > L_{\text{Critical}} \]
\[ \frac{dE}{dx} \propto \sqrt{E \hat{q}} \]

\[ L \]

Fixed $E$

Fixed $L$

\[ \Delta E \]

\[ E_c = 0.4 \cdot \left( \frac{L}{1 \text{ fm}} \right)^2 \text{ GeV} \]

\[ \Delta E_q = \frac{\alpha_s}{4} \Delta k_T^2 \cdot L = \frac{\alpha_s}{4} \hat{q} \cdot L^2 \]
How to *directly* measure quark energy loss?

- Energy loss: *independent of energy* for thin medium
- “Thin enough” depends on quark energy
- If energy loss is independent of energy, it will produce a *shift* of the energy spectrum, for higher energies.
- We can look for a *shift* of the Pb energy spectrum compared to that of the deuterium energy spectrum
Energy spectrum of $\pi^+$ produced in C, Fe, Pb compared to that of deuterium, normalized to unity, with energy shifted by $\Delta E$. Acceptance corrected.
Cut on $X_F > 0.1$ is applied
Consistent with simple energy shift + unchanged fragmentation.
The data is also selected in intervals, from 2.4 to 4.2 GeV in 0.2 GeV steps. The motivations for this is that (insert motivation!). The energy interval for the comparison is restricted to \( E < 2.5 \) GeV, to avoid (insert motivation!).

4. Corrections (space for description of acceptance, and radiation corrections).

5. Results.

The negative logarithm of the \( p \)-values obtained from the K-S test are presented as a function of \( E \) in Figure 1. This correspond to the interval \( 3.8 < \nu < 4 \) GeV. Data for the three heavy nuclei studied are presented as well as a constant line representing the value \( p = 0.05 \). The majority of the \( E \) values yield a \( p \)-value smaller than 0.05 (larger -log(\( p \))), and thus are rejected at 95% confidence level. All three curves have a well defined minimum which is taken as the nominal energy loss. These minimums are observed to be ordered, it takes the lowest value for Carbon data and the largest value for the Lead data. The shape of these curves is also driven by the statistics of the sample, which is the smallest for the Lead data.

---

Log of \( p \)-values of Kolmogorov-Smirnov test as a function of energy shift \( \Delta E \): carbon, iron, lead.

Dashed line corresponds to 95% confidence level
Table 1: Range of possible energy-loss (in MeV) obtained by Kolmogorov-Smirnov compatibility test between deuterium spectrum and shifted heavy nuclei spectrum. The results are presented in $\nu$ intervals and different nuclei. In some cases no allowed range is found.

<table>
<thead>
<tr>
<th>$\nu$/GeV</th>
<th>Carbon</th>
<th>Iron</th>
<th>Lead</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.4–2.6</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>2.6–2.8</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>2.8–3.0</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>3.0–3.2</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>3.2–3.4</td>
<td>20–35</td>
<td>—</td>
<td>75</td>
</tr>
<tr>
<td>3.4–3.6</td>
<td>10–25</td>
<td>50</td>
<td>70–85</td>
</tr>
<tr>
<td>3.6–3.8</td>
<td>10–25</td>
<td>55</td>
<td>50–70</td>
</tr>
<tr>
<td>3.8–4.0</td>
<td>5–25</td>
<td>40</td>
<td>45–65</td>
</tr>
<tr>
<td>4.0–4.2</td>
<td>5–10</td>
<td>35–40</td>
<td>50–65</td>
</tr>
</tbody>
</table>

Range of possible energy shift in MeV obtained by Kolmogorov-Smirnov test in $\nu$ intervals.
Approximately proportional to density, as expected. (fixed pathlength)
Supports the premise that what we measure is ~energy loss!
Direct Measurement of Quark Energy Loss in CLAS: Conclusions

• It is small in magnitude. Why?
  • Best explanation: \textit{short production time}
  • >500 MeV vs. 50 MeV in Pb

• It increases with nuclear size. Why?
  • Best explanation: \textit{average nuclear density increases}.
  • Rate of change of virtuality nearly the same in all nuclei, therefore:
    • Path length is short, \textasciitilde independent of nuclear size
    • Nuclear medium has little effect - simple to extrapolate to the vacuum case
Direct Measurement of Quark Energy Loss in CLAS: Extraction using a Dynamical Model
Oscar Aravena, Hayk Hakobyan, S. Peigne, WB

(a) 2D analysis in Lead
(b) 2D analysis in Lead Log Z representation

<table>
<thead>
<tr>
<th></th>
<th>$L$ (fm)</th>
<th>$\hat{q}$ (GeV/fm$^2$)</th>
<th>$\chi^2$/dof</th>
<th>$\omega_c$ GeV/fm$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>4.2</td>
<td>0.14</td>
<td>0.462963</td>
<td>1.23</td>
</tr>
<tr>
<td>Iron</td>
<td>3.5</td>
<td>0.14</td>
<td>2.31124</td>
<td>0.86</td>
</tr>
<tr>
<td>Lead</td>
<td>2.9</td>
<td>0.13</td>
<td>3.44176</td>
<td>0.55</td>
</tr>
</tbody>
</table>

O. Aravena, MSc Thesis (H. Hakobyan, advisor), UTFSM Valparaíso, 2017
\[ \omega_c = \frac{\mu^2 L^2}{\lambda_c} \]

\[ E_{\text{crit.}} = \frac{\mu^2 L^2}{\lambda} \]

\[ L_{\text{crit.}} = \sqrt{\frac{\lambda E}{\mu^2}} \]

Figure 3.4: Schematic representation of total induced energy loss as a function of the parton energy \( E \) (left) and total induced energy loss as a function of the medium size \( L \) (right).

\[ \lambda = \text{mean free path for multiple scattering} \]
Conclusions
Conclusions

- Completely new categories of physics studies - a broad and deep program of studies for the future.
Conclusions

• Completely new categories of physics studies - a broad and deep program of studies for the future.

• First direct measurement of quark energy loss
Conclusions

- Completely new categories of physics studies - a broad and deep program of studies for the future.

- First direct measurement of quark energy loss

- Extracting characteristic times: semi-inclusive DIS
  - HERMES data - we measure the production time, and independently obtain the Lund string constant of $1 \text{ GeV/fm}$
  - CLAS (exploratory) observation of time dilation, sensitivity to production length distribution form, comparison to HERMES results through Lorentz boost
  - Clear connections to confinement, QCD factorization, Electron Ion Collider, higher energies
Conclusions

- Completely new categories of physics studies - a broad and deep program of studies for the future.

- First direct measurement of quark energy loss

- Extracting characteristic times: semi-inclusive DIS
  - HERMES data - we measure the production time, and independently obtain the Lund string constant of 1 GeV/fm
  - CLAS (exploratory) observation of time dilation, sensitivity to production length distribution form, comparison to HERMES results through Lorentz boost
  - Clear connections to confinement, QCD factorization, Electron Ion Collider, higher energies

- Much more in future: 12 GeV and EIC:
  - Heavy quark puzzle; time dilation; pQCD enhanced broadening; flavor dependences; \( L_p \) distribution