A systematic approach to studying Quark Energy Loss in Nuclei using Positive Pions

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On behalf of the CLAS Collaboration

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1. Background and motivation
   - Motivation
   - Deep inelastic scattering
   - Hadronization
   - BDMPS prediction
   - Experimental setup

2. Data Analysis

3. Results

4. Conclusions

5. Further Work

Background and Motivation

- Our goal is to understand better the hadronization process, using nuclear size as a variable!
- Obtain a ’direct’ measurement of energy loss for a quark in the hadronization process.

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Deep inelastic scattering (DIS)

DIS probes the internal structure of nucleons by scattering high-energy leptons, revealing information about quarks and their interactions.

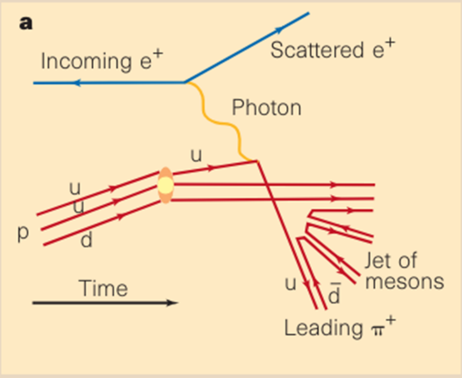

Figure 1: Miller, D. J. (1999). The undemocratic proton. Nature, 397(6719), 472473.

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Hadronization

Hadronization is the process by which the quark transforms into a hadron (in order to comply with color confinement).

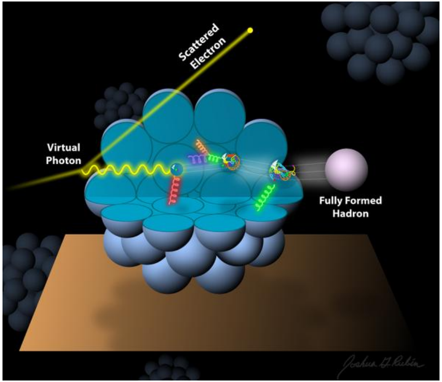

Figure 2: Illustration of hadronization in nuclei, picture by Joshua Rubin(2012)

BDMPS

One of the main results used in this work is for cold QCD matter the quark energy loss depends on nuclear length.

- R. Baier, Yu.L. Dokshitzer, A.H. Mueller, S. Peigné, D. Schiff - *Radiative energy loss of high energy quarks and gluons in a finite-volume quark-gluon plasma,*(1997)
- B. G. Zakharov - *Radiative energy loss of high energy quarks in finite-size nuclear matter and quark-gluon plasma* (1997)
- R. Baier, Yu.L. Dokshitzer, A.H. Mueller, S. Peigné, D. Schiff - *Radiative energy loss and* $P_\perp$*-broadening of high energy partons in nuclei,*(1997)
- R. Baier, Yu.L. Dokshitzer, A.H. Mueller, D. Schiff - *Medium-induced radiative energy loss; equivalence between the BDMPS and Zakharov formalisms* (1998)

Picturing our situation

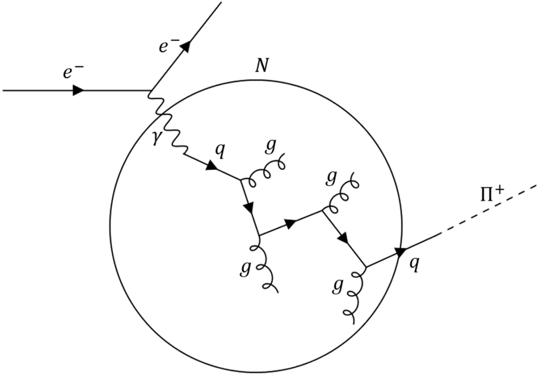

Figure 3: Schematic drawing of the entire process

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Experimental setup (CEBAF)

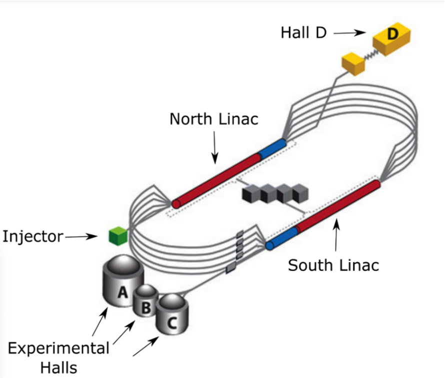
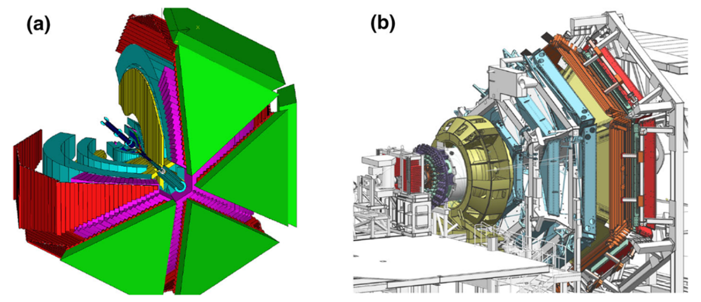


Figure 4: D. Turner, et al. SRF cavity instability detection with machine learning at CEBAF(2022)

CLAS (CEBAF large accelerator spectrometer)



Carman, D. S., et. al. "*Strong QCD Insights from Excited Nucleon Structure Studies with CLAS and CLAS12*" (2020)

Figure 5: Carman, D. S., et al. Strong QCD Insights from Excited Nucleon Structure Studies with CLAS and CLAS12 (2020)

Kinematic variables

- Q^2: 4-Momentum transferred (GeV^2)
- W^2: mass squared of the hadronic final state (GeV^2)
- X_B: Bjorken X, fraction of the momentum of the proton carried by the struck quark
- Y_B: Bjorken Y, fraction of the energy of the proton carried by the struck quark
- Z_h: virtual photon energy fraction carried by the measured hadron.
- ν: energy transferred by the lepton (GeV)
- P_T^2: hadron transverse momentum measured with regard to the virtual photon direction (GeV^2)
- Φ_{PQ}: angle between the leptonic plane and the hadronic plane (degrees)

Modified Feynman X

We introduced Modified Feynman X_F to distinguish between:

- Current Fragmentation Region (CFR): the particle were measuring(hadron) comes from the quark that was hit inside the nucleus (the nucleon).
- Target Fragmentation Region (TFR): the particle comes from the leftover bits of the target.

Modified Feynman X

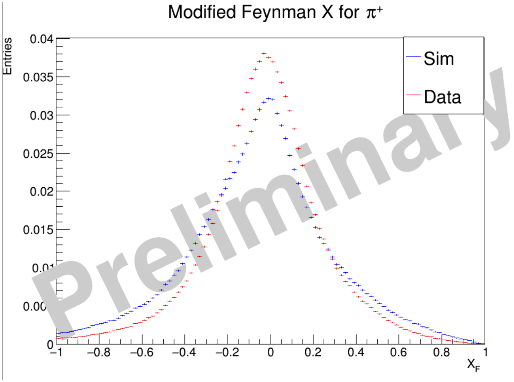


Figure 6: X_F comparison between simulated and preliminary data set for positive pions.

Modified Feynman X

The main goal by reducing fragmentation contribution is to ensure that we are using mostly hadrons from the struck quark. The cut $X_F > 0.1$ emphasizes the current fragmentation region.

Dynamical cut

This cut changes the shape of the energy distribution, in LAB frame X_F is defined as

$$X_F = \frac{2((\nu + m_p)\sqrt{P^2 - P_T^2} - \sqrt{Q^2 + \nu^2} Z_h \nu}{(\nu + m_N)\sqrt{(W^2 - m_N^2 + m_{\Pi^+}^2)^2 - 4W^2 * m_{\Pi^+}^2}} \tag{1}$$

Adding the energy shift dE (which we recognize as the quark energy loss)

$$X_F = \frac{2((\nu + m_p)\sqrt{(P + dE)^2 - (1 + (dE/P))^2 P_T^2} - \sqrt{Q^2 + \nu^2}(Z_h \nu + dE)}{(\nu + m_N)\sqrt{(W^2 - m_N^2 + m_{\Pi^+}^2)^2 - 4W^2 * m_{\Pi^+}^2}} \tag{2}$$

where M_p, M_n, M_{π^+} are the mass of proton, neutron and ion respectively.

Coulomb correction

In DIS experiments, a Coulomb correction is needed because the target nuclei's Coulomb field affects charged particles, especially at low energies (5 GeV). Produced field alters the momentum of incoming and scattered electrons and also impacts the particle.

Target	$dE(MeV)$
^{2}D	0
^{12}C	2.9
^{56}Fe	9.4
^{208}Pb	20.3

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2. Data Analysis
   - Kinematic variables
   - Modified Feynman X
   - Coulomb correction
   - Acceptance correction
   - Binning scheme
   - Kolmogorov-Smirnov test
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Acceptance correction

Applying a simulation factor to each bin in the experimental data corrects detector inefficiencies. For the CLAS detector, acceptance combines geometric acceptance with detector inefficiencies from drift chambers, scintillator counters, track reconstruction, and event selection. We introduce the acceptance factor A:

$$A = \frac{N_{rec}}{N_{gen}} \tag{3}$$

Where N_{rec} , N_{gen} are the number of entries for reconstructed and generated bin. The data are corrected by a weight $\omega = 1/A$.

Binning scheme

We define a binning scheme in order to correct the variables that do not directly affect the energy distribution.

Variables	Lower value	Upper value	Steps	Total Steps
Q^2	1.0	4.0	0.5	6
X_B	0.12	0.57	0.9	5
Φ_{PQ}	-180	180	30	12
P_T^2	0.0	1.0	0.2	5

avoidable regions

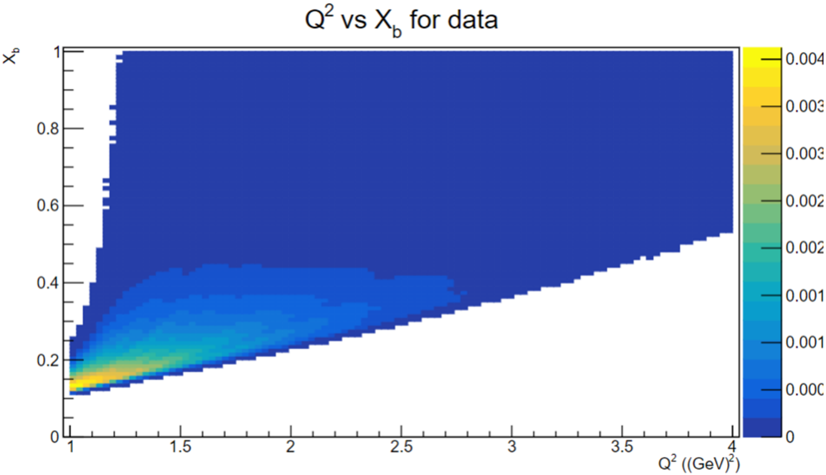

Figure 7: There are regions in which we have no events

Kolmogorov-Smirnov test

- The Kolmogorov-Smirnov test helps assess whether two datasets share the same underlying probability distribution.

- The P-value indicates the probability that the two datasets come from the same distribution.

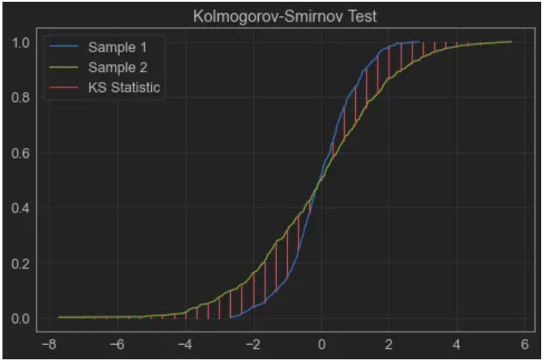

Figure 8: Example of two samples probability distribution, and the KS statistics

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   - Quark energy loss horizontal shift
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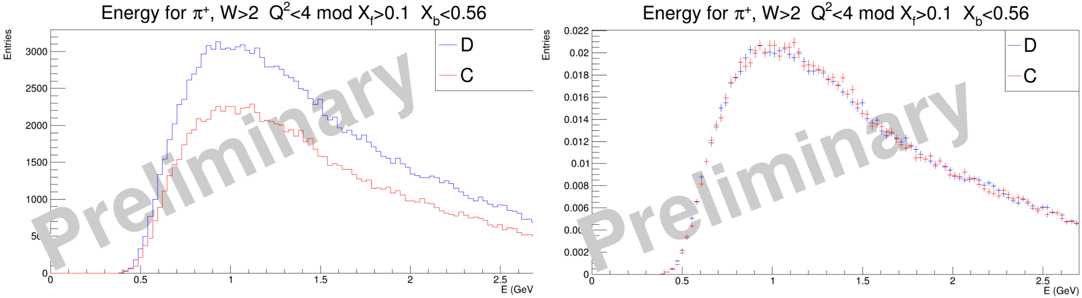
Normalization



Left: Energy distribution for π^+ in C and D.
Right: Normalized energy distribution.

Quark energy loss horizontal shift

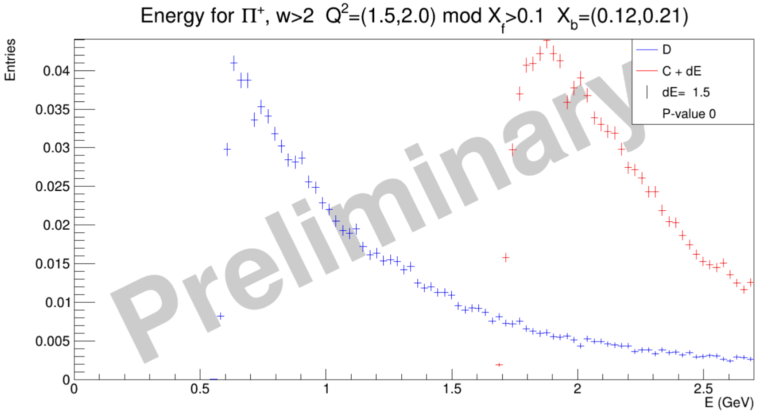
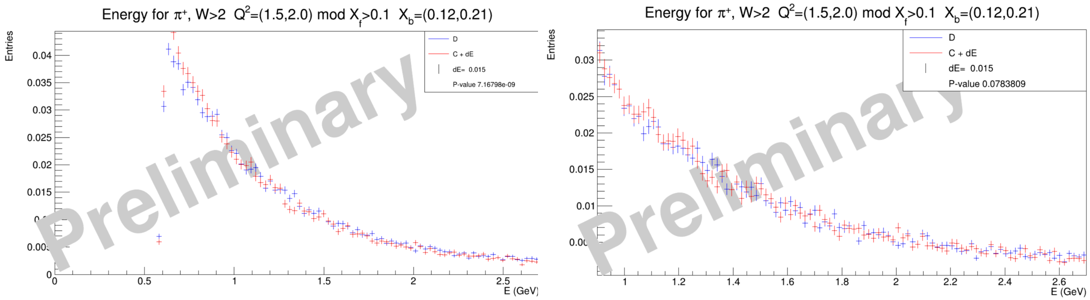


Figure 9: Example of high quark energy loss added in Carbon nuclei, we see that the quark energy loss corresponds to a shift in the π^+ energy distribution.

Estimating Quark energy loss



Examples on how the KS test depends on the selected energy range.

Conclusions

- Work with π^+.
- Introduce X_F to approximately identify π^+ produced outside the nuclei.
- Recognize an energy shift as the quark energy loss.
- Use KS-test to estimate the amount of quark energy loss.

Further Work

- Explore the concept of quark energy loss, particularly in associating the change of pion momentum with quarks. Investigate implications for two-pion events.
- Examine whether the fragmentation function, where a quark fragments into a pion, is significant for these studies. Are we overlooking it? Does it matter? This remains uncertain.

Thanks for your attention!

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