Color propagation in eA
with CLAS, CLAS12 and EIC

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Color propagation ($x>0.1$)
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Quarks in nuclei: experimental data

✓ EMC effect - observation that structure functions are modified in nuclei over ~1000 papers published in the past 35 years! NO CONSENSUS AS OF ITS ORIGIN

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- Short Range Correlations - short distance structure of nuclei, correlated nucleons.

Correlation between EMC effect and SRC high virtuality nucleons in nuclei?

talk by A. Schmidt

Higinbotham, Miller, Hen, and Rith. CERN Cour. 53N4, 35 (2013)
Quarks in nuclei: experimental data

- **EMC effect** - observation that structure functions are modified in nuclei over ~1000 papers published in the past 35 years! NO CONSENSUS AS OF ITS ORIGIN

- **Short Range Correlations** - short distance structure of nuclei, correlated nucleons.

- **Hadronization** - neutralization of color charge in colorless hadrons in nuclei

EMC data: μ beam on Cu and D

HERMES data: e+ beam on Ne, Kr, Xe and D


Quarks in nuclei: experimental data

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- Color transparency - decreased interaction in nuclei of small sized object

L. El Fassi et al. PLB 2012
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- Nuclear DVCS: 3D tomography of partonic structure of nuclei

In the eA context I will discuss:

- Color propagation - fundamental process of QCD
- Experimental realization: CLAS (E-02-104) at 5 GeV
- Continuation at CLAS12 (E-12-06-117)
- Future measurements at the EIC
**Color propagation - why is it interesting?**

**Color propagation is a fundamental QCD process**

Hadronization describes the transition between colored d.o.f to composite colorless objects.

Propagation of color relies on key property of QCD as color gauge theory - **asymptotic freedom**.

Restoration of color neutrality from QCD vacuum is dynamical enforcement of **confinement**.

---

**Visualization of QCD from D. Leinweber**

**Confinement**

Long distances
- color charge anti-screening
- color flux tube between qq

**Asymptotic freedom**

Short distances $l << 1\text{fm}$
- $q$ and $g$ in QCD vacuum

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Color propagation in DIS, DY and HI

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PARTON PROPAGATION AND FRAGMENTATION IN QCD MATTER

Fig. 2. – Quark propagation inside a target nucleus (“cold QCD matter”) in \( p+p \) collisions (left) and \( D-W \) collisions (centre). Right: Hard scattered parton traveling through the “hot QCD matter” produced in a nucleus-nucleus collision.

Transverse momentum hadron production in \( A+A \) compared to proton-proton (\( p+p \)) and hadron-nucleus \( h+A \) collisions at RHIC [25-28] (see Sect. 5), is also indicative of a breakdown of the universality of the fragmentation process. The standard explanation is that the observed suppression is due to parton energy loss in the strongly interacting medium. This assumes of course that the quenched light-quarks and gluons are long-lived enough to traverse the medium before hadronising, which can be expected at large enough transverse momentum because of the Lorentz boost of the hadronisation time scales. However, dynamical effects may alter this argument (see, e.g., Ref. [29]), with hadronisation starting at the nuclear radius scale or before. In this case, in-medium hadron inter-actions should also be accounted for, possibly leading to a different suppression pattern.

Such mechanisms may be especially important in the case of heavy (charm, bottom) quarks which – being slower than light-quarks or gluons – can fragment into \( D \) or \( B \) mesons still inside the plasma [30].

In summary, a precise knowledge of parton propagation and hadronisation mechanisms can be obtained from nDIS and DY data, allowing one to test the hadronisation mechanism and colour confinement dynamics. In addition, such cold QCD matter data are essential for testing and calibrating our theoretical tools, and to determine the (thermo)dynamical properties of the QGP produced in high-energy nuclear interactions.

1.3. Hadronisation and colour confinement. – While not having a direct bearing on the traditional topics of confinement such as the hadron spectrum, the hadronisation process nonetheless contains elements that are central to the heart of colour confinement, as already emphasised 30 years ago by Bjorken [6]. For instance, in the DIS process, a quark is briefly liberated from being associated with any specific hadron while traveling as a “free” particle, and it is the mechanisms involved in hadron formation that enforce the colour charge neutrality and confinement into the final state hadron. The dynamic mechanism leading to colour neutralisation, which is only implicitly assumed in the traditional treatments of confinement based on potential models [31] or lattice QCD [32], can be studied quantitatively using the theoretical and experimental techniques discussed in this review. As an example, the lifetime of the freely propagating quark may be inferred experimentally from the nuclear modification of hadron production on cold nuclei, which act as “detectors” of the hadronisation process.
Space-time view of $eA$ in DIS regime

Production length $L_p$ relates to ‘color lifetime’ of quark following hard collision; it is the length required for colored system to neutralize its color.

Formation length $L_f$ is a distance over which a color neutral object *pre-hadron* evolves into observed hadron.

Fundamental QCD processes:

- Partonic elastic scattering
- Gluon bremsstrahlung, vacuum and medium
- Color neutralization
- Hadron formation
- Final State Interactions
eA : nuclei of increasing size act as space-time analyzer
Observables & Measurements
In parton model, assuming factorization, Multiplicity Ratio is expressed in terms of the ratios of PDF and FF

\[ \Delta \langle p_T^2 \rangle = \langle p_T^2 \rangle_A - \langle p_T^2 \rangle_p \]

Transverse Momentum Broadening

Connects to color lifetime \( L_p \), quark \( k_T \), transport coefficient \( q \hat{\text{h}} \) and quark energy losses

Hadronic Multiplicity Ratio

Connects to hadron formation phase \( L_f \)

Particle yield \( N = \sigma L \), where \( L \) is luminosity
For a double target system with same \( L \),

Multiplicity Ratio is the ratio of cross sections

\[ R_A^h (\nu, Q^2, z, p_T) = \frac{N_h(\nu, Q^2, z, p_T)}{N_e(\nu, Q^2)|_{\text{DIS}} A} \]

In parton model, assuming factorization, Multiplicity Ratio is expressed in terms of the ratios of PDF and FF
Extraction of color lifetime: Brooks - Lopez model

First measurement of color lifetime $L_p$ from based on simultaneous fits to HERMES data on $p_T$ broadening and hadron attenuation as a function of $z$. 

\[
L_p = \frac{1}{2\kappa} \left( \frac{1}{M_p + \nu} \left( \frac{1}{1 + \frac{1}{1 + (Q^2)^2}} - 2\nu z \right) \right) \\
\kappa = 0.98 \pm 0.09 \text{ GeV/fm}, \chi^2/\text{dof} = 1.09
\]

\[
Q^2 = 2.4 \text{ GeV}^2, \nu = 13.1 \text{ GeV}
\]
HERMES multiplicities $R(z, pT^2)$ integrated over $\nu, Q^2$

Flavor separation: $\pi^{\pm/}$, $K^{\pm/-}$ and $p/\bar{p}$

2D distributions for charged hadrons

1D extraction of multiplicities for $\pi^0$


HERMES

multiplicities $R(z, pT^2)$ integrated over $v, Q^2$

Flavor separation: $\pi^{+/-}, K^{+/-}$ and $p/\bar{p}$

2D distributions for charged hadrons

1D extraction of multiplicities for $\pi^0$

Need multidimensional data to distinguish between proposed mechanisms: pure quark energy loss vs pure absorption vs dipole approach!
Experimental realization: CLAS at 5 GeV
Two targets in the beam simultaneously!

CLAS EG2 experimental conditions:

- Electron beam 5.014 GeV
- Targets $^2\text{H}$, $^{12}\text{C}$, $^{56}\text{Fe}$, $^{207}\text{Pb}$ (Al, Sn)
- $^2\text{H}$ separated from solid targets by 4cm
- Instant luminosity $2 \cdot 10^{34}$ $1/(s \cdot \text{cm}^2)$
3D $\pi^0$ Multiplicities $R_{\pi^0}(Q^2, \nu, z)$ on $^{12}\text{C}, ^{56}\text{Fe}, ^{207}\text{Pb}$ to D

- Attenuation depends on nuclear size
- Hadron attenuation at high $z$
- Quantitative behavior compatible with Hermes

Results corrected for acceptance, RC and CC on $e^-$. Average systematics does not exceed 6%.

Taisiya Mineeva
Analysis under review
Multiplicity ratios: data from EG2

3D $\pi^0$ Multiplicities $R_{\pi^0}(\nu, z, pT^2)$ on $^{12}\text{C}, ^{56}\text{Fe}, ^{207}\text{Pb}$ to D

Results corrected for acceptance, RC and CC on e-. Average systematics does not exceed 7%.
Multiplicity ratios: data from EG2

3D $\pi^+$ and $\pi^-$ Multiplicities $R_{\pi}(Q^2,\nu, z)$

Results corrected for acceptance.

Hayk Hakobyan, Sebastian Moran

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CLAS12
Approved experiment
E-12-06-117
Solid target assembly for CLAS12

New targets types will include: 4He, C, O, Ar, Pb and others. Unfortunately no Fe.

Extreme conditions @CLAS12

- High vacuum (6x10E-6 mbar)
- Magnetic field (5 Tesla)
- Cryotarget at 30 °K
- Radiation hardness
- Reduced space
**DIS channels: stable hadrons, accessible with 11 GeV JLab future experiment PR12-06-117**

Currently accessible at CLAS 5 GeV data measured by HERMES

<table>
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<th>flavor content</th>
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<td>ud</td>
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<tr>
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<td>1.3</td>
<td>uds</td>
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<tr>
<td>(K^0)</td>
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<td>ds</td>
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<tr>
<td>(K^{+}, K^-)</td>
<td>3.7 m</td>
<td>0.49</td>
<td>us</td>
</tr>
</tbody>
</table>
**eA kinematics: past & near future**

CLAS at 5 GeV  \( \sqrt{s} = 3.2 \) GeV

CLAS12 at 11 GeV  \( \sqrt{s} = 4.6 \) GeV *

HERMES at 27 GeV  \( \sqrt{s} = 7.2 \) GeV *

**eA EIC projected kinematics**

JLEIC  \( \sqrt{s} = 12-140 \) GeV

small \( x \), large \( \nu \), large \( Q^2 \) reach

Note, available kinematical phase space at CLAS 12 vs HERMES is not that far apart due to y-cut
I) Map the spin and spatial structure of quarks and gluons in nucleons

- **Sea quark and gluon** polarization
- Transverse spatial distributions
- Orbital motion of quarks/gluons
- Parton correlations: beyond one-body densities

*(show the nucleon structure picture of the day...)*

II) Discover the collective effects of gluons in atomic nuclei

- Color transparency: Small-size configurations
- **Nuclear gluons**: EMC effect, shadowing
- Strong color fields: Unitarity limit, saturation
- Fluctuations: Diffraction

*(without gluons there are no protons, no neutrons, no atomic nuclei)*

III) Understand the emergence of hadronic matter from color charge

- Materialization of color: **Fragmentation**, hadron breakup, color correlations
- Parton propagation in matter: Radiation, energy loss

*(how does \( M = E/c^2 \) work to create pions and nucleons?)*
The Physics Program of an EIC

I) Map the spin and spatial structure of quarks and gluons in nucleons

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III) Understand the emergence of hadronic matter from color charge

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(how does \( E = mc^2 \) work to create pions and nucleons?)

Needs high luminosity and range of energies

from Rolf Ent QNP2012

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Parton propagation studies in eA @ EIC

measurement of the saturation scale

access to quark energy loss

mechanisms of hadronization
Saturation scale
Saturation scale
What is saturation?

- From HERA, RHIC and LHC data we know that the PDFs of sea quarks and gluons grow at low x.
- No bound on number densities of q and g at low x; but, due to unitarity, non-linear recombination limits the density growth.

Saturation of parton densities, particularly for gluons.

Color Glass Condensate - high energy effective theory describing universal properties of saturated gluons.

Gluon transverse momentum $k_T$ characterizes degree to which saturation is occurring: $Q_s \sim k_T$.

eA @ EIC can probe saturation scale at far lower energies than ep since saturation scale is enhanced by the nuclear diameter!

\[ Q_s^2(x) \sim A^{1/3} \left( \frac{1}{x} \right)^\lambda \]
Saturation scale

How to access it experimentally?
Saturation scale

How to access it experimentally? (1)

Ratio of diffractive over total DIS events

Figure 1.6 (Right) shows that gluon saturation is predicted to suppress vector meson production in $e^+A$ relative to $e^+p$ collisions at the EIC. The vector mesons result from quark-antiquark pair fluctuations of the virtual photon, which hadronize upon the exchange of gluons with the beam proton or nucleus. The magnitude of the suppression depends on the size (or color dipole moment) of the quark-antiquark pair, being significantly larger for produced $\phi$ (red points) than for $J/\Psi$ (blue) mesons. An EIC measurement of the processes in Fig. 1.6 (Right) will provide evidence for gluon saturation.
Saturation scale

How to access it experimentally? (2)

Observable: transverse momentum broadening $\Delta p_T$

- $p_T$ broadening is a boost-invariant way of sampling the (transverse) gluon density distribution
- $p_T$ broadening is proportional to the gluon density

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

dipole model view of $p_T$ broadening


Final result: saturation momentum in infinite momentum frame found to be equal to $p_T$ broadening in target rest frame:

$$Q_{sat}^2(b, E) = \Delta p_T^2(b, E)$$
Saturation Scale

$pQCD$ view of $p_T$ broadening


Transverse Momentum Dependent (TMD) quark distribution function in nucleus:

$$f^A_q(x, \vec{k}_\perp) = \int \frac{dy^-}{2\pi} \frac{d^2y_\perp}{(2\pi)^2} e^{ixp^+y^- - i\vec{k}_\perp \cdot \vec{y}_\perp} \langle A | \bar{\psi}(0, \vec{0}_\perp) \frac{\gamma^+}{2} \mathcal{L}_{\text{TMD}}(0, y) \psi(y^-, \vec{y}_\perp) | A \rangle$$

$$\mathcal{L}_{\text{TMD}}(0, y) \equiv \mathcal{L}_{\|}^\dagger(-\infty, 0; \vec{0}_\perp)\mathcal{L}_{\perp}^\dagger(-\infty; \vec{y}_\perp, \vec{0}_\perp)\mathcal{L}_{\|}(-\infty, y^-; \vec{y}_\perp)$$

Complete gauge link

$$\mathcal{L}_{\perp}(-\infty; \vec{y}_\perp, \vec{0}_\perp) \equiv P \exp \left[ -ig \int_{\vec{0}_\perp}^{\vec{y}_\perp} d\vec{\xi}_\perp \cdot \vec{A}_\perp(-\infty, \vec{\xi}_\perp) \right]$$

Transverse and longitudinal gauge links

$$\mathcal{L}_{\|}(-\infty, y^-; \vec{y}_\perp) \equiv P \exp \left[ -ig \int_{y^-}^{-\infty} d\xi^- A_+(\xi^-, \vec{y}_\perp) \right]$$

$$\hat{q}_A(\xi_N, y_\perp^2) = \frac{4\pi^2\alpha_s C_A}{N_c^2 - 1} \rho_N^A(\xi_N) [x f^N_g(x, y_\perp^2)]_{x=0}$$

Gluon transport parameter

$$Q_{\text{sat}}^2(y_\perp^2) = \int d\xi_N^- \hat{q}_A(\xi_N, y_\perp^2) = \frac{4\pi^2\alpha_s C_A}{N_c^2 - 1} \int d\xi_N^- \rho_N^A(\xi_N) x f^N_g(x, y_\perp^2)$$

Saturation scale

Various approximations, and last step invokes dipole model, see paper from Will Brooks EIC meeting at CUA 2010
Quark energy loss
Energy loss in pQCD

General BDMPS version

- Vacuum energy losses are greater than medium-induced (cold matter)
- Energy losses due to gluon radiation are greater than collisional energy losses from parton elastic scattering (light particles)
- Energy loss is proportional to the gluon and parton density of the medium!!
- High importance in HI data; jet quenching is manifestation of quark energy loss

Energy loss in pQCD

(BDMPS version)

Partonic energy loss in pQCD depends on critical system length $L_c$ and critical $E_c$

- Linear vs quadratic behavior in $L$
- LMP effect suppresses gluon bremsstrahlung

\[ -\Delta E_q = \frac{\alpha_s}{4} \Delta k_T^2 \cdot L = \frac{\alpha_s}{4} \hat{q} \cdot L^2 \]

HERMES data: $q^{hat}=0.075$ GeV$^2$/fm

$L_{Xe} = 4$ fm

$E_{crit} \sim 6$ GeV, and $E_{crit} << v$


Quark energy loss at EIC

- Can be inferred *indirectly* via measurement of $p_T$ broadening and extracted from pQCD theory
Mechanisms of hadronization
Emergence of Hadrons from quarks & gluons

- Femtometer sized detector:
  - \( \nu = \frac{Q^2}{2mx} \)
  - Control of \( \nu \) and medium length!
  - Mass dependence of hadronization

- Apply to heavy-ion collisions:

Need the collider energy of EIC and its control on parton kinematics
Extrapolation of Lp from HERMES to EIC

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

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<th>$\beta^*\gamma$</th>
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At the EIC we can study a wide range of production lengths!
Conclusion

Measurements that color propagation physics can access in EIC:

• pT broadening observables
  • saturation scale !!
  • pQCD energy loss
  • effective quark lifetime
  • transport coefficient

• Multiplicity ratio observable
  • hadronization mechanisms
  • hadron formation length

+ azimuthal $\varphi$-modulation of produced hadrons
Conclusion

Measurements that color propagation physics can access in EIC:

*EIC can access all of this physics!*

- **pT broadening observables**
  - saturation scale !!
  - pQCD energy loss
  - effective quark lifetime
  - transport coefficient

- **Multiplicity ratio observable**
  - hadronization mechanisms
  - hadron formation length

+ azimuthal $\varphi$-modulation of produced hadrons
Additional slides
Measurements of $p_T$ broadening and hadron attenuation ratios as a function of nuclear size $A$ allow to calculate the length of color propagation and hadron formation processes at the femtometer scale.
Energy conservation: if hadron carried away energy $E_h = z \nu$, string only has $\nu - E_h$

If take, e.g., $z = E_h/\nu = 0.6$, $\nu = 5$ GeV, then $\tau_p \sim 2$ fm/c

Back-of-the envelope $\tau_f$

Given hadron of size $R_h$, can build color field of hadron in its rest frame in time no less than $t_0 \sim R_h/c$. In lab frame this is boosted.

If take, e.g., the pion mass, radius 0.66 fm, $E = 4$ GeV, then $\tau_f \sim 20$ fm/c
Comparison of CLAS and HERMES e+A

- Beam energy: 5.0 GeV at JLab vs 27.6 GeV at DESY

- Solid target in CLAS vs gas targets in HERMES
  Heaviest target $^{207}$Pb in CLAS vs $^{131}$Xe in HERMES

- Luminosity in CLAS is 100 times greater than HERMES
  Access to 3D binning in CLAS vs 1-2D binning in HERMES

<table>
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<tr>
<th></th>
<th>$\nu$ (GeV)</th>
<th>$Q^2$ (GeV$^2$)</th>
<th>$Z$</th>
<th>$pT^2$ (GeV$^2$)</th>
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<td>0.3 - 1.0</td>
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<td>HERMES</td>
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<td>1.0 - 10</td>
<td>0.2 - 1.0</td>
<td>0 - 1.1</td>
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Quark energy loss or Hadron absorption?

- **Pure quark energy loss models:** *a la* BDMPS (Arleo; Accardi)
  Higher twist FF (Wang; Majumder)

- **Pure hadron absorption models:** prehadron survival from transport model (Accardi)
  GiBUU transport Monte Carlo (Falter)

---

Both pure quark energy loss and pure hadron absorption models describe attenuation $R_h$ as a fnc of $z$ for HERMES

Modern Lund string model: abs. or en. loss (A.Accardi)

\[
\frac{1}{N_A^{DIS}} \frac{dN_A^h(z)}{dz} = \frac{1}{\sigma_{\ell A}^{\text{exp. cuts}}} \int dx \, d\nu \sum_f e_f^2 q_f(x, Q^2) \frac{d\sigma_{\ell f}}{dx d\nu} S_{f,h}^A(z, \nu) D_{\ell}^h(z, Q^2).
\]
Quark energy loss or Hadron absorption?

- **Pure quark energy loss models:** *a la* BDMPS (Arleo; Accardi)
  Higher twist FF (Wang; Majumder)

- **Pure hadron absorption models:**
  prehadron survival from transport model (Accardi)
  GiBuu transport Monte Carlo (Falter)

- **Color dipole model (z>0.5):** quark energy loss + prehadron absorption (B.Kopeliovich)

Dipole model which includes both quark energy loss and hadron absorption also ~ describes HERMES data

solid line: absorption and induced energy loss

Dashed line: absorption of color dipole qqbar

Kopeliovich et al., NPA 740(04)211
Transverse momentum broadening $\Delta k_T$ can be expressed in terms of gluon density $C$

$$\Delta k_T^2 = \frac{\Delta p_T^2}{z^2} = 2C \rho_A L = \hat{q}L$$

Space-time characteristics of struck quark

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

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: $Q^2 = 3$ GeV$^2$, $\nu = 3$ GeV. ($x_{Bj}\sim 0.5$) yields $\gamma = 1.73$, $\beta = 0.82$

$\textbf{Extrapolation to EIC kinematics!}$

Test of time dilation in CLAS/CLAS12!
Energy loss in pQCD

\( (BDMP \text{ version}) \)

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

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

Partonic energy loss in pQCD depends on critical system length \( L_c \) and critical \( E_c \).

For \( E > E_c \), energy loss depends on path \( L \):

\[ - \Delta E_q = \frac{\alpha_s}{4} \Delta k_T^2 \cdot L = \frac{\alpha_s}{4} \hat{q} \cdot L^2 \]
Fig. 2.3  Diagrams for collisional (left) and radiative (right) energy losses of a quark of energy $E$ traversing a quark-gluon medium

A.Festani “Measurement of the D0 meson production in PbPb and pPb”
FF for light and heavy mesons

Figure 3.22:
Left: A cartoon for the interactions of the parton moving through cold nuclear matter when the produced hadron is formed outside (upper) and inside (lower) the nucleus.
Right: Fragmentation functions as a function of $z$: from the charm quark to the $D^0$ meson (solid) [193] and from up quark to $\pi^0$ meson (dashed) [40].

It was evident from hadron production in $e^- + e^+$ collisions that the fragmentation functions for light mesons, such as pions, have a very different functional form with $z$ from that of heavy mesons, such as $D^0$-mesons. As shown in Fig. 3.22 (Right), the heavy $D^0$-meson fragmentation function has a peak while the pion fragmentation function is a monotonically decreasing function of $z$. The fact that the energy loss matches the active parton to the fragmentation function at a larger value of $z$ leads to two dramatically different phenomena in the semi-inclusive production of light and heavy mesons at the EIC, as shown in Fig. 3.23 [200].

In Fig. 3.23, simulation results were plotted for the multiplicity ratio of semi-inclusive DIS cross-sections for producing a single pion (Left) and a single $D^0$ (Right) in $e^+ + Pb$ collisions to the same produced in the $e^+ + d$ as a function of $z$ at the EIC with two different photon energies: $\nu = 35$ GeV at $Q^2 = 10 GeV^2$ (solid line and square symbols) and $\nu = 145$ GeV at $Q^2 = 35 GeV^2$ (dashed line and open symbols). The $p_T$ of the observed hadrons is integrated. The ratio for pions (red square symbols) was taken from the calculation of [194], extended to lower $z$, and extrapolated from a copper nucleus to a lead nucleus using the prescription of [195]. In this model approach, pions are suppressed in $e^+ + A$ collisions due to a combination of the attenuation of pre-hadrons as well as medium-induced energy loss. In this figure, the solid lines (red - $\nu = 145$ GeV, and blue - $\nu = 35$ GeV) are predictions of pure energy loss calculations using the energy loss parameters of [201]. The large differences in the suppression between the square symbols and solid lines are immediate consequences of the characteristic time scale for the color neutralization and the details of the attenuation of pre-hadrons, as well as the model.
Complication: Quark Pair Production

Two types of problems:

- Have $q\bar{q}$ pair instead of single propagating quark of known energy $\nu$
  - Measure both jets, or else have an error in calculation of $z$
- Pair can fluctuate into existence before entering the nucleus, or within the nucleus
  - "Ioffe time" $\sim 1/(\chi_B \, M_p)$ (up to 100+ fm for EIC)
  - Path length in nucleus varies
Quark energy loss

- Can be inferred *indirectly* via measurement of $p_T$ broadening and extracted from pQCD theory
- Can be measured *directly* via observed particle energy shift

For direct energy losses: sensitivity mostly at low energies!