In-Medium Hadronization

Raphaël Dupré

Argonne National Laboratory
Outline

- Introduction
- Existing data and open questions
- The energy loss scenario
- What can we do with an EIC?
- Conclusion
Parton Propagation and Fragmentation

- What are we measuring and why?
  - The fragmentation time scales to understand the dynamic of hadronization
  - The in-medium energy loss to characterize our medium

Observables

- $P_T$ distribution broadening in Cold Nuclear Matter

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

- Attenuation of hadrons measured in Cold Nuclear Matter with

\[ R_A^h(Q^2, x_{Bj}, z, P_T) = \frac{N_A^h(Q^2, x_{Bj}, z, P_T) / N_A^e(Q^2, x_{Bj})}{N_D^h(Q^2, x_{Bj}, z, P_T) / N_D^e(Q^2, x_{Bj})} \]
Existing and future experimental data

- EMC, SLAC & E665

- HERMES data (27.6 GeV beam)
  - Open several questions

- CLAS data are still analyzed (5 GeV beam)
  - Some preliminary results in few slides
  - Answer questions?

- Planned experiment at CLAS 12 (11 GeV beam)
  - “Quark Propagation and Hadron Formation” proposal, K. Hafidi et al.
HERMES multiplicity ratio

Solutions for $K/\pi$ absorption difference

- Hadron absorption
  - Cross section of $\pi > K^+$

- Energy loss / Medium modified FF
  - Gluon enhancement
Solutions for $K/\pi$ broadening difference

- Hadron absorption
  - Elastic cross section of $K^+ > \pi$

- Energy loss
  - Quark flavor dependence
CLAS Multiplicity Ratio

- The multi-dimensional binning reveal an underlying structure
- The description of $\nu$ is dependent of $z$

The study of $\Delta P_T^2$ show a dependence with $\nu$

Indication of non linearity with $A^{1/3}$
PyQM: Energy Loss Based Simulation

- PYTHIA is both used for
  - Parton level generator
  - Lund fragmentation of the products

- Apply BDMPS energy loss calculation to modify partons
  - Calculation from Salgado and Wiedmann (2002)
  - Attribute a transverse momentum according to the energy loss
Simulation Compared to HERMES Data (pions)

\[ q \text{ hat} = 0.55 \text{ GeV}^2 \text{ fm}^{-1} \]
Simulation Compared to HERMES Data (Kaons)

$q \text{ hat} = 0.55 \text{ GeV}^2 \text{ fm}^{-1}$

Oct 4th 2010 INT EIC Workshop - Raphaël Dupré
Simulation Compared to HERMES Data

\[ q \hat{=} 0.015 \text{ GeV}^2 \text{ fm}^{-1} \]
Simulation Compared to HERMES Data

\[ q \text{ hat} = 0.015 \text{ GeV}^2 \text{ fm}^{-1} \]
What do we learn from the energy loss simulation?

- Model reliable at high z only
  - Impossible to simulate target fragmentation with PYTHIA
  - No simple way to simulate gluon emission in the nuclear medium
  - Nevertheless it reproduce nicely data on a large scale

- Fundamental inconsistency in q hat determination

- $P_T$ is approximated
  - Transverse momentum distribution is a difficult observable to reproduce
Interesting observables at EIC energies

- **Light Quarks**
  - $\pi^0$, $\eta$ comparison (energy loss vs prehadron absorption)
  - Verify that Ratio → 1 at large $v$ as indicated by EMC
  - $p_T$-broadening:
    - vs. $Q^2$ - to understand HERMES data growing values
    - vs. $z$ - for precision tests of theory models
  - Cronin effect at large $p_T$ - test of fragmentation vs. recombination

- **Heavy Quarks**
  - heavy vs. light mesons in general
  - $B$ vs $D$ mesons (heavy flavor puzzle)

- **Jets**
  - Jet rates as a function of cone radius - gluon radiation will broaden jets
  - Semi-inclusive jet $p_T$-broadening - direct parton $p_T$-broadening
  - Compare to jets at RHIC

see https://eic.jlab.org/wiki/index.php/EA_Parton_propagation_and_fragmentation
**π vs η to discriminate between processes**

![Graphs showing energy loss and absorption models for Xe with data points for EIC η and π⁰, and HERMES π⁰.](Curves by A. Accardi)
Information from energy loss / $\Delta p_t^2$

- Energy loss calculations are linked with gluon content of the nuclei characterized by $q\hat{\alpha}$

- Recent work from Kopeliovich et al. Link directly the $\Delta p_t^2$ to the saturation scale

- Precise calculation of the process remain challenging
  - Quark flavor dependence for example

- $\Delta p_t^2$ of jets as direct measurement of $q\hat{\alpha}$
Multiplicity ratios going to 1

- Multiplicity ratios should go to 1 around $\nu \sim 100$ GeV

- This feature from EMC measurement need to be refined especially in function of $z$
  - Arvidson et al. (EMC) *Nucl. Phys. B246* 381-407, 1984

- Permit to separate energy loss from contamination by hadron absorption process

- Flavor dependence need to be checked with a large sample of particles to discriminate absorption effects
Target fragmentation

- Target fragmentation can permit to access energy loss from the other side and check consistency in the models

- Slow moving protons can give information on the impact parameter
Heavy quarks

- Numerous interests (see previous talk)

- By opposition with light particles, the multiplicity and the detection issues make their measurement challenging

- Following error bars predictions are based on PYTHIA simulation
Projection at EIC energies

11 GeV $e^-$ on 30 GeV/n iron at $L = 0.4 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ for a month
Projection at EIC energies

- $z > 0.4$
- DIS
- $0.1 < y < 0.8$

- $3 - 30$ GeV
  - $4 \times 10^{34}$ cm$^{-2}$ s$^{-1}$

- $11 - 30$ GeV
  - $4 \times 10^{32}$ cm$^{-2}$ s$^{-1}$

- $4 - 100$ GeV
  - $1.5 \times 10^{32}$ cm$^{-2}$ s$^{-1}$
Measurement issues

- For transverse momentum broadening it is necessary to have good resolution in angles due to the size of the measured effect.

- Zero angle nucleon detector can be very useful to explore the target fragmentation and slow nucleon production.

- Heavy quark identification can be achieved on a large scale only with high precision vertex determination <50μm.

- B mesons measurement require high luminosity.
Overview of the MC efforts in our group and future developments

- PYTHIA add-on
  - Fermi motion, BDMPS energy loss with Lund fragmentation (this work)

- Bose-Einstein Correlation
  - J. Gilfoyle presentation next week

- PYTHIA modification (based on Q-PYTHIA)
  - Adapt it to cold nuclear matter geometry
  - Extend it to treat HT energy loss (Majumder)

- Jet analysis with PYTHIA or (better) Q-PYTHIA

Which EIC configuration?

- For light particles, all configurations can give good results

- The main parameter for heavy quark production is the luminosity (D accessible with few $10^{32}$, B with few $10^{33}$ cm$^{-2}$ s$^{-1}$)

- It would be interesting to cover $\nu$ in those regions:
  - $\nu < 100$ GeV to measure multiplicity ratios
  - $\nu > 300$ GeV to measure pure energy loss (through jets for example)
    \[ \rightarrow s \sim 1000 \text{ GeV}^2 \]

- We need a strategy for heavy quark detection
Summary

- Dominant process to model hadronization in nuclei is still controversial, hopefully measurement are coming to answer this question.

- EIC provide a perfect tool to isolate quark energy loss process and study it:
  - Direct energy loss measurement
  - Gluon content of the nuclei

- RHIC measurements on heavy flavors lead to enhanced interest for D and B mesons in cold nuclear matter.