Hadronization in Cold Nuclear Matter

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The Hadronization Process

- **Non perturbative QCD process**
  - Need models and data

- **Production time → propagation of the colored quark**

- **Formation time → propagation of the color neutral prehadron**

- **Very wide theoretical prediction ranges but no experimental quantification of these times**!

- **With nuclear targets of different size we can measure them!**
  - However the large model uncertainty leads to complicated interpretations
  - We need very precise data on a wide set of nuclei and a wide kinematic range
Motivations

• **Understand the hadronization process**
  – Measuring the characteristic times
  – Calculating parton energy loss in QCD medium
  – Understanding the pre-hadron structure

• **Characterization of the QCD medium**
  – Using parton energy loss
  – Compare cold to hot nuclear matter
  – Understand QCD evolution in medium

• **Reduce systematic effects on measurements where attenuation needs to be corrected**
  – Neutrino experiments
  – Nucleon structure in nuclei
Fragmentation Functions

- They parametrize the fragmentation in vacuum
- They focus is on the current region
  - Fracture functions are used for the target region
- They respects evolution predicted by perturbative QCD
  - What about in medium?
- Yet, they are measured and cannot be predicted by QCD or models
Theoretical Models

• Three families of models
  – Parton energy loss
  – Modified fragmentation functions
  – Hadron absorption

• Parton energy loss or Hadron absorption ?
  – Important debate on which dominates

• Is there a significant modification of the evolution in medium ?
  – Leads to a modification of fundamental fragmentation functions
  – Has a huge impact on heavy ion measurements

• Many models exists with different answers to these questions
  – Pure models (see parton energy loss calculations in this talk for example)
  – Mixed models (with all possible combinations represented in the litterature)
DIS Kinematics

- 4-Momentum squared of the photon
  \[ Q^2 = -q^2 \]

- Energy of the photon
  \[ \nu = E_\gamma \]

- Fraction of energy of the hadron
  \[ z = \frac{k.p}{q.p} = \frac{E_h}{\nu} \]

- Transverse momentum
  \[ \vec{P}_t = \vec{P}_h - \frac{\vec{P}_h \cdot \vec{q}}{||\vec{q}||} \vec{q} \]
Energy Loss MC Simulation

• **Nuclear Fermi-motion of the nucleons**
  – Relevant mostly for the lower energies

• **PYTHIA Monte-Carlo**
  – Simulation of the electron-nucleon scattering

• **Parton Energy Loss**
  – Based on Salgado&Wiedmann calculation (PRD68 014008, 2003)
  – Simulating nuclear material using realistic density profile
  – Assuming fragmentation will occur outside the nuclei → we cross all the nuclear material

• **Back to PYTHIA**
  – Fragmentation of the partons

• **Basic acceptance cuts**
  – Allows more precise comparison with data

*Work with A. Accardi*
Attenuation from HERMES

- Good description with $q_{\text{hat}} = 0.36 \text{ GeV}^2/\text{fm}$
  - Single parameter model
  - Value is high but still in range to other calculation
- Not consistent with observed transverse momentum?
Transverse Momentum

• How do we got from $L \times 0.36$ to $\sim 0.03$?
  – Reduction by $z$ square ($\sim 0.1$)
  – Reduction due to lower parton energy
  – Reduction due to absorption

• It matches data for all kinetic variables
Can be implemented in many ways

- Here we test 4 options
- Good shape with A (Event by event MC model)
Jefferson Lab - EG2 exp

• **JLab continuous electron beam**
  - 5.012 GeV electrons
  - ~nA current
  - 2 cm long liquid deuterium target
  - 5 solid targets (C, Al, Fe, Sn and Pb)

• **In the Hall-B**
  - CLAS Collaboration spectrometer
  - Detect and trigger on scattered electron (selected in DIS kine.)
  - Detect hadrons from ~15 to 160 degrees
Nuclear effect saturates at high $A$ and do not follow either $A^{1/3}$ nor $A^{2/3}$ trends
- First measurement with enough coverage to reveal such structure
- Appears contradictory with hadron absorption models at first sight

Multiplicity ratio and $P_t$ broadening follow the same trend
- Do they originate from the same process or just a coincidence?
• Nu and z dependence behave in the same way than expected
  → Slope in ν similar to HERMES
  → However, the slope in z is not as pronounced as in HERMES (?)

• Results for Δp_{t}² consistent with HERMES
  – Shows interesting trend
Some models have important predictions for the $Q^2$ trend

Yet, we see no effect with $\Delta p_t^2$
→ to compare with expectations from theory

Small raise of the multiplicity ratio
→ Same as HERMES
→ Not very conclusive

We have more precision but less coverage than HERMES
→ More investigation is still needed to solve this question
The Electron Ion Collider (EIC)

- Project of electron ion collider (EIC)
  - JLab and RHIC projects \( s \approx 1000 \text{ GeV}^2 \) and more
  - Low to no attenuation region → centered on \( \Delta P_T^2 \) measurement
  - Isolate energy loss effects and eventually modification of FF
  - Access to heavy flavor for comparison with Heavy Ion Collisions
Summary

- Study of hadronization dynamics needs nuclei

- Hadronization in CNM is the best benchmark for energy loss models for heavy ion collisions

- Energy loss models can describe the HERMES attenuation with $q^2 \approx 0.36 \text{ GeV}^2/\text{fm}$

- Interpret transverse momentum of detected particles is biased!
  - They have by nature experienced only limited interaction
  - We found good match between the results from attenuation and broadening

- JLab results (CLAS coll.) provides for new high precision data to test models

- Future experiments are still necessary to have high enough energy as well as high enough statistics