Nuclear effects in hadron production at HERMES

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Overview

- Measuring nuclear effects in hadronization at HERMES
- Final results on hadron attenuation
- Final results on $p_t$ broadening
Semi-inclusive deep-inelastic scattering

\[
Q^2 = -q^2 = -(k - k')^2
\]

\[
\nu_{\text{lab}} = E - E'
\]

\[
X = \frac{Q^2}{2M\nu}
\]

\[
Z_{\text{lab}} = \frac{E_{\text{had}}}{\nu}
\]

Cross section contains Distribution Functions and Fragmentation Functions:

\[
\sigma^{ep\rightarrow eh} \sim \sum_q \text{DF}^{p\rightarrow q} \otimes \sigma^{eq\rightarrow eq} \otimes \text{FF}^{q\rightarrow h}
\]

DF: distribution of quarks in the nucleon

FF: fragmentation of (struck) quark into hadronic final state
Space-time evolution of hadronization

- parton
- pre-hadron
  - colorless
  - quantum numbers of final hadron
- final state hadron

Formation length $l_c \sim 1-10$ fm $\Rightarrow \mathcal{O}$ (size of nucleon)
Space-time evolution of hadronization

- **parton** ⇒ energy loss by q-q scattering and gluon radiation
- **pre-hadron** ⇒ hadronic final state interactions (FSI)
  - colorless
  - quantum numbers of final hadron
- **final state hadron** ⇒ hadronic final state interactions (FSI)

Formation length $l_c \sim 1$-10 fm ⇒ $\mathcal{O}$ (size of nucleon)
Nuclear effects in SIDIS

• use targets of different nucleon number $A$ for different length scales to investigate space-time development of hadronization
  ▶ HERMES: D, He, Ne, Kr, Xe
• nuclear effects:
  ▶ hadron attenuation
  ▶ $p_t$ broadening
Hadron attenuation & $p_t$ broadening

**Hadron attenuation**

$$R^h_A(\nu, Q^2, z, p_t^2) = \left( \frac{N^h(\nu, Q^2, z, p_t^2)}{N^e(\nu, Q^2)} \right)_A \frac{N^h(\nu, Q^2, z, p_t^2)}{N^e(\nu, Q^2)}_D$$

Caused by partonic and hadronic effects:
- shift to lower energy
- absorption

$\Rightarrow$ sensitive to $l_c$ and $l_h$

**$p_t$ broadening**

$$\Delta \langle p_t^2 \rangle^h_A = \langle p_t^2 \rangle^h_A - \langle p_t^2 \rangle^h_D$$

Dominated by partonic effects:
- inelastic scattering suppressed
- elastic cross section small

$\Rightarrow$ sensitive to $l_c$
• Forward acceptance spectrometer: $40 \text{ mrad} \leq \Theta \leq 220 \text{ mrad}$
• Kinematic coverage: $0.02 \leq x_{Bj} \leq 0.8$ for $Q^2 > 1 \text{ GeV}^2$ and $W > 2 \text{ GeV}$
• Tracking: $\delta P/P = 0.7\% - 2.5\%, \delta \Theta \leq 1 \text{ mrad}$
• PID: TRD, Preshower, Calorimeter, RICH (Cherenkov before 1998)
• Forward acceptance spectrometer: $40 \text{ mrad} \leq \Theta \leq 220 \text{ mrad}$
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Hadron attenuation

\[ R_A^h(\nu, Q^2, z, p_t^2) = \left( \frac{N^h(\nu, Q^2, z, p_t^2)}{N^e(\nu, Q^2)} \right)_A \left( \frac{N^h(\nu, Q^2, z, p_t)}{N^e(\nu, Q^2)} \right)_D \]

- attenuation: strong dependence on A
- large \( \nu \):
  - longer \( l_c \) (Lorentz boost)
  - less absorption
- \( z \) dependence:
  - partonic: \( \Delta z \) from energy loss & \( z \) dependence of FF
  - hadronic: decrease in hadron formation length & absorption

Hadron attenuation: $p_t$

$$R^h_A(\nu, Q^2, z, p_t^2) = \frac{\left( \frac{N^h(\nu,Q^2,z,p_t^2)}{N^e(\nu,Q^2)} \right)_A}{\left( \frac{N^h(\nu,Q^2,z,p_t)}{N^e(\nu,Q^2)} \right)_D}$$

- for heavier nuclei: rise at high $p_t^2$
- Cronin-effect in DIS (no ISI)
- rise is attributed to a broadening of the $p_t$ distribution

• broadening increases with mass number $A$
  • similar for $\pi^+/-$
  • seems systematically higher for $K^+$
• precision does not allow firm conclusion about functional form of the increase with $A$
• no saturation observed
  • $p_t$ broadening due to effects in the partonic stage
  • pre-hadron formation near/outside surface

$\langle Q^2 \rangle = 2.4 \text{ GeV}^2$
$\langle \nu \rangle = 14.5 \text{ GeV}$
$\langle z \rangle = 0.39$
\[ \Delta \langle p_t^2 \rangle_A^h = \langle p_t^2 \rangle_A^h - \langle p_t^2 \rangle_D^h \]

... vs. V:

- in models commonly connected with the formation length
- flat behavior

supports the notion that color neutralization mainly happens at the surface/outside of the nucleus

arXiv:0906.2478
\[ \Delta \langle p_t^2 \rangle_A = \langle p_t^2 \rangle_A - \langle p_t^2 \rangle_D \]

... vs. \(Q^2\) / vs. \(x_B\)

- similar behavior vs. \(Q^2\) and \(x_B\) (strong correlation in HERMES kinematics)
- slight increase with both variables
- direct interpretation difficult
- different model predictions

\( \Rightarrow \) result helps to distinguish models

arXiv:0906.2478
\[ \Delta \langle p_t^2 \rangle^h_A = \langle p_t^2 \rangle^h_A - \langle p_t^2 \rangle^h_D \]

... vs. \( z \):

- \( p_t \) broadening vanishes as \( z \to 1 \)
- \( z=1 \): no energy loss
  - no room for \( p_t \) broadening
  - except possible primordial \( k_t \) modification vs. \( A \)
- results indicates no or little dependence of \( k_t \) on the size of the nucleus
- \( p_t \) broadening not due to elastic scattering of (pre-) hadrons

\( \text{arXiv:0906.2478} \)
Conclusions

- HERMES provides the largest data set to study space-time evolution of hadronization
- **final results on hadron attenuation** \((\text{Nucl. Phys. B 780 (2007) 1})\)
  - strong A dependence
  - less attenuation with larger \(v\) and low \(z\)
  - multiplicity ratio rises at high \(p_t^2\) (Cronin effect)
- **final results on \(p_t\) broadening** \((\text{arXiv:0906.2478})\)
  - \(p_t^2\) broadening is mostly caused by partonic effects
  - color neutralization happens outside (or close to the surface) of the nucleus
### Hadron attenuation

#### Charged pions

\[
R_A^h(\nu, Q^2, z, p_t^2) = \frac{\left( \frac{N_h(\nu, Q^2, z, p_t^2)}{N_e(\nu, Q^2)} \right)_A}{\left( \frac{N_h(\nu, Q^2, z, p_t)}{N_e(\nu, Q^2)} \right)_D}
\]

- stronger attenuation for larger \( A \)
- low \( p_t^2 \) bin:
  strong \( \nu \) dependence
- less attenuation for large \( p_t \)
  (attr. to broadening of the \( p_t \) distribution, Cronin effect)
- high \( p_t^2 \) bin:
  effect vanishes for large \( z \)

\( \Rightarrow \) consistent with the idea that rise at large \( p_t^2 \) is of partonic origin

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**Figures:**

- Various plots showing the ratio \( R_A^h \) for different elements (He, Ne, Kr, Xe) and different values of \( Q^2 \) and \( z \). The plots indicate the behavior of hadron attenuation as a function of these variables.

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**References:**