Accessing space-time characteristics of hadronization from data

Valeria Muccifora

• The hadronization process
• Role of nuclear DIS
• Hadron production in semi-inclusive measurements on nuclei.
• Status of the theoretical models
Hadronization

• Hadronization: The process by which energetic quarks evolve into hadrons -> Fundamentally non perturbative
  Generally described through phenomenological models.

• Lepton DIS: Less ISI than in hA interactions -> partonic/hadronic FSI in ‘clean’ nuclear environment.

• Semi-Inclusive DIS -> Parton Fragmentation Functions

\[ d\sigma^h(z) \propto \sum_f q_f(x) \otimes d\sigma_f \otimes D_f^h(z) \]

\[ z = \frac{E_h}{\nu} \]
DIS and hadronization distance scales

Determine the scale of hadronization using nuclei

Nucleus acts as an ensemble of targets: reduction of multiplicity of fast hadrons due to both hard partonic and soft hadron interaction.

Interactions with the medium during $l_f \rightarrow$ space-time picture of hadronization
Connections to Relativistic Heavy Ions

Nuclear SIDIS is related to parton propagation in AA collisions

\[ P_T (A-A) \approx E_h = z \nu (DIS) \rightarrow \text{the relevant energies are few few tens of GeV.} \]

- Jet quenching (suppression of high \( P_T \) hadrons) and depletion of the Cronin effect at RHIC:

Jet quenching, ascribed to radiative energy loss, would be an indication of high partonic density, e.g. QGP.

(Pre-)hadron interaction in the nuclear medium might give alternative explanation.

Hadron multiplicity ratio

Experimental observable: hadron multiplicity ratio in nuclei and deuterium

\[ R_M(z, \nu) = \frac{\frac{N_h(z, \nu)}{N_{DIS}^{DIS}}}{\frac{N_h(z, \nu)}{N_{DIS}^{DIS}}} = \frac{1}{\sigma_{DIS}} \frac{d^2\sigma_h}{d\nu d\nu} \bigg|_A = \frac{\Sigma e_f^2 q_f(x) D_f^h(z)}{\Sigma e_f^2 q_f(x)} \bigg|_D \]

Determine \( R_M \) versus:

Leptonic variables: \( \nu = E - E', \ Q^2 \)

Hadronic variables \( z = E_h/\nu, \ P_t^2 \)

Flavor

Different nuclei

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Experiments

- **SLAC**: 20 GeV $e^-$-beam on Be, C, Cu, Sn  
  PRL 40 (1978) 1624

- **EMC**: 100-200 GeV $\mu^-$-beam on Cu  

- **WA21/59**: 4-64 GeV $\nu$($\overline{\nu}$)-beam on Ne  

- **HERMES**: 27.6 or 12 GeV $e^+$-beam on He, N, Ne, Kr, Xe.  
  PLB 577 (2003) 37

- **CLAS**: 5.4 GeV $e^-$-beam on C, Fe, Pb  
  E-02-104
The energy range ($\nu$ 3-27 GeV) is well suited to study medium effects.

Measurements over the full $z$ range

Possibility to use several different gas targets

PId: $\pi^+$, $\pi^-$, $\pi^0$, $K^+$, $K^-$, $p$, $\bar{p}$
Larger geometrical acceptance → detects more secondary particles from FSI.

High statistics and wide range of final states: \( \pi^+, \pi^-, \pi^0, K^+, K^-, K^0, p, \Lambda, \Sigma^+, \Xi^0 \).

6 GeV beam: \( Q^2 < 4 \text{ GeV}^2, \nu < 5 \text{ GeV} \).
12 GeV beam: \( Q^2 < 9 \text{ GeV}^2, \nu < 9 \text{ GeV} \).

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HERMES @ HERA

It is an experiment which studies the spin structure of the nucleon and not only ...

$E=27.5\, 12\text{ GeV} \, e^+ (e^-)$

$I \sim 30\text{ mA}$

$p$ beam of 920 GeV, not used by HERMES

Last part of the fill dedicated to high-density unpolarised target runs:

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The Spectrometer

- $e^+$ identification: 99% efficiency and < 1% of contamination
- PID: RICH, TRD, Preshower, e.m. Calorimeter
- For N target: by Cerenkov $\pi$ ID $4<p<14$ GeV
- For He, Ne, Kr target: by RICH $\pi$, K, p ID $2.5<p<15$ GeV
- $\pi^0$ ID by e.m. Calorimeter.

(V. Muccifora)

(NIM A417 (1998) 230)
Hadron multiplicity ratio vs transfer energy $\nu$

- Clear nuclear attenuation effect for charged hadrons.
- Increase with $\nu$ consistent with EMC data at higher energy.
- Discrepancy with SLAC due to the EMC effect, not taken into account at that time.
- HERMES kinematics is well suited to study quark propagation and hadronization.

HERMES, PLB 577 (2003) 37
SLAC PRL 40 (1978) 1624
Hadron Multiplicity Ratio vs $z=E_h/\nu$

EMC

$\langle \nu \rangle = 62$ GeV

$\langle \nu \rangle = 55$ GeV

WA21/WA59

SLAC

HERMES

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Multiplicity ratio for identified hadrons vs $\nu$

HERMES, PLB 577 (2003) 37
Multiplicity ratio for identified hadrons vs $\nu$

HERMES, PLB 577 (2003) 37
Multiplicity ratio for identified hadrons vs $\nu$
Experimental findings:

\[ \pi^+ = \pi^- = \pi^0 \sim K^- \]

\[ K^+ > K^- \]

\[ p > \bar{p}, p > \pi, p > K \]
Multiplicity ratio for identified hadrons vs $z$

Different FF modification for quark and anti-quark

Different $\tau_h$ for mesons and baryons

Different $\sigma_h$:
- $\sigma_{\pi^+} = \sigma_{\pi^-} \approx 20$ mb
- $\sigma_{K^+} \approx 17$ mb, $\sigma_{K^-} \approx 23$ mb
- $\sigma_p \approx 40$ mb, $\sigma_{p^-} \approx 60$ mb

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Multiplicity ratio on He, Ne, Kr

Data suggest $\alpha \sim 2/3$

nuclear attenuation: $1 - R^h = A^\alpha$
Multiplicity ratio vs $Q^2$

Dependence on $1 < Q^2 < 10 \text{ GeV}^2$: stronger at small $\nu$, weaker at high $\nu$

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Data show a $p_t$ enhancement similar to that observed in $pA$ scattering at $p_t \sim 1-2$ GeV.

Cronin effect: in $pA$ and $AA$ collisions hadrons gain extra transverse momentum due to the multiple scattering of projectile partons propagating through the nucleus.

In DIS neither multiple scattering of the incident particle nor interaction of its constituents $\rightarrow$ FSI contribution to the Cronin.

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**$P_t$ dependence for identified hadrons**

Dependence of the Cronin effect on the hadron species. Cronin effect for protons larger than for pions.

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Hadrons and Pions @ $E_{\text{beam}}=12$ & $27$ GeV

Extension of the $\nu$ range down to $2$ GeV

Measurements are in progress at HERMES
$2<\nu<23$ GeV $Q^2<10$ GeV$^2$

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12 GeV Anticipated Data

<table>
<thead>
<tr>
<th>$Q^2 = 2 \text{ GeV}^2$</th>
<th>$Q^2 = 3 \text{ GeV}^2$</th>
<th>$Q^2 = 4 \text{ GeV}^2$</th>
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<td>$\nu = 9 \text{ GeV}$</td>
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$Q^2 = 9 \text{ GeV}^2$

$\nu = 9 \text{ GeV}$

$R_{\mu}^{n+}$

14N
40Ar
84Kr
197Au

$Z$

$Z$

$Z$

$Z$

$Z$

$Z$
Examples of Experimental Data and Theoretical Predictions

Bins in yellow are accessible at 6 GeV
Theoretical Models At work
Models based on (pre-)hadronic absorption


T. Falter et al.,: nucl-th/0406023.


Models based on partonic energy loss


Gluon Bremsstrahlung

FF modification: Nuclear Suppression + Induced Radiation

Nuclear suppression: interaction of the $qq$ in the medium.
Energy loss: induced gluon radiation by multiple parton scattering in the medium.
Gluon Bremsstrahlung

B. Kopeliovich et al.,
NPA 740, 211 (2004)

Q²-dependence: mainly due to Induced Radiation.

Good description of ν, z, Q² and P⁺-dependence.
FSI in BUU Transport model

$\gamma$-A eA reaction splitted in 2 parts:

$-\gamma^* N \rightarrow X$ using PYTHIA & FRITIOF

-propagation of final state $X$ within BUU transport model.

- pre-hadron $\tau_F = 0.5$ fm,
  $\sigma^*$ by constituent quark model:
  $\sigma_{\text{meson}}^* = \#q_{\text{orig}}/2 \ \sigma_{\text{meson}}$

- purely absorbitive FSI
FSI in BUU Transport model

HERMES @ 12 GeV ($\tau_f=0.5\ \text{fm/c}$)

Model seems to work also at lower energy
FSI in BUU Transport model

- Jefferson Lab ($\tau_f = 0.5$ fm/c)
  - CLAS detector
    - larger geometrical acceptance
    - detects more secondary particles from FSI
  - CEBAF
    - lower energy
    - strong effect of Fermi-motion
FF modification

due to multiple parton scattering and induced parton energy loss
(without hadron rescattering)
pQCD approach: LPM interference effect → $A^{2/3}$ dependence

- 1 free parameter $C \equiv \text{quark-gluon correlation strength in nuclei.}$
- From $^{14}$N data $C = 0.0060 \text{ GeV}^2$:
  \[
  \Delta E = n < \Delta z_g > \propto C \alpha_s^2 m_N R_A^2
  \]
  \[
  < \frac{dE}{dL} > \approx 0.5 \text{ GeV/fm}.
  \]
dE/ dL and Gluon density at RHIC


\[ \Delta E_{\text{sta}} \propto \rho_0 R_A^2; \quad \rho_0 \text{ gluon density and } R_A \approx 6 \text{ fm} \]

\[ \Delta E_{\text{exp}} \approx \Delta E_{\text{sta}} (2\tau_0/R_A); \quad \tau_0 \text{ initial formation time of dense medium} \]

PHENIX: hot, expanding system.
HERMES: cold, static system.

\[ dE/dL_{\text{PHENIX}} \big|_{\text{Au}} \text{ predictions determined by using } C=0.0060 \text{ GeV}^2 \text{ from HERMES data.} \]

\[ \text{Gluon density in Au+Au} \sim 15 \text{ times higher than in cold matter} \]
FF modification + formation time effect

F. Arleo et al.,
NPA715(2003)899

- Gluon transport coefficient fixed from Drell-Yan
  \( \hat{q} = 0.14 \text{ GeV}^2 / \text{fm} \)

\[ \langle -dE / dL \rangle_{\text{cold} \text{ final}} \approx 0.6 \text{ GeV} / \text{fm} \]

With formation time effect

Without formation time effect
Models summary.

Absorption Models:

Important role of the pre-hadron formation and interaction. Hadron formation mainly outside the nucleus. Induced radiation smaller contribution compared to absorption. ⇒ Strong dependence on the pre-hadron interaction cross section.

Energy loss models:

Energy loss mechanism mainly, competing processes play a modest role. ⇒ Strong dependence on the gluon transport coefficient that reflects the medium gluon density.
Observables sensitive to the model assumptions.

• Investigation of the $Q^2$-dependence of the nuclear effects.

• $p_t$-broadening and its $z$-dependence.

• Investigation of the $Q^2$-dependence of “grey tracks” (GT) in SIDIS:
  $A(e,e'B)X$ where the recoil nucleus B does not survive, but breaks in fragments (predominantly protons) with few-hundred MeV/c momenta.

• Double/single hadron production
Double hadron/single hadron production

\[
R_{2h}(z_2) = \left( \frac{\frac{d^2N(z_1,z_2)}{dN(z_1)}}{\frac{d^2N(z_1,z_2)}{dN(z_1)}} \right)_A \cdot \left( \frac{\frac{d^2N(z_1,z_2)}{dN(z_1)}}{\frac{d^2N(z_1,z_2)}{dN(z_1)}} \right)_D
\]

Number of events with at least 2 hadrons \((z_{\text{leading}} = z_1 > 0.5)\)

Number of events with at least 1 hadron \((z_1 > 0.5)\)

If FSI effect: double-hadron over single hadron ratio is expected to be smaller in nucleus compared to deuterium.

If Energy loss effect: double-hadron over single hadron ratio in nucleus and deuterium is expected close to unity.
Double/single hadron production

- Reduction of $R_{2h}$ compared to 1
- Small variation with $A$. 
Double/single hadron production

- All $h \rightarrow$ rank 1, 2, 3
- No +− and −+ $\rightarrow$ no rank 2, only 1, 3
- Stronger reduction for higher rank (produced before, more inside the nucleus)

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Double/single hadron production


FSI in BUU Transport model

• Pre-hadron $\tau_F = 0.5$ fm,

$\sigma^*$ by constituent quark model:

$\sigma^*_{\text{meson}} = \frac{\# \text{q}_{\text{orig}}}{2} \sigma_{\text{meson}}$

• Purely absorptive FSI
Double/single hadron production


- Computation of dihadron FF and its modification from higher twist correction in DIS
Summary and outlook

HERMES is providing new results on hadron production in e-nucleus interaction:

- Nuclear attenuation in a new kinematical range, \( v, z, Q^2, p_t^2 \), for \(^4\text{He}, ^{14}\text{N}, ^{20}\text{Ne}, ^{84}\text{Kr}\).
- First measurements for identified hadrons: \(\pi^+, \pi^-, \pi^0, K^+, K^-, p, \bar{p}\).
- First observation of hadron-type dependence of the attenuation and of the Cronin effect.
- Ratio of double/single hadron production in A and D.

Measurements are in progress: D, Kr, Xe

The combination of HERMES and the upcoming Jlab data will provide new insight into:

- Space-time properties of hadron formation
- Fundamental process of gluon emission.

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Back slides
Multiplicity ratio on He, Ne, Kr

HERMES PRELIMINARY

sys. uncer. Ne(He) - 4.5 %
sys. uncer. Kr - 7.2 %

sys. uncer. Ne(He) - 3.0 %
sys. uncer. Kr - 3.5 %

INFIN Frascati

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• Internal storage cell
• Pure gas target, no dilution factor
• Nuclear targets: (H, D), $^3$He, $^4$He, $^{14}$N, $^{20}$Ne, $^{40}$Ar, $^{84}$Kr, $^{131}$Xe
• Densities: $\sim 10^{15} - 10^{17}$ nucl/cm$^2$
Particle Identification

Positron - hadrons separation:

Double radiator RICH: Aerogel + $C_4F_{10}$. Cerenkov photons detected by $\sim4000$ PMTs.

Detection efficiency: 99% ($\pi$), 90% (K), 85-95% (p)
Model interpretations

Deconfinement and absorption

(Pre-)hadron Final State Interaction

FF modification and transport coefficient
Model interpretations

- Gluon Bremsstrahlung model (energy loss, (pre-) hadron int.)

- String Model (full absorption)

- FF modification by pure induced energy loss
Gluon Bremsstrahlung

FF modification: Nuclear Suppression + Induced Radiation

- **Vacuum energy loss**: $q \rightarrow gq'$
  
  \[ \frac{dE}{dz} \sim 2.5 \text{ GeV/fm} \text{ by E772/E866 for DY on nuclei} \]

- **Energy loss induced by multiple interactions in the medium**
  
  (rising in $p_t$)

- **Color Transparency of the $qq$ ($\sim 1/Q^2$)**

\[
\widetilde{D}_{h/q}(z_h, Q^2) = \int_0^\infty dt W(t, z_h, Q^2)
\]

\[
\langle Q^2 \rangle = 3 \text{ GeV}^2
\]

\[
\langle \nu \rangle = 12 \text{ GeV}
\]

\[
z_h = 0.5, 0.6, 0.7, 0.8, 0.9
\]
Only prediction for $h$ containing target valence quark.

Good agreement also for $K^+$
FF and their QCD evolution are described in the framework of multiple parton scattering (DGLAP).

- The emitted $g$ and the leading $q$ propagate coherently → Landau-Pomeranchuk-Midgal interference effects.
- Different modification of quark and antiquark FF.

**Rescattering without gluon radiation:** $p_T$-broadening.

**Rescattering with another $q$:** mix of $q$ and $g$ FF.

**$g$-rescattering including $g$-radiation:** dominant contribution in QCD evolution of FF.

- The emitted $g$ and the leading $q$ propagate coherently → Landau-Pomeranchuk-Midgal interference effects.
- Different modification of quark and antiquark FF.
Rescaling + Absorption Model

\[ \lambda_A > \lambda_N; \quad \xi_A(Q^2) = \left( \frac{\alpha_s(\mu_A^2)}{\alpha_s(Q^2)} \right) \]

\[ q_f^A(x, Q^2) = q_f(x, \xi_A(Q^2)Q^2) \]

\[ D_f^{h|A}(z, Q^2) = D_f^h(z, \xi_A(Q^2)Q^2) \]

Nice agreement for p+, p-, K+ with Q²-rescaling + nuclear absorption (lower curves).
(Pre-)Hadron FSI and formation times

T. Falter et al., nucl-th/0303011

\[ R_M \text{ is very sensitive to the } \sigma_{\text{pre-h}} : (\sigma_{\text{pre-h}} = 0.33 \sigma_h) \]

\[ \tau_f > 0.5 \text{ fm/c compatible with data} \]
**DIS Tomography**

- **Energy Transfer**: $\nu = E - E'$
- **Radiative Energy Loss Fraction**: $\langle \Delta z \rangle$

**Equations**:

\[ x_B = \frac{Q^2}{(2p \cdot q)} \]
\[ x_A = \frac{1}{m_N R_A} \]

\[ \langle \Delta z \rangle = \tilde{C}(Q^2) \frac{C_A \alpha_s^2(Q^2)}{N_c} x_B \frac{1}{6 \ln \frac{2}{x_B}} \]

\[ \langle -\frac{dE}{dL} \rangle_{\text{cold}} \approx 0.5 - 0.6 \text{ GeV / fm} \]

**Graphs**:

Gluon transport coefficient fixed from Drell-Yan
\[ \hat{q} = 0.14 \text{ GeV}^2 / \text{fm} \]

Finite formation time

Large number of scatterings approximation

\[ \langle -dE / dL \rangle_{\text{final}} \approx 3 \langle -dE / dL \rangle_{\text{initial}} \]

\[ \langle -dE / dL \rangle_{\text{cold final}} \approx 0.6 \text{ GeV} / \text{fm} \]

\( \rho^0 \) and particle rank

\( z_1 > 0.5, \text{ all } h \)

\( z_1 > 0.5, \text{ only } ++, --, -0, 0-, +0, 0+, 00 \)

Clear \( \rho^0 \) suppression excluding +-, -+

Signals from \( \rho^+ \) and \( \rho^- \)
The $\rho^0$ contribution does not affect the results significantly; The differences between all-$h$ and $++,--,...$ are not due to the $\rho^0$ contribution.