Hadron Suppression in DIS @HERMES

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(on behalf of the HERMES Collaboration)

• DF and FF modification in a nuclear medium
• Nuclear attenuation measurements at HERMES
• Comparison with theory
• Hadron re-interaction vs partonic energy loss

Quark and Matter, Oakland Jan 11-17, 2004
DF and FF on Nucleon & Nuclear Medium

\[ d\delta^h(z) \quad q_f(x) \quad D^h_f(z) \]

Interpretation at both hadronic (nucleon's binding, Fermi motion, pions) and partonic levels (rescaling, multi-quark system)

Inclusive DIS on nuclei: EMC effect
DF and FF on Nucleon & Nuclear Medium

\[ d\frac{\Delta^h}{\Delta f}(z) \quad q_f(x) \quad d\frac{\Delta_f}{f} \quad D^h_f(z) \]

FFs are measured with good precision and follow pQCD evolution like DFs (HERMES: EPJ C21(2001) 599). What happens in a nuclear medium?
**Nuclear Attenuation**

**Observation:** reduction of multiplicity of fast hadrons due to both hard partonic and soft hadron interaction.

Production and Formation Time measurements + FFs are crucial for the understanding of the space-time evolution of the hadron formation process.
The energy range is well suited to study quark propagation and hadronization.

Measurements over the full z range

Possibility to use several different gas targets

PID: $\pi^+$, $\pi^-$, $\pi^0$, $K^+$, $K^-$, p, $\bar{p}$
It is an experiment which studies the spin structure of the nucleon ... and not only ...

- $27.5 \text{ GeV} e^+, I_e \sim 40 \text{ mA}$

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

(NIM A343 (1994) 334)

- 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$^{-2}$
The Spectrometer

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

(NIM A417 (1998) 230)
Particle Identification

Positron - hadrons separation:

Double radiator RICH: Aerogel + $\text{C}_4\text{F}_{10}$. Cerenkov photons detected by ~4000 PMTs.

Detection efficiency: 99% ($\pi$), 90% (K), 85-95% (p)
• Clear nuclear attenuation effect
• Increase with 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
Hadron Attenuation

EMC

- Significant attenuation of fast forward hadrons
- HERMES data provide information in the unexplored region $z > 0.8$

SLAC

- HERMES
Hadron separation vs \( Q^2 \)
Hadron separation vs \[\square\]

HERMES, PLB 577 (2003) 37
Hadron separation vs □

Experimental findings:

□^+ = □^− = □^0 \sim K^−

K^+ > K^−

p > p, p > □, p > K
Hadron separation vs \( z \)

Different FF modification for quark and anti-quark

Different \( R_h \) for mesons and baryons

Different \( R_h \):
\[
\begin{align*}
R^+_{p} & = R^-_{p} = 20 \text{ mb} \\
R^+_{p} & = 17 \text{ mb}, R^-_{p} = 23 \text{ mb} \\
p & = 40 \text{ mb}, p^- & = 60 \text{ mb}
\end{align*}
\]
Nuclear Attenuation on He, Ne, Kr
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Large effect as a function of the atomic mass number

Assuming the dependence: \( A^\pi = 1 - R^h_{\text{att}} \)

Data suggest \( \alpha \sim 2/3 \)
Nuclear Attenuation on He, Ne, Kr
Nuclear Attenuation vs $Q^2$

Dependence on $Q^2$: stronger at small $Q^2$, weaker at high $Q^2$
$P_t$ dependence

In pA collisions the p gains extra transverse momentum due to random soft collisions. Partons enter the final hard process with extra $k_t$ (Cronin eff.)

\[ \square_{pA} = A(\square_{pA})_{pp} \]

Multiple parton scattering effects become dominant at $p_t \sim 1-2$ GeV
**$P_t$ dependence**

In pA collisions the $p$ gains extra transverse momentum due to random soft collisions. Partons enter the final hard process with extra $kt$ (Cronin eff.).

Multiple parton scattering effects become dominant at $p_t \sim 1-2$ GeV at RHIC and PHENIX.
\( P_t \) dependence

In DIS neither multiple scattering of the incident particle nor interaction of its constituents complicate the interpretation.

Data show a \( P_t \) enhancement similar to that observed in \( pA \) scattering (Cronin effect).

The hard component of incoherent parton scattering becomes dominant at \( P_t \sim 1-2 \) GeV.

Clean and reliable information on quark transport in 'cold' nuclear matter.
Comparison with Theory

- F Arleo
- FF modification
- energy change

- T Falter
- FSI
- Transport model

- Bialas
- Gyulassy
- Formation Time

- A Accardi
- $Q^2$ rescaling
- Nucl absorption

- B Kopeliovich
- Ind radiation
- $h$ rescatt

- XN Wang
- Parton energy loss
- Induced rad
Gluon Bremsstrahlung

FF modification: Nuclear Suppression + Induced Radiation

- **Vacuum energy loss**: $q \rightarrow gq'$.
  
  (dE/dz $\sim$ 2.5 GeV/fm by E772/E866 for DY on nuclei)

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

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

\[
\widetilde{D}_{h/q} (z_h, Q^2) = \int_0^\infty dW(t, z_h, Q^2)
\]
Fast pions are consistent with GB model (production length \( l_p \) \((1-z_h)\overline{\pi}/Q^2\) vanish at \( z_h \to 1\))
Only prediction for h containing target valence quark.

Good agreement also for $K^+$
Gluon Bremsstrahlung

Combined effects:
• pre-hadron shrinks at large $Q^2$
• larger nuclear transparency
• production lengths contracts

Good description;
Faster rise at high $P_T$?
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.**

X.N.Wang et al., 
NPA 696 (2001) 788
PRL 89 (2002) 162301
FF modification
(parton energy loss)

•1 free parameter tuned on $^{14}$N (quark-gluon correlation strength inside nuclei)

•$dE/dx$ for HERMES $\rightarrow dE/dx$ for PHENIX (Au)

X.N. Wang et al.,
NPA 696 (2001) 788
PRL 89 (2002) 162301
Gluon Density

\[ E_{\text{exp}} = \frac{E_{\text{sta}} (2R_0/R_{\text{A}})}{2R_0 R_{\text{A}} R_0} \]

• Cold \(\leftrightarrow\) Hot nuclear matter correlation

• Gluon density in Au+Au \(\sim\) 15 times higher than in cold matter

Rescaling + Absorption Model

\[ \square_A > \square_N; \quad \square_A(Q^2) = \frac{\square_N^2}{\square_A^2} \]

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

\[ D_{f^A}(z, Q^2) = D_{f^h}(z, \square_A(Q^2)Q^2) \]

Nice agreement for p+, p-, K+ with \( Q^2 \)-rescaling + nuclear absorption (lower curves).
\( R_M \) is very sensitive to the \( \tau_{\text{pre-h}} \); (\( \tau_{\text{pre-h}} = 0.33 \, \tau_h \))
\( \tau_{\text{c}} > 0.5 \, \text{fm/c} \) compatible with data
FF modification + transport coef.

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

- Energy loss taken into account
- Soft gluons radiated in the dense QCD medium (transport coefficient calculated from DY)
- Nice agreement with both

With formation time effect

Without formation time effect

With formation time effect

Without formation time effect
Disentangling absorption and induced energy loss

In case of absorption, suppression for double-hadron production is SMALL compared to single-hadron production.

Could it be too naïve?

\[ R_2 = \frac{R^{2h}}{R^{1h}} \]

\( R_2 \) depends on:

- hadron production length
- local nuclear density
- absorption cross section
- \( p_+, z_1, z_2, \ldots \)
Disentangling absorption and induced energy loss

Preliminary $R_2$ calculated for Kr/D and N/D:

- $p > 7 \text{ GeV}, E_h > 1.4 \text{ GeV}, z_{\text{leading}} > 0.5$
- opposite charges neglected (rank-2)

$R_2(\text{Kr/D}) = 0.929 \pm 0.025$

$R_2(\text{N/D}) = 0.946 \pm 0.018$

Results from STAR show jet suppression is due to FSI (energy loss). No contribution from absorption ...
Disentangling absorption and induced energy loss

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\]

Results from STAR show jet suppression is due to FSI (energy loss). No contribution from absorption ... high $Pt$ events, different $z_h$ distributions. It’s difficult to compare HERMES-RHIC ... for the moment.
Conclusions

- Significant hadron suppression, in a wide region of the kinematical plane, measured for $^4$He, $^{14}$N, $^{20}$Ne, $^{84}$Kr
- First observation of hadron-type dependence of the attenuation: $\pi^+$, $\pi^-$, $\pi^0$, $K^+$, $K^-$, $p$, $\bar{p}$
- Large atomic mass number dependence
- The Cronin effect has been observed: transition occurs at $P_t \sim 1$ GeV
- Large final hadron re-interaction is unlikely
- Pre-hadronic re-interaction and/or partonic energy loss?

Outlook: Disentangle between $\bar{p}$ and $z$ dependence

$P_t$ broadening for different hadrons
Double/Single-hadron ratio
Conclusions

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GOAL

To obtain unambiguous information on hadron formation and transport in Cold Nuclear Matter

Double/Single-hadron ratio

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

Extension of the range down to 2 GeV