Particle Production and Propagation
in Nuclei

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an overview of
mostly \( e^- A \to h + X \)

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Is the nucleus just a “sum” of protons and neutrons?

If so, in DIS the photon would only see a bigger target, but the same number of hadrons per scattered electron would be produced:

\[
\frac{1}{N_A^\ell} \frac{dN_A^h}{dz} = \frac{1}{N_D^\ell} \frac{dN_D^h}{dz} \times R_M^h(z)
\]

with \( R_M^h(z) = 1 \).

BUT experimentally: \( R_M^h(z) \neq 1 \implies \text{NUCLEAR EFFECTS} \)

What is changing inside the nucleus?

- virtual photon penetration in the nucleus?
- quark composition of the nucleons? √
- struck quark propagation?
- hadron creation process? √
- hadron propagation (nuclear absorption)? √
**DIS and hadron production**

![Diagram of DIS and hadron production](image)

**Kinematic variables**

\[
\begin{align*}
    x &= \frac{-q^2}{2q \cdot P} = \frac{Q^2}{2M \nu} \\
    \nu &= \frac{q \cdot P}{\sqrt{P^2}} = E_\ell - E'_{\ell} \\
    z &= \frac{q \cdot p}{q \cdot P} = \frac{E_h}{\nu} \\
    Q^2 &= -q^2 = 2Mx\nu
\end{align*}
\]

**Experimentally**

Hadron production presented in terms of the multiplicity ratio

\[
R_M^h(z) = \frac{1}{N_A^\ell} \frac{dN_A^h}{dz} / \frac{1}{N_D^\ell} \frac{dN_D^h}{dz}
\]

Experiments: \( R_M^h(z) \neq 1 \implies \text{NUCLEAR EFFECTS} \)

**Theoretical models**

- nuclear absorption Bialas & Chmaji '83, Bialas & Gyulassy '87
- gluon-bremsstrahlung model Kopeliovich et al. '95
- higher-twist effects Guo & Wang '00, Qiu & Sterman '01, Wang '02
- rescaling models
Speculation about Higher twist Effect

from q-Gluon correlations (G. Sterman et al.)

\[ f_{q_0}(x_1, x_2, x_3) = \prod_i \left( \frac{dy_i}{2\pi} \right) e^{ip^+ \sum x_i y_i} \]

\[ \langle A(p)| \bar{q}(y_2) \gamma^+ F_2^+(y_2) F_2^+(y_3) q(0) | A(p) \rangle \]

\[ \Rightarrow \langle k^2 \rangle_A = \langle k^2 \rangle_n + \lambda^2 A^{1/3} \quad \chi = 0.26 V^2 \]

(Miccau hep-ph/9309128)
(X. N. Wang PRL 77(1996))
Bethe-Heitler Scattering Cross sections

\[ \frac{dn}{dl} \propto \frac{3 \alpha s (\vec{P}_i^2)}{\pi^2} \frac{4}{\omega} \frac{\vec{P}_i^2}{R_i^2 (\vec{P}_i^2 - \vec{P}_f^2)^2} \]

\[ \frac{dE_{\text{con}}}{dz} = -\frac{d}{dz} \int d^2k_1 \int w \, dw \frac{dn}{dw \, d^2k_1} \]

Cut \( \varepsilon \)

Time to separate photon from quark: \( \Delta T_s = \frac{z_s}{c} \)

\[ \frac{1}{\Delta T_s} = \frac{k_i^2}{\alpha(1-\alpha)} \frac{2E_q}{z} \approx \frac{k_i^2}{2\omega} = \frac{A}{z} \]

\( \frac{(\alpha, k_i)}{(4-\alpha, \vec{k}_f)} \)

Cut-off in energy (\( \varepsilon \)): \( \omega = \frac{z k_i^2}{z} = \text{Cut}(\varepsilon) \)

\[ \frac{dE_{\text{con}}}{dz} \propto \frac{3}{\pi^2} \left< \vec{P}_i^2 \right> \ln(\alpha s(\vec{P}_i)) \quad (k_i^2 \leq P_i^2) \]
\[ \langle \mathbf{p}^2 \rangle \sim \frac{\mathbb{E}}{A} \]

\[ \langle \mathbf{p}^2 \rangle_0 \frac{Z}{A} \]

\[ \lambda = \text{m.f. path} = \frac{4}{\delta qn} \mathbb{E}(b) \]

In my work (M.P. and P. Chiappetta NP B 284 (1984) 765) \[ Q^2 \] dependence cancels in \( \langle \mathbf{p}^2 \rangle \) and \( \frac{1}{\delta qn} \).

Typical \( \lambda \approx 20 \text{ fm} \); \( \langle \mathbf{p}^2 \rangle \approx 16 \text{ GeV}^2 \)

\[ E_{\text{elon}}(R_A) = \frac{3}{\pi^2} \int_0^{R_A} \left\langle \mathbf{p}^2 \right\rangle_0 \frac{Z}{A} \, dz \]

\[ = \frac{3}{\pi^2} \left\langle \mathbf{p}^2 \right\rangle_0 \frac{1}{2} \frac{R_A^2}{2} \]

Compare string energy loss & induced radiation:

<table>
<thead>
<tr>
<th></th>
<th>Mean traversal length:</th>
<th>( R_A (2R_A) )</th>
<th>String lon</th>
<th>Rad. lon</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N^4 )</td>
<td></td>
<td>2.76 GeV</td>
<td>5.4 GeV</td>
<td>0.3 GeV</td>
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<td></td>
<td></td>
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<td></td>
<td>1.2 GeV</td>
</tr>
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<td>( \text{Pb}^{208} )</td>
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<td>6.5 GeV</td>
<td>13 GeV</td>
<td>6.8 GeV</td>
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<td></td>
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</tbody>
</table>

Can one measure \( \left\langle \mathbf{p}^2 \right\rangle \)?
The radiation of a gluon takes the time
\[ t \approx \frac{2t}{k_T^2} \alpha(1 - \alpha). \]

The result projection leads to the fragmentation function of the quark into the hadron, which reads
\[ D(z_h) = \int_0^\infty dt W(t, \nu, z_h), \]
where \( W(t, \nu, z_h) \) is a distribution function of the leading hadrons over the production time
\[
W(t, \nu, z_h) \propto \int_0^1 \frac{d\alpha}{\alpha} \delta \left[ \alpha - 2 \left( 1 - \frac{z_h \nu}{E_q(t)} \right) \right] \int \frac{dk_T^2}{k_T^2} \delta \left[ k_T^2 - \frac{2\nu}{t} \alpha(1 - \alpha) \right] \times 
\int dt \frac{\delta [l_T^2 - \frac{9}{16} k_T^2]}{t} \int d\beta \delta \left[ \beta - \frac{\alpha}{2 - \alpha} \right] |\Psi_h(\beta, l_T)|^2.
\]

the quark energy \( E_q(t) = \nu - \Delta E_{\text{rad}}(t) \). We have chosen a hadronic wave function light-cone representation which satisfies the Regge end-point behaviour, \(|\Psi_h(l_T, \beta)|^2 \propto \frac{1}{(1 + l_T^2 r_h^2)^{-1}}\), where \( r_h \) is the charge radius of the hadron.
Nuclear absorption & rescaling of FF's

nucl. abs. factor = probability of exiting from the nucleus:

\[ N_A = \int d^2 b \int_{-\infty}^{\infty} dy \rho_A(b, y) [S_A(b, y)]^{A-1} \]

\[ S_A(b, y) = 1 - \sigma_h \int_y^{\infty} dy' P_h(y' - y) \rho_A(b, y') \]

prob. that \( h \) is formed at \( y' - y \) from interaction point:

\[ P_h(y' - y) = \left(1 - e^{-(y' - y)/\tau_F}\right) \]

Change of confinement scale in \( A \):

\[ \lambda_0 Q_0 = \lambda_A Q_A \]

\( Q_0 = \) start of DGLAP evolution

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

\[ D_{f}^{h|A}(x, Q) = D_{f}^{h}(x, \xi_A(Q) Q) \]
LUND string model & formation times
A. Bialas & H. Gyrlescu (1987)

Lorentz dilatation of rest-frame form. time:

$$\tau_F = \frac{z_h \nu}{m_h} \tau_0 \propto z_h \nu$$

see also Kopeliovich et al. '96 + recent talks
Airapetian et al. (HERMES) '01
Model vs. HERMES data

A.A, Muccifora, Pirner '03

- two-step hadronization
- $\sigma_q = 0 \quad \sigma_\ast = \sigma_h$
- $\tau_f \propto (1 - z_h) \nu$

free parameter:
"string tension k"

K$^-$ overestimated: (u,s not valence quarks of proton $\Rightarrow$ $T_f(K) < T_f(K^+)$
no final generation

shorter form. time
(or $\sigma_\ast$ - less natural)

$$\frac{dN_A}{dz} \frac{4}{N_A} = \frac{1}{\sigma_{\text{tot}}} \int d\epsilon d\nu \epsilon \sum_{f} e_f^2 q_f^2 \left( x \sigma_A \epsilon^2 \right) \frac{d\sigma}{dz} d\epsilon \epsilon^2 \left( z, \sigma_A \epsilon^2 \right) .$$

$N_A (z, \nu)$
Parton energy loss or final state interactions (FSI)?

STAR

energy loss
long formation times
FSI
short formation times

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Conclusions

- HERMES data have good precision for detailed study
- Formation times and assumptions vary strongly from model to model
- Both absorption and energy-loss models account for data

How to decide?

- K- production
- A systematics
  (D, N, Ne, Kr data available - Xe planned at HERMES: A=2-131)
- Study observables different for absorption and en. loss

Lessons from heavy-ions: Cronin effect?
  Two-particle azimuthal correlations?