Hadronization via $\pi$ electroproduction off nuclear targets

Taisiya Mineeva
Why study hadronization?

- Mysterious: how all the color from initial state is neutralized into colorless hadrons, dynamical enforcement of confinement
- Fundamental: comes from non-Abelian feature of QCD
QGP produced in high-energy nuclear interactions. In addition, such cold QCD matter can be obtained from nDIS and DY data, allowing one to test the hadronisation mechanism and colour confinement dynamics, as already emphasised 30 years ago by B. Jackson.

The lifetime of the freely propagating quark may be related to the mechanism leading to colour neutralisation, which is only implicit in the traditional treatments of confinement based on potential models [31] or lattice QCD [32].

DIS process, a quark is briefly liberated from being associated with the nuclear target, traveling as a "free" particle, and it is the mechanisms involved in hadronisation starting at the nuclear radius scale or before. In this case, in-medium hadronisation mechanisms can explain the observed suppression pattern.

Such mechanisms may be especially important in the case of heavy (charm, bottom) quarks, which – being slower than light-quarks or gluons – can fragment only after traversing the medium. This assumption is that the observed suppression pattern is due to parton energy loss in the strongly interacting medium. This assumes of course that the quenched light-quarks and gluons are long-lived enough to traverse the medium before hadronisation.


Fig. 2. – Quark propagation inside a target nucleus (“cold QCD matter”) in lepton-nucleus (left) and hadron-nucleus (right) collisions.

**Production time** $\tau_p$ - propagating quark  
**Formation time** $\tau_f$ - dipole grows to hadron
Deep-Inelastic Scattering in Medium

**Hadron forms outside the medium or ....**

Partonic multiple scattering: medium-stimulated gluon emission, broadening of pT.
Deep-Inelastic Scattering in Medium

Hadron can form inside the medium

Then additionally have prehadron/hadron interaction
Observables

Transverse momentum broadening
defined with respect to the $\gamma^*$ direction

$$\Delta p_T^2 = < p_T^2 >_A - < p_T^2 >_D$$

The production time $\tau_p$ can be presumably accessed via broadening($A$)

Hadronic multiplicity ratio

$$R^h_A (\nu, Q^2, z, p_T, \phi) = \frac{N_h(\nu, Q^2, z, p_T, \phi)}{N_e(\nu, Q^2)}\bigg|_{DIS} A$$

The formation time $\tau_f$ can be accessed via $R^h_A(Q^2, u, p_T, z_h)$
Observables

Transverse momentum broadening
defined with respect to the $\gamma^*$ direction

Not in this talk

The production time $\tau_p$ can be presumably accessed via broadening($A$)

Hadronic multiplicity ratio

$$R_h^A (\nu, Q^2, z, p_T, \phi) = \frac{\frac{N_h (\nu, Q^2, z, p_T, \phi)}{N_e (\nu, Q^2)|_{DIS}^A}}{\frac{N_h (\nu, Q^2, z, p_T, \phi)}{N_e (\nu, Q^2)|_{DIS}^D}}$$

The formation time $\tau_f$ can be accessed via $R_h^A (Q^2, u, p_T, z_h)$
CLAS: experiment, analysis, results
Experiment

CLAS EG2 (2004)
- Electron beam 5.014 GeV
- Targets $^2$H, $^{12}$C, $^{56}$Fe, $^{207}$Pb (Al, Sn)
- Luminosity $2 \times 10^{34}$ 1/(s · cm$^2$)

EG2 data on C, Fe, Pb (+D) was recooked (2009) using new tracking and EC clustering algorithms: recovered 44% more ‘clean’ electrons and 90% more $\pi^0$

Integrated Statistics (C, Fe, Pb +D): 130M DIS e-; 6.6 M $\pi^+$, 2.8 M $\pi^-$, 2.0 M $\pi^0$
\[ \pi^0 \text{ Analysis} \]

- Electron identification using all component of CLAS detector: DC, SC, CC, EC. DIS kinematics: \( Q^2 > 1 \text{ GeV}^2 \); \( W > 2 \text{ GeV} \); \( P > 0.75 \text{ GeV} \)

- Photon identification in EC, energy corrections

- \( \pi^0 \) is reconstructed via \( 2\gamma \) inv. mass, background treated using the shape from mixing two uncorrelated events and accounting for the differences in event topology

- Acceptance correction, purity cut off

- Radiative Corrections
Semi-inclusive radiative corrections off nuclear target

Available tools

- **HAPRAD(2)**: SI RC for $\pi^+$ on proton + exclusive tail
  calculations for internal radiation are based
  on the convolution of leptonic and hadronic tensors

  I.Akushevich, A.Ilyichev, M.Osipenko, Lowest order QED radiative corrections to five-fold differential cross section of hadron leptoproduction, arXiv:0711.4789

- **SEMIRC**: SI RC for three pion states off nuclear (polarized) targets
  model for cross section is based on experimental data
  calculations for external&internal radiation
  are based on Mo&Tsai approach + exclusive contribution

  P.Bosted, note in preparation

- **RADGEN + MC Event Generator**: inclusive spectrum from RADGEN
  is input in the MC to produce SI RC
  all mesons on light nuclei

  HERMES

* Original code written in FORTRAN, adaptation to C++: https://github.com/usm-data-analysis/HAPRAD_cpp
Semi-inclusive radiative corrections off nuclear target

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Semi-inclusive RC from modified HAPRAD (1)

**HAPRAD formalism (SI)**

\[
\sigma_{SIDIS} = \sigma_{SIDIS}(H_1, H_2, H_3, H_4)
\]

\[
H_1 = \sum_q e^2 f_q D_q G
\]

\[
H_2 \approx H_1
\]

\[
H_3 = f(x, Q^2, z) |_{cos(\phi)} \sum_q e^2 f_q D_q G
\]

\[
H_4 = f(x, Q^2, z) |_{cos(2\phi)} \sum_q e^2 f_q D_q G
\]

\[
G = \frac{1}{2\pi\sigma} \cdot \exp - \frac{(p_T - \mu)^2}{2\sigma^2}
\]

Method: substitute default structure functions \((H_1, H_2, H_3, H_4)\) on proton by those on nuclei by performing fit to transverse momentum distribution \(G\) on a given dataset.
A slice of acceptance corrected $p_T$ distribution (red points) for $\pi^0$ candidate in $(x,z)$ bins on the example of iron target.

Blue line illustrates Gaussian fit to $p_T$ performed simultaneously in $(x,z)$. The parametrization of $p_T$ with $\mu(x,z)$ and $\sigma(x,z)$ enters in $H_n$ via:

$$G = \frac{1}{2\pi \sigma} \cdot \exp\left(-\frac{(p_T - \mu)^2}{2\sigma^2}\right)$$
Semi-inclusive RC from modified HAPRAD (3)

A slice of acceptance corrected φ distributions in bins (x, Q^2, z) on the example of iron target: black points - w/o acceptance correction, red - corrected for acceptance.

Red and green curves correspond to the fit: 1 + A cos(φ) + B cos(2φ). The coefficients in the red, used in H_3, H_4, depend only on z.
Semi-inclusive RC from modified HAPRAD (4)

RC factors for D, Fe and Fe/D ratio in set of ($Q^2$, $\nu$, $z$)
Exclusive Cross Section

\[ \sigma_{\text{EXCL}} = \frac{d\sigma}{dE'd\Omega d\Omega_h^*} = \Gamma \frac{d\sigma}{d\Omega_h^*} \]

\[ \Gamma = \frac{\alpha}{2\pi^2} \frac{E'}{E} \frac{k_\gamma}{Q^2} \frac{1}{1 - \epsilon} \]

The structure functions for exclusive cross section come from two sources:
1. W<2 GeV: MAID2007 parametrization (MAID2003 in default version for \( \pi^* \))
2. W>2 GeV: Cornell interpolation * based on \( \pi^* \) electroproduction in 1.2<W<3.0 (GeV)

Alternative for \( \pi^0 \) case:
Employ structure functions from parametrization (V.Kubarovsky) based on phenomenological model (V.Kubarovsky) fitted to exclusive \( \pi^0 \) data at W>2 (GeV) **

* A. Browman et al., Electroproduction of single pions with large transverse momenta Phys. Rev. Lett. 35 (1975) 1313.
** I. Bedlinskiy et al., Measurement of exclusive \( \pi^0 \) electroproduction structure functions and their relationship to transversity GPD Phys.Rev.Lett. 109 (2012) 112001
Semi-inclusive RC + Exclusive contribution

RC factors for D, Fe and Fe/D ratio in set of (Q^2, \nu, z)

Pion Multiplicities
$R_{\pi^0}$ in 3D set of $(Q^2, \nu, z)$ integrated over $pT^2$

- Attenuation systematically increases for the larger nuclei
- Attenuation of high $z$ hadrons
- Small dependence on $Q^2$ and $\nu$

Results do not include systematic errors
\( \pi^0 \) Multiplicities

\( R_{\pi^0} \) in 3D set of \((\nu, z, pT^2)\) integrated over \(Q^2\)
\( \pi^0 \) Multiplicities: comparison

**CLAS**

\[ 2.2 < \nu < 4.2 \text{ (GeV)} \]
\[ 1. < Q^2 < 4.1 \text{ (GeV}^2) \]
\[ W^2 > 4 \]

**HERMES**

\[ 7 < \nu < 23 \text{ (GeV)} \]
\[ 1 < Q^2 < 10 \text{ (GeV}^2) \]
\[ W^2 > 10 \]
\( \pi^0 \) Multiplicities: comparison

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- Attenuation systematically increases for the larger nuclei
- Attenuation of high z hadrons, enhancement for high $pT^2$
**π⁺ Multiplicities**

**R_{π⁺} slice in 3D set of bins (Q^2, 3.2<ν<3.7, z) integrated over pT^2**

- Results do not include radiative corrections and systematic errors.

**H. Hakobyan**

**R_{π⁺} slice in 3D set of bins (1.0<Q^2<1.3, ν, pT^2) for 0.4<z<0.7**

- Results do not include radiative corrections and systematic errors.

**H. Hakobyan**

- Attenuation systematically increases for the larger nuclei.
- Attenuation of high z hadrons, enhancement for high pT^2.
Future Program

- Extraction of timescales and quark energy loses based on the finalized data analysis
- Measurement from existing EG2 set of $\pi^0$ vs $\eta$ suppression (not previously accessed in cold matter), extraction of transverse momentum broadening for both mesons.
- The program to pursue hadronization studies at CLAS12 (E12-06-117) with 11 GeV electron beam has been approved for 120 beam days. It will provide by far the best experimental access to medium-simulated quark energy loss, and enable extraction of 4D multiplicities for wide range of hadrons.
- EIC will offer high energy eA collisions with $E_{e^-}=11$ GeV/c and unpolarized heavy nuclei $E_A=12-40$ GeV/c per nucleon for $A>200$ (Au, Pb). Long parton life time, direct access to pQCD $E_{\text{loss}}$. 
Summary

- Hadronization in DIS, also Drel-Yan and heavy ion collision
- Production time related to transverse momentum broadening
- Formation time related to hadronic multiplicity ratio

- CLAS eg2 three pion state analysis, on $^2$H, $^{12}$C, $^{56}$Fe, $^{207}$Pb
- Multidimensional multiplicity analysis: 3D for $\pi^0/\pi^+$, 2D for $\pi$
- RC for $\pi$ off nuclear target + exclusive contribution

- Hadronization studies reach precision era
- Future program with CLAS12 (E12-06-117)
BACKUP SLIDES
## Accessible hadrons in CLAS

**W. Brooks**

### The tools: stable hadrons, accessible with 11 GeV experiment PR12-06-117

W.K. Brooks, J.G. Gilfoyle, K. Hafidi, M. Holtrop + 7 others not in this room

Actively underway with existing 5 GeV data

Hayk Hakobyan, Taya Mineeva, Raphaël Dupré, Lamiaa El Fassi, Aji Daniel, Ken Hicks, Ioana and Gabriel Niculescu

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Existing 2D Data on Multiplicities: HERMES


Models

Phenomenological
A. Bialas and T. Chmaj, PhL 133B (1983) 241
A. Bialas and M. Gyulassy, NPh B291 (1987) 793
one or two time scales plus corresponding cross sections

Energy loss type
E. Wang and X.N. Wang, PRL 89 (2002) 162301
F. Arleo EPJ C30 (2003) 213
gluon radiation and quark-quark interaction
effective (increased) $z$ in fragmentation function

Energy loss and absorption
B.Z. Kopeliovich, J. Nemchik, E. Predazzi, A. Hayashigaki,
NPh A740 (2004) 211
nuclear absorption cross sections after ‘formation’ time

‘Full FSI’
coupled-channel treatment of FSI by means of BUU transport model

“None of the existing models are able to describe all aspects of hadronization”, Gunar Schnell, HERMES
Analysis: Acceptance Ratio ($e\pi^0$)

$$(\nu, z, pT^2) = 108 \text{ bins}$$

$$(Q^2, \nu, z) = 54 \text{ bins}$$
Purity

\((\nu, z, pT^2)\)

**Fig. 1.25:** 3D Purities in \((\nu, z, pT^2)\) bins for Deuterium (top) and Iron (bottom). We further exclude bins from our analysis for which Purity \(< 30\%\).

Integration of multidimensional purity down to \(Q^2, \nu, z\) given purity values less by \(x\%\) on average per bin as compared to a purity calculated directly in 3D bins by integrating over all \(pT^2\) values. This difference is caused by the poor resolution in \(pT^2\). If instead we choose a different variable of integrations for example \(Q^2\) the difference between the two methods would be negligible due to a fine resolution in \(Q^2\).

Purity is not used directly but rather as a 'control distribution'. Flat cross section with perfect efficiency in \(xD\) bin which has a minimum resolution of \(x\sigma\) would yields Purity = 68\%. From this assumption we can deduct a rule of thumb asking for Purity > 68\% for an \(nD\) dimensional binning. Therefore for \(n=4\) \((\nu, z, pT^2)\)

**Fig. 1.26:** 3D Purities in \((Q^2, \nu, z)\) bins for Deuterium (top) and Iron (bottom). The example of \(pT^2\) cutoffs of the integration correspond to Deuterium from Carbon and Lead targets as determined in data. These two targets correspond to the smallest available statistics, hence larger fluctuations and more stringent cutoffs. On average, independent of which of the six \(pT^2\) cutoffs is used, purities this set of bins never drop below 50\%.
Purity

($\nu$, $z$, $pT^2$)

**Fig. 1.25:** 3D Purity values in ($\nu$, $z$, $pT^2$) bins for Deuterium (top) and Iron (bottom). We further exclude bins from our analysis for which Purity $< 30\%$.

To the reconstructed bin in all four variables simultaneously, from 4D binning there are two ways to go down in the number of dimensions in which purity is measured. Let us consider an example of 3D binning in $(Q^2, \nu, z, pT^2)$. One can either sum already calculated 4D number of counts in $(Q^2, \nu, z, pT^2, pT^2)$ over $pT^2$ or construct a new Purity in $(Q^2, \nu, z)$ requiring that reconstructed $\pi_0$ kinematics match generated kinematics in both $(Q^2, \nu, z)$ bins. The latter condition omits the requirement on the purity in $(pT^2)$ bin by simply integrating over this variable. Integration of multidimensional purity down to $(Q^2, \nu, z)$ given purity values less by $\sigma$ on average per bin as compared to a purity calculated directly in 3D bins by integrating over all $pT^2$ values. This difference is caused by the poor resolution in $pT^2$. If instead we choose a different variable of integrations for example $Q^2$, the difference between the two methods would be negligible due to a fine resolution in $Q^2$.

For illustration of the two methods refer to [?].

Purity is not used directly but rather as a 'control distribution'. Flat cross section with perfect efficiency in 1D bin with minimum resolution $1\sigma$ would have Purity = 68%. In n-dimensions this yields $(0.68)^n$. For $n=3$ dimensions we apply a cut off at Purity $> 30\%$.

**Ansatz:** flat cross section with perfect efficiency in 1D bin with minimum resolution $1\sigma$ would have Purity = 68%. In n-dimensions this yields $(0.68)^n$. For $n=3$ dimensions we apply a cut off at Purity $> 30\%$.
Purity
($\nu, z, pT^2$)

Fig. 1.25: 3D Purities in ($\nu, z, pT^2$) bins for Deuterium (top) and Iron (bottom). We further exclude bins from our analysis for which Purity < 30%.

Integration of multidimensional purity down to ($Q^2, \nu, z$) given purity values less by $\sigma$ on average per bin as compared to a purity calculated directly in 3D bins by integrating over all $pT^2$ values. This difference is caused by the poor resolution in $pT^2$. If instead we choose a different variable of integrations for example $Q^2$, the difference between the two methods would be negligible due to a fine resolution in $Q^2$.

Purity is not used directly but rather as a 'control distribution'. Flat cross section with perfect efficiency in 1D bin which has a minimum resolution of $\sigma$ would have Purity = 68%. From this assumption we can deduct a rule of thumb asking for Purity > 0.68 for an n-dimensional binning. In 4-dimensional case bins with Purity < 0.3z should be excluded, and for n=3 case we exclude bins with Purity < 0.3z. The purities of each bin in ($Q^2, \nu, z$) set exceed 0.5z and show little dependence on the target type. Meanwhile, purities in ($\nu, z, pT^2$) are significantly lower, in particular for Deuterium target; hence, the bins with Purity < 0.3z will be excluded from being presented in our final results.

Ansatz: flat cross section with perfect efficiency in 1D bin with minimum resolution 1σ would have Purity = 68%. In n-dimensions this yields (0.68)^n, n=3 dimensions we apply a cut off at Purity > 30%.
Hadronic broadening or partonic broadening?

$\rho_T$ broadening for Pb does not show any strong trend with pion energy, while hadronic elastic scattering cross section changes by an order of magnitude.