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Review on DIS Electroproduction on Nuclei

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These are preliminary lecture notes, intended only for distribution to participants
Review on DIS
Electroproduction on nuclei

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• Fragmentation Function modifications in the nuclear medium
• HERMES recent results
• Expectation from Jlab
• Interpretation
• Connection with RHIC and with LHC
DF on Nucleon & Nuclear Medium

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

Inclusive DIS on nuclei:
- EMC effect

Medium modifications of Distribution Functions:
- Interpretation at both hadronic (nucleon's binding, Fermi motion, pions) and partonic levels (rescaling, multi-quark system)
Fragmentation Functions on Nucleon

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

FFs are measured with precision in e+e-
FFs follow pQCD Q^2-evolution like DFs
FFs scale with \( z = \frac{E_h}{\nu} \) like DFs with x
FFs probabilistic interpretation like DFs

SIDIS multiplicities are also good measurements of FFs:

\[
\frac{1}{N_{DIS}} \frac{dN^h(x, z)}{dz} = \frac{\sum_f e_f^2 q_f(x) D_f^h(z)}{\sum_f e_f^2 q_f(x)}
\]
SIDIS multiplicities on Nucleon


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 Times + FF modifications are crucial for the understanding of the space-time evolution of the hadron formation process.
Hadron multiplicity ratio

Experimental observable: hadron multiplicity ratio in nuclei and deuterium

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

Determine \( R_M \) versus:

Leptonic variables: \( \nu \) (or \( x \)) and \( Q^2 \)

Hadronic variables: \( z \) and \( P_t^2 \)

Different nuclei: size and density

Different hadrons: flavors and mixing of FFs
**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.  
  http://www-hermes.desy.de/notes/pub/trans-public-subject.html#HADRON-ATTENUATION

- **CLAS**: 5.4 GeV $e^-$-beam on C, Fe, Pb  
  E-02-104
The energy range ($\nu$ 3-25 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, $\bar{p}$
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:
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 targets: by RICH $\pi$, K, p ID $2.5<p<15$ GeV
- $\pi^0$ ID by e.m. Calorimeter.
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

**References**

HERMES, PLB 577 (2003) 37


SLAC PRL 40 (1978) 1624
Experimental findings:

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

\[ K^+ > K^- \]

\[ p > \bar{p}, p > \pi, p > K \]

Different ff modification for different hadrons
Multiplicty ratio on He, Ne, Kr

Data suggest $\alpha \sim 2/3$

nuclear attenuation: $1-R^h = A^\alpha$
SIDIS show a $p_t$ enhancement similar to that observed in AA scattering. The enhancement in AA is typically explained at $p_t \sim 1-2$ GeV assuming ISI.

In SIDIS Cronin only from FSI: no multiple scattering of the incident particle nor interaction of its constituents.
Experiments with CLAS and CLAS++

(NIM A503 (2003) 513)

5.4 GeV exp. in 2003
$Q^2 \leq 4 \text{ GeV}^2$, $\nu \leq 5 \text{ GeV}$

11 GeV in 2012 (?) with Jlab upgrade
$Q^2 \leq 9 \text{ GeV}^2$, $\nu \leq 9 \text{ GeV}$

- Charged particle angles $8^\circ - 144^\circ$
- Neutral particle angles $8^\circ - 70^\circ$
- Momentum resolution $\sim 0.5\%$ (charged)
- Angular resolution $\sim 0.5 \text{ mr}$ (charged)
- Identification of $p$, $\pi^+/\pi^-$, $K^+/K^-$, $e^-/e^+$
CLAS EG2, very preliminary, 5% of total data set
DIS kinematics, $Q^2 > 1$, all $\nu$

No acceptance correction (small, two targets in the beam)
Not final calibrations (should be nearly irrelevant, bins are huge)
No fiducial cuts (probably ok, two targets in beam)
No radiative correction (effect primarily cancels in ratios)
No correction for $\pi^+$ from rho (need full statistics to correct for this)***
Few-percent kaon contamination in region 2-2.7 GeV
No isospin correction for heavy targets (~5%?)
No $x_F$ cuts

Ask this plot to Will Brooks
brooksw@jlab.org
Expectations from Hall-A E04-002

For fixed kinematics a high precision meas. at large $z$

Figure 8: Attenuation of $\pi^+$ (blue x, larger) and proton (red o, smaller) in carbon (top), copper (central) and tungsten (bottom) as a function of $z$ for $Q^2 = 2.81\,(GeV/c)^2$, $\nu = 4\GeV$ and $P_T = 0-0.25\,GeV/c$. 
Models based on pre-hadronic interaction


Important role of the pre-hadron formation and interaction:
Which time and cross section? Absorption or rescattering?
Hadron formation mainly outside the nucleus.
Induced radiation is a smaller contribution compared to absorption or rescattering.

Models based on partonic energy loss


Energy loss mechanism for the hadron suppression, parton rescattering for the enhancement at large $p_T$
Pre-hadron FSI and formation times

\[ \tau_p = 0 ; \tau_f > 0.5 \text{ fm/c compatible with data} \]

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

multiple parton scattering and induced parton energy loss (without hadron rescattering)

pQCD approach: LPM interference effect $\rightarrow A^{2/3}$ dependence

- Consistency with the quadratic nuclear size dependence $[A^{2/3}]_{th}$

- 1 free parameter $C=\text{quark-gluon correlation strength in nuclei}$.

- From $^{14}\text{N}$ data $C=0.0060$ GeV$^2$: \[ \Delta E = n < \Delta z_g > \propto C \alpha_s^2 m_N R_A^2 \]
dE/dL and Gluon density at RHIC

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

\[ \langle dE/dL \rangle \approx 0.5 \text{ GeV/fm for 10-GeV quark in Au.} \]

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

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

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

- Gluon density in hot matter much higher than in cold matter (about 30 times)
Leading hadrons at RHIC

Medium characterised by gluon transport coeff.: \( \hat{q} = \frac{\mu^2}{\lambda} \)

\( \mu = \) typical momentum transfer
\( \lambda = \) gluon mean free path

• Photons are not suppressed
• High \( p_T \) hadrons are suppressed according to pQCD + partonic energy loss
• Hadron suppression supplies only a lower limit on the energy loss
• Need to go to higher \( p_T \) to study QCD evolution
• Need to study full jet quenching
Perspectives at LHC

Why jets?

• transverse mom. of associated particles transverse to jet axis ($j_T$) are small respect jet mom.
• 80% of jet energy in $R < 0.3$
• Leading particle has only approximately the direction and energy of the original parton
• Jet as an entity (p-h duality) stays unchanged
• Map out observables as a function of parton energy
• Partons in a dense color medium loose energy via medium induced gluon radiation, “jet quenching”, depending on the gluon density of the medium

Why LHC?

• hard scattering at low x dominates particle production: huge increase in yield of hard probes
• fireball hotter and denser (and weakly interacting?), lifetime longer
• initial gluon density at LHC 5-10x RHIC
• dynamics dominated by partonic degrees of freedom
EmCal for ALICE

ALICE experiment:
• Excellent tracking: ITS, TPC
• Excellent PID: TOF, RICH, TRD
• High resolution but small acceptance Calorimetry

↓

Large acceptance EmCal for Jet and high $p_T$ physics
$\Delta \eta = 1.4$, $\Delta \Phi = 110^\circ$
Shashlik technique: 12k channels
USA - Fra - Ita collaboration

- fast, efficient trigger for high $p_T$ jets, $\gamma(\pi^0)$, electrons $\Rightarrow$ recorded yields enhanced by factor $\sim 10-60$
- markedly improves jet reconstruction through measurement of EM fraction of jet energy with less bias
- discrimination $\gamma/\pi^0$, augmenting ALICE direct photon capabilities at high $p_T$
- $e$/had discrimination, augmenting and extending to high $p_T$ the ALICE capabilities for heavy quark jet quenching studies
Summary and outlook

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

- Nuclear attenuation in a wide kinematical range, \( \nu, z, Q^2, p_t^2 \) for \(^4\text{He}, ^{14}\text{N}, ^{20}\text{Ne}, ^{84}\text{Kr} \) \(^{131}\text{Xe} \) is coming
- Effects for identified hadrons: \( \pi^+, \pi^-, \pi^0, K^+, K^-, p, p^- \)
- Clear observation of the Cronin effect in SIDIS.
- Effect in Ratio of double/single hadron production in \( A \) over \( D \) is small and with almost no \( A \)-dependence.

Measurements are also in progress at Jlab!

- Nuclear modification of the fragmentation functions
- Parton energy loss: gluon density at RHIC 30 times higher
- Perspectives at LHC for higher \( P_t \) and full jet quenching studies
Backup slides
Multiplicity ratio on He, Ne, Kr

\[ R_A^K \]

\[ R_A^p \]
Multiplicity ratio vs $Q^2$

$Q^2$ Dependence: indication of FF evolution modification
Stronger at small $\nu$ (large $x$); weaker at high $\nu$ (small $x$)
Hadrons and Pions @ $E_{\text{beam}}=12$ & $27$ GeV

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

- Measurements are still in progress at HERMES

$2<\nu<23$ GeV $Q^2<10$ GeV$^2$
Dependence of the Cronin effect on the hadron species. Cronin effect for protons larger than for pions.
**Factorization issues at Jlab**

Given the relatively low energy of Jlab (max 6 GeV) the factorization of SIDIS into DF and FF maybe questionable.

\[ \sigma^e H \rightarrow e h X = \sum_q \sigma^q \rightarrow q \otimes D^q \rightarrow h \]

Cross section reproduced by Monte-Carlo based on LO x-z factorization (Hall C).

LO x-z factorization is not (much) violated at 6 GeV.
Anticipated CLAS Data

Can measure $\pi^{+,-,0}$, $\eta$, $\omega$, $\eta'$, $\phi$, $K^{+,-,0}$, $p$, $\Lambda$, $\Sigma^{+,-0}$, $\Xi^0,-$
Expectations from CLAS++ upgrade
Disentangling hadronic and partonic effects

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

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

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 only partonic effect: double-hadron over single hadron ratio in nucleus and deuterium is expected to be close to unity.
Two hadron production

- Small effect in $R_{2h}$ compared to single hadron multiplicity
- Small $A$-dependence
Two hadron production
Soft gluons radiated in the dense QCD medium (gluon transport coefficient from DY)

Energy loss $\propto 0.6 \text{ GeV/fm}$ in agreement with X-N Wang

Nice agreement with both HERMES and old EMC data
Gluon Bremsstrahlung

FF modification: Nuclear Suppression + Induced Radiation

**Nuclear suppression**: interaction of the $\bar{q}q$ in the medium.

**Energy loss**: induced gluon radiation by multiple parton scattering in the medium
Hadron Multiplicity Ratio vs $z=E_h/\nu$

**EMC**

- Cu / D₂
- Sn / D₂

**SLAC**

- Be / D₂
- Cu / D₂
- C / D₂
- Sn / D₂

**WA21/WA59**

- $<\nu>$ = 62 GeV
- $<\nu>$ = 55 GeV

**HERMES**
Particle Identification

Positrons – hadrons separation:

Double radiator RICH: Aerogel + $C_4F_{10}$. Cerenkov photons detected by ~4000 PMTs.

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

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

\[ K^+ > K^- \]

\[ p > \bar{p}, \ p > \pi, \ p > K \]

Different ff modification for different hadrons
Rescaling + Absorption Model

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

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

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

Nice agreement for p+, p-, K+ with Q²-rescaling + nuclear absorption (lower curves).