SEARCH FOR THE ONSET OF COLOR TRANSPARENCY THROUGH $\rho^0$ ELECTROPRODUCTION ON NUCLEI

Outline

1. introduction
2. Theoretical introduction
3. Experiments
4. CLAS EG2
5. Results
6. Future $\rho^0$ measurements at JLAB
7. Conclusions
8. Backup

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Introduction

Color Transparency

is a QCD phenomenon which predicts a reduced level of interaction for reactions where the particle state is produced in a point-like configuration.
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EG2 experiment using the CLAS detector at Jefferson Lab

The Nuclear Transparency was measured in $\rho^0$ electro-production through nuclei. A signal of Color Transparency will be an increase of the Nuclear Transparency with a correspondent increase in $Q^2$. 
Coherence Length effect with the Glauber model

An approximation of scattering through Quantum Mechanics

”High-Energy collision theory”, by R.J. Glauber

Using hadron picture for Nuclear Interaction.
Coherence Length effect with the Glauber model

K. Ackerstaff, PRL 82, 3025 (1999)
Exclusive $\rho^0$ electro-production, Coherence length ($l_c$) effect

\[ l_c = \frac{2\nu}{M_V^2 + Q^2} \]

- Cross section dependence on $l_c$
- Mimics CT signal for incoherent $\rho^0$ production
QCD model and Color Transparency

What is missing in the previous model?

In the Glauber model, that gives a Quantum mechanical description of the interaction with matter, there is no mention of the particles to be considered as a composite system of quarks.
QCD model and Color Transparency

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Glauber model

No other $Q^2$ dependence other than the one due to the coherence length effect
What is it?

High $Q^2$ in the reaction will select a very special configuration of the hadron wave function, where all connected quarks are close together, forming a small size color neutral configuration.
# Point like configuration

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High $Q^2$ in the reaction will select a very special configuration of the hadron wave function, where all connected quarks are close together, forming a small size color neutral configuration.

## Momentum
Each quark, connected to another one by hard gluon exchange carrying momentum of order $Q$ should be found within a distance of the order of $\frac{1}{Q}$.
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Color Transparency

Such an object is unable to emit or absorb soft gluons $\Rightarrow$ its interaction with the other nucleons is significantly reduced
A lot of EXPERIMENTS since 1988

- Quasi-elastic A(p,2p) [Brookhaven]
- Quasi-elastic A(e,ep) [SLAC and Jlab]
- Di-jets diffractive dissociation. [Fermilab]
- Quasi-elastic D(e,ep) [Jlab - CLAS]
- Pion Production $^4He, (\gamma n \rightarrow p \pi^-)$ [Jlab]
- Pion Production A(e,ep$^+$) [Jlab]
- $\rho^0$ lepto production. [Fermilab, HERMES]
- $\rho^0$ lepto production & D(e,ep) [Jlab - CLAS]
D. Dutta, PRC 68, 021001 (2003)
Pion photo-production on $^4$He, ($\gamma n \rightarrow p\pi^-$)

at $\theta_{cm} = 70^{\circ}$

at $\theta_{cm} = 90^{\circ}$
Thomas Jefferson Lab: Hall C

B. Clasie, PRL 99, 242502 (2007)
Pion e-production on $^2H, ^{12}C, ^{27}Al, ^{63}Cu$ and $^{197}Au$, $(\gamma^* p \rightarrow n \pi^+)$

$T = \frac{Y_{MC}^A}{Y_{MC}^H}$

$T = A^{\alpha-1}$, with $\alpha \sim 0.76$
A. Airapetan, PRL 90, 052501 (2003)
Measurement of the Nuclear Transparency, incoherent $\rho^0$ prod.
$T_A = P_0 + P_1 Q^2$, with $P_1 = (0.089 \pm 0.046 \pm 0.020) \text{GeV}^{-2}$
Thomas Jefferson Lab: CLAS EG2 experiment

- Electron Beam 5GeV (50 days) & 4GeV (7 days)
- Targets: D&Fe, D&C, D&Pb
- Luminosity $\sim 2 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$
Eg2 experiment target
Eg2 experiment target
B.M. developed the Monte-Carlo simulation code. K.H and W.K.B were the run coordinators for the experiment, which lasted 3 consecutive months. H.H. implemented the targets configuration in the simulation code and X.Z. studied the systematic effects related to the determination of deuterium target thickness. K.H. coordinated the manuscript preparation. L.E., L.Z. K.H., M.H and B.M. made equivalent contributions and should be considered joint first authors. All the other authors are members of CLAS collaboration and contributed to the preparation of the experiment, data taking, data analysis review and manuscript review.
Reaction Variables and kinematical cuts

\begin{itemize}
\item $Q^2 = -(q_{\gamma^*}^\mu)^2 \sim 4E_e E_{e'} \sin^2(\frac{\theta}{2})$
\item $\nu = E_e - E_{e'}$
\item $t = (q_{\gamma^*}^\mu - p_{\rho^0}^\mu)^2$
\item $W^2 = (q_{\gamma^*}^\mu + p_N^\mu)^2 \sim -Q^2 + M_p^2 + 2M_p\nu$
\end{itemize}

Data Selection:
\begin{itemize}
\item $W > 2\text{GeV}$, to avoid the resonance region
\item $-t > 0.1\text{GeV}^2$ to exclude coherent production off the nucleus
\item $-t < 0.4\text{GeV}^2$ to be in the diffractive region
\item $z = \frac{E_p}{\nu} > 0.9$ to select the elastic process
\end{itemize}
M_{\pi\pi} invariant mass, showing \rho^0 peak

Kinematical cuts:
- Select the physics of interest
- Enhance the \rho^0 peak
- Cut a lot of data
$M_{\pi\pi}$ invariant mass, showing $\rho^0$ peak

Invariant mass for $H_2$, $C$ and $Fe$
Extraction of the Nuclear Transparency

The goal of the experiment is to determine the Nuclear Transparency $T_{\rho^0}^A$ as a function of $Q^2$ and $l_c$

$$T_{\rho^0}^A = \frac{\left( \frac{N_{\rho^0}^A}{L_{int}^A} \right)}{\left( \frac{N_{\rho^0}^D}{L_{int}^D} \right)}$$

where $L_{int}^A$ is the integrated luminosity for the target $A$

$$L_{int}^A = n_{A}^{\text{nucleons}} \frac{Q_{int}}{q_e}$$
Nuclear Transparency for Iron and Carbon

$l_c$ dependence of Nuclear Transparency

The corrected transparency ratio was found to vary between 0.4 and 0.5, with the contribution of deuterium vector meson production. The radiative correction to the transparency ratio was found to vary between 0.35 and 0.44. Radiative corrections were extracted for each process and taken as free parameters in the fit of the simulation. The magnitudes of each contributing source are shown in Fig. 3. As expected, they do not exhibit the same dependence because the nuclear transparency as a function of $l_c$ is much shorter than the dependence of nuclear transparency on the nucleon radius. Note that in the absence of CT, hadronic Glauber calculations would predict nuclear transparency to be 0.47, which is in agreement with both Kopeliovich-Nemchik-Schmidt (KNS) and Gallmeister-Kaskulov-Mosel (GKM) predictions. The carbon data has been scaled by a factor 0.77 in the figure.) with acceptance and background subtraction being taken into account for the contribution of deuterium.

Consequently, the coherence length $e_{cF}$ and $e_{cFe}$ are 2.7 and 4.6 fm, respectively. The rise in transparency with $l_c$ dependence of 0.36 and 0.37 cannot mimic the expectations of CT. Note that in the absence of CT effects, hadronic Glauber calculations would predict nuclear transparency to be 0.47, which is in agreement with both Kopeliovich-Nemchik-Schmidt (KNS) and Gallmeister-Kaskulov-Mosel (GKM) predictions.

The systematics uncertainties were separated into point-to-point (aline rf or form) uncertainties, which are independent of the kinematics. The systematics uncertainties were separated into tematic uncertainty of 1.9% for carbon and 1.8% for iron (not shown in Fig. 3).
Nuclear Transparency for Iron and Carbon

Figure 3: (color online) Nuclear transparency as a function of $Q^2$ for $^{12}\text{C}$ and $^{56}\text{Fe}$, with the Kopeliovich-Nemchik-Schmidt (KNS) [37] and Gallmeister-Kaskulov-Mosel (GKM) [38] predictions. Both models include the pion absorption and Fermi motion, and radiative correction were studied and taken into account in the systematic uncertainties.

The transparency ratio was found to vary between 0.4 and 4%. An additional correction of around 2.5% was required in the figure with the iron data. The corrected transparency ratio. The rise in transparency with $Q^2$ dependence because any systematic uncertainty of 1.9% for carbon and 1.8% for iron (not included in quadrature). The curves are predictions of the FMS [35] and GKM [38] models with (dashed-dotted and dashed curves, respectively) and without (dotted and solid curves, respectively) CT. Note that in the absence of CT the CT signal in this experiment.

Consequently, the coherence length $\alpha$ is much shorter than the Fermi motion and radiative correction were studied and taken into account in the systematic uncertainties. There is an additional normalization uncertainty of 2.4% for carbon and 2.1% for iron (not included in quadrature). The slopes extracted from the simulations are $3.59 \pm 0.5$, $3.67 \pm 0.6$, $3.72 \pm 0.6$, and $4.6 \pm 0.5$ for $^{12}\text{C}$, $^{56}\text{Fe}$, $^{212}\text{Pb}$, and $^{238}\text{U}$, respectively.

The extracted slope parameters are reasonably consistent with the CLAS [35] hydrogen measurements of $2.63 \pm 0.04$. The systematics uncertainties were separated into kinematic cuts, model dependence in the expectations of CT, and decays inside the nucleus. The rise in transparency with $Q^2$ dependence because any systematic uncertainty of 1.9% for carbon and 1.8% for iron (not included in quadrature).

The $Q^2$ dependence of the transparency was fitted by an exponential form in $Q^2$. The extracted slope parameters are $3.59 \pm 0.5$, $3.67 \pm 0.6$, $3.72 \pm 0.6$, and $4.6 \pm 0.5$ for $^{12}\text{C}$, $^{56}\text{Fe}$, $^{212}\text{Pb}$, and $^{238}\text{U}$, respectively.

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Nuclear Transparency for Iron and Carbon

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Measured Slopes GeV$^{-2}$</th>
<th>Model Predictions</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>$0.044 \pm 0.015_{\text{stat}} \pm 0.019_{\text{syst}}$</td>
<td>0.06 0.06 0.025</td>
</tr>
<tr>
<td>Fe</td>
<td>$0.053 \pm 0.008_{\text{stat}} \pm 0.013_{\text{syst}}$</td>
<td>0.047 0.047 0.032</td>
</tr>
</tbody>
</table>

Thomas Jefferson Lab 12GeV upgrade: CLAS12 in Hall-B

- Up to 20 times more luminosity than CLAS
- Improved particle identification
- Access to higher masses
- Much larger kinematical range
Future $\rho^0$ measurements with CLAS12 at JLAB

JLab 12 GeV $\rho^0$ electroproduction measurements C, Fe and Sn

E12-06-106
Future $\rho^0$ measurements with CLAS12 at JLAB

SSC vs. formation effects

Long $l_c$ and fixed
$Q^2$ increases $\Rightarrow T_A$ increases because the mean transverse separation of the $\{q,q\text{-bar}\}$ fluctuation decreases

$l_c$ small and fixed (@ low $Q^2$ $l_f \sim l_c$)
$Q^2$ increases $\Rightarrow l_f$ increases
$\Rightarrow$ CT increases for two reasons:
$\Rightarrow$ transverse separation and $l_f$ effects

Coherence length $l_c = 2v/(Q^2 + M(p)^2)$
Formation length $l_f = 2v/(M(p')^2 - M(p)^2)$

Radius (C) = 2.7 fm
Radius (Fe) = 4.6 fm
Radius (Sn) = 5.7 fm
Conclusions

- We see a rise in the Transparency of $\rho^0$ electro-production with increasing $Q^2$
- We have different model calculations by KNS, GKS, FMS which well interpret the data.
Conclusions

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- We have different model calculations by KNS, GKS, FMS which well interpret the data.
- Approved experiment with CLAS12 at the future 12GeV upgraded Jefferson Laboratory with increased $Q^2$ range.
Conclusions

- We see a rise in the Transparency of $\rho^0$ electro-production with increasing $Q^2$
- We have different model calculations by KNS, GKS, FMS which well interpret the data.
- Approved experiment with CLAS12 at the future 12GeV upgraded Jefferson Laboratory with increased $Q^2$ range
- Thank you for your time
Backup Slides

- **Data Analysis**
  - Lengths in the reaction
  - Kinematical cuts
  - Diffractive region test
  - Simulation, Background, Acceptance
  - Extraction of the Nuclear Transparency

- **Results**
  - FMS Model
  - GKM Model
  - KNS Model
  - Comparison $\rho^0$ data and $\pi$ data (FMS)

- **Glauber model**
  - $l_c$ effect
  - $l_c$ effect Hermes data
  - $l_c$ effect Hermes, EG2 data

- **QCD model**
  - PLC definition
  - PLC and Nuclear filtering
  - Color Transparency
Glauber model

An approximation of scattering through Quantum Mechanics

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Using hadron picture for Nuclear Interaction.
Glauber model

\[ \Gamma_A^{\gamma^*V}(\vec{b}) = \sum_{j=1}^{A} \Gamma_N^{\gamma^*V}(\vec{b} - \vec{s}_j) e^{i q L z_j} \prod_{k \neq j}^{A} \left[ 1 - \Gamma_N^{VV}(\vec{b} - \vec{s}_k) \theta(z_k - z_j) \right] \]
**Glauber model**

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\]

- \( \Gamma_N^{\gamma^* V}(\vec{b} - \vec{s}_j) \) is the vector meson photo-production amplitude on a nucleon
Glauber model

\[ \Gamma_{A}^{\gamma^*V}(\vec{b}) = \sum_{j=1}^{A} \Gamma_{N}^{\gamma^*V}(\vec{b} - \vec{s}_j) e^{i q_L z_j} \prod_{k (\neq j)}^{A} \left[ 1 - \Gamma_{N}^{VV}(\vec{b} - \vec{s}_k) \theta(z_k - z_j) \right] \]

- Considering the quantities Longitudinal and transverse to the axis \( z \) of symmetry,

\[ q_L = p_L^{\gamma^*} - p_L^V = \frac{Q^2 + M_{V}^2}{2\nu} \]

\[ l_c = \frac{1}{q_L} = \frac{2\nu}{Q^2 + M_{V}^2} \]

- for \((z_{j1} - z_{j2}) < l_c\) contributions will add coherently
Glauber model

\[
\Gamma_A^{\gamma^*} (\vec{b}) = \sum_{j=1}^A \Gamma_N^{\gamma^*} (\vec{b} - \vec{s}_j) e^{i q_L z_j} \prod_{k \neq j} \left[ 1 - \Gamma_N^{VV} (\vec{b} - \vec{s}_k) \theta(z_k - z_j) \right]
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\[ \Gamma_{A}^{V*}(\vec{b}) = \sum_{j=1}^{A} \Gamma_{N}^{V*}(\vec{b} - \vec{s}_j) e^{i q L z_j} \prod_{k(\neq j)}^{A} \left[ 1 - \Gamma_{N}^{VV}(\vec{b} - \vec{s}_k) \theta(z_k - z_j) \right] \]

- small scattering ($\vec{k} \sim \vec{k}'$) on the nuclei with $z_k > z_j$
- $\vec{k} \sim \vec{k}' \sim \parallel \hat{z} \implies (\vec{k} - \vec{k}') \sim \perp \hat{z}$
- $\Gamma(\vec{b}) = (e^{i \chi(\vec{b})} - 1)$ and $\chi_{tot}^{VV} = \sum_{m} \chi_{m}^{VV}(\vec{b} - \vec{s}_m)$

\[ e^{i \sum_{m} \chi_{m}^{VV}(\vec{b} - \vec{s}_m)} = \prod_{m}(1 - \Gamma_{m}^{VV}(\vec{b} - \vec{s}_m)) \]
Glauber model

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with this easy model (J.Hüfner et al., Phys. Lett. B383 (1996) 362) were able to parameterize the \( Q^2 \) and \( \nu \) dependence of the Nuclear Transparency due to Coherence length effect.
Glauber model

\[(c)\]

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HERA positron storage ring at DESY: HERMES

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1. Inter-nuclear spacing
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Inter-nuclear spacing ($<r^2>^{1/2} \sim 0.8\text{fm}$)
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1. Inter-nuclear spacing ($\langle r^2 \rangle^{1/2} \sim 0.8\text{fm}$)
2. Atom size
EG2 and HERMES kinematical range

HERMES experiment kinematical range:
- $0.8 \text{GeV}^2 < Q^2 < 4.5 \text{GeV}^2$
- $5 \text{GeV} < \nu < 24 \text{GeV}$
EG2 and HERMES kinematical range

EG2 experiment kinematical range:
- $0.9\text{GeV}^2 < Q^2 < 2\text{GeV}^2$
- $2.2\text{GeV} < \nu < 3.5\text{GeV}$
EG2 and HERMES kinematical range

EG2 experiment kinematical range:

- $0.9 \text{GeV}^2 < Q^2 < 2 \text{GeV}^2$
- $2.2 \text{GeV} < \nu < 3.5 \text{GeV}$
EG2 experimental $l_c$ dependence?

$l_c$ vs $Q^2$ range for Iron target
EG2 experimental $l_c$ dependence?

$l_c$ vs $Q^2$ range for Iron target

$1.0 \text{GeV}^2 < Q^2 < 1.6 \text{GeV}^2$
EG2 experimental $l_c$ dependence?

$l_c$ vs $Q^2$ range for Iron target

$1.0 \text{GeV}^2 < Q^2 < 2.2 \text{GeV}^2$
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Such an object is unable to emit or absorb soft gluons $\Rightarrow$ its interaction with the other nucleons is significantly reduced
Point like configuration: The distribution amplitude

The distribution amplitude is (Lepage and Brodsky, PRD 22, 2157)

\[ \phi(Q^2, x) = \int_0^{Q^2} d^2 k_T \psi(k_T, x) ; (x = \text{Longitudinal momentum fraction}) \]
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- if we expand this expression in Fourier series

\[ \phi(Q^2, x) = \int_0^{Q^2} d^2 k_T \int d^2 b_T e^{ib_T \cdot k_T} \tilde{\psi}(b_T, x) \]
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if we expand this expression in Fourier series

\[ \phi(Q^2, x) = \int_0^{Q^2} d^2k_T \int d^2b_T e^{i\vec{b}_T \cdot \vec{k}_T} \tilde{\psi}(b_T, x) \]

and assume cylindrical symmetry around \( \vec{k}_T \)

\[ \phi(Q^2, x) = (2\pi)^2 \int_0^{\infty} db \ Q \ J_1(Qb) \tilde{\psi}(b_T, x) \]
Point like configuration: The distribution amplitude

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- At high \( Q^2 \) the distribution amplitude tends to evaluate the wave function at points of small transverse space separation (\( b_T \)).
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- Short distance is a statement about a dominant integration region
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- At high \( Q^2 \) the distribution amplitude tends to evaluate the wave function at points of small transverse space separation \( b_T \).
- Short distance is a statement about a dominant integration region.
- Each quark, connected to another one by hard gluon exchange carrying momentum of order \( Q \) should be found within a distance \( O\left(\frac{1}{Q}\right) \).
Color Interaction: Simple model (P. Jain et al., PR271, 93)

\[ K(x_i, x'_j) \propto \]

\[ V(x_1 - x_2) V(x_1 - x_2) - V(x_1 - x_2) V(x'_1 - x_2) + V(x'_1 - x_2) V(x'_1 - x_2) - V(x'_1 - x_2) V(x_1 - x_2) \]
Color Interaction: Simple model (P. Jain et al., PR271, 93)

\[ K(x_i, x'_j) \propto [V(x'_1 - x_2) - V(x_1 - x_2)]^2 \]

- for \( b_T = |x'_1 - x_1| \Rightarrow 0 \), I have \( f(x'_1) - f(x_1) \sim |x'_1 - x_1| \frac{df}{dx_1} \)
- \( K(x_i, x'_j) \sim \{ b_T \cdot \nabla[V(x_1 - x_2)] \}^2 \)
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- \( K(x_i, x'_j) \sim \{ b_T \cdot \nabla[V(x_1 - x_2)]\}^2 \)

\[
\downarrow
\]

\[
K(x_i, x'_j) \propto (b_T)^2
\]
Finally: Color Transparency

At the time of the reaction, the hadron has to fluctuate to a Point Like configuration.
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This configuration will experience a reduced interaction in the nucleus.
Finally: Color Transparency

1. At the time of the reaction, the hadron has to fluctuate to a Point Like configuration.

2. This configuration will experience a reduced interaction in the nucleus.

3. A signature of Color Transparency will be an increase in nuclear transparency $T_A$ with an increase in the hardness of the reaction, driven by $Q^2$. 
Fluctuation $q \bar{q} \sim \frac{\nu}{Q^2}$
Lengths in the reaction, order of magnitude

Formation length $\rho^0 \sim \frac{2E_{\rho^0}}{M^2_{\rho^1} - M^2_{\rho^0}}$

$\rho^0 \sim 2 E_{\rho^0} / M^2_{\rho^1} - M^2_{\rho^0}$
Kinematical cuts

- $W > 2\,\text{GeV}$, to avoid the resonance region
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Kinematical cuts

- $W > 2\text{GeV}$, to avoid the resonance region
- $-t > 0.1\text{GeV}^2$ to exclude coherent production off the nucleus
- $-t < 0.4\text{GeV}^2$ to be in the diffractive region
Kinematical cuts

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- $z = \frac{E_\rho}{\nu} > 0.9$ to select the elastic process
Kinematical cuts

- $W > 2\text{GeV}$, to avoid the resonance region
- $-t > 0.1\text{GeV}^2$ to exclude coherent production off the nucleus
- $-t < 0.4\text{GeV}^2$ to be in the diffractive region
- $z = \frac{E_{\rho}}{\nu} > 0.9$ to select the elastic process
Diffractive $\rho^0$ production

\[ \text{Fit to: } A e^{bt} \]

-t dependence show the rapid fall expected for incoherent diffractive $\rho^0$ production, consistent with CLAS data: (2.63 ± 0.44)

Morrow JLAB-PHY-08-831, arXiv:0807.3834
Background Study and Simulation

- As event generator used the one implemented by B. Mustapha (ANL)
- Tune to the Eg2 experiment configurations
- Radiative Effects, Fermi motion of target
- Possibility of using experimental cross section (D.Cassel, Physical Review D, 24 (1981)) for tuning the different contributions in our kinematics
- Background assumed composition:
  1. $\gamma^* + p \rightarrow \Delta^{++} + \pi^-$
  2. $\gamma^* + p \rightarrow \Delta^0 + \pi^+$
  3. $\gamma^* + p \rightarrow p + \pi^+ + \pi^-$
Acceptance correction

In CLAS comprehensive of:

- **Acceptance**: Geometry of CLAS is not $4\pi$
- **Efficiency**: considering together:
  1. Detectors
  2. Reconstruction protocol
  3. Analysis
Acceptance correction

- Unexpectedly large effect of acceptance
- Due to:
  1. tight kinematic cuts,
  2. complicated detector
  3. targets not at identical location (5 cm from each other)
Acceptance correction

Iron at 4 GeV

- Determined the correction with 2 methods:
  1. green: bin to bin
  2. red: bin to migration
  3. consider as systematic error
Extraction of the Nuclear Transparency

- The goal of the experiment is to determine the Nuclear Transparency $T_A^{\rho^0}$ as a function of $Q^2$ and $l_c$

$$T_A^{\rho^0} = \left( \frac{N_A^{\rho^0}}{L_A^{\text{int}}} \right) \left( \frac{N_D^{\rho^0}}{L_D^{\text{int}}} \right)$$
Extraction of the Nuclear Transparency

- The goal of the experiment is to determine the Nuclear Transparency \( T_A^{\rho^0} \) as a function of \( Q^2 \) and \( l_c \)

\[
T_A^{\rho^0} = \left( \frac{N_A^{\rho^0}}{L_A^{\text{int}}} \right) \left( \frac{N_D^{\rho^0}}{L_D^{\text{int}}} \right)
\]

- where \( L_A^{\text{int}} \) is the integrated luminosity for the target \( A \)

\[
L_A^{\text{int}} = n_A^{\text{nucleons}} \frac{Q_{\text{int}}}{q_e}
\]
L. Frankfurt, G.A. Miller, M. Strikman, Model

- Glauber based calculation.
- Includes experimental conditions.
- Includes the $\rho^0$ decay.
- With or without the Color Transparency effect.
\[
\frac{d\sigma}{dt} = \sum_{n=0}^{\infty} \frac{d\sigma_n}{dt} \Rightarrow T_A = \frac{d\sigma}{dt} A \frac{d\sigma}{d\gamma^* V} = \sum_{n=0}^{\infty} \frac{d\sigma_n}{dt} A \frac{d\sigma}{d\gamma^* V} = \sum_{n=0}^{\infty} T_n
\]

- The full cross section will be given by the sum of all the possible different number of elastic re-scattering (\( n \) in equation)
\[
\frac{d\sigma}{dt} = \sum_{n=0}^{\infty} \frac{d\sigma_n}{dt} \quad \Rightarrow \quad T_A = \frac{d\sigma}{A d\sigma^* V dt} = \sum_{n=0}^{\infty} \frac{d\sigma_n}{A d\sigma^* V dt} = \sum_{n=0}^{\infty} T_n
\]

\[
\frac{d\sigma_0}{dt} = A \frac{d\sigma^* V}{dt} \int d^2 b \int_{-\infty}^{\infty} dz \rho(b, z) (1 - \int_{z}^{\infty} dz' \sigma_{tot} \rho(b, z'))^{A-1}
\]

- (a) represents the sum of all the possible contributions for scattering a Vector meson from a $\gamma^*$ in a target with density given by $\rho(b, z')$

- (b) refers to the probability of not having an elastic re-scattering $(1 - \int_{z}^{\infty} dz' \sigma_{tot} \rho(b, z'))$ from all the remaining nucleons ($A - 1$) starting from the point $z$ of the vector meson’s creation
L. Frankfurt, G.A. Miller, M. Strikman Model

\frac{d\sigma}{dt} = \sum_{n=0}^{\infty} \frac{d\sigma_n}{dt} \implies T_A = \frac{\frac{d\sigma}{dt}}{A} = \frac{\sum_{n=0}^{\infty} \frac{d\sigma_n}{dt}}{A} = \sum_{n=0}^{\infty} T_n

\frac{d\sigma_0}{dt} = A \frac{d\sigma_0^* V}{dt} \int d^2 b \int_{-\infty}^{\infty} dz \rho(b, z)(1 - \int_z^{\infty} dz' \sigma_{tot} \rho(b, z'))^{A-1}

\sigma_{\text{eff}}^D(z' - z, p_{\rho^0}) = \sigma_{\text{tot}}(p_{\rho^0}) \left[ \left( \frac{n^2 < k_T^2 >}{Q^2} + \frac{z}{l_h} \left(1 - \frac{n^2 < k_T^2 >}{Q^2} \right) \right) \theta(l_h - (z' - z)) \right]

+ \sigma_{\text{tot}}(p_{\rho^0}) \left[ \theta((z' - z) - l_h) \exp \left(-\frac{\Gamma_{\rho^0}}{\gamma_{\rho^0}}(z' - z)\right) \right]

+ 2\sigma_{\pi N}(\frac{p_{\rho^0}}{2}) \left[ \theta((z' - z) - l_h) \left(1 - \exp \left(-\frac{\Gamma_{\rho^0}}{\gamma_{\rho^0}}(z' - z)\right) \right) \right].
L. Frankfurt, G.A. Miller, M. Strikman Model

\[
\sigma_{\text{eff}}^{D}(z' - z, p_{\rho}) = \sigma_{\text{tot}}(p_{\rho}) \left[ \left( \frac{n^2 < k_T^2 >}{Q^2} + \frac{z}{l_h} \left( 1 - \frac{n^2 < k_T^2 >}{Q^2} \right) \right) \theta(l_h - (z' - z)) \right] \\
+ \sigma_{\text{tot}}(p_{\rho}) \left[ \theta((z' - z) - l_h) \exp \left( -\frac{\Gamma_{\rho}}{\gamma_{p_{\rho}}} (z' - z) \right) \right] \\
+ 2\sigma_{\pi N}(\frac{p_{\rho}}{2^n}) \left[ \theta((z' - z) - l_h) \left( 1 - \exp \left( -\frac{\Gamma_{\rho}}{\gamma_{p_{\rho}}} (z' - z) \right) \right) \right].
\]

- Point Like Configuration interaction
\[
\sigma_{\text{eff}}^D(z' - z, p_{\rho^0}) = \sigma_{\text{tot}}(p_{\rho^0}) \left[ \left( \frac{n^2 < k_T^2 >}{Q^2} + \frac{z}{l_h} \left( 1 - \frac{n^2 < k_T^2 >}{Q^2} \right) \right) \theta(l_h - (z' - z)) \right] \\
+ \sigma_{\text{tot}}(p_{\rho^0}) \left[ \theta((z' - z) - l_h) \exp \left( -\frac{\Gamma_{\rho^0}}{\gamma_{p_{\rho^0}}} (z' - z) \right) \right] \\
+ 2\sigma_{\pi N}(p_{\rho^0}) \left[ \theta((z' - z) - l_h) \left( 1 - \exp \left( -\frac{\Gamma_{\rho^0}}{\gamma_{p_{\rho^0}}} (z' - z) \right) \right) \right].
\]

- PLC evolution in \( \theta(l_h - (z' - z)) \)
- \( l_h = 2p_{\rho^0}/\Delta M^2 \) is the formation time
σ_{eff}^D(z' - z, p_{ρ^0}) = σ_{tot}(p_{ρ^0}) \left[ \left( \frac{n^2 < k_T^2 >}{Q^2} + \frac{z}{l_h} \left( 1 - \frac{n^2 < k_T^2 >}{Q^2} \right) \right) \theta(l_h - (z' - z)) \right]

+ σ_{tot}(p_{ρ^0}) \left[ \theta((z' - z) - l_h) \exp \left( -\frac{Γ_{ρ^0}}{γ_{ρ^0}} (z' - z) \right) \right]

+ 2σ_{πN}(\frac{p_{ρ^0}}{2}) \left[ \theta((z' - z) - l_h) \left( 1 - \exp \left( -\frac{Γ_{ρ^0}}{γ_{ρ^0}} (z' - z) \right) \right) \right].

- PLC evolution in \( θ(l_h - (z' - z)) \)

- \( l_h = 2p_{ρ^0}/ΔM^2 \) is the formation time
L. Frankfurt, G.A. Miller, M. Strikman Model

\[
\sigma_{\text{eff}}^D(z' - z, p_{\rho^0}) = \sigma_{\text{tot}}(p_{\rho^0}) \left[ \left( \frac{n^2 < k_T^2 >}{Q^2} + \frac{z}{l_h} \left( 1 - \frac{n^2 < k_T^2 >}{Q^2} \right) \right) \theta(l_h - (z' - z)) \right] \\
+ \sigma_{\text{tot}}(p_{\rho^0}) \left[ \theta((z' - z) - l_h) \exp \left( -\frac{\Gamma_{\rho^0}}{\gamma_{p_{\rho^0}}} (z' - z) \right) \right] \\
+ 2\sigma_{\pi N}(\frac{p_{\rho^0}}{2}) \left[ \theta((z' - z) - l_h) \left( 1 - \exp \left( -\frac{\Gamma_{\rho^0}}{\gamma_{p_{\rho^0}}} (z' - z) \right) \right) \right].
\]

- Vector meson interaction + decay
- Interaction of decay product
GKM Model

- Coupled channel Giessen Boltzmann-Uehling-Uhlenbeck (GiBUU) transport equation.
- Includes rho decay and subsequent pion absorption.
- Includes experimental cuts and acceptance.
- With and without CT effects.
KNS Model

Kopeliovich, Nemchik, Schafer, Tarasov PRC 65 (2002) 035201

- Light Cone QCD Formalism for q q-bar dipole.
- $\sigma(q\bar{q})$ - Universal dipole cross section for q q-bar interaction with a nucleon, fit to proton structure functions over a large range of x, $Q^2$.
- LC wave function for q q-bar fluctuation of photon.
- LC wave function for vector meson.
- Parameter free (apart from initial fit).

Will add the rho decay soon.

Tuesday, September 27, 11
Comparison $\rho^0$ data and $\pi$ data (FMS)

Using the same ingredients the FSM (LSM) model agrees well with both data sets.