SEARCH FOR THE ONSET OF COLOR TRANSPARENCY

THROUGH ρ^0 ELECTROPRODUCTION ON NUCLEI

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CLAS collaboration

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Introduction

Color Transparency

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EG2 experiment using the CLAS detector at Jefferson Lab

The Nuclear Transparency was measured in ρ^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

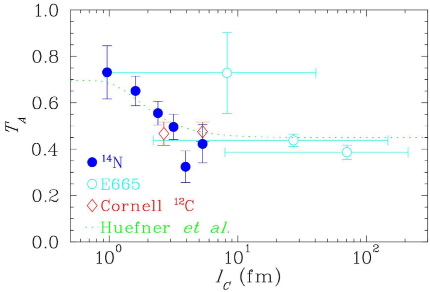
"High-Energy collision theory", by R.J. Glauber

Using hadron picture for Nuclear Interaction.

Coherence Length effect with the Glauber model

K. Ackerstaff, PRL 82, 3025 (1999)
Exclusive ρ^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 ρ^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.

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Glauber model

No other Q^2 dependence other than the one due to the coherence length effect

Point like configuration

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.

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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 $\frac{1}{Q}$

Color Transparency

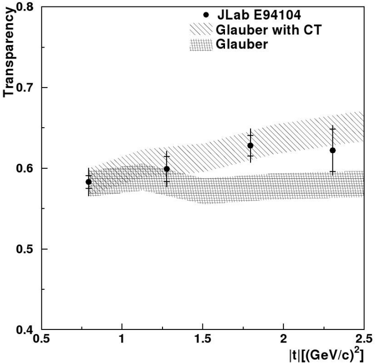
Such an object is unable to emit or absorb soft gluons $\Rightarrow$ its interaction with the other nucleons is significantly reduced

A lot of EXPERIMENTS since 1988

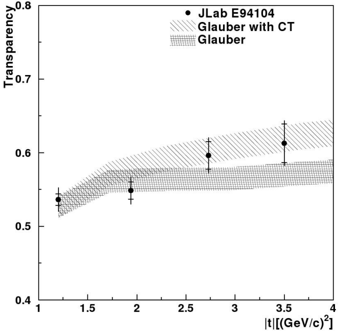
- Quasi-elastic A(p,2p) [Brookhaven]
- Quasi-elastic A(e,ep) [SLAC and Jlab]
- Di-jets diffractive dissociation. [Fermilab]
- Quasi-elastic D(e,ep) [Jlab - CLAS]
- Pion Production ^4He,($\gamma\, n \rightarrow p\, \pi^-$) [Jlab]
- Pion Production A(e,eπ^+) [Jlab]
- ρ^0 lepto production. [Fermilab, HERMES]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

OTHER EXPERIMENTS, Thomas Jefferson Lab: Hall A

D. Dutta, PRC 68, 021001 (2003)
Pion photo-production on ^4He, $(\gamma\, n \rightarrow\ p\, \pi^-)$



at $\theta^{\pi}_{cm} = 70^{\circ}$

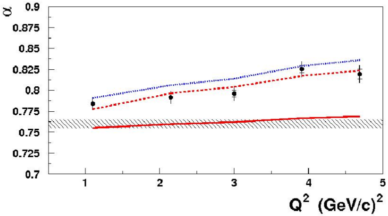


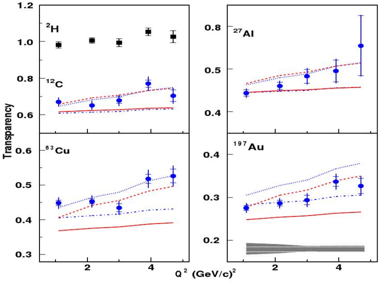
at $\theta^{\pi}_{cm} = 90^{\circ}$

Thomas Jefferson Lab: Hall C

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

$$T = \frac{(\frac{\bar{Y}}{\bar{Y}_{MC}})_A}{(\frac{\bar{Y}}{\bar{Y}_{MC}})_H}$$

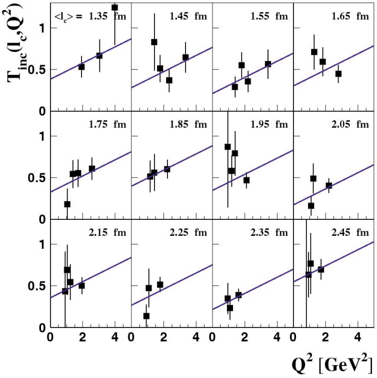




$T = A^{\alpha-1}$, with $\alpha \sim 0.76$

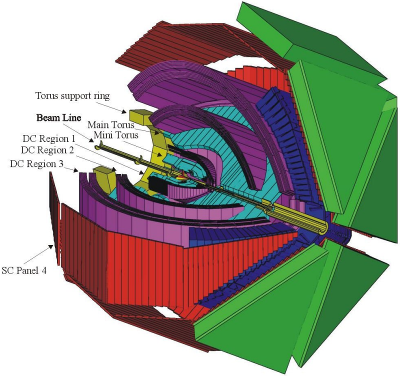
HERA positron storage ring at DESY: HERMES

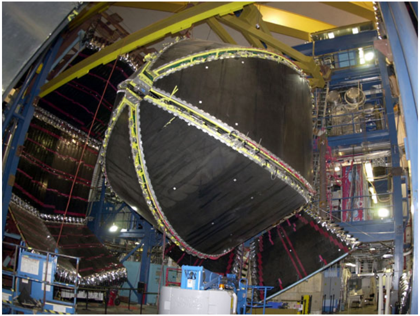
A. Airapetan, PRL 90, 052501 (2003)
Measurement of the Nuclear Transparency, incoherent ρ^0 prod.
$T_A = P_0 + P_1\,Q^2$,with $P_1 = (0.089 \pm 0.046 \pm 0.020)\,GeV^{-2}$



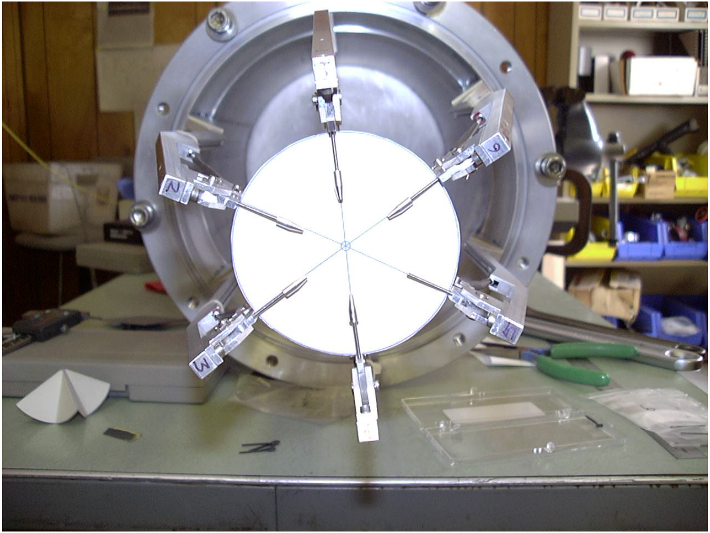
Thomas Jefferson Lab: CLAS EG2 experiment

- Electron Beam $5 GeV$ (50 days) & $4 GeV$ (7days)
- Targets: D&Fe, D&C, D&Pb
- Luminosity $\sim 2x10^{34} cm^{-2} s^{-1}$





Eg2 experiment target



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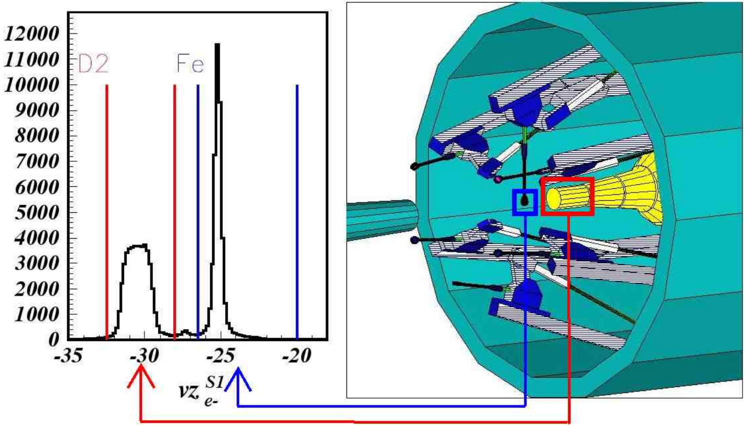
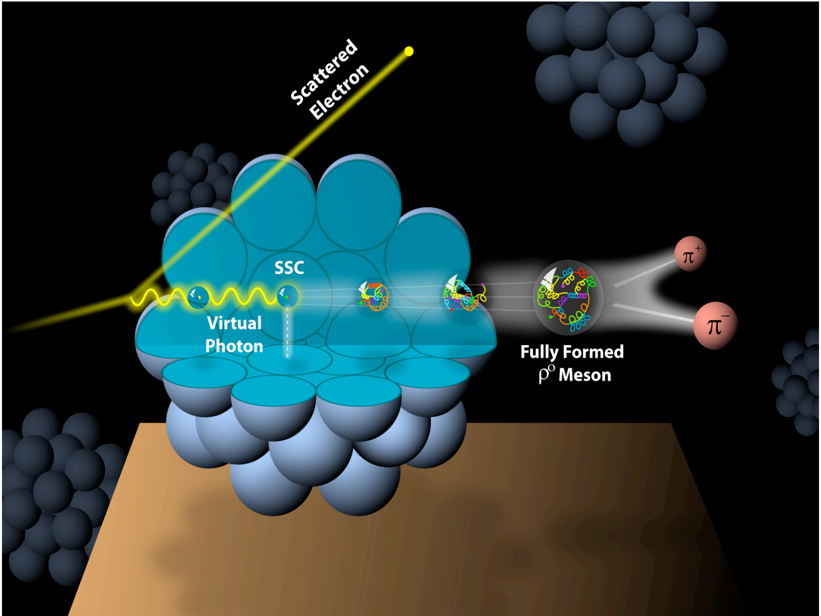
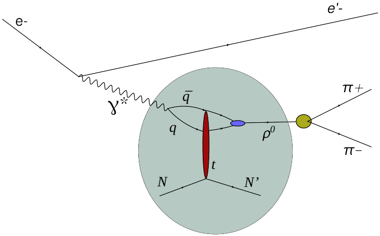


Reaction


Scattered Electron
SSC
Virtual Photon
Fully Formed
ρ° Meson
π+
π−

Reaction Variables and kinematical cuts

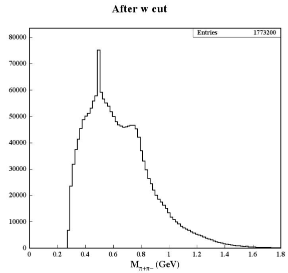


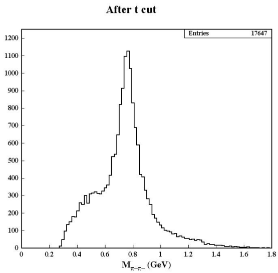
- $Q^2 = -(q^\mu_{\gamma^*})^2 \sim 4E_e E_{e'} \sin^2(\frac{\theta}{2})$
- $\nu = E_e - E_{e'}$
- $t = (q^\mu_{\gamma^*} - p^\mu_{\rho^0})^2$
- $W^2 = (q^\mu_{\gamma^*} + p^\mu_N)^2 \sim -Q^2 + M_p^2 + 2M_p\nu$

Data Selection:

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

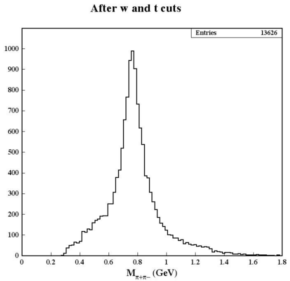
$M\pi\pi$ invariant mass, showing ρ^0 peak

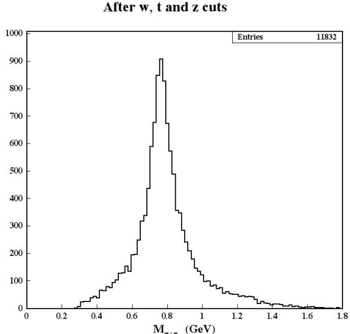




Kinematical cuts:

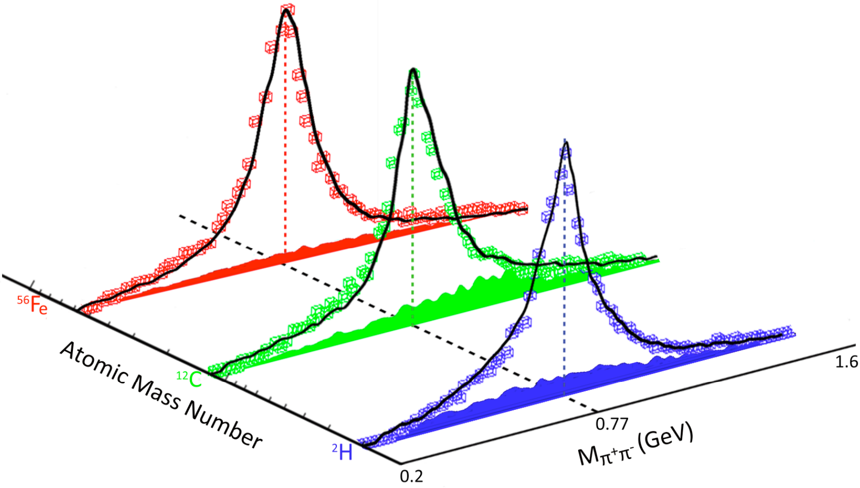
- Select the physics of interest
- Enhance the ρ^0 peak
- Cut a lot of data





$M\pi\pi$ invariant mass, showing ρ^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 $T_A^{\rho^0}$ as a function of Q^2 and l_c

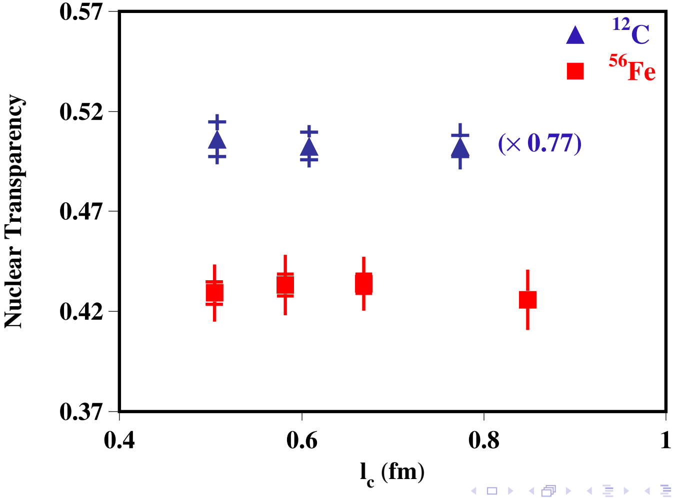
$$T_A^{\rho^0} = \frac{\left(\frac{N_A^{\rho^0}}{L_A^{int}}\right)}{\left(\frac{N_D^{\rho^0}}{L_D^{int}}\right)}$$

- where L_A^{int} is the integrated luminosity for the target A

$$L_A^{int} = n_A^{nucleons} \frac{Q_{int}}{q_e}$$

Nuclear Transparency for Iron and Carbon

l_c dependence of Nuclear Transparency



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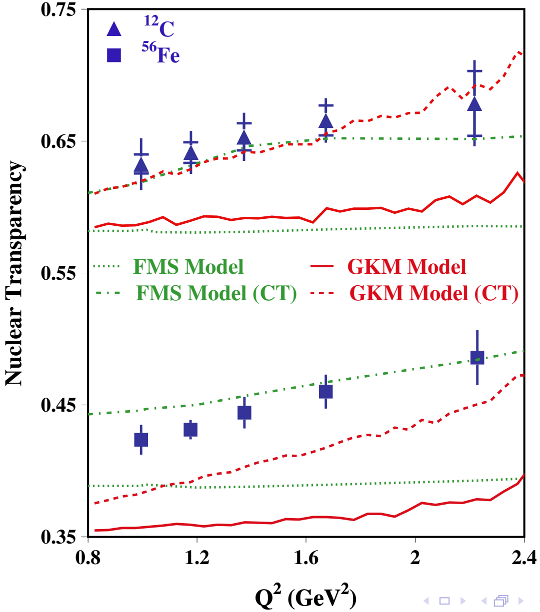

Nuclear Transparency for Iron and Carbon

	Measured Slopes	Model Predictions		
Nucleus	GeV^{-2}	KNS	GKM	FMS
C	$0.044 \pm 0.015_{\mathrm{stat}} \pm 0.019_{\mathrm{syst}}$	0.06	0.06	0.025
Fe	$0.053 \pm 0.008_{\mathrm{stat}} \pm 0.013_{\mathrm{syst}}$	0.047	0.047	0.032

- B. Z. Kopeliovich, J. Nemchik and I. Schmidt, Phys. Rev. C 76, 015205 (2007).
- K. Gallmeister, M. Kaskulov and U. Mosel, Phys. Rev. C 83, 015201 (2011).
- L. Frankfurt, G. A. Miller and M. Strikman, Private Communication based on Phys. Rev. C 78, 015208 (2008).

Conclusions

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

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- 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 ρ^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

- 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
- 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 ρ^0 data and π data (FMS)

Glauber model

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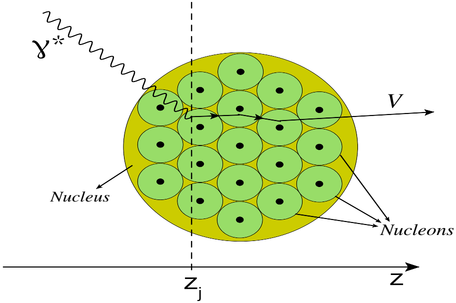
$$\Gamma_A^{\gamma^* V}(\vec{b}) = \sum_{j=1}^{A} \overbrace{\Gamma_N^{\gamma^* V}(\vec{b}-\vec{s_j})}^{(a)} \overbrace{e^{i\,q_L z_j}}^{(b)} \overbrace{\prod_{k\,(\neq j)}^{A} \left[1 - \Gamma_N^{VV}(\vec{b}-\vec{s_k})\,\theta(z_k - z_j)\right]}^{(c)}$$



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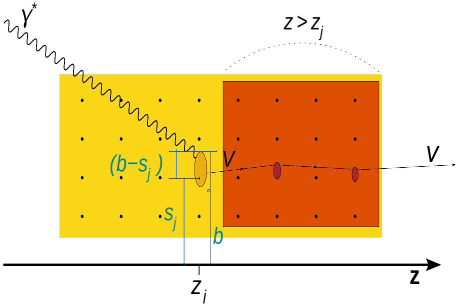

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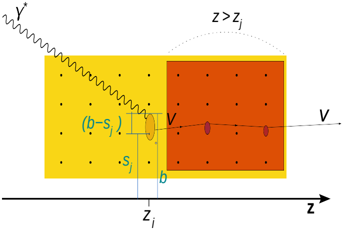


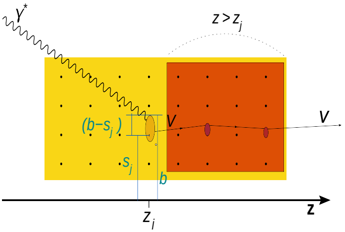
(a)

- $\Gamma_N^{\gamma^* V}(\vec{b}-\vec{s_j})$ is the vector meson photo-production amplitude on a nucleon

Glauber model

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

(b)



- 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 $(z_{j^1} - z_{j^2}) < l_c$ contributions will add coherently

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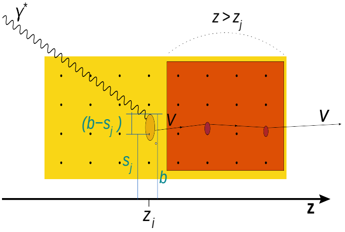


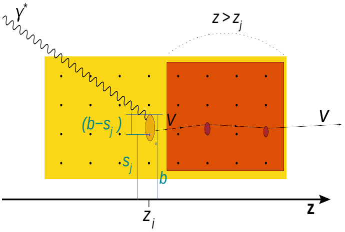
(b)

- $$l_c = \frac{1}{q_L} = \frac{2\nu}{Q^2+M_V^2}$$
- The γ^* interacts simultaneously with all the target nucleons within a distance l_c

Glauber model

$$\Gamma_A^{\gamma^* V}(\vec{b}) = \sum_{j=1}^{A} \overbrace{\Gamma_N^{\gamma^* V}(\vec{b}-\vec{s_j})}^{(a)} \overbrace{e^{i\,q_L z_j}}^{(b)} \overbrace{\prod_{k\,(\neq j)}^{A} \left[1-\Gamma_N^{VV}(\vec{b}-\vec{s_k})\,\theta(z_k-z_j)\right]}^{(c)}$$

(c)



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

$$\Downarrow$$

$$e^{i\sum_m \chi_m^{VV}(\vec{b}-\vec{s_m})} = \prod_m (1-\Gamma_m^{VV}(\vec{b}-\vec{s_m}))$$

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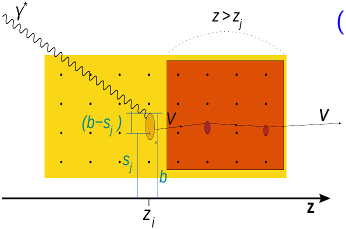

(c)

- with this easy model (J.Hüfner et al., Phys. Lett. B383 (2996) 362) were able to parameterize the Q^2 and ν dependence of the Nuclear Transparency due to Coherence length effect

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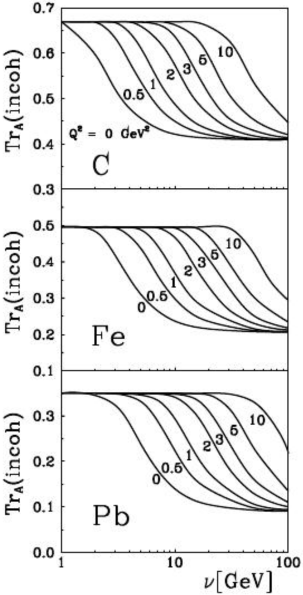

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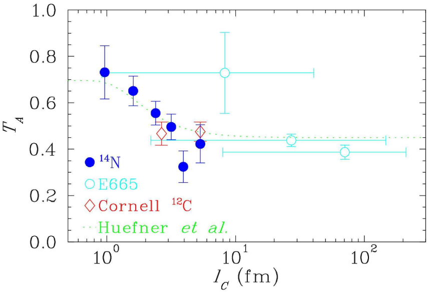

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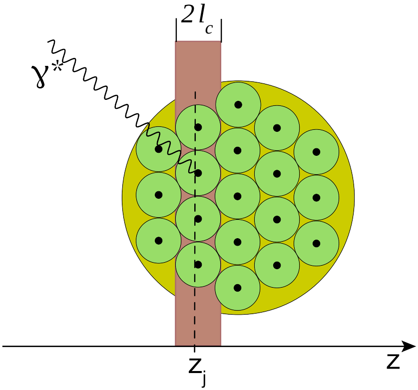

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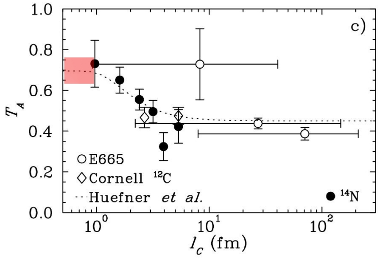

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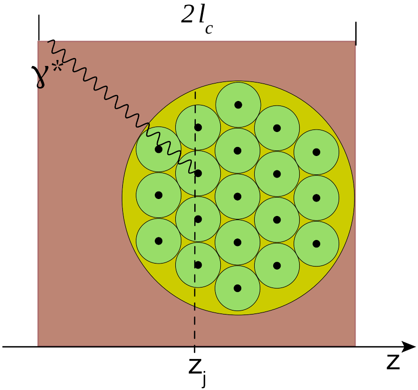
2. Atom size



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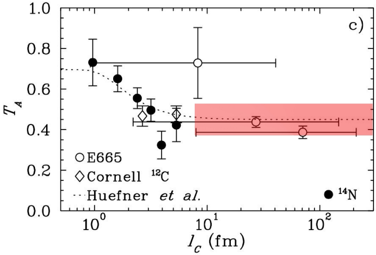

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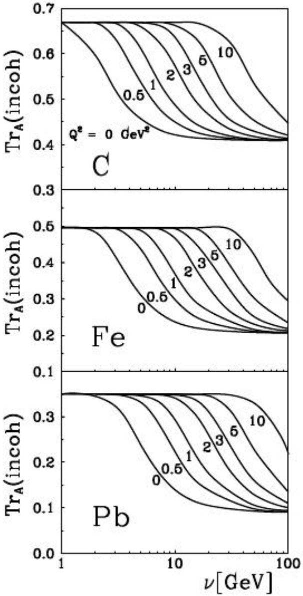
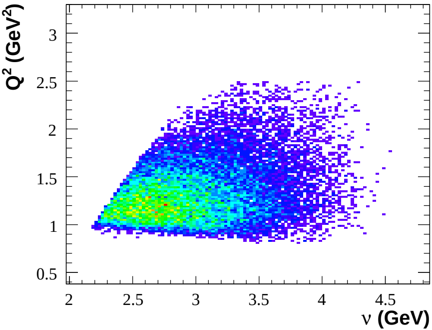
EG2 and HERMES kinematical range



HERMES experiment kinematical range:

- $0.8GeV^2 < Q^2 < 4.5GeV^2$
- $5GeV < \nu < 24GeV$

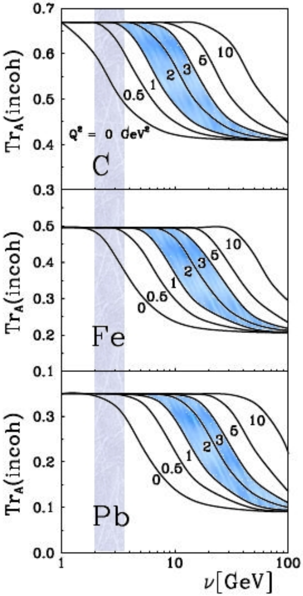
EG2 and HERMES kinematical range



EG2 experiment kinematical range:

- $0.9 GeV^2 < Q^2 < 2 GeV^2$
- $2.2 GeV < \nu < 3.5 GeV$

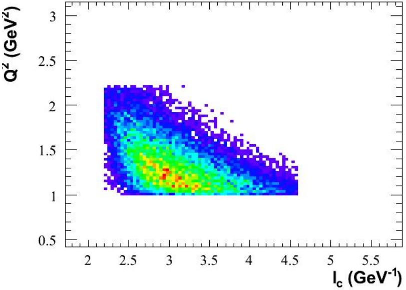
EG2 and HERMES kinematical range



EG2 experiment kinematical range:

- $0.9 GeV^2 < Q^2 < 2 GeV^2$
- $2.2 GeV < \nu < 3.5 GeV$

EG2 experimental l_c dependence?



l_c vs Q^2 range for Iron target

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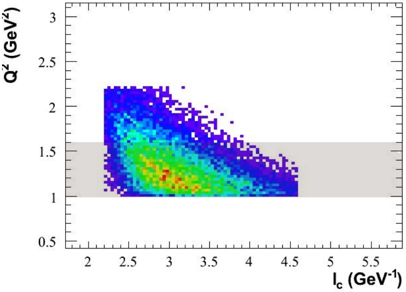
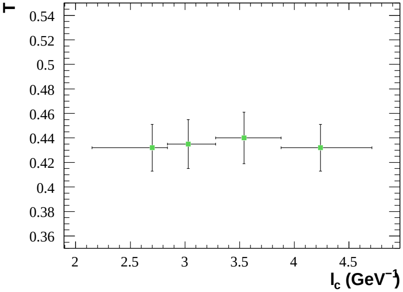


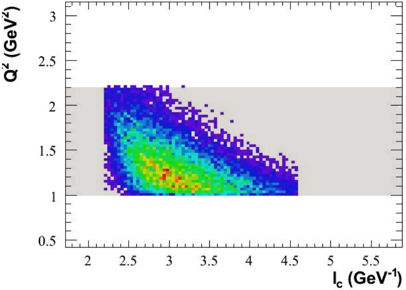
- $1.0 GeV^2 < Q^2 < 1.6 GeV^2$

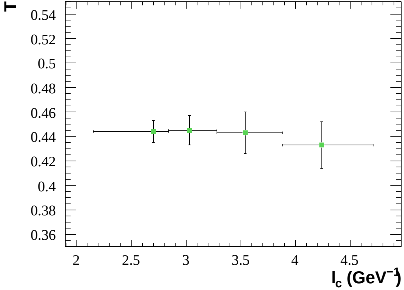


EG2 experimental l_c dependence?

l_c vs Q^2 range for Iron target

- $1.0 GeV^2 < Q^2 < 2.2 GeV^2$





Point like configuration

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.

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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

Point like configuration: The distribution amplitude

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

$$\phi(Q^2, x) = \int_0^{Q^2} d^2k_T \psi(k_T, x) \ ; \ (x = \text{Longitudinal momentum fraction})$$

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- and assume cylindrical symmetry around $\vec{k_T}$

$$\phi(Q^2,x) = (2\pi)^2 \int_0^{\infty} db\, Q\, J_1(Qb) \tilde{\psi}(b_T,x)$$

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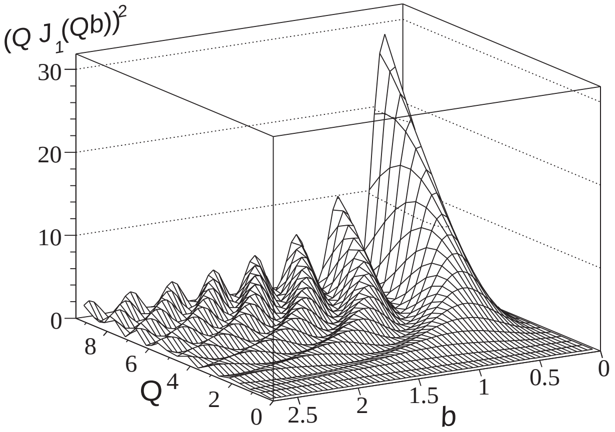

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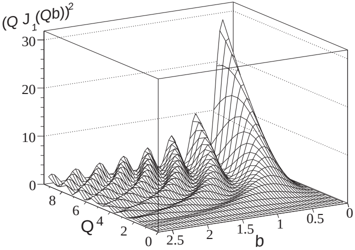

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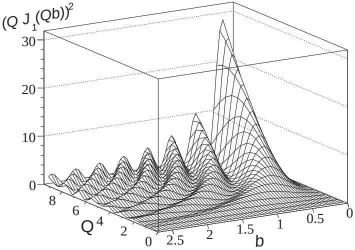

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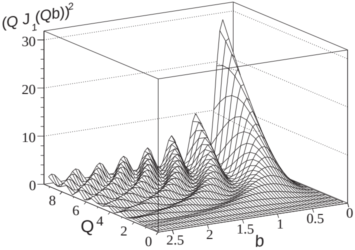

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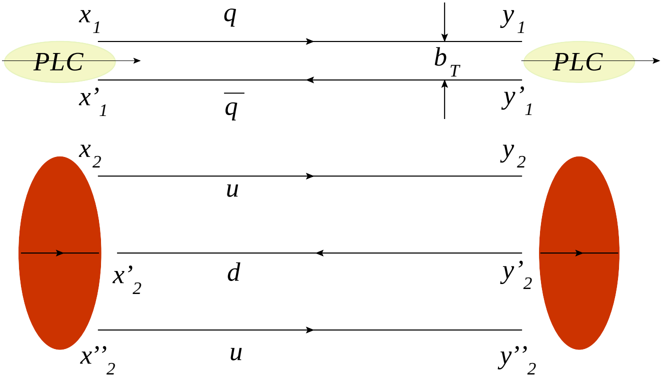
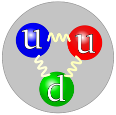
Color Interaction: Simple model (P. Jain et al., PR271, 93)

See P. Jain et al. , Physics Report 271 (1996) 93





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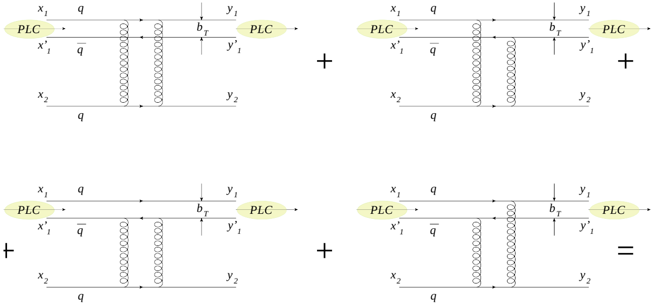

$$\overbrace{V(x_1-x_2)V(x_1-x_2) - V(x_1-x_2)V(x_1'-x_2) + V(x_1'-x_2)V(x_1'-x_2) - V(x_1'-x_2)V(x_1-x_2)}^{K(x_i,x_j')\,\propto}$$

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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$$\Downarrow$$

$$K(x_i, x_j') \propto (b_T)^2$$

Finally: Color Transparency

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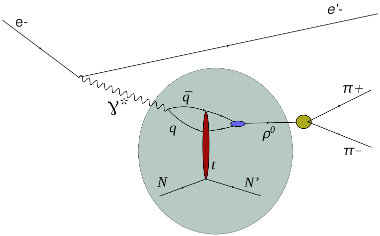
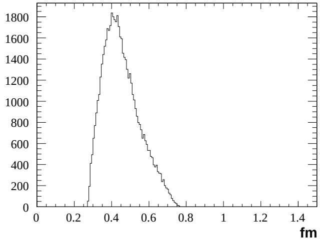
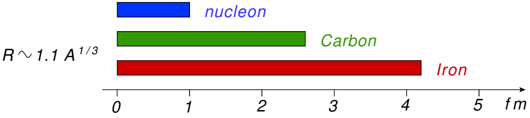
(3) A signature of Color Transparency will be an increase in nuclear transparency T_A with an increase in the hardness of the reaction, driven by Q^2

Lengths in the reaction, order of magnitude

Fluctuation $q\ \bar{q} \sim \frac{\nu}{Q^2}$







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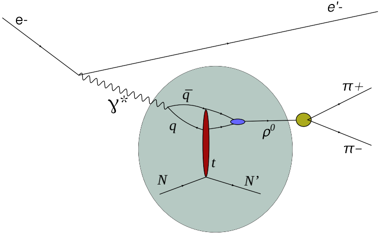
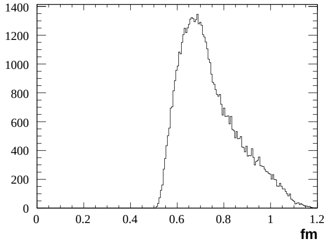
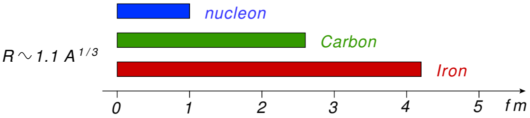
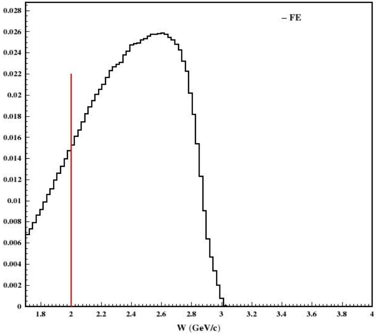


Formation length $\rho^0 \sim \frac{2E_{\rho^0}}{M^2_{\rho^1} - M^2_{\rho^0}}$



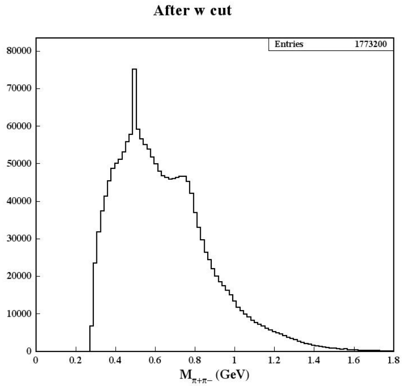


Kinematical cuts



- $W > 2GeV$, to avoid the resonance region

Kinematical cuts



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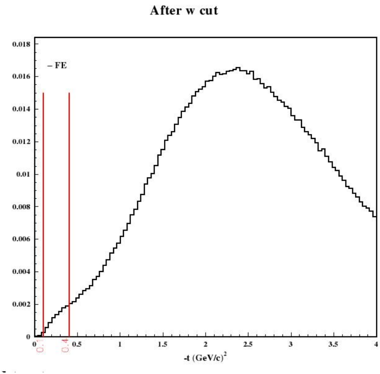

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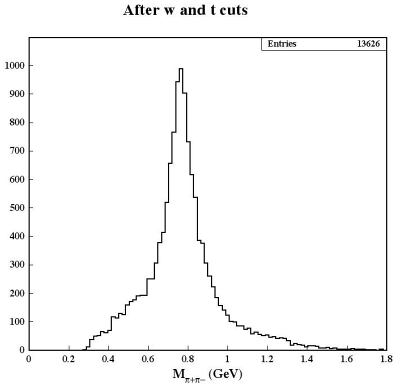

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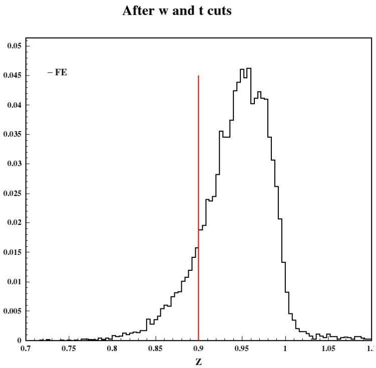

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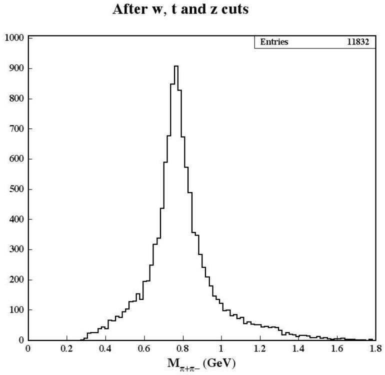

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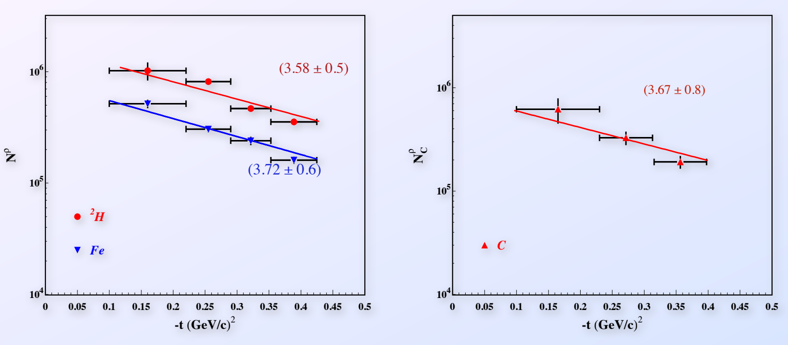
Diffractive ρ^0 production

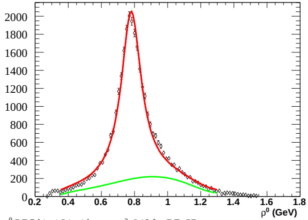
Fit to: Ae^{bt}



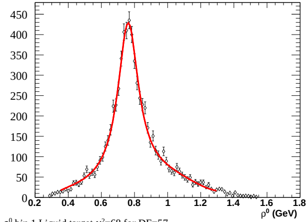
-t dependence show the rapid fall expected for incoherent diffractive ρ^0 production, consistent with CLAS data: (2.63 ± 0.44)

Morrow JLAB-PHY-08-831, arXiv:0807.3834

Background Study and Simulation



ρ^0 REC bin 1 Liquid target χ^2=246 for DF=57



ρ^0 bin 1 Liquid target χ^2=68 for DF=57

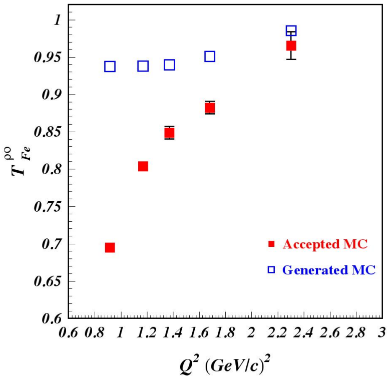
- As event generator used the one implemented by B. Mustapha (ANL)
- Tune to the Eg2 experiment configurations
- Radiative Effects, Fermi motion of target
- Possibility of using experimental cross section (D.Cassel, Physical Review D, 24 (1981)) for tuning the different contributions in our kinematics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

Acceptance correction

In CLAS comprehensive of:

- Acceptance: Geometry of CLAS is not 4π
- Efficiency: considering together:
  1. Detectors
  2. Reconstruction protocol
  3. Analysis

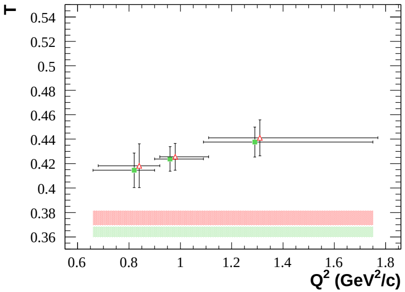
Acceptance correction



- 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

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

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- where L_A^{int} is the integrated luminosity for the target A

$$L_A^{int} = n_A^{nucleons} \frac{Q_{int}}{q_e}$$

L. Frankfurt, G.A. Miller, M. Strikman Model

- L. Frankfurt, G.A. Miller, M. Strikman, arXiv: 0803.4012v2 [nucl-th]
- Glauber based calculation.
- Includes experimental conditions.
- Includes the ρ^0 decay.
- With of without the Color Transparency effect.

L. Frankfurt, G.A. Miller, M. Strikman Model

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

- The full cross section will be given by the sum of all the possible different number of elastic re-scattering (n in equation)

L. Frankfurt, G.A. Miller, M. Strikman Model

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

- (a) represents the sum of all the possible contributions for scattering a Vector meson from a γ^* 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

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

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

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

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

L. Frankfurt, G.A. Miller, M. Strikman Model

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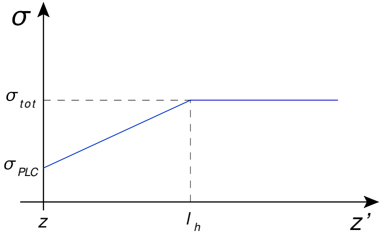
- PLC evolution in $\theta(l_h-(z'-z))$
- $l_h = 2p_{\rho^0}/\Delta M^2$ is the formation time



L. Frankfurt, G.A. Miller, M. Strikman Model

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$$+ \sigma_{tot}(p_{\rho^0}) \left[\theta((z' - z) - l_h) \exp\left(-\frac{\Gamma_{\rho^0}}{\gamma p_{\rho^0}}(z' - z) \right) \right]$$
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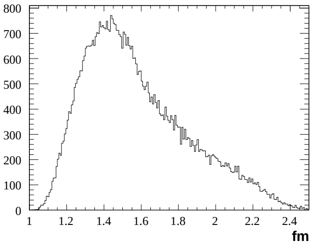
- $l_h = 2p_{\rho^0}/\Delta M^2$ is the formation time



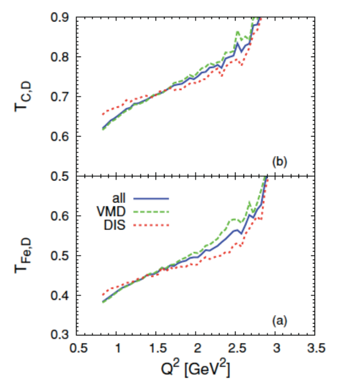
L. Frankfurt, G.A. Miller, M. Strikman Model

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

- Vector meson interaction + decay
- Interaction of decay product

GKM Model

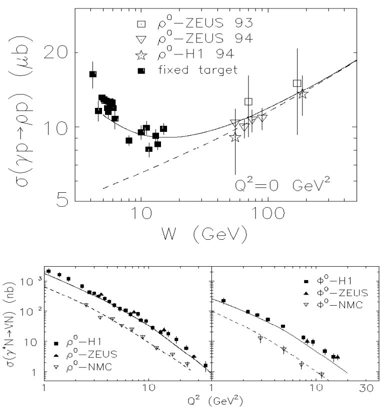
- Gallmeister, Kaskulov, Mosel . *PRC* **83,** 015201 (2011)
- Coupled channel Giessen Boltzmann-Uehling-Uhlenbeck (GiBUU) transport equation.
- Includes rho decay and subsequent pion absorption.
- Includes experimental cuts and acceptance.
- With and without CT effects.



KNS Model

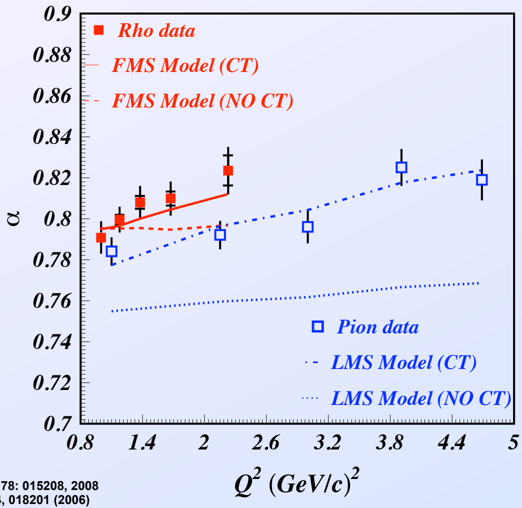
Kopeliovich, Nemchik, Schafer, Tarasov PRC 65 (2002) 035201

- Light Cone QCD Formalism for q q-bar dipole.
- σ(qq) - 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).



Comparison ρ^0 data and π data (FMS)

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



FMS: Frankfurt, Miller and Strikman, PRC 78: 015208, 2008
LSM: Larson, Miller and Strikman, PRC 74, 018201 (2006)