Chasing Color Transparency with Pions

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Hall C Summer Workshop

Aug 24-25, 2006

Outline

- Nuclear Transparency and Color Transparency (CT)
- Why are we still looking for CT?
  - the usual motivations
  - the new motivations
- Nuclear Transparency with mesons
  - 2-slide review of old experiments
  - E01107
- Summary

How Transparent is Your Nucleus?

Ratio of cross-sections for exclusive processes[1] from nuclei to those from nucleons is termed as **Nuclear Transparency**

$$T = \frac{\sigma_N}{A\sigma_0}$$

σ_0 = free (nucleon) cross-section

σ_N parameterized as = $\sigma_0 A^{\alpha}$

Experimentally α = 0.72 – 0.78, for p, k, π

[1](processes with completely determined initial & final states)

How Transparent is Your Nucleus?

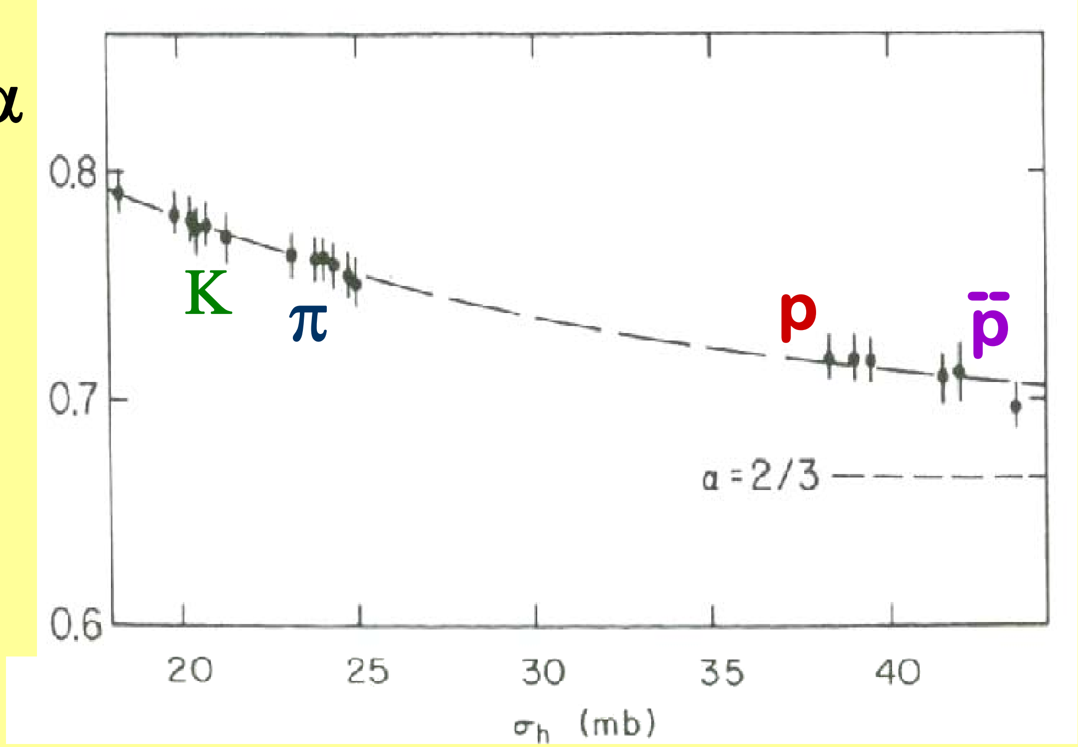
σ_N Hadron- Nucleus total cross-section

Fit to $\sigma(A) = \sigma_0 A^{\alpha}$ → α

α = 0.72 – 0.78,

for π, κ, p

Hadron momentum
60, 200, 250 GeV/c

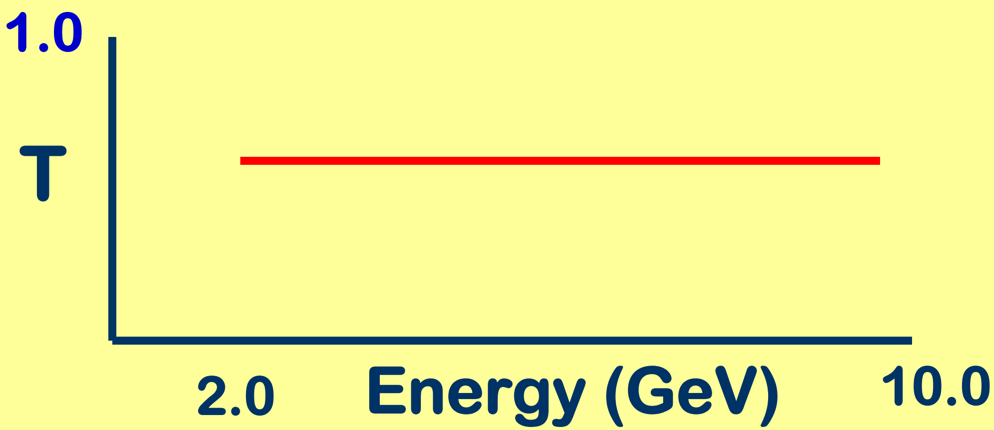


$\alpha < 1$ interpreted as due to the strong interaction nature of the probe

A. S. Carroll *et al.* Phys. Lett 80B 319 (1979)

Nuclear Transparency

Traditional nuclear physics calculations (Glauber calculations) predict transparency to be **energy independent** (when the h-N cross-section is energy independent).



Ingredients

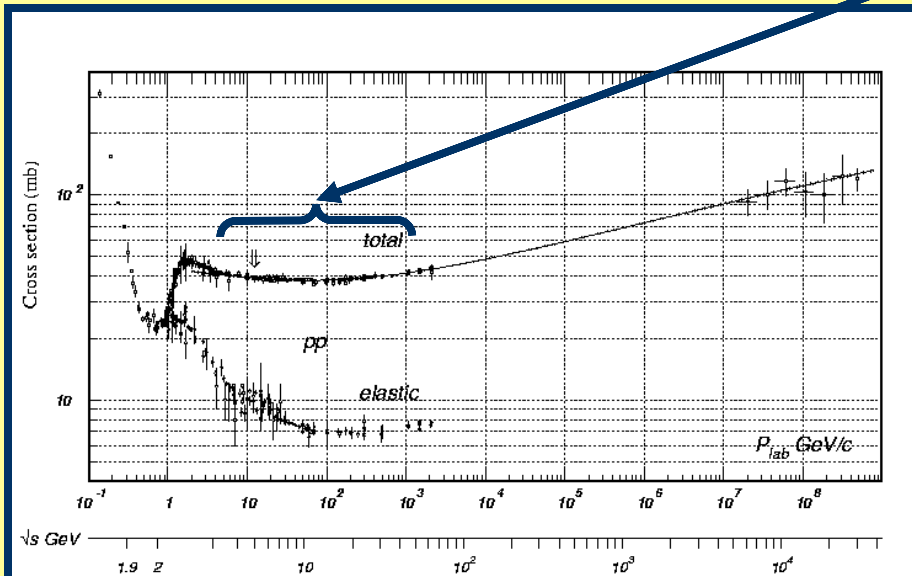
- σ_{hN} h-N cross-section
- Glauber multiple scattering approximation
- Correlations & FSI effects.

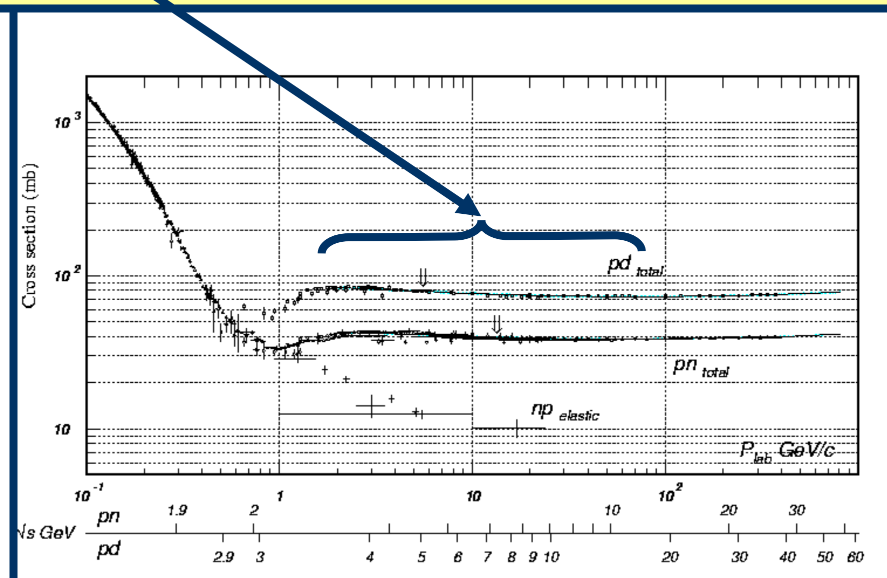
For light nuclei very precise calculations of are possible.

Nuclear Transparency

Traditional nuclear physics calculations (Glauber calculations) predict transparency to be **energy independent** .

N-N cross-section is energy independent





σ_{PP} pp scatt. cross-section

σ_{PN} pn scatt. cross-section

Color Transparency

CT refers to the vanishing of the h-N interaction for h produced in exclusive processes at high Q

Original concept of CT introduced by Mueller and Brodsky in 1982

- At high Q , the hadron involved fluctuates to a small transverse size – called the PLC (quantum mechanics)

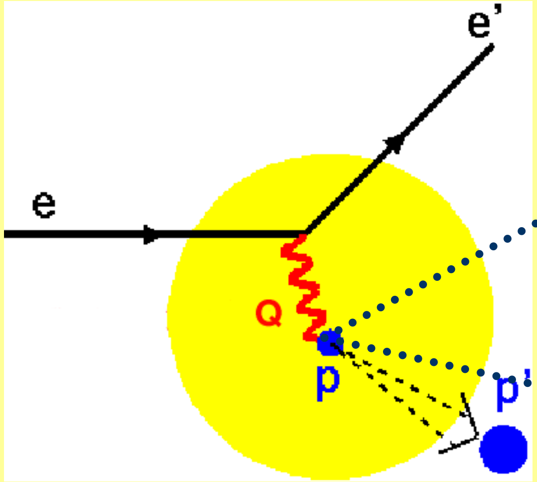
- The PLC remains small as it propagates out of the nucleus (relativity).

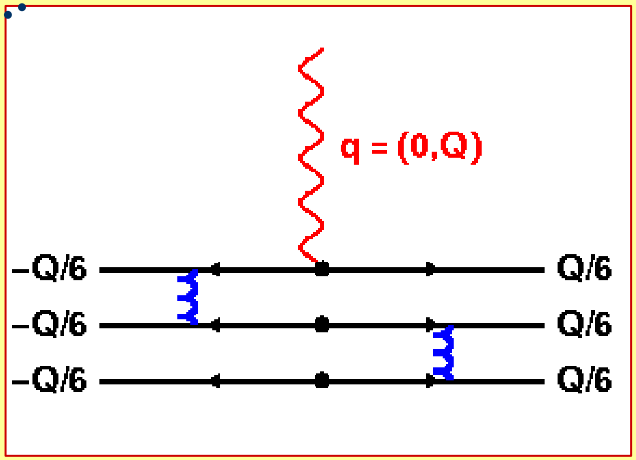
- The PLC experiences reduced attenuation in the nucleus – it is color screened (nature of the strong force).

A.H.Mueller in Proc. of 17th recontre de Moriond, Moriond, p13 (1982)
S.J.Brodsky in Proc. of 13th intl. Symposium on Multiparticle Dynamics, p963 (1982)

Why is the PLC Selected Out?

Using e-p scattering as an example





Lifetime $\cong \hbar/cQ \Rightarrow$ **range** $\cong \hbar/Q$

- At high Q an exclusive interaction can occur only if the transverse size of the hadron involved is smaller than the equilibrium size.

Color Screening and Lifetime of the PLC

The color field of a color neutral object vanishes with decreasing size of the object .

$$\sigma_{PLC} \approx \sigma_{hN} \frac{b^2}{R^2_h}$$

(Analogues to electric dipole in QED)

The lifetime of the PLC is dilated in the frame of the nucleus

$$\gamma t_f = \frac{E}{m} t_f$$

The PLC can propagate out of the nucleus before returning to its equilibrium size.

The Parton-Hadron Transition

Exclusive processes can be used to look for signatures for the transition from quark-gluon degrees of freedom of QCD to the nucleon-meson effective degrees of freedom.

Exclusive Processes

Nucleons

- Quark counting rules
- Hadron helicity conservation

Nuclei

- Color transparency
- Nuclear filtering

CT is totally unexpected in a strongly interacting hadronic picture. But it is quite natural in a quark-gluon framework. It is very good indicator of a transition from hadron to quark dof.

Connecting GPDs & CT

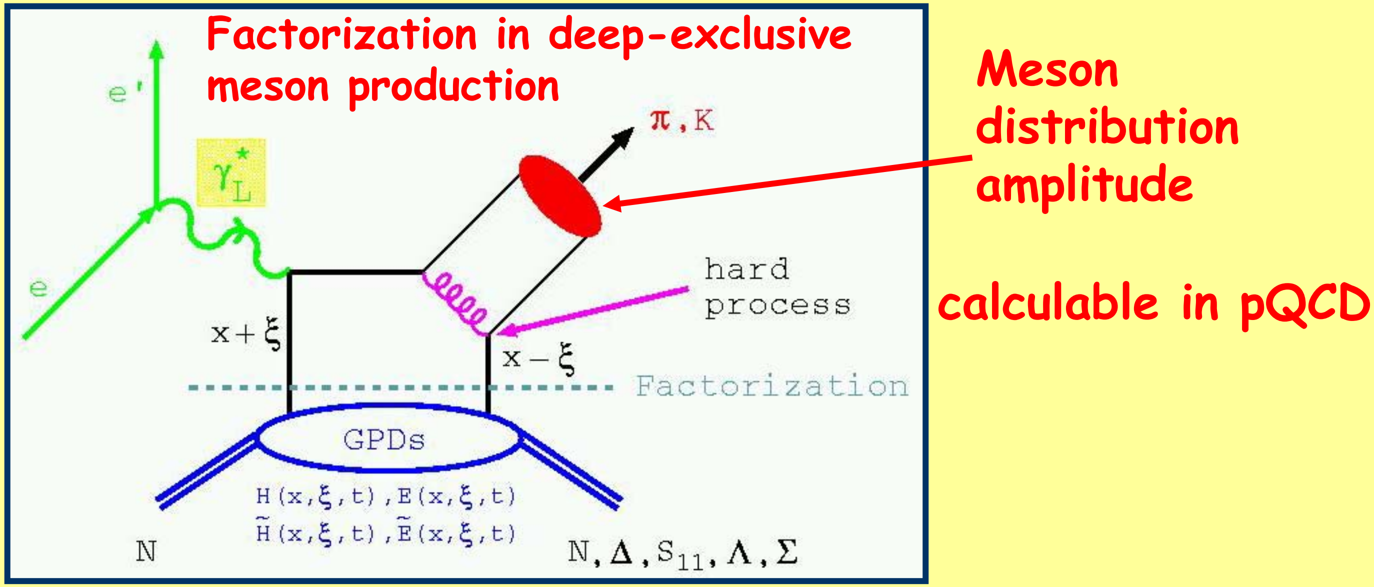
Recent theoretical work identifies connections between GPDs and CT.

M. Burkardt and G. Miller (hep-ph/0312190) have derived the effective size of a hadron in terms of GPD's:
The existence of color transparency would place constraints on the analytic behavior and would provide testable predictions for GPD's

S. Liuti and S. K. Taneja (PRD 70,07419 (2004)) have explored structure of GPD in impact parameter space to determine characteristics of small transverse-separation components
Nuclei can be used as filters to map the transverse components of hadron wave function: i.e.a new source of information on GPD's

CT & Factorization

Factorization theorems have been derived for deep-exclusive processes and are essential for access to GPDs.



It is still uncertain at what Q^2 value reaches the factorization regime

Factorization is not rigorously possible without the onset of CT. - Strikman, Frankfurt, Miller and Sargsian

CT is a necessary but not sufficient condition for factorization

Color Transparency Search- The Experimental Status

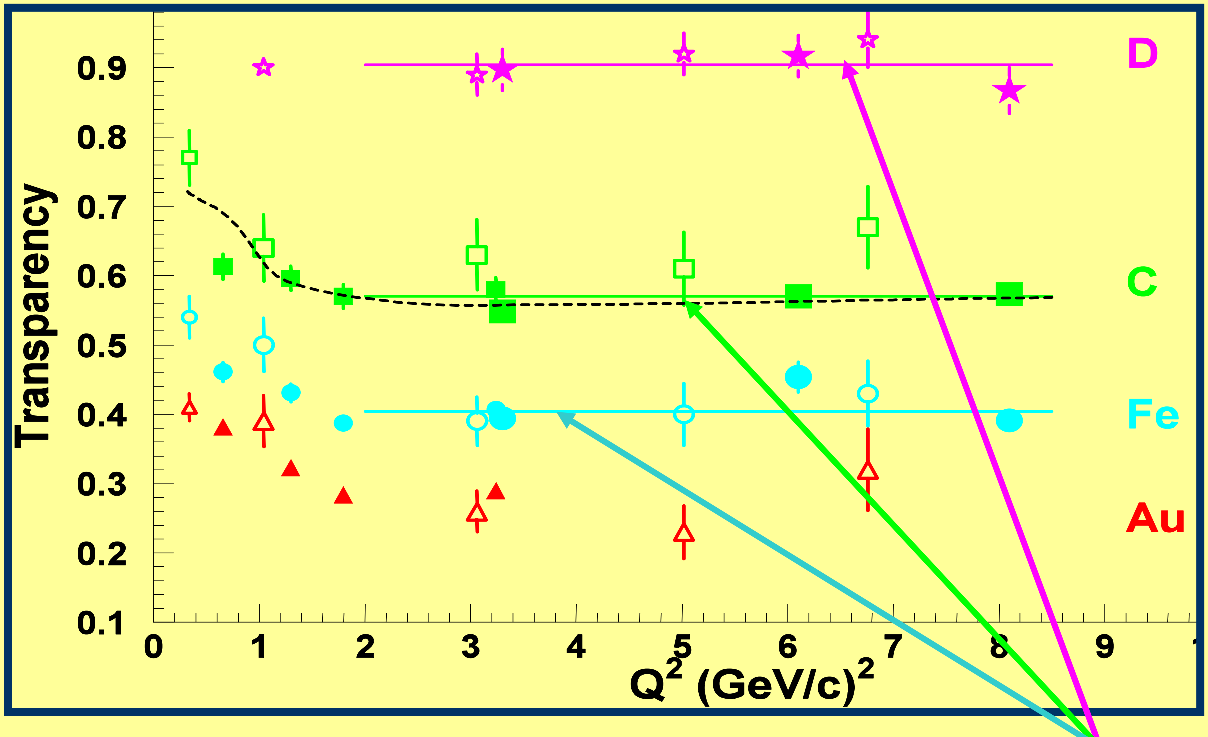
CT refers to the vanishing of the h-N interaction for h produced in exclusive processes at high Q

h can be : $q\bar{q}$ system (e^+e^- in QED)
qqq system (unique to QCD)

- Color Transparency in A(p,2p) BNL
- Color Transparency in A(e,e' p) *SLAC*, JLab
- Color Transparency in A(l,l' ρ) FNAL,HERMES,JLab
- Color Transparency in di-jet production FNAL
- Color Transparency in A(γ,p π), A(e,e' π) JLab

A(e,e'p) Results

Q² dependence consistent with standard nuclear physics calculations



Solid Pts - JLab

Open Pts -- other

Constant value fit for Q^2 > 2 $(GeV/c)^2$ has $\chi^2/\mathbf{df} \cong 1$

N. C. R. Makins et al. PRL 72, 1986 (1994)

G. Garino et al. PRC 45, 780 (1992)

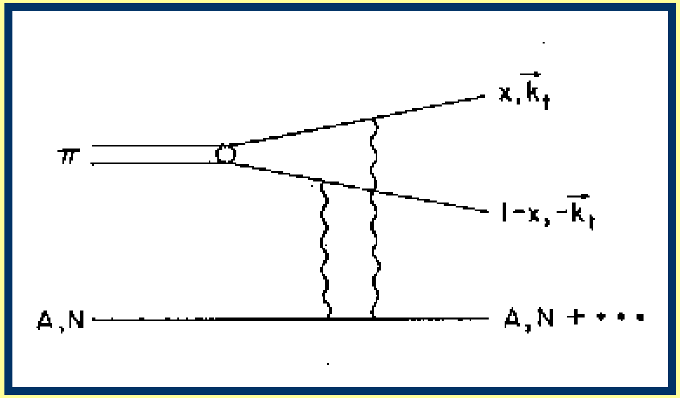
D. Abbott et al. PRL 80, 5072 (1998)

K. Garrow et al. PRC 66, 044613 (2002)

$A(\pi,$ dijet) Data from FNAL

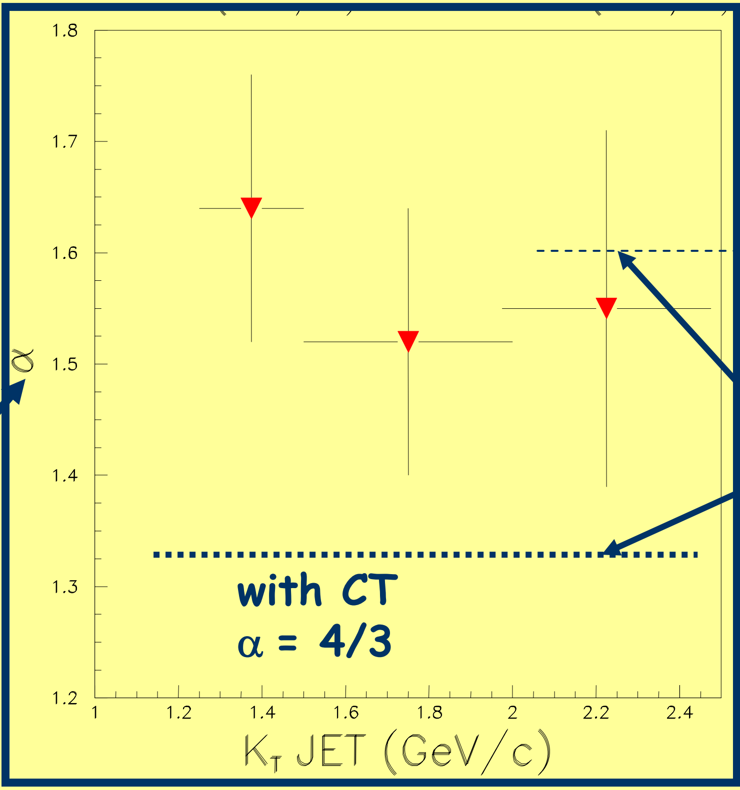
Coherent π^+ diffractive dissociation with 500 GeV/c pions on Pt and C.

$\pi + A \rightarrow$ (2 jets) + A'



diffractive dissociation cross-section fit to:

$$\sigma = \sigma_0 \, A^{\alpha}$$



Considered to be evidence for CT

Aitala *et al.*, PRL 86 4773 (2001)

qqq vs $q\bar{q}$ systems

- There is no unambiguous, model independent, evidence for CT in qqq systems.

- Small size is more probable in 2 quark system such as pions than in protons.

  \- B. Blattel et al., PRL 70, 896 (1993)

- Onset of CT expected at lower Q^2 in $q\bar{q}$ system.

- Formation length is ~ 10 fm at moderate Q^2 in $q\bar{q}$ system.

- Onset of CT is directly related to the onset of factorization required for access to GPDs in deep exclusive meson production.

  \- Strikman, Frankfurt, Miller and Sargsian

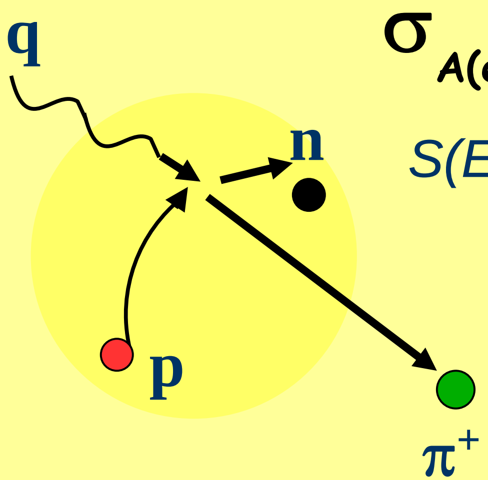
For a Conclusive Experiment

- Use 2 quark systems.
- Need reliable baseline calculation to look for onset.
- Look at both momentum transfer and *A* dependence

Pion electro production reactions may be an ideal candidates.

The $A(e,e'\pi^+)$ Reaction

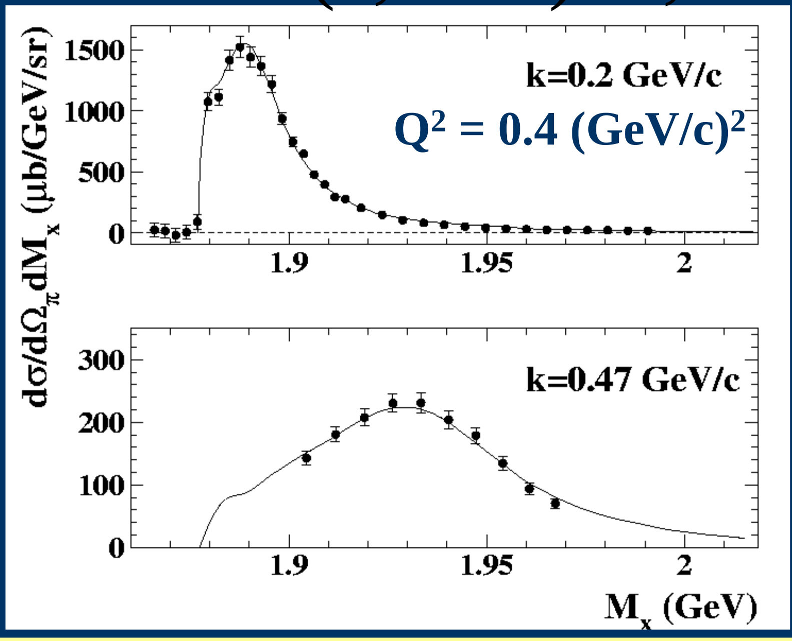
If π^+ electroproduction from a nucleus is similar to that from a proton we can determine nuclear transparency of pions.



$$\sigma_{A(e,e'\pi^+)X} = \sigma_{p(e,e'\pi^+)n} \otimes S(E,p)$$

$S(E,\mathbf{p})$ = Spectral function for proton

$${}^{2}H(e,e'\pi^{+})nn,$$



E91003 has demonstrated the ability to describe data via a quasifree reaction including fermi smearing, FSI and off-shell effects.

D.Gaskell, Ph.D Thesis

Transparency Experiment with Pions

JLab Experiment E01-107: A(e,e' π^+) on H, D, C, Cu, Au

Spokespersons:
D. Dutta, R. Ent & K. Garrow
Thesis Student: Ben Clasie (MIT)

$$T = \frac{\sigma_A^{Expt} / \sigma_A^{Model}}{\sigma_p^{Expt} / \sigma_p^{Model}}$$

Measurable effect predicted for $Q^2 < 5\ (GeV/c)^2$

Very important to look at both Q^2 and A dependence

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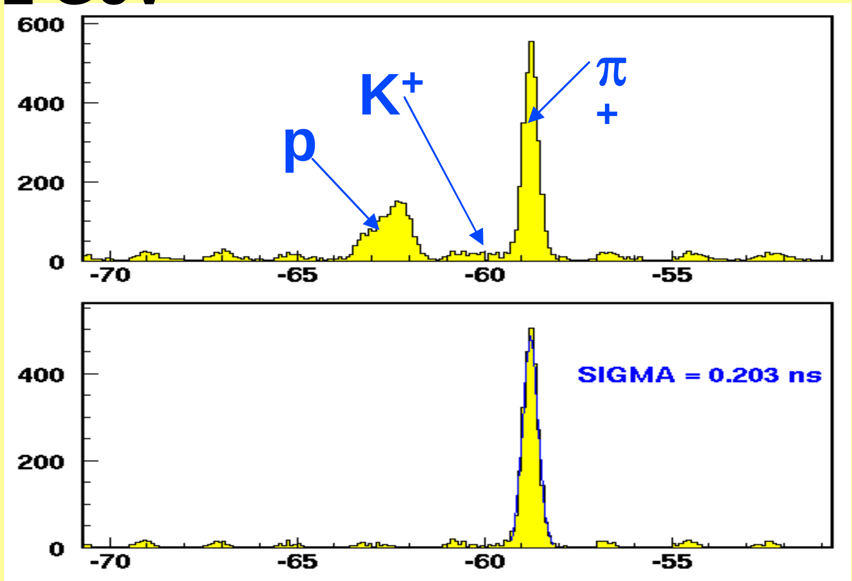
JLab Experiment E01-107

Experiment ran in July `04 for 18 days and December `04 for 12 days

Collected data on
LH_2, LD_2, ^{12}C, ^{63}Cu, and ^{197}Au at
Q^2 of 1.1, 2.15, 3.0, 4.0 and 4.7 $(GeV/c)^2$
and also L/T separation data at Q^2 of 2.15 and 4.0

P_{HMS} = 3.2 GeV

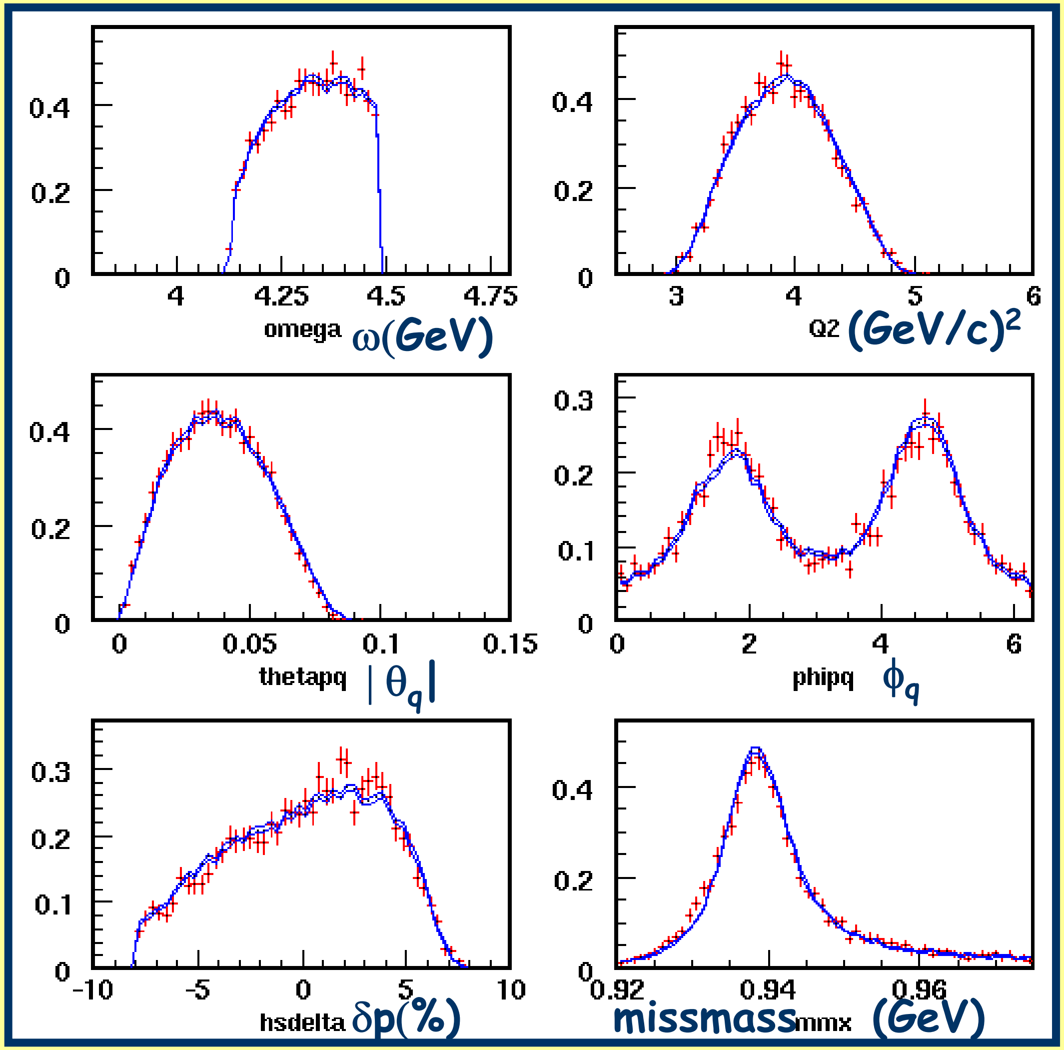


Coincidence time (ns)

Raw Coincidence time without PID

With HMS gas Cerenkov and aerogel cuts

The $p(e,e'\pi^+)n$ Data



Data in Red Blue is simulation

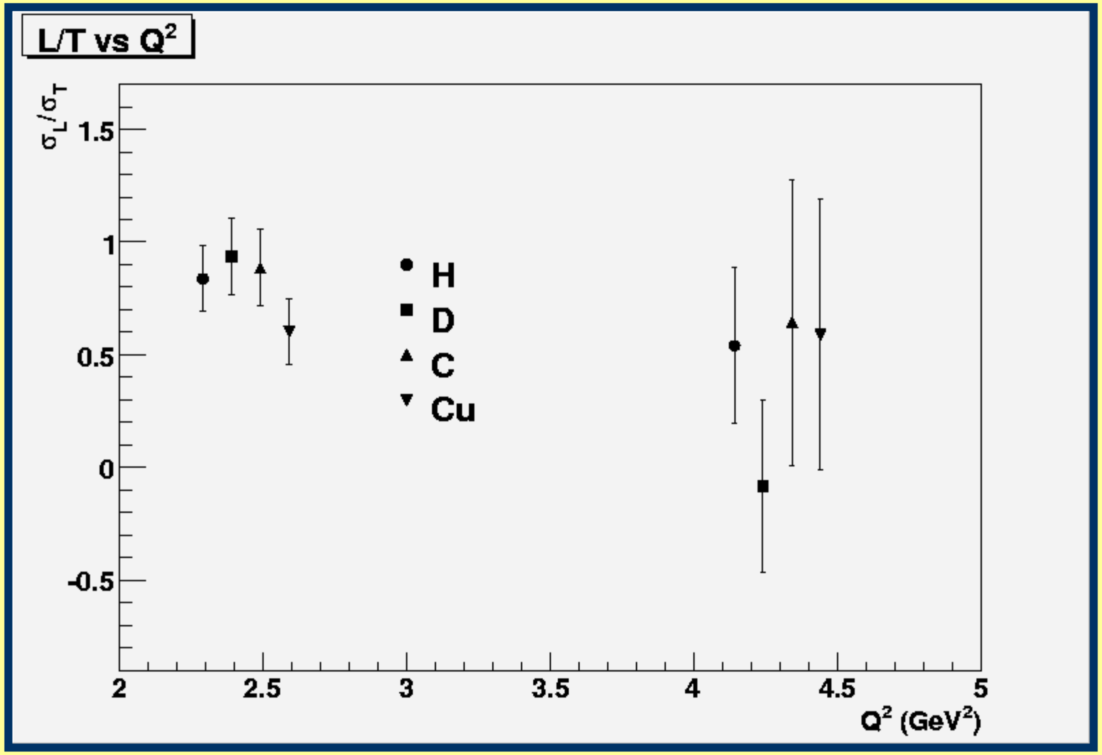
The model for $p(e,e'\pi^+)n$ is iterated until it agrees with the data.

This new parametrization of the pion electroproduction cross-section from the nucleon is used as an input for the quasi-free model for the rest of the target nuclei.

analysis by
Ben Clasie (MIT)

L/T Separation of $A(e,e'\pi^+)$

Preliminary results from L/T separation at Q^2 =2.1 & 4.0$(GeV/c)^2$ on all targets suggests that data is consistent with the quasi-free approximation.



analysis in progress
by Xin Qian (Duke)

The Quasi-free Model

virtual photon flux

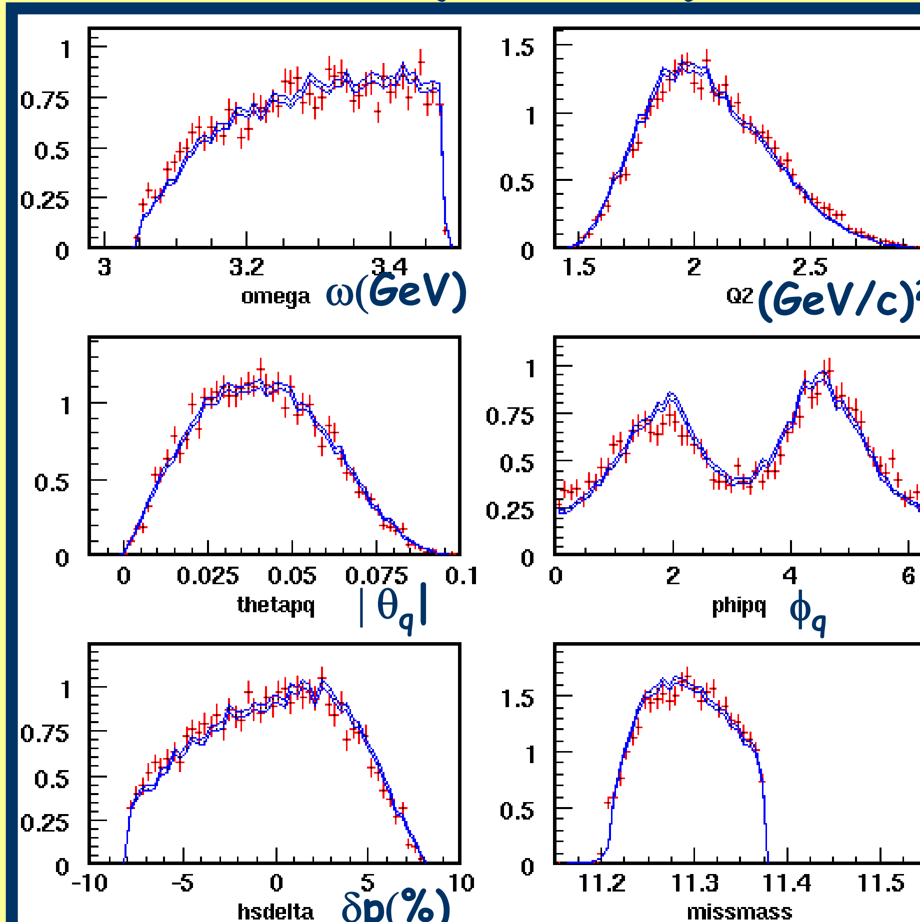
nucleon cross section from hydrogen data

$$\frac{d^6\sigma_A}{d\Omega_e dE d\Omega_\pi dP} = \frac{d}{dP}\int dE_m dp_m S(E_m, p_m) f_\Gamma \Gamma_v J \frac{d^2\sigma}{dt d\varphi}$$

spectral function

correction to flux for a moving proton

$^{12}C(e,e'\ \pi^+)$



Data in Red

Blue is quasi-free model with

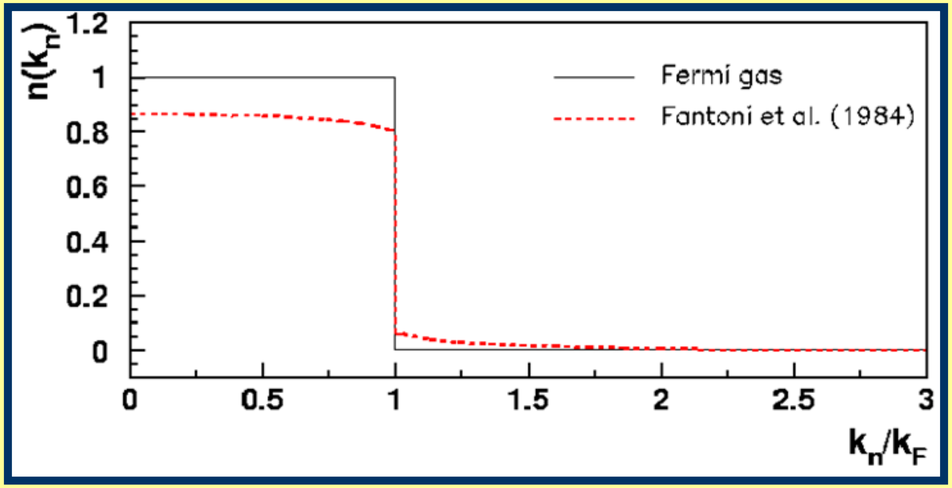
- ^{12}C spectral function
- Pauli Blocking[1]
- off-shell effects (both proton and spectator)

[1]Fermi distribution of Fantoni et al. (1984) including correlations

Pauli Blocking

The **recoiling neutron** in the $p(e,e'\pi^+)n$ process can be Pauli Blocked, when occurring inside a nucleus.

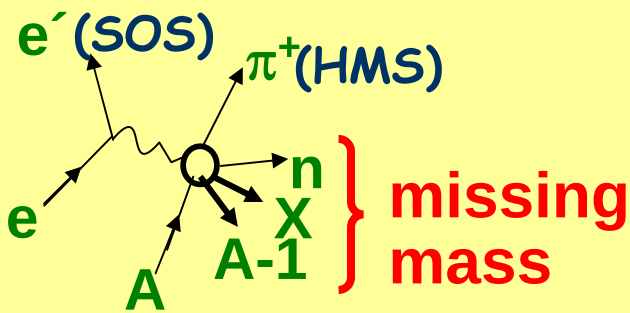
The momentum of the recoiling neutron can be reconstructed from the generated momentum of p, e, e' and π^+,

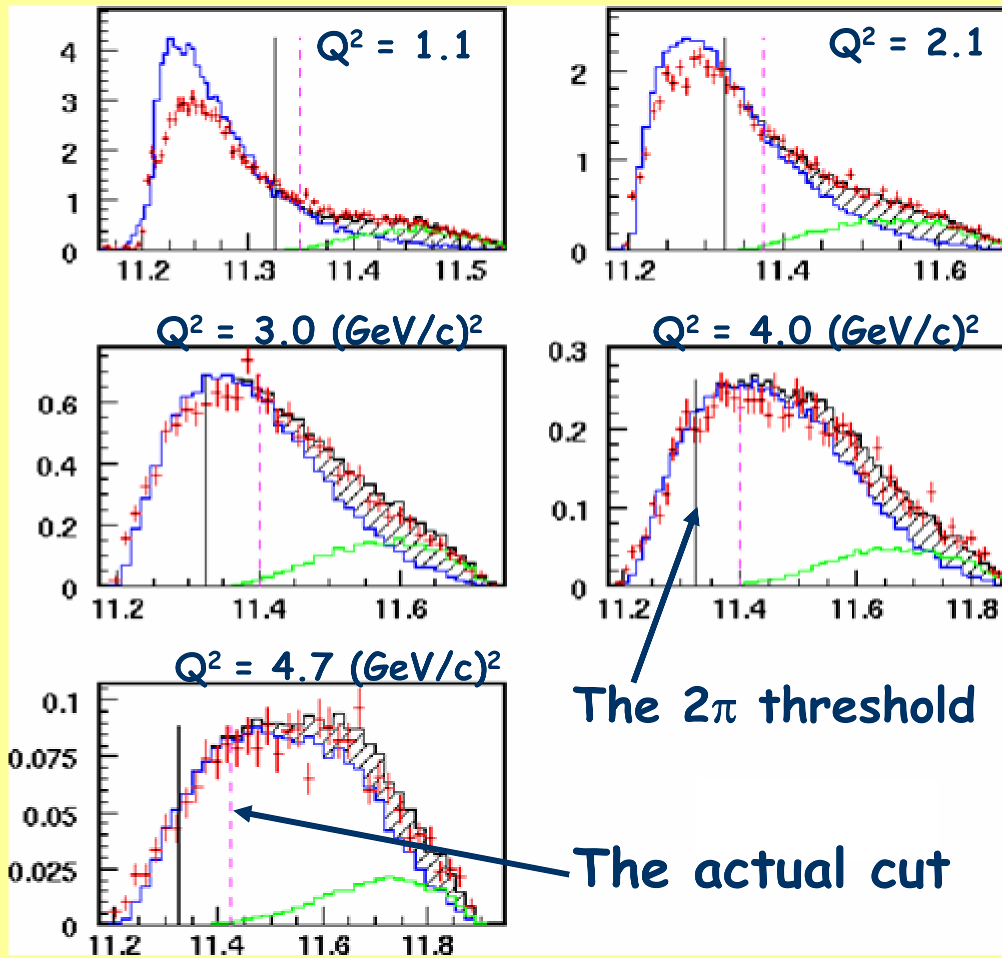


The neutron distribution function of Fantoni *et al.* is used to simulate the effect of Pauli Blocking & correlations.

The multi-pion Background

$^{12}C(e,e'\,\pi^+)$





The 2π threshold

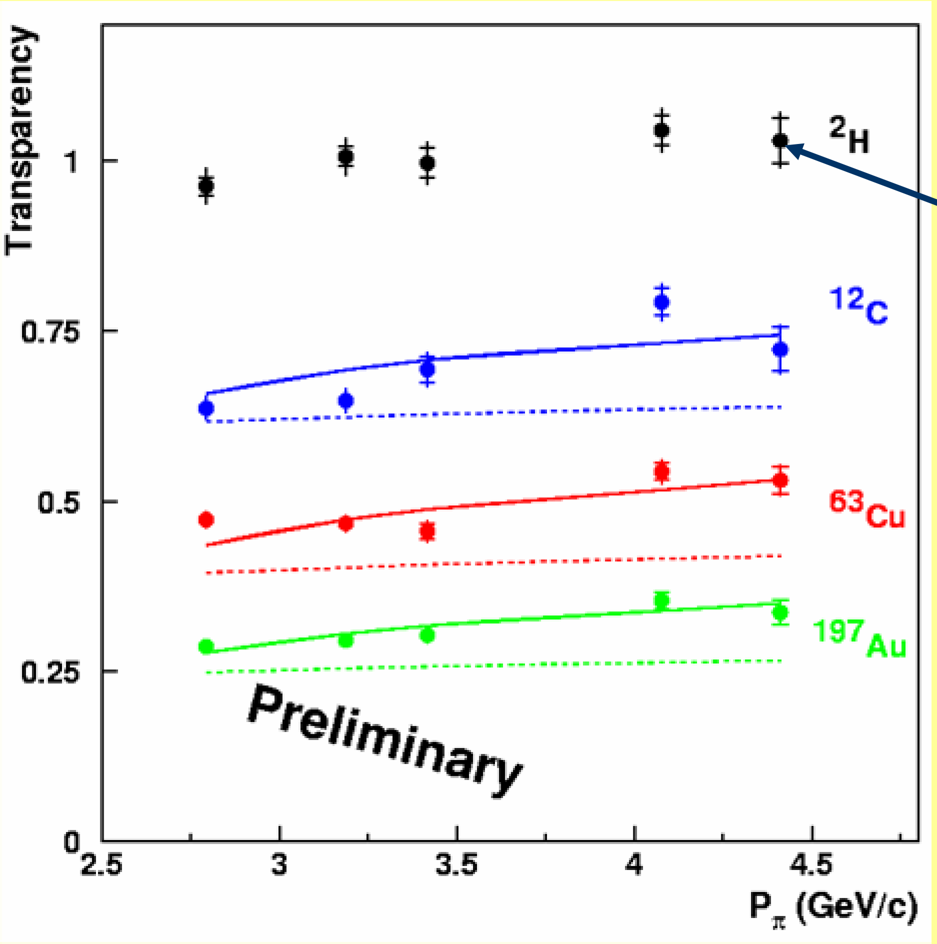
The actual cut

Missing mass

Data in Red

Blue is quasi-free model with
- ^{12}C spectral function
- Pauli Blocking
- off-shell effects

'P_π' Dependence of Transparency



$$T = \frac{(\text{Data/Simulation})_A}{(\text{Data/Simulation})_p}$$

Inner error bar are statistical uncertainties outer error bar are the quadrature sum of statistical and pt. to pt. systematic uncertainties.

Al data from the dummy target is not shown

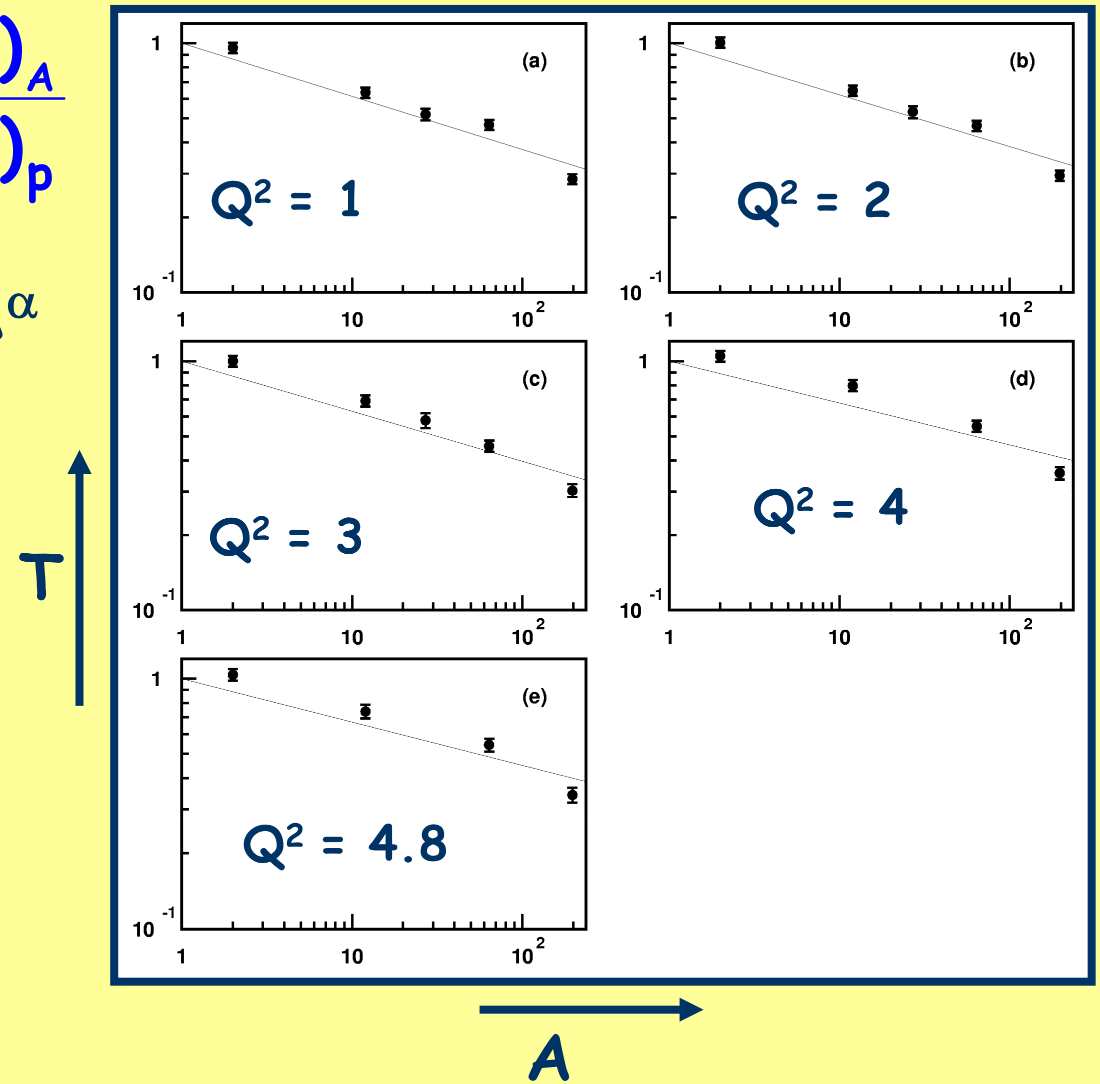
Solid/Dashed lines are predictions with and without CT
A. Larson, G. Miller and M. Strikman, nuc-th/0604022

'A' Dependence of Transparency

$$T = \frac{(\text{Data/Simulation})_A}{(\text{Data/Simulation})_p}$$

Usually $\sigma(A) = \sigma_0\, A^{\alpha}$

$\therefore\ T = A^{\alpha-1}$



Fit of
$T(A) = A^{\alpha-1}$
at fixed Q^2

'A' Dependence of Transparency

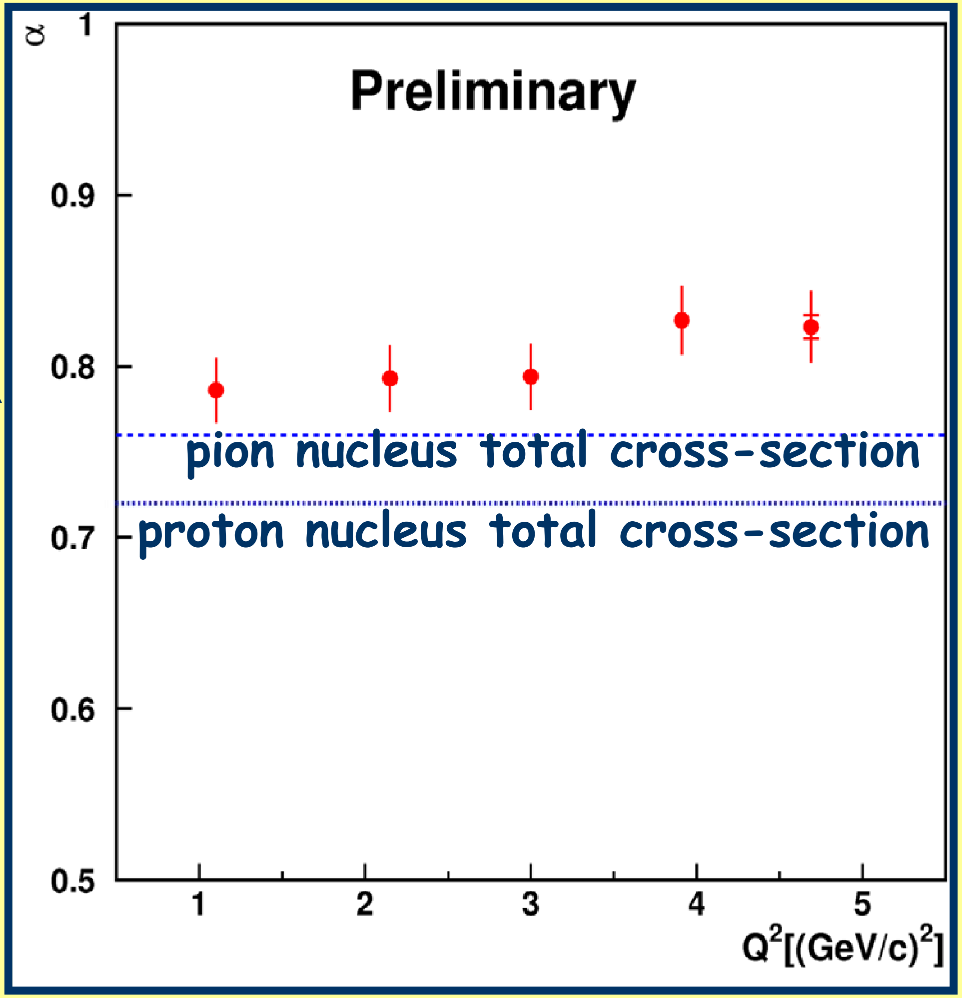
$$T = \frac{(\text{Data/Simulation})_A}{(\text{Data/Simulation})_p}$$

Usually $\sigma(A) = \sigma_0 \, A^{\alpha}$

$\therefore \; T = A^{\alpha-1}$

α

from fit of
$T(A) = A^{\alpha-1}$ at fixed Q^2



Systematic Uncertainties of E01107

Item	point-to-point (%)	scale(%)	total(%)
Particle ID	0.3	0.4 - 0.7	
Charge	0.3	0.5	
Target thickness	0.5		
Coin blocking	0.1		
Trigger(HMS+SOS)	0.7		
Dead time correction	0.1		
Tracking(HMS+SOS)	0.5	0.5	
Pion Absorption	0.5	2.0	
Beam Energy	0.1	0.1	
Cut dependence	0.5	0.5	
Pion Decay	0.5	1.0	
Pauli Blocking	0.5		
Radiative Corrections	0.5	1.0	
collimator	1.0		
Acceptance	0.5	2.0	
Iteration	1.0	2.0	
Spectral Function	1.0	2.0	
TOTAL	2.4	4.4	5

Future Experiments

A detailed study of the parton-hadron transition region is an essential part of the planned upgrade of JLab to 12 GeV.

…understanding the mechanisms at work in this transition region is of primary importance to our understanding of the rich variety and structure and phases that emerge out of QCD…..

-Science Review of the proposed 12 GeV upgrade

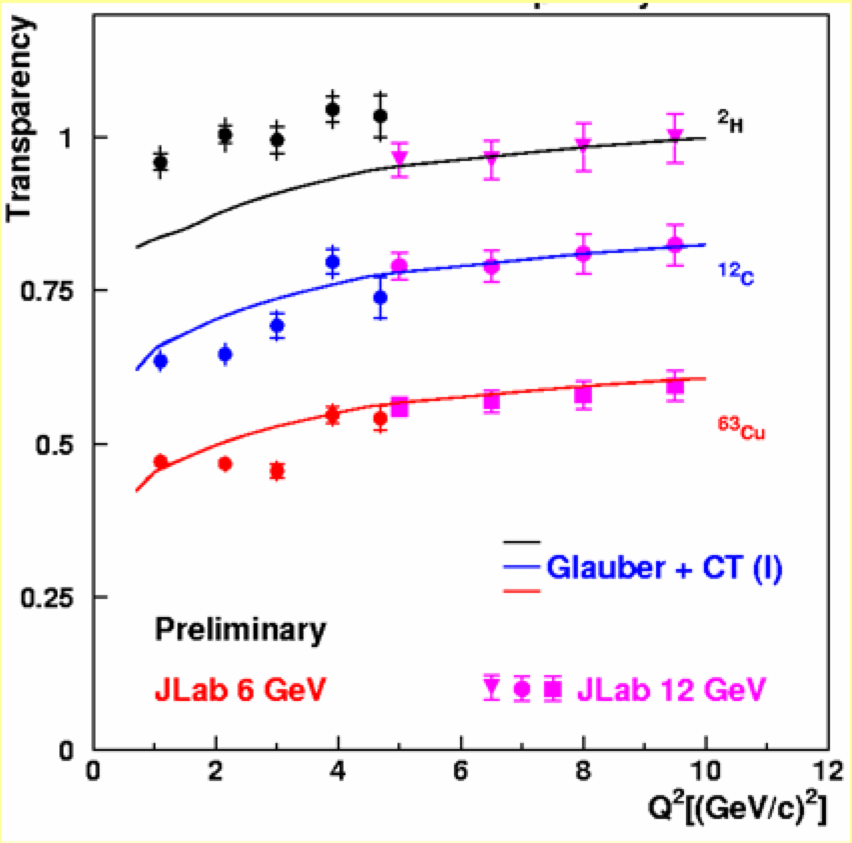
A thorough search for an unambiguous evidence for CT is an important part of the physics driving the 12 GeV upgrade.

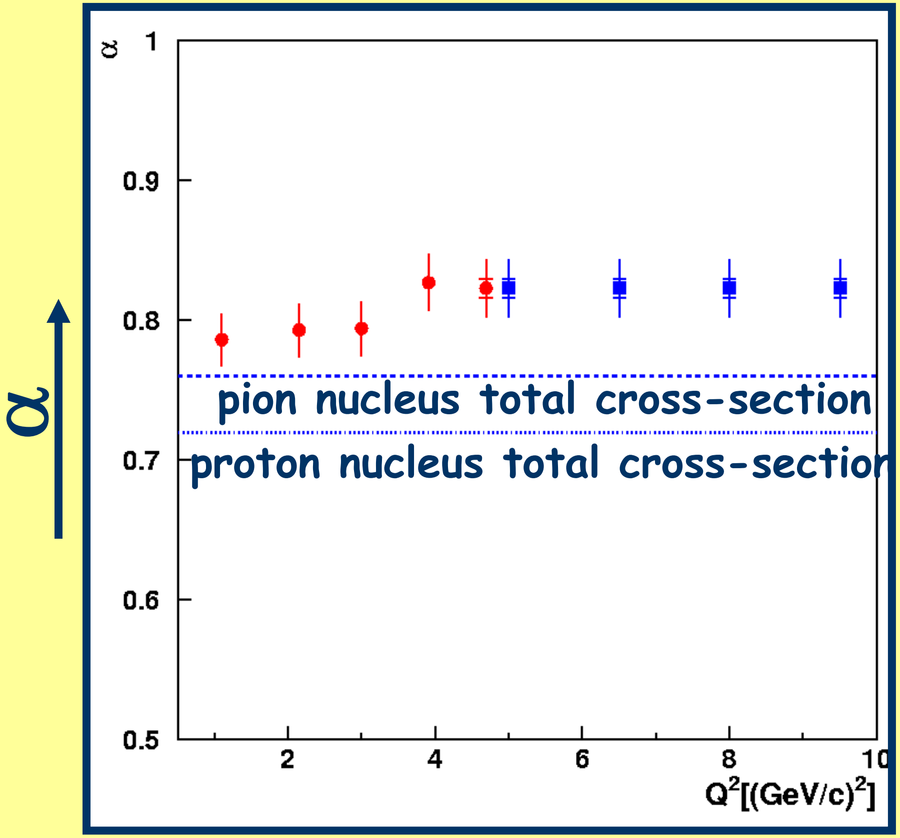
Projected Results

Cu theory curve scaled by 10% to match data.

$A(e,e'\pi^+)$

Preliminary results and projections shown with stat. + pt-to-pt syst. uncertainties only





Solid lines : Kundu et al. PRD 62, 113009 (2000)

$A(e,e'\pi)$ results will verify the strict applicability of factorization theorems for meson electroproduction

Summary

- Exclusive processes are crucial in studying the transition from the nucleon-meson to the quark-gluon picture.

- By comparing exclusive processes on both nucleons and nuclei, one of the signatures of this transition – namely color transparency can be studied.
  - Recent theoretical work identifies connections between GPDs and CT.

- Proton transparency data can be well described by conventional nuclear physics.

- Meson production data from JLab seem to show hints of QCD dynamics, but the transition seems to be slower than most predictions.

- With the proposed upgrade of JLab to 12 GeV along with the results obtained at 6 GeV we should be able to make significant progress in identifying the energy threshold for the transition from quarks to nuclei.