Hadron propagation in the nuclear matter

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Introduction

Interactions of hadrons produced in nuclear matter are a tool for, and a measure of, our understanding of the strong force.

<u>**Relevance to neutrino experiments**</u>

- **Nuclear effects in precision measurement of ν - oscillation parameters.**
- **Nuclear effects in E_{ν} reconstruction.**

How do we measure the effects of propagation through cold nuclear matter?

Exclusive Processes in Nucleons and Nuclei

Exclusive processes (processes with completely determined initial and final states), **can be used to study propagation of hadrons in the medium.**

Exclusive Processes

Nucleons

$$A + B \rightarrow C + D$$

$B \Downarrow N$

Nuclei

$$A + B \rightarrow C + D + X$$

$B \Downarrow {}^{A}N_{Z}$

Nuclear Transparency

Ratio of cross-sections for exclusive processes from nuclei and nucleons is termed as Transparency

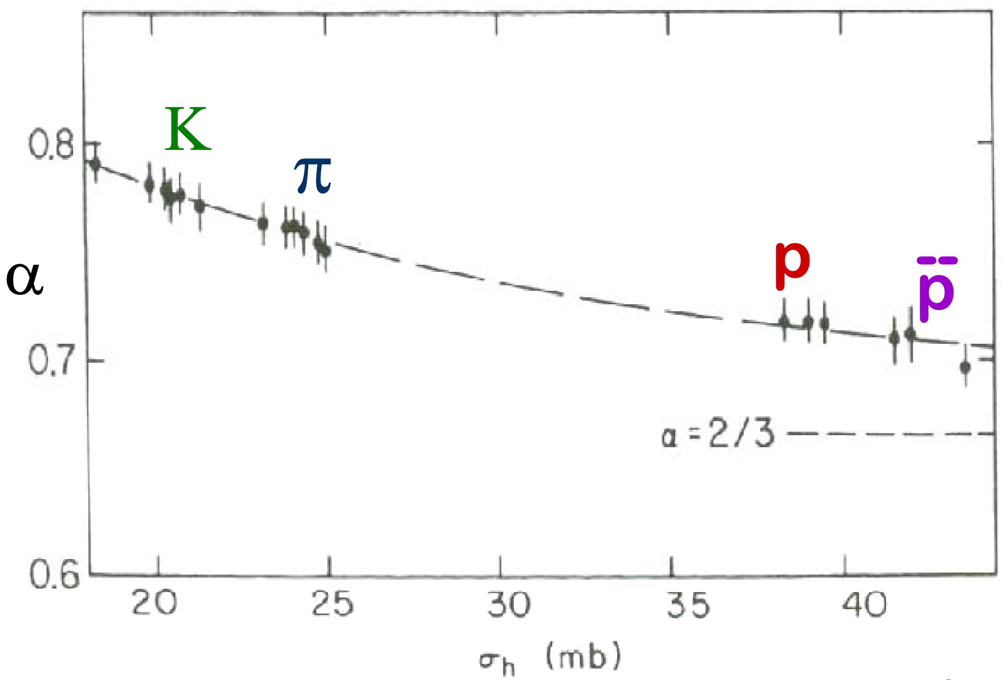
$$T = \frac{\sigma_N}{A\sigma_0}$$

σ_0 = free (nucleon) cross-section

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

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

Total Cross-sections



Hadron– Nucleus total cross-section

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

Hadron momentum 60, 200, 250 GeV/c

α **= 0.72 – 0.78, for** π, κ**, p**

$\alpha < 1$ **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 .

Ingredients

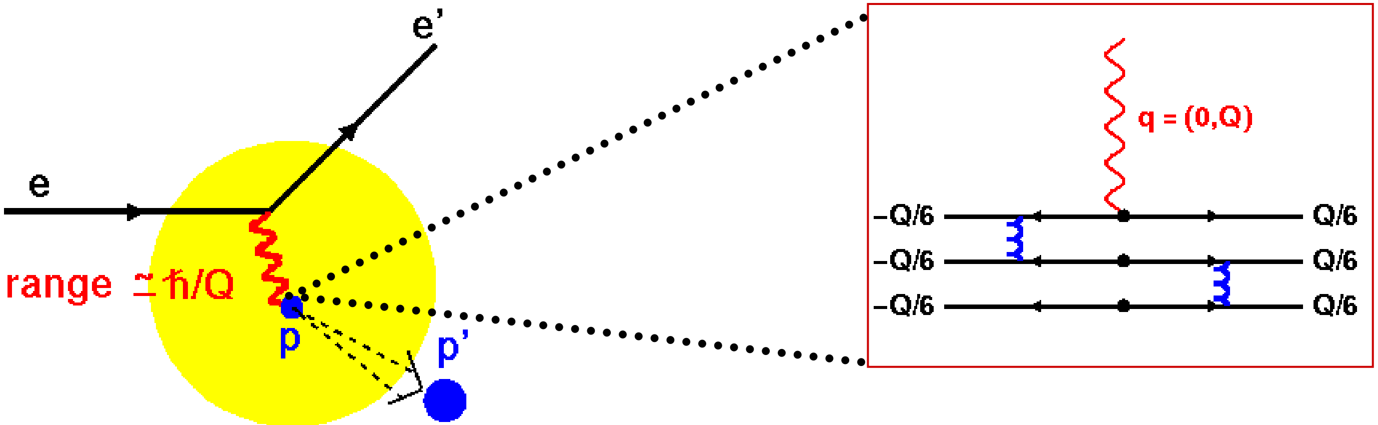
- σ_{hN} h-N cross-section
- Glauber multiple scattering approximation
- Correlations & FSI effects.

Color Transparency

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

- At high Q , the hadron involved fluctuates to a small transverse size – called the PLC (quantum mechanics).
- The PLC experiences reduced interaction with the nucleus – it is color screened (nature of the strong force).
- The PLC remains small as it propagates out of the nucleus (relativity).

Why is the PLC Selected Out?



Using e-p scattering as an example

- The momentum is distributed roughly equally among the quarks,

(for it to be elastic scattering) ⇨ lifetime $\simeq \hbar/cQ$

⇨ range $\simeq \hbar/Q$

- At high Q an elastic 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.

Color Transparency - Experimental Status

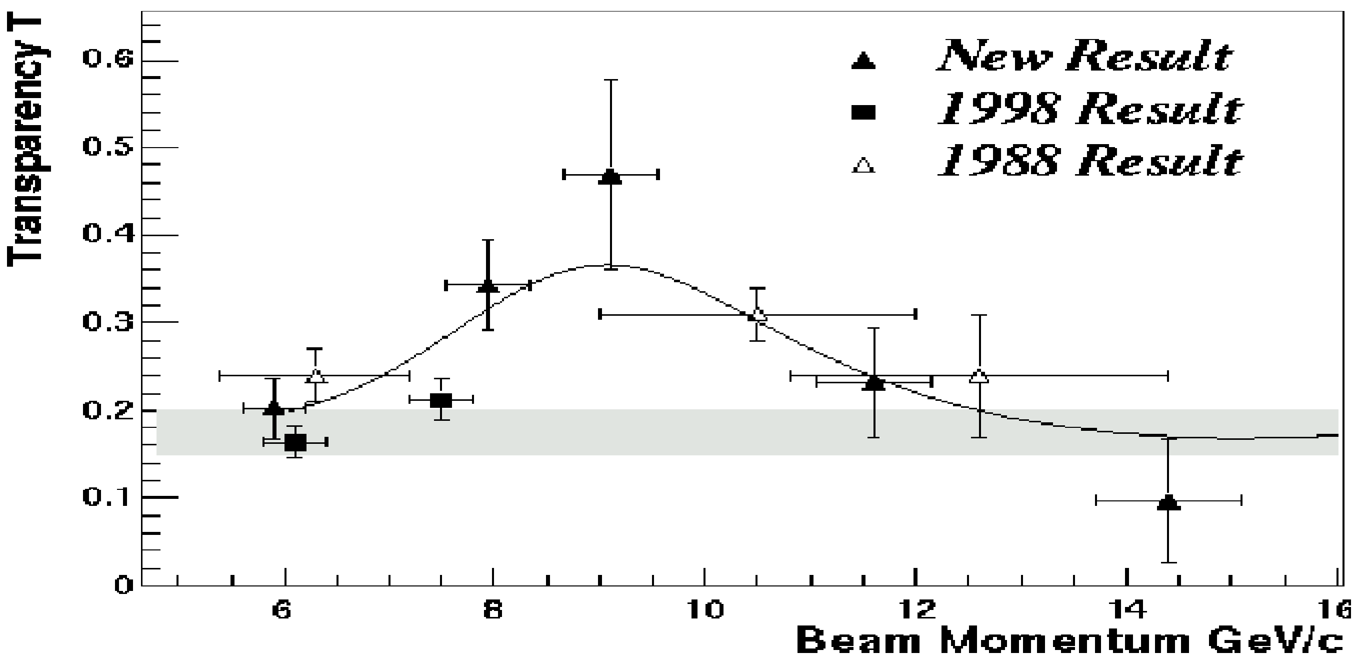
CT refers to the vanishing of the h-N interaction for h produced in exclusive processes at high Q

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) Jlab
- Color Transparency in A(ℓ,ℓ' ρ) FNAL, HERMES
- Color Transparency in di-jet production FNAL
- Color Transparency in A(e,e'π) Jlab
- Color Transparency in A(γ,πp) JLab

Transparency in A(p,2p) Reaction

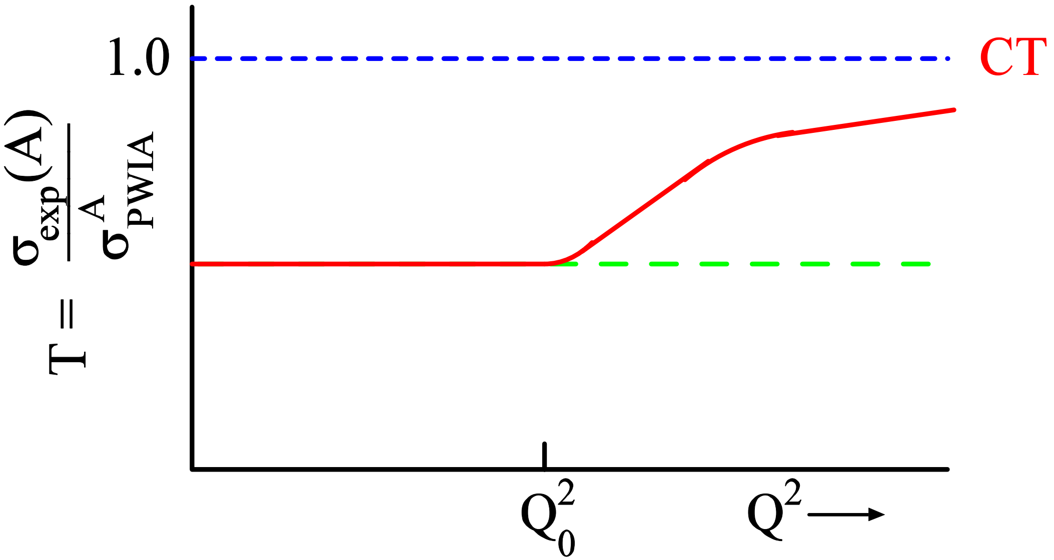
First experiment to look for color transparency



Results inconsistent with CT but explained in terms of nuclear filtering or charm resonance states.

Transparency in A(e,e'p) Reaction

The prediction of CT implies: Fast protons have reduced final state interactions.



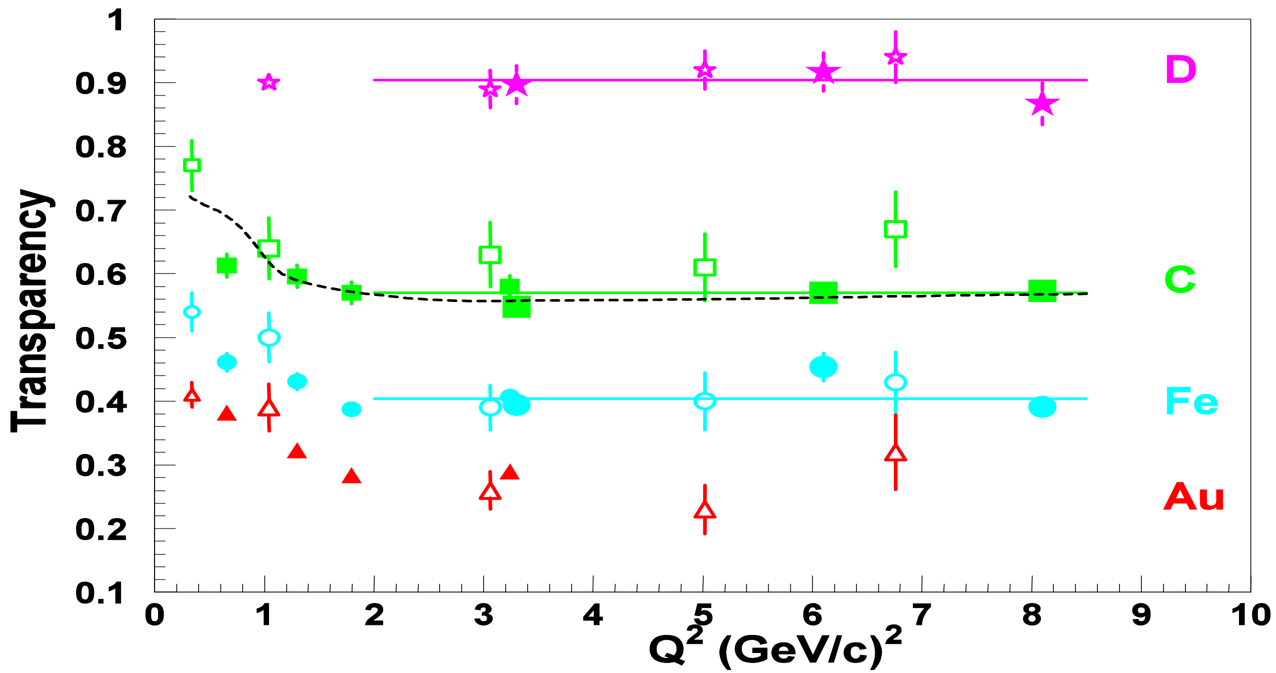
e + A → e' + p + X

Q^2 is square of the momentum transfer

At JLab search for CT focused on A(e,e'p)
E91-013 & E94-139

A(e,e'p) Results

Q^2 dependence consistent with standard nuclear physics calculations

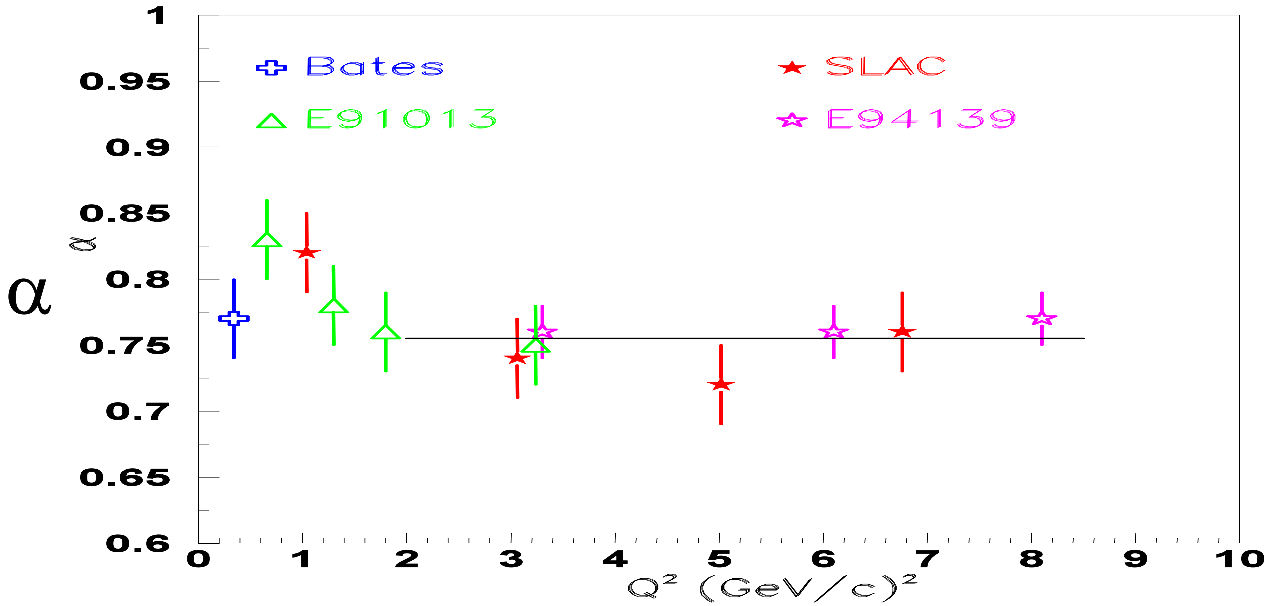


Constant value fit for $Q^2 > 2$ $(GeV/c)^2$ has $\chi^2/df \cong 1$

K. Garrow et al. submitted to PRC

A(e,e'p) Results -- A Dependence

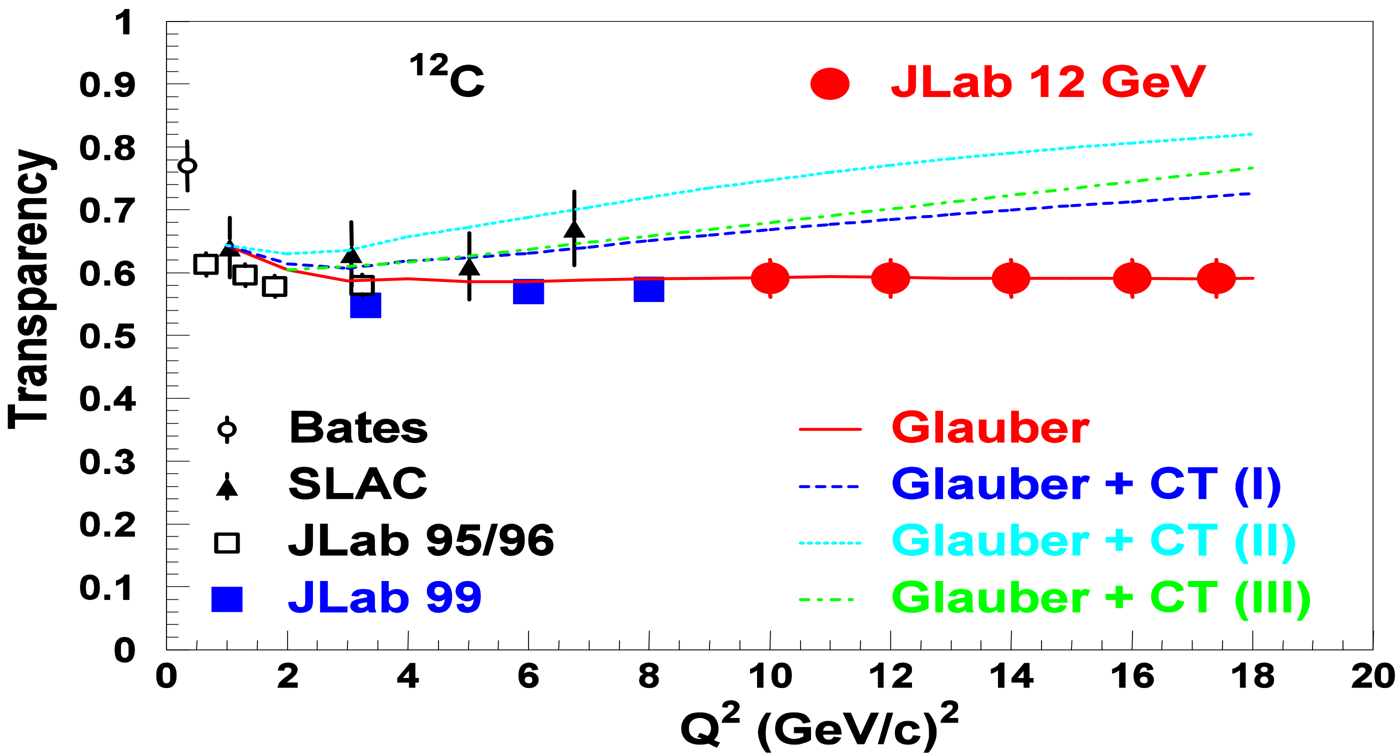
Fit to $\sigma = \sigma_o A^{\alpha}$



α **= constant = 0.76**

for $Q^2 > 2\ (GeV/c)^2$

A(e,e'p) at 12 GeV



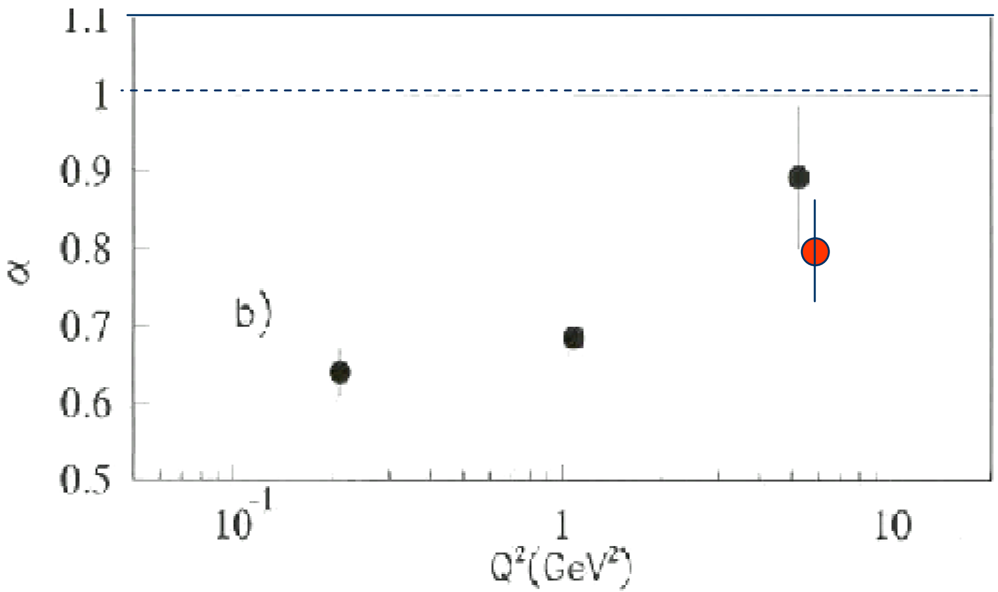
With HMS and SHMS @ 12 GeV

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.
- 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.

Incoherent ρ^0 Meson Production

FNAL A(μ, μ' ρ^o) with E_μ = 470 GeV, A = H, D, C, Ca, Pb



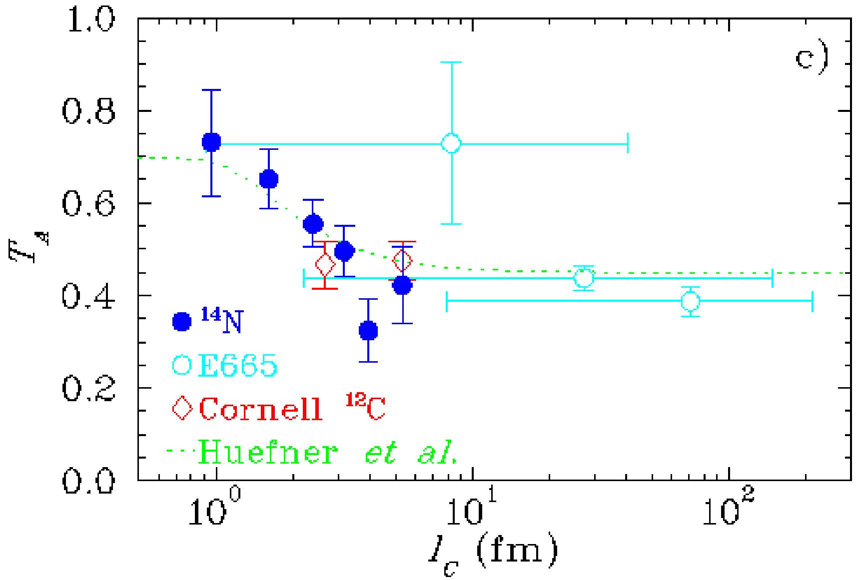
Fit to $\sigma = \sigma_0 A^\alpha$

Evidence for CT statistically less significant with NMC data

FNAL E665: Adams *et al.*, PRL 74, 1525 (1995)
NMC: Ameada *et al.*, NPB 429, 503 (1994)

Incoherent ρ^0 Meson Production

HERMES (e,e' ρ^o) **with E_e = 27 GeV, A = D, ^{3}He, ^{14}N**



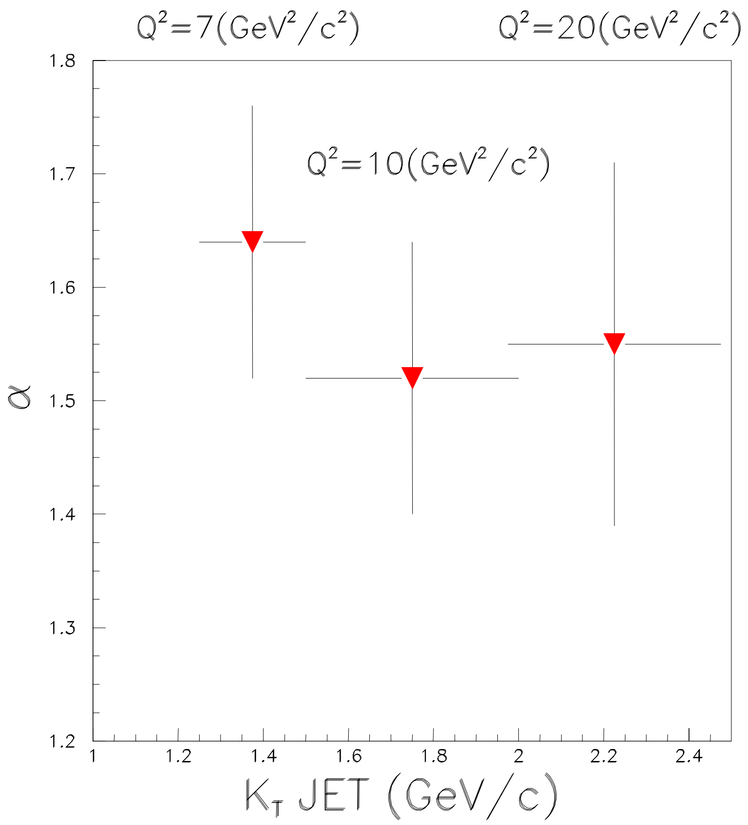
Transparency vs coh. length

l_c distance in front of the nucleus the virtual photon fluctuates into a ρ^o.

Evidence of coherence length effect, can be confused with CT a formation length effect.

Akerstaff *et al.* , PRL 82, 3025 (1999)

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



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

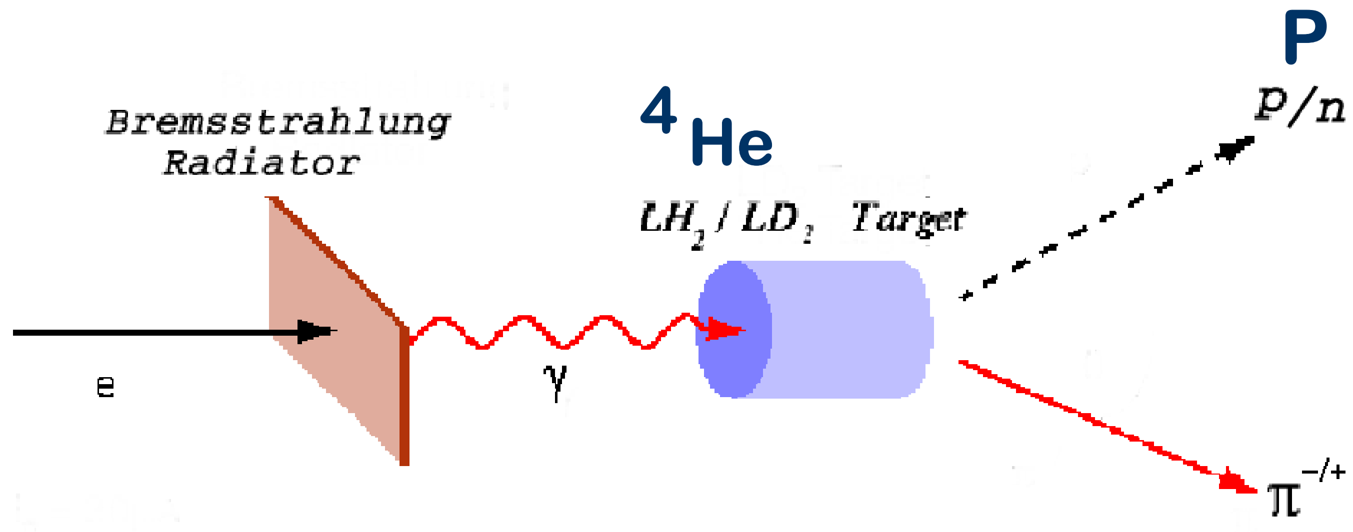
Fit to $\sigma = \sigma_0 A^\alpha$

α > 0.76 from pion-nucleus total cross-section.

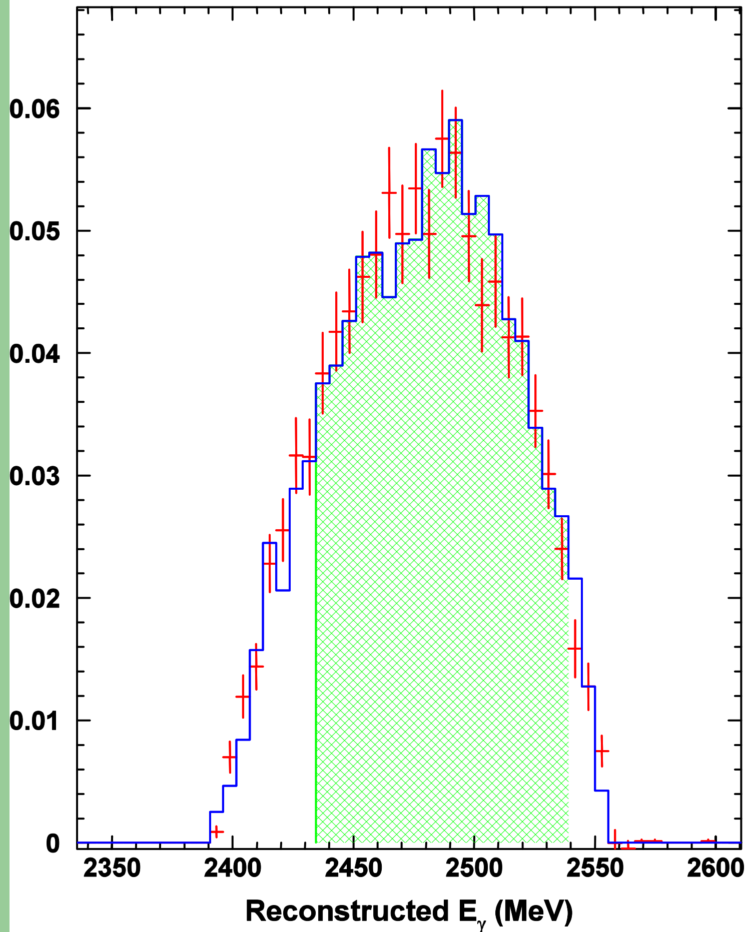
Aitala *et al.*, PRL 86 4773 (2001)

Pion-photoproduction

$\gamma\ n \rightarrow \pi^{-} p$ in ^{4}He



Pion Photoproduction

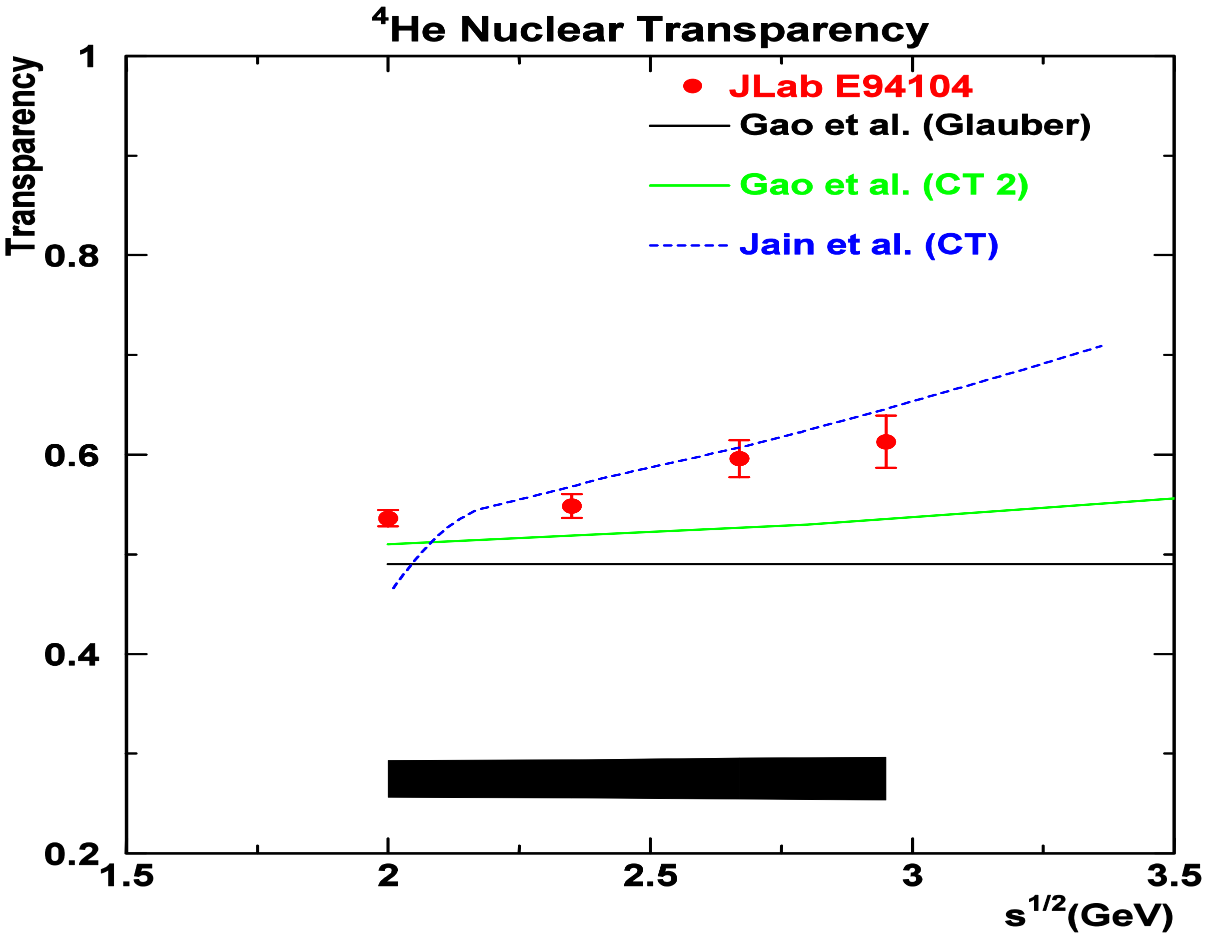


$$\gamma + {}^4\mathrm{He} \longrightarrow \pi^- + p + X$$

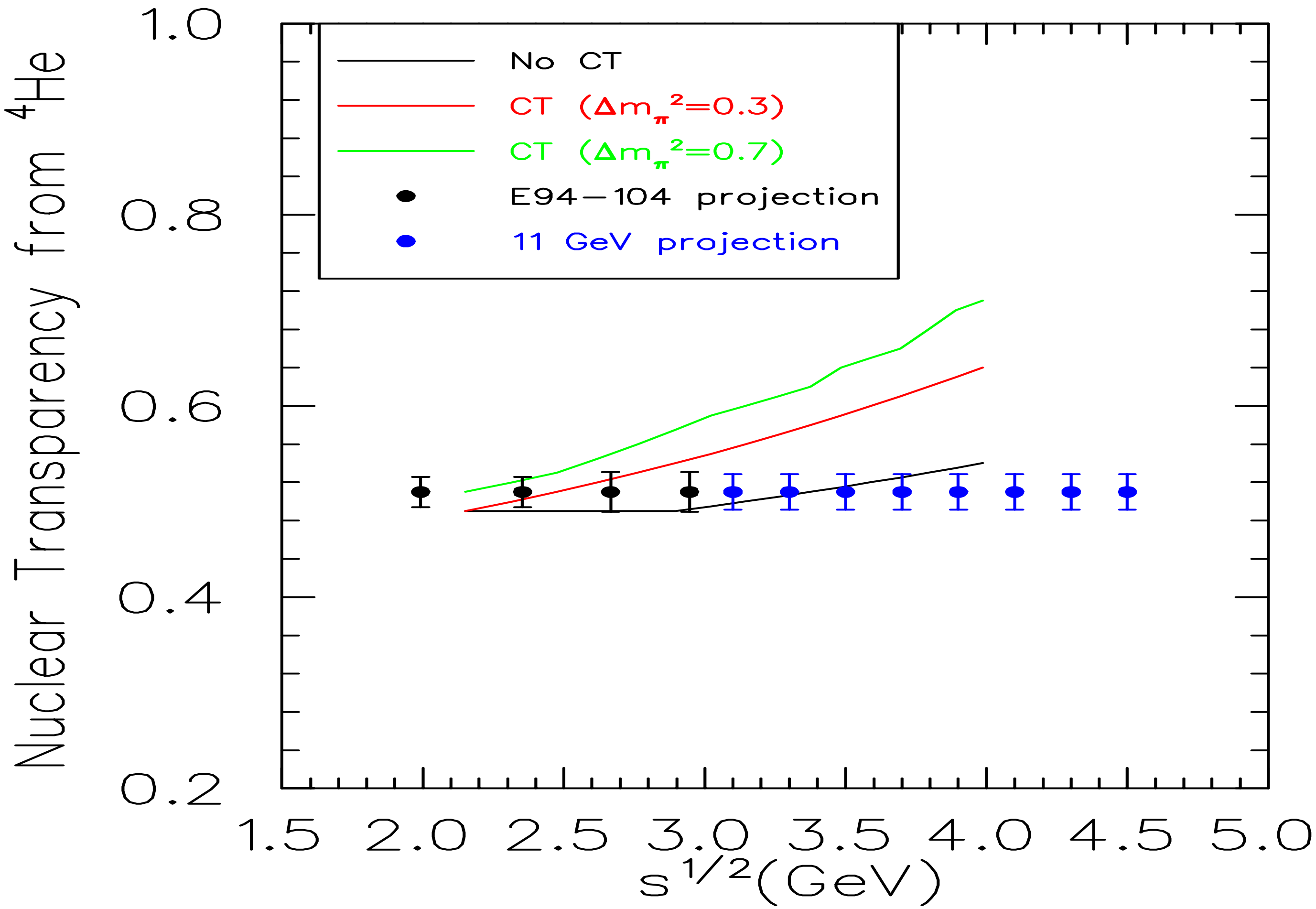
Assume *X* remains in the ground state

$$T \approx \frac{\gamma + {}^4\mathrm{He} \longrightarrow \pi^- + p + X}{\gamma + n \rightarrow \pi^- + p}$$

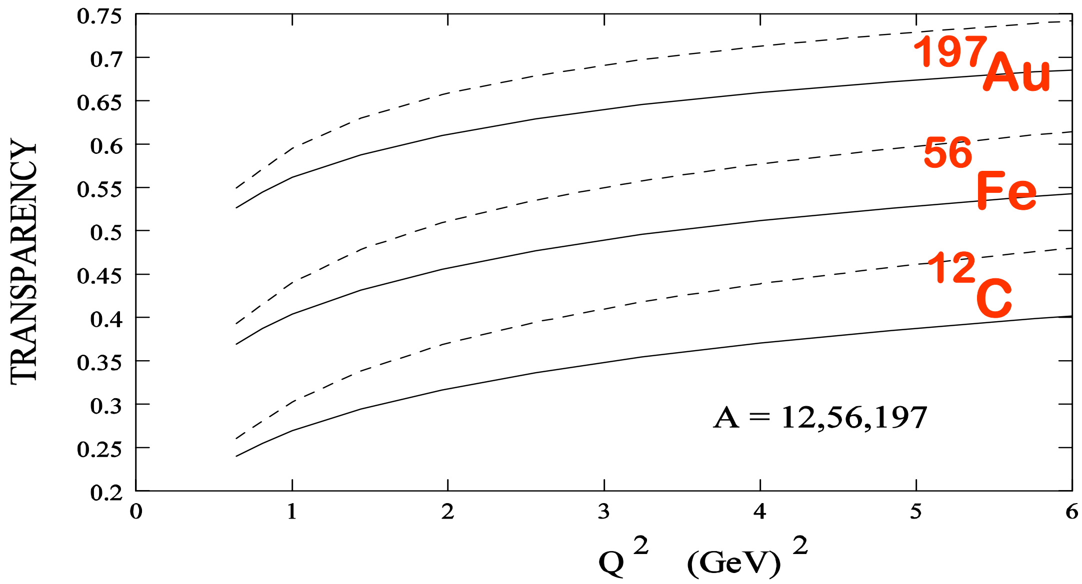
Transparency in ^4He



Transparency in ^{4}He



The A(e,e' π) Reaction



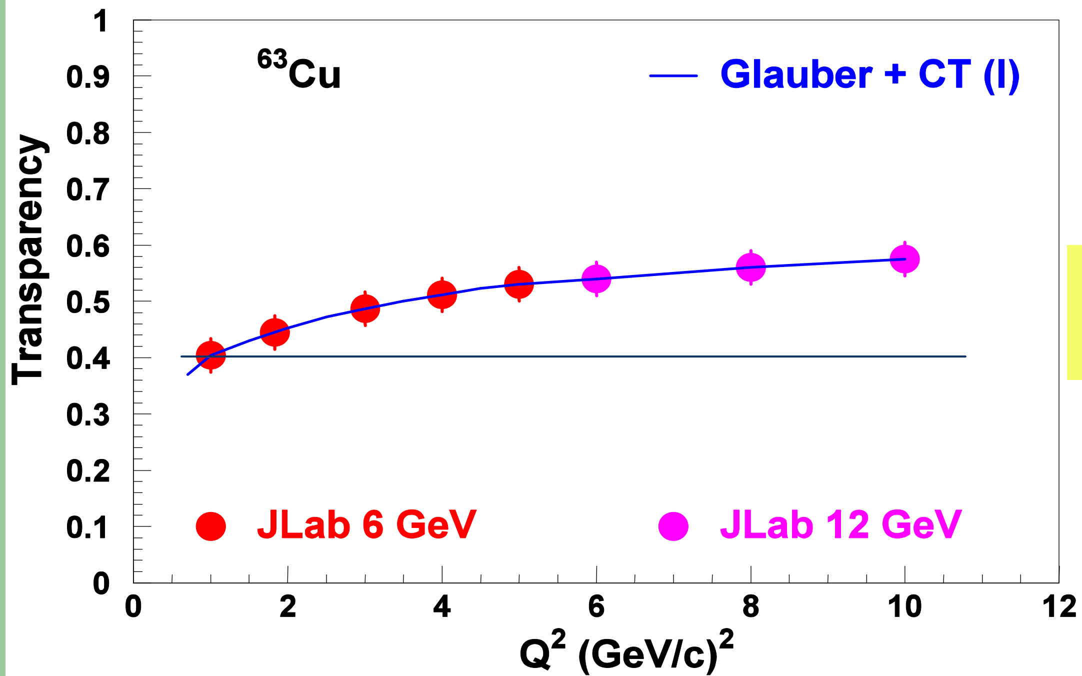
$e + A \rightarrow e + \pi + X$

These predictions are consistent with existing data and independent calculations.

- Most of the CT effect is at $Q^2 > 10\ (GeV/c)^2$
- Two different quark distributions predict effects > 40 % at Q^2 between $1 - 5\ (GeV/c)^2$ for Gold nucleus.

A Pion Transparency Experiment

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



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

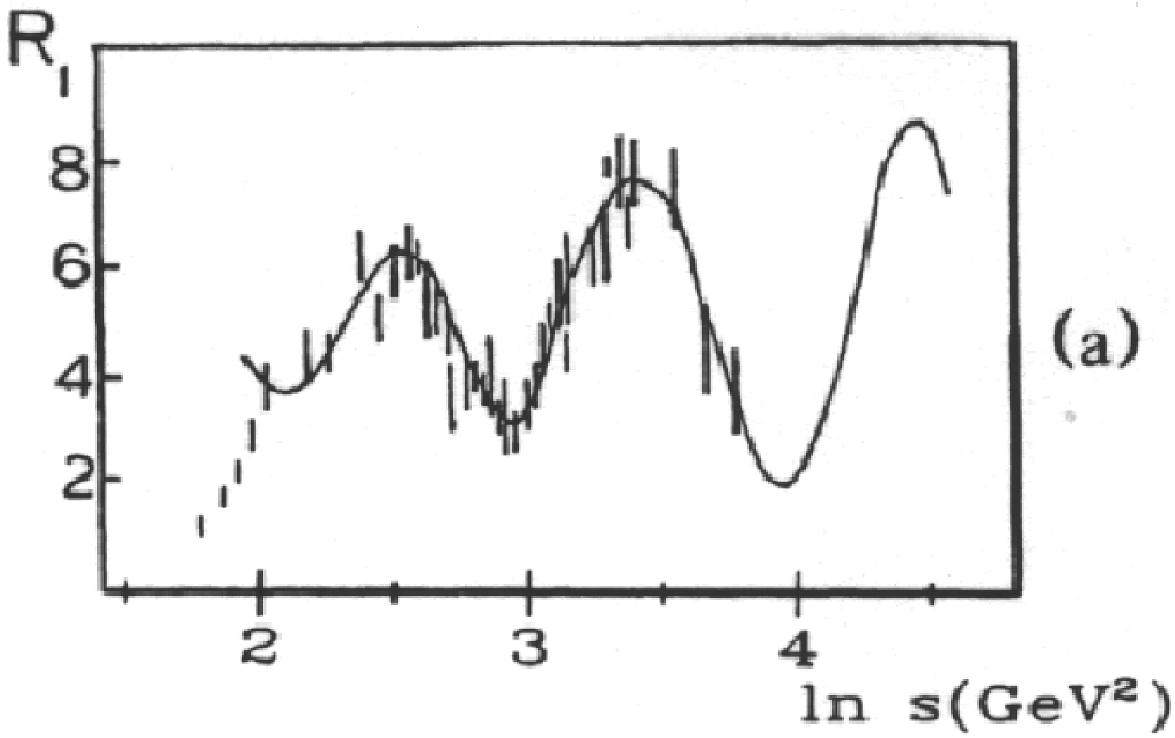
Projected combined statistical & systematic uncertainty of 5 – 10 % and the combined A & Q^2 effect measurable.

Nuclear Filtering

- Some N-N cross-sections show oscillations about the pQCD predicted quark counting rule.
- It has been suggested that these oscillations are damped out in the nuclear medium.
- This is called “ Nuclear Filtering.”
- This implies there should be oscillations in nuclear transparency 180^o out-of-phase with the oscillations in the free cross-section.

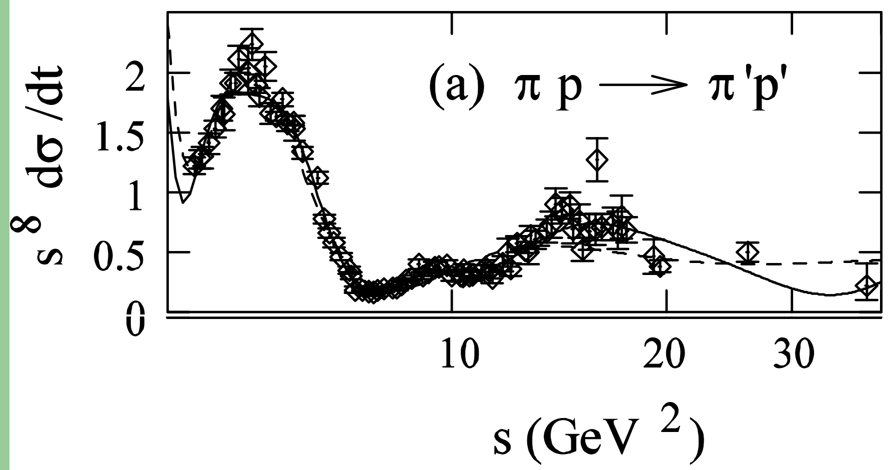
Elastic *p-p* Scattering

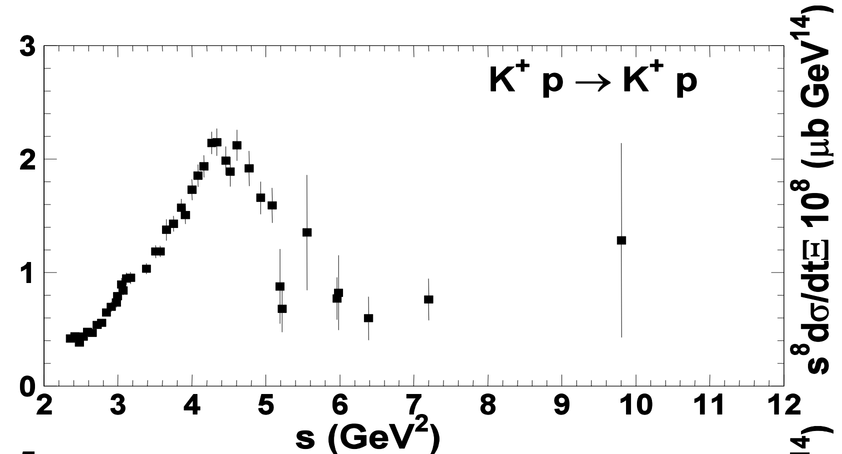
$$R_1 \propto s^{10} \frac{d\sigma}{dt}$$

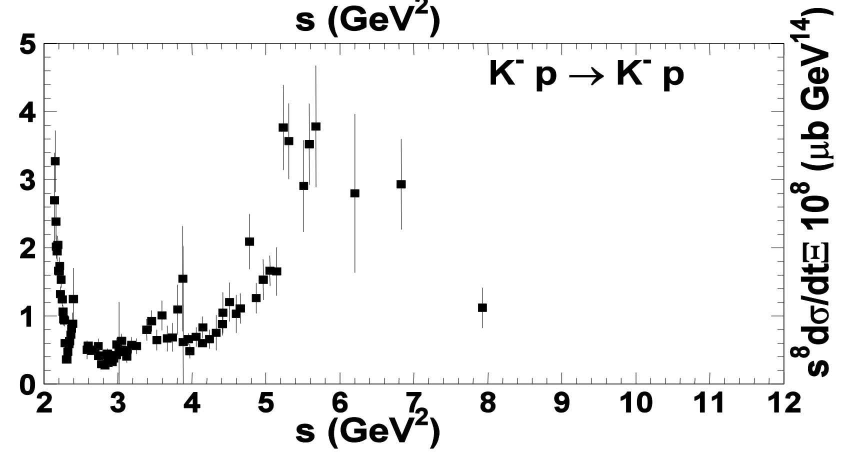


J. P. Ralston and B. Pire, PRL 61, 1823 (1988)

Are Oscillations Unique to *p-p* Scattering?





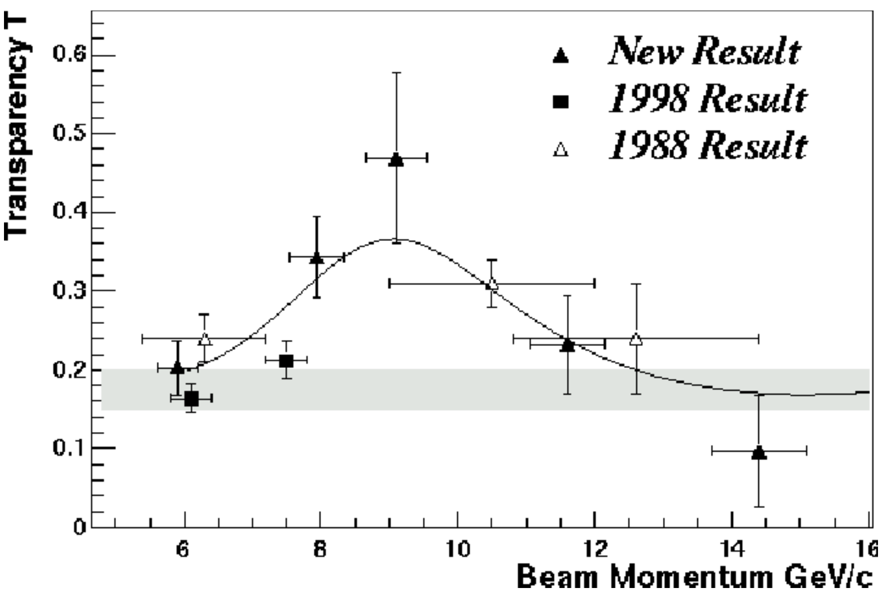


Nuclear Filtering vs CT

- **Nuclear filtering** uses the medium **actively** to suppress the long-distance amplitude.
- In **CT** the large momentum transfer selects the short distance amplitude which is then free to propagate through the **passive** medium.
- The CT limit is $Q \rightarrow \infty$, and the onset of CT is expected to be sooner on lighter nuclei.
- The nuclear filtering limit is $A >> 1$, and the effect bigger in heavier nuclei.

Transparency in A(p,2p) Processes

$p + {}^{A}N_{Z} \rightarrow p + p + X$ @ BNL

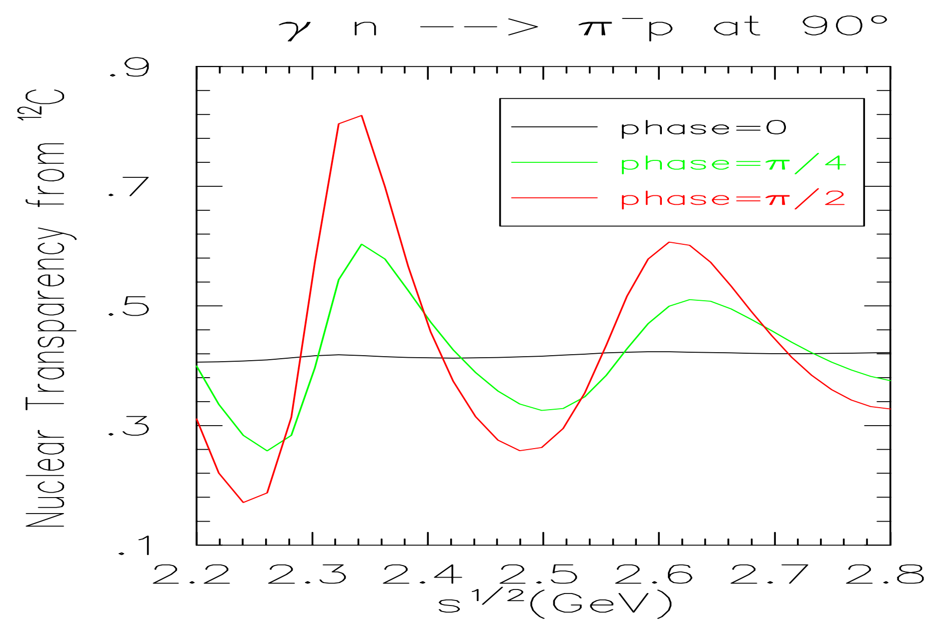


Shaded band is from a conventional nuclear physics calculation

Solid line is fit to 1/oscillation in p-p scattering data

- BNL results explained in terms of Nuclear Filtering (Ralston & Pire)
- In terms of charm resonance states (Brodsky & Le page).

Nuclear Filtering with Photo-pions



$$\gamma + {}^{12}C \rightarrow \pi^- + p + X$$

$$T \approx \frac{\gamma + {}^{12}C \rightarrow \pi^- + p + X}{\gamma + n \rightarrow \pi^- + p}$$

- **Large oscillations in photo-pion transparency predicted by Jain, Kundu and Ralston.**
- **Amplitude depends on an additional nuclear phase.**
- **Can be tested with photo-pion production from Carbon.**

Summary

- Hadron propagation in a nuclear medium has been and continues to be studied with exclusive processes.
- Traditional nuclear physics calculations predict an energy independent Transparency.
- An interesting effects predicted at higher energies is Color Transparency.
- No conclusive experimental evidence for CT has been seen yet.
- Experiments in the near future look promising for a resolution of this issue.