The Search for Color Transparency & Nuclear Filtering

Dipangkar Dutta
Laboratory for Nuclear Science
Massachusetts Institute of Technology

Outline

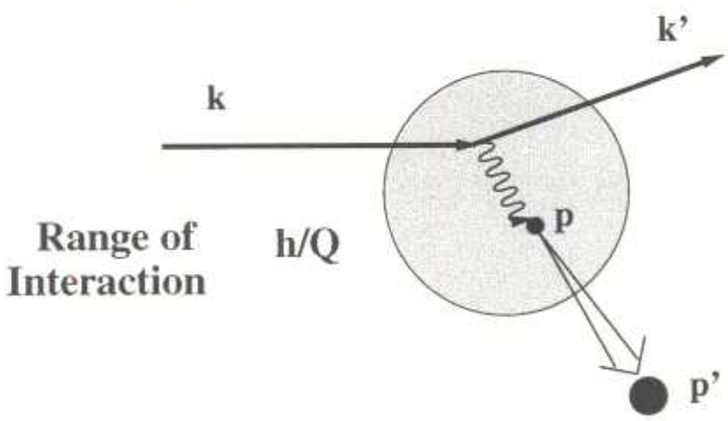
- **Introduction**
  - Color transparency as a probe of pQCD in Nuclei.
  - The theoretical prediction
- **Experimental Status**
  - Past, Present &
  - Future
- **Nuclear Filtering**
  - An effect complementary to CT
  - Experimental status
- **Summary**

Color Transparency

Color Transparency refers to the suppression of strong interactions in exclusive processes at high momentum transfer Q)

It is based on [redacted] arguments.

- The hadrons involved in exclusive processes at high Q^2 fluctuate to a small transverse size - refered to as the PLC (quantum mechanics)
- This PLC experiences reduced interaction with the nucleus, or it is color screened (nature of the strong interaction)
- The PLC remains small while it propagates out of the nucleus (relativity)



To CT or not to CT

Vanishing of $h - N$ interaction cross section for h produced in high-Q exclusive process

Requirements:	Quantum Mechanics Relativity Nature of Strong Interaction

- **The prediction of CT contradicts conventional nuclear physics in the domain of its validity**
- **It has also been shown that a wide variety of models with non-perturbative reaction mechanisms also predict CT**
- **Among other things onset of CT is required for the QCD factorization theorems to hold for various DIS exclusive processes, which gives access to the GPDs**

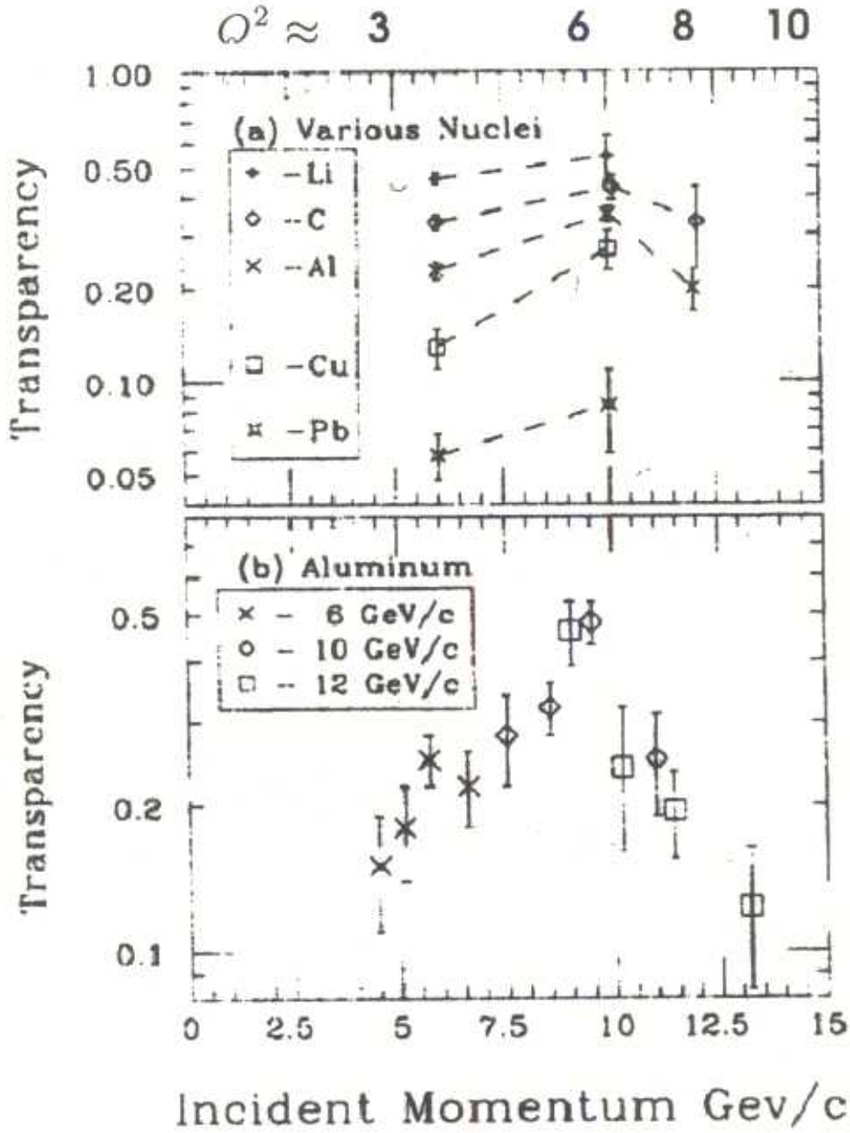
Searching for Color Transparency
Experimental Status

Vanishing of $h - N$ interaction cross section for h produced in high-Q exclusive process

$h = q\bar{q}$	QED analogy in e^+e^-
$h = qqq$	Unique for QCD !!!

- **Color Transparency in A(p,2p) BNL**
- **Color Transparency in A(e,e′p) SLAC, JLab**
- **Color Transparency in A($l, l'\rho$) FNAL, HERMES**
- **Color Transparency in di-jet production FNAL**
- **Color Transparency in A(e,e′π^+) JLab**

Color Transparency in A(p,2p)
BNL Results



Color Transparency in A(e,e′p) – History

Experiment	Date	Main personnel	Spokespersons
SLAC NE-18	1991		Richard Milner (MIT) Bob McKeown (CIT)
		Wolfgang Lorenzon **Rolf Ent** **Tom O'Neill** **Naomi Makins**	
JLab E91-013	1995/6		Don Geesaman (ANL)
		Dave Potterveld **Derek Van Westrum** **Dipangkar Dutta**	
JLab E94-139	1999		Richard Milner (MIT) Rolf Ent (JLab)
		Ken Garrow **Dave McKee**	

JLab E94-139 Collaboration

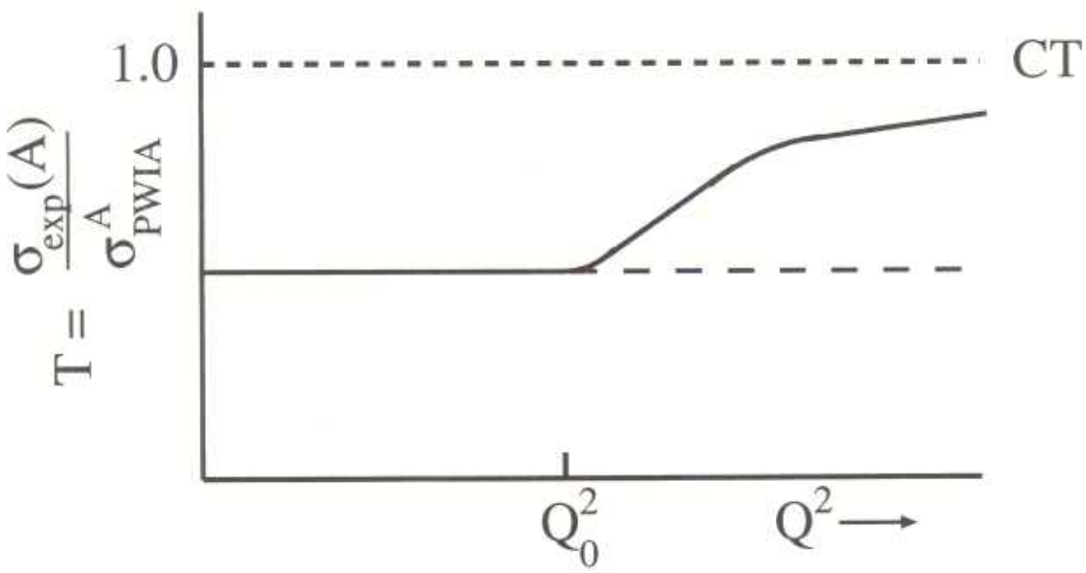
K. Garrow,[18] **D. McKee,**[13] A. Ahmidouch,[14] C. S. Armstrong,[18] J. Arrington,[2] R. Asaturyan,[22] S. Avery,[7] O. K. Baker,[7,18] D. H. Beck,[8] H. P. Blok,[20] C. W. Bochna,[8] W. Boeglin,[4,18] P. Bosted,[1,a] M. Bouwhuis,[8] H. Breuer,[9] D. S. Brown,[9] A. Bruell,[10] R. D. Carlini,[18] N. S. Chant,[9] A. Cochran,[7] L. Cole,[7] S. Danagoulian,[14] D. B. Day,[19] J. Dunne,[12] D. Dutta,[10] R. Ent,[18] H. C. Fenker,[18] B. Fox,[3] L. Gan,[7] D. Gaskell,[2,16] A. Gasparian,[7] H. Gao,[10] D. F. Geesaman,[2] R. Gilman,[17,18] P. L. J. Guèye,[7] M. Harvey,[7] R. J. Holt,[8,b] X. Jiang,[17] C. E. Keppel,[7,18] E. Kinney,[3] Y. Liang,[1,7] W. Lorenzon,[11] A. Lung,[18] D. J. Mack,[18] P. Markowitz,[4,18] J. W. Martin,[10] K. McIlhany,[10] D. Meekins,[5,c] M. A. Miller,[8] R. G. Milner,[10] J. H. Mitchell,[18] H. Mkrtchyan,[22] B. A. Mueller,[2] A. Nathan,[8] G. Niculescu,[15] I. Niculescu,[6] T. G. O'Neill,[2] V. Papavassiliou,[13,18] S. Pate,[13,18m] R. B. Piercey,[12] D. Potterveld,[2] R. D. Ransome,[17] J. Reinhold,[4,18] E. Rollinde,[18,21] P. Roos,[9] A. J. Sarty,[5,d] R. Sawafta,[14] E. C. Schulte,[8] E. Segbefia,[7] C. Smith,[19] S. Stepanyan,[22] S. Strauch,[17] V. Tadevosyan,[22] L. Tang,[7,18] R. Tieulent,[9,18] A. Uzzle,[7] W. F. Vulcan,[18] S. A. Wood,[18] F. Xiong,[10] L. Yuan,[7] M. Zeier,[19] B. Zihlmann,[19] and V. Ziskin[10].

[1]American University, [2]Argonne National Laboratory, [3]University of Colorado, [4]Florida International University, [5]Florida State University, [6]The George Washington University, [7]Hampton University, [8]University of Illinois, [9]University of Maryland, [10]Massachusetts Institute of Technology, [11]University of Michigan, [12]Mississippi State University, [13]New Mexico State University, [14]North Carolina A & T State University, [15]Ohio University, [16]Oregon State University, [17]Rutgers University, [18]Thomas Jefferson National Accelerator Facility, [19]University of Virginia, [20]Vrije Universiteit, [21]College of William and Mary, [22]Yerevan Physics Institute.

Search for Color Transparency at JLab

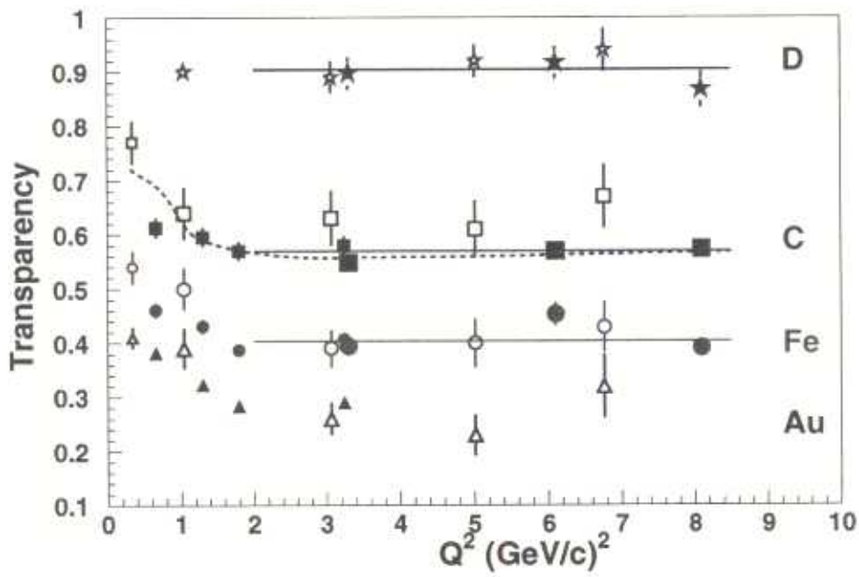
At JLab Search for Color Transparency Involves Quasifree A(e,e′p) Scattering

From fundamental considerations (quantum mechanics, relativity, nature of strong interaction) it is predicted (Brodsky, Mueller) that **fast** protons scattered from the nucleus will have **decreased** final state interaction.



JLab E94-139 Results

- Constant Value fits for $Q^2 > 2$ (GeV/c)$^2 \rightarrow \chi^2/df \approx 1$
- Dashed line is correlated Glauber calculation (Pandharipande et al)

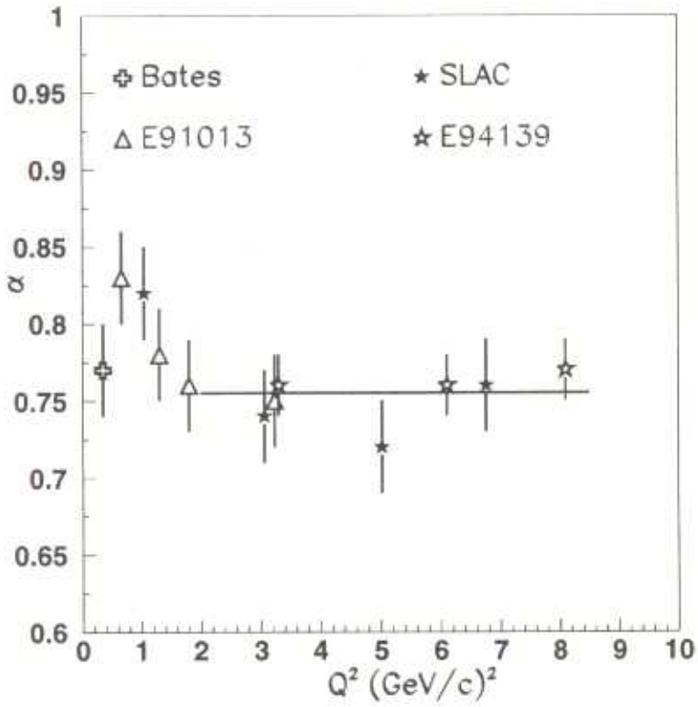


Q^2 dependence consistent with standard Glauber

E94-139 Results (Submitted to Phys. Rev.)

E94-139 Results - A Dependence

Fit to $\sigma(A) = \sigma_0 A^{\alpha}$ **or** $T = cA^{1-\alpha}$

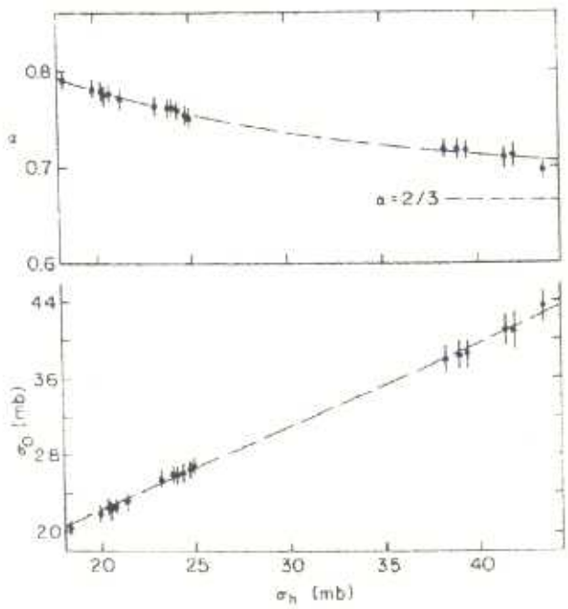


α = constant = 0.76 for $Q^2 > 2\ (\mathrm{GeV/c})^2$

Hadron-Nucleus and Hadron-Proton Total Cross Sections

Two plots show $\sigma(A) = \sigma_0 A^{\alpha}$ and $\sigma_0 = \sigma_{hN}$

(Hadron momentum = 60, 200, 280 GeV/c)[2]



Results $\alpha \sim$ **0.78 for Kaons**
$\alpha \sim$ **0.76 for Pions**
$\alpha \sim$ **0.72 for Protons**
$\alpha \sim$ **0.71 for Anti-Protons**

Quasifree scattering off A nucleons within the nucleus where $\alpha < 1$ can be interpreted as due to the strong interaction nature of the probe

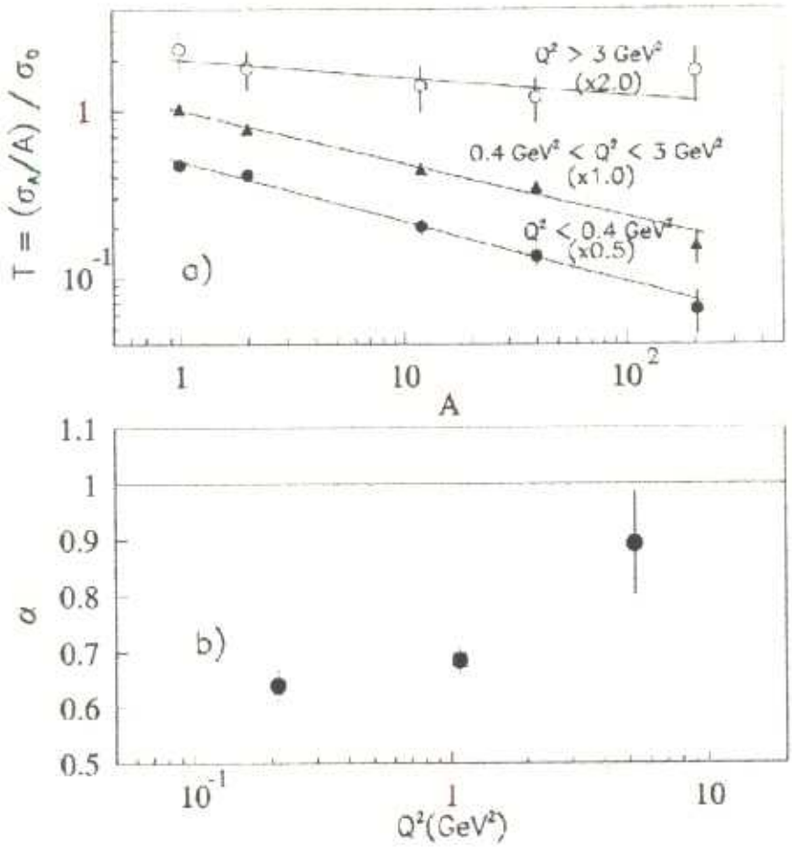
[2] A.S. Carroll et al., Phys. Lett. 80B, 319 (1979)

Try the $q\bar{q}$ System

- No unambiguous, model-independent , evidence for the onset of CT exists.
- Small size is more probable in the 2 quark system such as pions than in the protons
- Onset of CT expected at lower Q^2 ($q\bar{q}$ vs qqq)
- Formation lengths easily $\sim$ 10 fm at moderate Q^2

FNAL A($\mu, \mu' \rho^0$) incoherent production

E_μ = 470 GeV; A = H, D, C, Ca, Pb[3]



Fit with constant $\alpha \approx$ 0.69

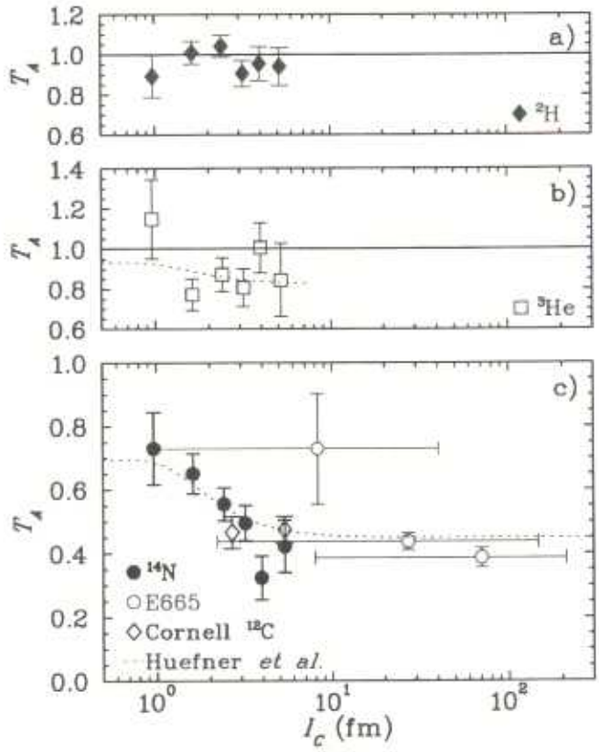
Evidence less statistically significant when adding NMC[4] data (at average $Q^2 \approx$ 5) $\rightarrow$ α = 0.76 $\pm$ 0.07

[3] E665, Adams et al, Phys. Rev. Lett. 74, 1525 (1995)

[4] NMC, Arneodo et al, Nucl. Phys. B429, 503 (1994)

HERMES A($e, e'\rho^0$) incoherent production

E_{e+} = 27 GeV; A = D, ^{3}He, ^{14}N [5]



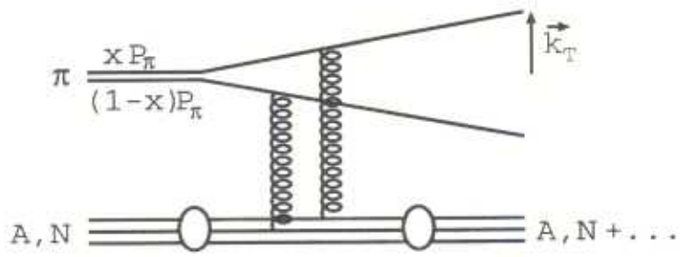
Virtual photon fluctuates into a $q\bar{q}$ pair with transverse separation $\sim \frac{1}{Q}$ a distance l_c in front of the nucleus
Data interpreted as evidence for coherence length l_c effects

Confuses with formation length dependent CT effects (the distance traveled before a small-size $q\bar{q}$ configuration evolves to its regular hadron size).

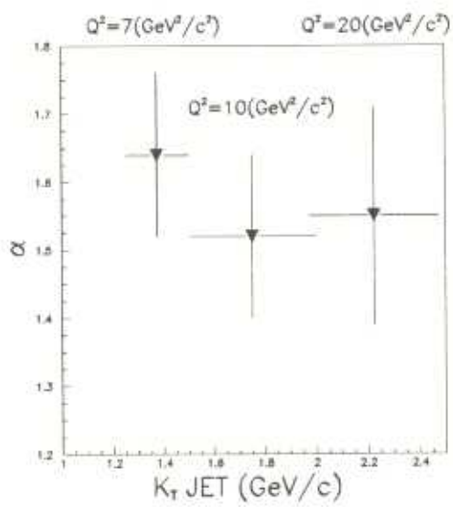
[5] HERMES, Ackerstaff et al, Phys. Rev. Lett. 82, 3025 (1999), open circles are E665 data

FNAL A(π,dijet) Data

Coherent π^+ diffractive dissociation at [6] T_π = 500 GeV/c



Parameterized as $\sigma(A) = \sigma_0 A^\alpha$, using ^{12}C and ^{195}Pt nuclei, with $Q^2 \geq 4k_T^2$

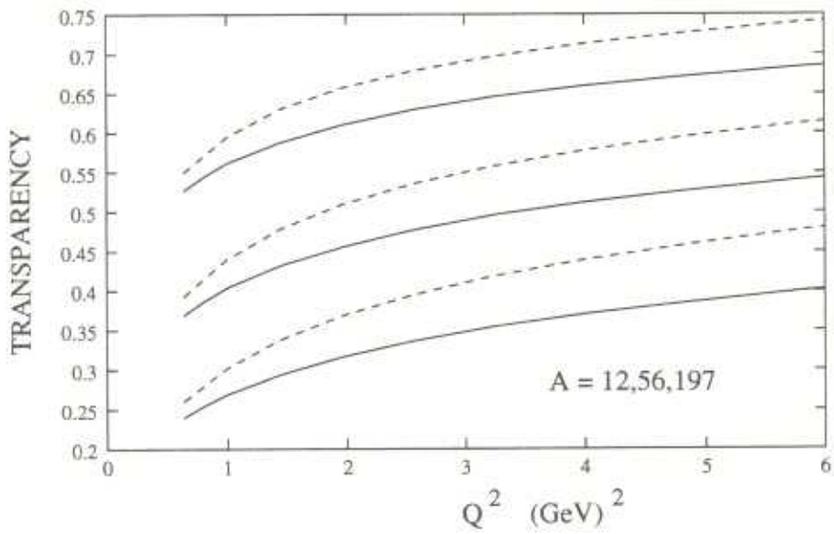


$\alpha >$ 0.76 from pion-nucleus total cross sections

[6] Aitala et al, Phys. Rev. Lett. 86, 4773 (2001)

E01-107 – Pion Transparency

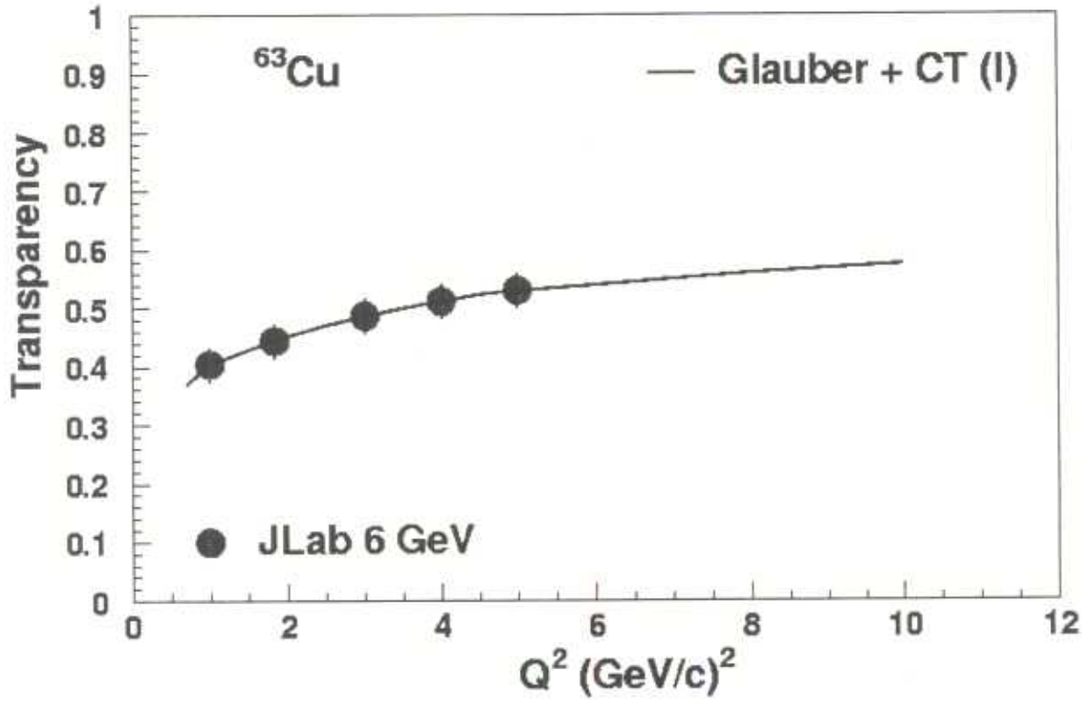
A(e,e'π) next best case, beyond A(e,e'p)[1]



- Predictions consistent with all present data, and with independent calculations by Miller
- Predictions show most of CT effect at $Q^2 \sim 10$ (GeV/c)^2
- Both CZ end point (solid) and asymptotic (dashed) quark distribution amplitudes give >40% increase in pion transparency for Q^2 = 1-5 (GeV/c)^2 and ^{197}Au

[1] Kundu, Samuelsson, Jain, and Ralston, Phys. Rev. D 62, 113009 (2000)

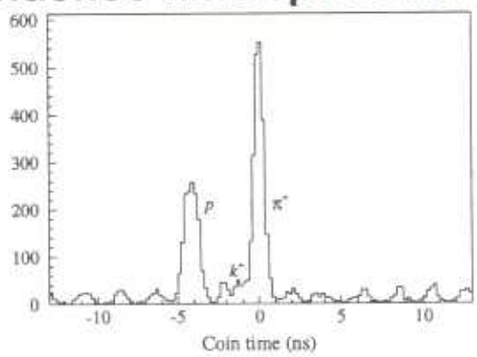
E01-107 – Pion Transparency



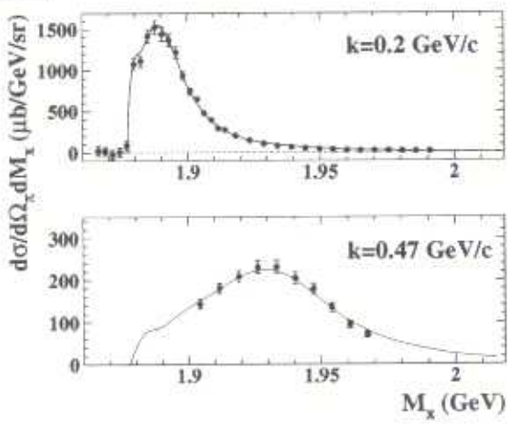
- E01-107 uses the (e,e$'\pi^+$) reaction on H, D, ^{12}C, ^{27}Al, ^{63}Cu, and ^{197}Au in the Q^2 range 1-5 (GeV/c)^2 to look for onset of CT
- Measurable effects predicted for $Q^2 \leq 5$ (GeV/c)^2
- Projected combined statistical and systematic uncertainty 5-10%. The combined (A, Q^2) effect is measurable

E01-107 – Pion Transparency

Typical Coincidence Time Spectrum for ^{1}H(e,e$'\pi^+$)



[redacted], ^{2}H(e,e$'\pi^+$)nn, Q^2 = 0.4 (GeV/c)^2



- E91-003 demonstrated ability to describe data via a quasifree reaction including fermi smearing, FSI, and off-shell effects
- <u>IF</u> π electroproduction in a nucleus is similar to free-proton, we can reliably determine a pion transparency

Summary

[redacted] signature found for the onset of CT!

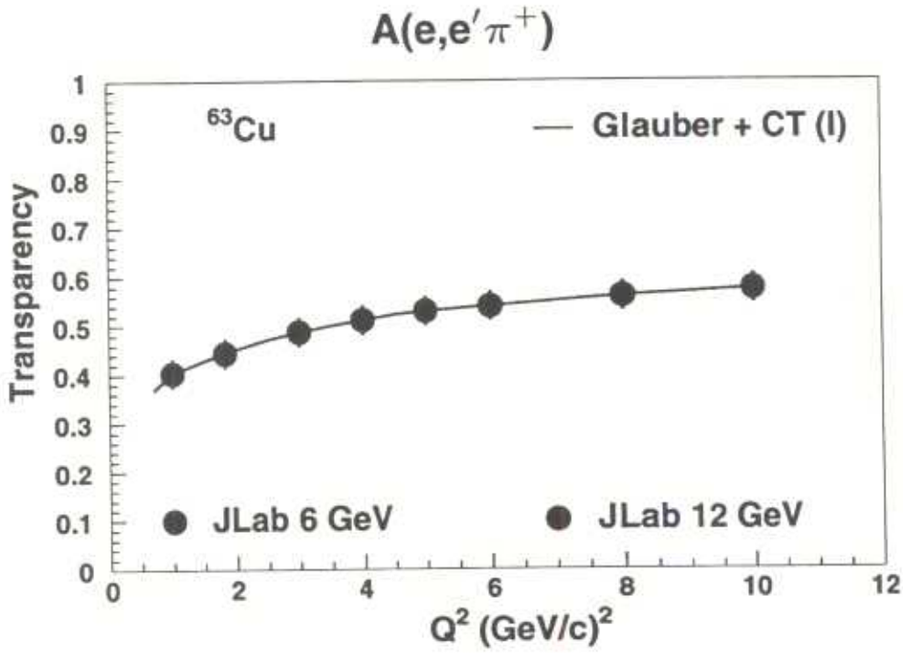
1. A(p,2p) Oscillation in Transparency Data
2. A(e,e′p) Consistent with conventional nuclear physics
3. A($l, l'\rho$) Coherence/Formation Length Issues
4. A(π,di-jet) claims full CT at $Q^2 \approx 10$ (GeV/c)^2, but only A-dependence
5. Looking just at Q^2-dependence or just at A-dependence of reaction is dangerous
6. Need reliable baseline calculations to conclusively look for the onset of CT!

Next best immediate cases: [redacted]

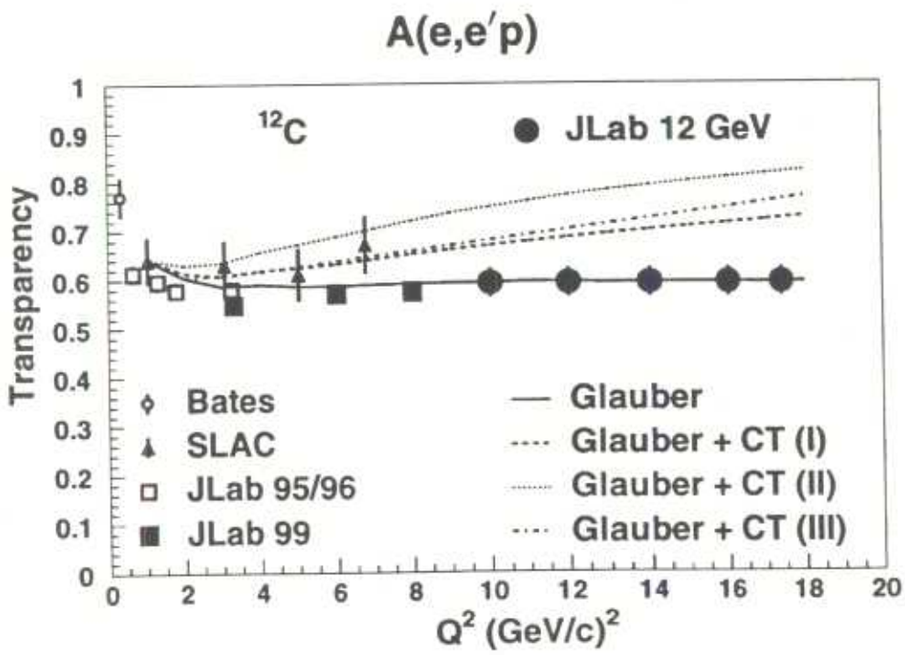
More di-jet data?

Future Color Transparency Searches

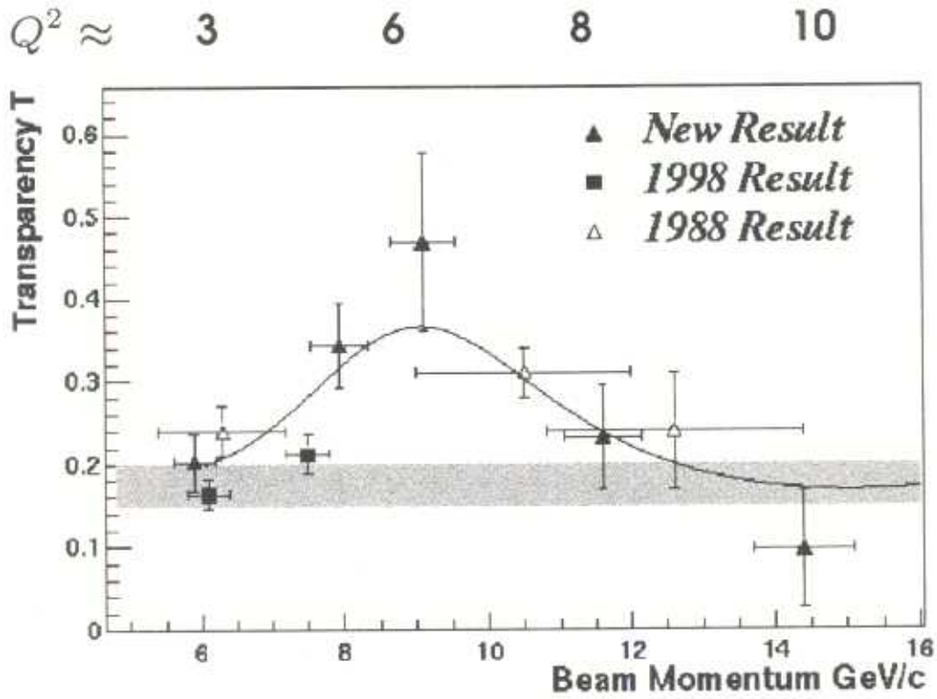
JLab at 12 GeV, HMS + SHMS



Higher Q^2 ($\approx$ 14 (GeV/c)^2) IF one releases the demand $t \leq 0.5$ GeV^2



Nuclear Transparency in A(p,2p)
BNL Results



Shaded area is Glauber calculation, solid line is 1/oscillation in p-p scattering

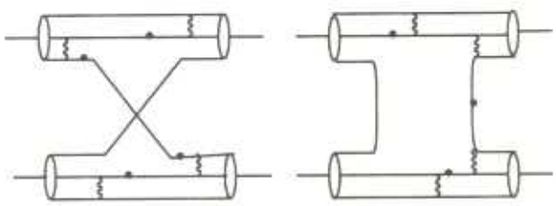
- Explained in terms of "Nuclear Filtering Effects": refers to the suppression of the long distance amplitude in the strongly interacting nuclear environment.

Nuclear Filtering

Nuclear filtering refers to the suppression of the long distance amplitude (Landshoff amplitude) in the strongly interacting nuclear environment.

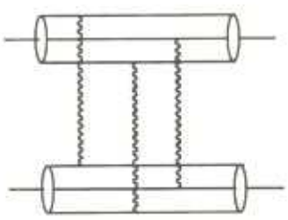
Born vs Independent Scattering Amplitude in pp Scattering

- Born Amplitude



  - off-shell quark propagators shown as dots

- Independent Scattering Amplitude



+ Corrections due to gluon radiation (Sudakov Effect)

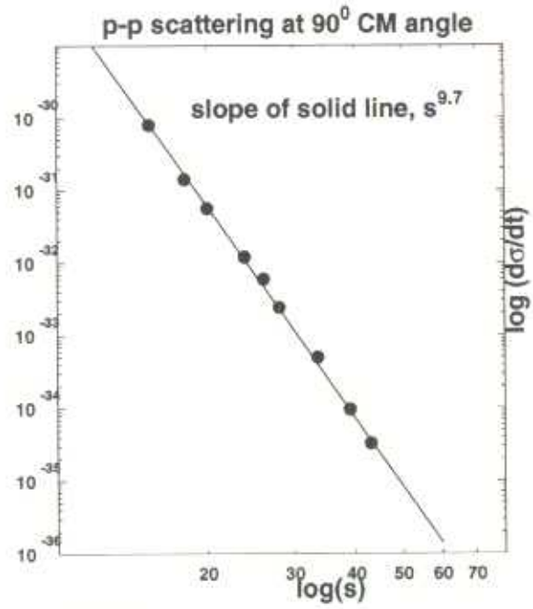
The Quark Counting Rule

In the short distance pQCD framework of
Brodsky & Le Page

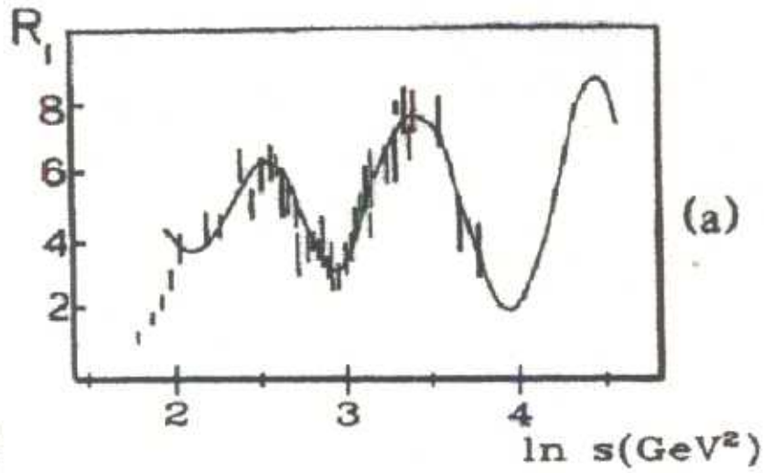
Exclusive two-body reactions at high energy and large momentum transfer, scale as :

$$\frac{d\sigma}{dt} \propto f(\theta_{\rm CM})\frac{1}{s^{n-2}}$$

- Many exclusive process at large angles seem to show global quark counting rule behavior



Oscillatory Scaling Behavior



$R_I \propto s^{10} \frac{ds}{dt}$

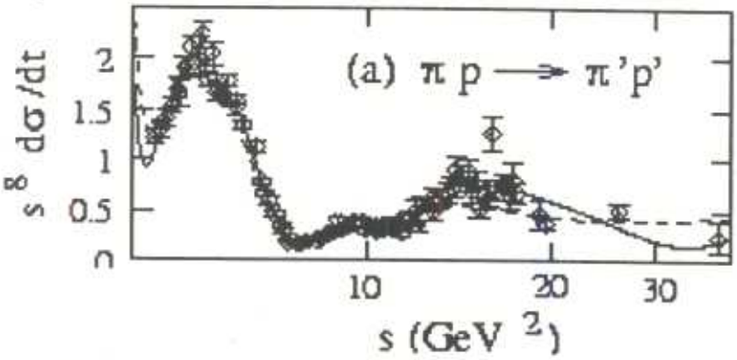
- Interference between short distance (Born) and long distance (Landshoff) amplitude and an energy dependent phase due to gluon radiation (Ralston & Pire and Carlson, Chachkhunashvili & Myhrer).
  - explains oscillation in pp cross-section
  - explains large spin correlation in pp scattering

Nuclear Filtering vs Color Transparency

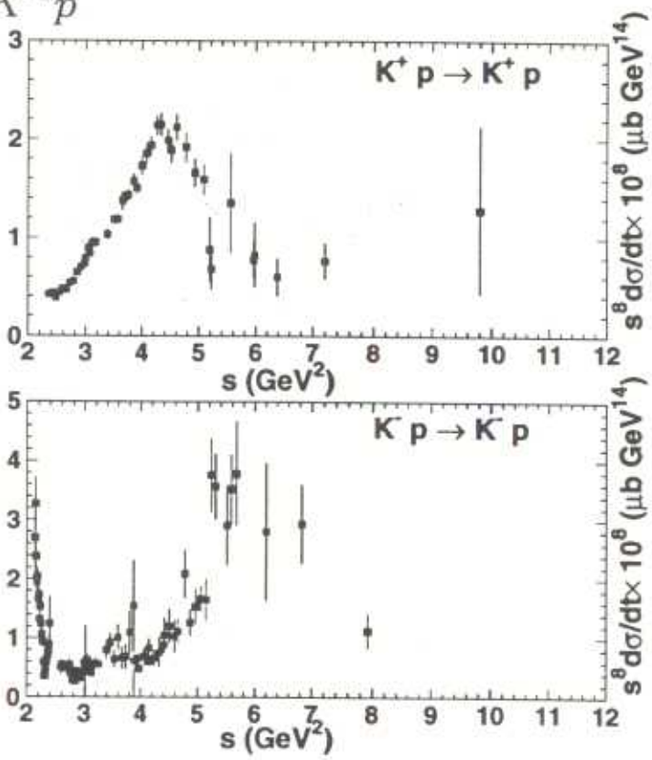
- Nuclear filtering uses the nuclear medium actively, by suppressing large quark separations.
- In CT the large momentum transfers select out the short distance amplitude which are then free to propagate through the passive nuclear medium.
- Color transparency limit is $Q^2 \rightarrow \infty$ and the onset of CT is expected to be sooner in light nuclei compared to heavier nuclei.
- While nuclear filtering limit is $A >> 1$;
  large $A \Rightarrow$ larger nuclear filtering effect, with a perturbatively calculable limit for $A >> 1$.

Is Oscillations unique to pp Scattering ?

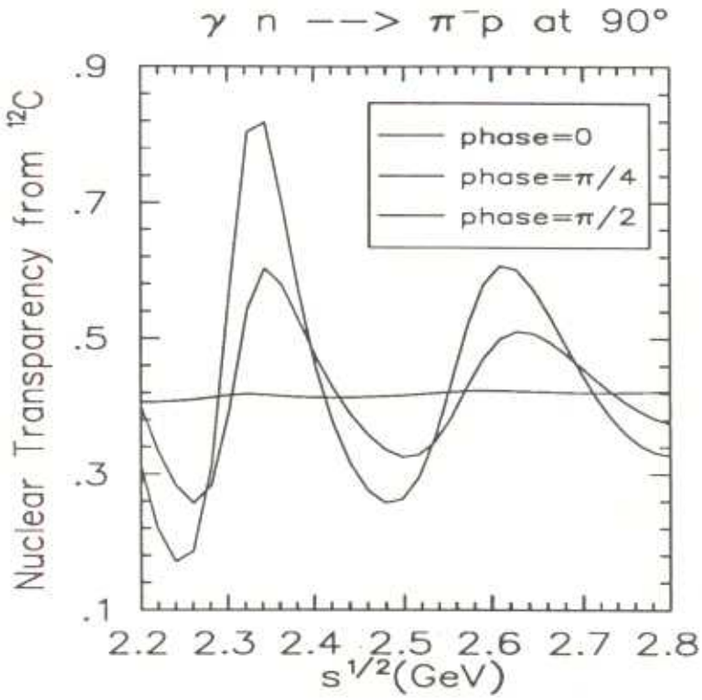
- $\pi p \to \pi p$



- $K^{\pm}p \to K^{\pm}p$

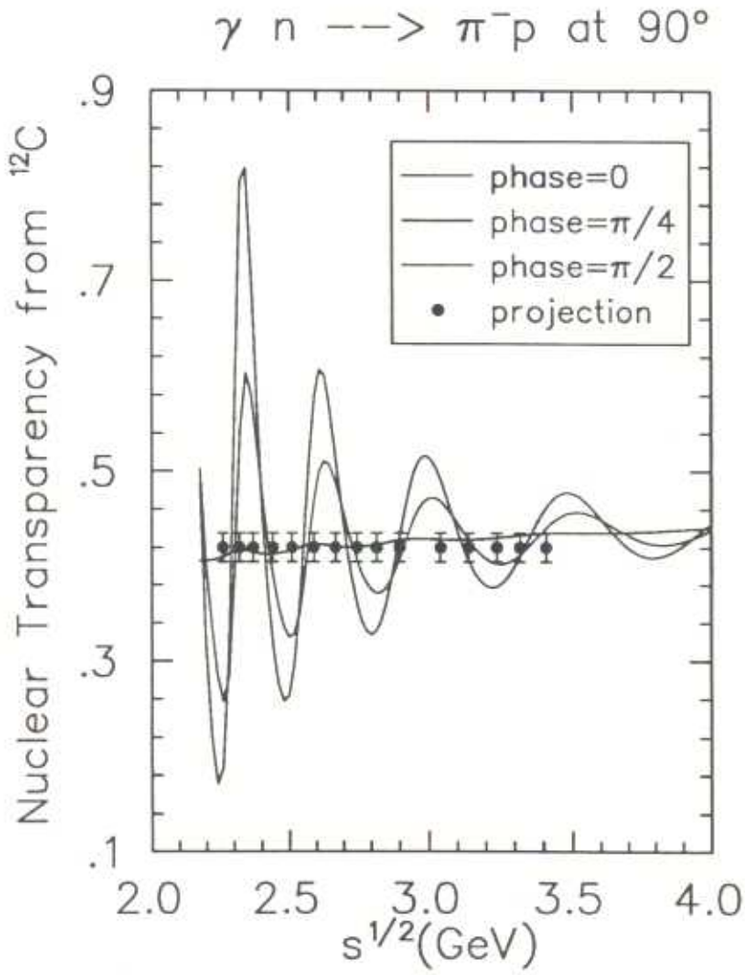


Nuclear Filtering Effects



- Predicted by the two-component model of Jain, Kundu and Ralston (explains BNL transparency data).
- An additional undetermined phase difference from the effective nuclear potentials in the nuclear medium (phase = 0 is not favored by BNL data).
- One can investigate the nuclear filtering effect by measuring transparency in pion photoproduction.

Projected Result for $\gamma^{12}C \rightarrow \pi^- pX$



Summary

- CT is essential in the search for the energy threshold where pQCD becomes applicable.
- Onset of CT is required for the QCD factorization theorems to hold, which will give us access to the GPDs.
- No unambiguous signature for the onset of CT has been found yet.
- Next best immediate case: A(e,e$'\pi$) will done at JLab
- The complementary nuclear filtering effect can be studied at JLab with photo-pion production from nuclei.
- All these programs can be extended to higher energies with a JLab upgraded to 12 GeV and the SHMS.