Hadron Propagation Through The Nuclear Medium

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Mississippi State University

Hall-C Summer Workshop

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Hadron Propagation

- Hadron propagation through the nuclear medium is a key element of the nuclear many body problem.

- Understanding hadron propagation is important for the interpretation of many phenomena and experiments, and remains an active area of interest.

N. C. R. Makins et al. PRL 72, 1986 (1994) (cited 114 times)
G. Garino et al. PRC 45, 780 (1992) (cited 65 times)
D. Abbott et al. PRL 80, 5072 (1998) (cited 65 times)
K. Garrow et al. PRC 66, 044613 (2002) (cited 62 times)

- At high energies the main process is reduction of flux, which is called Nuclear Transparency.

Nuclear transparency is also be used to search for signature of QCD in Nuclei.

Introduction

We know QCD works, but there is no consensus on how it works

pQCD mechanisms dominate at high energies and small distances ⟷ what energy is high enough for pQCD to be un-ambiguously applicable

Questions being addressed, as part of JLab's Scientific mission

+ What is the mechanism of confinement?
+ Where does the q-q interaction make a transition from the confinement to the perturbative QCD regime (understand N-N force in terms of QCD)?
+ How does the nucleon shape, mass, spin etc come about from the quarks/anti-quarks and gluons (How hadrons are constructed)?
+ Do quarks and gluons play any direct role in Nuclear Matter?

Introduction

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pQCD mechanisms dominate at high energies and small distances ⟷ what energy is high enough for pQCD to be un-ambiguously applicable

How do we address this problem @ JLab

+ Look for signatures of QCD such as Color Transparency & Nuclear Filtering.
+ Explore role of heavy quarks (such as intrinsic charm, J/Ψ-N interaction).
+ Study properties of quarks in-medium (e.g. unpacking the "EMC effect").
+ Study quark distributions at $x>1$ (super-fast quarks).
+ Measure quark propagation through nuclei.
+ Look for rare processes such as "hidden color", Φ-N & J/Ψ-N bound state

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An understanding of of hadron propagation is essential for this entire program

Also connected to a recent framework which advocates the dominance of the handbag mechanism (measure GPDs).

Outline

- Nuclear Transparency and Hadron Propogation
- Color Transparency & Small size configurations
- CT and soft-hard factorization/GPDs
- Experimental Status and Outlook
- Comparing proton, pion and kaon propagation
- Summary

How Transparent is Your Nucleus?

Ratio of cross-sections for exclusive processes 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 = $\sigma_0 A^{\alpha}$

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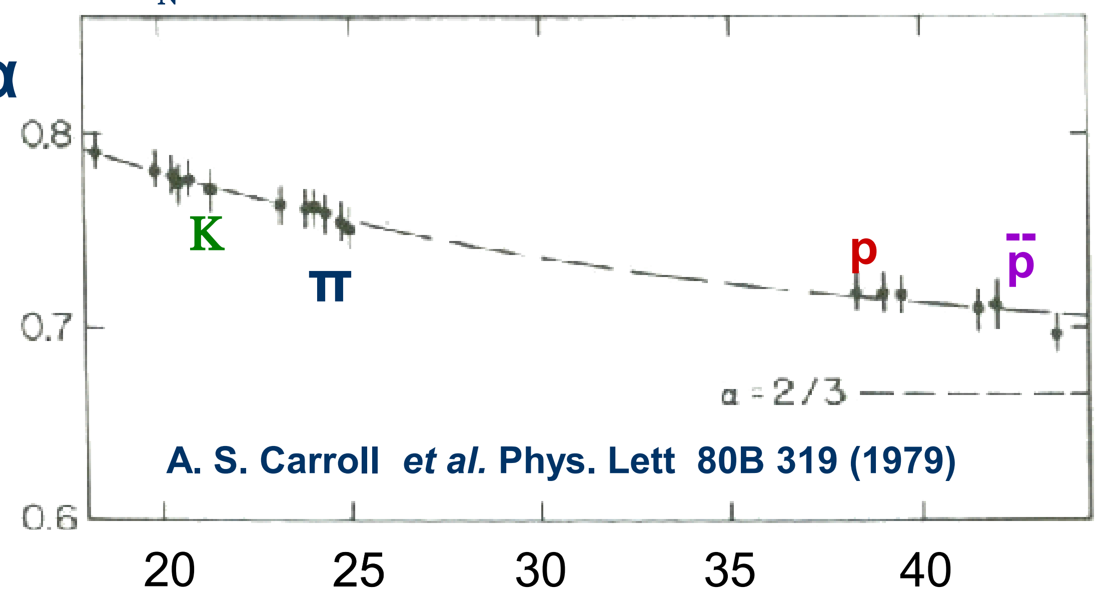
σ_N Hadron- Nucleus total cross-section

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

α = 0.72 – 0.78, for π, κ, p

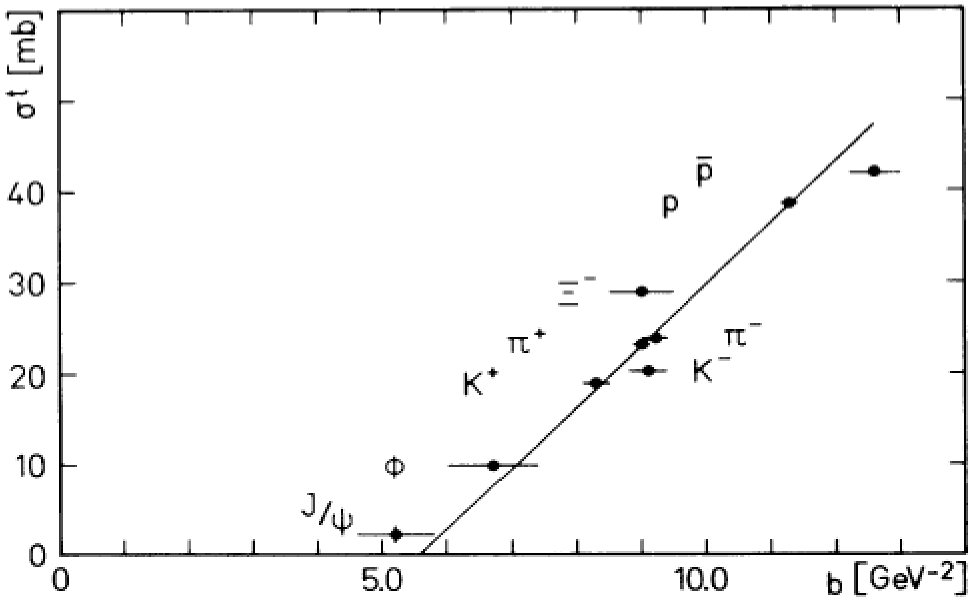
Hadron momentum
60, 200, 250 GeV/c

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



α < 1 interpreted as due to the strong interaction nature of the probe

Size Matters!



$$b = \frac{d}{dt}\ln\left(\frac{d\sigma_{hp}^{el}}{dt}\right) = \frac{1}{3}\left(R_h^2 + R_p^2\right)$$

RMS radius from slope of the elastic scattering cross section as a function of $Q^2 = t$

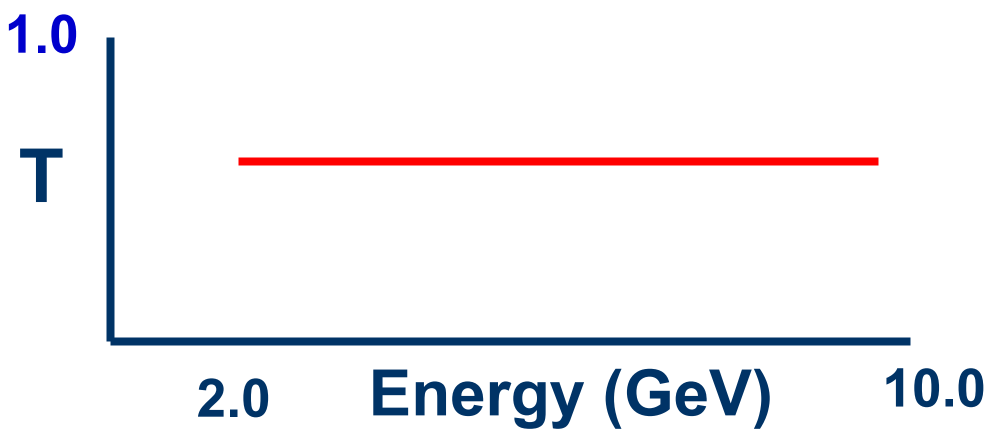
Povh and Hufner, PRL 58,1612(1987)

Total hadron-proton cross section vs the slope parameter *b* at c.m. energy of 16 GeV

Total hadron-proton cross-section scales linearly with size for wide range of hadrons

Nuclear Transparency

Traditional nuclear physics calculations (Glauber multiple scattering 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

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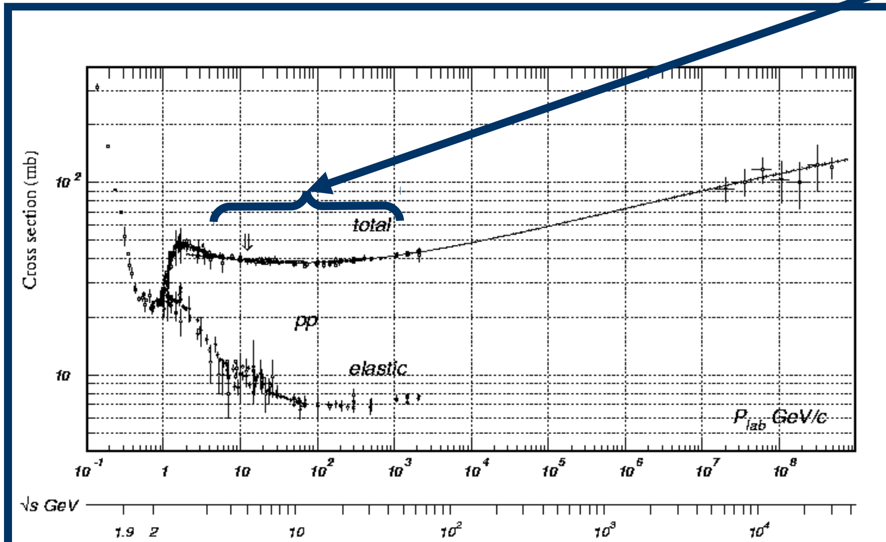
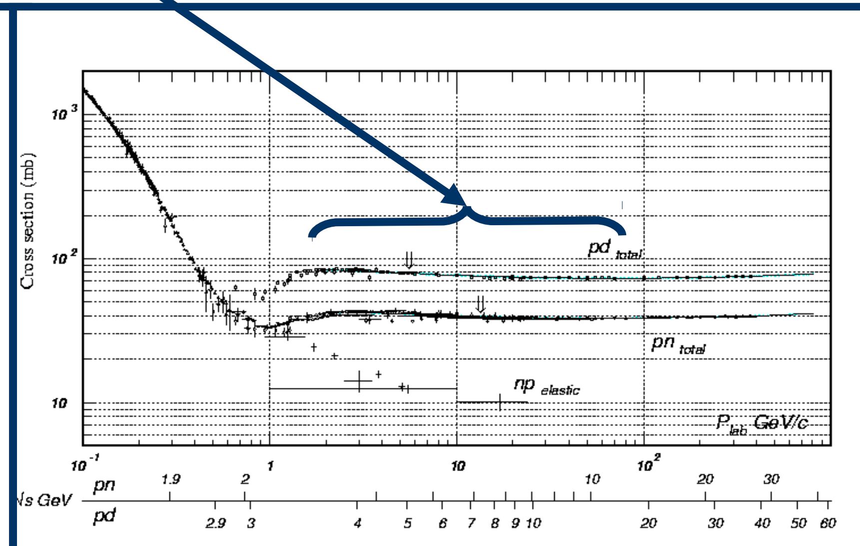
N-N cross-section is energy independent





σ_{PP} **pp scatt. cross-section**

σ_{PN} **pn scatt. cross-section**

All other reaction mechanisms are energy independent!

Color Transparency:a color coherence property of QCD

CT refers to the vanishing of the hadron-nucleon interaction for hadrons produced in exclusive processes at high momentum transfers

CT introduced by Mueller and Brodsky in 1982

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)

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✓ At sufficiently high momentum transfers, scattering takes place via selection of amplitudes characterized by small transverse size (PLC) - "squeezing" (readily achievable at high energies).

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✓ The compact size is maintained while traversing the nuclear medium - "freezing".

✓ The PLC is 'color screened' - it passes undisturbed through the nuclear medium.

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

CT is unexpected in a strongly interacting hadronic picture. But it is natural in a quark-gluon framework. CT is mportant for understanding nuclei in terms of quarks and gluons.

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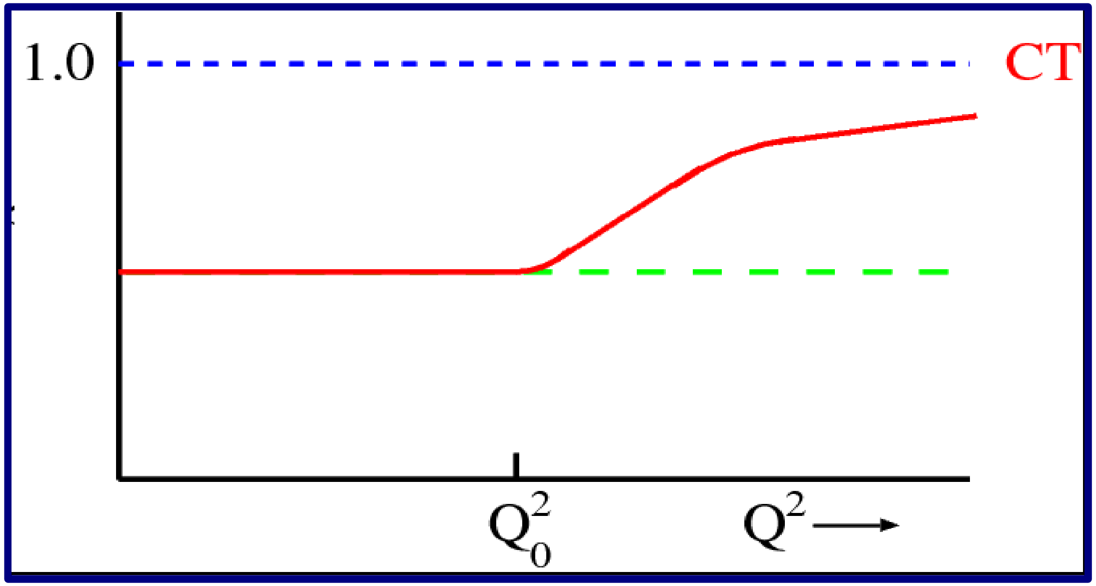
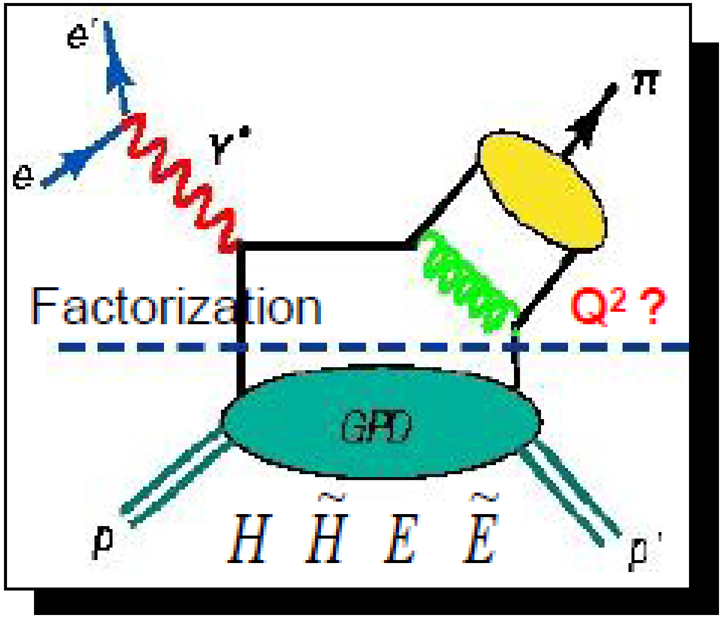


CT is well established at high energies, we are interested in identifying the onset of CT

Onset of CT would be a signature of the onset of QCD degrees of freedom in nuclei

An Alternate Framework



Assumes the dominance of the handbag mechanism.

The reaction amplitude factorizes into a sub-process involving a hard interaction with a single quark from the incoming and outgoing nucleon ($\gamma q_a \rightarrow \pi q_b$) and GPDs.

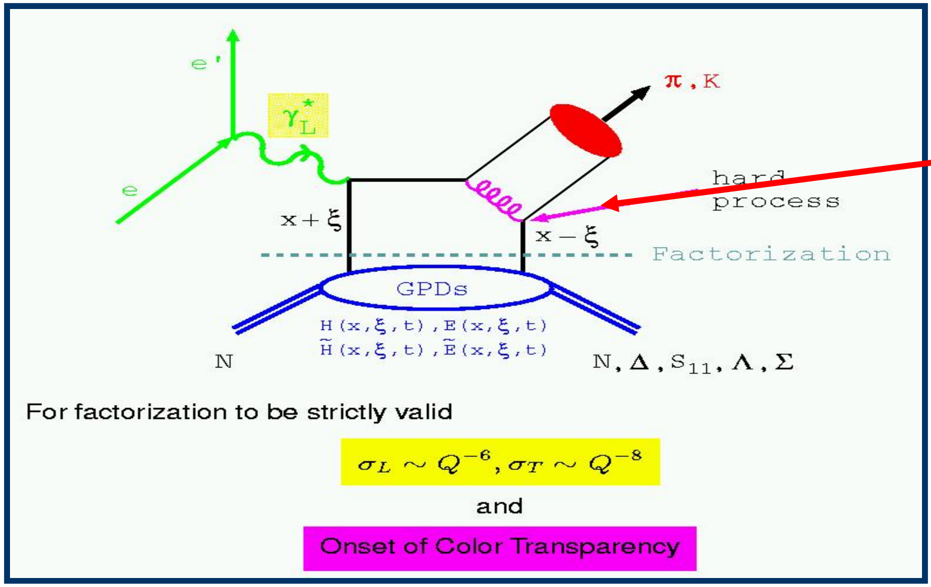
Recent DVCS and wide angle Compton scattering results disagree with pQCD predictions but are consistent with the dominance of handbag mechanism.

The soft/hard factorization is key to accessing GPDs

CT & Factorization

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

small size configurations (SSC) needed for factorization:



Meson distribution amplitude

calculable in pQCD

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

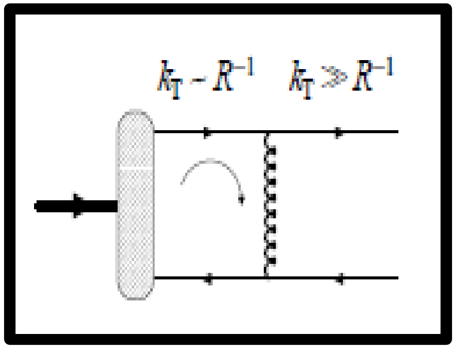
Small Size Configurations & Factorization

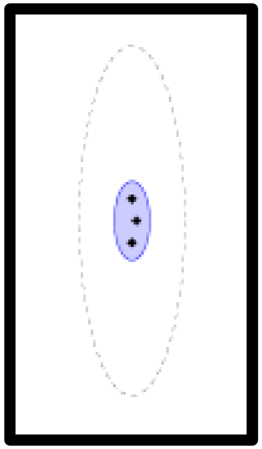
Factorization theorems have been derived for deep-exclusive processes

small size configurations (SSC) needed for factorization:

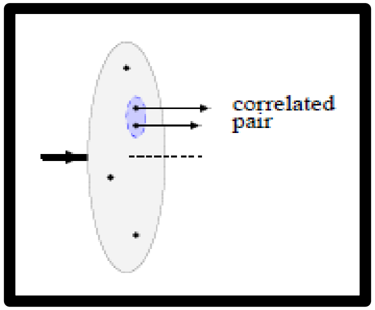
Multiple origins of the SSC

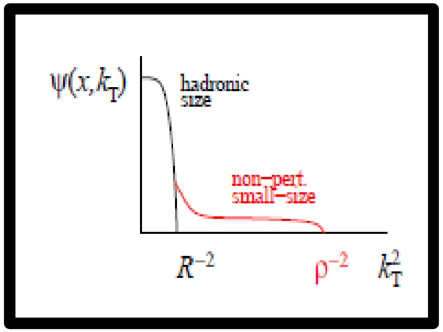
- perturbative interactions
  high momentum components of the wavefn., $k_T \sim R^{-1}$





- non-perturbatively due to the QCD vacuum structure
  gluon field of size ~ 0.2-0.3 fm
  correlated q-qbar pairs
  semi-hard components of wavefn.





-C. Weiss (workshop on small size configs. JLab 25 March,2011)

Connecting GPDs & CT

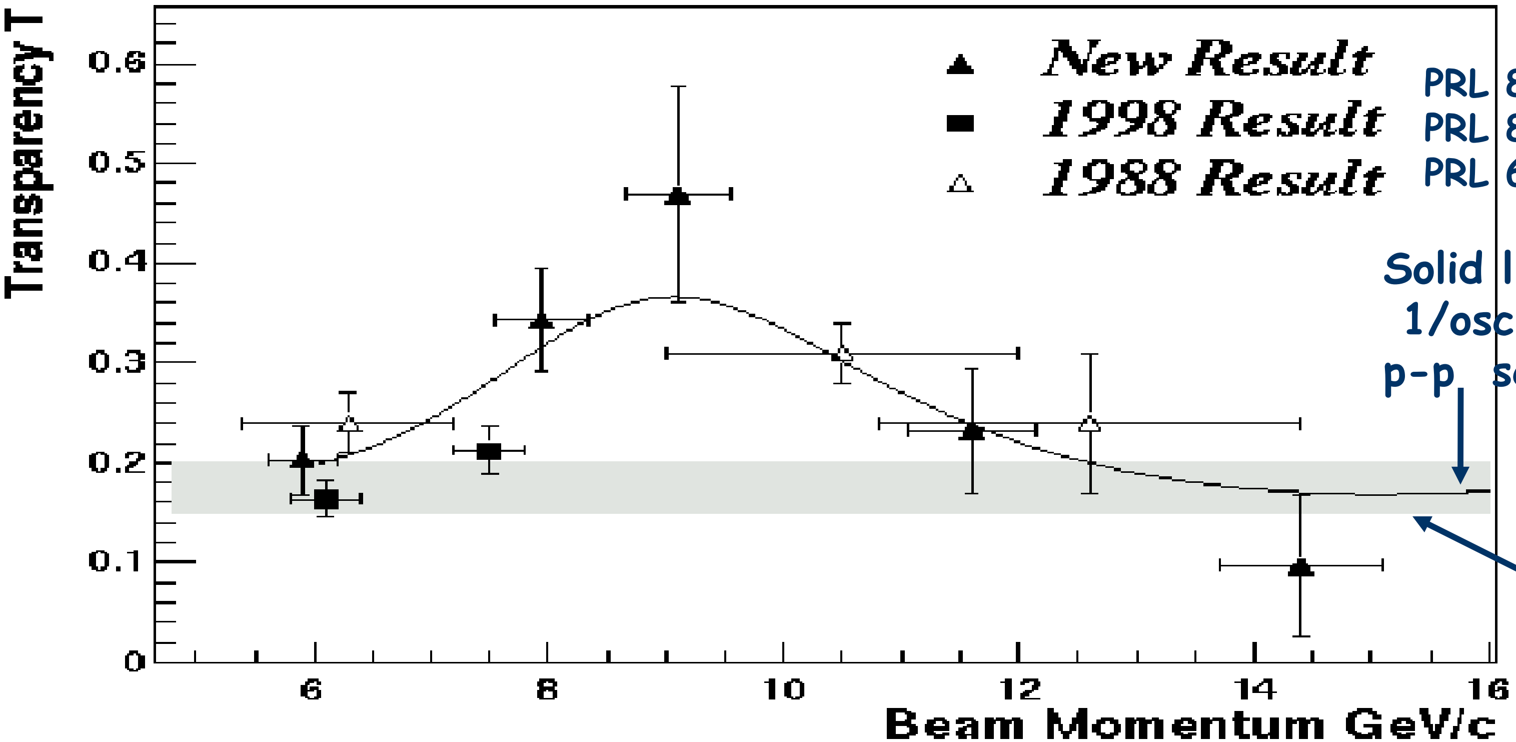
Connections between GPDs and CT have been identified by several theorists

M. Burkardt and G. Miller
(PRD 74, 034015 (2006), hep-ph/0312190)
have derived the effective size of a hadron in terms of GPD's:_
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

First direct search for color transparency

Transparency in A(p,2p) Reaction from BNL



PRL 87, 212301 (2001)
PRL 81, 5085 (1998)
PRL 61, 1698 (1988)

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

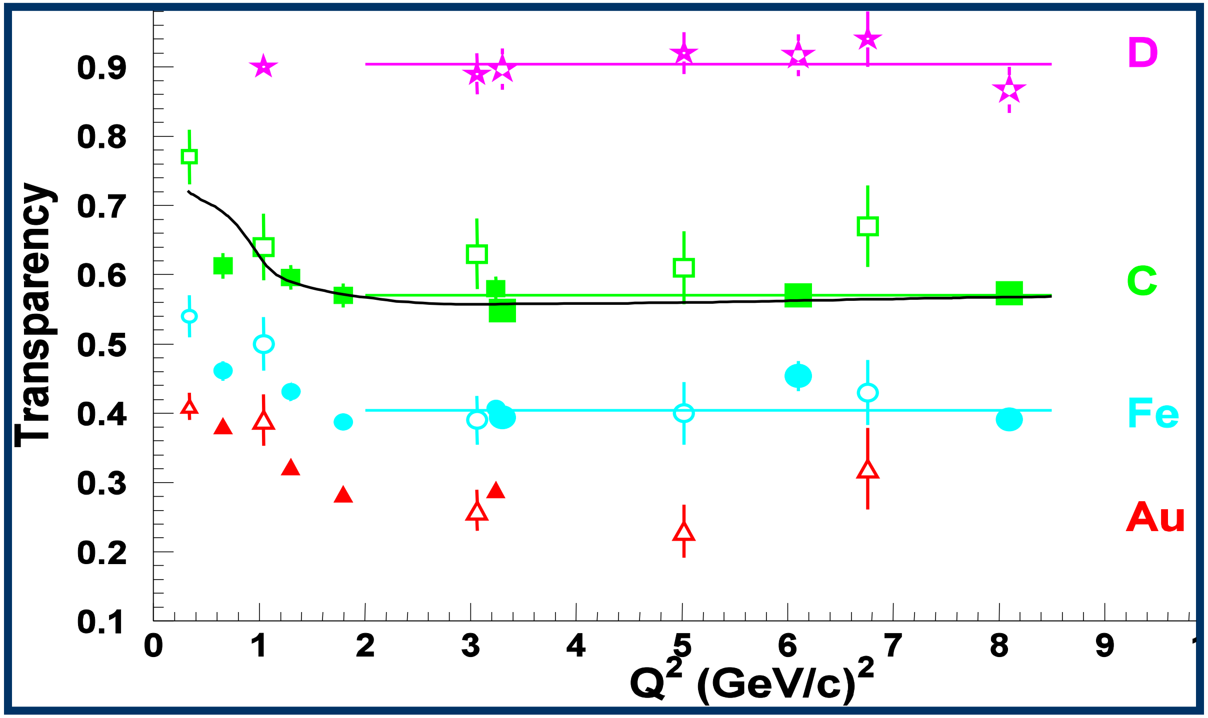
Shaded band Glauber calculation

Results inconsistent with CT only. But can be explained by including additional mechanisms such as nuclear filtering or charm resonance states.

Current Status of CT
(Search for the onset of CT)

Q^2 dependence consistent with standard nuclear physics calculations

A(e,e'p) results



Solid Pts – JLab
Open Pts -- other

N. C. R. Makins et al. PRL 72, 1986 (1994)
G. Garino et al. PRC 45, 780 (1992)
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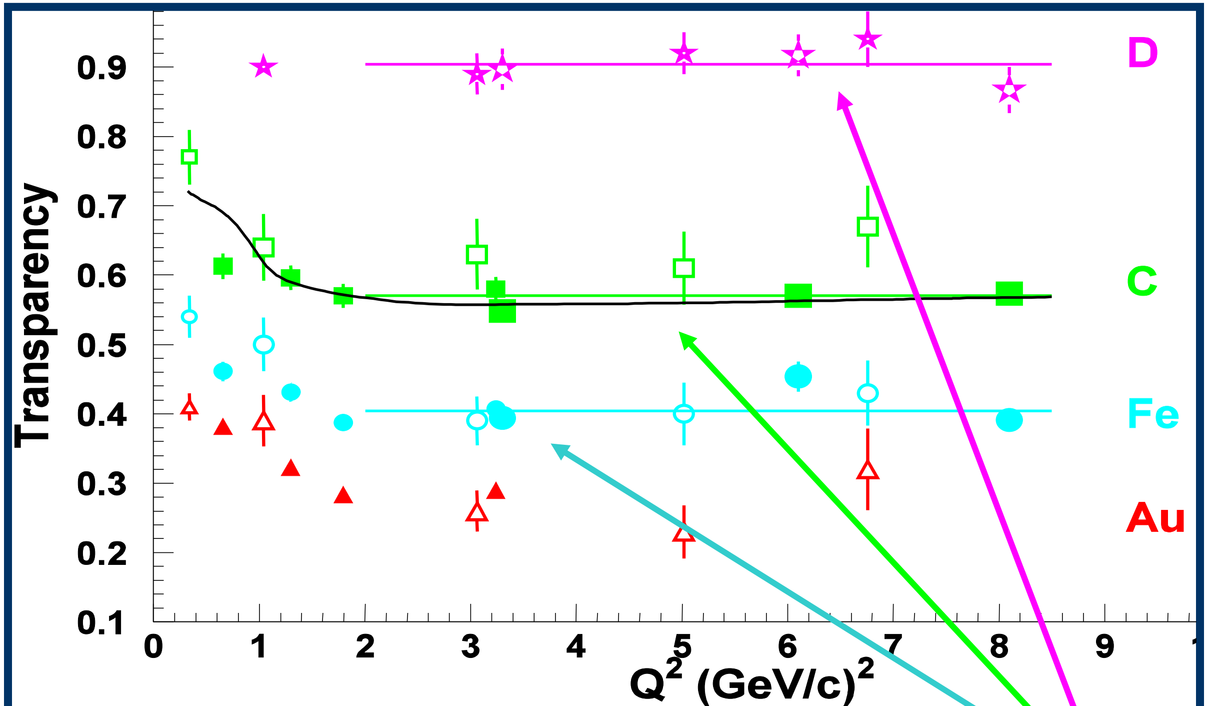


Solid Pts – JLab
Open Pts -- other

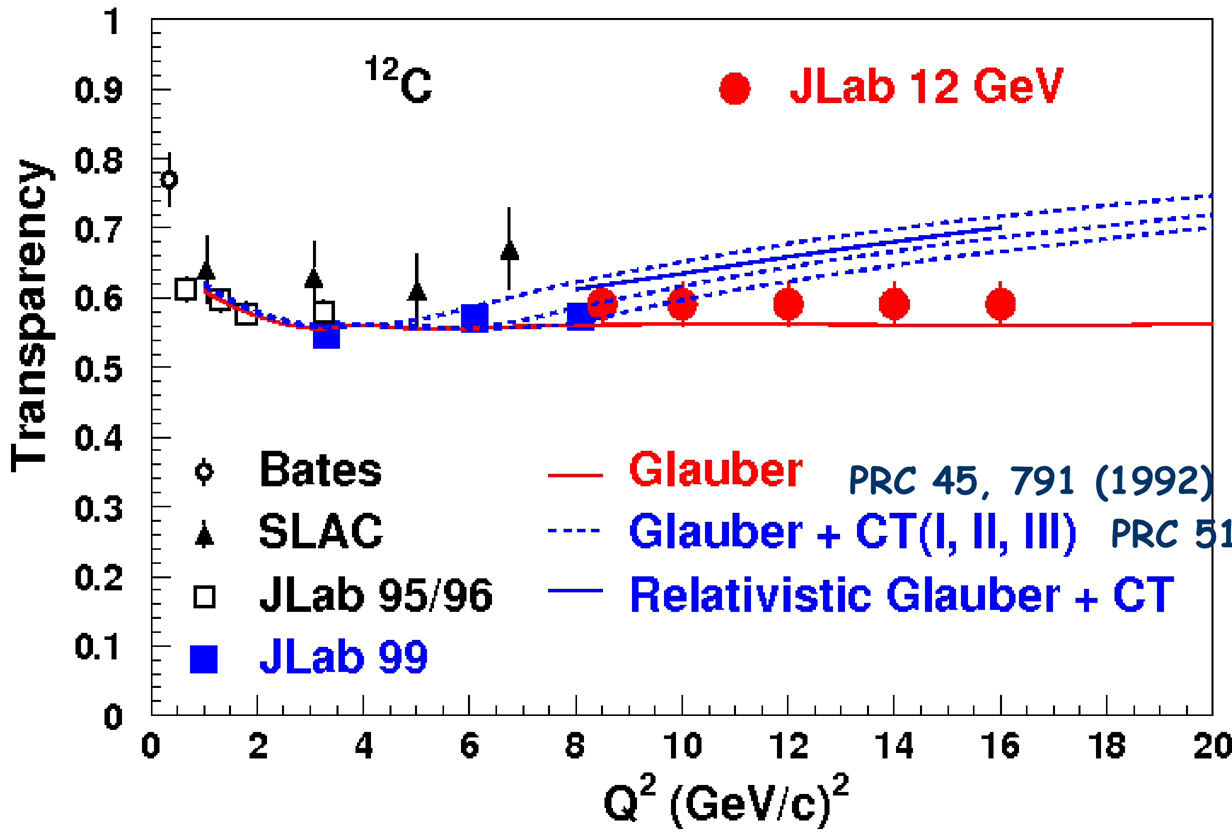
Constant value fit for $Q^2 > 2$ (GeV/c)² has $\chi^2/\mathrm{df} \cong 1$

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(e,e'p) @ 11 GeV JLab

A(e,e'p)

stat + syst. uncertainties



PRC 45, 791 (1992)
PRC 51, 3435 (95), 50, R1296 (94)
PRC 74, R062201 (2007)

2.9 5.1 7.3 9.6 P_p (GeV/c)

Can help interpret the rise seen in the BNL A(p,2p) data.

The rise in BNL A(p,2p) results at P_p = 6 - 9 GeV/c

qqq vs $q\bar{q}$ systems

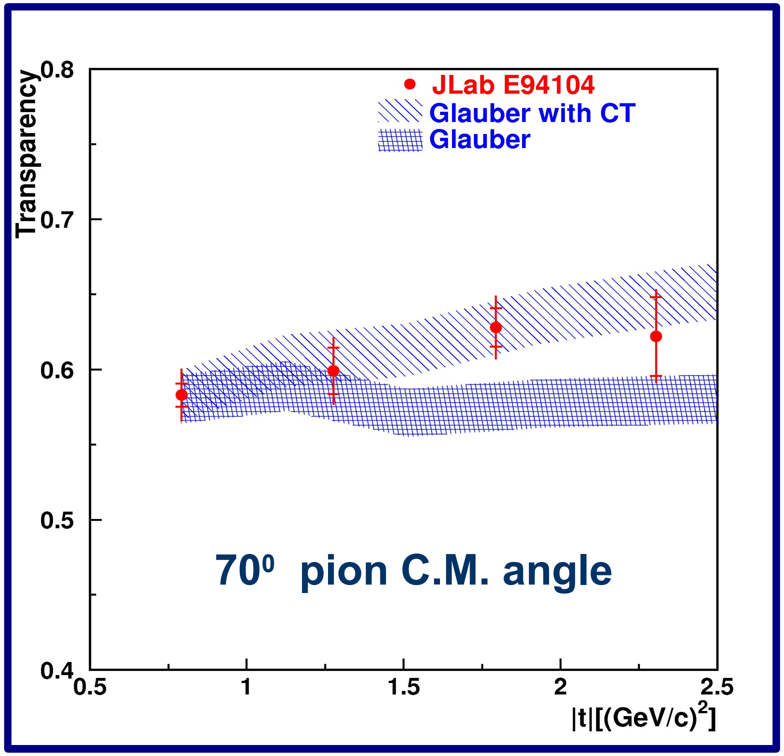
- There is no unambiguous, model independent, evidence for the onset of CT in qqq systems.
- Small size is more probable in 2 quark system such as pions than in protons.
  - B. Blattel et al., PRL 70, 896 (1993)
- Onset of CT expected at lower Q^2 in $q\bar{q}$ system.
- Formation length is ~ 10 fm at 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

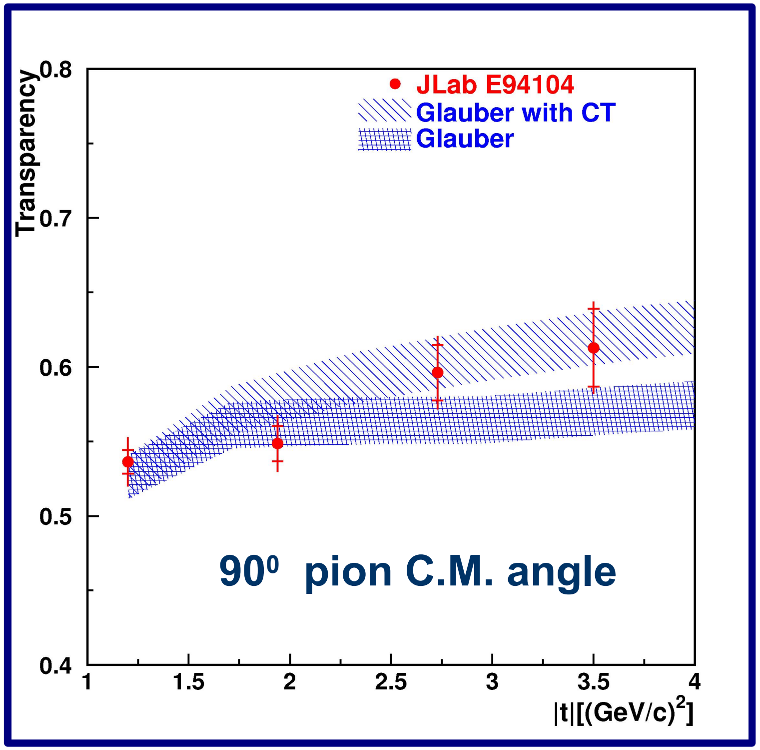
Pion Photoproduction $^4He(\gamma, \pi^- p)$

Positive hints from pion photoproduction in JLab Hall A

(H. Gao & R. Holt Spokespersons)

$$(\gamma + {}^4He \rightarrow \pi^+ + p + X) \;/\; (\gamma + D \rightarrow \pi^+ + p + p)$$



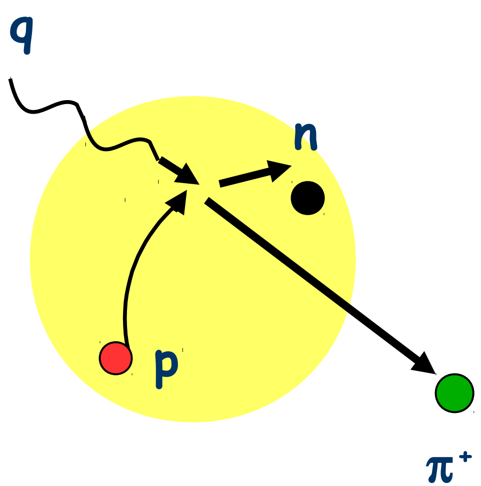


Deviations from Glauber !

Dutta et al. PRC 68, 021001R (2003)
Gao et al. PRC 54, 2779 (1996)

$A(e,e'\pi^+)$ for CT Search

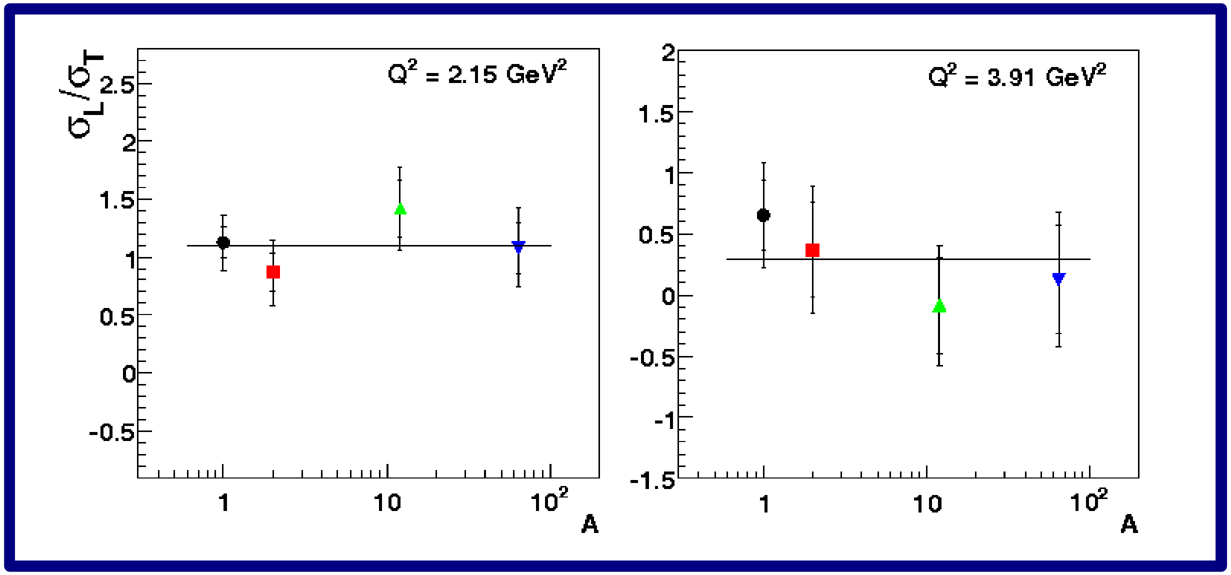
If π^+ electroproduction from a nucleus is similar to that from a proton we can determine nuclear transparency of pions.



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

$S(E,p)$ = Spectral function for proton

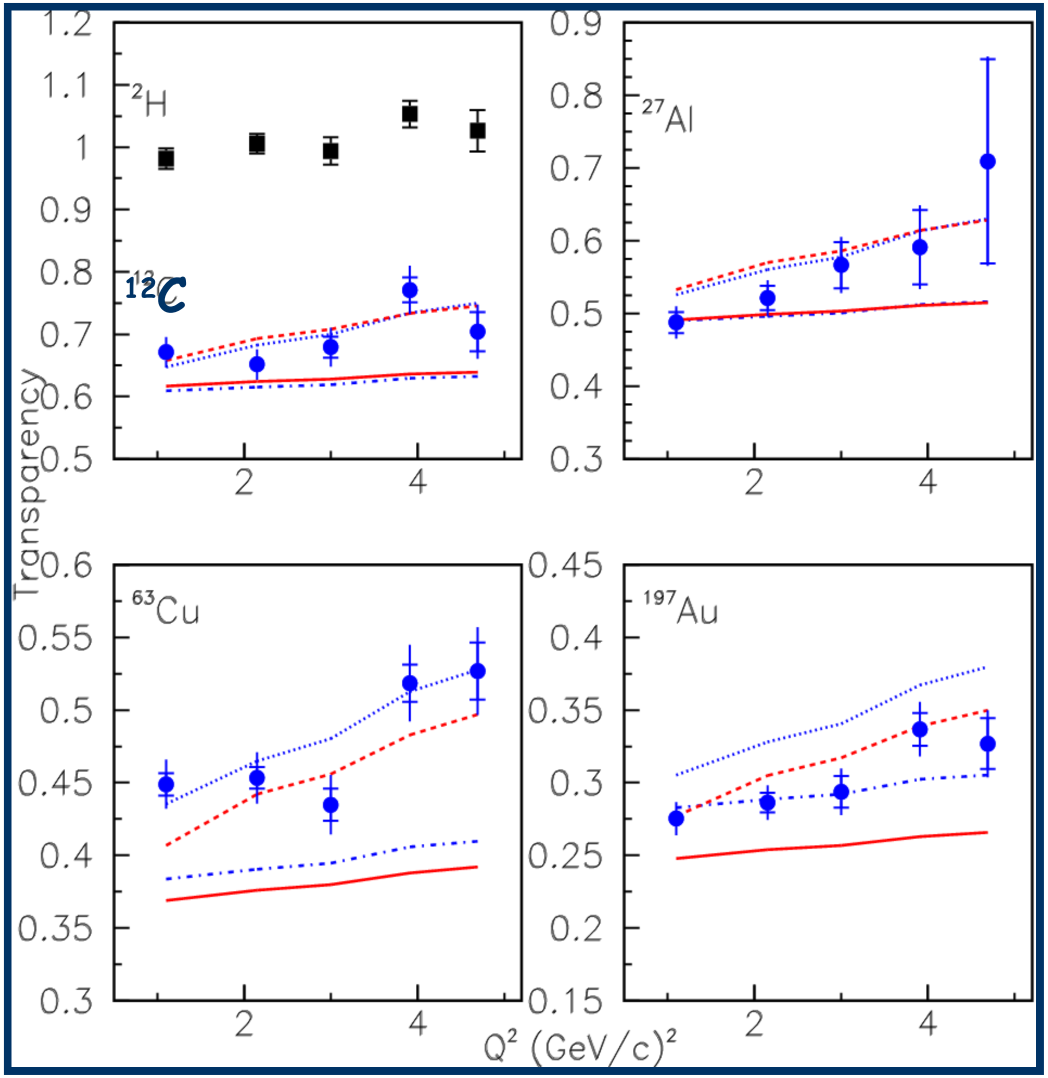
X. Qian et al., PRC81:055209 (2010),



data well described via a MC simulation of a quasifree model including Fermi smearing, FSI and off-shell effects.

The quasi-free assumption was verified by L/T separation

Pion Transparency: Q^2 Dependence



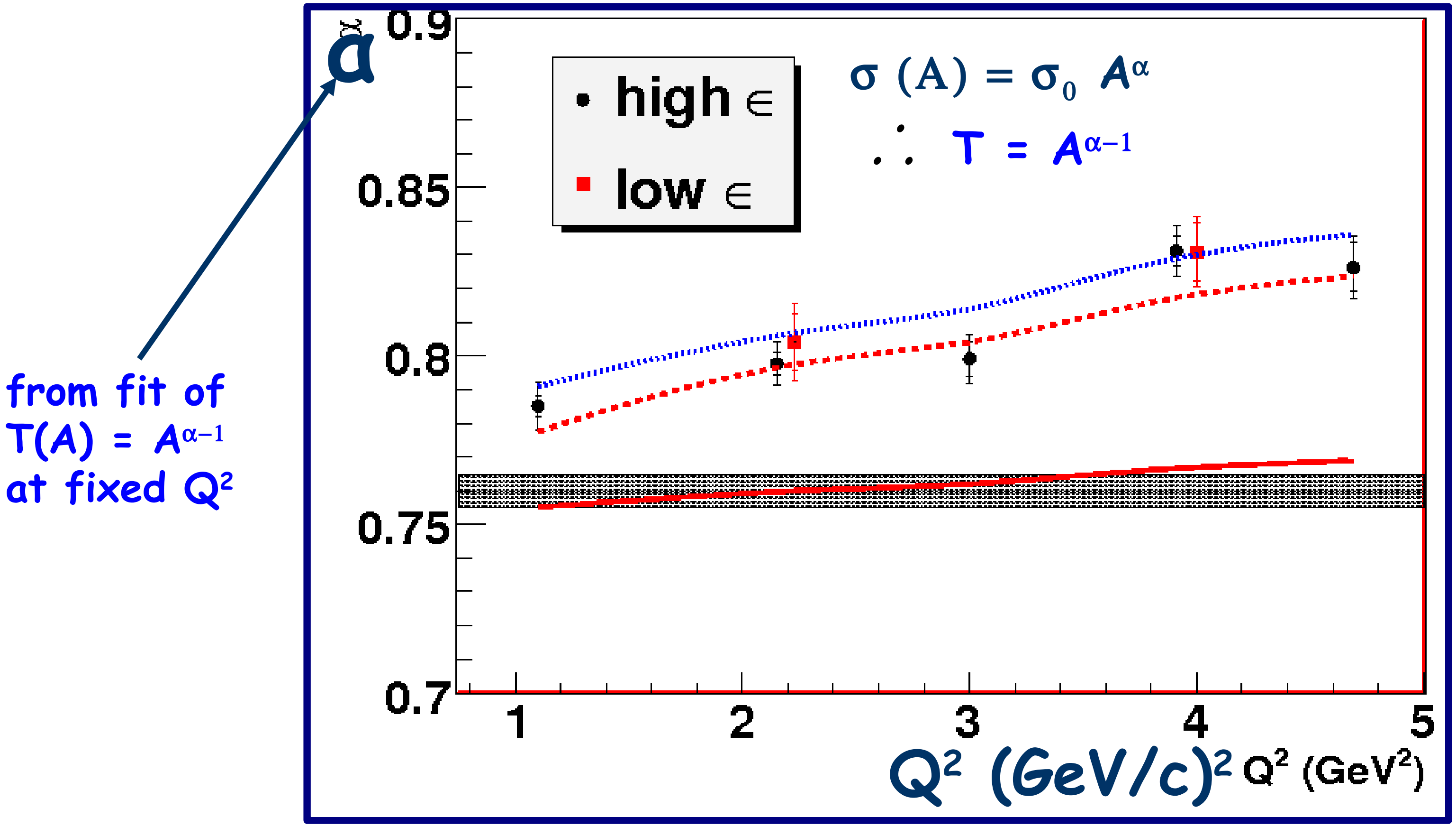
B. Clasie et al. PRL 90, 10001, (2007)
X. Qian et al., PRC81:055209 (2010),

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

solid : Glauber (semi-classical)
dashed : Glauber +CT (quantum diff.)
Larson, Miller & Strikman, PRC 74, 018201 ('06)

dot-dash : Glauber (Relativistic)
dotted : Glauber +CT (quantum diff.) +SRC
Cosyn, Martinez, Rychebusch & Van Overmeire, PRC 74, 062201R ('06)

Pion Transparency: 'A' Dependence



Band: Fit to Pion nucleus scattering; α = 0.76
Carroll et al., PLB 80, 319 ('79)

Larson, Miller & Strikman, PRC 74, 018201 ('06)

B. Clasie et al. PRL 90, 10001, (2007)
X. Qian et al., PRC81:055209 (2010),

Cosyn, Martinez, Rychebusch & Van Overmeire, PRC 74, 062201R ('06)

E01107 Results generated wide interest

Physical Review Focus

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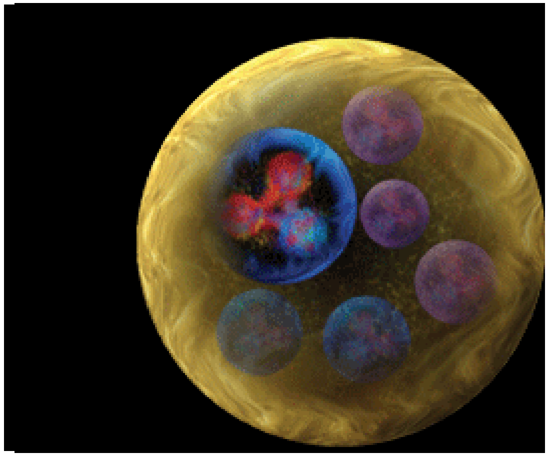
Previous Story / Next Story / Volume 20 archive

Phys. Rev. Lett. **99**, 242502
(issue of 14 December 2007)
Title and Authors

21 December 2007

Transparent Nuclei

A two-quark particle shot into a large nucleus is ordinarily absorbed, as its quarks interact with the nuclear quarks. But in some cases it can sail right through. Now a team reports in the 14 December *Physical Review Letters* that they have observed this so-called color transparency in the lower energy realm, where such quark-scale effects aren't normally seen. The results--which are somewhat controversial--could help theorists who hope to bring the clean calculations of high energy, particle physics down into the messy world of lower energy nuclear physics.

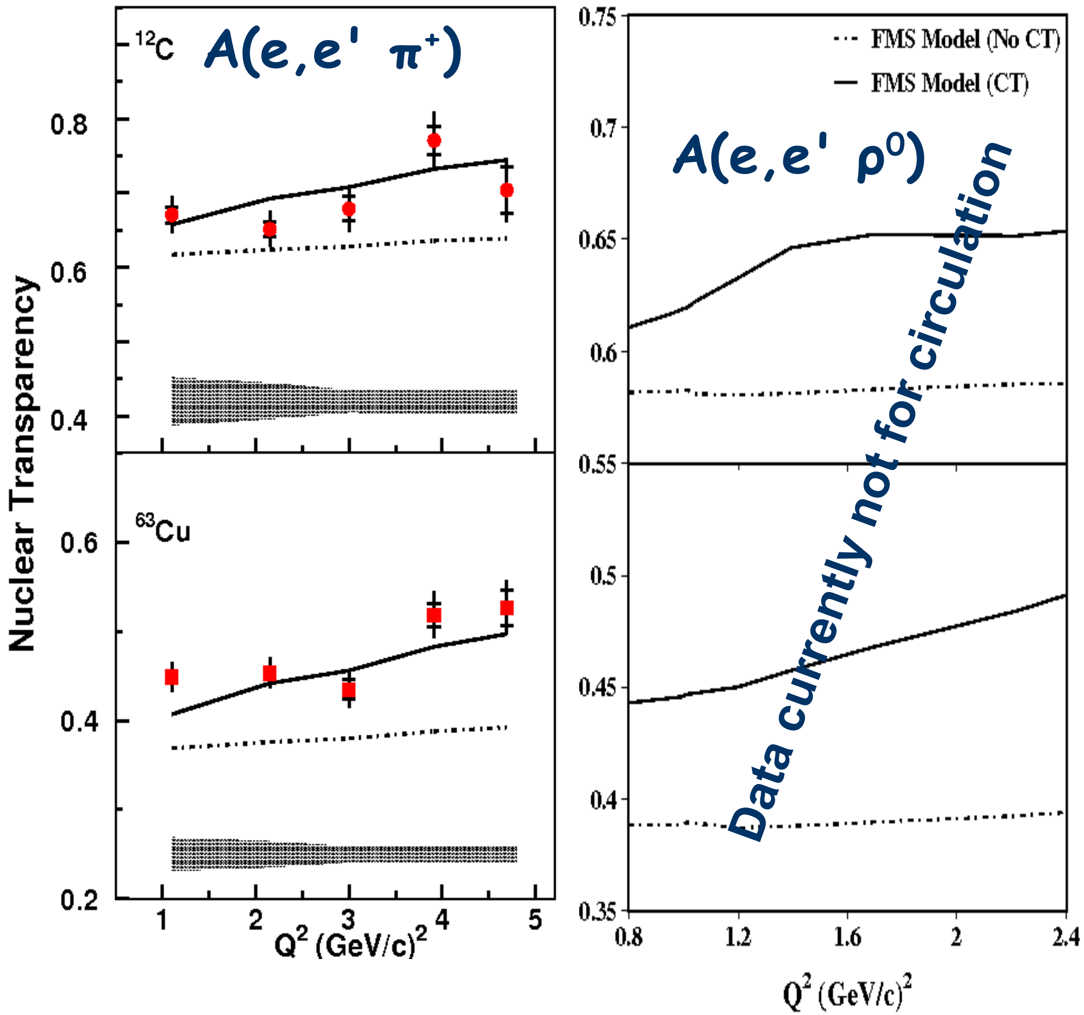


J. Griffin/Jefferson Lab

Skinny particles. An electron (bright green) has just scattered from a nucleus

Quarks have a "color" that attracts them to one another, somewhat like an electric

JLab Experiments conclusively find the onset of Color Transparency



- Hall-C Experiment E01-107 pion electroproduction from nuclei found an enhancement in transparency with increasing Q^2 & A, consistent with the prediction of CT.
(X. Qian et al., PRC81:055209 (2010), B. Clasie et al, PRL99:242502 (2007))

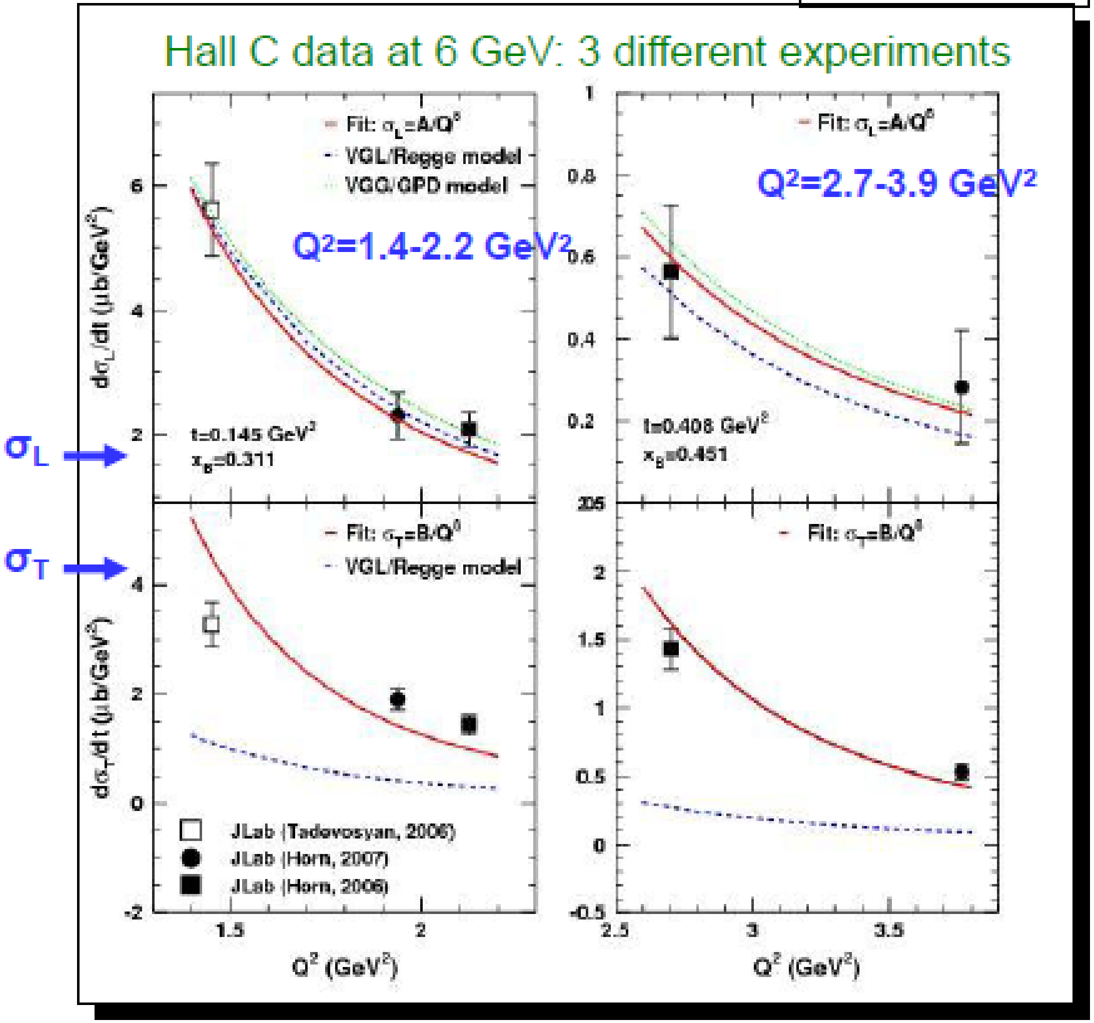
- CLAS Experiment E02-110 rho electroproduction from nuclei found a similar enhancement, consistent with the same predictions
(to be submitted to Nature)

FMS: Frankfurt, Miller and Strikman, Phys. Rev., C78: 015208, 2008

Q^2 dependence of σ_L and σ_T

$ep \rightarrow e'\pi^+ n$

- The Q^{-6} QCD scaling prediction is consistent with the JLab σ_L data
  - Limited Q^2 coverage and large uncertainties make it difficult to draw a conclusion
- The two additional predictions that $\sigma_L >> \sigma_T$ and $\sigma_T \sim Q^{-8}$ are not consistent with the data
- Testing the applicability of factorization requires larger kinematic coverage and improved precision



T. Horn et al., Phys. Rev. C 78, 058201, (2008); arXiv:0707.1794 (2007)

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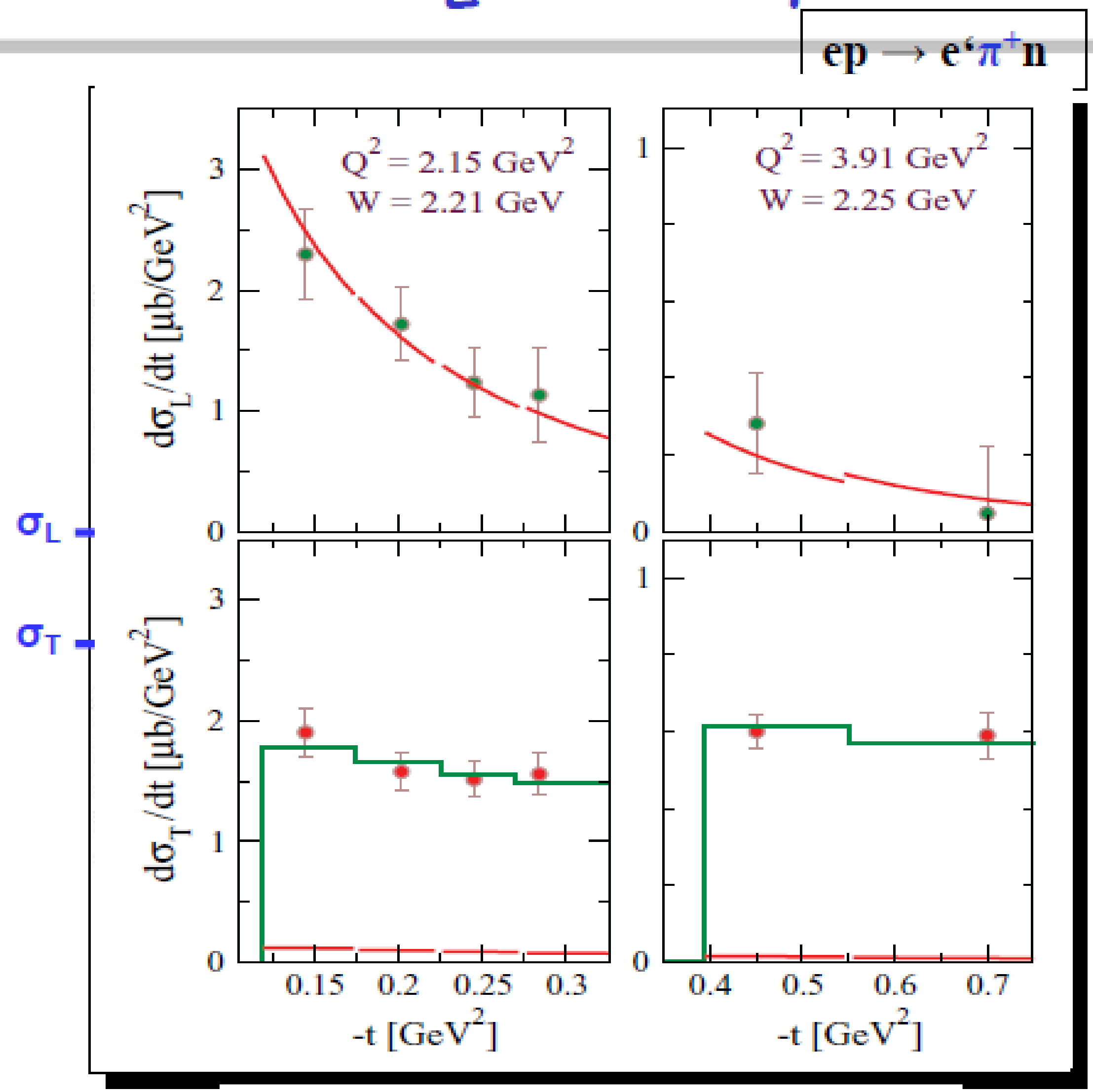
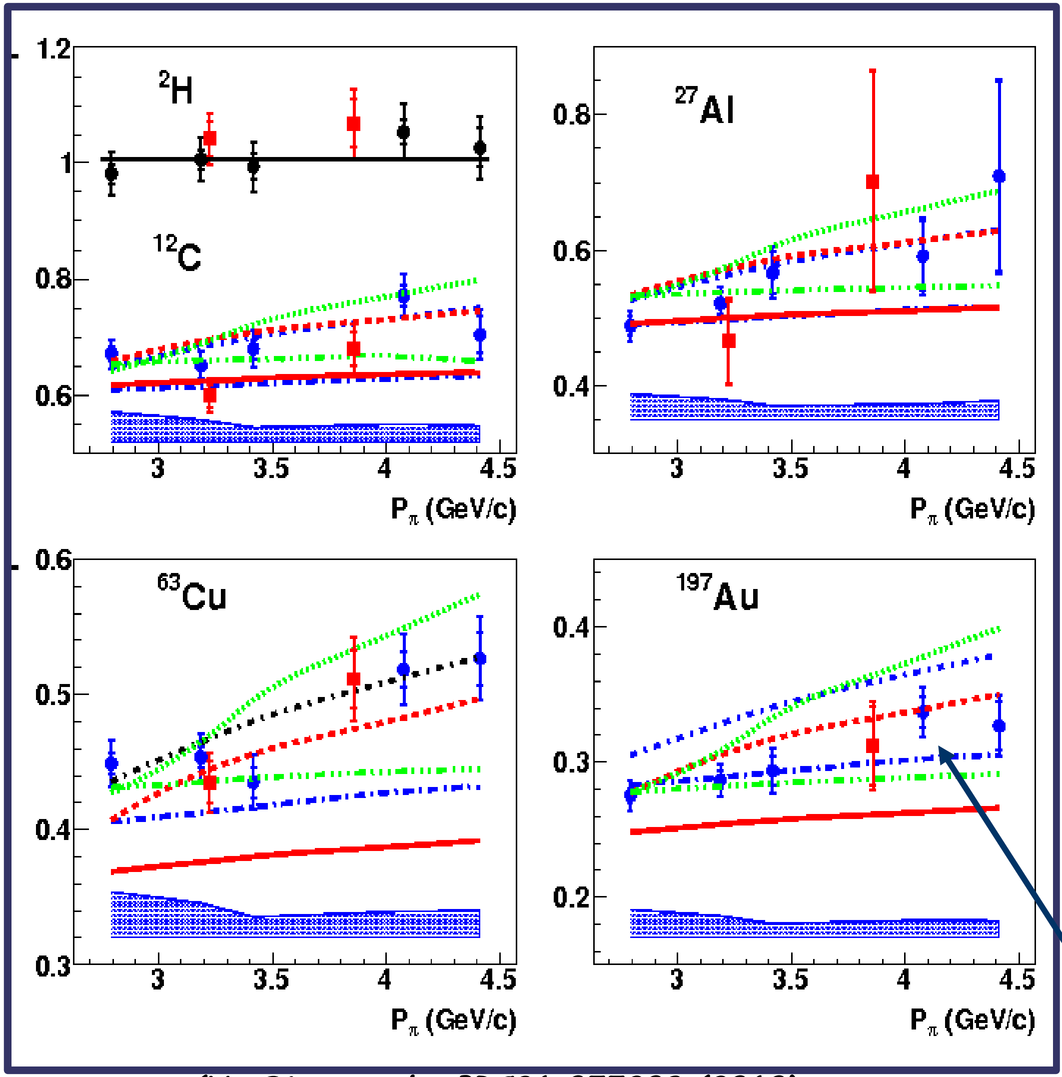


Kaskulov, Galmiester & Mosel, PRC 79, 015207 ('09)

Energy Dependence of Pion Transparency



(X. Qian et al., PRC81:055209 (2010), B. Clasie et al, PRL99:242502 (2007))

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

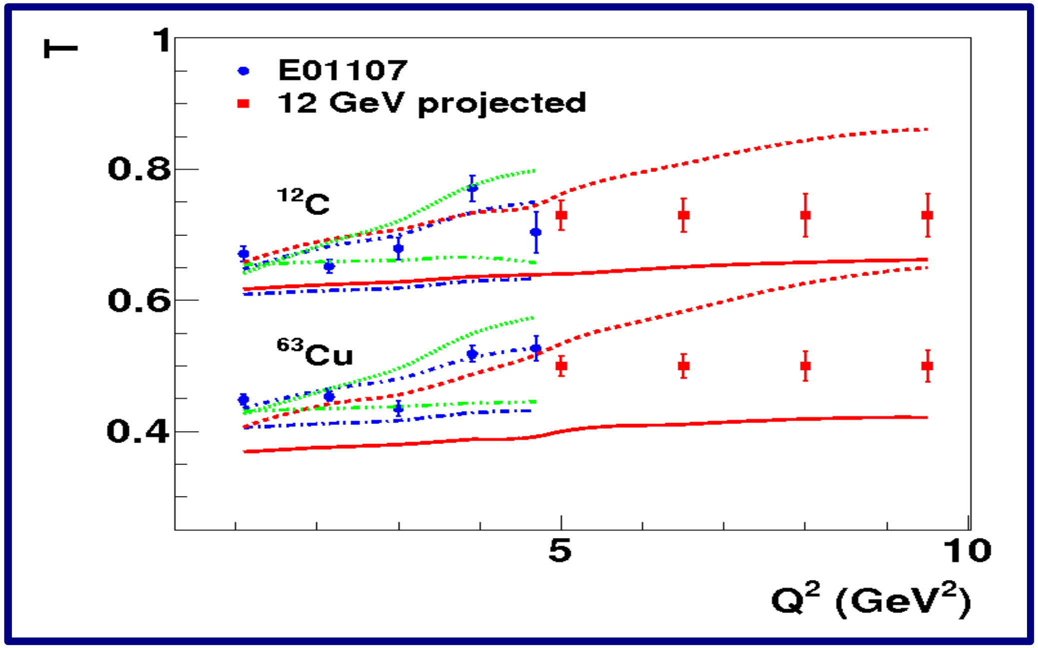
Red solid : Glauber (semi-classical)
Red dashed : Glauber +CT (quantum diff.)
Larson, Miller & Strikman, PRC 74, 018201 ('06)

Blue dot-dash : Glauber (Relativistic)
Blue dotted : Glauber +CT (quantum diff.) +SRC
Cosyn, Martinez, Rychebusch & Van Overmeire, PRC 74, 062201R ('06)

Green dot : BUU Transport
Green dot-dot-dash : BUU Transport + CT (quantum diff.)
Kaskulov, Galmiester & Mosel, PRC 79, 015207 ('09)

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

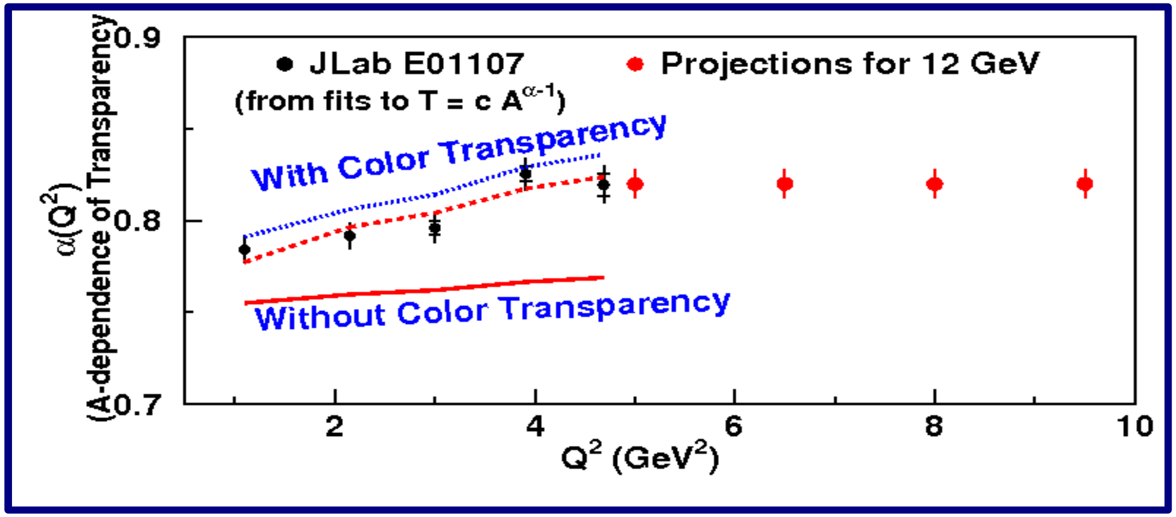
A(e,e'π⁺) @ 11 GeV



Will help confirm the onset of CT observed at 6 GeV

will verify the strict applicability of factorization theorems for meson electroproduction

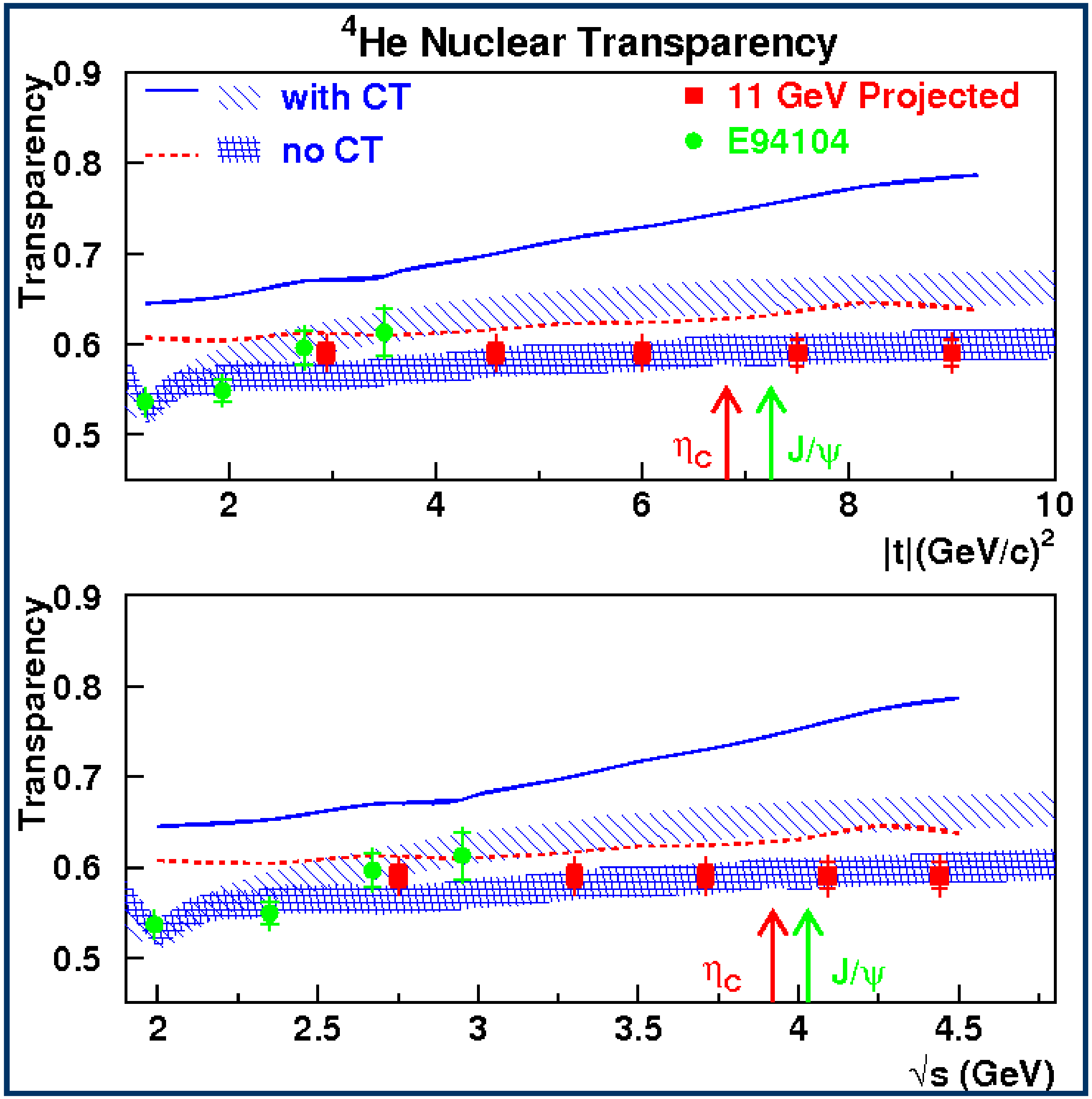
Need both C and Cu targets to extract Q^2 and A dependence and thus disentangle the CT effect



$^4He(\gamma, p\pi^-)$ @ 12 GeV

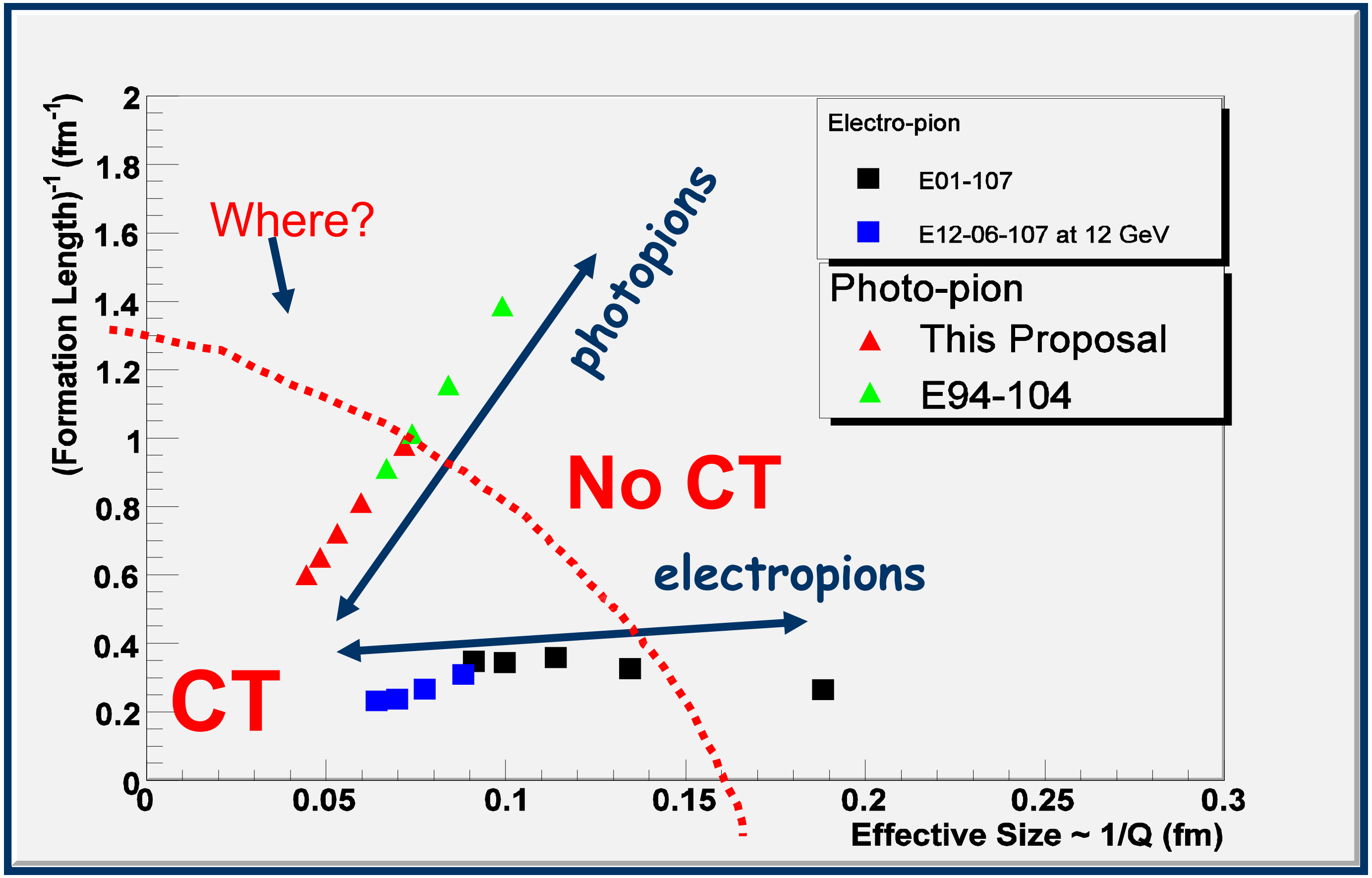
$$T = \frac{\gamma + {}^4He \rightarrow \pi^- + p + X}{\gamma + {}^2H \rightarrow \pi^- + p} T({}^2H)$$

Measures across the charm threshold, it could help understand the p2p results from BNL



Need Both Electro and Photo Pions

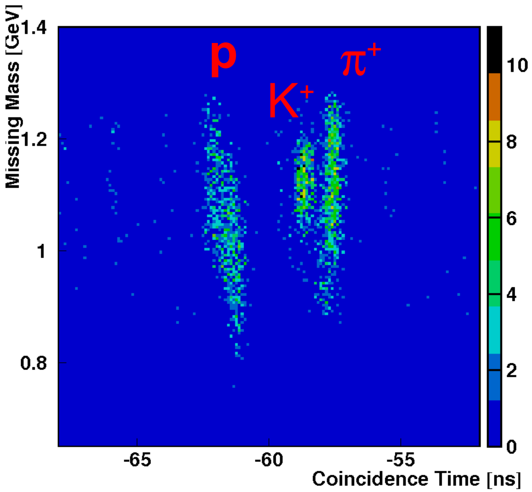
Formation length
~ $P_h * \Delta t / m_h$



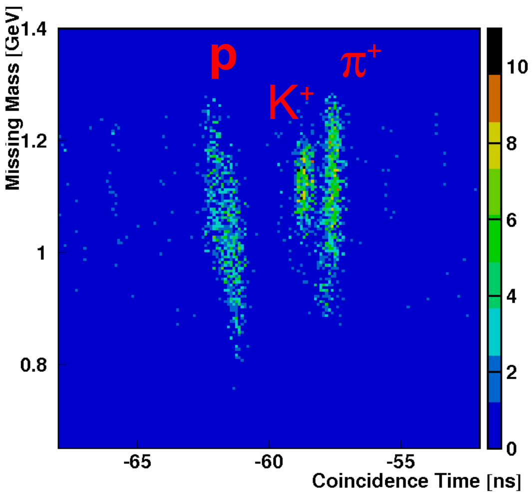
Effective Size ~ 1/Q

- Electro produced pions and photo produced pions sample different regions of the "Formation Length" vs " PLC Size" space

Kaon Transparency: Q^2 Dependence



Kaon Transparency: Q^2 Dependence

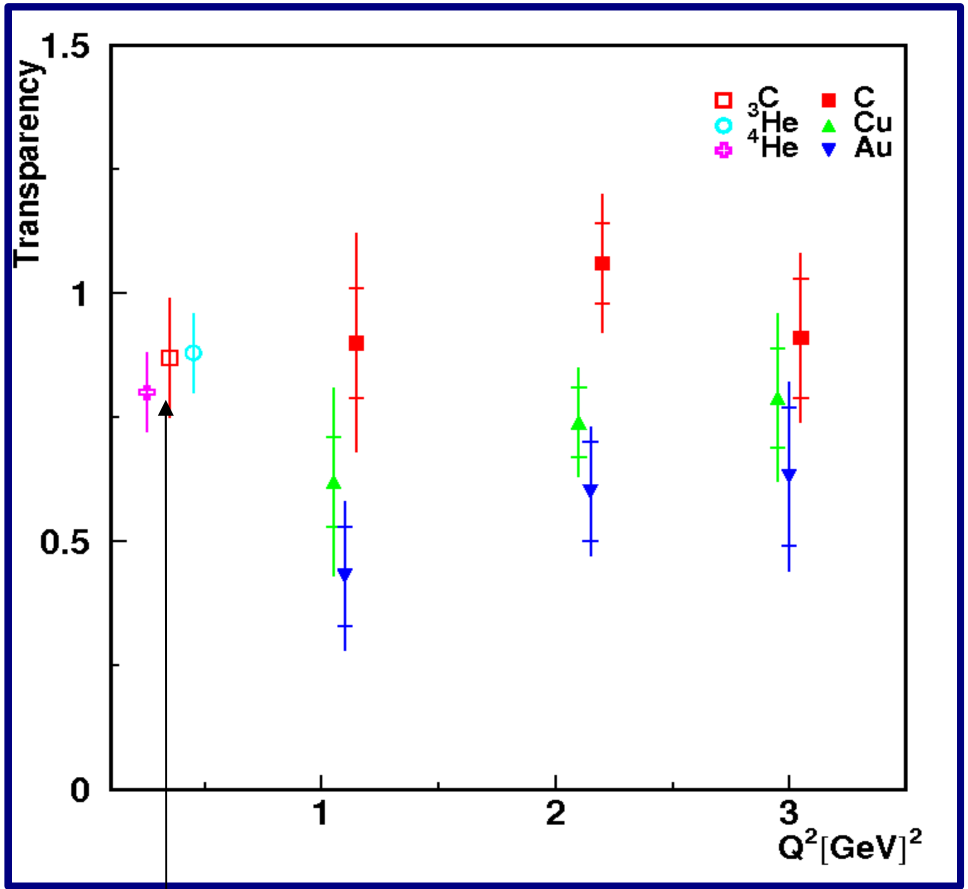


$$T = \frac{\sigma_A^{Expt} / \sigma_A^{Model}}{\sigma_D^{Expt} / \sigma_D^{Model}}$$

Compared with D to minimize impact of non-isoscaler effects

No energy dependence within uncertainties

Nuruzzaman et al., PRC 84, 015210 (2011)

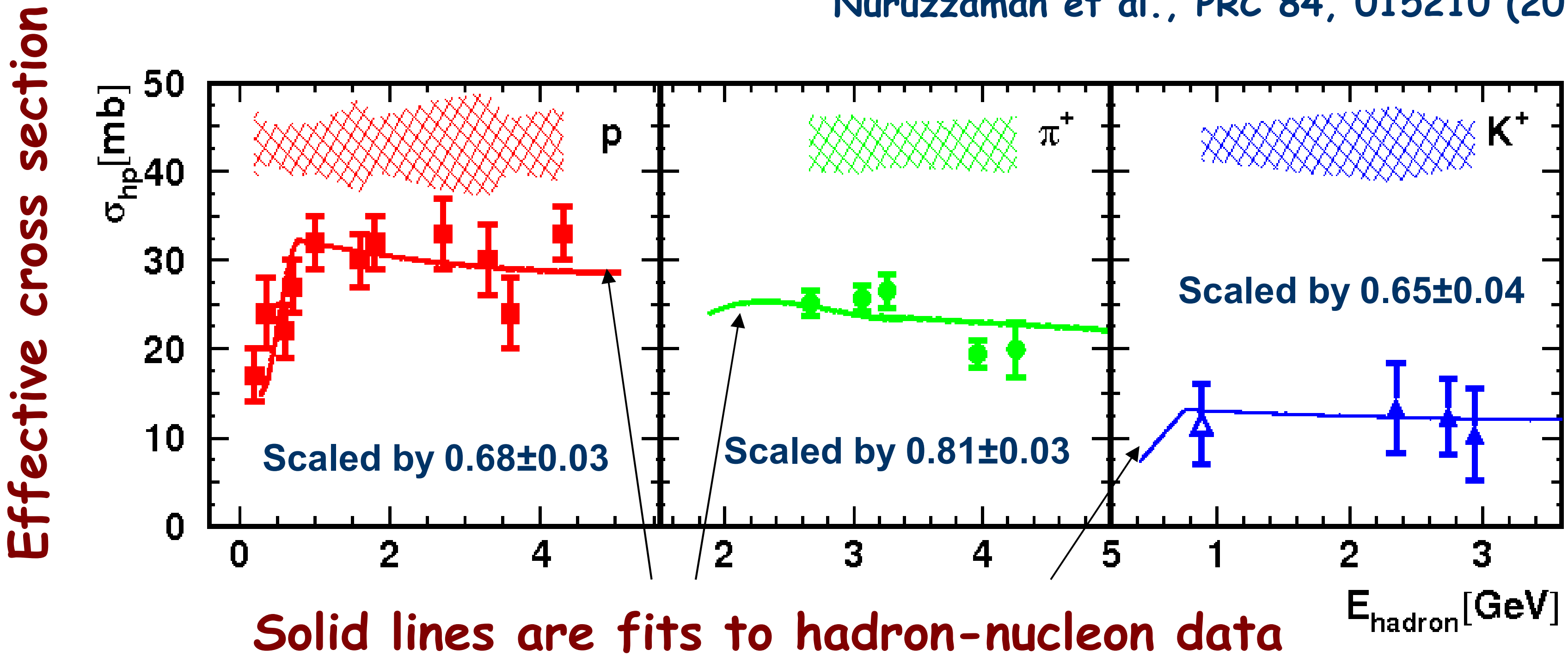


Earlier data on light nuclei

Dohrmann et al. PRC, 76, 054004 (2007)

Hadron Propagation in Nuclear Medium

Nuruzzaman et al., PRC 84, 015210 (2011)

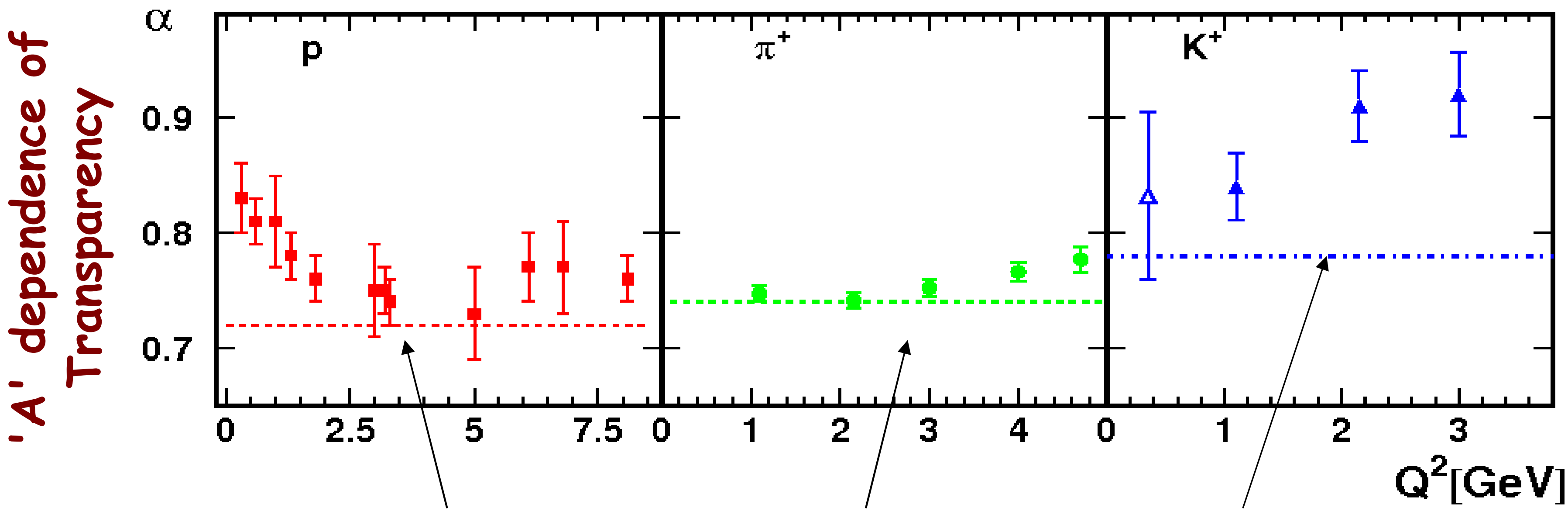


Effective cross section from fitting the measured transparency to a simple geometric model

Energy dependence is consistent with free cross sections but absolute magnitude is significantly smaller than free cross section

Hadron Propagation in Nuclear Medium

Nuruzzaman et al., PRC 84, 015210 (2011)

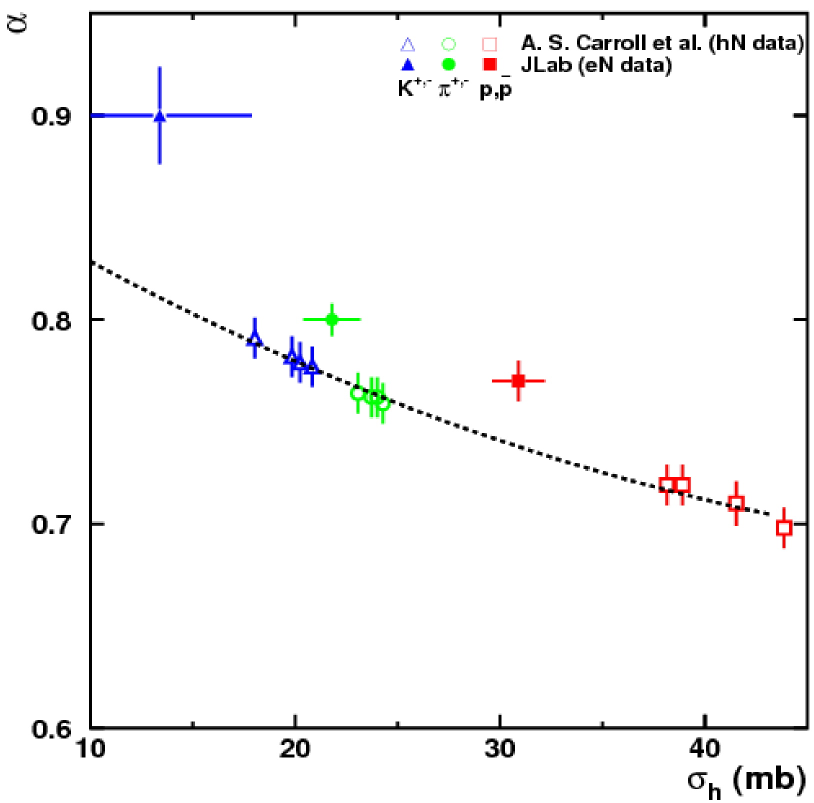


dashed lines are α values from hadron-nucleus data

'A' dependence of Transparency
is quantified using $\sigma(A) = \sigma_0 A^{\alpha}$ which implies that $T = \left(\frac{A}{2}\right)^{\alpha - 1}$

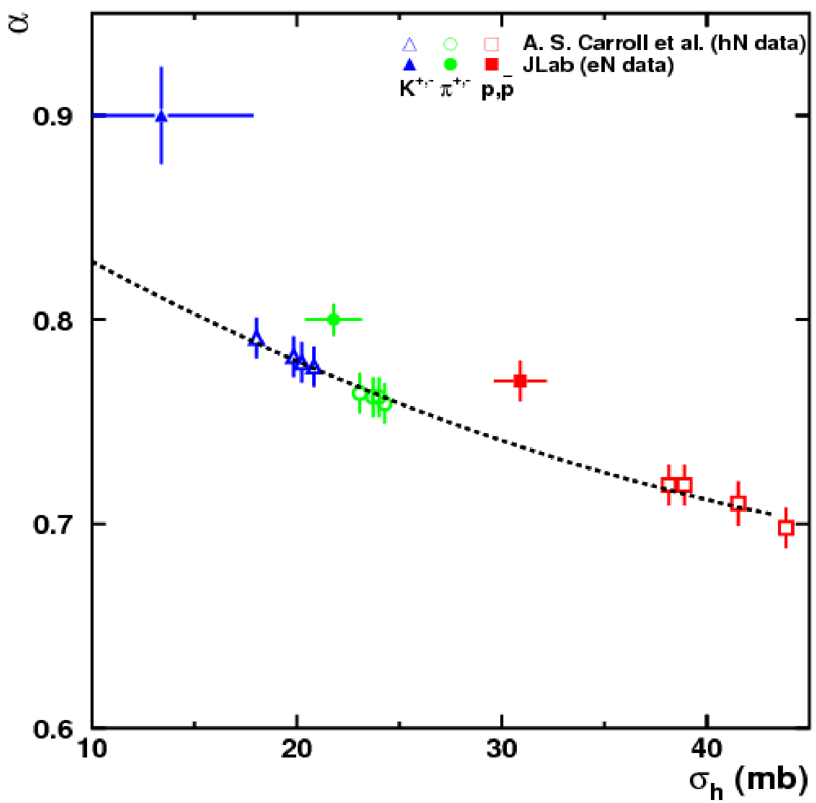
α from electron scattering is larger than those obtained from hadron scattering for all hadrons, the difference is largest for kaons

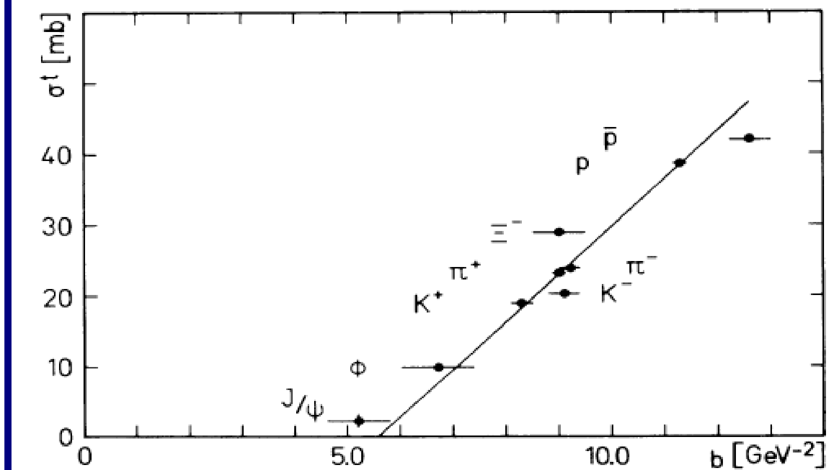
Hadron Propagation in Nuclear Medium



α and the effective cross section from electron scattering differ from those obtained from hadron scattering for all hadrons, the difference is largest for kaons

Hadron Propagation in Nuclear Medium





The electron scattering data does not seem to follow the simple scaling suggested by hadron data

α and the effective cross section from electron scattering differ from those obtained from hadron scattering for all hadrons, the difference is largest for kaons

Summary

- Measurement of hadron transparencies will provide an understanding of the propagation of highly energetic particles through the nuclear matter.
- By comparing exclusive processes on both nucleons and nuclei, one of the signatures of the transition from quarks to hadrons - 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.

- Experiments at JLab have conclusive shown the onset of CT in mesons

- All of these studies will be extended to higher energies at the upgraded JLab

Summary

- These 11 GeV experiments will extend searches for the onset of CT in A(e,e'p) and A(e,e'π^+) reactions to the highest Q^2 reachable with JLab at 11 GeV, and help understand proton and pion propagation in the nuclear medium, a topic that remains of general interest.

- The range in Q^2 covered by the A(e,e'p) experiment has significant overlap with the BNL A(p,2p) experiment and will help interpret the rise in transparency observed in the BNL experiment.
- The A(e,e'π) will cover a range from the onset to CT observed in 6 GeV experiments to ~Q^2 = 10 GeV^2, which will help verify the strict applicability of the factorization theorems for meson electroproduction.

- Electron scattering results for protons, pions and kaons are different from hadron scattering results and the simple geometrical scaling with size seems to break down.