Color Transparency: past, present and future

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Mississippi State University

JLab User Group Meeting
May 29 – 31, 2013

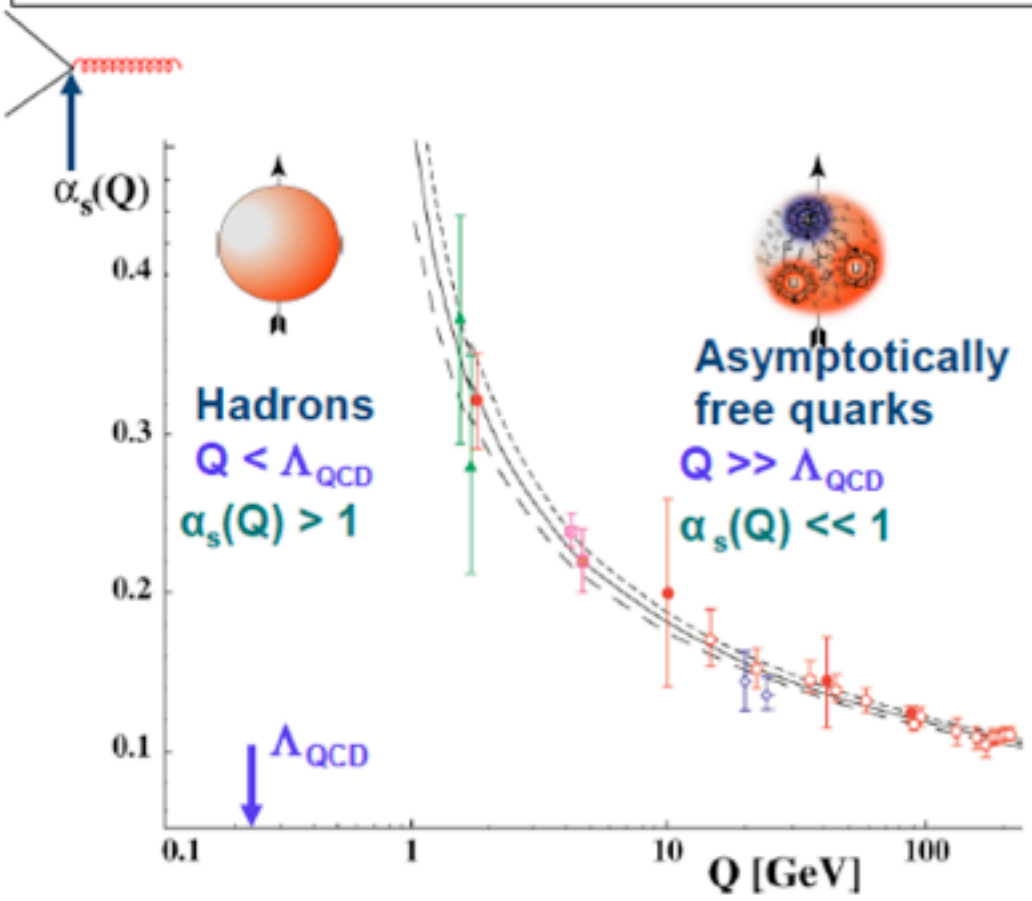
Outline

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

D. D. , K. Hafidi, and M. Strikman, *Color transparency: Past, present and future,* Prog. Part. Nucl. Phys., 69,1 (2013).

Introduction

Quantum Chromo Dynamics (QCD): The fundamental theory describing the strong force in terms of **quarks and gluons** carrying **color** charges.



Λ_{QCD}, ~ Mass Scale or Inverse Distance Scale where $a_s(Q) = 1$, "Separates" Confinement and Perturbative Regions

$\Lambda_{QCD} \approx 213$ MeV

quarks and gluons in nucleons & nuclei are non-perturbative.

What is Role of QCD in Nuclei ?

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**

- What is the mechanism of confinement ?
- Do quarks and gluons play a direct role in Nuclear Matter ?
- Where does the q-q interaction make a transition from the confinement to the perturbative QCD regime (ie can we understand the N-N interactions in terms of QCD) ?

What is Role of QCD in Nuclei ?

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**

Some of these questions can be addressed by studying propagation of hadrons through nuclei

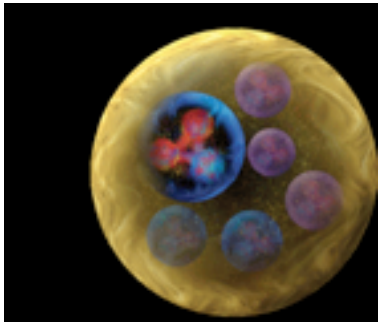
1. **Look for the onset of QCD predictions associated with hadron propagation through nuclei.**

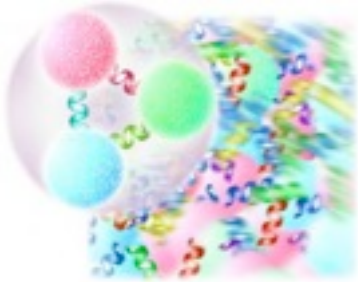
2. **Establish connections with an alternative framework, which advocates the dominance of the handbag mechanism.**

Hadron Propagation

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

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





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

Nuclear transparency is used in the search for signature of QCD in Nuclei.

Nuclear Transparency

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

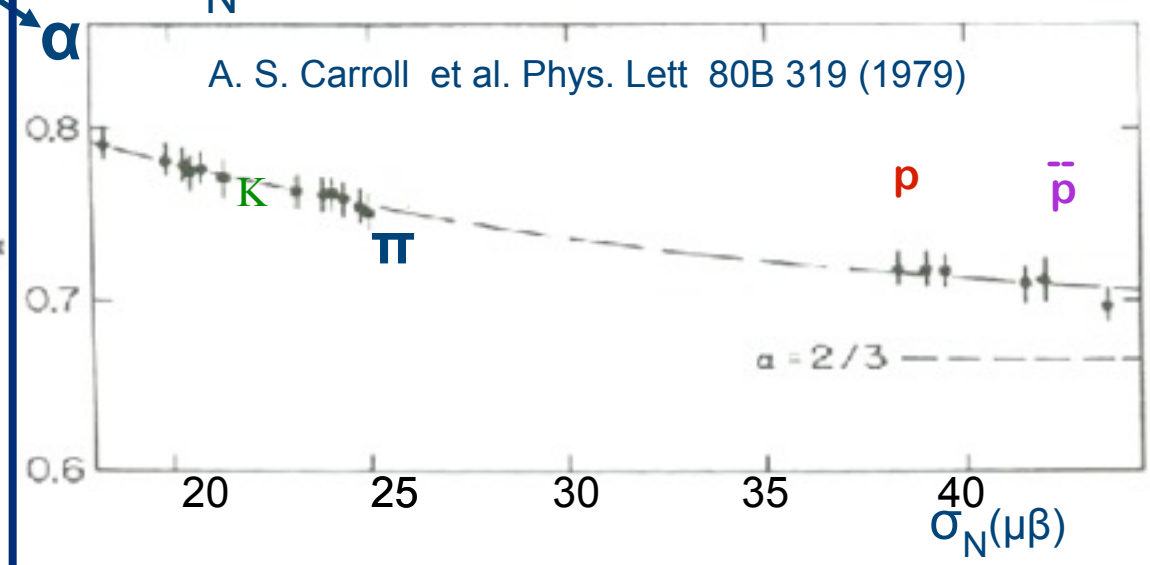
α = 0.72 – 0.78,

for π, K, p

Hadron momentum 60, 200, 250 GeV/c

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

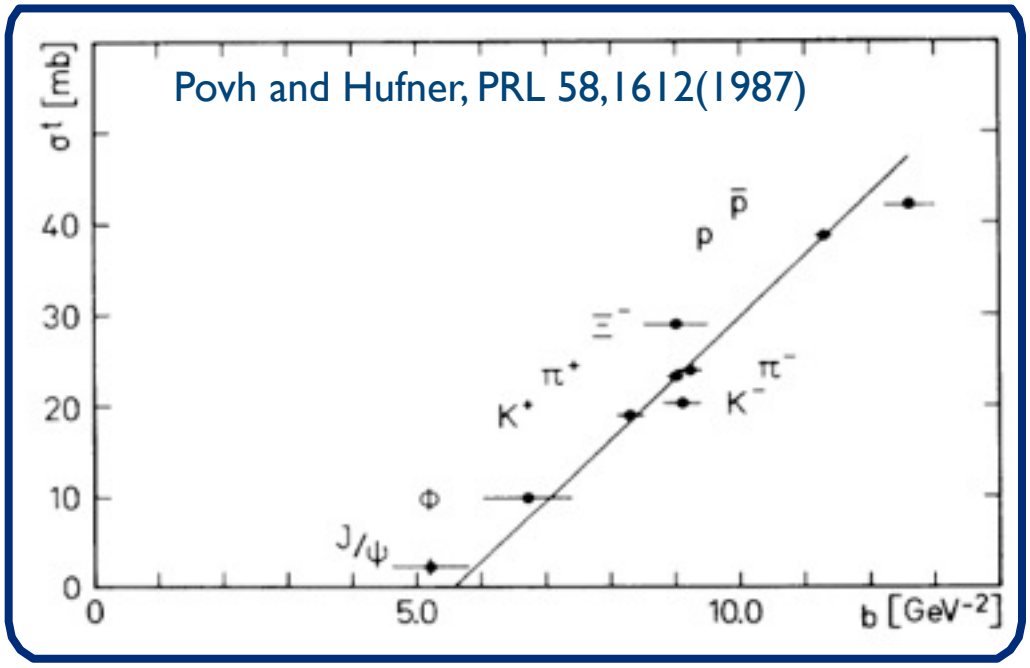
σ_N Hadron– Nucleus total cross-section



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

Size Dependence

Total hadron-proton cross section



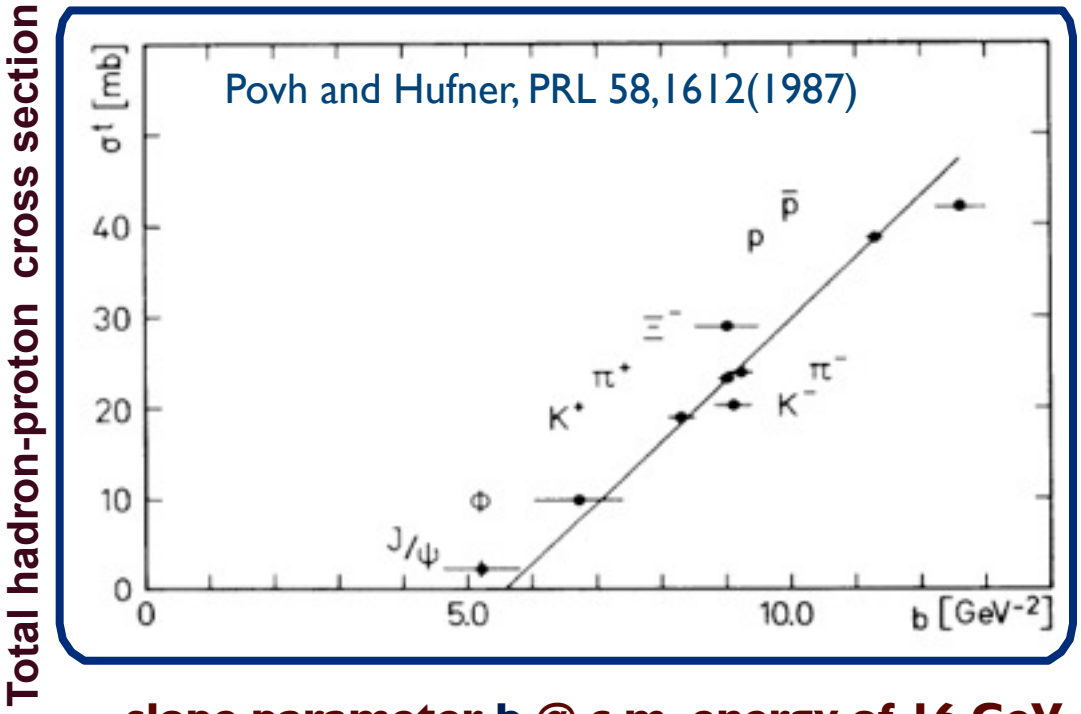
slope parameter b @ c.m. energy of 16 GeV

$d\sigma/dt \propto e^{-bt}$

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

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

Size Dependence



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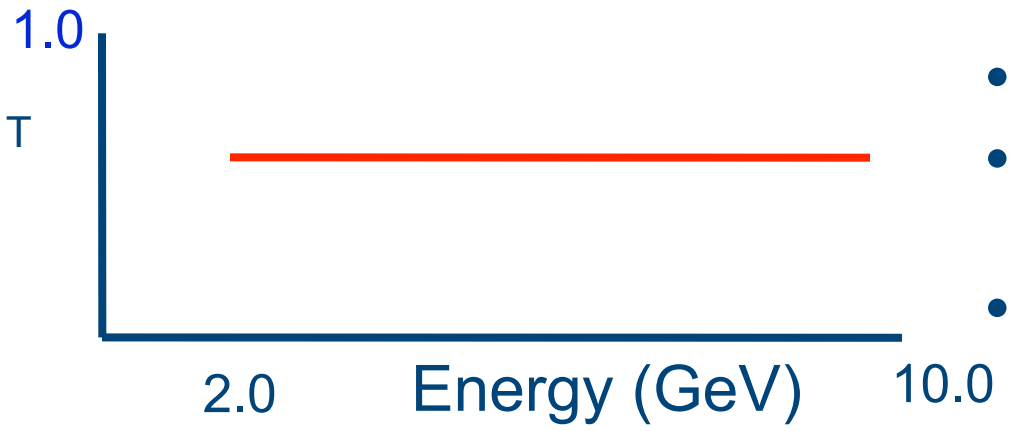
RMS radius from slope of the elastic scattering cross section as a function of $Q^2 = t$

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

Nuclear Transparency

Traditional nuclear physics calculations (Glauber multiple-scattering) 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.

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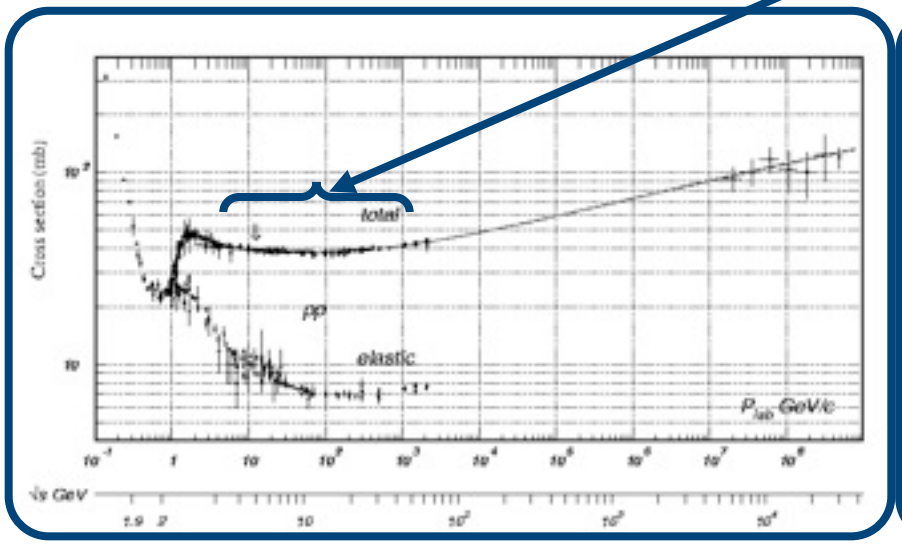
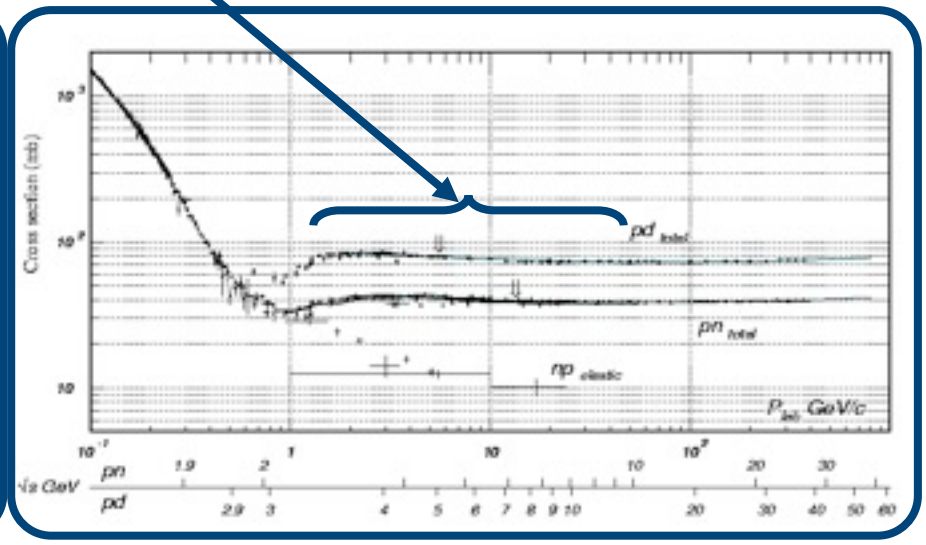
N-N cross-section is energy independent



pp scatt. cross-section



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 is the result of "Squeezing and Freezing"

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- CT is the result of "Squeezing and Freezing"

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

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

✓

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

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

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CT is unexpected in a strongly interacting hadronic picture. But it is natural in a quark-gluon framework.

Color Transparency

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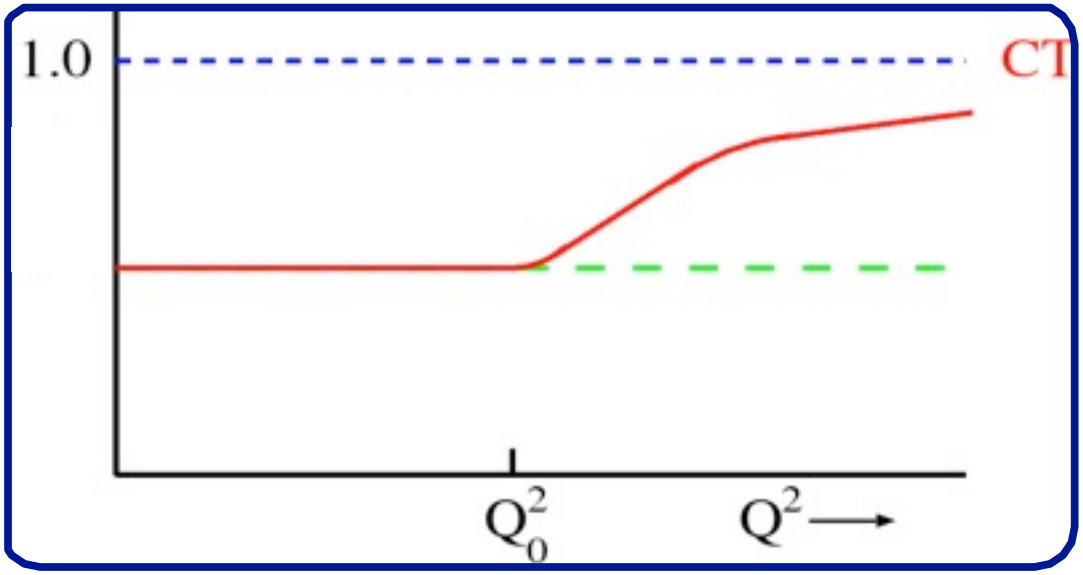
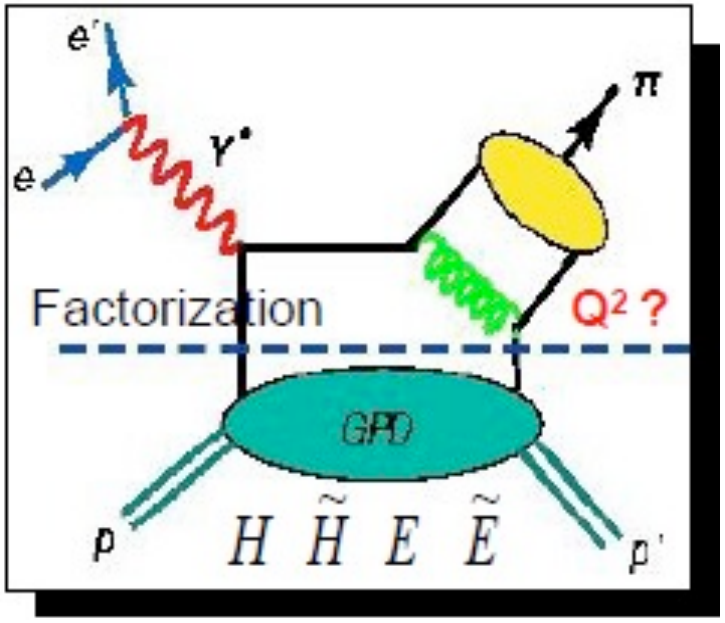


CT is well established at high energies, we are interested in identifying the onset of CT

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 soft part parametrized as GPDs.

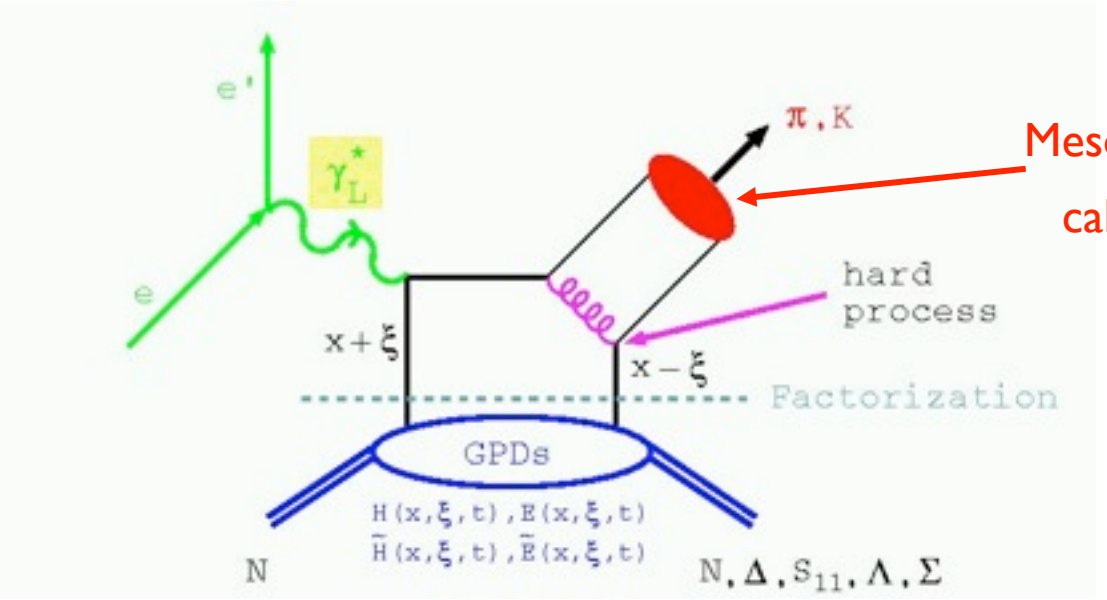
Recent DVCS and wide angle Compton scattering results disagree are consistent with the dominance of handbag mechanism.

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

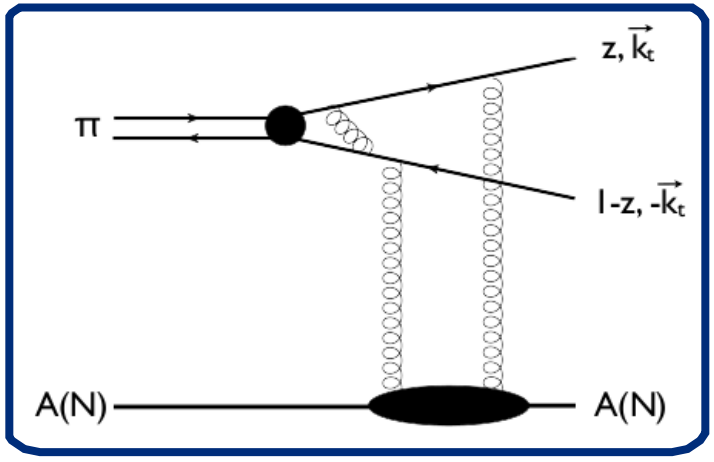
Factorization is not rigorously possible without the onset of CT

-Strikman, Frankfurt, Miller and Sargsian

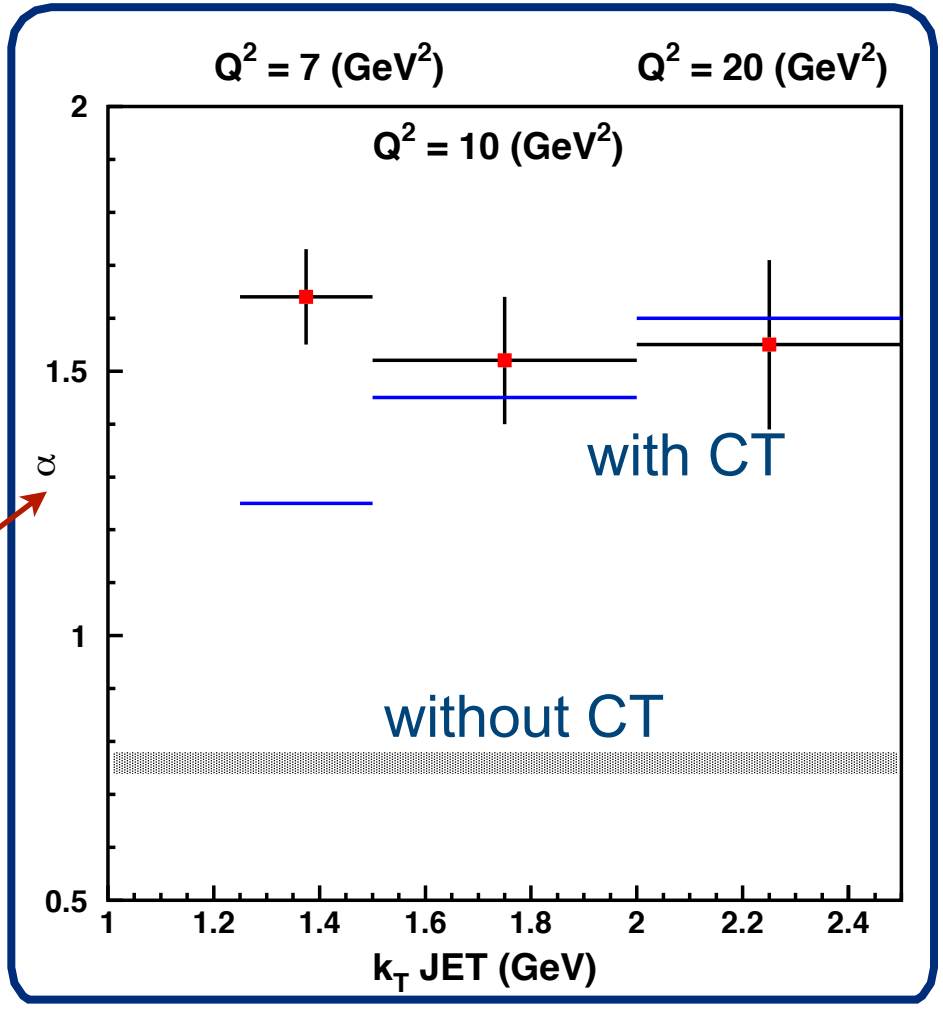
CT at High Energies

Coherent diffractive dissociation of 500 GeV/c pions on Pt and C.

$\pi + A \rightarrow (2\ \text{jets}) + A'$



diffractive dissociation cross-section fit to: $\sigma_0 A^{\alpha}$



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

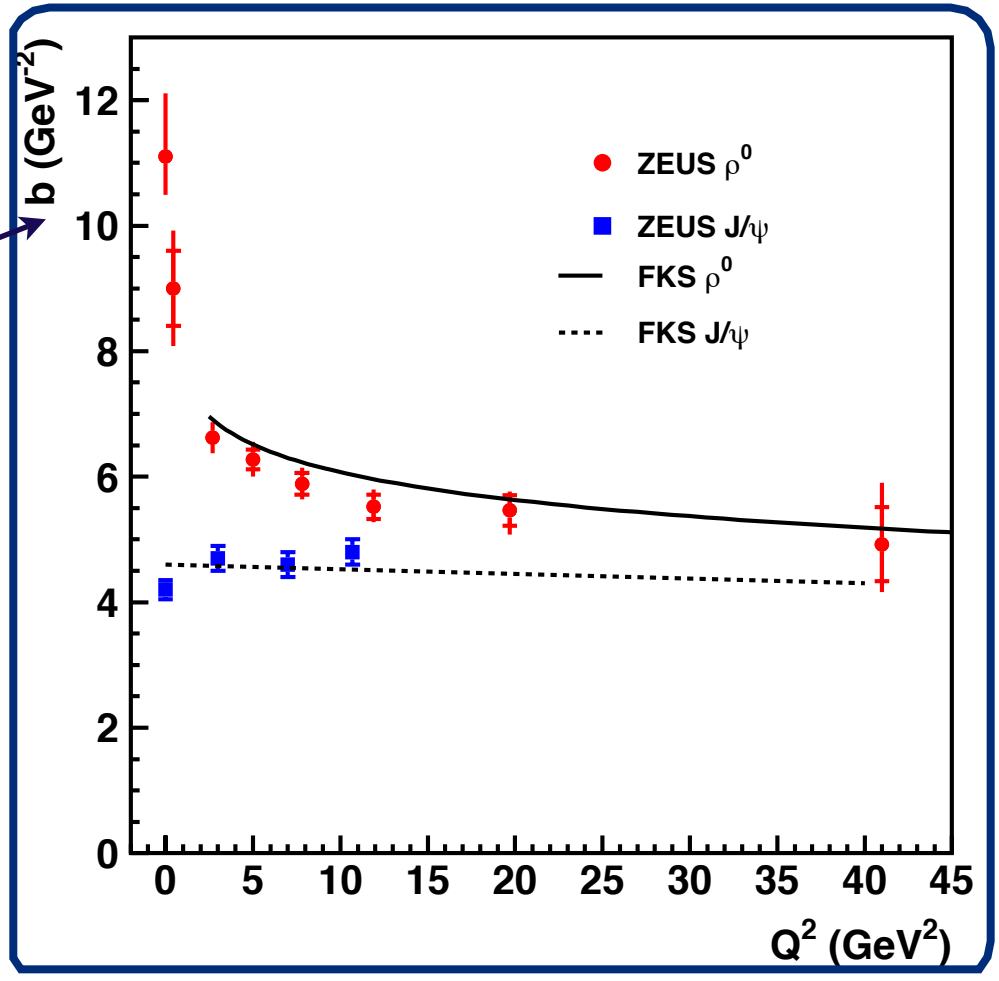
CT at High Energies

Vector Meson production at large Q^2 at HERA

$d\sigma/dt \propto e^{-bt}$

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

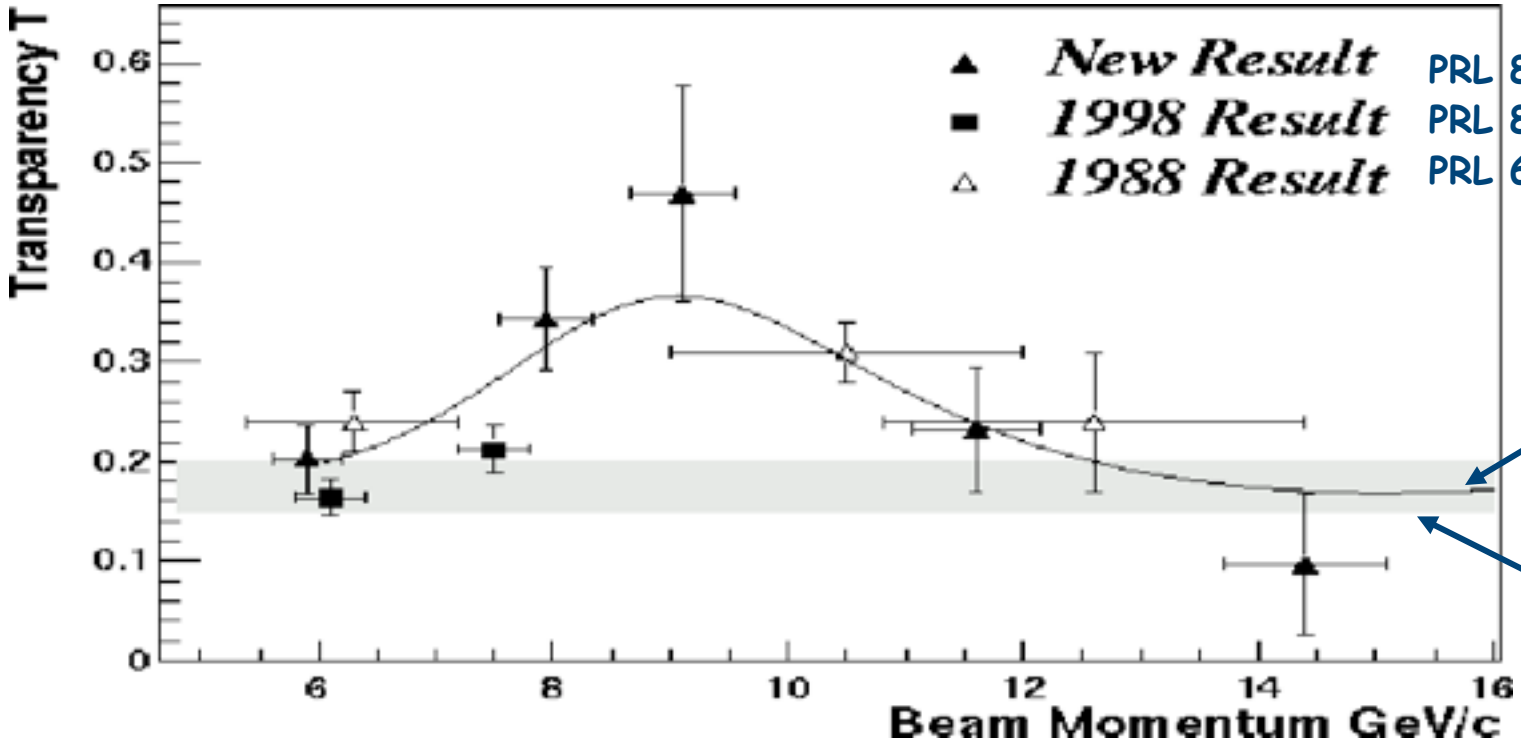
Convergence of "*b*" for ρ and J/ψ electroproduction at large Q^2 predicted by the presence of small size qq-bar state



CT at Intermediate Energies

First direct search for the onset of CT

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



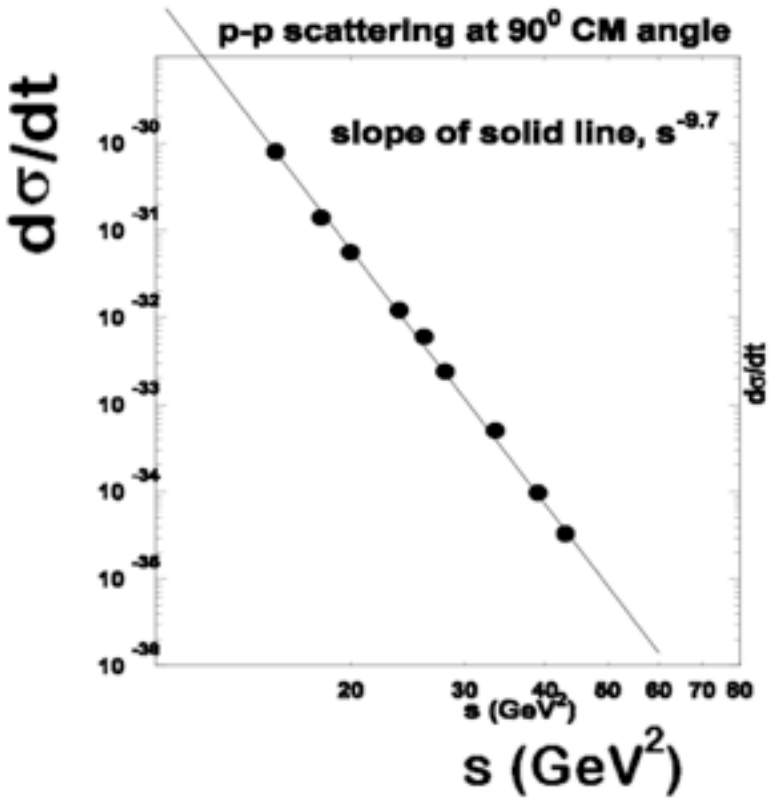
PRL 87, 212301 (2001)
PRL 81, 5085 (1998)
PRL 61, 1698 (1988)

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.

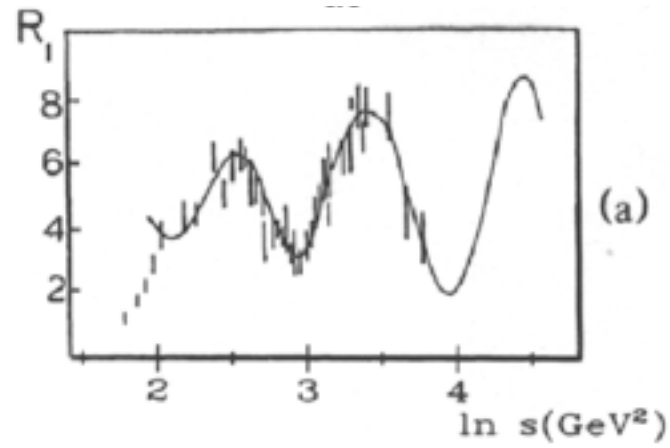
p-p Scattering Cross Section



quark counting rule predicts $\frac{d\sigma}{dt} \propto s^{-10}$

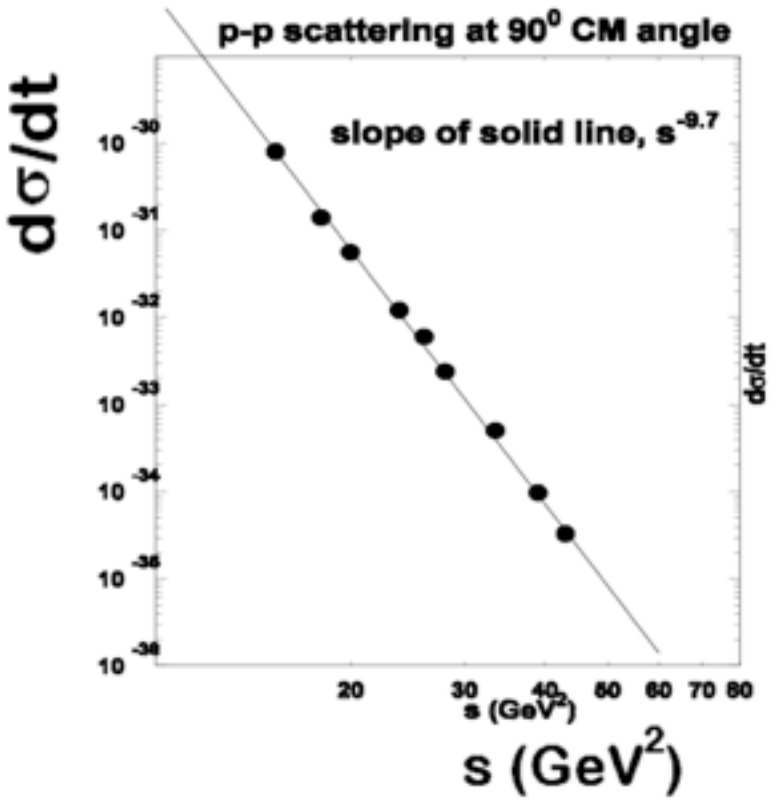
data from Landshoff and Polkinghorne

$R_I \propto s^{10}\, d\sigma/dt$



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

p-p Scattering Cross Section



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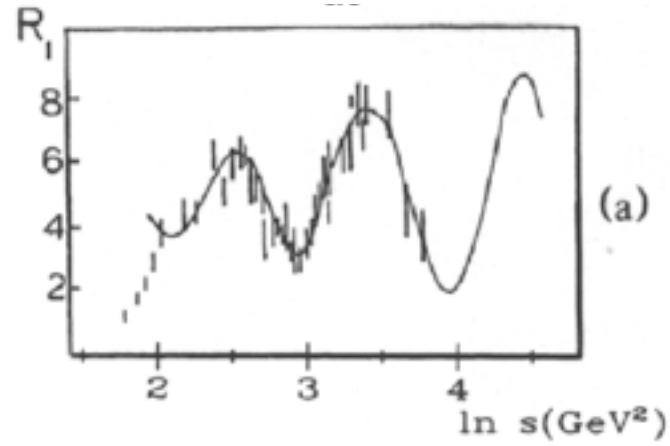

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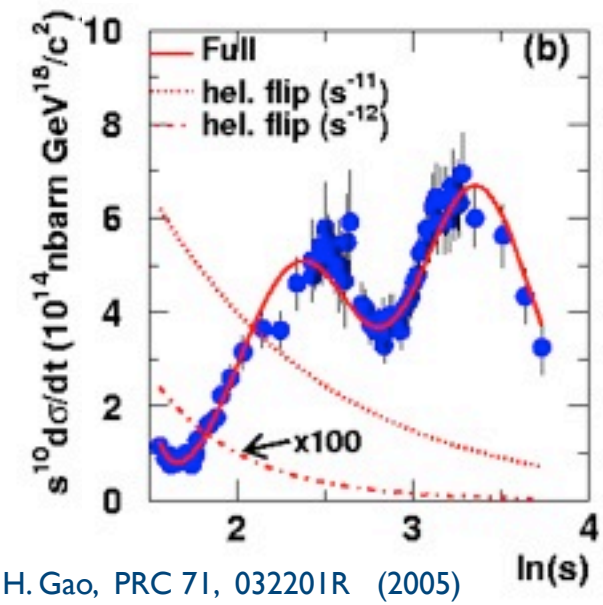
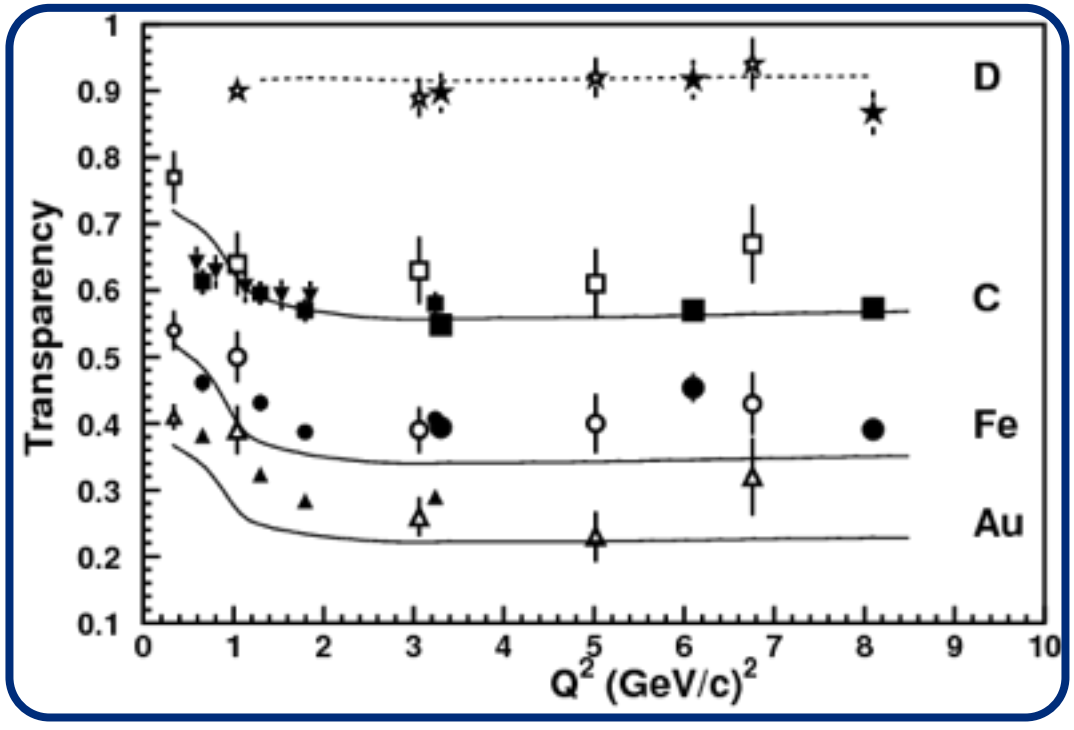


D.Dutta and H. Gao, PRC 71, 032201R (2005)

CT at Intermediate Energies

A(e,e'p) results



Solid Pts – JLab
Open Pts -- other
Black Lines -- Glauber Calculations

Q^2 dependence consistent with standard nuclear physics calculations

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)
D. Rohe et al. PRC 72, 054602 (2005)

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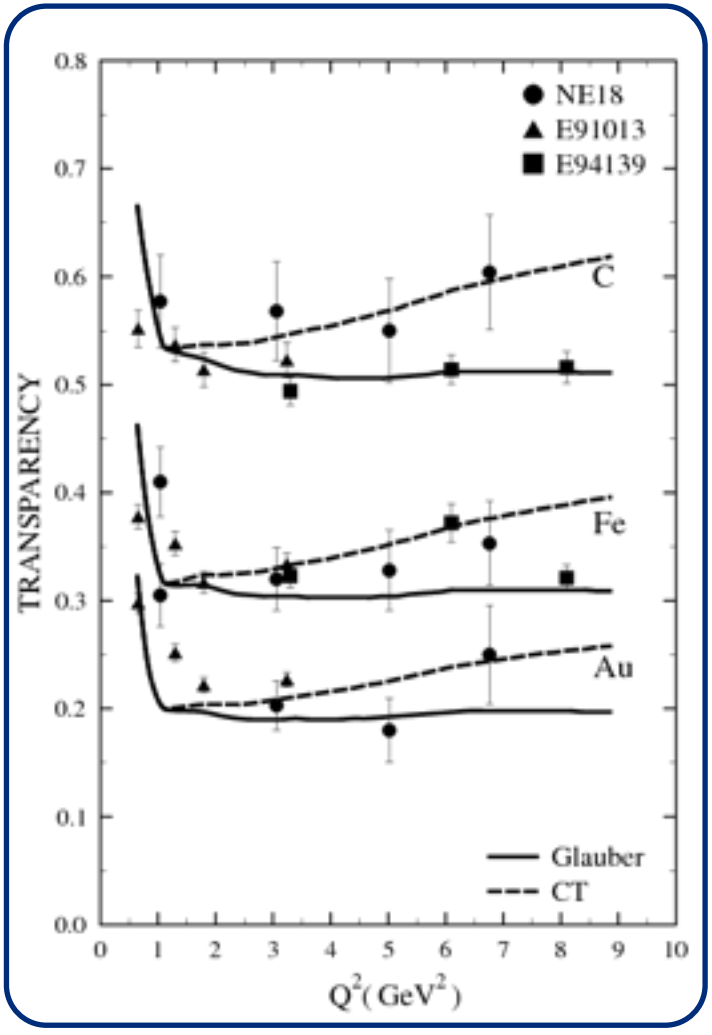

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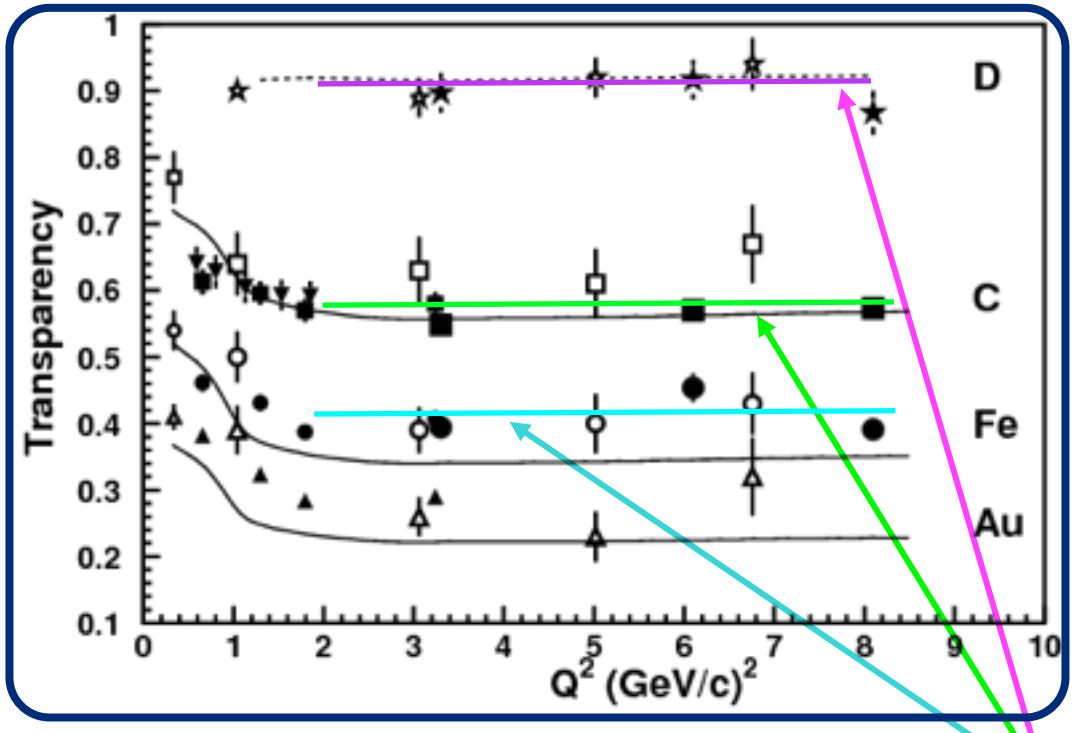

Solid Pts – JLab
Open Pts -- other
Black Lines -- Glauber Calculations

Constant value fit for Q^2 > 2 (GeV/c)^2 has χ^2 / df ~ 1

N. C. R. Makins et al. PRL 72, 1986 (1994)
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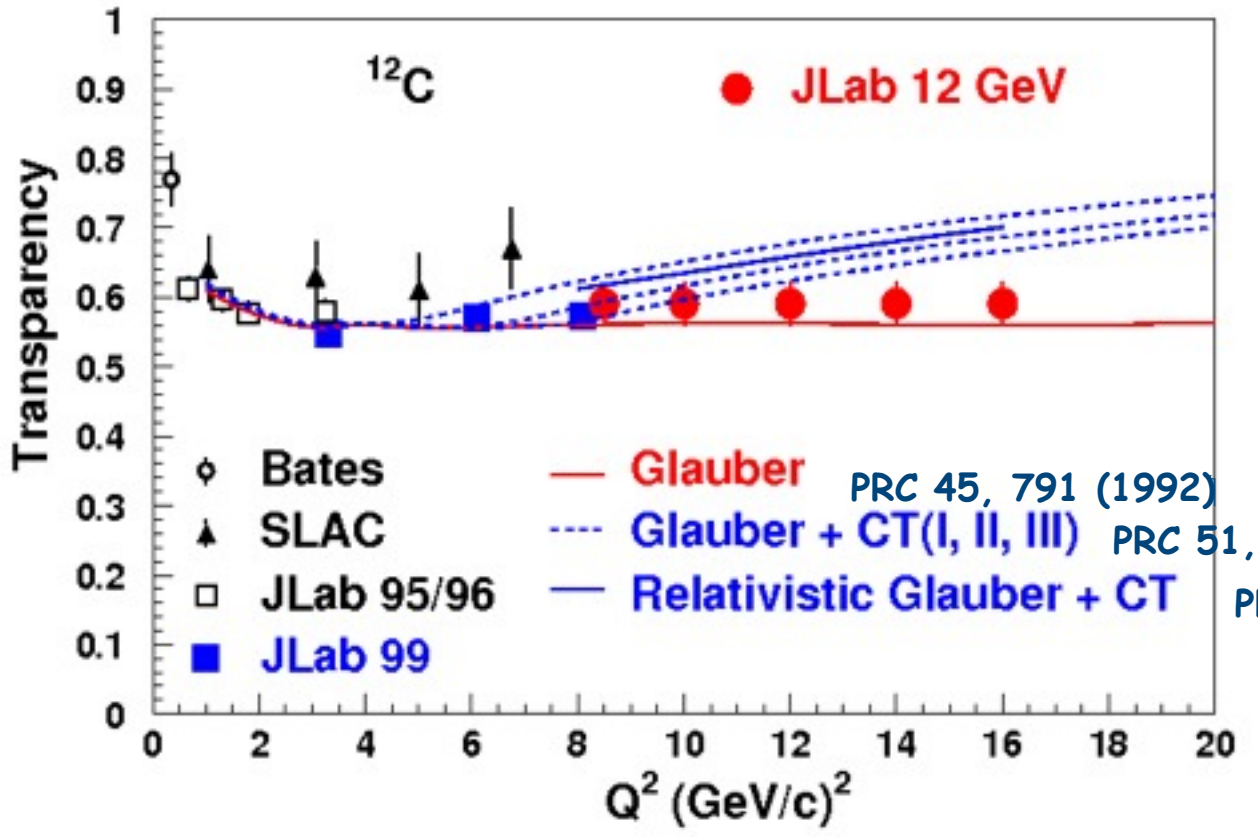
CT at Intermediate Energies

A(e,e'p) @ 11 GeV JLab
E12-06-107



PRC 45, 791 (1992)

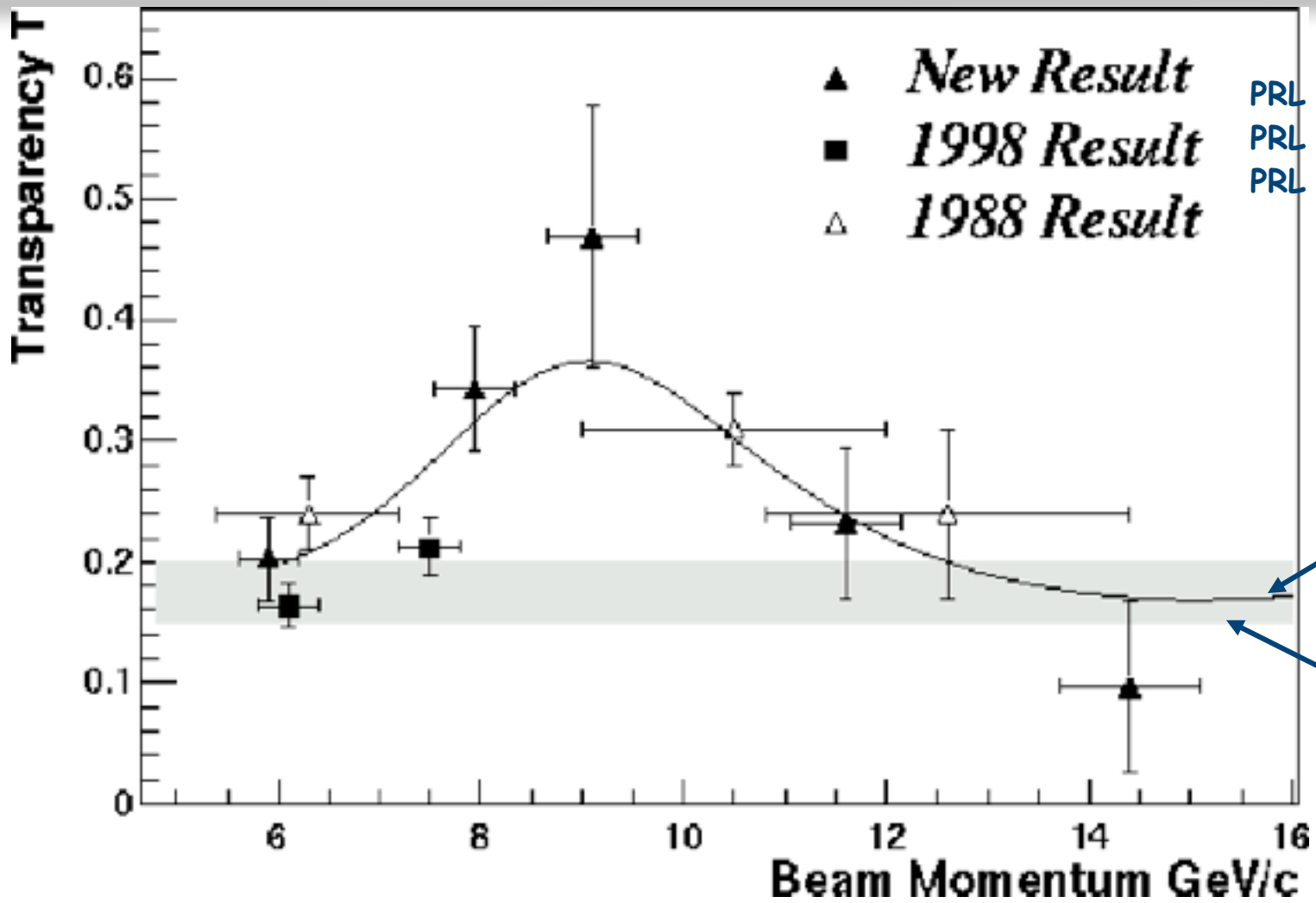
PRC 51, 3435 (95), 50, R1296 (94)

PRC 74, R062201 (2007)

Can help interpret the rise seen in the BNL A(p,2p) data at P_p = 6 - 9 GeV/c

2.9 5.1 7.3 9.6 P_p (GeV/c)

A(p, 2p) at Large C.M. Angles



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

Shaded band Glauber calculation

Nucleon vs Meson Transparency

- 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 mesons
- Formation length is ~ 10 fm at moderate Q^2 in mesons
- Onset of CT is directly related to the onset of factorization required for access to GPDs in deep exclusive meson production.

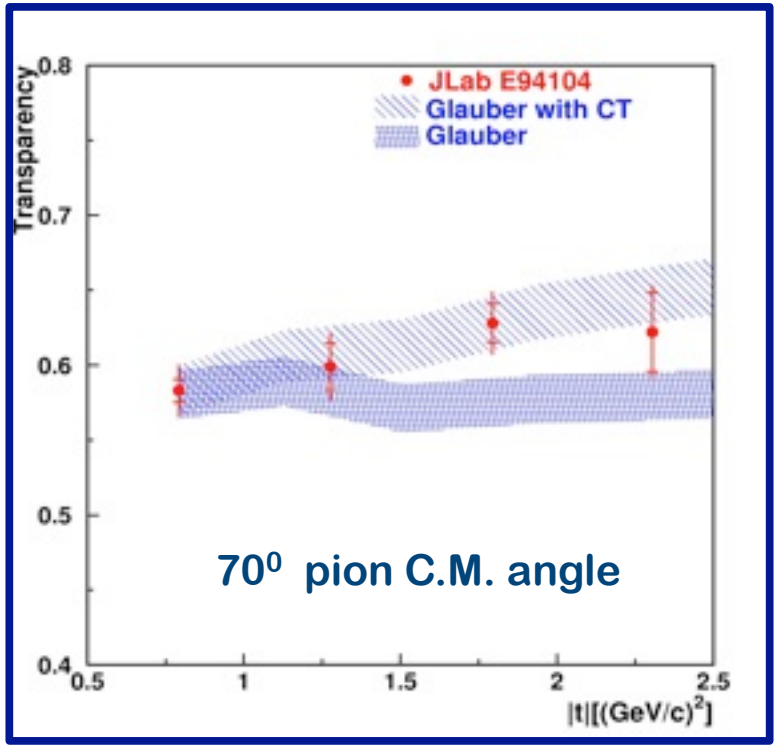
- Strikman, Frankfurt, Miller and Sargsian

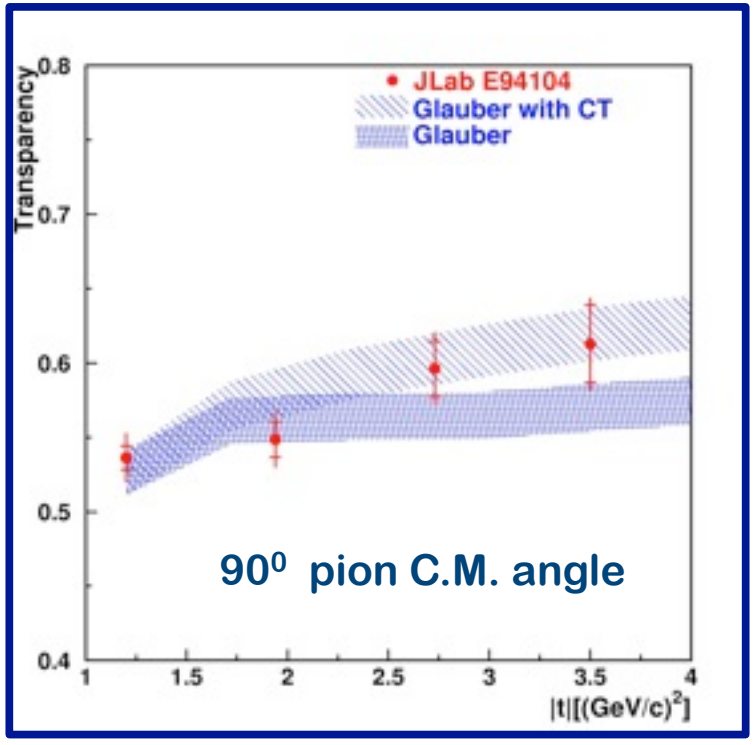
Pion Photoproduction $^4He(\gamma,\pi^- p)$

Positive hints from pion photoproduction in JLab Hall A

(H. Gao & R. Holt Spokespersons)

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



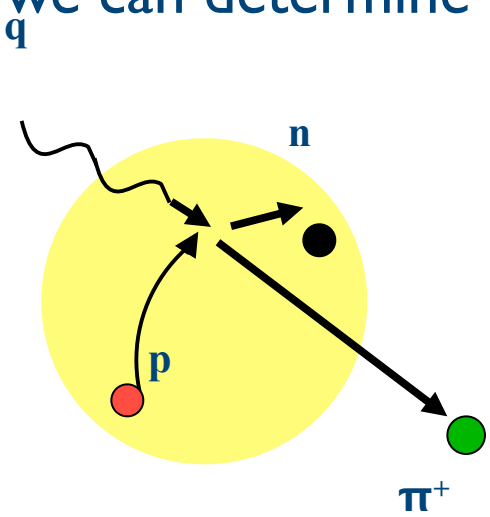


Deviations from Glauber !

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

Pion Electroproduction

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



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

$\Delta(E,p)$ = Spectral function for proton

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

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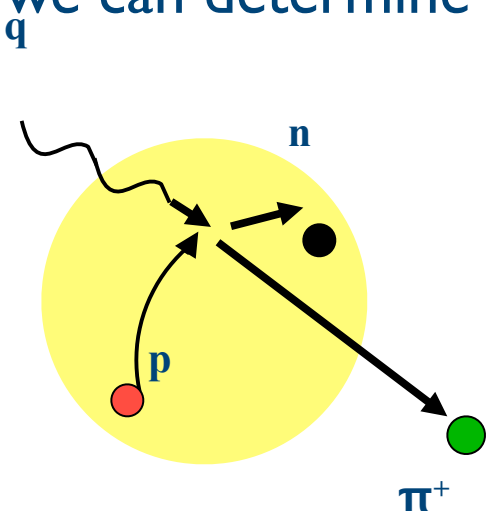

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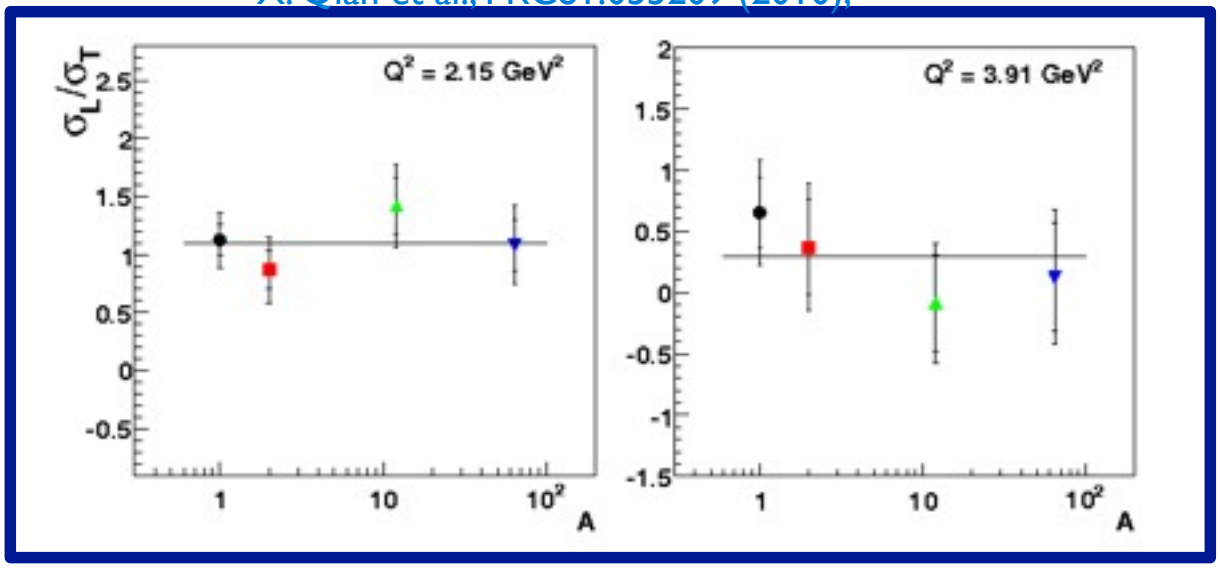
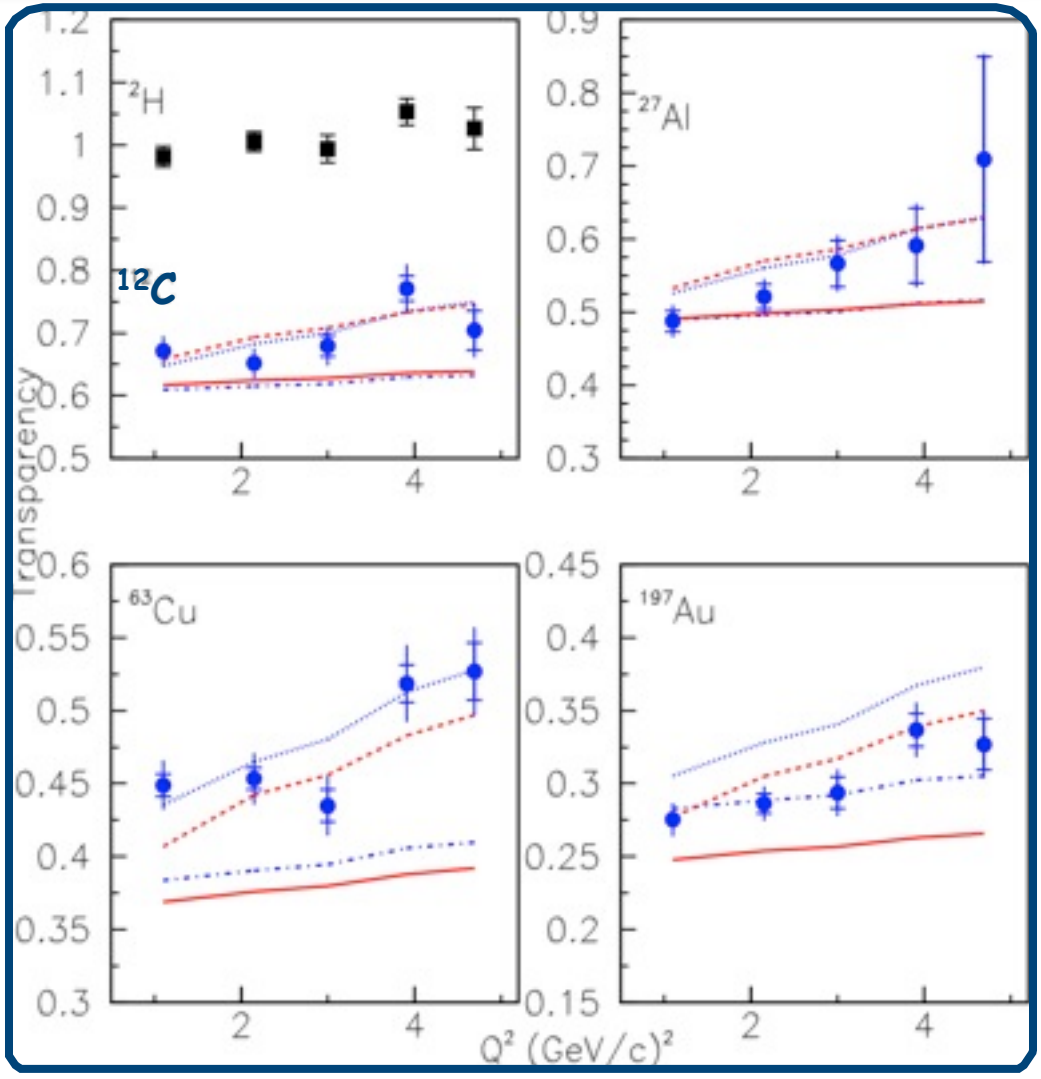
data well described via a MC simulation of a quasifree model including Fermi smearing, FSI and off-shell effects.

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

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



Pion Transparency



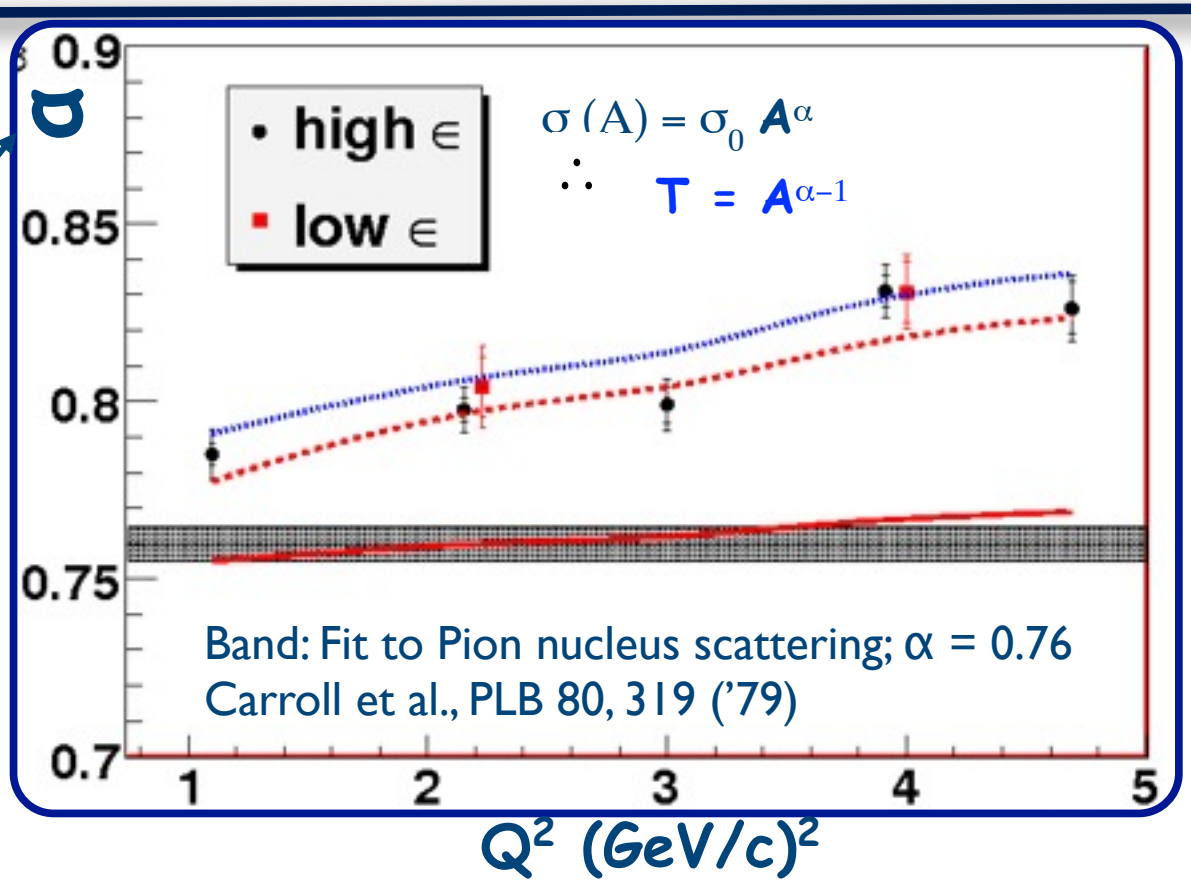
$$T = \frac{\sigma_A^{Expt} / \sigma_A^{Model}}{\sigma_p^{Expt} / \sigma_p^{Model}}$$

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)

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

Pion Transparency



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

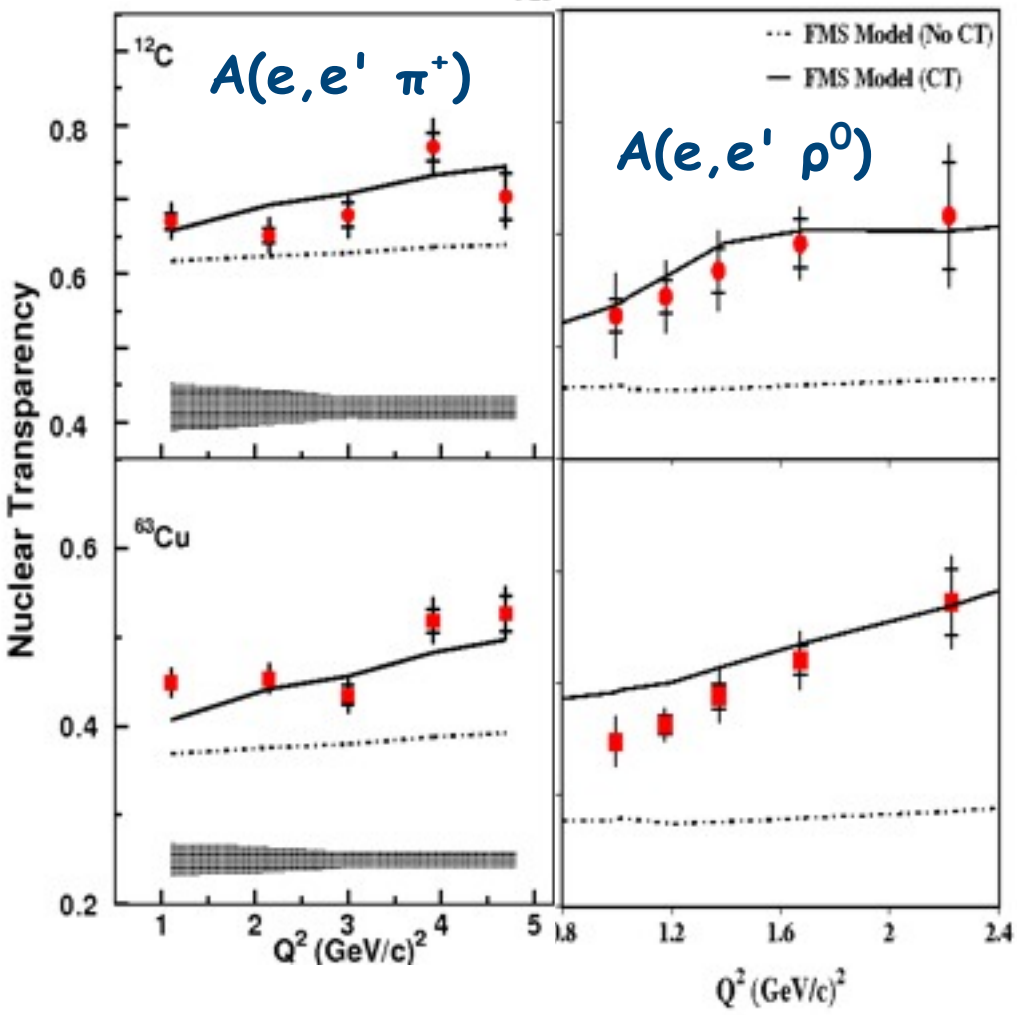
B. Clasie et al. PRL 90, 10001, (2007)
X. Qian et al., PRC81:055209 (2010),

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

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

The Onset of CT

JLab Experiments conclusively find the onset of CT

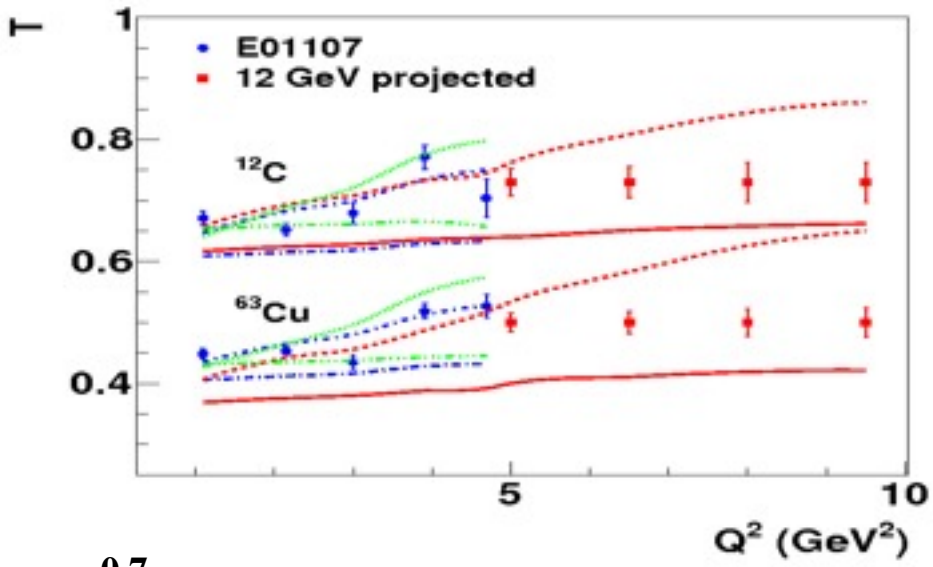


· Hall-C Experiment E01-107 pion electroproduction from nuclei found an enhancement in transparency with increasing Q^2 & A, consistent with the prediction of CT.
(X. Qian et al., PRC81:055209 (2010), B. Clasie et al, PRL99:242502 (2007))

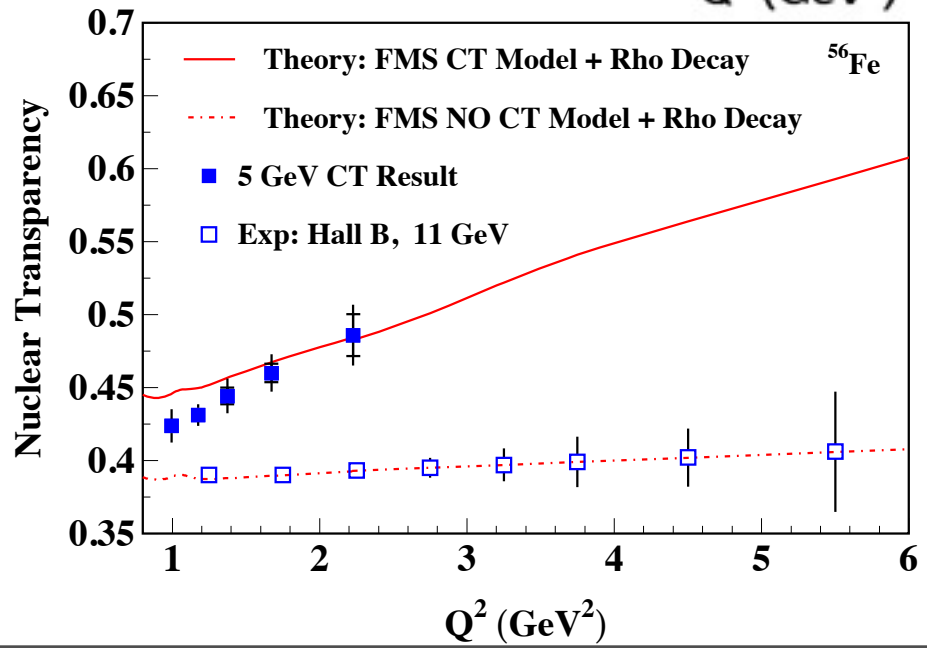
· CLAS Experiment E02-110 rho electroproduction from nuclei found a similar enhancement, consistent with the same predictions
(L. El-Fassi, et al., PLB 712, 326 (2012))

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

Meson Transparency @ 11 GeV



Both pion and rho transparency measurements will be extended at 11 GeV to the highest Q^2 accessible

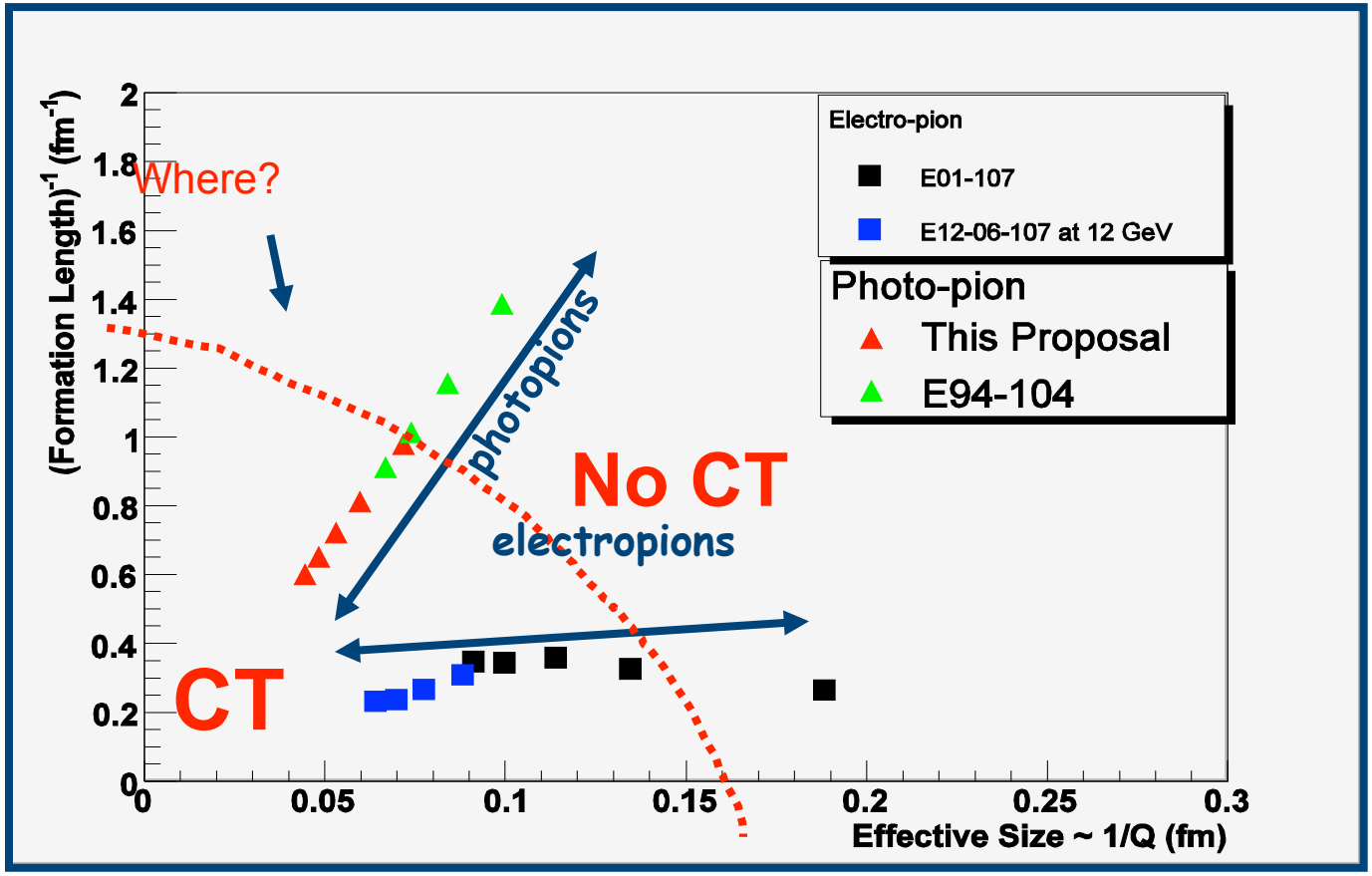


Will help confirm the onset of CT observed at 6 GeV

will verify the strict applicability of factorization theorems for meson electroproduction

Need Both Electro and Photo Pions

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



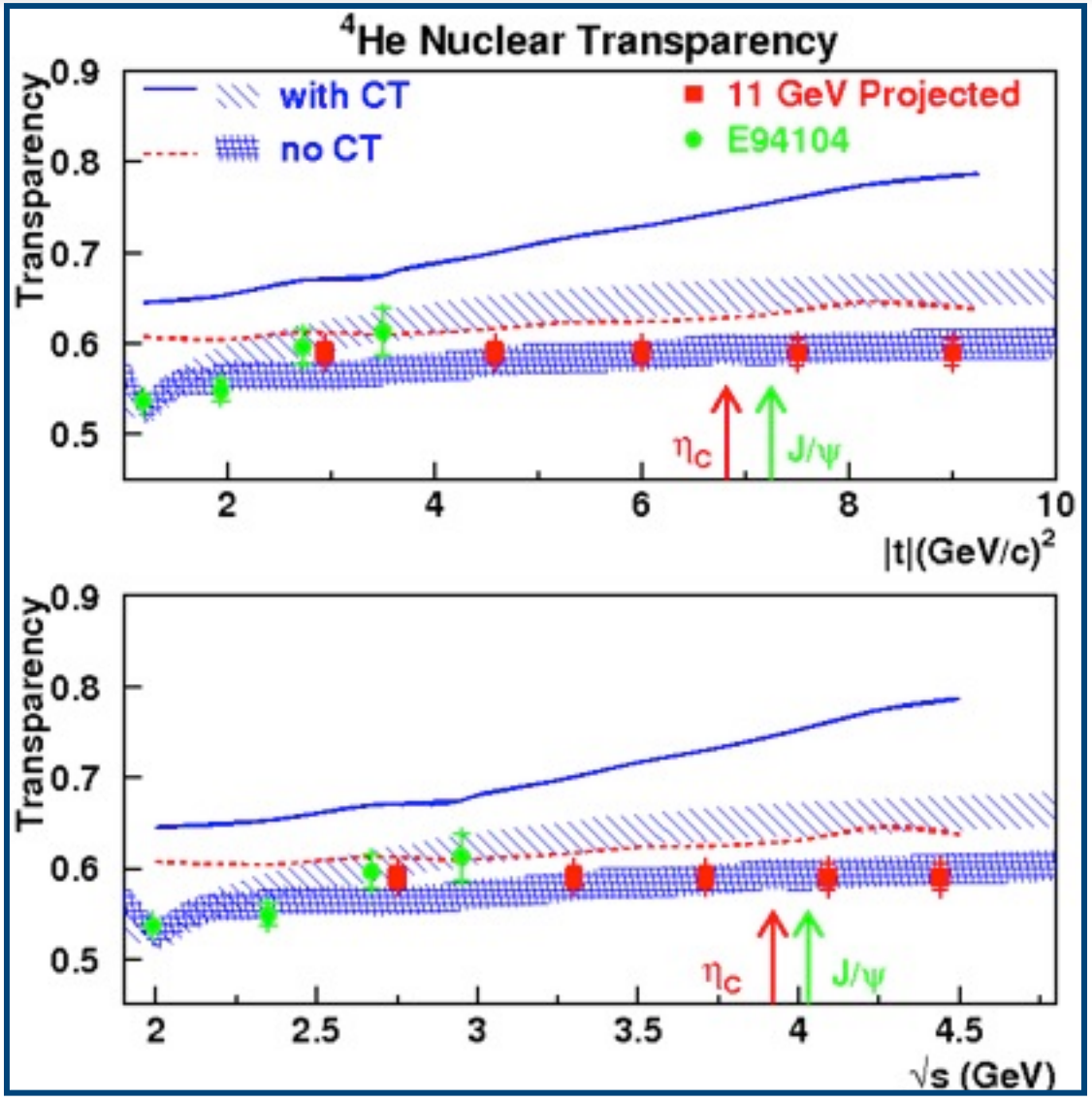
Effective Size ~ 1/Q

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

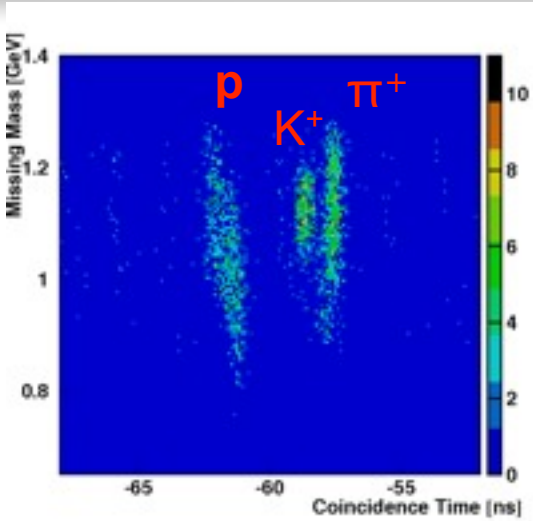
$^4He(\gamma,p\pi^-)$ @ 12 GeV

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

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

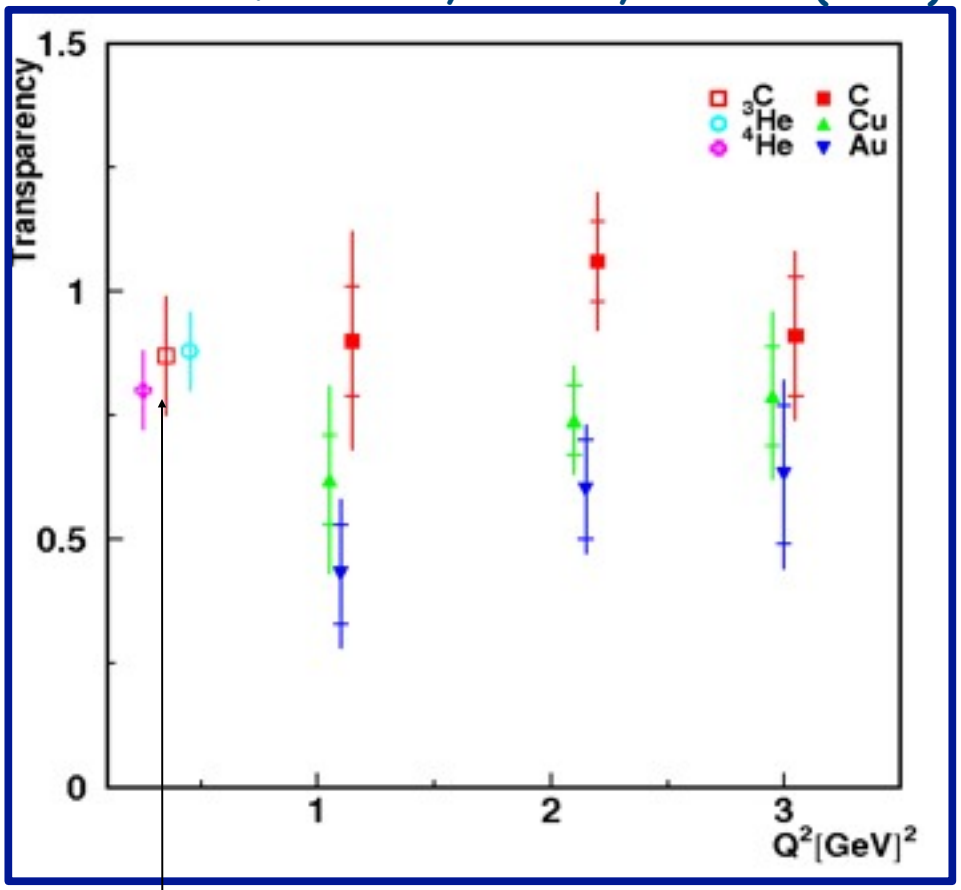


Kaon Transparency



No energy dependence within uncertainties

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



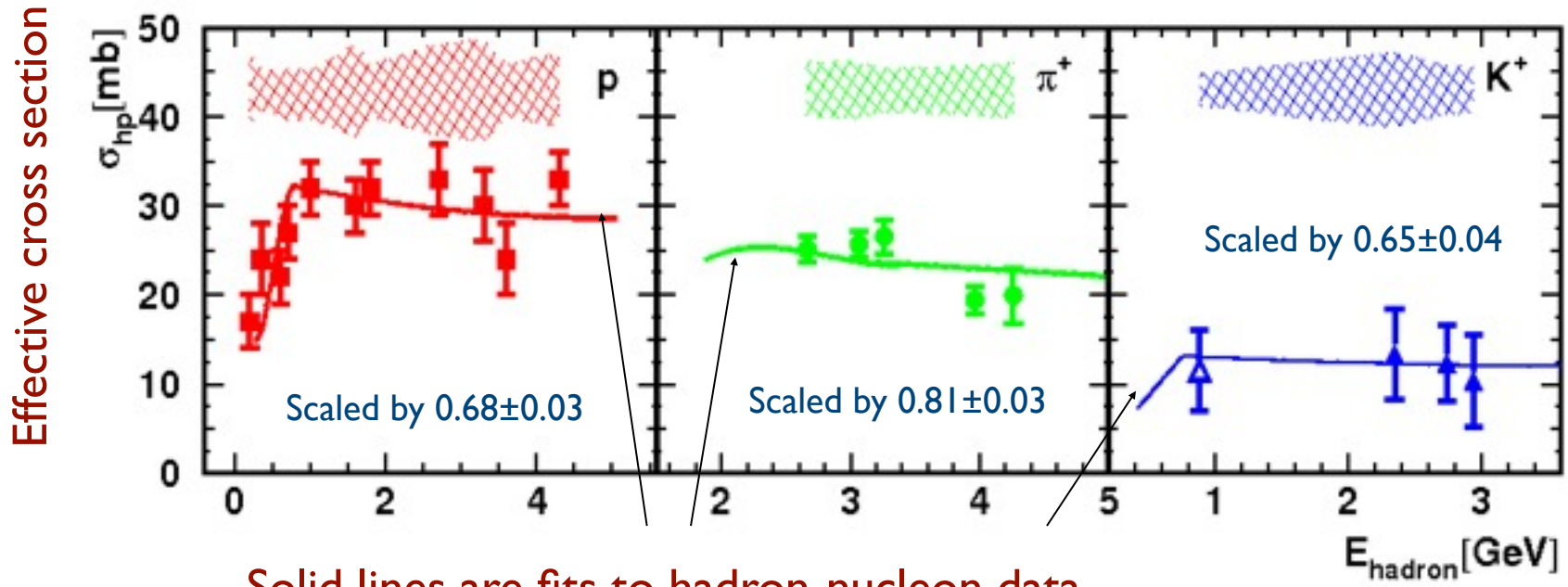
$$T = \frac{\sigma_A^{Expt} / \sigma_A^{Model}}{\sigma_D^{Expt} / \sigma_D^{Model}}$$

Compared with D to minimize impact of non-isoscaler effects

Earlier data on light nuclei
Dohrmann et al. PRC, 76, 054004 (2007)

Hadron Propagation in Medium

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



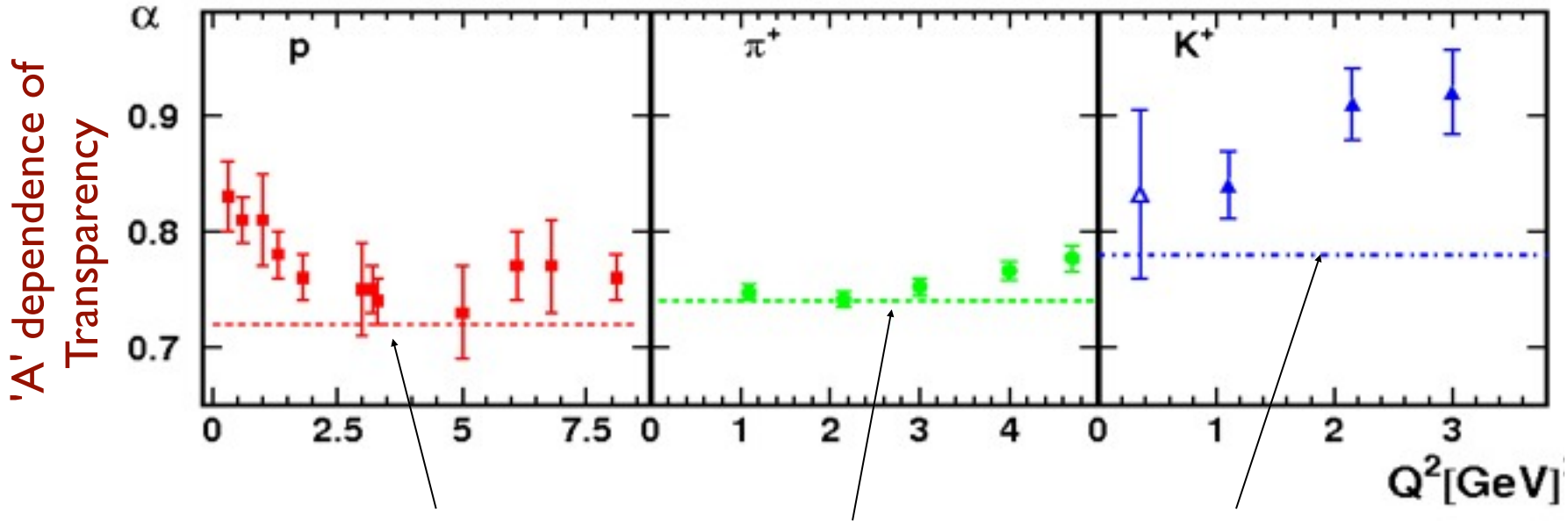
Solid lines are fits to hadron-nucleon data

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 Medium

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

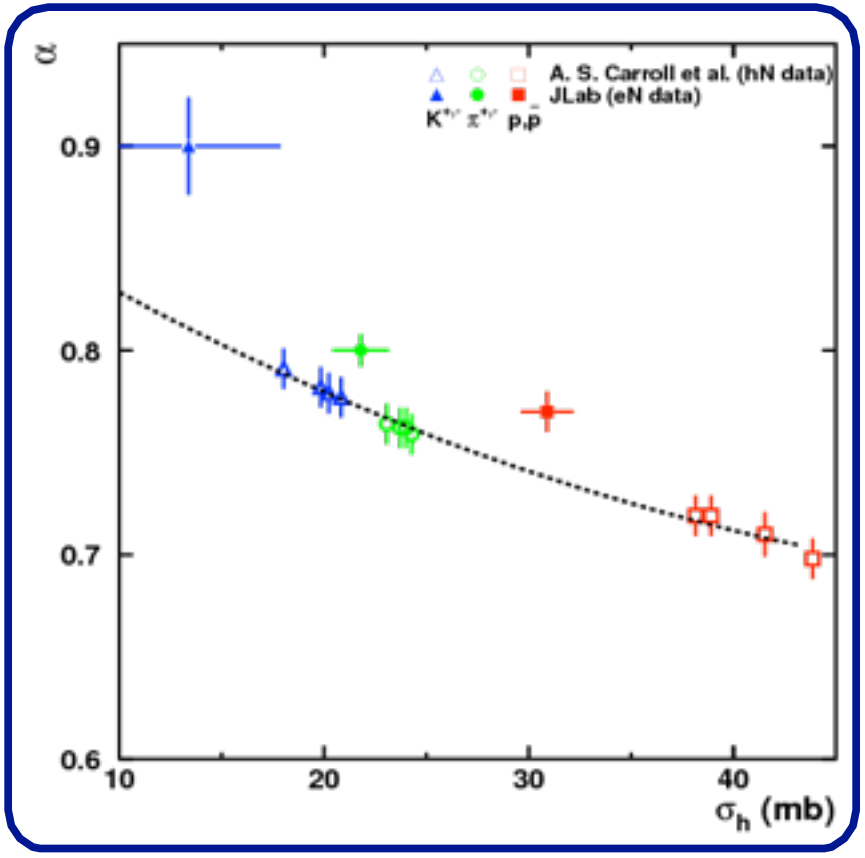


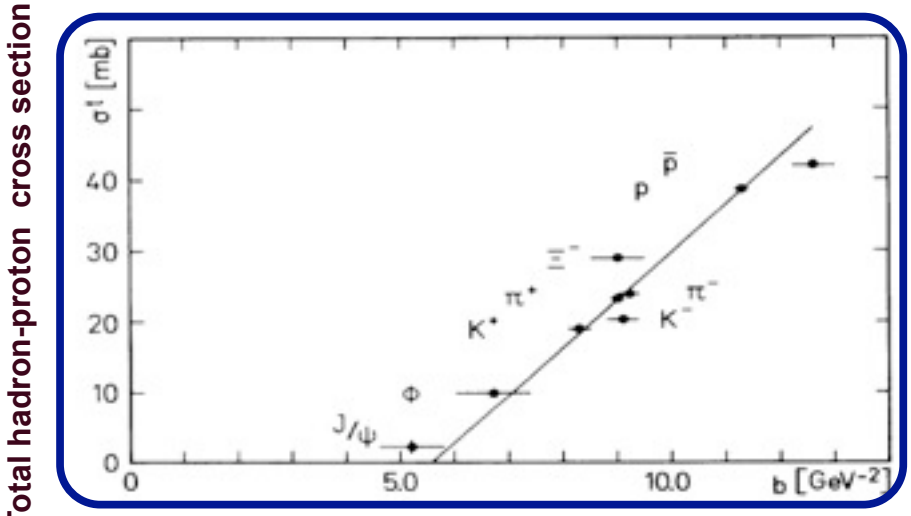
dashed lines are α values from hadron-nucleus data

'A' dependence of Transparency is quantified using $\sigma(A) = \sigma_0 A^{\alpha}$

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

Hadron Propagation in Medium





slope parameter b

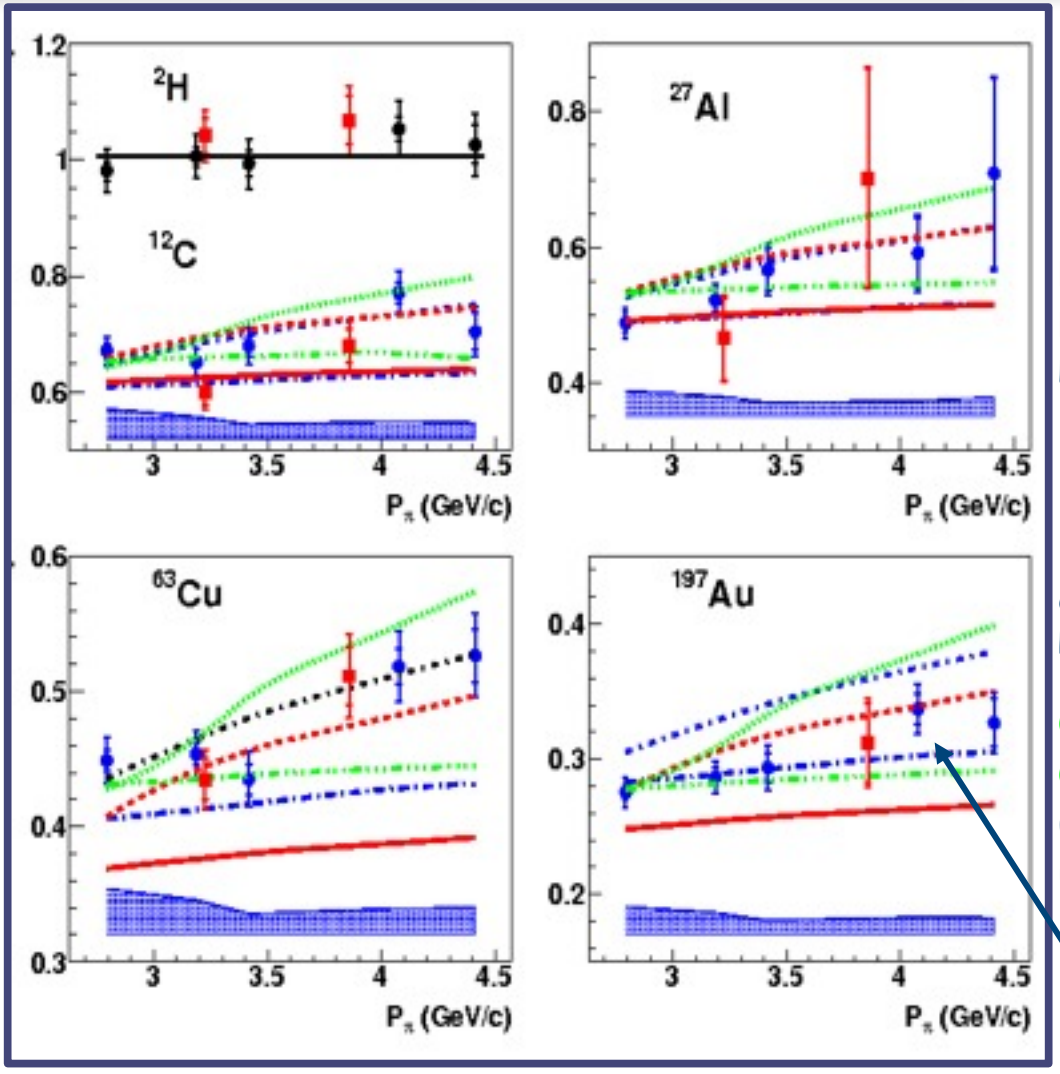
The electron scattering data does not seem to follow the simple scaling suggested by hadron data

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 provides an understanding of the propagation of highly energetic particles through the nuclear matter.
- Proton transparency data can be well described by conventional nuclear physics. These studies will be extended to higher energies at the upgraded JLab.
- The range in Q^2 covered by the A(e,e'p) experiment will have significant overlap with the BNL A(p,2p) experiment and will help interpret the rise in transparency observed in the BNL experiment.
- Experiments at JLab have conclusive shown the onset of CT in mesons. These meson electroproduction experiments will also be extended to higher energies at the upgraded JLab.
- Electron scattering results for protons, pions and kaons are different from previous hadron scattering results and the simple geometrical scaling with size seems to break down.

P_π Dependence of Pion Transparency



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

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.

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