Hadron Propagation Through Nuclear Matter

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EMMI Workshop on Cold Dense Nuclear Matter: from short range nuclear correlations to neutron stars

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Outline

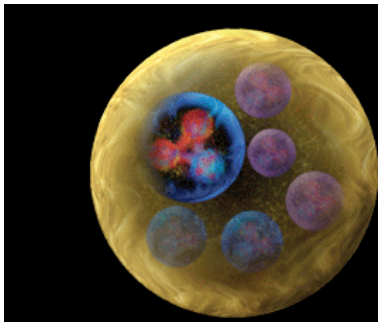
- Nuclear Transparency and Hadron Propagation
- Color Transparency & Small size configurations
- CT and soft-hard factorization/GPDs
- Experimental Status and New Opportunities
- Comparing proton, pion and kaon propagation
- Summary

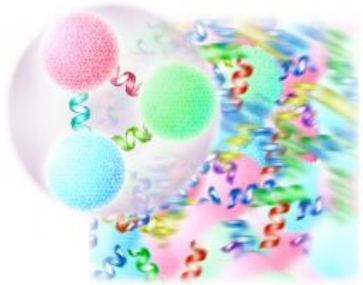
Hadron Propagation through nuclear matter is a key element of the nuclear many body problem.

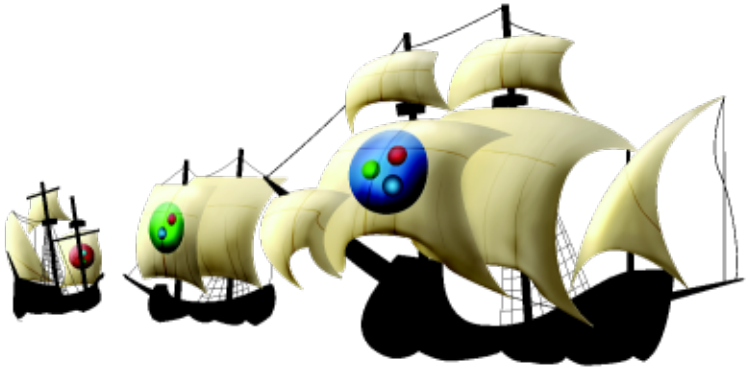
Needed for interpretation of experiments involving hadrons in the nuclear matter and searches for QCD in nuclei.

An active area of interest.

N. C. R. Makins et al. PRL 72, 1986 (1994) (cited 153 times);
K. Garrow et al. PRC 66, 044613 (2002) (cited 92 times);
B. Clasie et al. PRL (2007) (cited 59 times)
L. El-Fassi et al. PLB 712, 326 (2014) (cited 15 times)







At high energies it is dominated by **reduction of flux**, which is quantified by **Nuclear Transparency**.

Nuclear Transparency is the ratio of cross-sections for exclusive processes from nuclei to nucleons.

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

σ_0= free (nucleon) cross-section

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

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

α = 0.72 - 0.78,

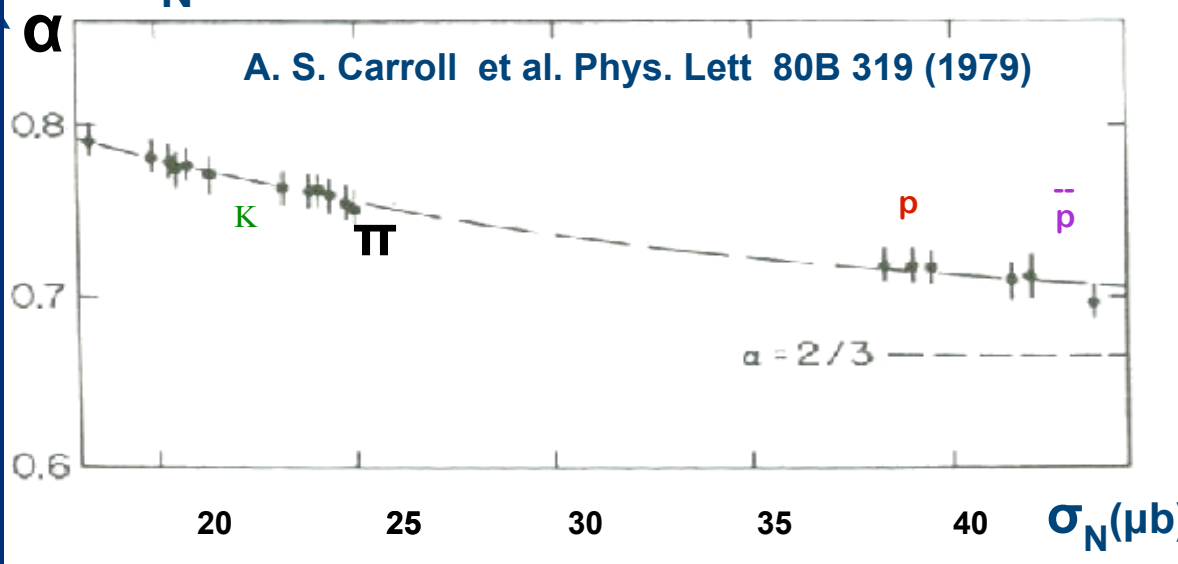
for π, K, p

Hadron momentum

60, 200, 250 GeV/c

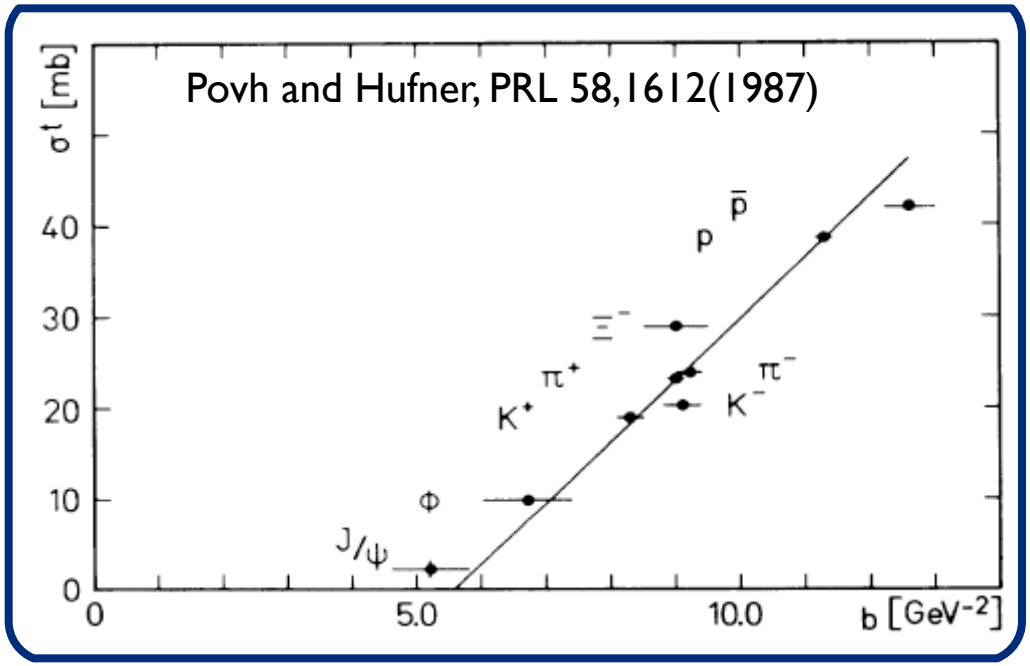
$$T = A^{\alpha-1}$$

σ_N Hadron– Nucleus total cross-section



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

The free cross-section scales linearly with size for wide range of hadrons.



Total hadron-proton cross section

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

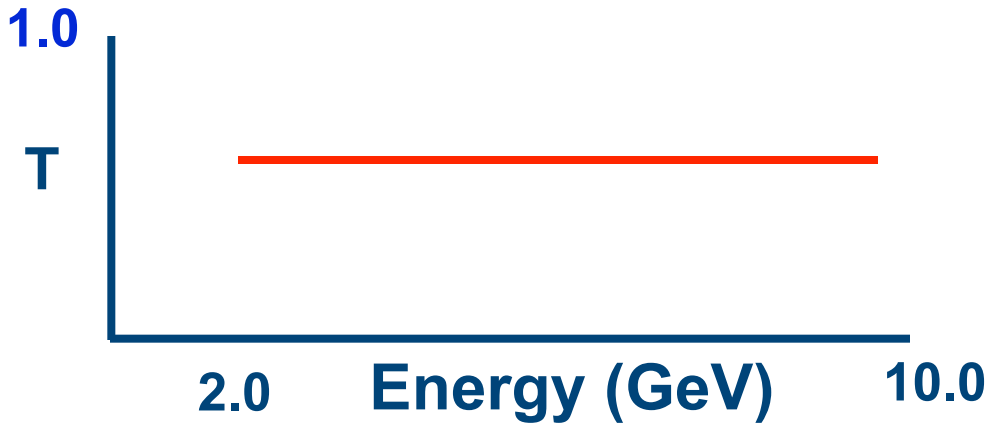
$$d\sigma/dt \propto e^{-bt}$$

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

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

Nuclear Transparency is expected to be energy independent.

Traditional NP calculations



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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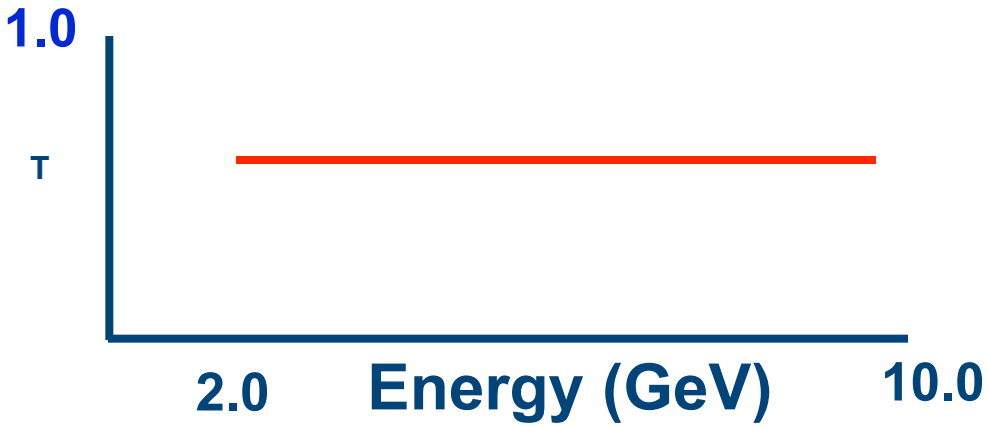
Traditional NP calculations



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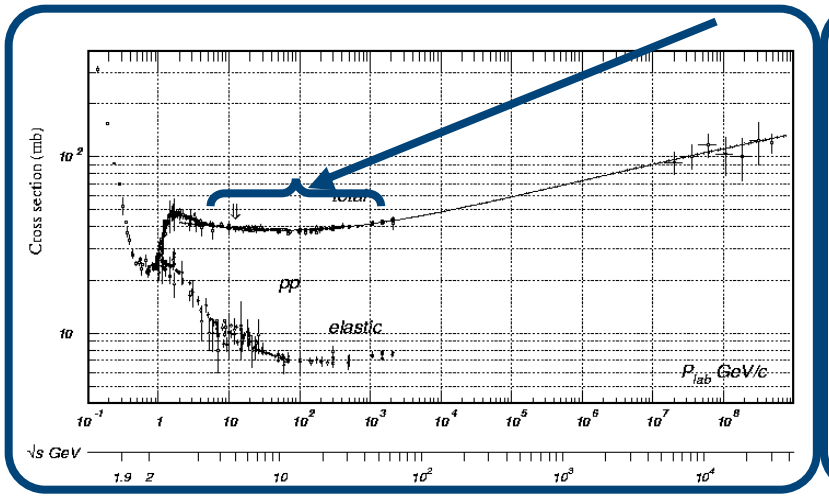
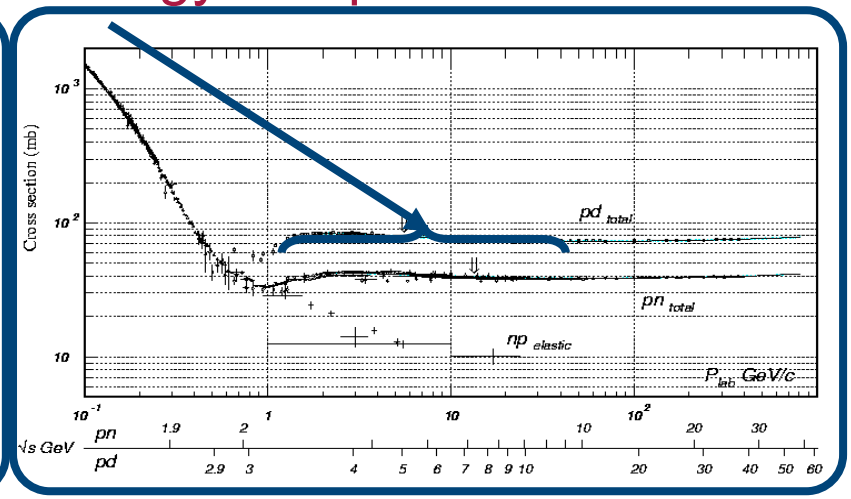


pp scatt. cross-section



pn scatt. cross-section

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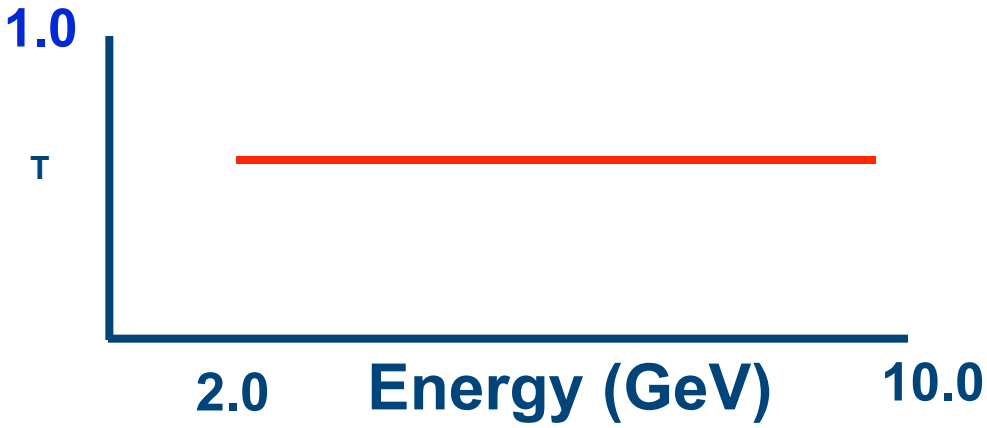

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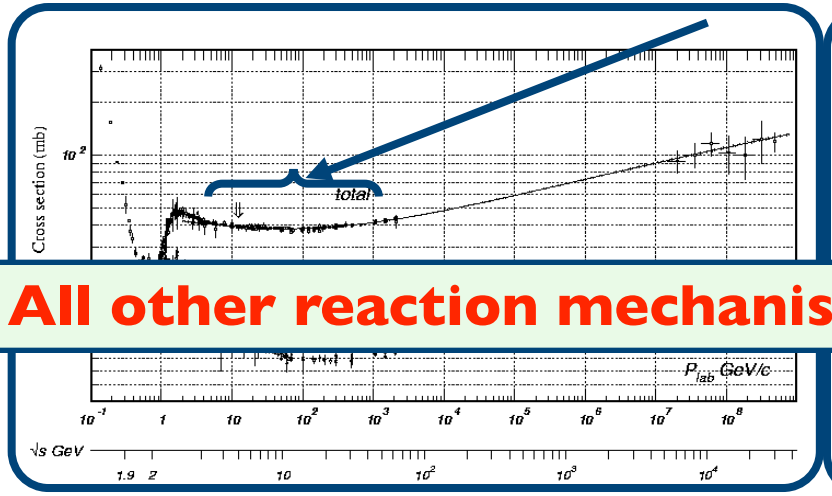
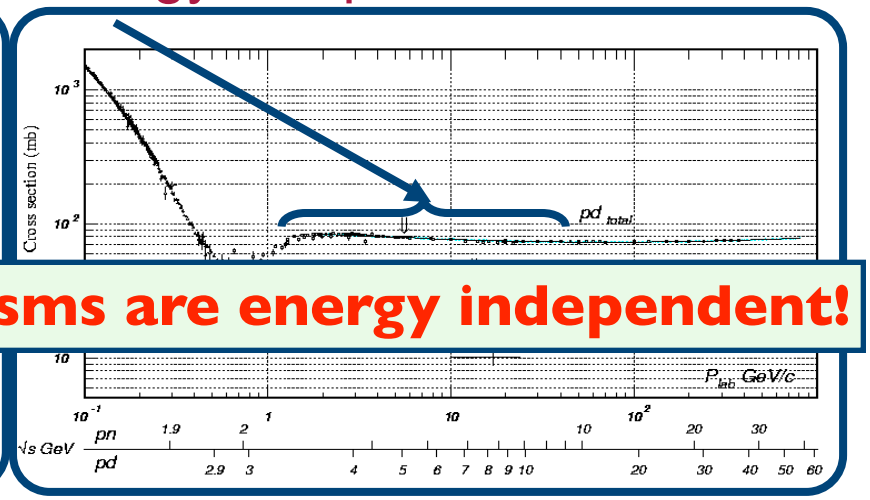


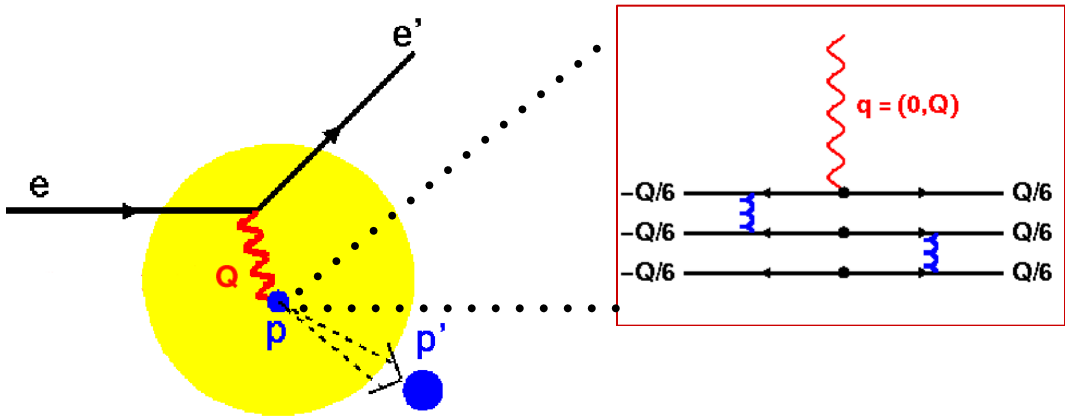
pp scatt. cross-section



pn scatt. cross-section

All other reaction mechanisms are energy independent!

Color Transparency is the result of “squeezing and freezing”.



At high momentum transfers, scattering takes place via selection of amplitudes characterized by small transverse size (PLC) - “squeezing”

The compact size is maintained while traversing the nuclear medium - “freezing”.

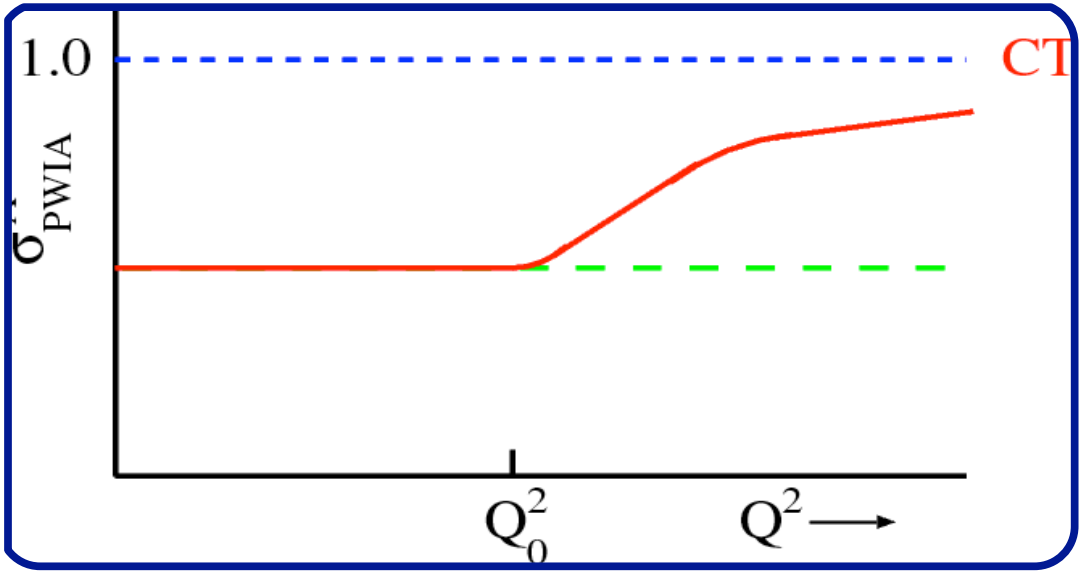
The PLC is ‘color screened’ - it passes undisturbed through the nuclear medium.

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

Color Transparency is a color coherence property of QCD.

CT leads to vanishing of the hadron-nucleon interaction for hadrons produced at high momentum transfers

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

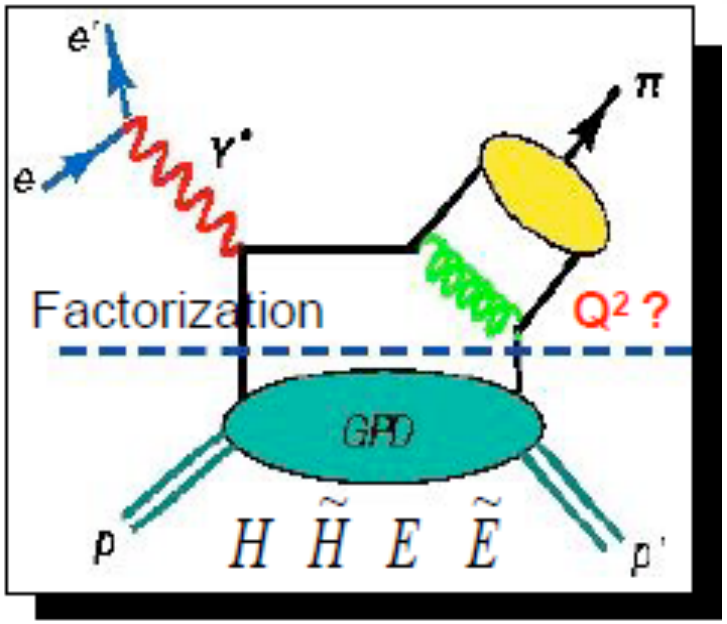


CT is well established at high energies (DIS data cannot be described without assuming CT).

The onset of CT is of primary interest.

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

CT is also connected to the new framework of GPDs developed in the last two decades.



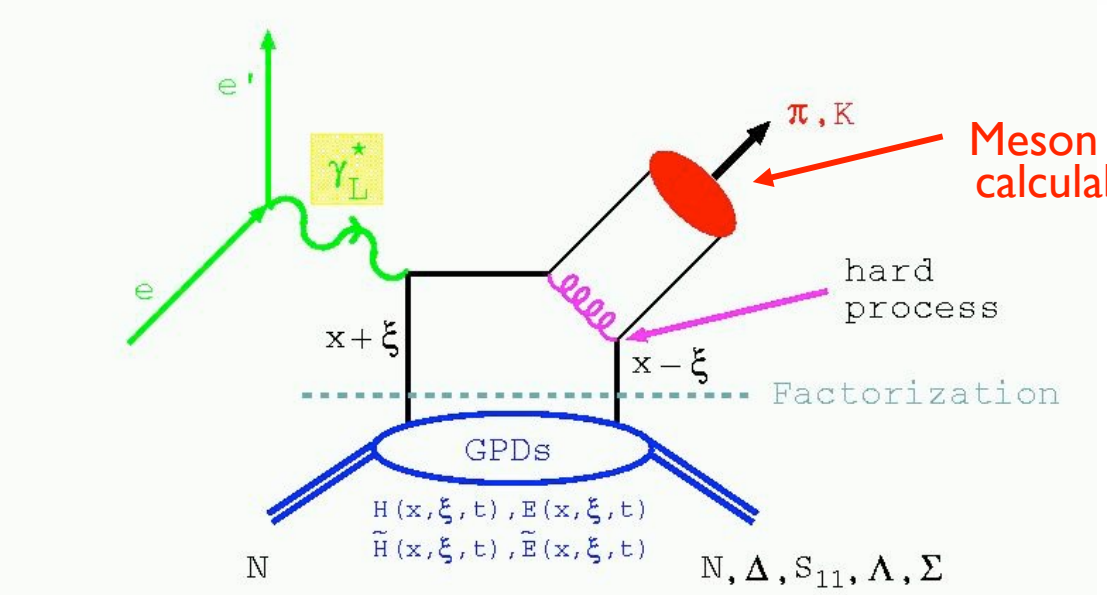
The new framework, assumes the dominance of the handbag mechanism.

-factorizes into a hard interaction with a single quark and a soft part parametrized as GPDs.

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

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

Factorization is not rigorously possible without the onset of CT



small size configurations (SSC/PLC) needed for factorization:

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

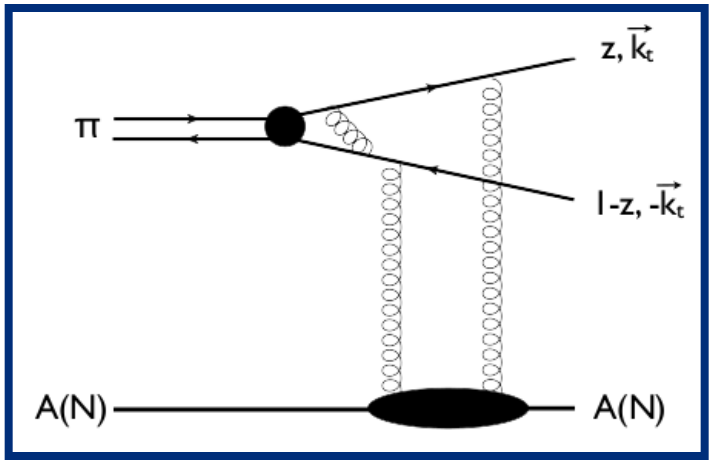
The onset of CT is a necessary (but not sufficient) conditions for factorization.

-Strikman, Frankfurt, Miller and Sargsian

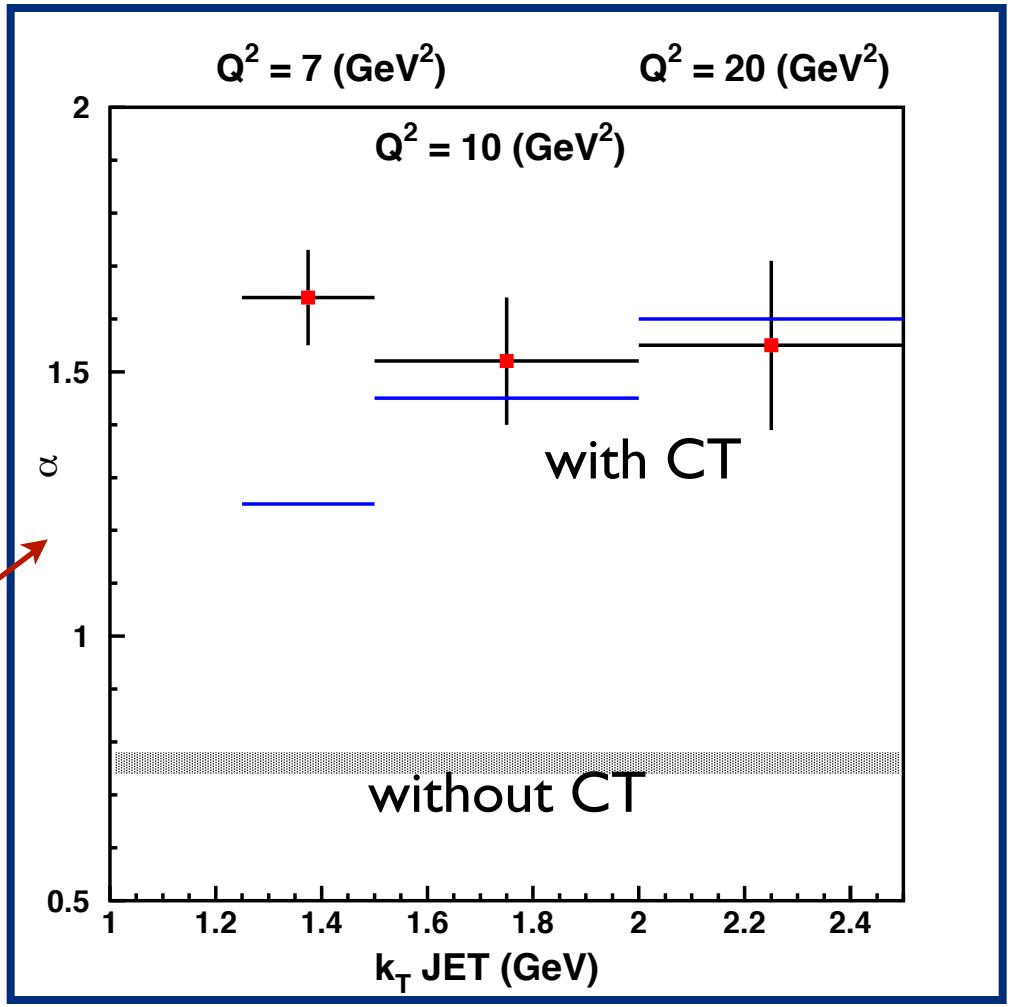
CT is well established at high energies.

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)

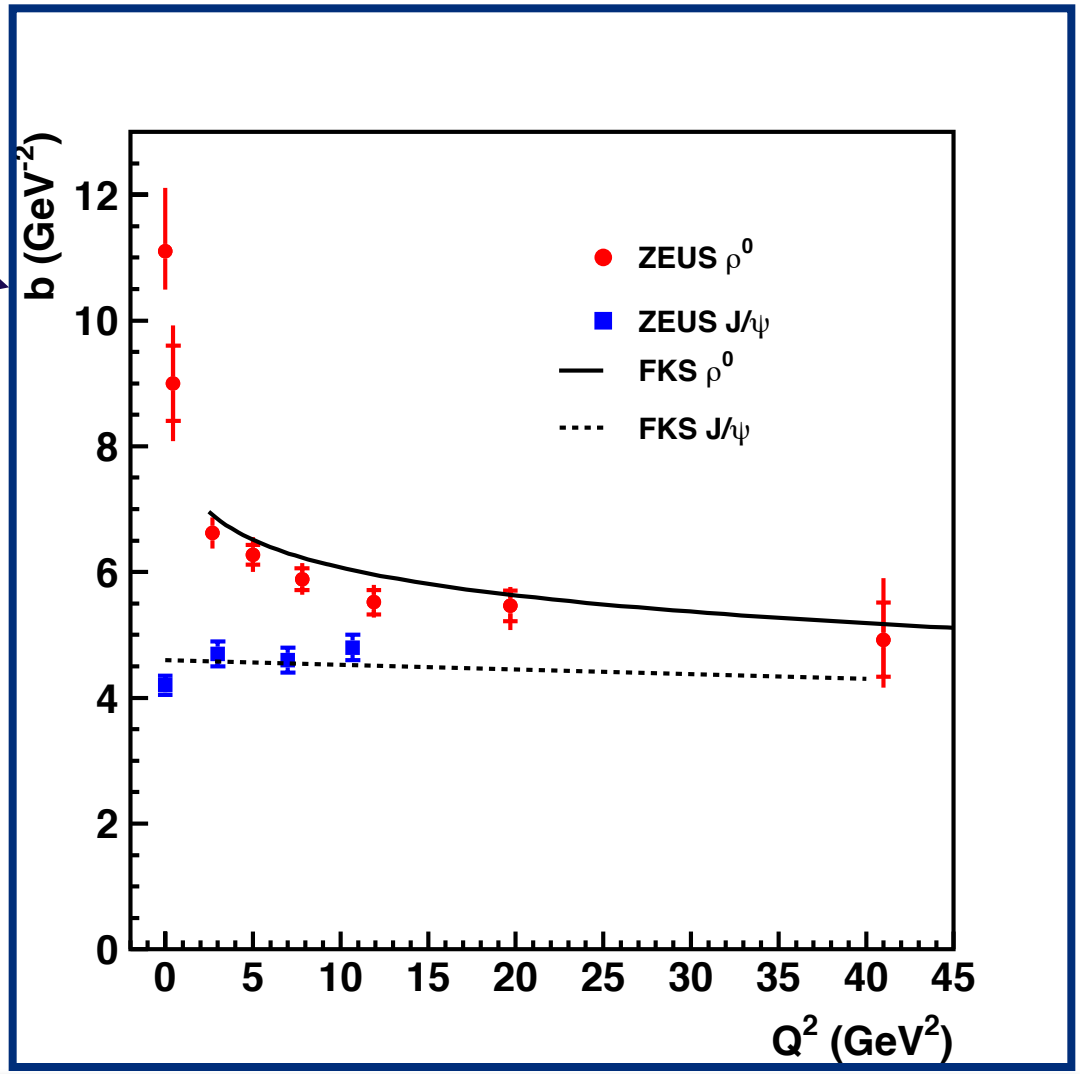
CT is well established at high energies.

Vector Meson production at large Q^2 at HERA

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

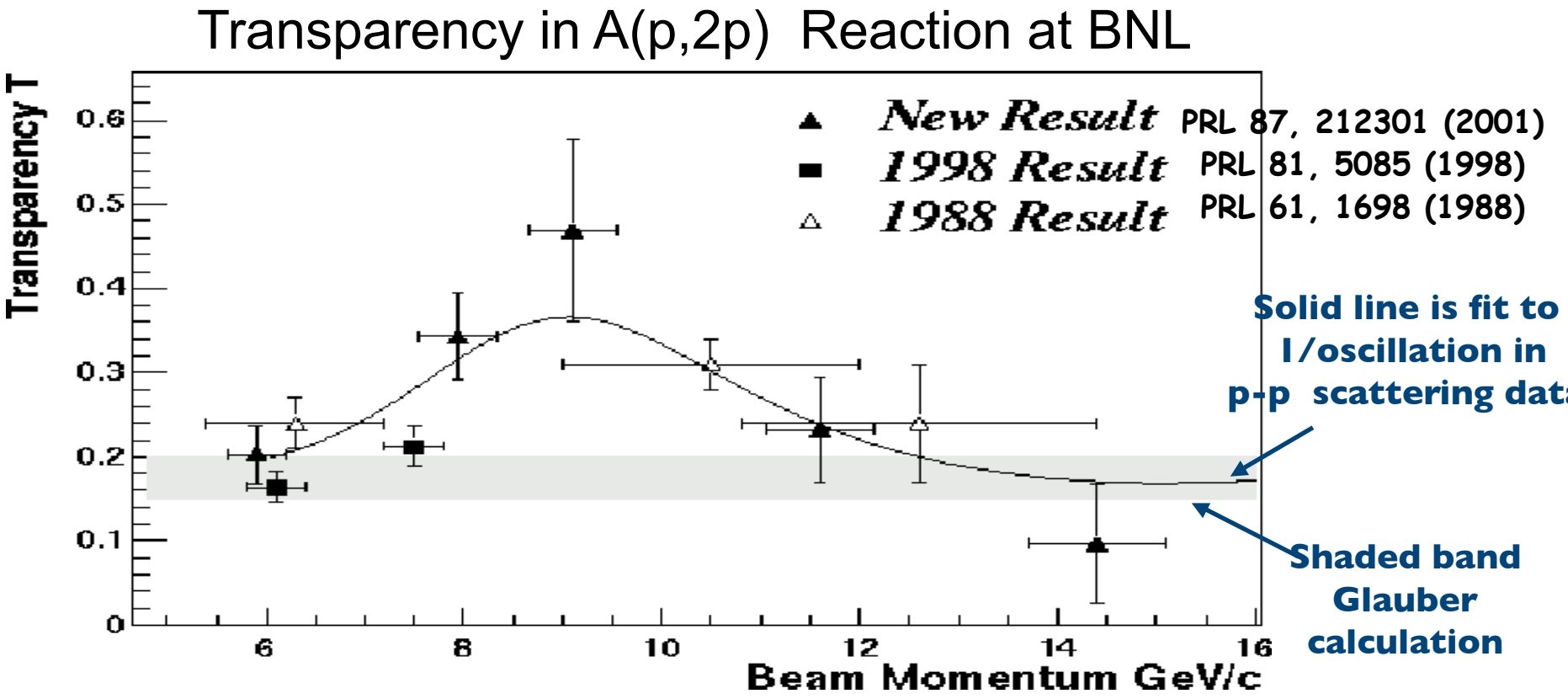
$$b = \frac{d}{dt}\ln\left(\frac{d\,\sigma^{el}_{hp}}{dt}\right) = \frac{1}{3}\left(R_h^2 + R_p^2\right)$$

Convergence of the t-slope of ρ and J/ψ electroproduction at large Q^2 predicted by the presence of small size qq-bar state



Evidence for CT at intermediate energies is a mixed bag.

First direct search for the onset of CT

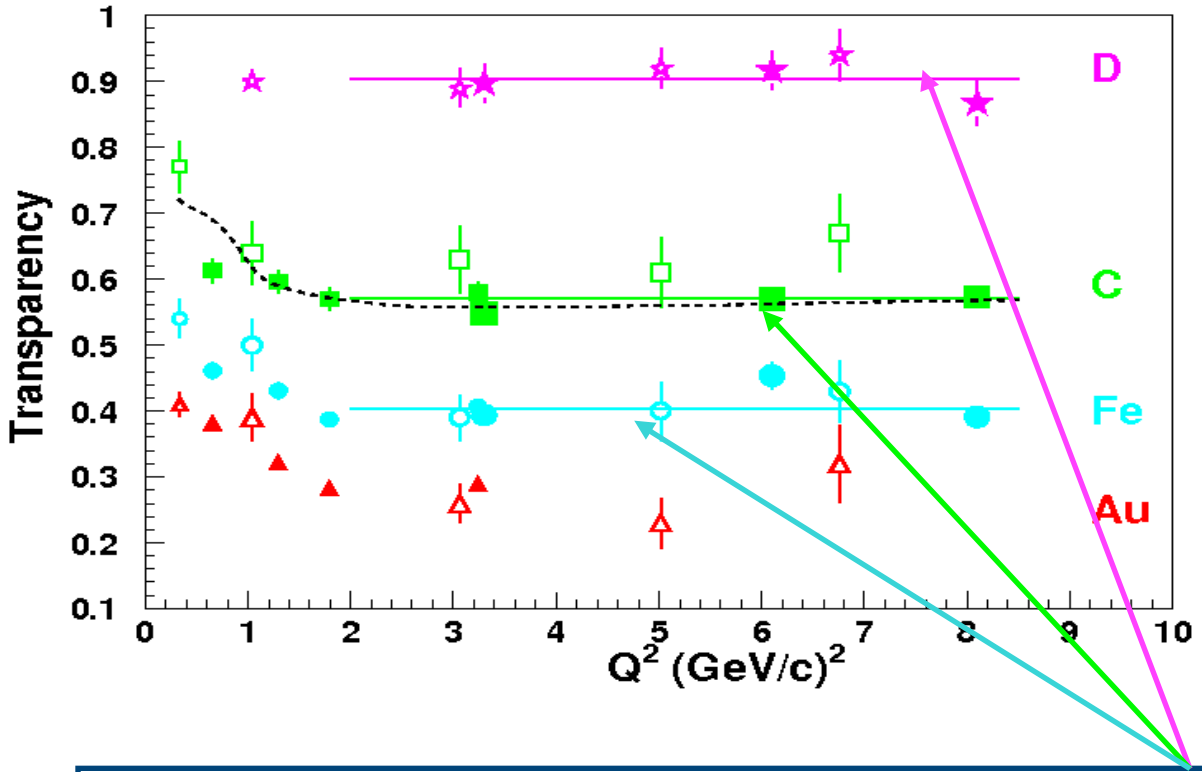


Results inconsistent with CT only. But can be explained by including additional mechanisms such as nuclear filtering or charm resonance states.

Evidence for CT at intermediate energies is a mixed bag.

A(e,e'p) results

Q^2 dependence consistent with standard nuclear physics calculations



Solid Pts – JLab

Open Pts -- other

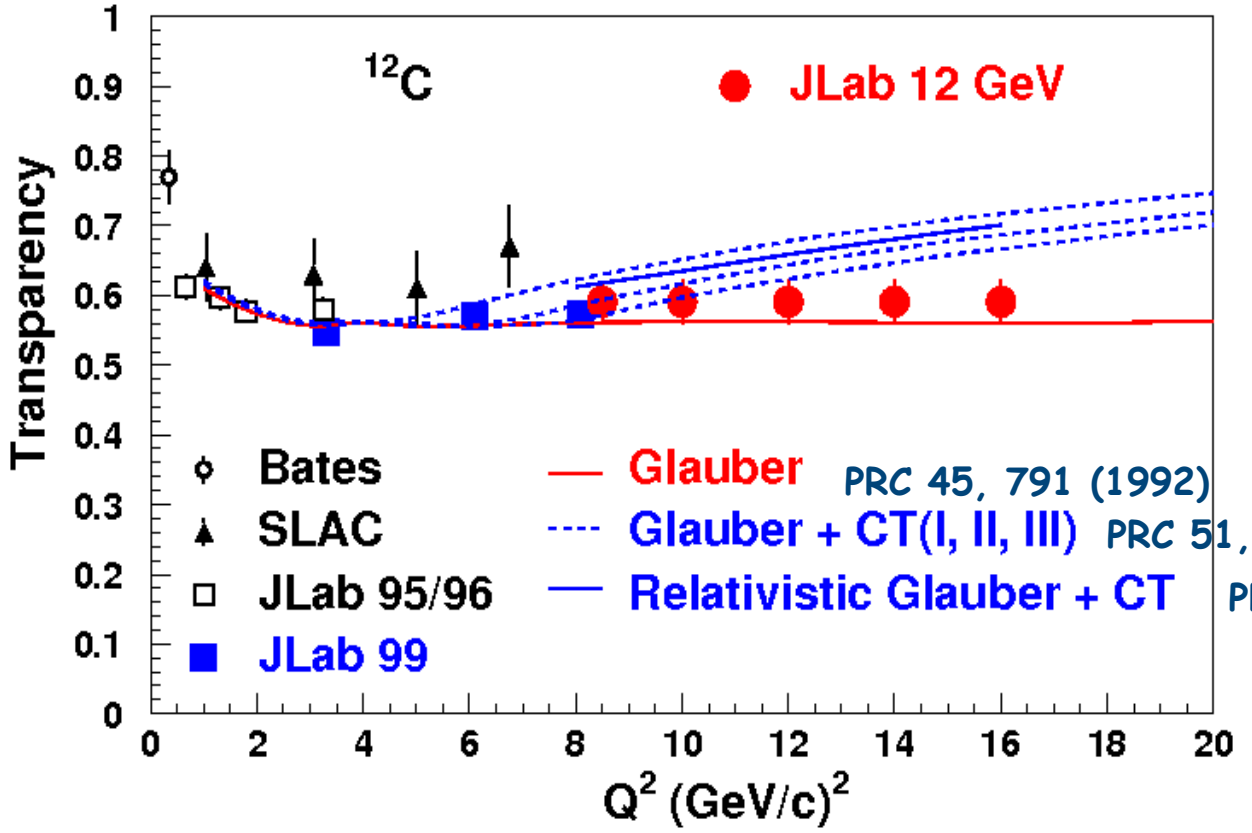
Constant value fit for Q^2 > 2 (GeV/c)^2 has χ^2 / df ~ 1

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

D. Abbott et al. PRL 80, 5072 (1998)
K. Garrow et al. PRC 66, 044613 (2002)

Upcoming experiments at JLab will provide answers.

A(e,e'p) @ 11 GeV JLab



PRC 45, 791 (1992)

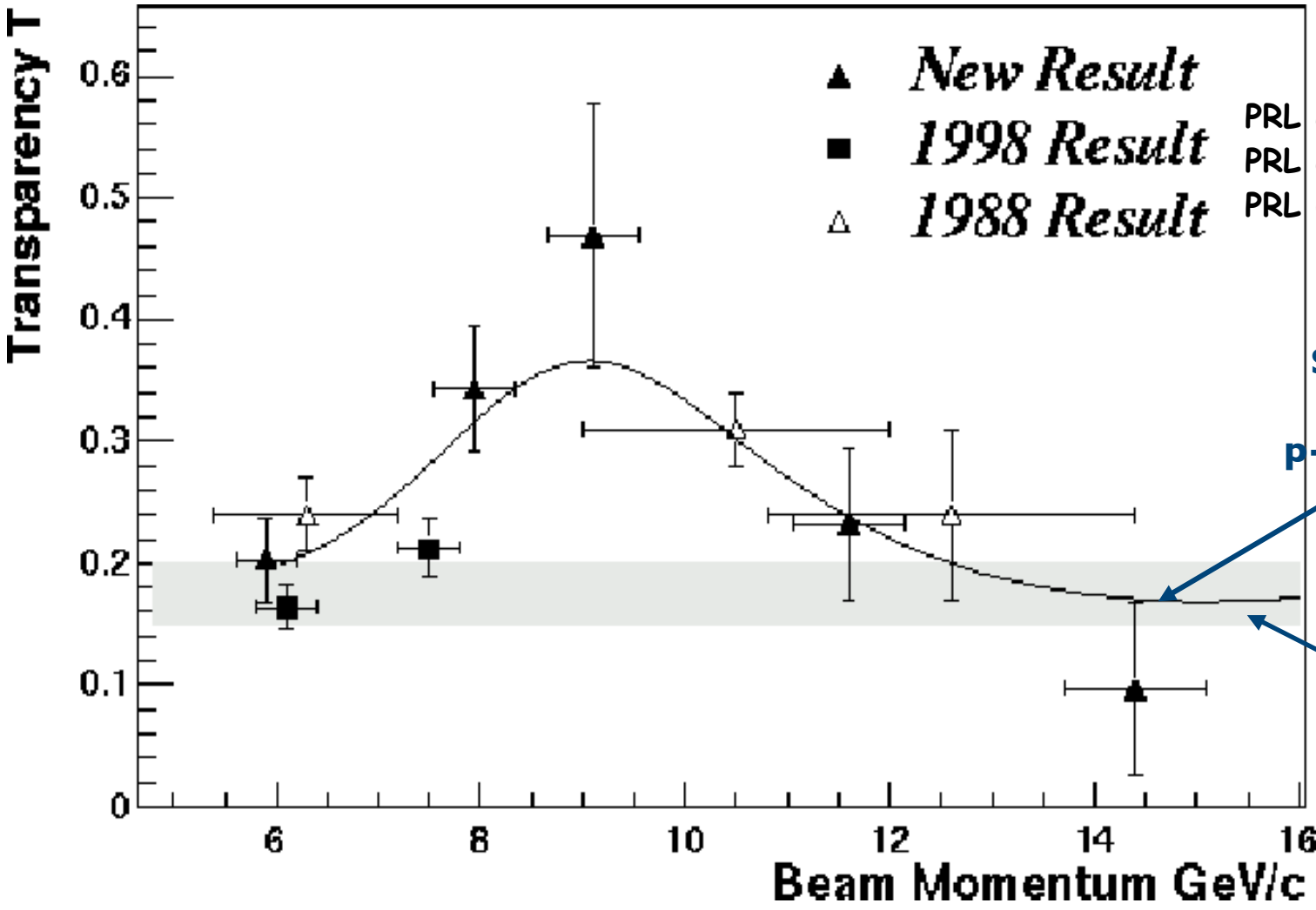
PRC 51, 3435 (95), 50, R1296 (94)

PRC 74, R062201 (2007)

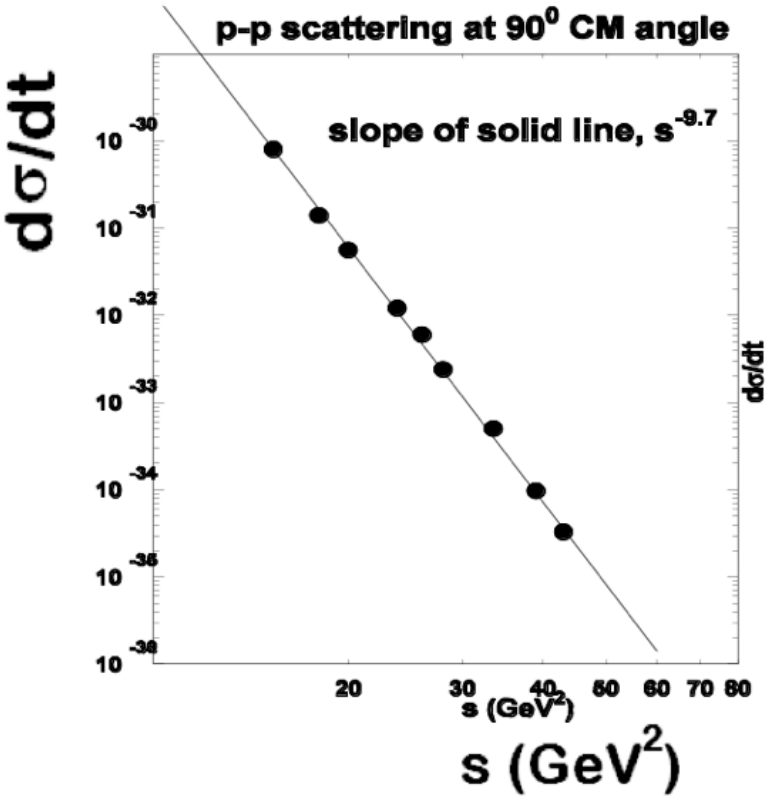
Can help interpret the rise seen in the BNL A(p,2p) data at P_p = 6 - 9 GeV/c

2.9 5.1 7.3 9.6 P_p (GeV/c)

(p,2p) results are related to oscillations in p-p cross sections.

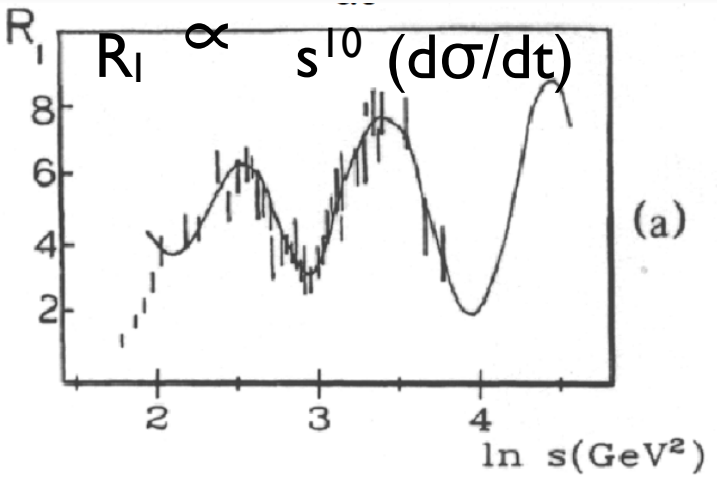


Oscillations in p-p cross sections with energy is well known.

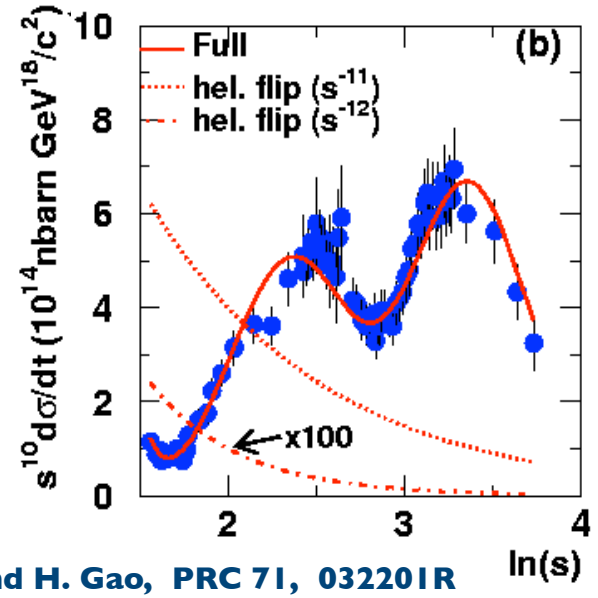


quark counting rule predicts $\frac{d\sigma}{dt} \propto s^{-10}$

data from Landshoff and Polkinghorne

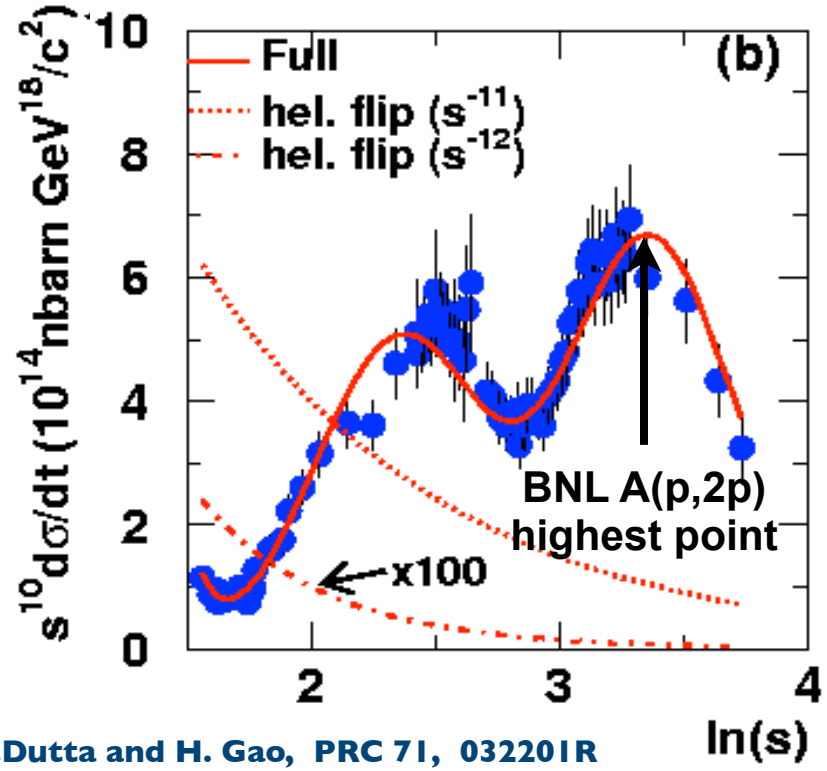


J. P. Ralston and B. Pire, PRL 61, 1823 (1988)



D.Dutta and H. Gao, PRC 71, 032201R

Transparency measurements with proton/anti-protons should be extended.

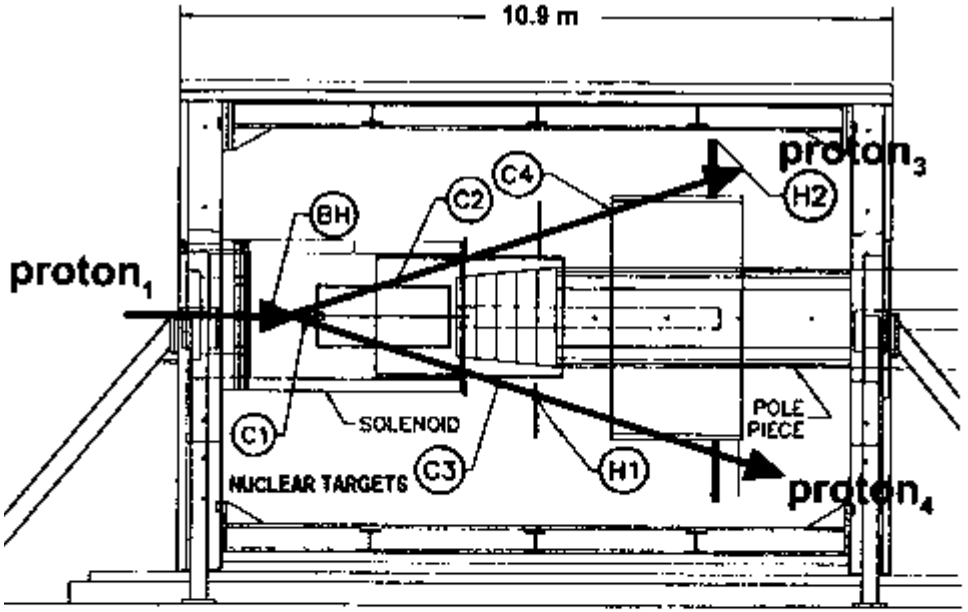


D.Dutta and H. Gao, PRC 71, 032201R

Experiment may need
a solenoid spectrometer
similar to E850 (EVA) at BNL

It is possible to extend measurement up to the highest available p-p data at 90^0 C.M. angle

Complementary to JLab experiment and essential for unambiguous understanding of A(p,2p) and A(e,e'p) data



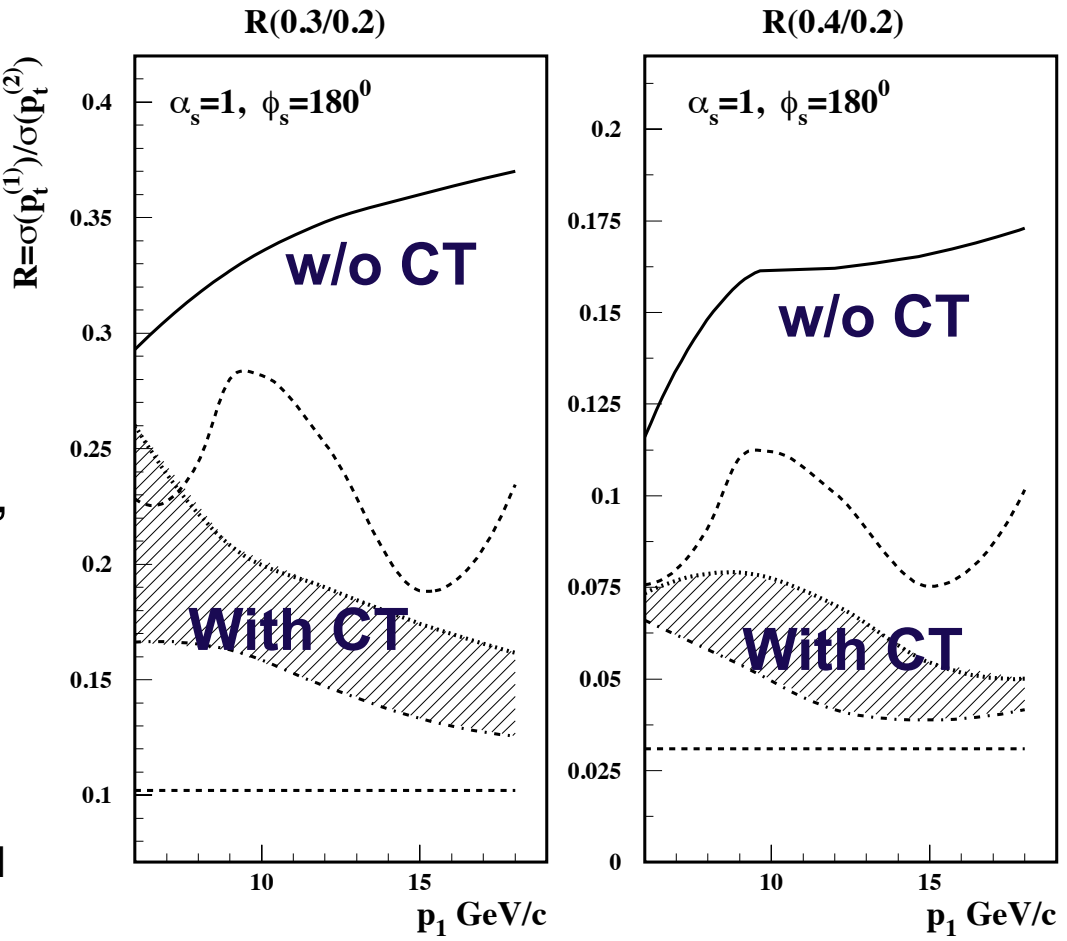
There are additional new observables for proton induced reactions.

Mapping re-scattering in hard exclusive reactions on ^2H

$p + {}^2H \rightarrow p + p + n$ (slow)

$\alpha_s/2$ = fraction of the deuteron momentum carried by the spectator neutron

Ratio of cross section at two different transverse momentum, P_t of the scattered proton



L. Frankfurt, E. Piasetzky, M. Sargsian and M. Strikman, PRC 56, 2752 (1997)

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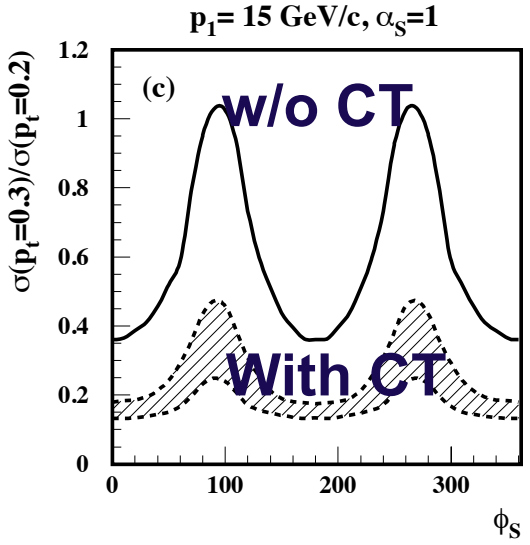
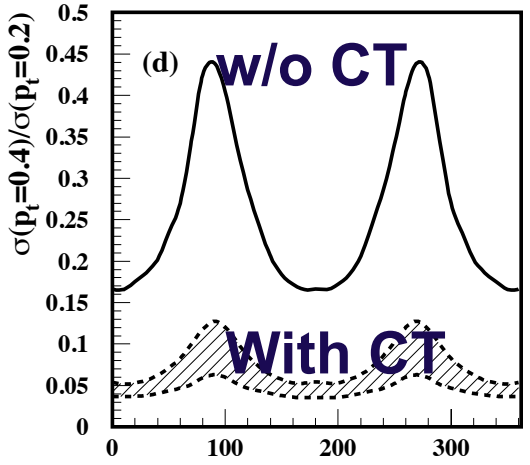
Requires high resolution spectrometer for the fast protons and pion veto.

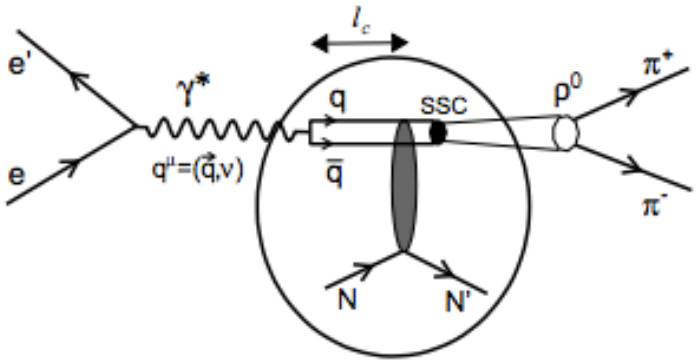




L. Frankfurt, E. Piasetzky, M. Sargsian and M. Strikman PRC 56, 2752 (1997)

ϕ_s = spectator azimuthal angle

CT is relatively easier to find with mesons.



Small size configurations are more probable in 2 quark system such as pions than in protons.

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

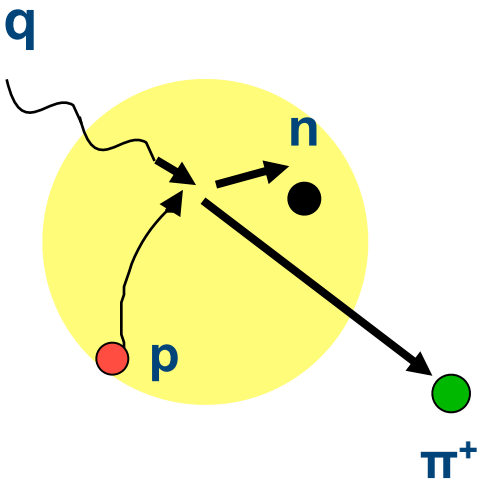
Onset of CT expected at lower Q^2 in mesons

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

Electroproduction of π^+ from a nucleus is similar to electroproduction of protons.



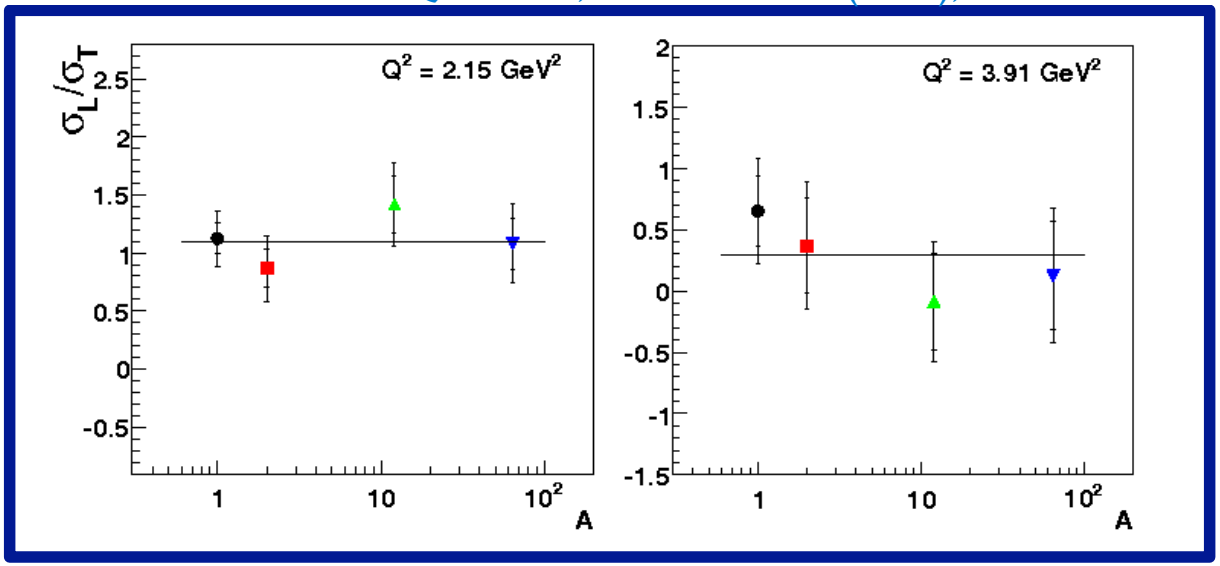
$$\sigma_{A(e,e'\pi^+)X} = \sigma_{p(e,e'\pi^+)n} \otimes \Delta(E,p)$$

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

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

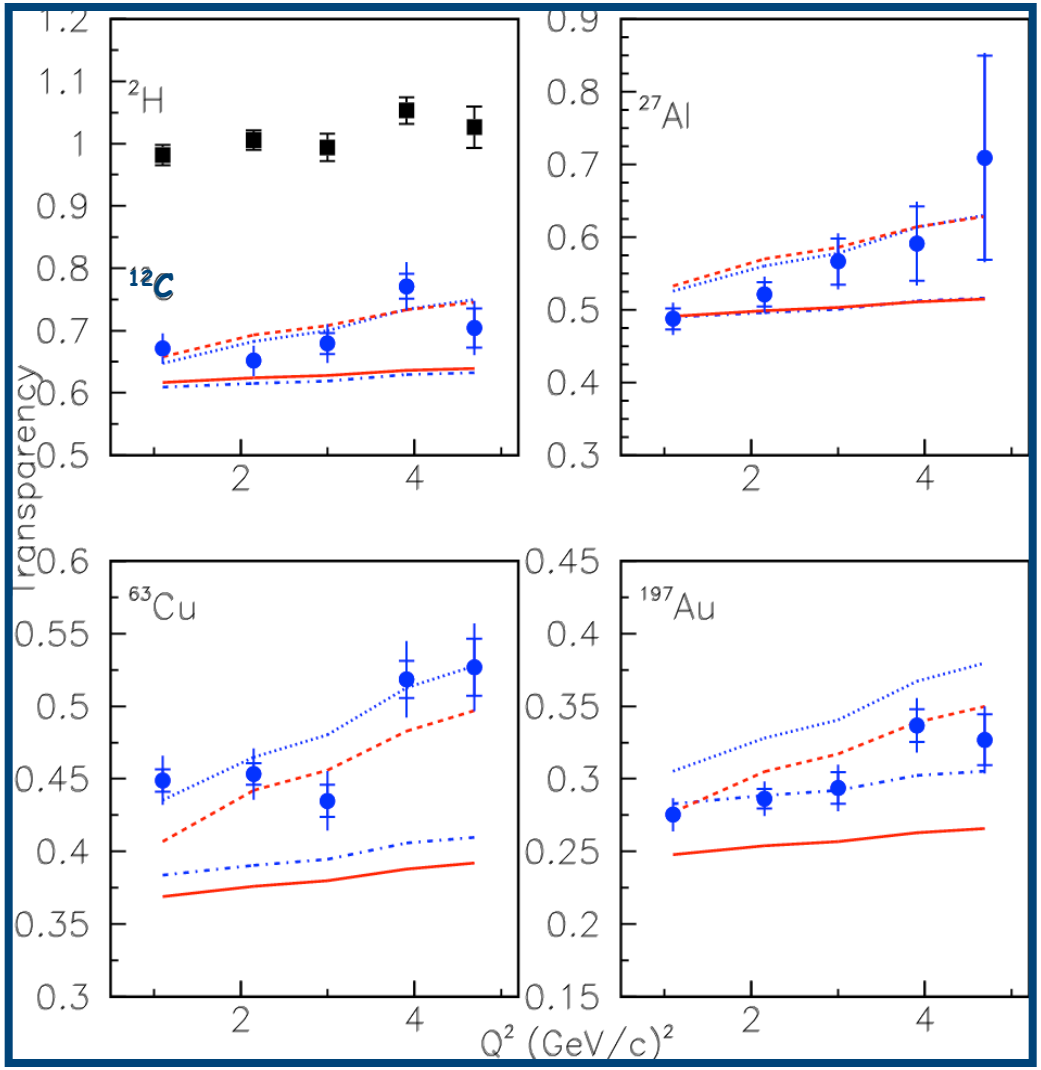
X. Qian et al., PRC81:055209 (2010),

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



Therefore nuclear transparency of pions can be described as ratio of cross section for nuclei to cross section for nucleons.

Pion transparency results are consistent with onset of CT



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

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),

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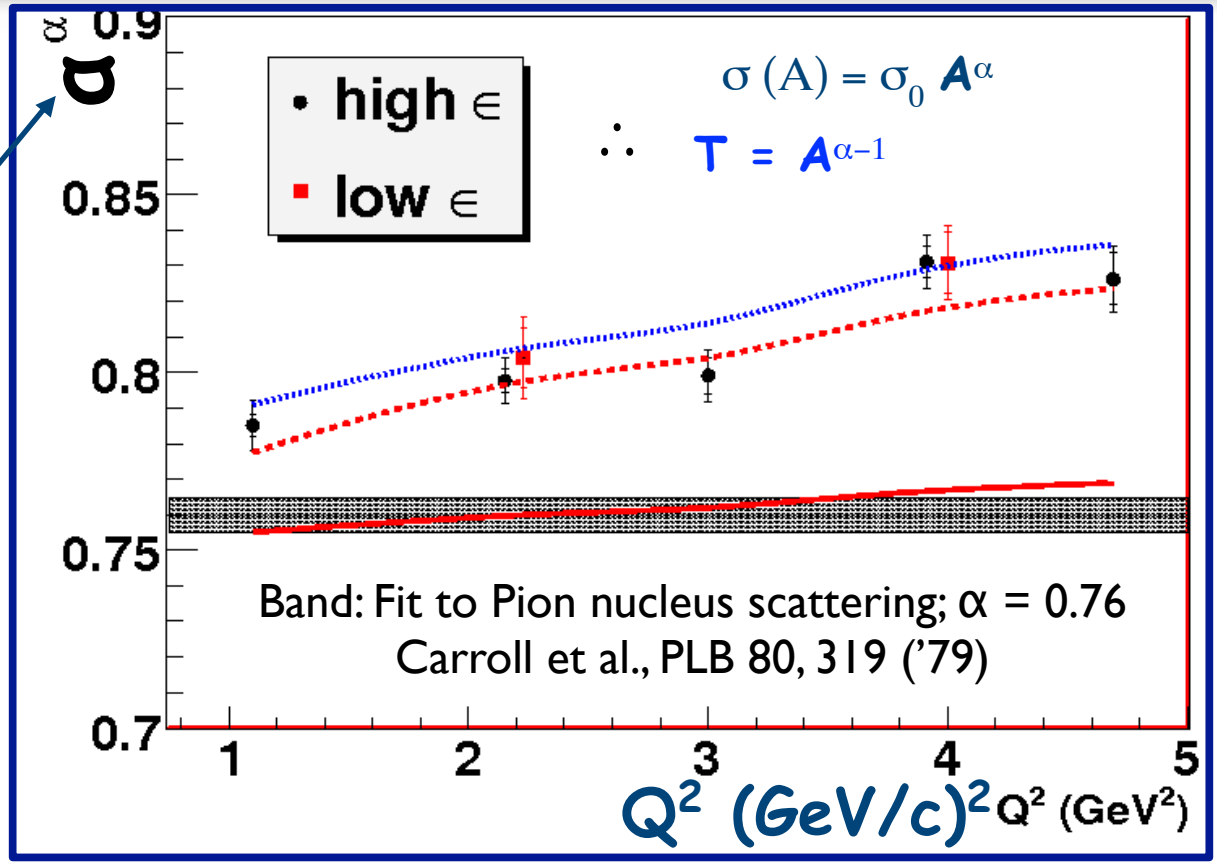


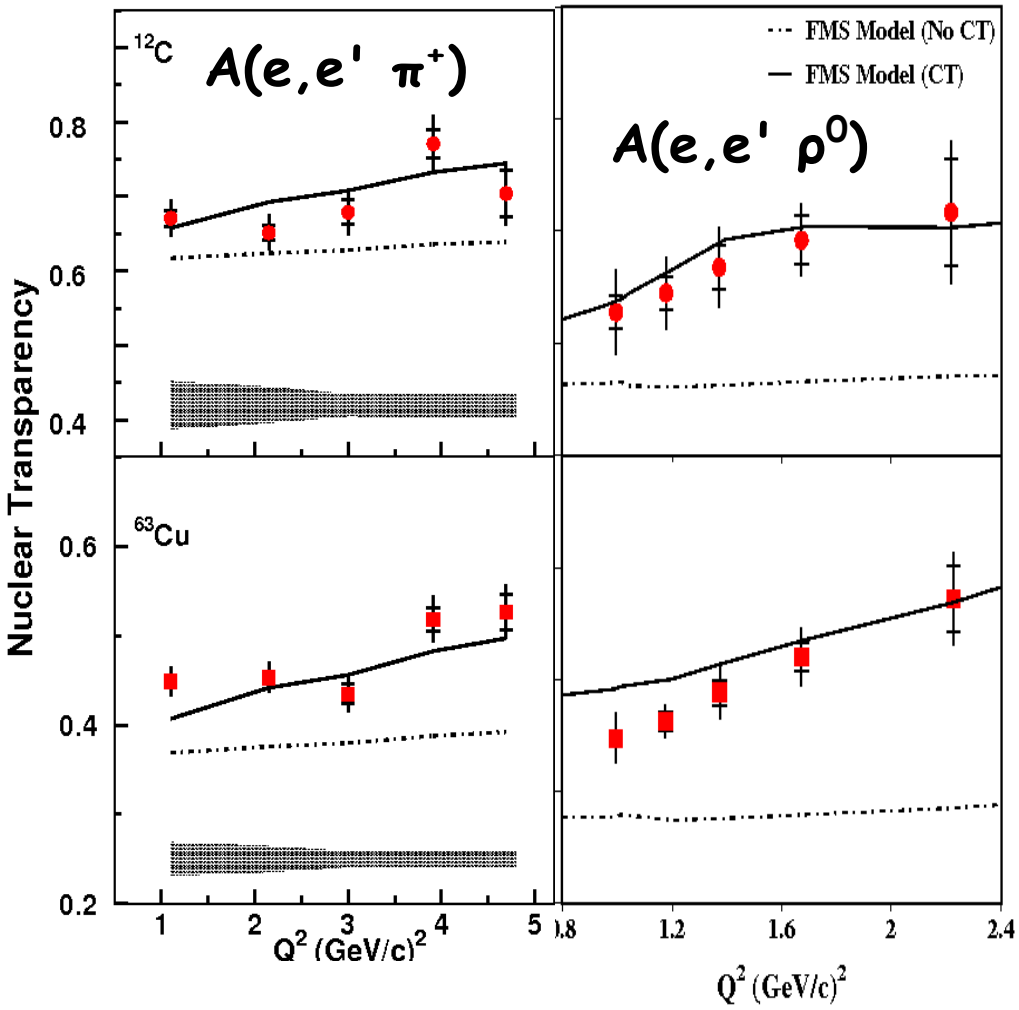
from fit of $T(A) = A^{\alpha-1}$ at fixed Q^2

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)

JLab Experiments conclusively find the onset of CT.

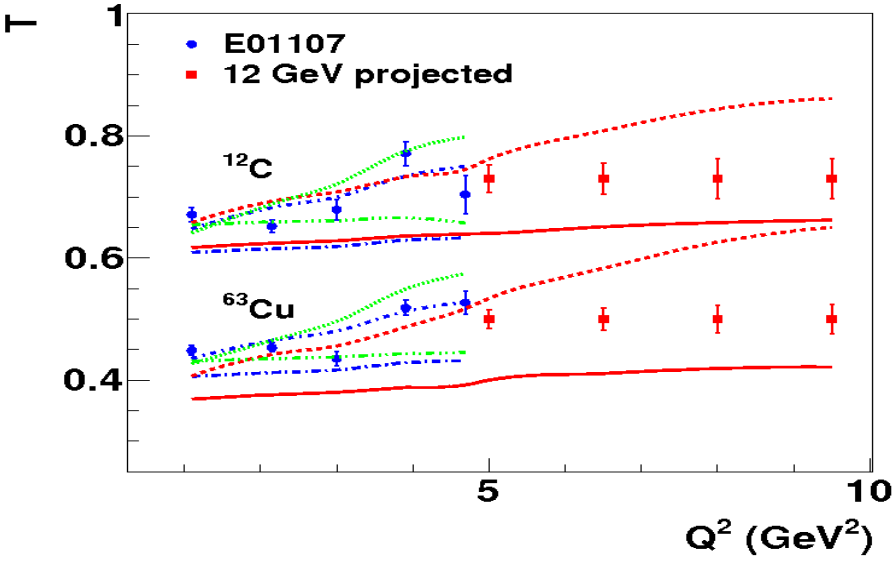


- Hall-C Experiment E01-107 pion electroproduction from nuclei found an enhancement in transparency with increasing Q^2 & A, consistent with the prediction of CT.
  (X. Qian et al., PRC81:055209 (2010), B. Clasie et al, PRL99:242502 (2007))

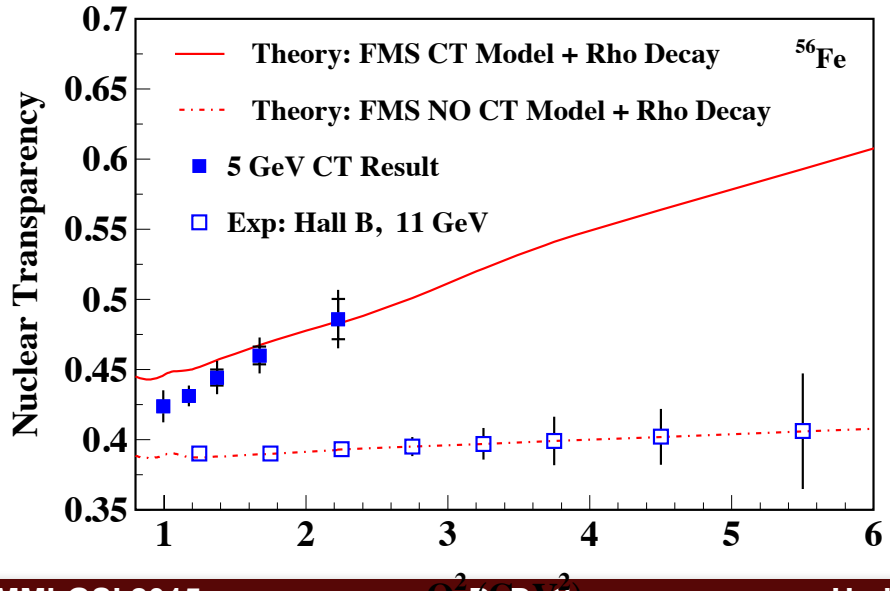
- CLAS Experiment E02-110 rho electroproduction from nuclei found a similar enhancement, consistent with the same predictions
  (L. El-Fassi, et al., PLB 712, 326 (2012))

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

Upcoming experiments at JLab will help confirm 6 GeV results.



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

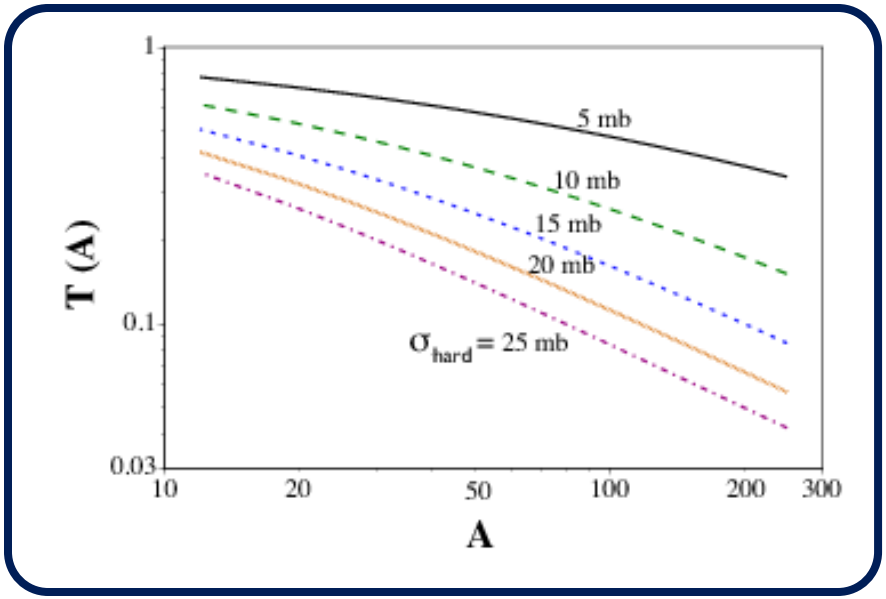
will verify the strict applicability of factorization theorems for meson electroproduction

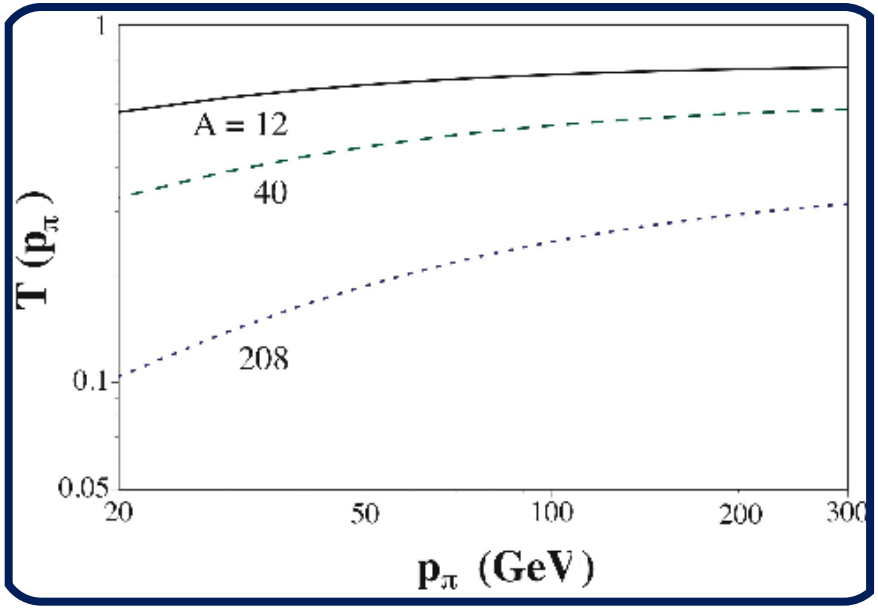
There are new observables for pion induced reactions too.

$2 \rightarrow 3$ processes with pions

$$\pi + A \rightarrow \underbrace{\pi + \pi}_{\text{hard sub-process}} + A^*$$

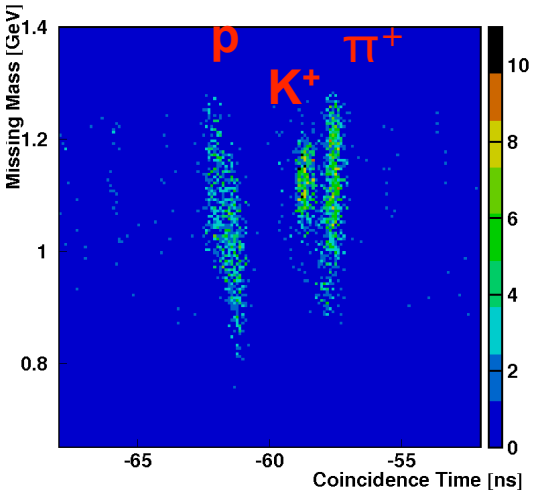
S. Kumano and M. Strikman PLB 683, 259 (2010)
S. Kumano, M. Strikman and K. Sudoh PRD 80, 073004 (2009)





If the CT is observed, the space time evolution of the small size configuration can be studied by changing the initial pion momentum

The pion CT experiment also provided data on kaon transparency.

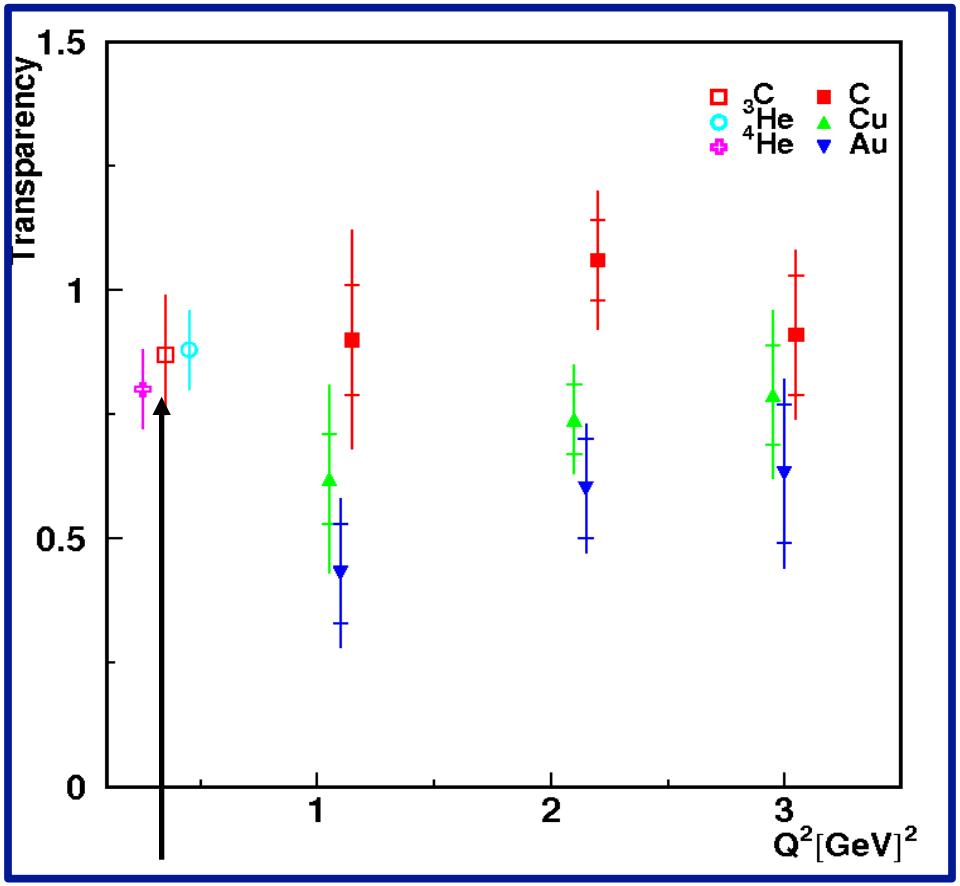


$$T = \frac{\sigma_A^{Expt} / \sigma_A^{Model}}{\sigma_D^{Expt} / \sigma_D^{Model}}$$

Compared with D to minimize impact of non-isoscaler effects

No energy dependence within uncertainties

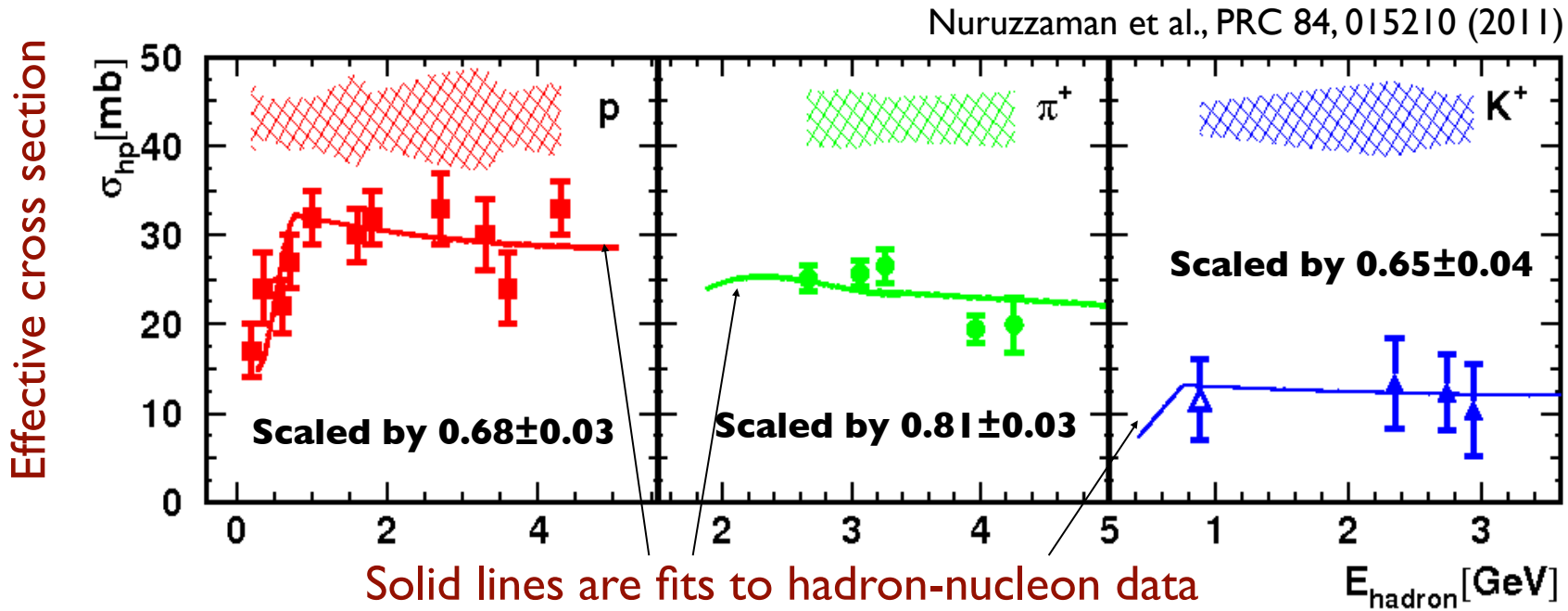
Nuruzzaman et al., PRC 84, 015210 (2011)



Earlier data on light nuclei

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

Free cross-section extracted from nuclear transparency is smaller than those measured with hadrons.

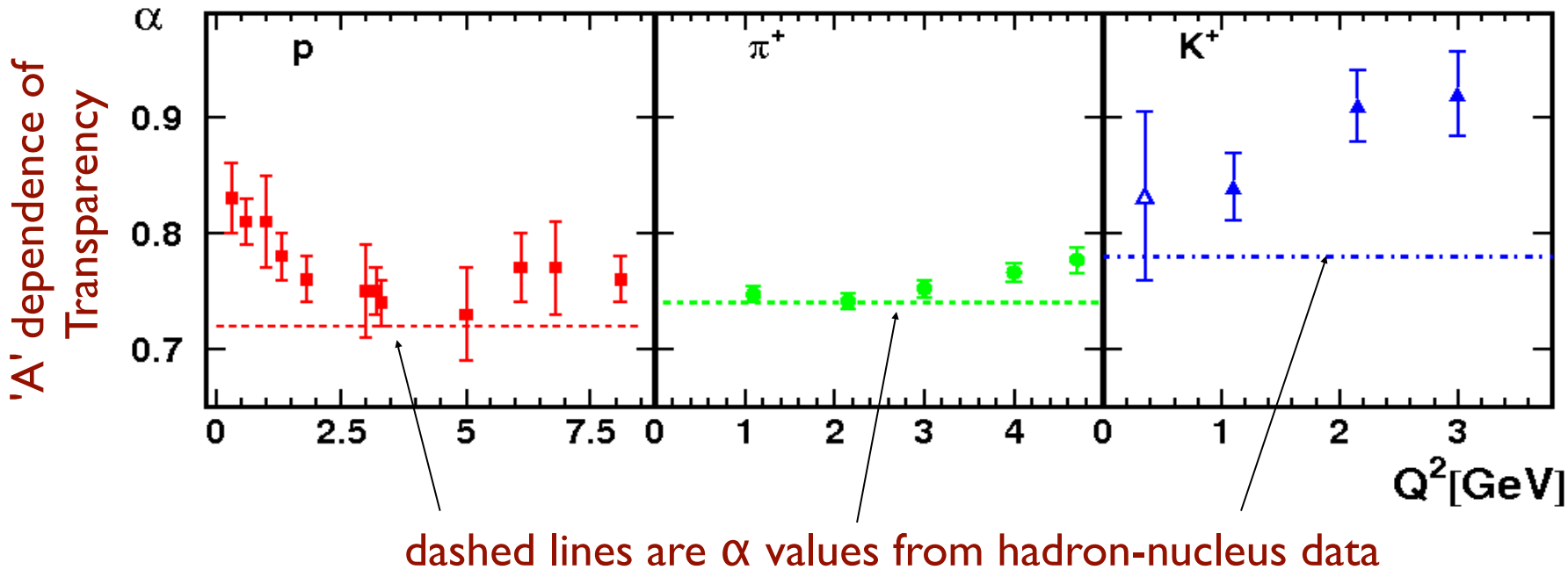


Effective cross section from fitting the measured transparency to a simple geometric model

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

The A dependence of nuclear transparency is different from those measured in hadron induced reactions.

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

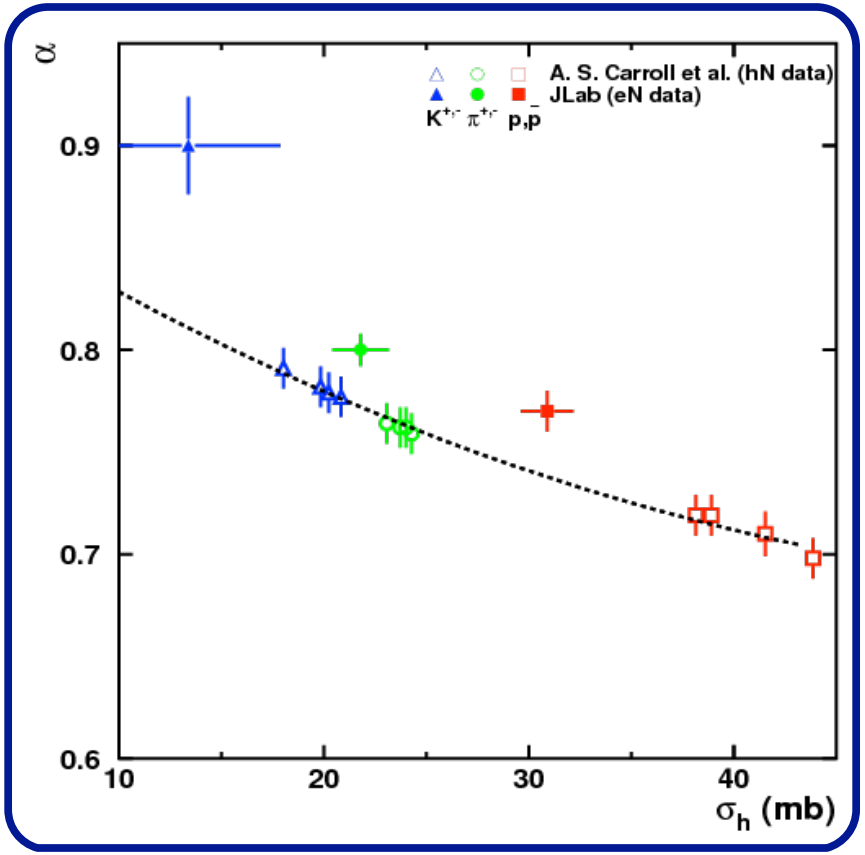


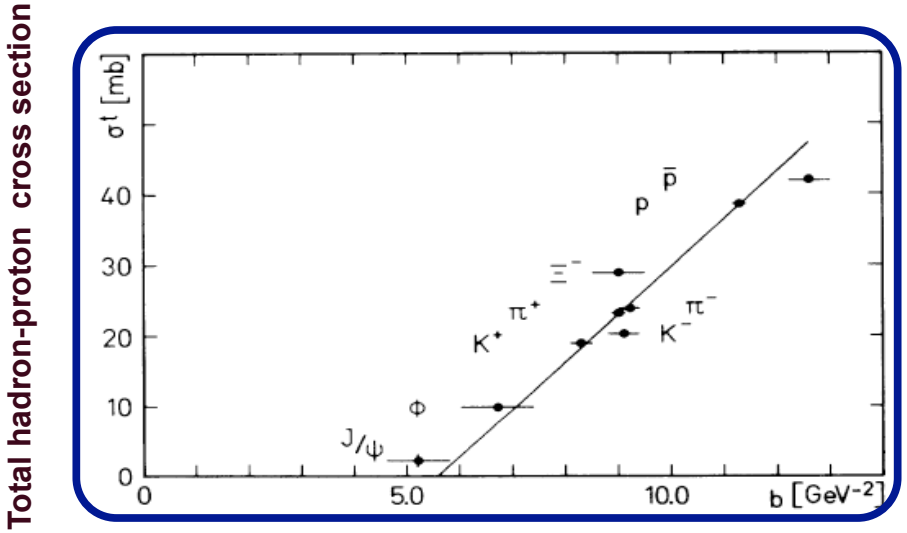
dashed lines are α values from hadron-nucleus data

'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

e-N and h-N measurements seem to differ for key observables.





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.

- 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.

- 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.

- A complementary program is very desirable with a high momentum hadron beamline. This will require a high resolution spectrometer similar to EVA at BNL and possibility of several different beam energies.

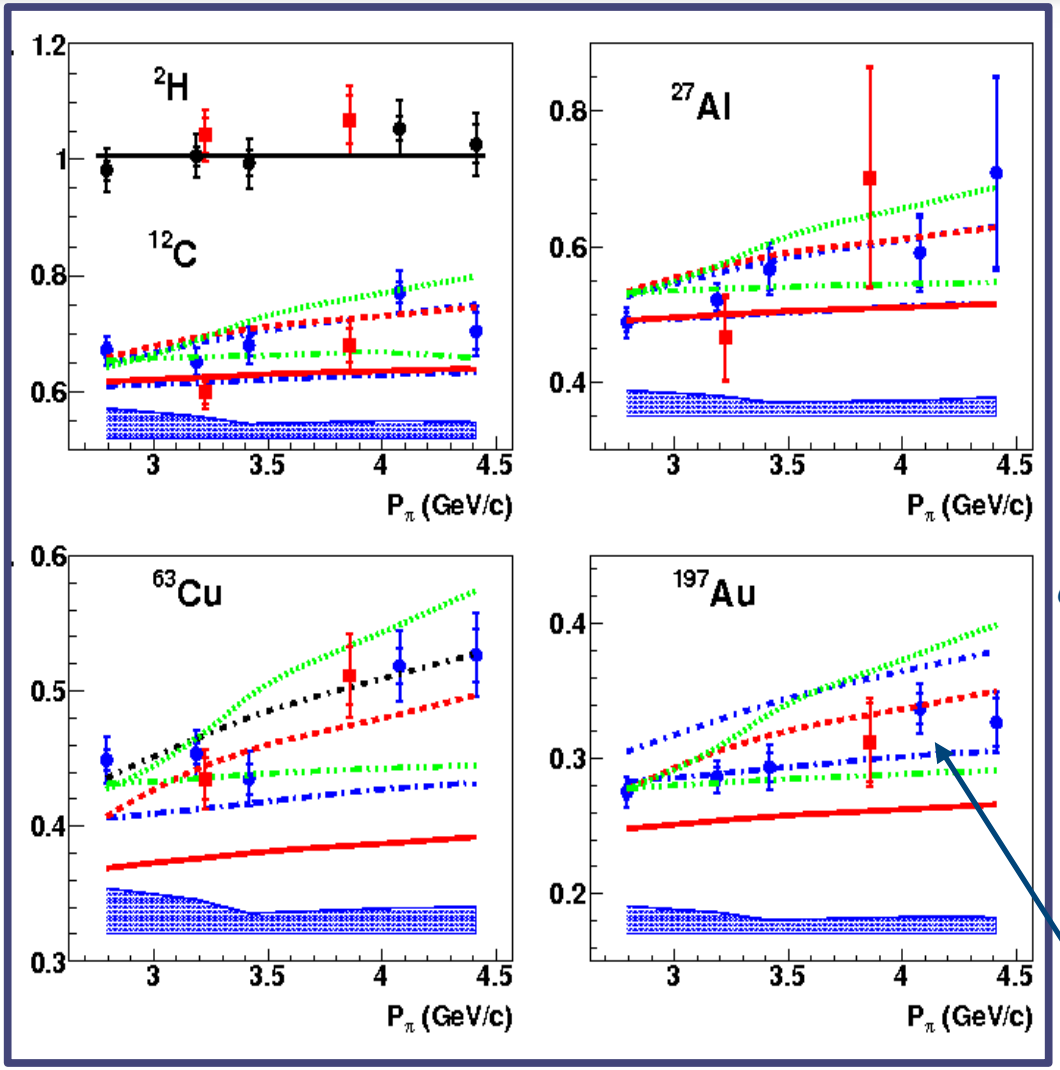
Summary

- 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.

- A complimentary program with new observables is desirable using the proposed pion/kaon beamline. A high resolution spectrometer and a range of beam energies is necessary.

- 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, PR 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.

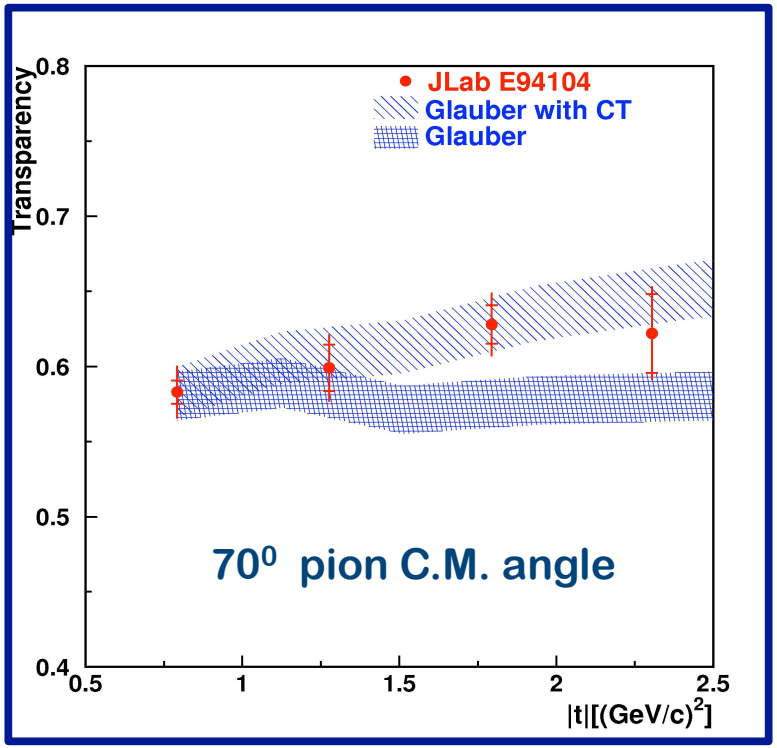
(X. Qian et al., PRC81:055209 (2010), B. Clasie et al. PRL99:242502 (2007))

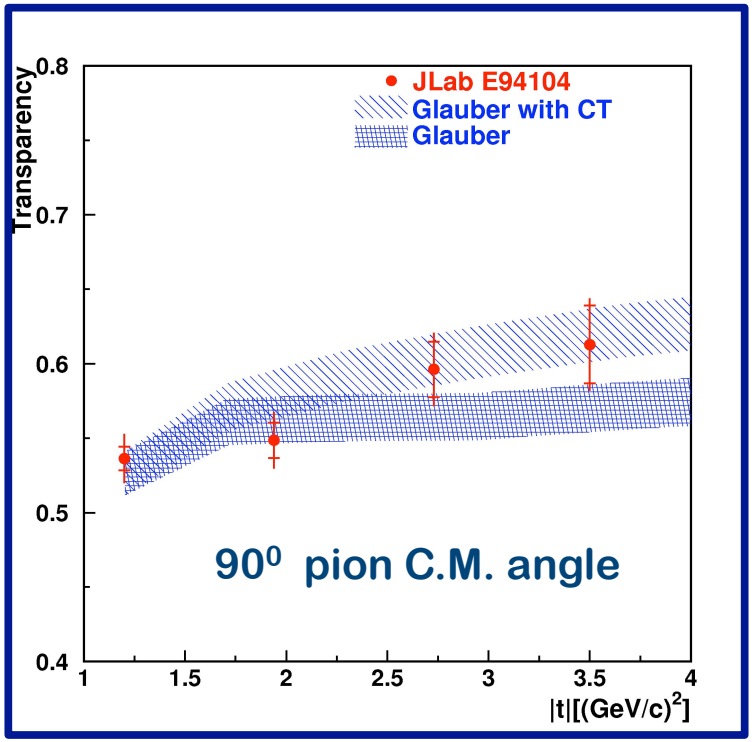
Pion Photoproduction $^4He(\gamma,\pi^- p)$

Positive hints from pion photoproduction in JLab Hall A

(H. Gao & R. Holt Spokespersons)

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





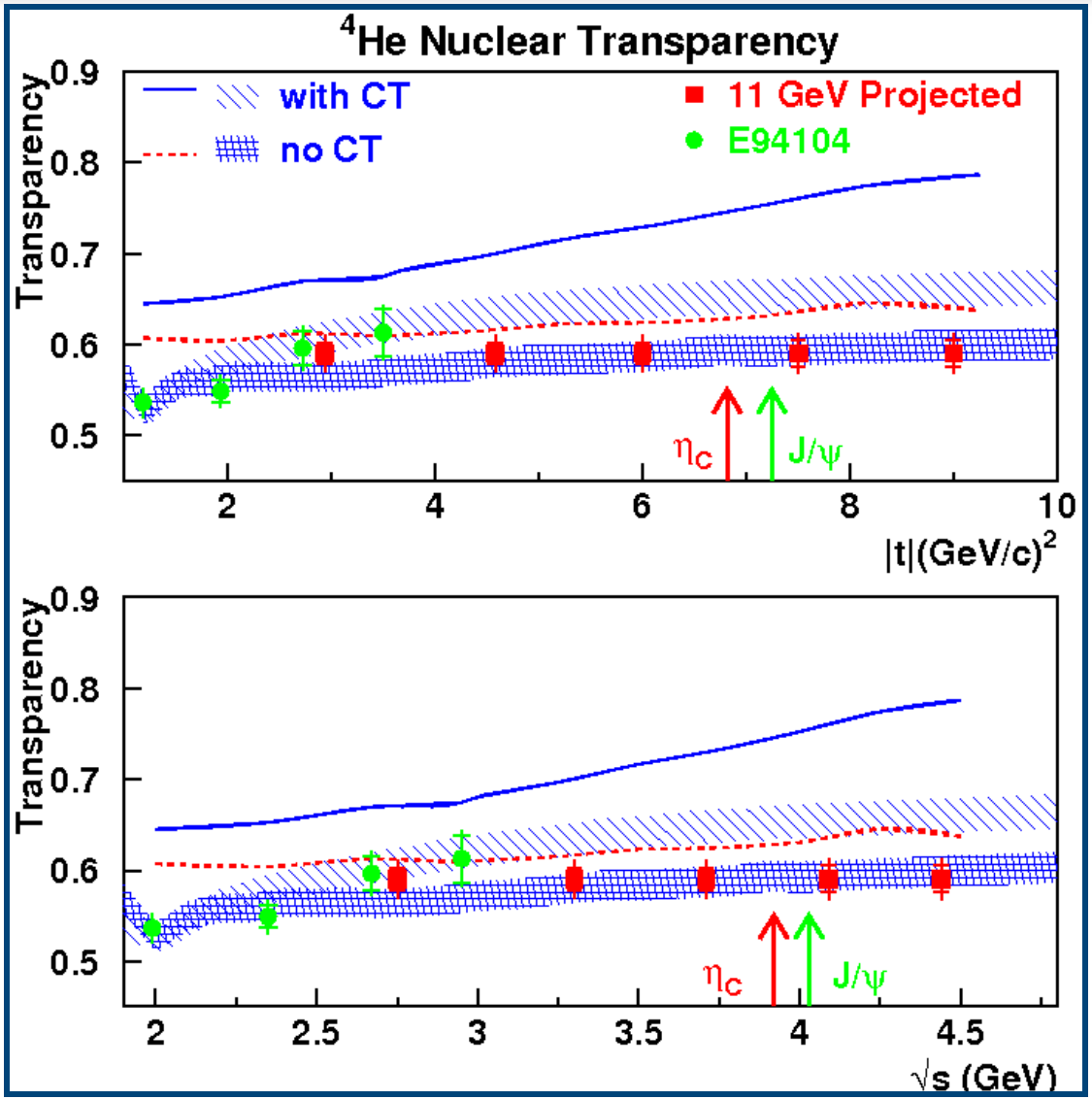
Deviations from Glauber !

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

^{4}He(γ,pπ$^-$) @ 12 GeV

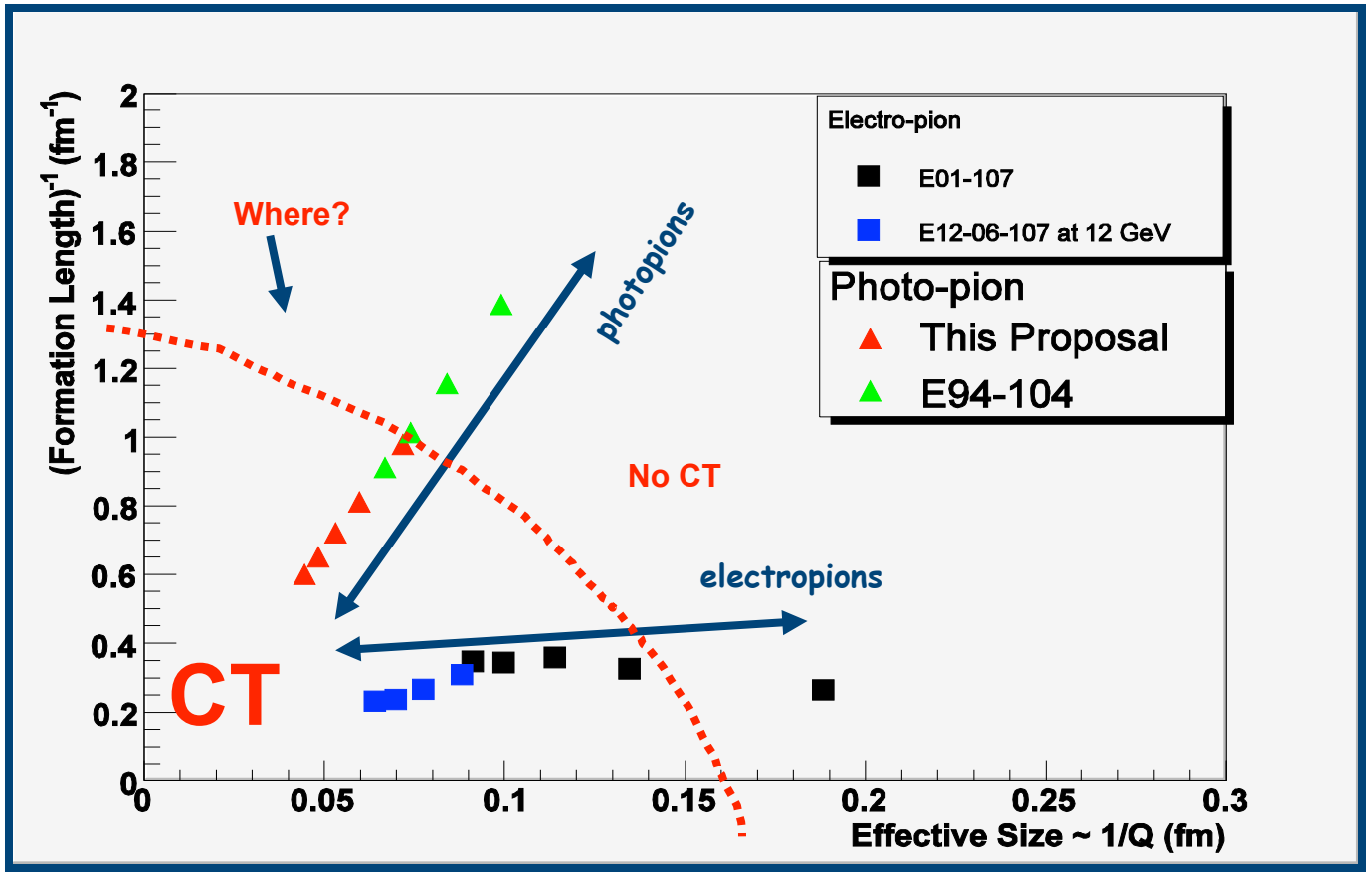
$$T = \frac{\gamma + {}^4He \rightarrow \pi^- + p + X}{\gamma + {}^2H \rightarrow \pi^- + p} T({}^2H)$$

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



Need Both Electro and Photo Pions

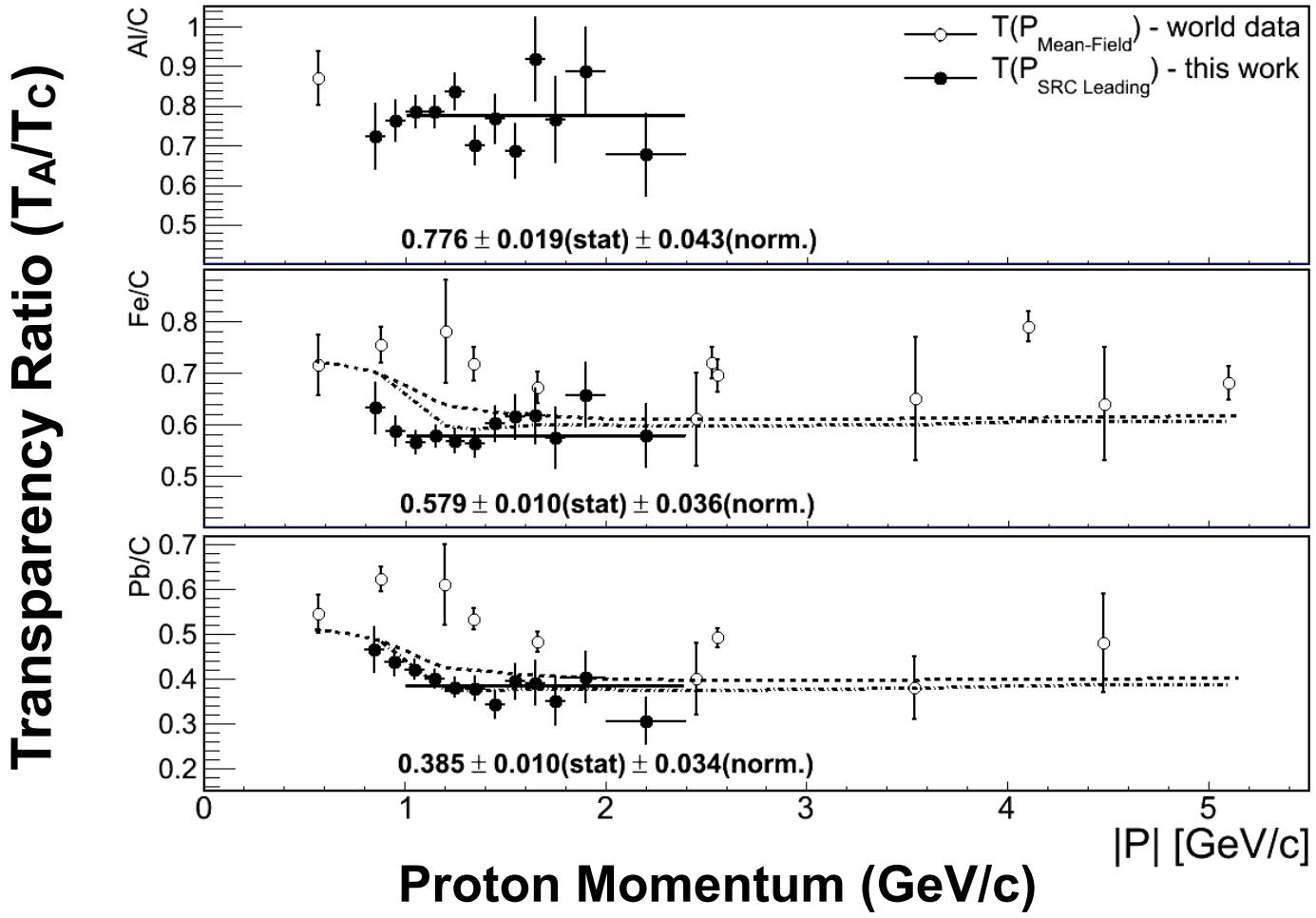
Formation length ~ $P_h^* \Delta t / m_h$



Effective Size ~ 1/Q

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

O. Hen et al., PLB 722, 63 (2013)



from fit of
$T_{ratio} = A^{\alpha-1}$
at fixed Q^2

O. Hen et al., PLB 722, 63 (2013)