Hadron Propagation Through Nuclear Matter

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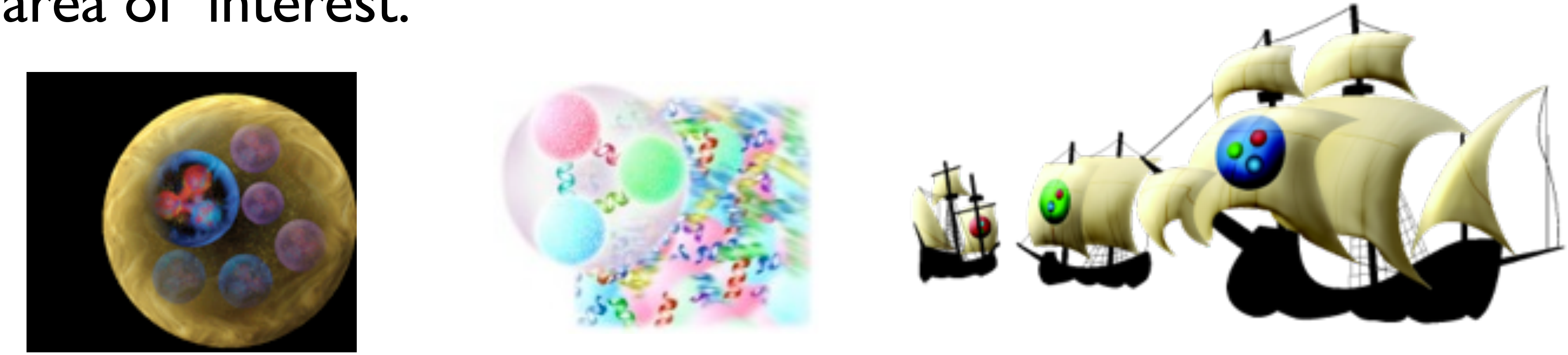
KEK theory center workshop on
Hadron physics with high-momentum hadron beams at J-PARC
Jan 15 – 18, 2013

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.

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 understand N-N interactions in terms of QCD) ?

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

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

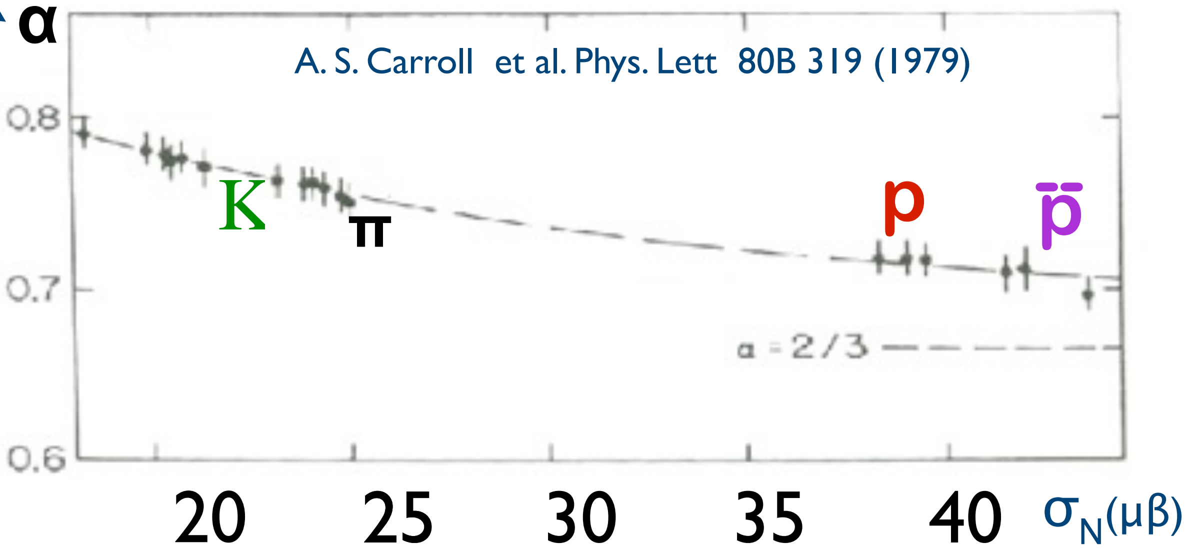
α = 0.72 – 0.78,

for π, K, p

Hadron momentum
60, 200, 250 GeV/c

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

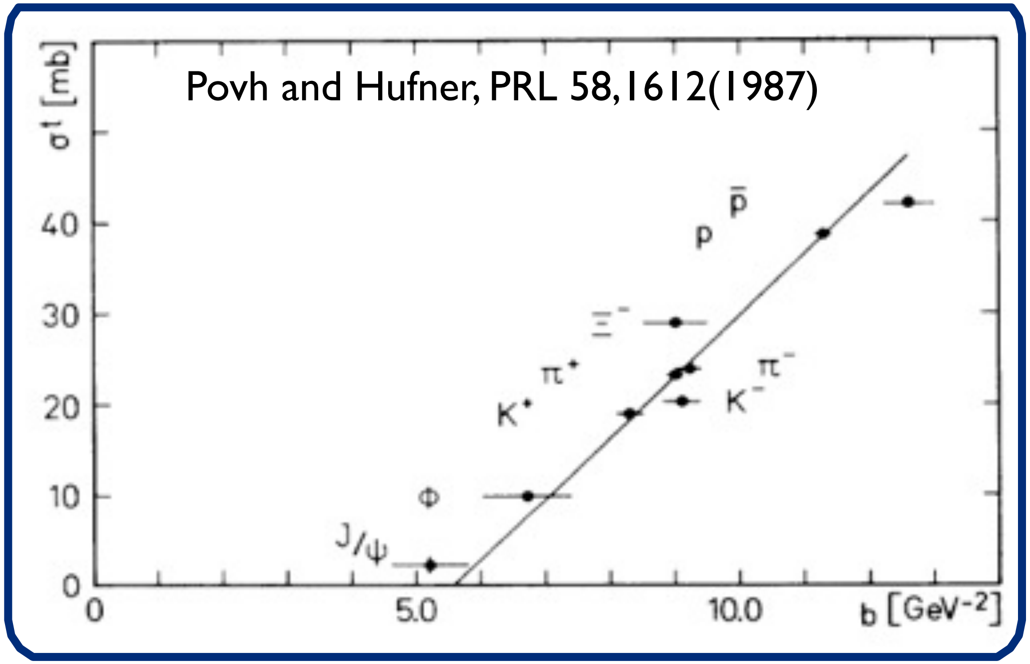
σ_N Hadron– Nucleus total cross-section



A. S. Carroll et al. Phys. Lett 80B 319 (1979)

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

Size Dependence



Povh and Hufner, PRL 58,1612(1987)

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 $Q^2 = t$

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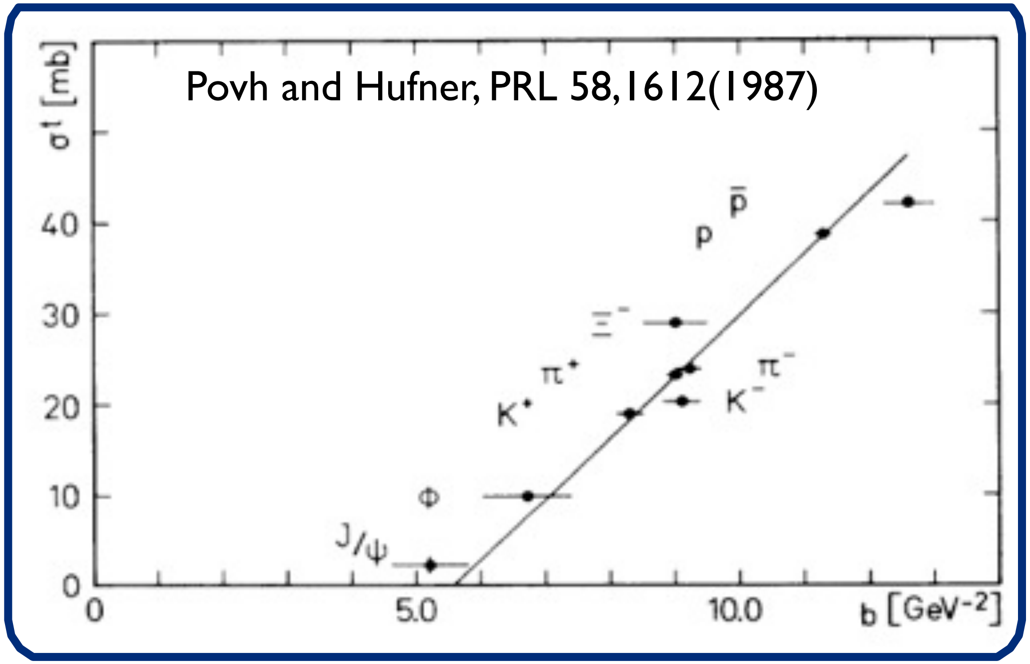

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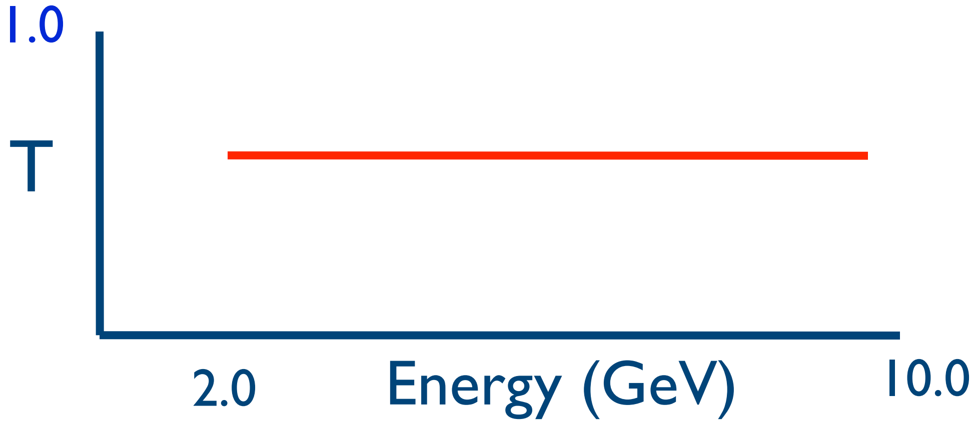
RMS radius from slope of the elastic scattering cross section as a function of $Q^2 = t$

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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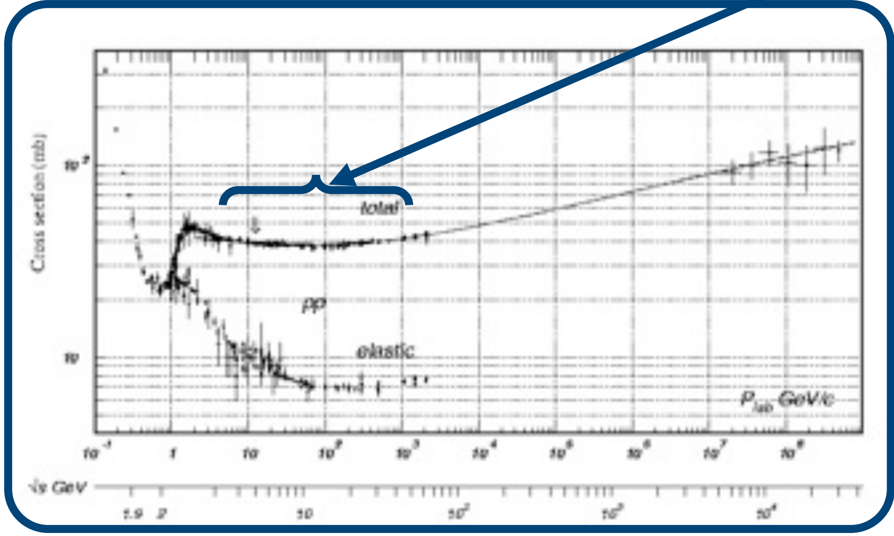
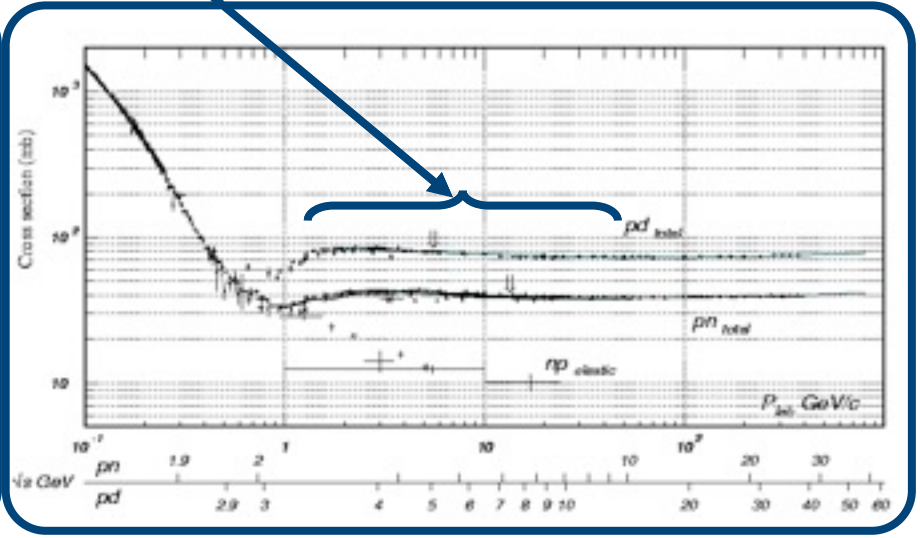
N-N cross-section is energy independent



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

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a color coherence property of QCD

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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.

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

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

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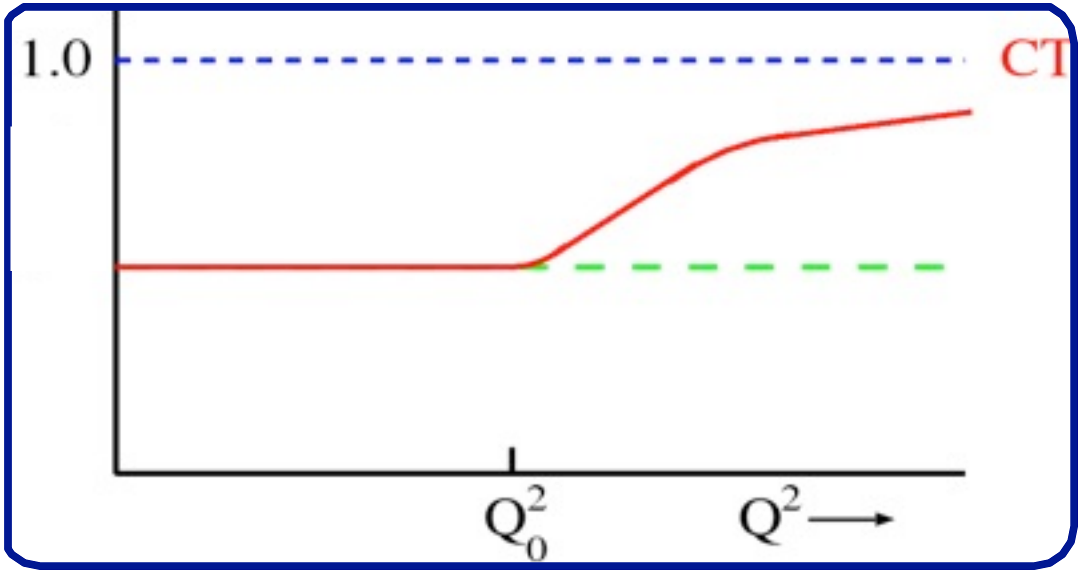
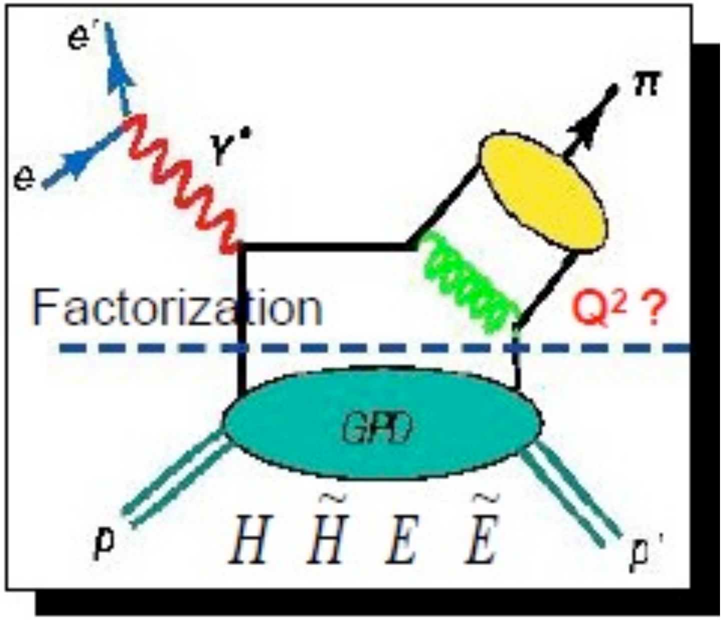


CT is well established at high energies, we are interested in identifying the onset of CT

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 ($\gamma^* q_a \to \pi q_b$) and soft part parametrized as GPDs.

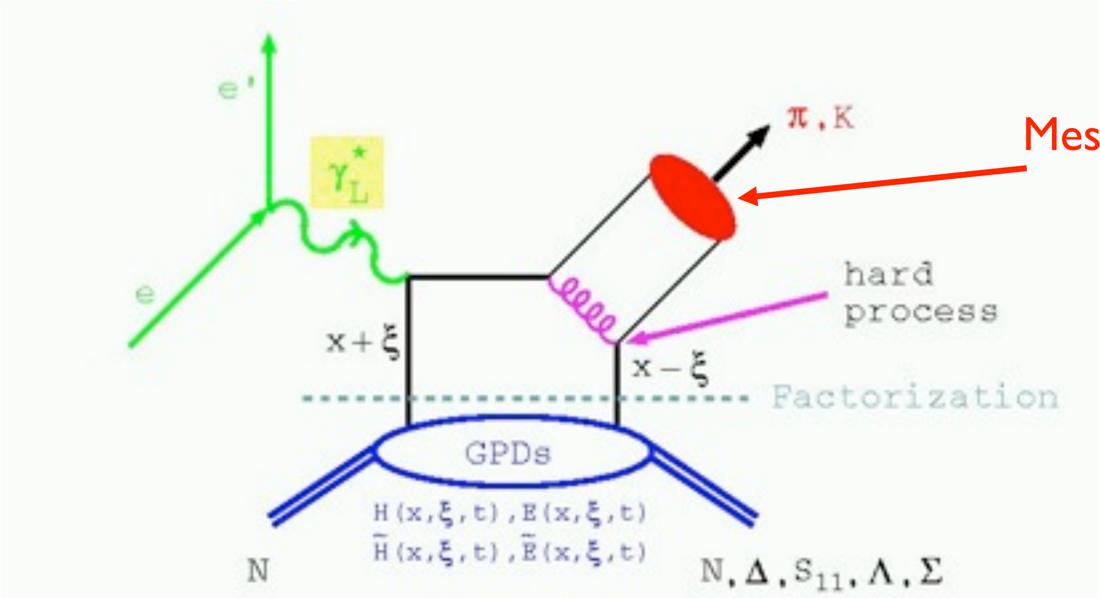
Recent DVCS and wide angle Compton scattering results disagree with pQCD predictions but are consistent with the dominance of handbag mechanism.

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

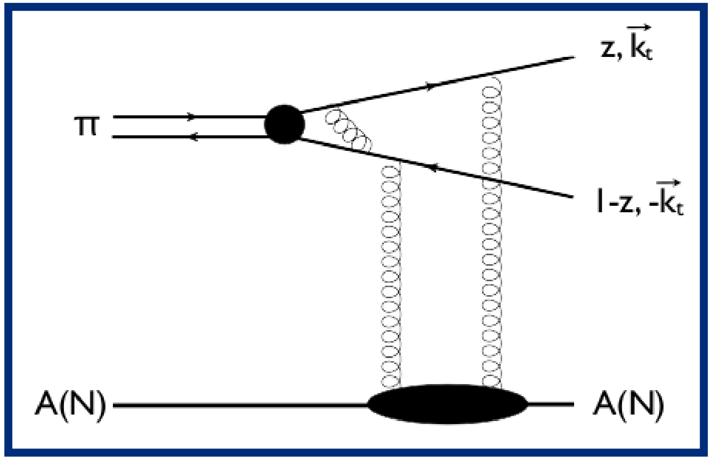
Factorization is not rigorously possible without the onset of CT

-Strikman, Frankfurt, Miller and Sargsian

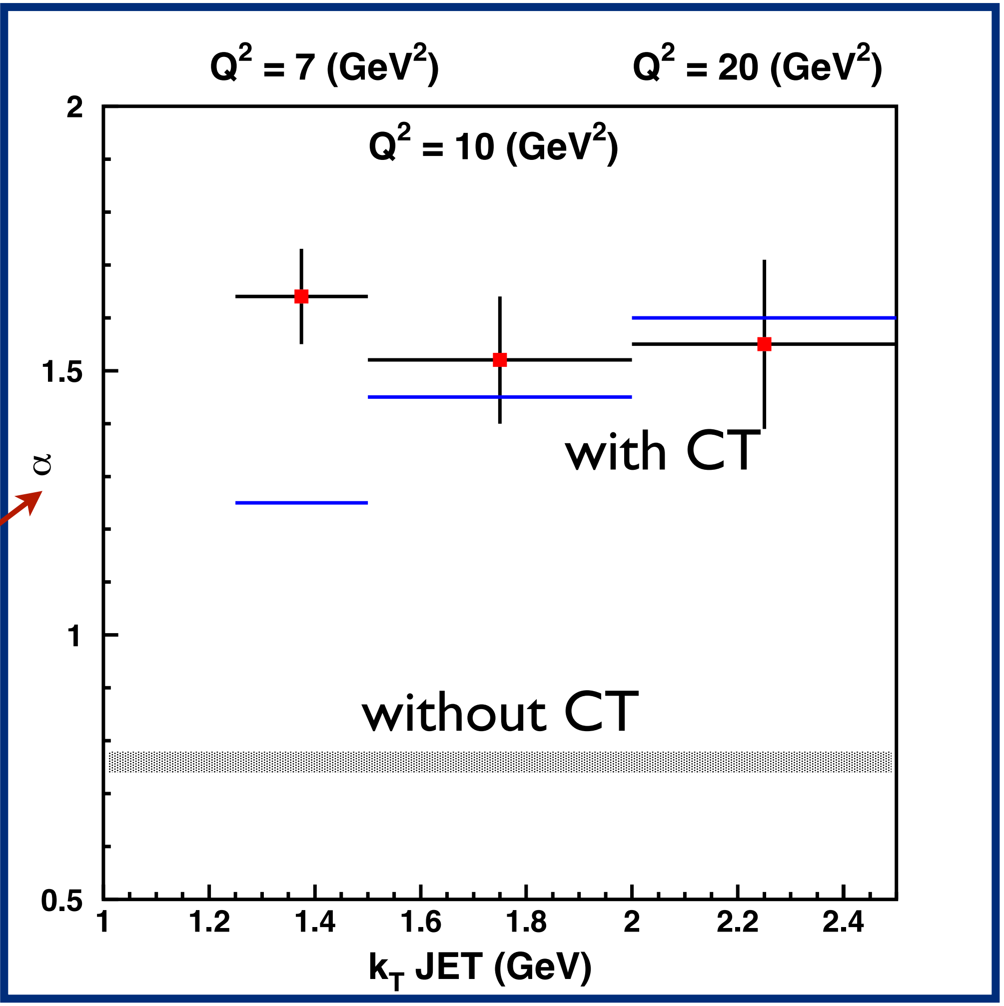
CT at High Energies

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)

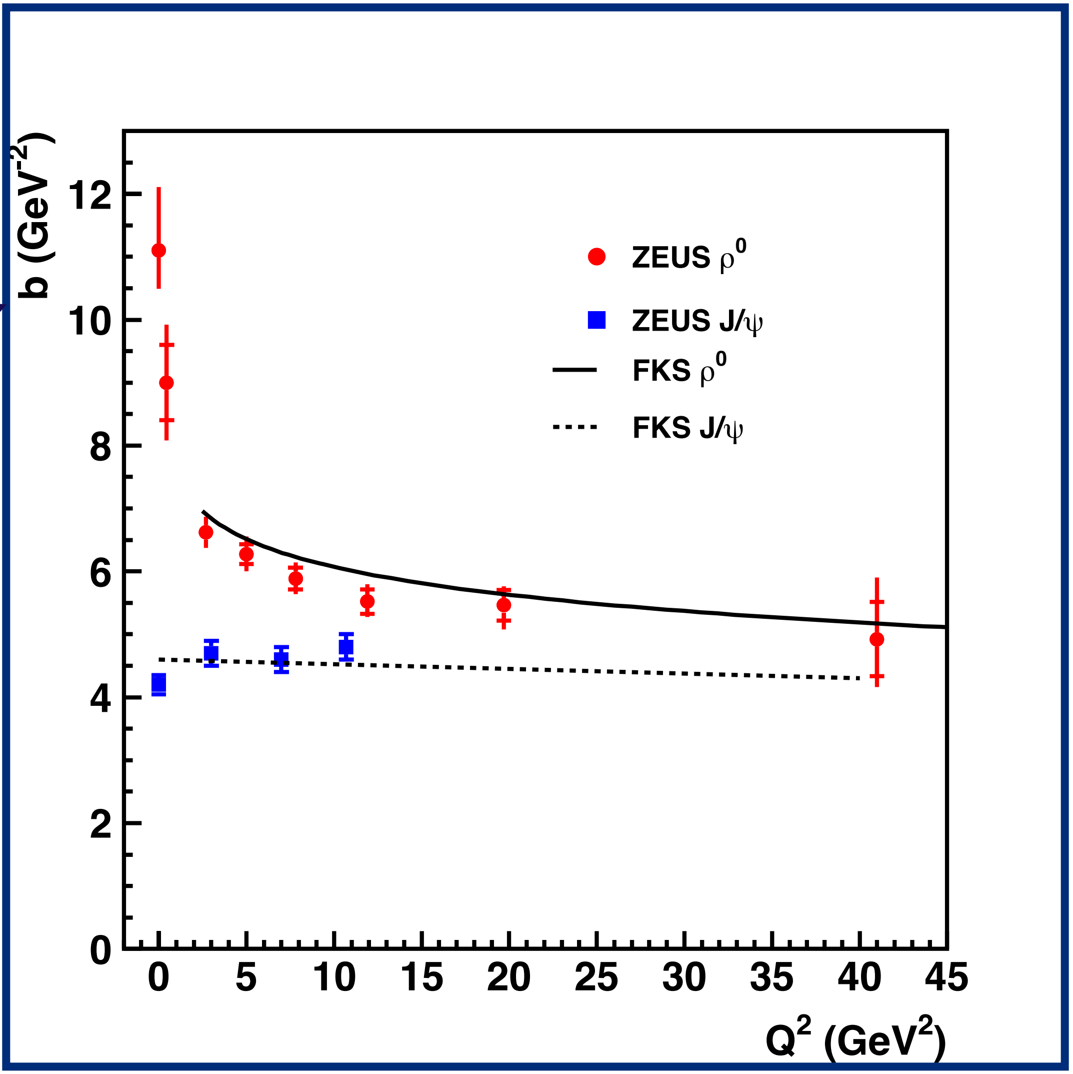
CT at High Energies

Vector Meson production at large Q^2 at HERA

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

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

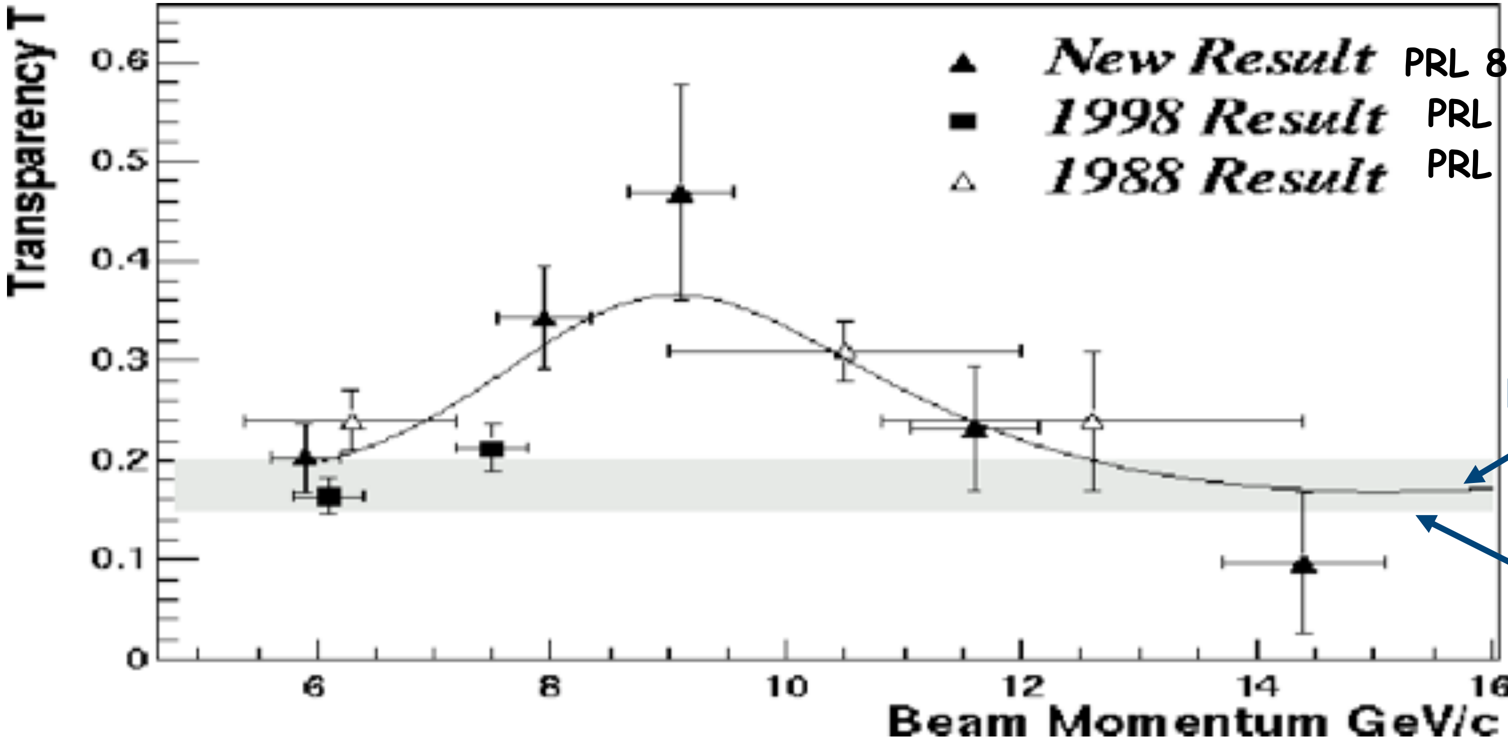
Convergence of the t-slope of ρ and J/ψ electroproduction at large Q^2 predicted by the presence of small size qq-bar state



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

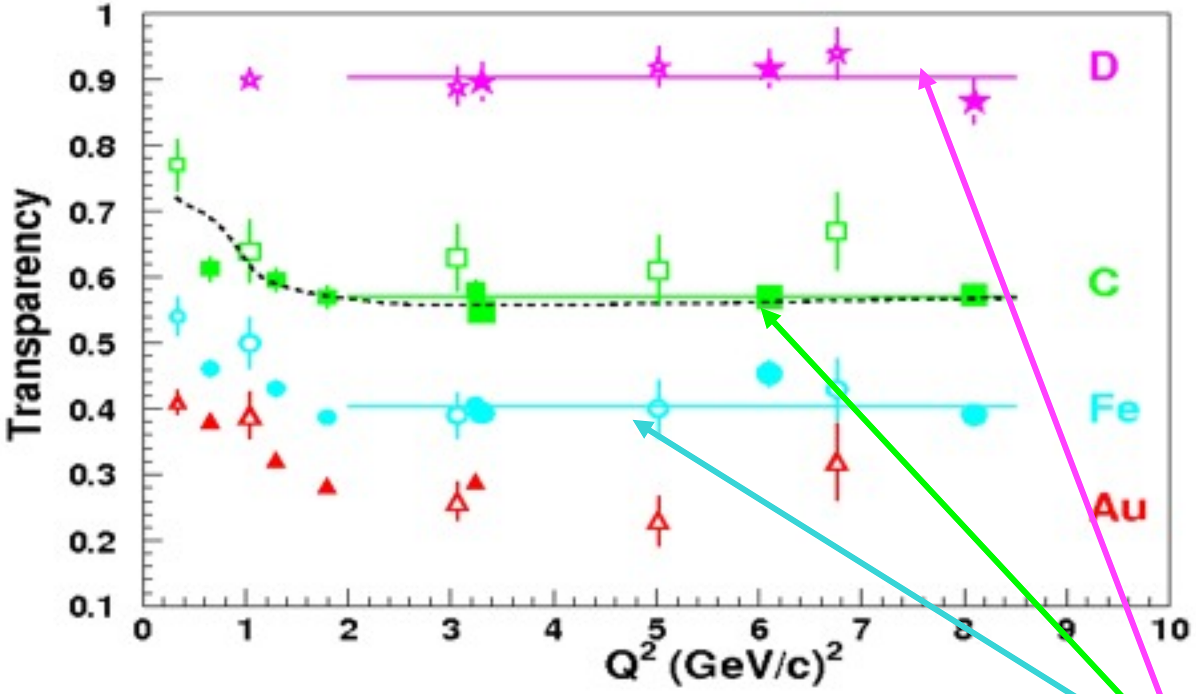
Shaded band
Glauber
calculation

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

CT at Intermediate Energies

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 $\chi^2 / \delta\phi \sim 1$

N. C. R. Makins et al. PRL 72, 1986 (1994)

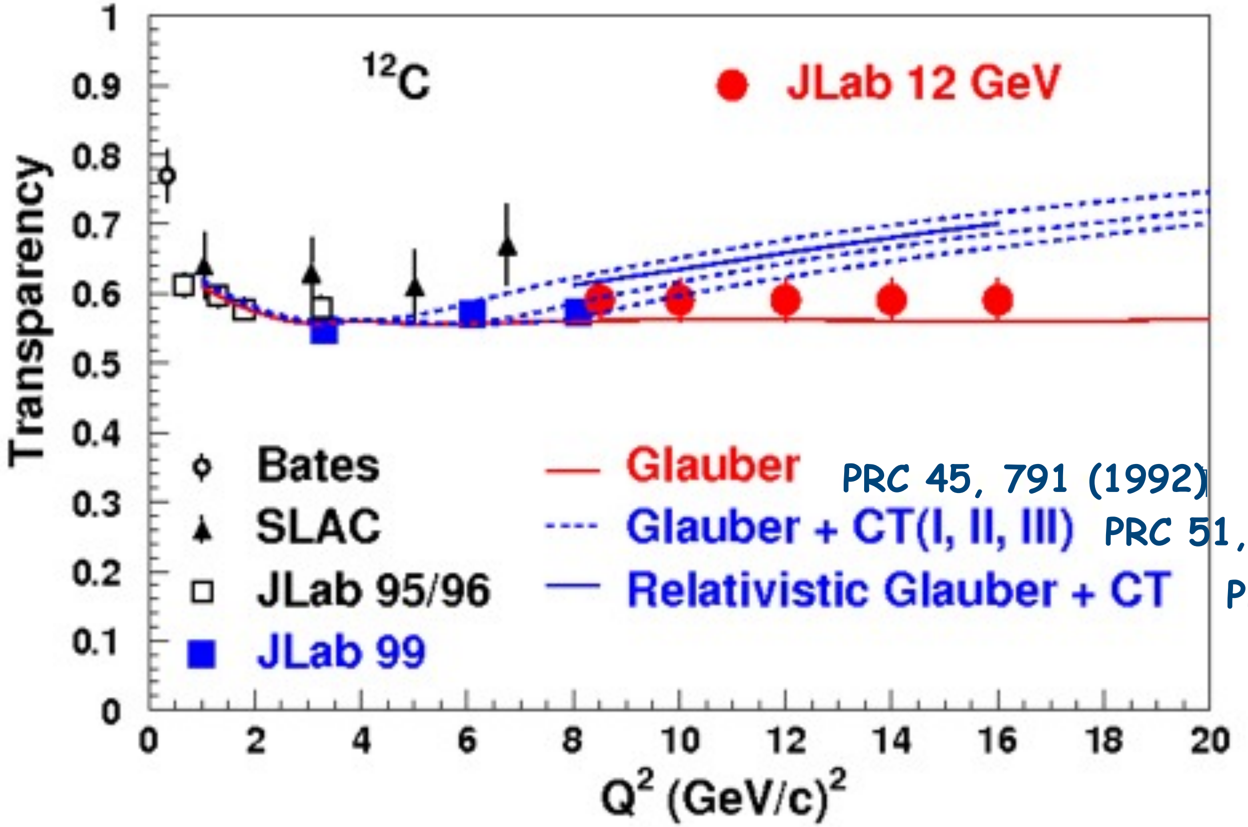
G. Garino et al. PRC 45, 780 (1992)

D. Abbott et al. PRL 80, 5072 (1998)

K. Garrow et al. PRC 66, 044613 (2002)

CT at Intermediate Energies

A(e,e’p) @ 11 GeV JLab



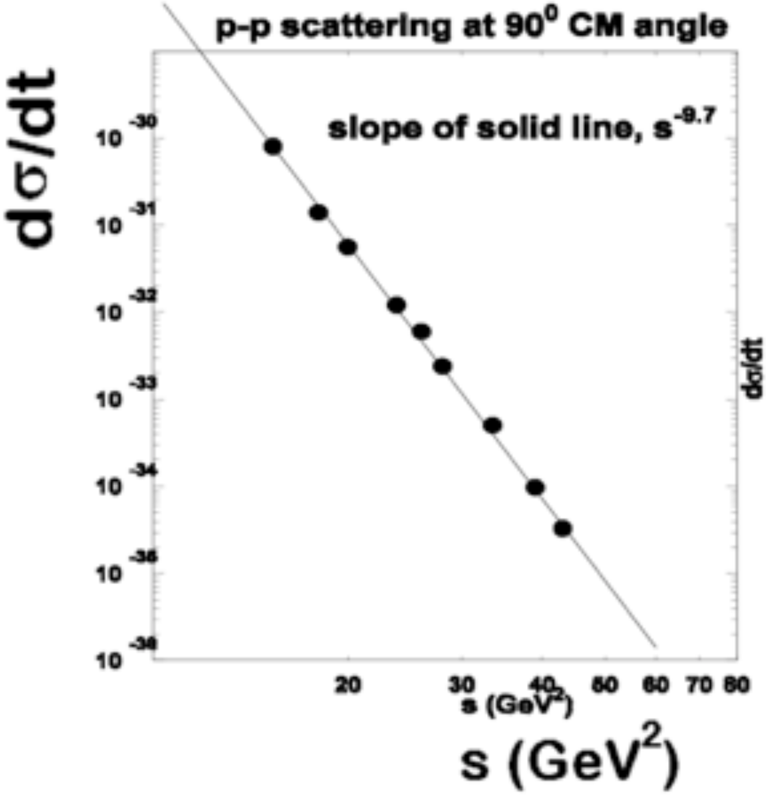
PRC 45, 791 (1992)

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

p-p Scattering Cross Section



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

data from Landshoff and Polkinghorne

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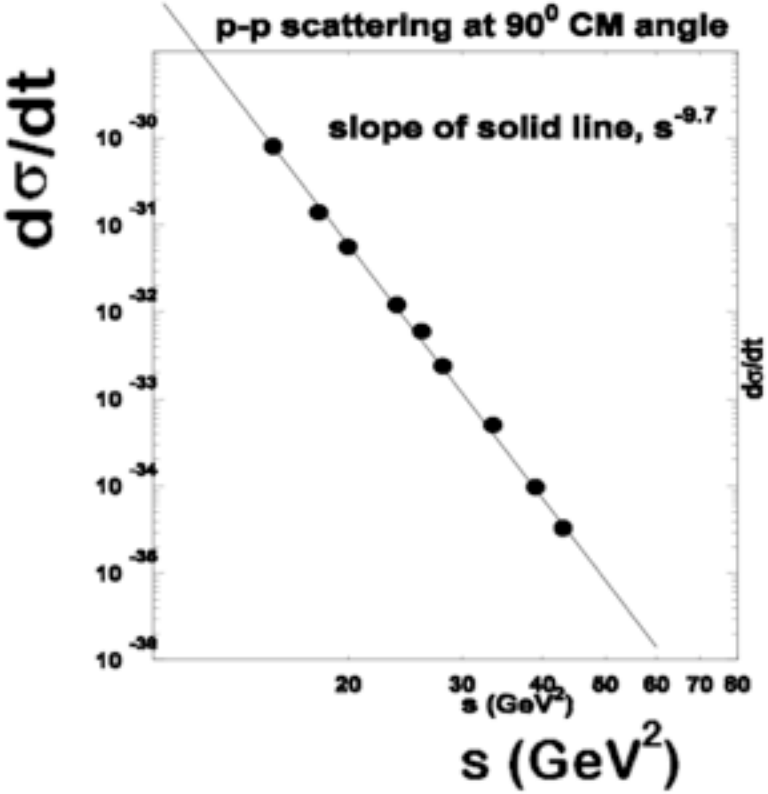

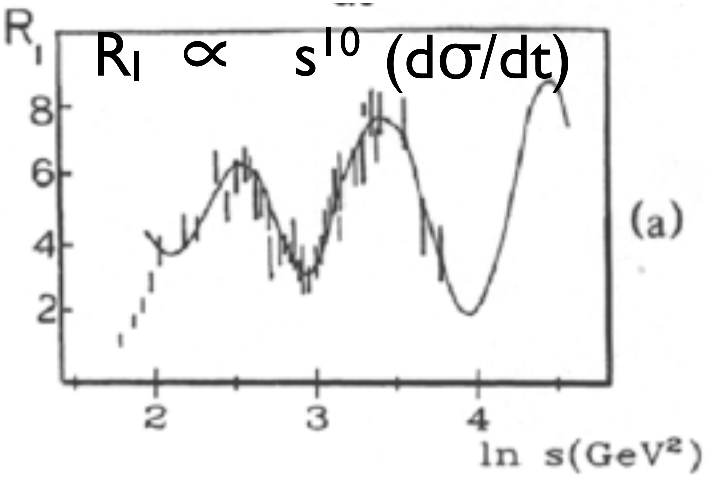

$R_I \propto s^{10}\,(d\sigma/dt)$

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

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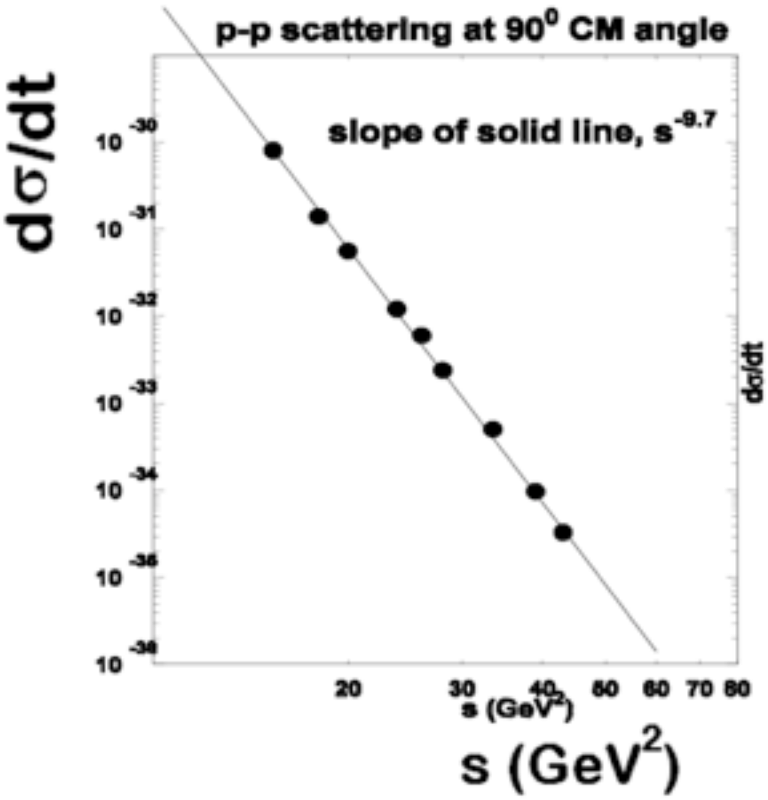

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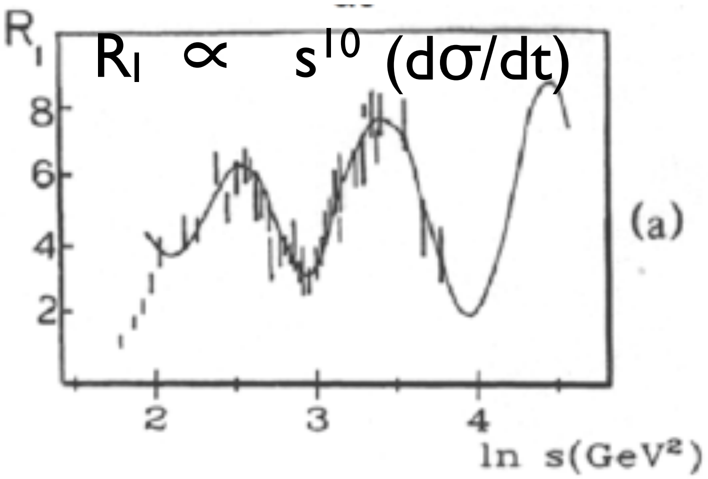

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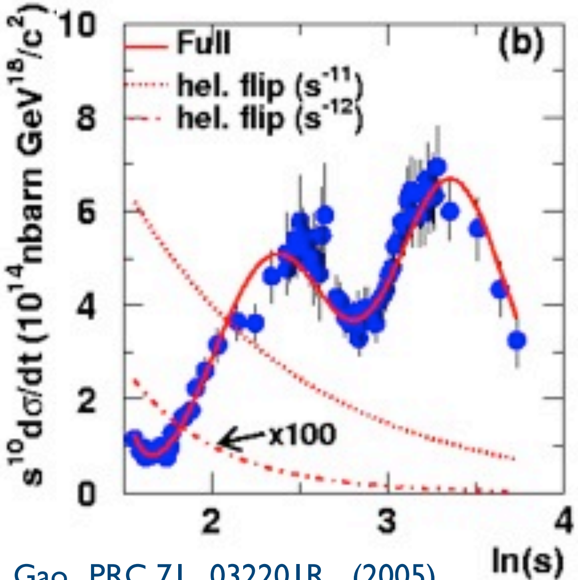
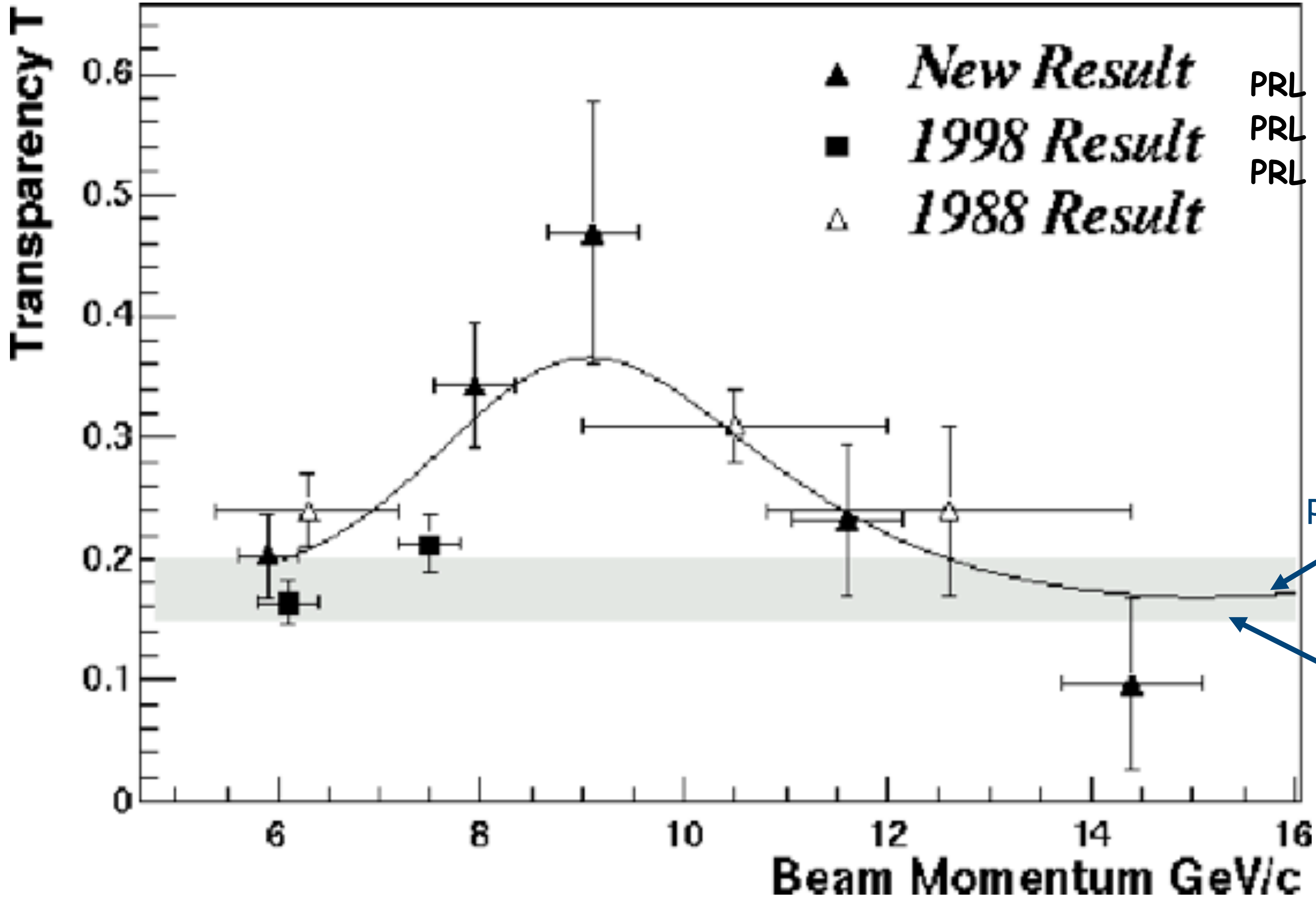


D.Dutta and H. Gao, PRC 71, 032201R (2005)

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



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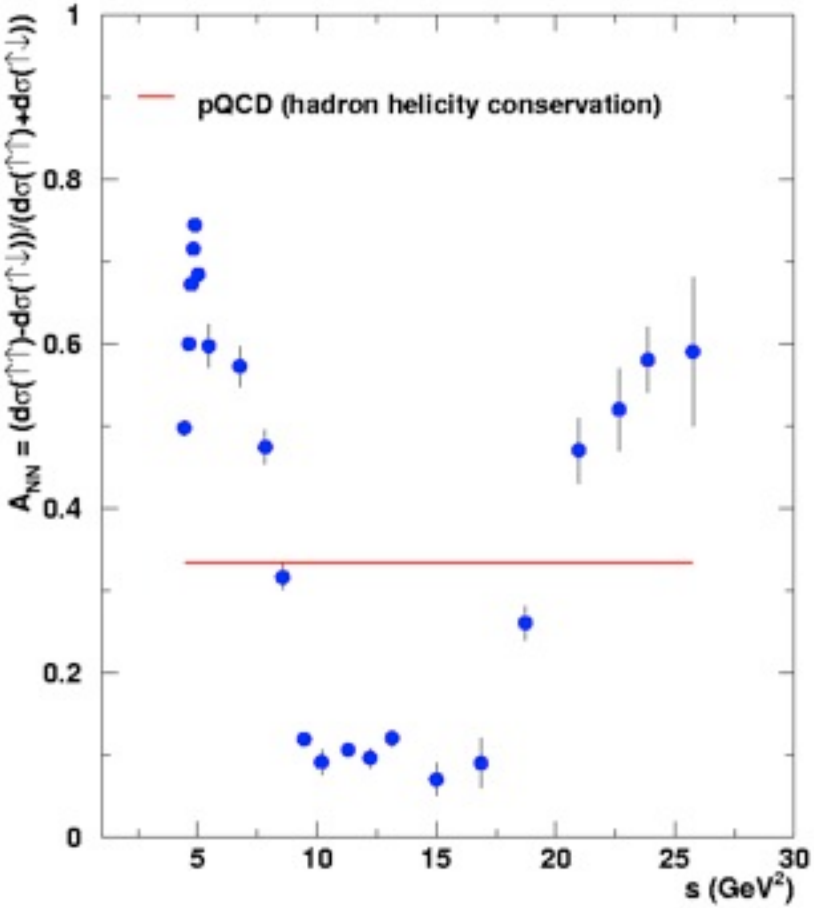
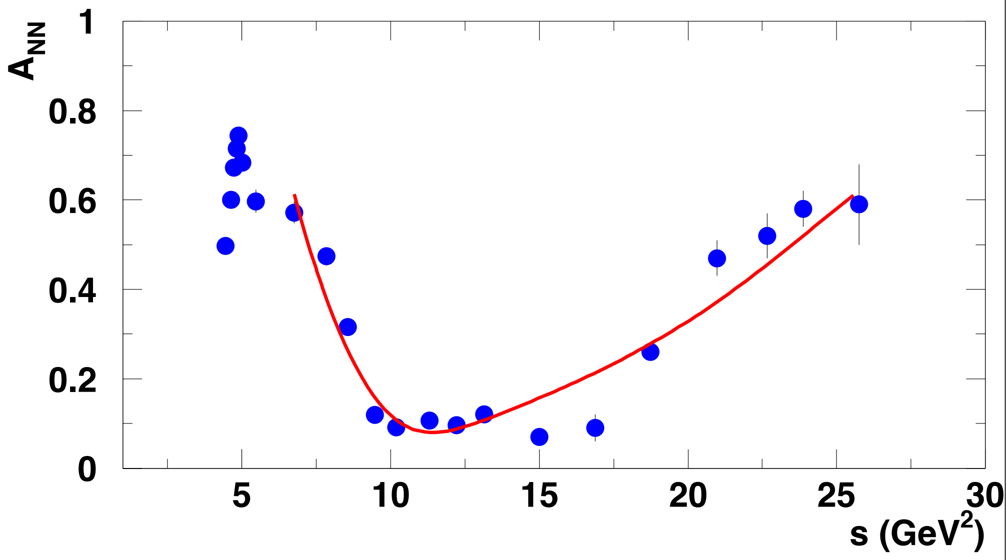
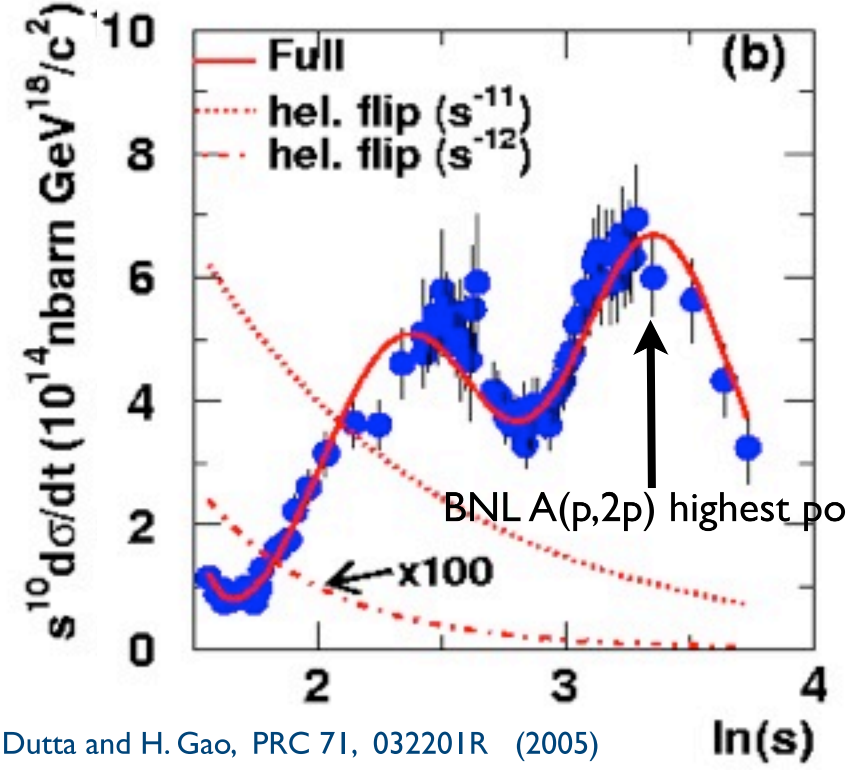


D.G. Crabb et al., PRL 41, 1257 (1978)



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

Opportunities at J-PARC



BNL A(p,2p) highest point

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

At J-PARC 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 complete unambiguous understanding of A(p,2p) and A(e,e'p) data

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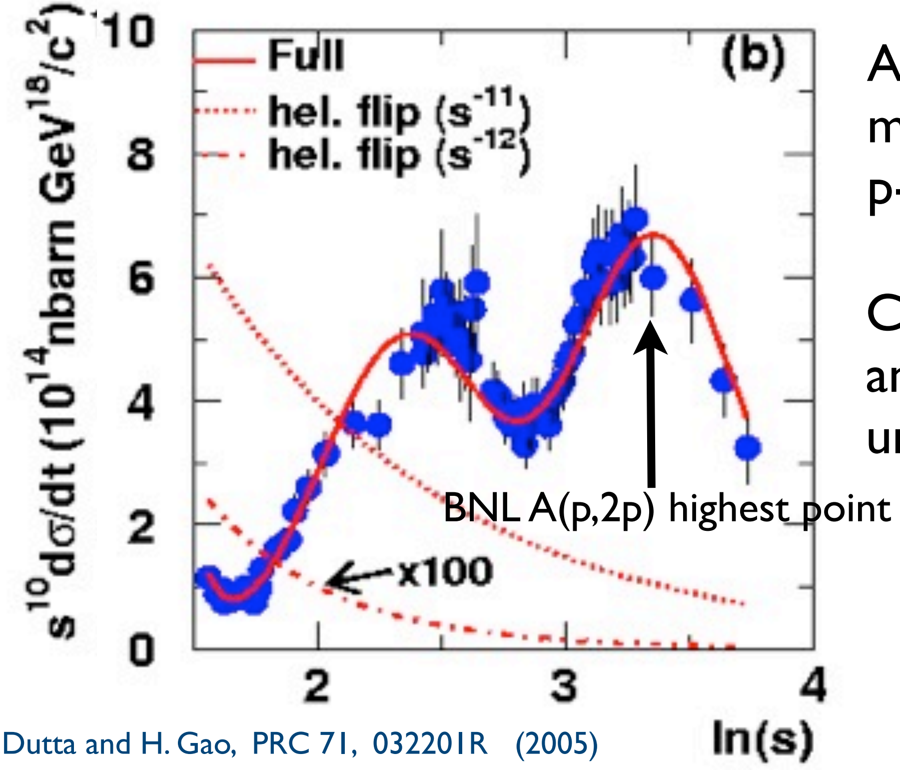

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Experiment would need
a solenoid spectrometer
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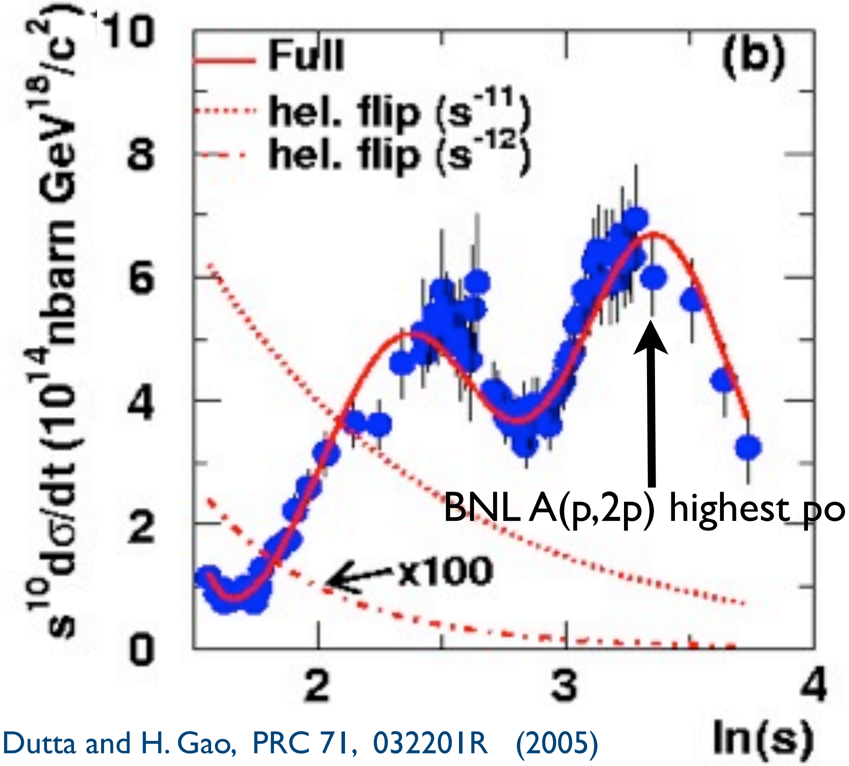

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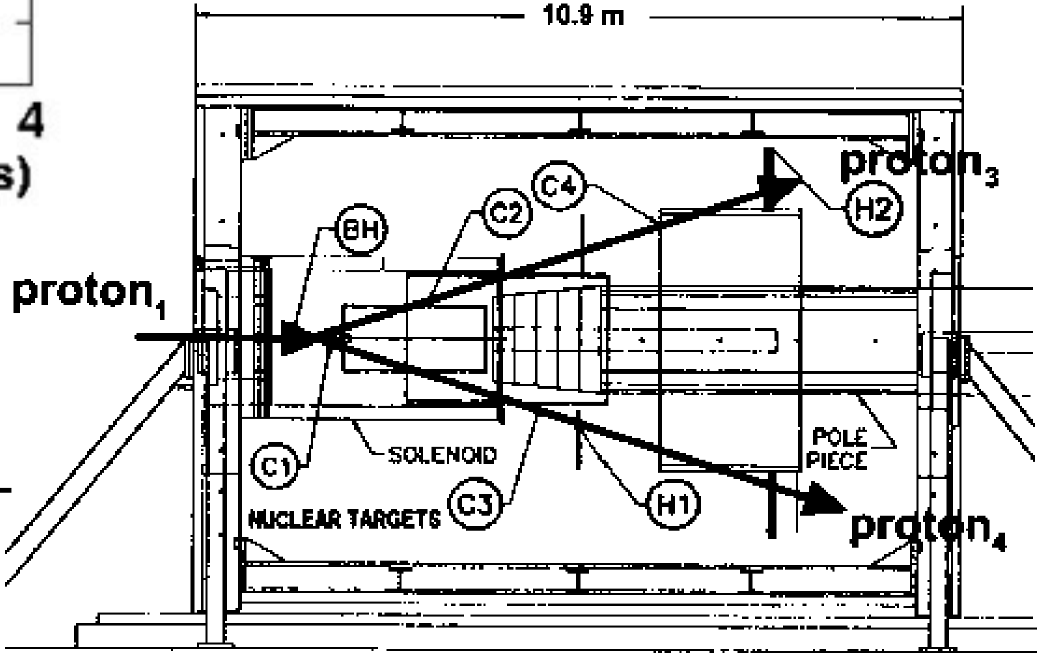

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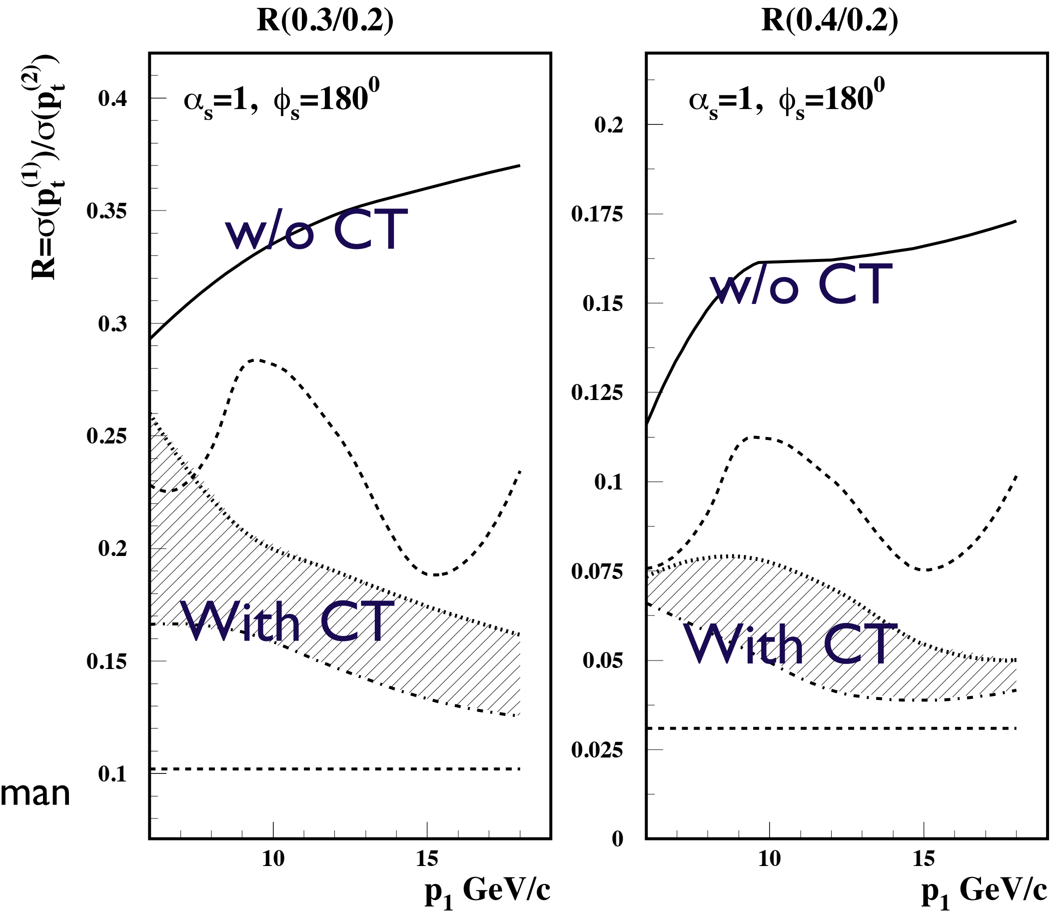
New Observables

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

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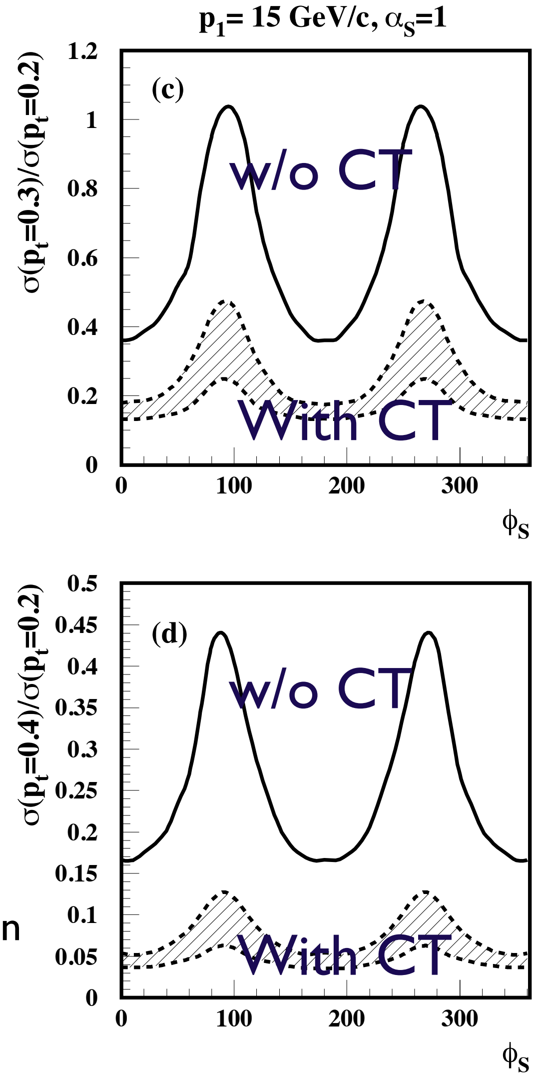


Requires high resolution spectrometer for the fast protons and pion veto

Nucleon vs Meson Transparency

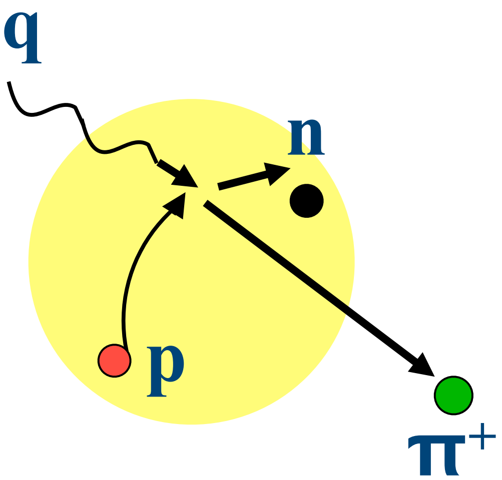
- There is no unambiguous, model independent, evidence for the onset of CT in qqq systems.
- Small size is more probable in 2 quark system such as pions than in protons.

  \- 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 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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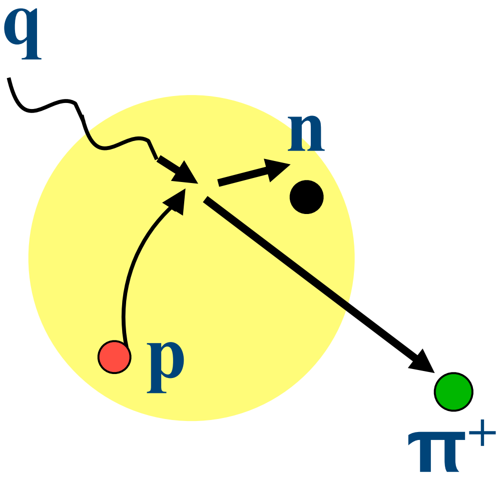

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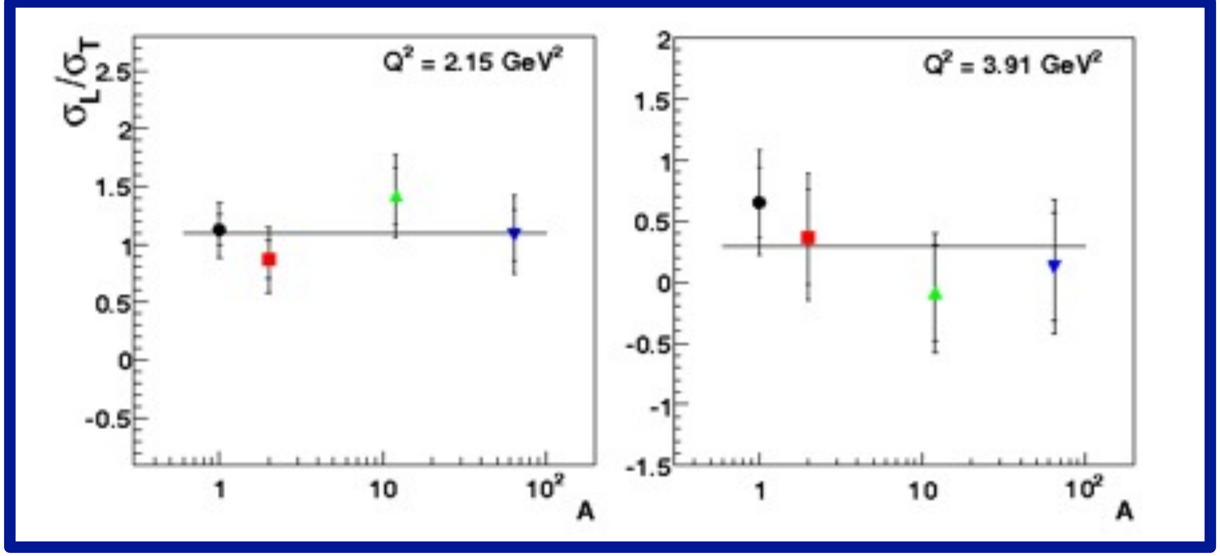
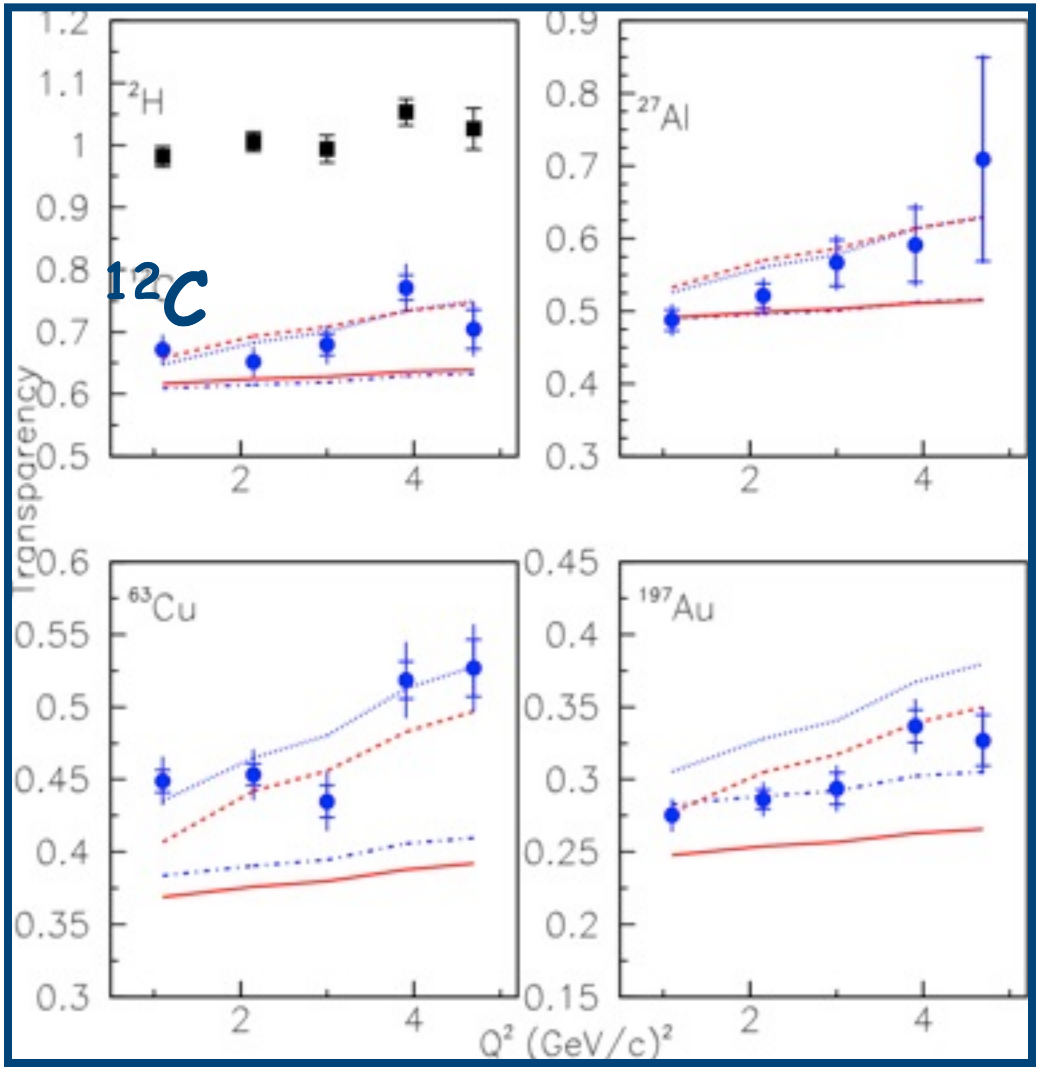
X. Qian et al., PRC81:055209 (2010),



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

Pion Transparency



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

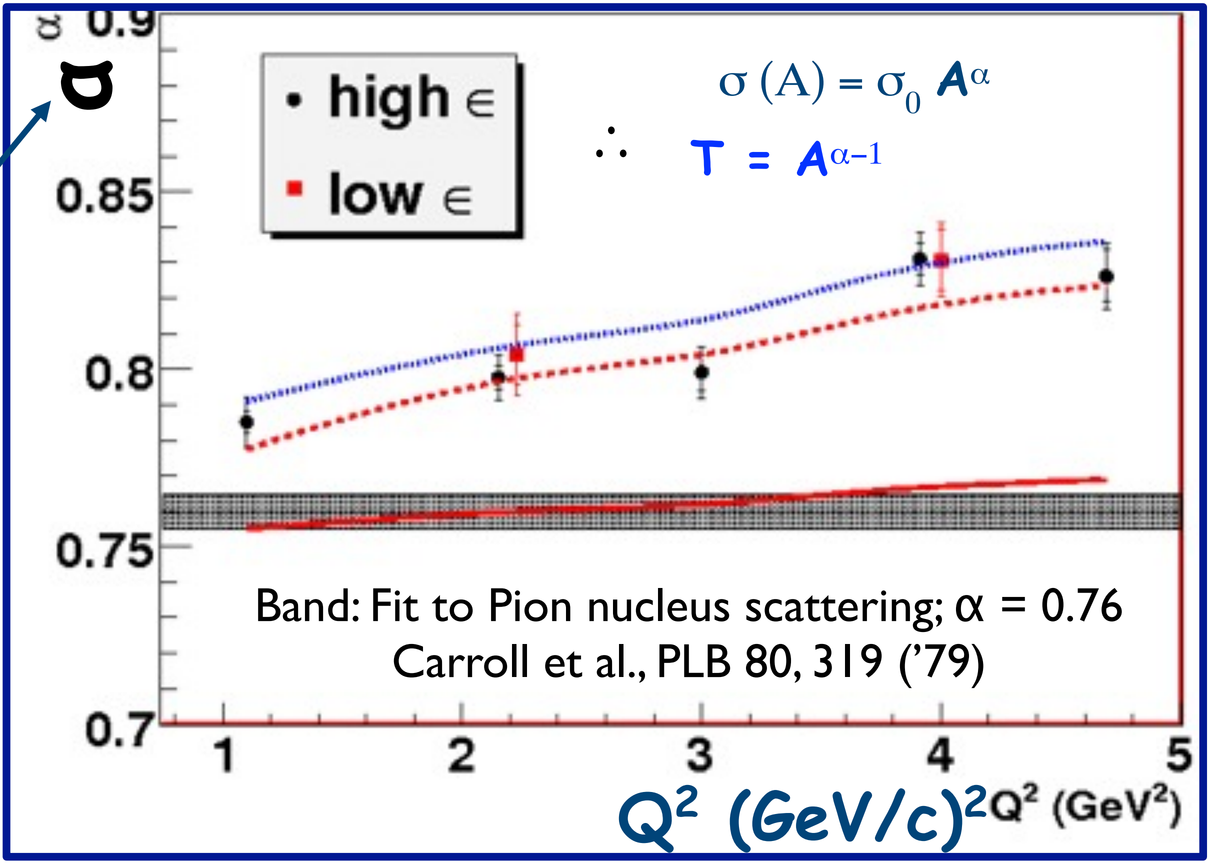
$$T = \frac{\sigma_A^{\text{Expt}} / \sigma_A^{\text{Model}}}{\sigma_p^{\text{Expt}} / \sigma_p^{\text{Model}}}$$

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

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



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

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

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

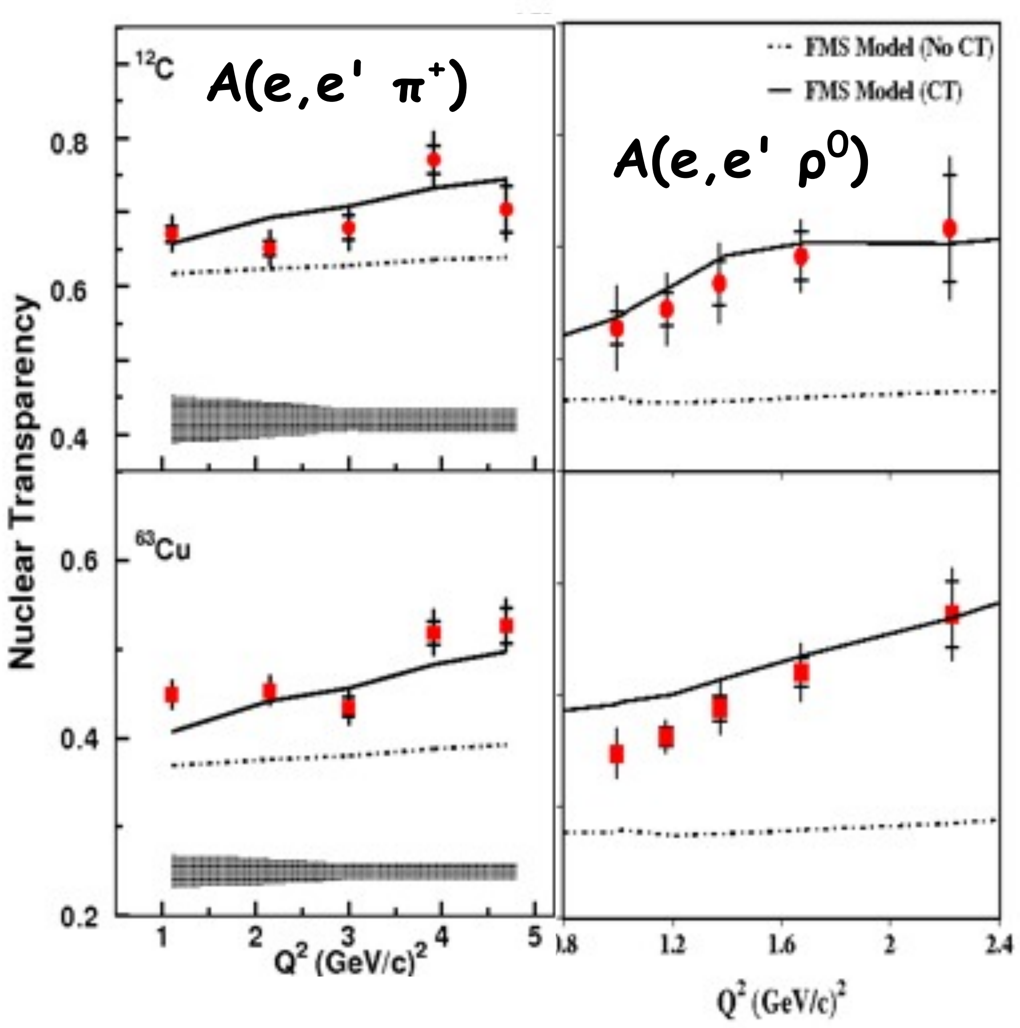
B. Clasie et al. PRL 90, 10001, (2007)
X. Qian et al., PRC81:055209 (2010),

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

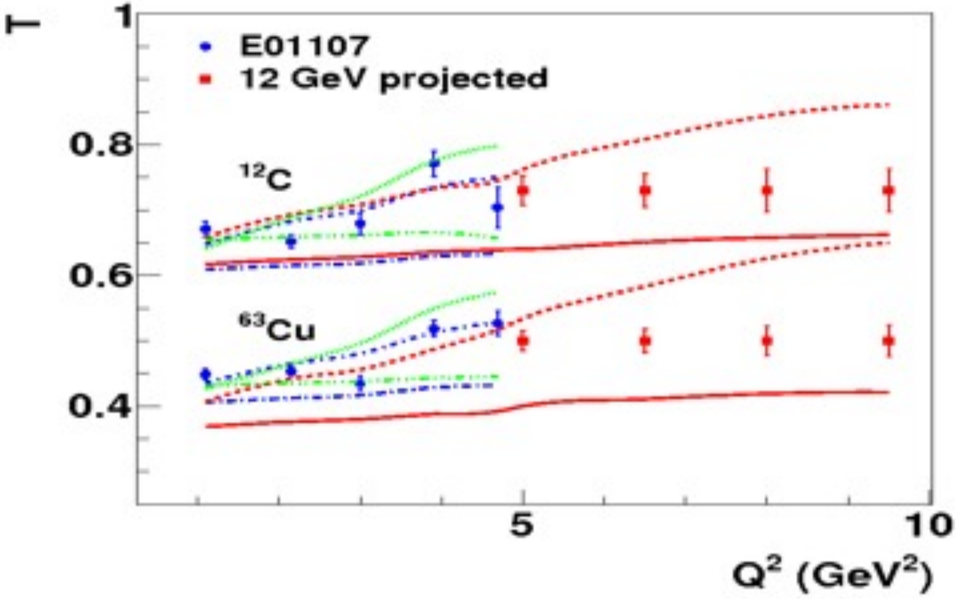


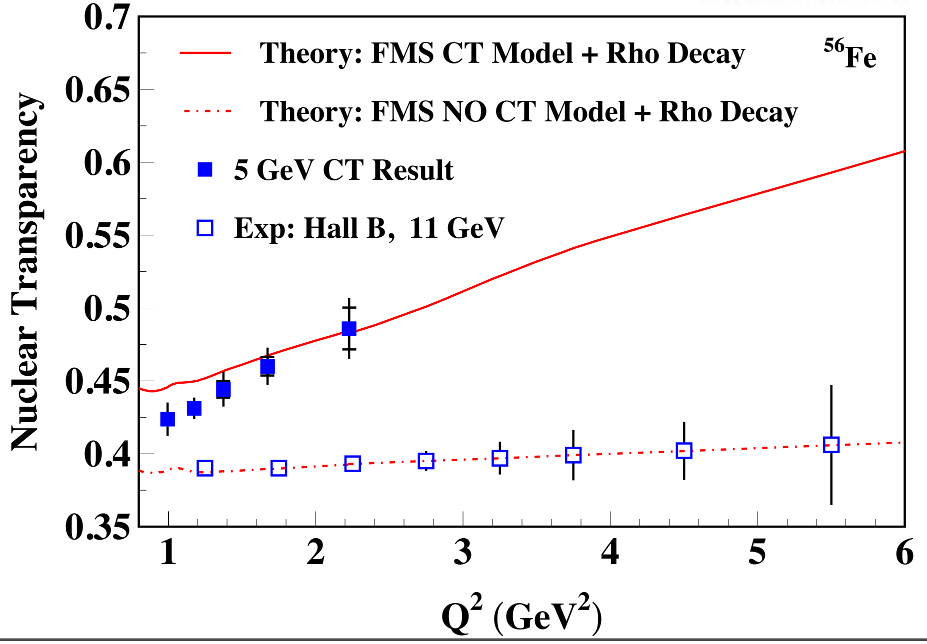
- Hall-C Experiment E01-107 pion electroproduction from nuclei found an enhancement in transparency with increasing Q^2 & A, consistent with the prediction of CT.
  (X. Qian et al., PRC81:055209 (2010), B. Clasie et al, PRL99:242502 (2007))

- 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

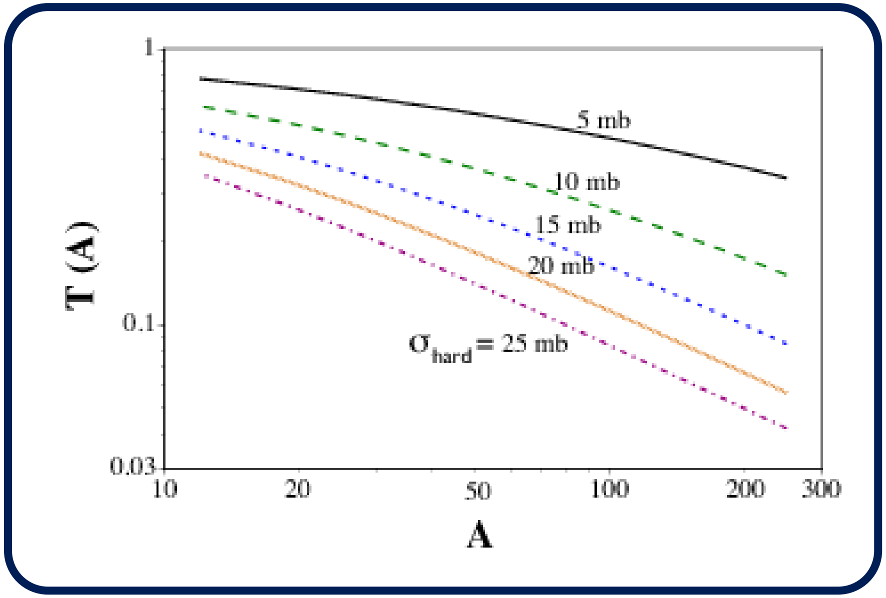
Will help confirm the onset of CT observed at 6 GeV

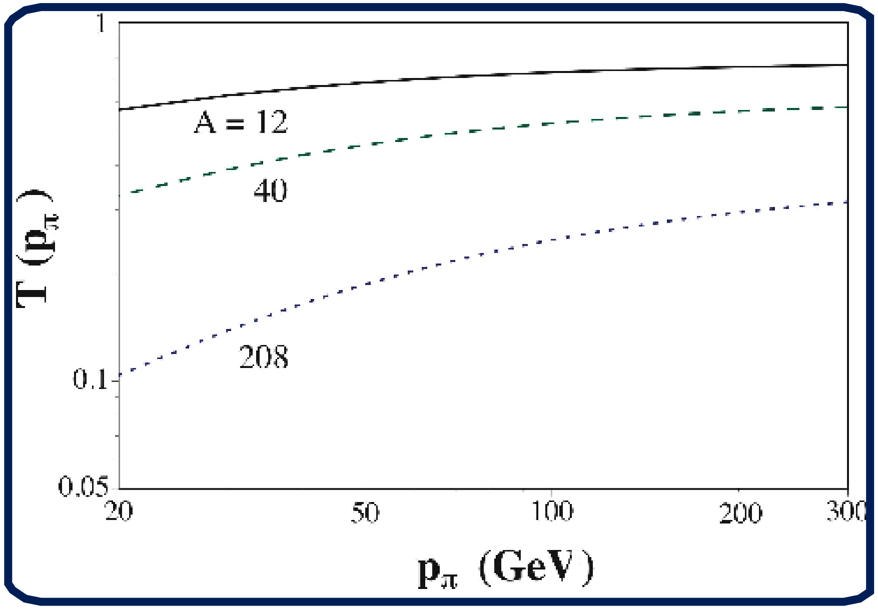
will verify the strict applicability of factorization theorems for meson electroproduction

New Observables

2 → 3 processes with pions $\pi + A \rightarrow \underbrace{\pi + \pi}_{\text{hard sub-process}} + A^*$

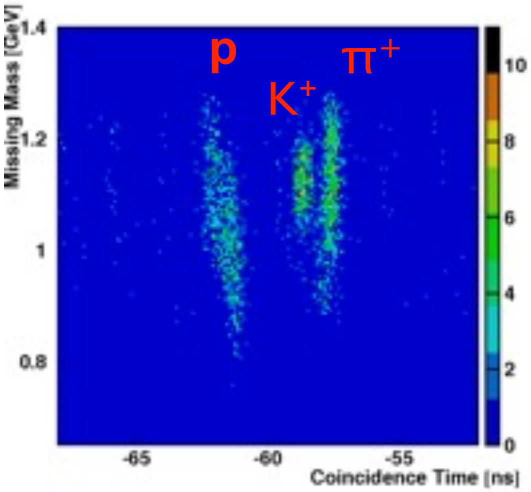
S. Kumano and M. Strikman PLB 683, 259 (2010)
S. Kumano, M. Strikman and K. Sudoh PRD 80, 073004 (2009)





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

Kaon Transparency

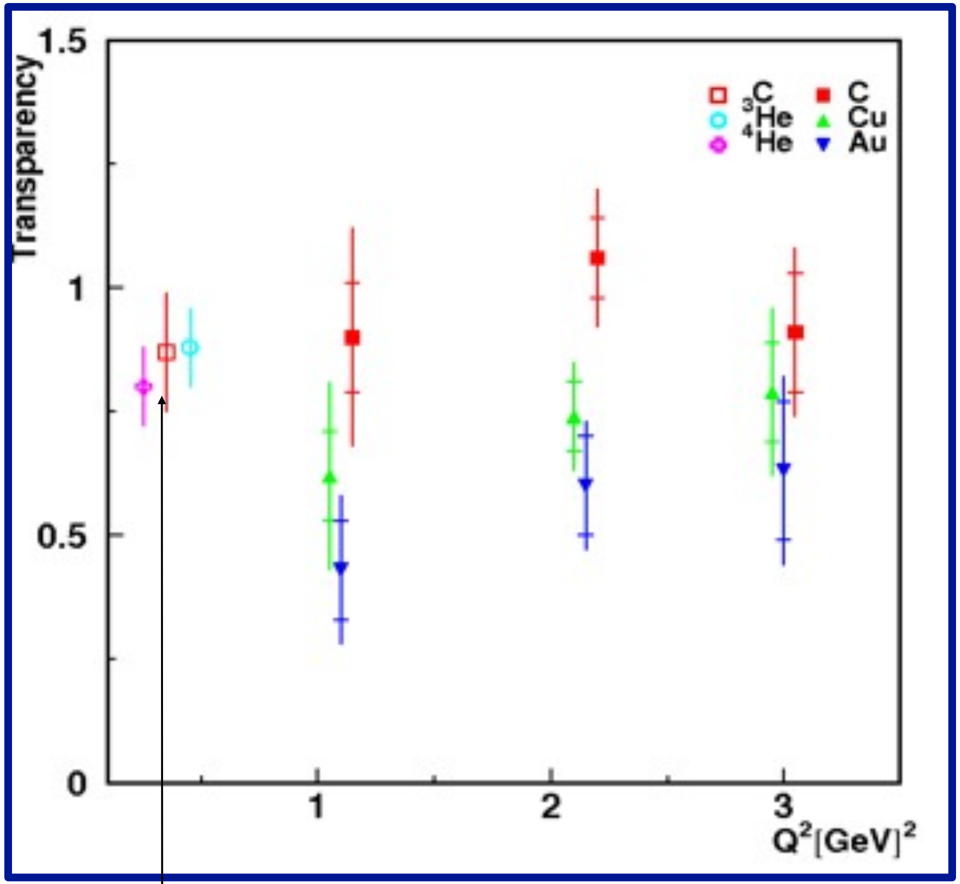


$$T = \frac{\sigma_A^{\mathrm{Expt}} / \sigma_A^{\mathrm{Model}}}{\sigma_D^{\mathrm{Expt}} / \sigma_D^{\mathrm{Model}}}$$

Compared with D to minimize impact of non-isoscaler effects

No energy dependence within uncertainties

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

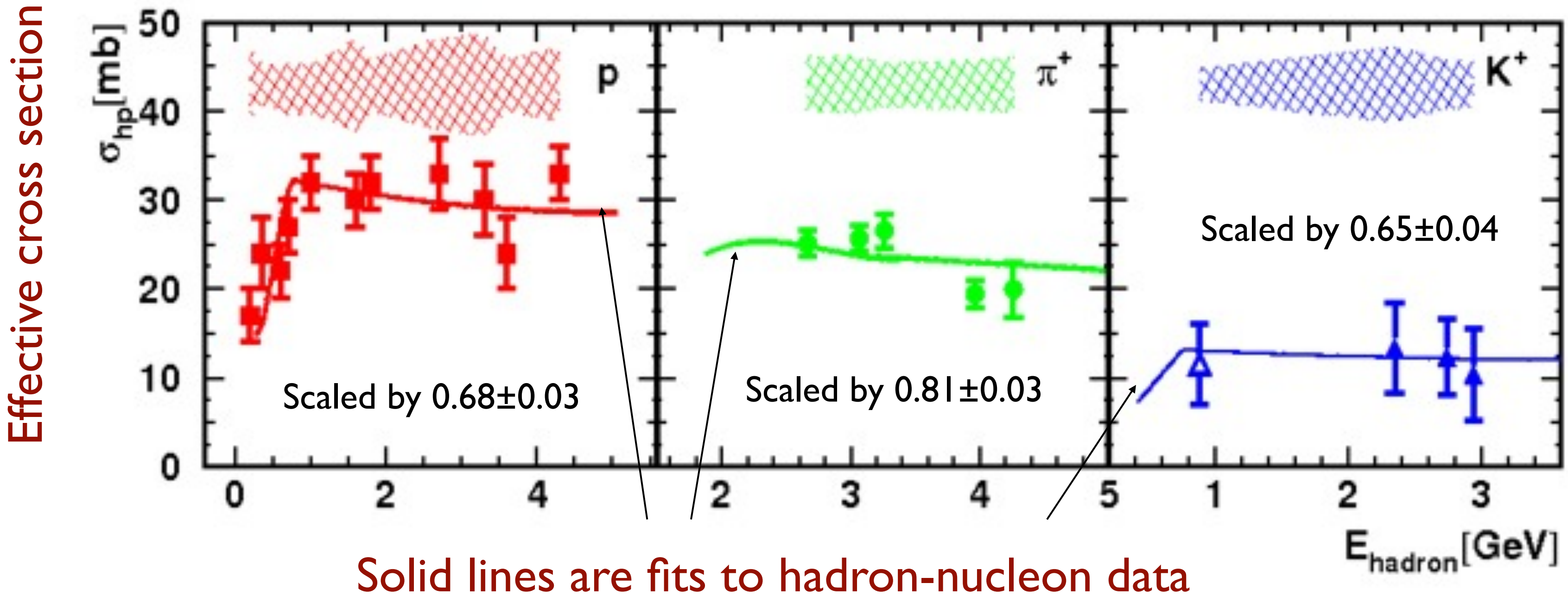


Earlier data on light nuclei

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

Hadron Propagation in Medium

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



Solid lines are fits to hadron-nucleon data

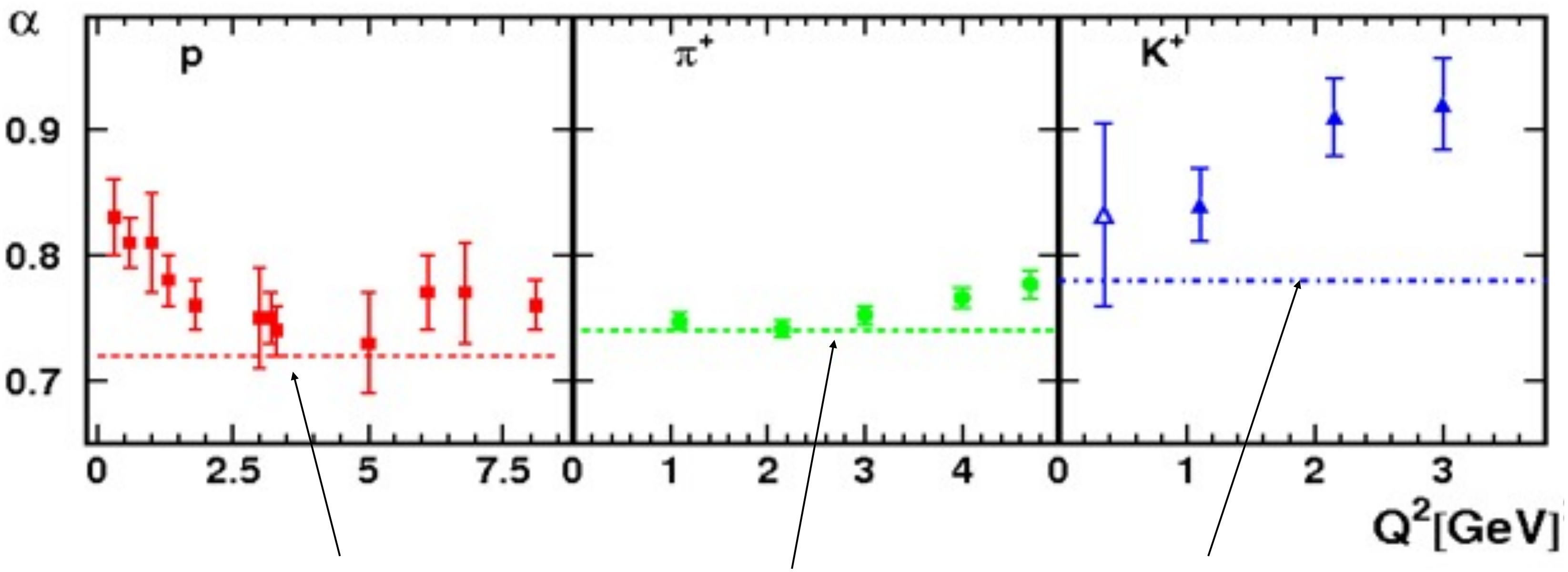
Effective cross section from fitting the measured transparency to a simple geometric model

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)

'A' dependence of Transparency

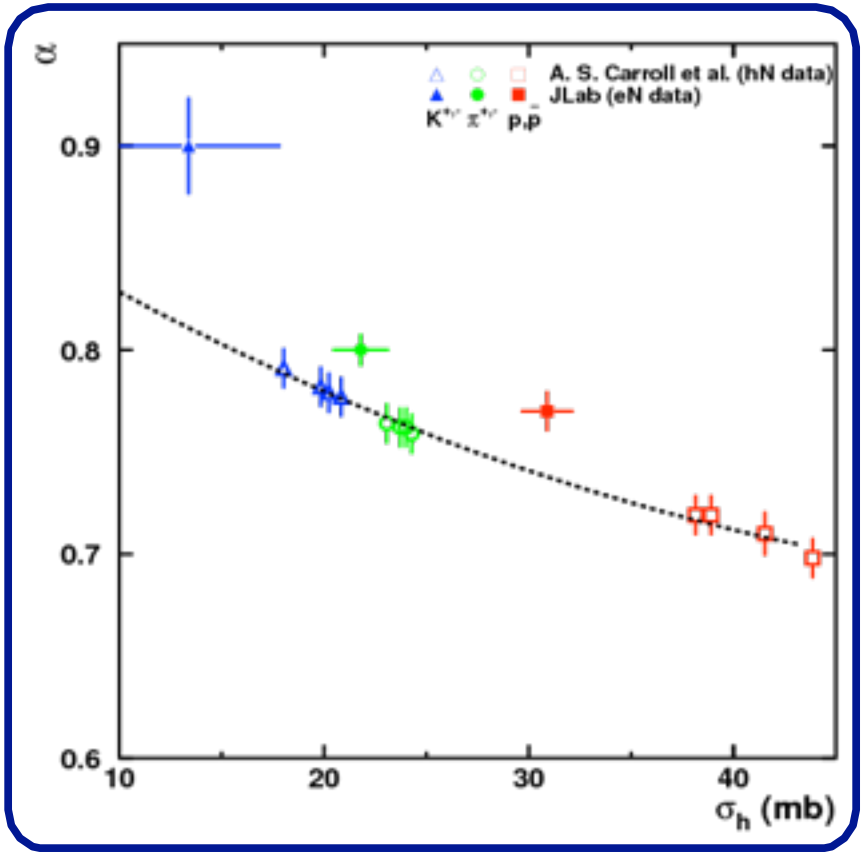


dashed lines are α values from hadron-nucleus data

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

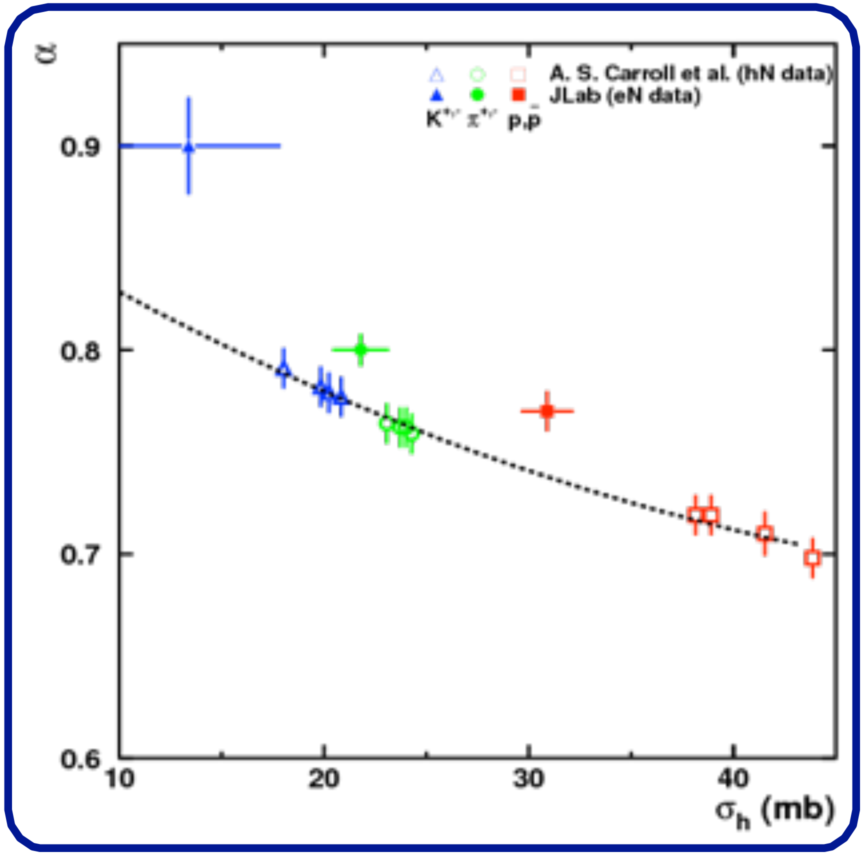
α from electron scattering is larger than those obtained from hadron scattering for all hadrons, the difference is largest for kaons

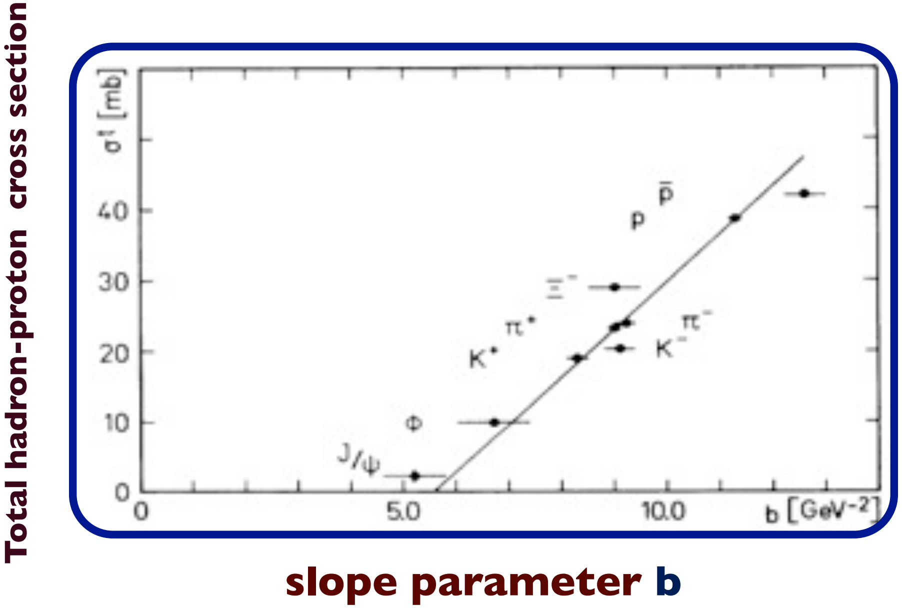
Hadron Propagation in Medium



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 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 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 and possible at J-PARC using the new high momentum hadron beamline. This will require a new high resolution spectrometer similar to EVA at BNL and accelerator operation at several different beam energies.

Summary

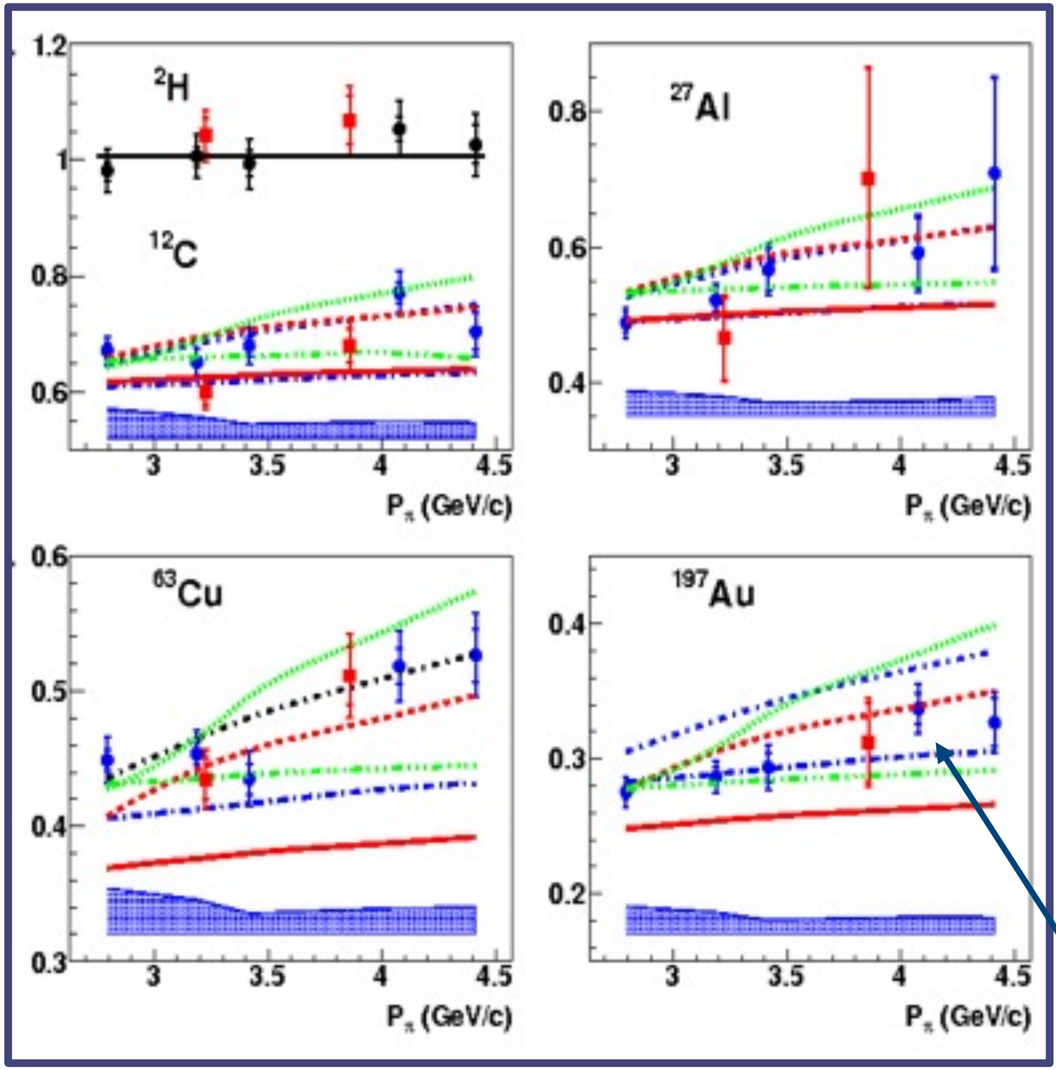
- Experiments at JLab have conclusive shown the onset of CT in mesons. These meson electroproduction experiments will also be extended to higher energies at the upgraded JLab.

- 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.

- J-PARC is in a great position to investigate these results.

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, P
74, 062201R ('06)

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

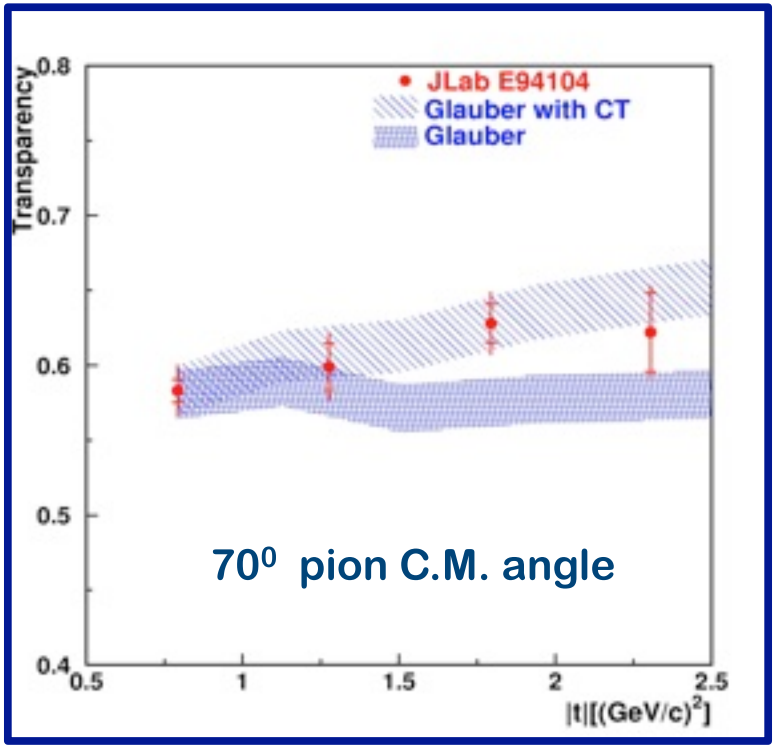
Inner error bar are statistical uncertainties outer error bar are the quadrature sum of statistical and pt. to pt. systematic uncertainties.

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

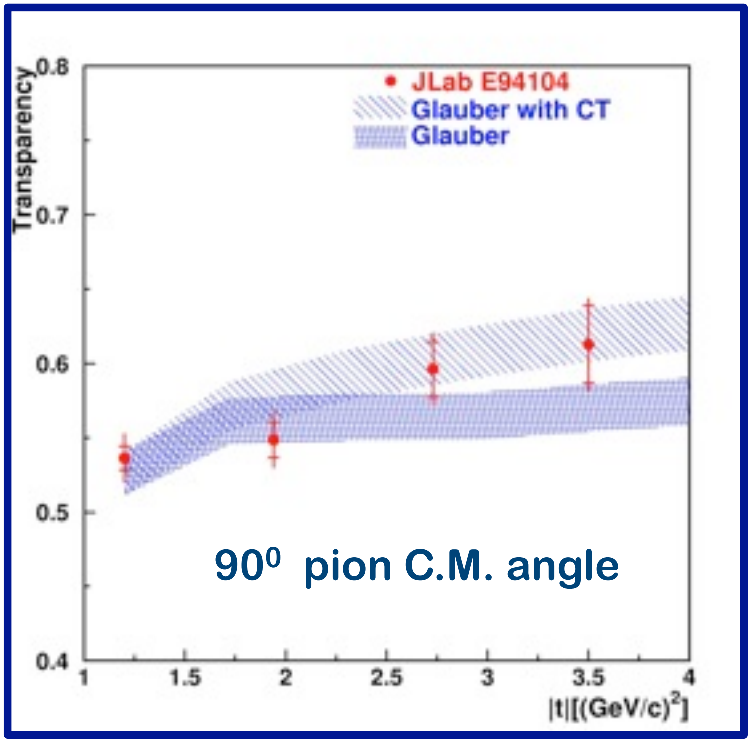
Pion Photoproduction $^4\mathrm{He}(\gamma,\pi^- p)$

Positive hints from pion photoproduction in JLab Hall A
(H. Gao & R. Holt Spokespersons)

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



70^0 pion C.M. angle



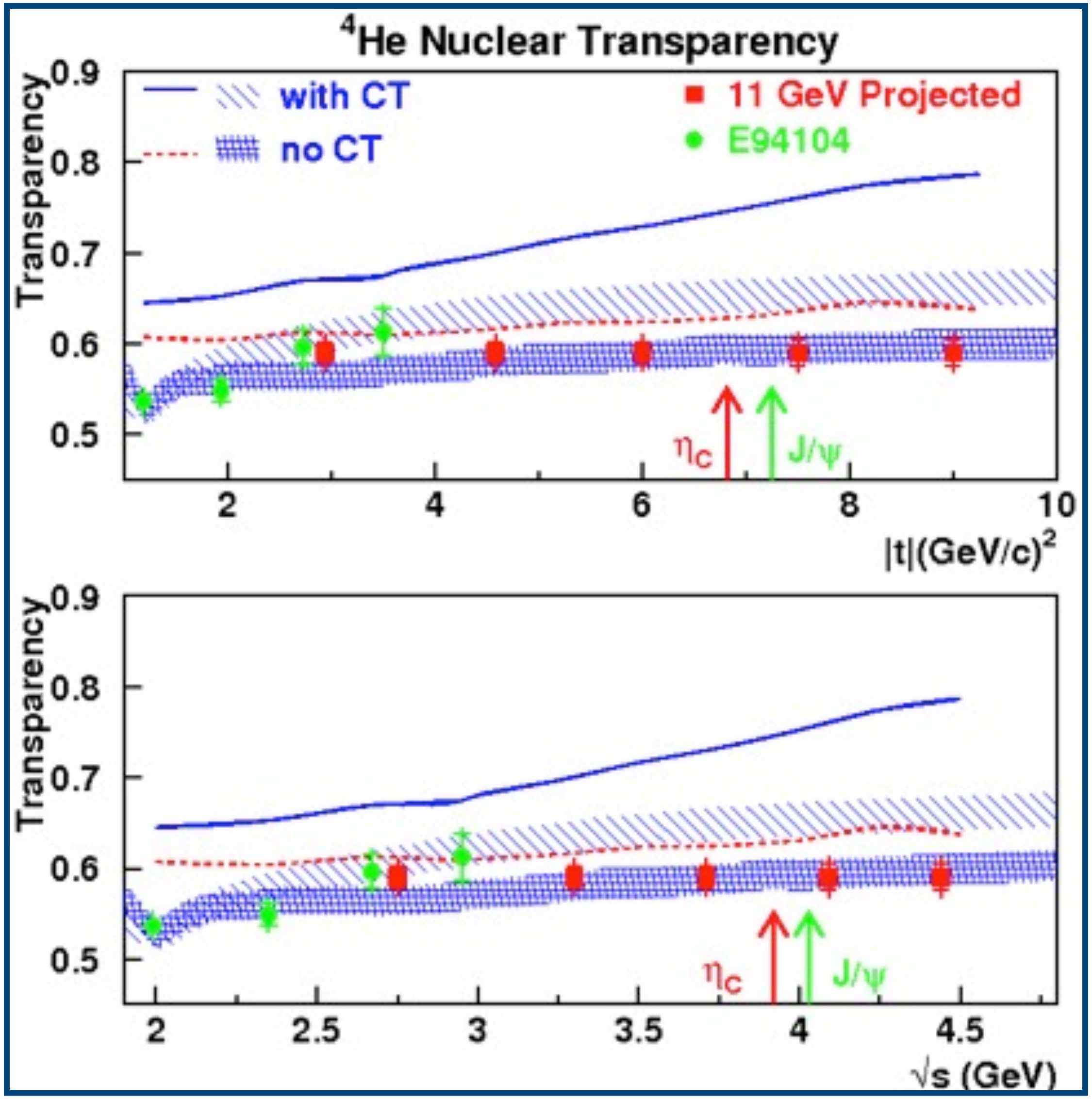
90^0 pion C.M. angle

Deviations from Glauber !

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

^{4}He(γ,pπ^-) @ 12 GeV

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

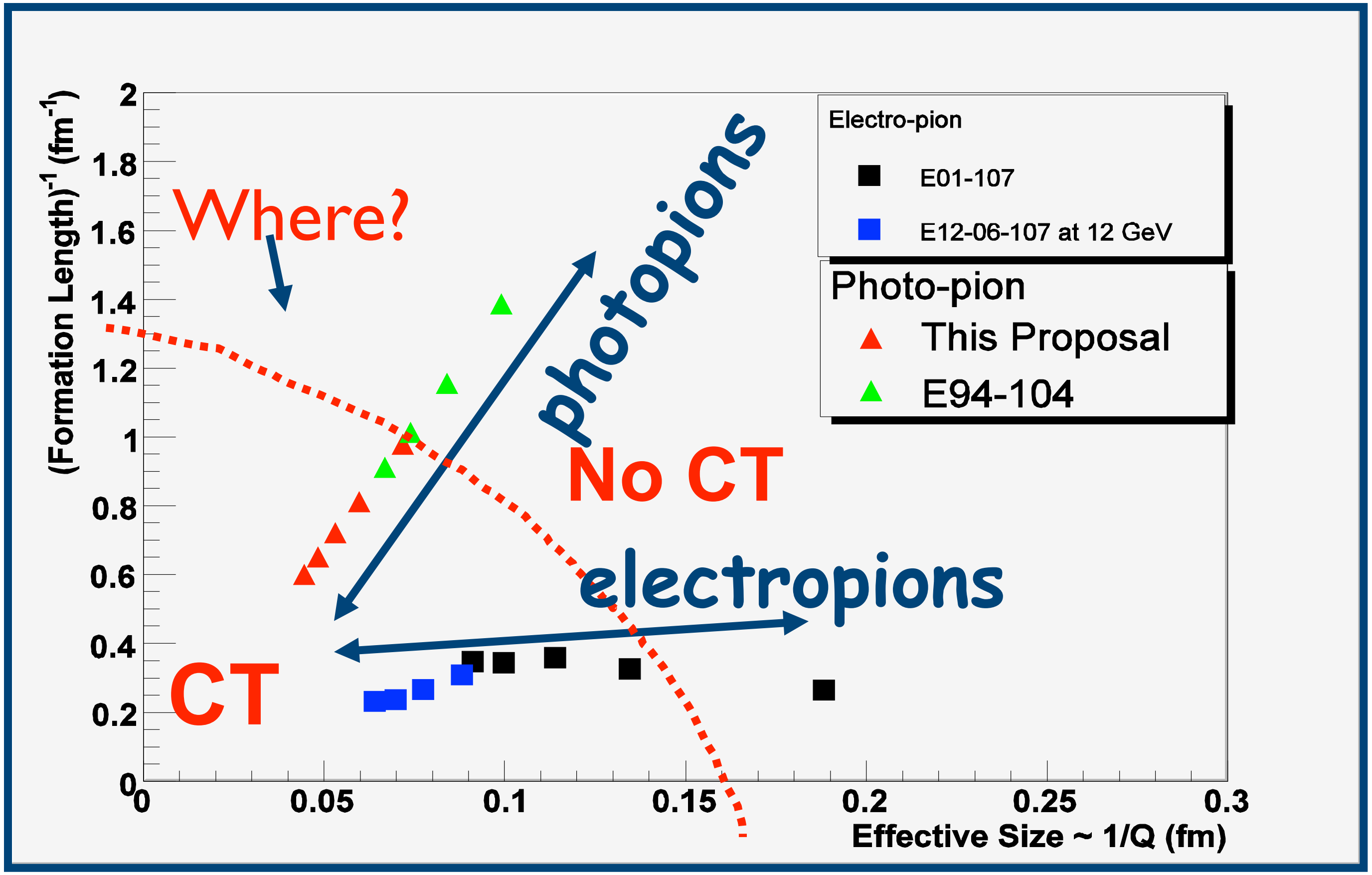


Measures across the charm threshold, it could help understand the p2p results from BNL

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