Color Transparency and the role of fixed-target proton beam experiments

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[redacted]

Jefferson Lab
Exploring the Nature of Matter

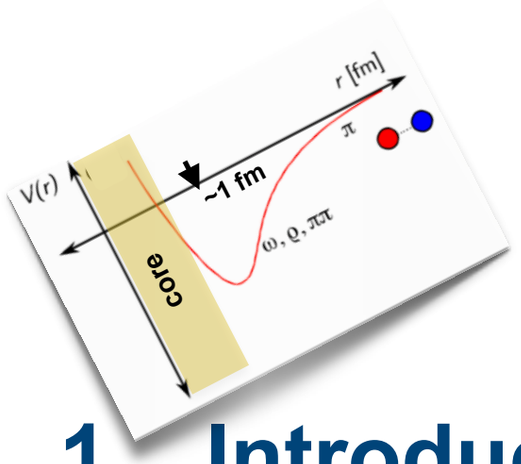
Center for Frontiers in Nuclear Science

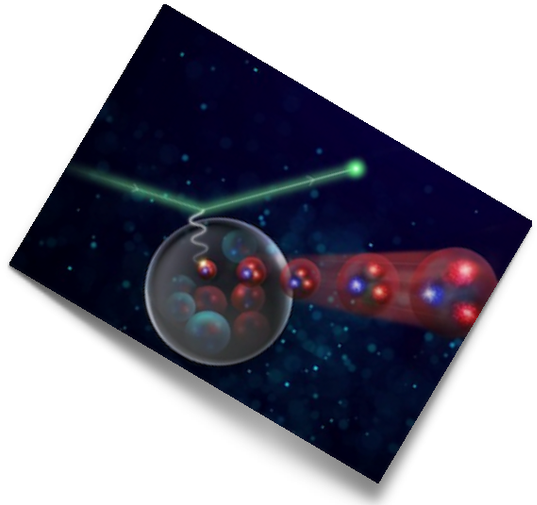
Advancing Nuclear Physics: New Horizons with Fixed-Target Proton-Nucleus Experiments at Intermediate Energies

CFNS

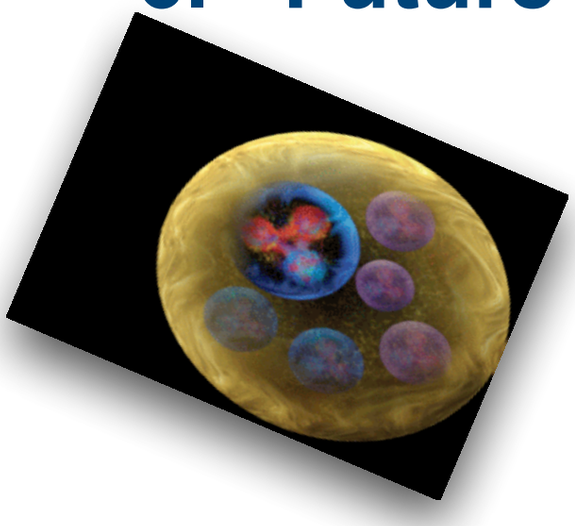
July 10-11, 2025

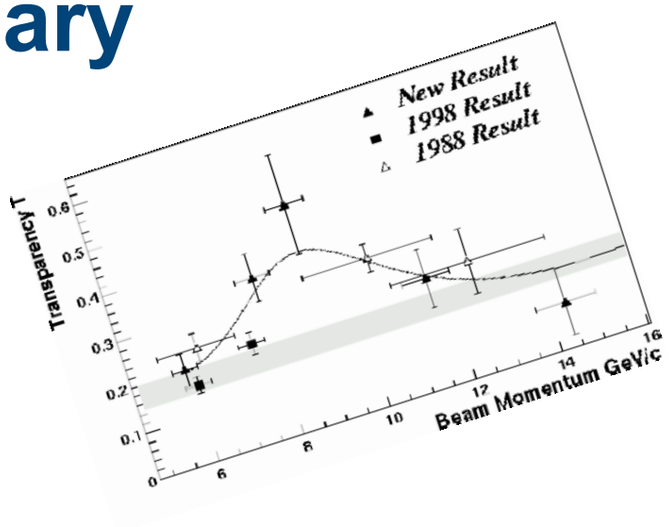
Outline





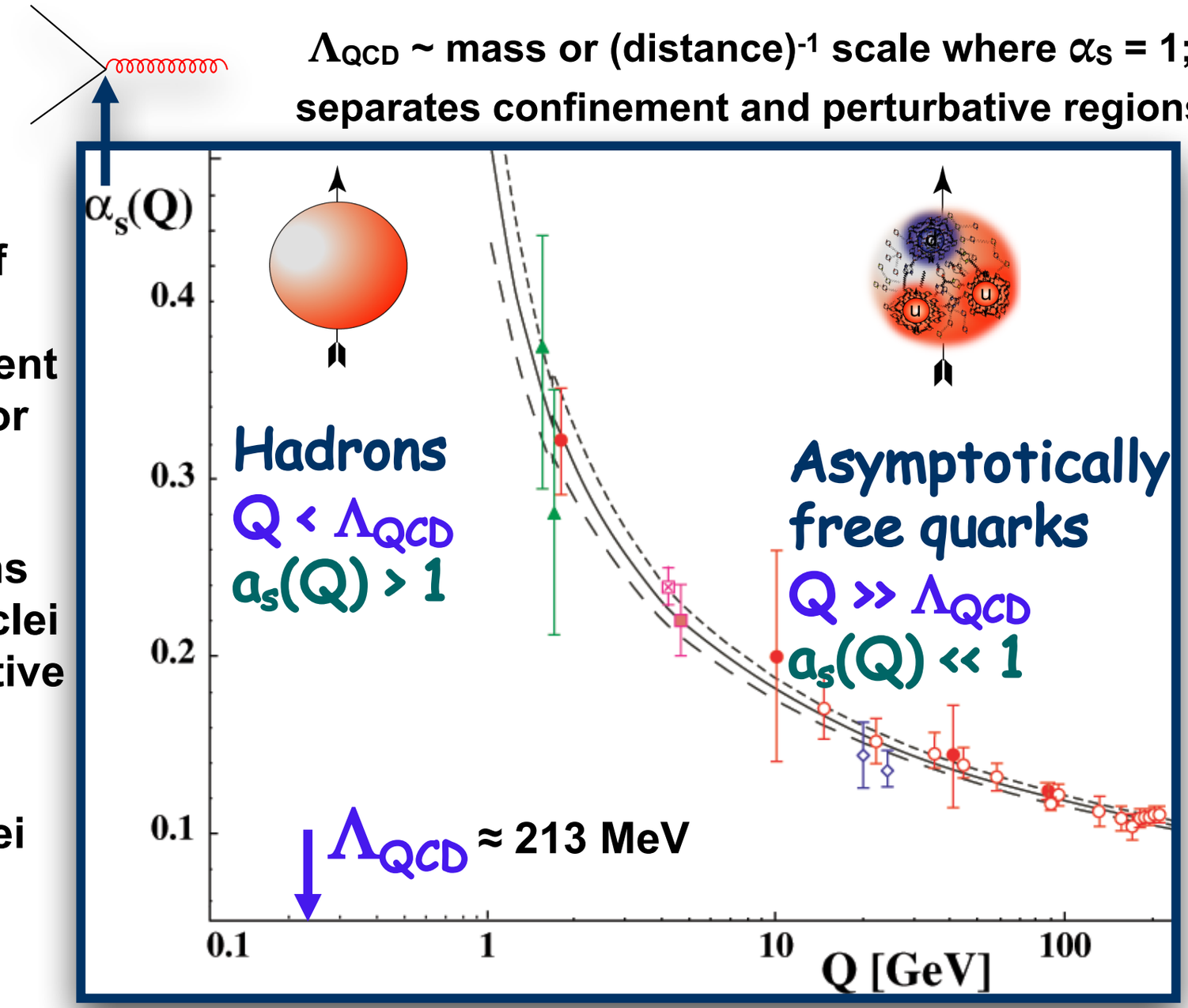
1. Introduction
2. Nuclear transparency and Hadron propagation
3. Color transparency & Small size configuration
4. Some recent results and a **new puzzle**.
5. Fixed target proton beam experiments can help.
6. Future possibilities and Summary





The role of quarks and gluons in nuclei is still one of the important unsolved and much debated problems.

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



Nuclei as stable systems made of quarks & gluons should be excellent testing ground for QCD.

quarks and gluons in nucleons + nuclei are non-perturbative (hidden)

Hadrons in nuclei are strongly interacting.

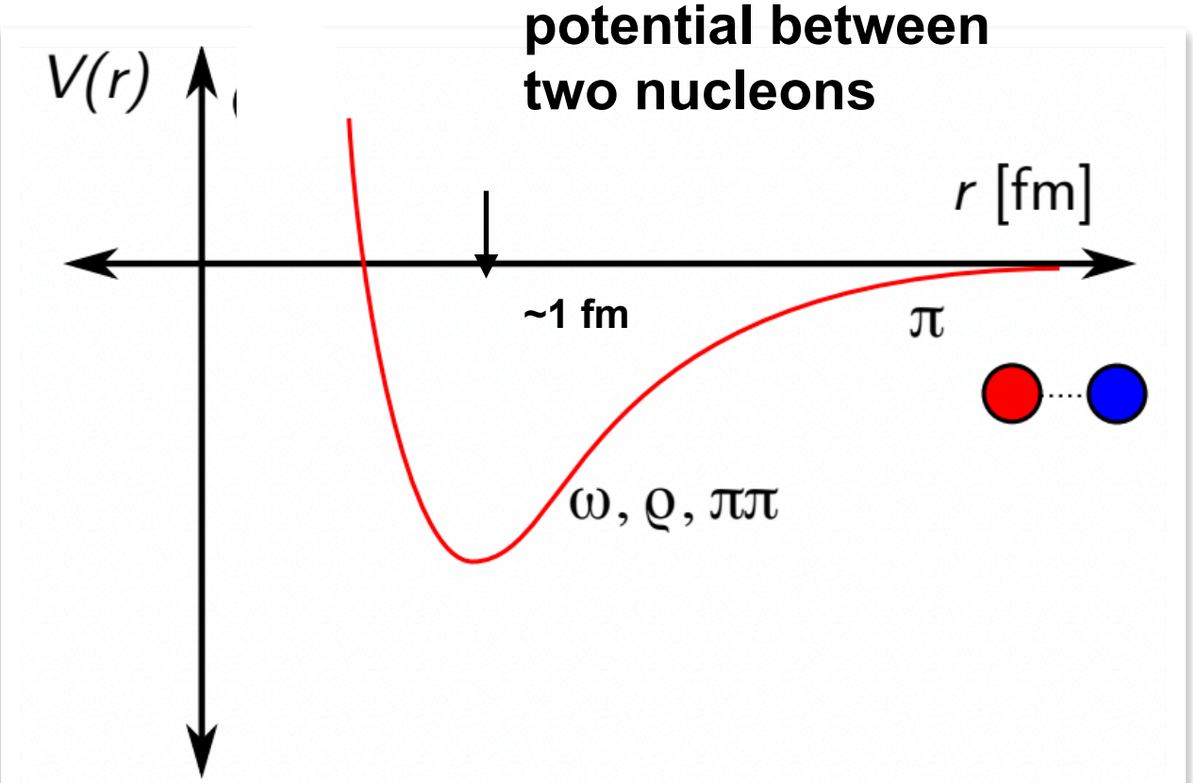
Unclear what energy is high enough for pQCD to be un-ambiguously applicable

pQCD mechanisms dominate at high energies or short distances

QCD is the only legitimate candidate for a theory of the strong force, but there is no consensus on how it works.

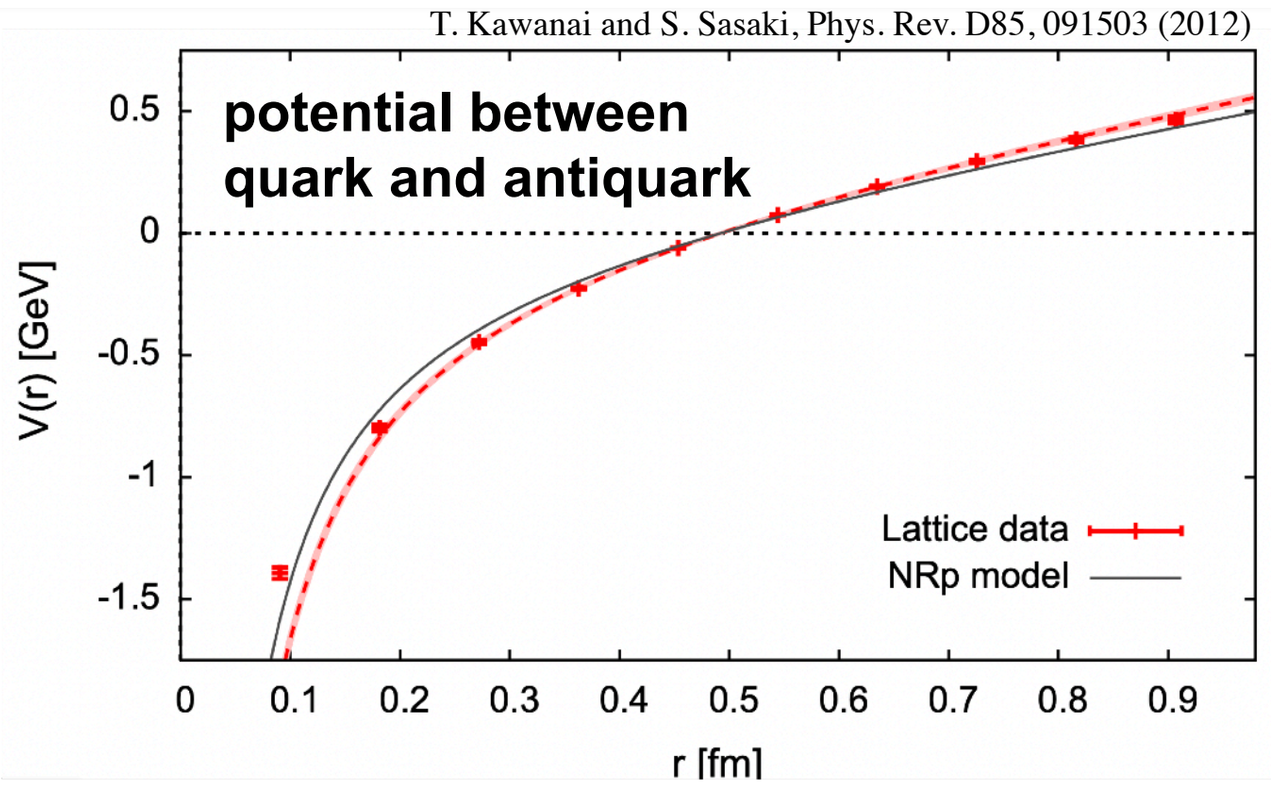
Matter is colorless

Traditional nuclear physics: nucleons + mesons



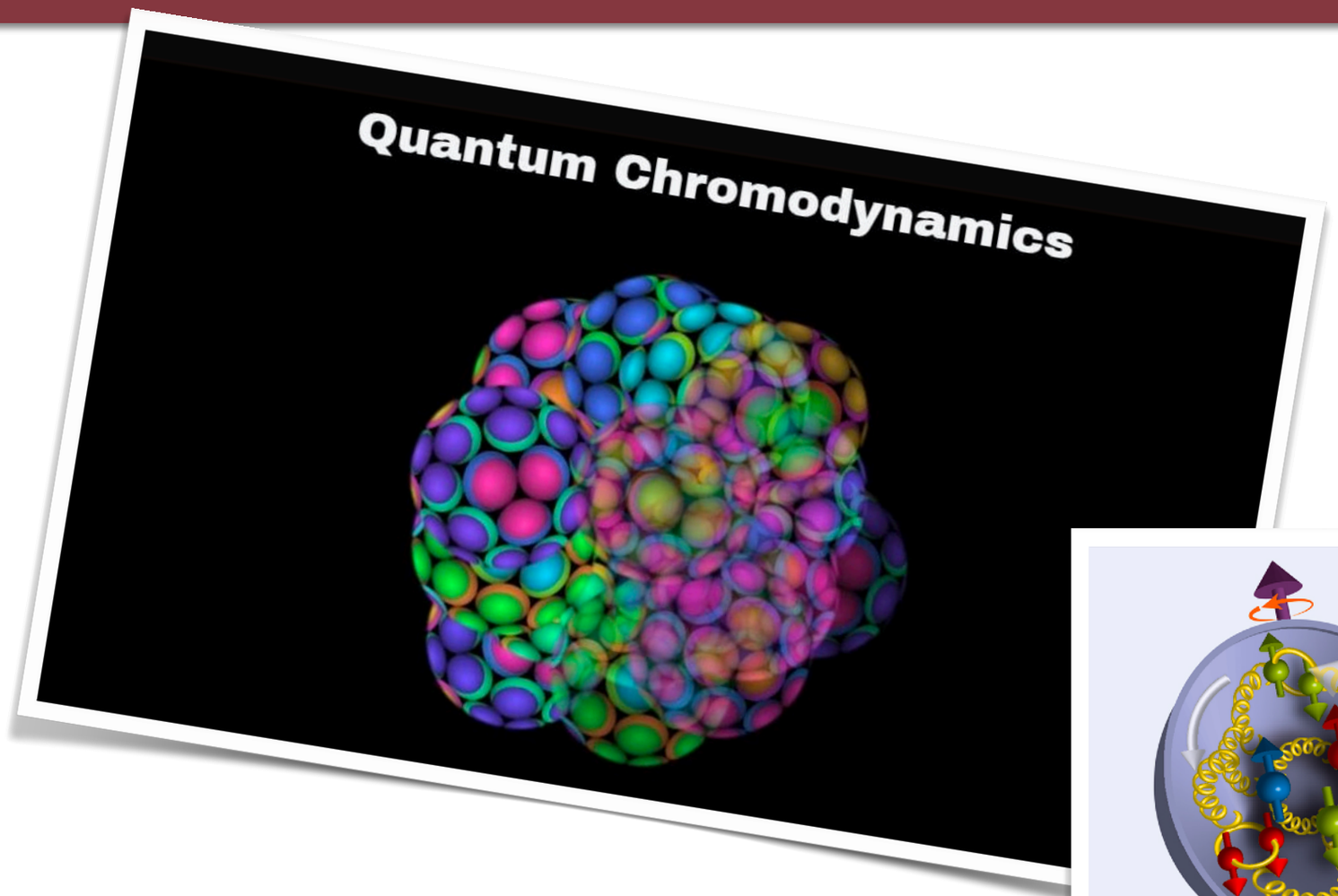
QCD: quarks + gluons with linear confining potential for r > 0.5 fm

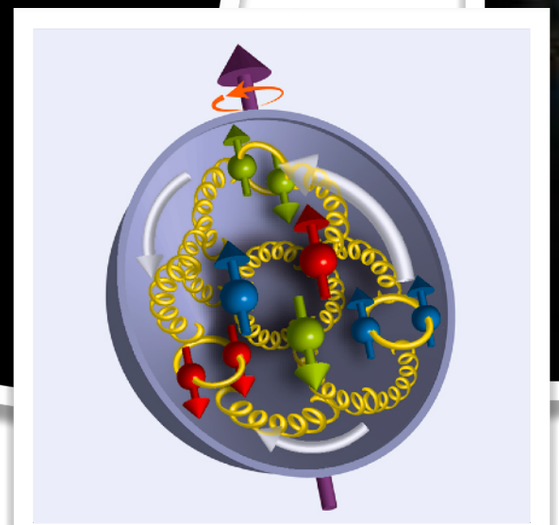
T. Kawanai and S. Sasaki, Phys. Rev. D85, 091503 (2012)



How to describe nuclei in terms of quarks & gluons of QCD?
What is the energy threshold for the transition?

Can the strong nuclear force be rigorously understood in terms of accepted fundamental theory?

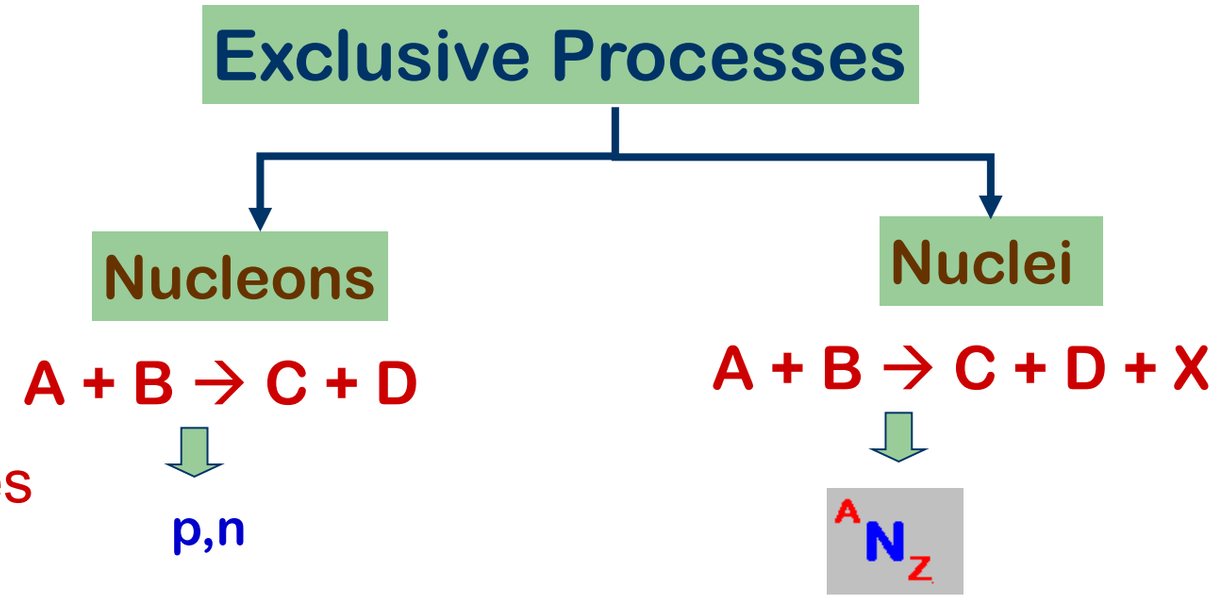




(How exactly are protons and neutrons built starting with the underlying quarks and gluons?
What is the origin of quark confinement in the strong force?)

Study of propagation of hadrons in nuclei with exclusive processes can be used to search for onset of QCD predictions

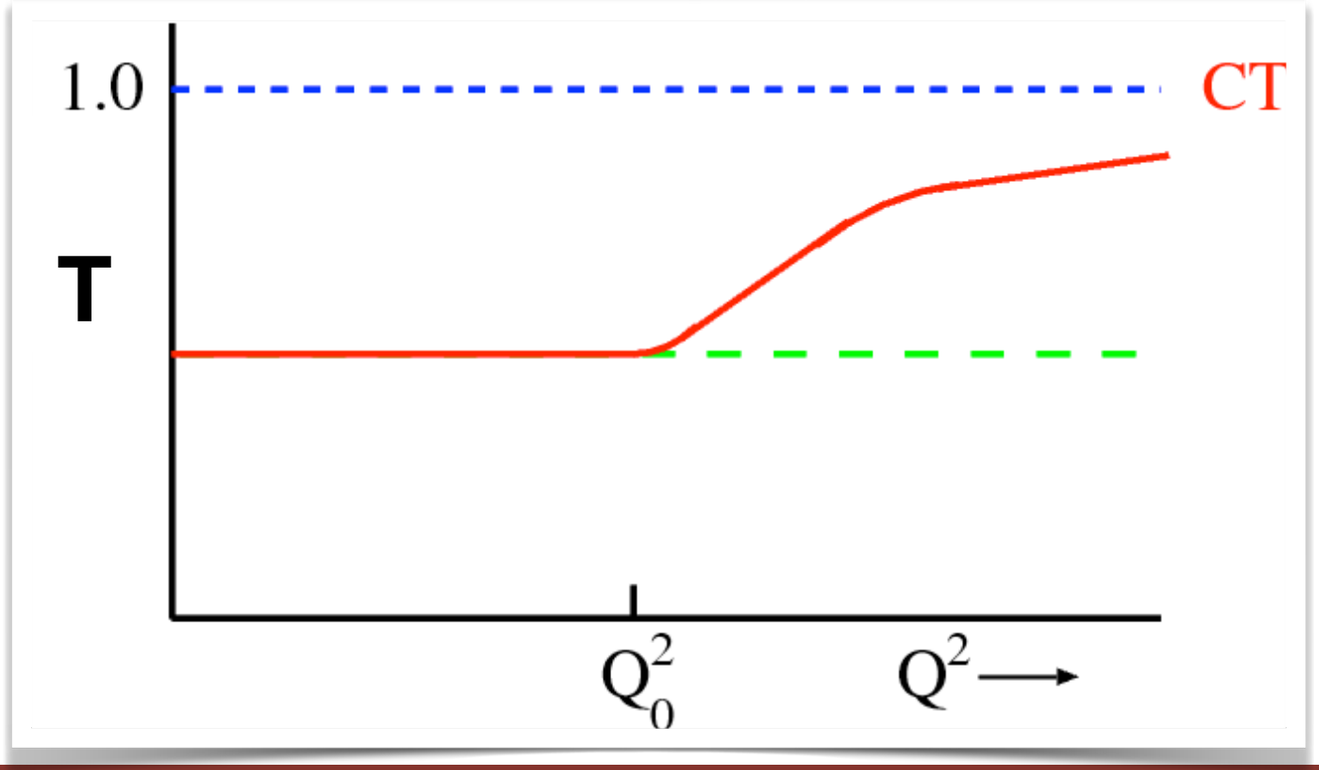
Exclusive processes (processes with completely determined initial and final states)



1. Quark counting rules
2. Hadron helicity conservation

1. Color transparency
2. Nuclear filtering

Look for the onset of QCD predictions associated with hadron propagation in nuclei (such as reduction of Final State Interaction, FSI)



Nuclear transparency is energy independent in the strongly interacting hadronic picture.

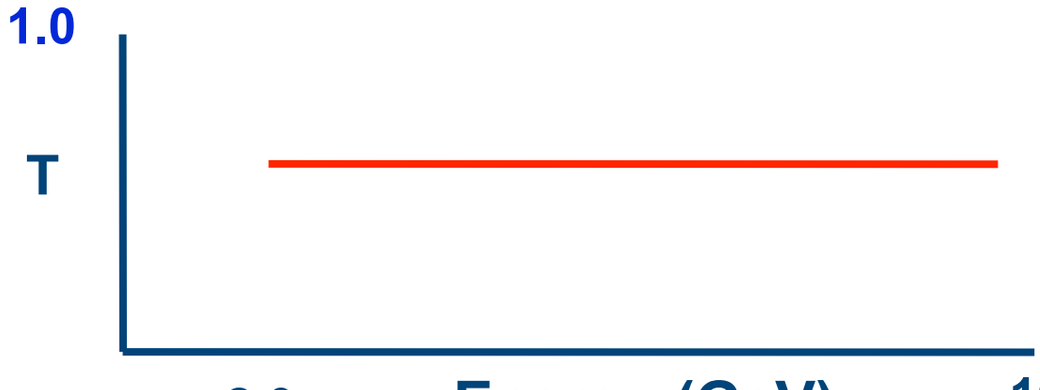
At high energies hadron propagation is dominated by **reduction of flux**, which is quantified by **Nuclear Transparency**.

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

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

σ_0 = free (nucleon) cross-section

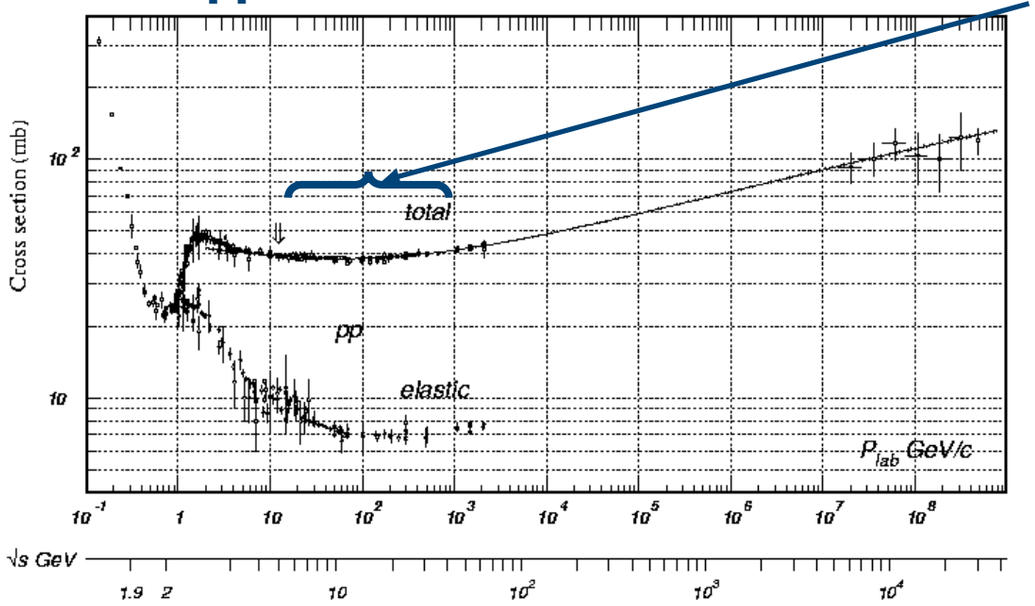
Traditional NP calculations



Ingredients

- σ_{hN} h-N cross-section
- Glauber multiple scattering approximation
- Correlations & FSI effects.

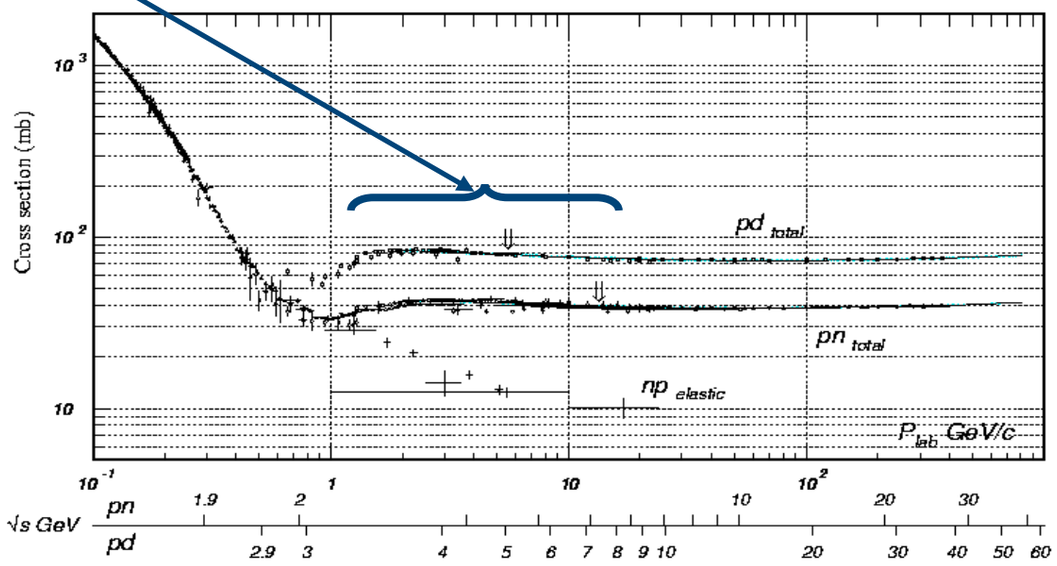
pp scatt. cross-section



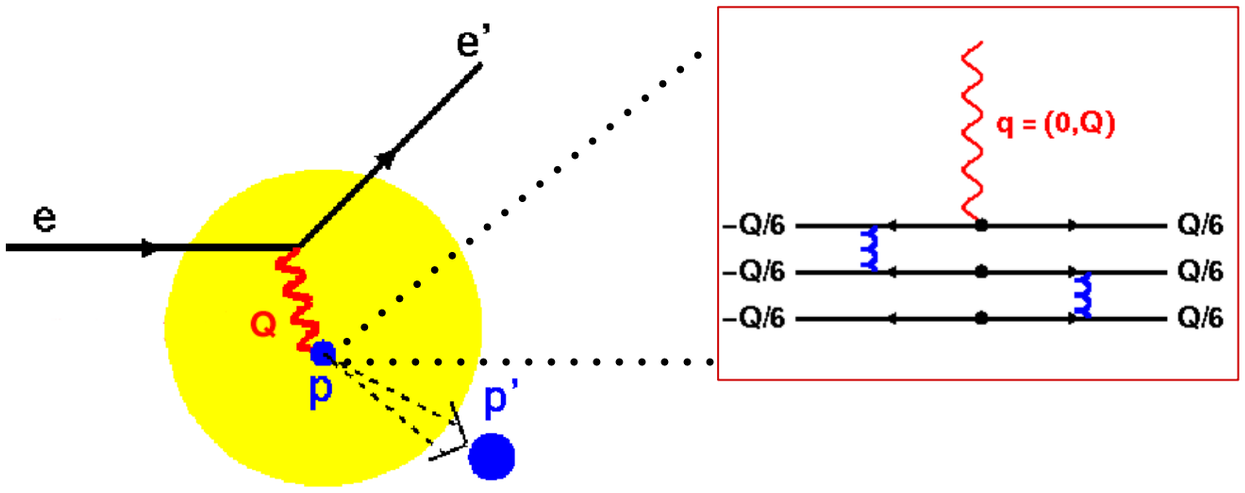
energy independent

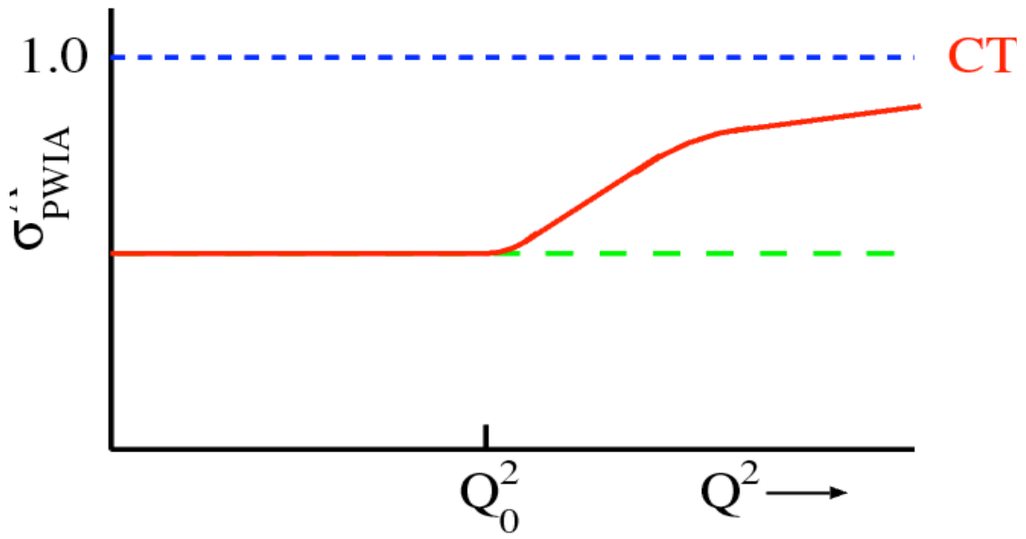
pn scatt. cross-section

plots from PDG



QCD predicts that h-N interaction for hadrons produced in exclusive processes at high Q should vanish.





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".

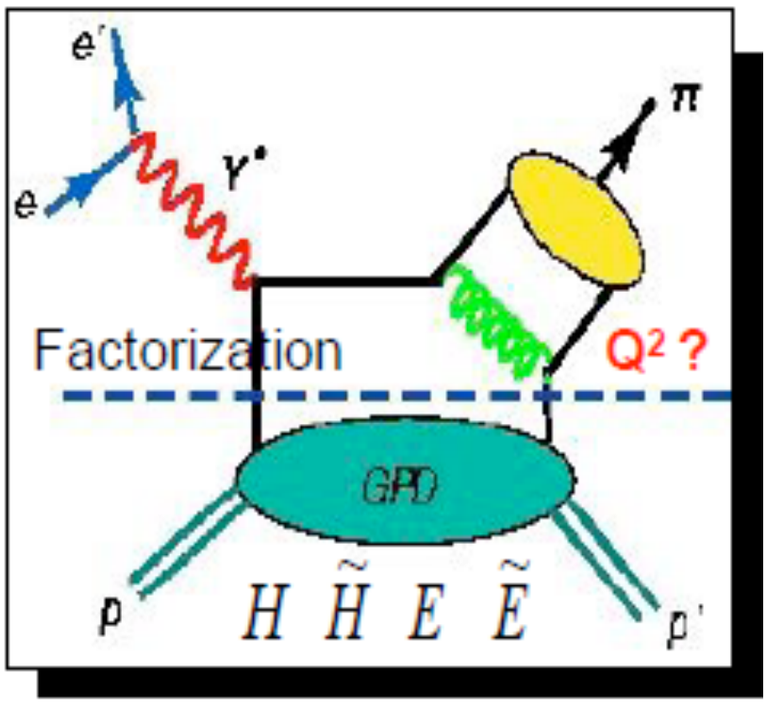
The PLC is 'color screened' - it passes undisturbed through the nuclear medium.

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

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

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

CT is also connected to the framework of GPDs and essential to account for Bjorken scaling in DIS at small x.



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

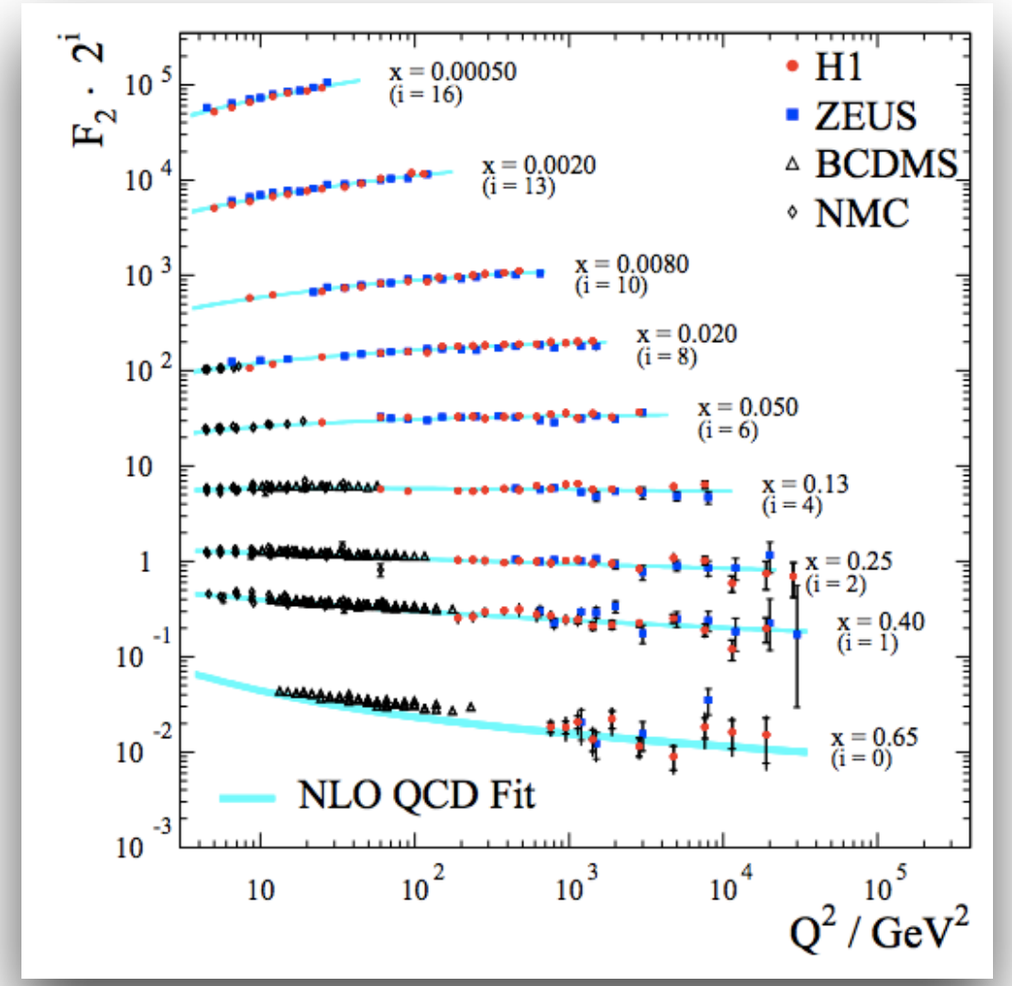
-Strikman, Frankfurt, Miller and Sargsian

- small size configurations (SSC/PLC) needed for factorization
- It is still uncertain what Q^2 value reaches the factorization regime

Reduced interaction at high energies due to “squeezing and freezing”(i.e. due to CT) is assumed in calculations of structure functions.

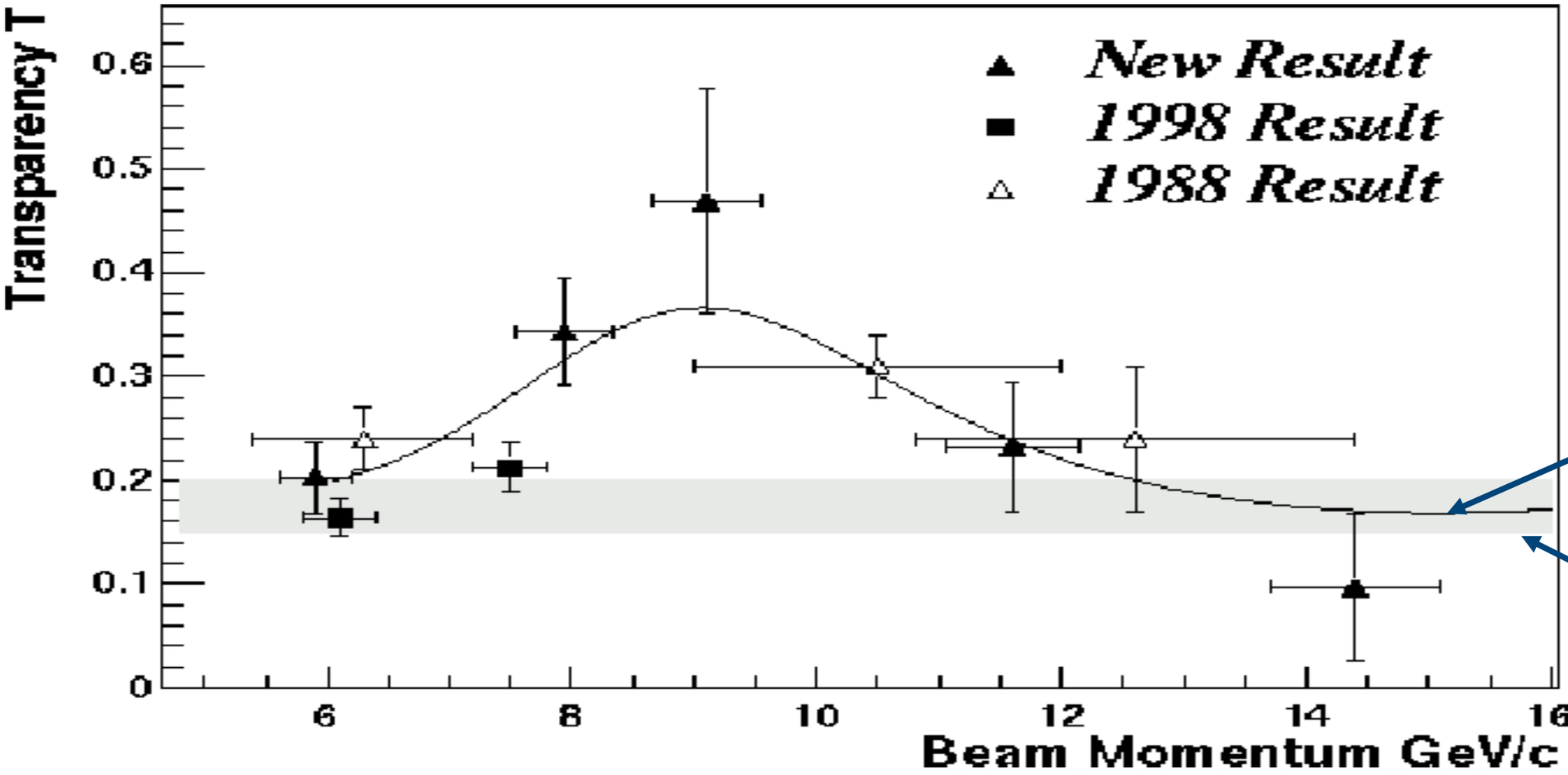
L. Frankfurt and M. Strikman, Phys Rep. 160, 235 (1988).

CT is implied by the successful description of DIS.



Although CT is well established at high energies the evidence at intermediate energies is lacking for baryons.

First direct search for the onset of CT used a 6 - 14.5 GeV proton beam on a Carbon target 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

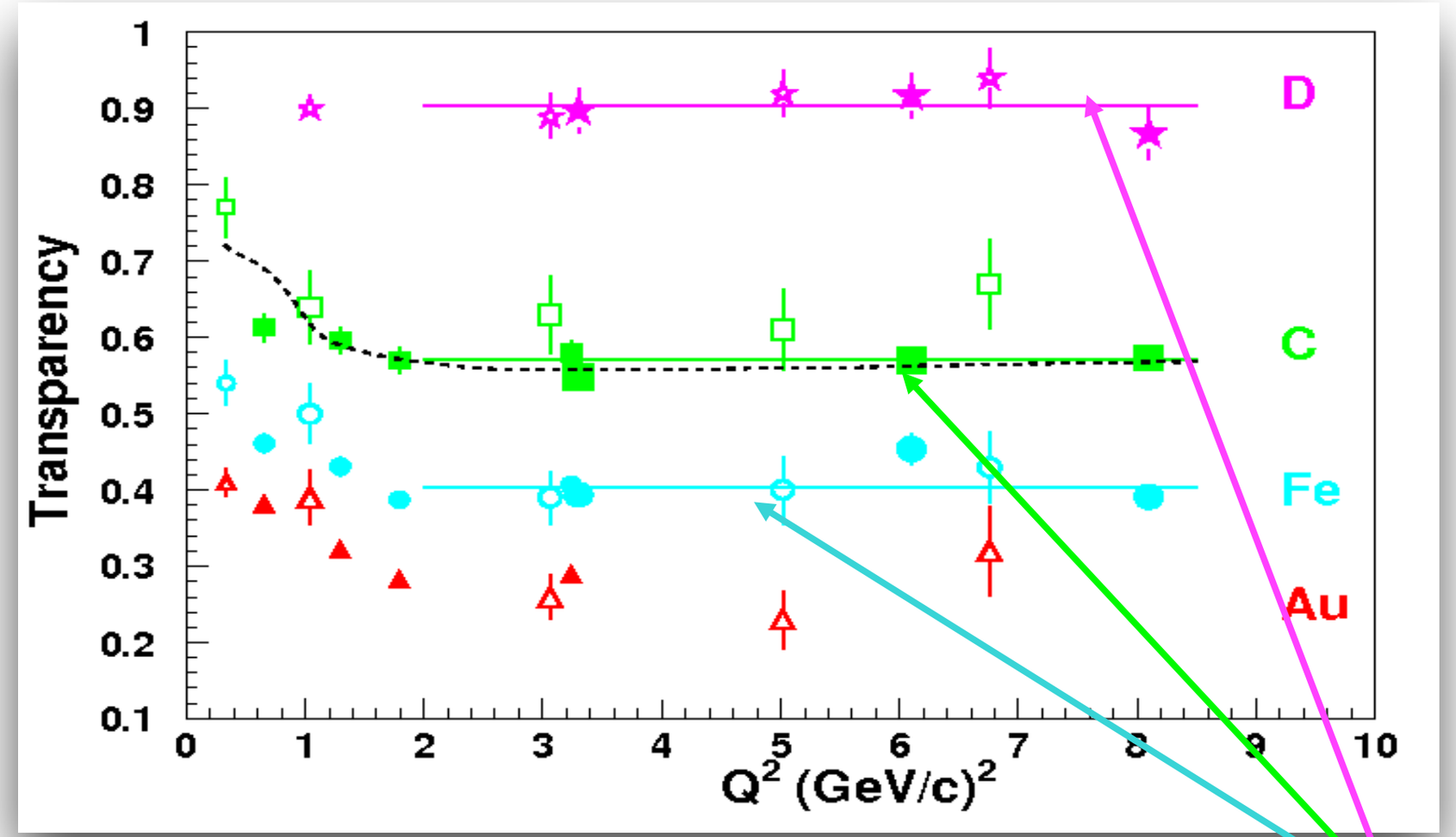
Shaded band Glauber calculation

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

There has a been a long ongoing effort to measure CT in protons using the A(e,e'p) reaction.

A(e,e'p) results

Q^2 dependence consistent with standard nuclear physics calculations



Solid Pts – JLab

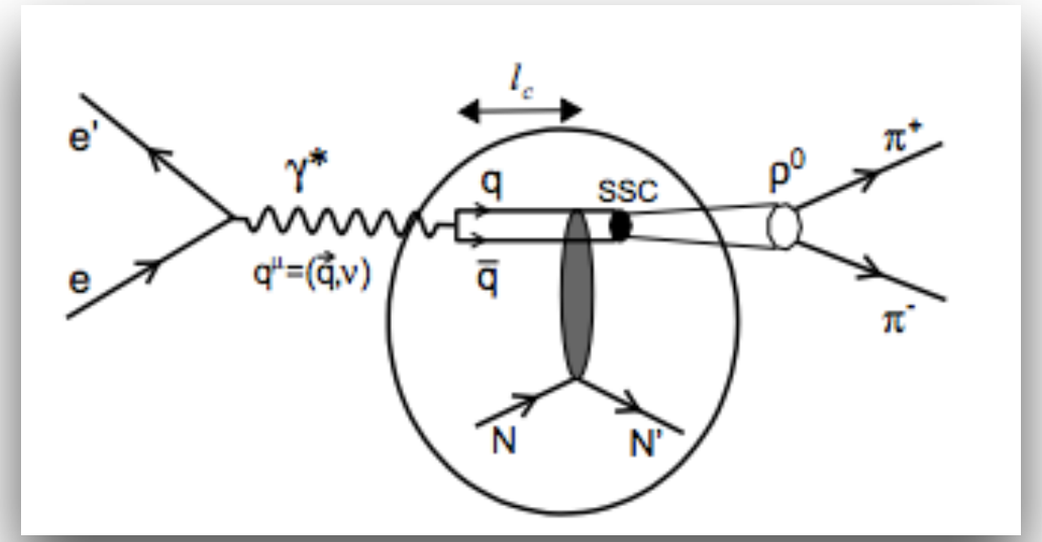
Open Pts -- other

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)

CT expected to be 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)

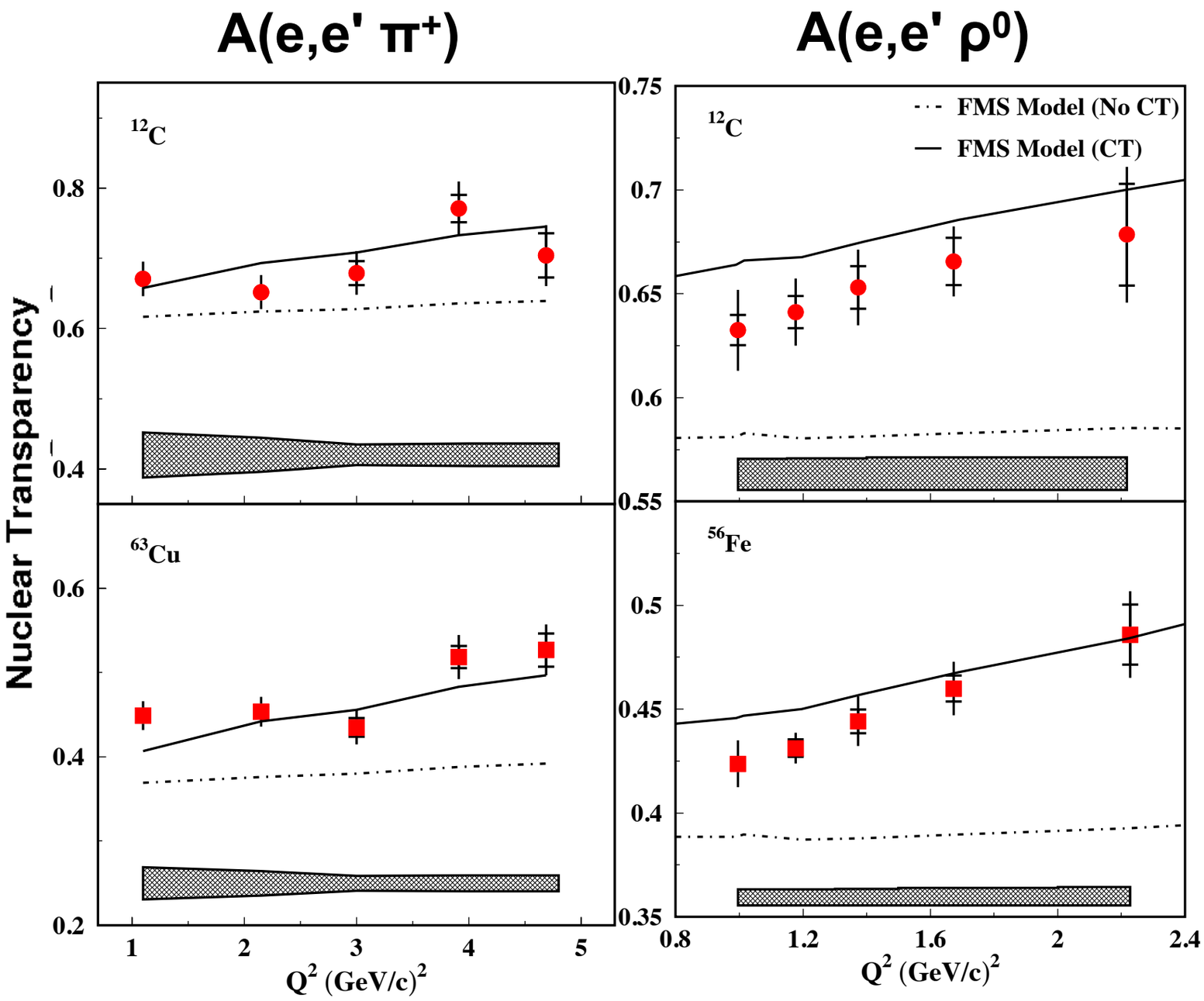
Onset of CT expected at lower Q^2 in mesons

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

But, JLab experiments from the 6-GeV era have conclusively observed the onset of CT in mesons.



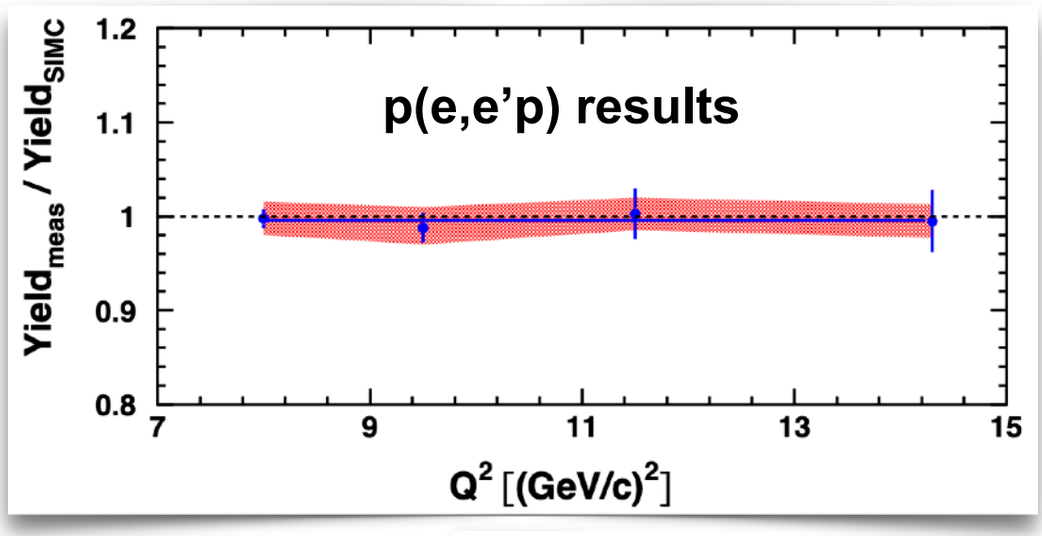
- **Hall-C Experiment E01-107 pion electroproduction from nuclei found an enhancement in transparency with increasing Q^2 & A, consistent with the prediction of CT.**
  (X. Qian et al., PRC81:055209 (2010), B. Clasie et al, PRL99:242502 (2007))

- **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

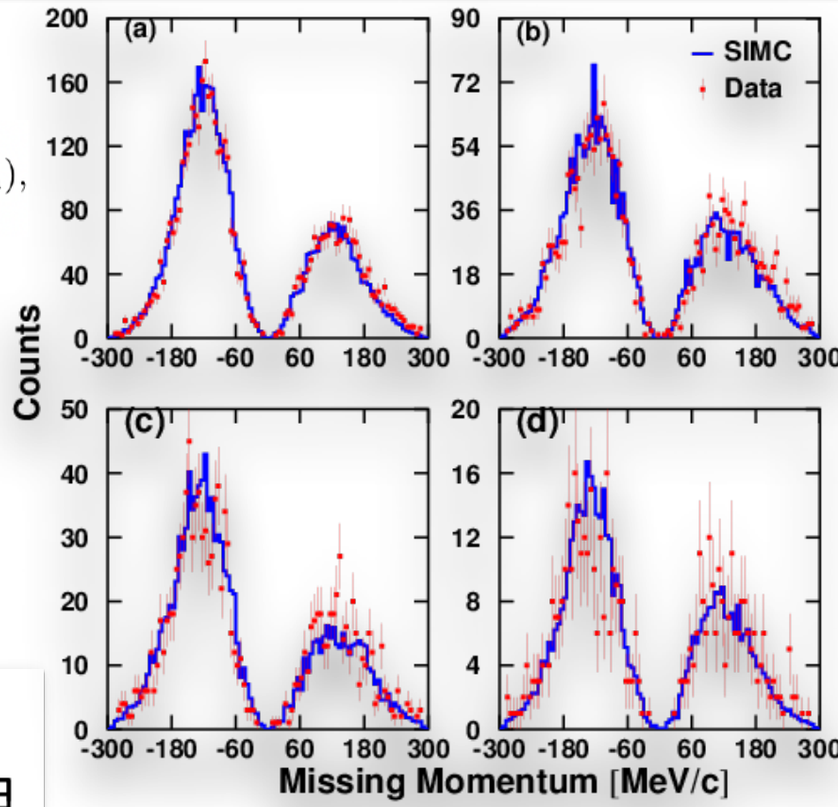
The results from the JLab 12 GeV experiment rule out the onset of CT in (e,e'p) up to Q^2 = 14.3 GeV^2

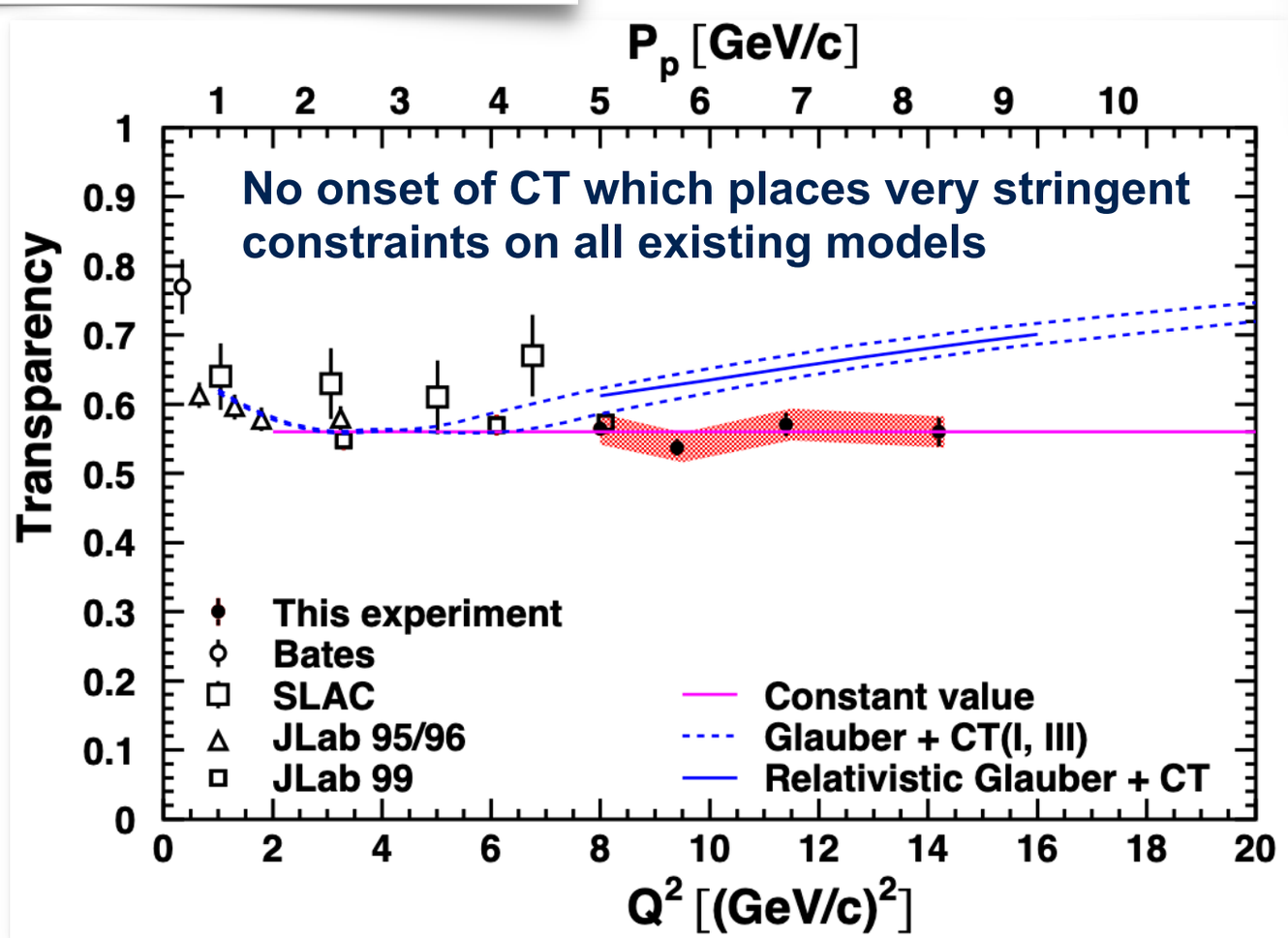
agrees with parametrization of known *ep* elastic data & simulation of experiment



$$\frac{d^6\sigma}{dE_{e'}d\Omega_{e'}dE_{p'}d\Omega_{p'}} = E_{p'}|p_{p'}|\sigma_{ep}S(E_m,\vec{p}_m),$$

spectral functions agree with PWIA reaction mechanism.





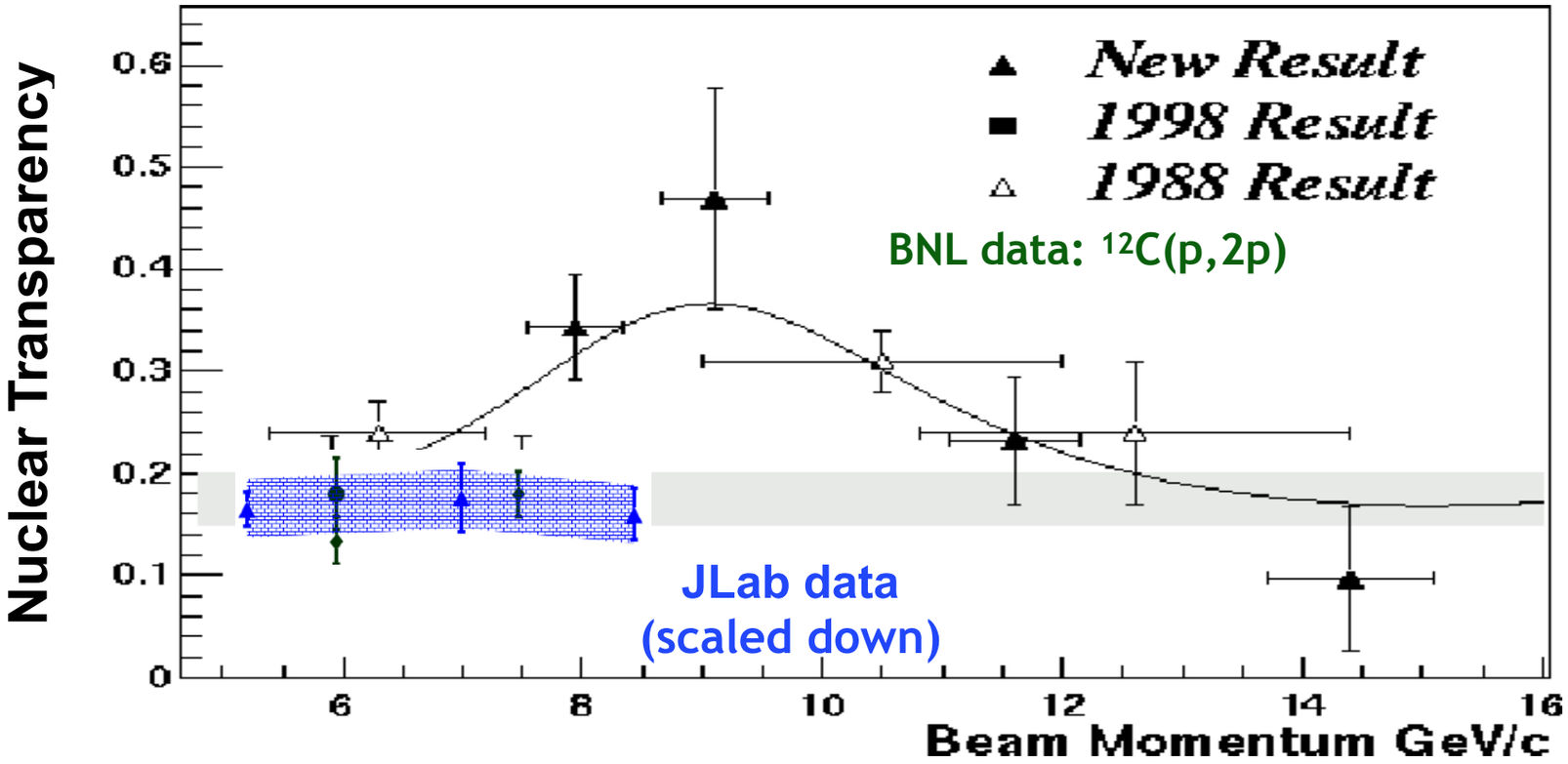
BNL observations unlikely to be because of CT

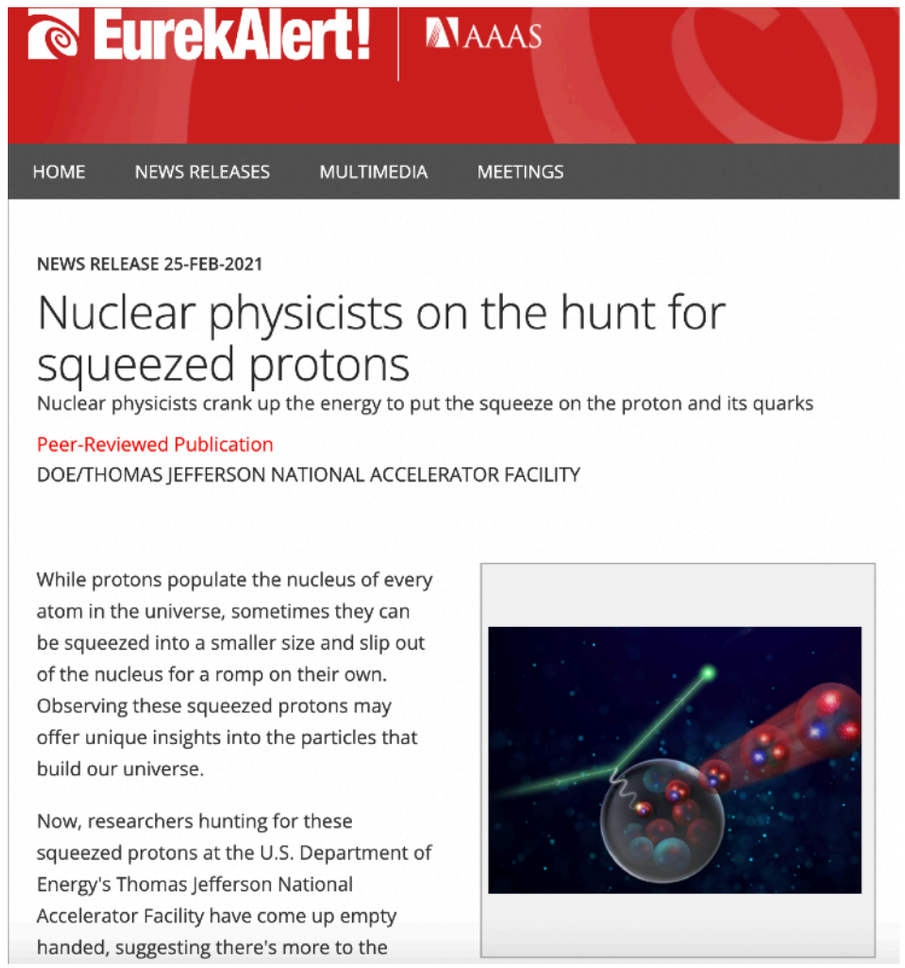
D. Bhetuwal et al.,
Phys. Rev. Lett., 126, 082301 (2021)

These results do not show the enhancement observed in BNL (p,2p) experiment.

BNL observations unlikely to be because of CT

Places very stringent constraints on all existing CT models

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NEWS RELEASE 25-FEB-2021

Nuclear physicists on the hunt for squeezed protons

Nuclear physicists crank up the energy to put the squeeze on the proton and its quarks

Peer-Reviewed Publication

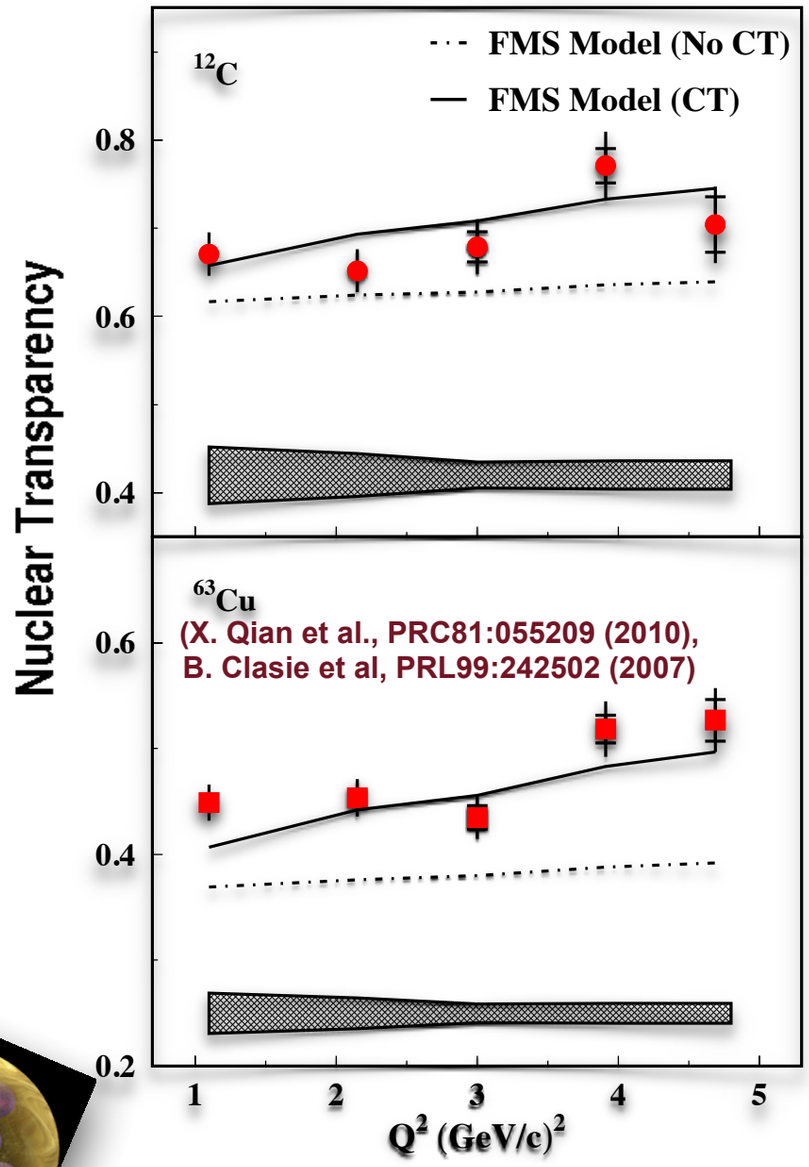
DOE/THOMAS JEFFERSON NATIONAL ACCELERATOR FACILITY

While protons populate the nucleus of every atom in the universe, sometimes they can be squeezed into a smaller size and slip out of the nucleus for a romp on their own. Observing these squeezed protons may offer unique insights into the particles that build our universe.

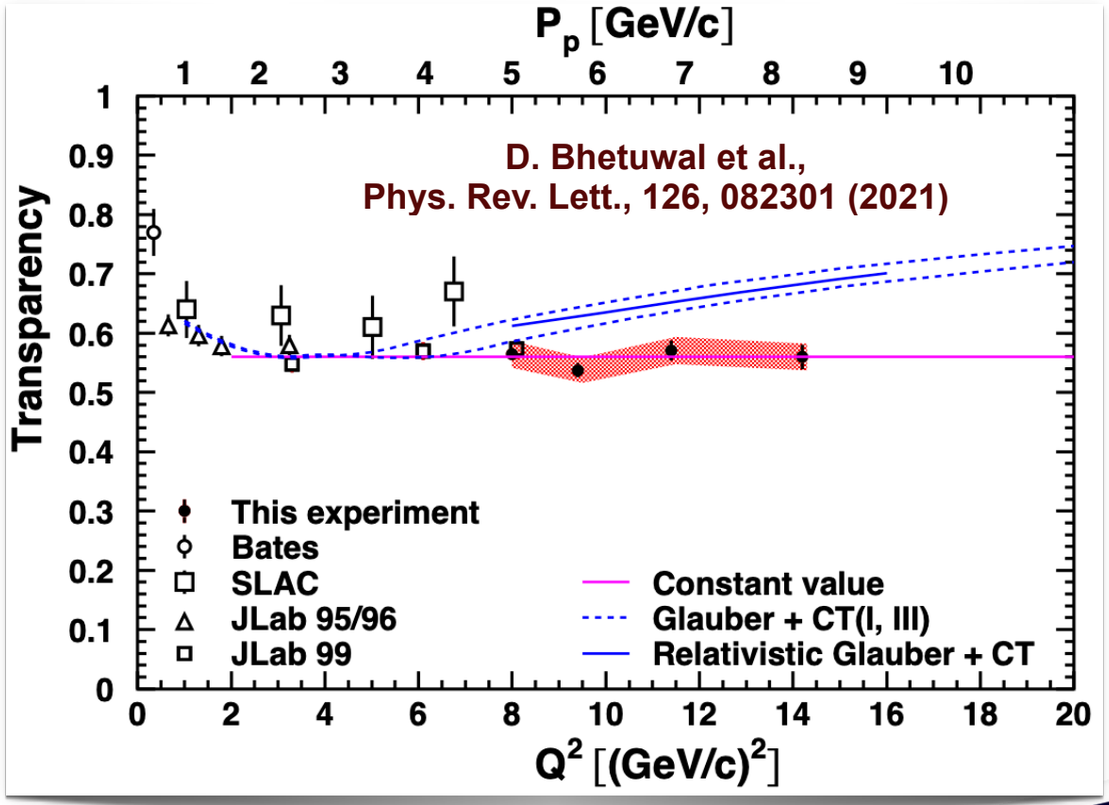
Now, researchers hunting for these squeezed protons at the U.S. Department of Energy's Thomas Jefferson National Accelerator Facility have come up empty handed, suggesting there's more to the

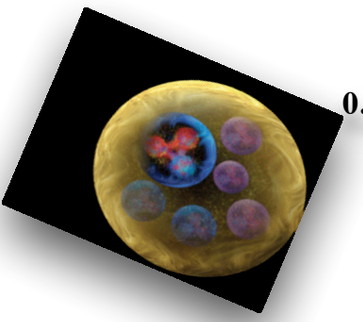
A new puzzle has arisen for final state interactions (FSI) of hadrons propagating through nuclei.

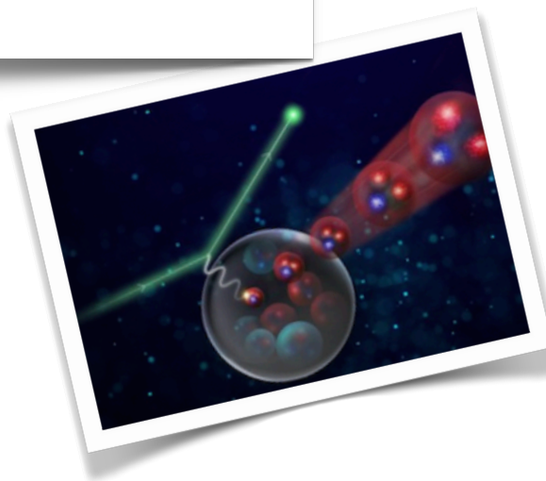
A(e,e' π⁺)



A(e,e' p)



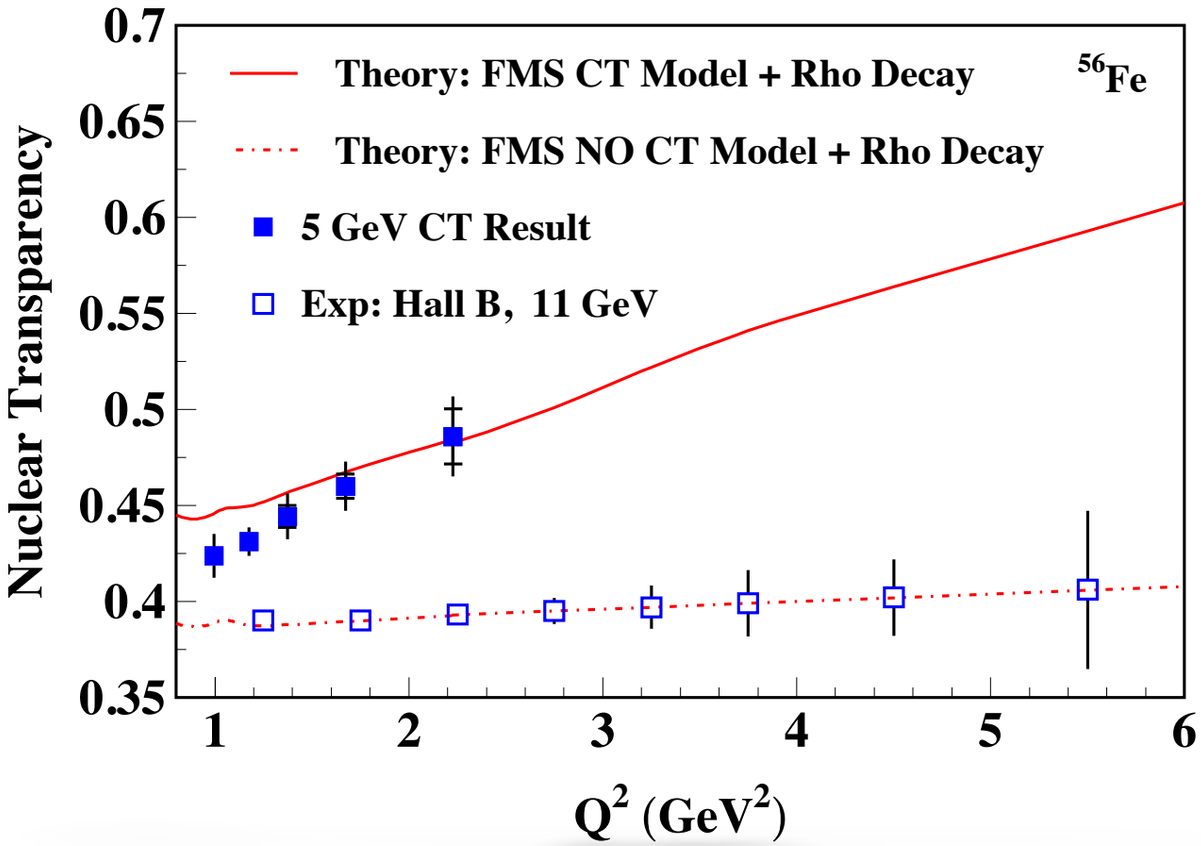




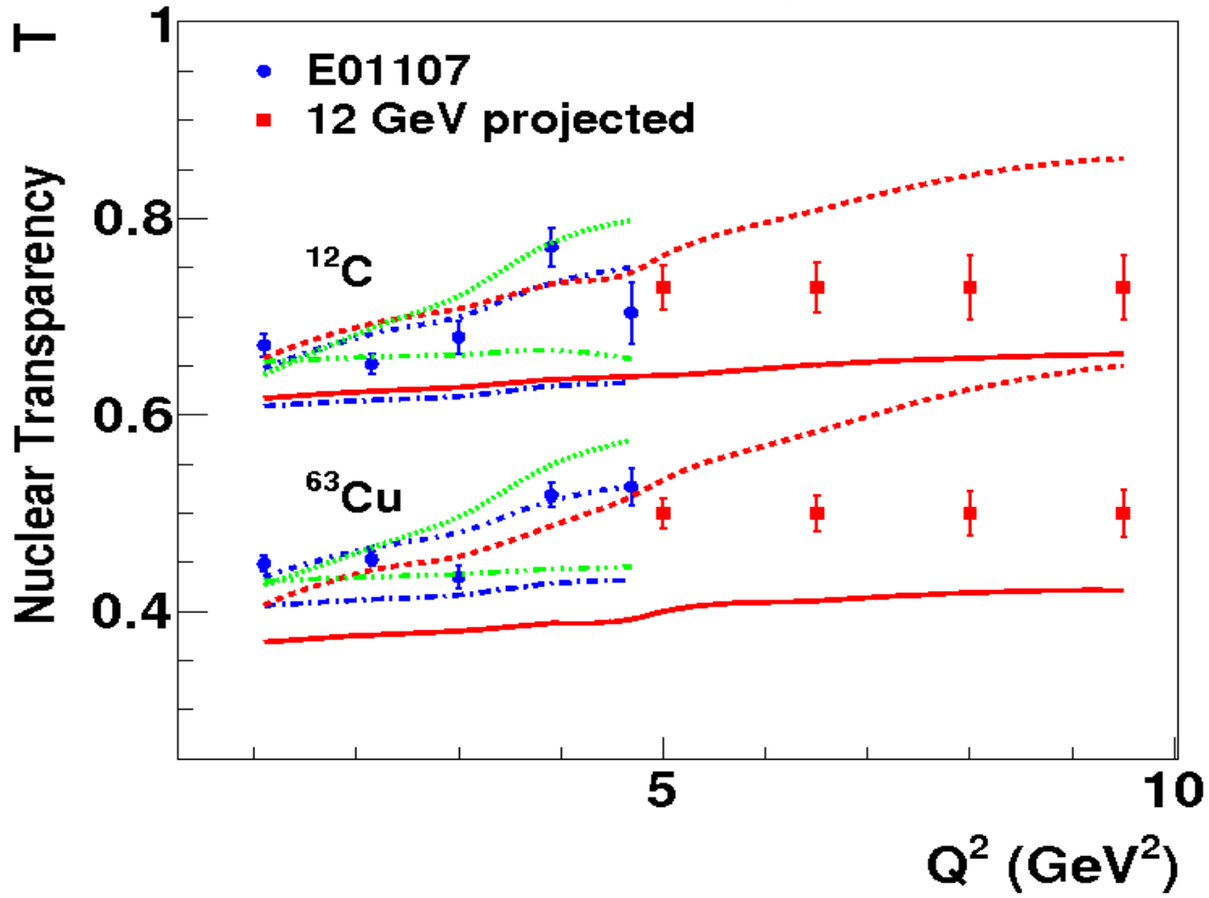
Onset of Color Transparency (i.e. suppression of FSI in exclusive processes) observed for meson at $Q^2 \sim 1$ GeV^2 but not in protons for $Q^2 \sim 14$ GeV^2

Recent and upcoming experiments will verify the meson results

A(e,e' ρ^0)

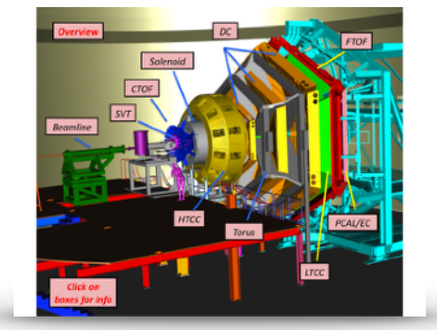


A(e,e' π^+)



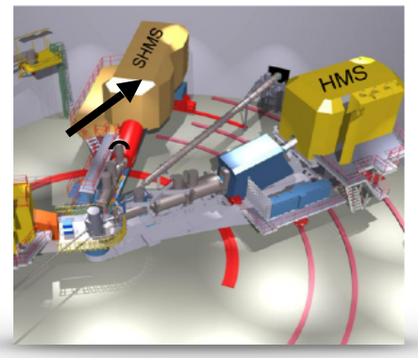
CLAS12 Run group D ran in 2024

Hall C E12-06-107 - part II scheduled for 2026

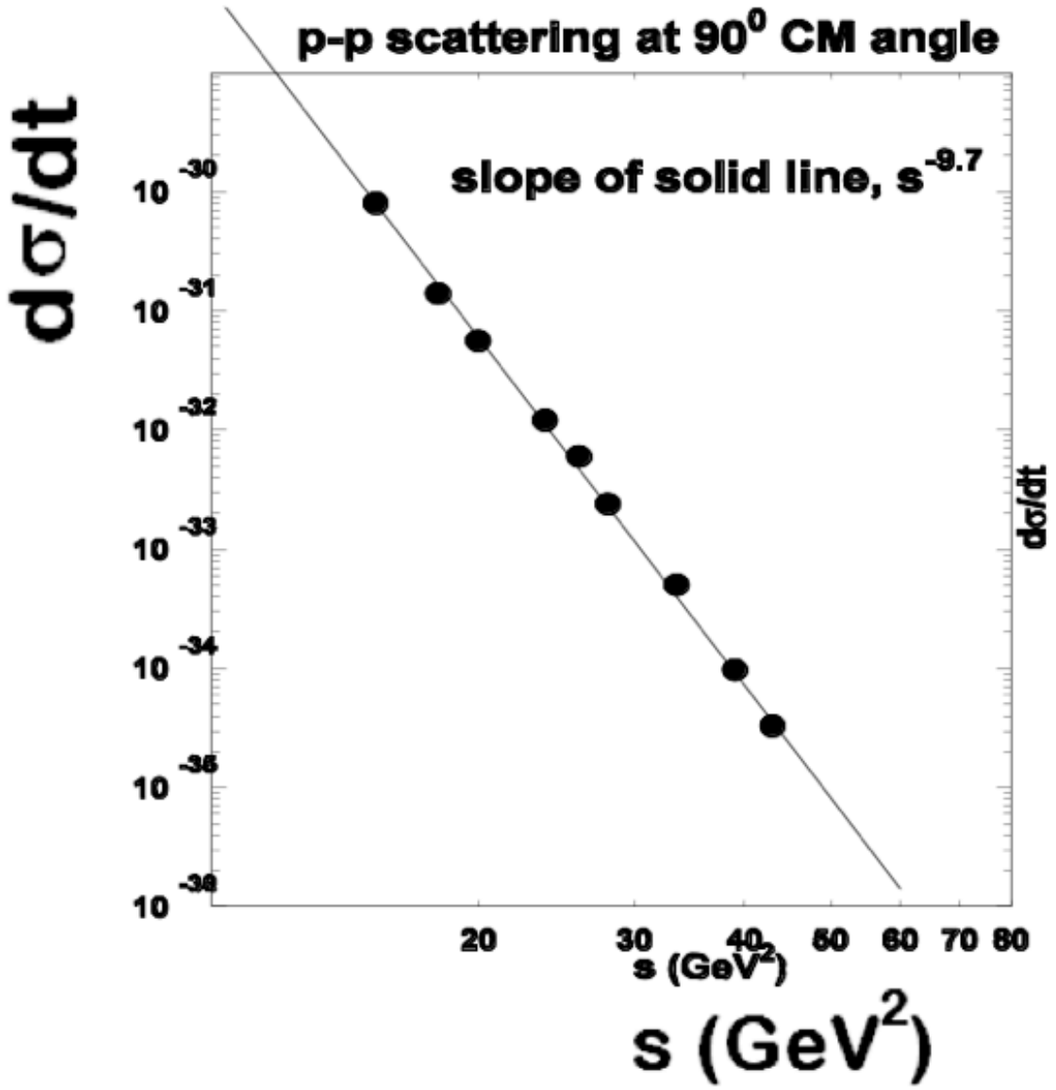


But the lack of CT in protons needs further investigations

Searching for the suppression of FSI in exclusive processes at high energy/momentum transfer!

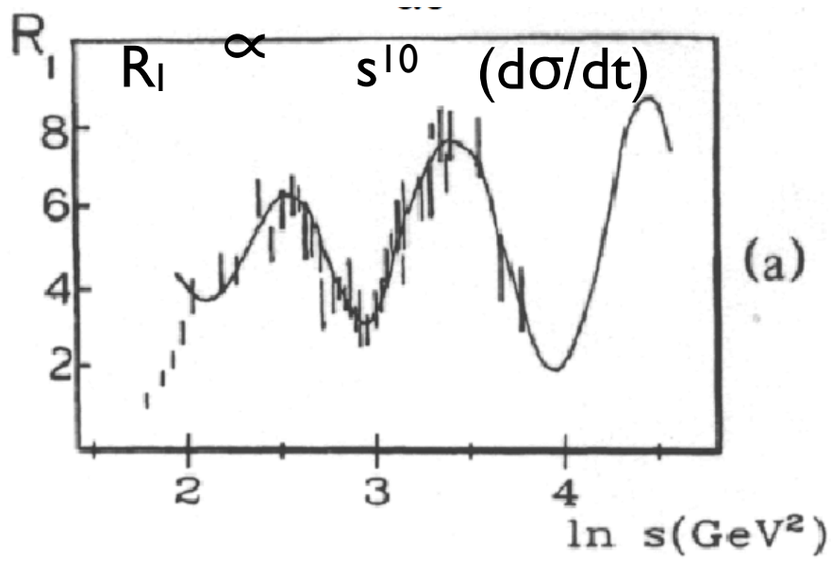


The p-p scattering cross section is known to have oscillations in its energy dependence.

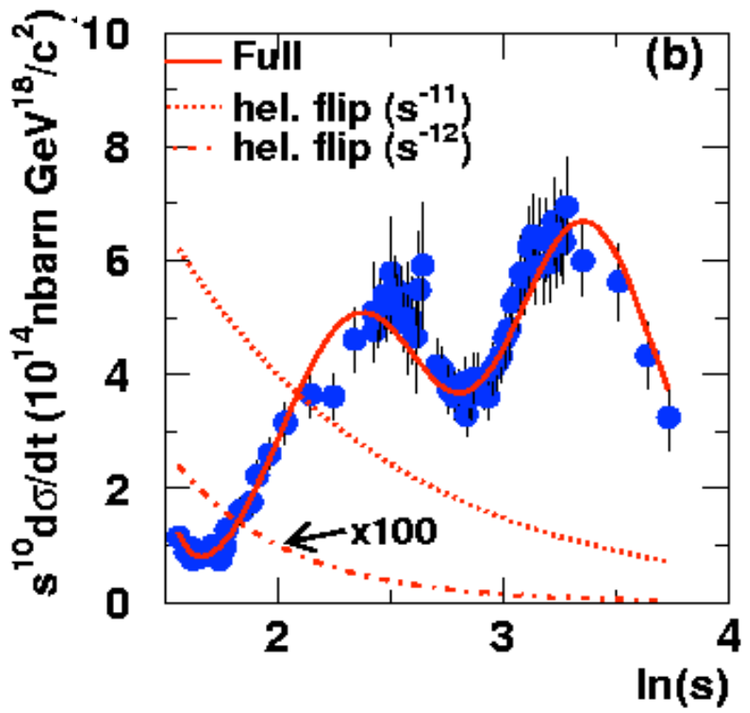


quark counting rule predicts $\frac{d\sigma}{dt} \propto s^{-10}$

data from Landshoff and Polkinghorne



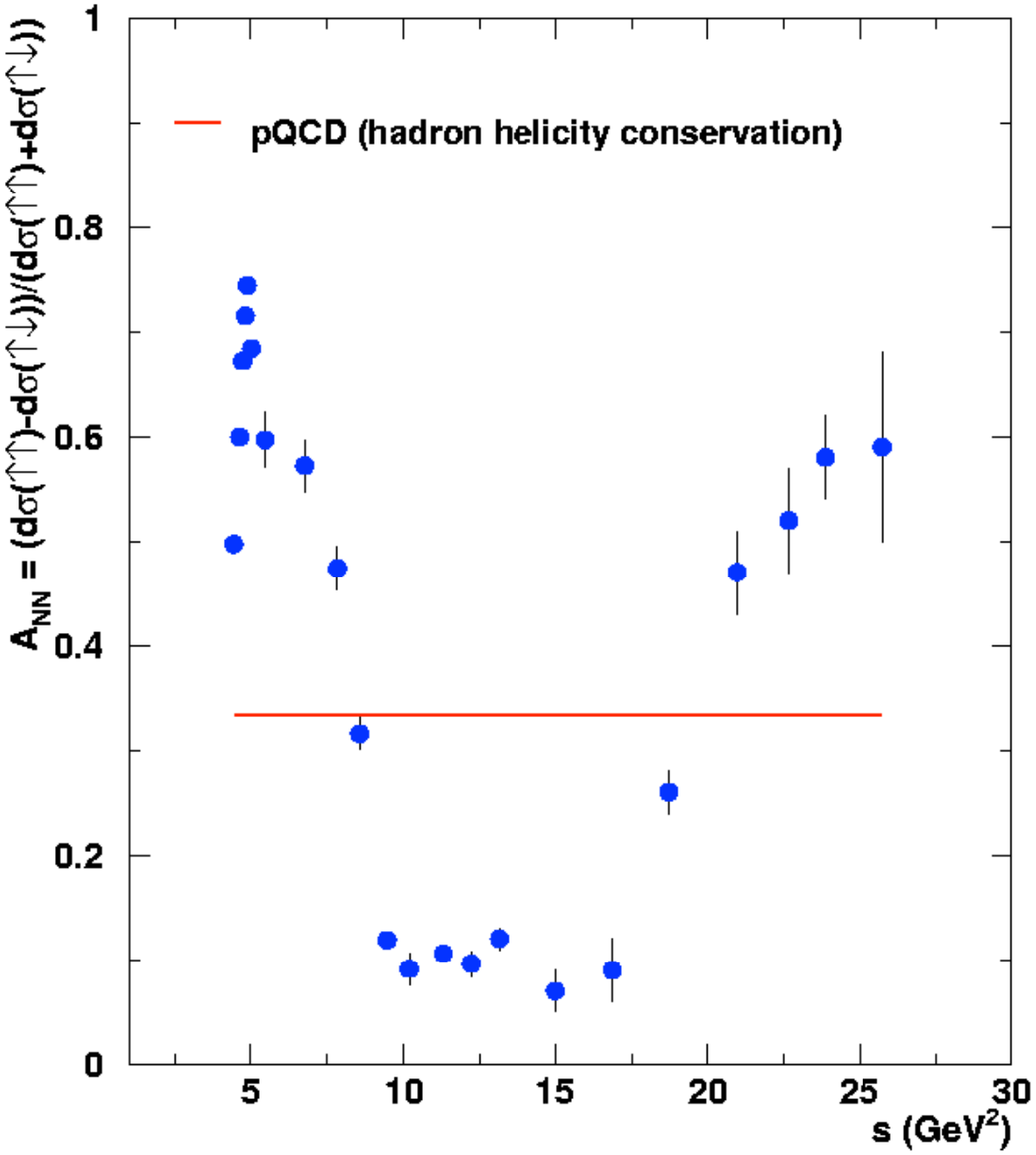
J. P. Ralston and B. Pire, PRL 61, 1823 (1988)



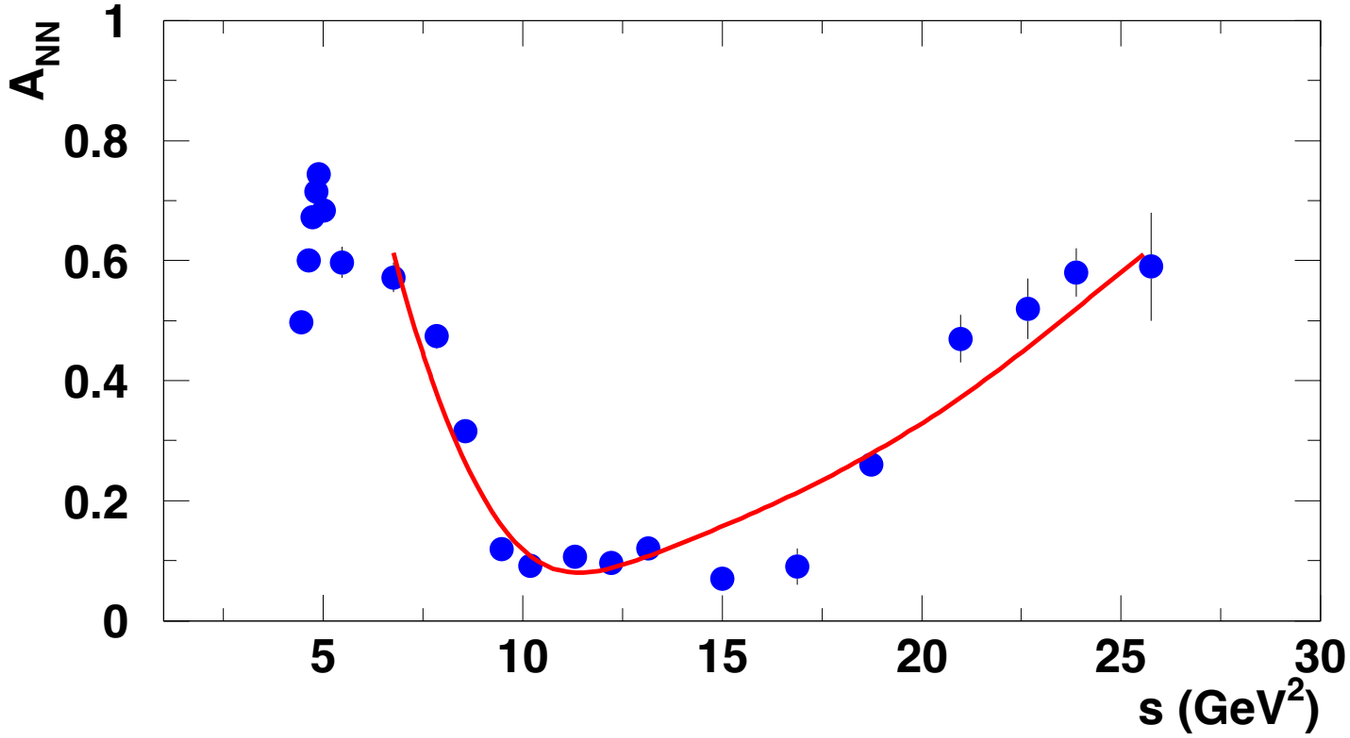
D.Dutta and H. Gao, PRC 71, 032201R (2005)

Other p-p phenomena also show similar oscillations

A_{NN} in p-p Scattering

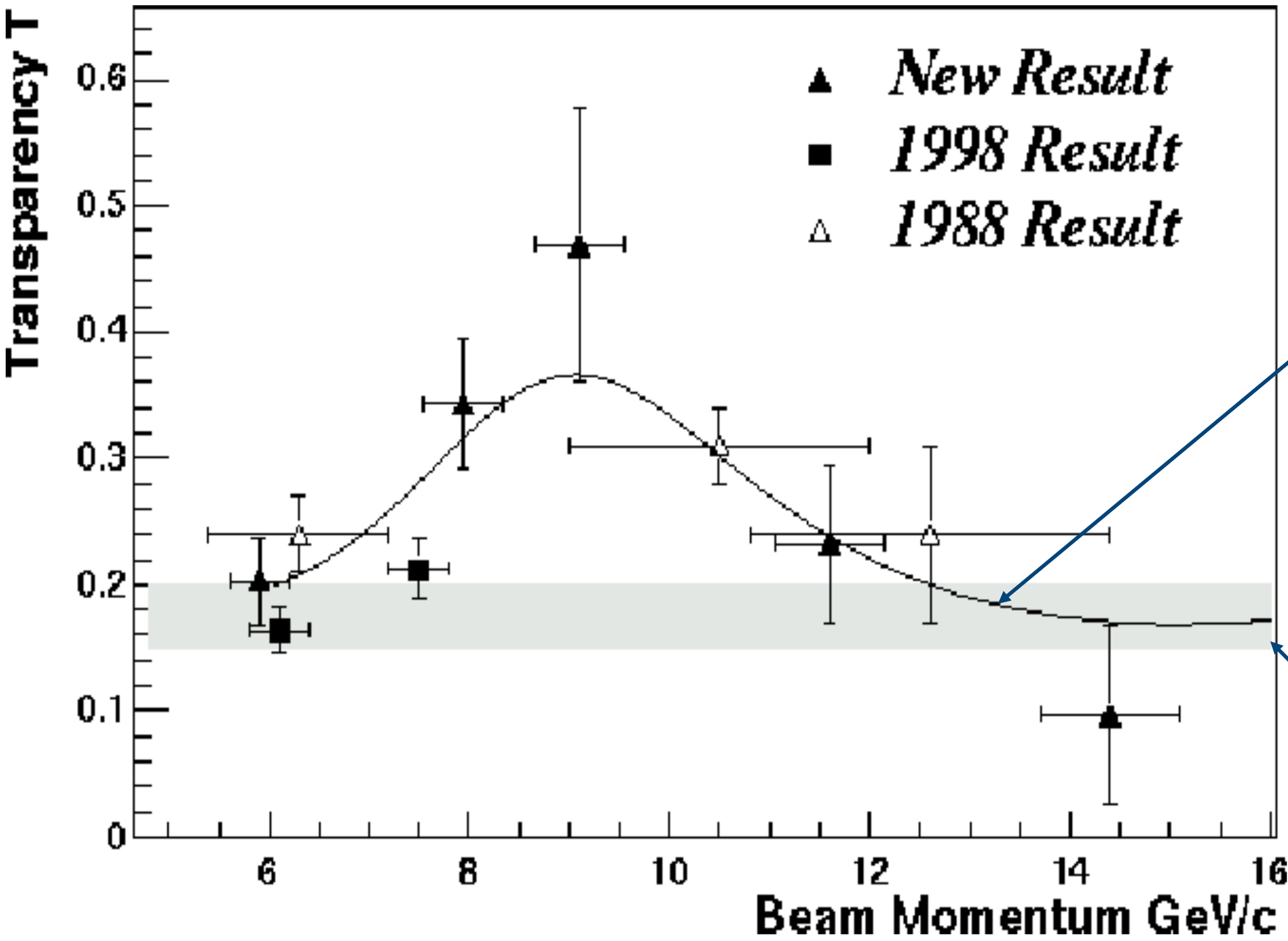


D.G. Crabb et al., PRL 41, 1257 (1978)



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

The enhancement observed in BNL (p,2p) experiment could be due to nuclear filtering of the oscillations in the cross section

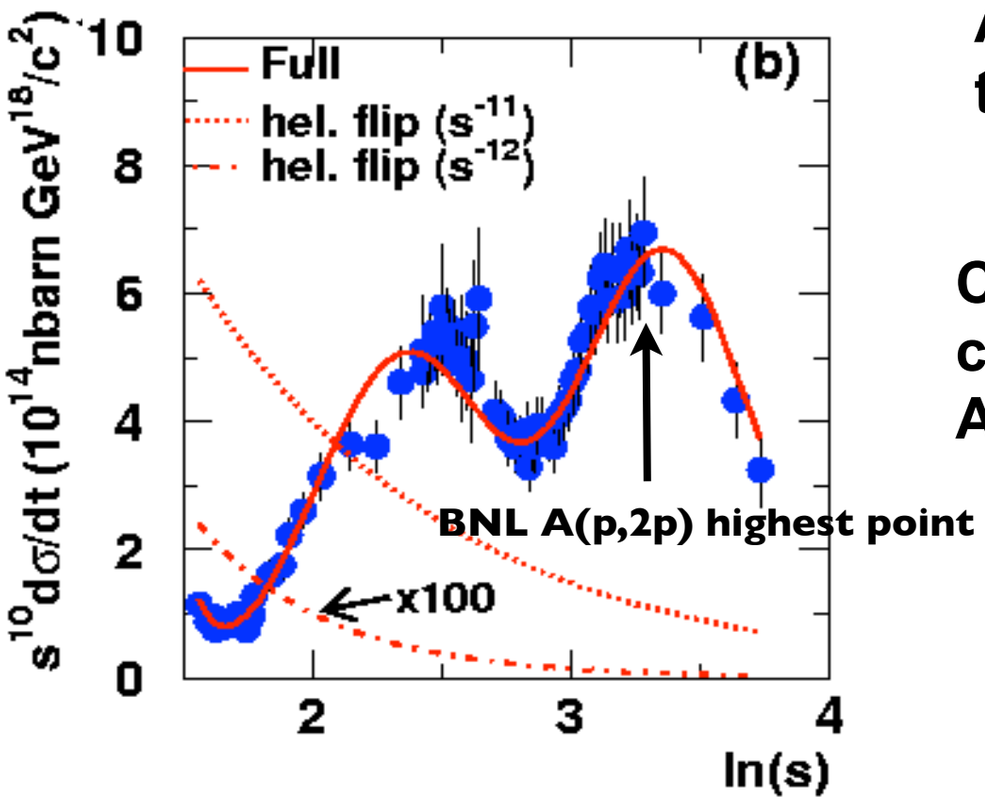


PRL 87, 212301 (2001)
PRL 81, 5085 (1998)
PRL 61, 1698 (1988)

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

Shaded band Glauber calculation

A fixed target proton-nucleus experiment at the AGS can help solve this puzzle.

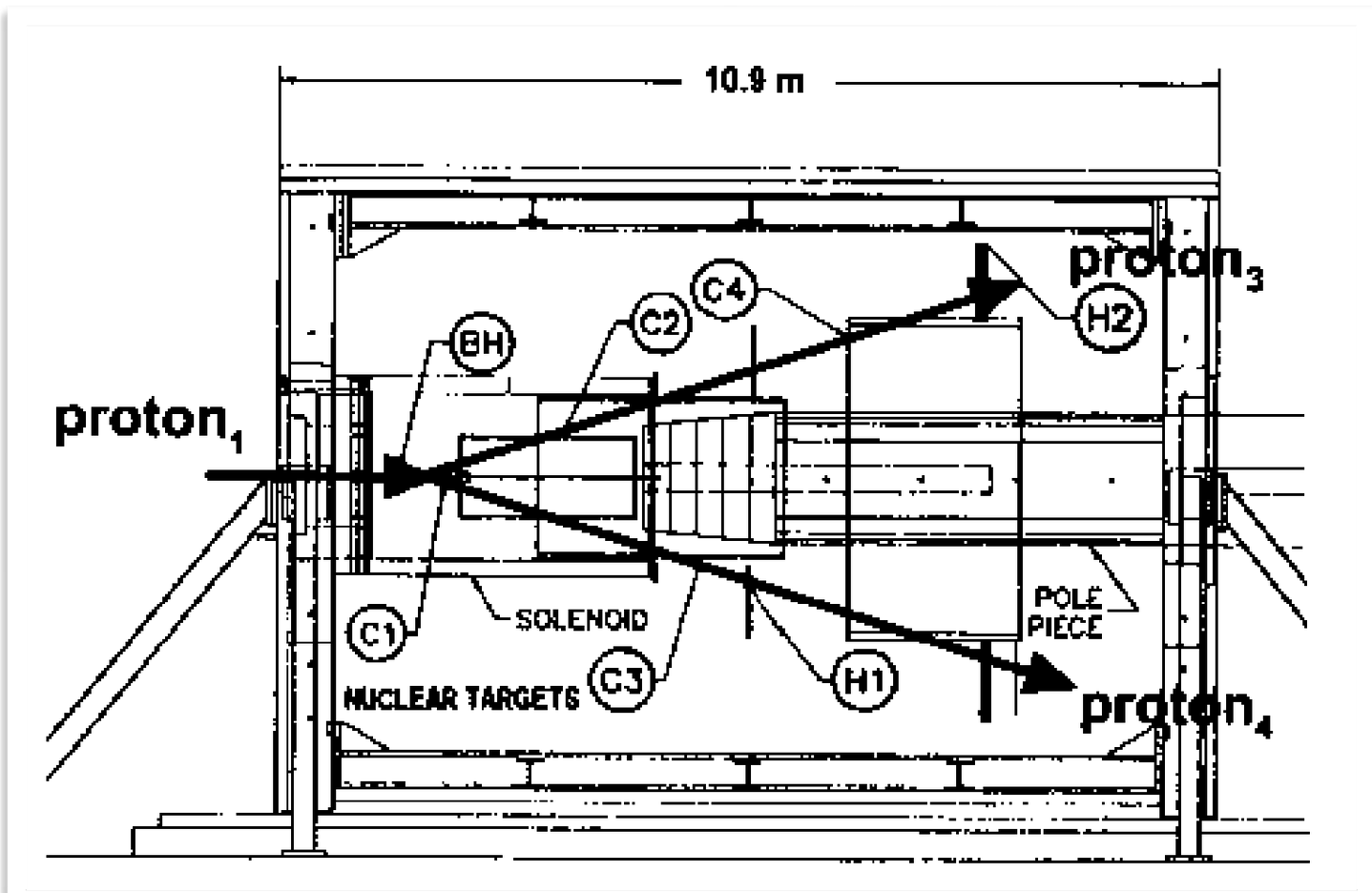


D.Dutta and H. Gao, PRC 71, 032201R (2005)

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

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

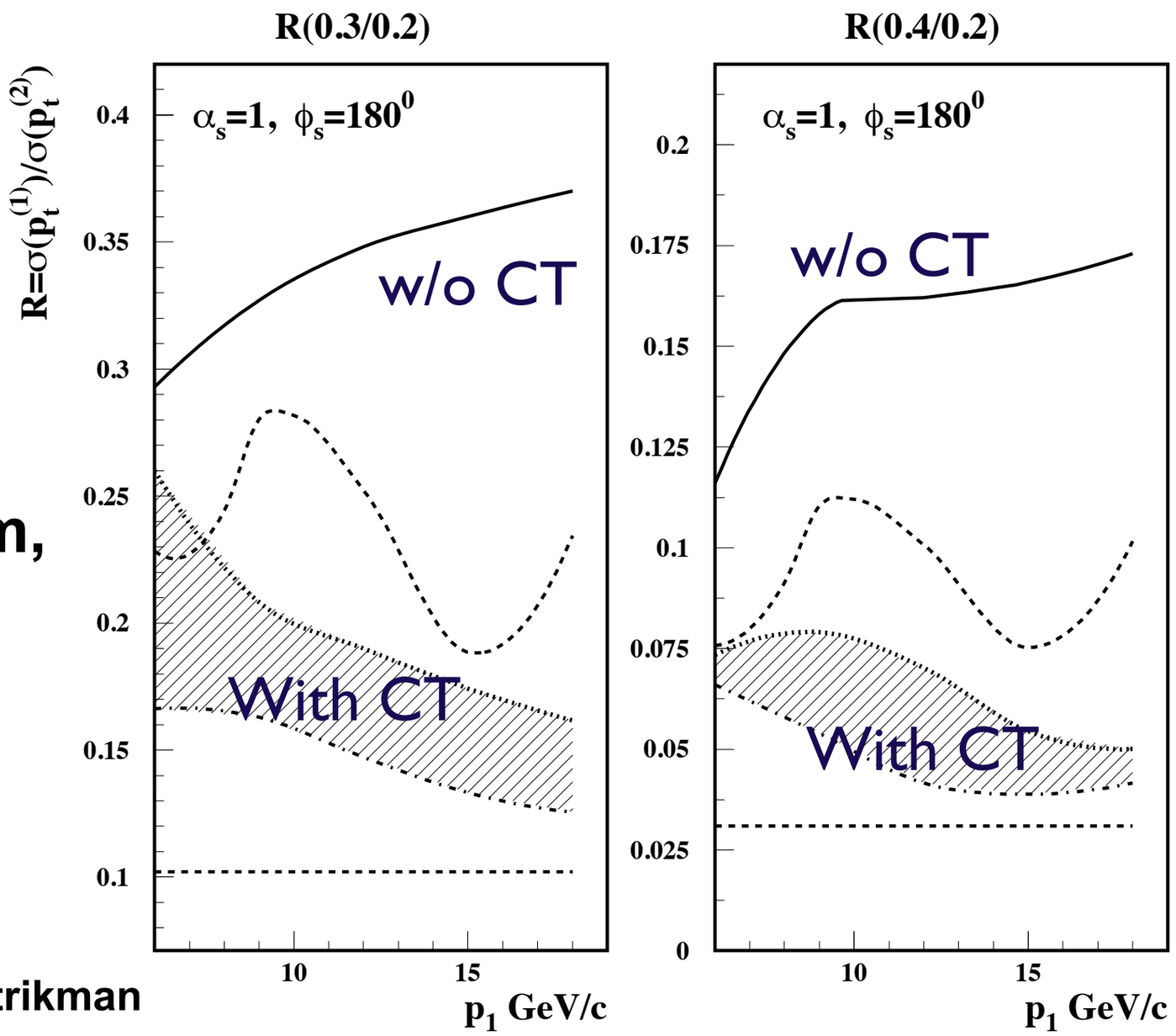
Experiment would need a solenoid spectrometer similar to E850 (EVA) at BNL



Other possibilities include mapping re-scattering in hard exclusive reactions on ^2H

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

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



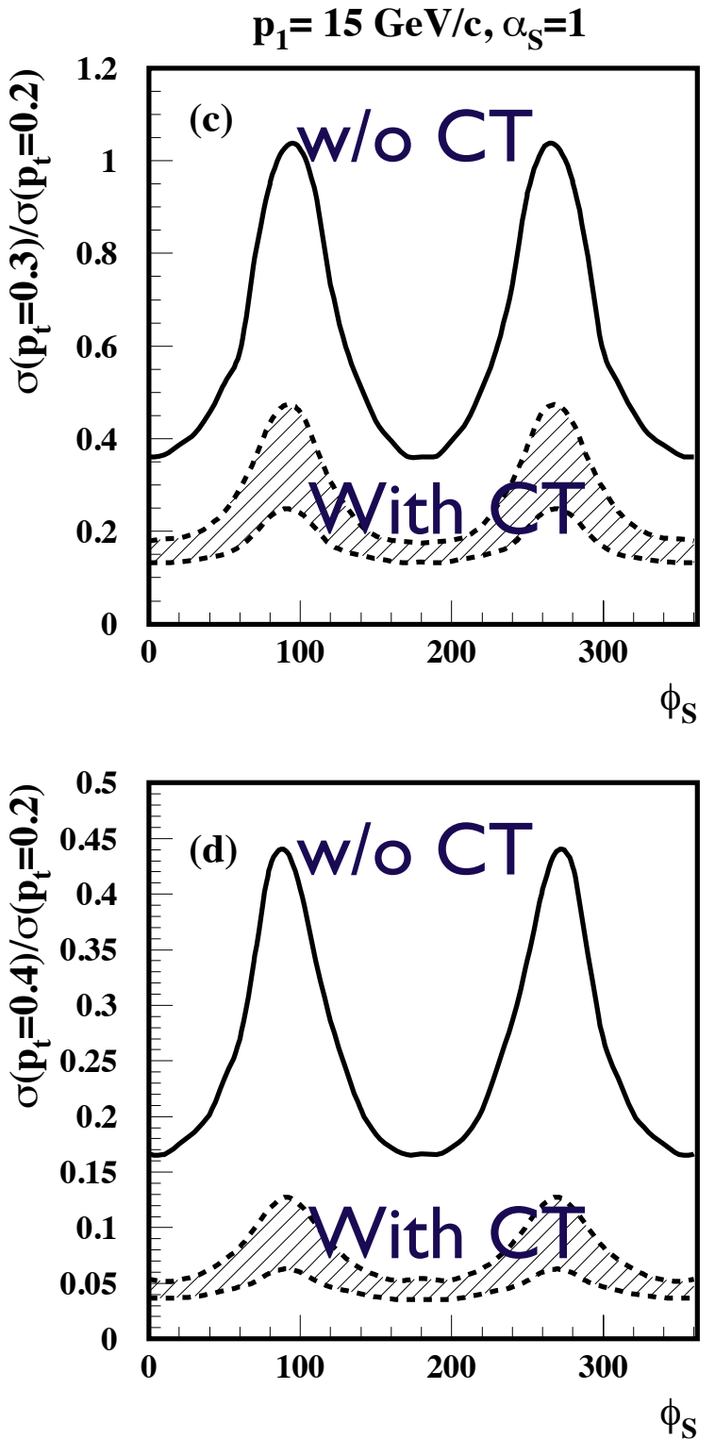
Ratio of cross section at two different transverse momentum, P_t of the scattered proton

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

Other possibilities include mapping re-scattering in hard exclusive reactions on ^2H

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

ϕ_s = spectator azimuthal angle



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

Requires high resolution spectrometer for the fast protons and pion veto

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

Summary

- Experiments at JLab have conclusively demonstrated the onset of color transparency in mesons.
- But no such onset is observed for protons with order of magnitude higher momentum transfer.
- This is a new (old) puzzle in hadronic physics.
- A complementary program with proton beams on fixed targets and new observables is highly desirable.
- The AGS @ BNL is well-positioned to investigate this puzzle. Requires a new high resolution spectrometer

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