Experimental efforts searching for the onset of Color Transparency

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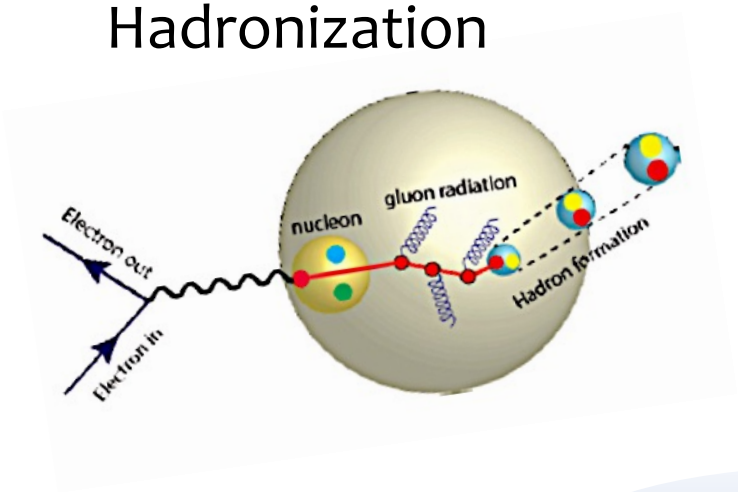
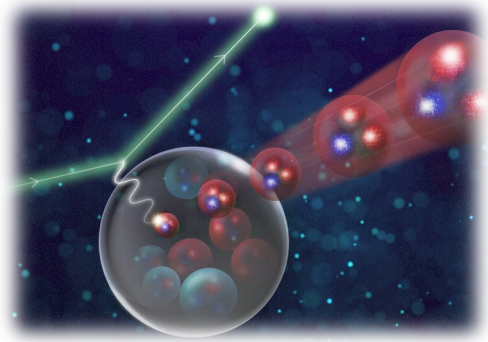
Hadronization

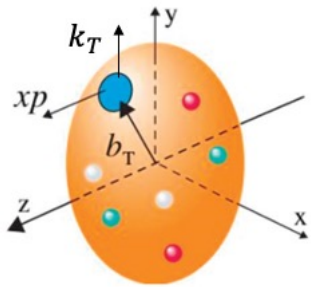


Small-size hadrons

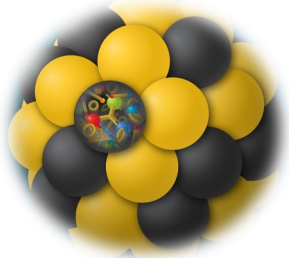


Hadron propagation through matter is fundamental to the many body problem

3D mapping
(nuclear GPDs and TMDs)



Short range structure
(NN short-range correlations)

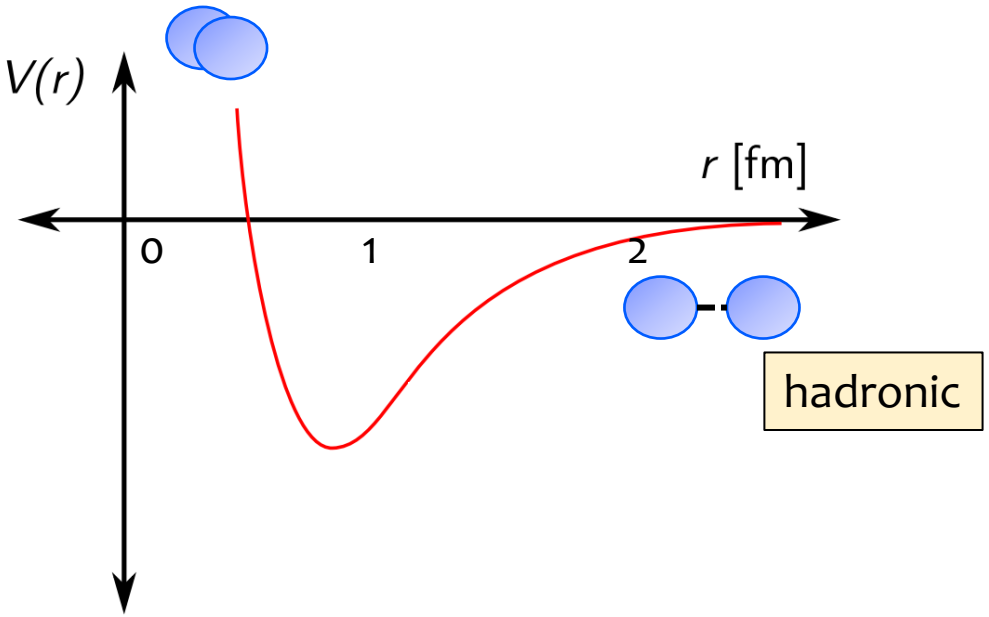


Medium modification of quark distributions
(EMC Effect)

Two descriptions of nuclear physics

What is the energy threshold for this transition?

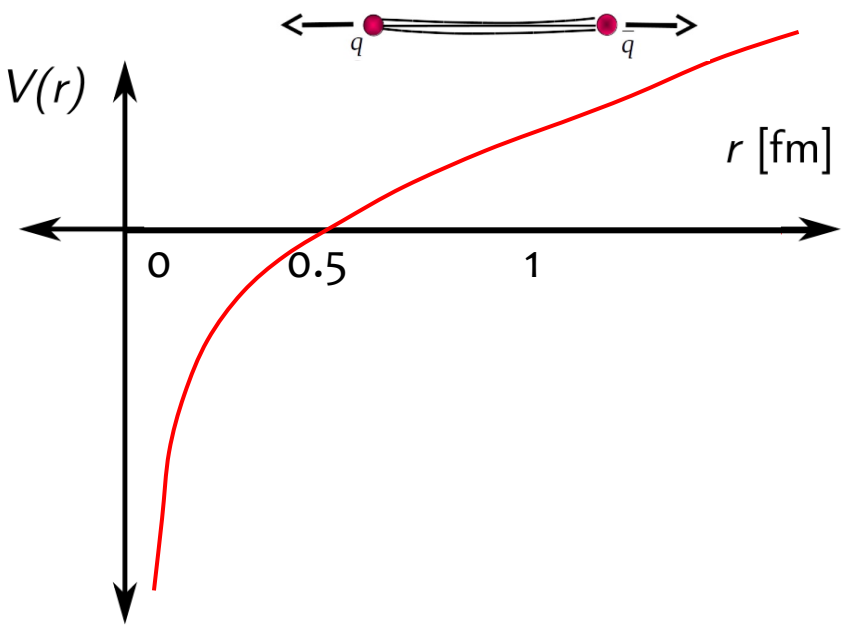
Potential between nucleons



hadronic

nucleons & mesons

Potential between quarks

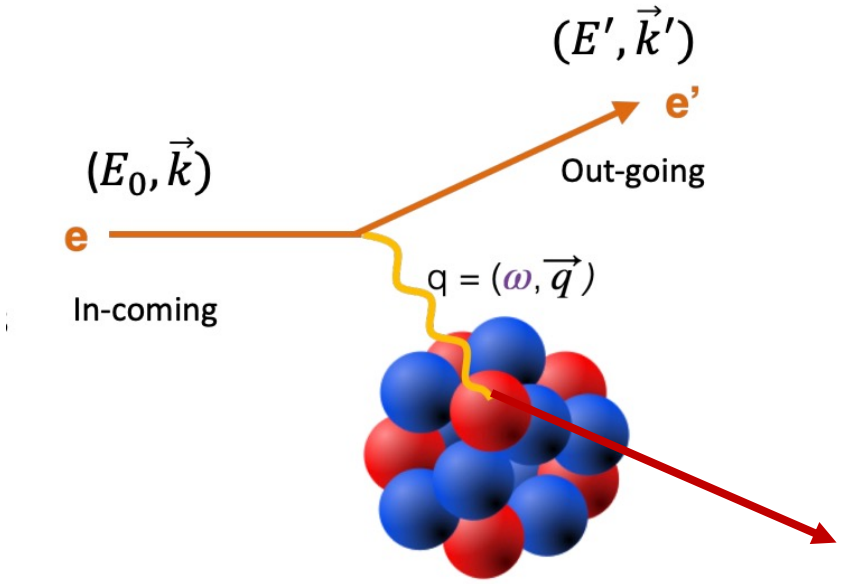


QCD

quarks & gluons

Nuclear transparency

Transparency is the probability that the struck hadron emerges from the nucleus without being deflected or absorbed.



Ratio of cross-sections for exclusive processes from nuclei and nucleons is the Transparency:

$$T_A = \frac{\sigma_A}{A\ \sigma_N}$$

(σ_A: nuclear cross section; σ_N: free nucleon cross section)

A is the mass number

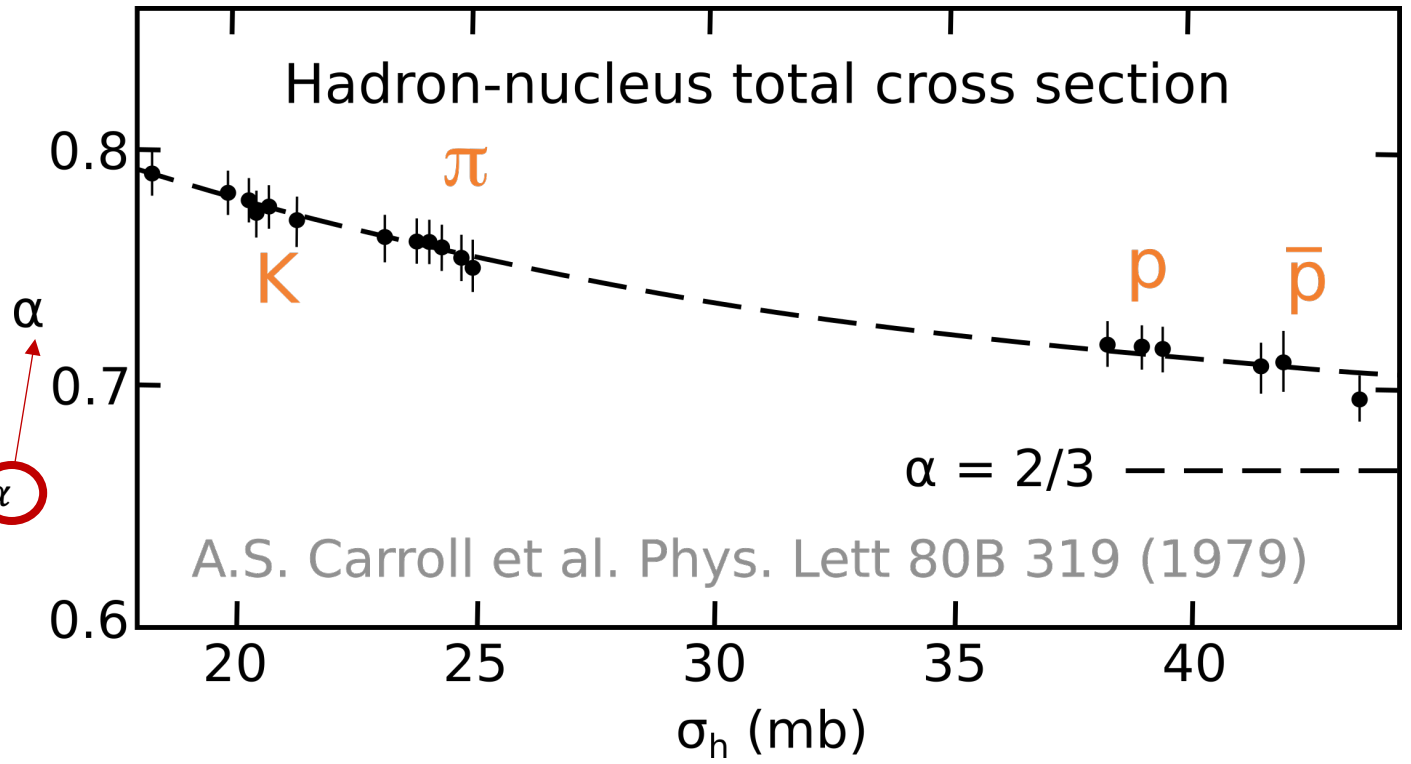
Absorption cross section is momentum independent

$$T_A = \frac{\sigma_A}{A\,\sigma_N} \rightarrow \sigma_A(A) = \sigma_N\,A^{\alpha} \rightarrow \boxed{T_A = A^{\alpha-1}}$$

Hadron momenta:
60, 200, 280 GeV/c

Targets of
Al, Li, C, Sn, Pb

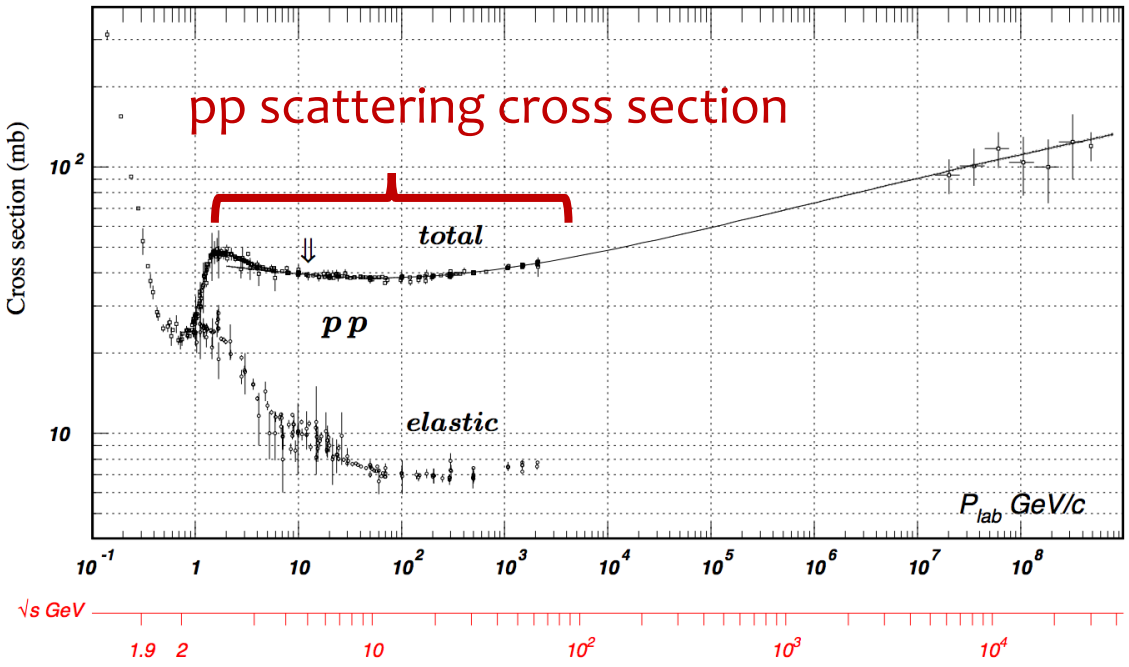
Fit to $\sigma_A(A) = \sigma_N\,A^{\alpha}$

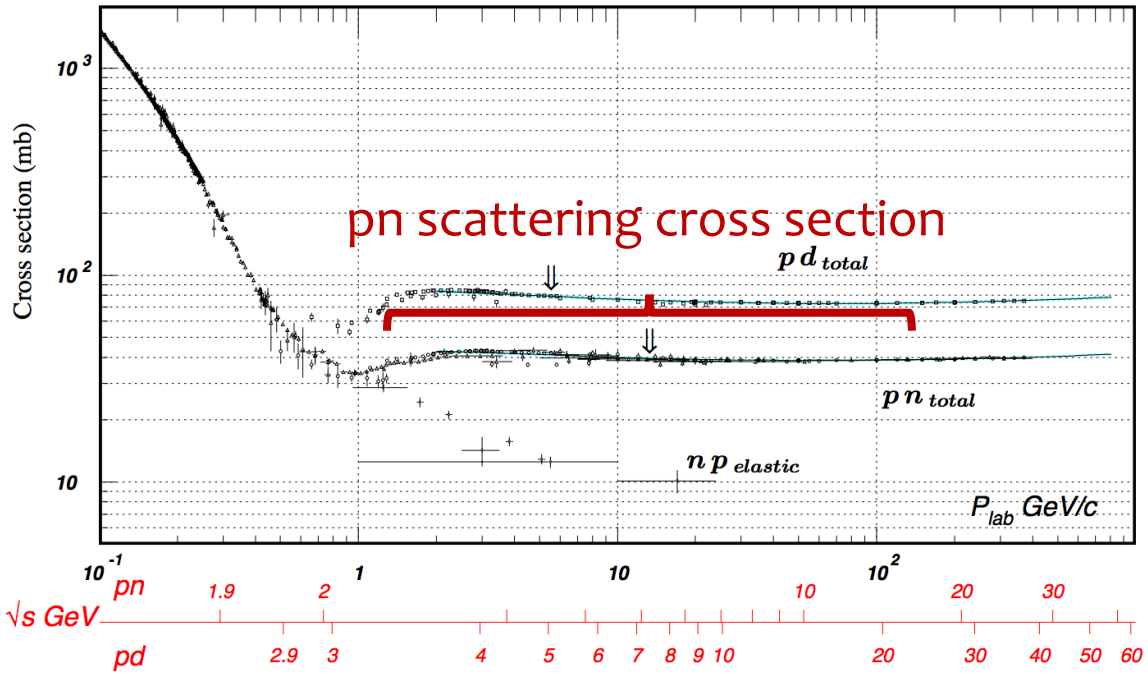


α <1 due to strong interaction nature of the probe

Tendency of $\alpha \rightarrow 2/3$ expected for opaque nucleus

NN cross section is essentially energy independent

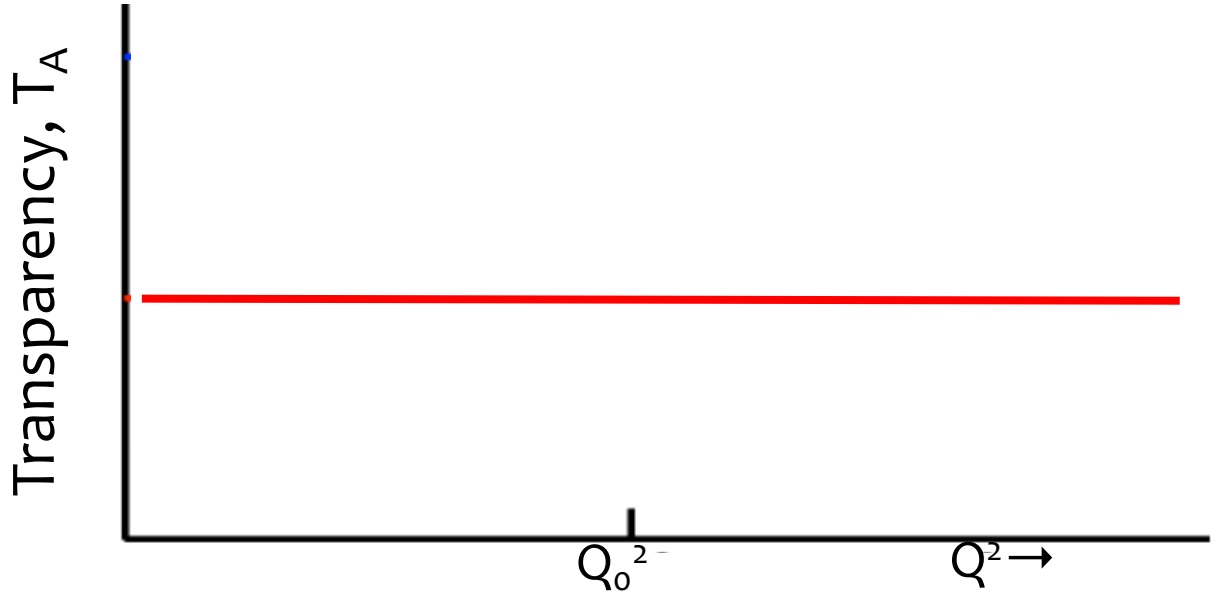




S. Navas et al. (Particle Data Group), Phys. Rev. D **110**, 030001 (2024)

Transparency should be momentum independent (in the strongly interacting hadronic picture)

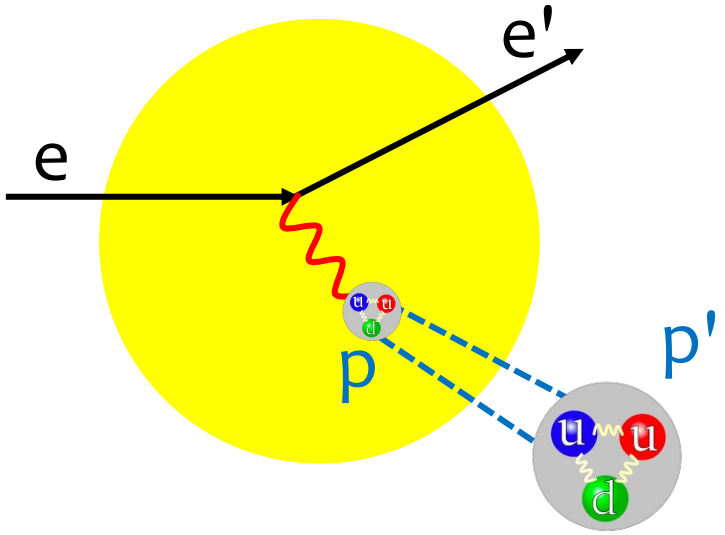
$$T_A = \frac{\sigma_A}{A\,\sigma_N}$$



- scattering cross section
- Glauber multiple scattering
- NN Correlations and Final State Interaction (FSI) effects

Color transparency is a fundamental prediction of pQCD

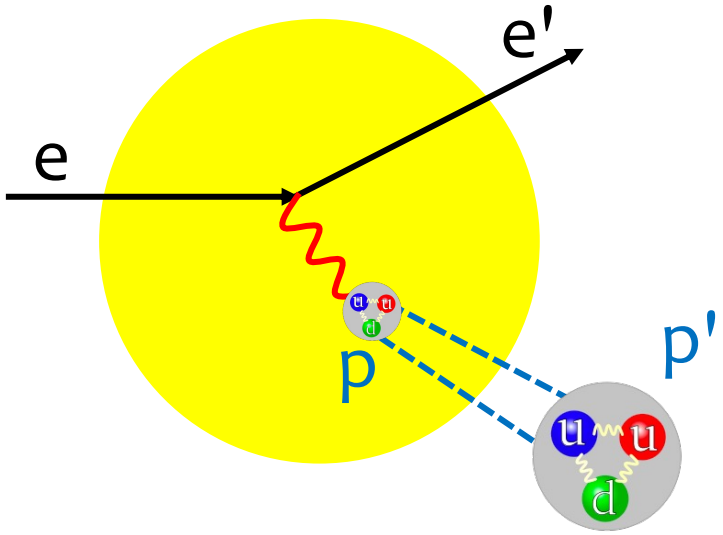
Introduced by
Mueller and Brodsky, 1982



Vanishing of final state interactions of hadrons with nuclear medium in exclusive processes at high momentum transfer

Color transparency is a fundamental prediction of pQCD

Quantum mechanics:
Shorter wavelength photons are absorbed on smaller-size hadrons (*squeezing*)



Relativity:
Maintains this small size as it propagates out of the nucleus (*freezing*)

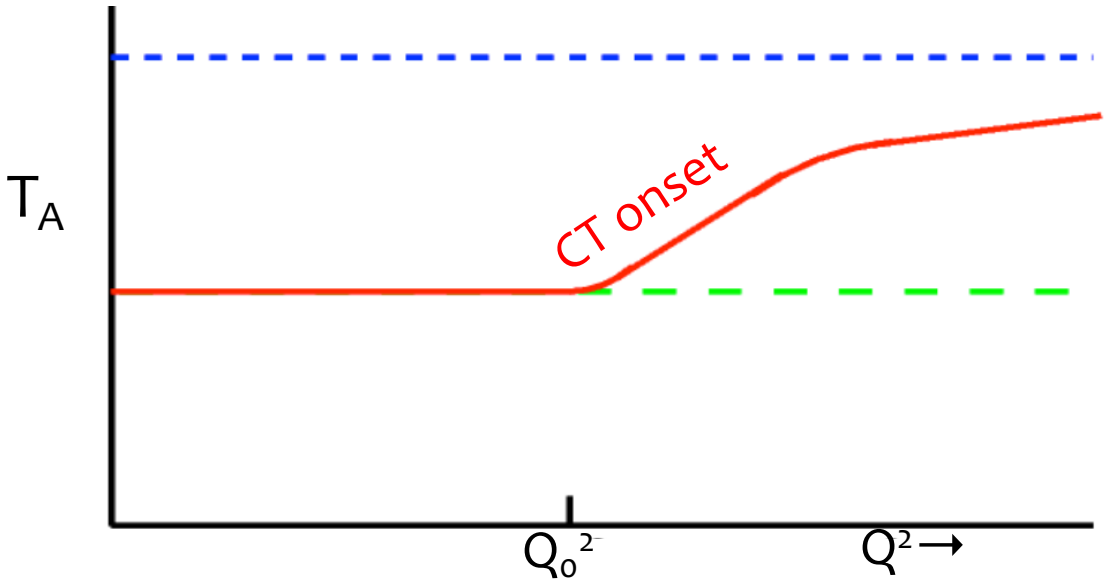
$$\gamma t_l = \frac{E}{m} t_l$$

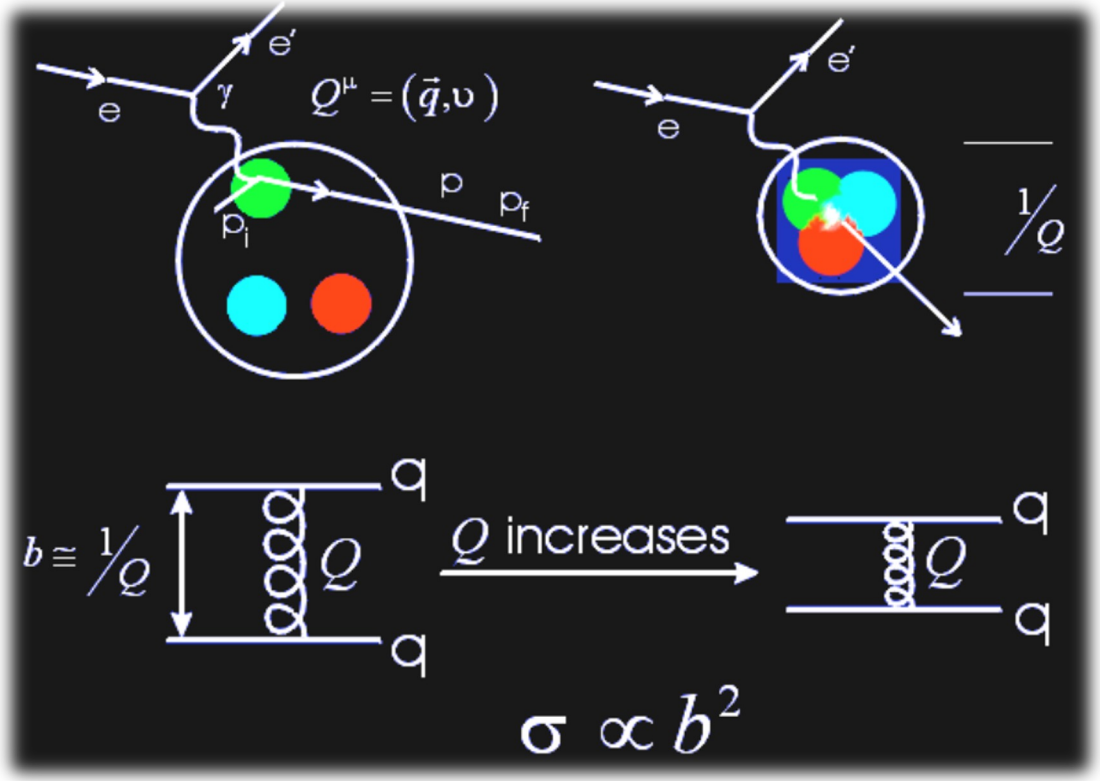
Strong force:
Experience reduced attenuation in the nucleus, color screened

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

Onset of CT indicates the transition to quark-gluon degrees of freedom

CT is not expected in the strongly interacting hadronic picture

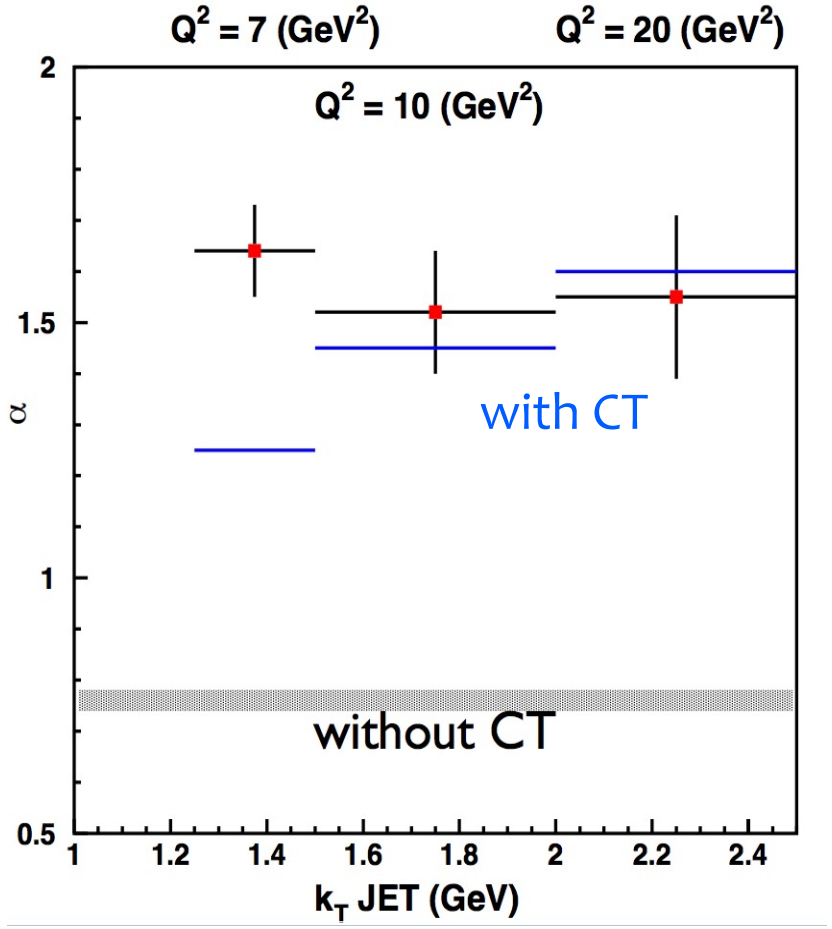


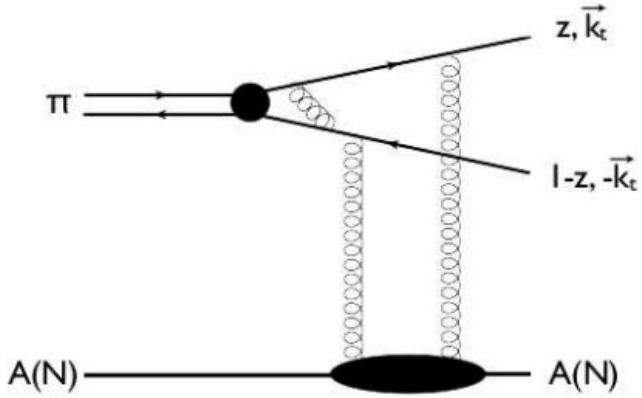


CT established at high energies

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

$\pi + A \rightarrow 2$ jets + A'





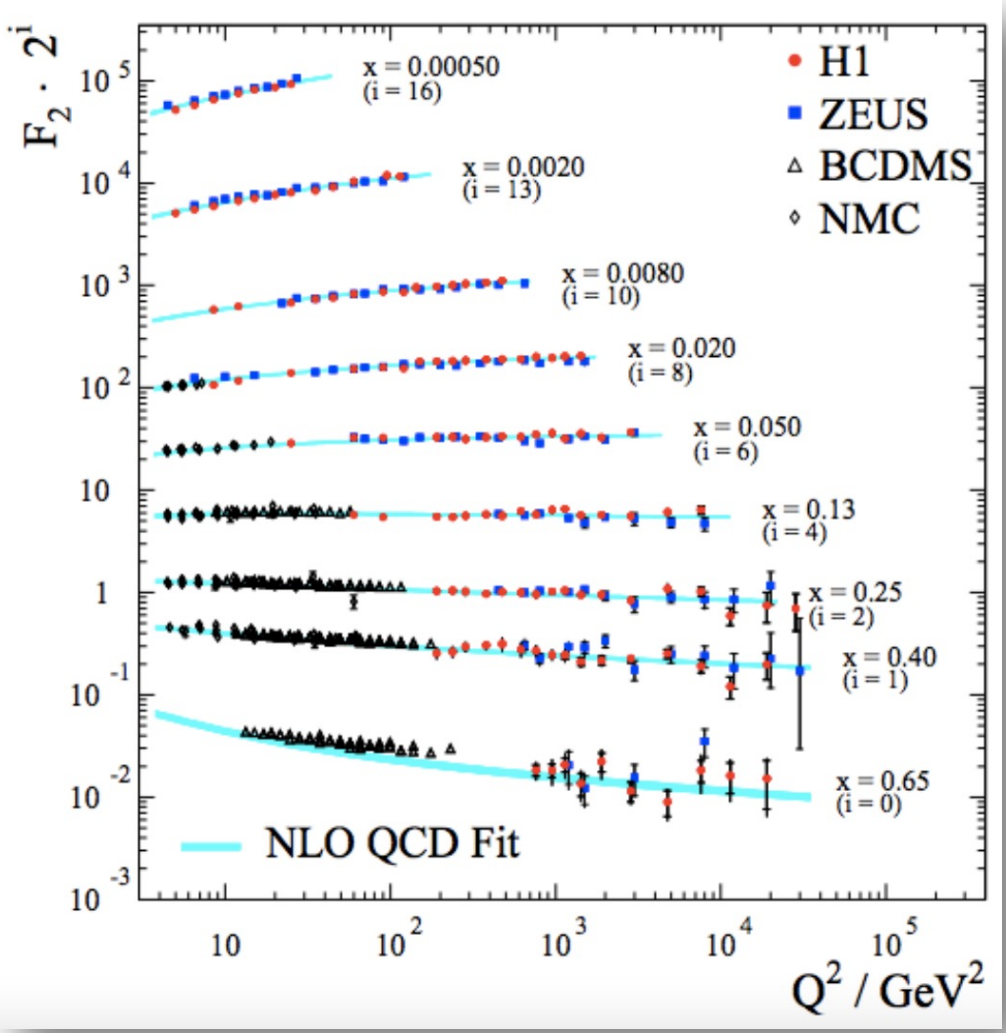
Fit to $\sigma = \sigma_0 A^{\alpha}$

Pion-nucleus total cross section, α=1.6

CT predictions by L. L. Frankfurt, G. A. Miller, and M. Strikman, Phys. Lett. B304, 1 (1993)

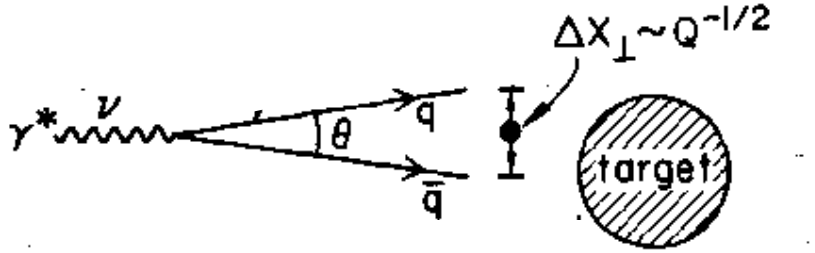
Aitala et al., PRL 86, 4773 (2001)

First indirect evidence of CT: Bjorken scaling at small x



Small x ($\leq 10^{-2}$) → long longitudinal distances

Virtual photon fluctuates into a $q\bar{q}$ pair



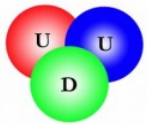
Scaling shows no evidence of this interaction

Bjorken, SLAC-PUB-1756

Frankfurt and Strikman, Phys Rep 160, 235 (1988)

CT experiments

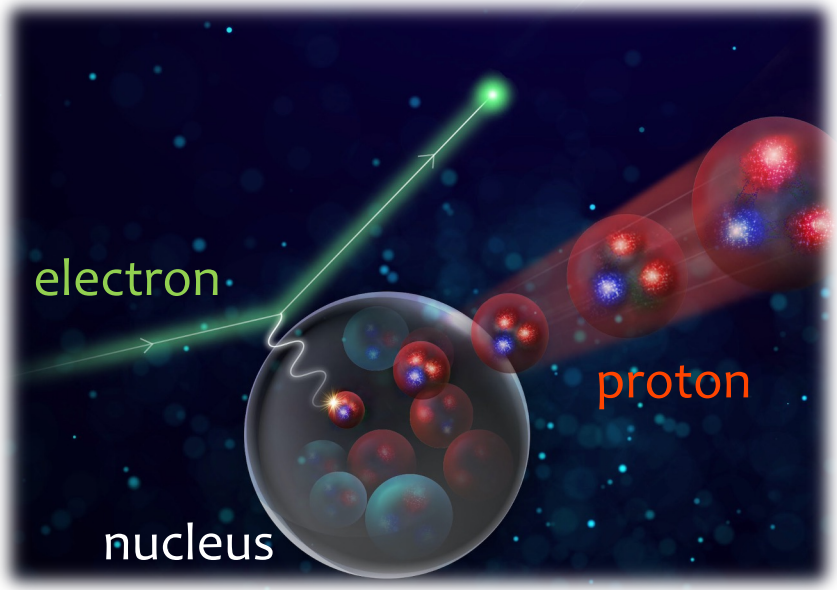
Baryon

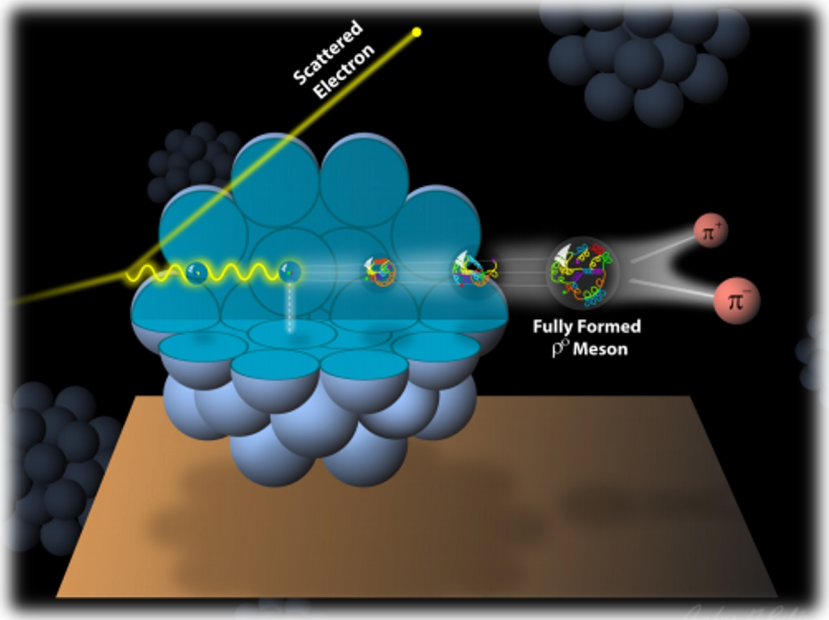


A(p,2p): BNL
A(e,e'p): SLAC, JLab

Meson

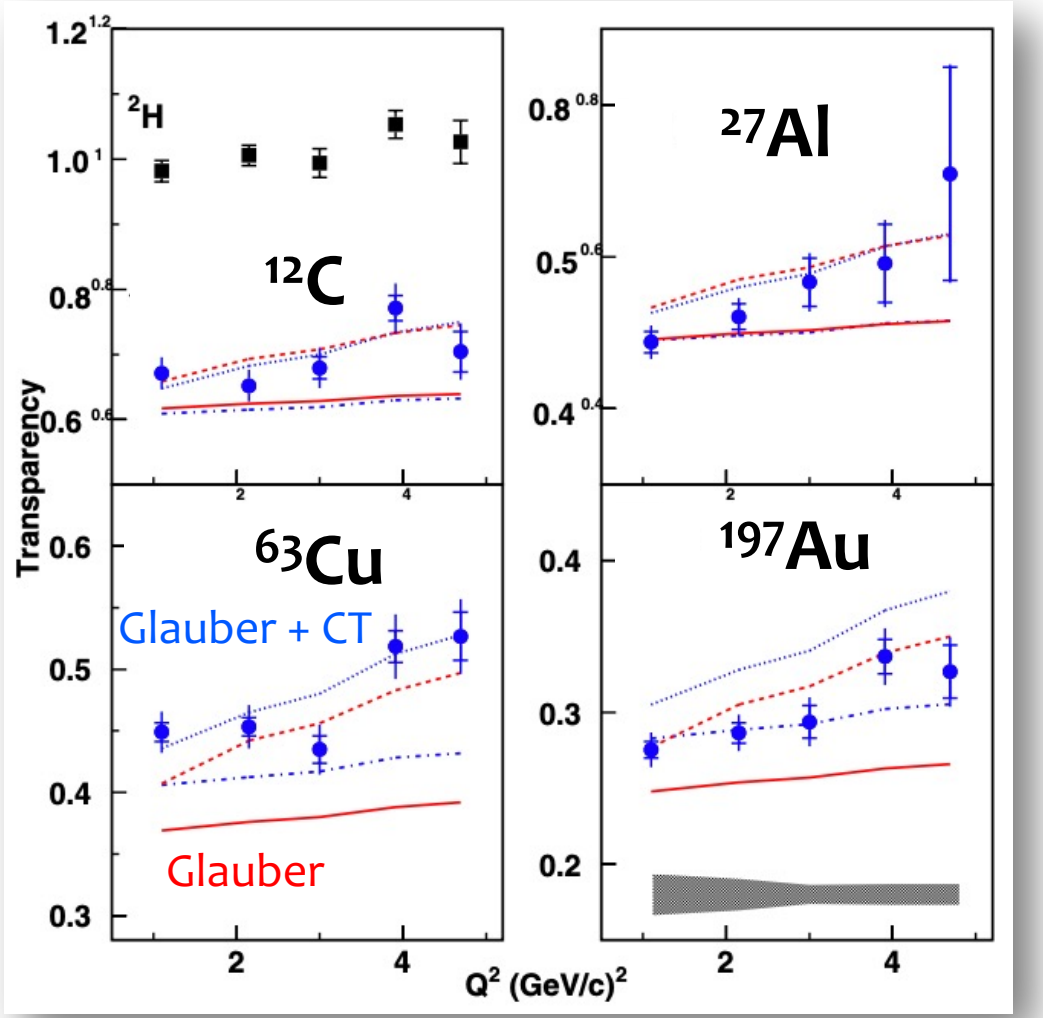
A(π,di-jet): FNAL
A(γ, π^- p): JLab
A(e, e'π^+): JLab
A(e, e'ρ^0): DESY & JLab





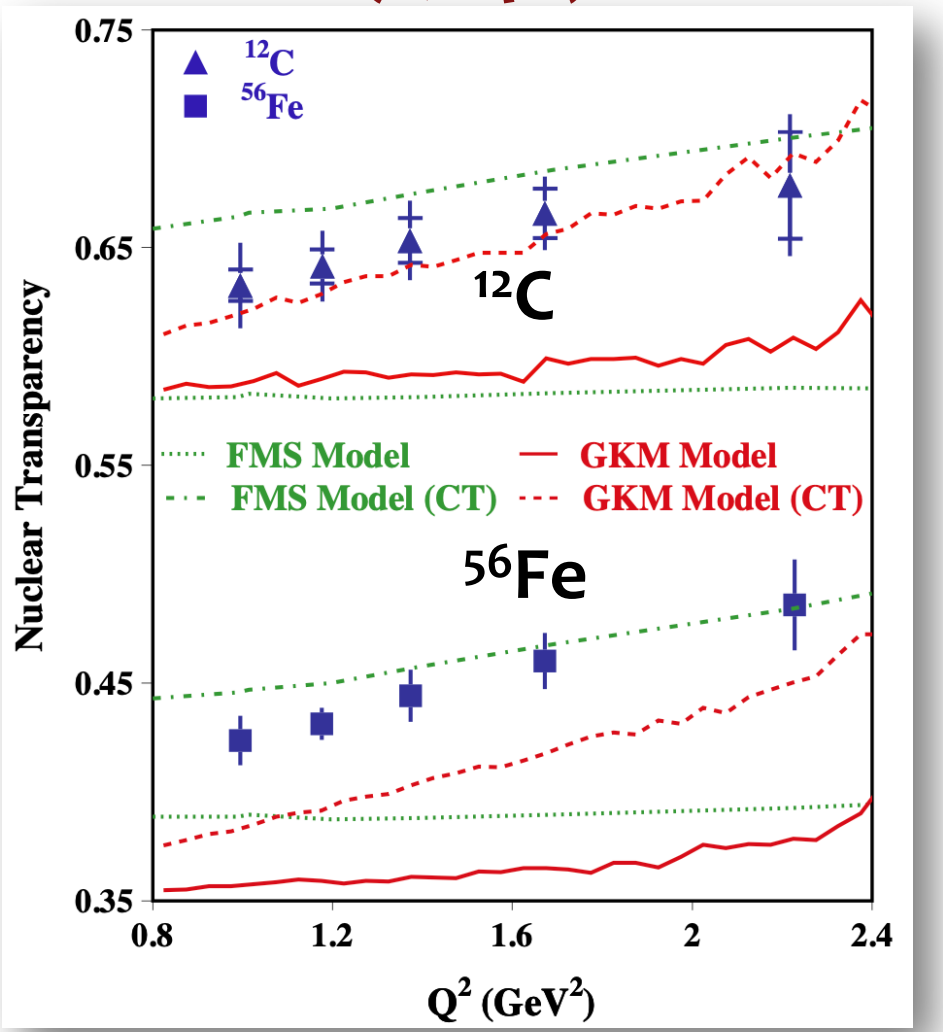
CT onset for mesons observed at a few GeV²

A(e,e'π^+)



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

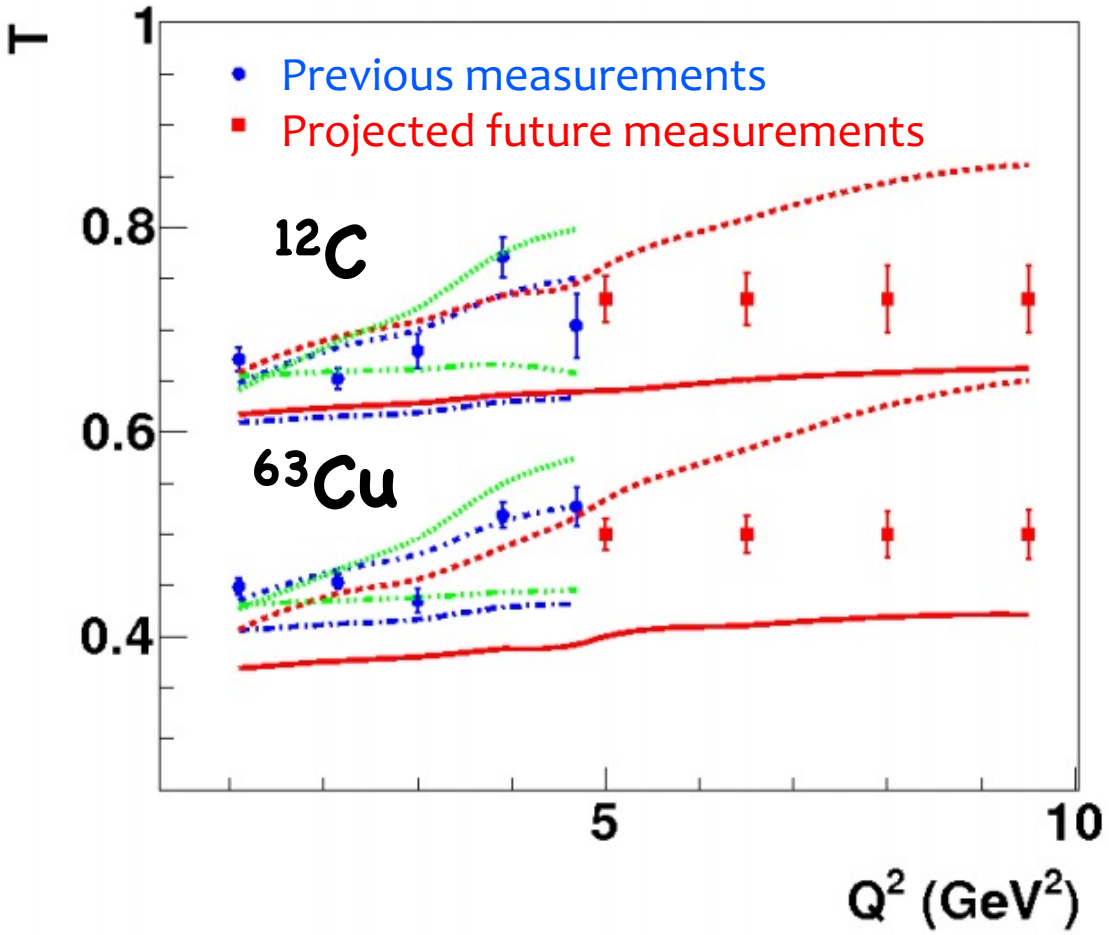
A(e,e'ρ^0)

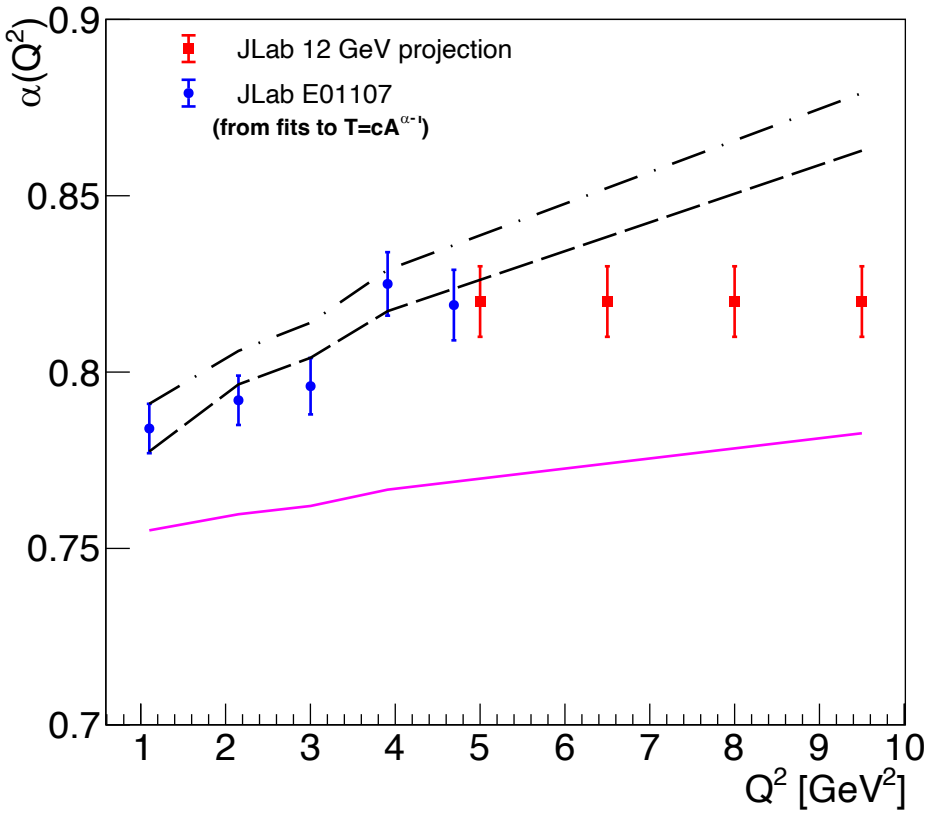


L. El Fassi et al, PLB 712,326 (2012)
L. El Fassi, Physics 4, no. 3 (2022)

Extend and confirm onset of CT for pions (running in 2025)

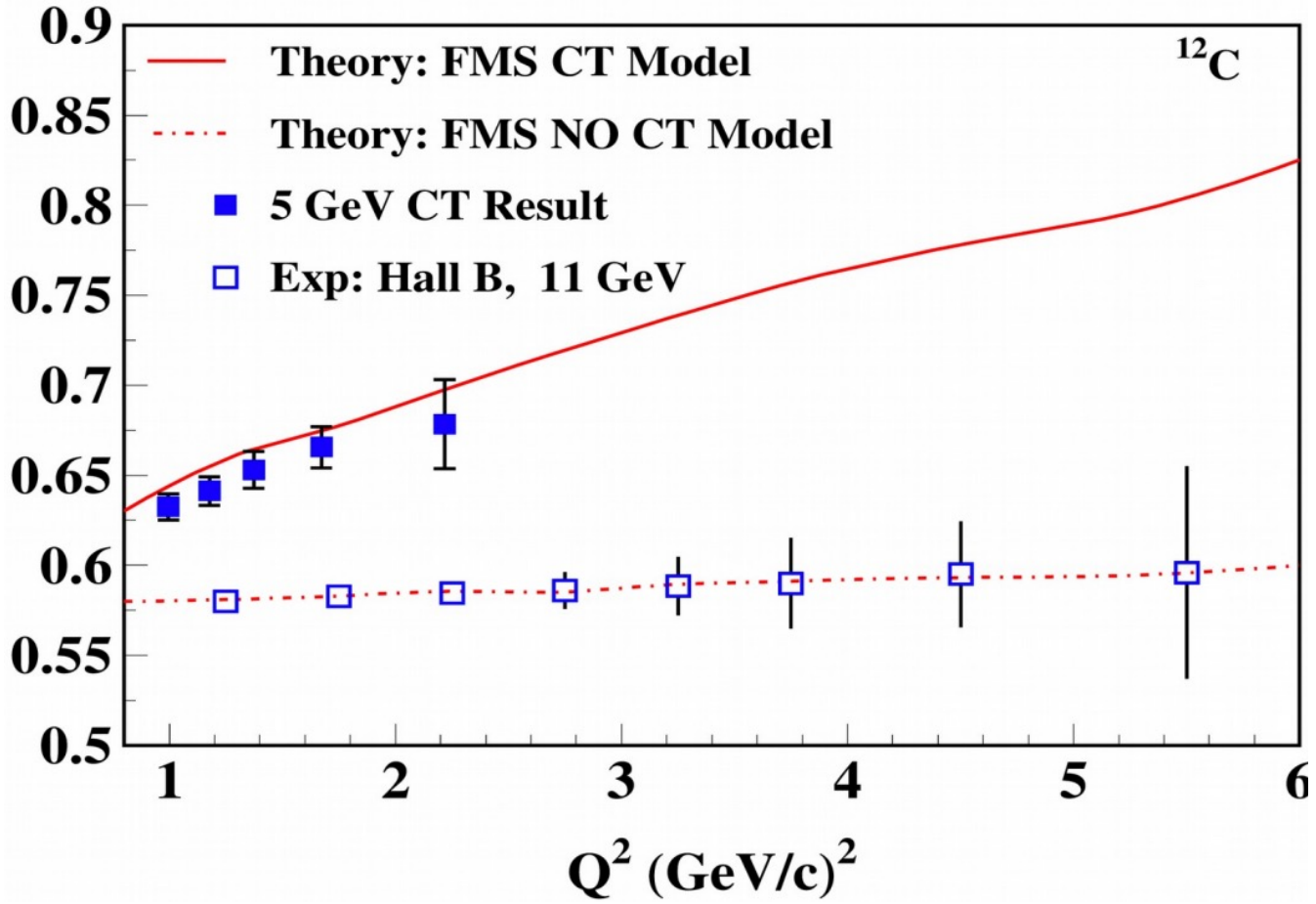
Extend the T and nuclear dependence



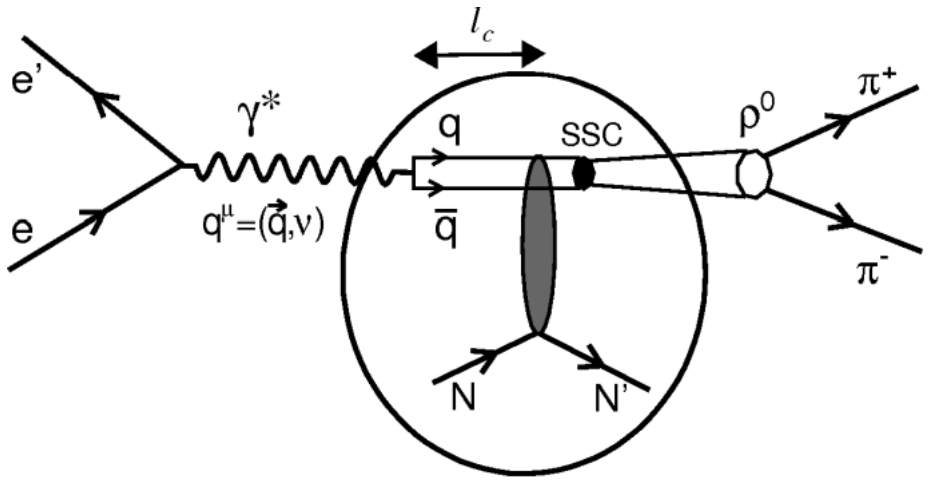


Extend measurements in the rho-meson

Rho transparency measurements will be extended to highest Q^2 in Hall B
Experiment completed running Dec 2023



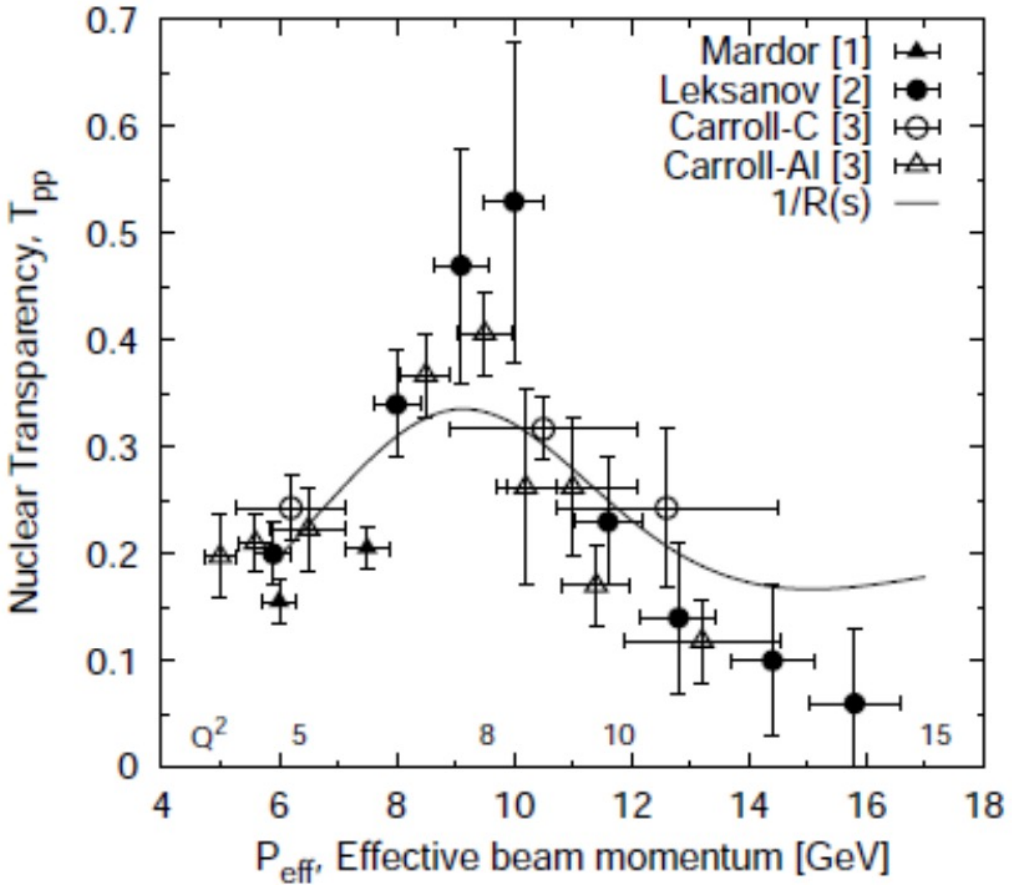
A(e,e'ρ⁰)



Targets: deuterium, ^{12}C, ^{63}Cu, ^{120}Sn

L. El Fassi + CLAS Collaboration

First attempt to measure the onset in protons



A. Leksanov et al. PRL 87 (2001)
J. L. S. Aclander et al., PRC 70 (2004)

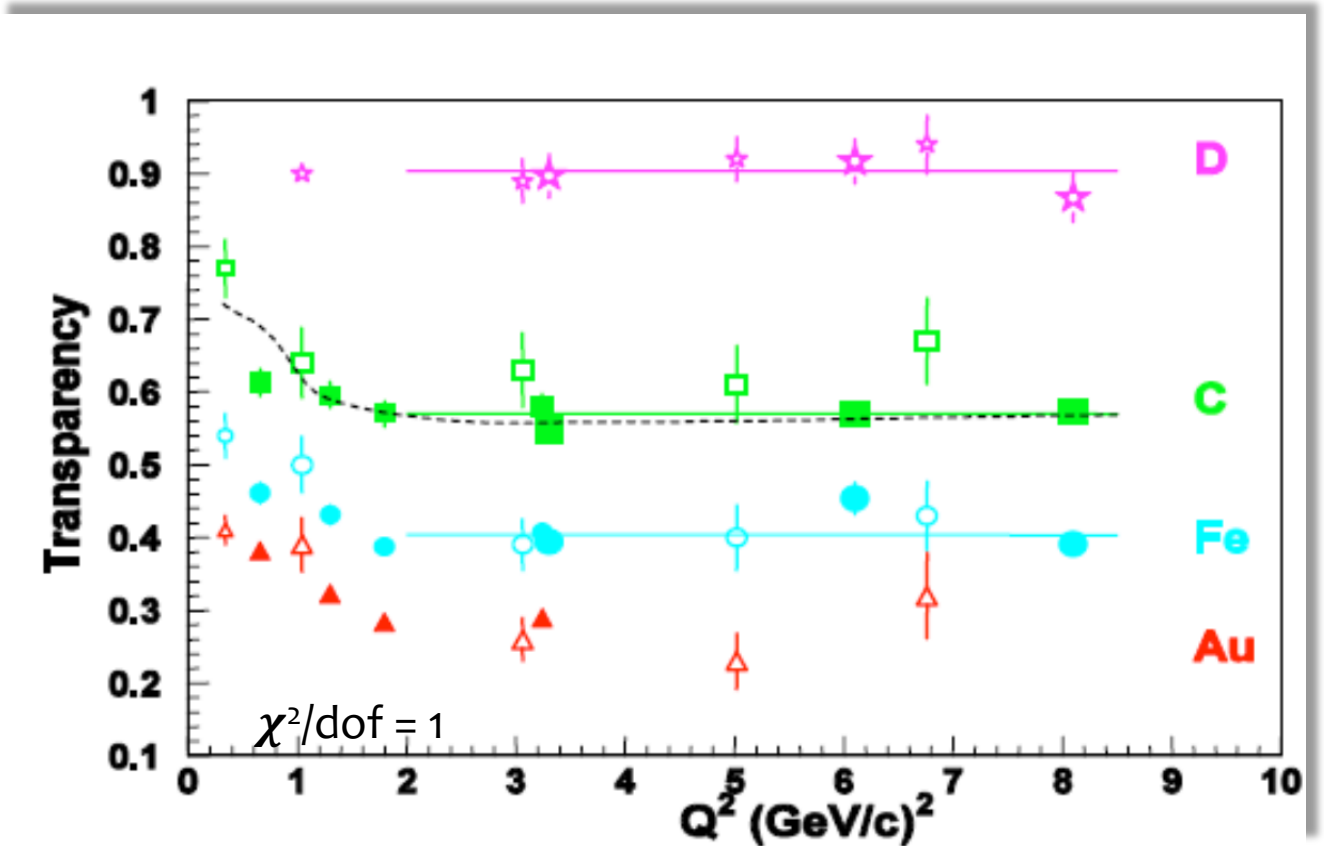
Transparency in A(p,2p) experiment at Brookhaven:

- observed enhancement in transparency
- inconsistent with CT only
- could be explained by including nuclear filtering[1] or charm resonance[2]

[1](Jain, Pire, Ralston)
[2](Brodsky, de Teramond)

Protons are historically challenging

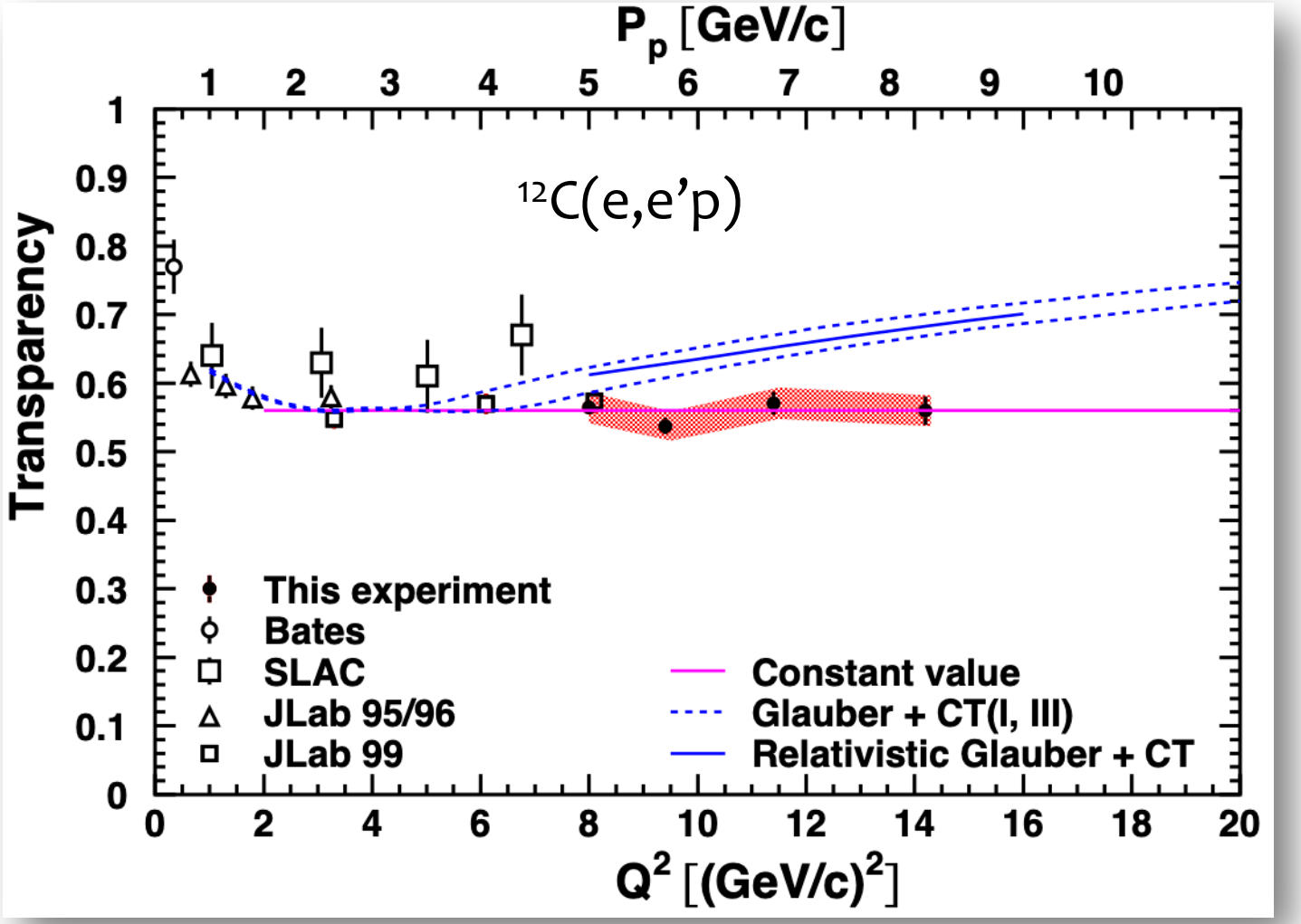
No evidence for CT in A(e,e'p) up to $Q^2<8$ GeV^2



JLab at 6 GeV couldn't rule out the possibility that the proton momentum was higher in the BNL (*p*,*pp*) results.

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)

No CT onset up to Q^2<14 GeV^2

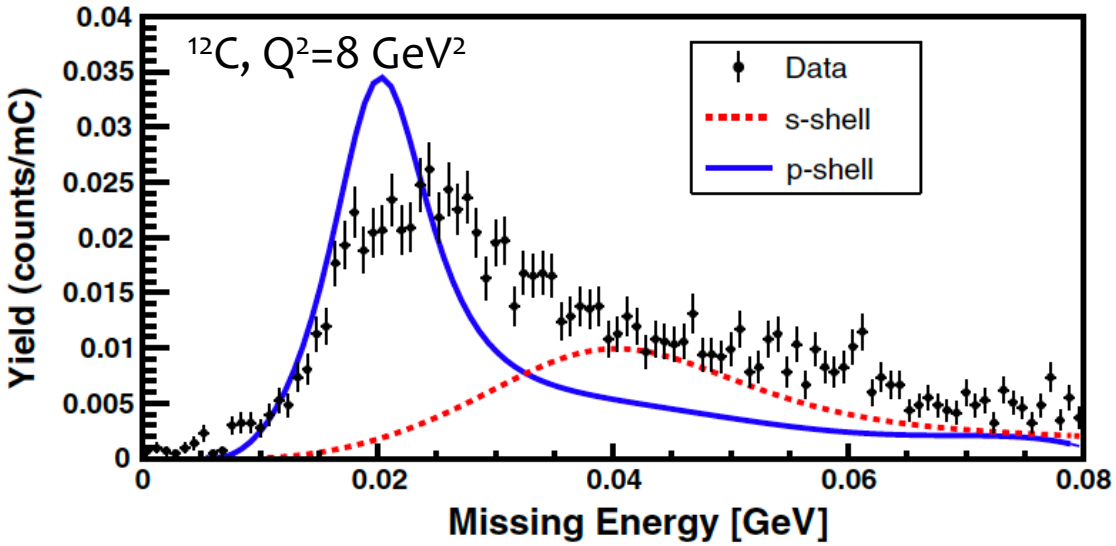


D. Bhetuwal et al, PRL126:082301 (2021)

No CT in the shell-dependent transparencies for ^{12}C

CT predicted to be more prominent for $1s_{1/2}$ protons

Frankfurt, Nuclear Physics A515 (1990)



In terms of shell-model orbitals:

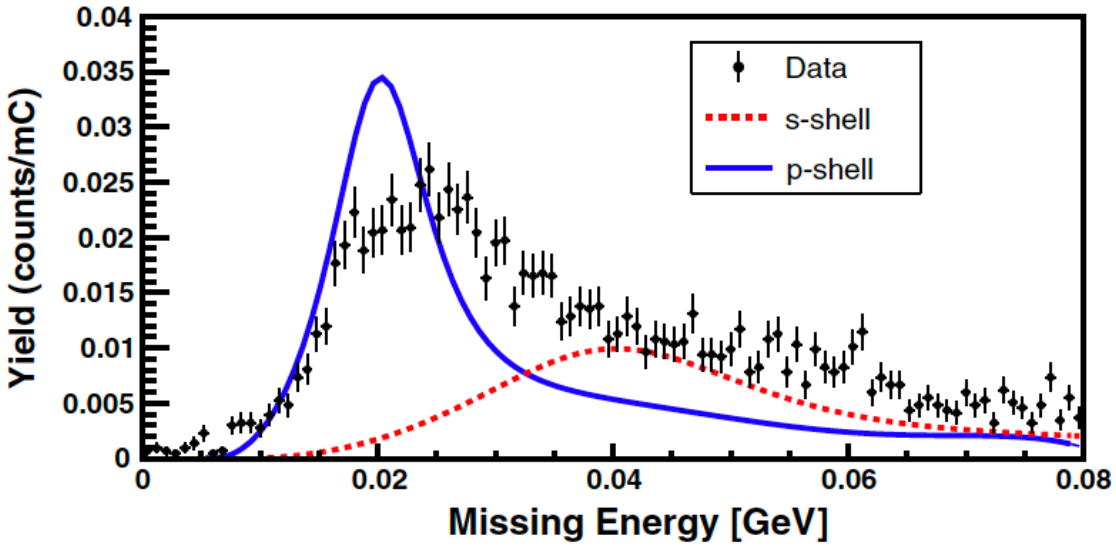
- p-shell protons are surface peaked (4)
- s-shell protons are more in the interior of carbon (2)

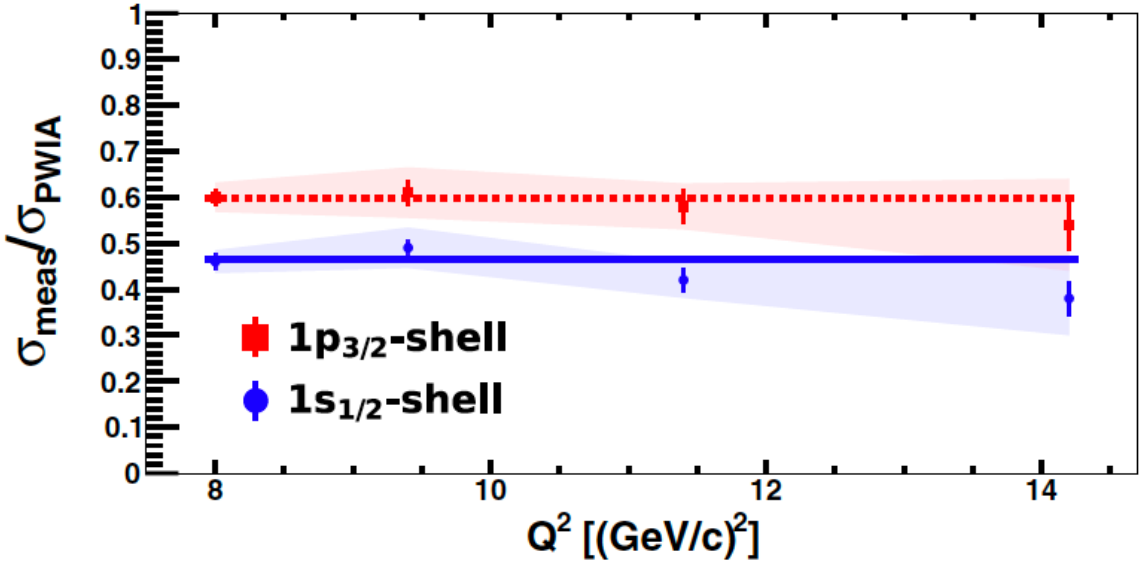
D. Bhetuwal, et al, Phys. Rev. C **108**, 025203 (2023)

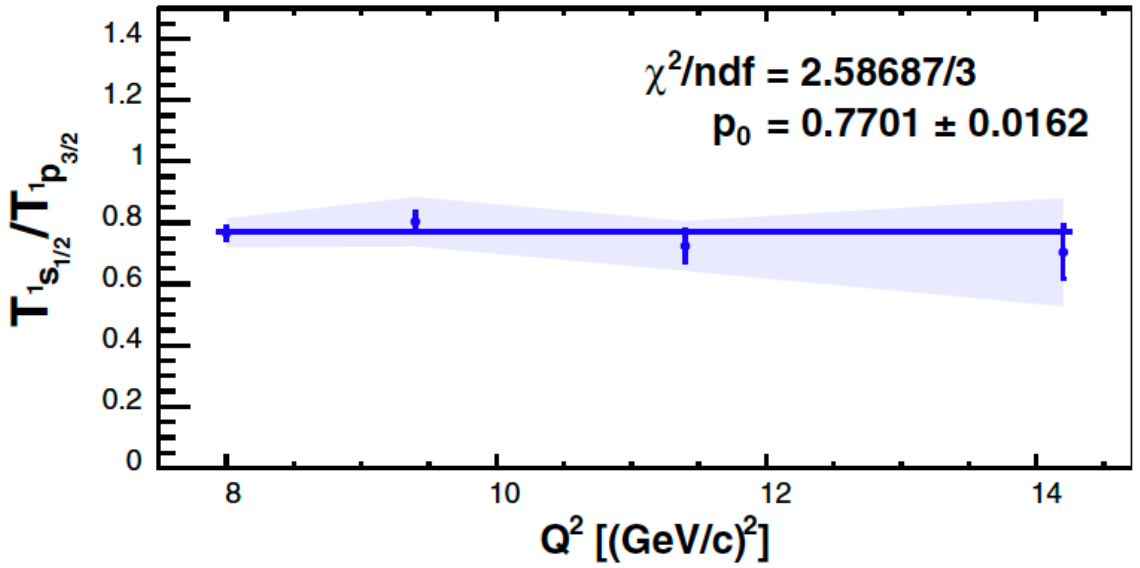
No CT in the shell-dependent transparencies

CT predicted to be more prominent for $1s_{1/2}$ protons

Frankfurt, Nuclear Physics A515 (1990)

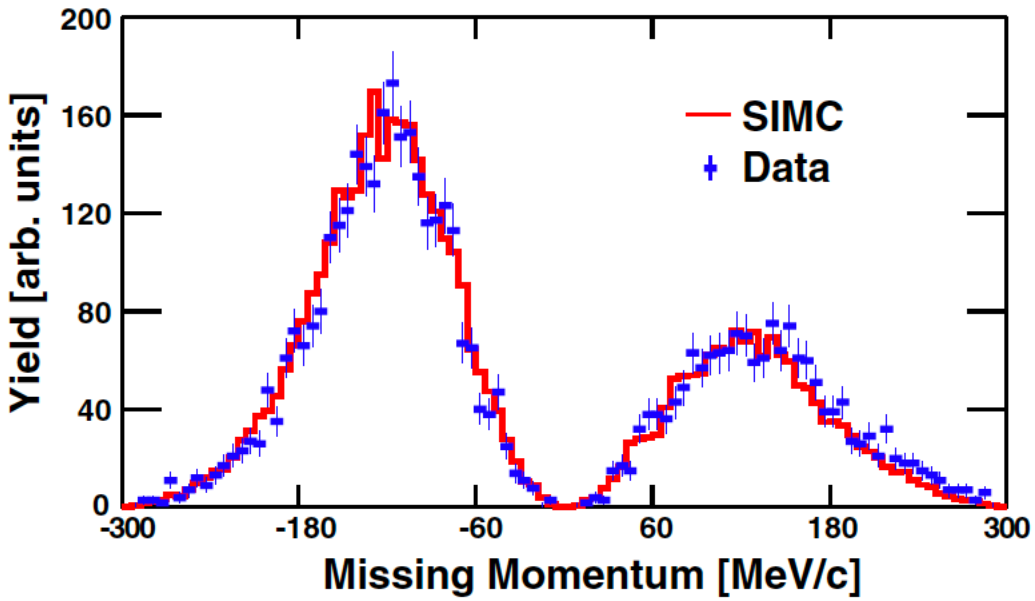






D. Bhetuwal, et al, Phys. Rev. C **108**, 025203 (2023)

No CT in the asymmetry relative to $\vec{q}$



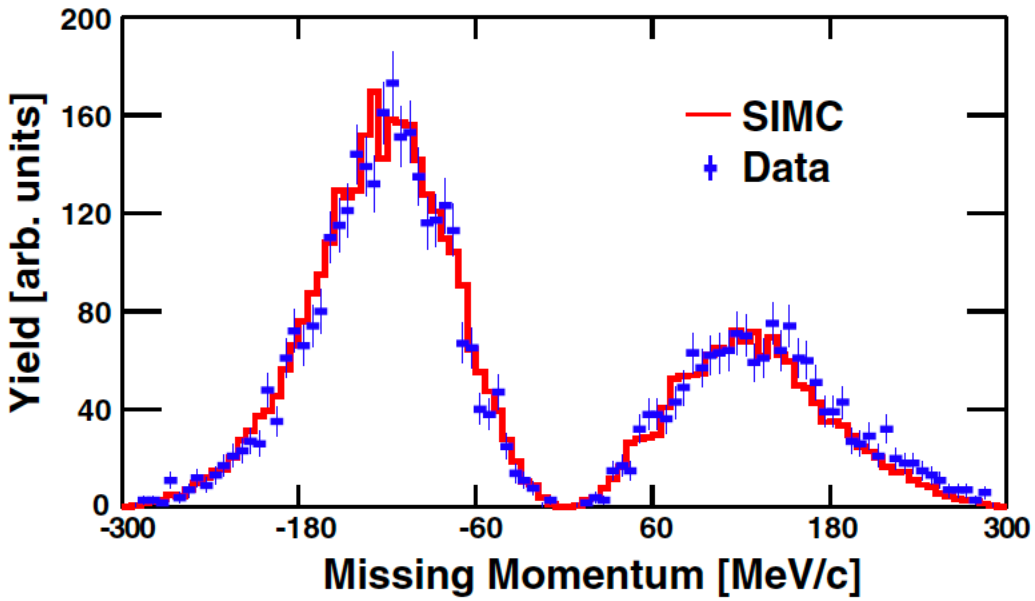
$\vec{p}_m \parallel \vec{q}$ $\quad\quad$ $\vec{p}_m \parallel -\vec{q}$

$$A_{pm} = \frac{N_+ - N_-}{N_+ + N_-}$$

CT arising from Fermi motion predicted to occur when $\vec{p}_m \parallel -\vec{q}$

Jennings and Kopeliovich PRL 70 (1993)
Bianconi et al, PLB 325 (1994)

No CT in the asymmetry relative to $\vec{q}$

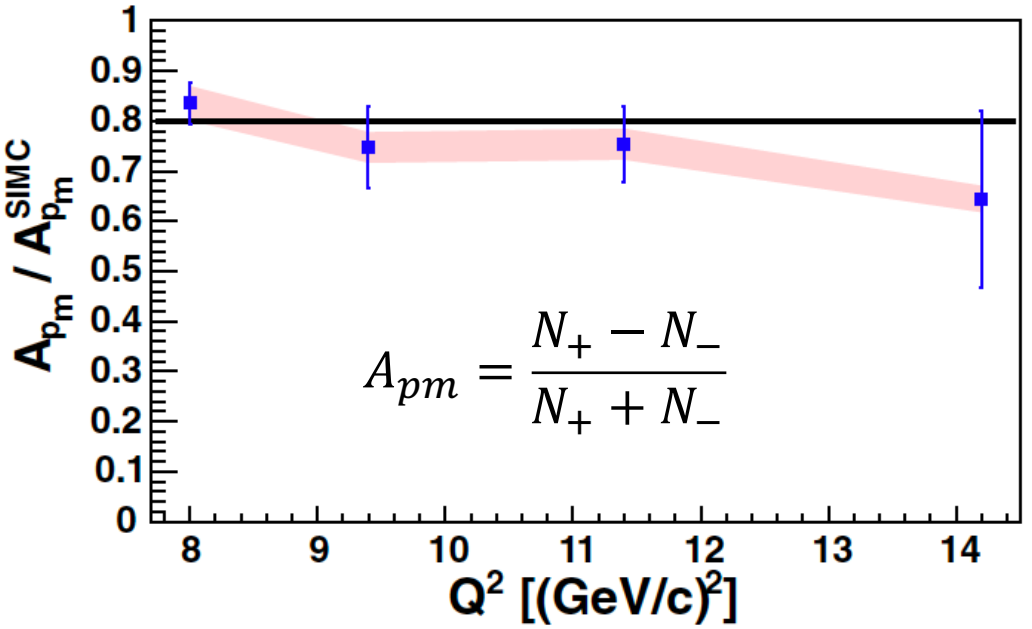


$\vec{p}_m \parallel \vec{q}$ $\vec{p}_m \parallel -\vec{q}$

CT arising from Fermi motion predicted to occur when $\vec{p}_m \parallel -\vec{q}$

Jennings and Kopeliovich PRL 70 (1993)
Bianconi et al, PLB 325 (1994)

Studied A_{pm} in bins of missing energy and missing momentum
→ no CT-like effect observed

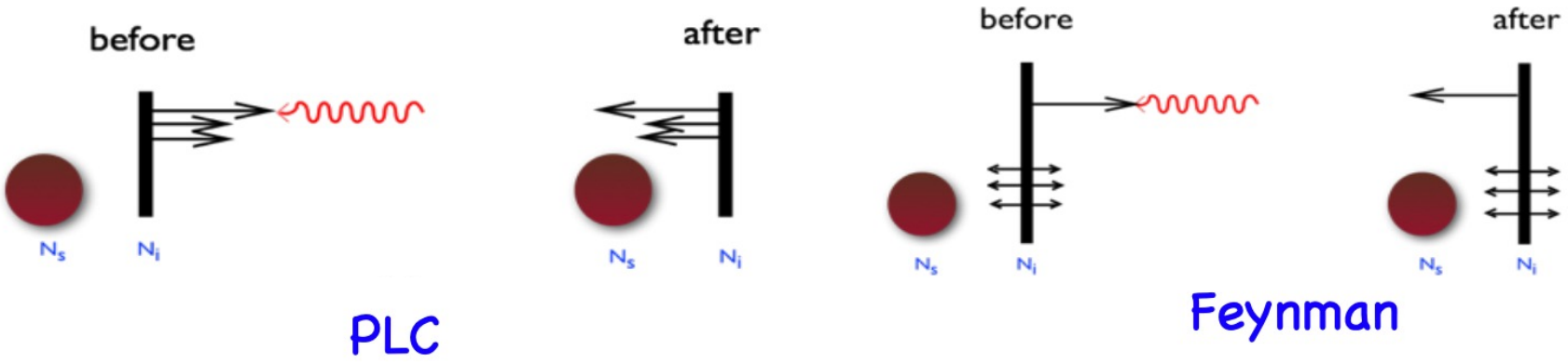


D. Bhetuwal, et al, Phys. Rev. C **108**, 025203 (2023)

Probably no PLC was formed…

Squeezing didn't work (Feynman Mechanism)

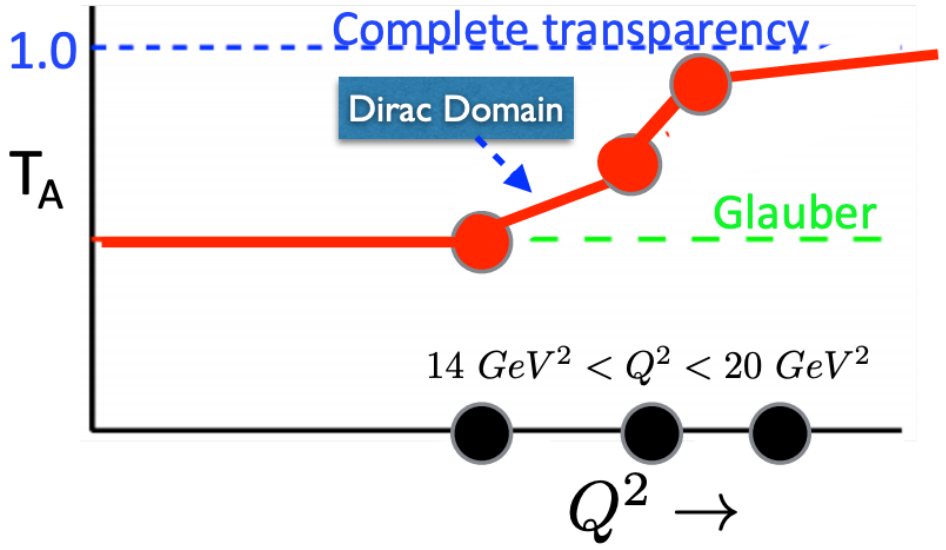
G. Miller, Physics 2022
O. Caplow-Munro and G. Miller, PRC 104 (2021)



Other considerations…

HLFQCD now predicting a higher Q^2

Brodsky and de Téramond, Physics 2022



In all the previous experiments of (e,e'p), kinematics were unable to distinguish the observation of a PLC from its expansion → susceptible to expansion effects

Future proton experiment will change kinematics and target strategy

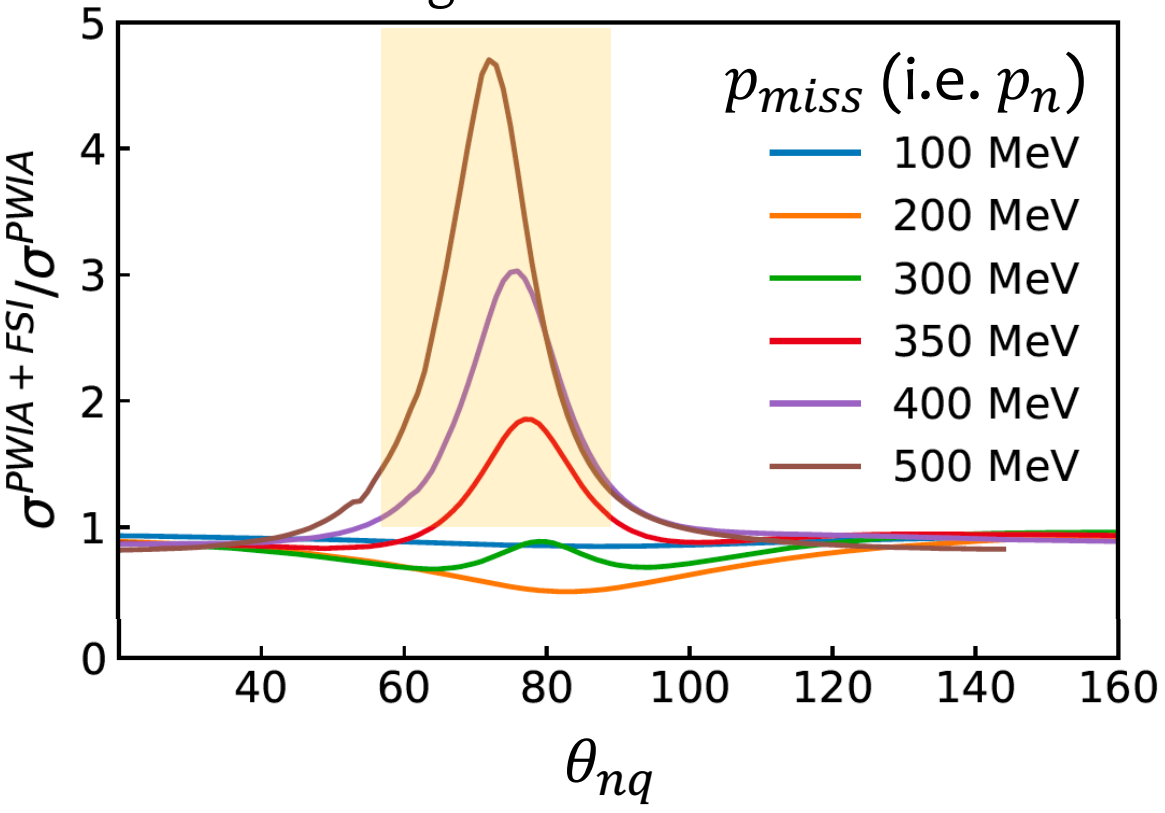
Deuterium is well-described through Generalized Eikonal Approximation (GEA)

Measuring d(e,e'p)n →
measure protons from re-scattering vertices!

Larger spectator momentum corresponds to a shorter distance between the production and the re-scattering vertices.

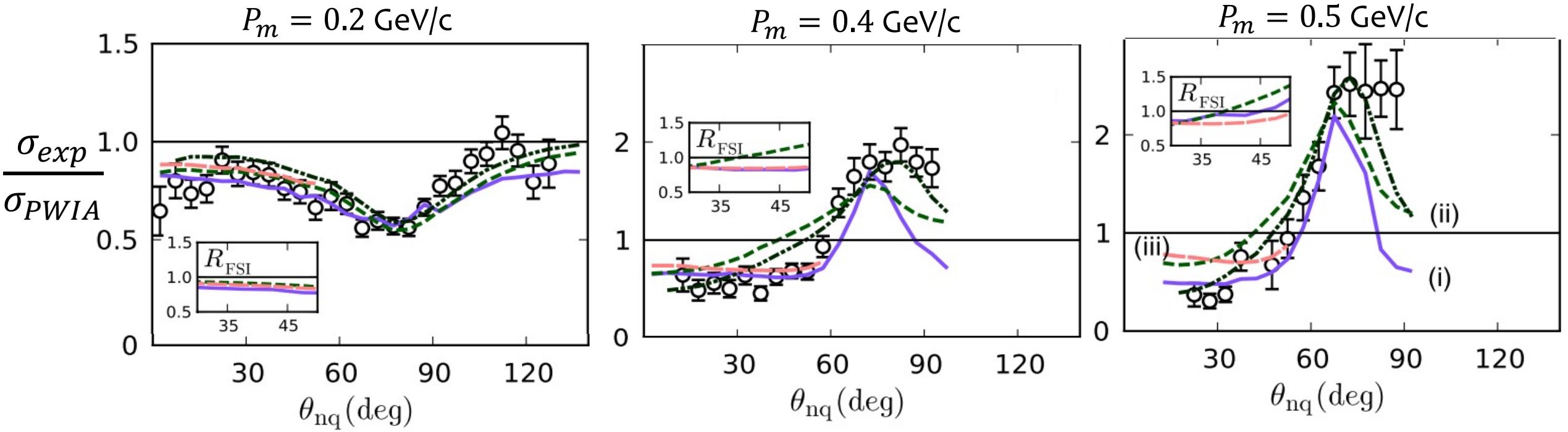
Enables separation of the observation of the PLC from its expansion (for the first time)!

Re-scattering dominates here!



Larger missing momentum increases the sensitivity to FSIs (shown from data)

$Q^2 = 3.5$ (GeV/c)²

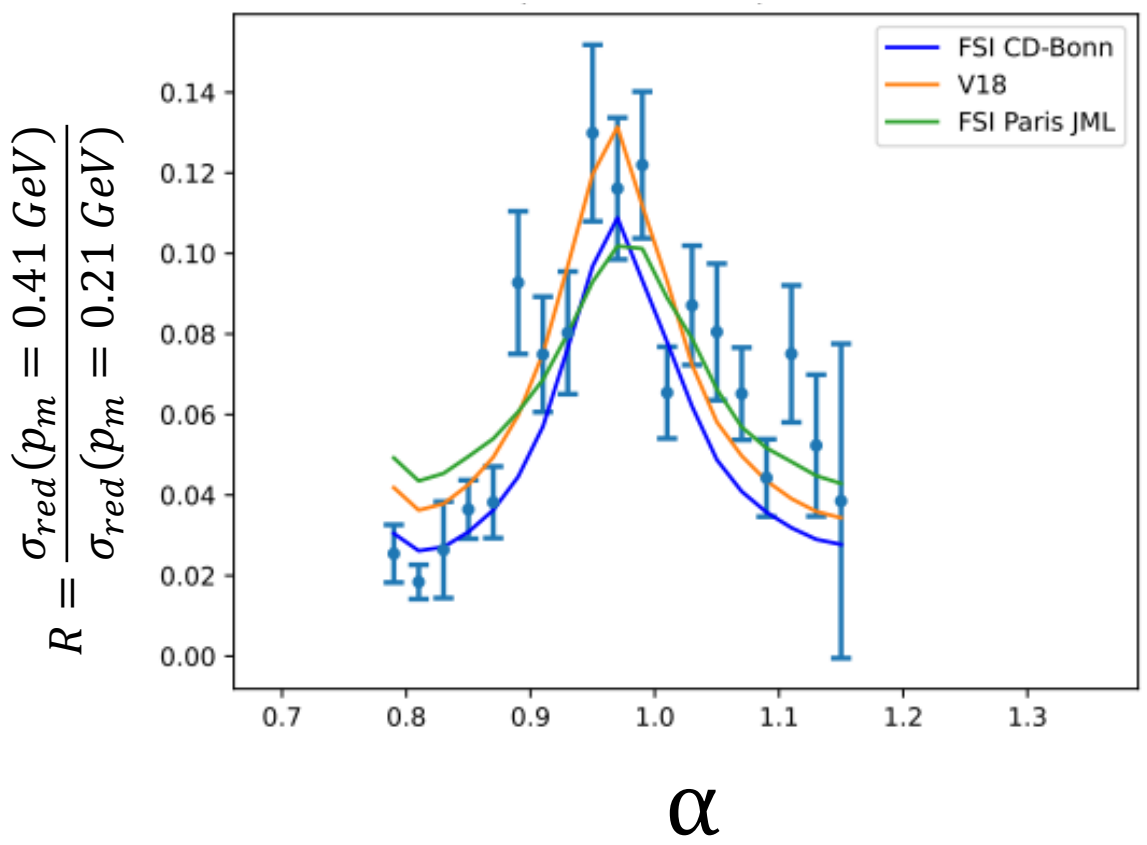


W. Boeglin et al., PRL (2011)

Ratio is well-calculable using GEA framework (data)

$$R = \frac{\sigma(high\ Pm)}{\sigma(low\ Pm)}$$

$Q^2 = 3.5$ (GeV/c)²

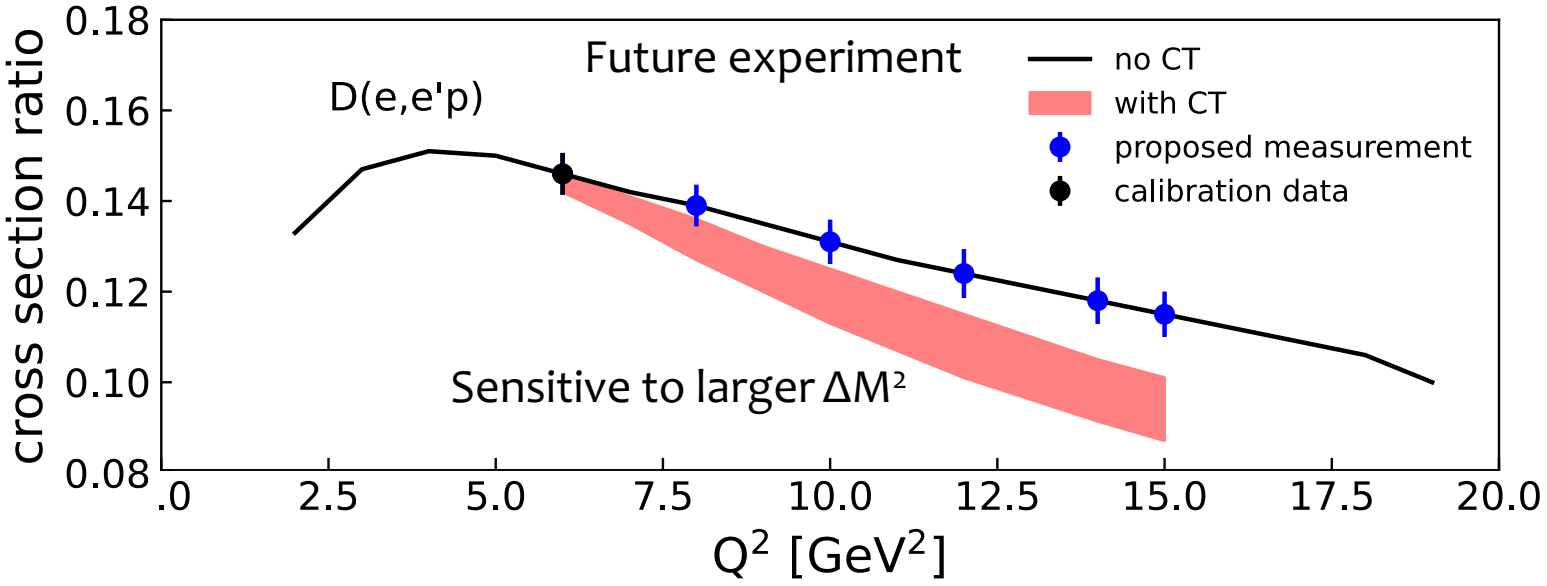


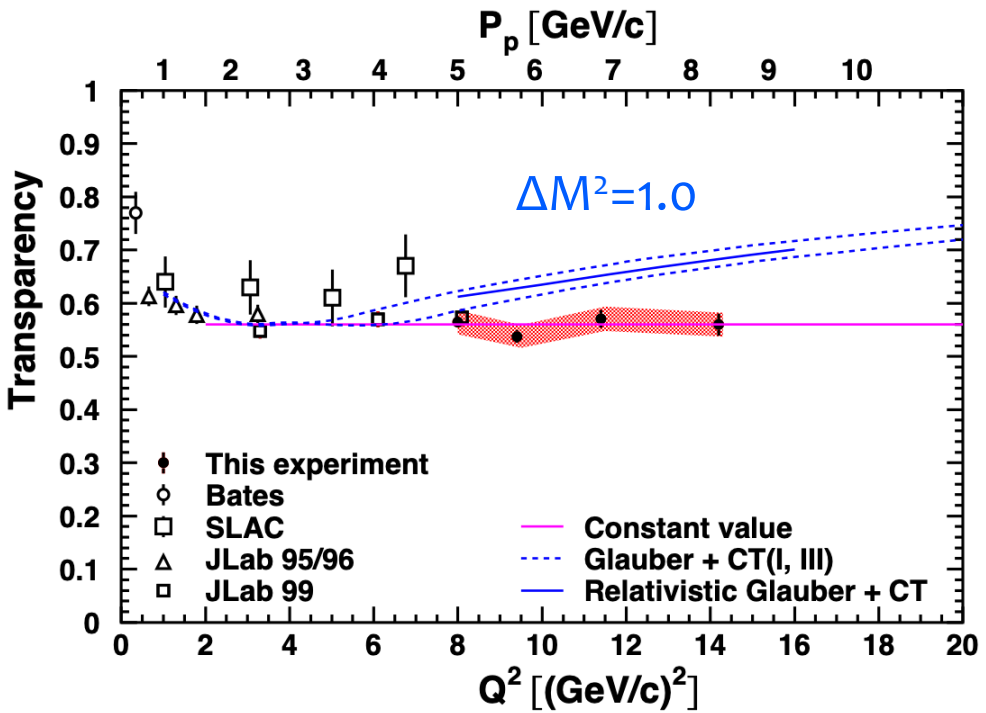
Light cone momentum fraction optimal near 1: $\alpha = (E_n - p_n cos\theta_{\gamma n})/m_n$

W. Boeglin, M. Sargsian PLB 854 (2024)

Sensitivity to shorter PLC lifetimes

$$R = \frac{\sigma(high\ Pm)}{\sigma(low\ Pm)}$$





Farrar et al., PRL (1988)

Larger ΔM^2 → shorter PLC lifetime → delays CT onset

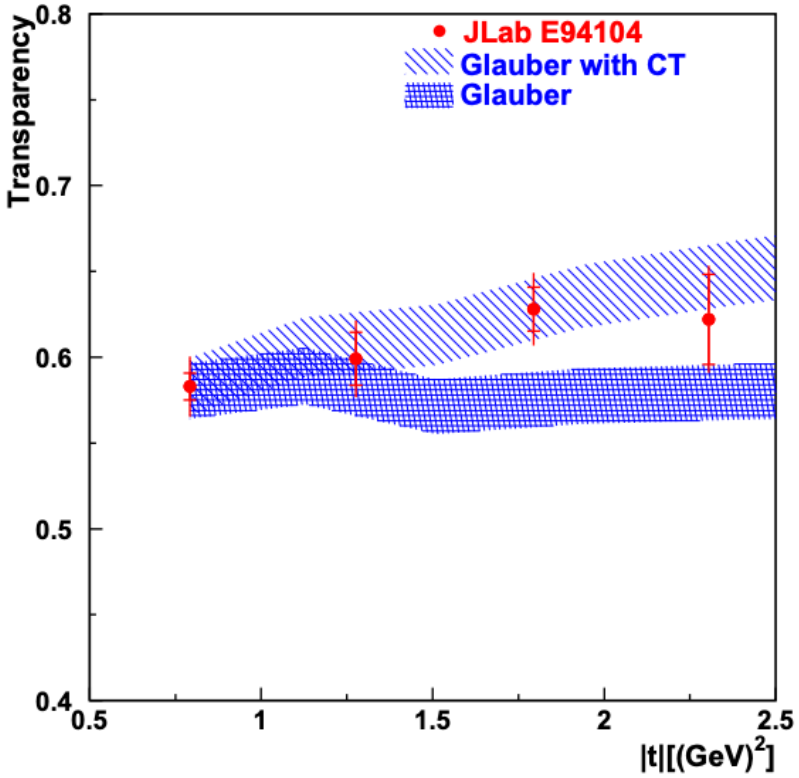
$$l_h = 2p_h/\Delta M^2$$

Larger ΔM^2 consistent with lack of observation of weakly interacting QGP

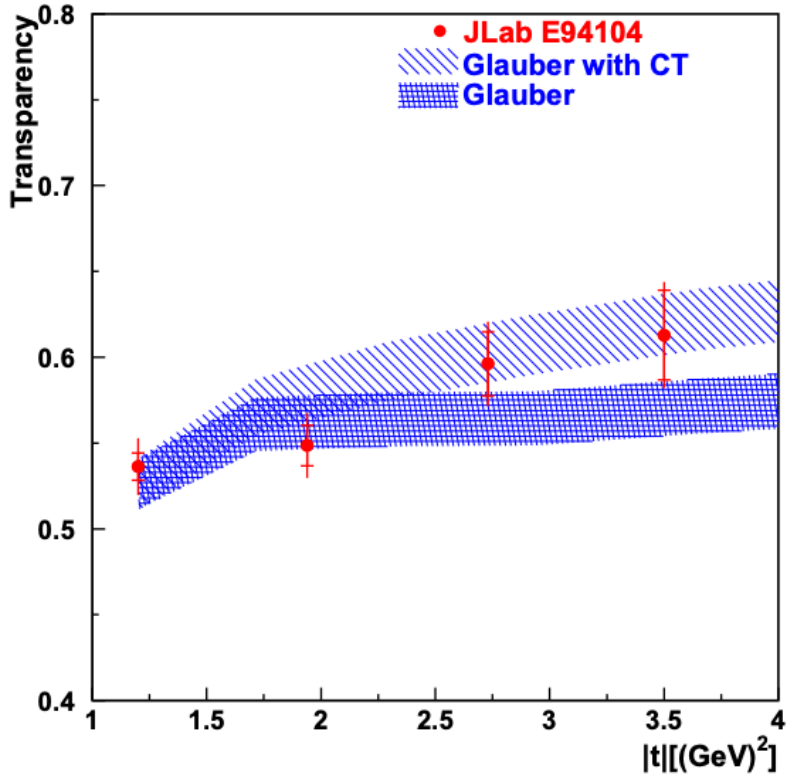
Other reaction mechanisms: pion photoproduction

$\gamma n \rightarrow \pi^- p$ in ^{4}He in Hall A

70° c.m. scattering



90° c.m. scattering



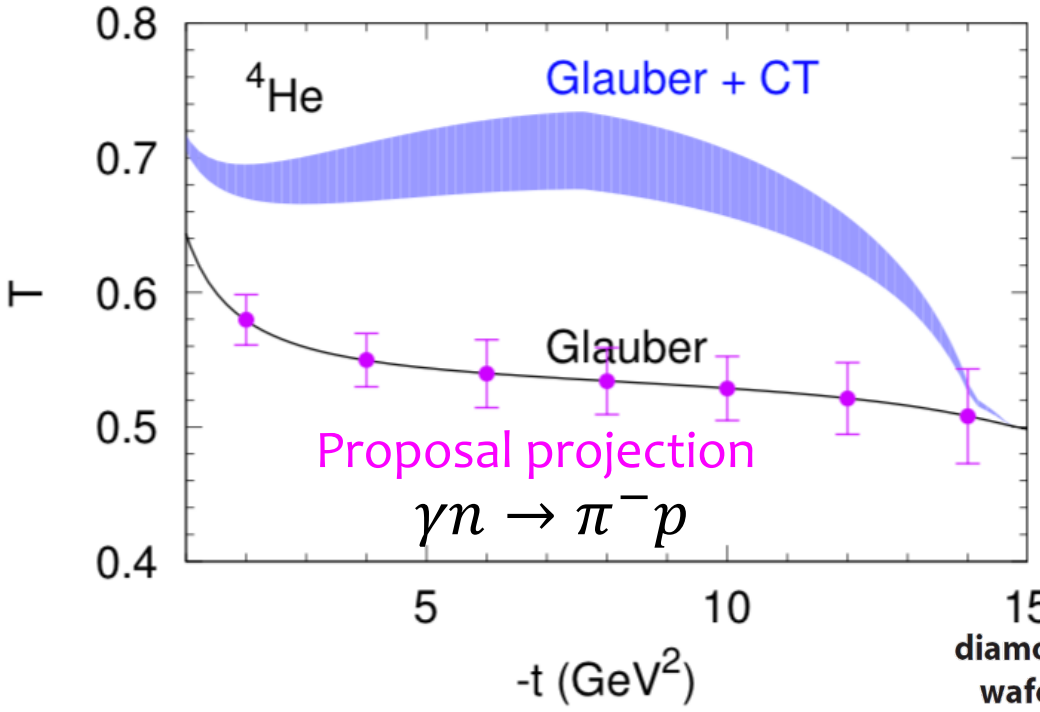
Possible onset?

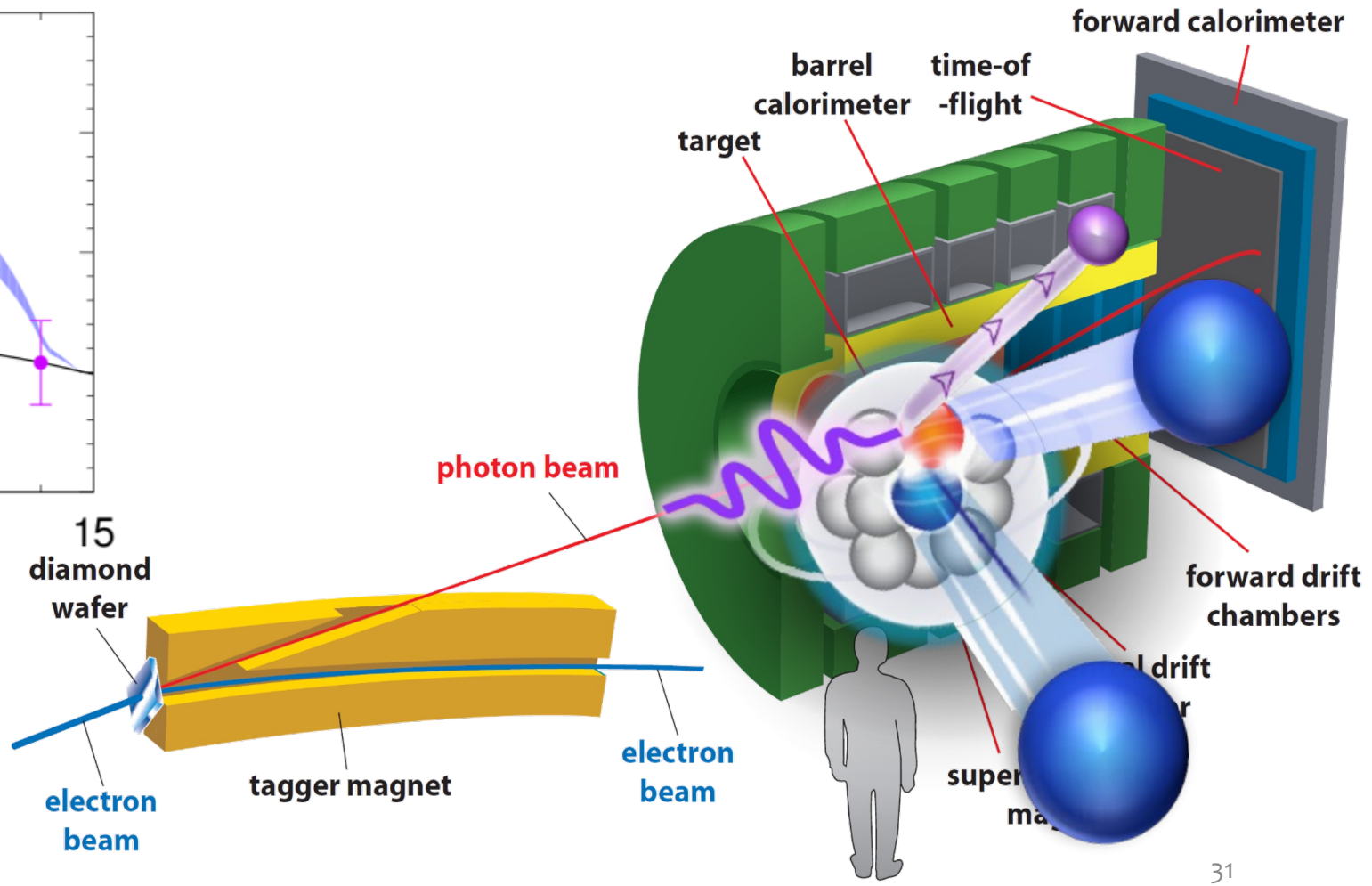
D. Dutta *et al.* PRC 68.021001 (2003)

Photoproduction in Hall D at JLab

Experiment ran in 2021 on ^{4}He, ^{12}C and deuterium

- Goal to study SRCs and test our assumptions
- Look for CT effects using photons

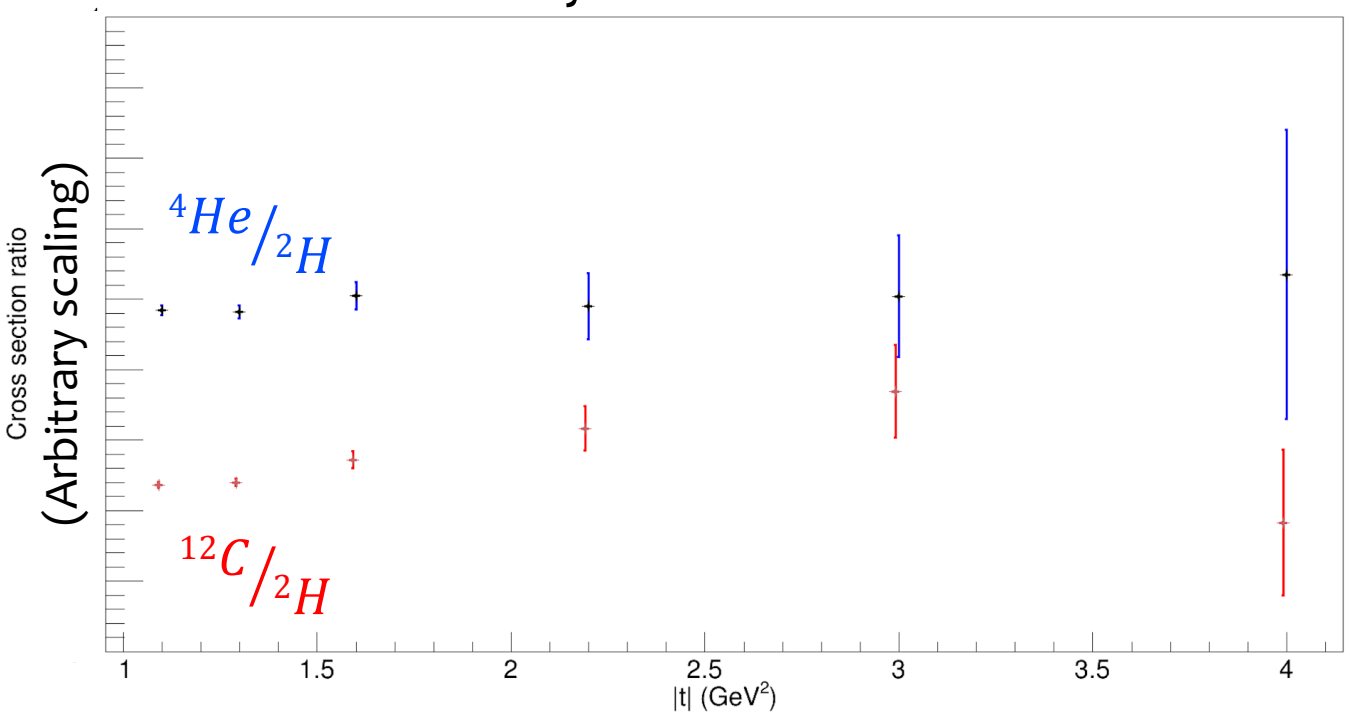




Photoproduction in Hall D at JLab

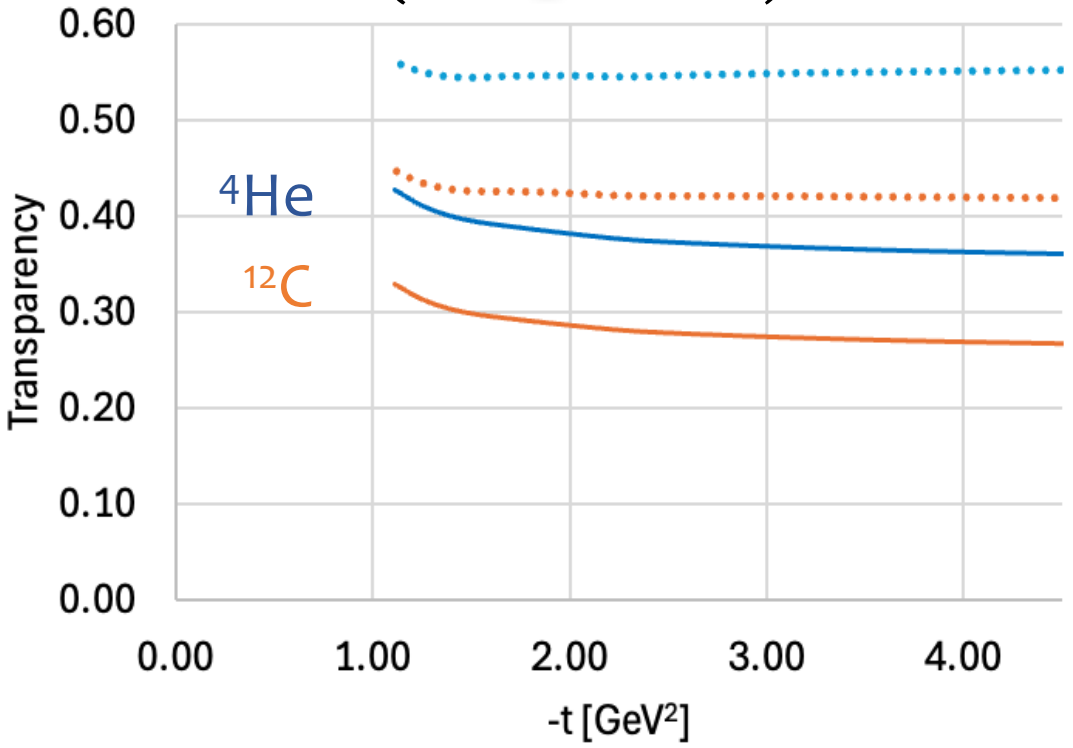
$$\gamma p \rightarrow \rho^0 p$$

Preliminary cross section ratios



Analysis of Bhesha Devkota,
Mississippi State University

Theory calculations from A. Larionov
(CT dashed line)



(Also observe resolved photon
vs point-like photon)

Summary

- The onset of CT connects the hadronic and partonic descriptions of matter
- CT onset has been indicated in mesons starting a a few GeV^2→ new results coming soon that will confirm and extend these observations!
- No CT onset observed in protons yet, but a future experiment with a change in kinematics will also be able to separate PLC production from expansion
- Photo nuclear program will provide more information on the reaction dependence of CT and photon structure

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