Experimental outlook on exploring color transparency phenomena

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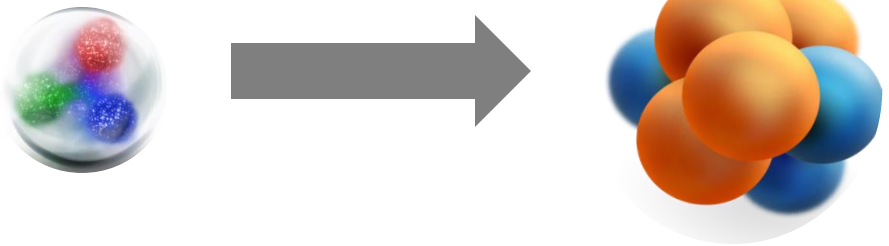
Florida International University

15 March 2025
11th workshop of the APS topical Group on Hadronic Physics
Anaheim, CA

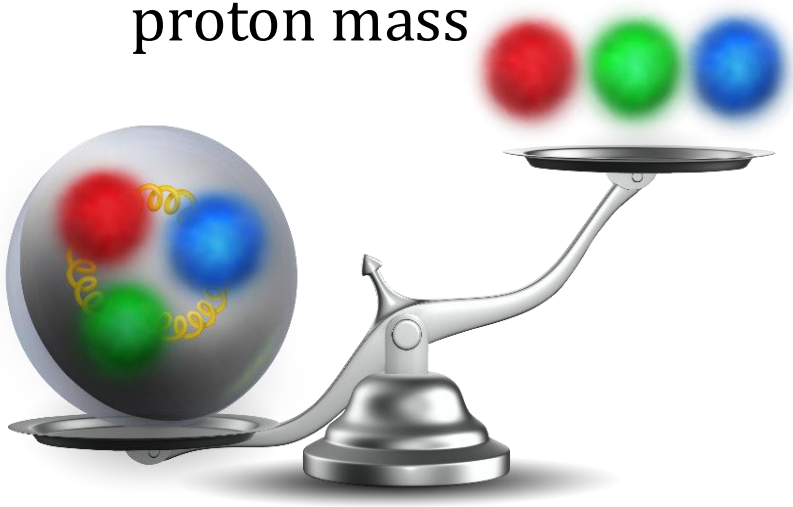
FIU FLORIDA INTERNATIONAL UNIVERSITY

From quarks to nuclei?



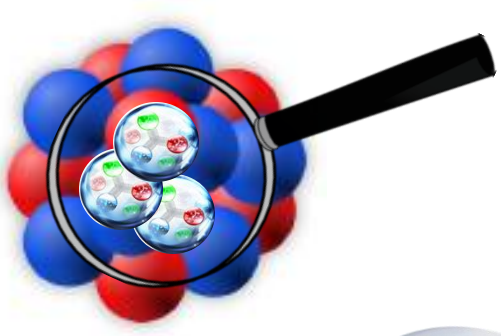
More than just constituent particles

Quark masses account for <1% of the proton mass



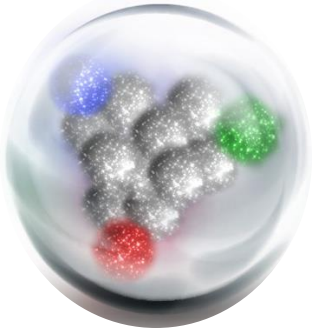
Quantum Chromodynamics (QCD) governs the strong force between *quarks* and *gluons*

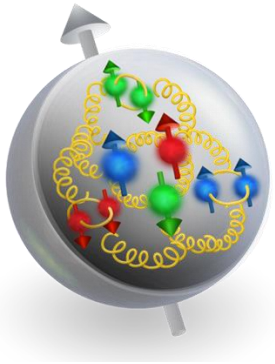
Consequences of QCD



Properties of nucleons and nuclei emerge from this complex system of *interacting* quarks and gluons

$$|p\rangle = |uud\rangle + |uudq\bar{q}\rangle + |uudg\rangle + \ldots$$



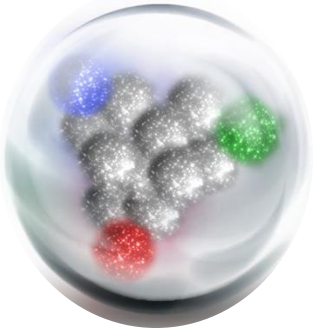


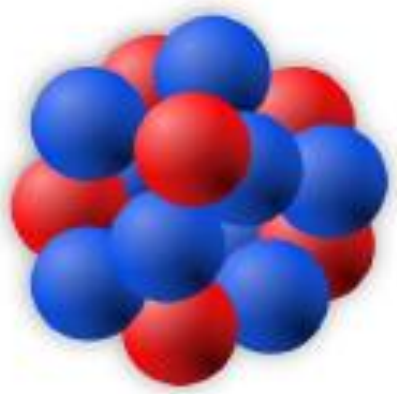
Two-component proton model

Frankfurt, Strikman, Miller

$$|p\rangle = \underbrace{|uud\rangle}_{\text{Point-like configuration}} + \underbrace{|uudq\bar{q}\rangle + |uudg\rangle + \ldots}_{\text{Blob-like configuration}}$$

$$H_0 = \begin{bmatrix} E_B & V \\ V & E_P \end{bmatrix}$$



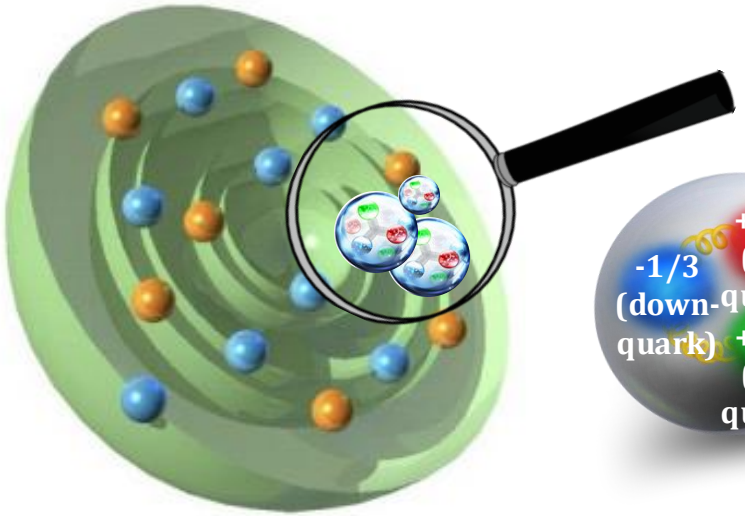


No interaction with nucleus

Interacts with nucleus

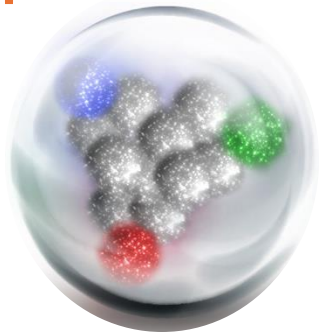
$$H = \begin{bmatrix} E_B - |U_{(n,p)}| & V \\ V & E_P \end{bmatrix}$$

Different size configurations

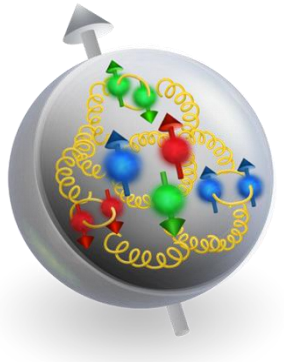


Tripole?

$$|p\rangle = |uud\rangle + |uudq\bar{q}\rangle + |uudg\rangle + \ldots$$



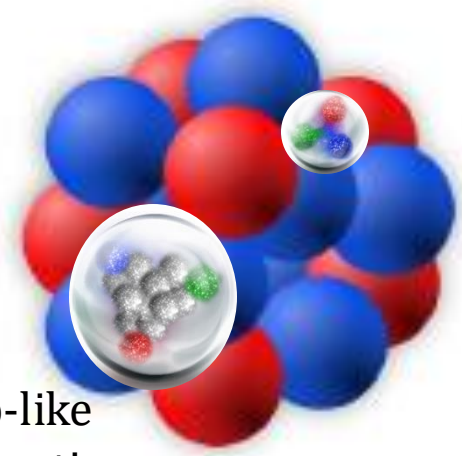
Smaller tripoles
interact less



Small-Size configurations interact less:
→ Color transparency

Point-like configurations in nuclei

$$|p\rangle = |uud\rangle + |uudq\bar{q}\rangle + |uudg\rangle + \ldots$$



Point-like configurations (3q, reduced size)

Blob-like configurations (3q+, larger size)

1) Point-like configurations have a higher probability that any single quark carries a higher momentum fraction of the nucleon

2) Point-like configurations interact less
   → Less bound
   → Less probable!

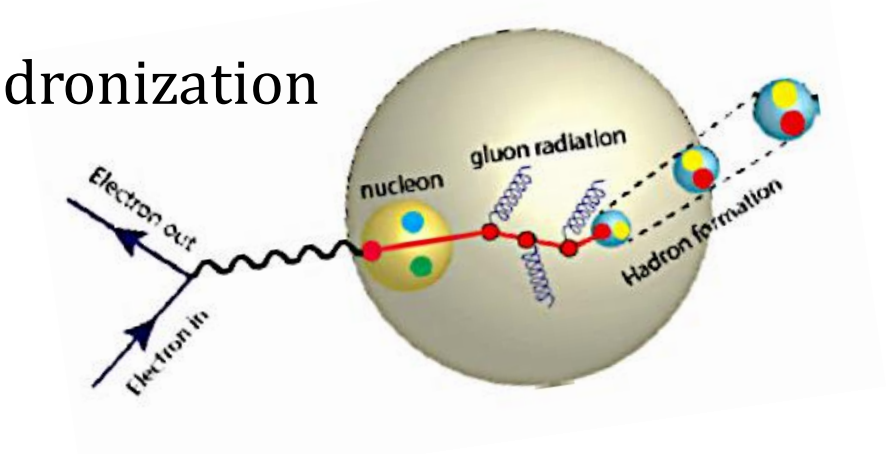
→ Fewer high momentum quarks!

(Bound proton modification? Think EMC Effect….)

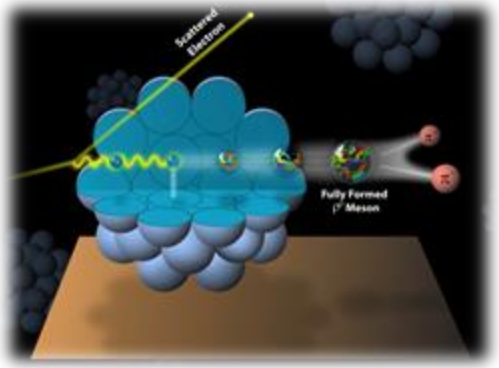
Hadron propagation through matter is fundamental to the many body problem

Hard processes probe QCD confinement:

Hadronization



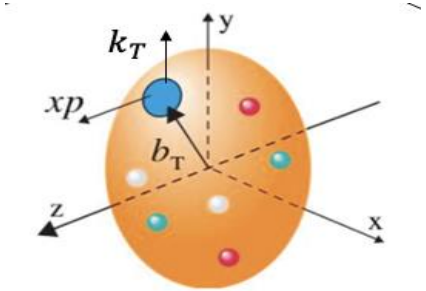
Creation and evolution of small-size hadrons



Medium modification of quark distributions (EMC Effect)

Short range structure (NN short-range correlations)

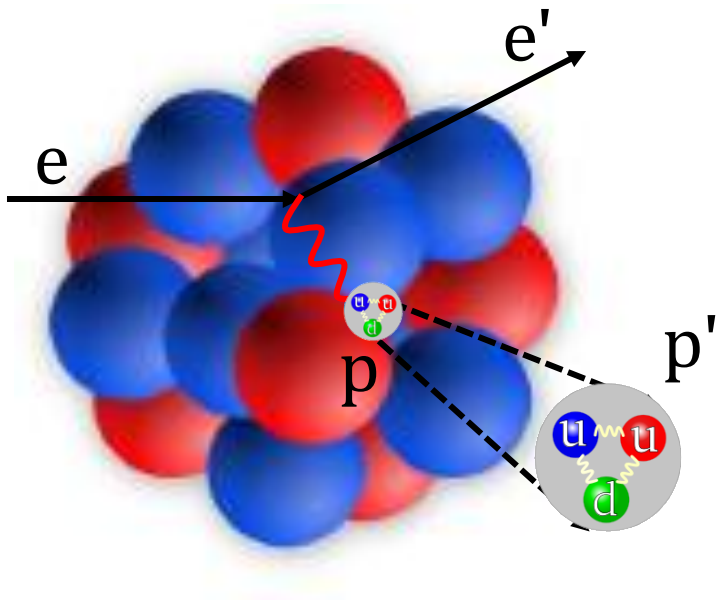
3D mapping (nuclear GPDs and TMDs)



QCD predicts Color Transparency

$$|p\rangle = |\boldsymbol{uud}\rangle + |uudq\bar{q}\rangle + |uudg\rangle + \ldots$$

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



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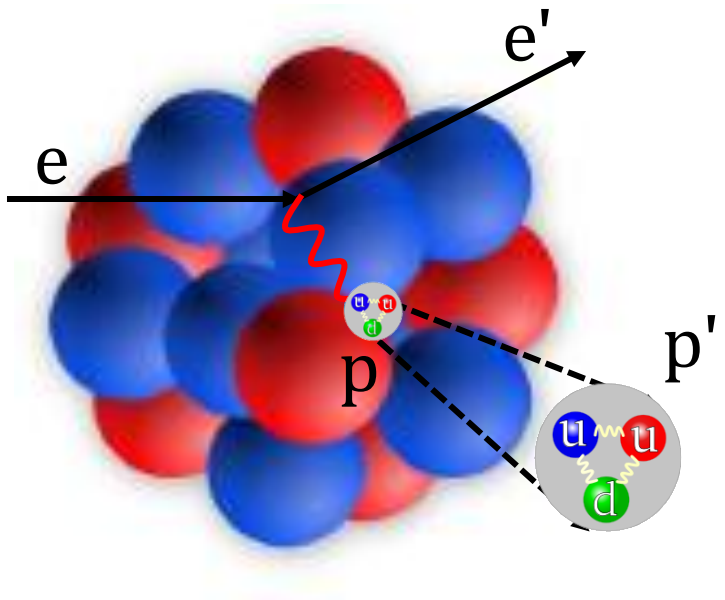

Relativity:
Time dilation slows proton expansion (*freezing*, transferred energy)

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

QCD predicts Color Transparency

$$|p\rangle = |\boldsymbol{uud}\rangle + |uudq\bar{q}\rangle + |uudg\rangle + \ldots$$

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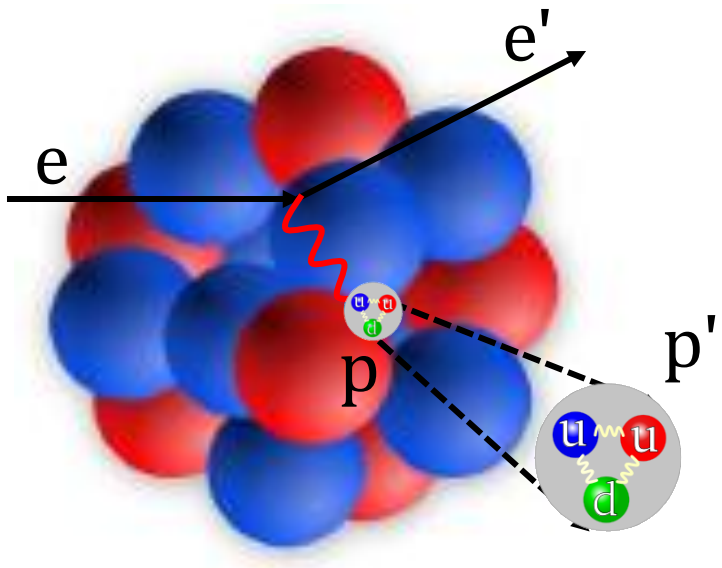


Relativity:
Time dilation slows proton expansion (*freezing*, transferred energy)

Strong force:
Smaller protons interact less, color screened

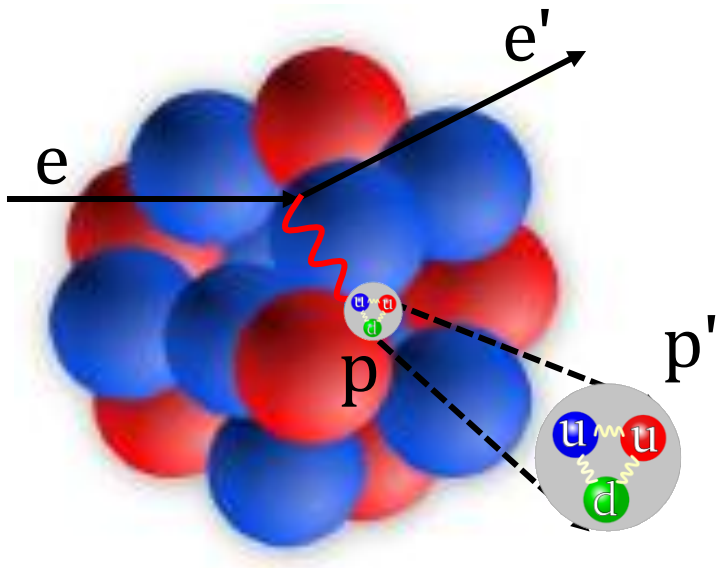
$$\sigma_{PLC} \approx \sigma_{hN} \frac{b^2}{R_h^2}$$

Introduced by
Mueller and Brodsky, 1982

QCD predicts Color Transparency

$$|p\rangle = |\boldsymbol{uud}\rangle + |uudq\bar{q}\rangle + |uudg\rangle + \ldots$$

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



Relativity:
Time dilation slows proton expansion (*freezing*, transferred energy)

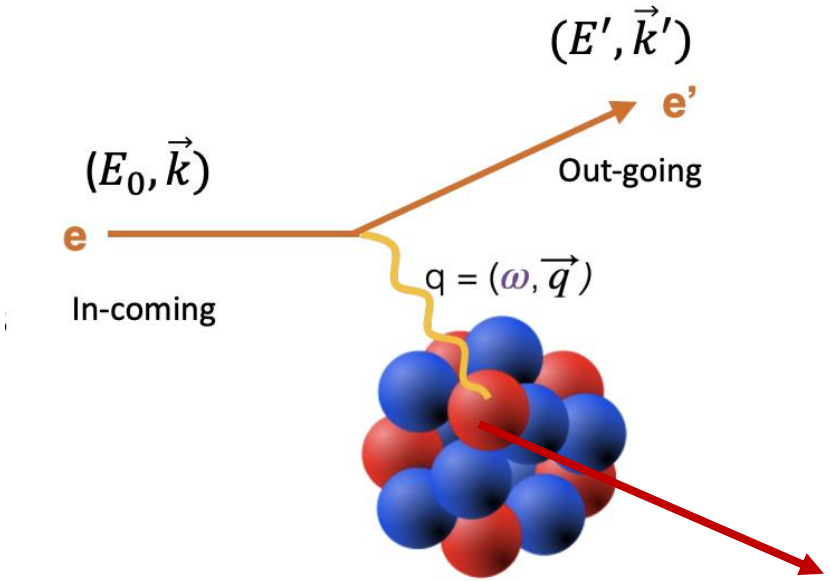
Strong force:
Smaller protons interact less, color screened

Proton transmission should increase with momentum transfer, Q^2

Measuring transparency

Hit a proton hard.

Transparency (proton transmission) is the probability that the struck proton emerges from the nucleus without significant re-interaction.



$$T_A = \frac{\sigma_A}{Z\ \sigma_p}$$

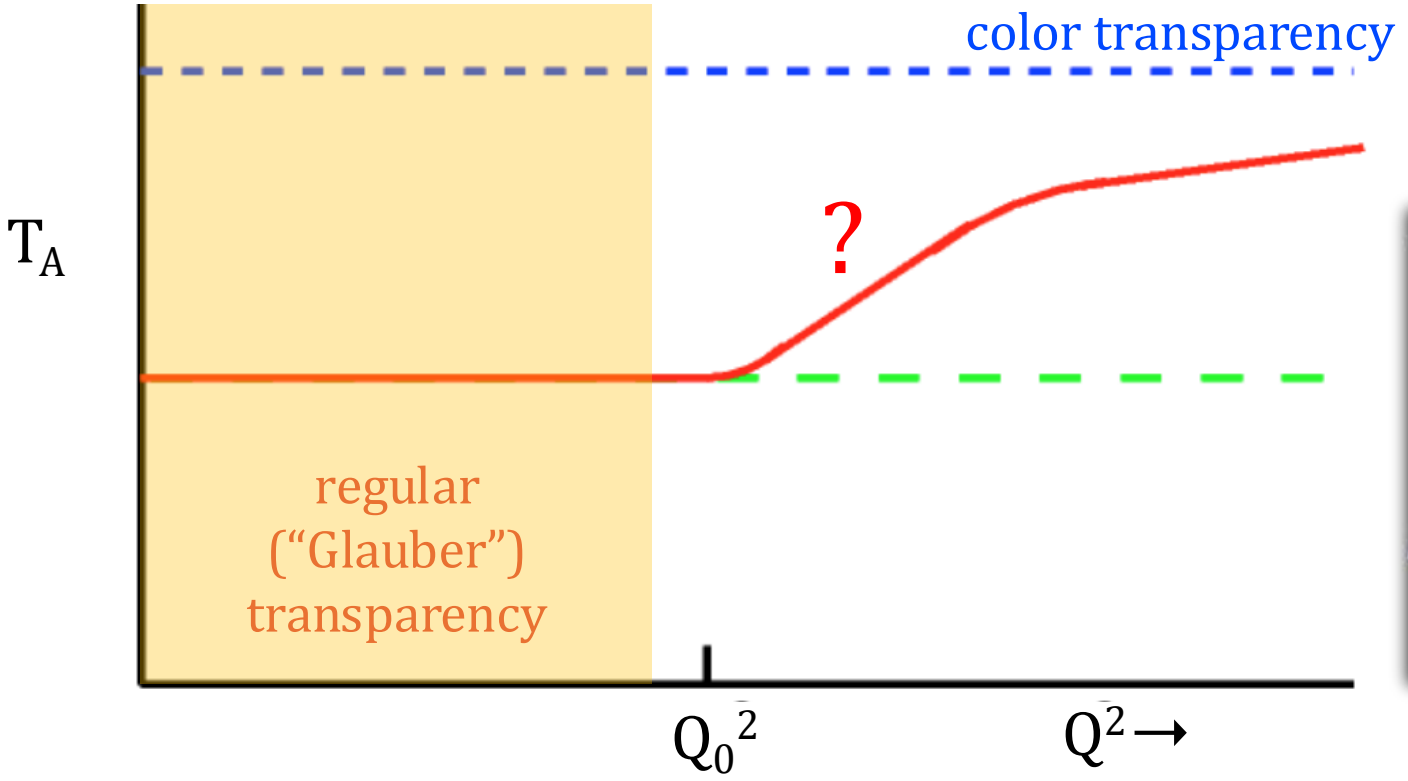
σ_A (nuclear cross section)

σ_p (free proton cross section)

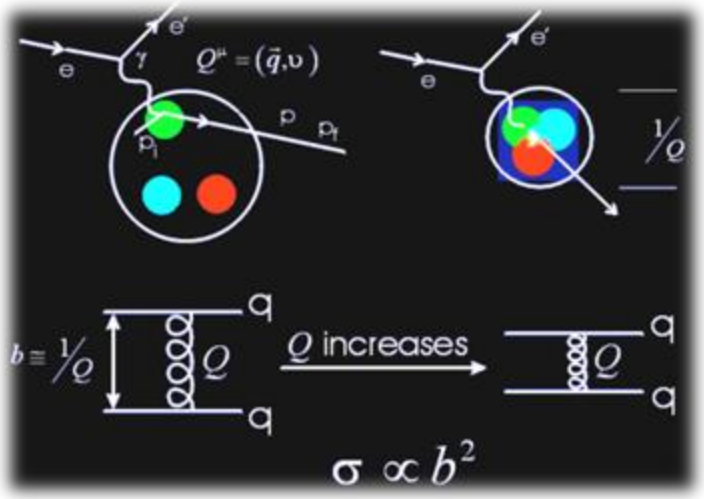
Z: atomic number

CT predicts momentum dependence of the transparency

Onset of CT indicates where quark-gluon degrees of freedom become relevant



Why do we expect this?



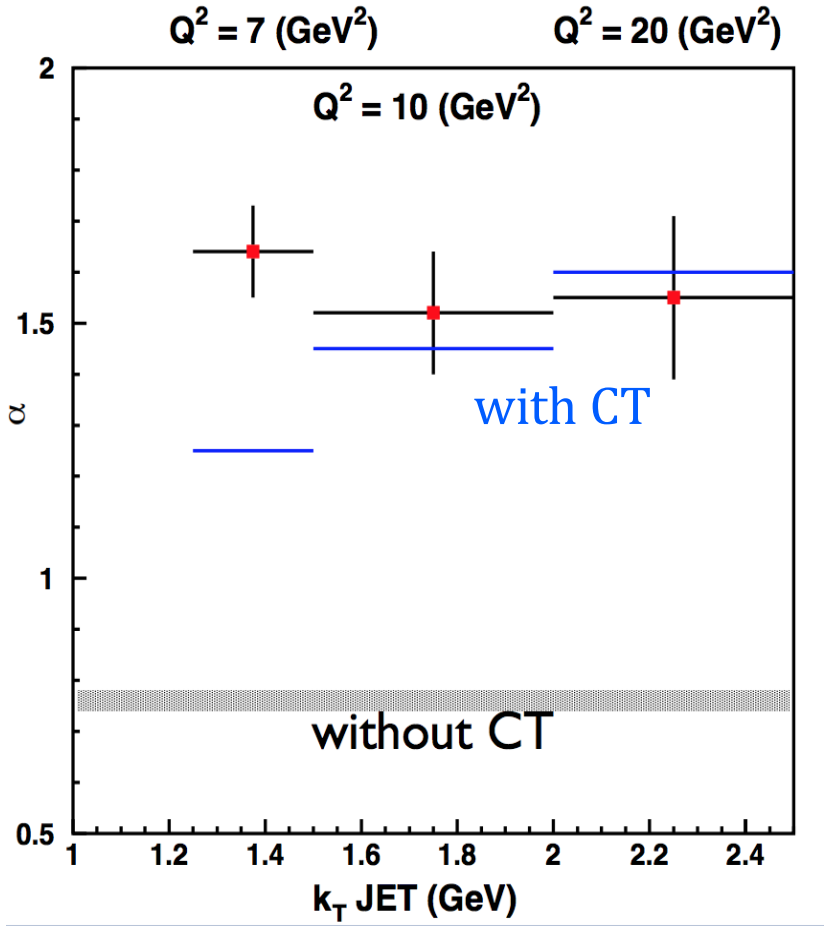
FNAL E791

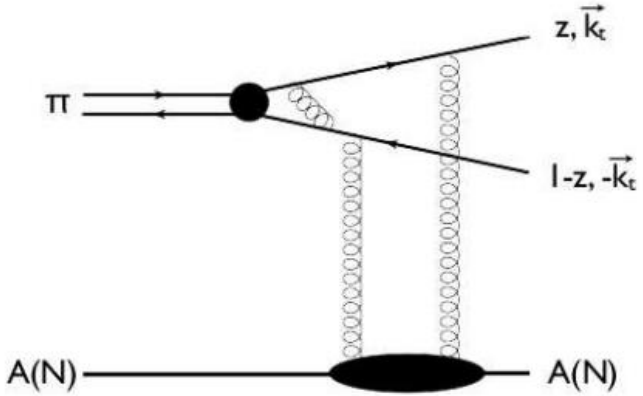
CT at high energies

$$|\pi^-\rangle = |d\bar{u}\rangle + |d\bar{u}g\rangle + |d\bar{u}gg\rangle + \ldots$$

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

π + A → 2 jets + A'





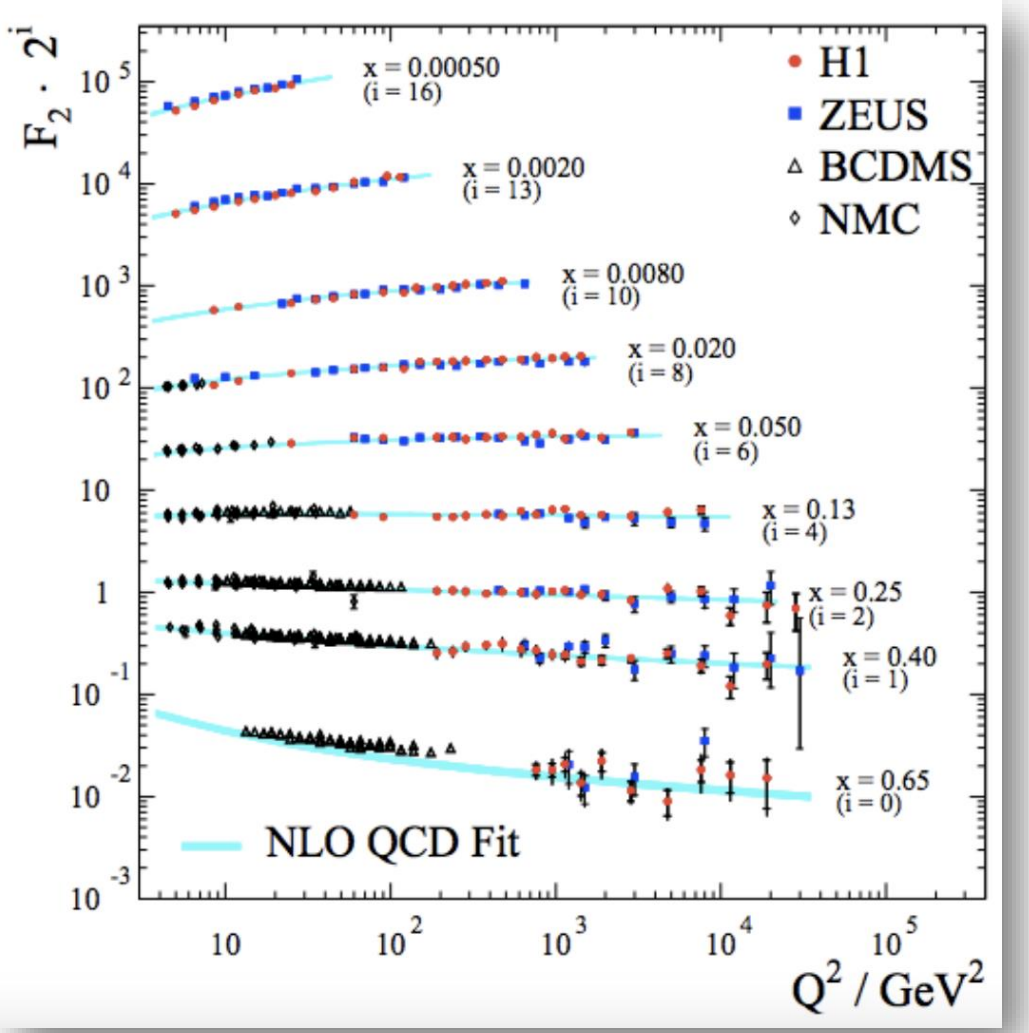
Fit to $\sigma = \sigma_0 A^{\alpha}$

Pion-nucleus total cross section, α=1.6

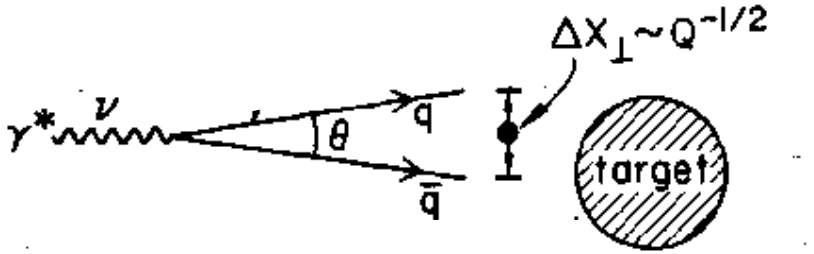
CT predictions by L. L. Frankfurt, G. A. Miller, and M. Strikman, Phys. Lett. B304, 1 (1993)

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

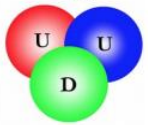


Scaling shows no evidence of this interaction

Bjorken, SLAC-PUB-1756
Frankfurt and Strikman, Phys Rep 160, 235 (1988)

CT (onset) experiments

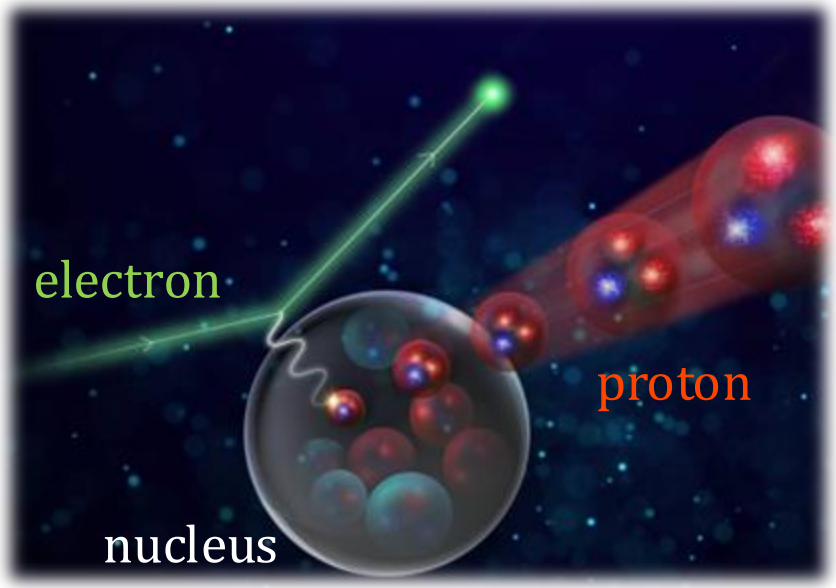
Baryon

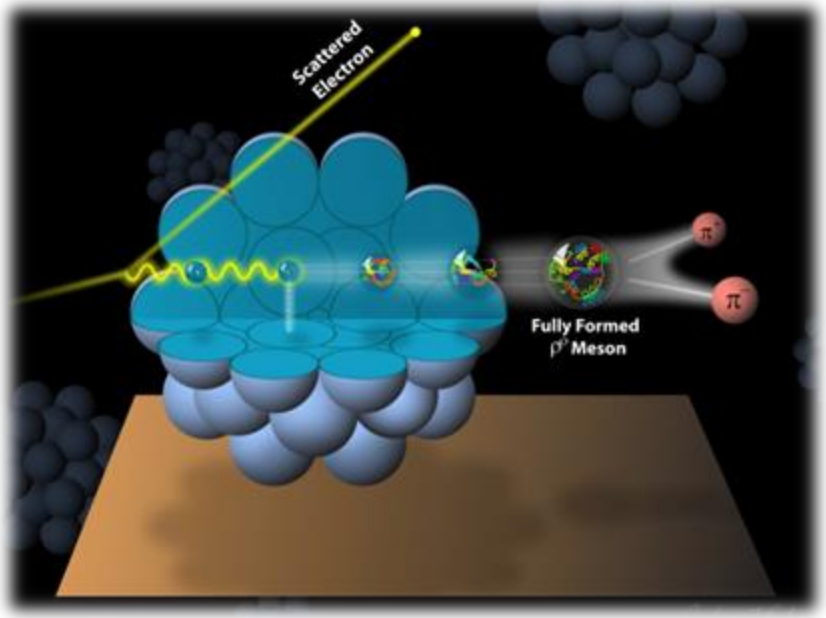


A(p,2p): BNL
A(e,e'p): SLAC, JLab

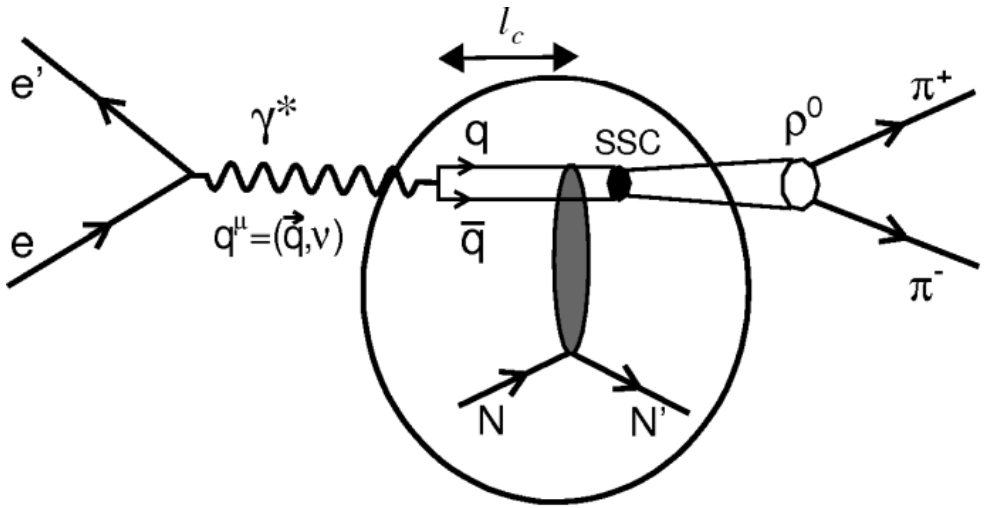
Meson

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

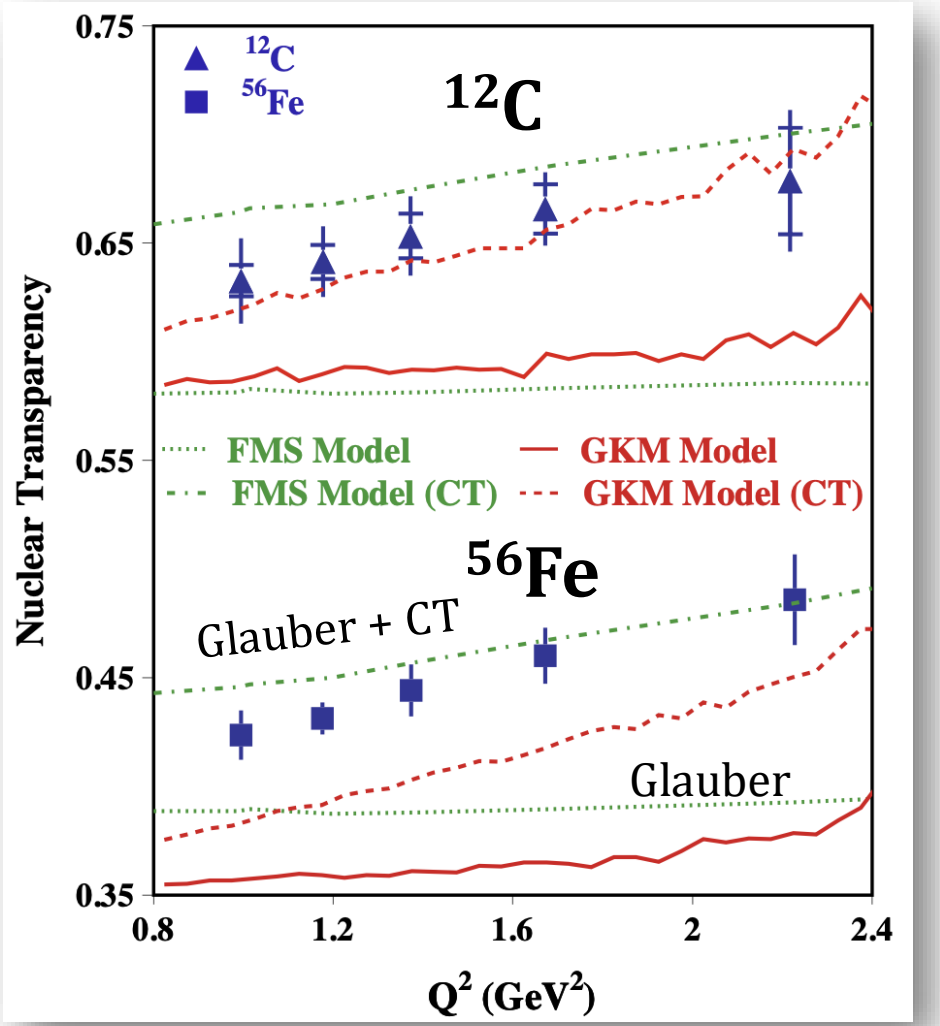




CT onset for mesons observed at a few GeV^2



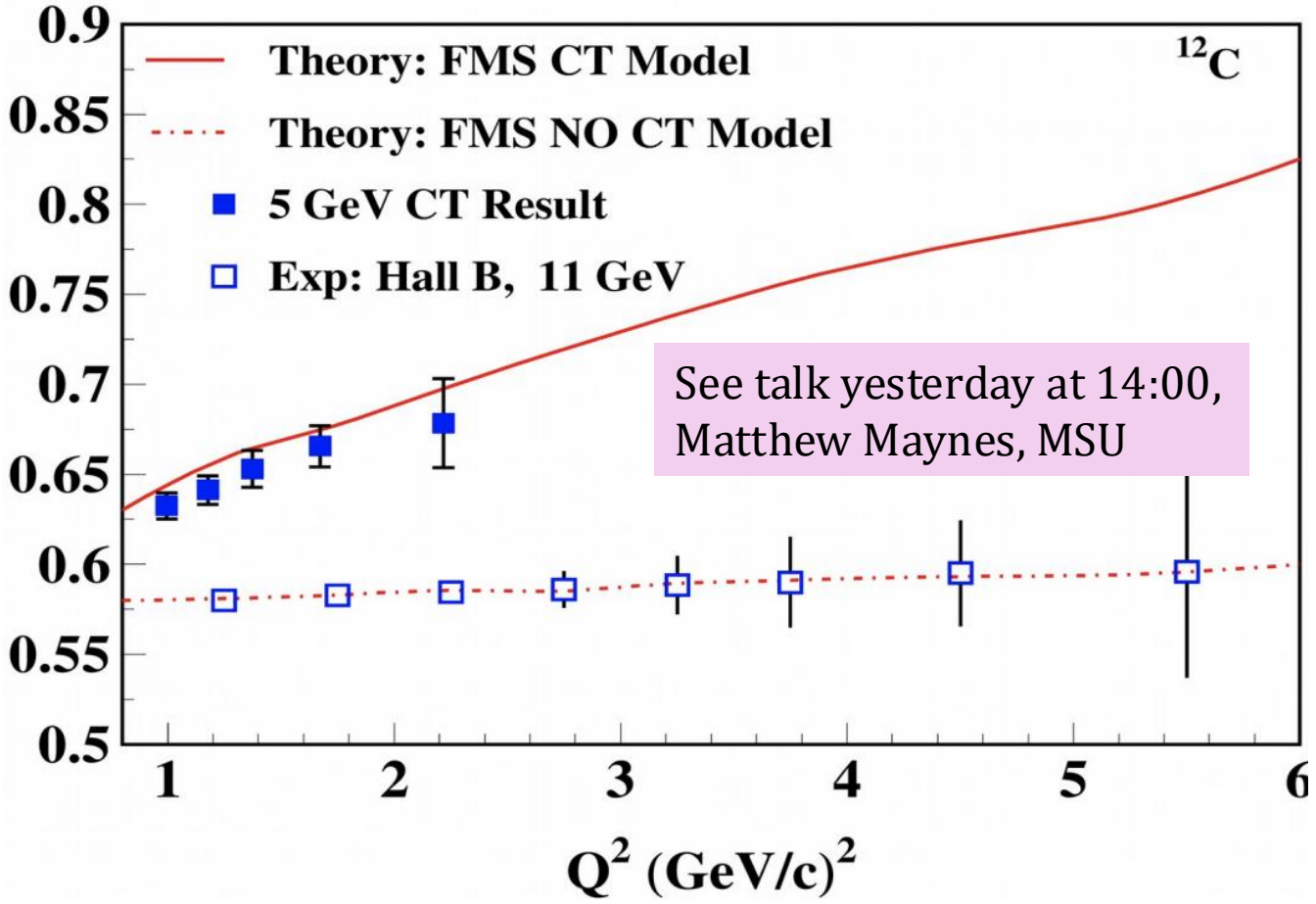
$A(e,e'\rho^0)$



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

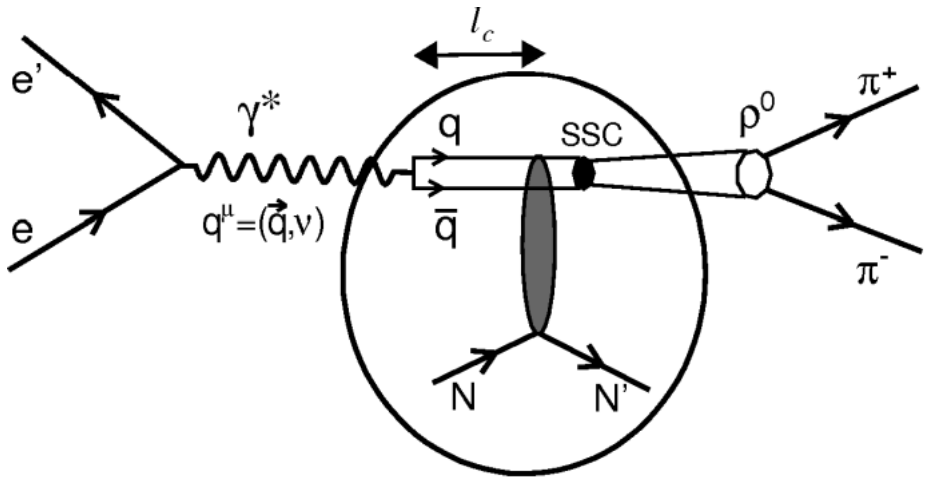
Extend measurements in the rho-meson

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



See talk yesterday at 14:00, Matthew Maynes, MSU

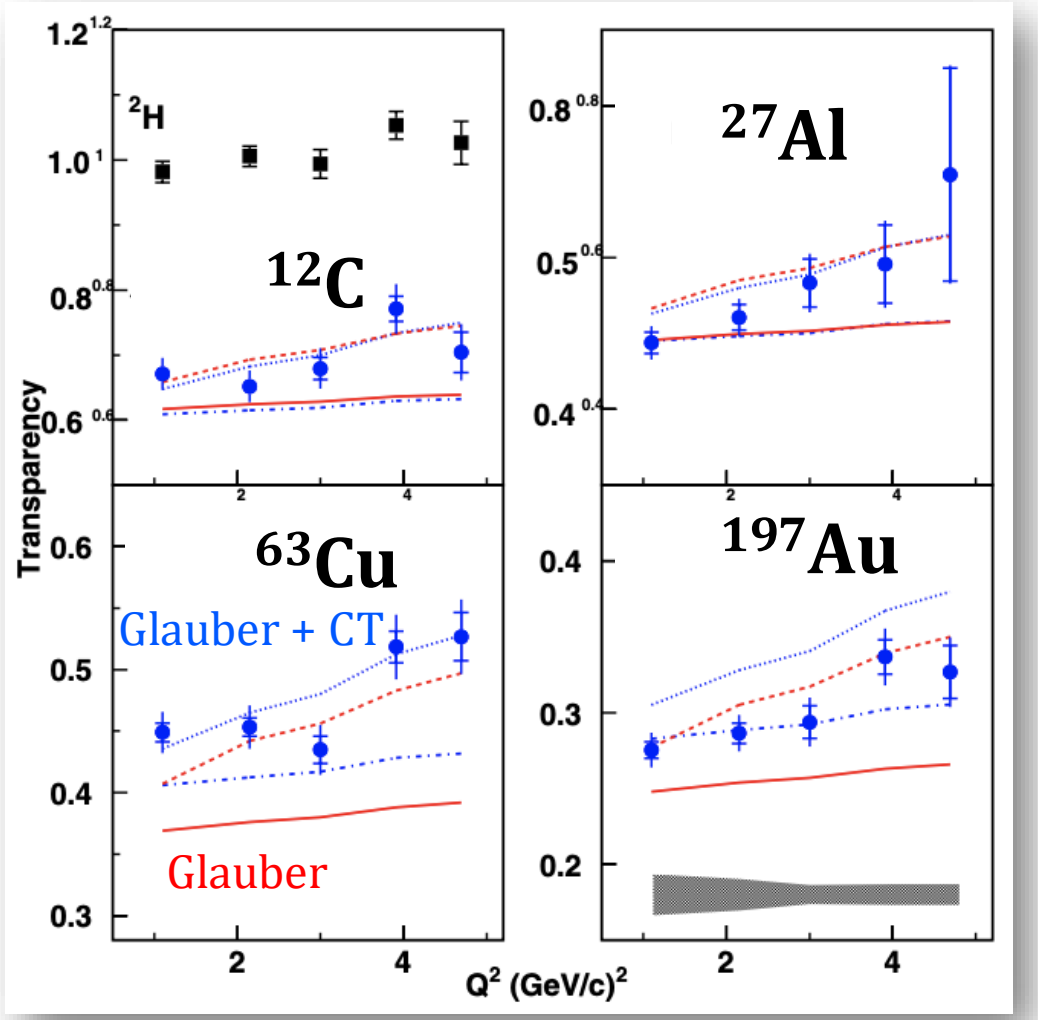
A(e,e'ρ^0)



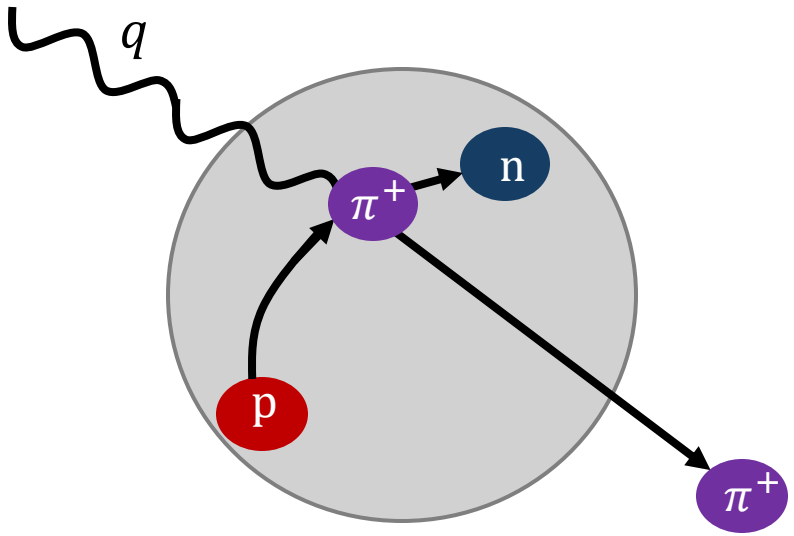
Targets: deuterium, ^{12}C, ^{63}Cu, ^{120}Sn

CT onset for mesons observed at a few GeV^2

$A(e,e'\pi^+)$

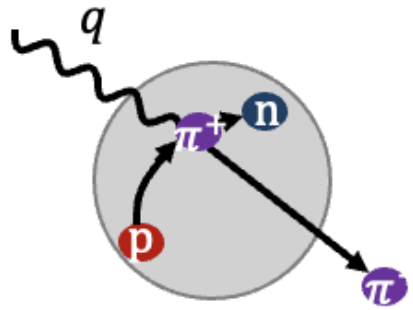


$$|\pi^+\rangle = |u\bar{d}\rangle + |u\bar{d}g\rangle + |u\bar{d}gg\rangle + \ldots$$

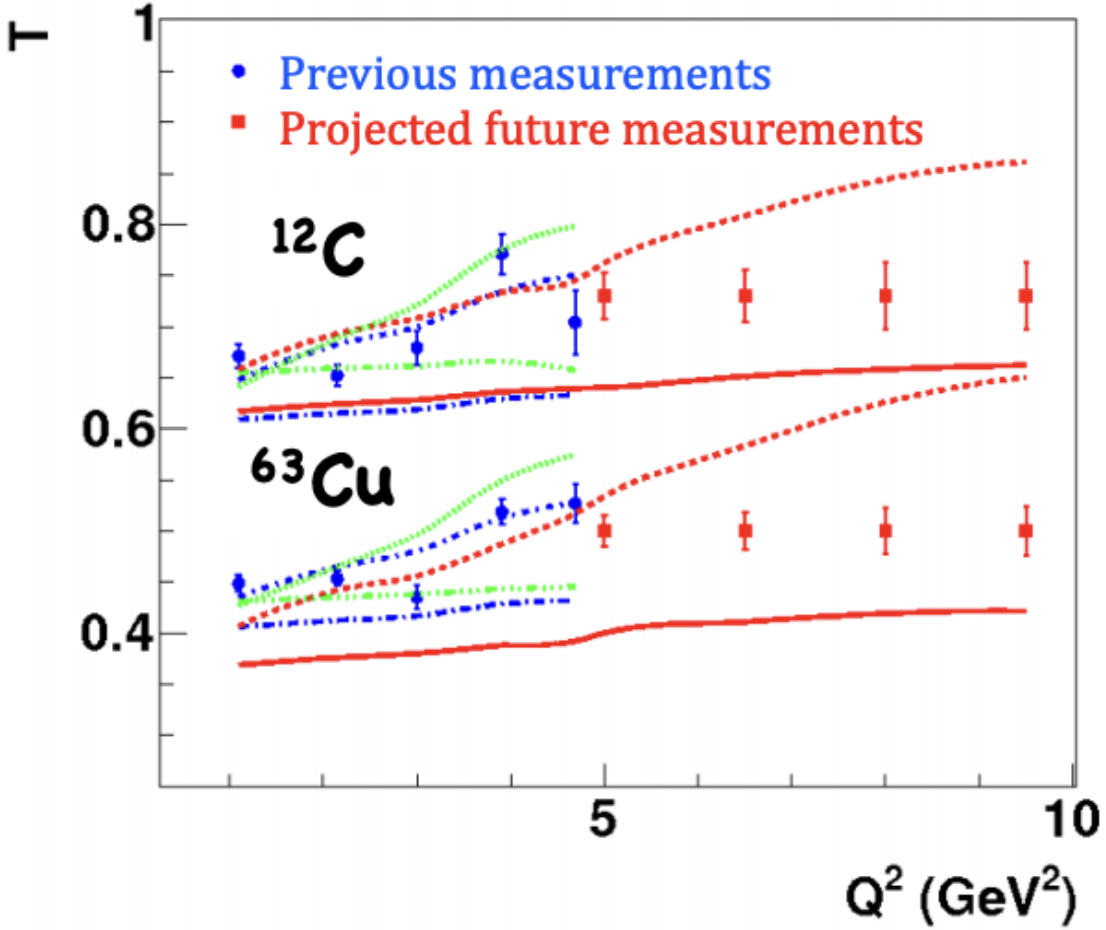


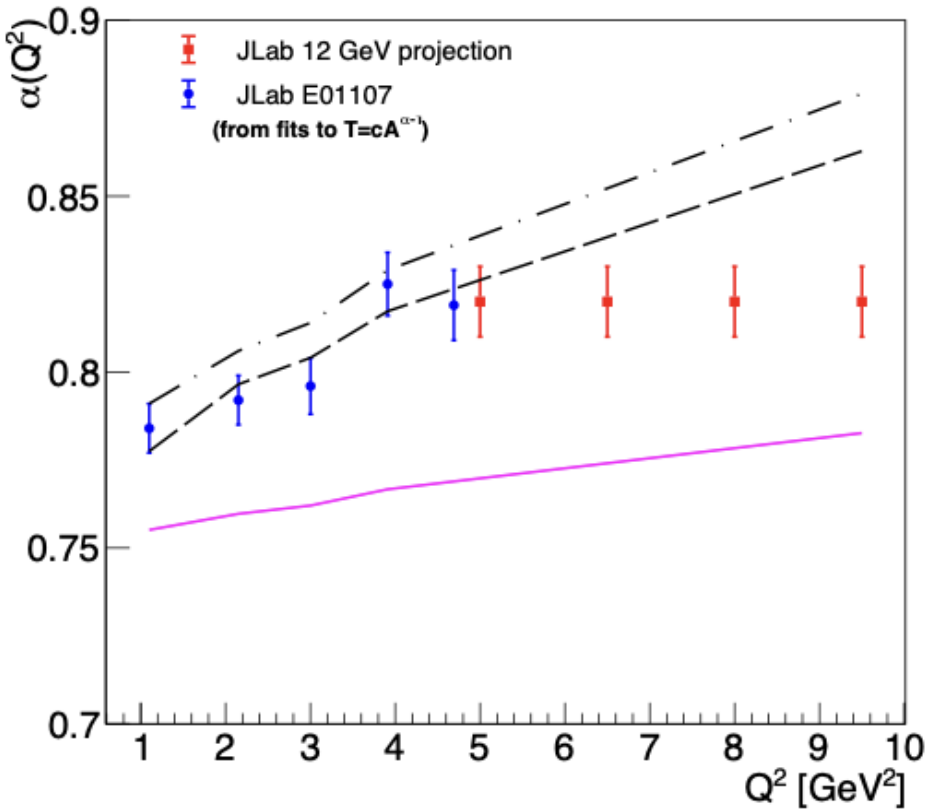
B. Clasie et al, PRL99:242502 (2007)
X. Qian et al, PRC81:055209 (2010)

Future: Extend pion CT measurements (2026)

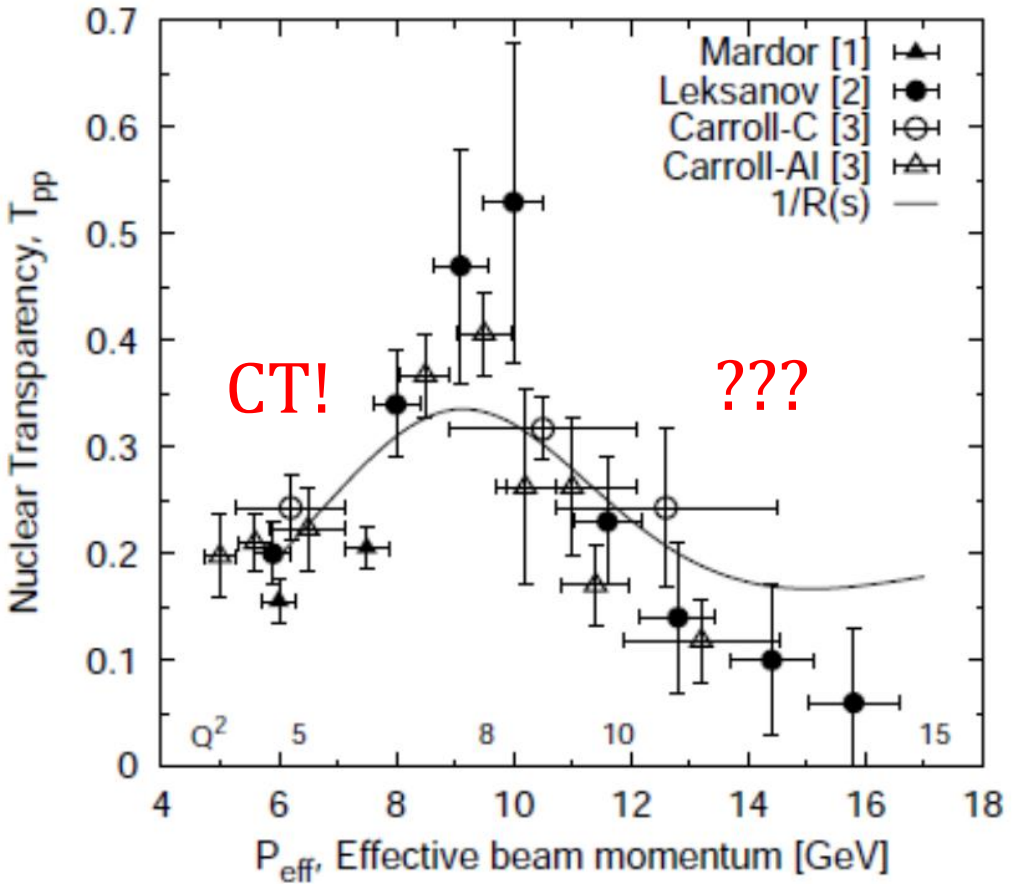


Extend the T and nuclear dependence





Proton CT observed?



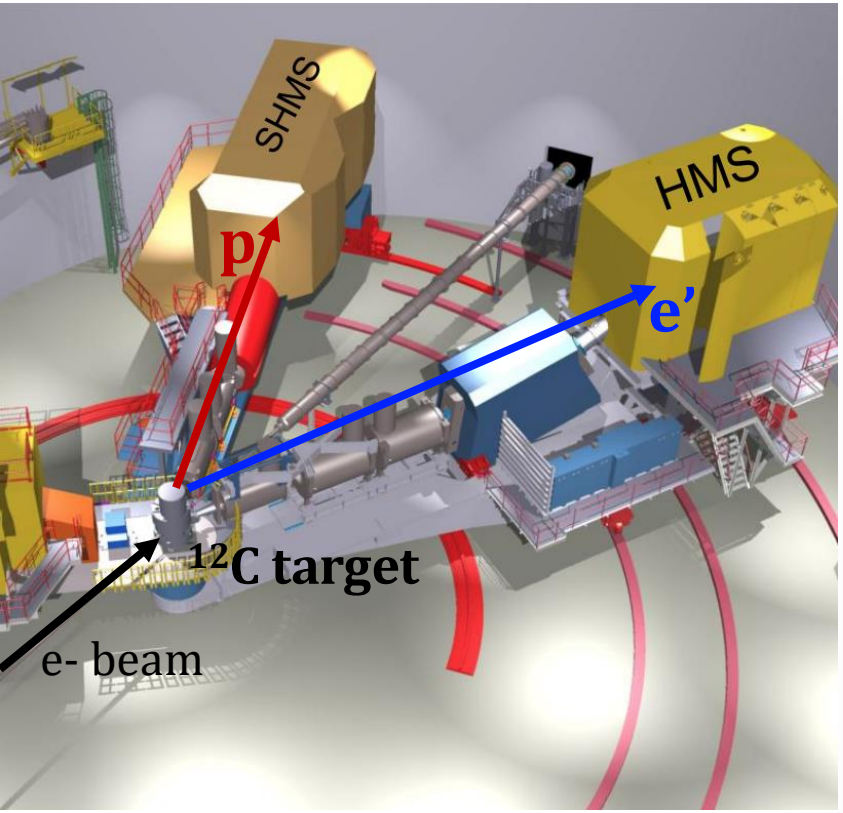
A. Leksanov et al. PRL 87 (2001)
J. L. S. Aclander et al., PRC 70 (2004)

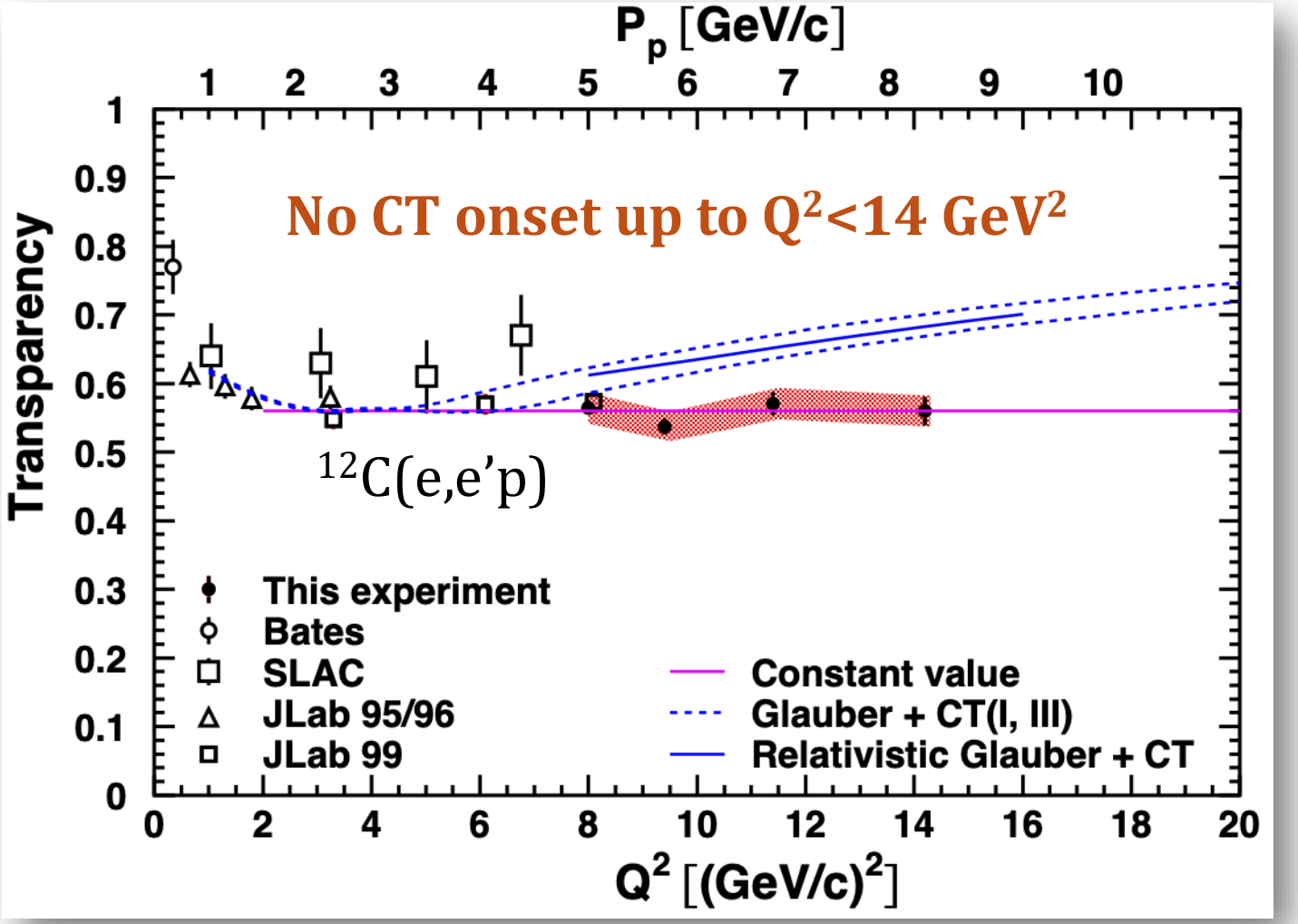
Transparency in A(p,2p) experiment at Brookhaven:

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

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

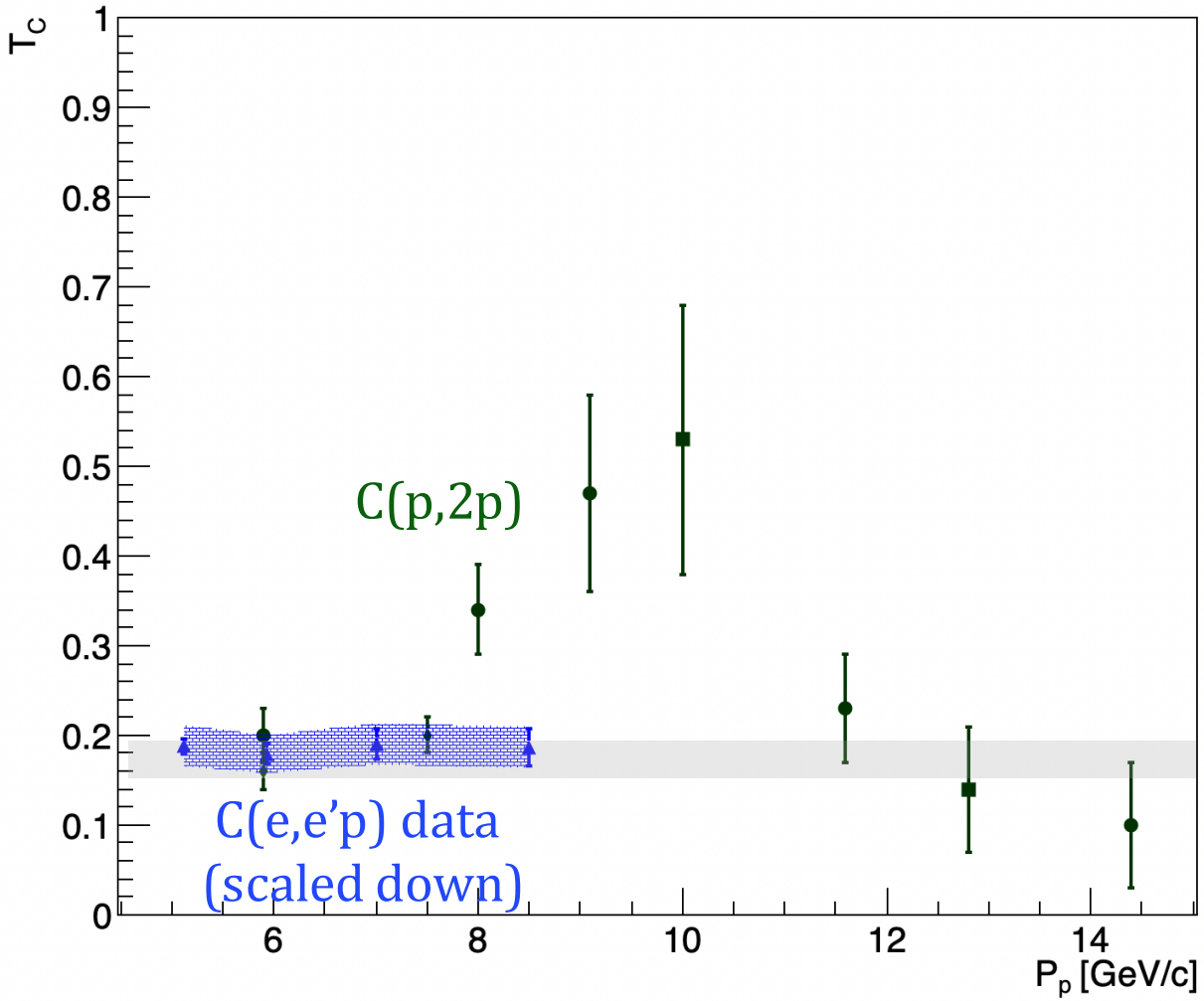
A(e,e'p) tells another story…

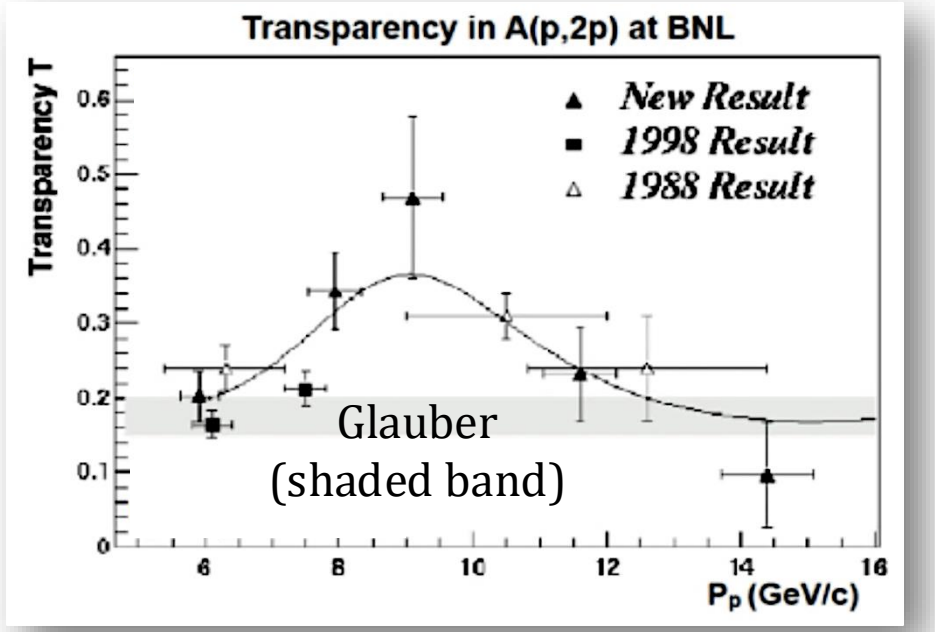




D. Bhetuwal et al, PRL126:082301 (2021)

A(e,e'p) tells another story…



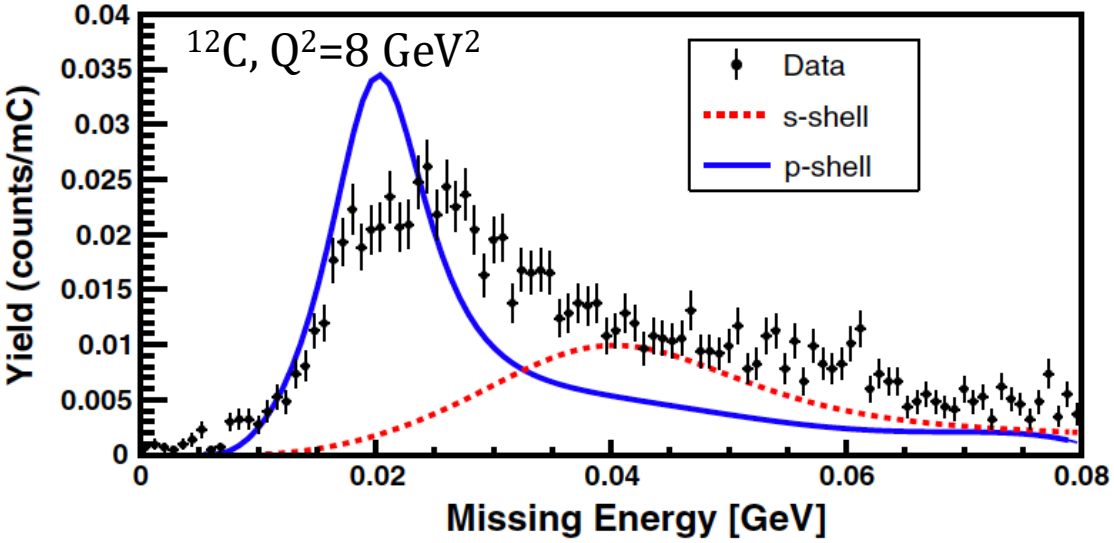


PRL 87, 212301 (2001)
PRL 81, 5085 (1998)
PRL 61, 1698 (1988)

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)

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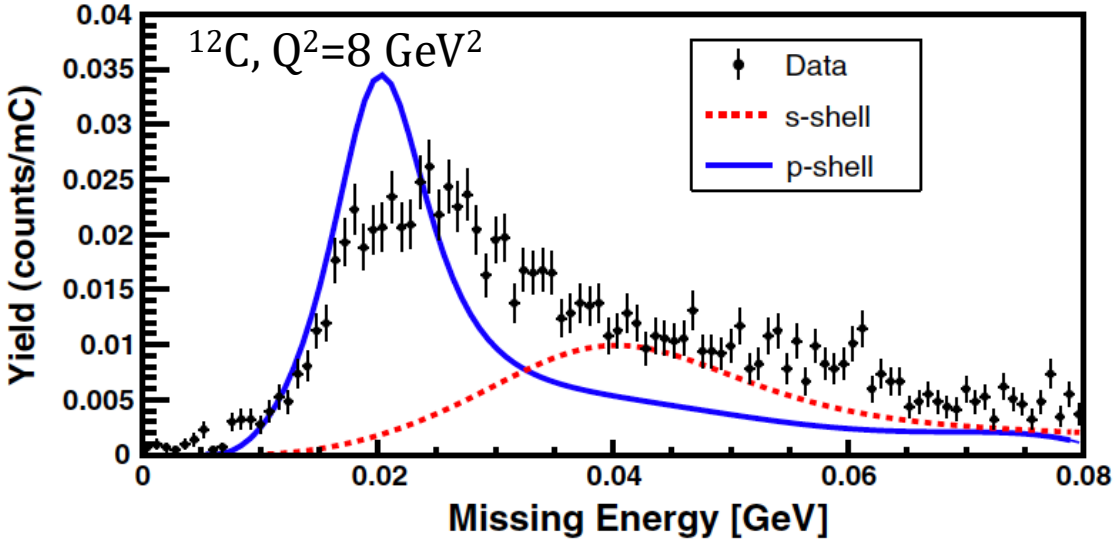
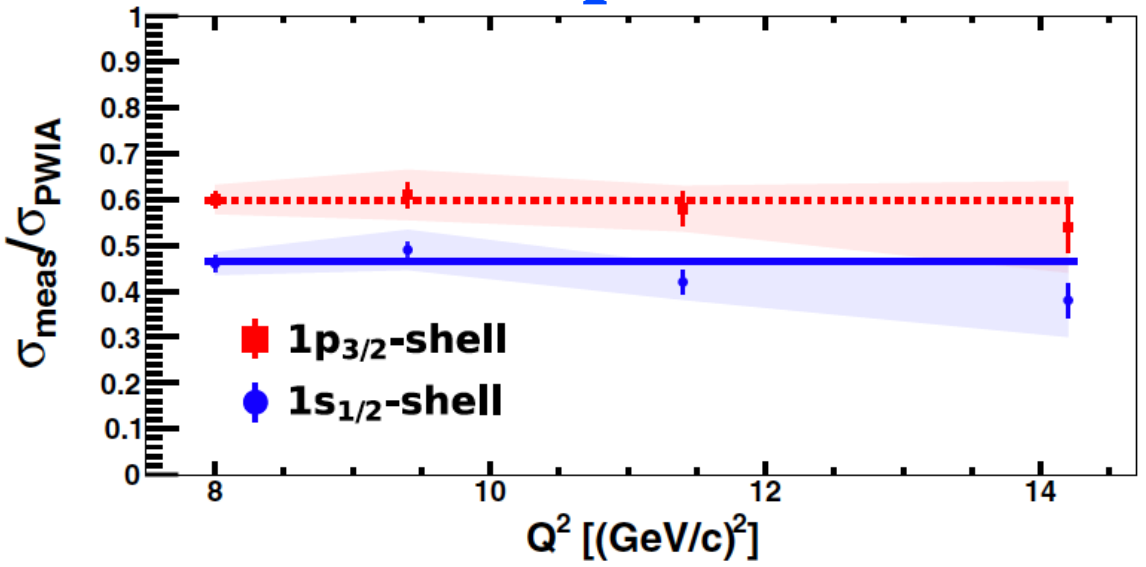
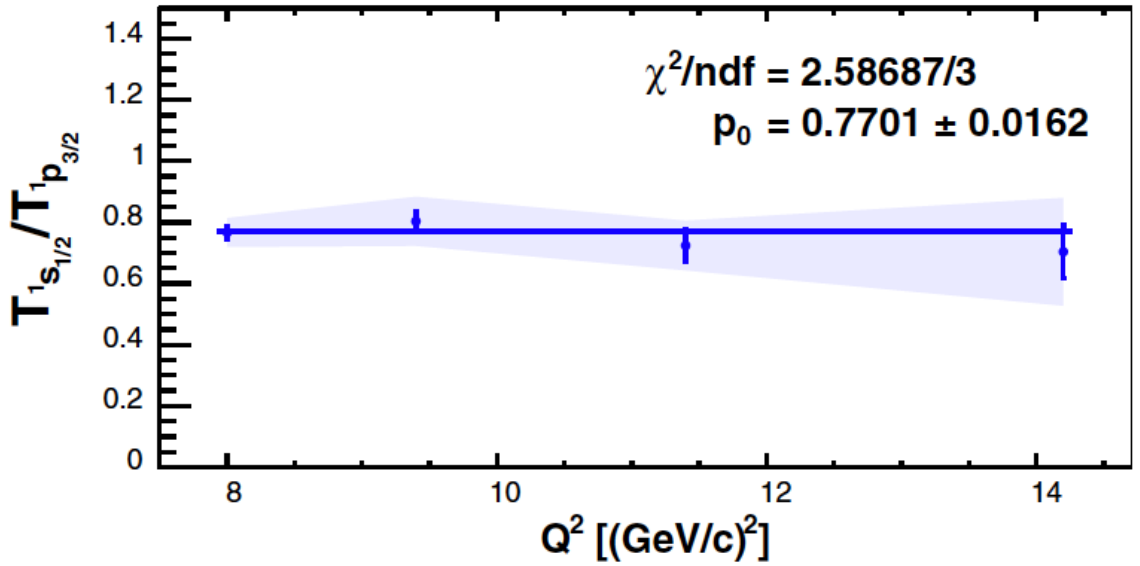




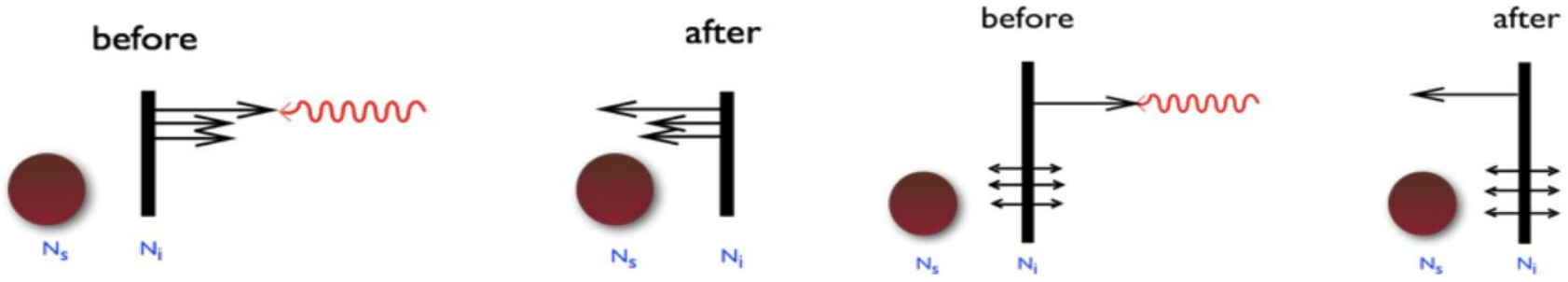


D. Bhetuwal, et al, Phys. Rev. C **108**, 025203 (2023)

(Some) interpretations

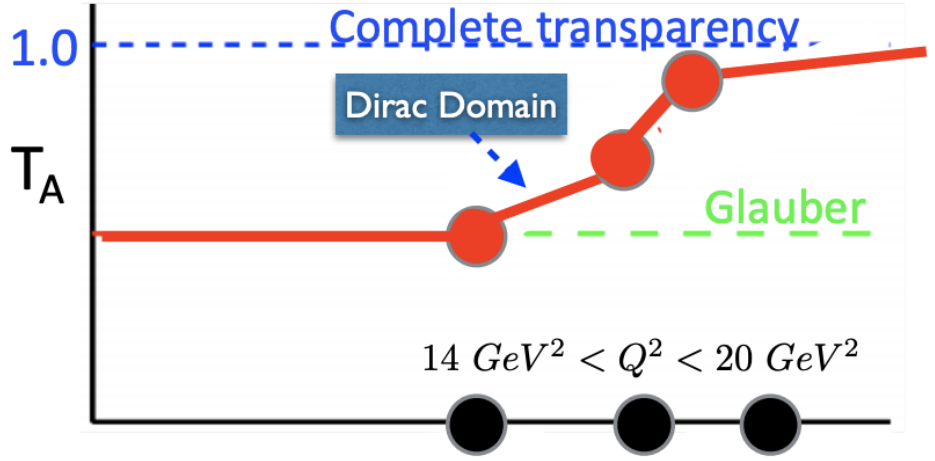
Squeezing didn't work – Feynman Mechanism dominates!

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



CT Feynman Mechanism

Need higher Q^2



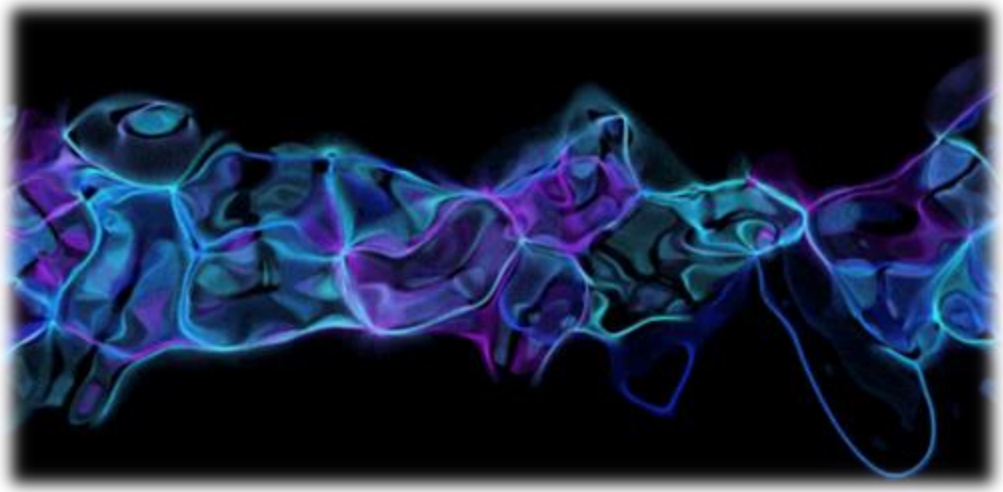
Brodsky and de Téramond, Physics 2022

Need better kinematics?

Knocking out protons along the $\vec{q}$
→Looking where rescattering is small
→(p,2p) accessed larger transverse momenta

S. Li, et al, *MDPI Physics* 2022

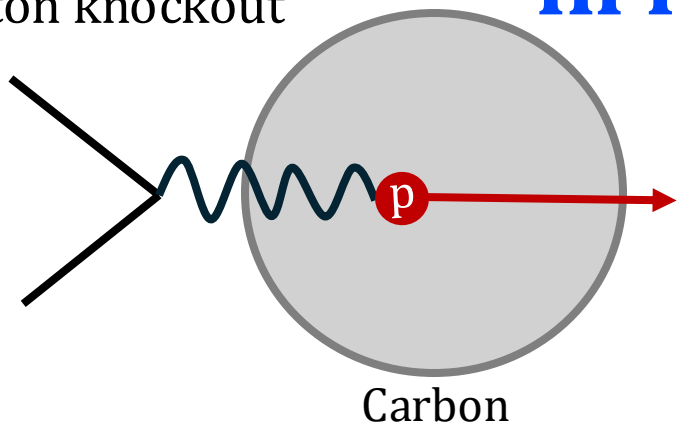
Why observed in mesons and not baryons?



Is there a reaction dependence?

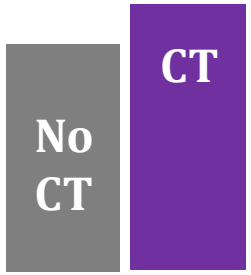
Future experiment: Enhance the CT signal in rescattering kinematics

Proton knockout

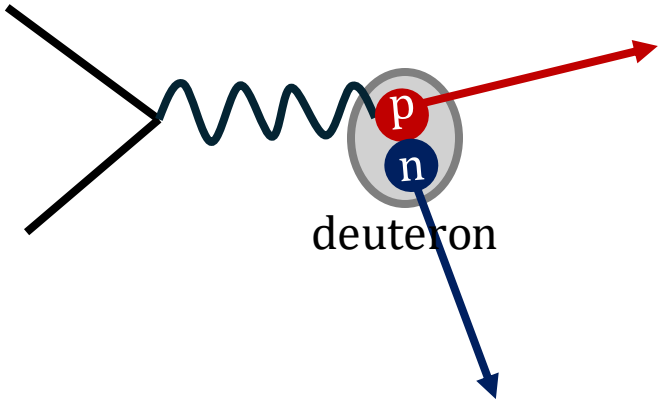


All previous (e,e'p) experiments, assumptions:

- Proton cannot expand before exiting
- Small increase in transmission

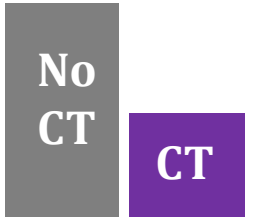


Proton rescattering



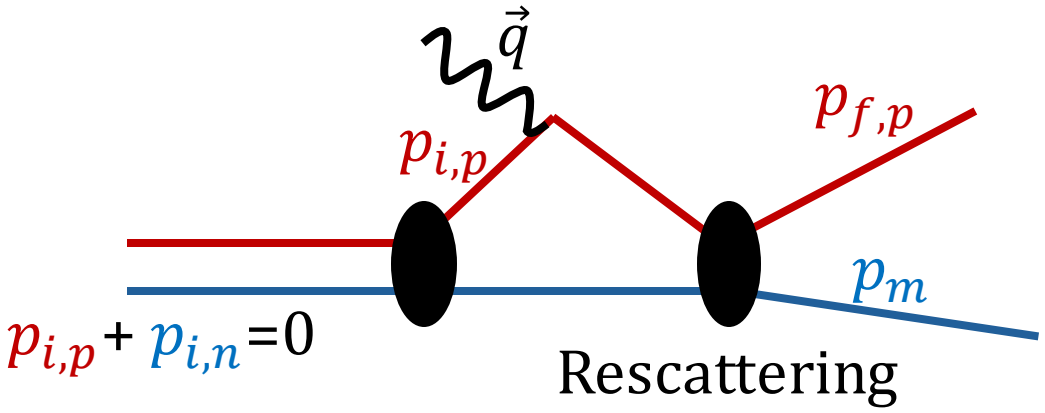
Future (e,e'p) experiment, assumptions:

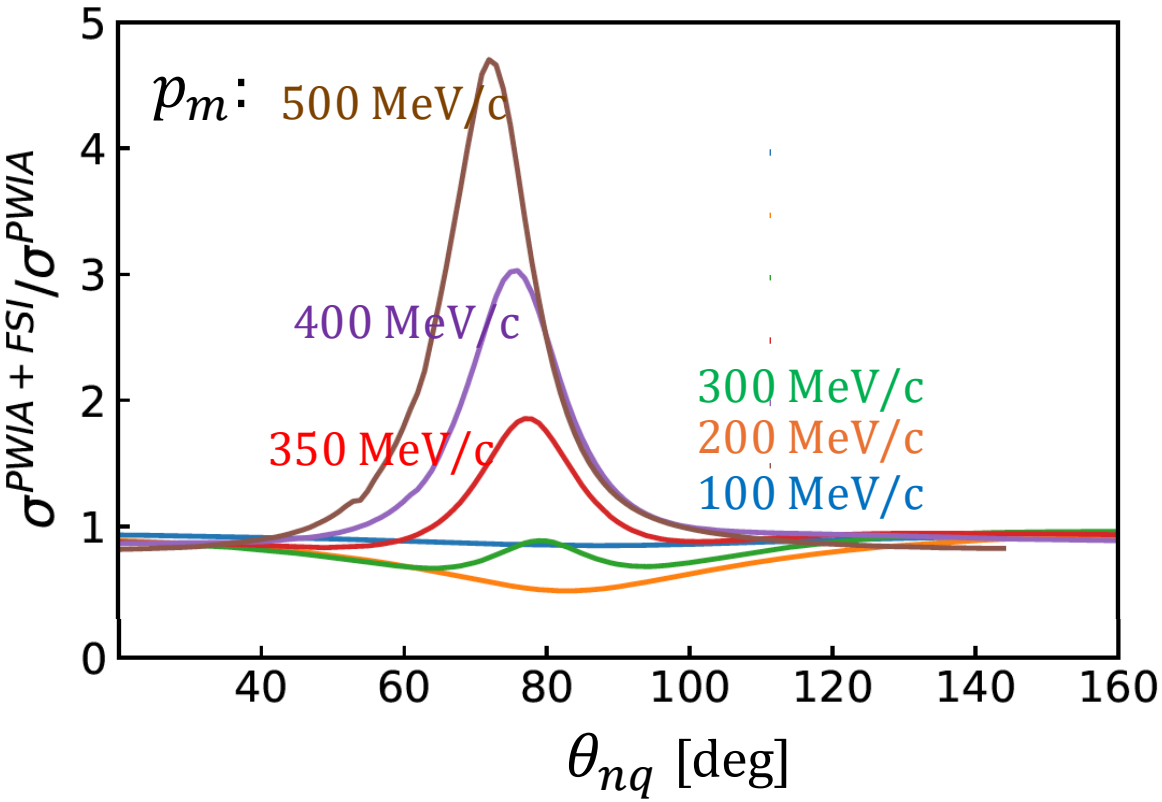
- Proton cannot expand before rescattering
- Large decrease in rescattering



Future experiment: Enhance the CT signal in rescattering kinematics

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





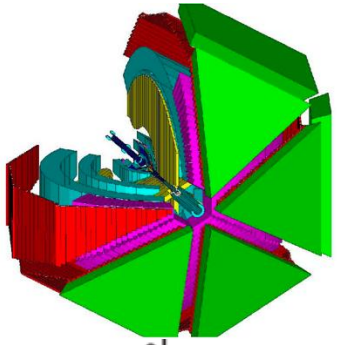
From $d(e,e'p)n$, reconstruct the undetected neutron:

Missing momentum $\overrightarrow{p_m} = \vec{q} - \overrightarrow{p_p}$

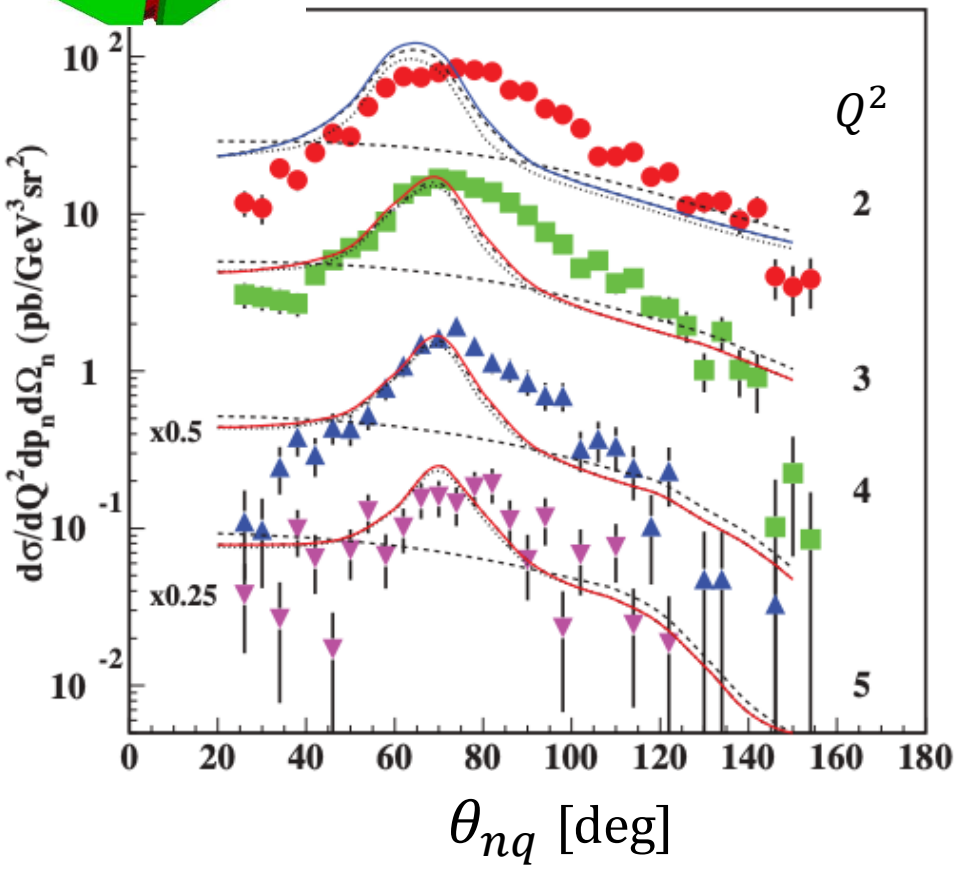
Angle θ_{nq}

Rescattering concentrated in small region

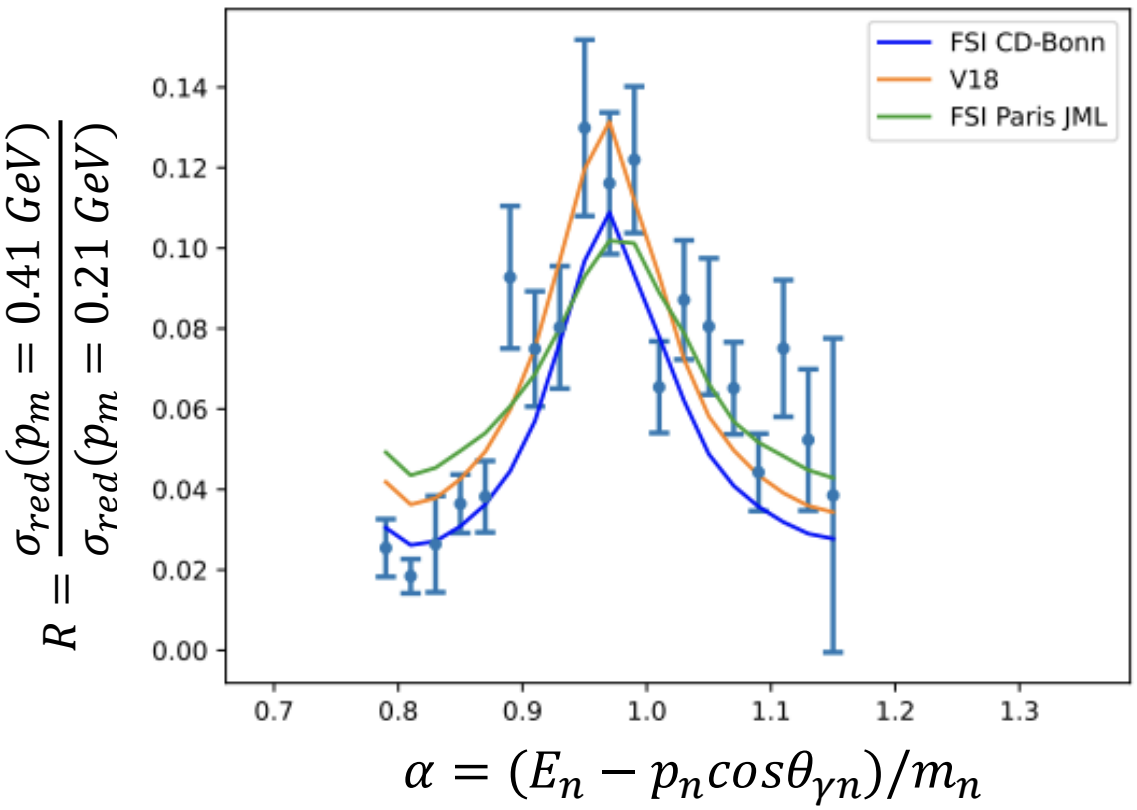
Rescattering observed in data



CLAS results



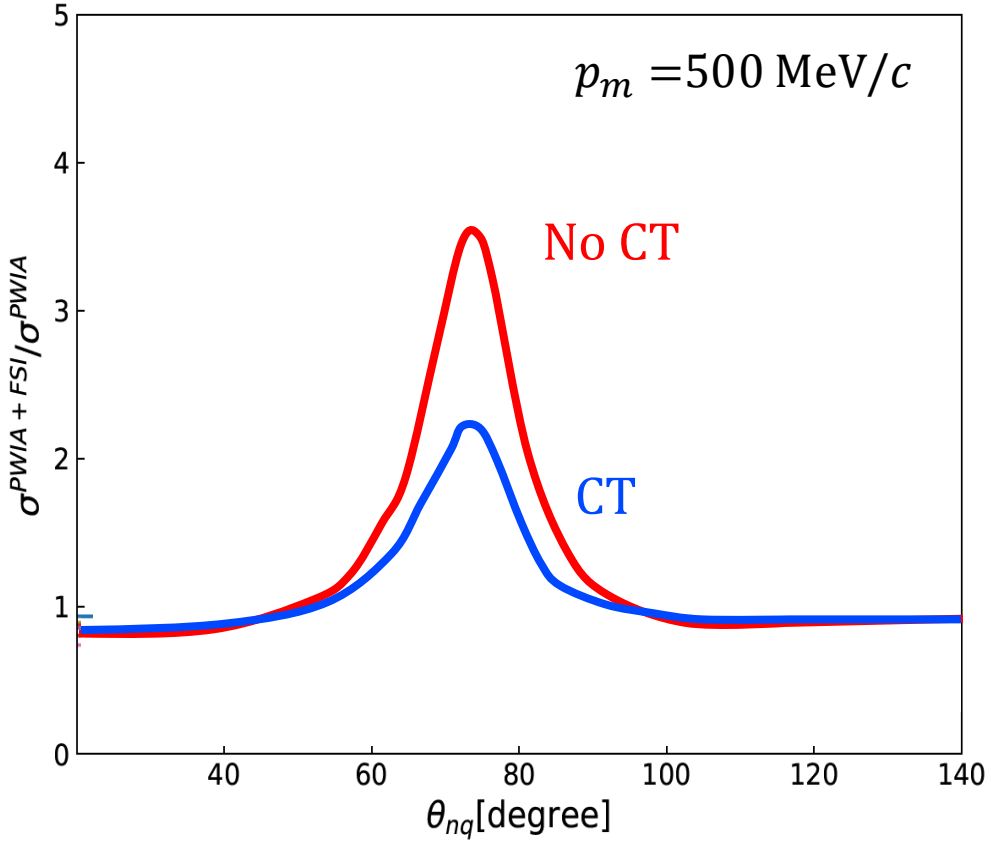
$Q^2 = 3.5$ (GeV/c)^2, Hall A



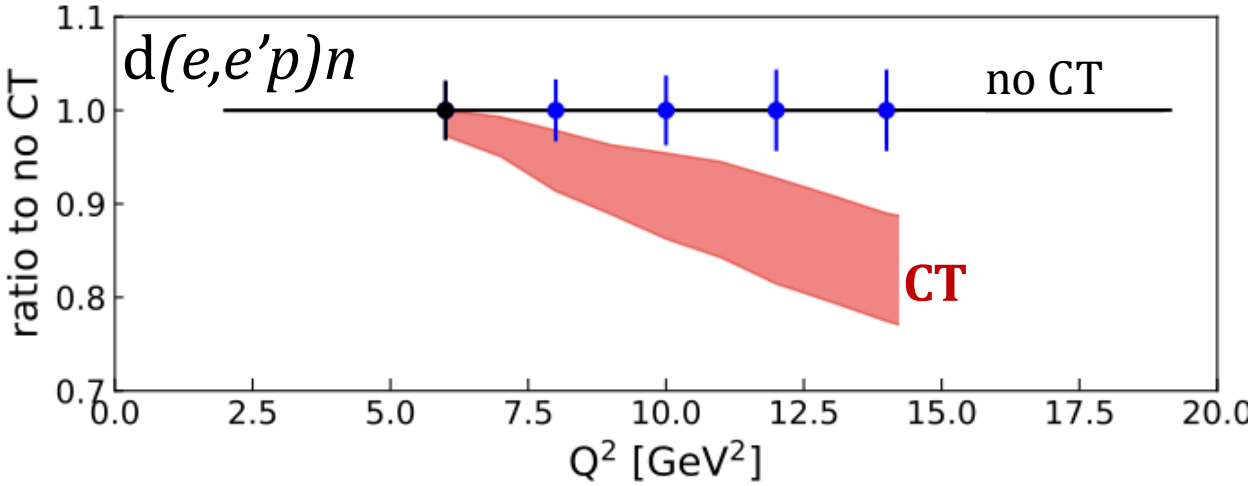
K. S. Egiyan et al., PRL 98:262502 (2007)

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

CT: Measure protons from re-scattering, look for decrease with Q^2 (2027)



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



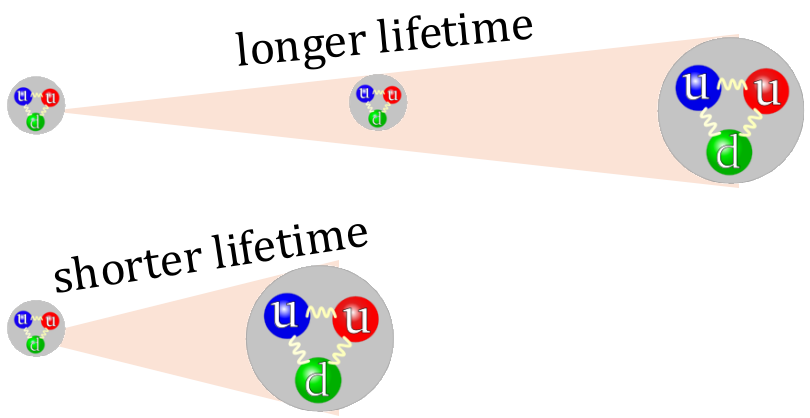
CT: Measure protons from re-scattering, look for decrease with Q^2 (2027)

Farrar et al., PRL (1988)

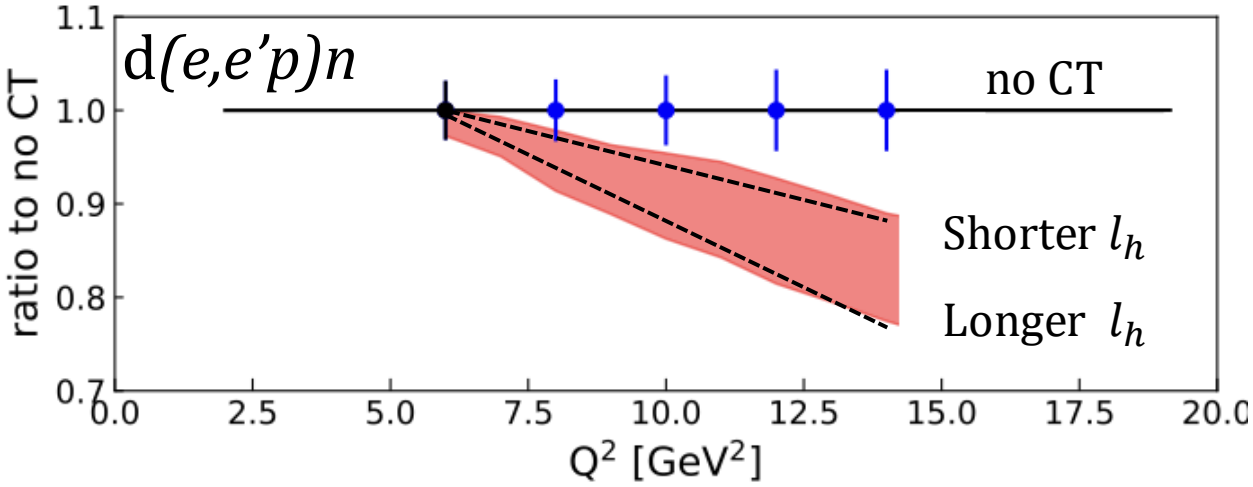
Larger ΔM^2 → $l_h = 2p_h/\Delta M^2$

shorter PLC lifetime →

delays CT onset



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

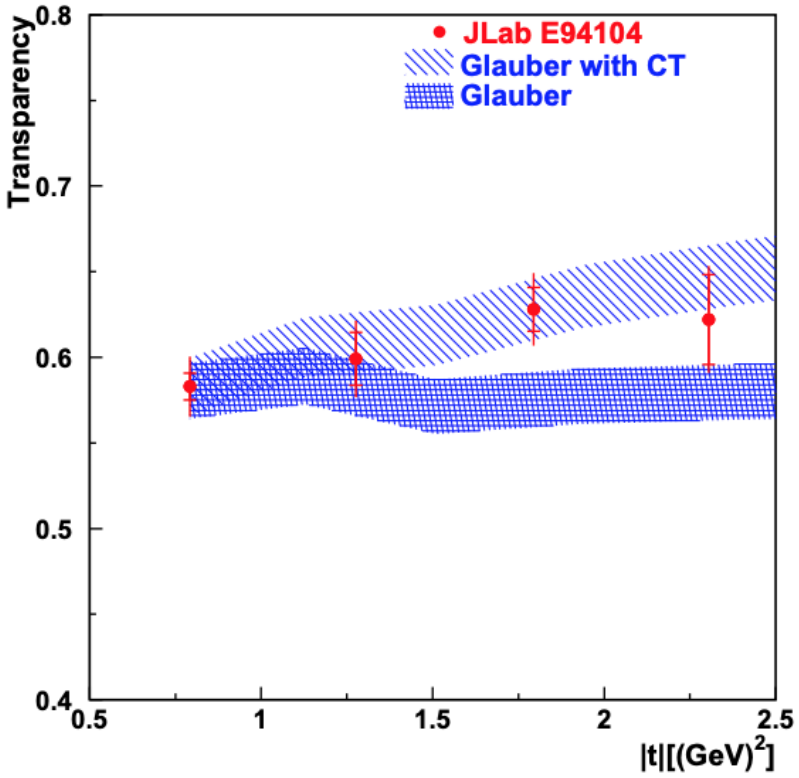


First experiment where expansion can be disentangled from PLC observation

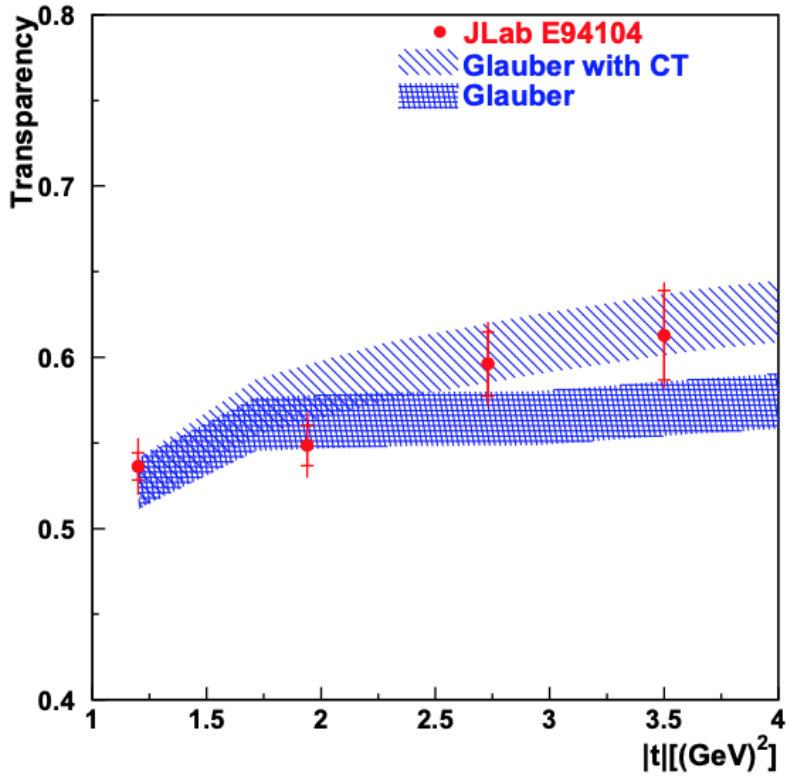
Reaction mechanism dependent? Photoproduction!

$\gamma n \rightarrow \pi^- p$ in ^{4}He in Hall A (6 GeV era)

70° c.m. scattering



90° c.m. scattering



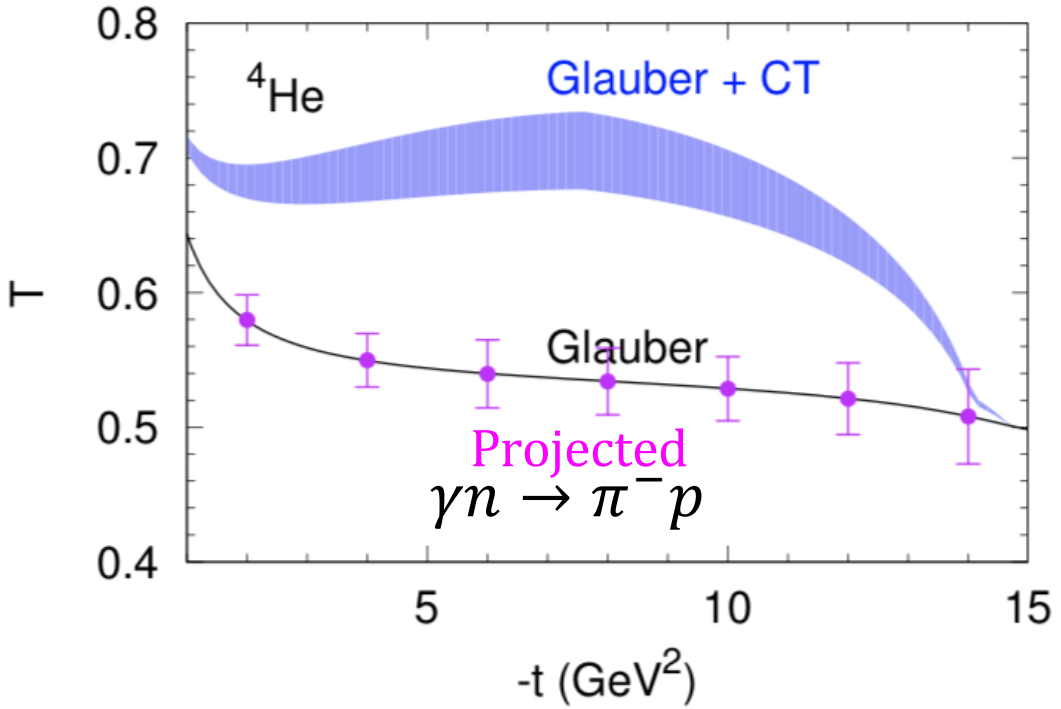
Possible onset?

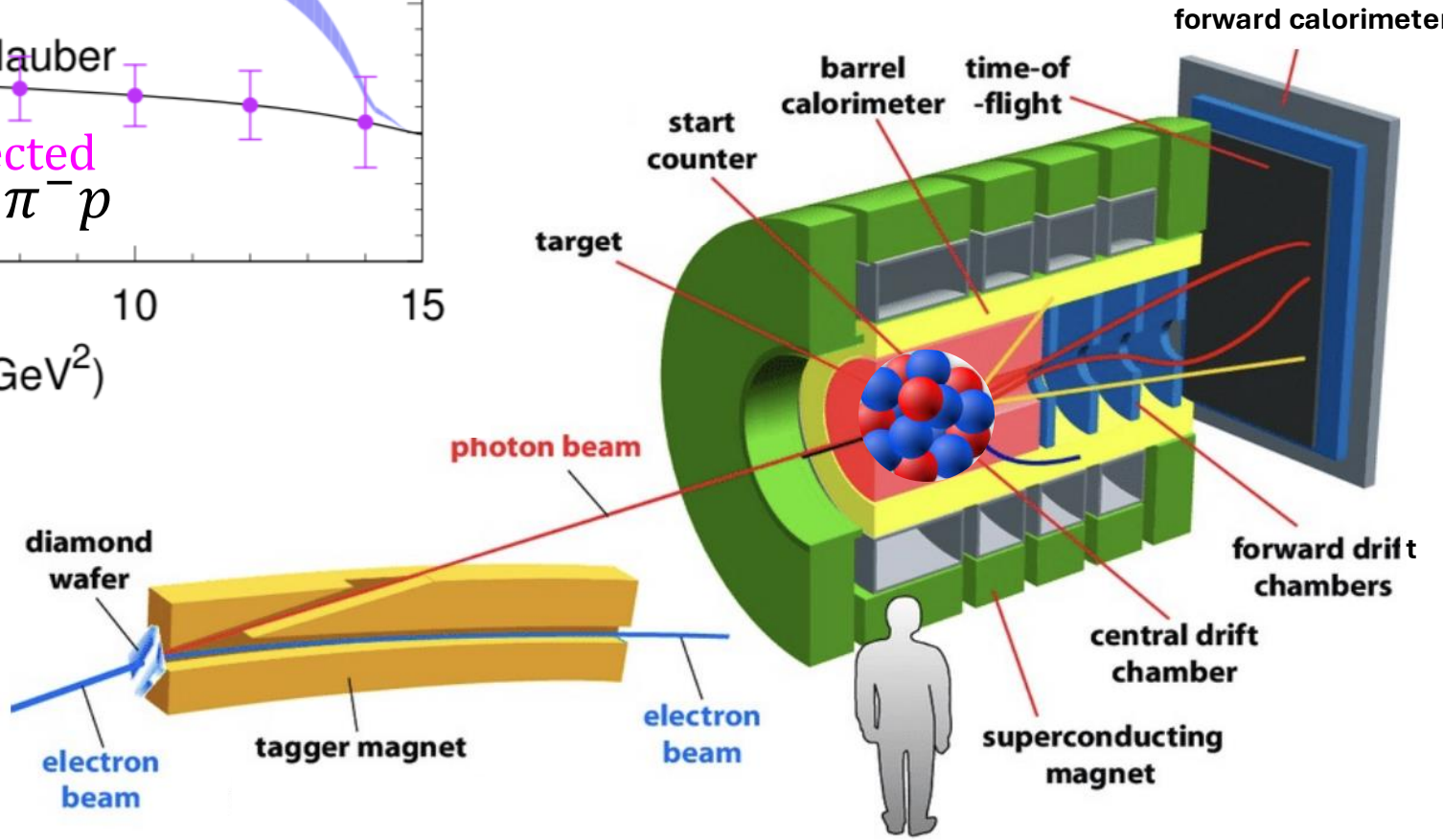
Important to reach high enough "freezing"!

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

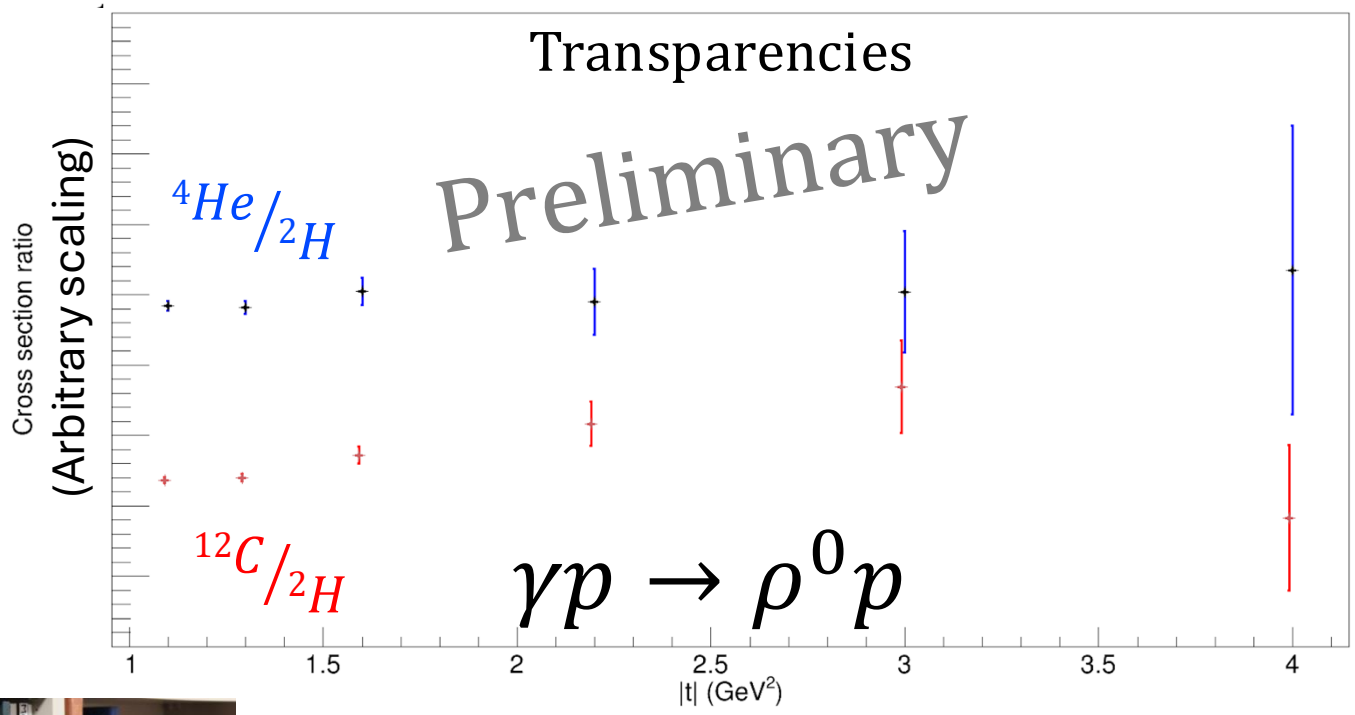
Other reaction mechanisms: photoproduction!

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

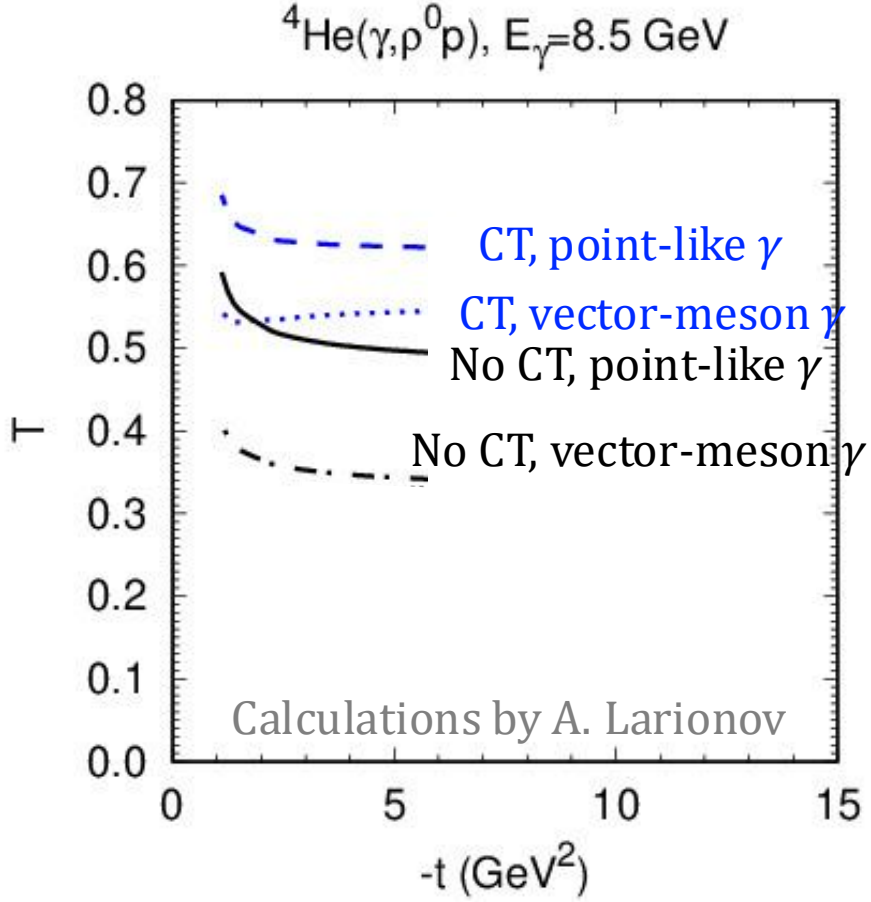




CT from photoproduction reaction in Hall D

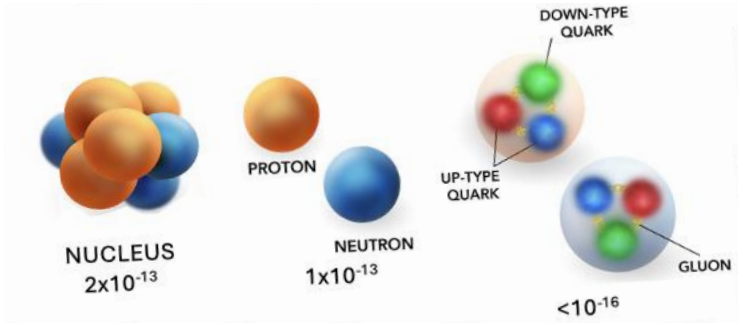


Analysis of Bhesha Devkota,
Mississippi State University



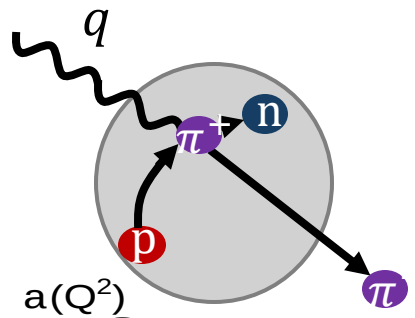
Summary

$$|p\rangle = |uud\rangle + |uudq\bar{q}\rangle + |uudg\rangle + \ldots$$



- PLC part of proton description
- CT: Smaller sizes → reduced interactions!
- Observation of CT directly (finding regime to effectively turn off strong interactions) connects q-g and hadronic degrees of freedom.
- New CT experiments explore the connections between the baryonic and mesonic sectors and reaction mechanisms.

Future: Extend pion CT measurements (2026)



Extend the T and nuclear dependence