Nucleons in nuclei as the experimentalist's roadmap to QCD

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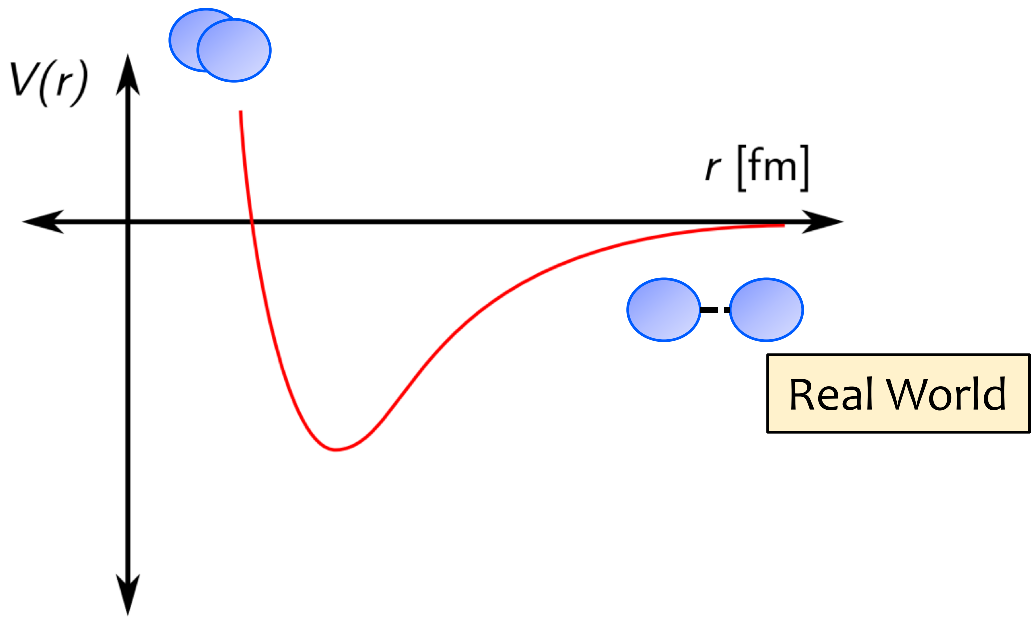
4 September 2023
Lepton Interactions with Nucleons and Nuclei
Marciana Marina, Isola d'Elba

Jefferson Lab

Two descriptions of nuclear physics

Potential between nucleons



nucleons & mesons

Two descriptions of nuclear physics

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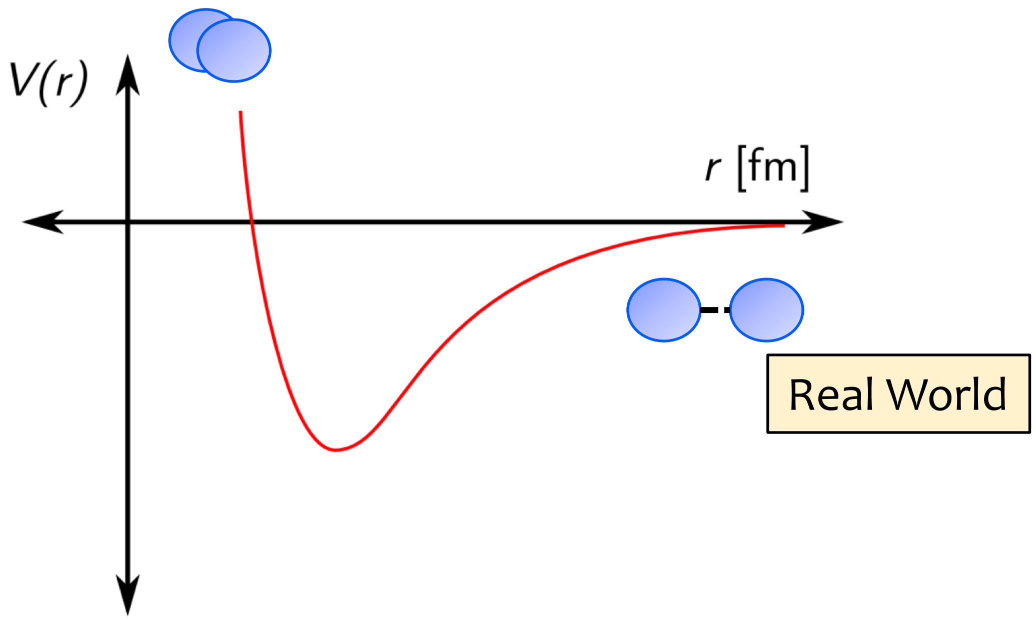
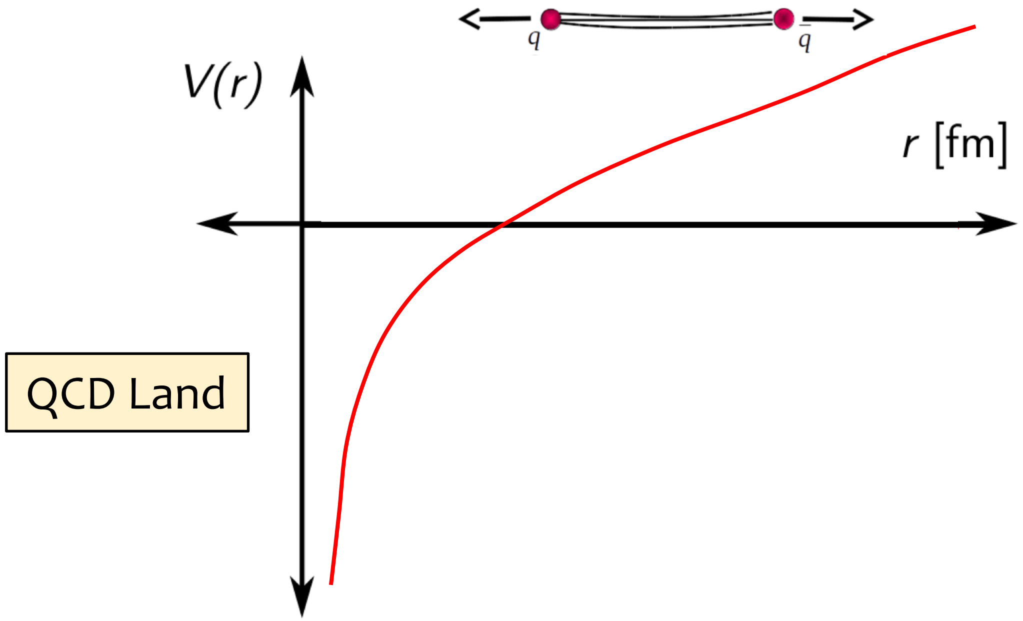


nucleons & mesons

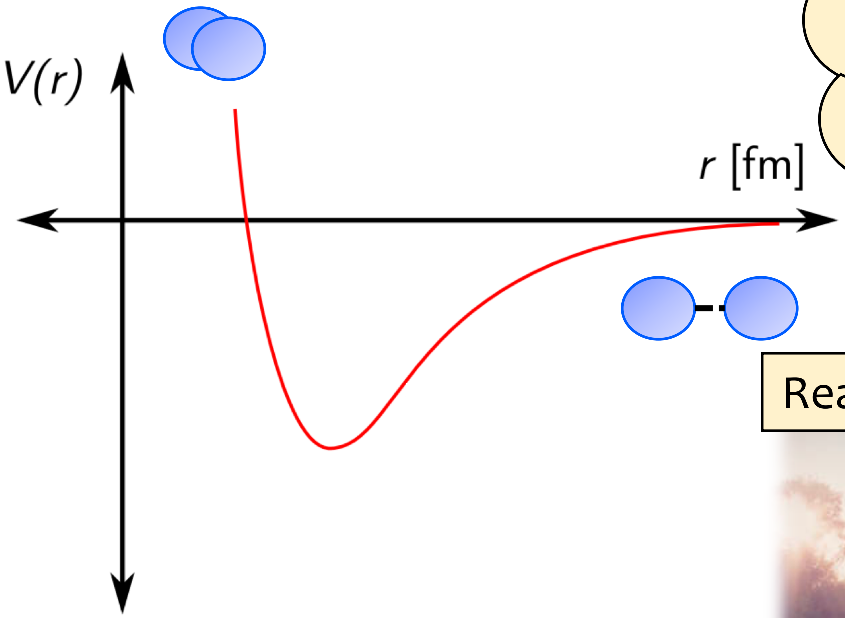
Potential between quarks



quarks & gluons

Two descriptions of nuclear physics

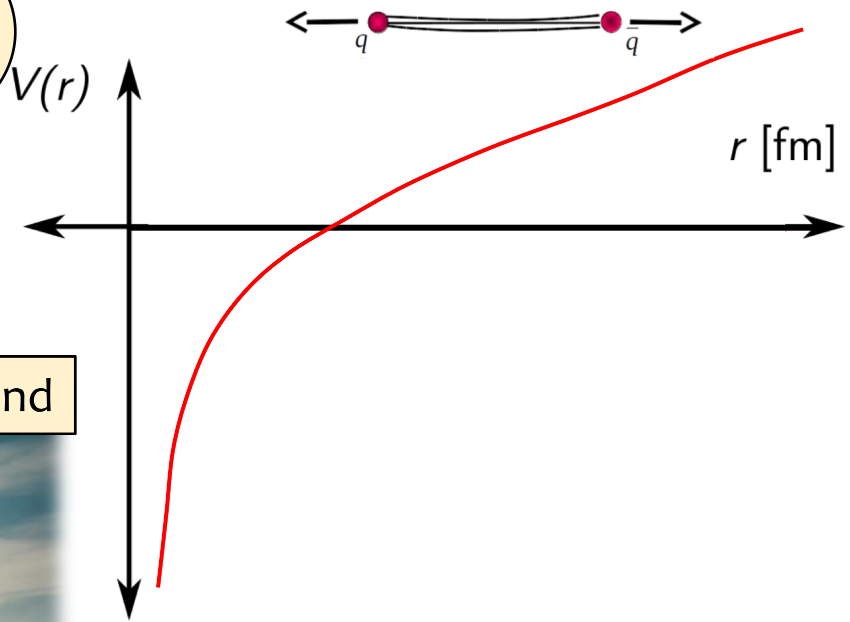
Potential between nucleons



nucleons & mesons

What is the roadmap between these two regimes?

Potential between quarks



quarks & gluons

Drawing the roadmap

QCD is the leading theory for the strong force interaction.

Yet, we are still trying to fully describe nucleons and nuclei in terms of quarks and gluons.

We have to connect the Real World to QCD Land using data

Useful clues:

Modifications in the structure and interactions of hadrons in the nucleus.

The transition from quark-gluon to nucleon-meson degrees of freedom.

Drawing the roadmap

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Useful clues:

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The transition from quark-gluon to nucleon-meson degrees of freedom.

Nuclear transparency

Probability knocked out proton in scattering to be deflected or absorbed.

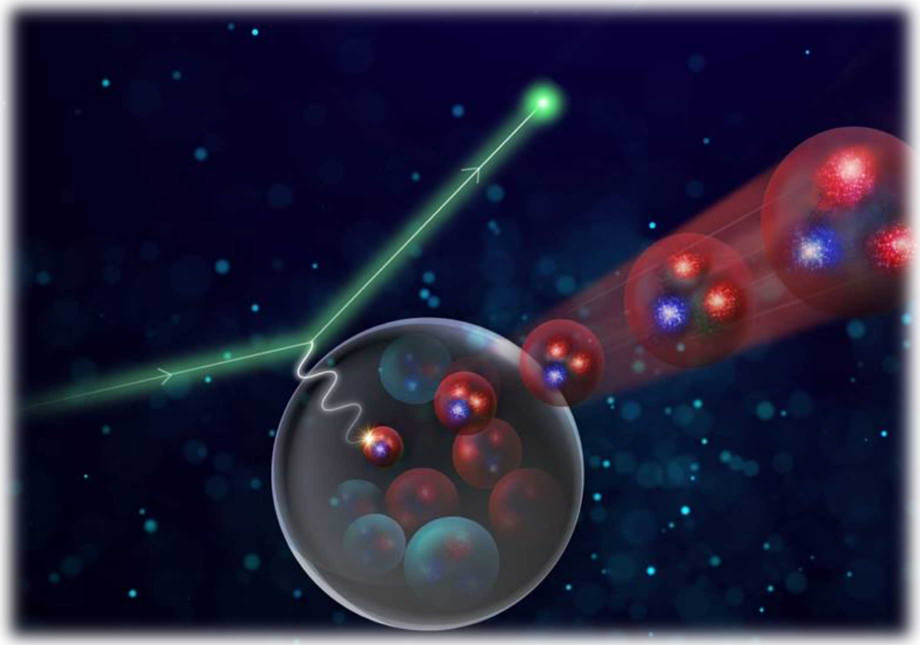
Ratio of cross-sections for exclusive processes from nuclei and nucleons is the Transparency.

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

σ_A (nuclear cross section)

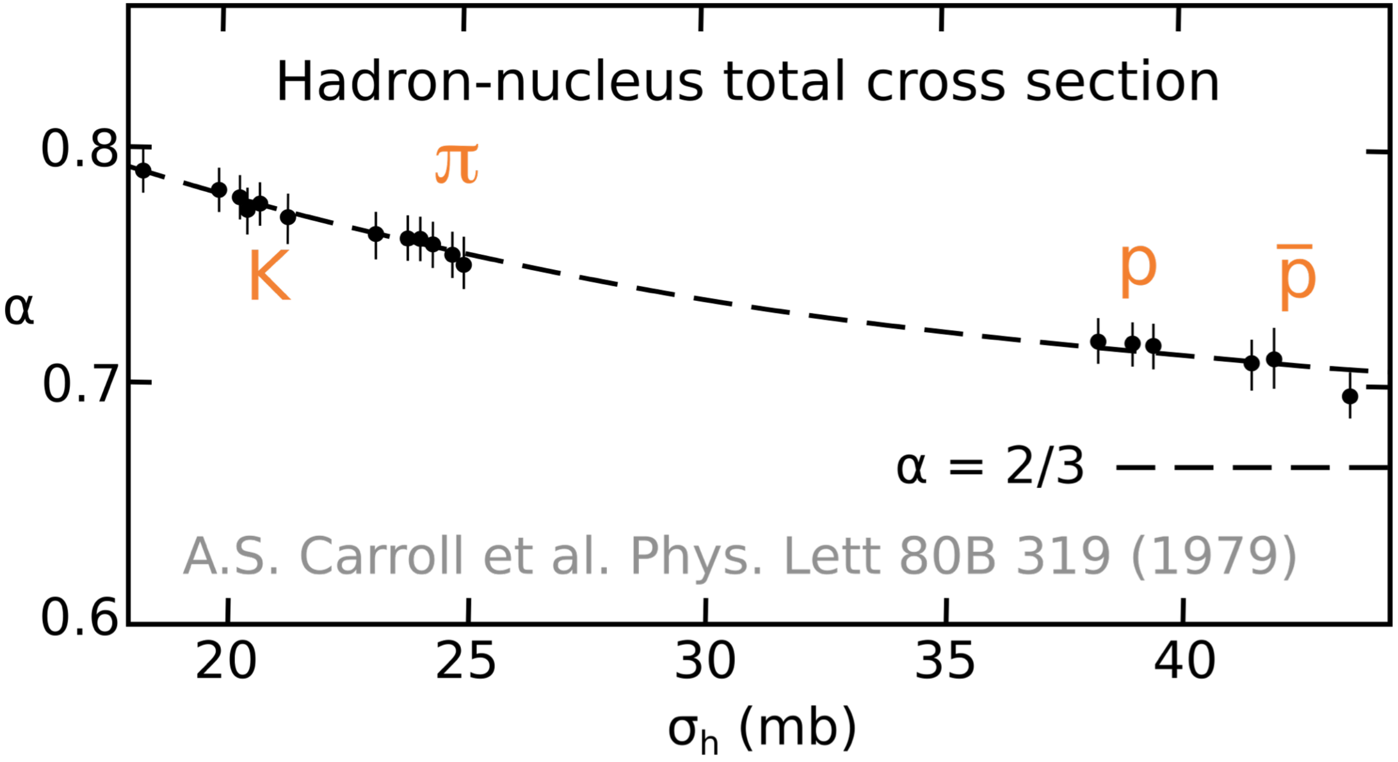
σ_N (free nucleon cross section)

$$\sigma_A = \sigma_N A^{\alpha}$$



Absorption cross section is momentum independent

Hadron momenta:
60, 200, 280 GeV/c



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

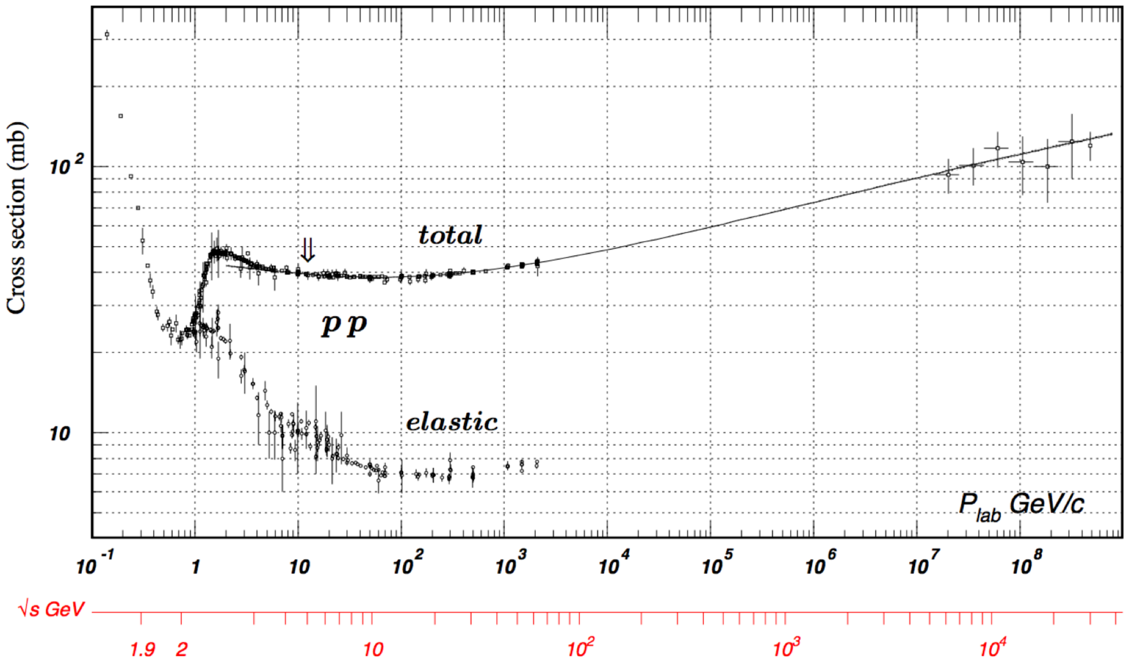
$\boldsymbol{\alpha}$ <1 due to strong interaction nature of the probe

Tendency of $\boldsymbol{\alpha} \to 2/3$ expected for opaque nucleus

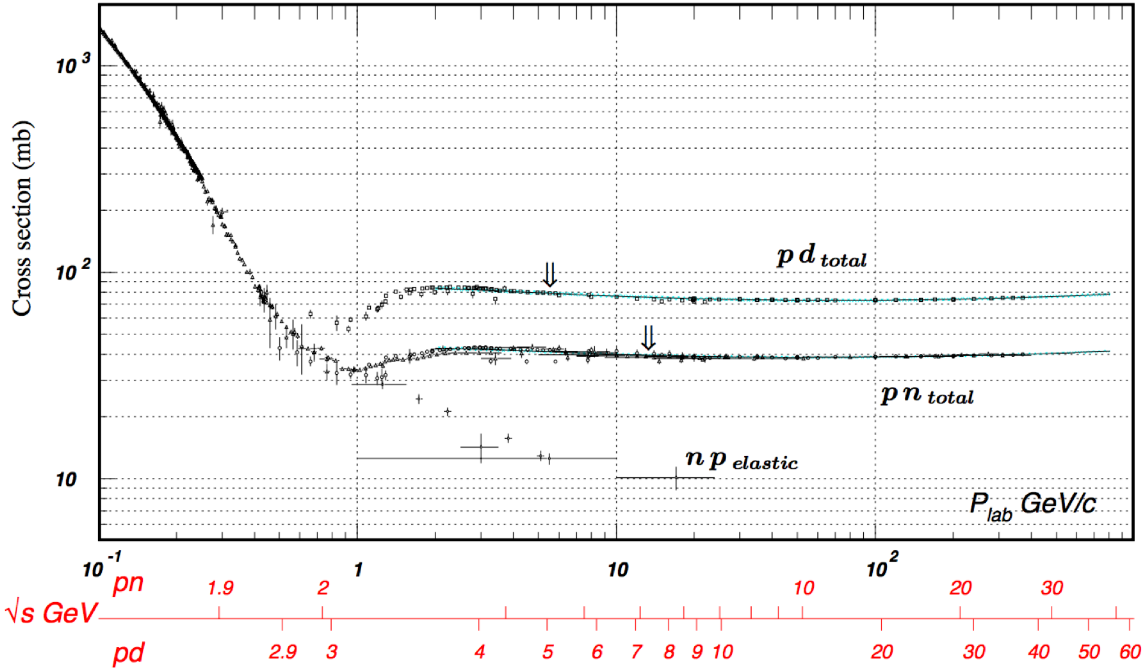
NN cross section

NN cross section is essentially energy independent

pp scattering cross section



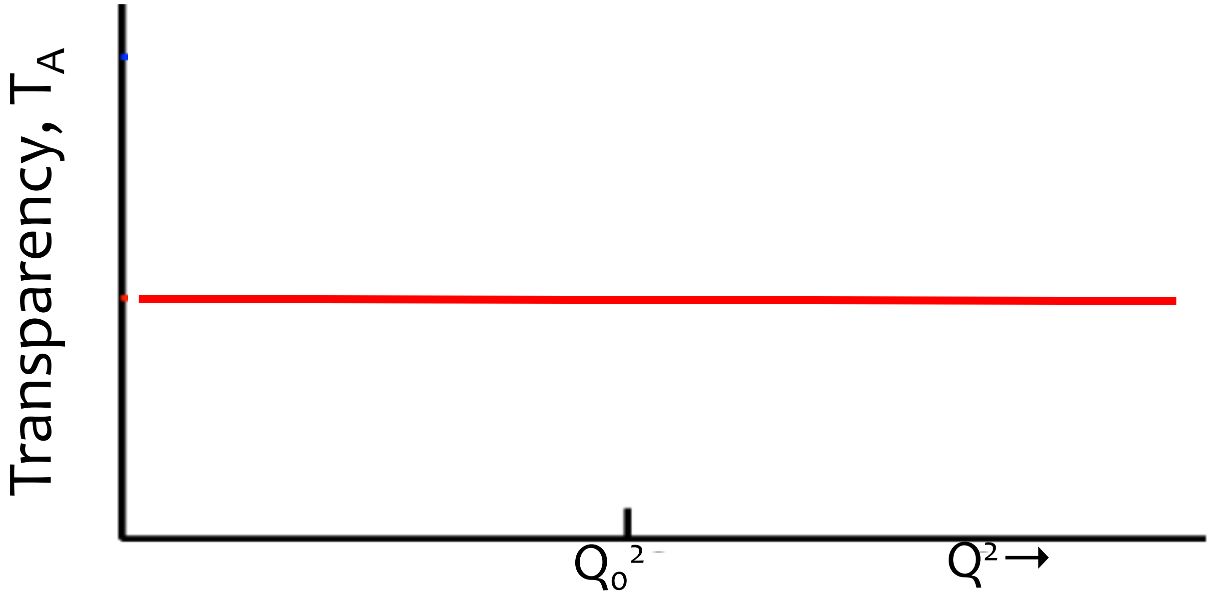
pn scattering cross section



Transparency is momentum independent (in the strongly interacting hadronic picture)

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

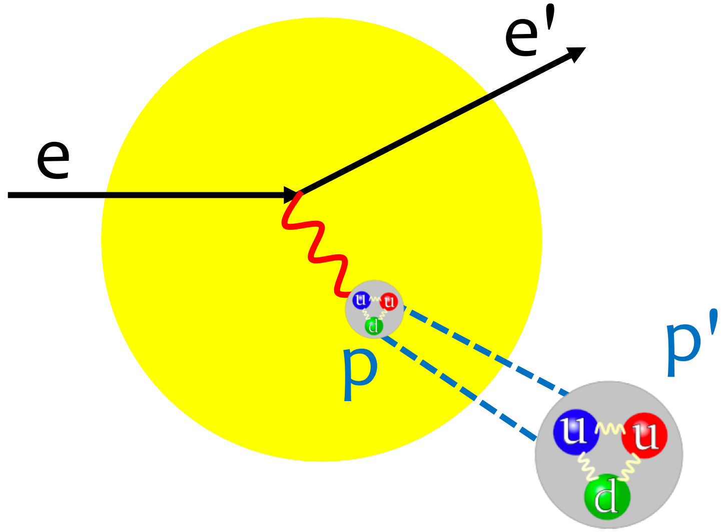
$$\sigma_A = \sigma_N\ A^{\alpha}$$



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

Color transparency is a fundamental prediction of pQCD

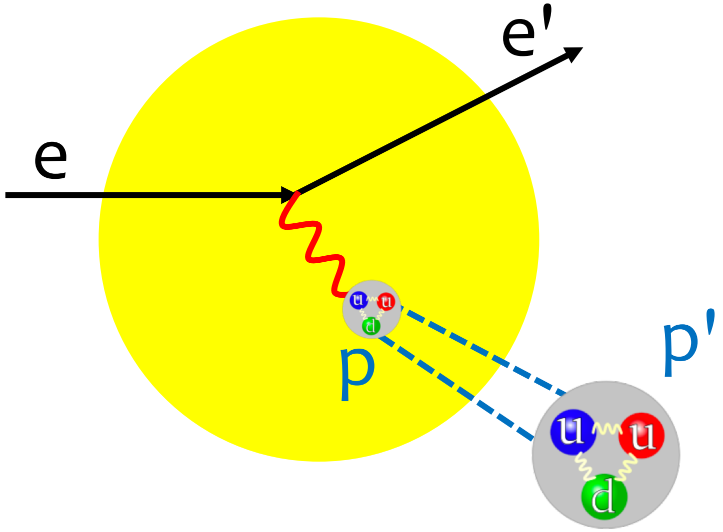
Introduced by
Mueller and Brodsky, 1982



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:
Hadrons fluctuate to small transverse size (*squeezing*, transferred momentum)



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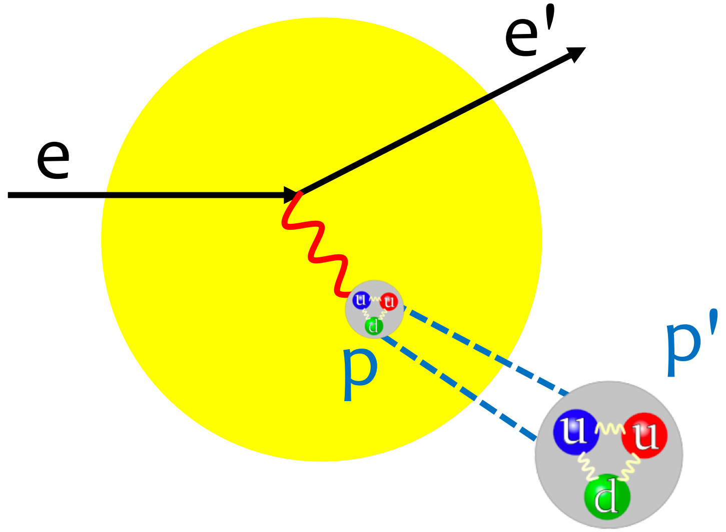

Relativity:
Maintains this small size as it propagates out of the nucleus (*freezing*, transferred energy)

Color transparency is a fundamental prediction of pQCD

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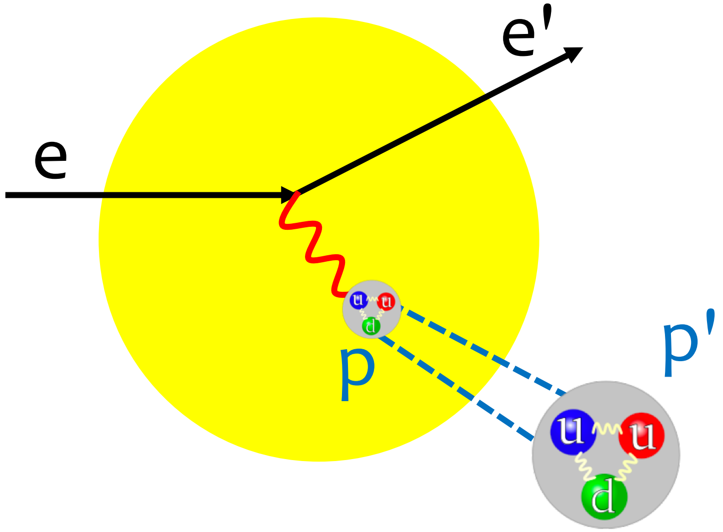
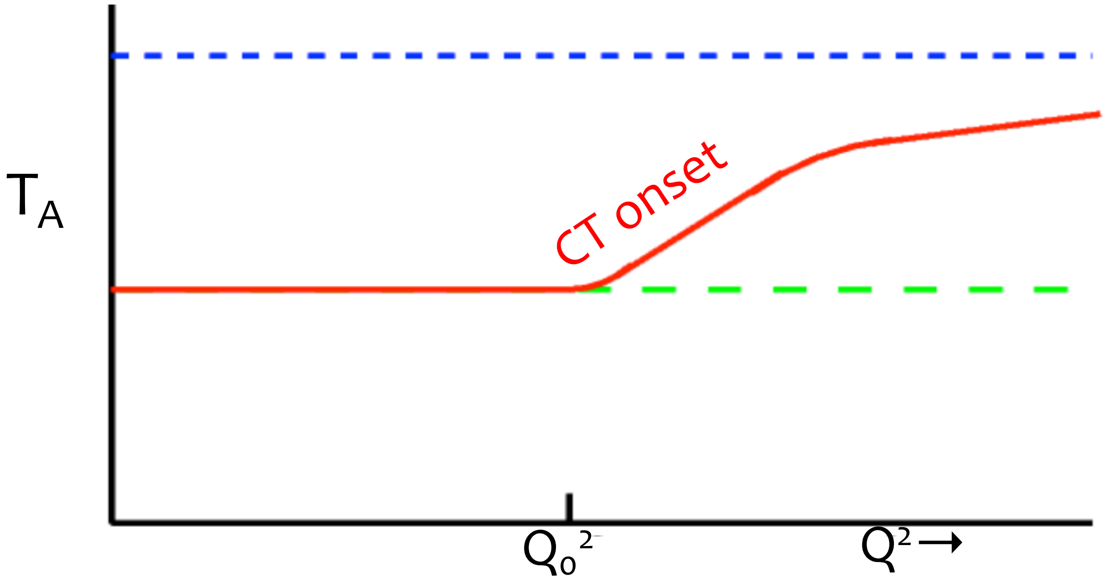


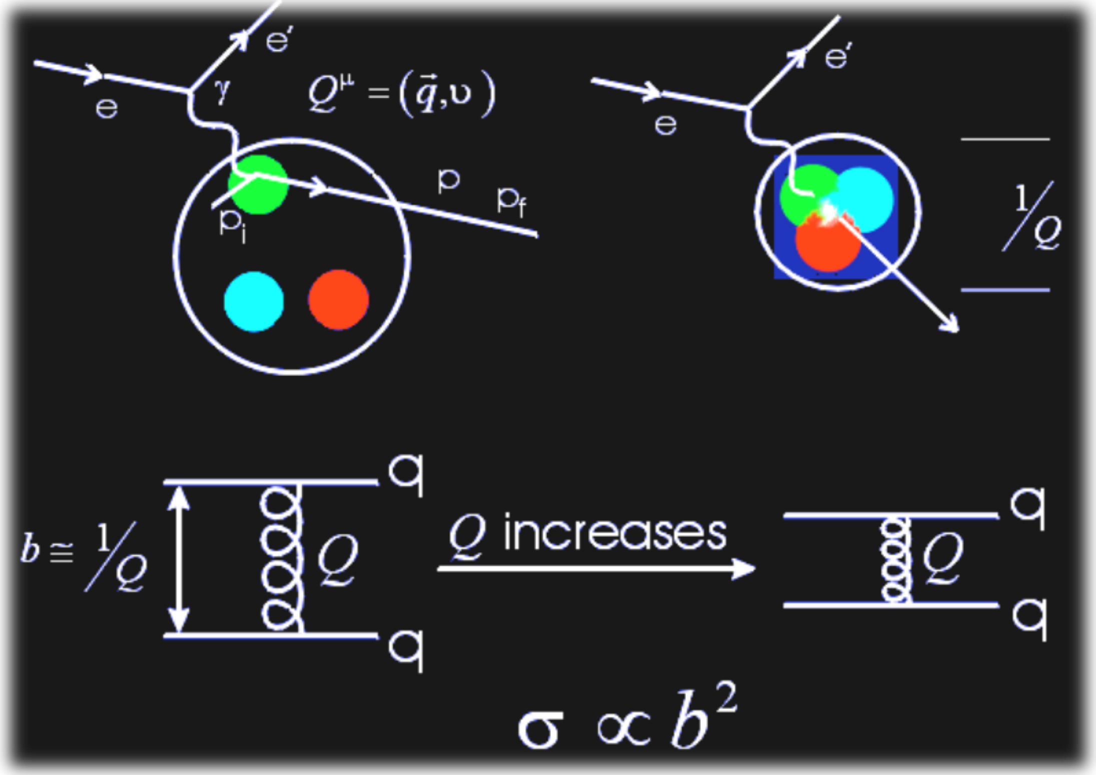
Relativity:
Maintains this small size as it propagates out of the nucleus (*freezing*, transferred energy)

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

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

CT is unexpected in the strongly interacting hadronic picture

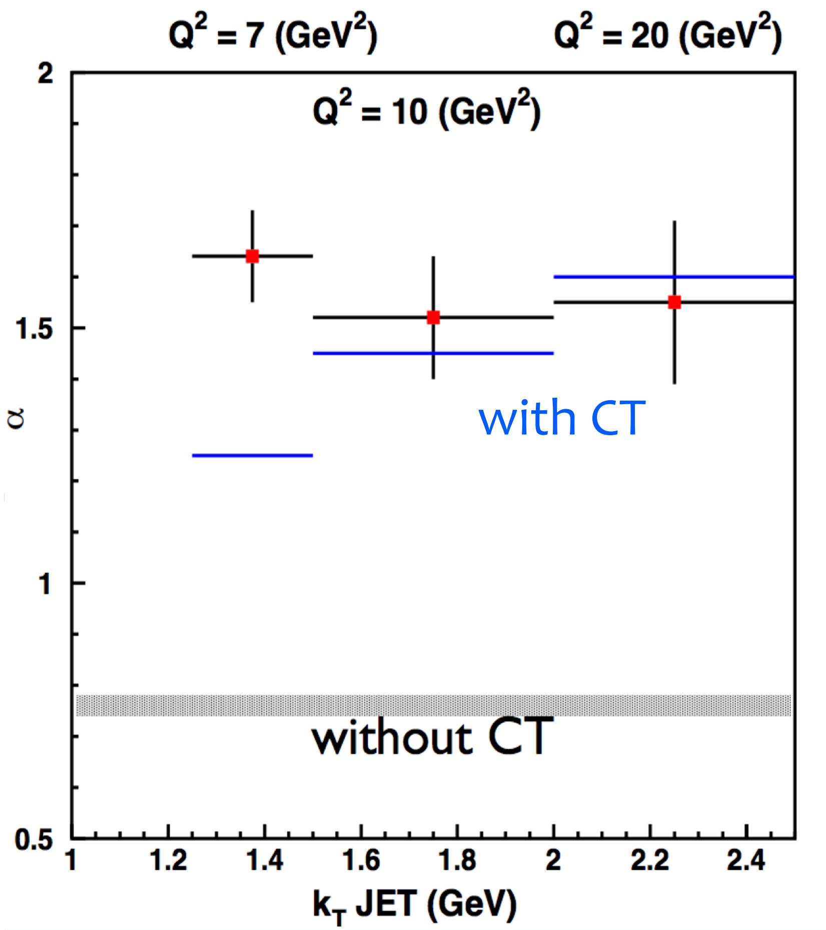




CT established at high energies

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

π + A ⟶ 2 jets + A'



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

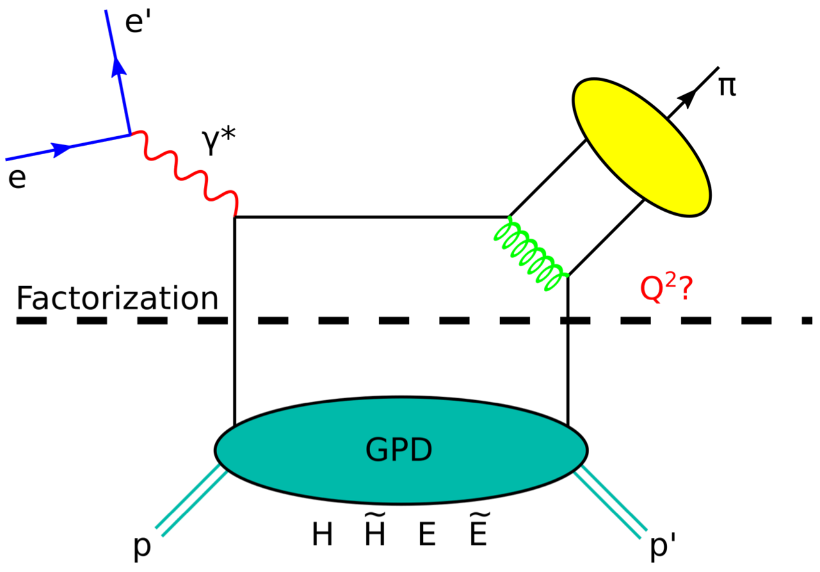
Pion-nucleus total cross section, α=1.6

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

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

CT is connected to other physics interpretations

GPD framework requires factorization into a hard interaction with single quark and soft part (GPDs).



Color cancellation required for factorization:
-> small size configurations
-> at high Q^2, small size object moves through nucleus with no further interactions

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

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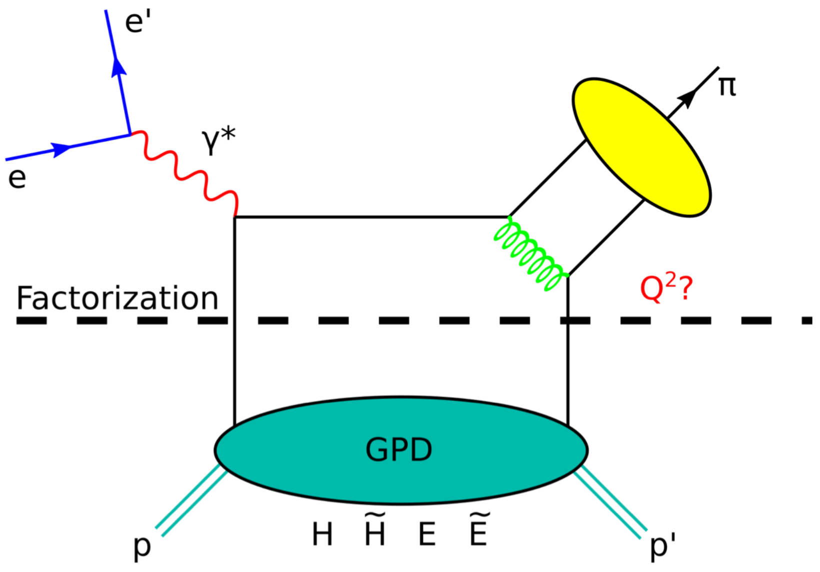

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-> small size configurations
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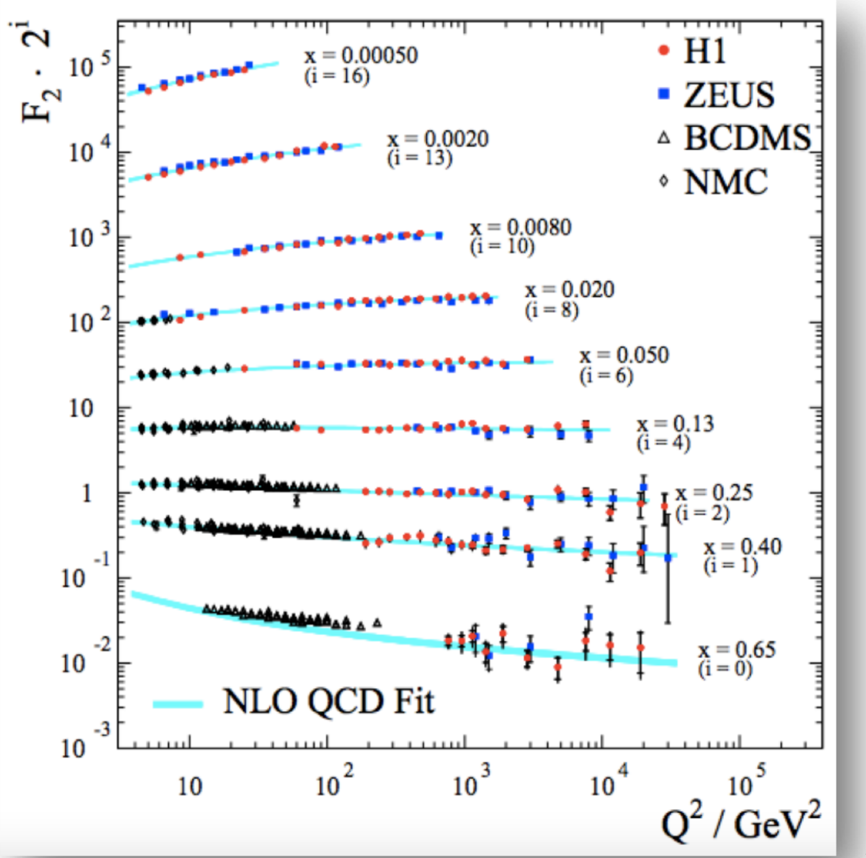
CT is implied by successful description of DIS.

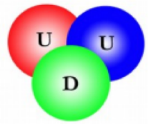
Scaling at low x requires a suppression of interaction.



CT experiments

CT experiments

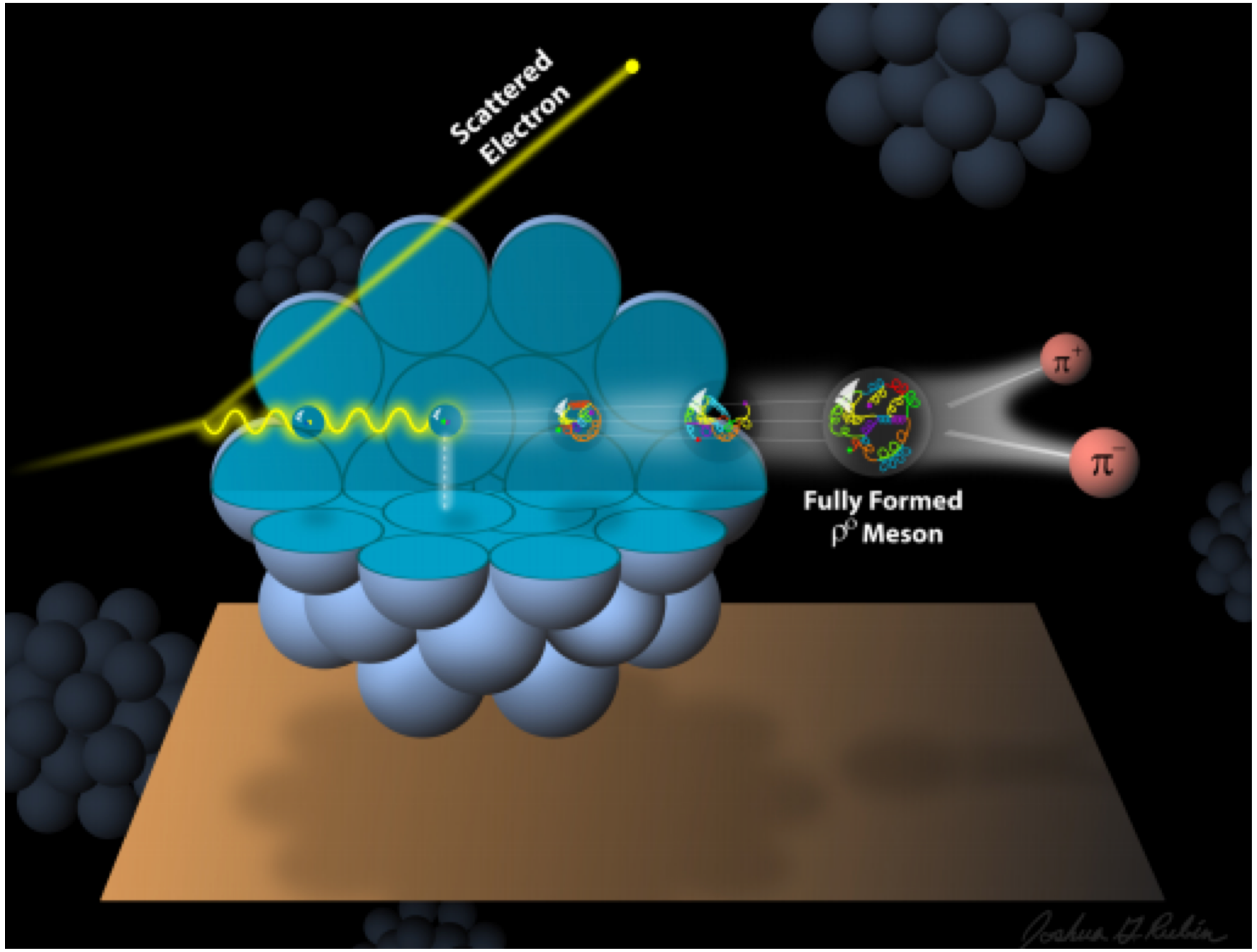
Baryon



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

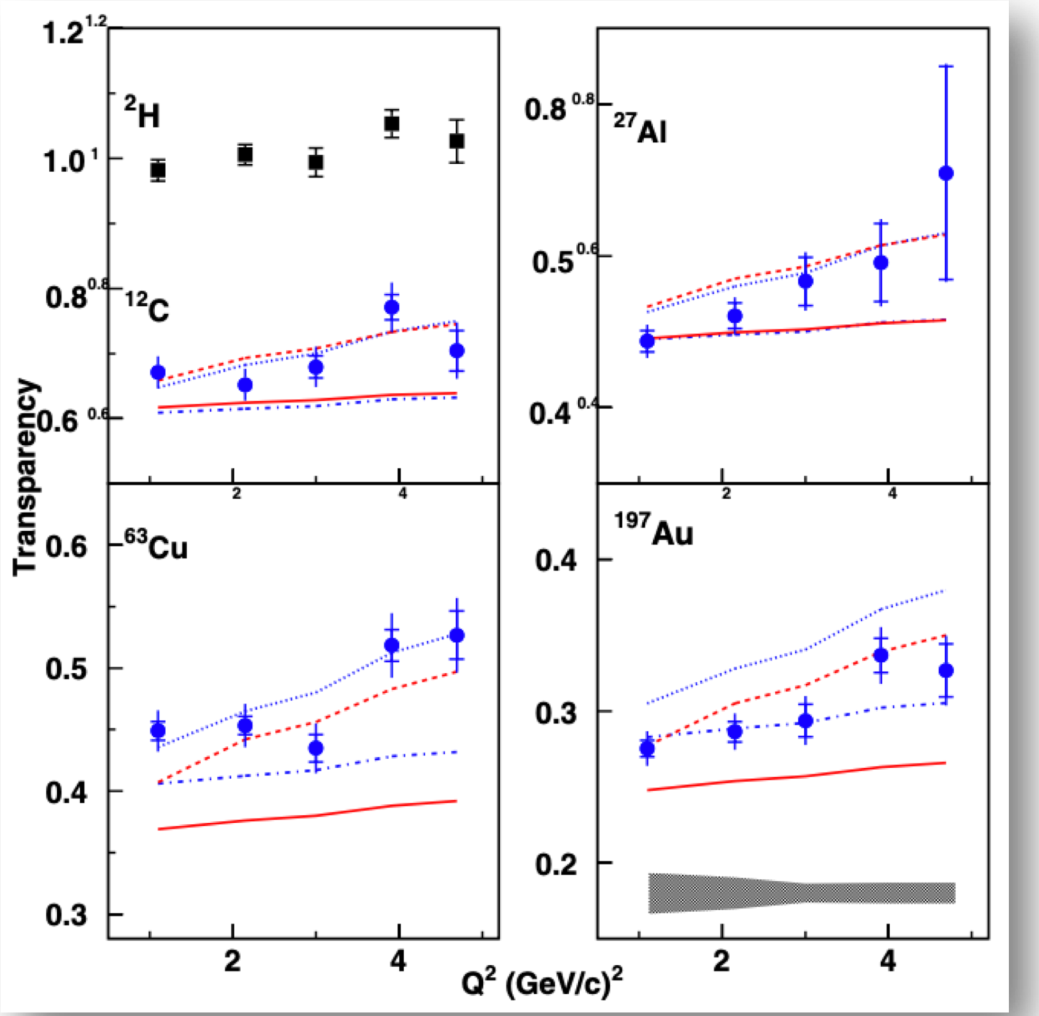
Meson

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

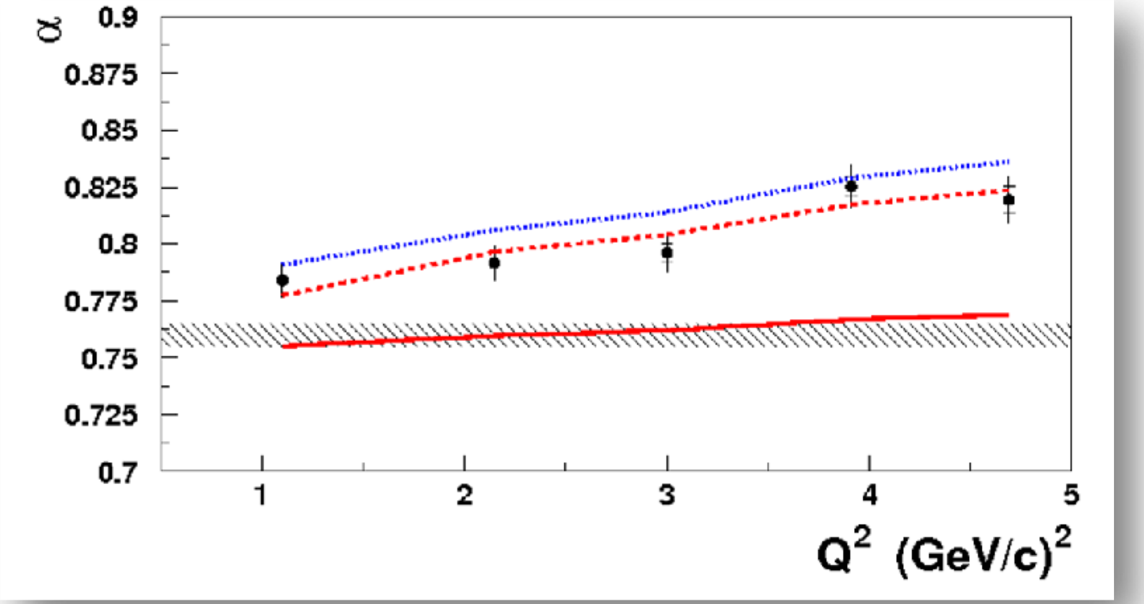


Onset for mesons observed at few GeV²

A(e,e’π^+)



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



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

Onset for mesons observed at few GeV^2

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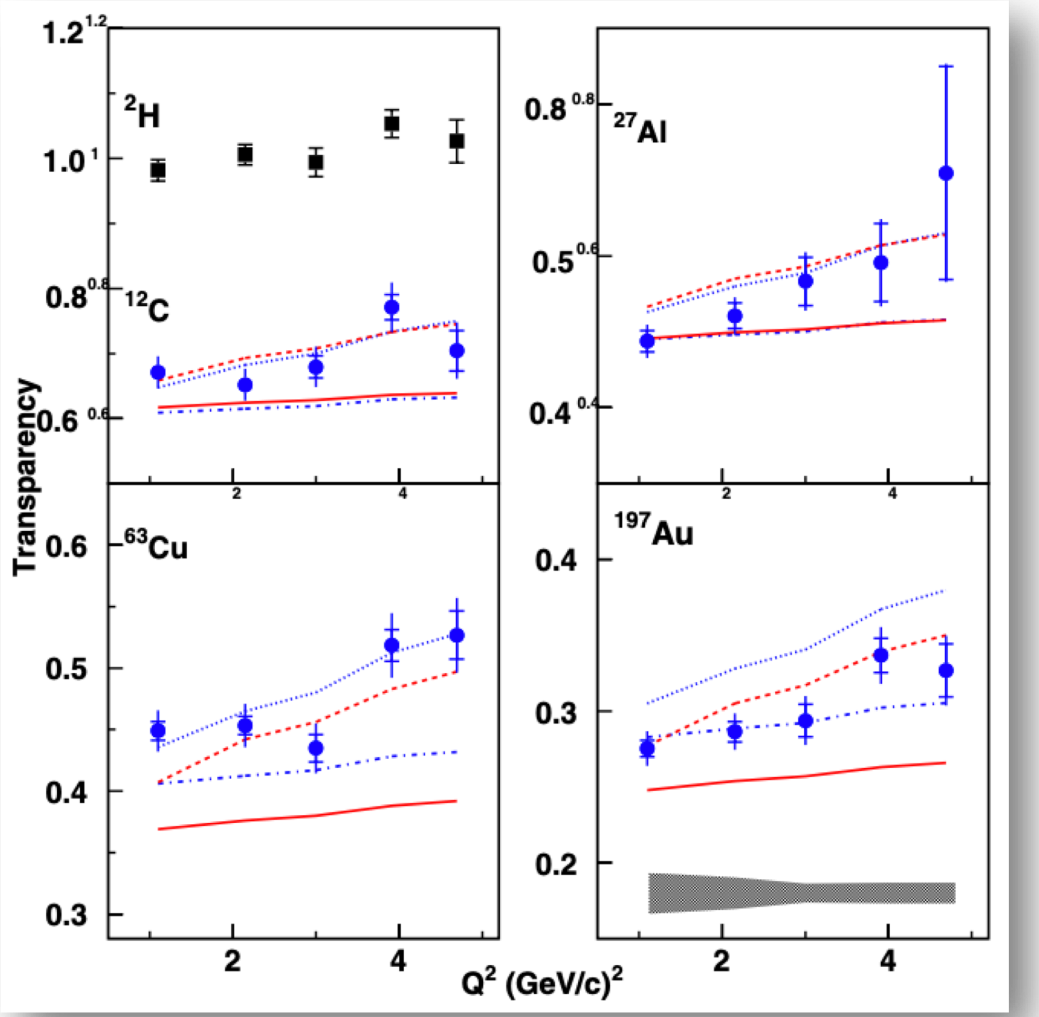
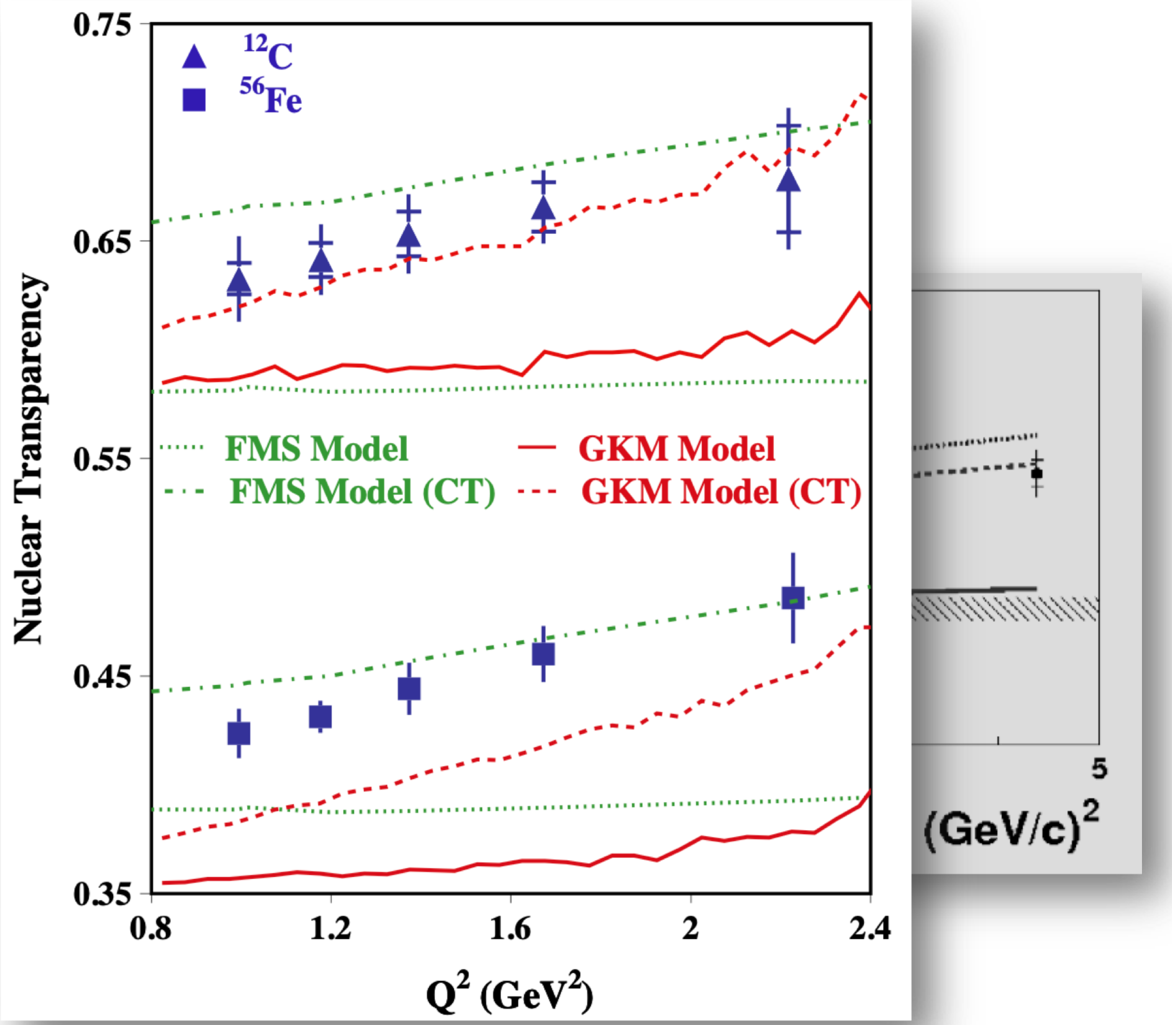


B. Clasie et al, PRL99:242502 (2007)
X. Qian et al, PRC81:055209 (2010)

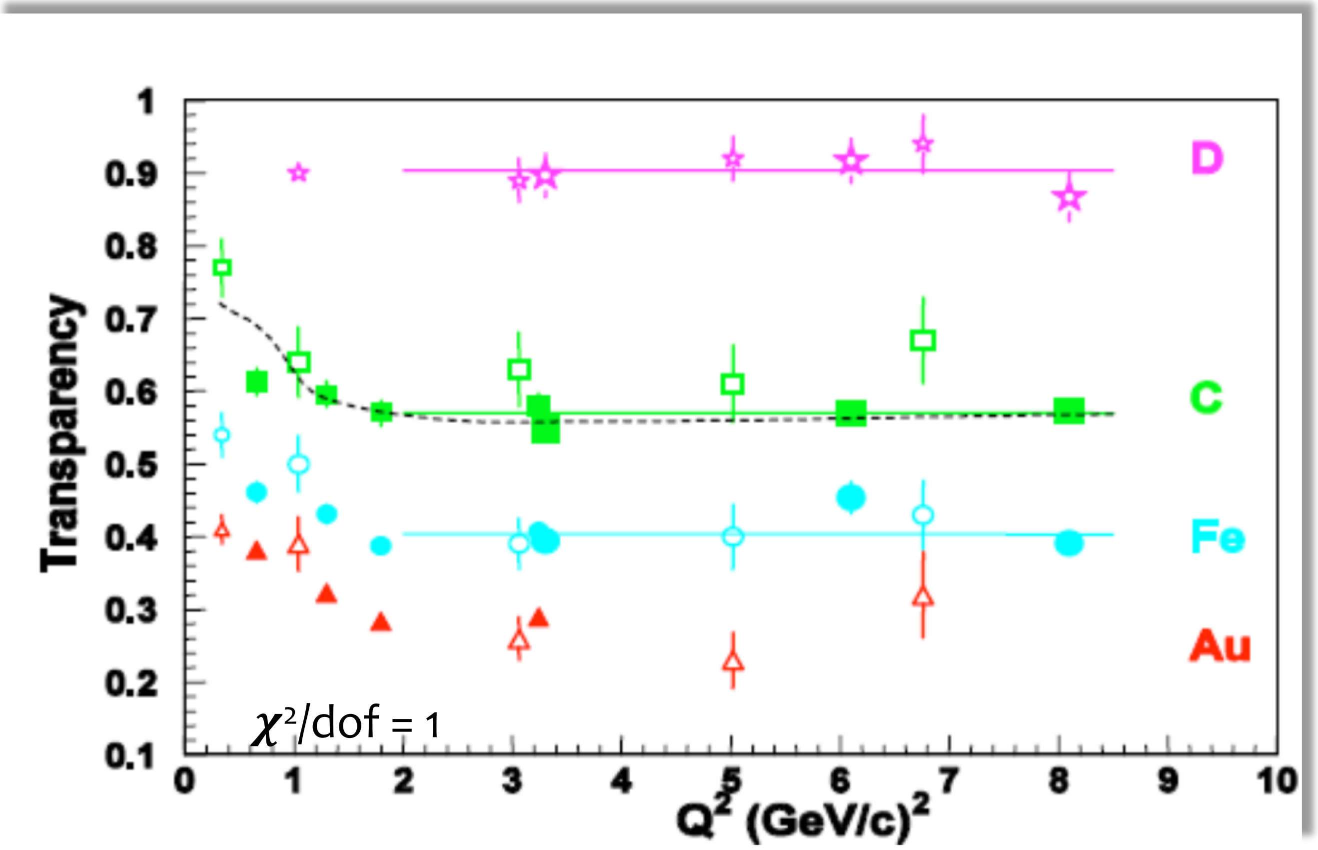
A(e,e'ρ^0)



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

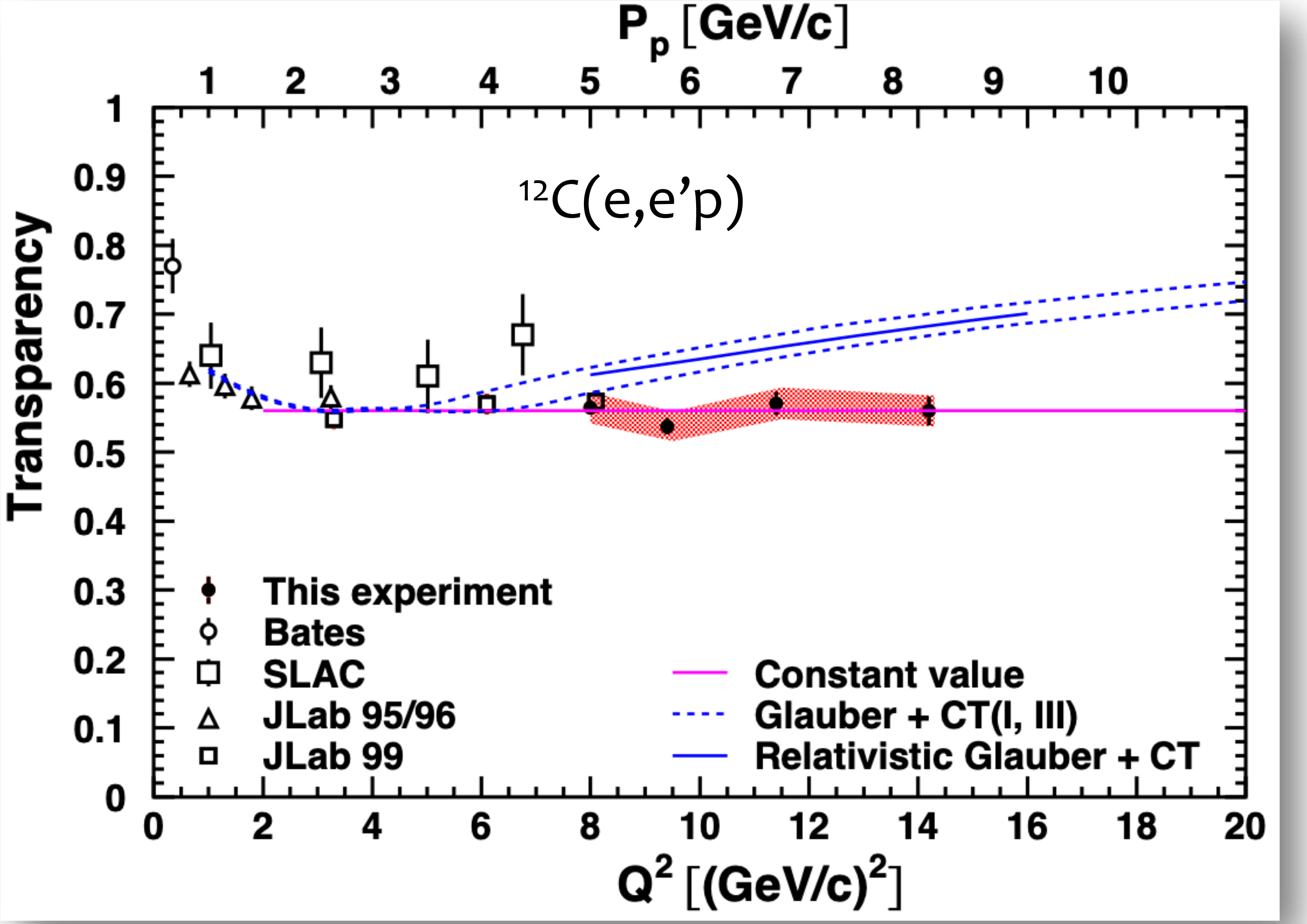
Protons are historically challenging

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



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)

And continue to show a lack of CT onset up to Q²<14 GeV²…

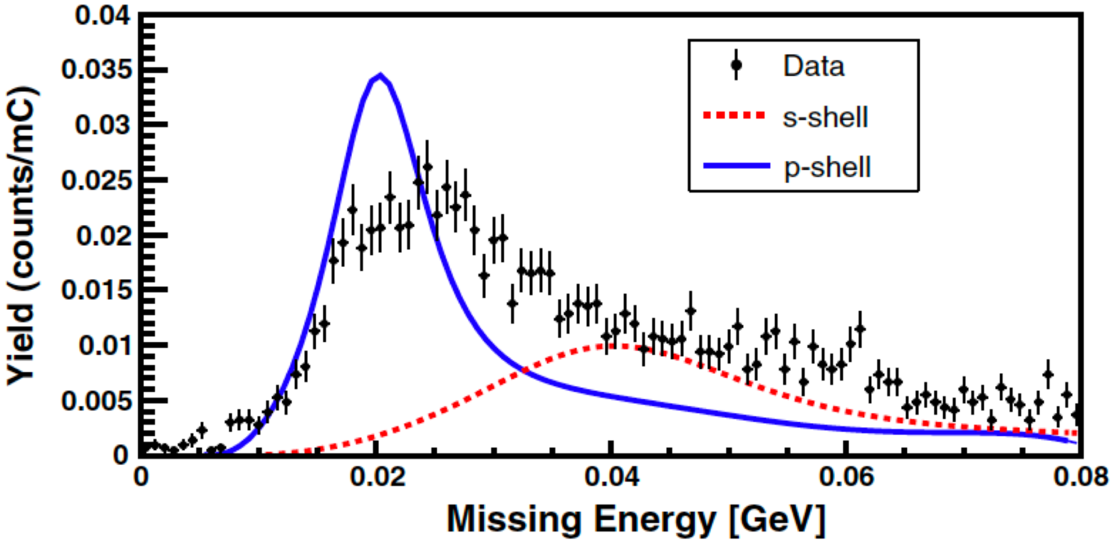


D. Bhetuwal et al, PRL126:082301 (2021)

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)

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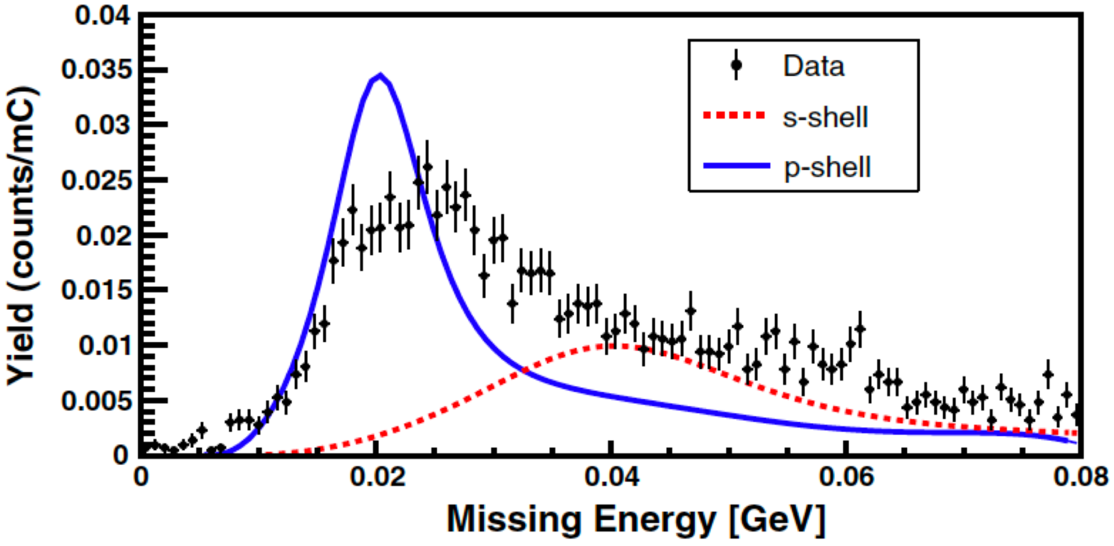
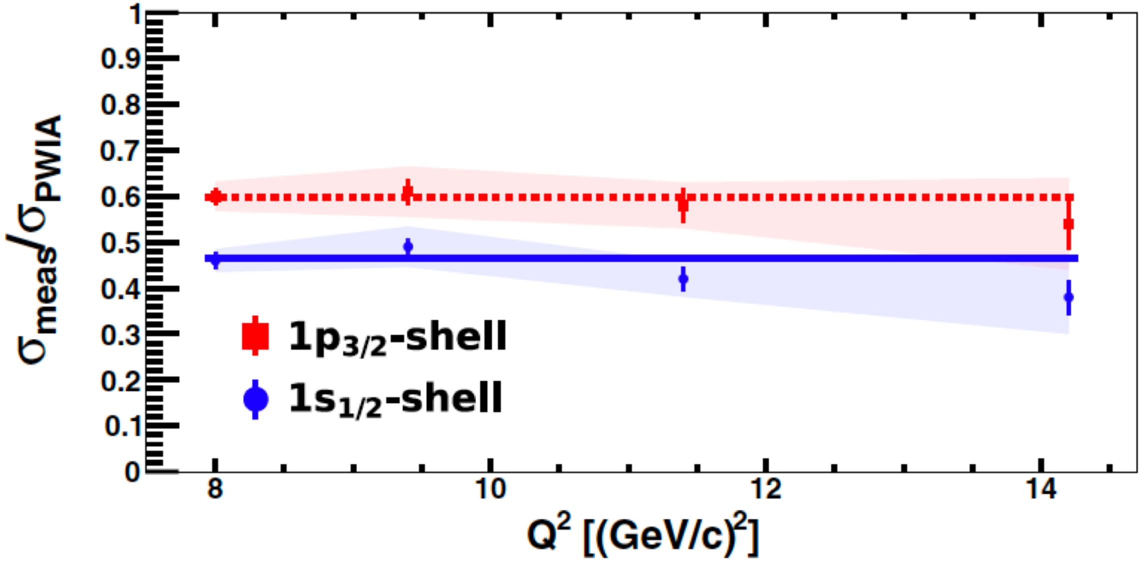
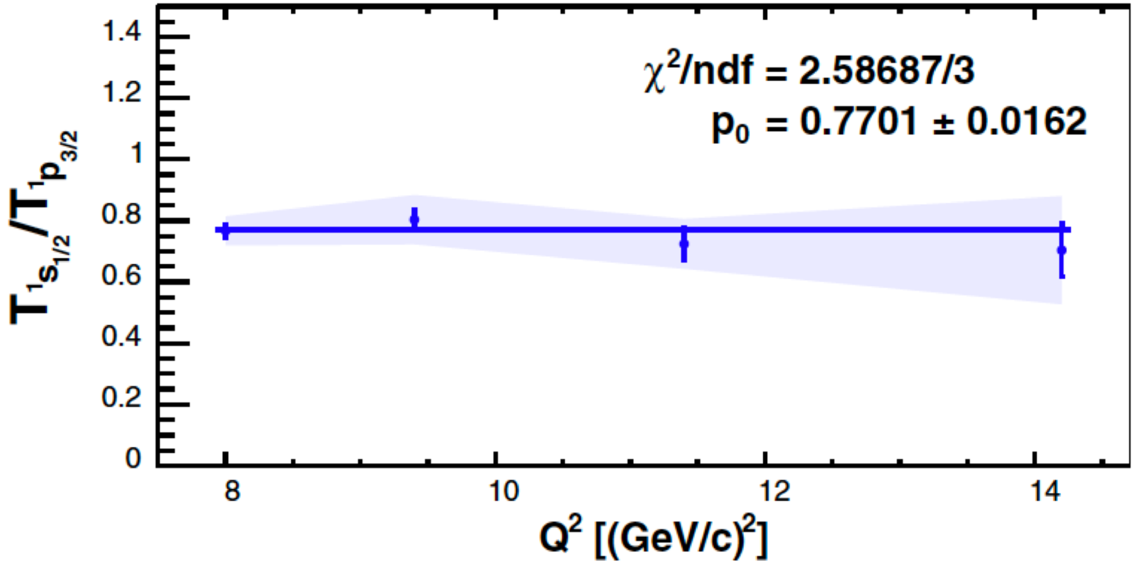
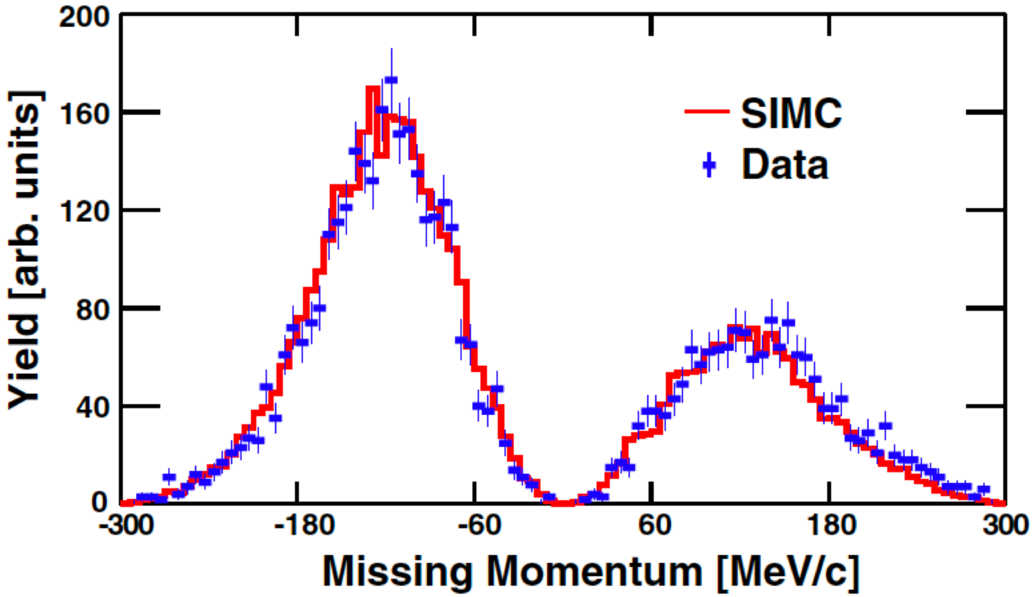






D. Bhetuwal, et al, Phys. Rev. C **108**, 025203 (2023)

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



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

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

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)

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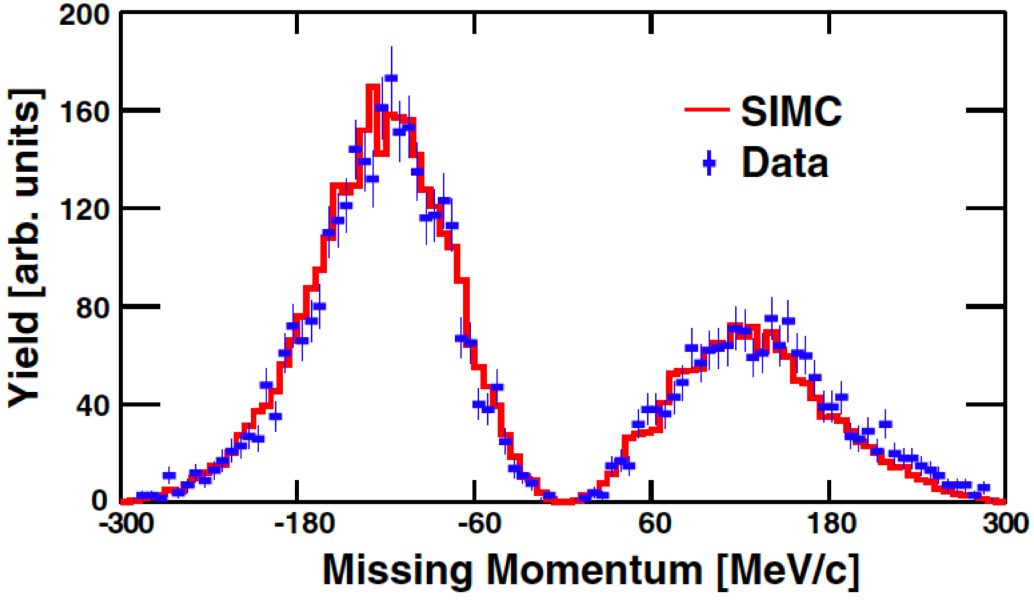

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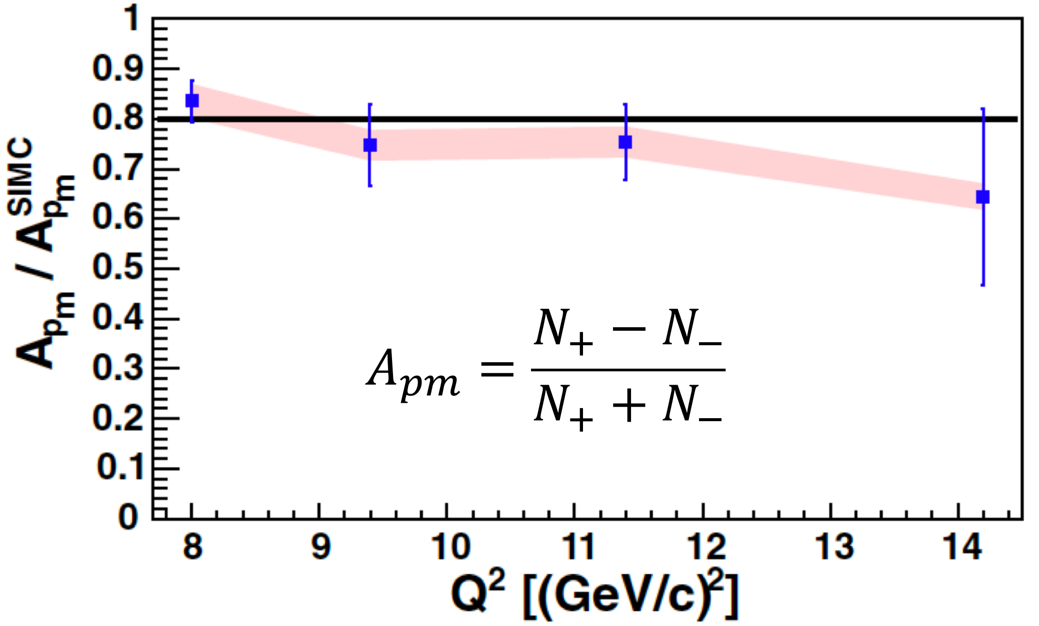
Jennings and Kopeliovich PRL 70 (1993)
Bianconi et al, PLB 325 (1994)

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



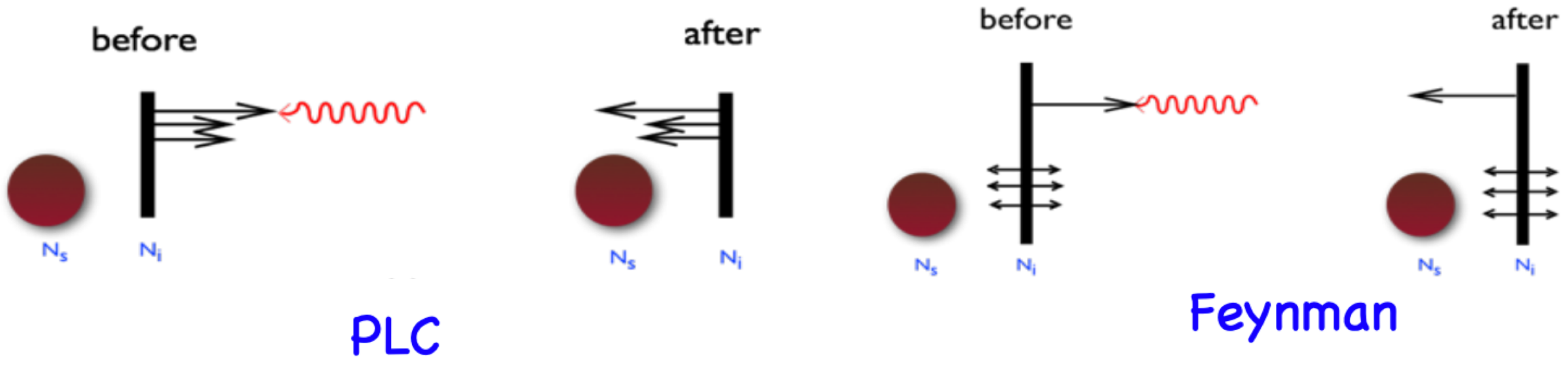
$$A_{pm} = \frac{N_+ - N_-}{N_+ + N_-}$$

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

(Some) interpretations

No PLC was formed (Feynman Mechanism)

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



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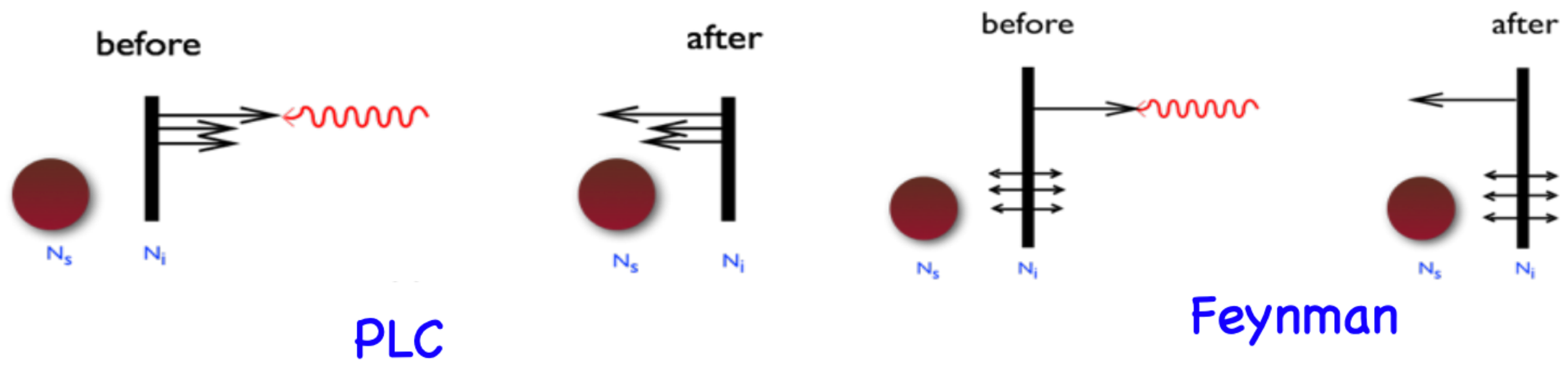
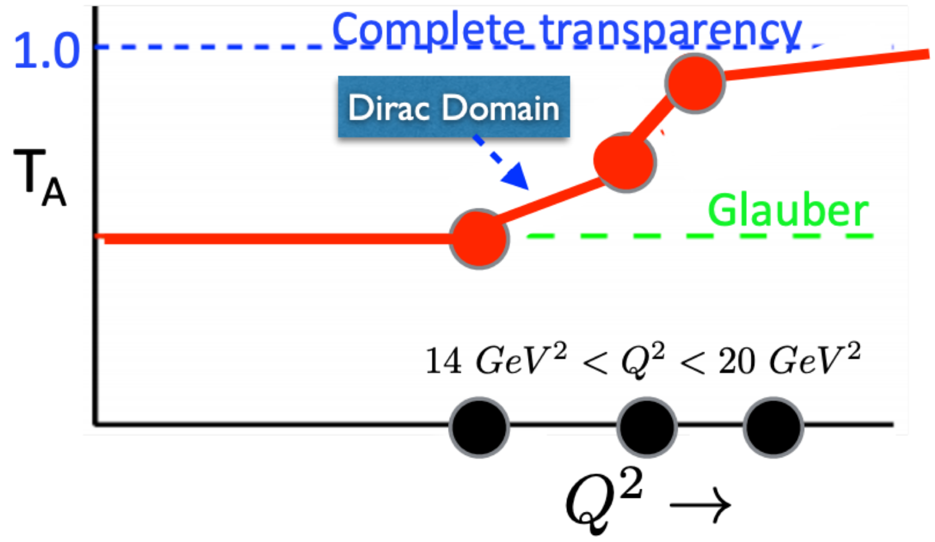
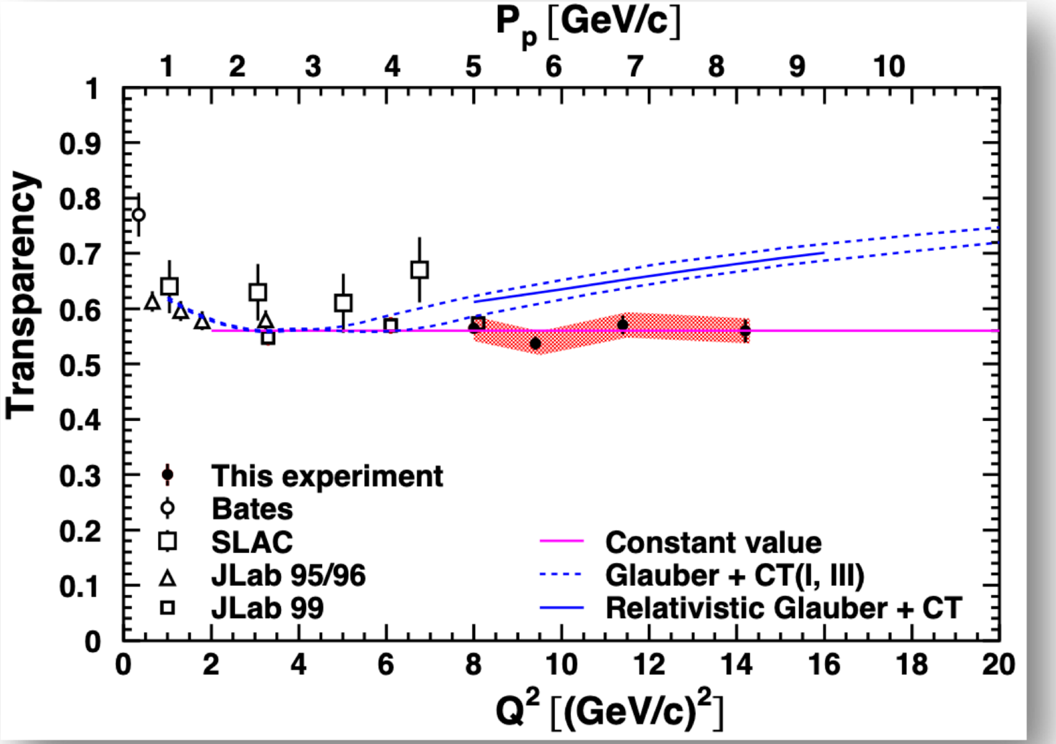


HLFQCD says we need higher Q^2

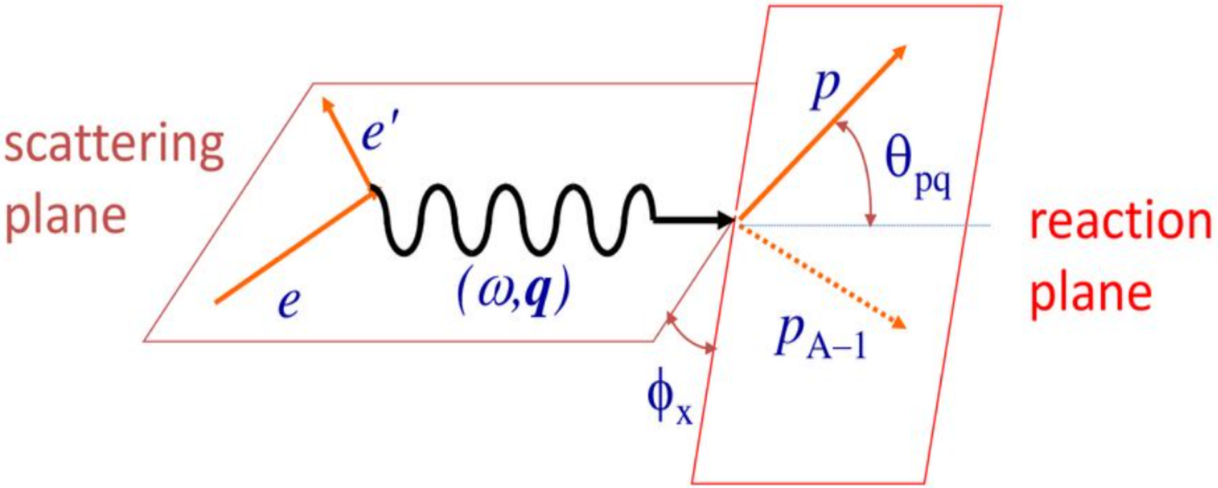
Brodsky and de Téramond, Physics 2022



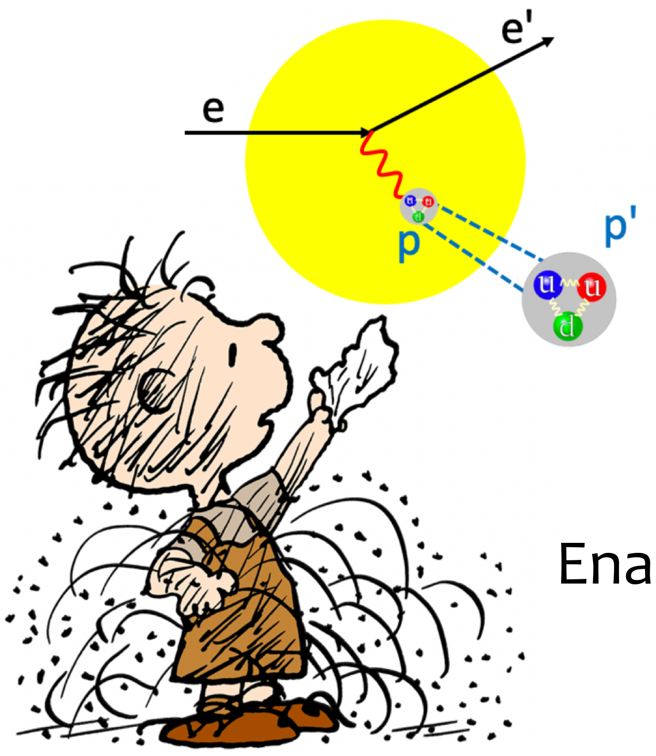
Could it be a sensitivity problem?



- Parallel kinematics -> high rates, small FSI
- PLC remains frozen while exiting the nucleus



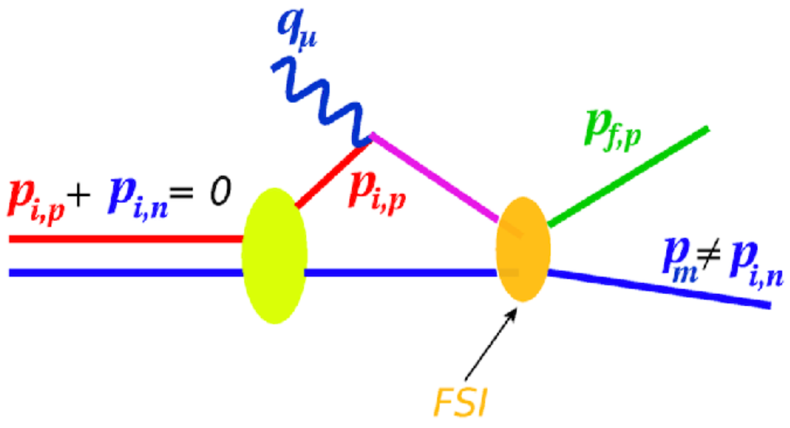
Moving to "dirty" kinematics



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

Higher FSI regime → greater influence from CT if present

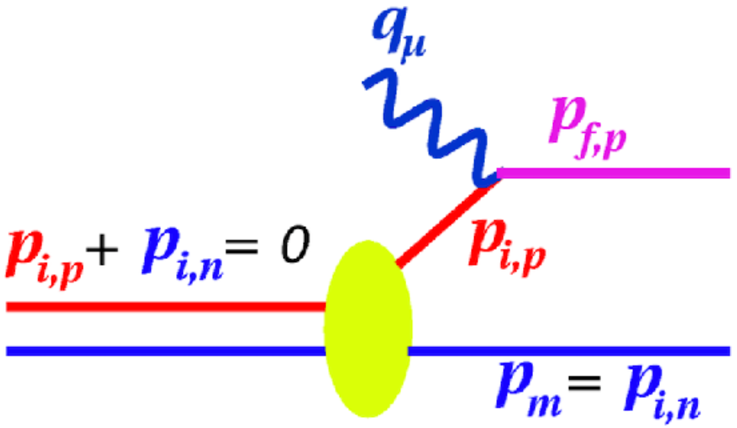
Enables separation of the observation of the PLC from its expansion



Final State Interactions (FSI)

Deuteron breakup reaction

$$e + d \rightarrow e' + p + n$$



Plane Wave Impulse Approximation
(PWIA)

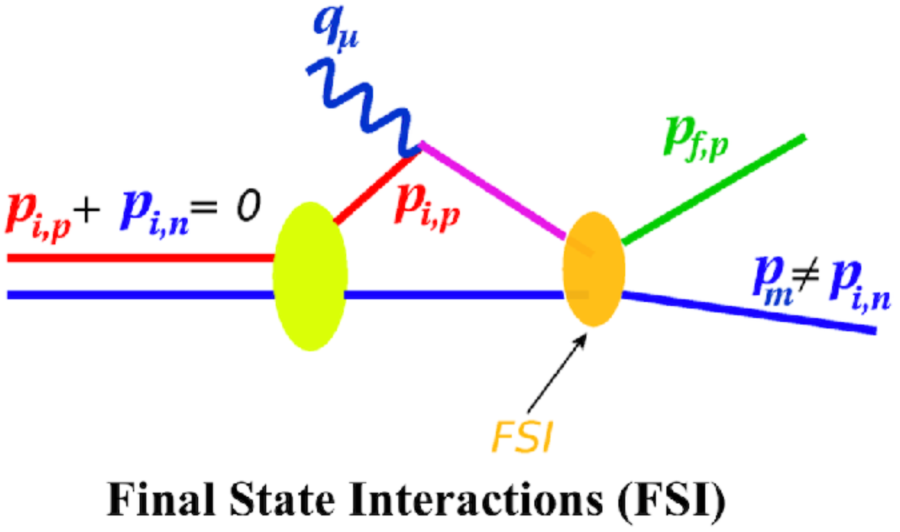
Detect the scattered electron and the knocked out proton.

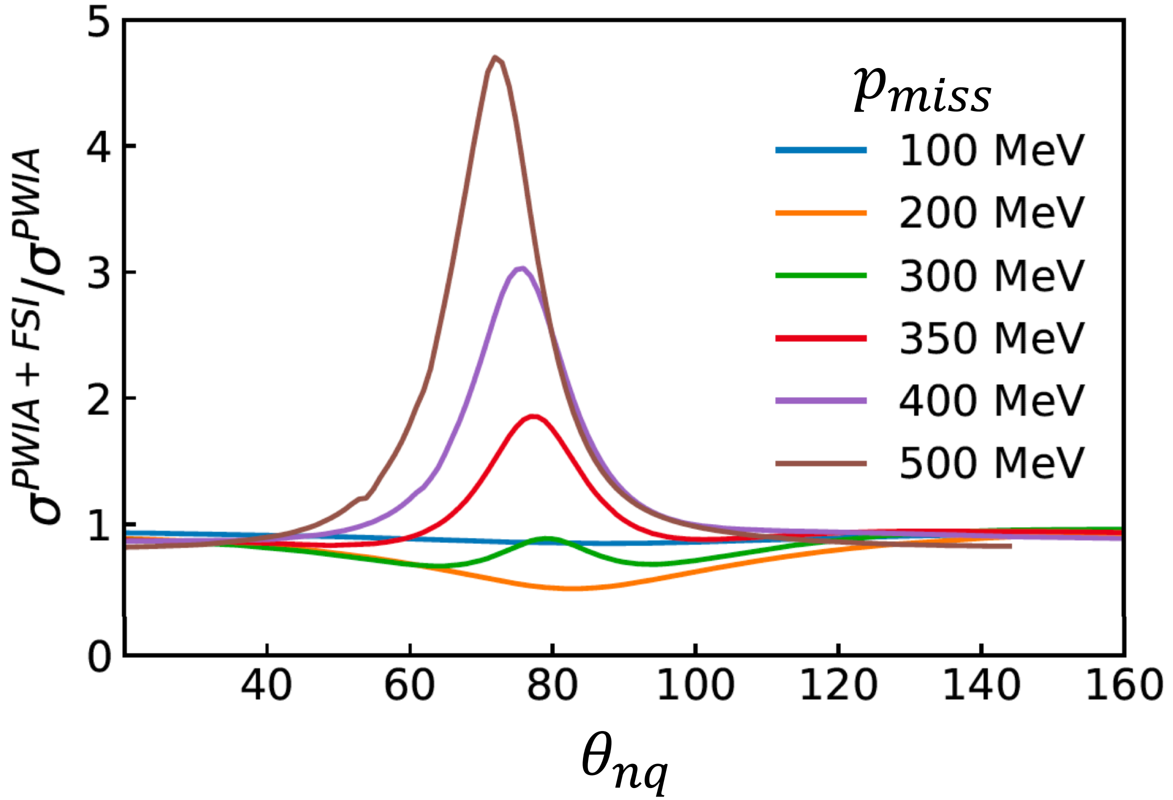
Observables - reconstruct the undetected **neutron:**

$\vec{p}_m = \vec{q} - \vec{p}_{f,p}$ "recoil" momentum

θ_{nq} "recoil" angle

Double scattering FSIs



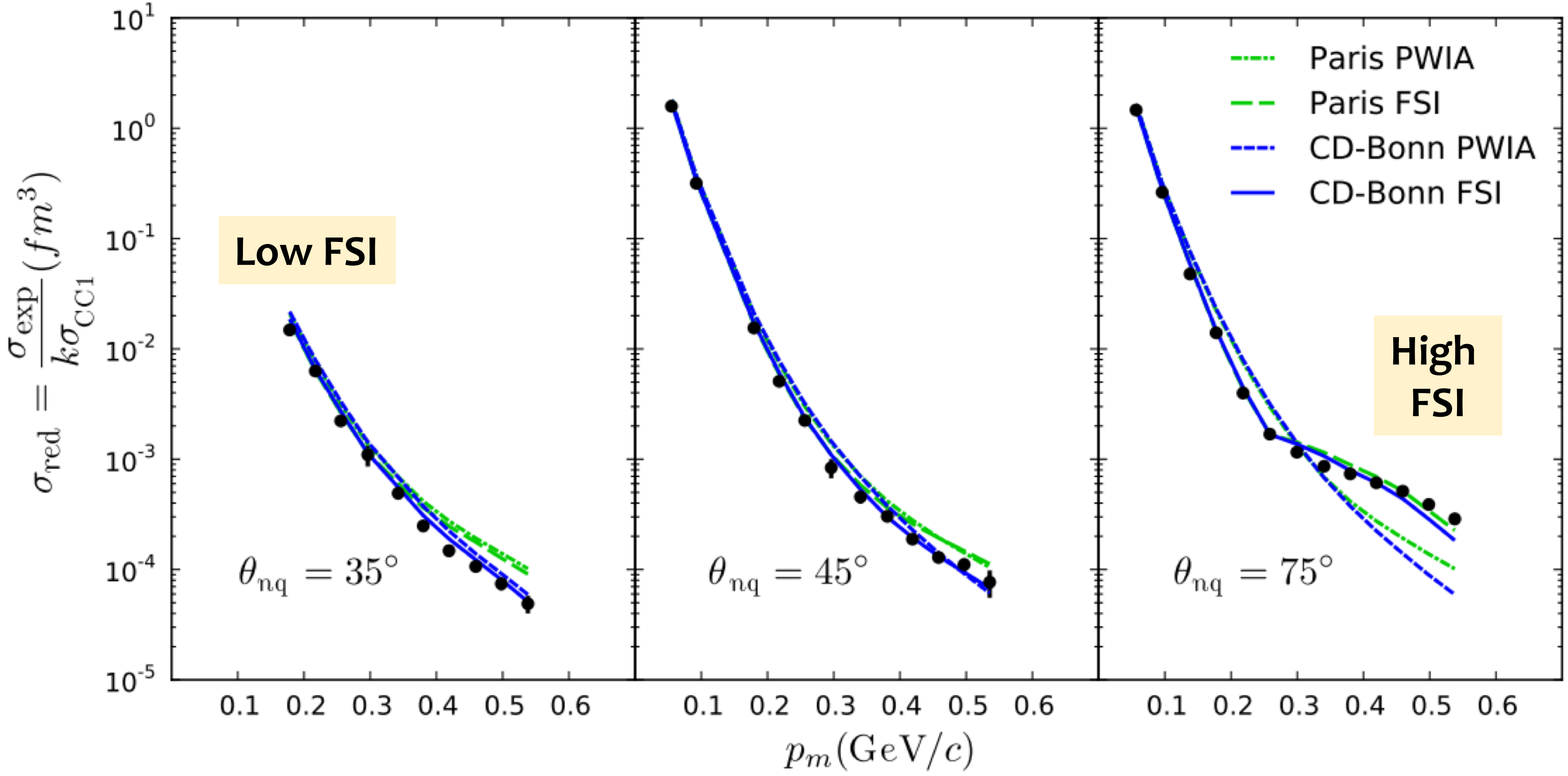


Double-scattering is the square of re-scattering amplitude of knocked out nucleon

Larger spectator momentum →
smaller distances between the production and rescattering vertices

Kinematics with enhanced FSI are well-known

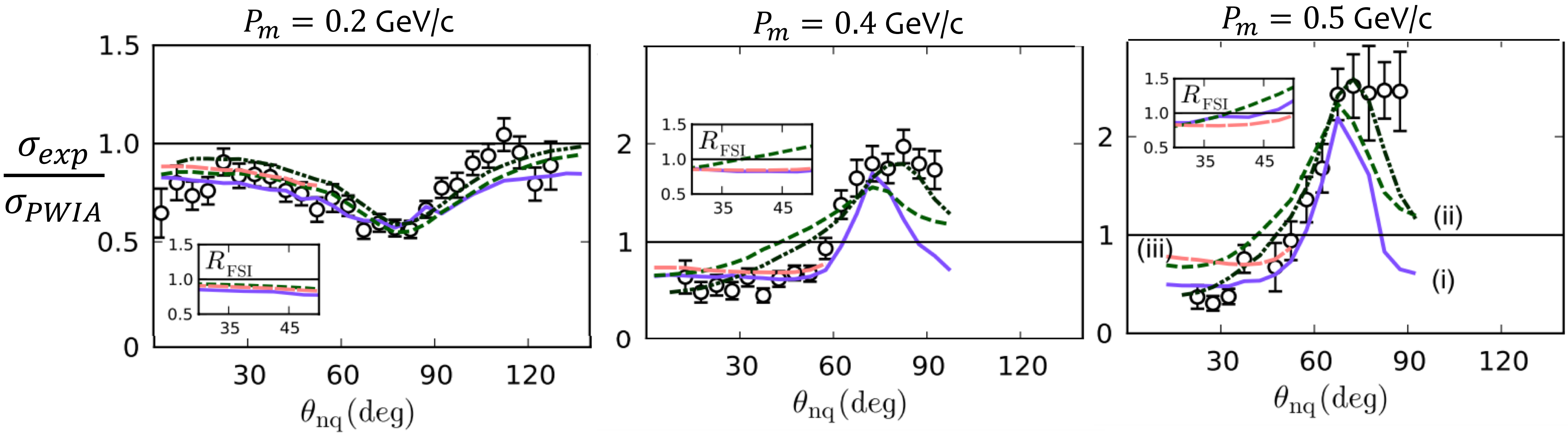
$Q^2 = 3.5$ (GeV/c)²



W. Boeglin et al., PRL (2011)

Larger missing momentum increases the sensitivity to FSIs

Q^2 = 3.5 (GeV/c)²



W. Boeglin et al., PRL (2011)

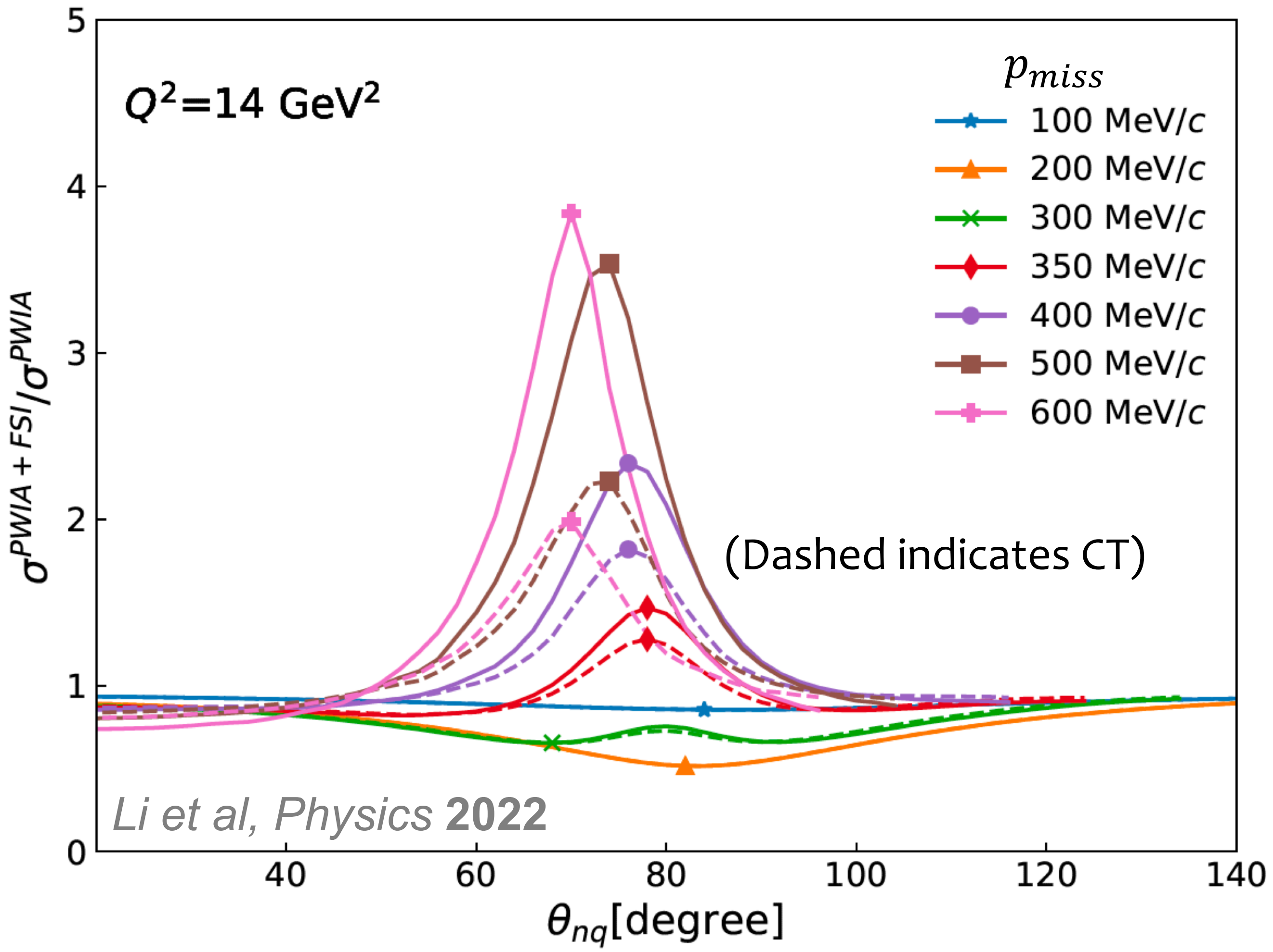
CT signal in deuterium

$$R = \frac{\sigma(p_r = 400\ MeV)}{\sigma(p_r = 200\ MeV)}$$

- Measured cross section ratio
- Double cross section ratio / PWIA
- Reduced cross section ratio

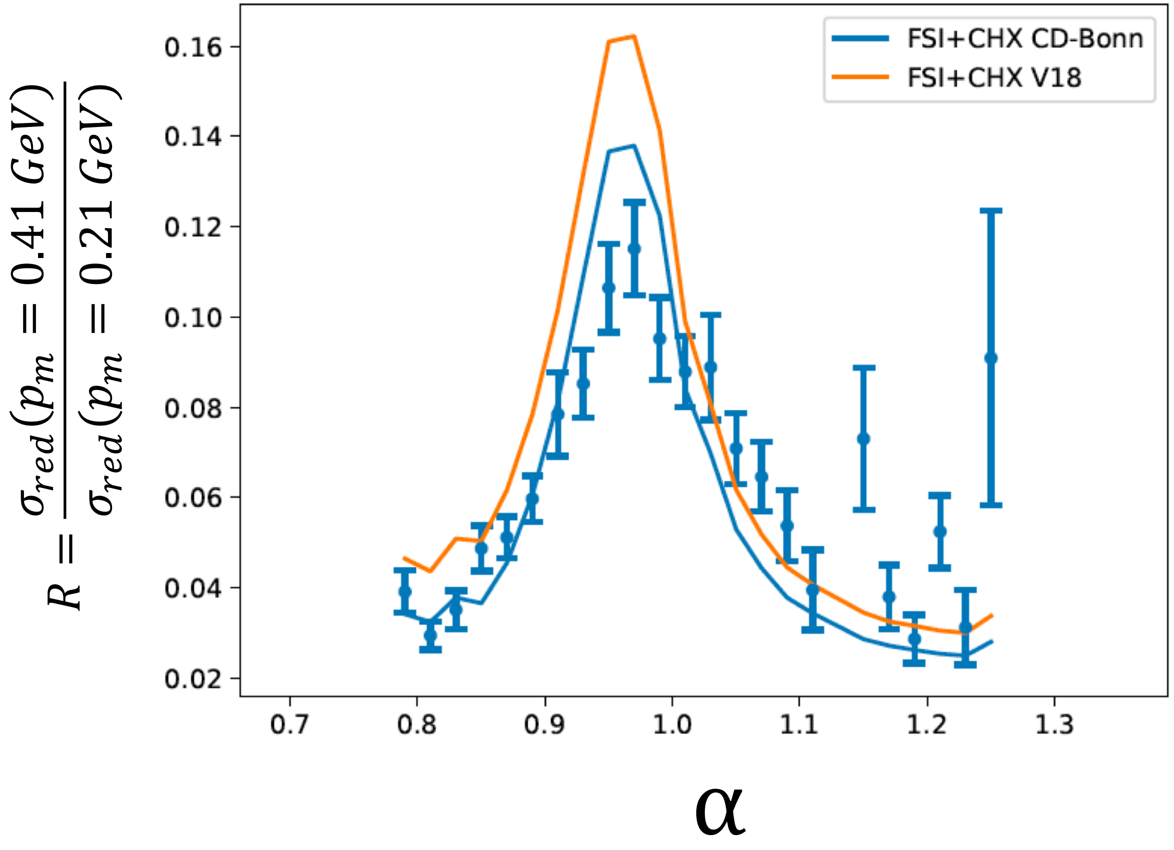
In the case of CT, reduced FSIs:

$$\downarrow R = \frac{\sigma(p_r = 400\ MeV)\downarrow}{\sigma(p_r = 200\ MeV)\uparrow}$$

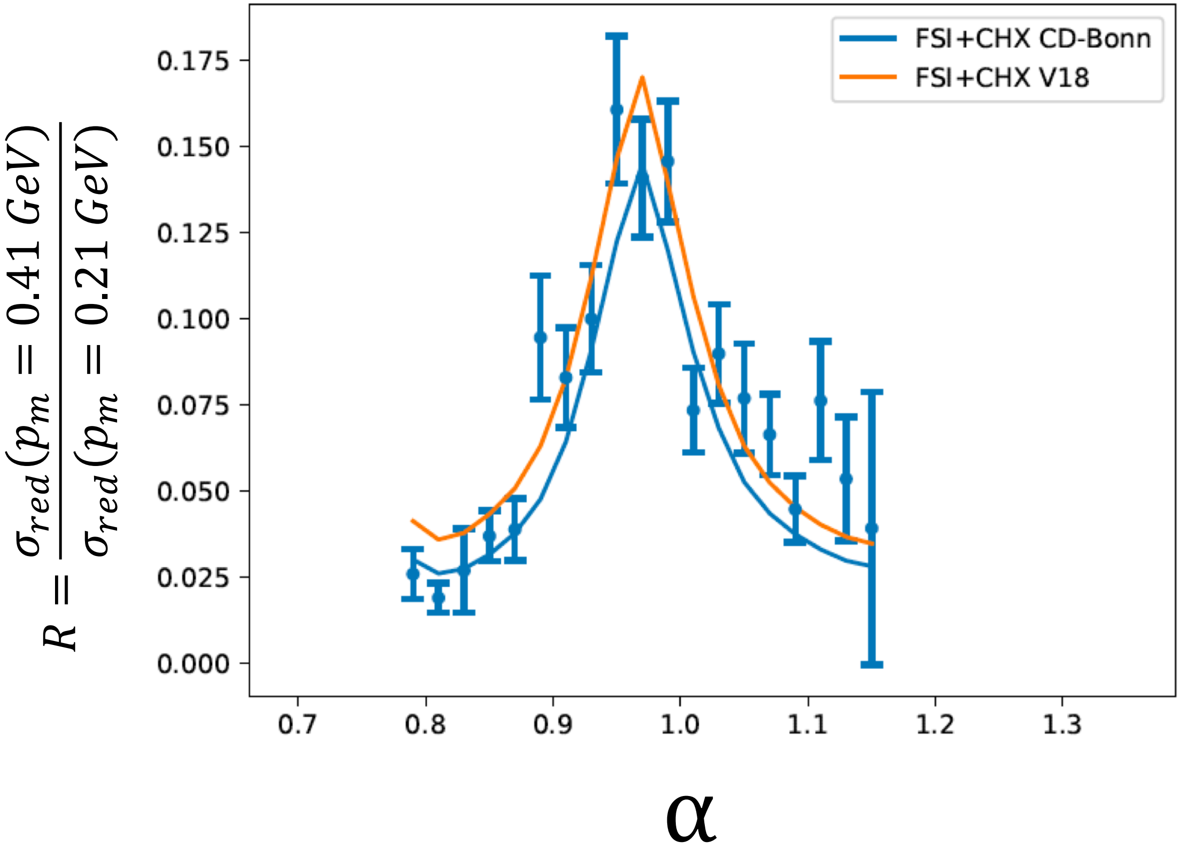


Ratio is well-calculable using GEA framework

Q^2 = 2.1 (GeV/c)²



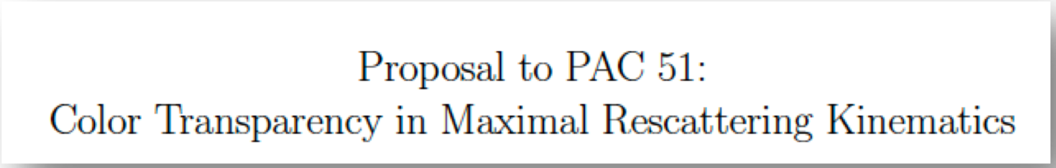
Q^2 = 3.5 (GeV/c)²



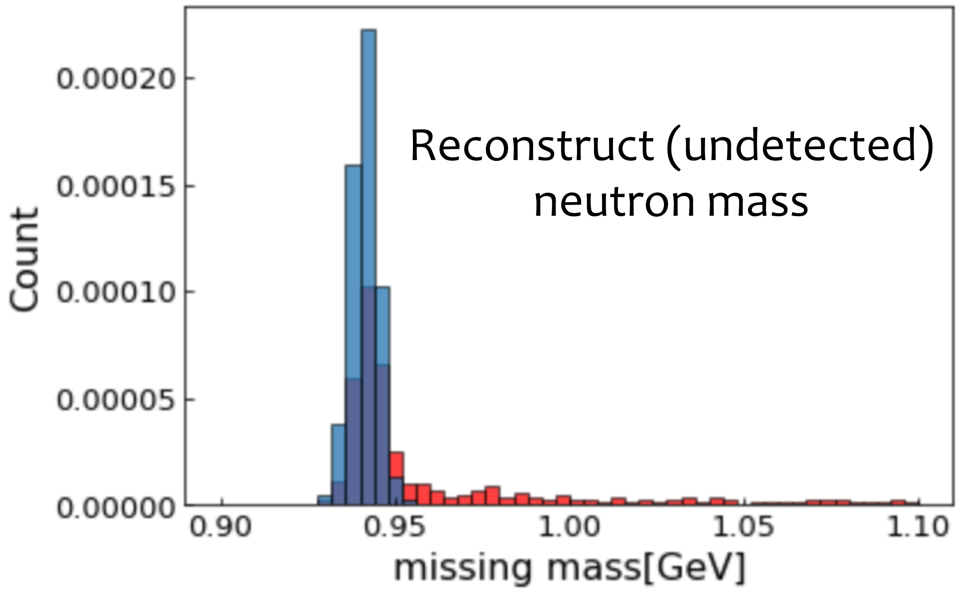
Light cone momentum fraction optimal near 1: $\alpha = (E_n - p_n cos\theta_{\gamma n})/m_n$

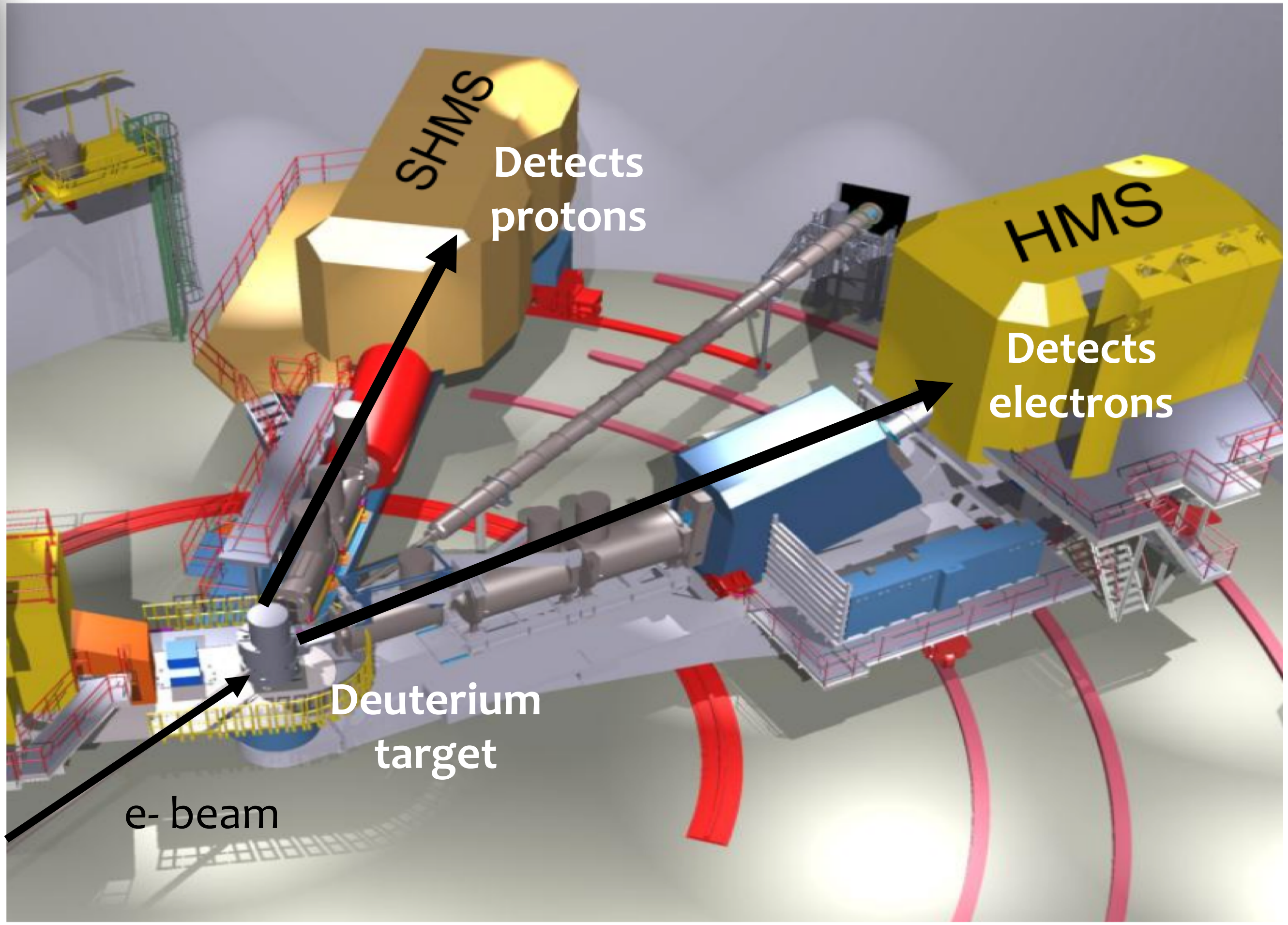
Courtesy of W. Boeglin

New and approved Hall C experiment


Proposal to PAC 51:
Color Transparency in Maximal Rescattering Kinematics

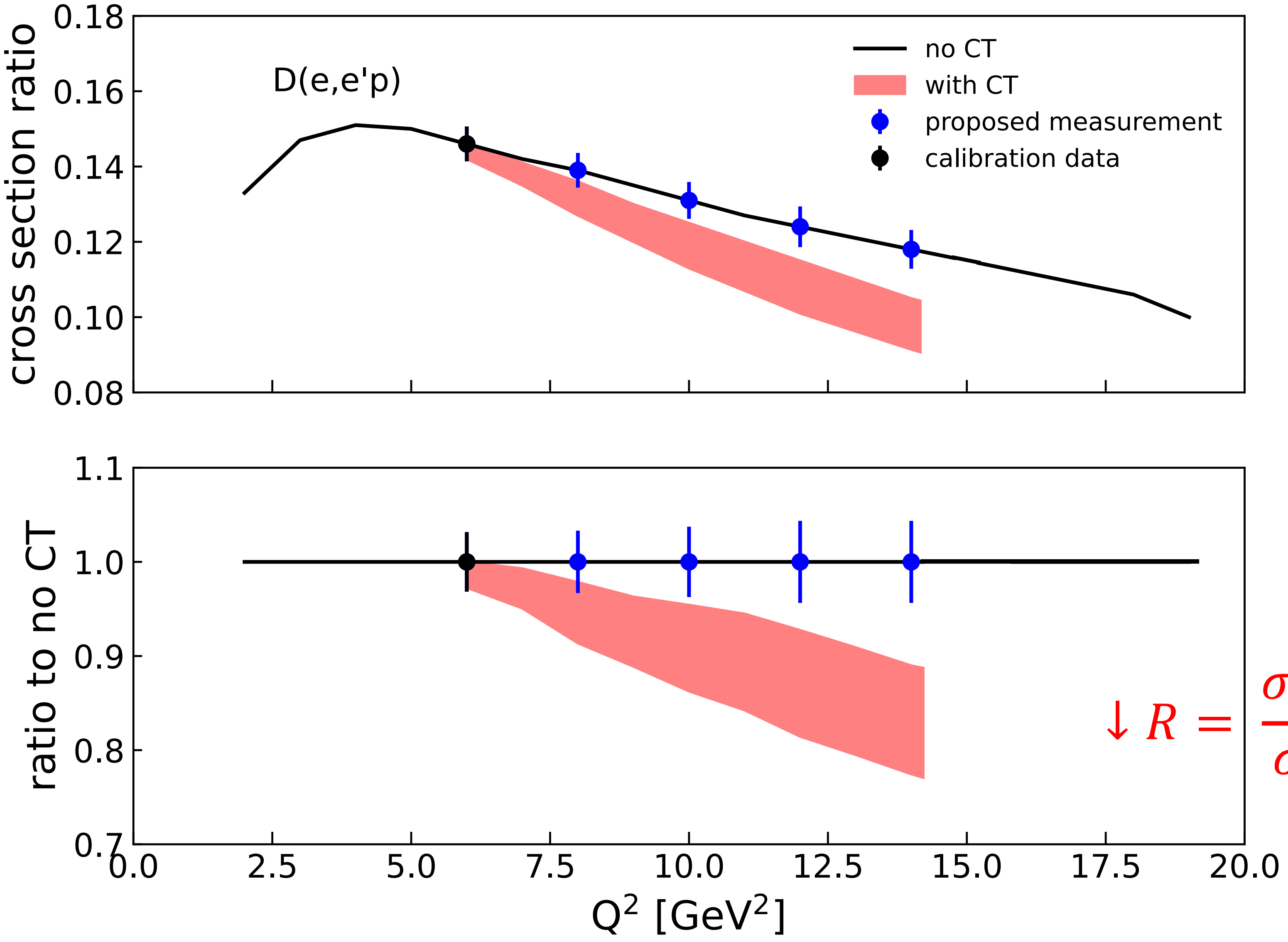
11 GeV electron beam
40 days of running
80 μA on 25-cm LD_2 cell





Increased sensitivity for detecting the onset of CT!

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



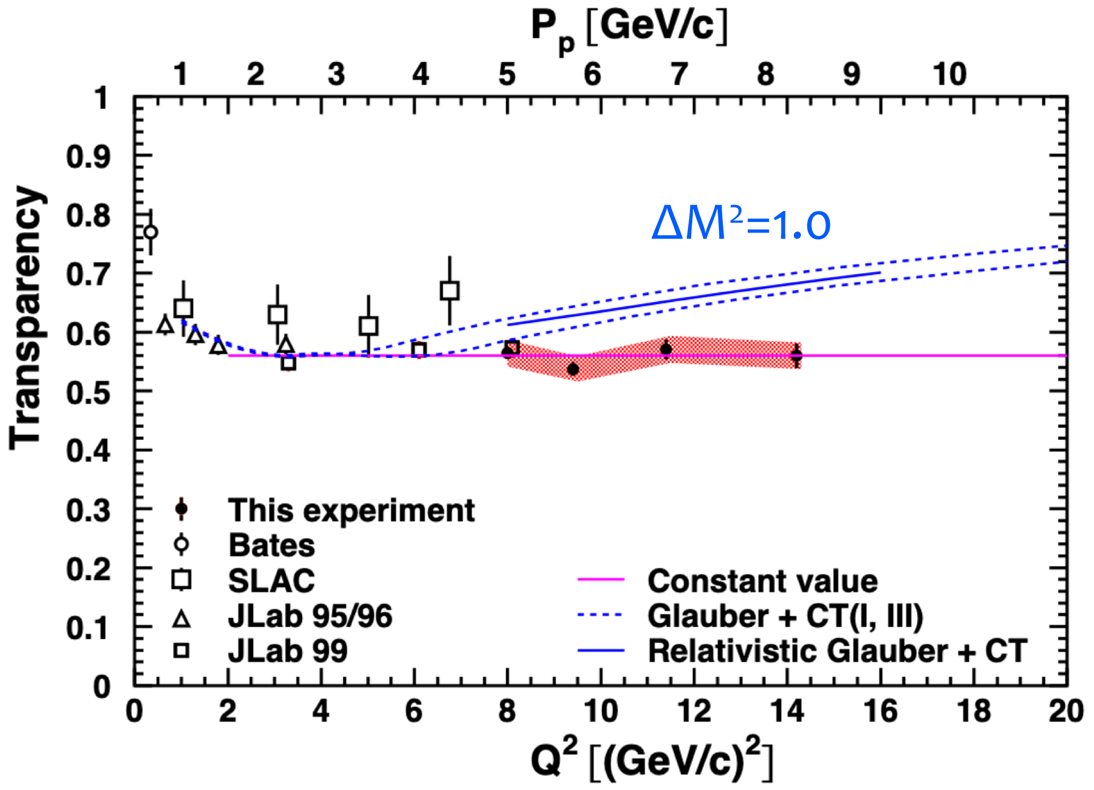
$$\downarrow R = \frac{\sigma(high\ Pm)\downarrow}{\sigma(low\ Pm)\uparrow}$$

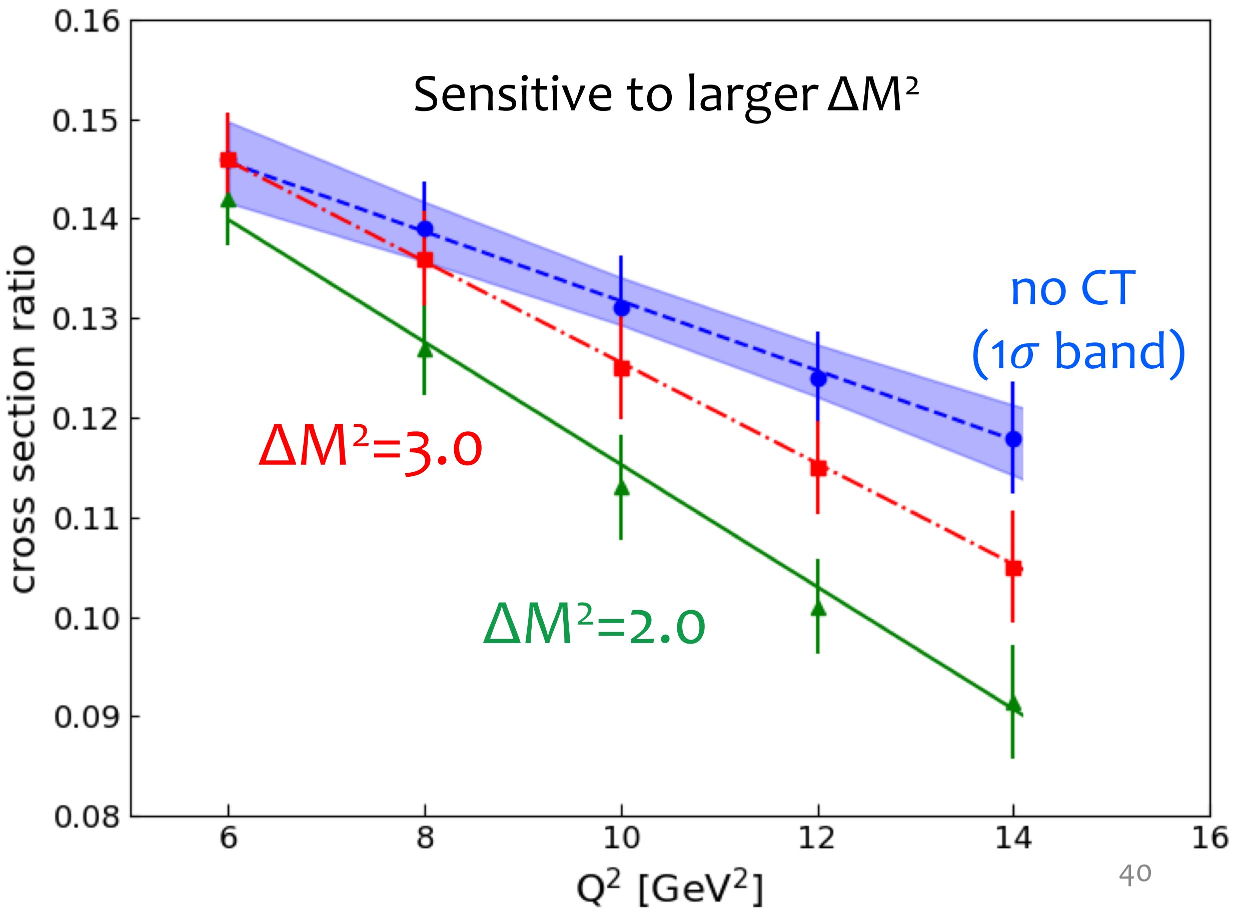
Sensitivity in the Quantum Diffusion Model

Farrar et al., PRL (1988)

Larger ΔM² →
shorter PLC lifetime →
delays CT onset

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

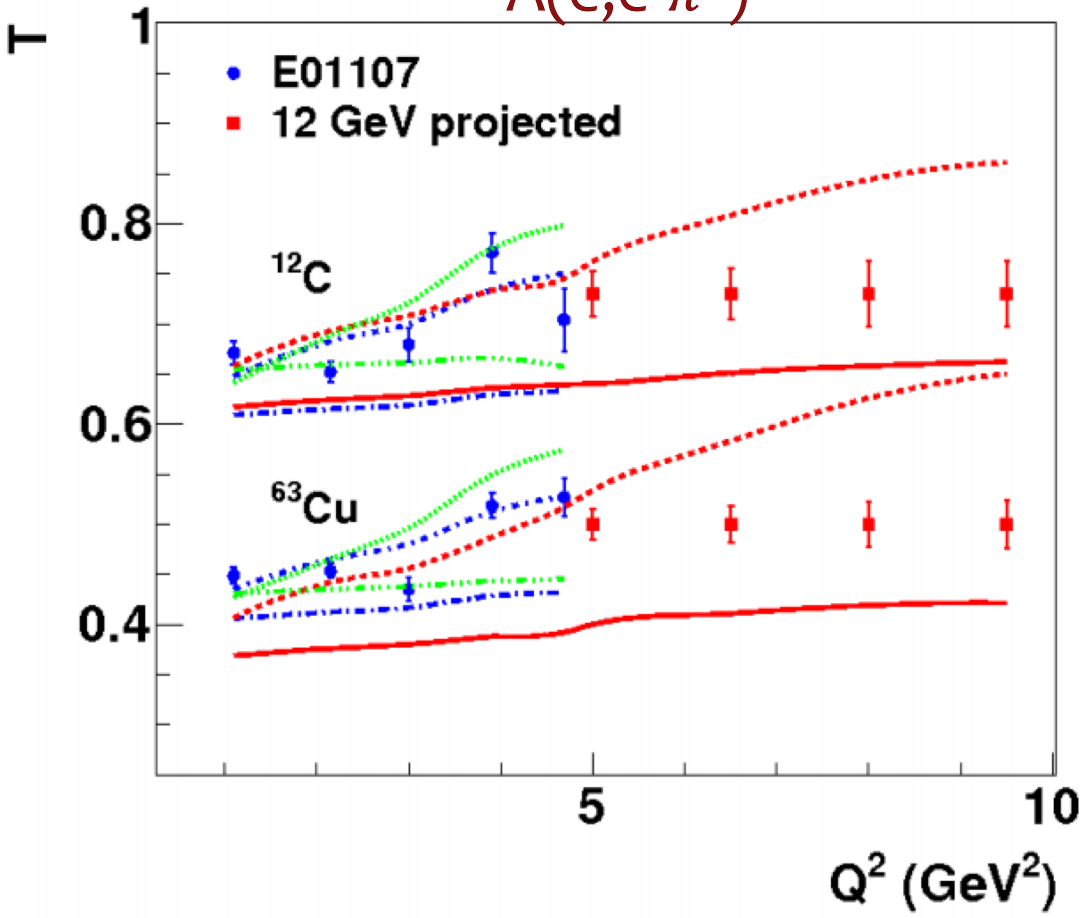


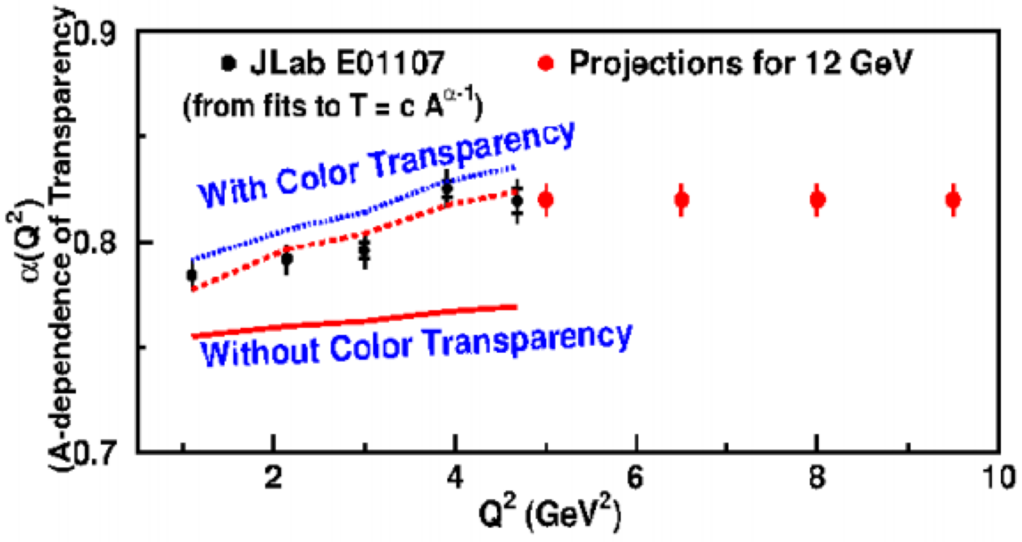


Imminent experiments examining the onset of CT in mesons

Measure the onset in pion electro-production over large momentum range in Hall C

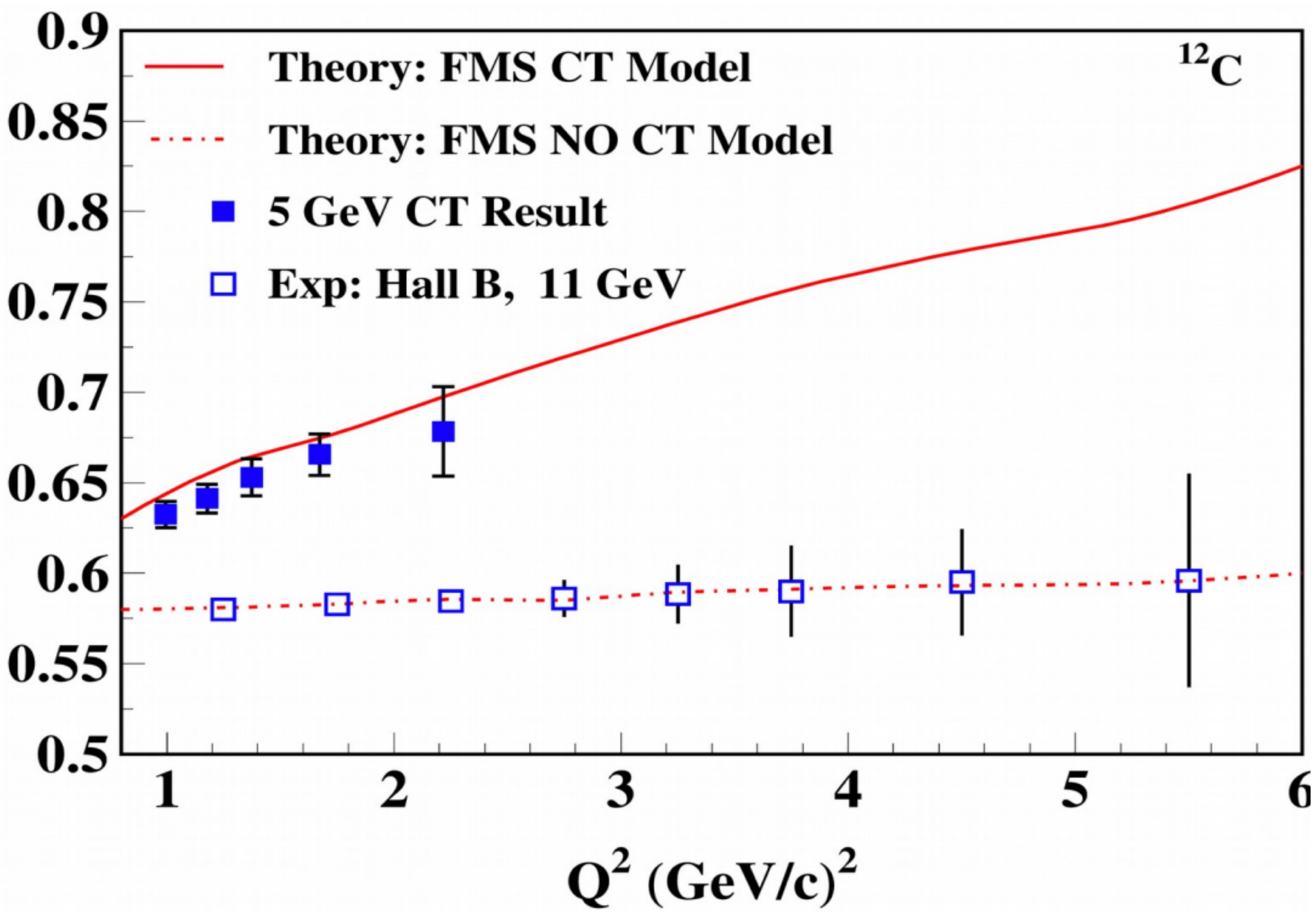
A(e,e'π^+)



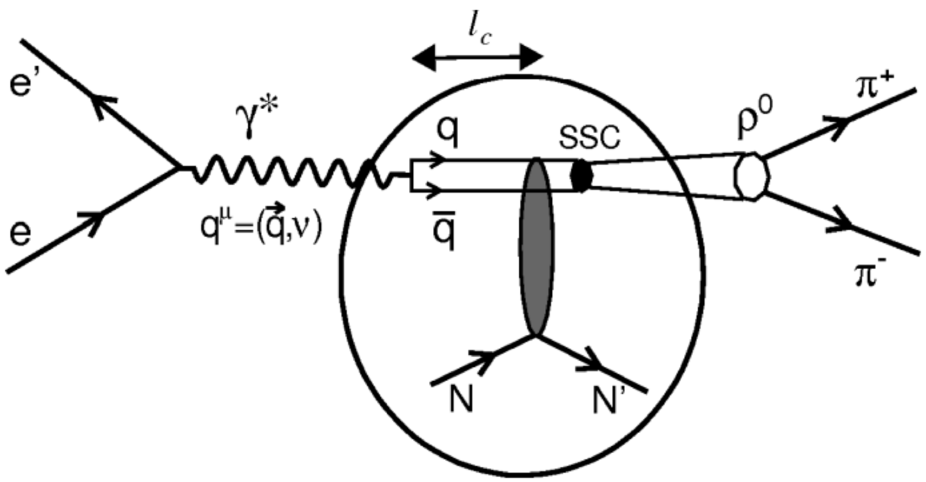


Onset of CT in the rho-meson

Rho transparency measurements will be extended to highest Q^2 in Hall B



A(e,e'ρ⁰)



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

Summary

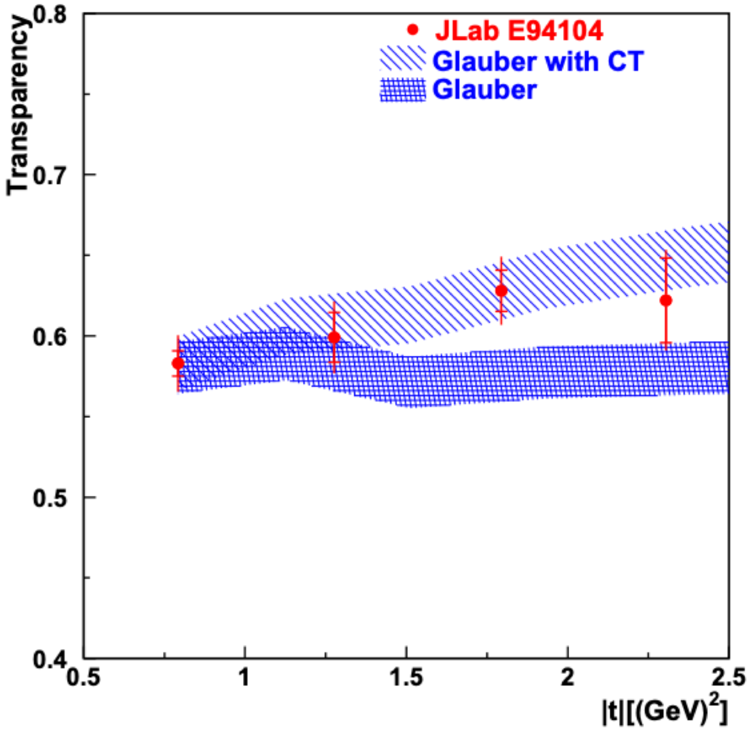
- Nucleons in nuclei give us lots of interesting checks on our picture of QCD
- Color Transparency is a fundamental QCD prediction that can give us a direct handle in the transition to quark-gluon degrees of freedom.
  - Not yet observed in protons…still working on that
  - Encouraging results from mesons to be extended soon at JLab
- New experiment approved for protons which could enhance the CT signal and separate the PLC production from expansion

Backup

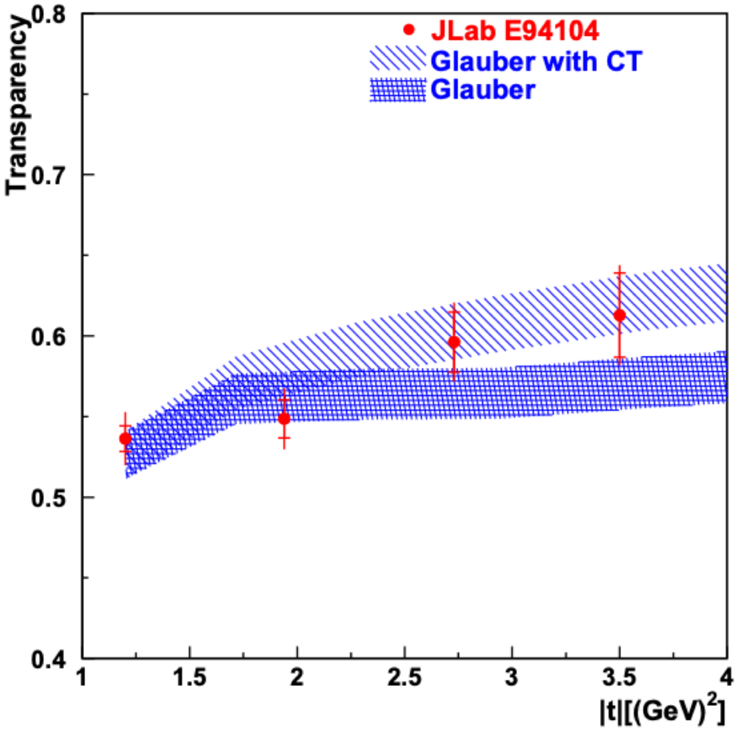
Previous Measurements: Testing pion photoproduction

γn->π⁻p in 4He in Hall A

70° c.m. scattering



90° c.m. scattering

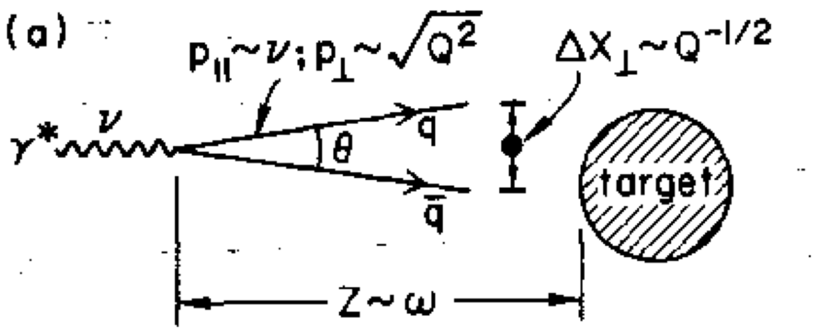


D. Dutta *et al*. PRC 68.021001 (2003)

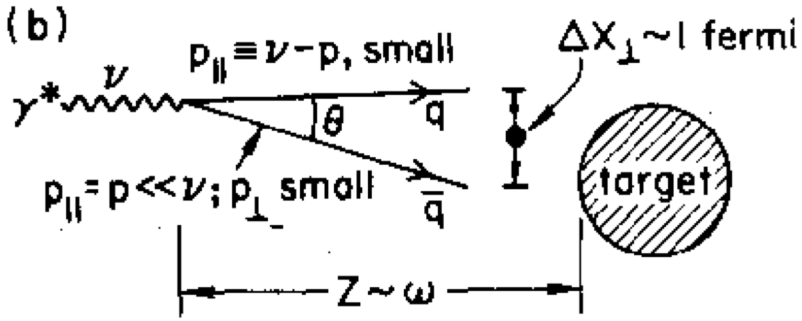
DIS picture

Small-x picture

No interaction

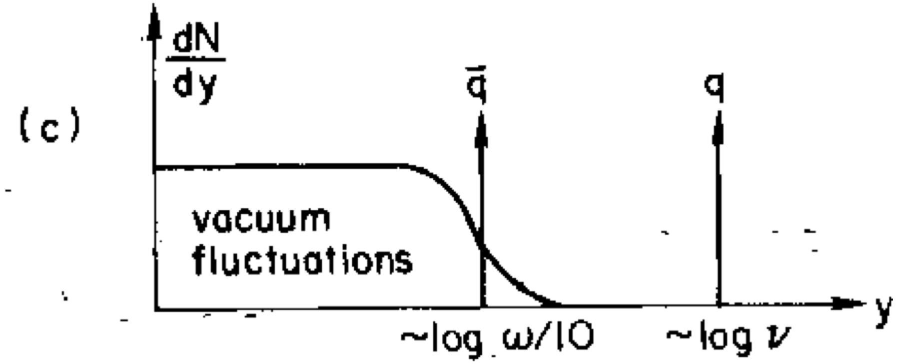


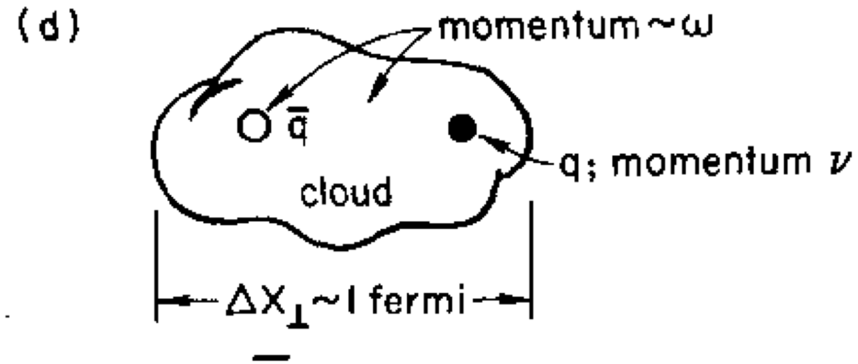
Interaction



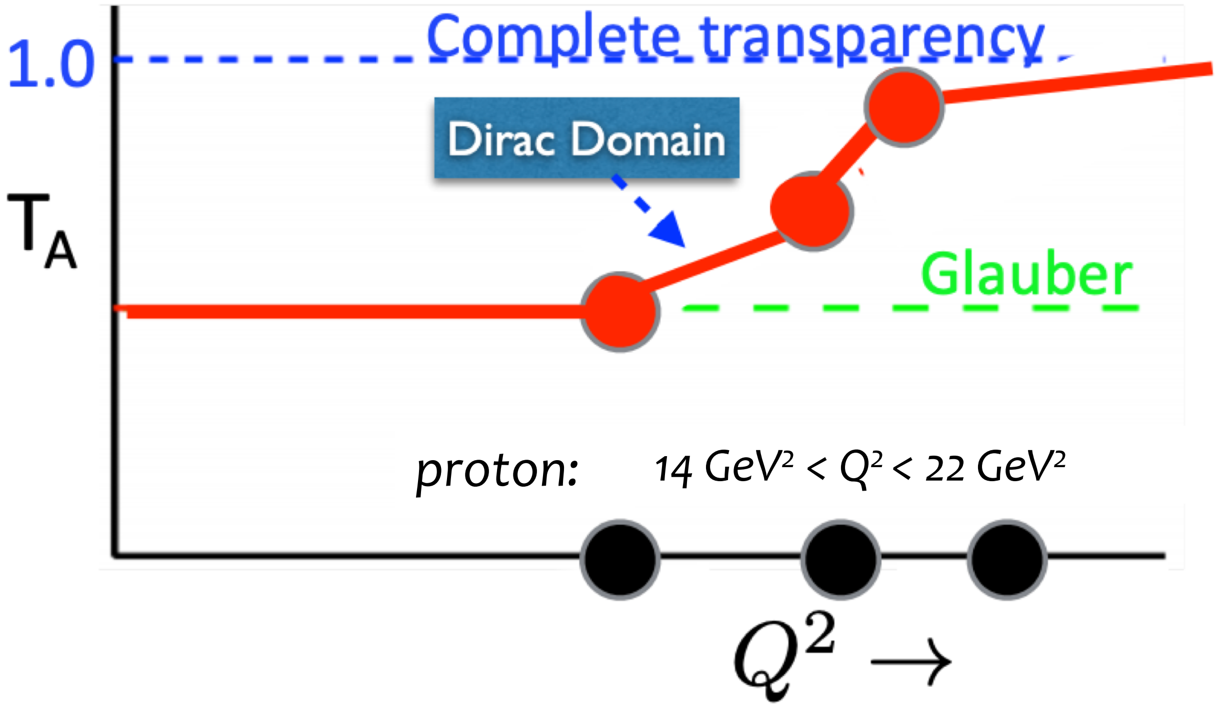
Large-x picture

Interaction



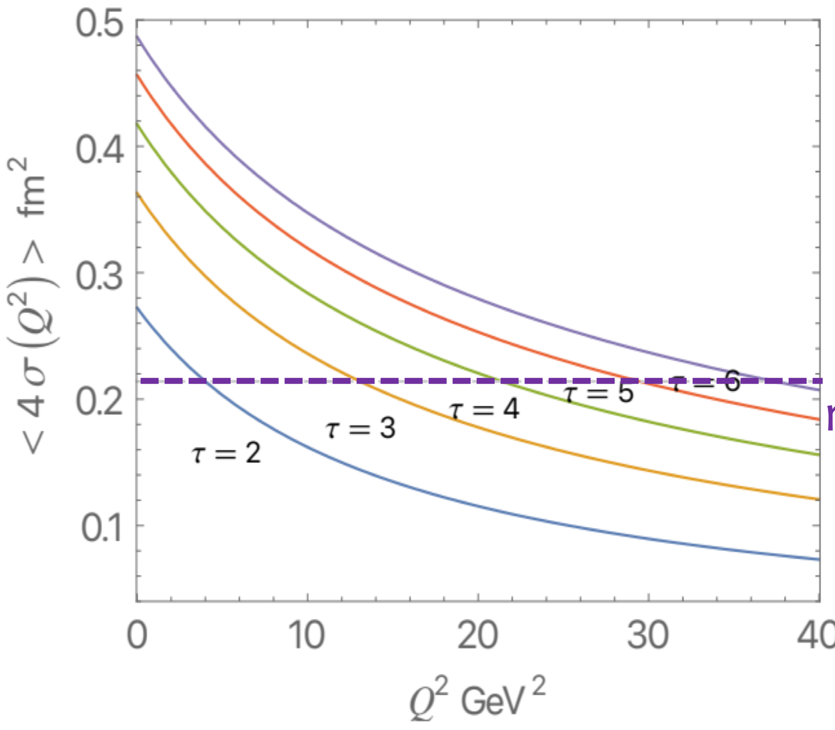


Q^2>14 GeV^2 is of special interest to HLFQCD



τ (twist), number of constituents:
Proton: $\tau = 3,\ L = 0$ and
$\tau = 4,\ L = 1$

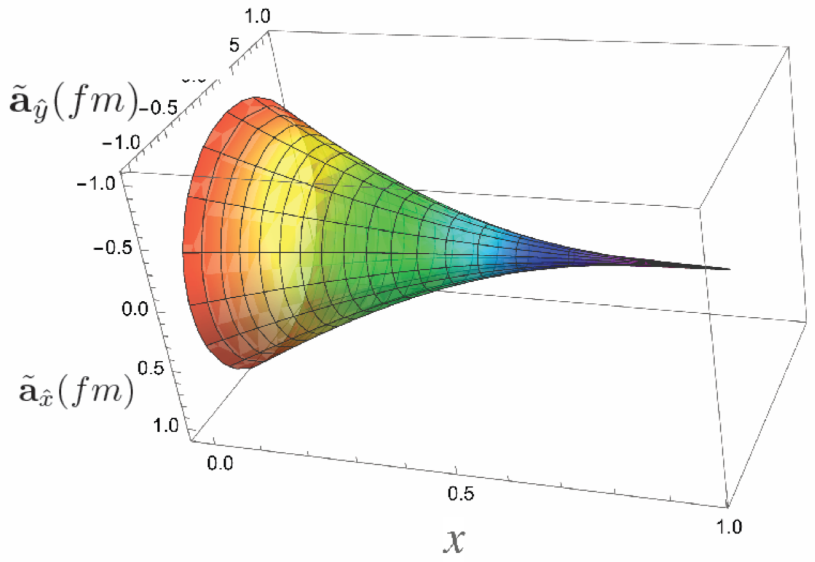
Transverse impact area



Characteristic transverse size required for the onset of CT

Brodsky and de Téramond, Physics 2022

Holographic LFQCD predictions



$$< \tilde{\mathbf{a}}_\perp^2(x) >= \frac{\int d^2\mathbf{a}_\perp \mathbf{a}_\perp^2 q(x,\mathbf{a}_\perp)}{\int d^2\mathbf{a}_\perp q(x,\mathbf{a}_\perp)}$$

$$\langle \mathbf{a}_\perp^2(Q^2)\rangle_\tau \to \frac{4(\tau-1)}{Q^2}.$$

Mean transverse size as a function of Q and Twist

Brodsky and de Téramond, Physics 2022