From Quarks to Nuclei: new insights from the search for squeezed hadrons at Jefferson Lab.

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Outline

1. Introduction
2. Nuclear transparency and Hadron propagation
3. Color transparency & Small size configuration
4. Some recent results and future possibilities.
5. Summary

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

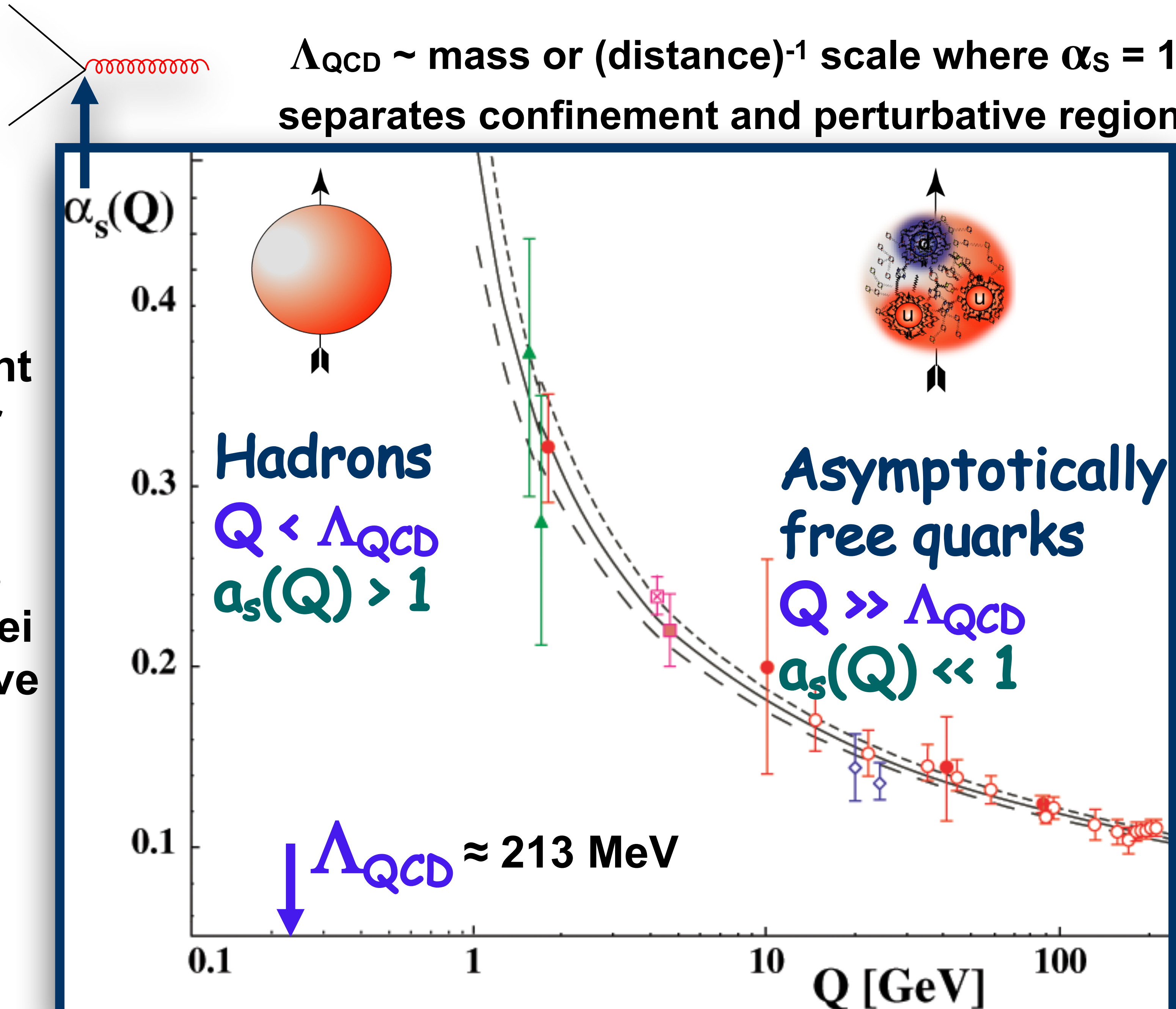
Quantum Chromo Dynamics (QCD) is the fundamental theory describing the strong force in terms of quarks and gluons carrying color charges.

Λ_{QCD} ~ mass or (distance)$^{-1}$ scale where $\alpha_S = 1$; separates confinement and perturbative regions

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.



pQCD mechanisms dominate at high energies or short distances

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

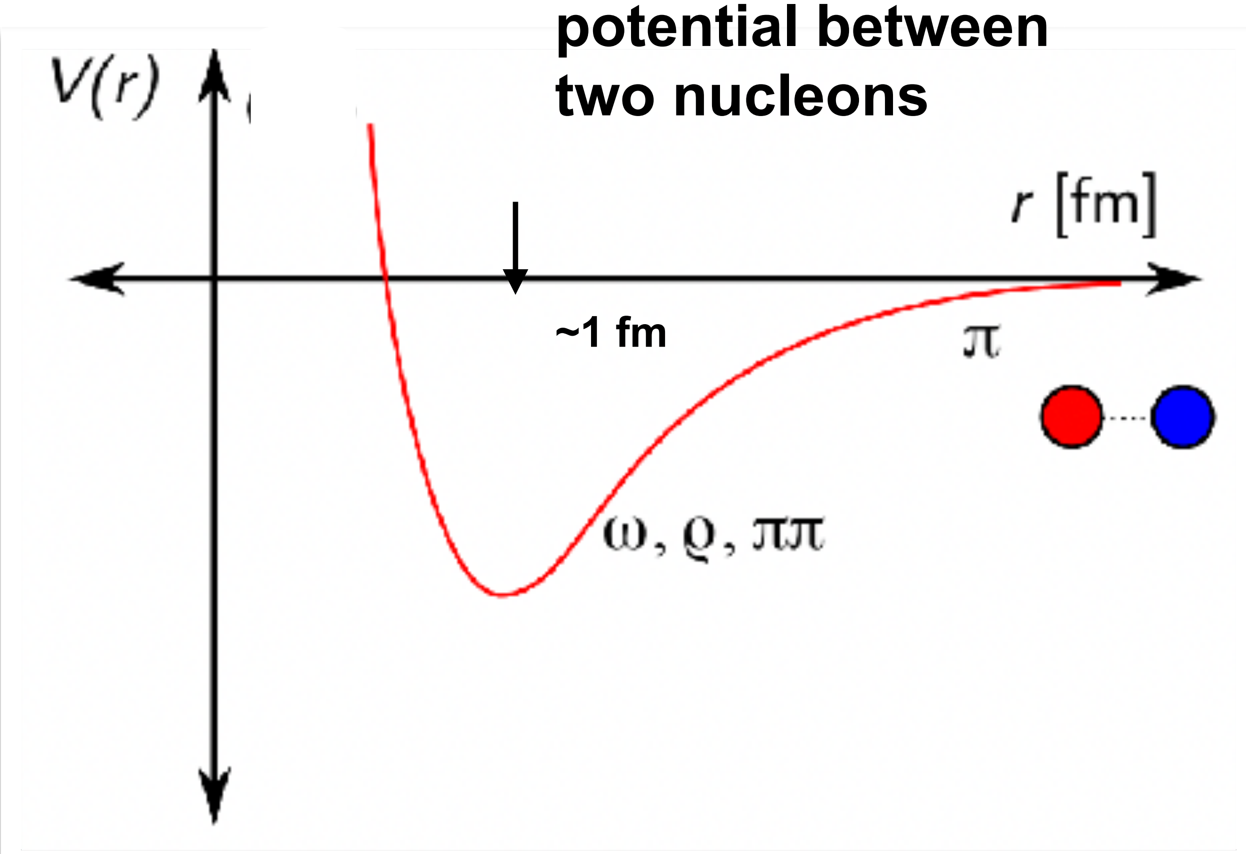
100 years since the discovery of the nucleus and 50 years after the invention of QCD

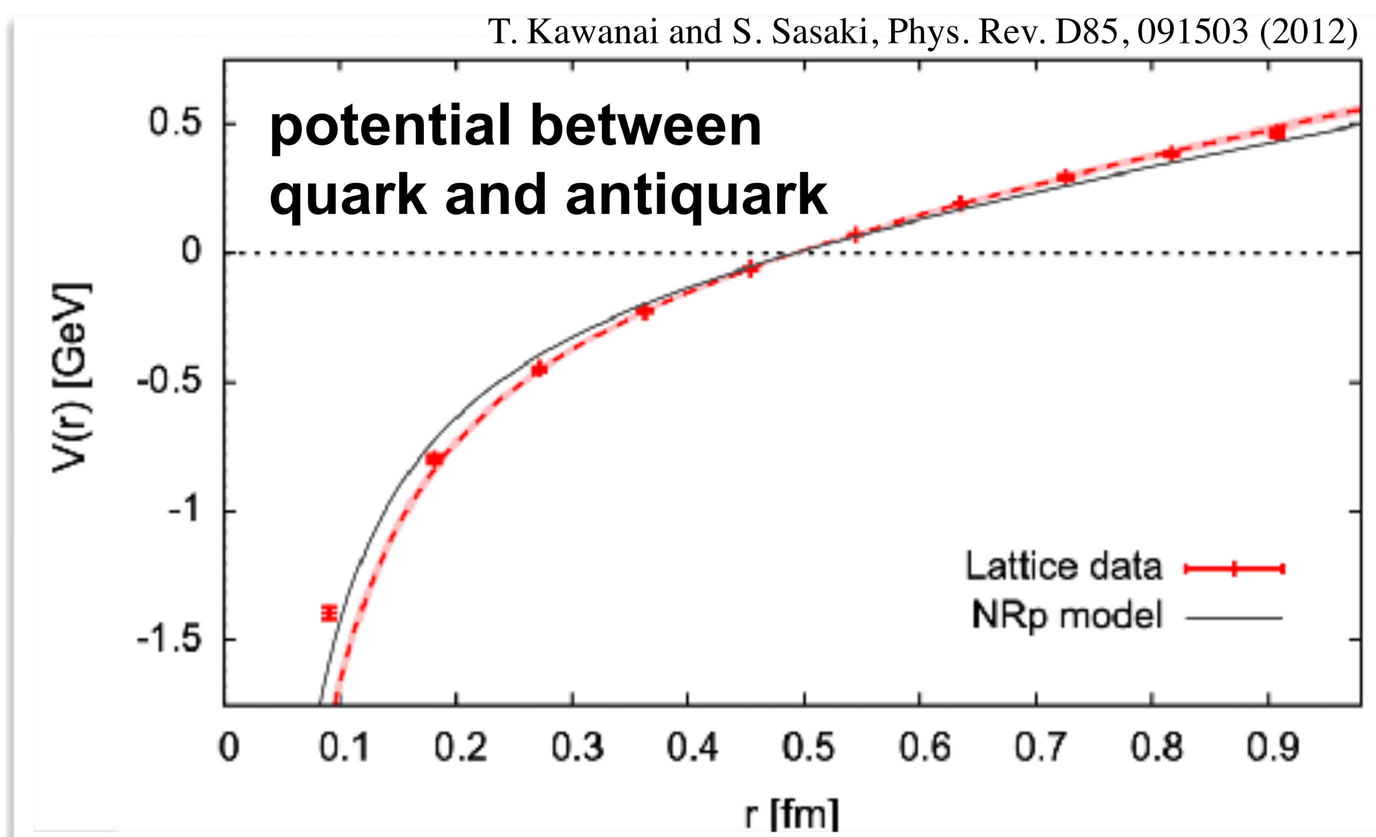
QCD is the only legitimate candidate for a theory of the strong force, but there is no consensus on how it works.

Matter is colorless

Traditional nuclear physics:
nucleons + mesons

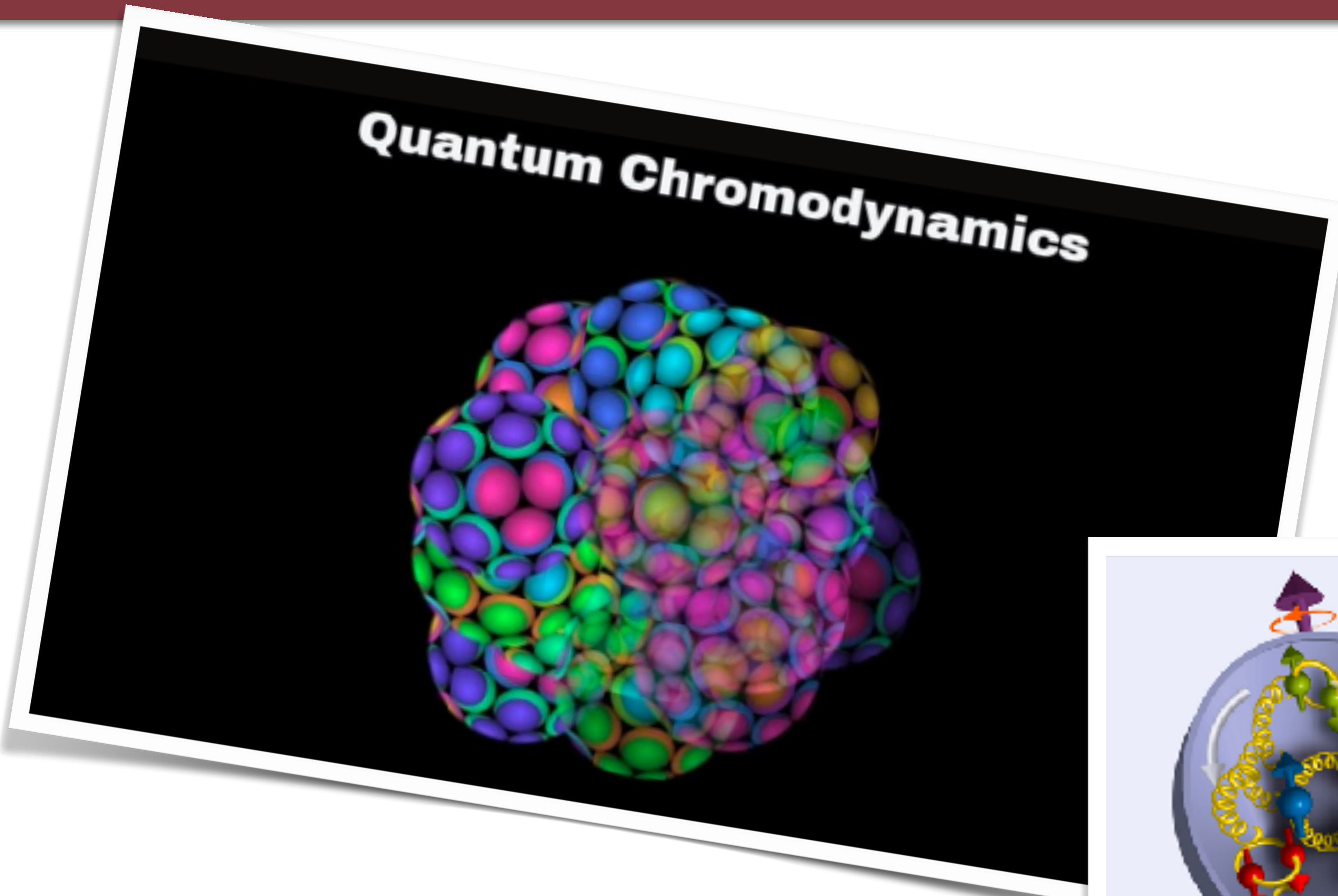
QCD: quarks + gluons
with linear confining potential
for r > 0.5 fm





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

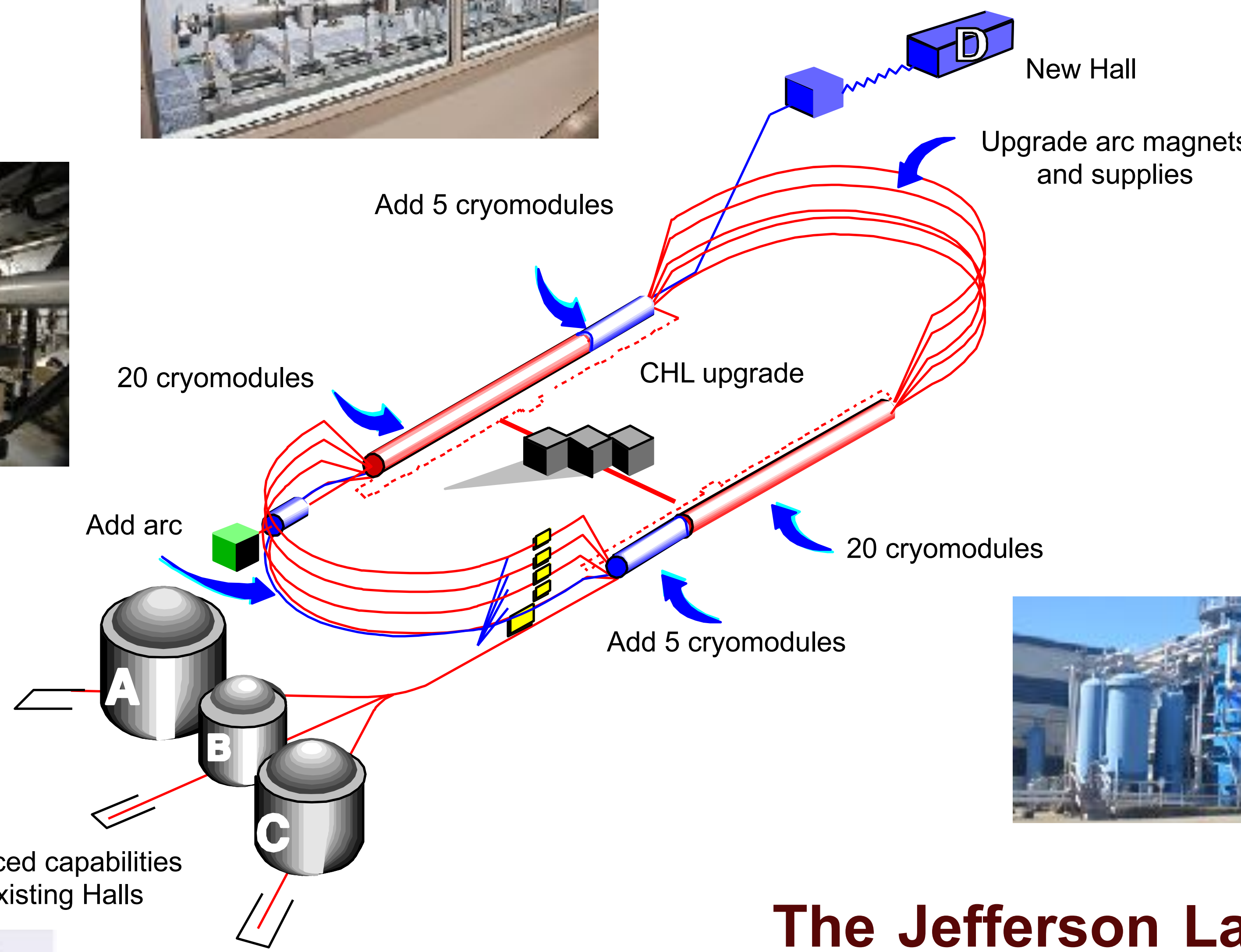
Can the strong nuclear force be rigorously understood in terms of accepted fundamental theory?

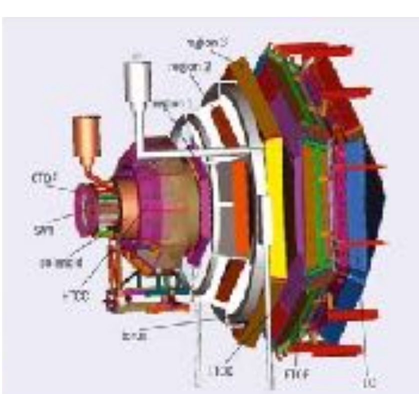


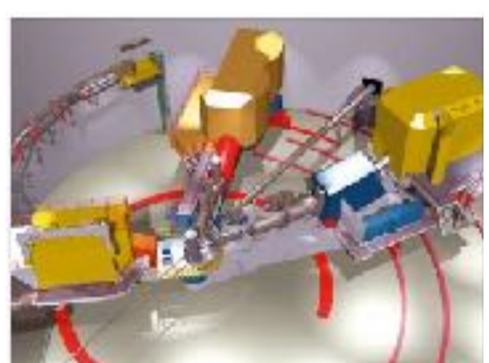
**(How exactly are protons and neutrons built starting with the underlying quarks and gluons?
What is the origin of quark confinement in the strong force?)**

Electron scattering experiments at Jefferson Lab are addressing these questions.

Recently, Jefferson Lab was upgraded to better address this problem.





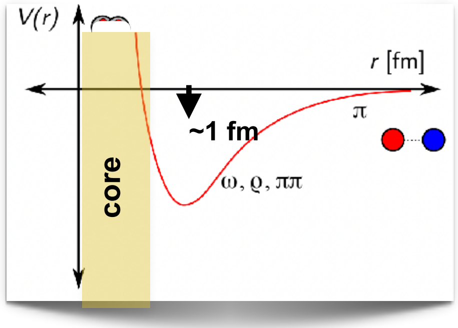


The Jefferson Lab 12 GeV upgrade project was declared completed on September 27, 2017.

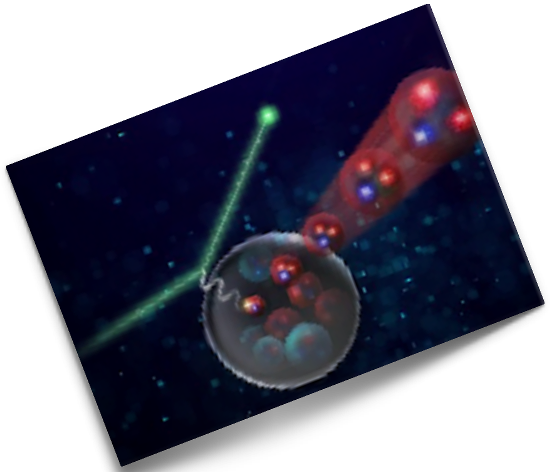
28 experiments or ~1/3 of the program already completed.

The early experiments address a wide range of basic nuclear physics questions.

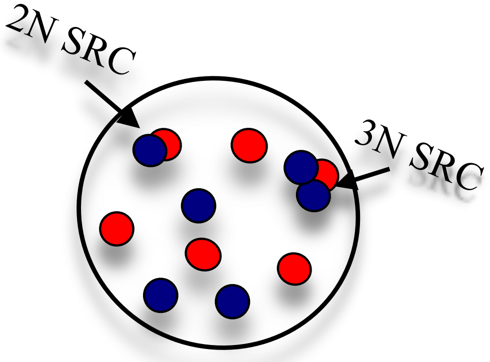
Examine nuclear structure at short distance scales to reveal QCD as the ultimate source of the strong interaction.



Understand the role of color in nuclei by studying the propagation of hadrons through nuclei with exclusive processes.



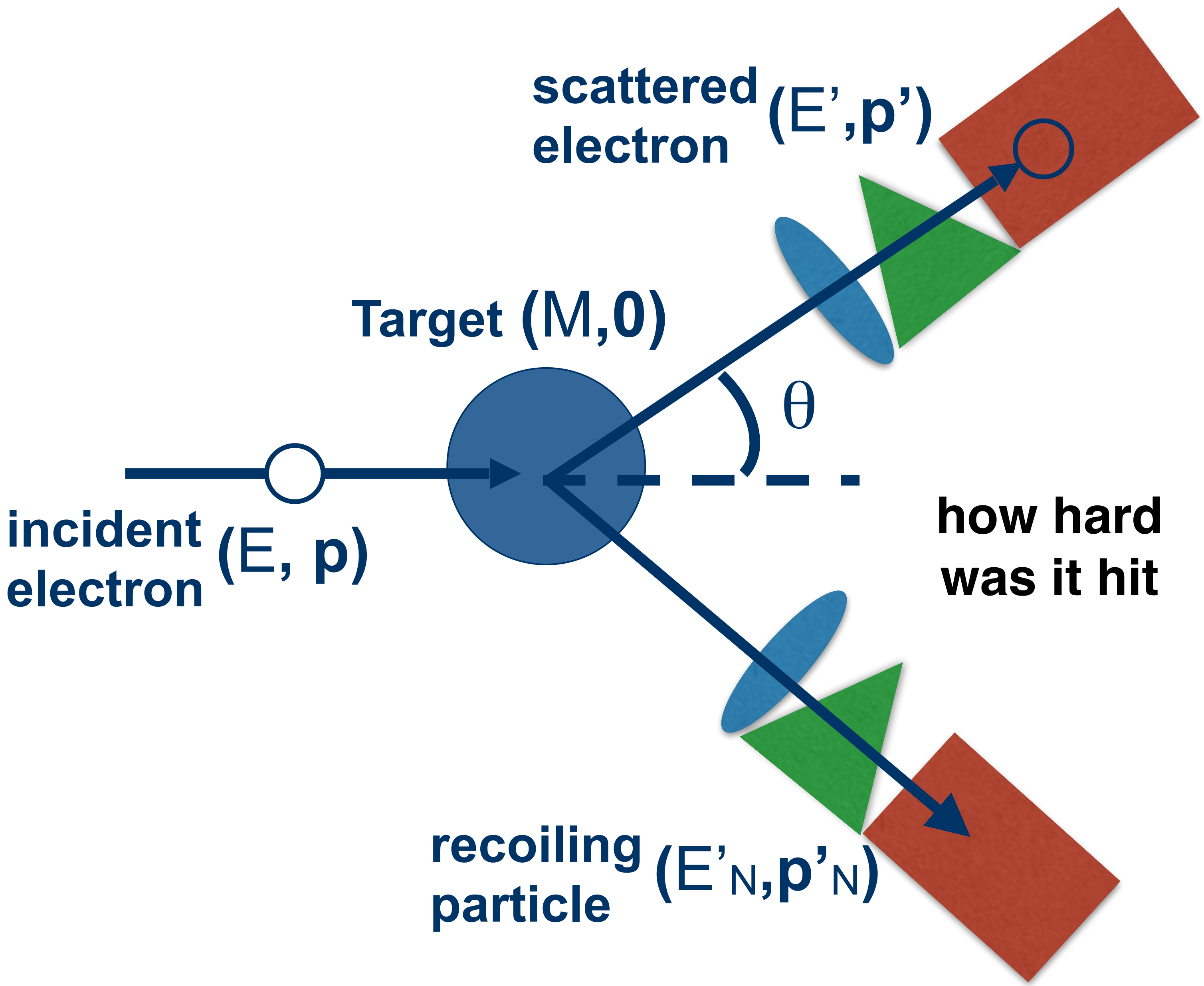
Probe the properties of superdense fluctuations of nuclear matter and their correlation to the modification of quark distributions in nuclei.



Exclusive electron scattering tells us about the propagation of hadrons through nuclei.

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

$$A + B \rightarrow C + D$$



$\omega = E - E'$ **Energy transfer**

$\mathbf{q} = \mathbf{p} - \mathbf{p}'$ **momentum transfer**

Missing energy $(E_m) = \omega - E'_N$

Missing momentum $(p_m) = p'_N - q$

Exclusive electron scattering is used to measure final state interactions (FSI).

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

Exclusive Processes

Nucleons

A + B → C + D

p,n

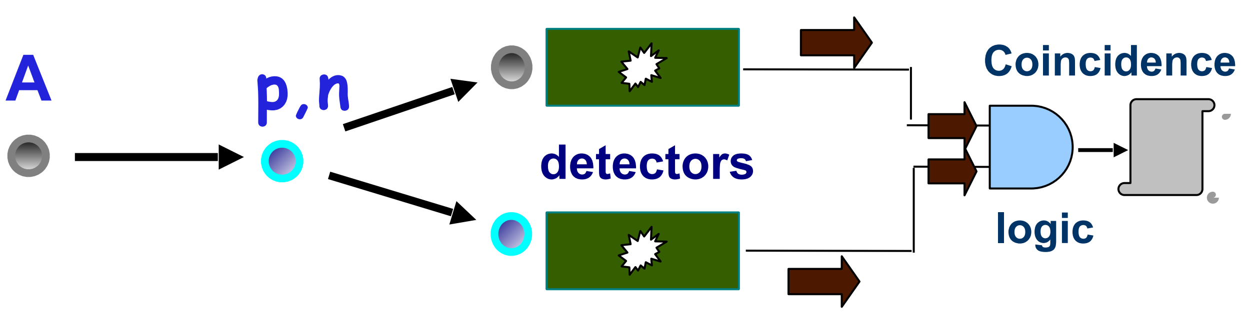
1. Quark counting rules
2. Hadron helicity conservation

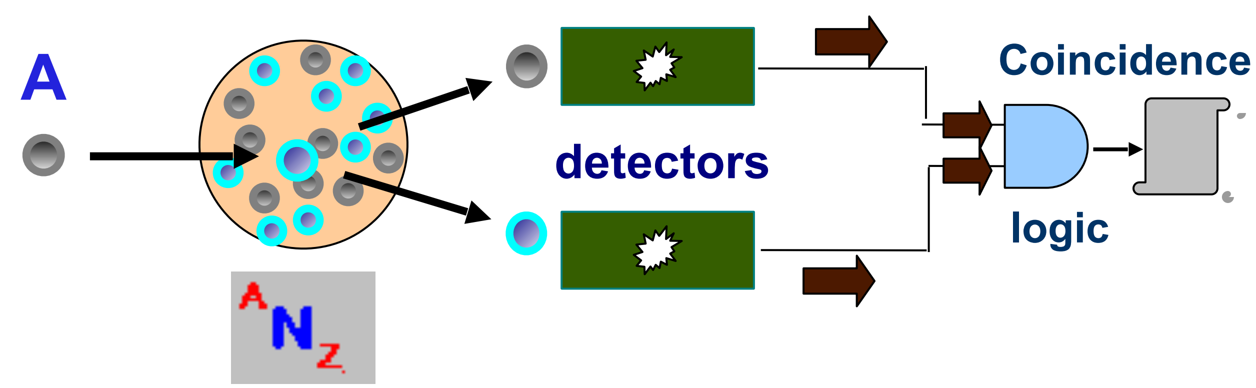
Nuclei

A + B → C + D + X

$^{A}N_{Z}$

1. Color transparency
2. Nuclear filtering





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

Nuclear Transparency is a measure of **Final State Interactions (FSI)**

Final state interactions in exclusive processes can be used to search for onset of QCD predictions.

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

Exclusive Processes

Nucleons

A + B → C + D

p,n

1. Quark counting rules
2. Hadron helicity conservation

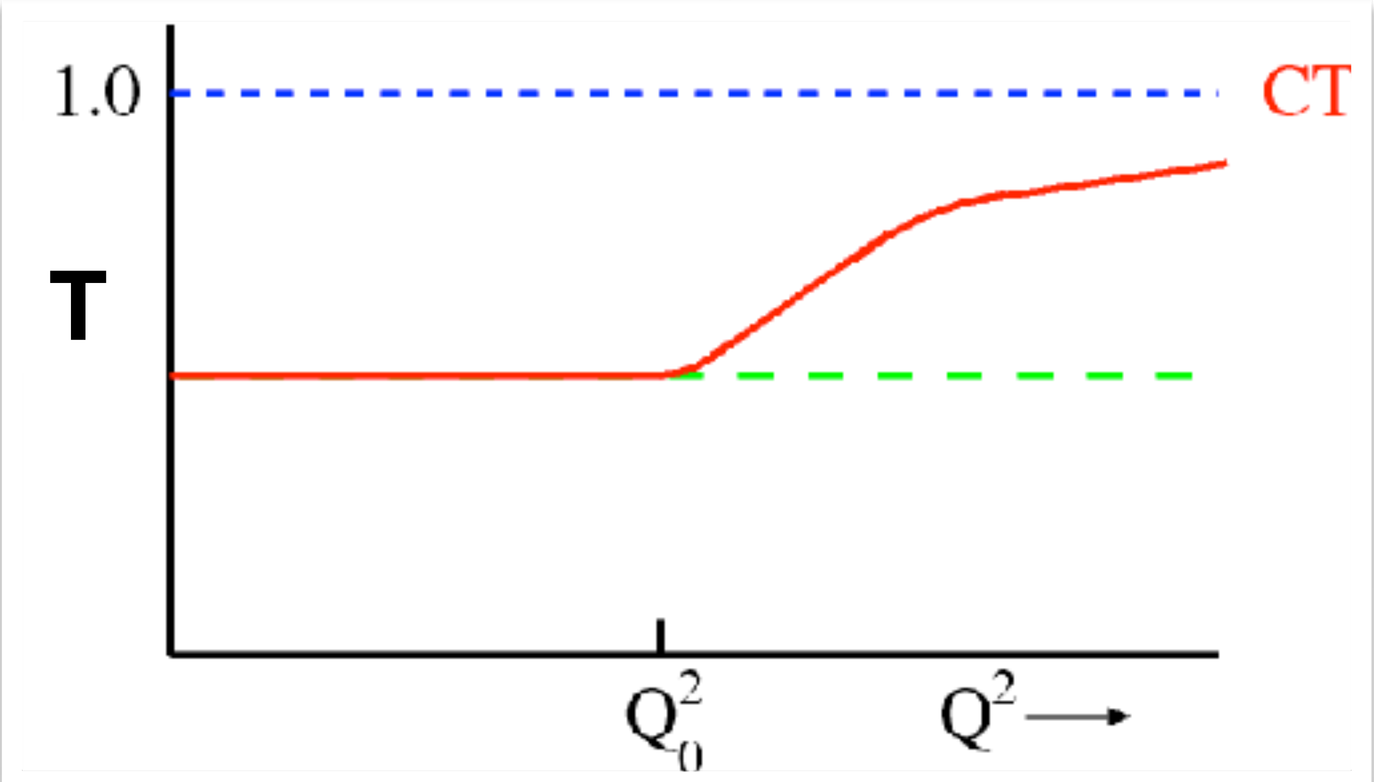
Nuclei

A + B → C + D + X

$^{A}N_{Z}$

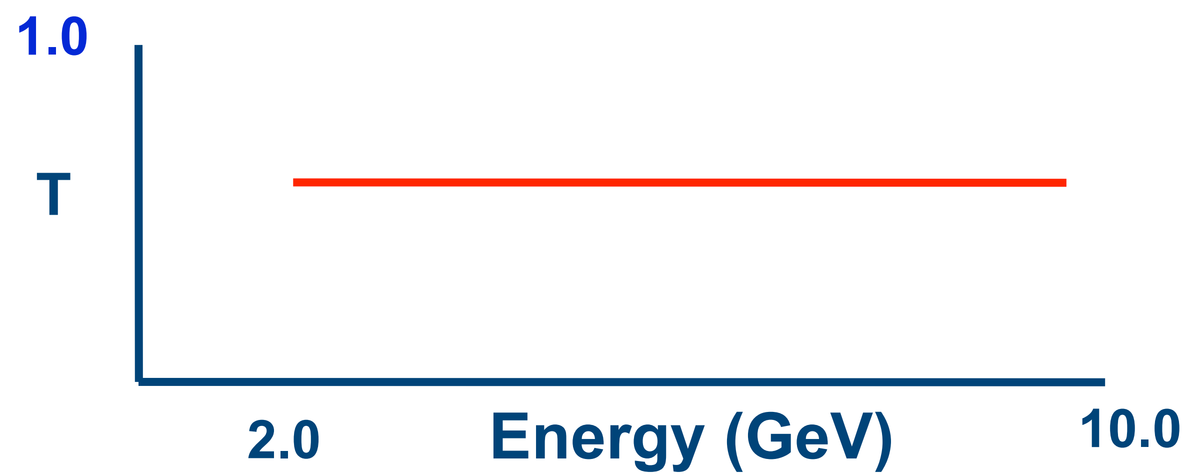
1. Color transparency
2. Nuclear filtering

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.

Traditional NP calculations



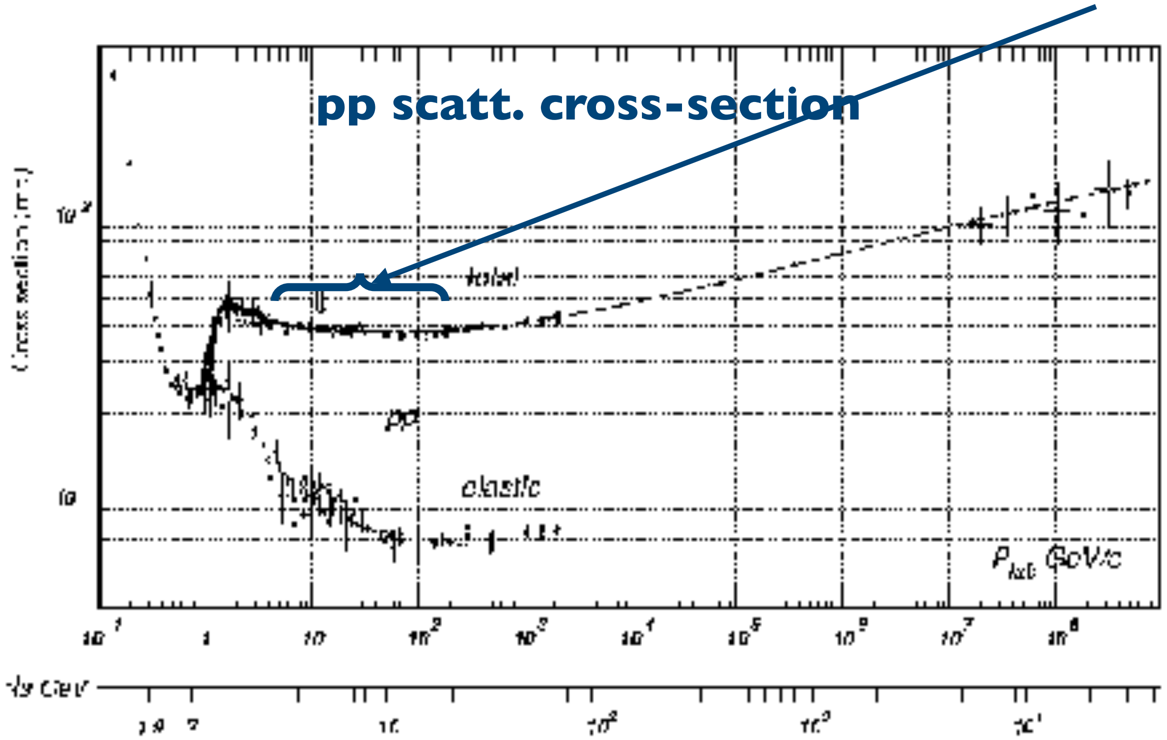
Ingredients

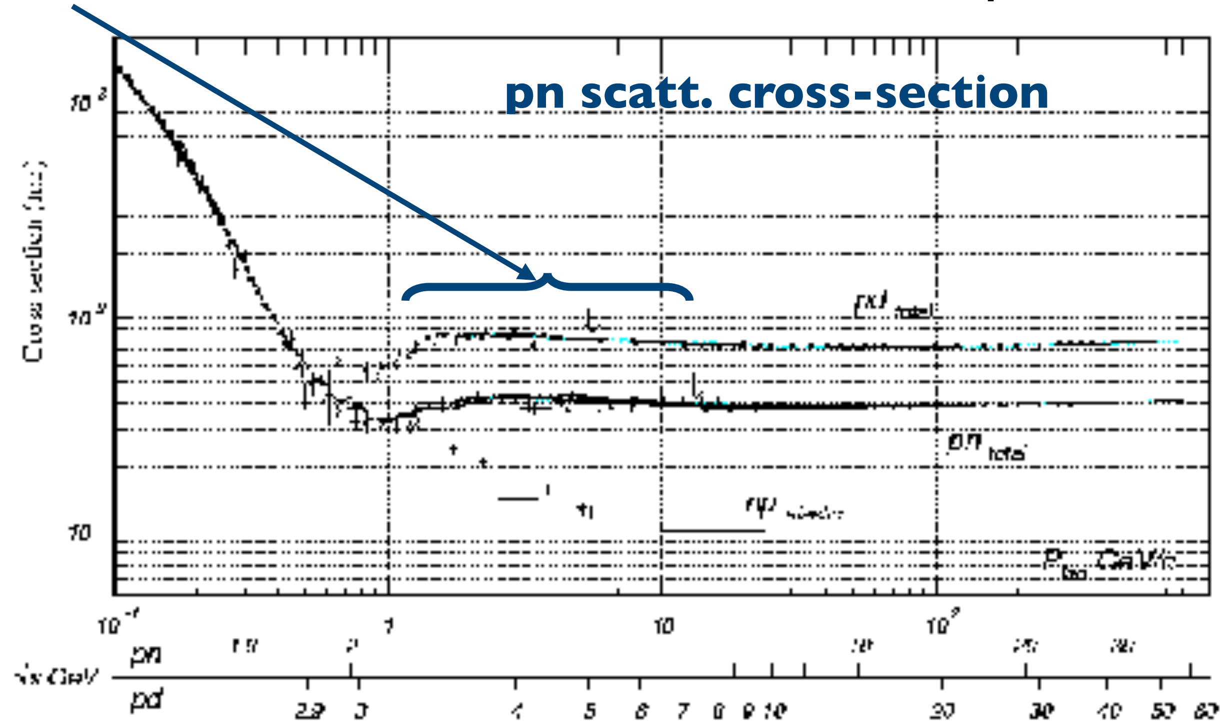
- σ_{hN} h-N cross-section
- Glauber multiple scattering approximation
- Correlations & FSI effects.

For light nuclei very precise calculations of are possible.

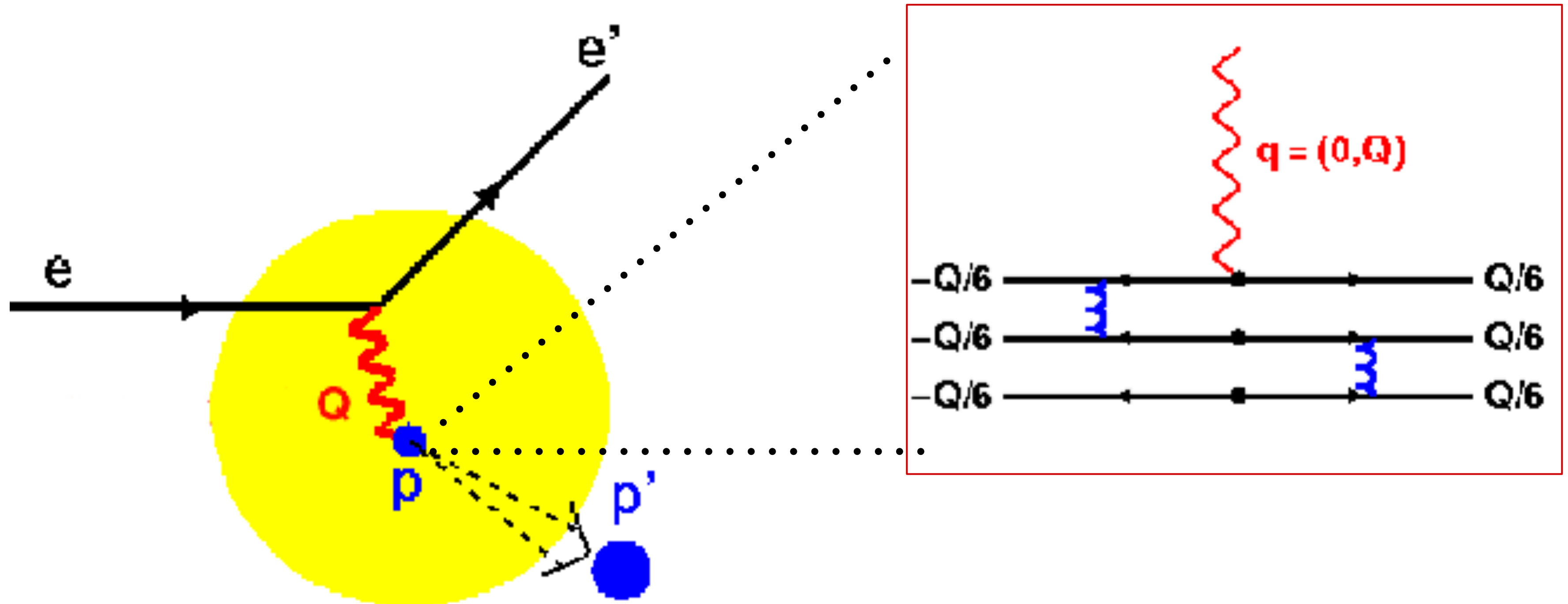
energy independent

plots from PDG





QCD predicts that h-N interaction in exclusive processes at large momentum transfers should vanish.



At high momentum transfers, scattering takes place via selection of amplitudes characterized by small transverse size (PLC) - "squeezing"

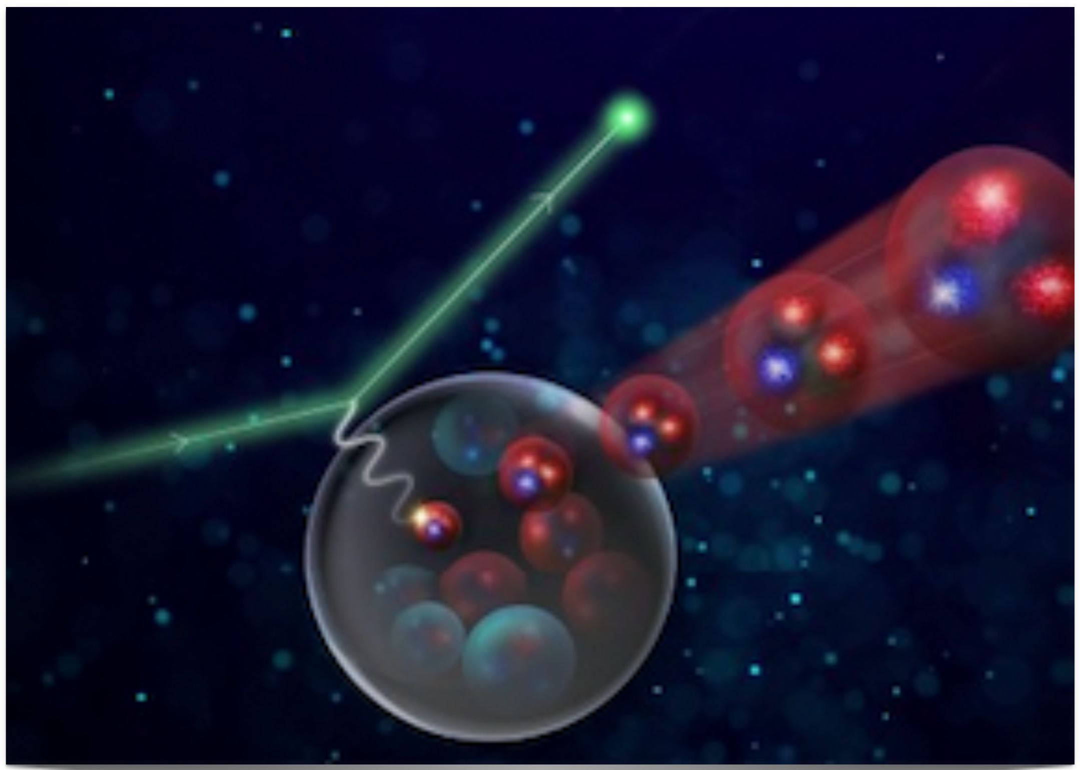
The compact size is maintained while traversing the nuclear medium - "freezing".

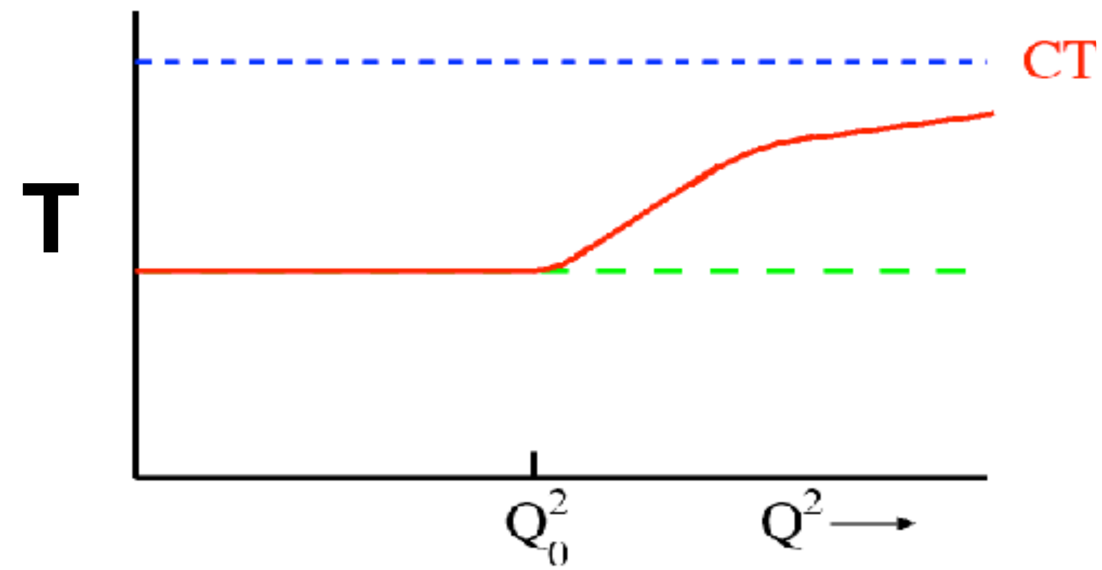
The PLC is 'color screened' - it passes undisturbed through the nuclear medium.

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

QCD predicts final state interactions in exclusive processes at large momentum transfers should vanish.

At sufficiently high energies because of “squeezing”, “freezing” and color screening, nuclei should become completely transparent (color transparency, CT).





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

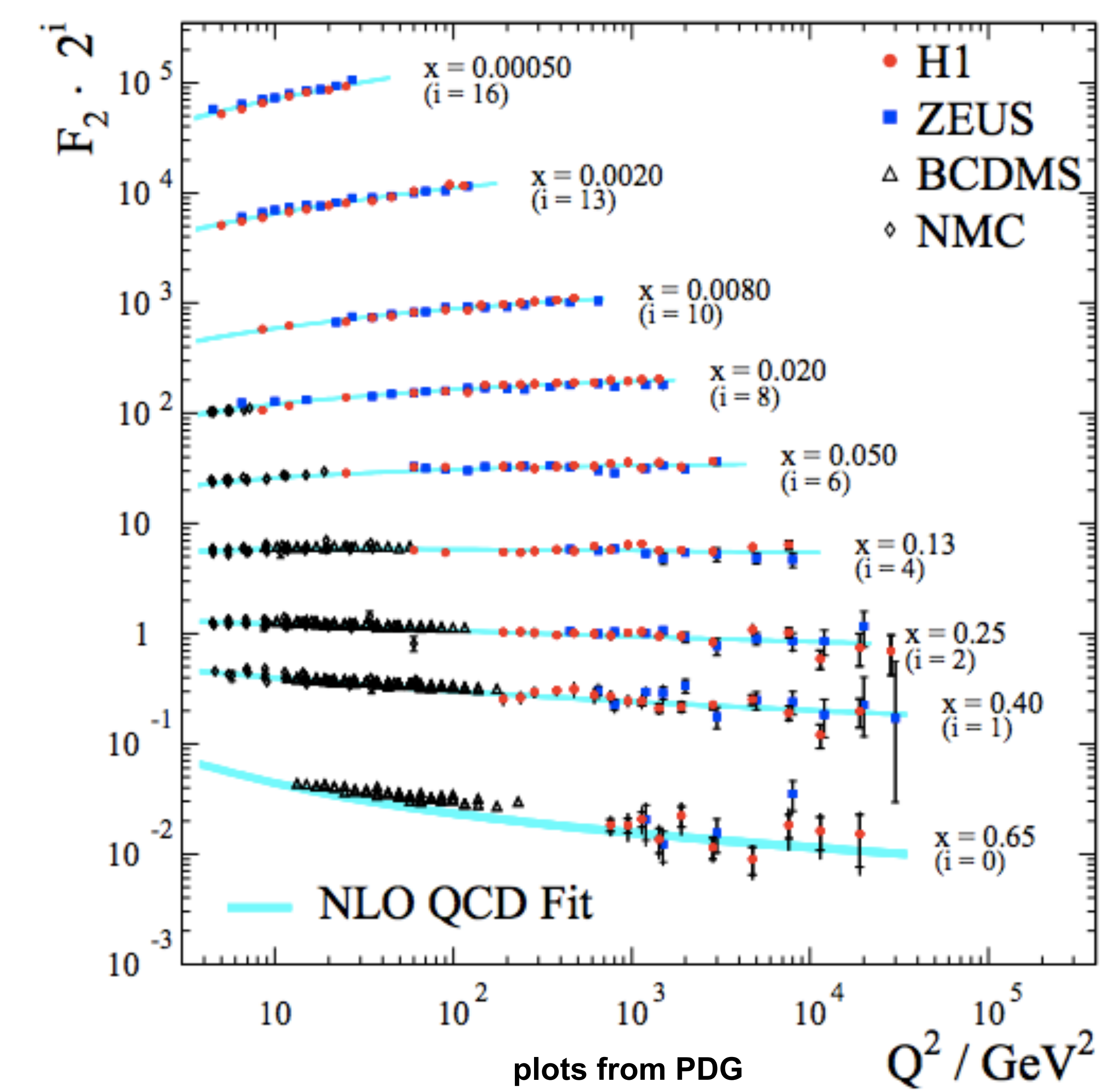
Onset of CT would be a signature of the onset of QCD degrees of freedom in nuclei

Bjorken scaling in DIS at small x is seen as evidence for CT at very high energies.

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 pQCD description of DIS.

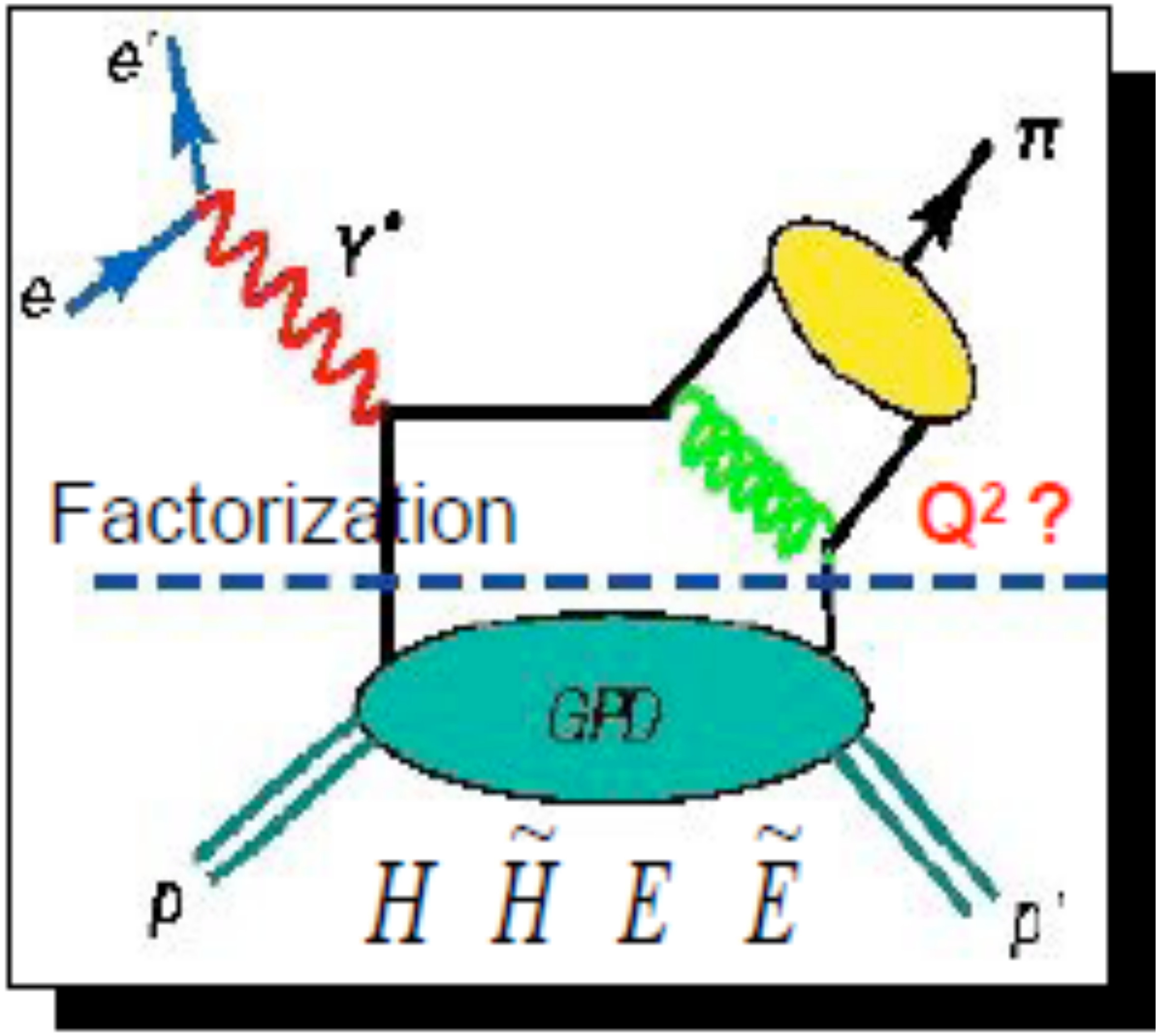


plots from PDG

CT is also connected to the framework of Generalized Parton Distributions (GPDs) - the modern description of nucleons.

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

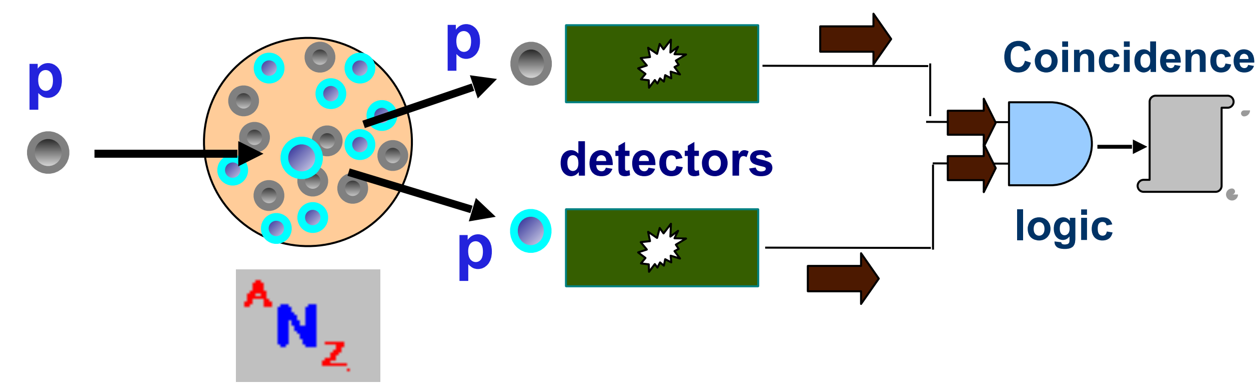
- It is still uncertain what Q^2 value reaches the factorization regime

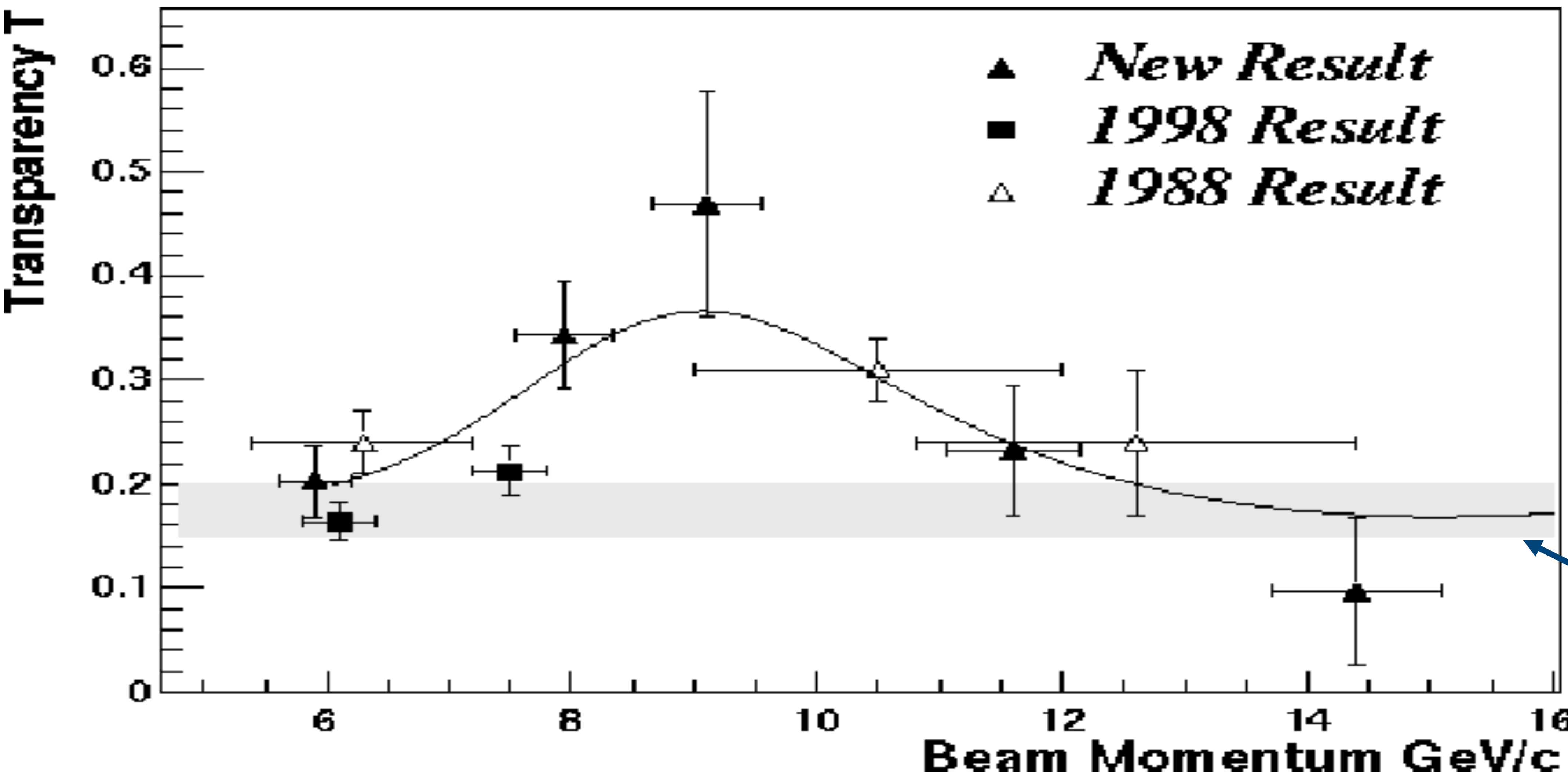
Although CT is well established at high energies the evidence of its onset is lacking for baryons.

First direct search for the onset of CT

$p + A \rightarrow p + p + X$
@ BNL
$p + p \rightarrow p + p$

$$T = \frac{\sigma_{pA}}{Z\,\sigma_{pp}}$$





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

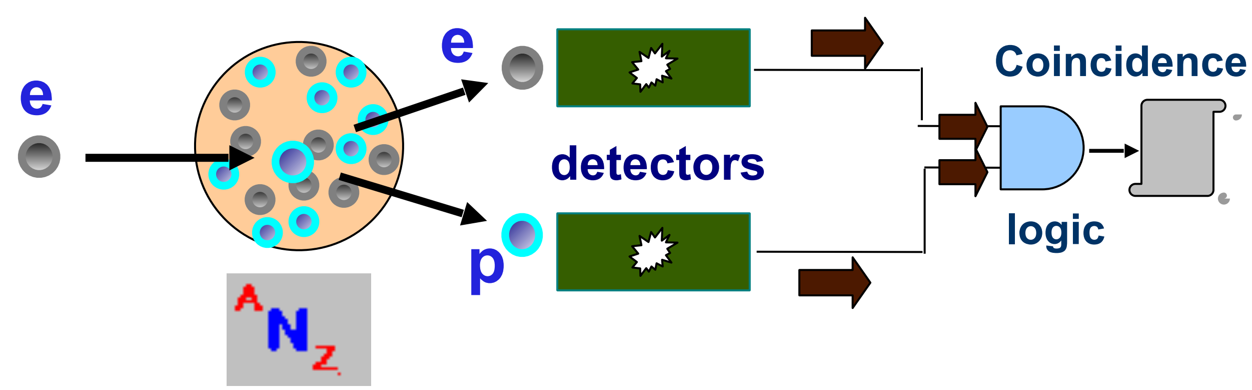
Solid line is fit to 1/oscillation in p-p scattering data

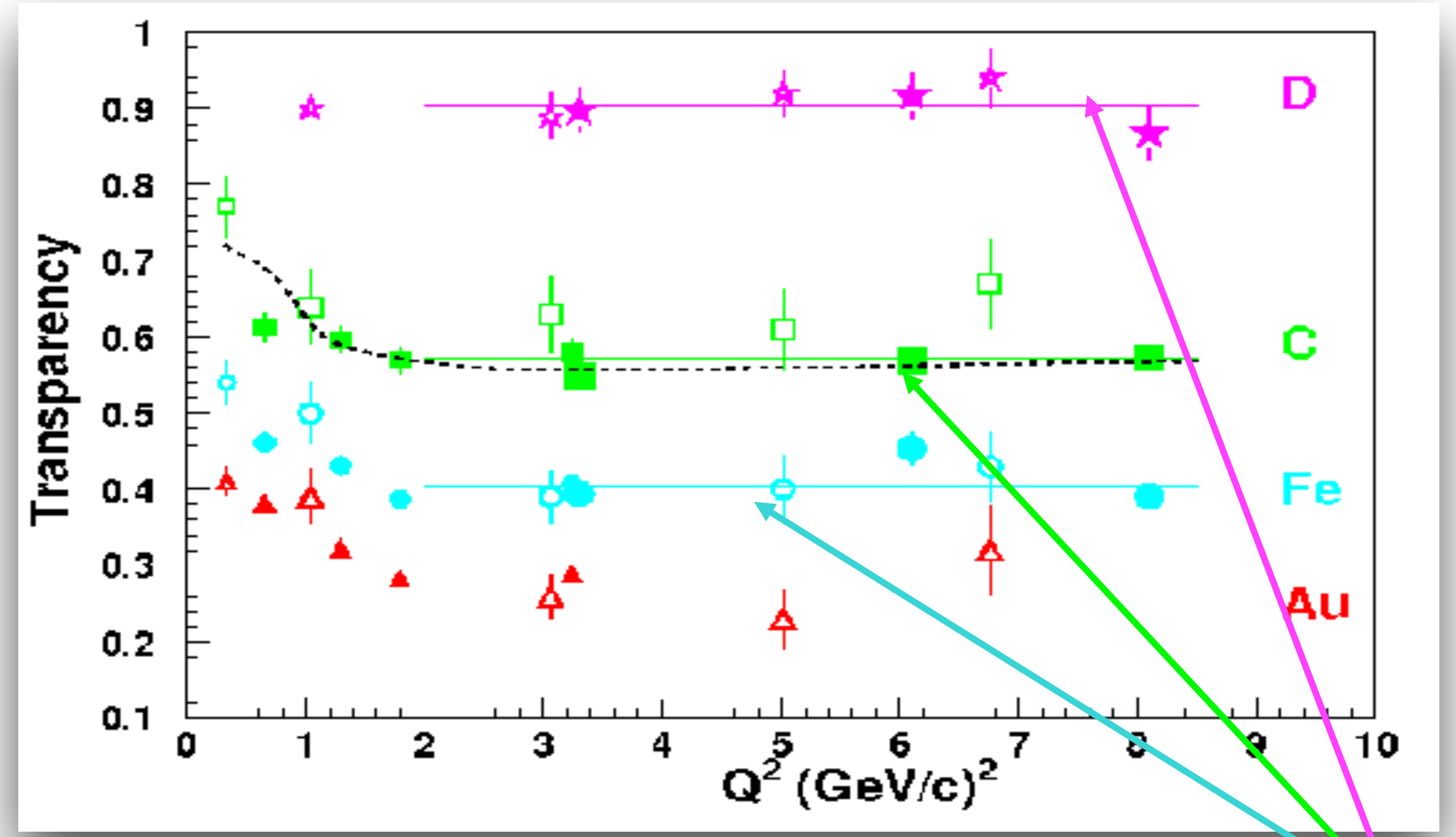
Shaded band Glauber calculation

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





Q² dependence consistent with standard nuclear physics calculations

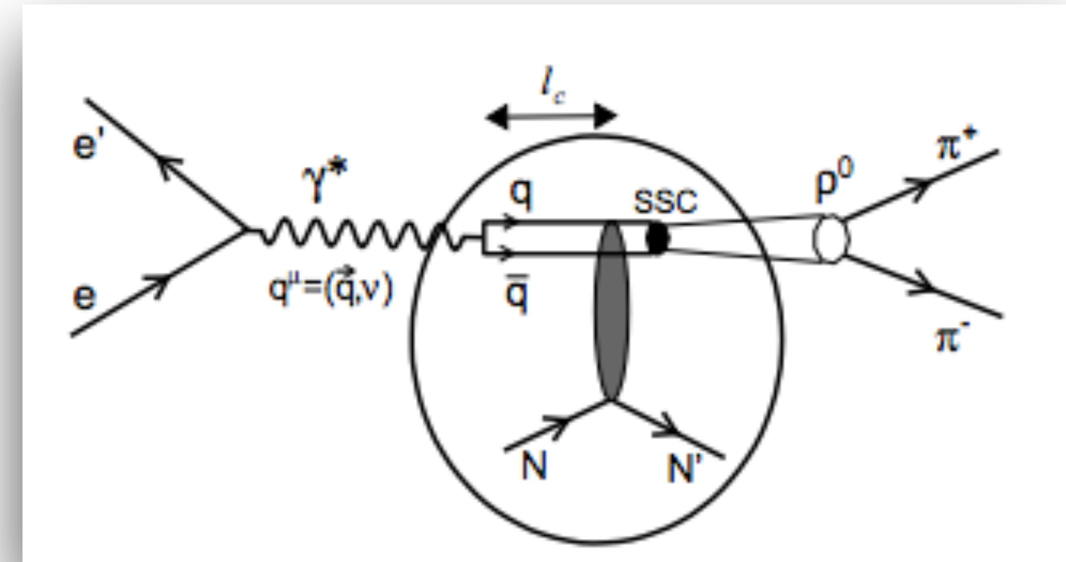
Solid Pts – JLab

Open Pts -- other

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)

Constant value fit for Q^2 > 2 (GeV/c)^2 has χ^2 / df ~ 1

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)

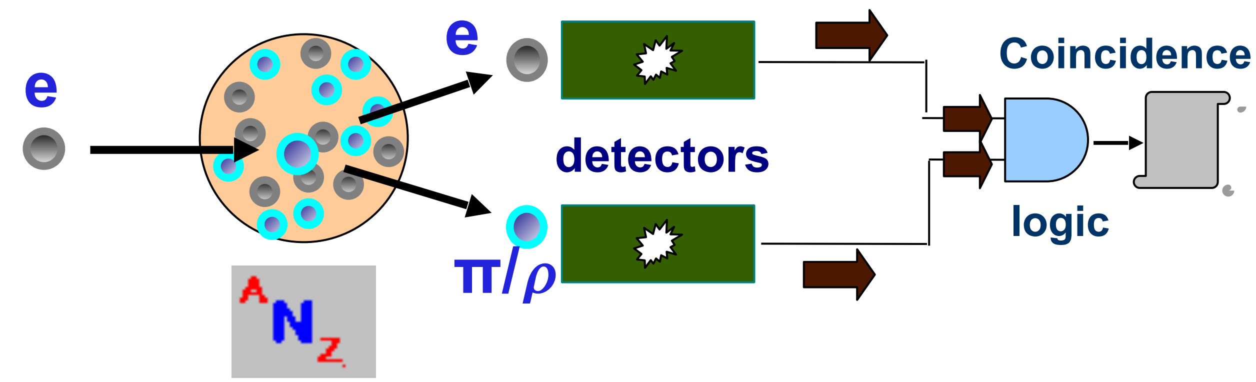
Onset of CT expected at lower Q^2 in mesons

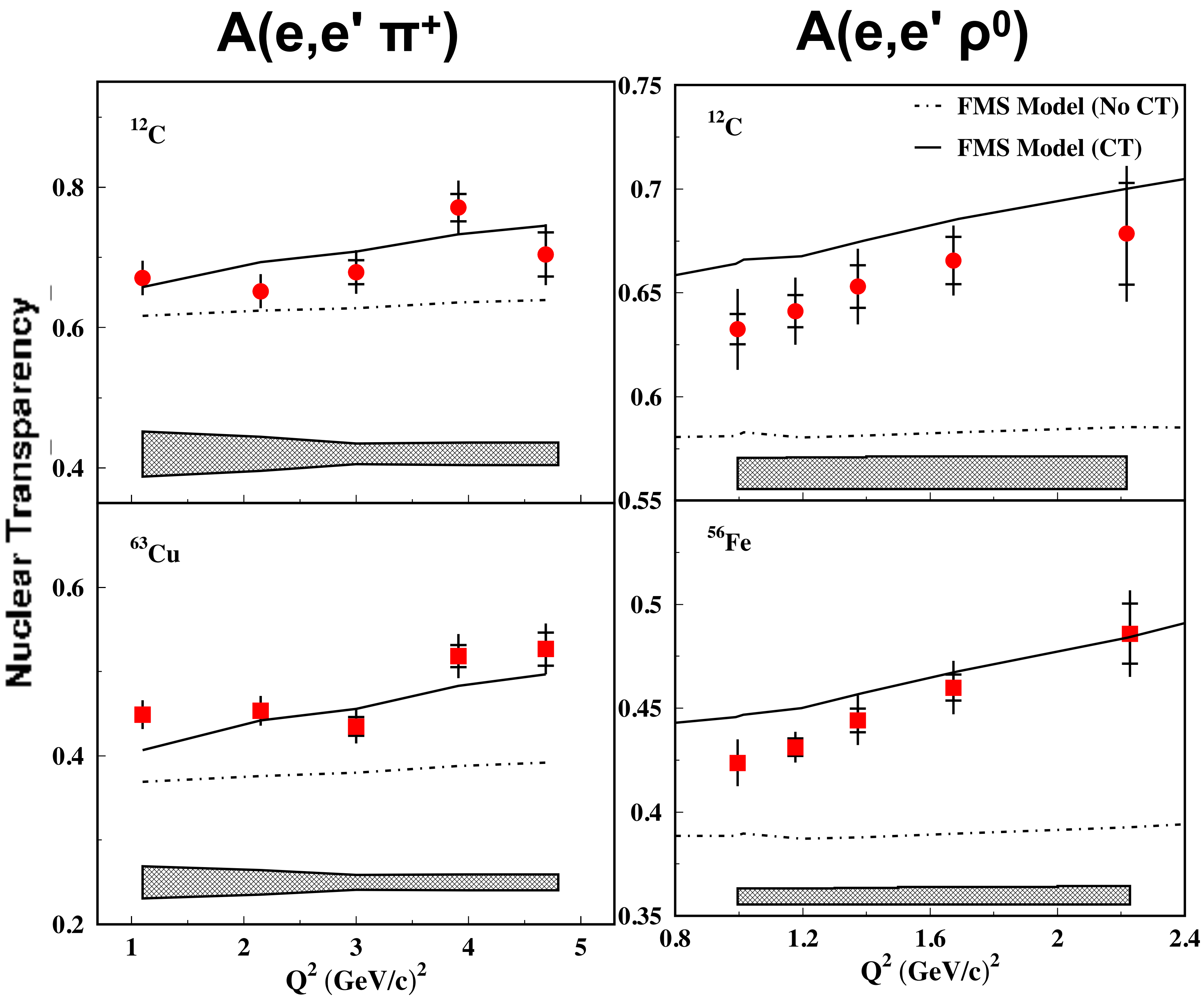
Formation length is ~ 10 fm at moderate Q^2 in mesons

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

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





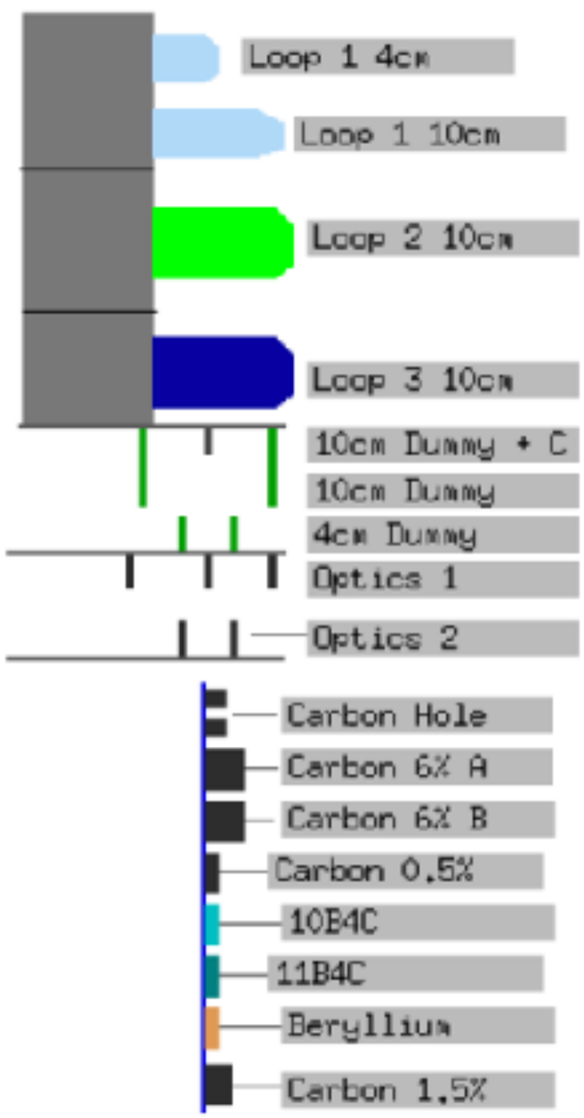
- Hall-C Experiment E01-107 pion electroproduction from nuclei found an enhancement in transparency with increasing Q^2 & A, consistent with the prediction of CT.
  (X. Qian et al., PRC81:055209 (2010), B. Clasie et al, PRL99:242502 (2007))

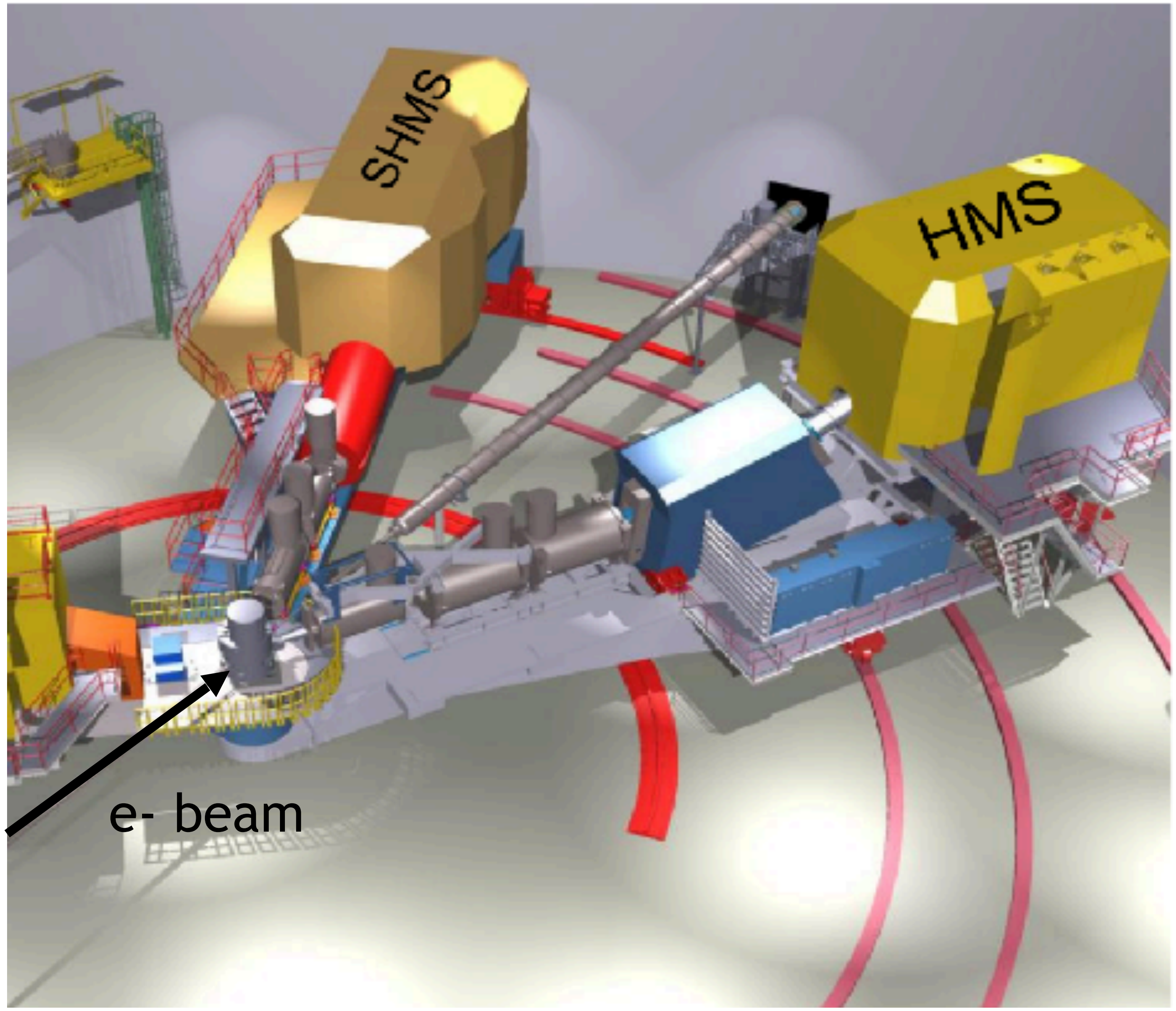
- CLAS Experiment E02-110 rho electroproduction from nuclei found a similar enhancement, consistent with the same predictions
  (L. El-Fassi, et al., PLB 712, 326 (2012))

FMS: Frankfurt, Miller and Strikman, Phys. Rev., C78: 015208, 2008

The first experiment to run in JLab Hall C in the 12 GeV era, was a search for the onset of CT in protons.

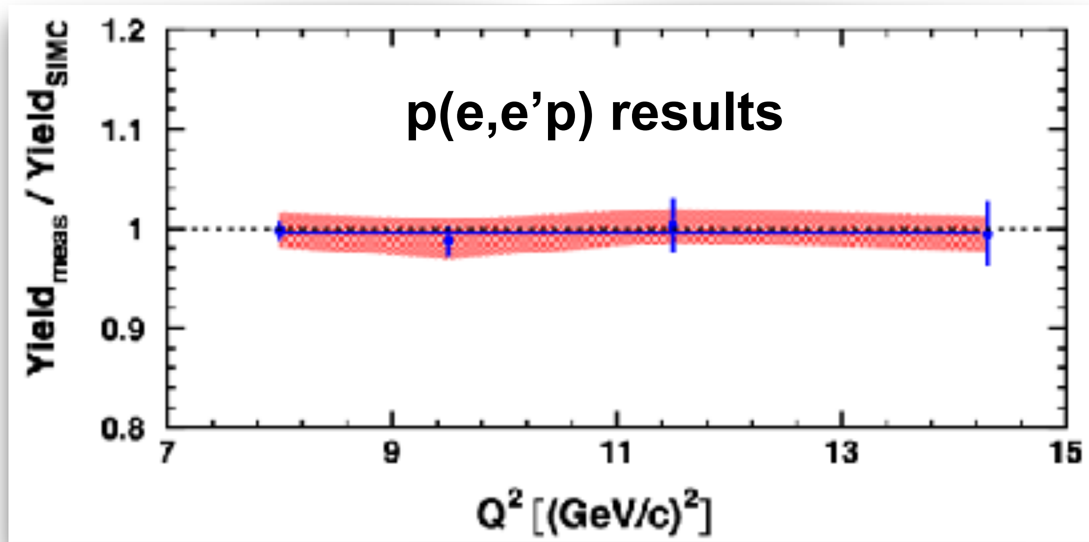
- Coincidence trigger: SHMS measures protons, HMS measures electrons
- Targets: 10 cm LH_2 (H(e,e'p) normalization),
- 6% ^{12}C (production),
- Al dummy (background)





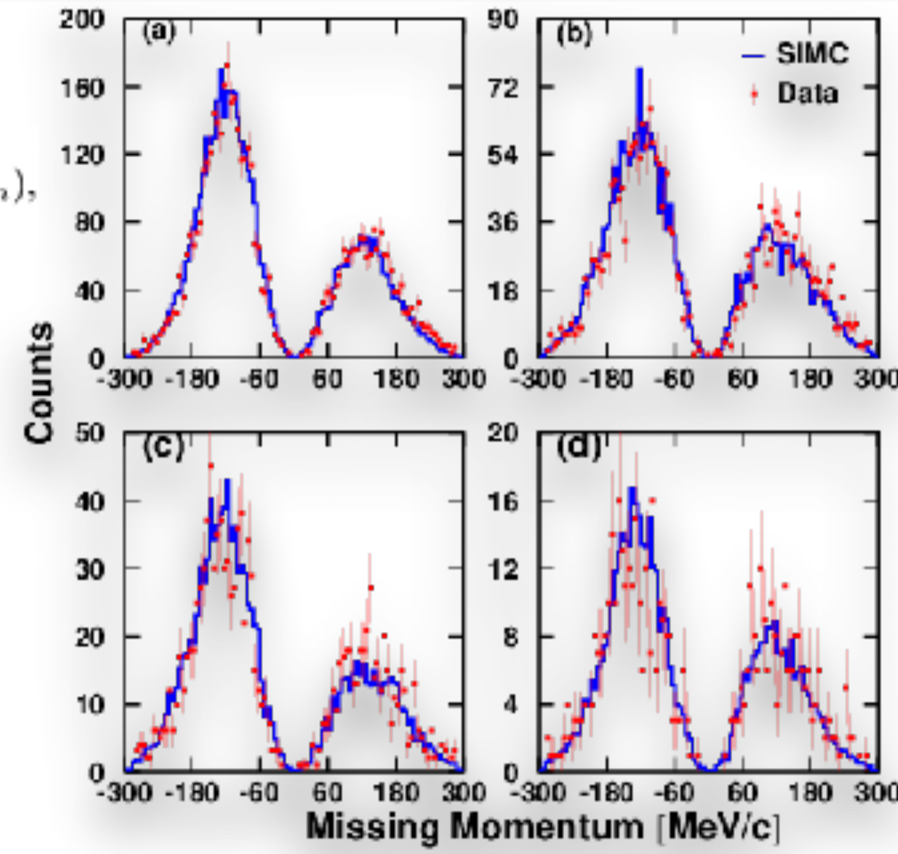
The results from the first Hall C experiment rule out the onset of CT in (e,e'p) up to Q^2 = 14.3 GeV^2

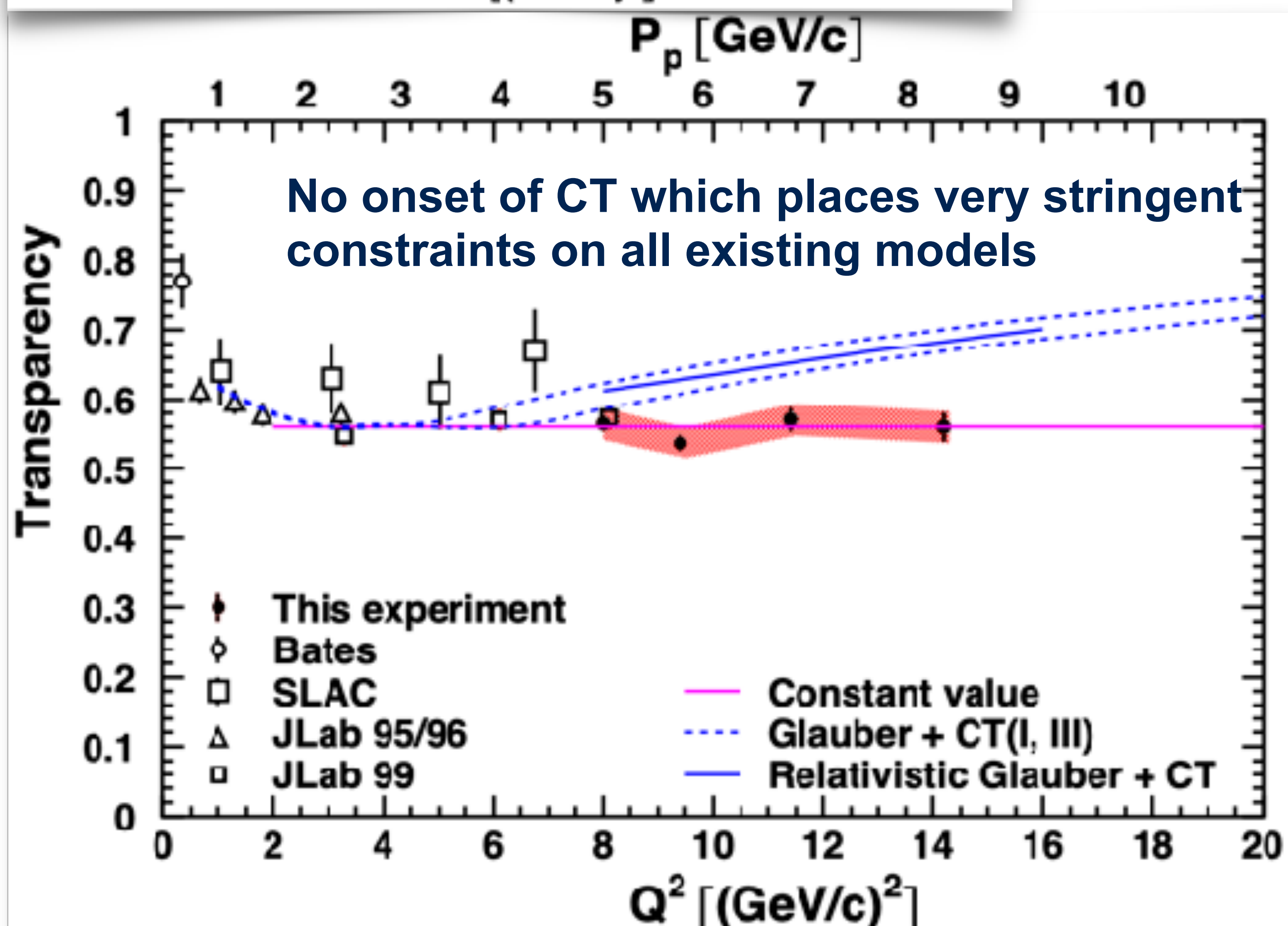
agrees with parametrization of known *ep* elastic data & simulation of experiment



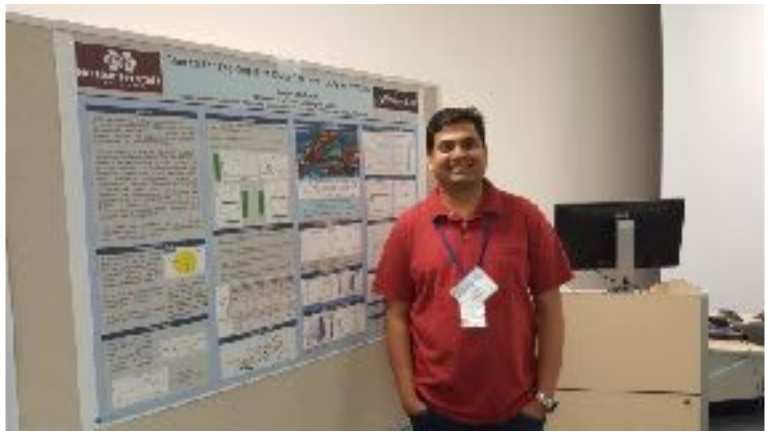
$$\frac{d^5\sigma}{dE_{e'}d\Omega_{e'}dE_{p'}d\Omega_{p'}} = E_{p'}|p_{p'}|\sigma_{ep}S(E_m,\vec{p}_m),$$

spectral functions agree with PWIA reaction mechanism.





BNL observations unlikely to be because of CT



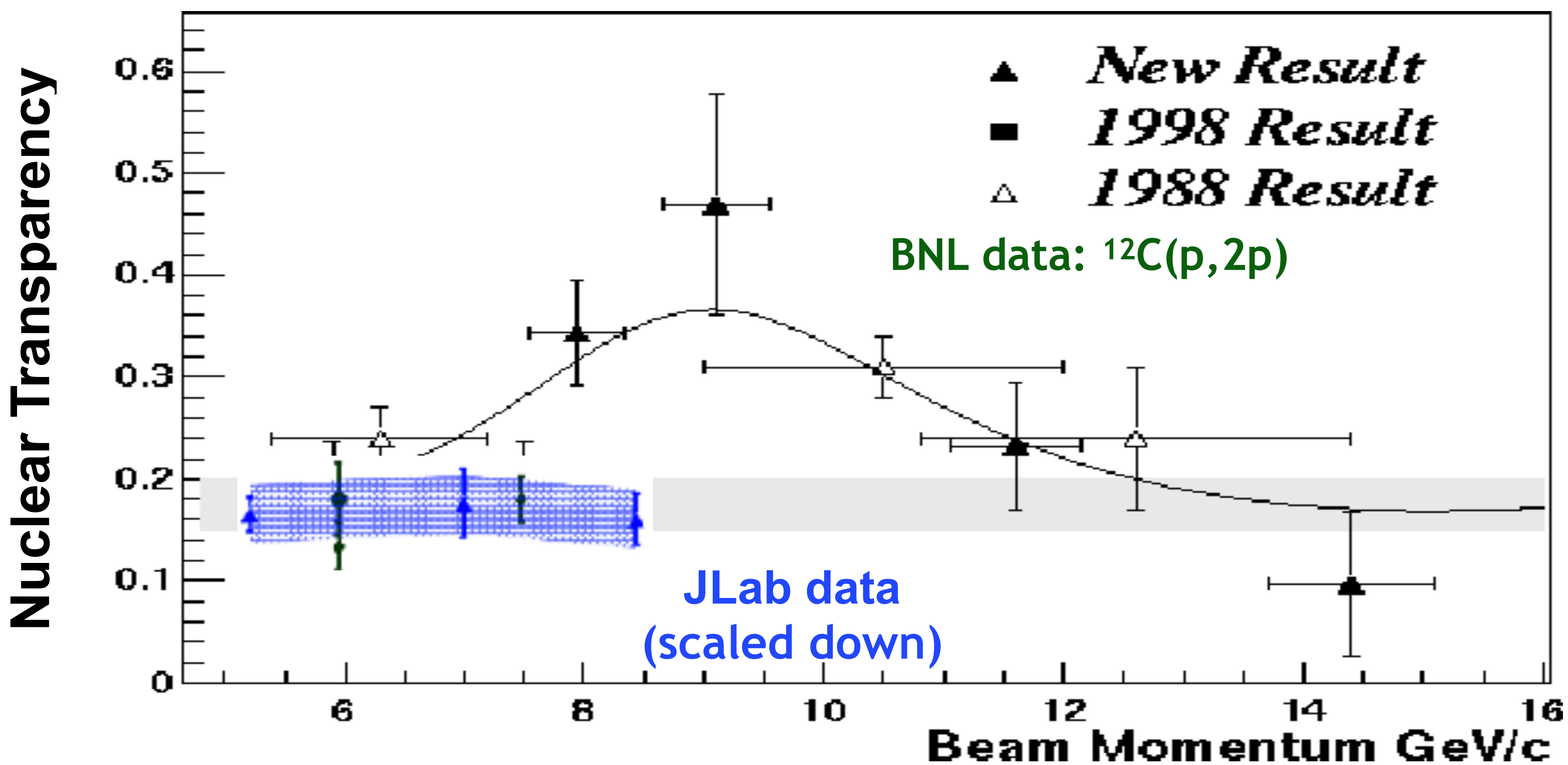
Thesis of MSU grad student Deepak Bhetuwal

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



EurekAlert! AAAS

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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

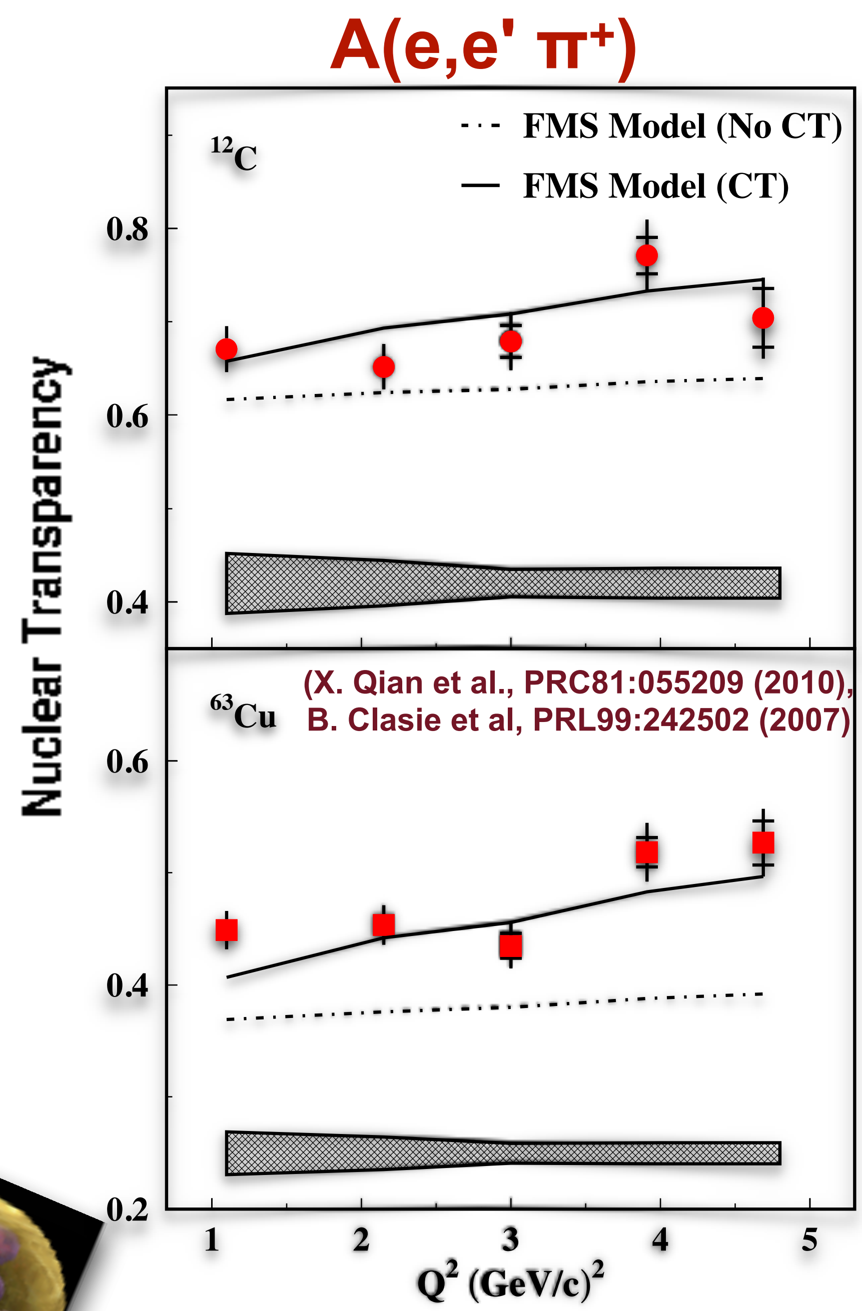
Peer-Reviewed Publication

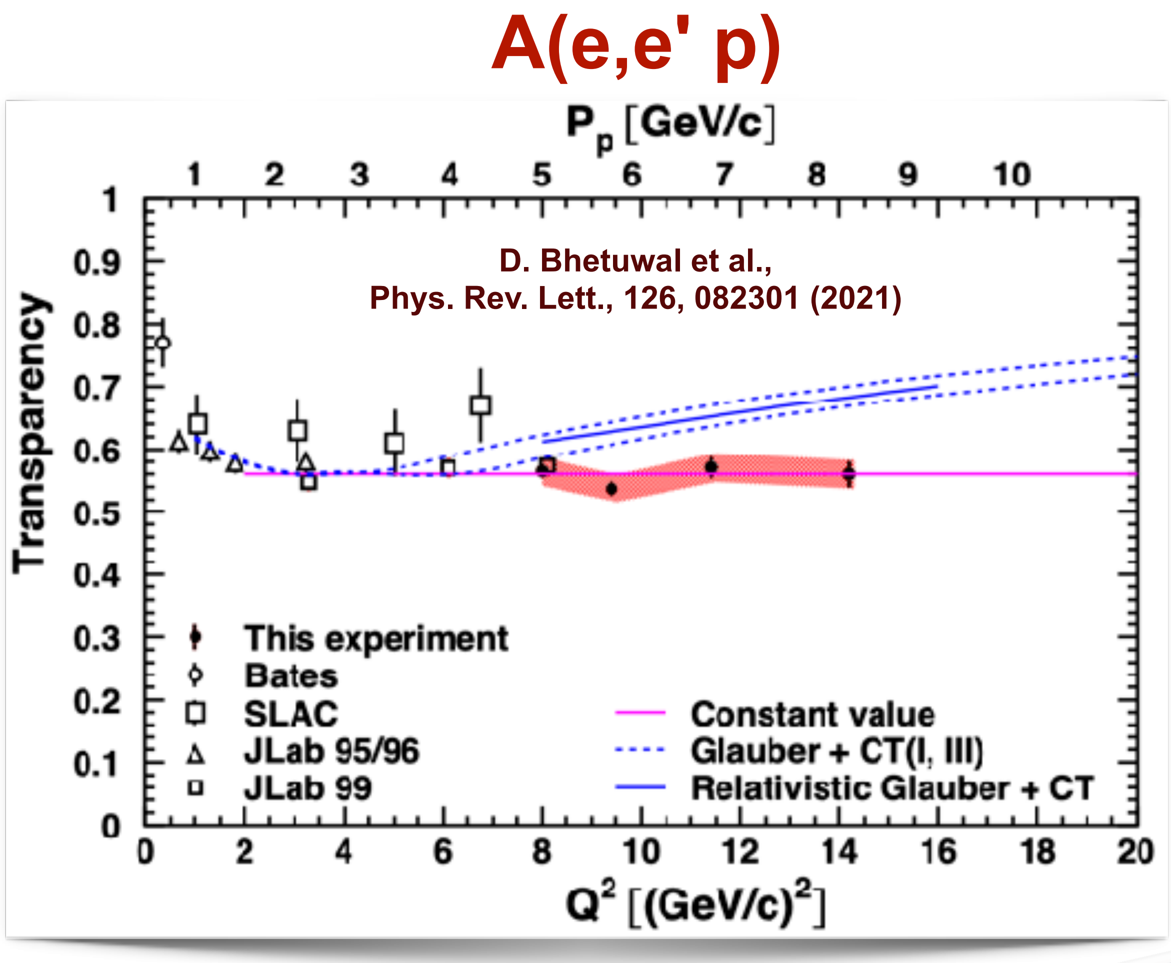
DOE/THOMAS JEFFERSON NATIONAL ACCELERATOR FACILITY

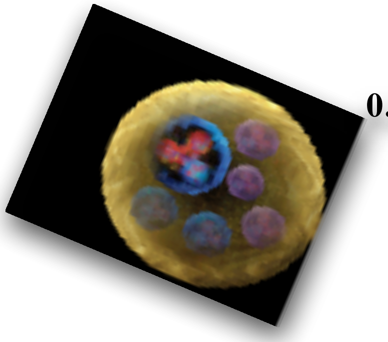
While protons populate the nucleus of every atom in the universe, sometimes they can be squeezed into a smaller size and slip out of the nucleus for a romp on their own. Observing these squeezed protons may offer unique insights into the particles that build our universe.

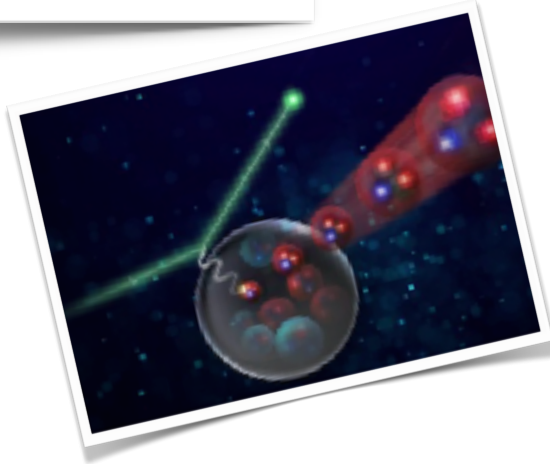
Now, researchers hunting for these squeezed protons at the U.S. Department of Energy's Thomas Jefferson National Accelerator Facility have come up empty handed, suggesting there's more to the

A new puzzle has arisen for Final State Interactions (FSI) in hadrons (where are the squeezed protons?)





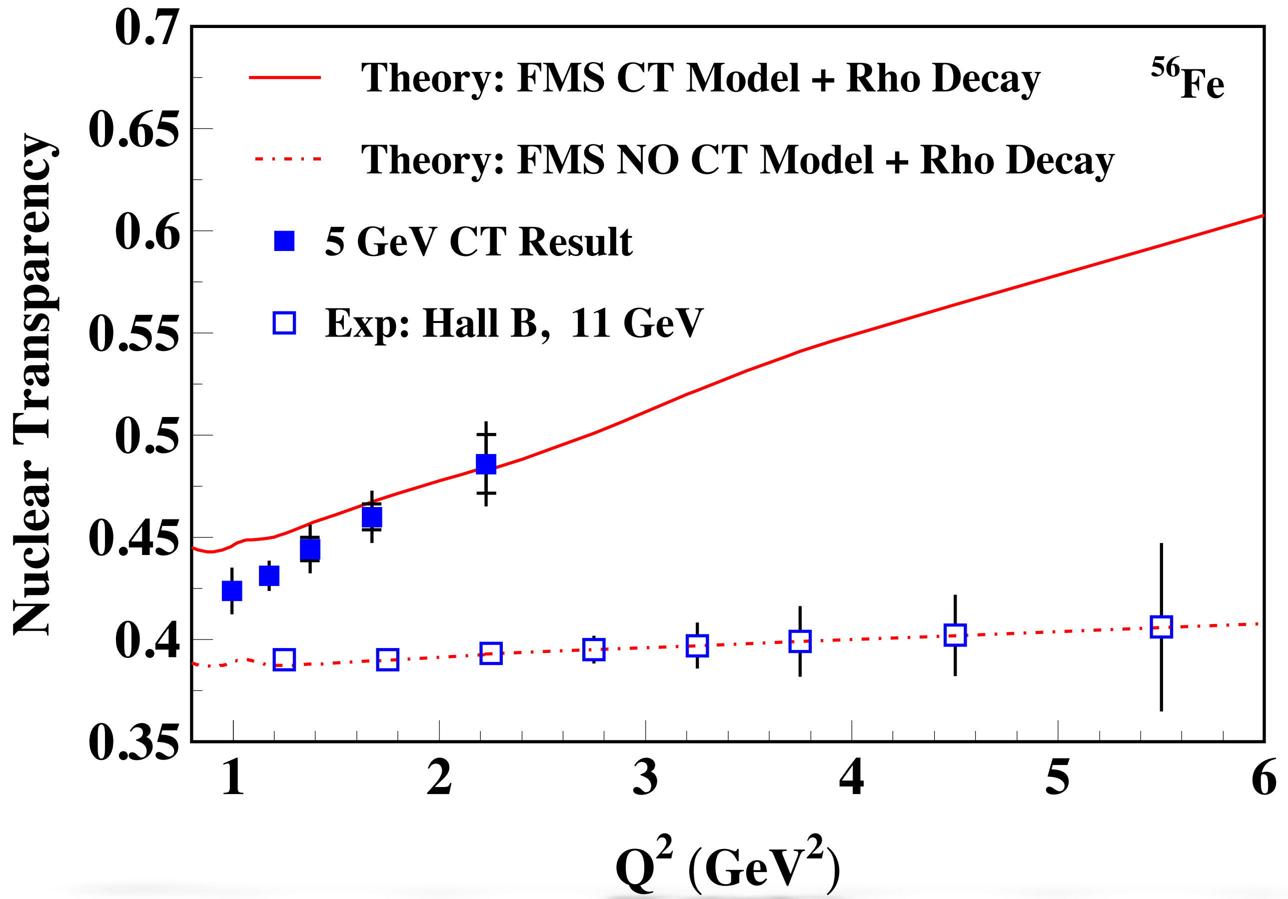




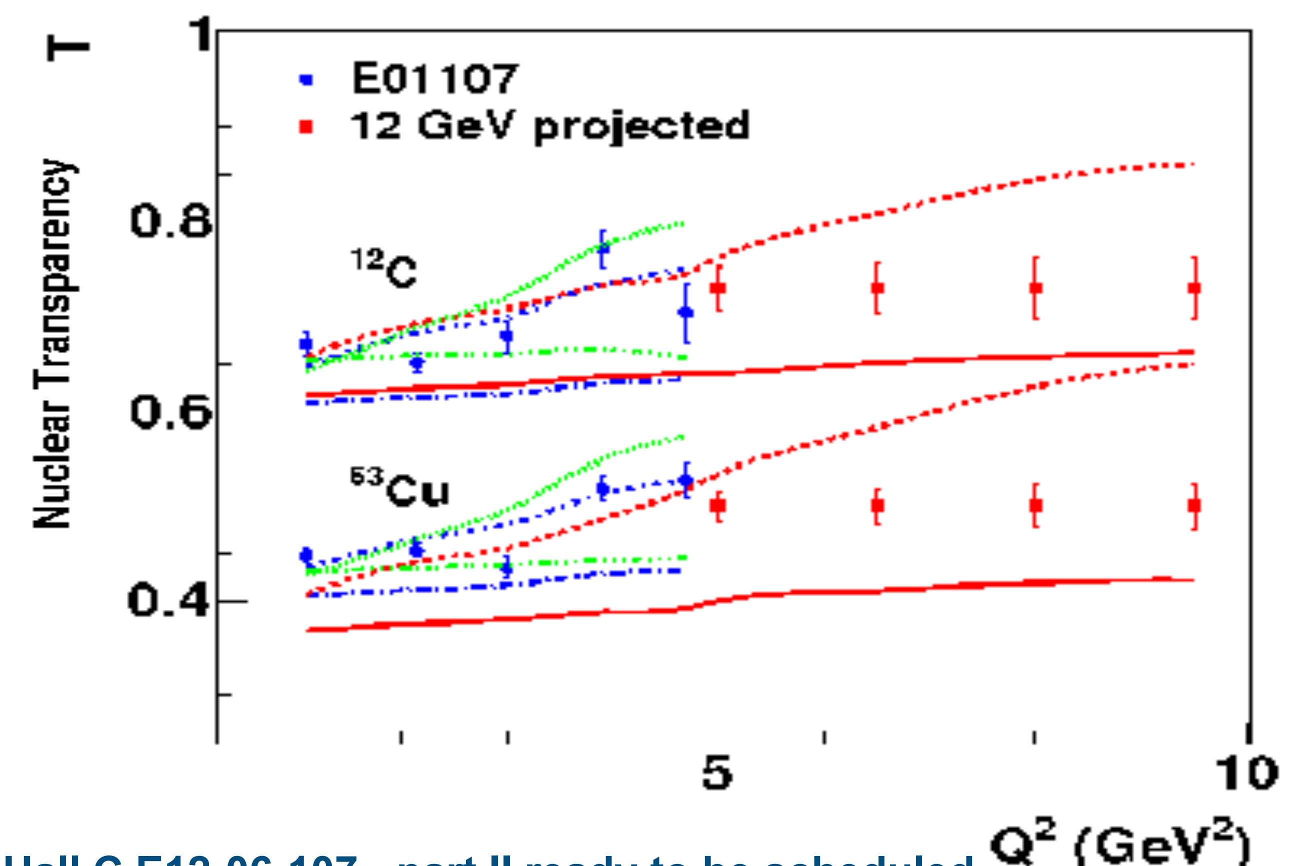
Onset of Color Transparency (i.e. suppression of FSI in exclusive processes) observed for meson at $Q^2 \sim 1$ GeV^2 but not in protons for $Q^2 \sim 14$ GeV^2

The meson results will be verified soon in upcoming experiments.

A(e,e' ρ⁰)

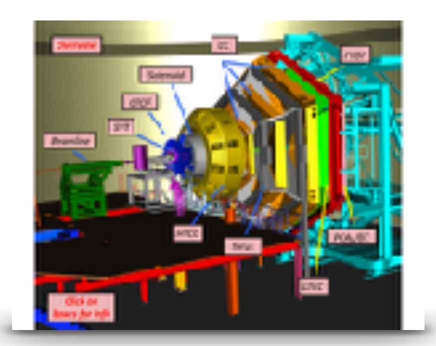


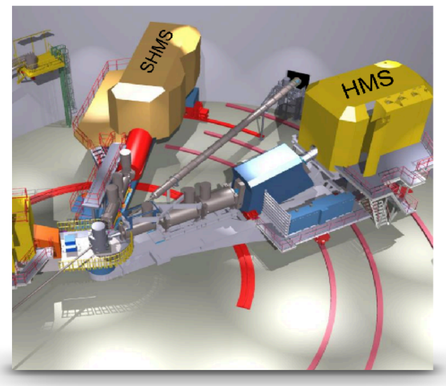
A(e,e' π⁺)



Hall C E12-06-107 - part II ready to be scheduled

CLAS12 Run group D ready to be scheduled





But the lack of CT in protons remains puzzling

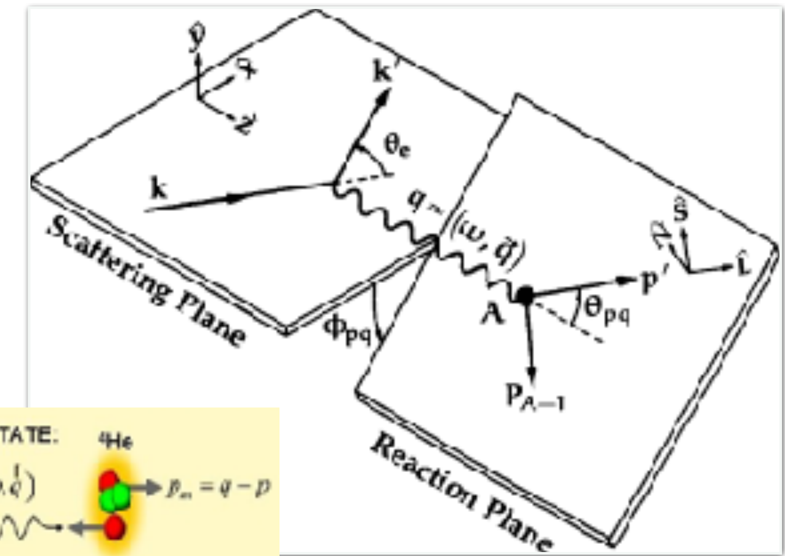
Maybe we need move away from parallel kinematics and embrace FSI and shift to “dirty kinematics”.

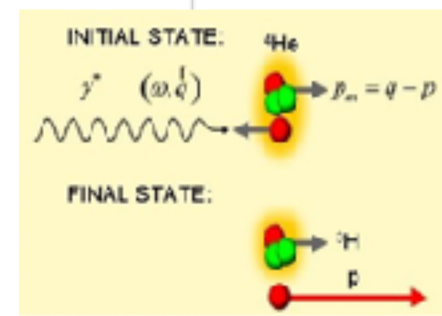
The “street lamp effect”

Move away from parallel kinematics (highest rates but small FSI)

Parallel kinematics

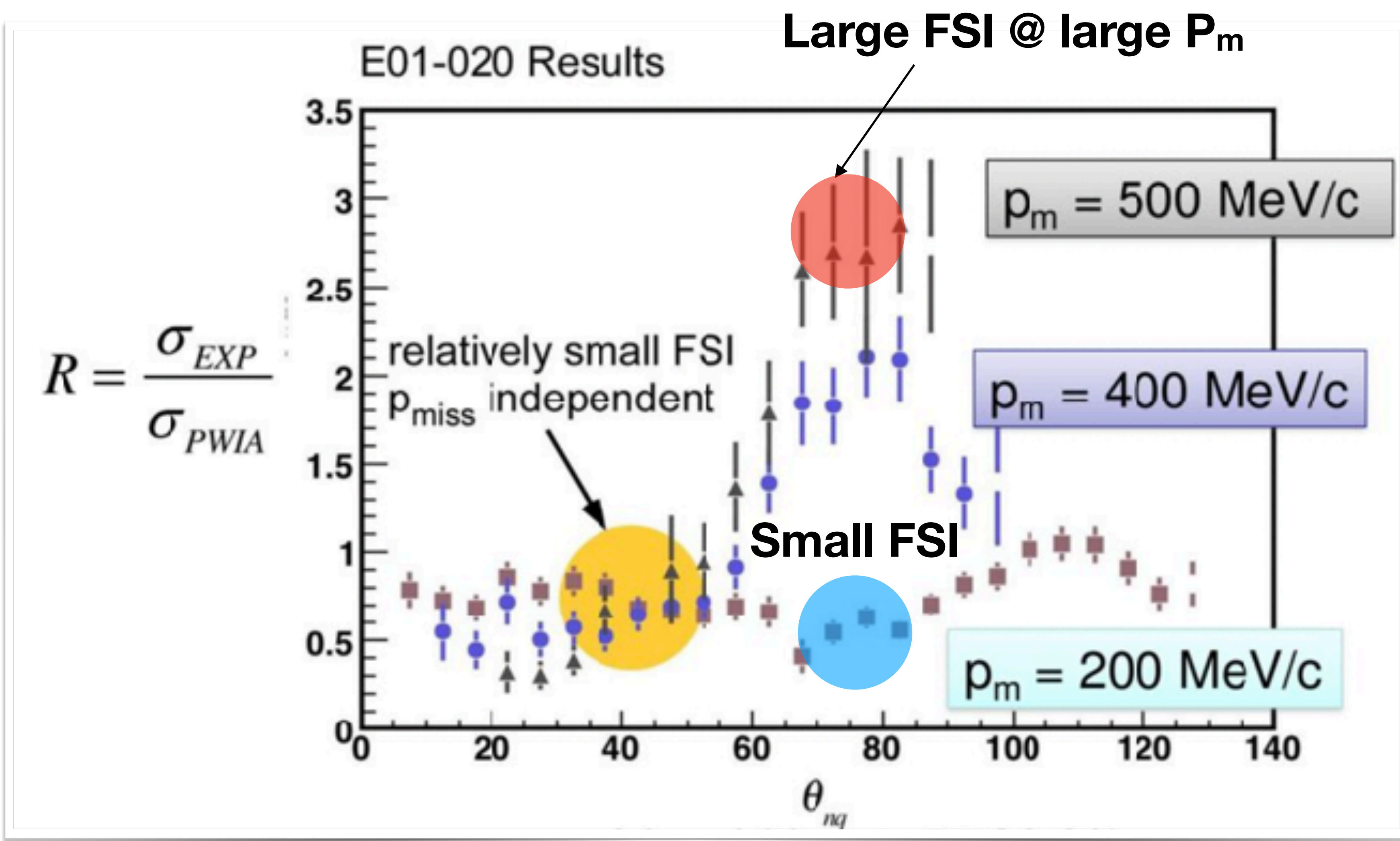
Proton’s initial-momentum is parallel to the q-vector





“Dirty kinematics”: kinematics where the FSI is very large and compare it against kinematics where the FSI is small and map the Q^2 dependence of their ratio.

Recent measurements on D(e,e'p) at large P_m provide clues on how to access "dirty kinematics".



D(e,e'p) at large P_m

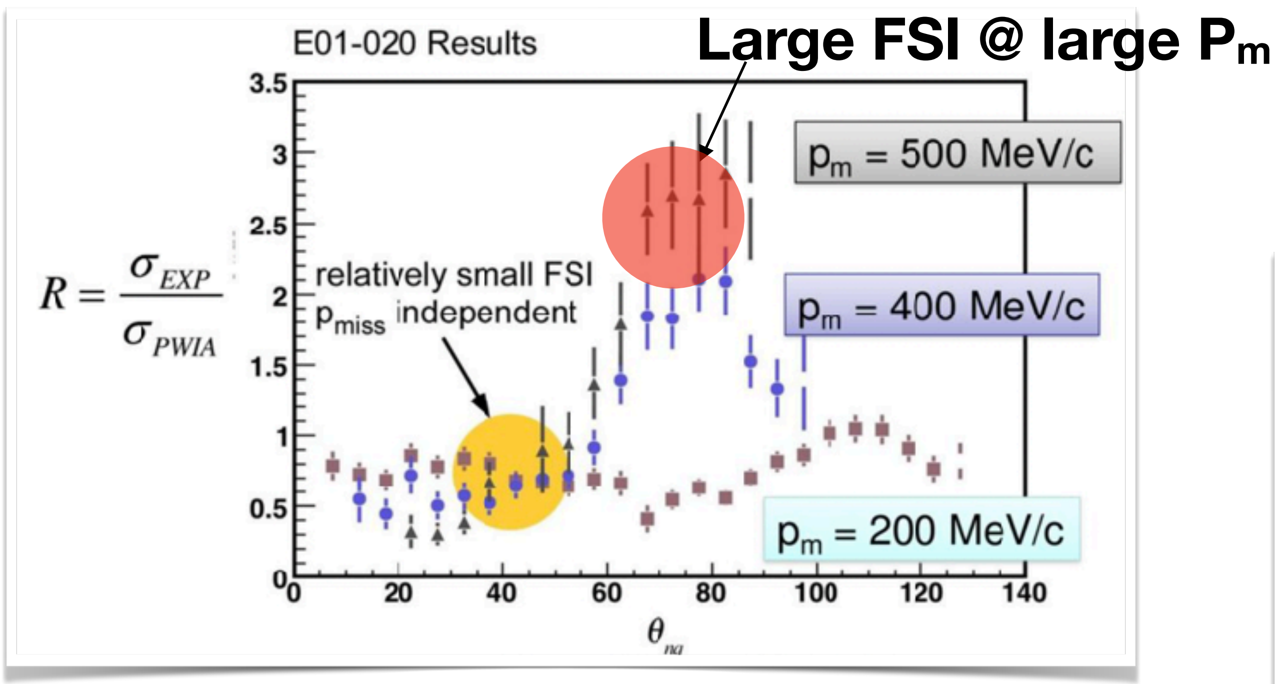
Measure Q^2 dependence of the ratio of yield at θ_{nq} = 75 for P_m > 400 MeV/c to P_m ~ 200 MeV/c

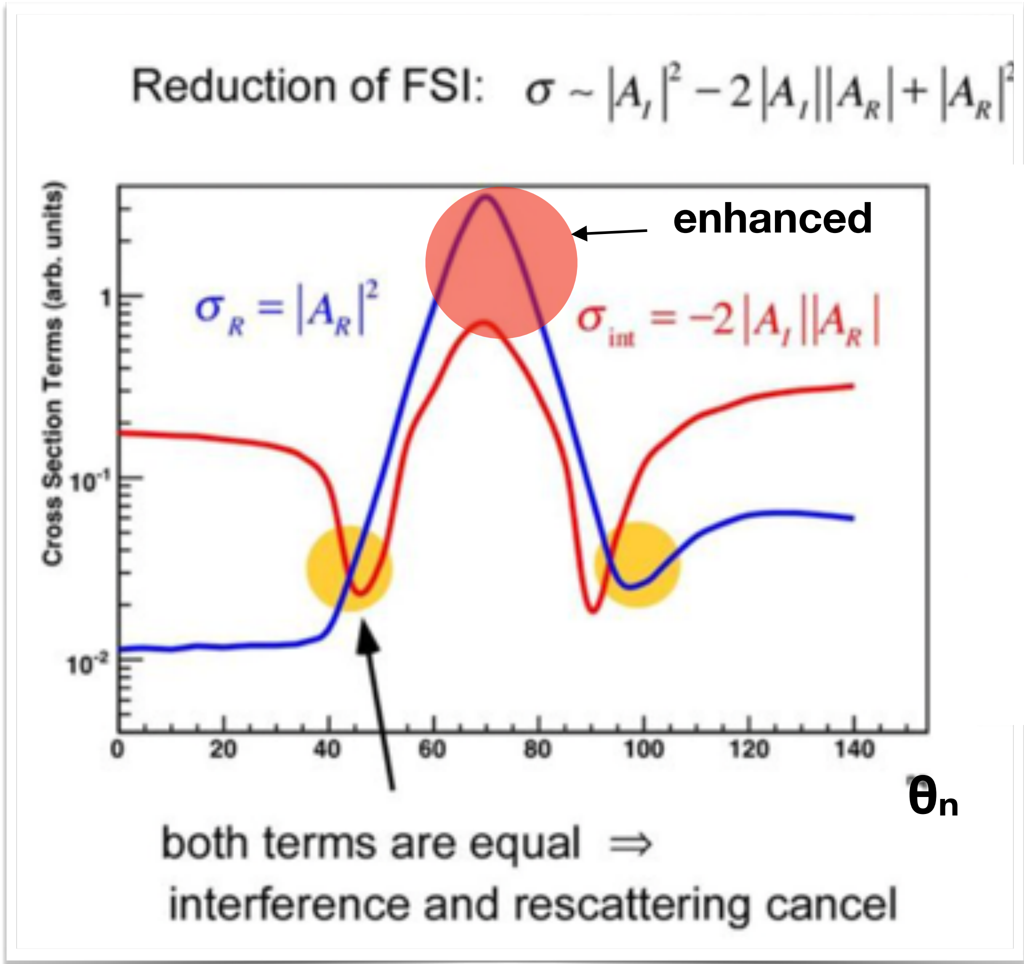
CT would lead to reduction of the ratio as Q^2 increases

plots courtesy of W. Boeglin

Recent measurements on D(e,e'p) at large P_m provide clues on how to access "dirty kinematics".

D(e,e'p) at large P_m





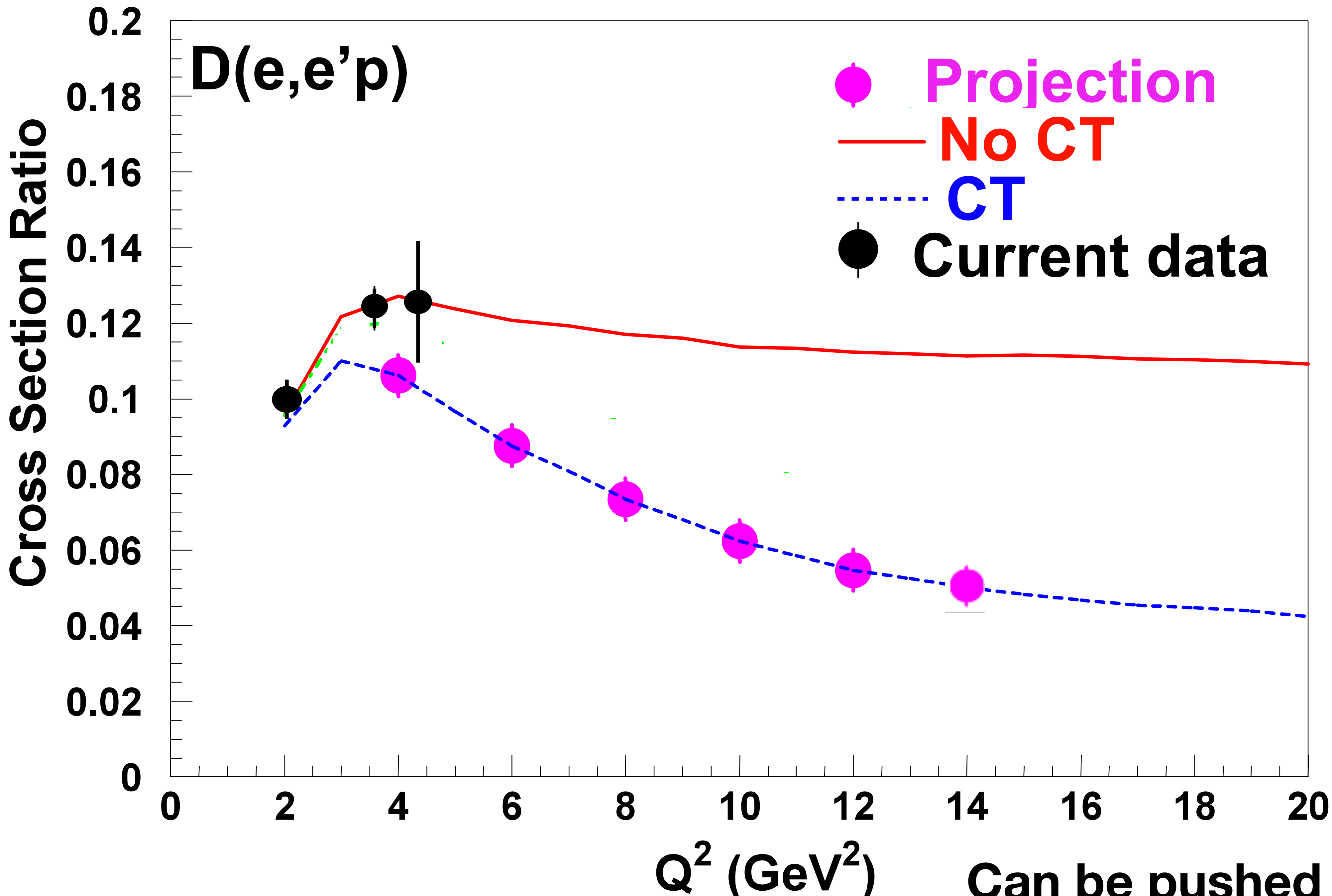
Measure Q^2 dependence of the ratio of yield at
$P_m > 400$ MeV/c and $\theta_{nq} = 75$ to $\theta_{nq} = 45$

CT would lead to reduction of the ratio as Q^2 increases

plots courtesy of W. Boeglin

Ratios can be extracted from existing data, but need to extend the measurements to higher Q^2.

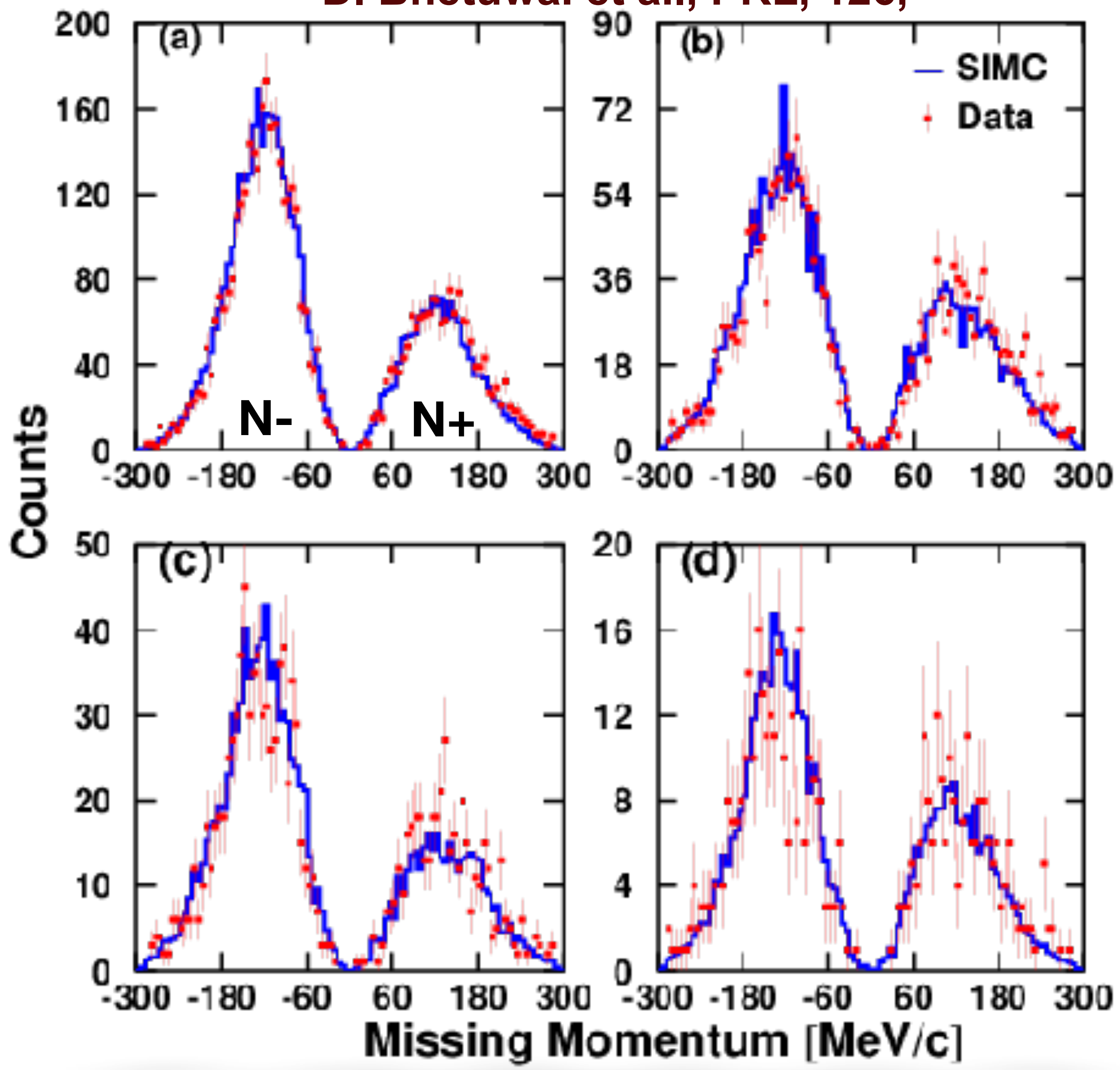
Currently statistics are poor for Q^2 = 4.5 GeV^2
(second part of experiment is scheduled)

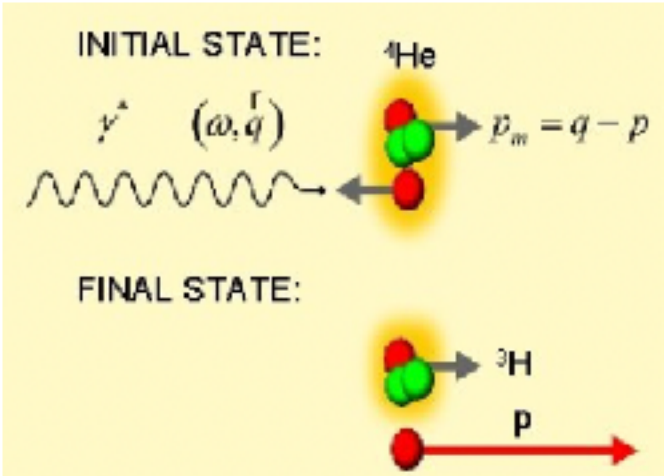


Can be pushed to Q^2 ~ 16 GeV^2

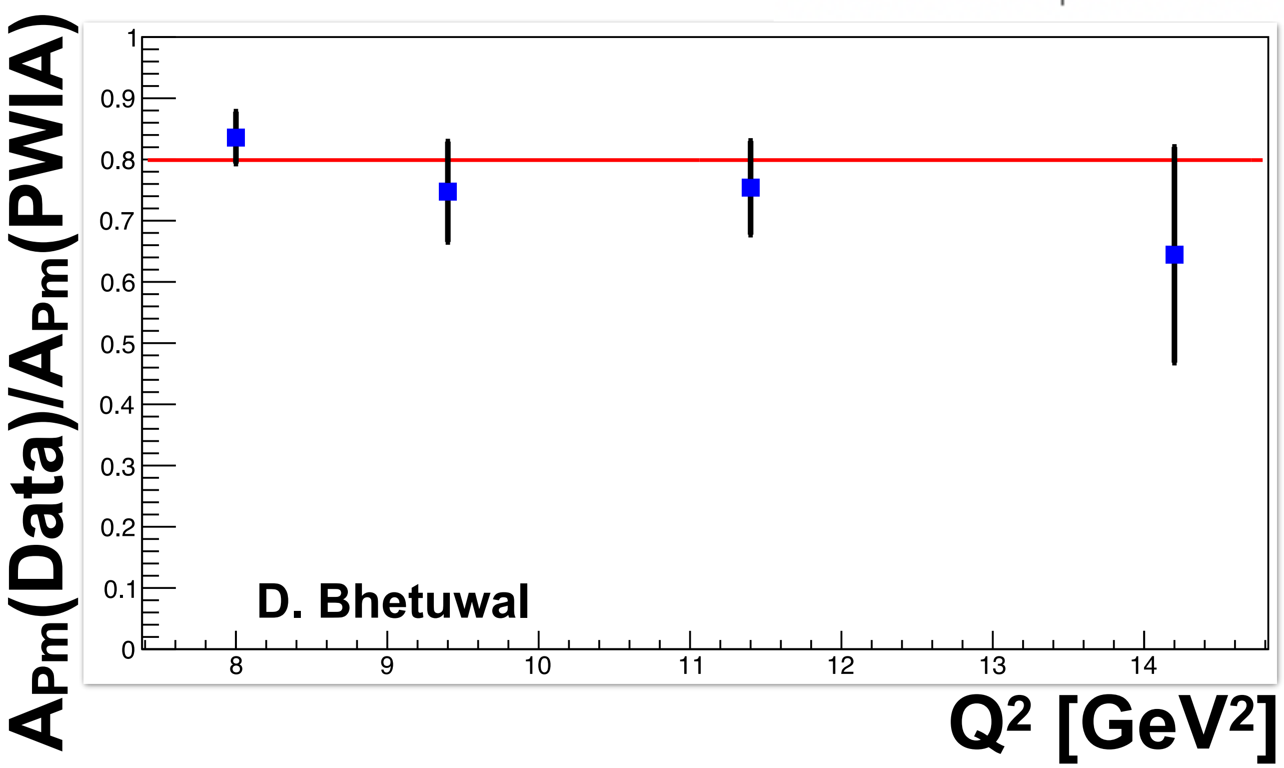
Substantial left-right asymmetry in A(e,e'p) exists even in parallel kinematics.

D. Bhetuwal et al., PRL, 126,





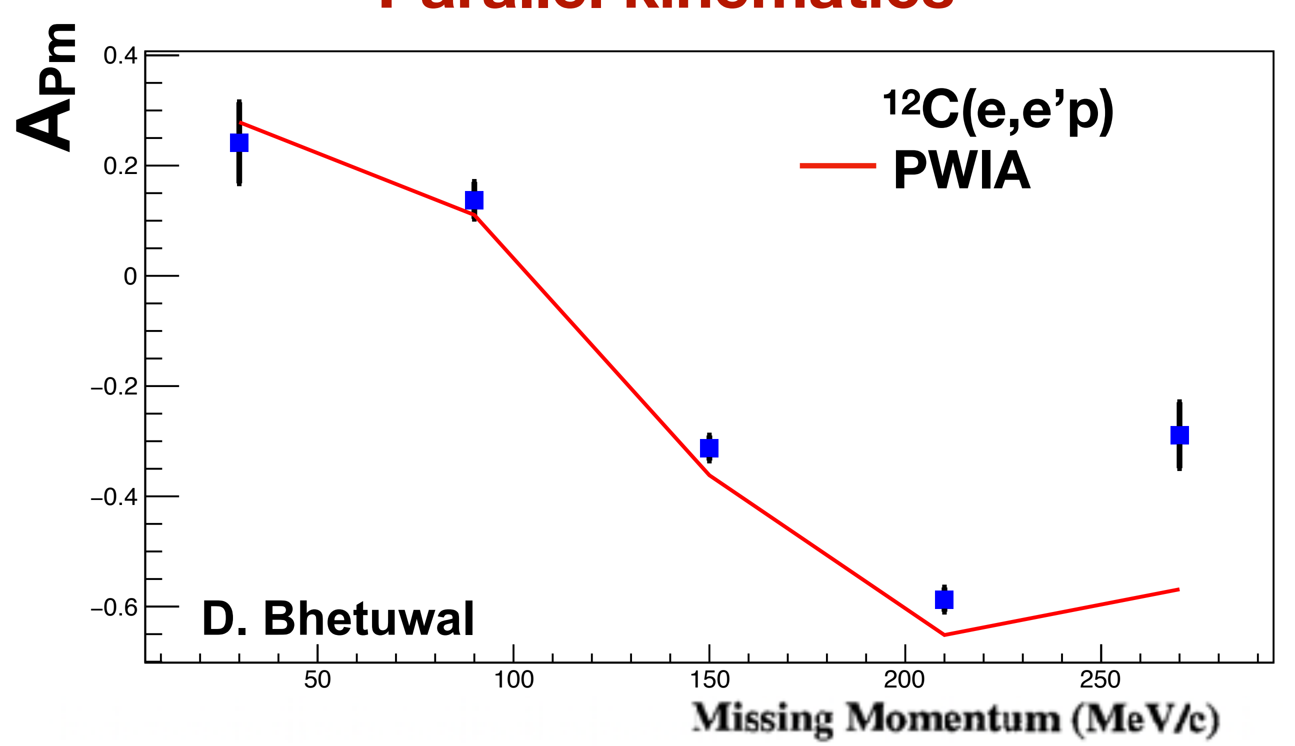
$$A_{p_m} = \frac{N_+ - N_-}{N_+ + N_-}$$



Q^2 dependence of A_{LT} consistent with PWIA in parallel kinematics

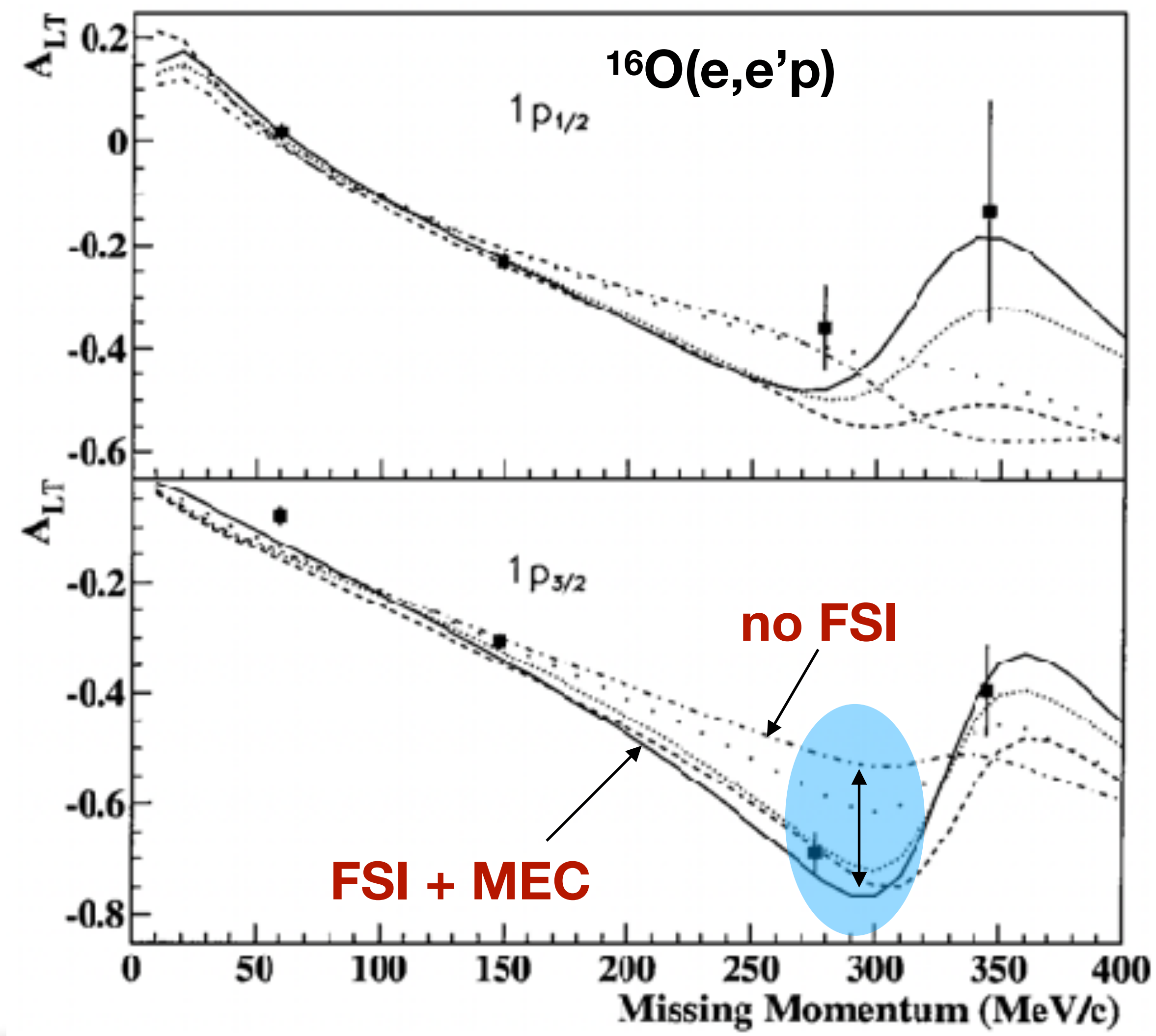
Left-right asymmetry for A(e,e'p) in perpendicular kinematics is another example of "dirty kinematics".

Parallel kinematics



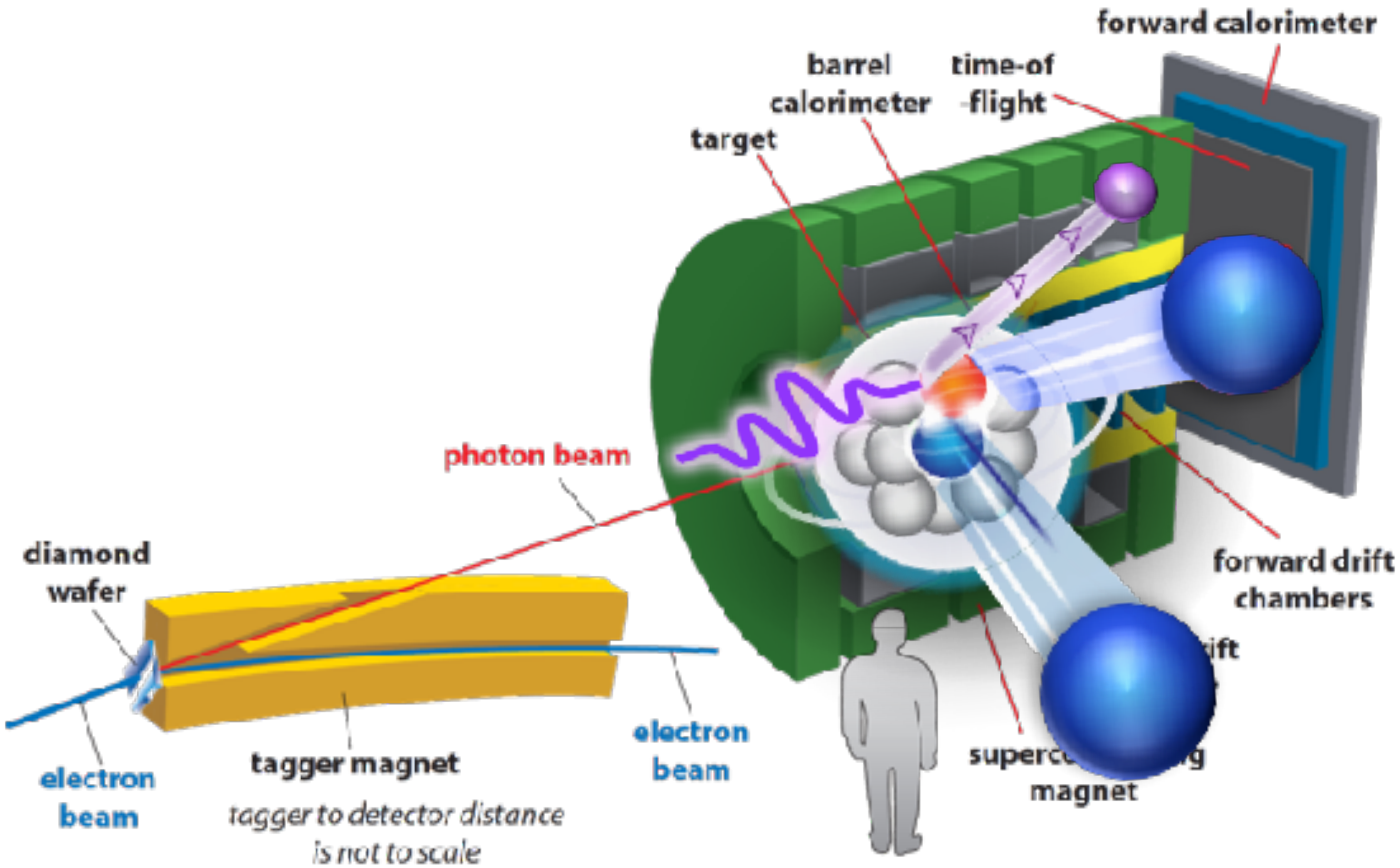
Perpendicular kinematics

J. Gao *et al.*, PRL, 84, 3265 (2000).



L-R Asymmetry is very sensitive to FSI at large P_m and away from parallel kinematics ($|\theta_{pq}| > 0$).

A new photo-nuclear program was just completed in Hall-D at JLab



Targets: D, ^{4}He, ^{12}C

Exclusive Proton Reactions	Exclusive Neutron Reactions
$\gamma + p \rightarrow \quad \pi^0 + p$	$\gamma + n \rightarrow \quad \pi^- + p$
$\gamma + p \rightarrow \quad \pi^- + \Delta^{++}$	$\gamma + n \rightarrow \quad \pi^- + \Delta^{++}$
$\gamma + p \rightarrow \quad \rho^0 + p$	$\gamma + n \rightarrow \quad \rho^- + p$
$\gamma + p \rightarrow \quad K^+ + \Lambda^0$	$\gamma + n \rightarrow \quad K^0 + \Lambda^0$
$\gamma + p \rightarrow \quad K^+ + \Sigma^0$	$\gamma + n \rightarrow \quad K^0 + \Sigma^0$
$\gamma + p \rightarrow \quad \omega + p$	x
$\gamma + p \rightarrow \quad \varphi + p$	x
…	…

8.5 GeV photons on 3 targets

Two Observables to probe photon structure, and CT:

Transparency for a given nucleus, $T = \sigma_{\gamma A} / A\sigma_{\gamma N}$

A-dependence of transparency (i.e. ratio for different nuclei)

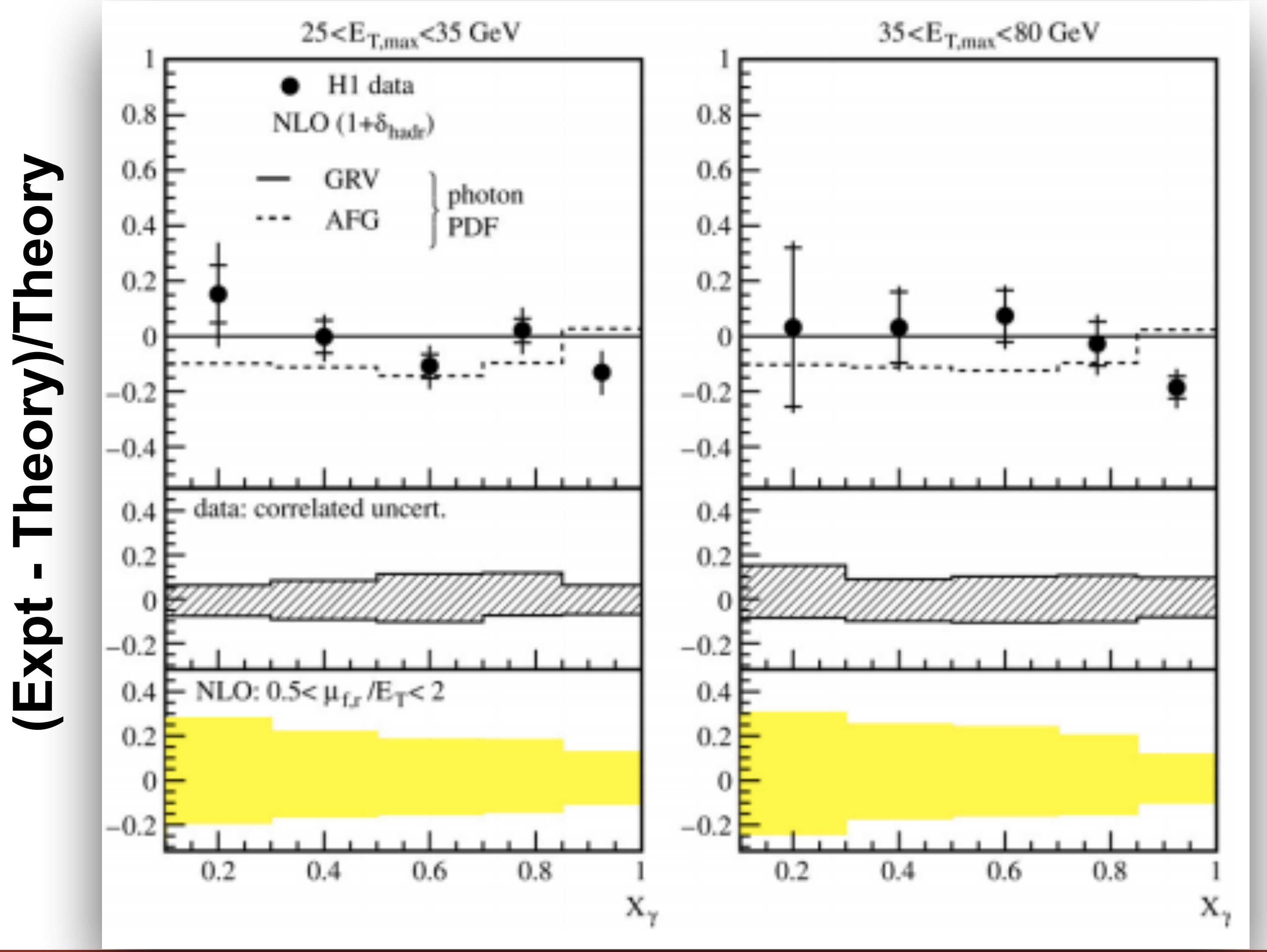
Spokespersons:
Hen, Zumila-Vance, Piasetzky, Dutta, Gao, Somov, Weinstein.

At high momentum transfers, photons fluctuate to a point like configuration.

photon structure

superposition of vector meson states
@ low momentum transfers

point like photon
@ high momentum transfers,
1/t suppression of the VM states

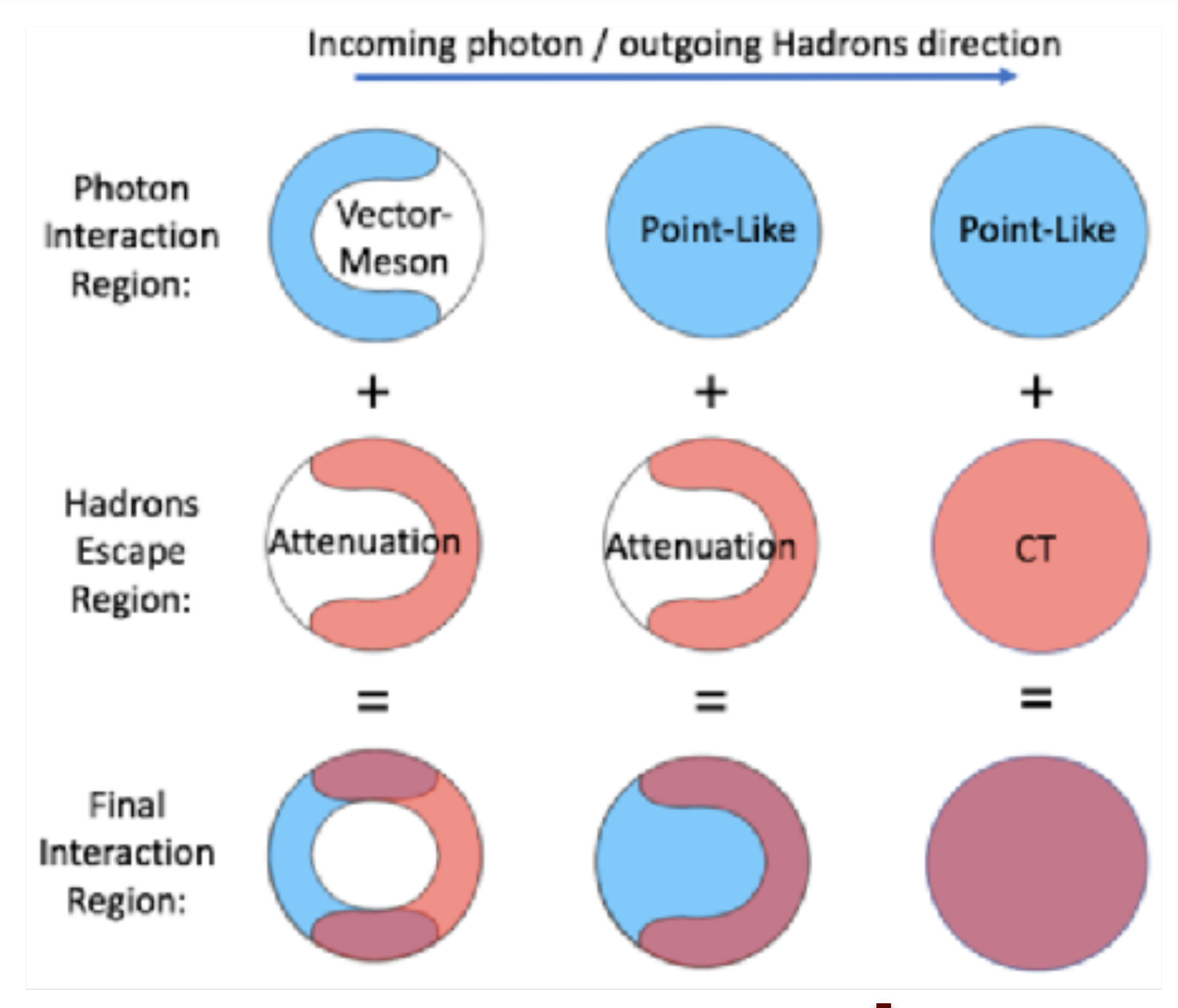


partonic description of the photon demonstrated in high energy H1 data

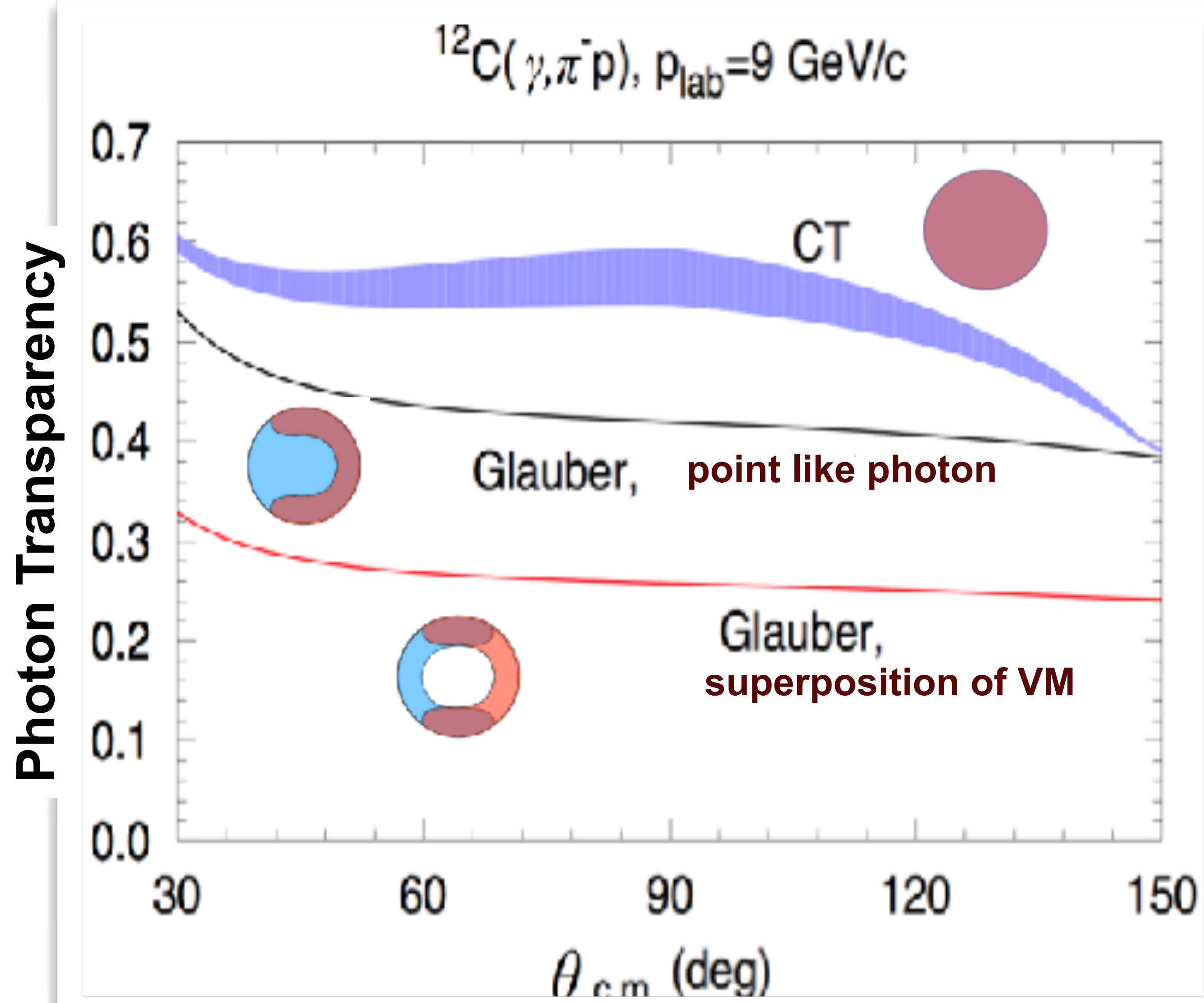
but the transition between these two regimes is unknown

A.J. Baltza et al., Phys. Rep. 458, 1 (2008)

Onset of CT may also be probed using the photo-nuclear processes.



$T = \sigma_{\gamma A} / A\sigma_{\gamma N}$

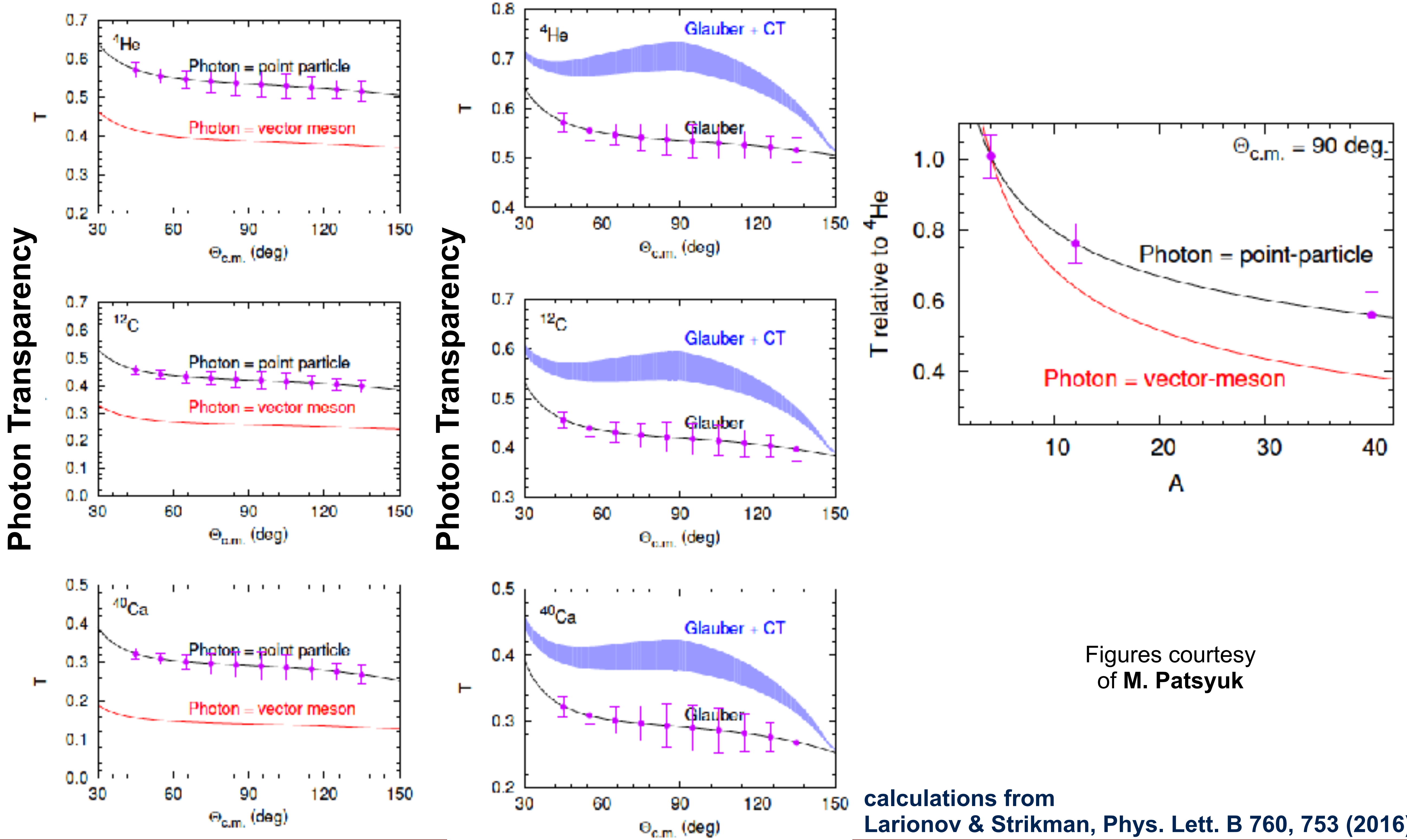


Figures courtesy of **M. Patsyuk**

Larionov & Strikman, Phys. Lett. B 760, 753 (2016).

The new photo-nuclear program should provide additional clues.

Projected transparency and transparency ratios



Figures courtesy
of **M. Patsyuk**

calculations from
Larionov & Strikman, Phys. Lett. B 760, 753 (2016).

Take Away

- The upgraded accelerator at JLab is fully operational and the extensive experimental program is underway in earnest.

- Exciting new results on the role of quarks in nuclei are trickling in and some have already been published.

- Some of these results are very puzzling.

- Look out for the deluge about to come, and move us closer to an eventual resolution to the problem of quarks in nuclei.

- A shift towards non-traditional kinematics -“dirty kinematics” seems warranted.

This work is supported by US DOE under contract #DE-FG02-07ER41528

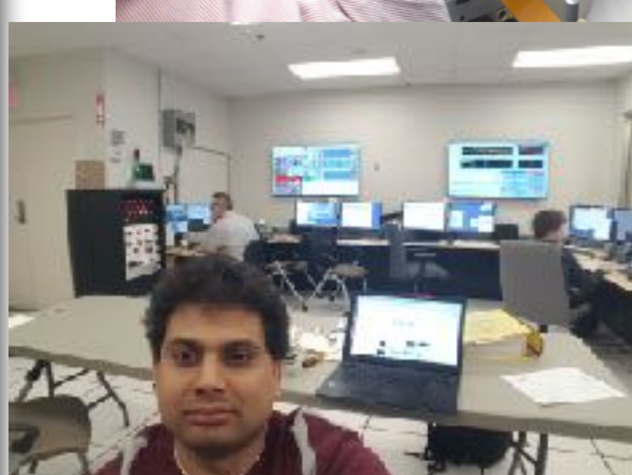
A big shout out to the army of graduate students and post docs working on these experiments.

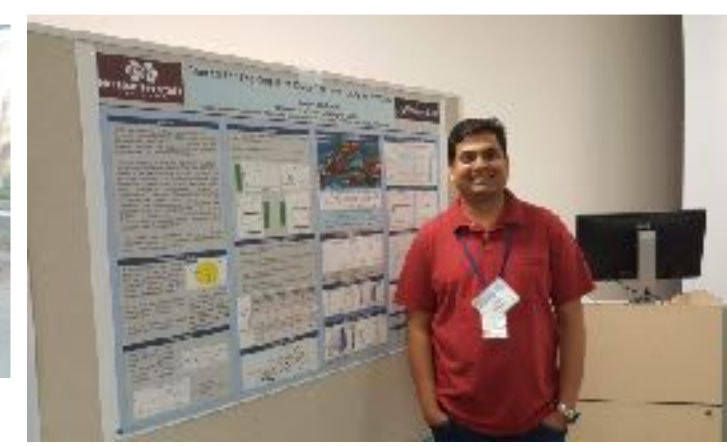
Students at Work







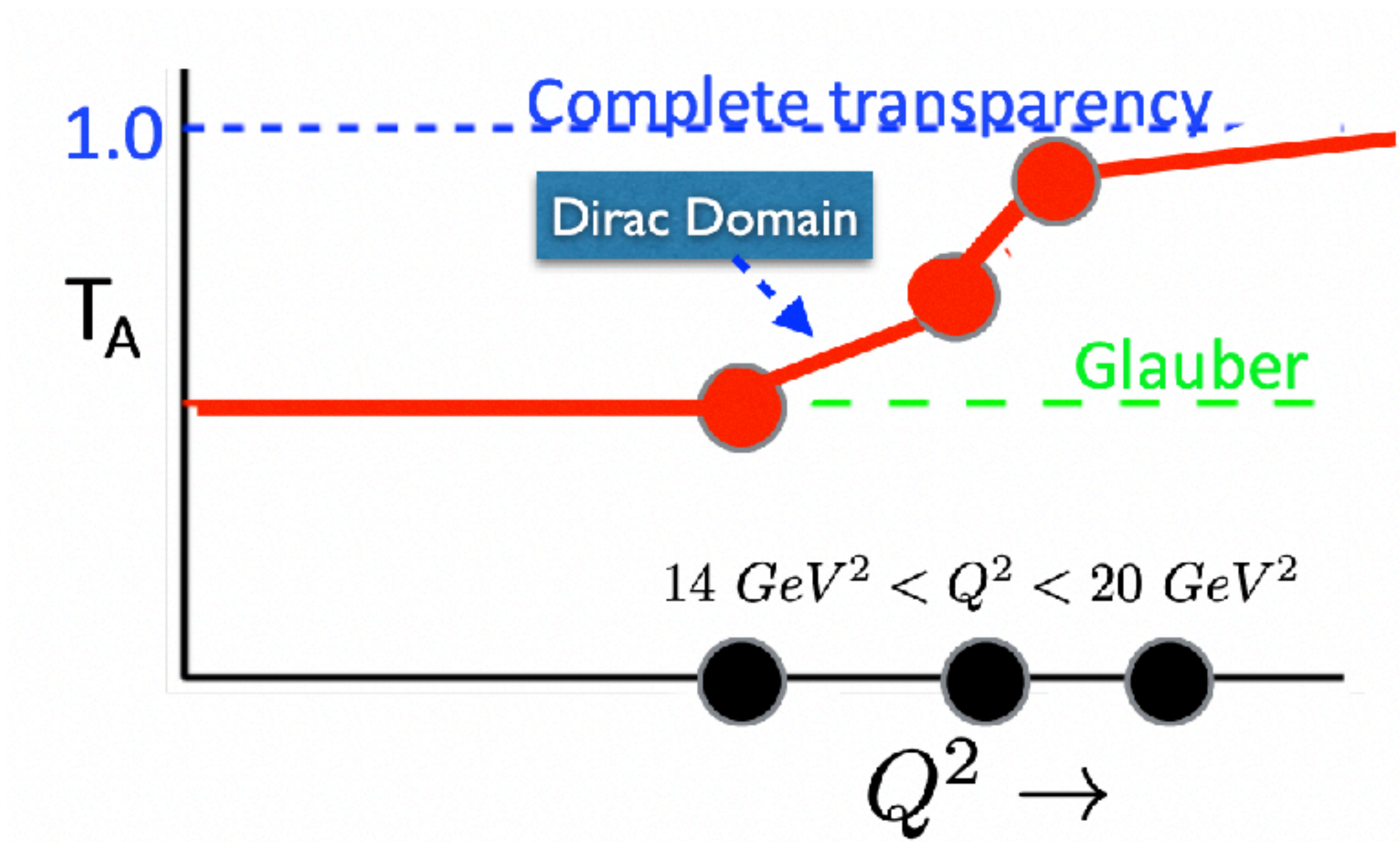



Two ideas were presented at a recent workshop on CT

Two-Stage Color Transparency

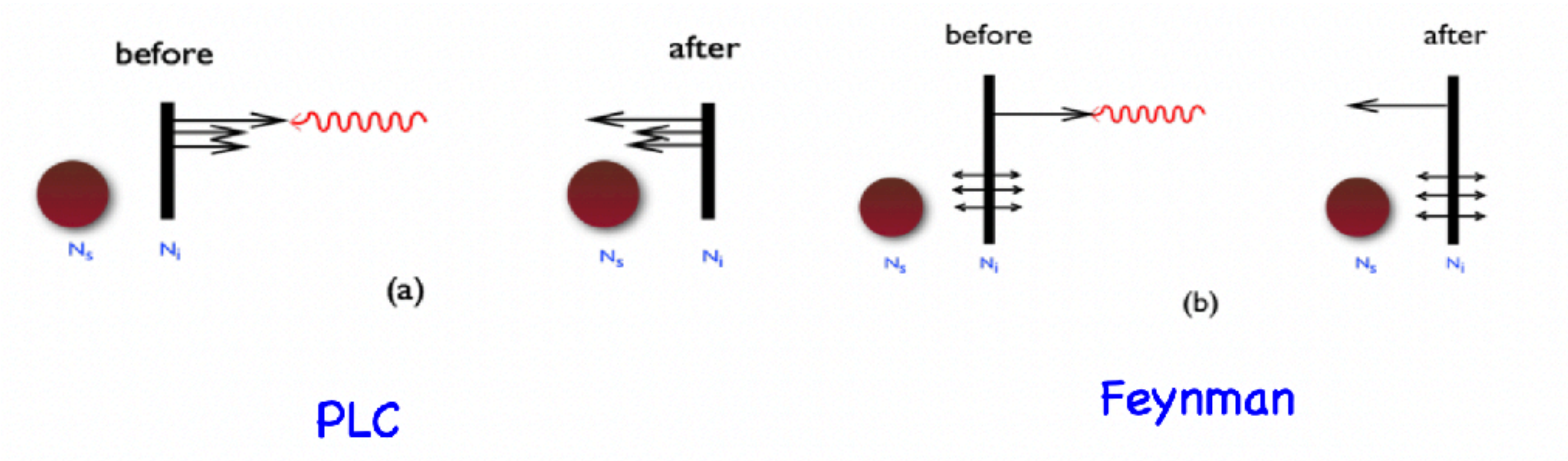
Stan Brodsky
Halographic light-front QCD



Two ideas were presented at a recent workshop on CT

Conclude PLC is not formed
Feynman mechanism is responsible for proton em form factor at high Q^2

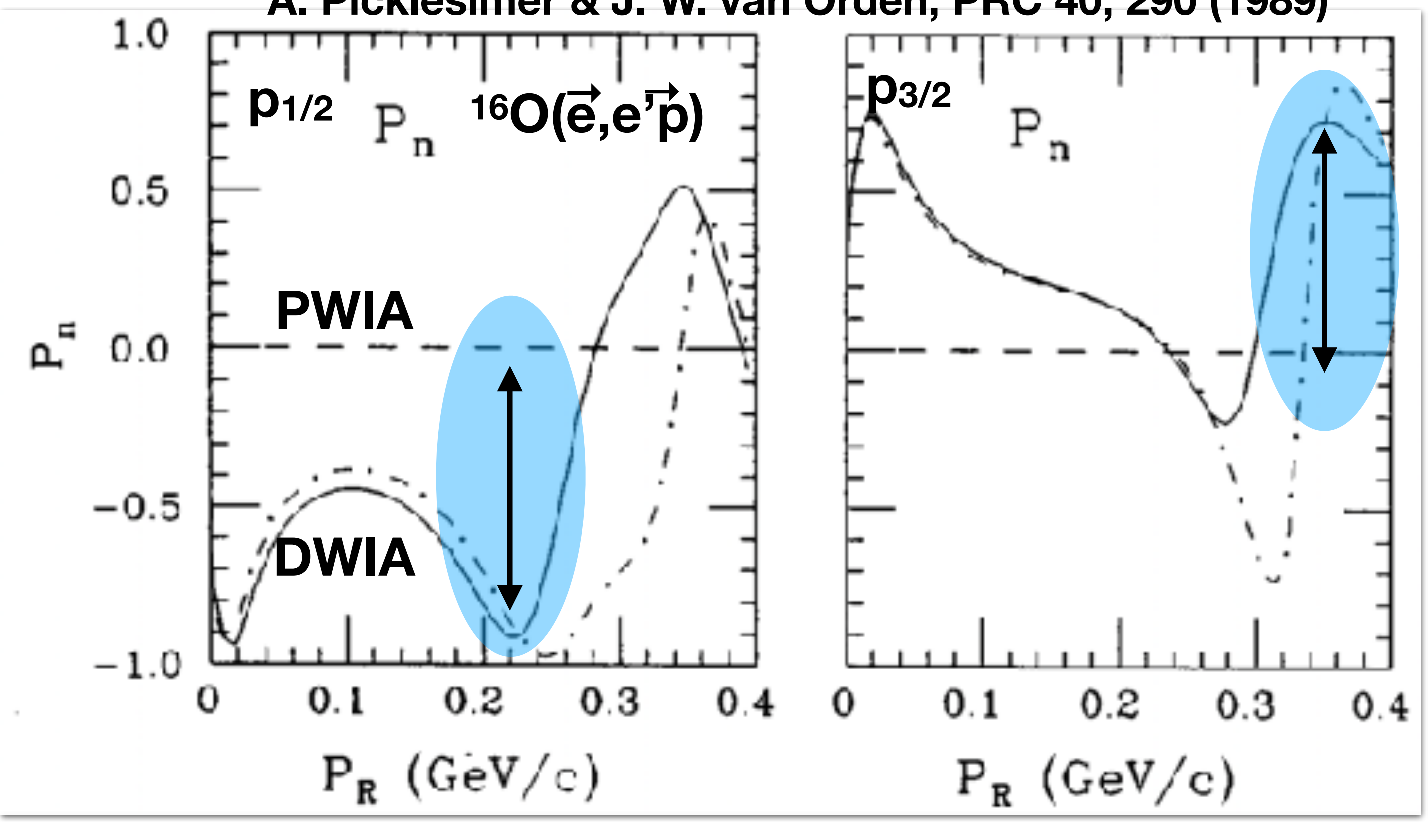
Jerry Miller



The normal component of recoil proton polarization (P_n) in A($\vec{e}$,e'$\vec{p}$) is a "FSI-meter"

$P_n = 0$ (in the absence of medium effect) ⇒ can be used as FSI filter

A. Picklesimer & J. W. van Orden, PRC 40, 290 (1989)



For in-plane kinematics: cosβ = nπ, and summing over helicities

$$\frac{d^3\sigma}{d\omega d\Omega_e d\Omega_p} = \sigma_0[1 + P_n]$$

$$\sigma_0 = K[v_L R_L + v_T R_T + v_{TT} R_{TT} \cos 2\beta + v_{LT} R_{LT} \cos\beta]$$

$$P_n = \frac{K}{\sigma_0}[v_L R_L^n + v_T R_T^n + v_{TT} R_{TT}^n \cos 2\beta + v_{LT} R_{LT}^n \cos\beta]$$

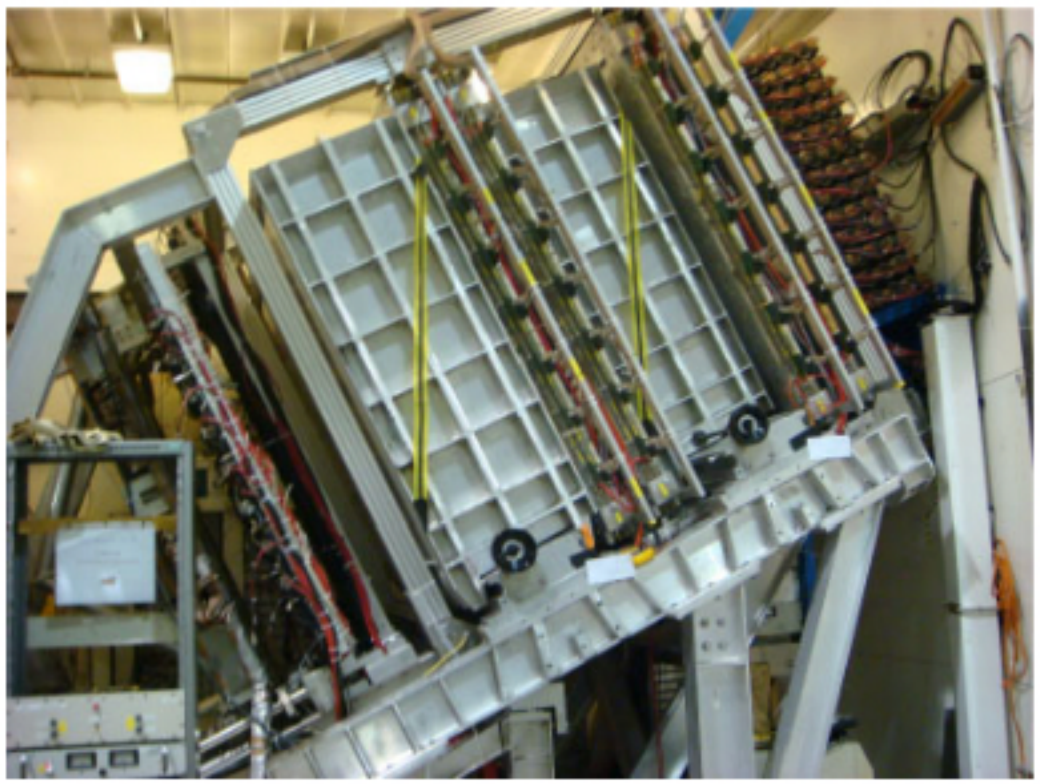
$$K = \frac{m|\vec{p}\,'|}{2(2\pi)^3}\left[\frac{d\sigma}{d\Omega_e}\right]_{Mott}$$

"Dirty kinematics" = large P_R

Signature of CT: Pn → 0 with increasing Q^2

The normal component of recoil proton polarization (P_n) in $A(\vec{e},e'\vec{p})$ is a "FSI-meter"

Focal Plane Polarimeter in SHMS to measure the P_n for ^2H, ^{12}C and ^{63}Cu.
p(e,e'p) for self-calibration (analyzing power, A_c) and false asymmetry.
Use proton form factors already measured.



$$\Delta P_n = \frac{\pi}{2}\sqrt{\frac{1}{N_\sigma \epsilon}}$$

$\epsilon = A_c^2 f$;

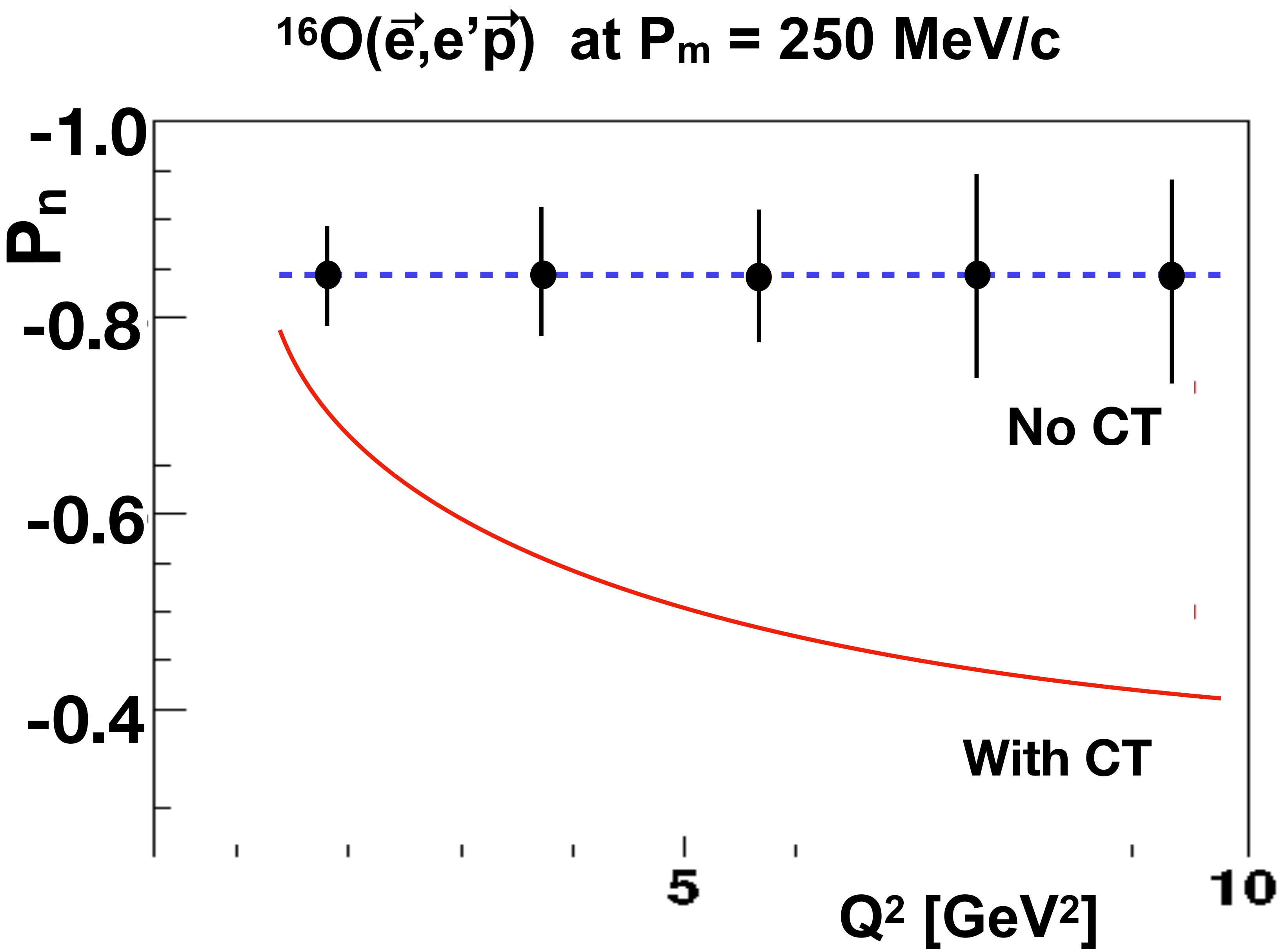
f = useful fraction of events in the FPP acceptance

Using efficiency ~ 0.003 and $\Delta P_n < 0.1$
a Q^2 range of 1 - 10 GeV^2 can be scanned
in about 500 hrs.

Signature of CT: $P_n \to 0$ with increasing Q^2

A. Saha et al., PR 91-006, Hall A proposal.
Anklin H. et al., The ELFE Project: an Electron Laboratory for Europe, Conference Proceedings, Vol. 44, p.223 (1993)

P_n in $A(\vec{e},e'\vec{p})$ at large missing momentum as a function of Q^2 will be an ideal observable.



Using ϵ ~ 0.003 and ΔP_n < 0.1, a Q^2 range of 1 - 10 GeV^2 can be scanned in about 500 hrs.

Signature of CT: $P_n \rightarrow 0$ with increasing Q^2