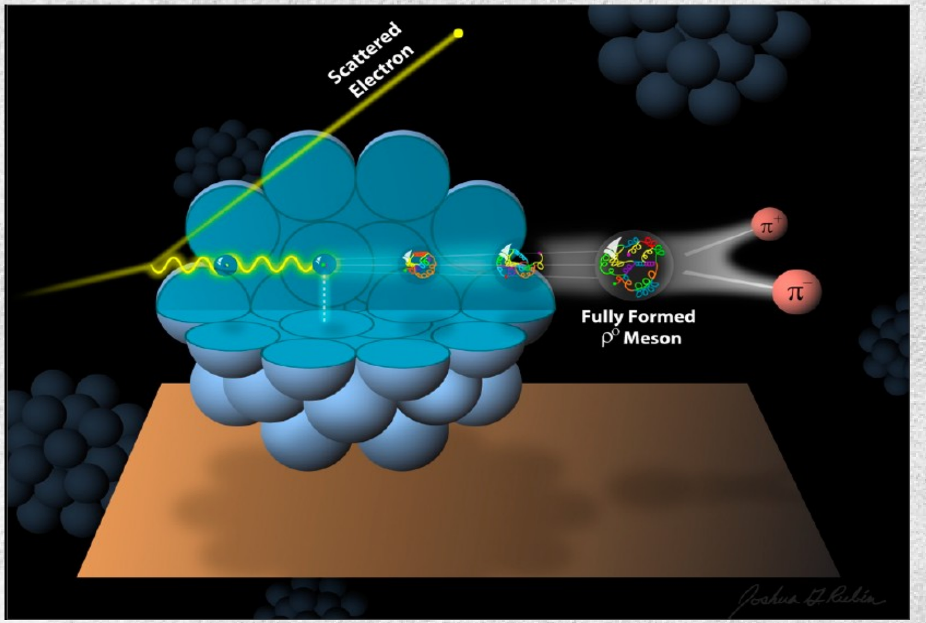
PAC-48 Jeopardy Update: RG-D Experiment
Study of Color Transparency in Exclusive Vector Meson Electroproduction off Nuclei



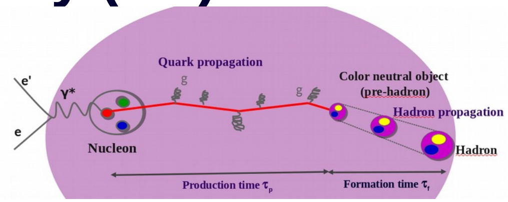
Lamiaa El Fassi
For the Run Group and the CLAS Collaboration

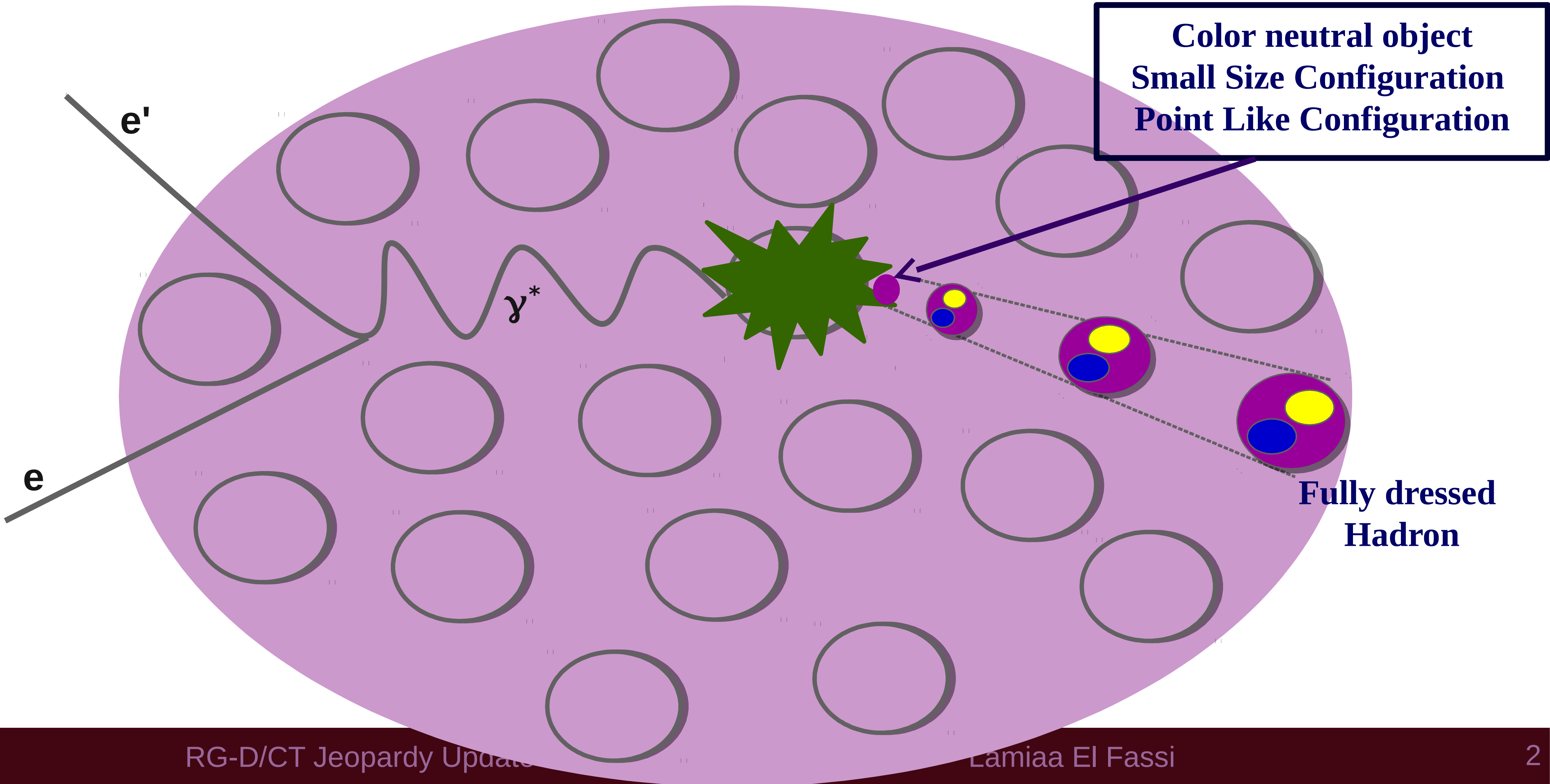
September 25th, 2020

RG-D Addition: Nuclear TMDs in CLAS12 (E12-06-106A)(R. Dupré *et al.*)
Endorsed by PAC-48

Probes of QCD Signatures in Nuclei

- Study hard processes in nuclei to probe the QCD confinement dynamics:
  - Creation and evolution of small size hadrons - **color transparency (CT)**
  - Color propagation and fragmentation - **Hadronization process** (See W. Brooks talk).

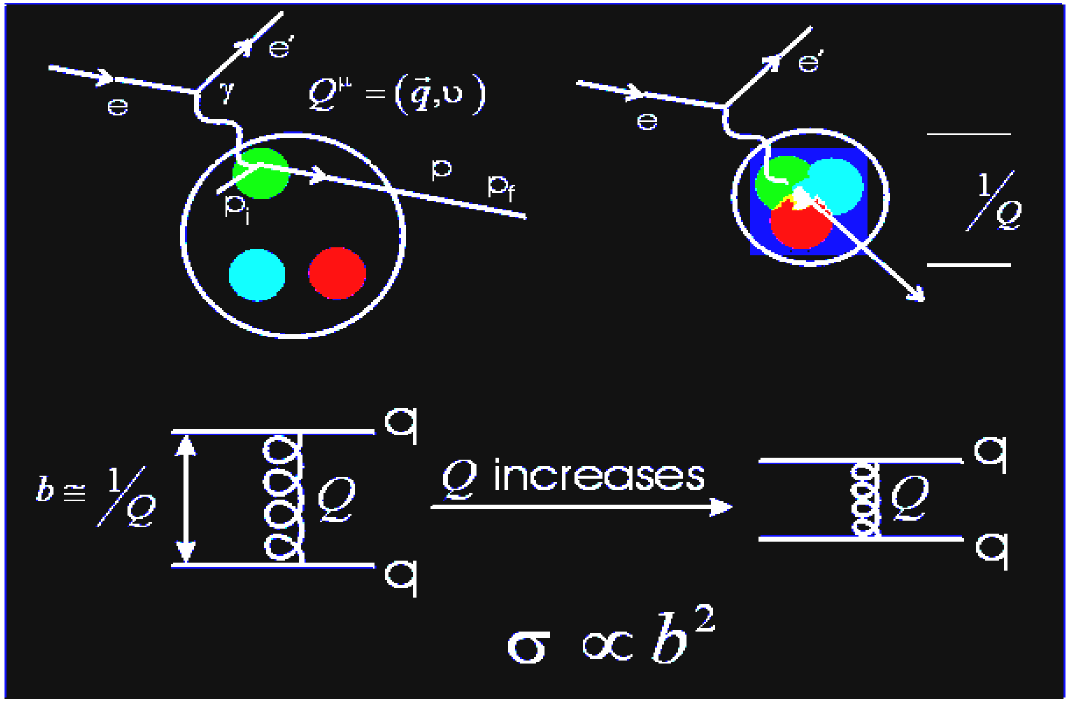




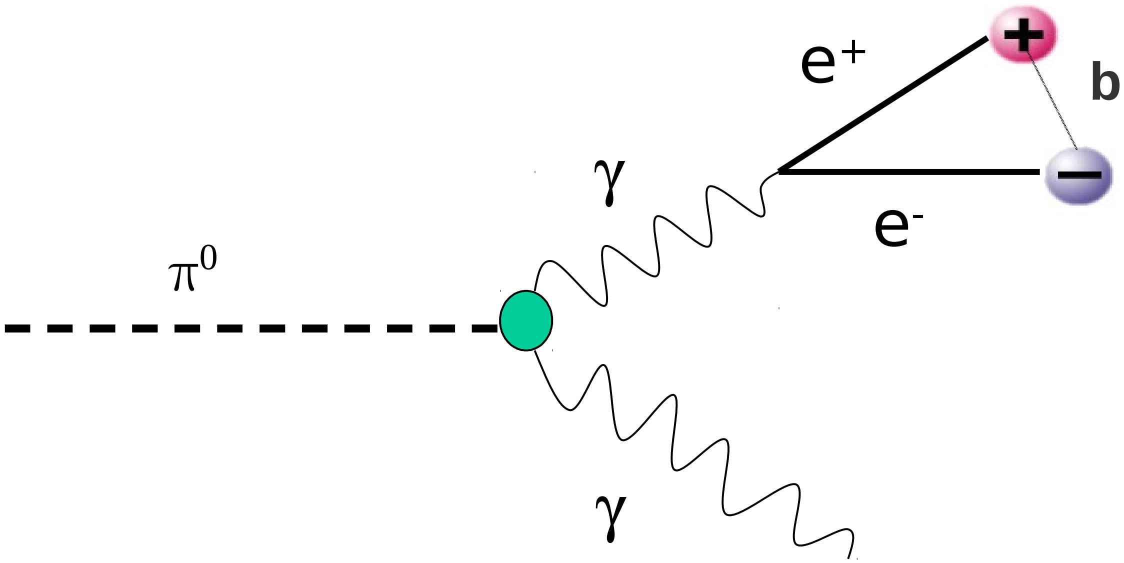
CT Basics: The Survival of the Smallest!

- Creation of small size configurations (SSC) in hard and exclusive reactions,
- SSC experiences reduced attenuation before evolving to the fully dressed hadron,

QCD Color Screening: Squeezing and freezing



QED Charge Screening



200 GeV π^0 emulsion produced in cosmic rays (Perkins 1955)

- In QCD, the color field of singlet objects vanishes as their size is reduced.

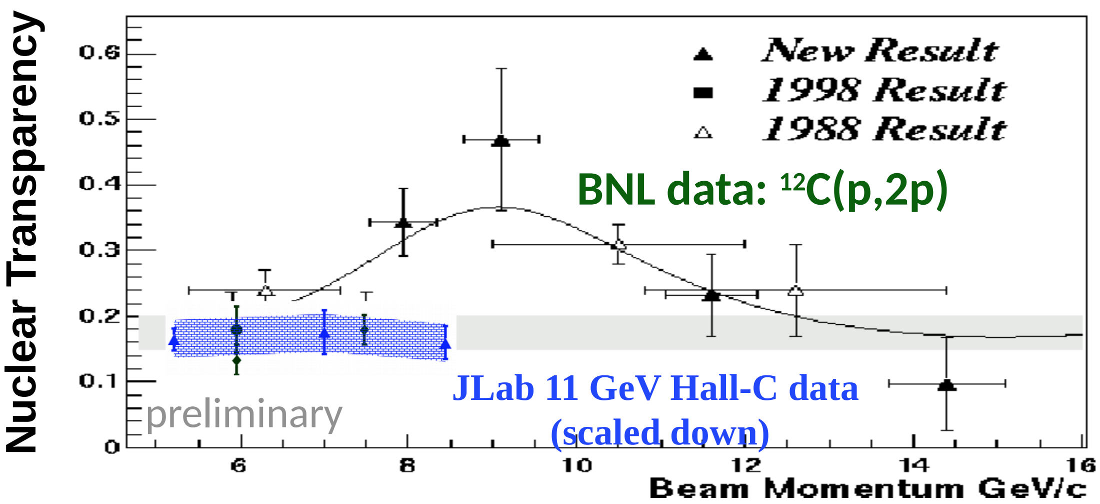
- The SSC expansion length is at least as large as the nuclear radius.

Highlights of CT Studies

Baryon

- A(p, 2p) BNL
- A(e, e′p) SLAC, MIT-Bates and JLab

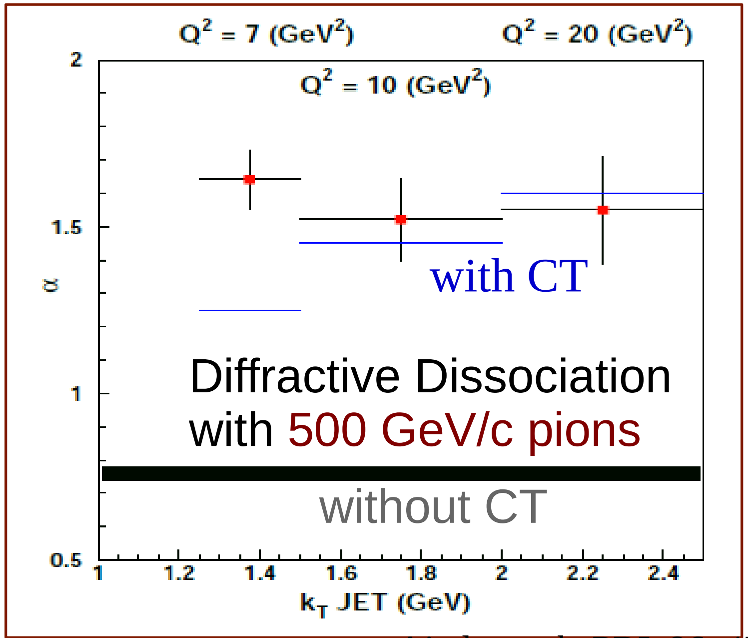
All CT results in the baryon sector were deceiving!



Plot courtesy of D. Dutta

Meson

- A(π, di-jet) FNAL
- A(γ, π⁻p) JLab
- A(e, e'π⁺) JLab
- A(μ, μ'ρ⁰) FNAL
- A(e, e′ρ⁰) DESY & JLab



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

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

qqq versus qq-bar systems

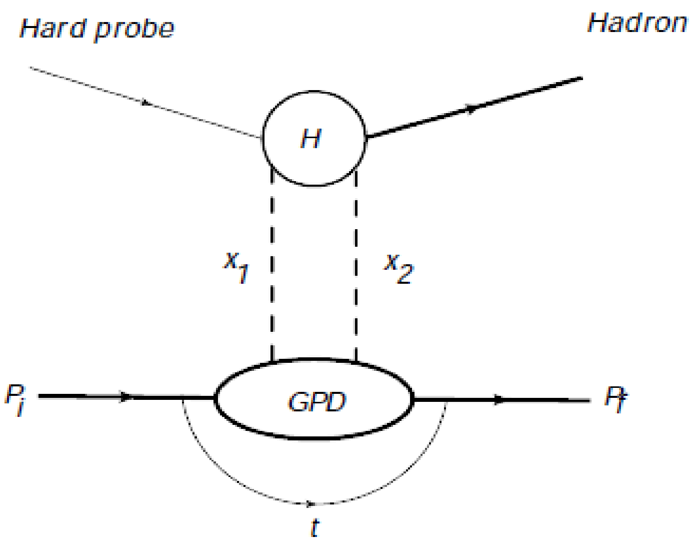
- **Small size is more probable in two-quark systems such as pions** and **rho mesons than in protons**.

B. Blattel et al., PRL 70, 896 (1993)

- **Onset of CT** is expected at **lower Q^2 in qq-bar system**.

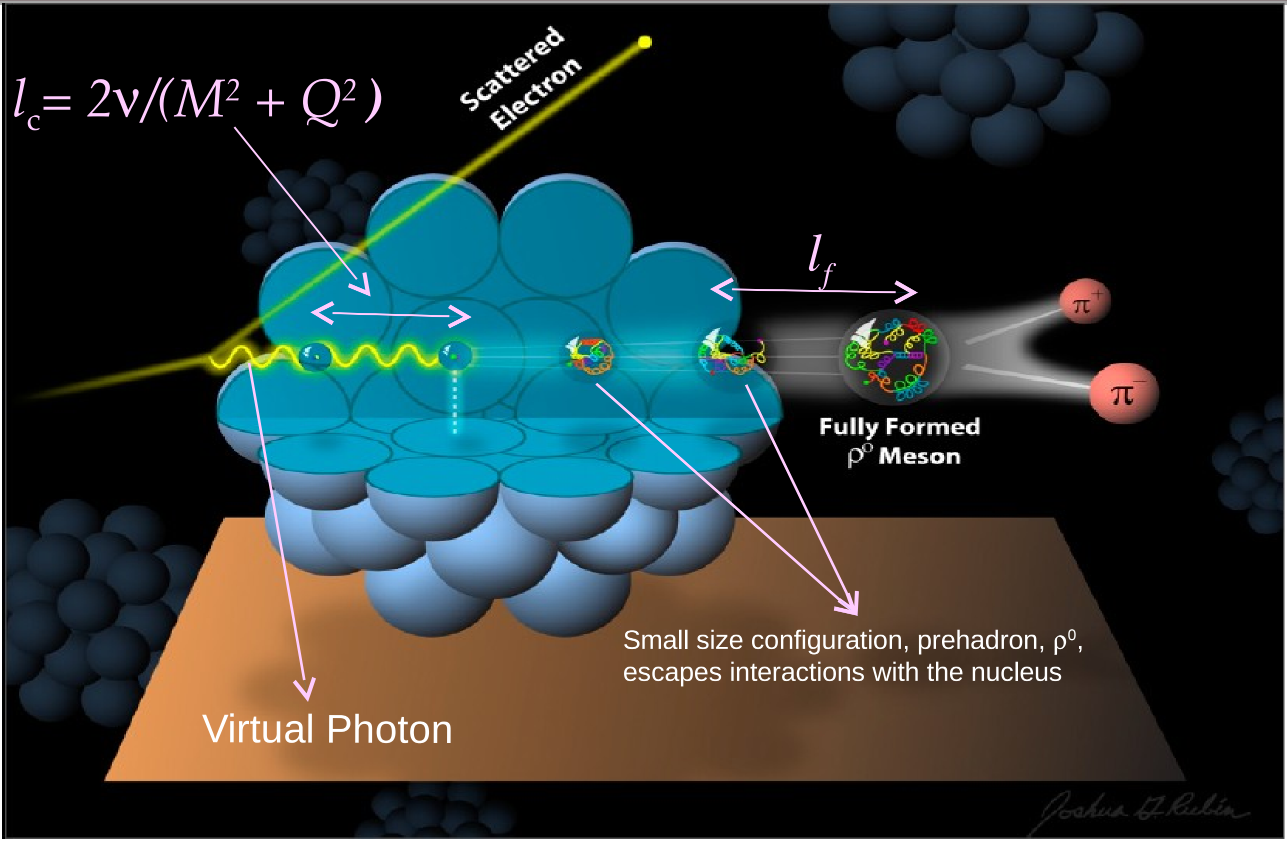
- **Onset of CT** is crucial to test the validity of the **factorization theorem** (GPDs framework), and determine **its onset** for exclusive meson production in deep inelastic scattering.

Collins, Frankfurt, Miller, Sargsian and Strikman



Process amplitude factorizes into a hard interaction with a single quark and a soft part parametrized as Generalized Parton Distribution functions (GPDs).

CT Study in Exclusive Diffractive ρ^0 Electroproduction

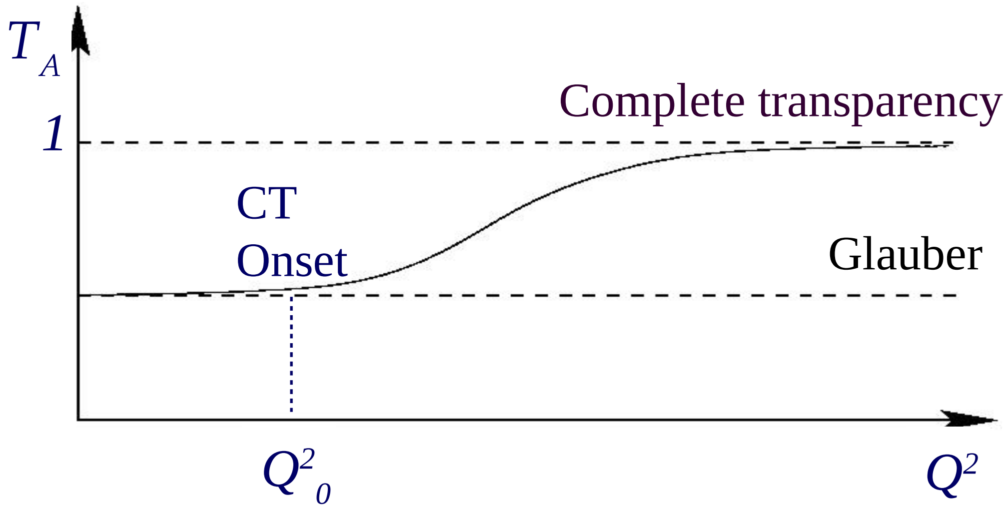


- The CT signature is the increase of the medium "nuclear" transparency, T_A, as a function of the four-momentum transfer squared, Q^2.

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

σ_A is the nuclear cross section

σ_N is the free (nucleon) cross section



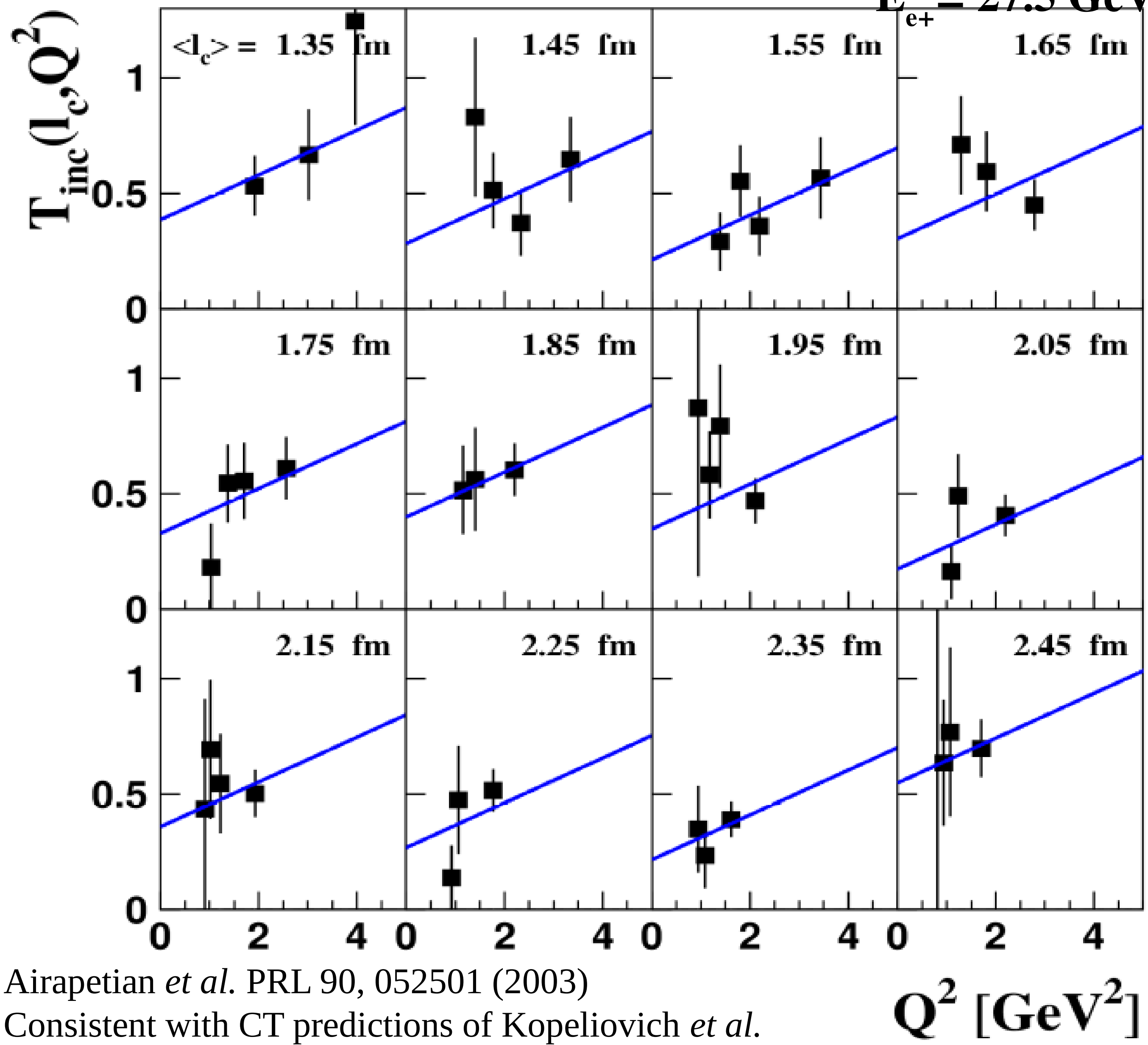
- Coherence length, l_c: the lifetime of the qq-bar pair.
- Formation time, l_f: the time needed for the small size configuration to evolve to an on-shell ρ^0 meson.

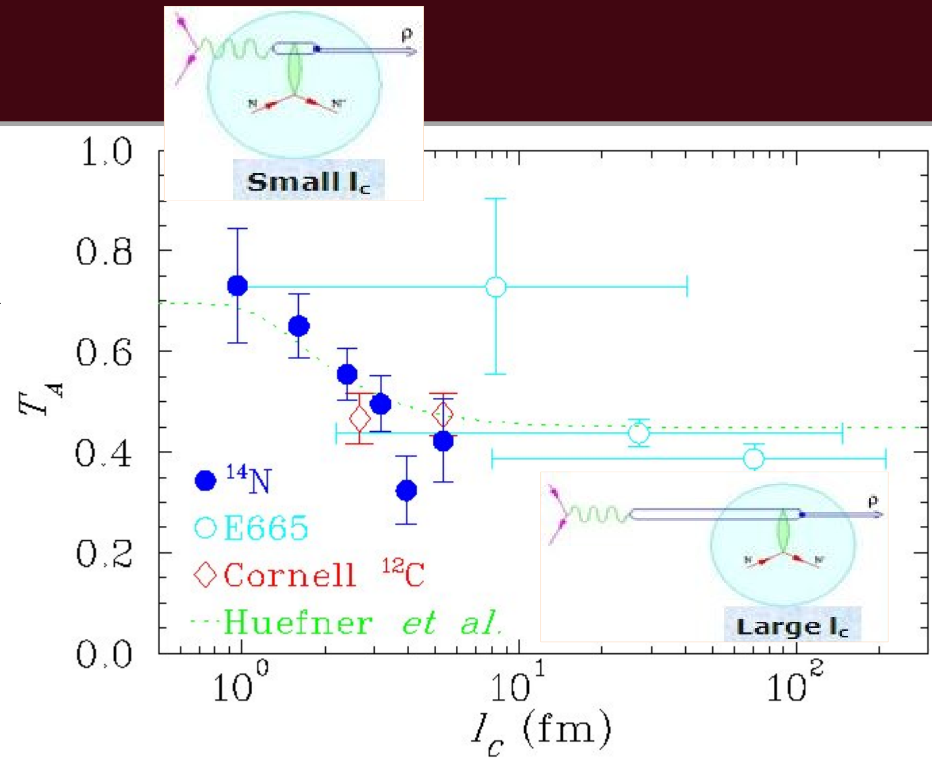
Exclusive ρ^0 Leptoproduction: Hermes

- HERMES ^{14}N Data: $T_{inc}(l_c, Q^2) = P_0 + P_1 Q^2$

  $P_1 = (0.089 \pm 0.046_{stat} \pm 0.008_{sys})\ (\text{GeV}^{-2})$

$E_{e+} = 27.5$ GeV

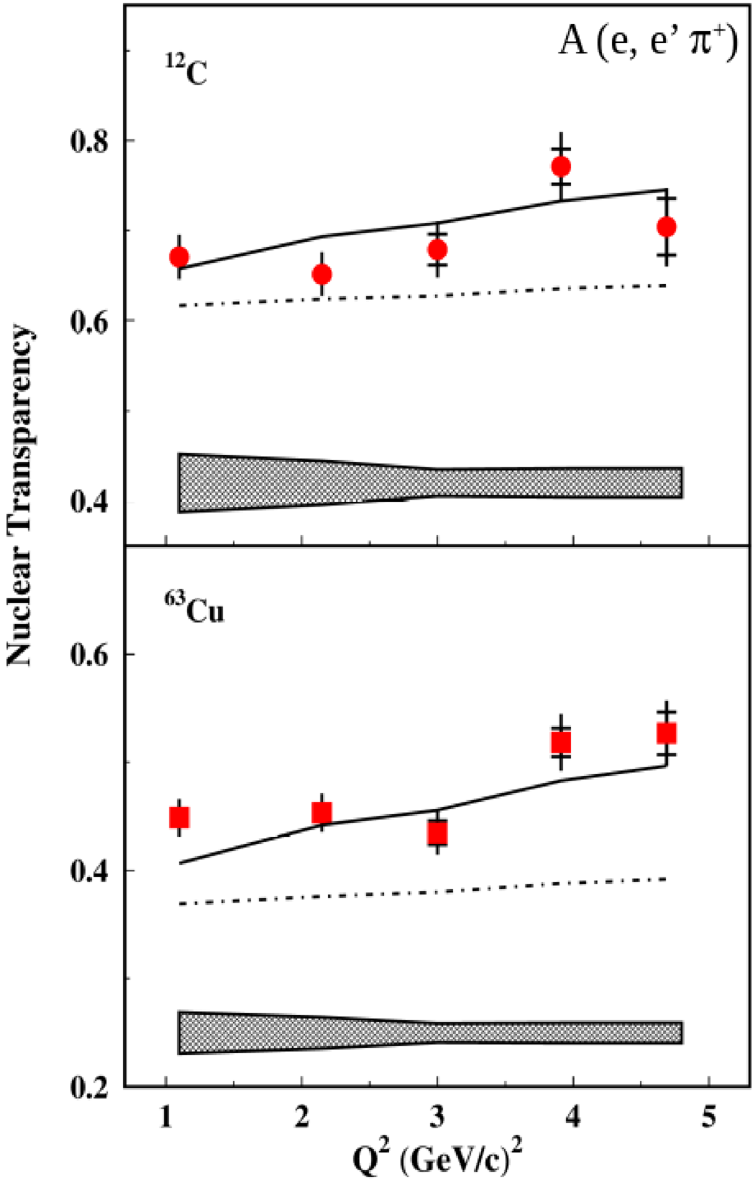




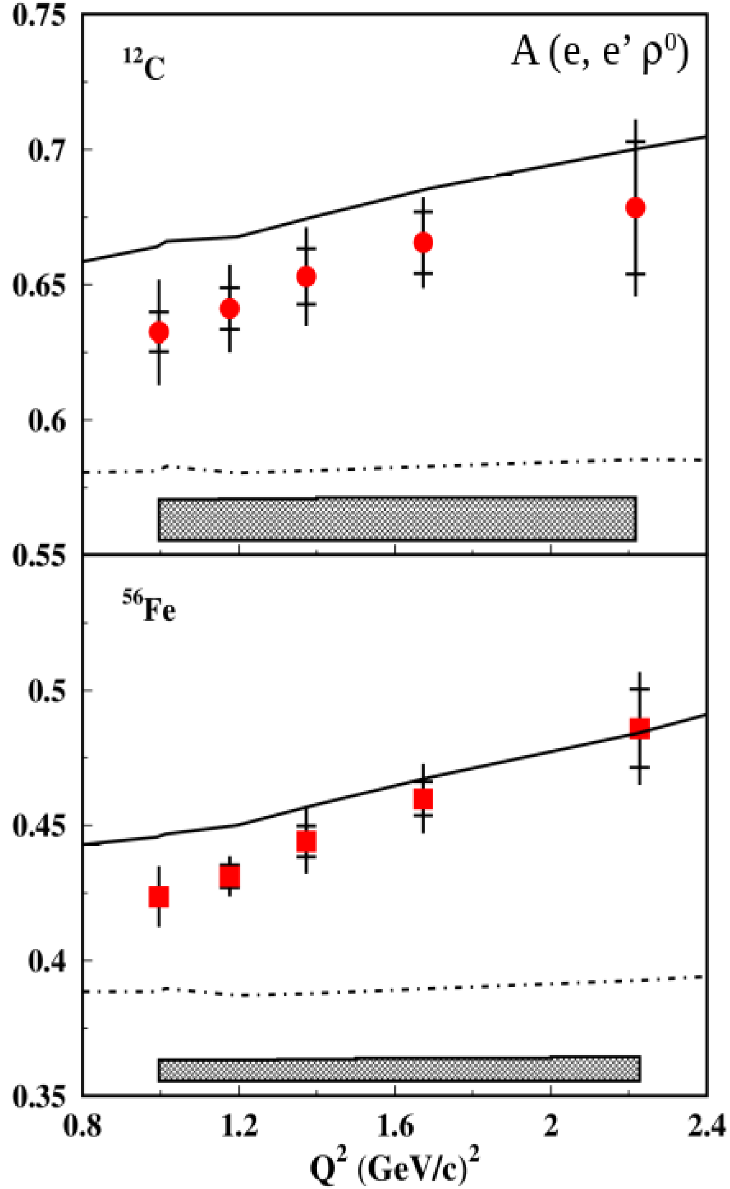
- Coherence length (CL) could mimic the CT with increasing Q^2, decreasing $l_c = 2\nu/(M^2 + Q^2)$.
- To exclude CL, the Q^2 dependence of T_A must be measured at small or fixed l_c.

Airapetian *et al.* PRL 90, 052501 (2003)
Consistent with CT predictions of Kopeliovich *et al.*

JLab CT Results at 6 GeV Era

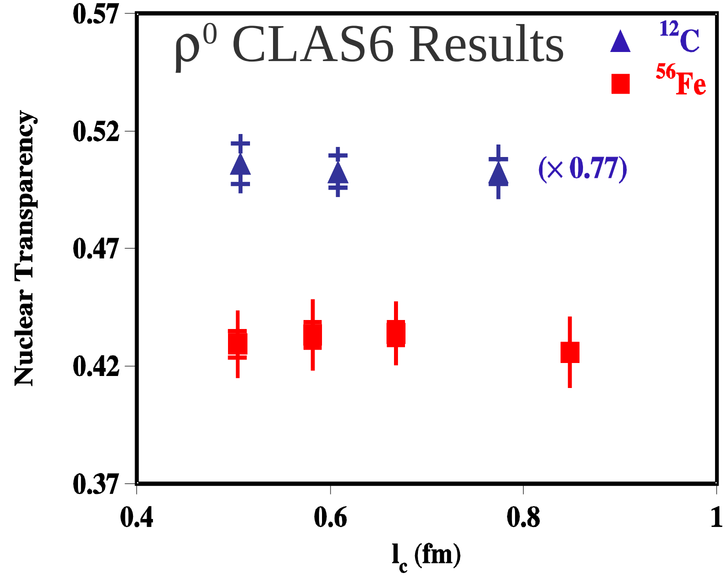


B. Clasie *et al.* PRL 90, 10001 (2007)

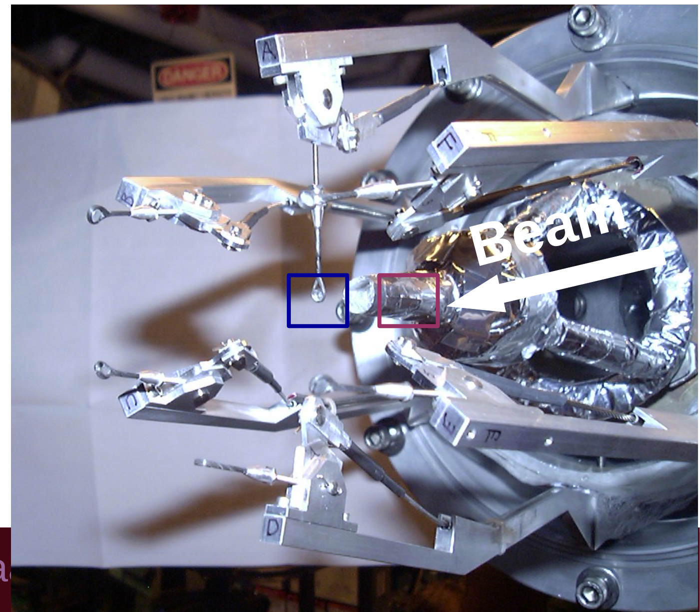


L. El Fassi *et al.* PLB 712, 2012

No l_c dependence observed



Target Setup for CLAS6 ρ^0 Experiment

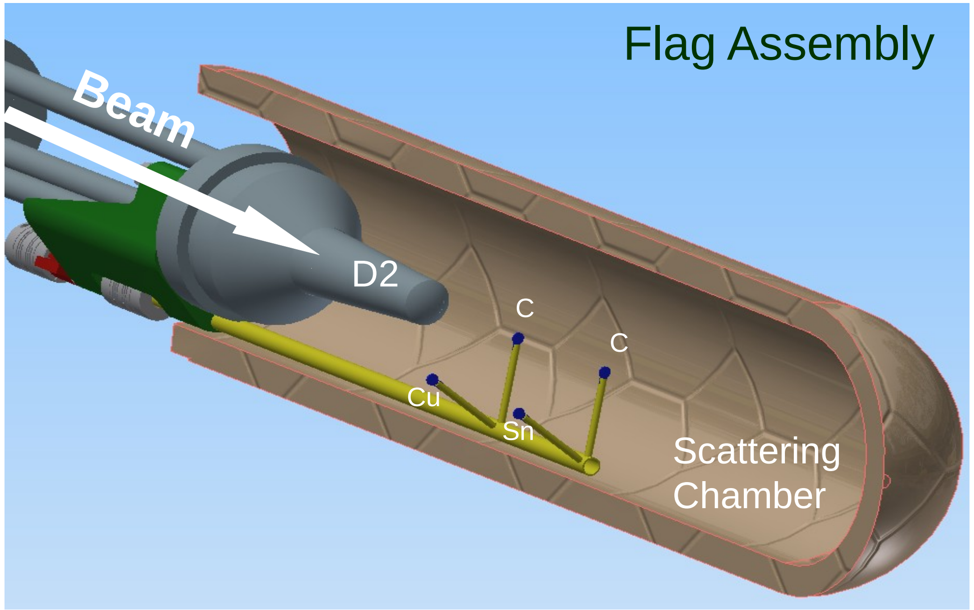


The π^+ CT extension to Q^2 of about 10 $(GeV/c)^2$ successfully passed the PAC-47 Jeopardy review.

Updated 11 GeV CT Run Plan & Projections for New Target Flag Assembly

- Adjusted run plan to dedicate beam time for the separate cryo-target and solid targets runs (*modified solid foils' thicknesses to respect the 2% radiation length requirement*):

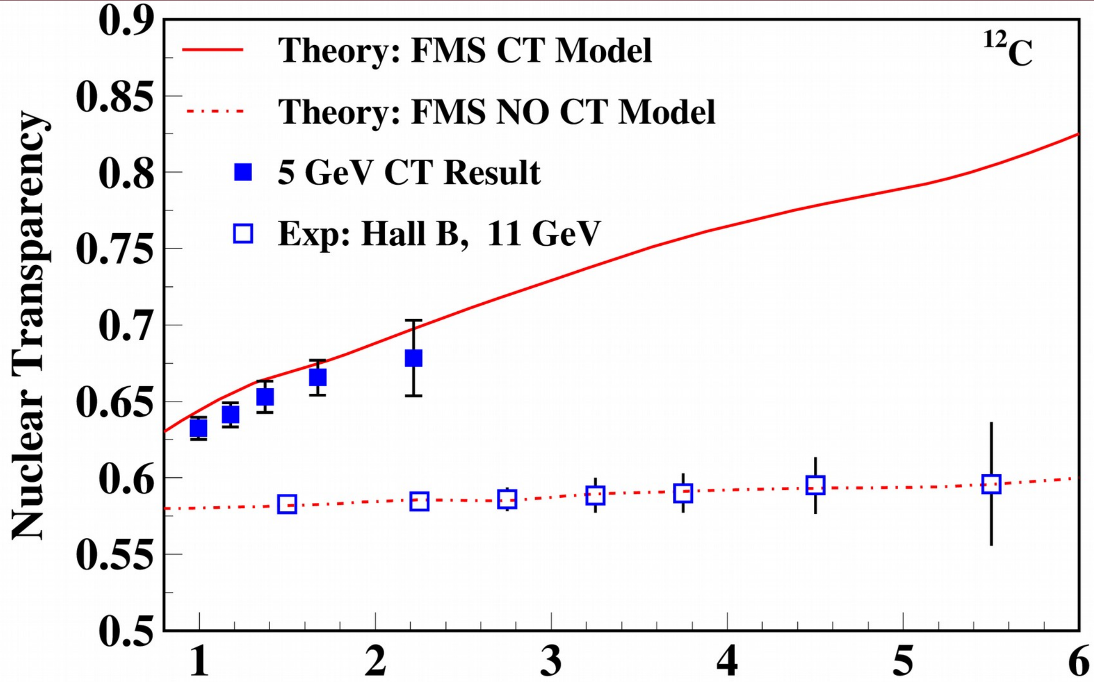
Targets/Plan	Beam Time (PAC days)
^{12}C / ^{12}C (each 0.185 cm thick)	14
LD_2	14
^{63}Cu / ^{118}Sn (0.009/0.018 cm thick)	28
LH_2	4

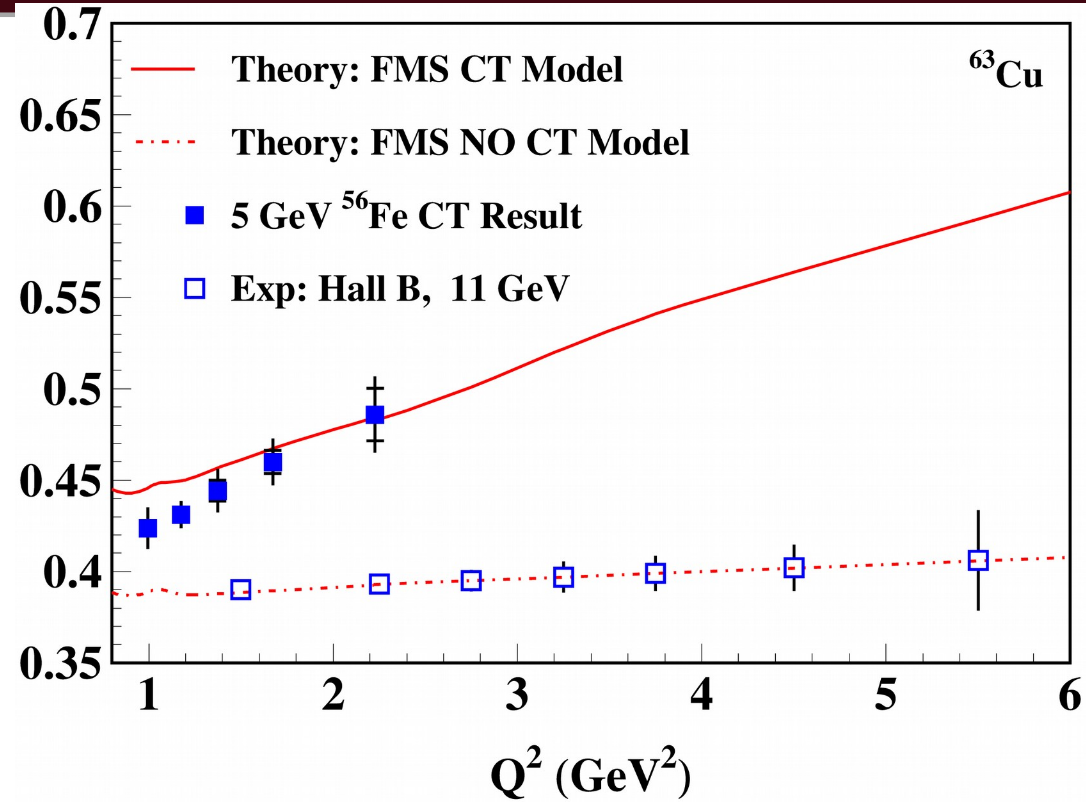


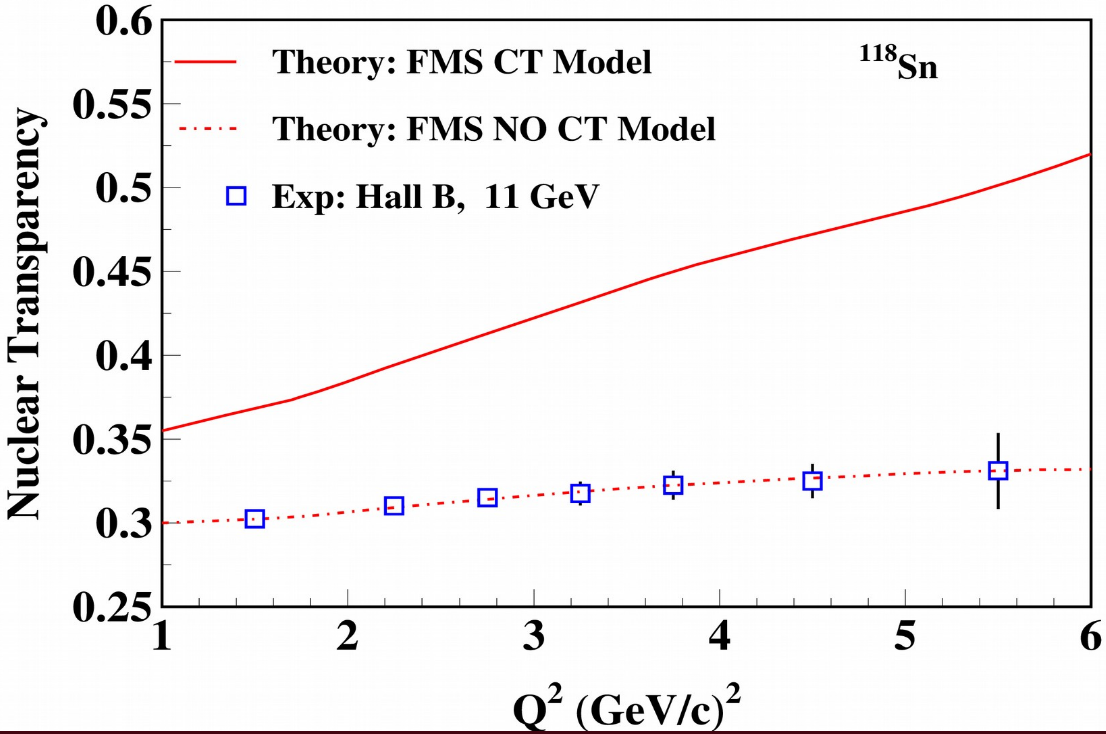
- Expected statistical precision for the new run plan and one coherence length bin (0.4–0.5 fm):

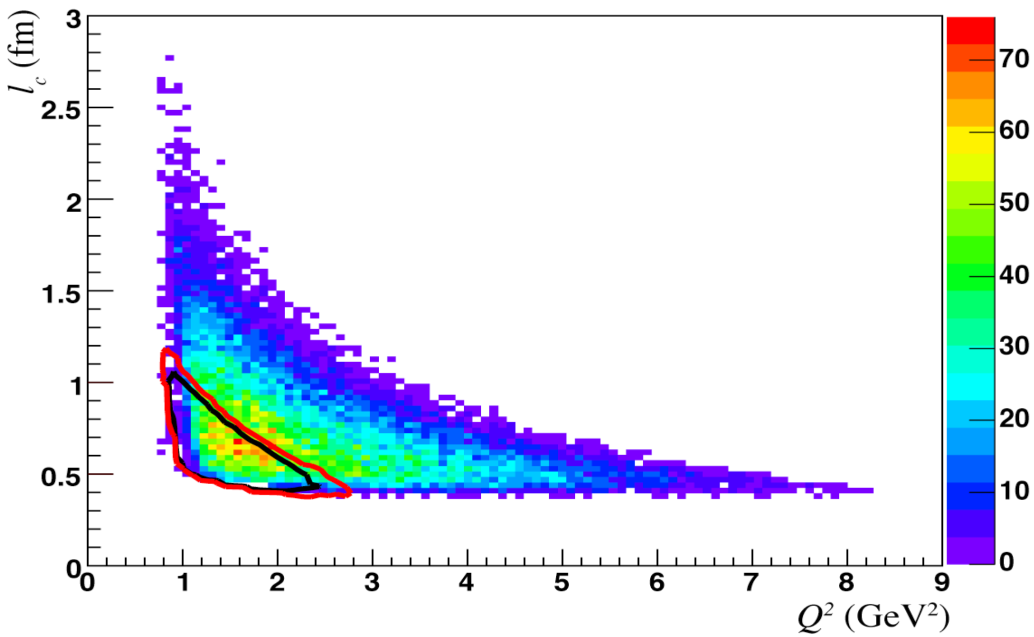
Q^2(GeV^2) / Targets	1.5 ± 0.5	2.25 ± 0.25	2.75 ± 0.25	3.25 ± 0.25	3.75 ± 0.25	4.5 ± 0.5	5.5 ± 0.5
^{12}C (%)	0.8	1.1	1.3	2.0	2.2	3.1	6.8
^{63}Cu (%)	0.9	1.2	1.5	2.2	2.5	3.3	7.0
^{118}Sn (%)	0.9	1.3	1.6	2.3	2.7	3.2	7.1

11 GeV CT Projections for the Lowest l_c Bin









Summary and Outlook

- Strong evidence for the onset of CT using ρ^0 electroproduction off nuclei: CLAS-6 5 GeV dataset showed 11 ± 2.3% (12.5 ± 4.1%) decrease in the absorption of ρ^0 in iron (carbon).
- CLAS12 measurement on several nuclei will allow to disentangle different CT effects (SSC creation, its formation and interaction with the nuclear medium).
- We request the re-approval of RGD CT experiment and review of its rating.

Growing Theoretical Interest on CT Studies in Meson and Proton-knockout Production

i. W. Cosyn, and J. Ryckebusch, "Nuclear ρ meson transparency in a relativistic Glauber model", Phys. Rev. C 87, 064608 (2013).

ii. A. B. Larionov, M. Strikman, and M. Bleicher, "Color transparency in π^--induced dilepton production on nuclei", Phys. Rev. C 9 3, 034618 (2016).

iii. S. Gevorkyan, "Vector mesons polarization versus color transparency", EPJ Web Conf. 138, 08004 (2017) & "Hadronic properties of the photon", EPJ Web Conf. 204, 05012 (2019).

iv. D. Y. Villar Arrebato, A. Bell, and F. Guzman, "Color transparency in ρ^0, ϕ, and J/Ψ mesons photoproduction", Astron. Nachr. 338, 1118-1122 (2017).

v. S. Das, "Color transparency of K^+ mesons in inclusive (e, e') reactions on nuclei", Phys. Rev. C 100, 035203 (2019).

vi. A. B. Larionov and M. Strikman, "Color transparency in $\bar{p}d \rightarrow \pi^-\pi^0 p$ reaction", Eur. Phys. J. A 56, 21 (2020).

vii. A. B. Larionov and M. Strikman, "Color Transparency and Hadron Formation Effects in High-Energy Reactions on Nuclei", Particles 3, 2438 (2020).

Backup Slides

Hall B Run Group D: PR12-06-106: *Study of Color Transparency in Exclusive Vector Meson Electroproduction off Nuclei*

J. W. Van Orden, R. Schiavilla

The phenomenon of color transparency (CT) is a consequence of the proposition that electron scattering from a hadron at large Q^2 requires the coupling of the virtual photon to spatially small fluctuations of the colorless hadron. This fluctuation is referred to as a small size configuration (SSC). The small virtual configuration has small color-multipole moments that cause this hadron to have small interactions within the nuclear medium. This small configuration must become larger as it propagates in time to obtain its asymptotic physical size. So as the hadron propagates, its interaction with the nuclear medium increases. This should result in smaller final state interactions with the nucleus than it would be the case if the photon were absorbed on a hadron of the final asymptotic size. By measuring reactions as a function of Q^2 on nuclei of different sizes it is potentially possible to detect the systematic effects of CT.

Experimental evidence of this effect has been sought since it was first proposed about thirty years ago. The results have been mixed with some experiments showing signs of CT of various magnitudes, while others, such as the preliminary results from Hall C on $^{12}C(e,e'p)$, show no signs of CT.

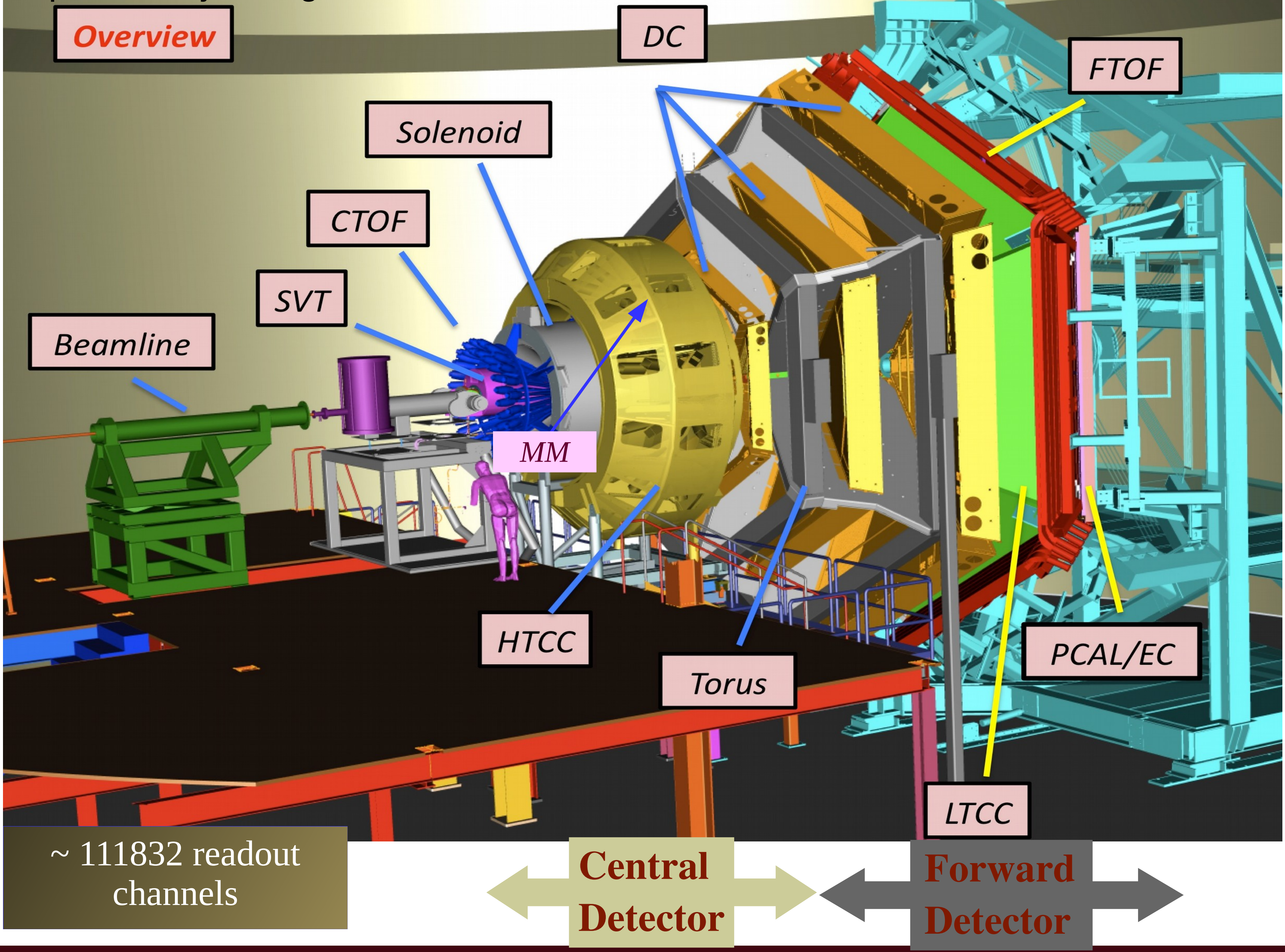
The approach to CT is expected to depend on the momentum transfer Q^2 (how strongly the configurations are squeezed), the energy ν (how long the configurations propagate before expending into a hadron), and the hadron produced (the prevalence of small-size configurations in the hadron). Measurements in different kinematic regions and different hadron channels are essential for disentangling the different contributions and understanding the approach to the SSC regime at the quantitative level.

The measurement of coherent neutral meson electro-production may be the best means of settling this problem, since the initial production of the neutral meson by the virtual photon must occur at a point. The coherent electro-production of ρ^0 is the goal of this proposal. There has been no substantial progress in the theory of CT since this proposal was approved by PAC36 due to the paucity of new data. The results of this experiment would help to stimulate new theory efforts in CT.

11 GeV CT Experiment will use CLAS12 in its Standard Configuration

- Design luminosity
  L ~ 10^{35} cm^{-2} s^{-1}
- High luminosity & large acceptance: concurrent measurement of exclusive, semi-inclusive, and inclusive processes
- Acceptance for photons and e-s: **2.5° < θ < 125°**
- Acceptance for all charged particles: **5° < θ < 125°**
- Acceptance for neutrons: **5° < θ < 120°**

https://www.jlab.org/Hall-B/clas12-web/



~ 111832 readout channels

Approved RG-D Experiment Projections

- E12-06-106: CT experiment was initially endorsed by PAC30 in 2006 and approved by PAC36 in 2010 for 60 PAC days with B^+ rating.
- Initial beam time was estimated assuming the dual-target concept like the 6 GeV era.

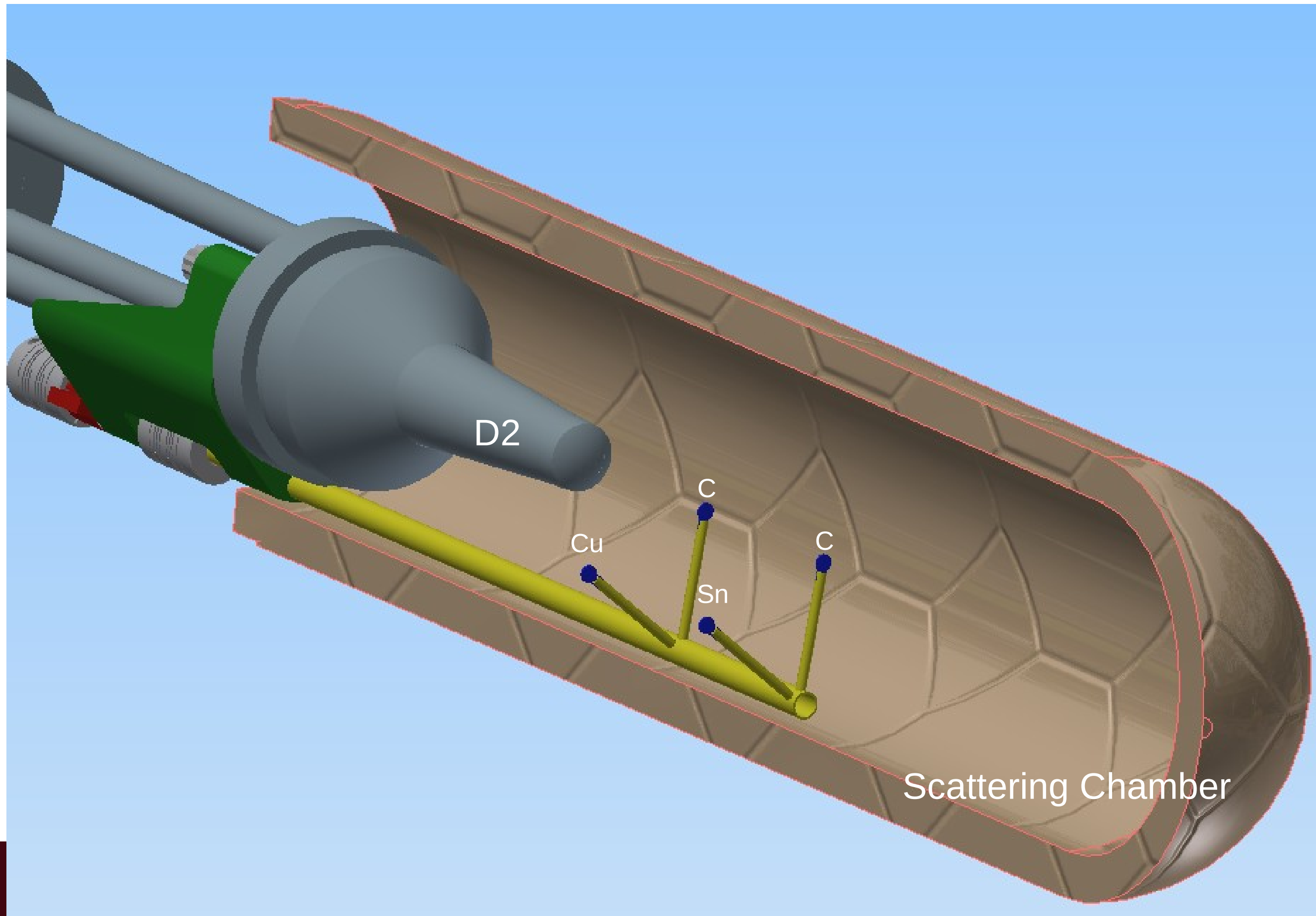
Targets	Beam Time (days)
^{1}H	8
C (+ LD2)	12
~~Fe~~ Cu (+ LD2)	16
Sn (+ LD2)	24

- Expected statistical uncertainties for the approved beam time and one coherence length bin (0.4 – 0.5 fm):

Q^2 (GeV^2) / Targets	1.25 ± 0.25	1.75 ± 0.25	2.25 ± 0.25	2.75 ± 0.25	3.25 ± 0.25	3.75 ± 0.25	4.5 ± 0.5	5.5 ± 0.5
^{12}C (%)	0.6	0.5	0.8	1.2	2	3	3.5	7
^{56}Fe (%)	0.6	0.5	0.8	1.2	2	3.2	3.6	7.4
^{118}Sn (%)	0.6	0.5	0.6	1	1.6	2.4	3.4	6.9

Hall-B Flag Assembly Motivation

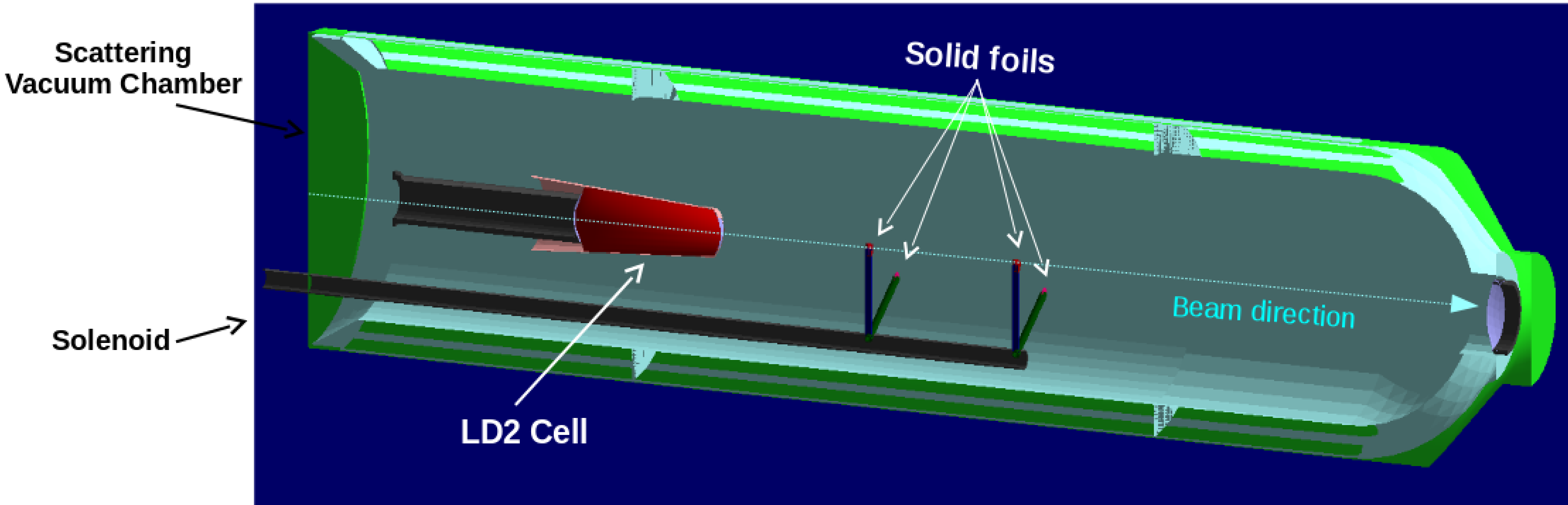
- The driving force behind the use of the single target assembly is:
  - Take liquid and solid targets data in the same vertex position which will minimize the acceptance correction,
  - Reduce the amount of collected deuterium data as one set can be used with all nuclear targets to extract the physics results,
  - Can accommodate several thinner solid targets, allowing to take full luminosity even on heavy targets.



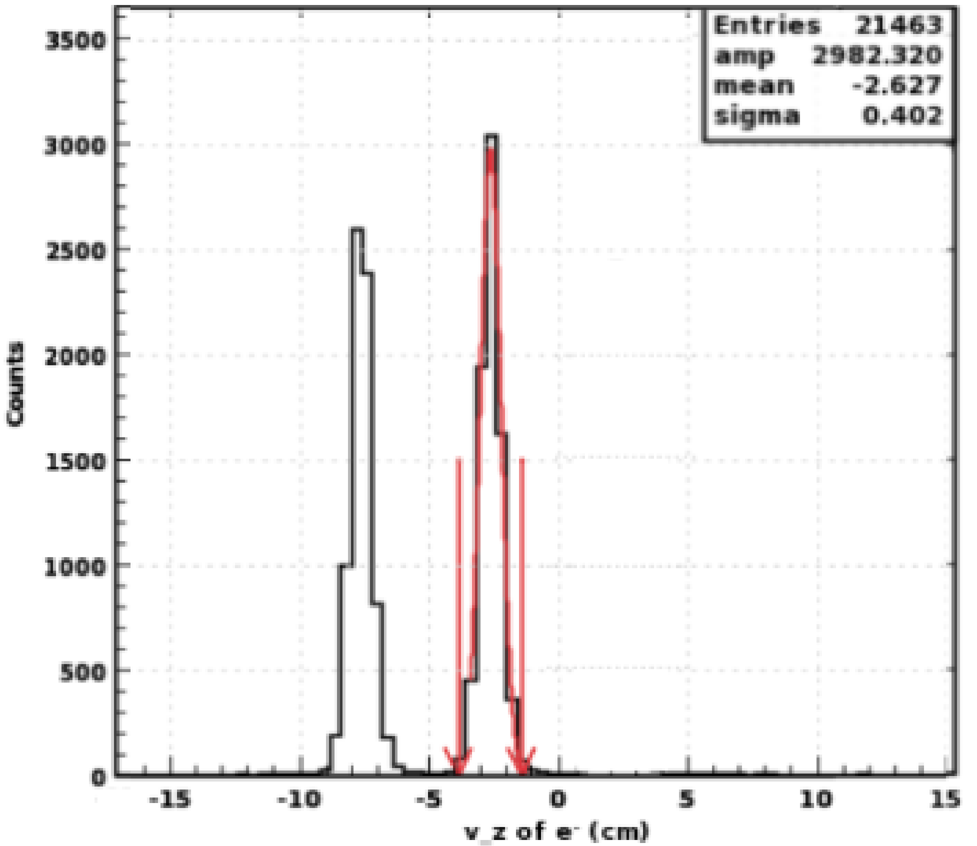
Beam & Target Configurations

- Run with 11 GeV beam energy, different beam currents, and target's thicknesses (*modified to respect the 2% radiation length requirement*) to achieve the nominal luminosity of 10^{35} $cm^{-2}s^{-1}$.

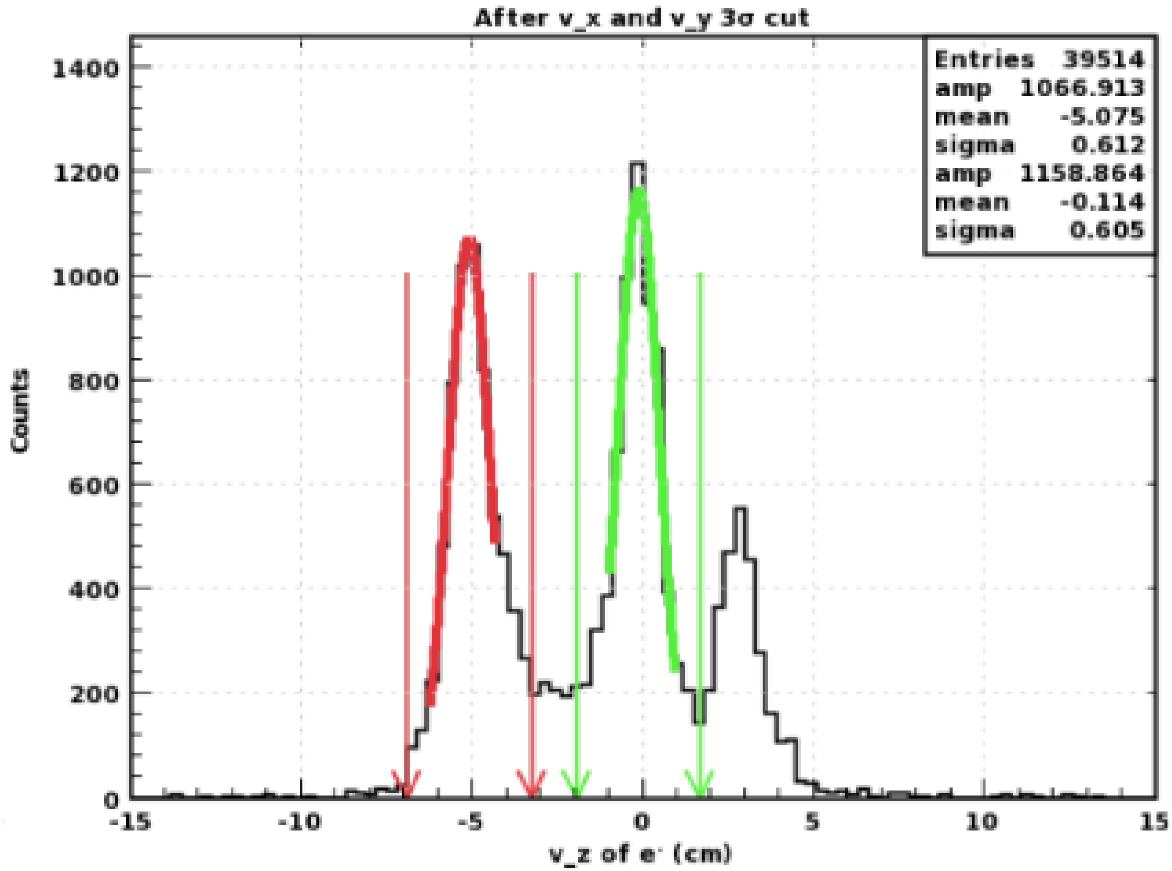
Targets	Thickness (2 foils) (cm)	Density ($g.cm^{-3}$)	Areal Density (T) ($mg.cm^{-2}$)	Radiation Length (r.l.) (X_0) ($g.cm^{-2}$)	Radiation Lengths (T/X_0)	Beam Current (nA)	Per-Nucleon Luminosity (cm^{-2} s^{-1})
D2	5	0.164	820	125.98	0.0065	35	1. 10^{35}
^{12}C	0.185 (0.37)	1.747	323	42.7	0.0076	45	1. 10^{35}
^{63}Cu / ^{118}Sn	0.009 / 0.018	8.96 / 7.31	80.64 / 131.58	12.86 / 8.82	0.00627 / 0.01492	125	1. 10^{35}



Reconstructed Vertex Distribution



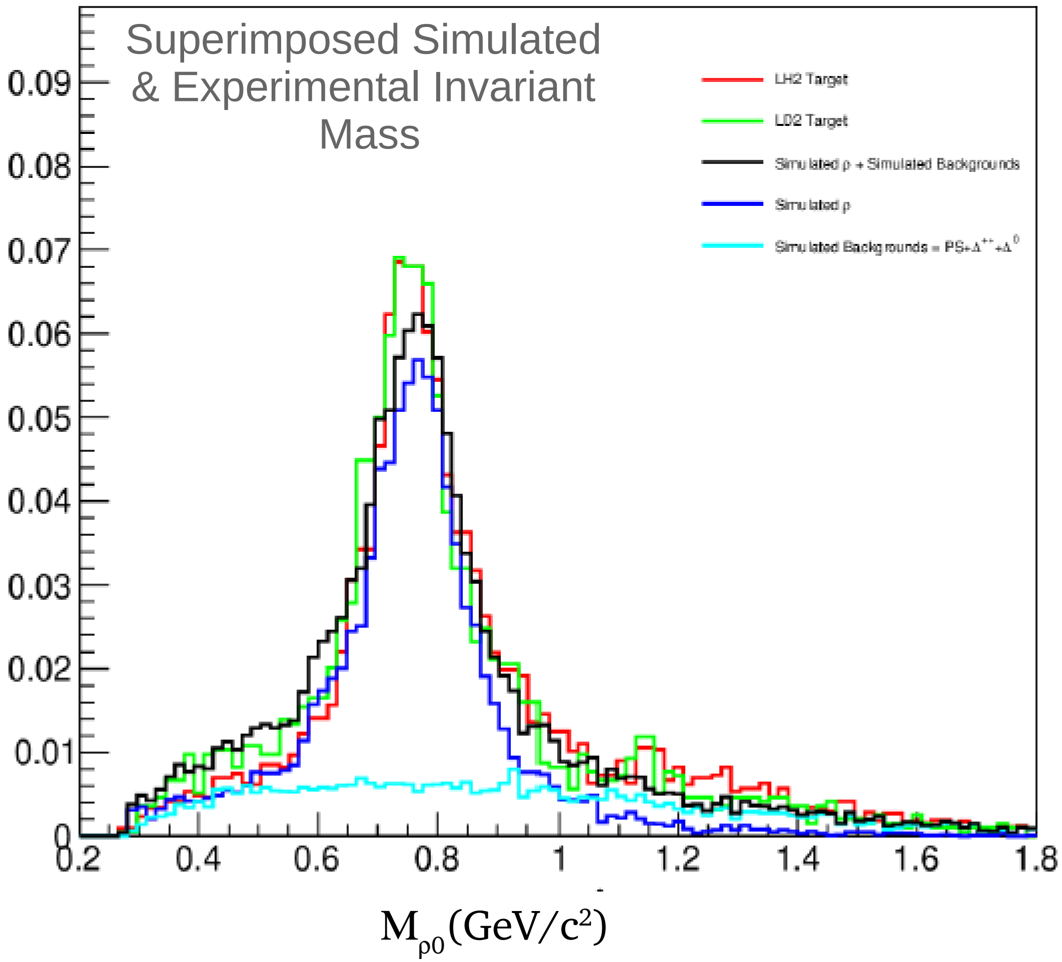
Simulated Electron z-vertex distribution for the Hall-B 5 cm apart solid foils assembly

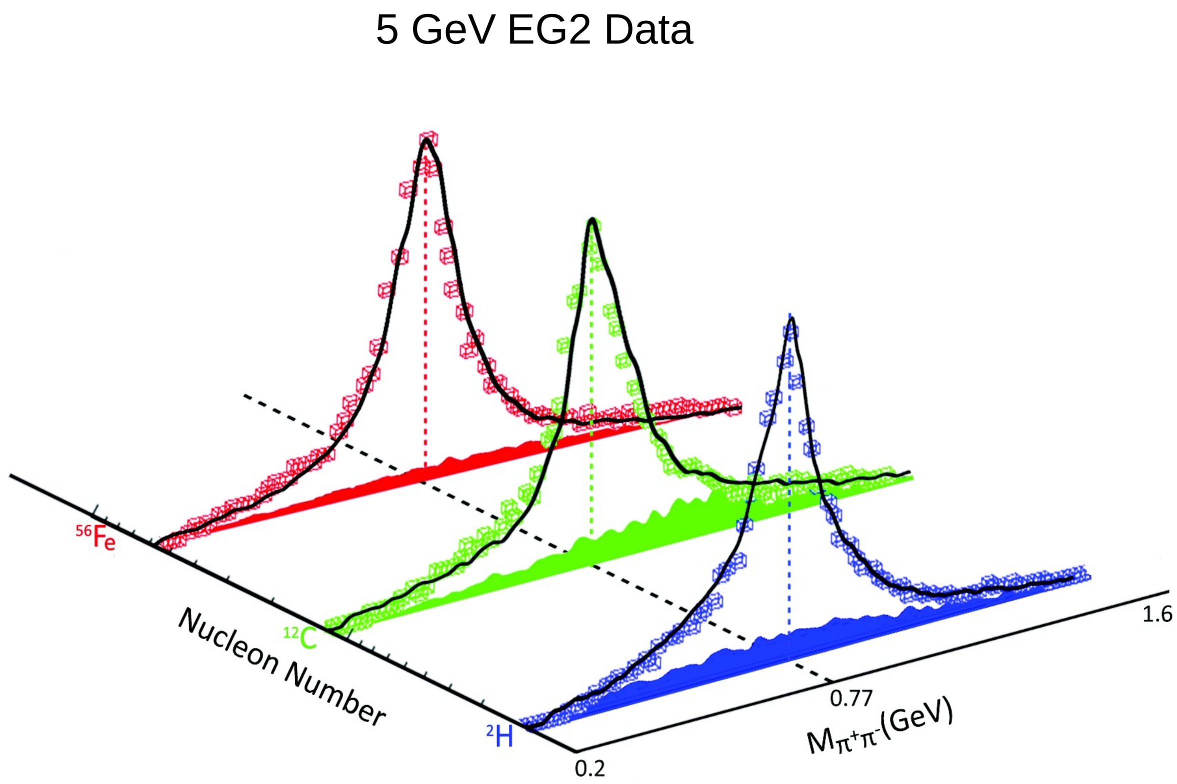


Electron z-vertex distribution from an empty target RG-A run

Comparison of Simulated and Experimental Negative Polarity Data

- The reconstructed ρ^0 invariant mass distribution in our kinematical range,





Simulated Background's Shapes

$e + p \rightarrow e + p + \pi^+ + \pi^-$

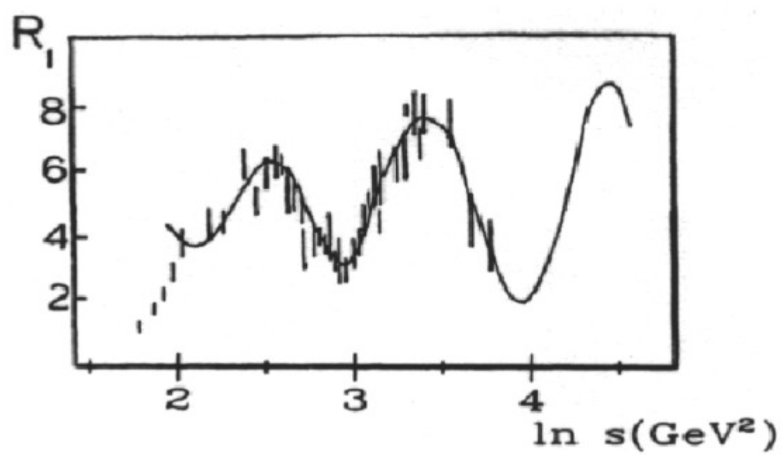
$e + p \rightarrow e + \Delta^{++} + \pi^-$

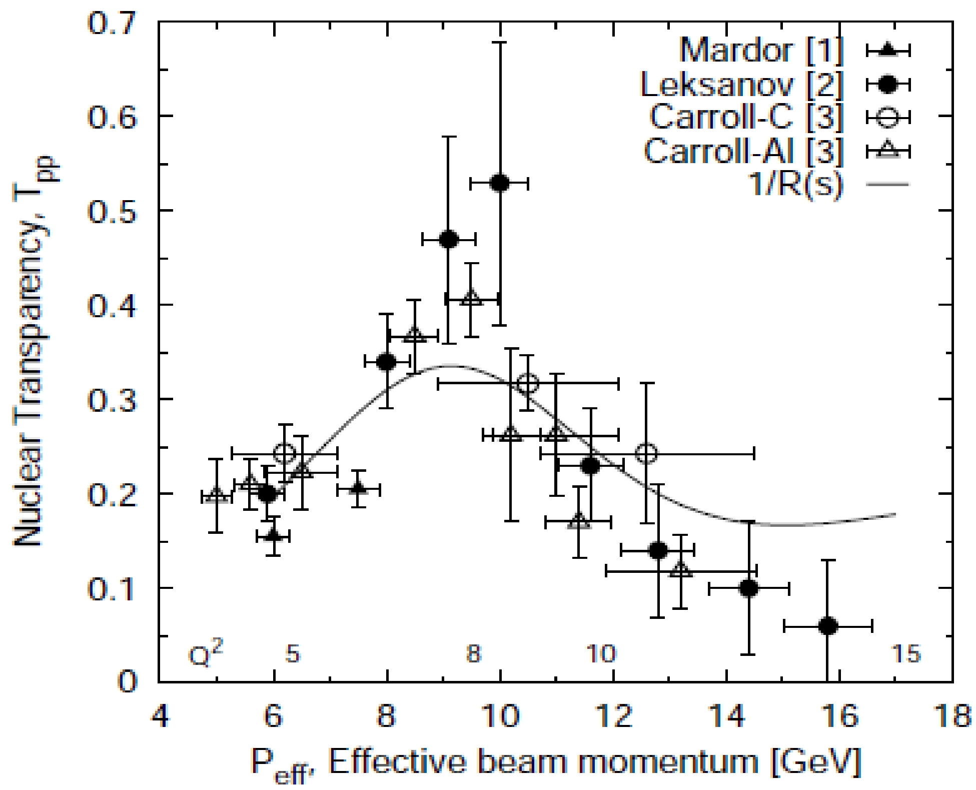
$e + p \rightarrow e + \Delta^0 + \pi^+$

ρ^0 production: $e + p \rightarrow e + p + \rho^0$

Quasi-elastic A(p, 2p): BNL

$$\frac{d\sigma}{dt}_{pp}(\theta = 90^\circ_{C.M.}) = R(s)\, s^{-10}$$



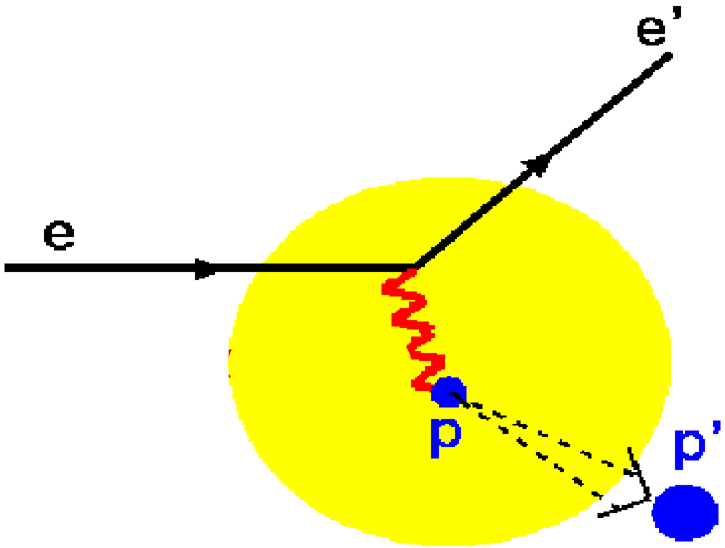


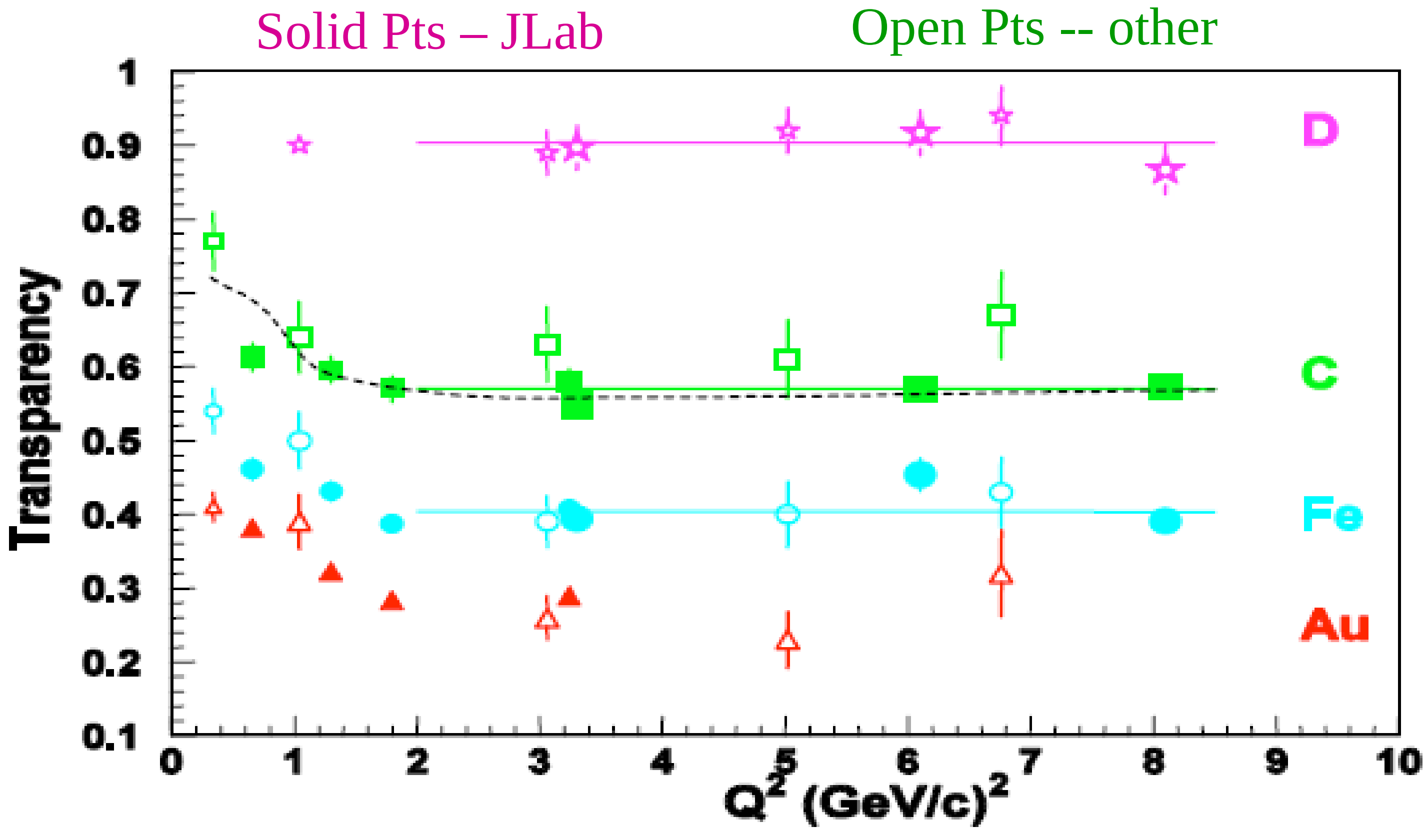
A. Leksanov *et al.* PRL 2001

- Initial rise in transparency at low momentum is consistent with CT predictions.
- Subsequent drop at high momentum was explained by
  - Ralston and Pire as a nuclear filtering of soft amplitudes arising from higher order radiative processes (Landshoff mechanism).
  - Brodsky and De Teramond as a threshold of new resonant (charmed quark) multi-quark states.

Quasi-free A(e, e'p): No evidence for CT

- Constant value fit for $Q^2 > 2$ $(GeV/c)^2$ has χ^2 /ndf ≈ 1.
- Conventional Nuclear Physics Calculation by Pandharipande *et al.* gives a good description.

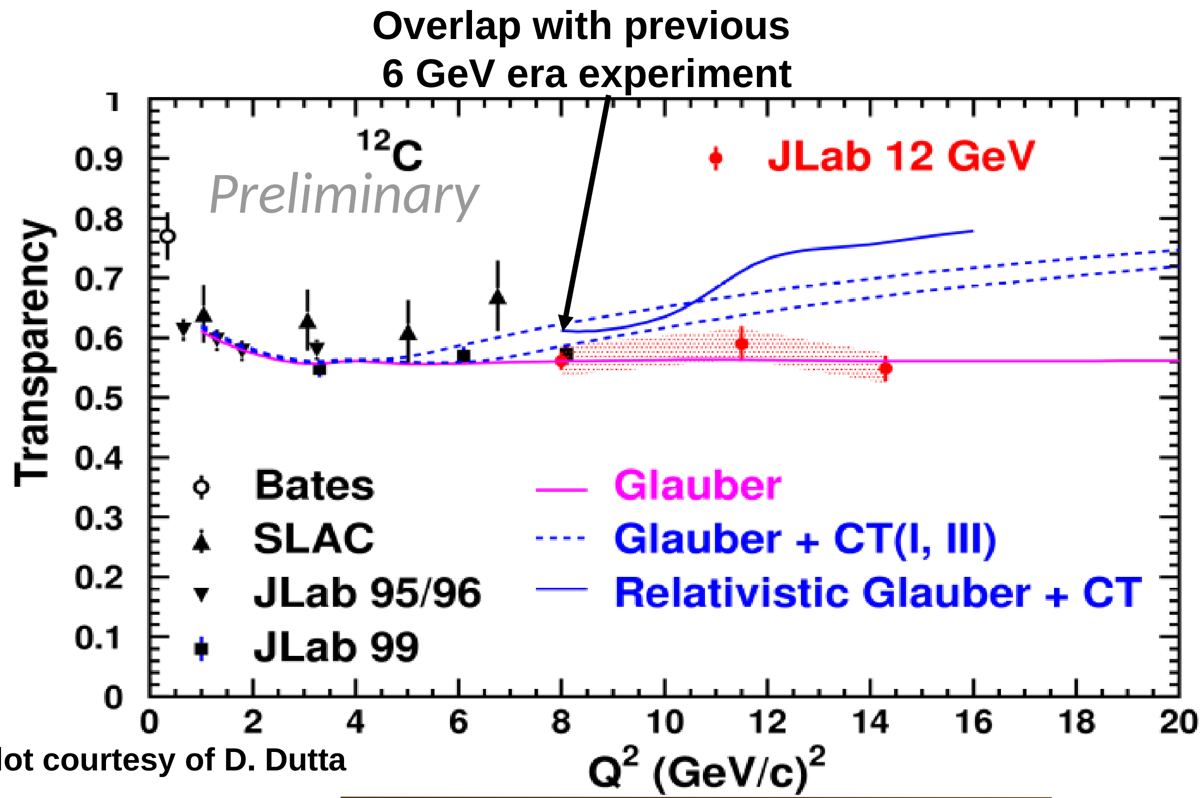




N. C. R. Makins *et al.* PRL 72, 1986 (1994)
G. Garino *et al.* PRC 45, 780 (1992)
D. Abbott *et al.* PRL 80, 5072 (1998)
K. Garrow *et al.* PRC 66, 044613 (2002)

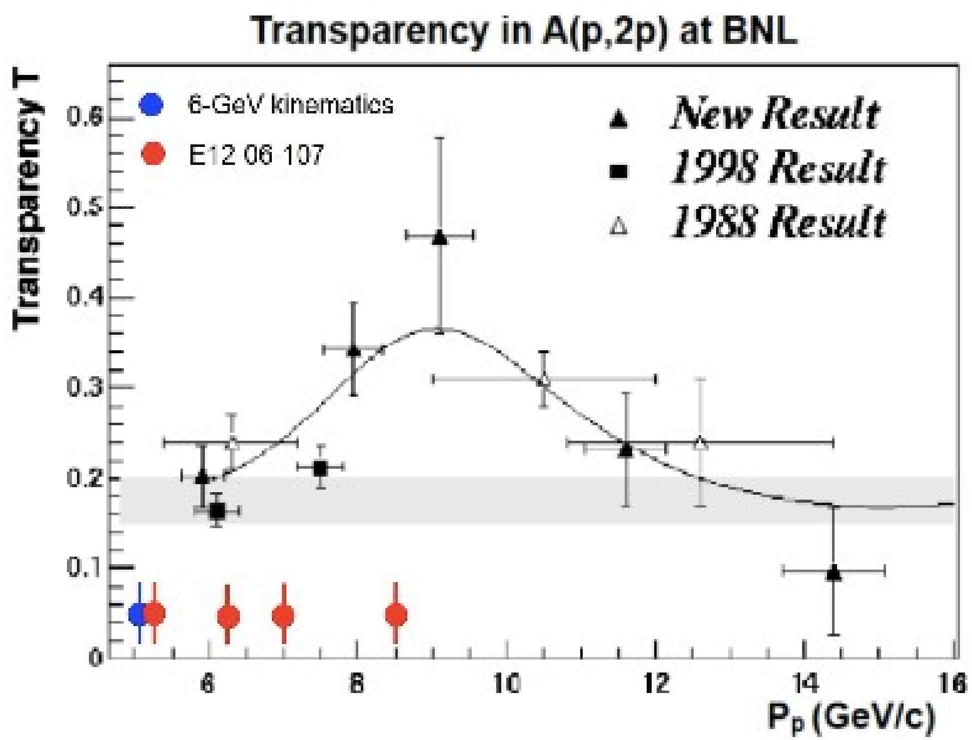
Preliminary Hall-C Proton results do not show the onset of CT

- Experiment E12-06-107: Spokespersons - D. Dutta & R. Ent
- Collected 10 days of the A(e,e'p) proton knockout data @ 8.8 GeV and 11 GeV beam energy.
- Extracted the preliminary results of T_A^p for four Q^2 bins (8, 9.5, 11.5, 14.3 $(GeV/c)^2$).
- Help interpret the rise seen in the BNL A(p, 2p) data at p_p= 6 - 9 GeV/c.
- Search for the onset of CT in three quarks state.
- No enhancement observed as in the BNL (p, 2p) experiment.

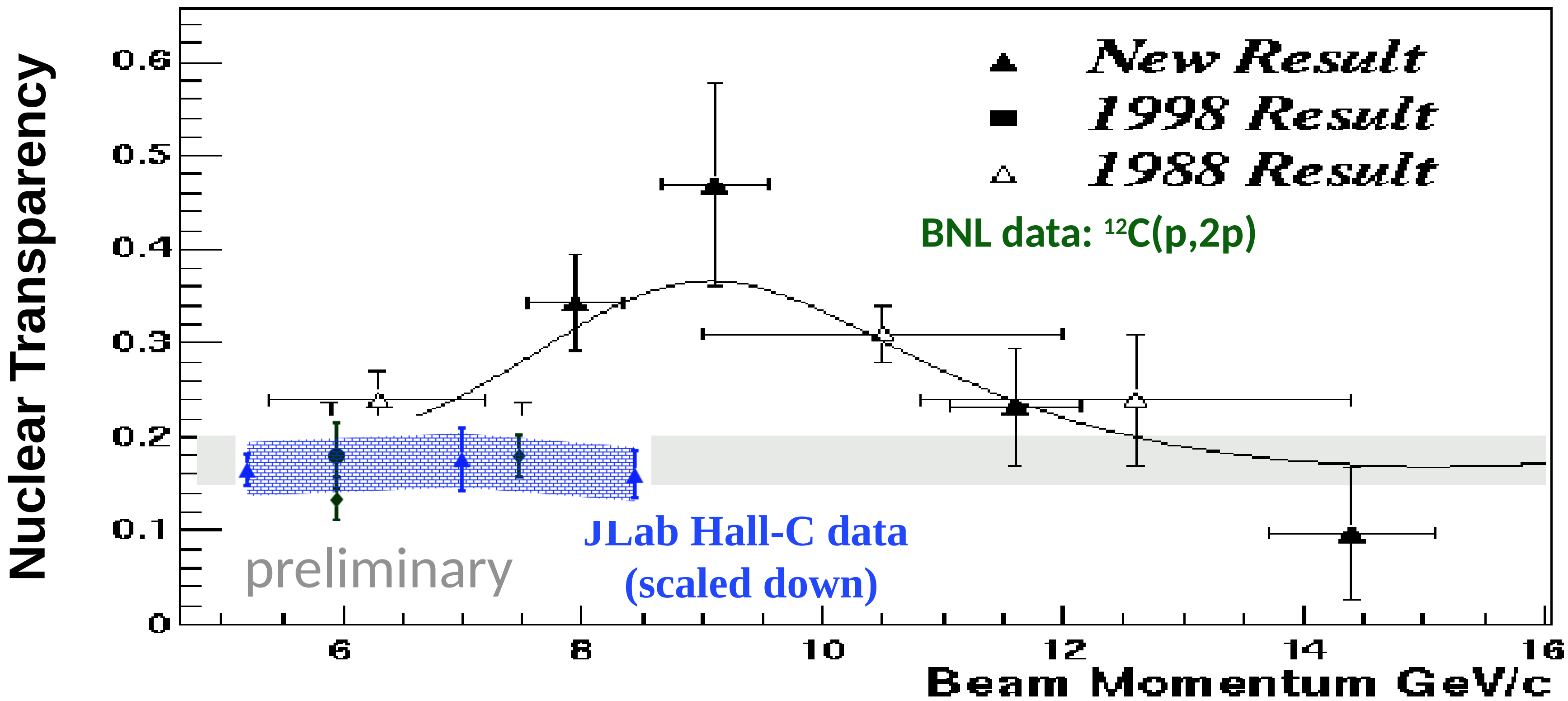


Plot courtesy of D. Dutta

2.9 4.0 5.1 6.3 7.3 8.3 P_p [GeV] (for comparison with BNL data)



Preliminary ^{12}C transparency results do not show the onset of CT

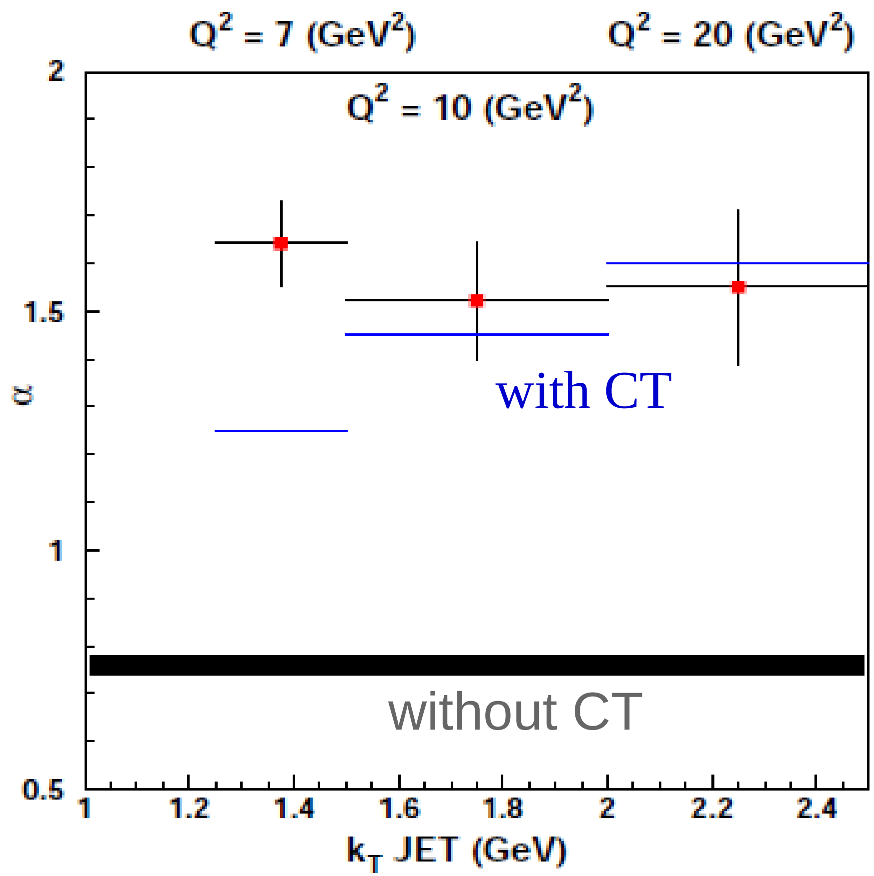


- BNL observations unlikely to be because of CT (?)
- Places very stringent constraints on all existing CT models.

Plot courtesy of D. Dutta

A(π, dijet) Data from FNAL

- Coherent π^- diffractive dissociation with 500 GeV/c pions on Pt and C.
- Fit to $\sigma = \sigma_0 A^\alpha$
- Extracted $\alpha = 1.6 > 2/3$ from pion-nucleus total cross-section.
- CT predictions of L. L. Frankfurt, G. A. Miller, and M. Strikman, Phys. Lett. B304, 1 (1993)

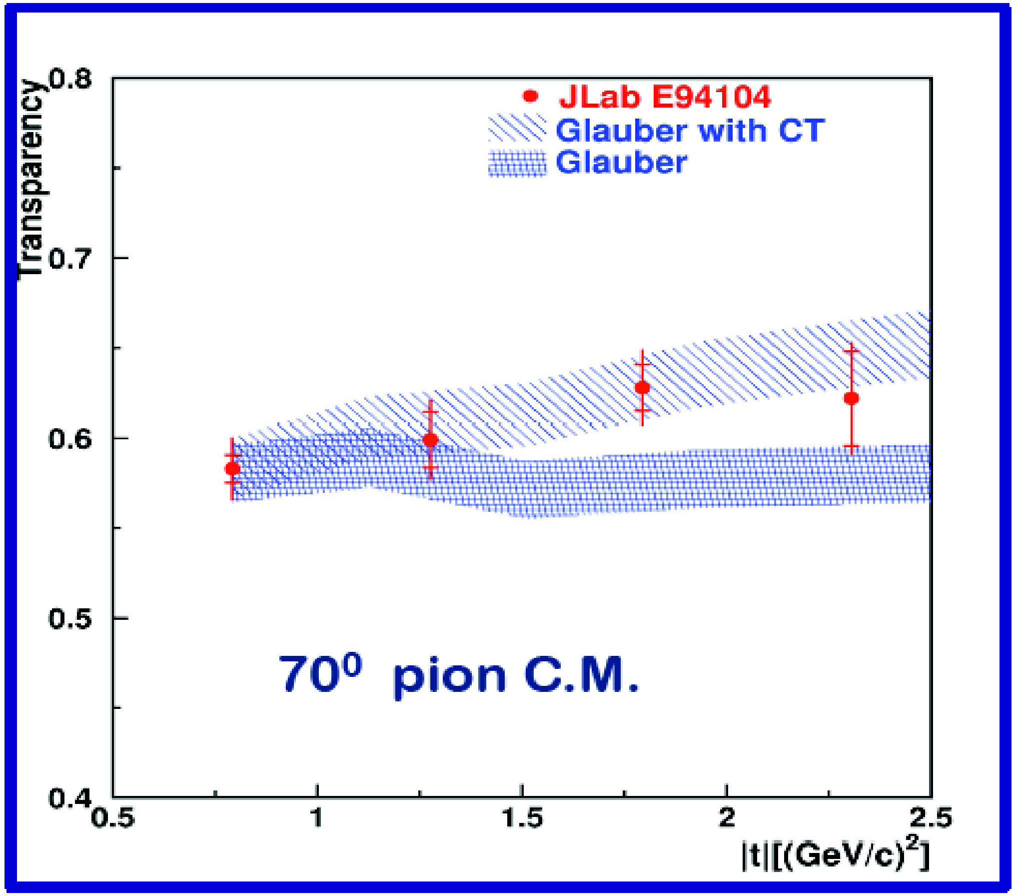


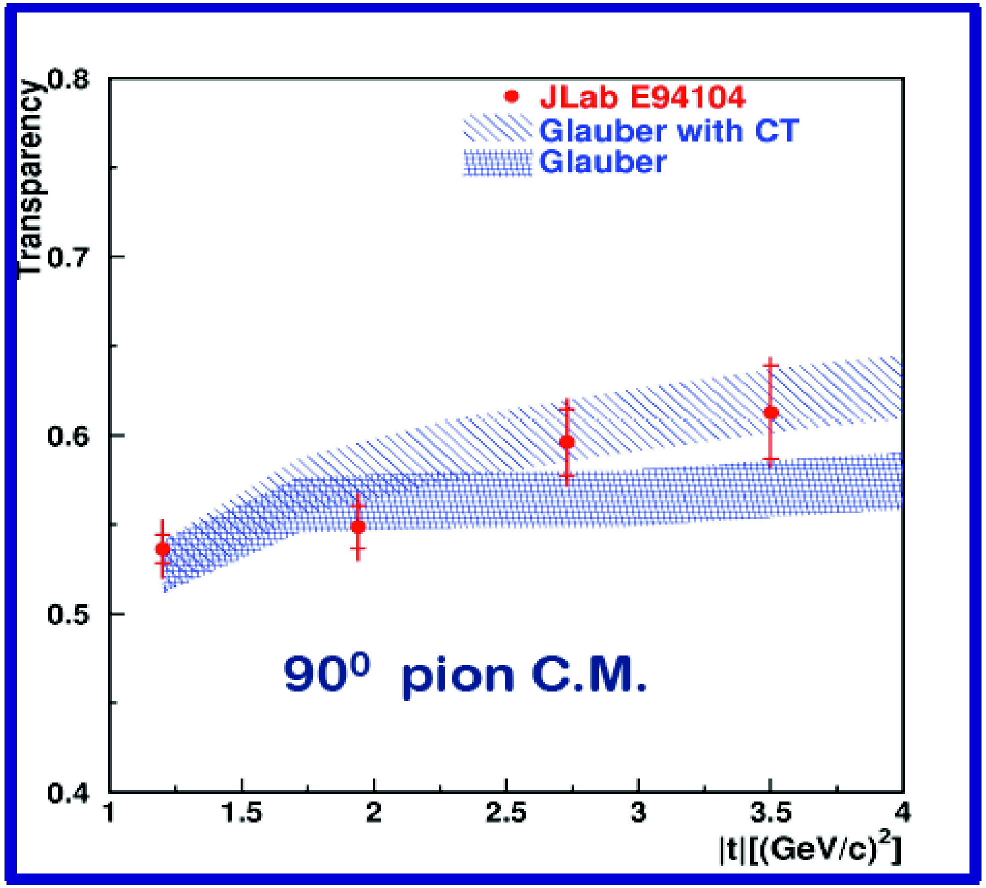
Aitala *et al.*, PRL 86, 4773 (2001)

Pion Photo-production $\gamma\, n \rightarrow \pi^- p$ in ^4He

- Positive hint from JLab Hall-A experiment but the transparency slopes deviate from Glauber uncertainties only by 1σ (2σ) for 70° (90°) pion CM angle.

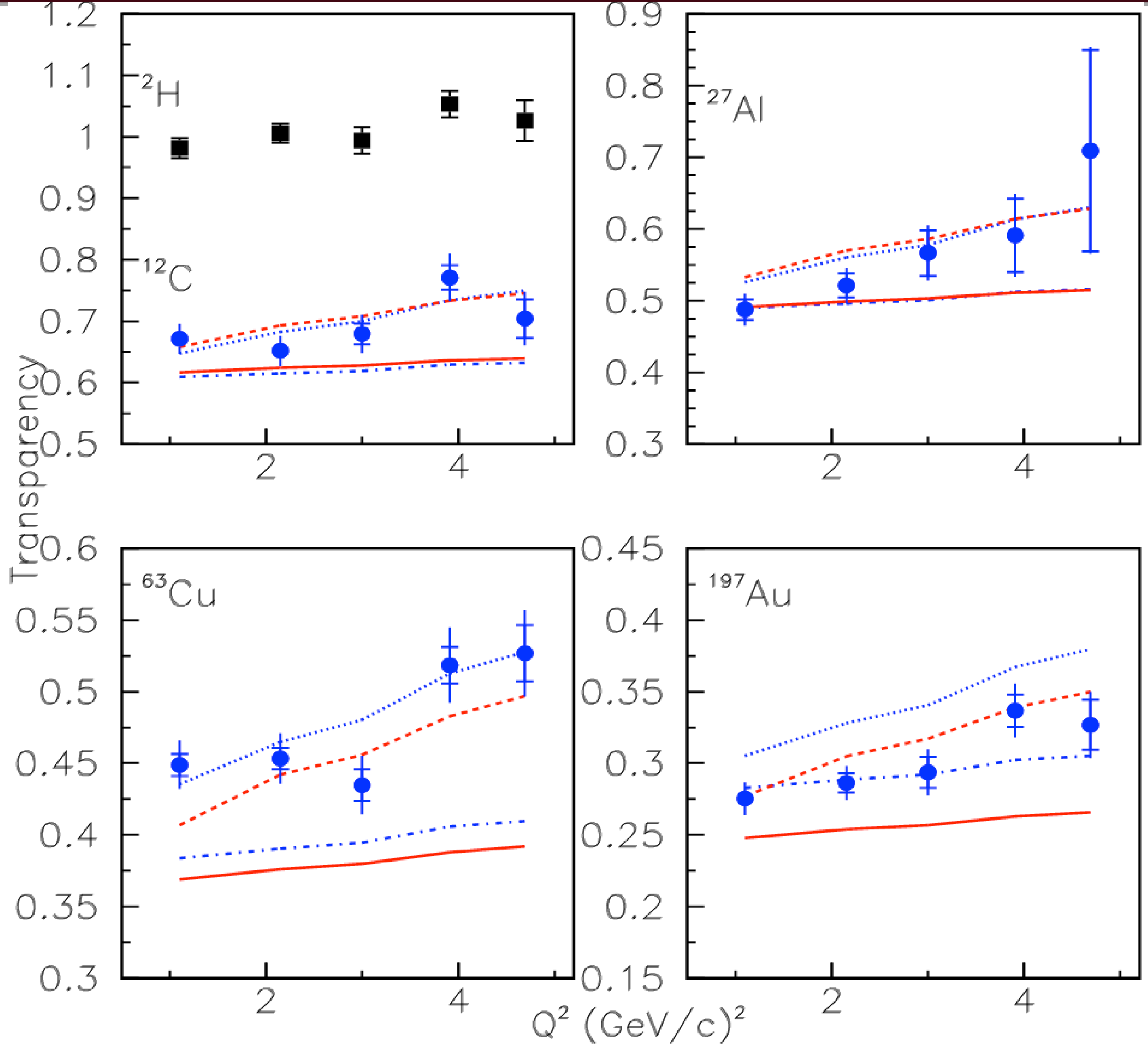
$$(\gamma + {}^4He \rightarrow \pi^- + p + X) \; / \; (\gamma + D \rightarrow \pi^- + p + p)$$





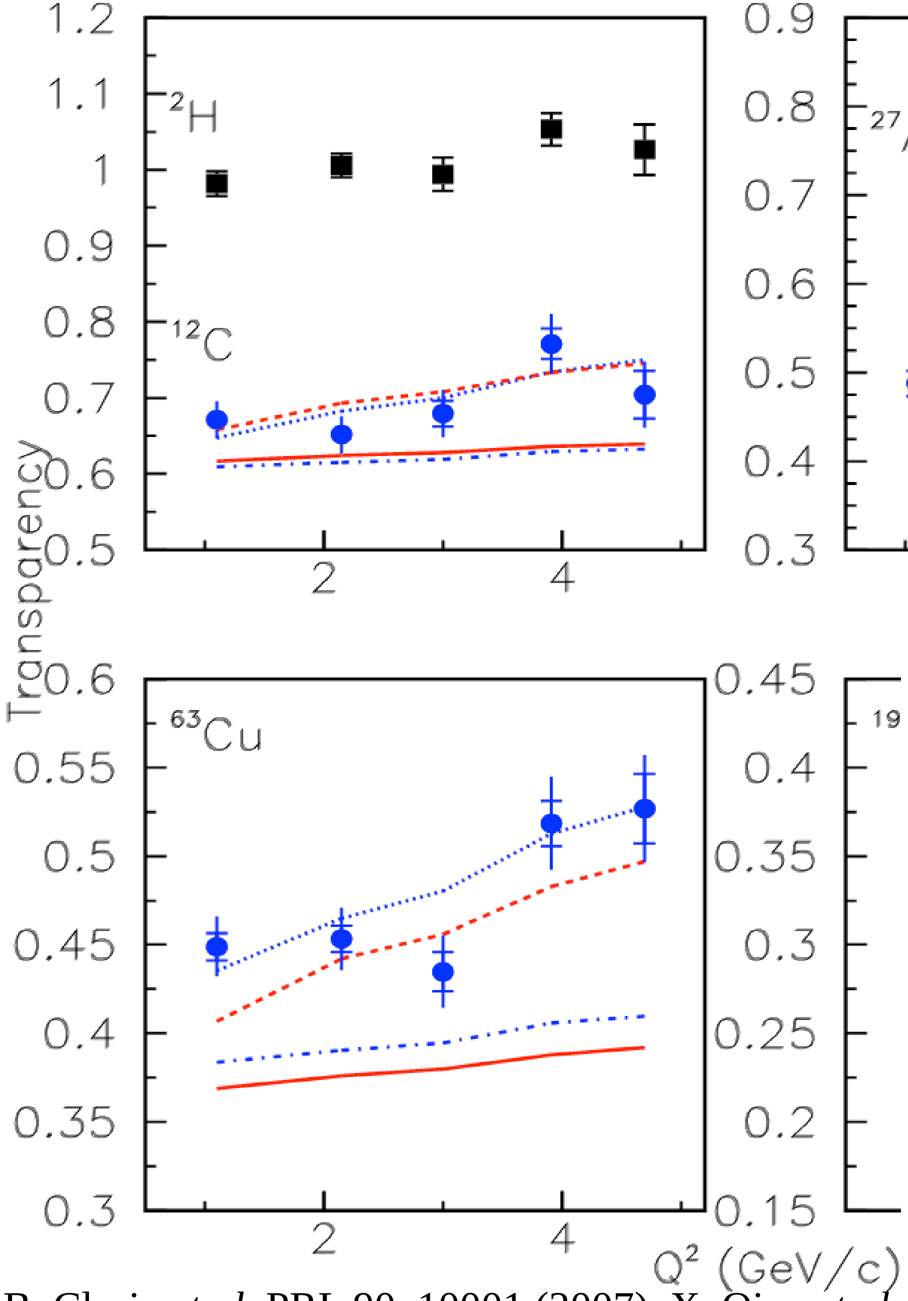
Dutta et al. PRC 68, 021001R (2003)
Gao et al. PRC 54, 2779 (1996)

Pion Electroproduction A(e, e' π⁺) at JLab



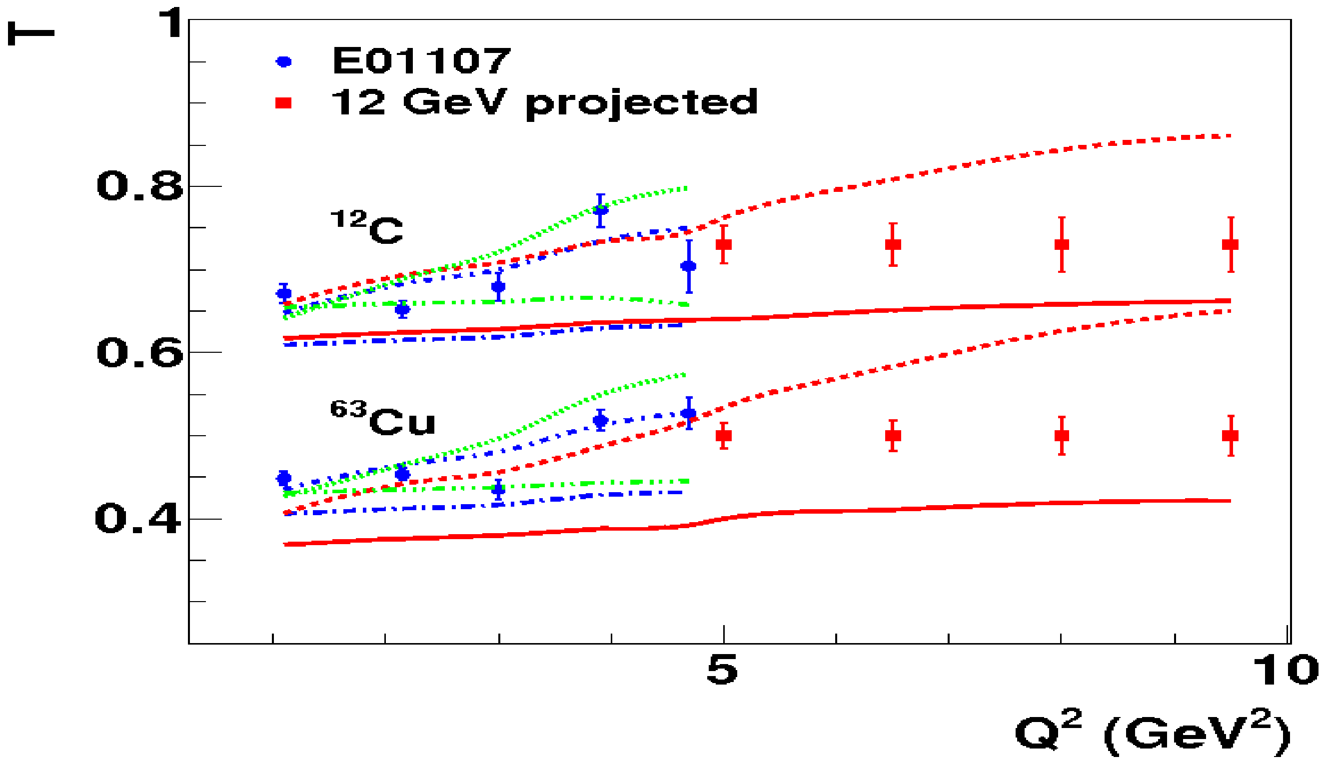
B. Clasie *et al.* PRL 90, 10001 (2007), X. Qian *et al.*, PRC 81, 055209 (2010)

Pion Electroproduction A(e, e' π^+) at JLab

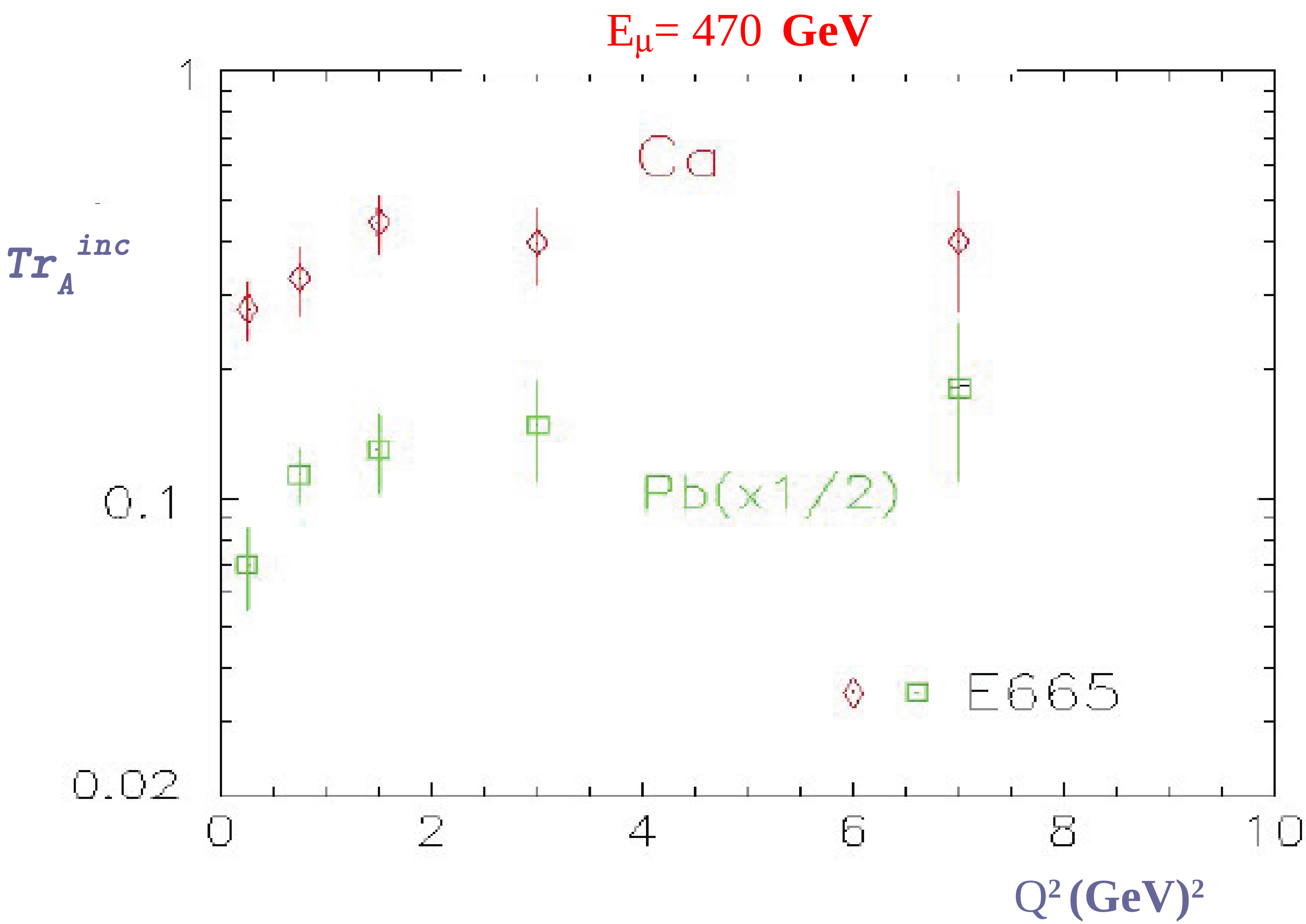


B. Clasie *et al.* PRL 90, 10001 (2007), X. Qian *et al.*

These measurements will be extended to Q^2 of about 10 $(GeV/c)^2$ using an 11 GeV beam energy and Hall-C two-arm spectrometers.



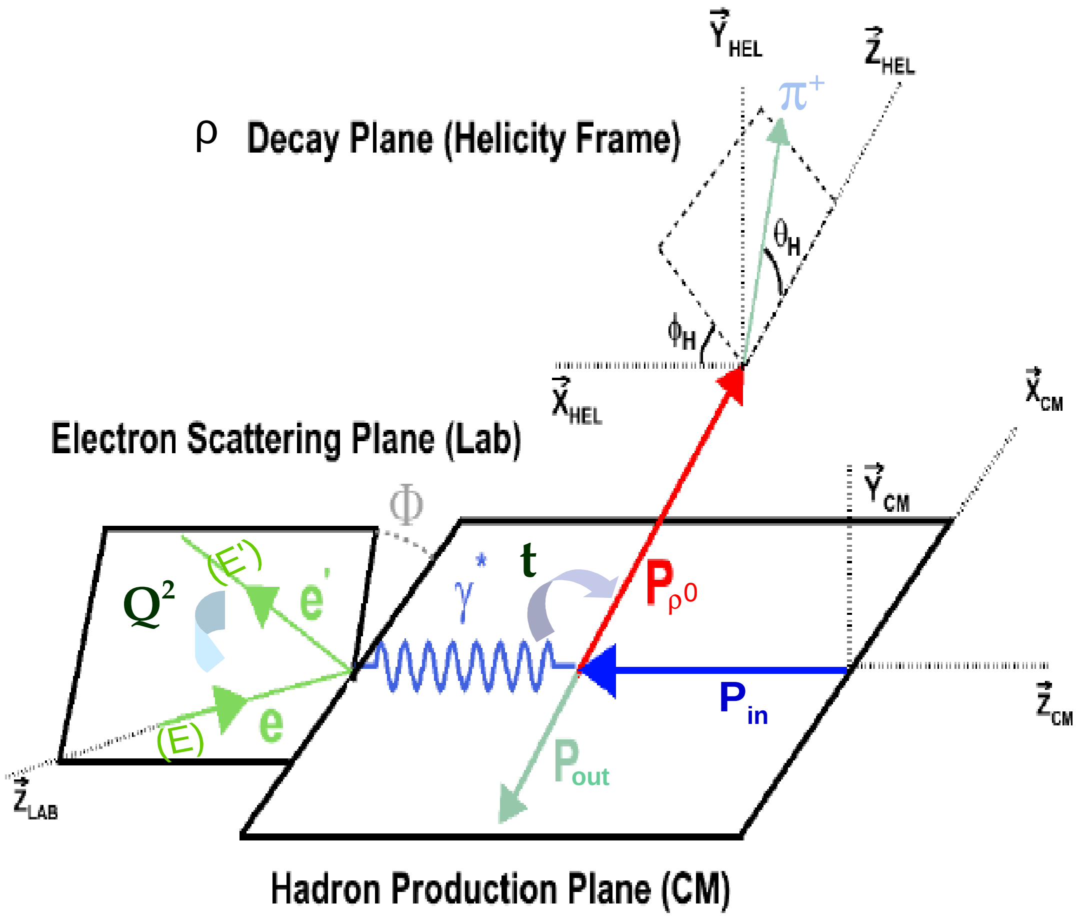
Exclusive ρ^0 Leptoproduction: FNAL 665



Adams *et al.* PRL 74, 1525 (1995)

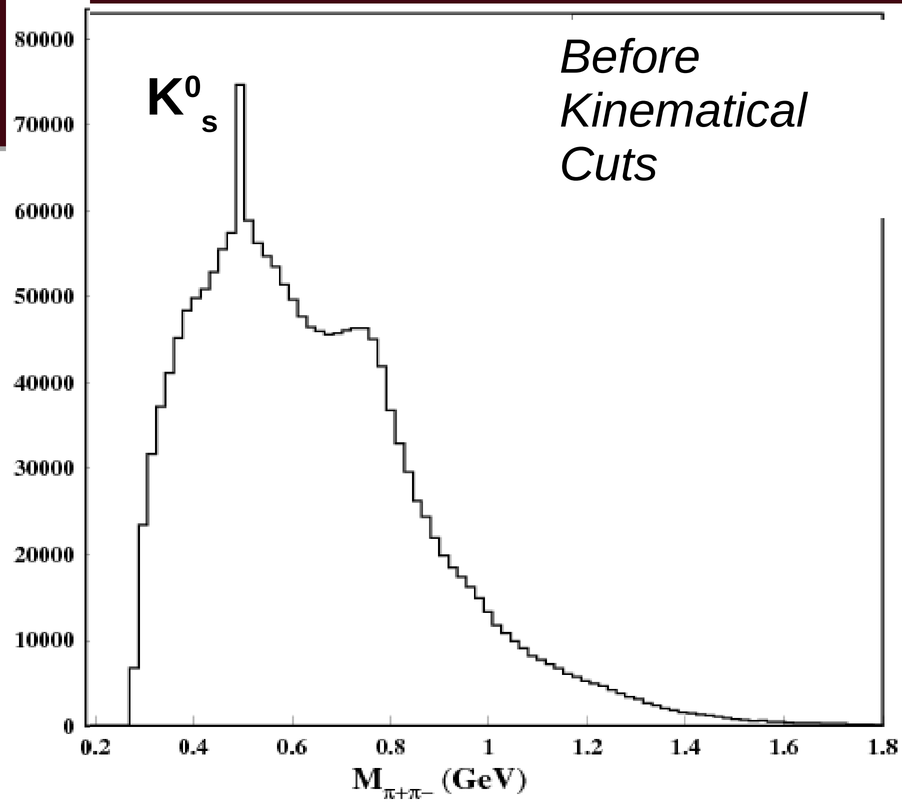
ρ^0 Electroproduction Kinematics

- $\nu = E - E'$: virtual photon (γ^*) energy in the Lab frame,
- $Q^2 = -(P_e - P_{e'})^2 = 4\,E\,E'\sin^2(\theta/2)$: photon virtuality,
- $t = (P_{\gamma^*} - P_\rho)^2$: momentum transfer square,
- $W^2 = (P_{in} + P_{\gamma^*})^2 = -Q^2 + M_p^2 + 2M_p\nu$: invariant mass squared in (γ^*, p) center of mass (CM).

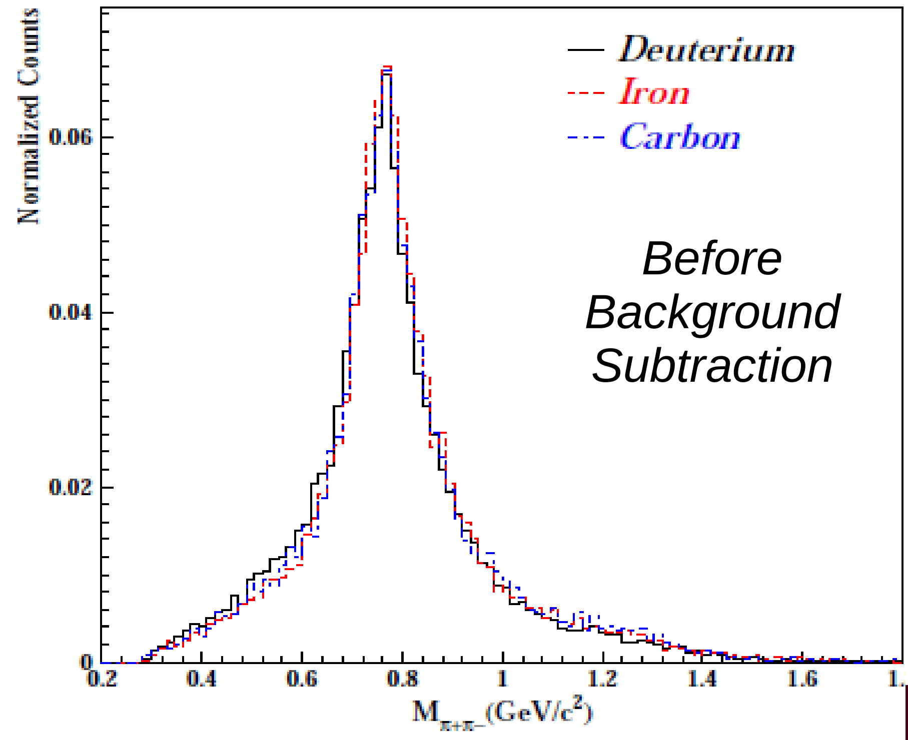


- $W > 2$ GeV
  $\Rightarrow$ avoid resonance region
- $-t < 0.4$ GeV^2
  $\Rightarrow$ select diffractive process
- $-t > 0.1$ GeV^2
  $\Rightarrow$ exclude coherent production
- $Z_h = E_h/\nu \geq 0.9$
  $\Rightarrow$ select elastic channel

Two Pions Invariant Mass



After
Kinematical Cuts



Two Pions Invariant Mass

- Our event generator incorporated the measured cross sections for the electroproduction of ρ^0 and main background processes by Cassel et al.

D. G. Cassel, Phys. Rev. D 24, 2787 (1981)

Simple Breit-Wigner

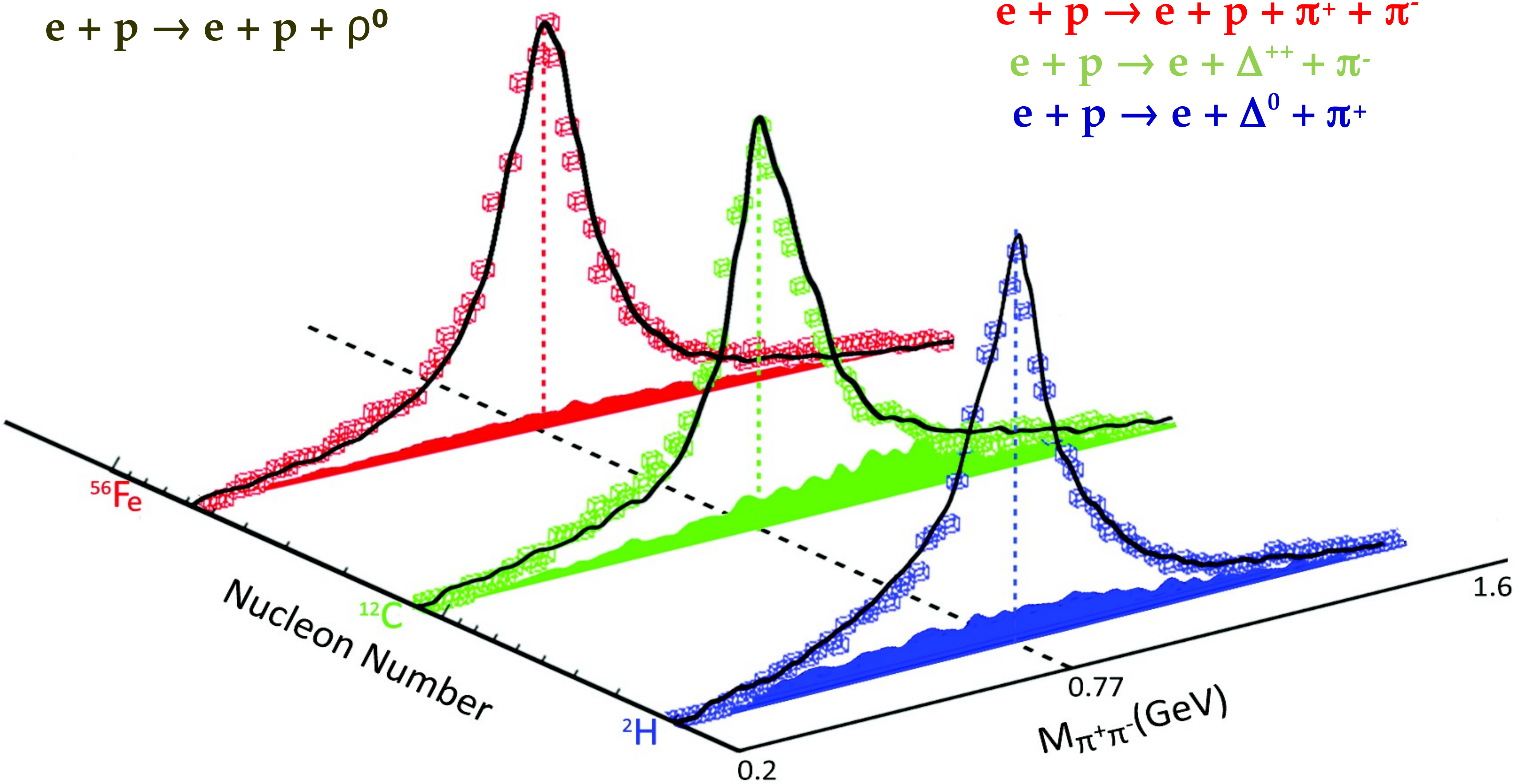
$$e + p \rightarrow e + p + \rho^0$$

Simulated Background's Shapes

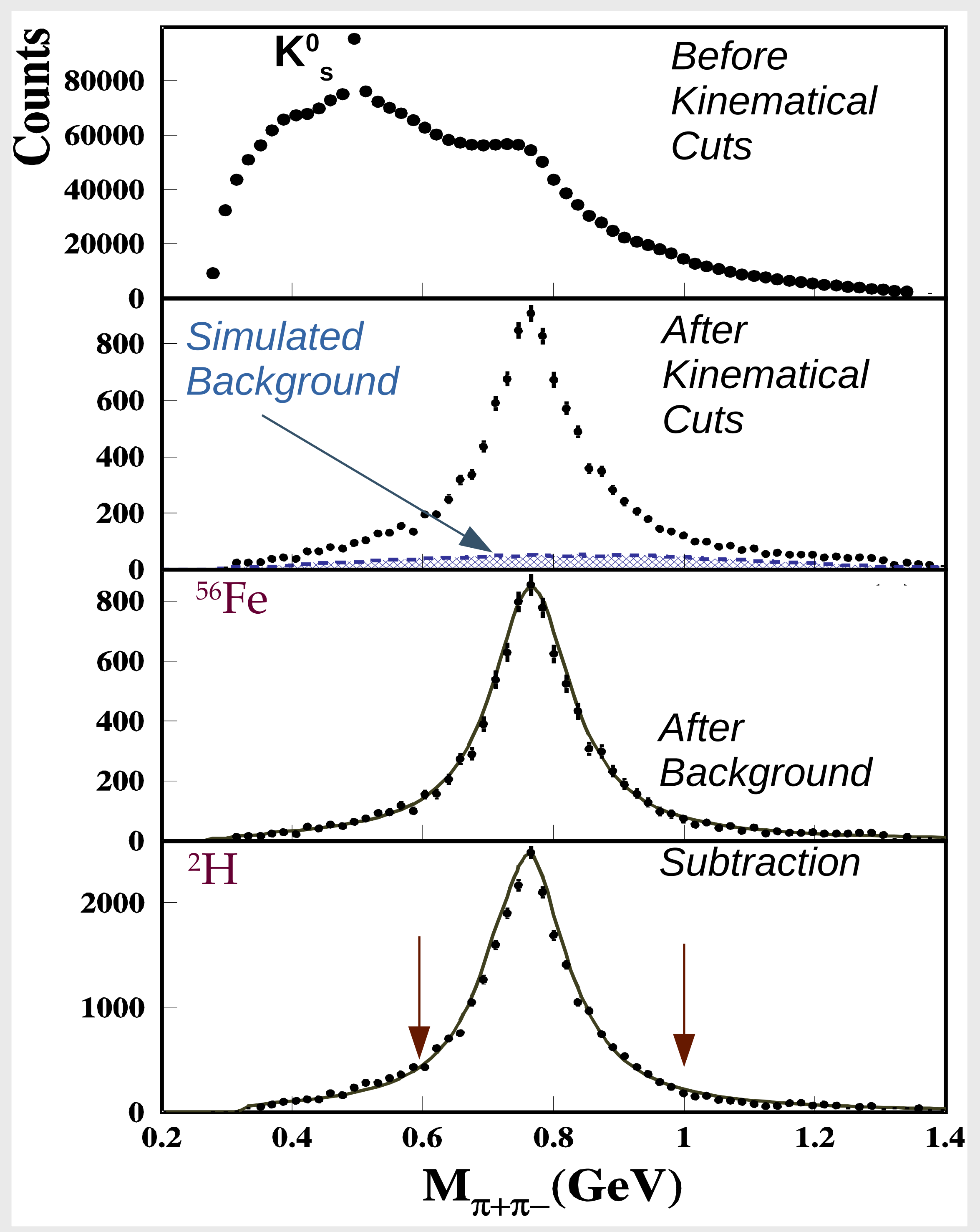
$$e + p \rightarrow e + p + \pi^+ + \pi^-$$

$$e + p \rightarrow e + \Delta^{++} + \pi^-$$

$$e + p \rightarrow e + \Delta^0 + \pi^+$$



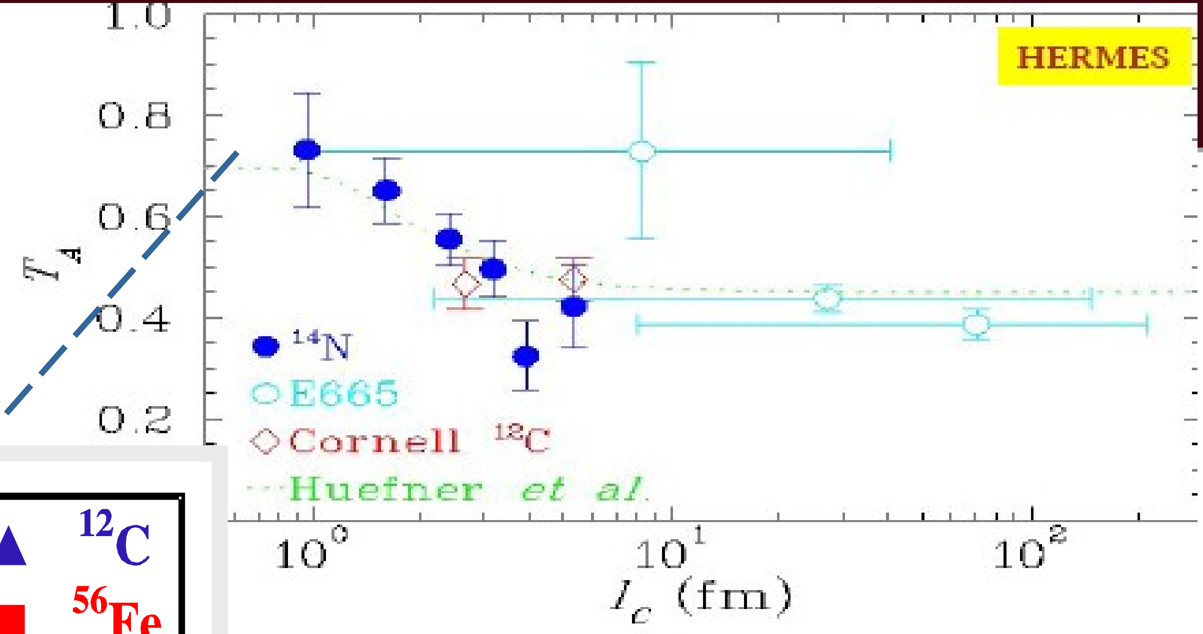
Two Pions Invariant Mass

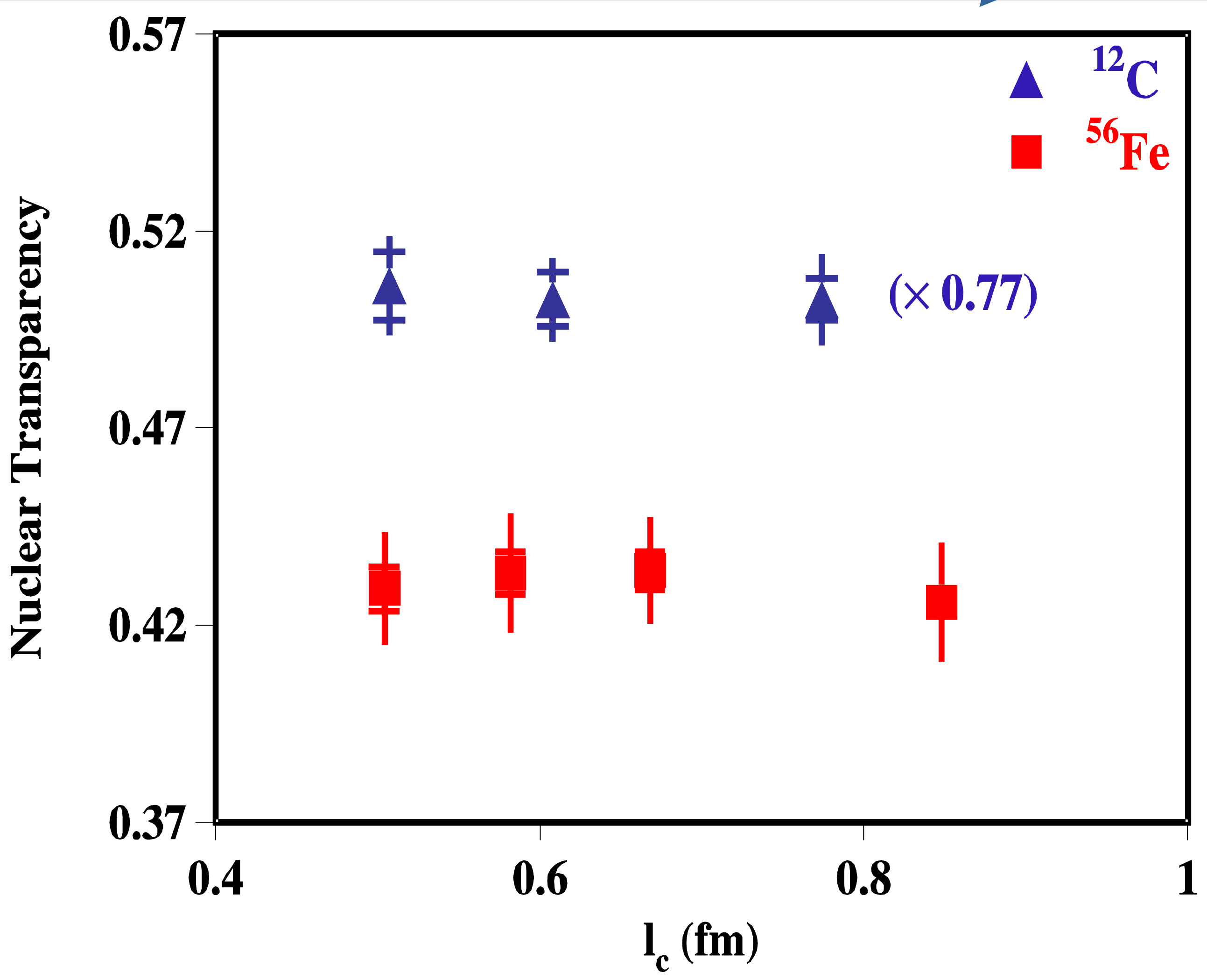


l_c Dependence on T_A

Coherence Length

$l_c = 2\nu / (M^2 + Q^2)$





Nuclear Transparency

$$T^{\rho}_{A} = N^{\rho}_{A} / N^{\rho}_{D} \times (\rho_D \times t_D) / (\rho_A \times t_A)$$

- ρ_D and ρ_A are target's densities
- t_A is the solid target thickness
- t_D= 2 cm, liquid target length

L. El Fassi *et al.* PLB 712, 2012

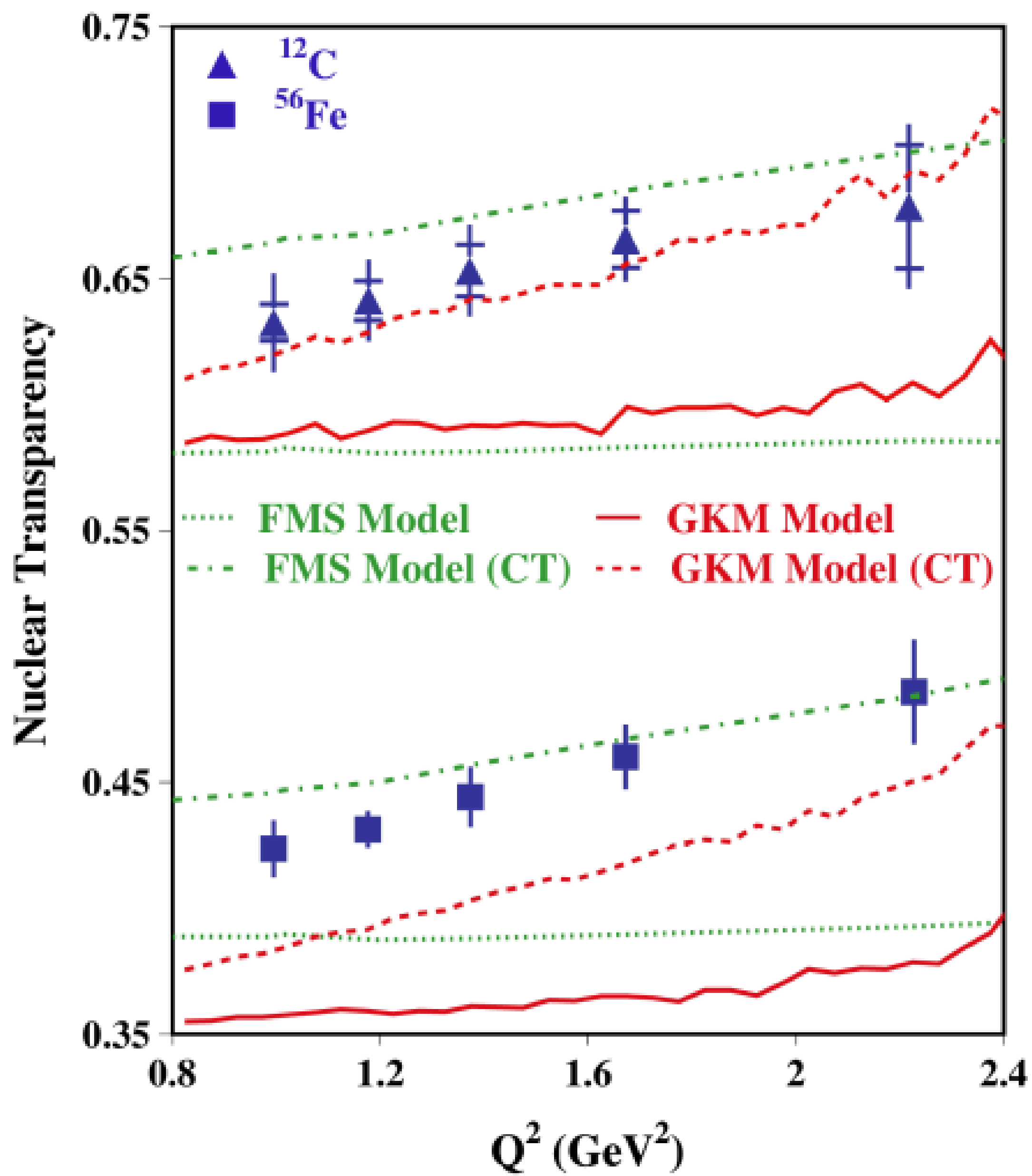
ρ^0 CT Results for 5 GeV Iron & Carbon Data-sets

- **FMS**: Semi-classical Glauber formalism based on quantum diffusion model.
- Dashed-dotted curve includes CT effects, FSI and ρ^0 decay.

Frankfurt, Miller & Strikman, PRC 78 (08) & Private communications

- **GKM**: Transport Model (GiBUU)
- Dashed curve includes CT effects for ρ^0 produced in DIS regime only!

Gallmeister, Kaskulov & Mosel, PRC 83, 015201 (2011)



L. El Fassi *et al.* PLB 712, 2012

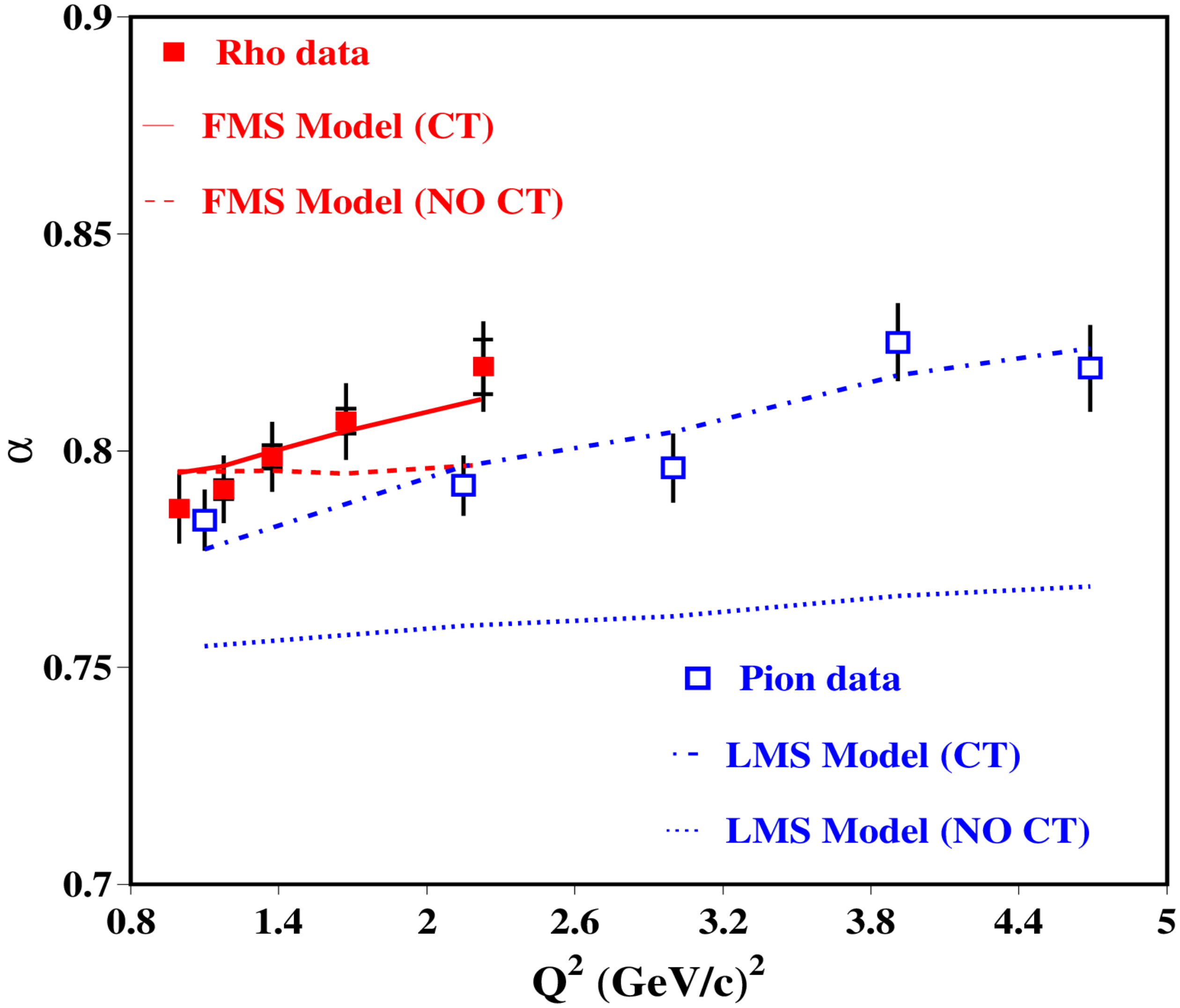
ρ^0 CT slopes from linear fit of Q^2 dependence, $T_A = a\, Q^2 + b$

Targets / Models	Carbon slopes (GeV^{-2})	Iron slopes (GeV^{-2})
FMS	0.029	0.032
GKM	0.06	0.047
KNS	0.06	0.047
CLAS Data	$0.044 \pm 0.015_{stat} \pm 0.019_{syst}$	$0.053 \pm 0.008_{stat} \pm 0.013_{syst}$

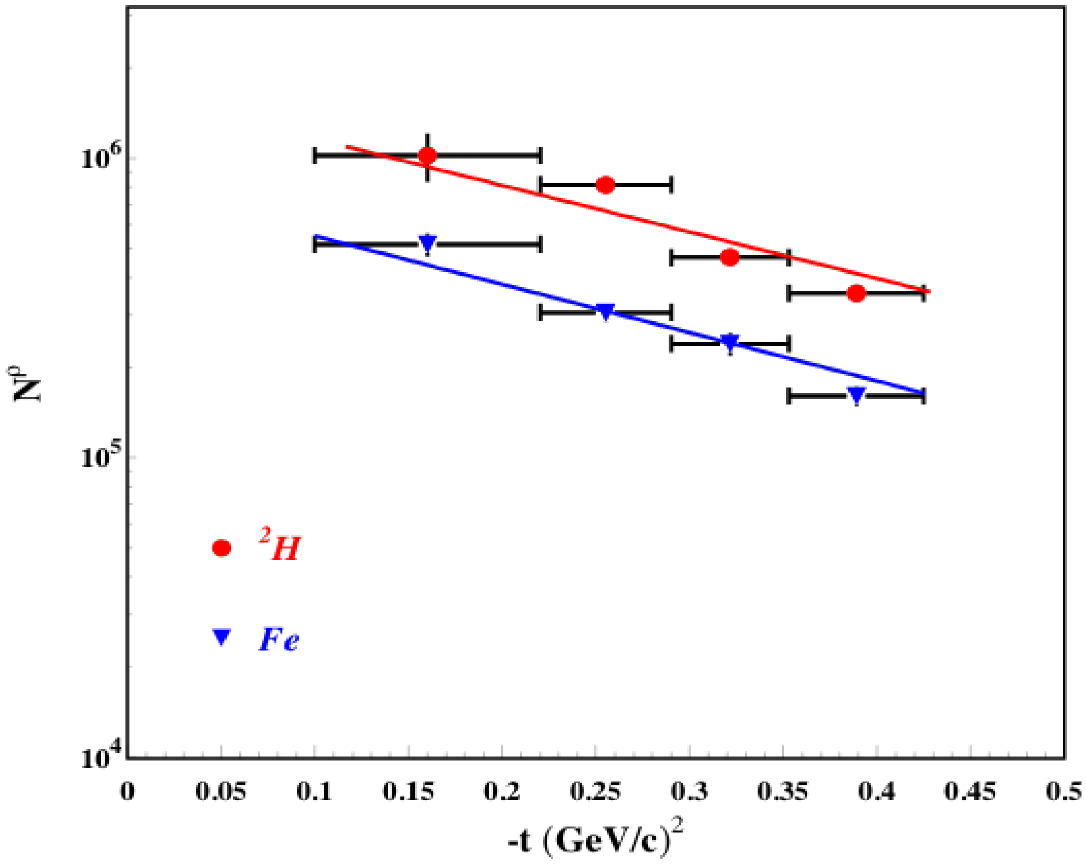
- KNS: Light Cone QCD Formalism

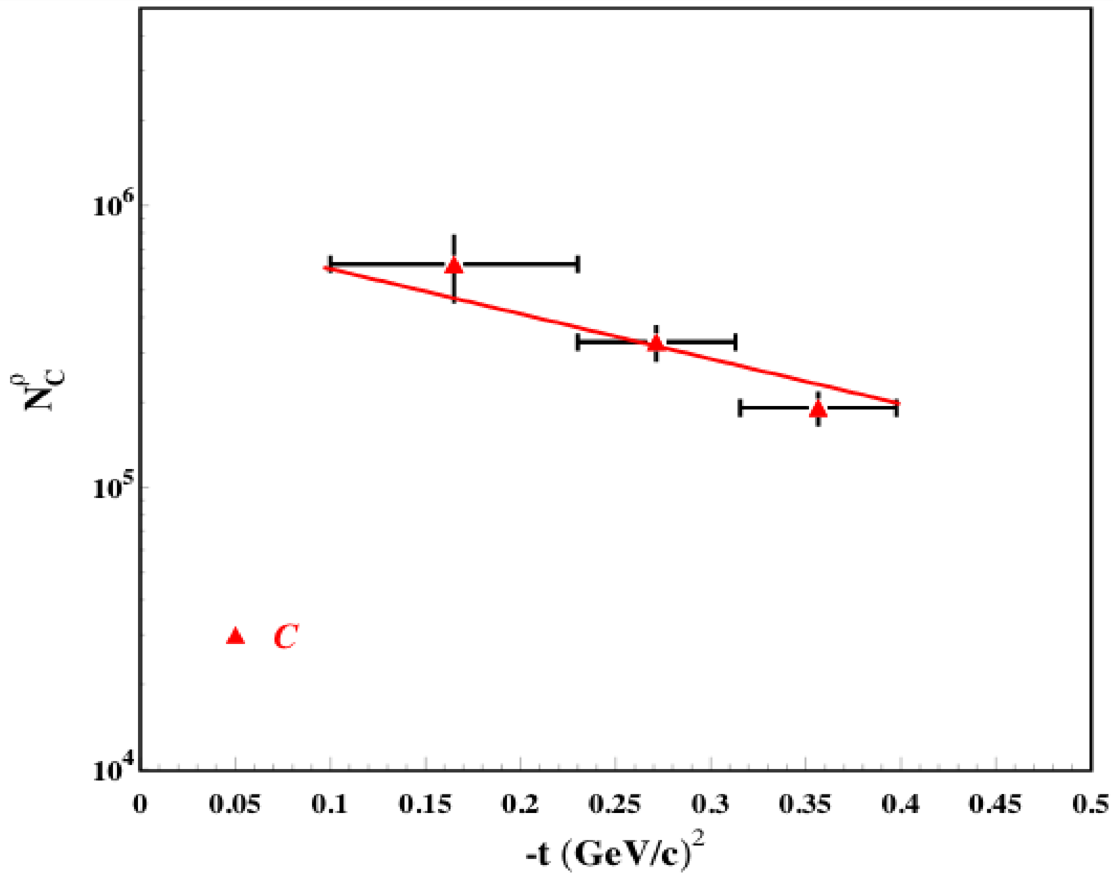
Kopeliovich, Nemchik & Schmidt, PRC 76, 015205 (2007)
& Private communication.

Mass-dependent Fit, $T = A^{\alpha - 1}$ of 6 GeV JLab CT Results



t Slopes





A e^{bt} fit b(^{2}H) = 3.58 ± 0.5 GeV^{-2}
b(C) = 3.67 ± 0.8 GeV^{-2}
b(Fe) = 3.72 ± 0.6 GeV^{-2}

CLAS Proton data

$0.22 < x_B < 0.28$, $1.6 < Q^2 < 1.9$ GeV^2

$2.4 < W < 2.8$ GeV

b= 2.63 ± 0.44 GeV^{-2}

CT Model: Frankfurt, Miller & Strikman (FMS), PRC 78 (2008)

- FMS is based on multiple diffusion scattering formalism,
- Effective interaction depends on the propagation length (l_h) of (qq-bar) pair,
- CT effect depends on the l_h and the PLC formation length τ_f:
  - Smaller l_h than τ_f are designated to the interaction of the expanding PLC,
  - Larger l_h than τ_f are associated to a typical Glauber-like interaction.

CT Model: Gallmeister, Kaskulov & Mosel, PRC 83, 015201 (2011)

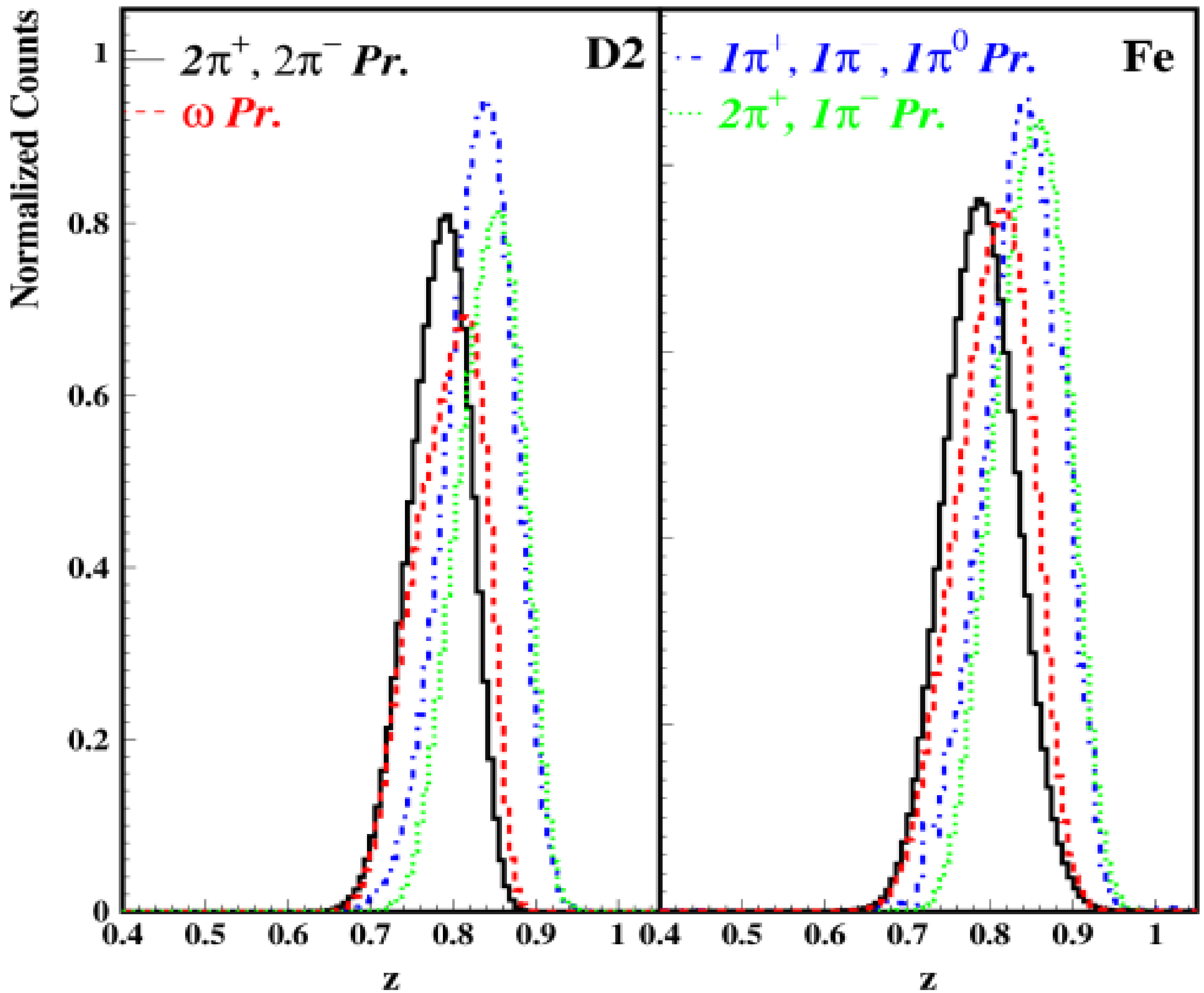
- GKM model is based on coupled-channel semi-classical GiBUU (Giessen-Boltzmann Uehling-Uhlenbeck) transport equation.
- Primary electron-nucleon interaction is described by the impulse approximation which assumes interacting with only one nucleon at a time.
- Exclusive ρ^0 electroproduction is dominated by the hard partonic interaction based on a color string breaking mechanism of DIS.
- CT theoretical framework is essentially a Glauber calculation, with the pre-hadronic interactions being described by the pQCD-inspired cross section of Farrar assuming that the formation time (τ) corresponds to the expansion time of the SSC. In this picture, the cross section in FSI, that has a $1/Q^2$–dependent starting value, grows linearly with time τ till it reaches the full hadron-nucleon cross section.

CT Model: Kopeliovich et al., PRC 65 (2002) 035201

- Model based on light-cone (LC) approach,
- LC dipole phenomenology for elastic production of vector meson (VM): $\gamma^*N \rightarrow V\,N$,
- $M(\gamma^*N \rightarrow V\,N) = \langle V|\sigma(q\bar{q})|\gamma^*\rangle$.

  - ✓ σ(qq-bar): universal flavor independent dipole cross section for qq-bar interaction with a nucleon fitted to the proton structure function data over a large range of x_B and Q^2.
  - ✓ Ψ_{γ^*}: LC wave function for qq-bar fluctuation of the virtual photon.
  - ✓ Ψ_v: LC wave function for the vector meson.

- $\mathbf{Z_h \geq 0.9}$ is effective in removing muti-pions final state contribution.



Reconstructed Vertex Distribution

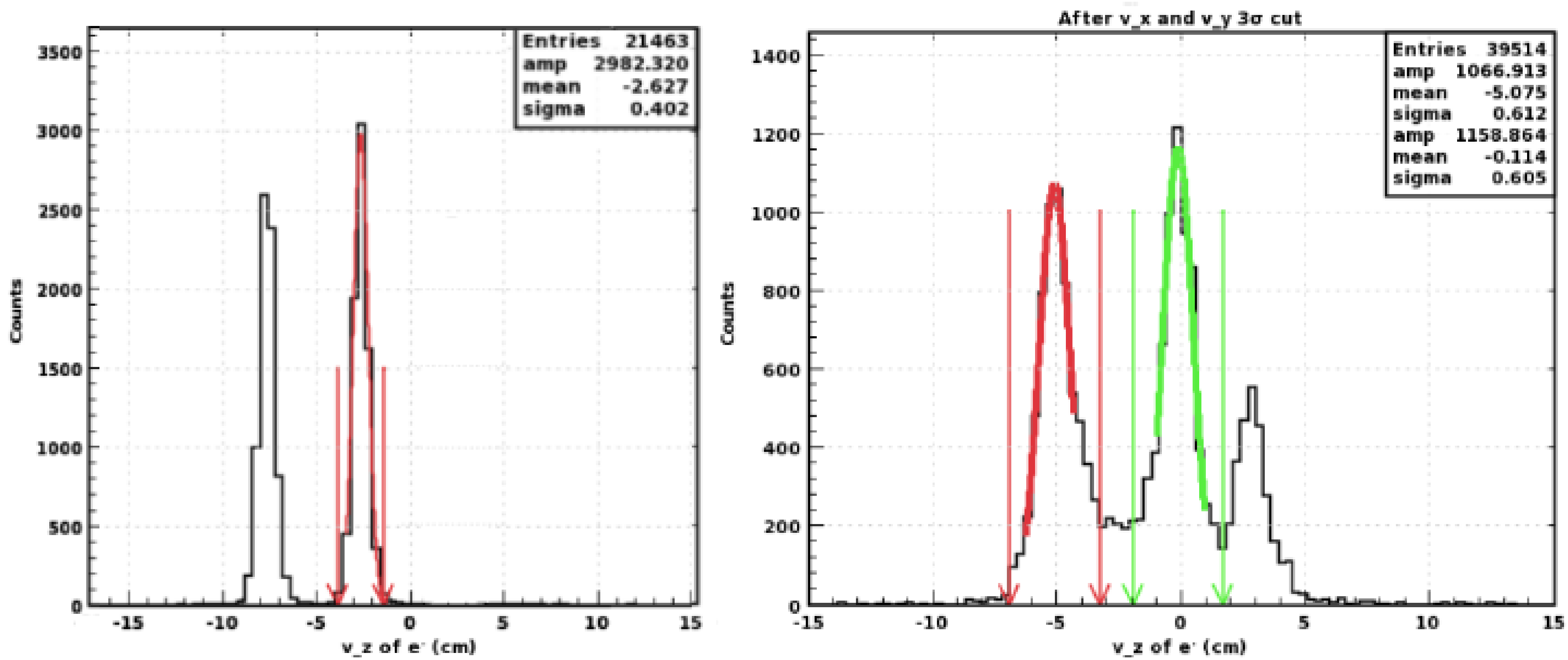


Figure 4: Left: The simulated electron z-vertex distribution showing the peaks of the 5-cm apart solid foils. The second peak is fitted and the two arrows indicate the 3 σ limit. Right: Electron z-vertex distribution from an empty target RG-A run. The three peaks are respectively the 5 cm apart entrance and exit windows (30 μm Al) of the LD2 cell and a thermal insulation foil, 12 μm, heat shield, which doesn't exist in the flag design because it is not needed in this case. The distribution is plotted after applying 3 σ cut on the electron's transverse vertex components, V_x and V_y, to reduce the background contribution. The vertex resolution is in the range of 6 mm, and the red and green arrows indicate the 3 σ limit which is sufficient to resolve the two 5 cm apart Al windows from each others.

from the RG-D Jeopardy document