Chasing QCD Signatures in Nuclei using Color Coherence Phenomena

"The Future of Color Transparency and Hadronization Studies at JLab and Beyond" Workshop

June 7, 2021

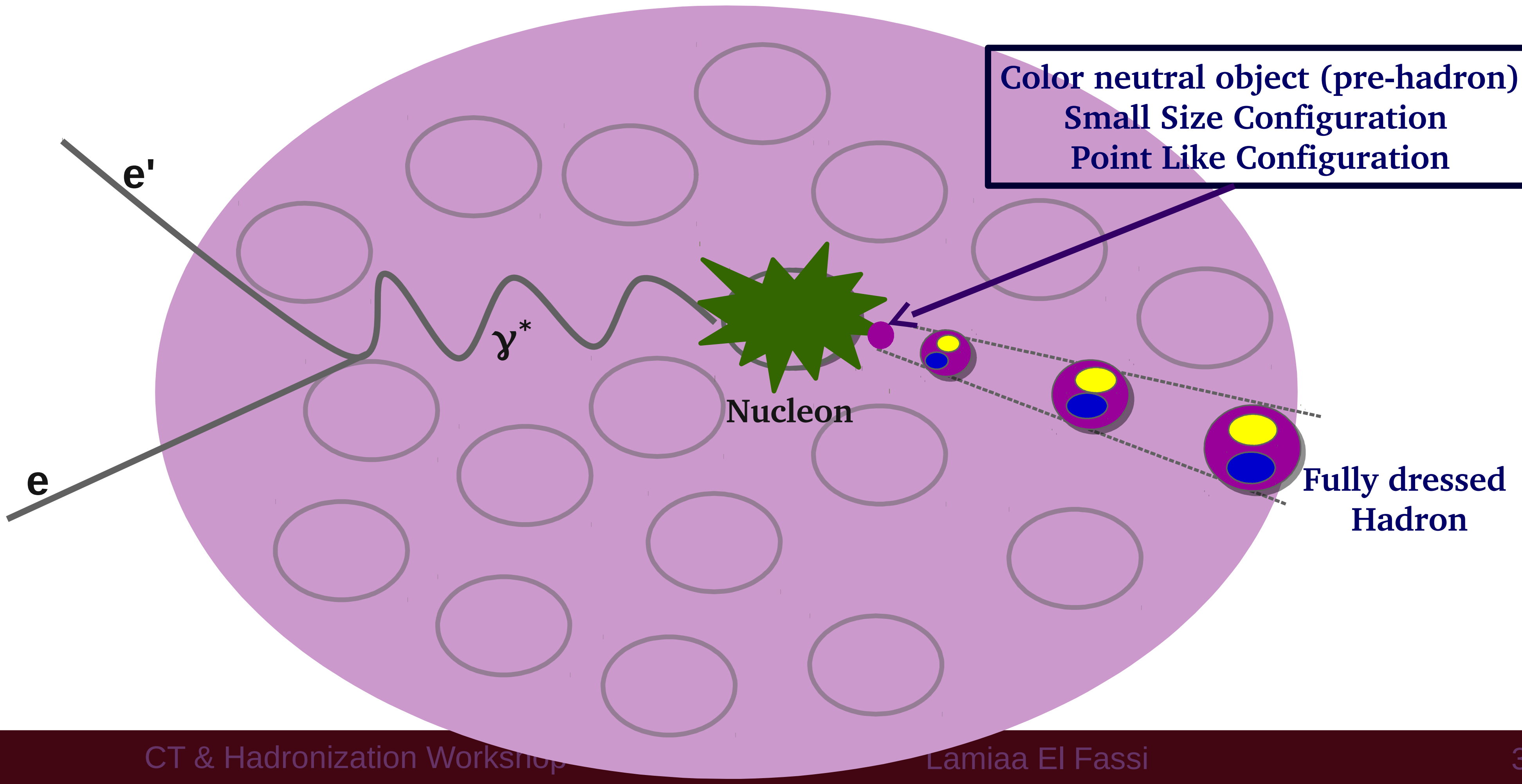
Lamiaa El Fassi
Mississippi State University

Outline

- Physics Motivation
- Highlights of Color Transparency Studies
- Summary and Outlook
- Lambda Hadronization Study Discussion (on Discussion 4 session)

How does the colored bare, quark, evolves to a fully dressed hadron?

- Study hard processes in nuclei to probe the QCD confinement dynamics:
  - Creation and evolution of small size hadrons - **Color Transparency (CT)**



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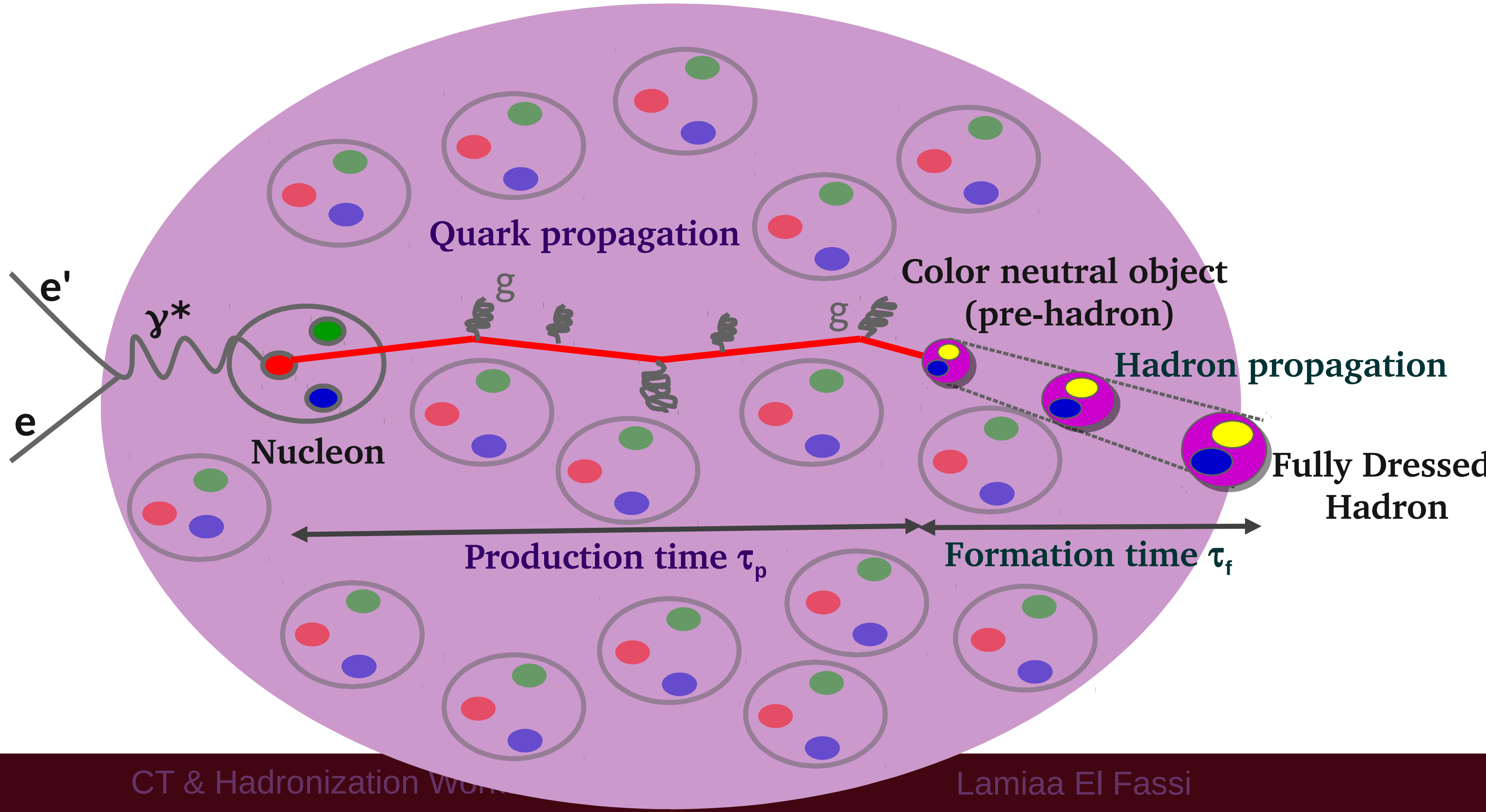

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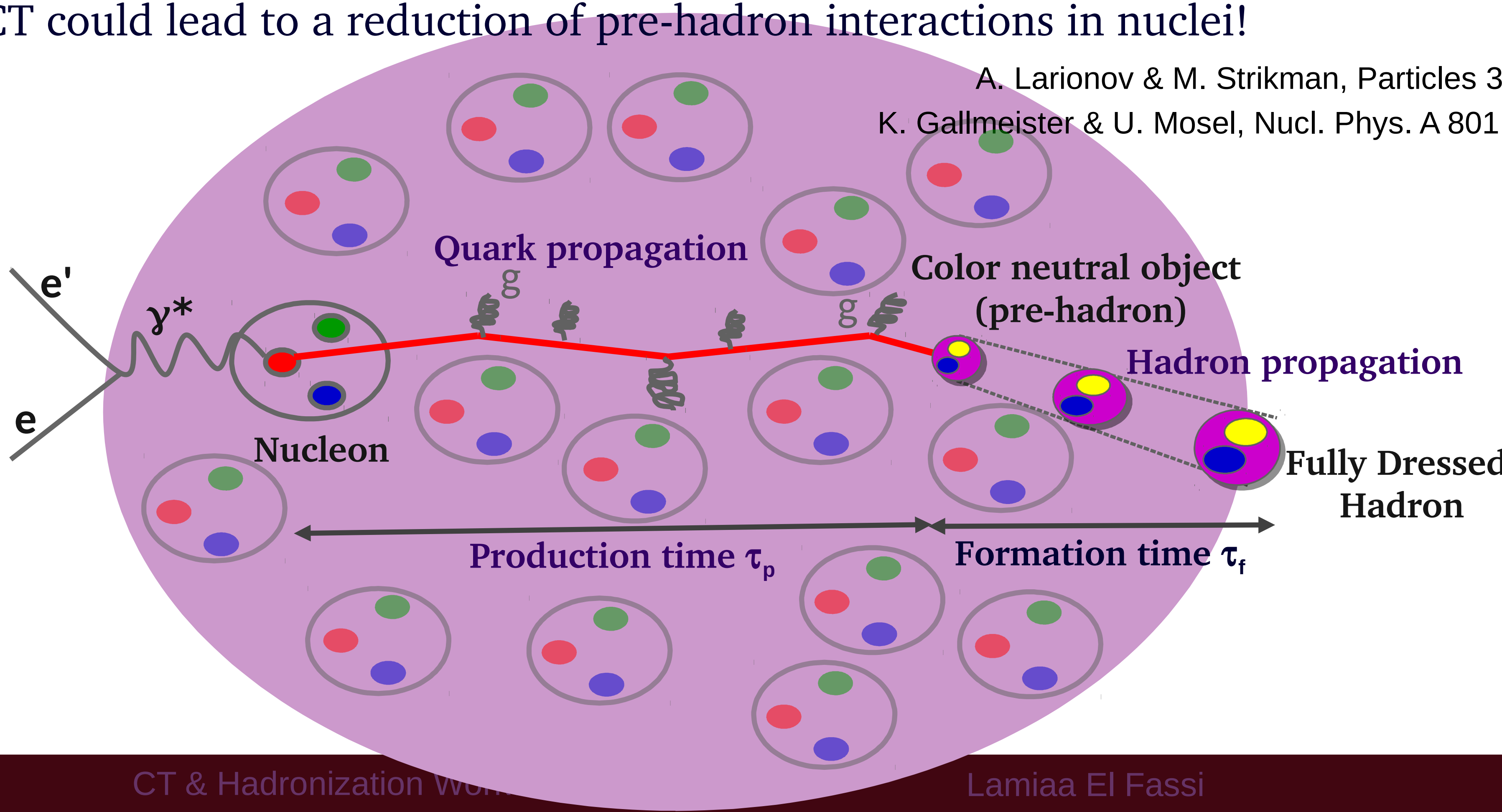
    - CT could lead to a reduction of pre-hadron interactions in nuclei!

A. Larionov & M. Strikman, Particles 3 (2020)
K. Gallmeister & U. Mosel, Nucl. Phys. A 801 (2008)



Hard Probe .vs. Medium

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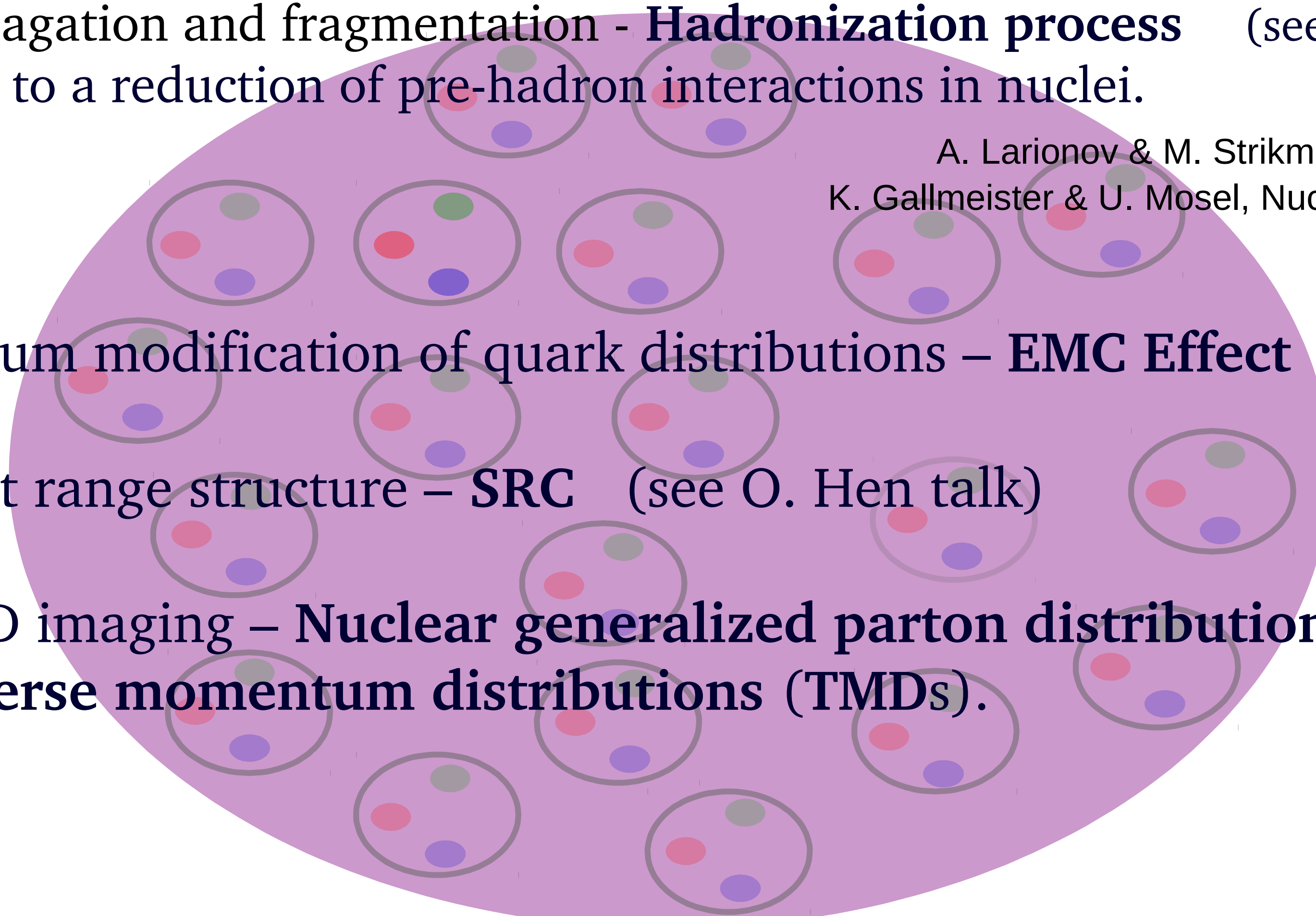
- Study medium modification of quark distributions – **EMC Effect**
- Access short range structure – **SRC** (see O. Hen talk)
- Perform 3-D imaging – **Nuclear generalized parton distributions** (**GPD**s) and **transverse momentum distributions** (**TMD**s).



CT Basics: The Survival of the Smallest

- Creation of small size configurations (SSCs) in hard and exclusive reactions:
  - Study of quark and gluons scattering and their formation into hadrons at the amplitude level,
  - Elasticity is guaranteed due to the small transverse separation (b) of SSC quark constituents.

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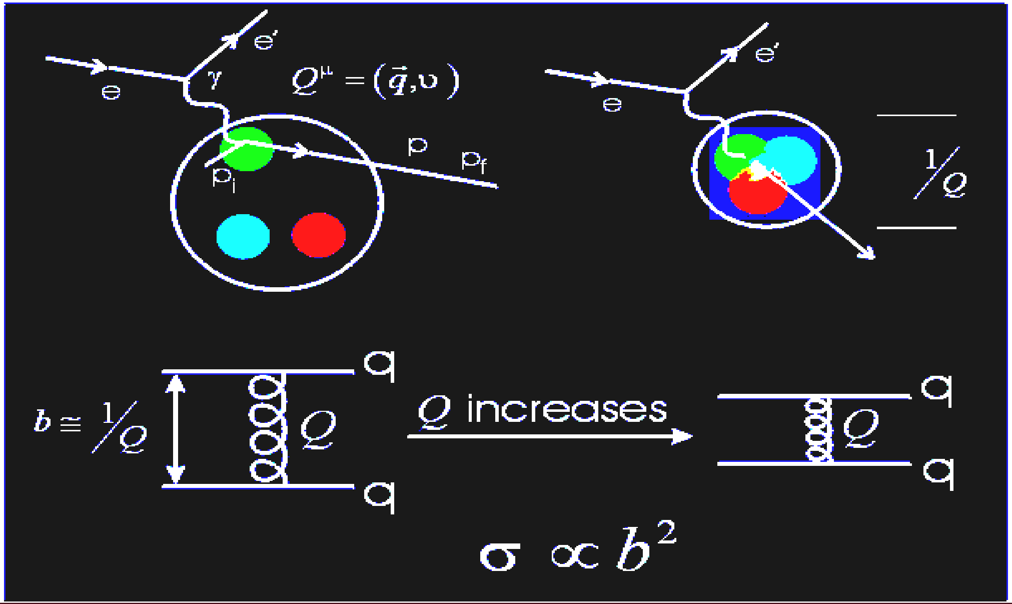
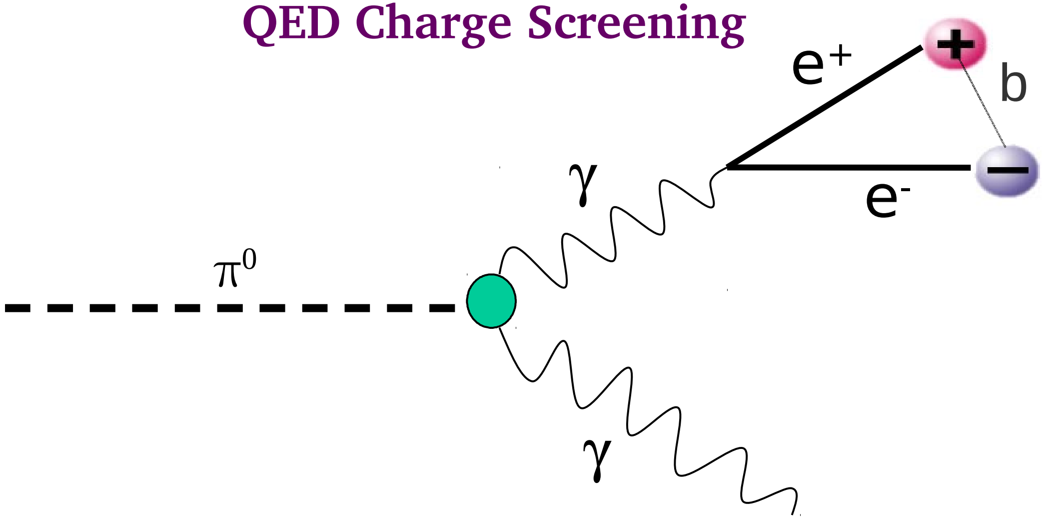
- SSC experiences reduced attenuation before evolving to fully dressed hadron,
  - In QCD, the color field of singlet objects vanishes as their size is reduced.

QCD Color Screening: Squeezing and freezing



QED Charge Screening



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

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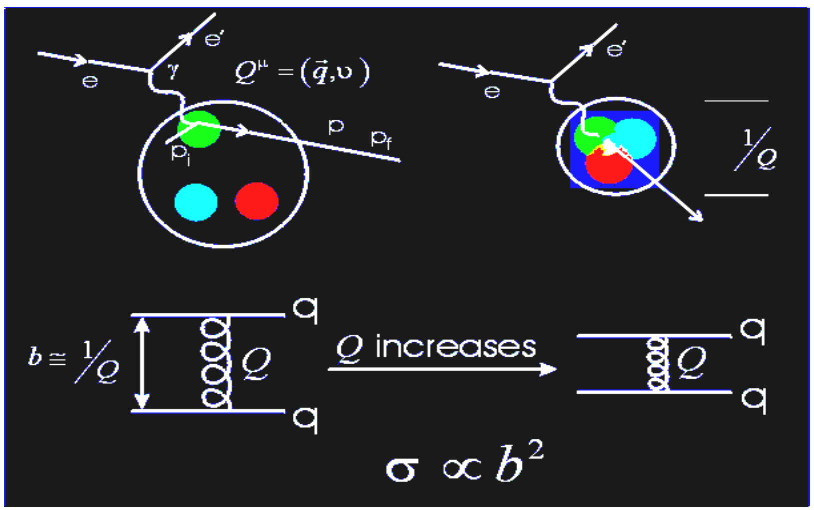

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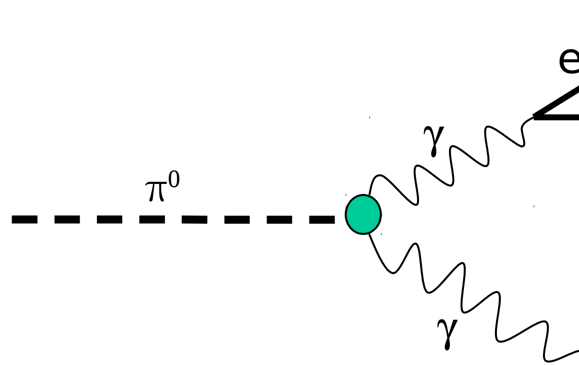


200 GeV π^0 emulsion produced in cosmic rays (Perkins 1955)

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

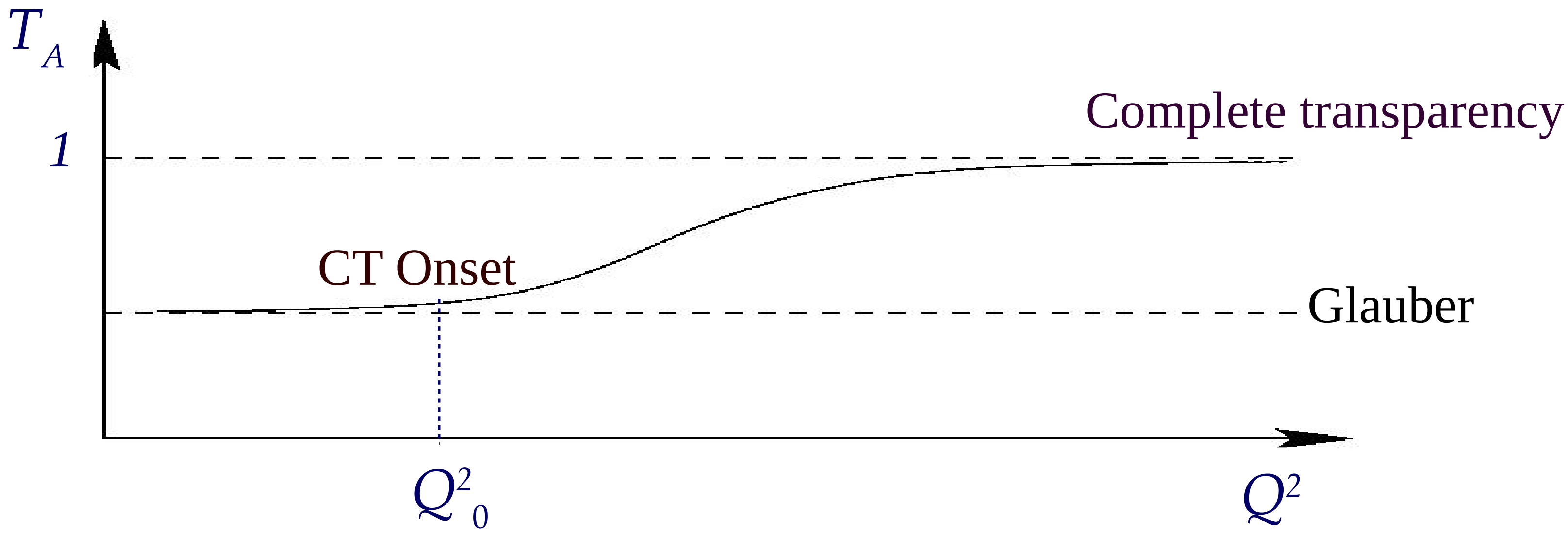
CT Experimental Signature

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

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

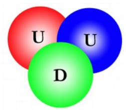
σ_A is the nuclear cross section

σ_N is the free (nucleon) cross section



Highlights of CT Studies

Baryon



A(p, 2p) BNL

A(e, e′p) SLAC, MIT-Bates & JLab

Meson

A(π, di-jet) FNAL

A(γ, J/ψ) FNAL

A(e, e’ J/ψ) DESY

A(γ, π^- p) JLab

A(e, e'π^+) JLab

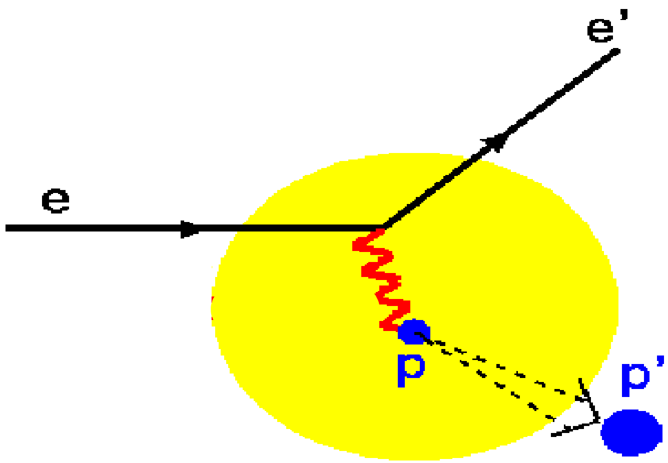
A(e, e'k^+) JLab

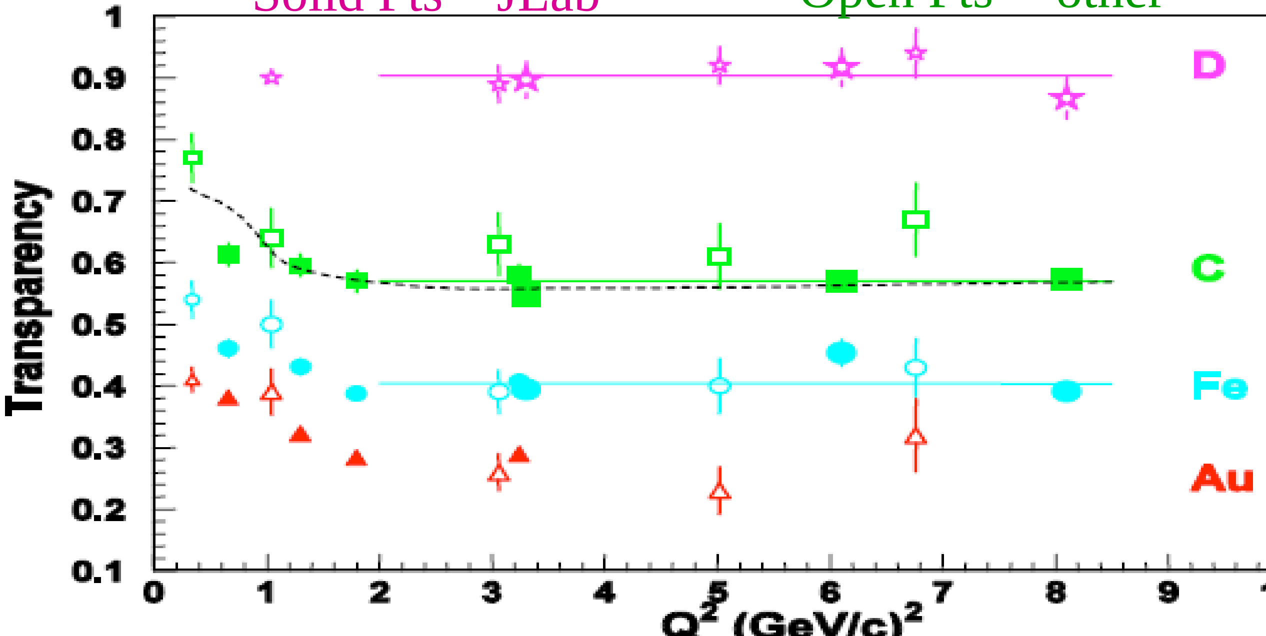
A(μ, μ'ρ^0) FNAL

A(e, e′ρ^0) DESY & JLab

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

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



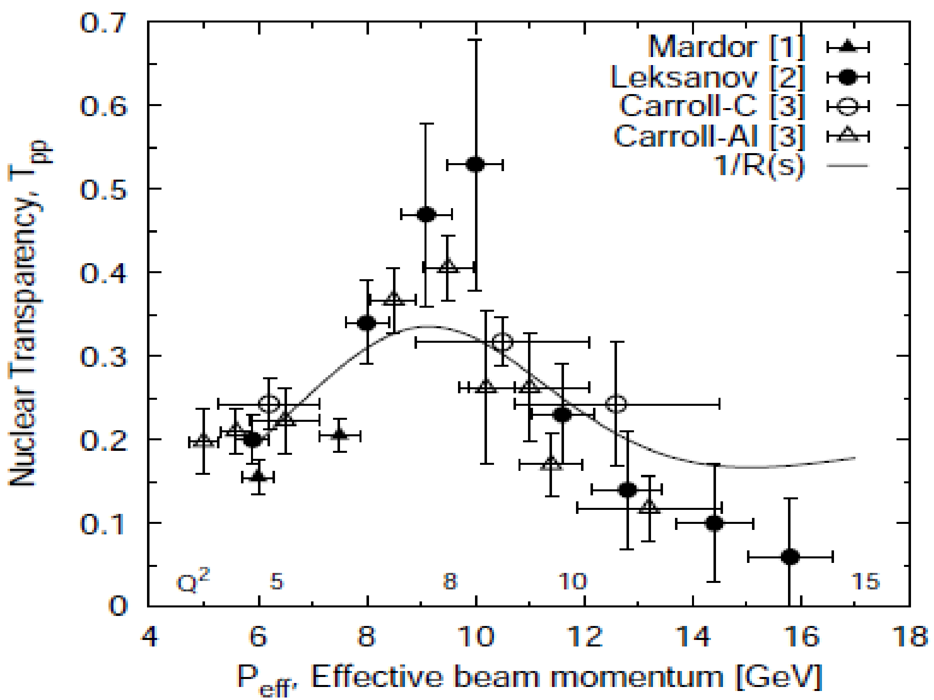


N. C. R. Makins *et al.* PRL 72 (1994)
G. Garino *et al.* PRC 45 (1992)
D. Abbott *et al.* PRL 80 (1998)
K. Garrow *et al.* PRC 66 (2002)

Details in H. Szumilla-Vance talk

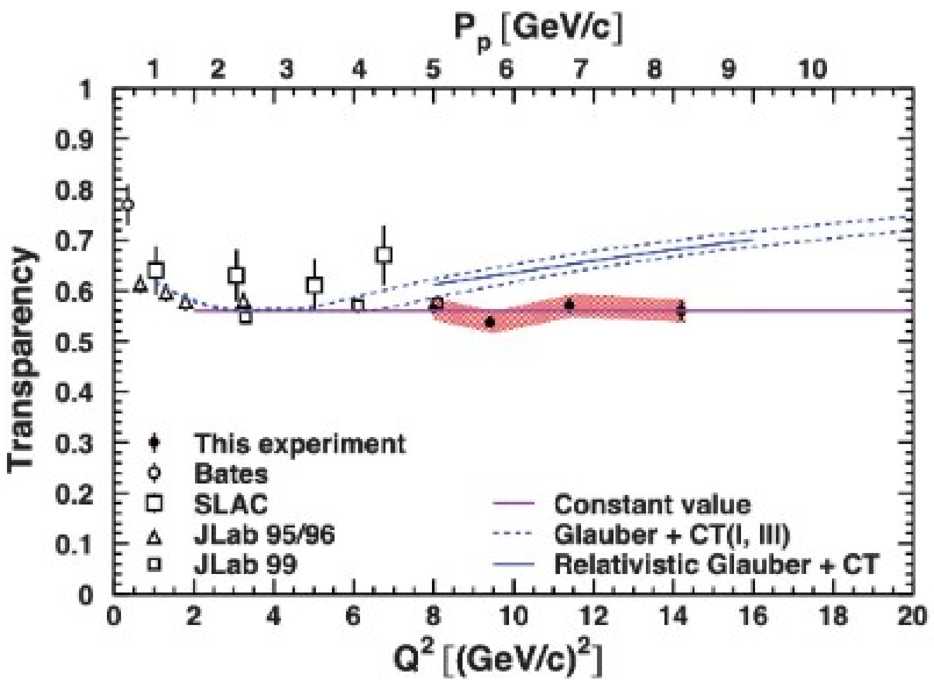
BNL A(p, 2p) .vs. JLab A(e, e'p)

BNL A(e, e′p)



A. Leksanov *et al.* PRL 87 (2001)

12 GeV JLab $^{12}C(e, e'p)$: No CT Onset



D. Bhetuwal *et al.* PRL 126 (2021)

Details in H. Szumilla-Vance talk

qqq versus qq-bar systems

- **Small size is more probable in two-quark systems such as pions, 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.**

qqq versus qq-bar systems

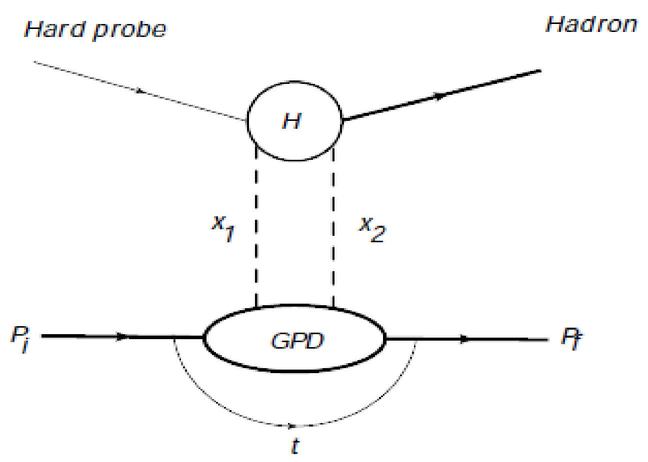
- **Small size is more probable in two-quark systems such as pions, rho mesons than in protons.**

B. Blattel et al., PRL 70 (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.

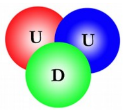
Collins, Frankfurt, Miller, Sargsian and Strikman



Process amplitude factorizes into a hard interaction with a single quark and a soft part parametrized as GPDs.

Highlights of CT Studies

Baryon



A(p, 2p) BNL

A(e, e′p) SLAC, MIT-Bates & JLab

All CT results in the baryonic sector are deceiving!

Meson

A(π, di-jet) FNAL

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A(γ, π^- p) JLab

A(e, e'π^+) JLab

A(e, e'K^+) JLab

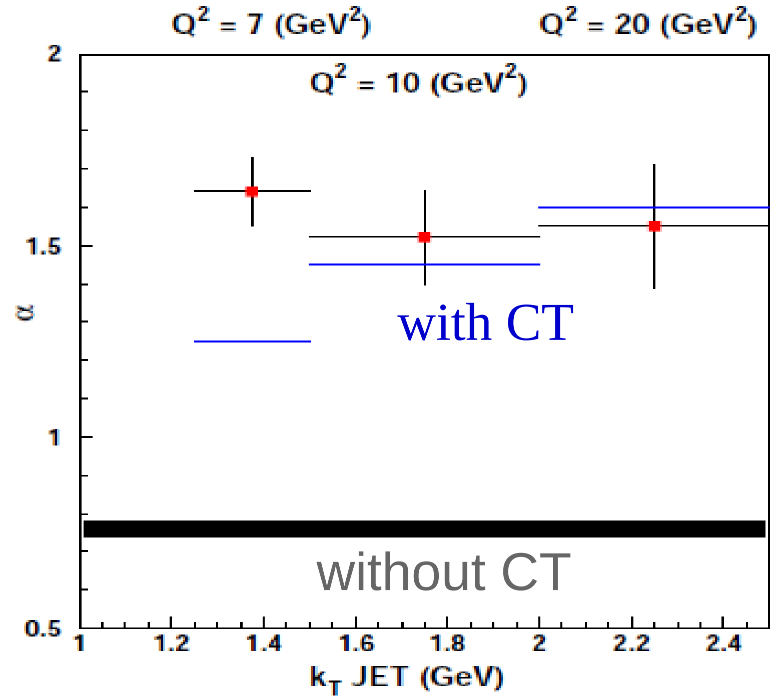
A(μ, μ'ρ^0) FNAL

A(e, e′ρ^0) DESY & JLab

All CT results in the mesonic sector are promising!

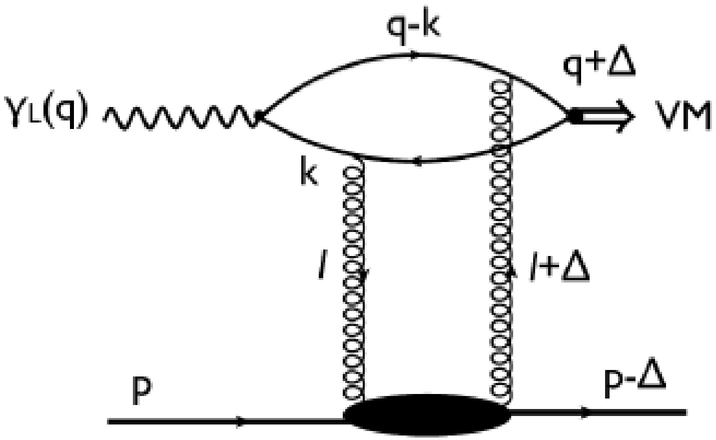
A(π, dijet) Study @ FNAL

- 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. Frankfurt, G. Miller, and M. Strikman, Phys. Lett. B 304 (1993).

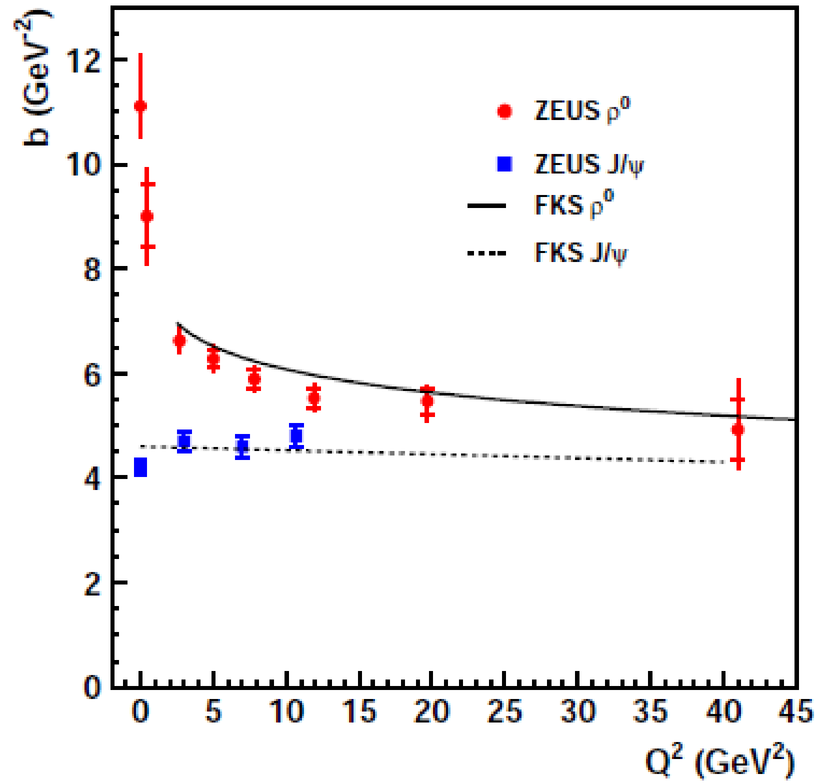


Aitala *et al.*, PRL 86 (2001)

J/ψ & ρ Exclusive Electroproduction @ HERA

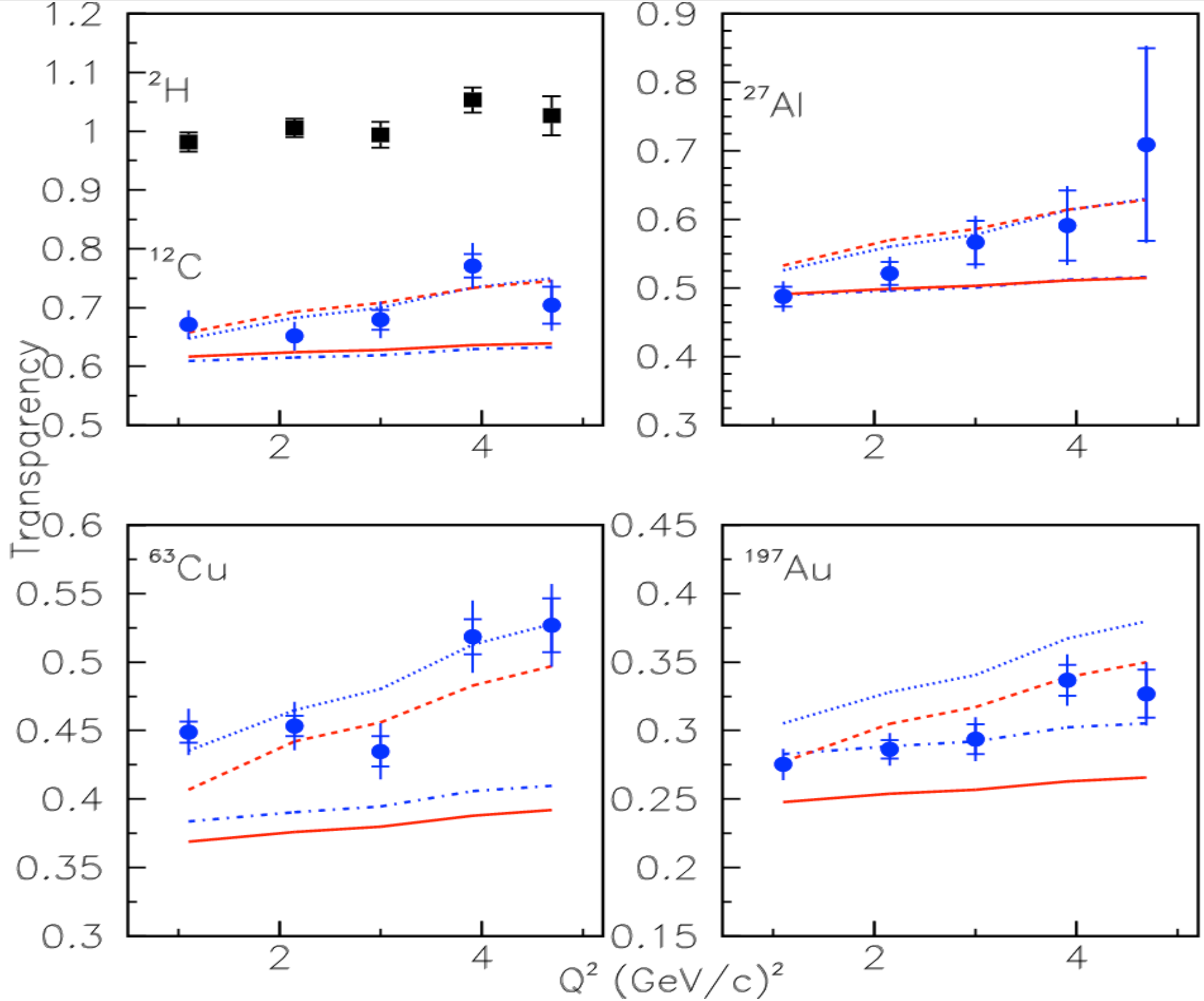


- Fit to $\frac{d\sigma}{dt} \propto e^{-b|t|}$
- Convergence of the t-slope of ρ and J/ψ electroproduction at large Q^2 confirmed the presence of small size qq-bar states.



S. Chekanov et *al.*, Nucl. Phys. B 695 (2004)
S. Chekanov et *al.*, PMC Phys. A 1 (2007)
Frankfurt, Koepf and Strikman, Phys. Rev. D 57 (1998)

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



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

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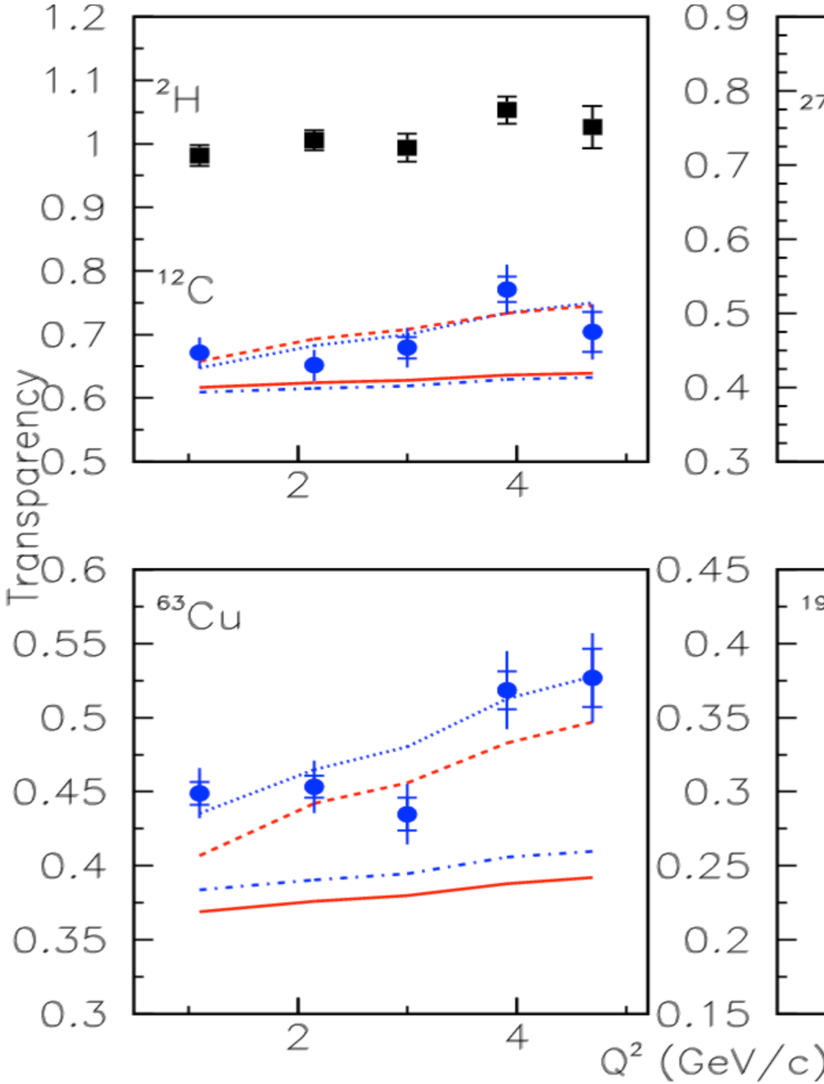
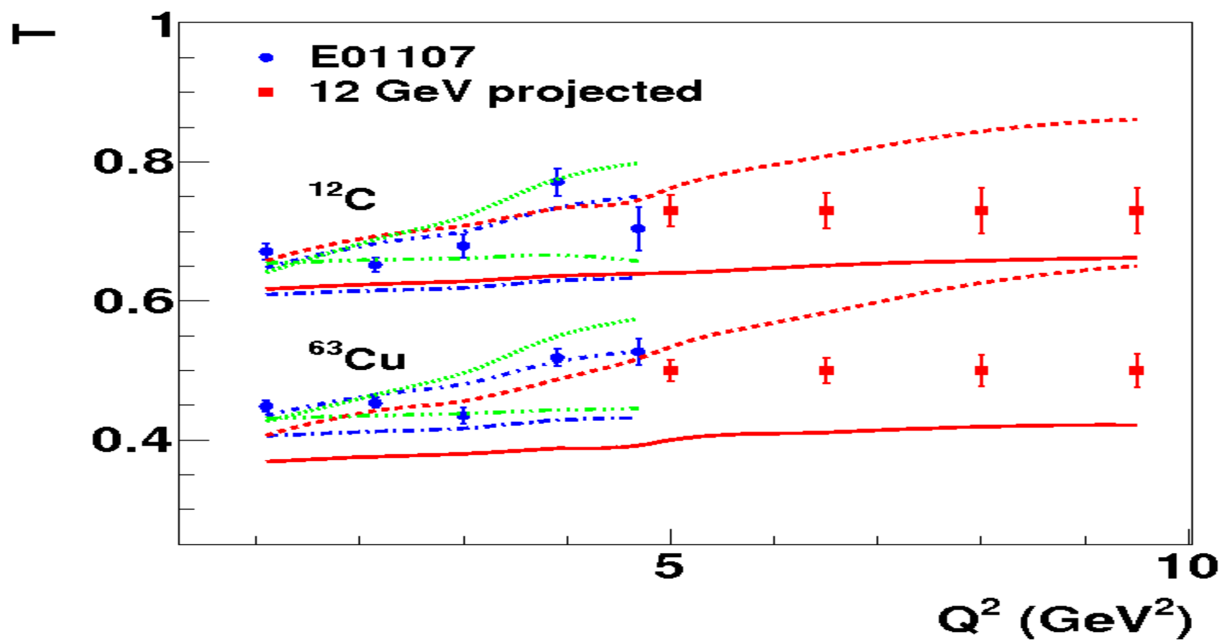
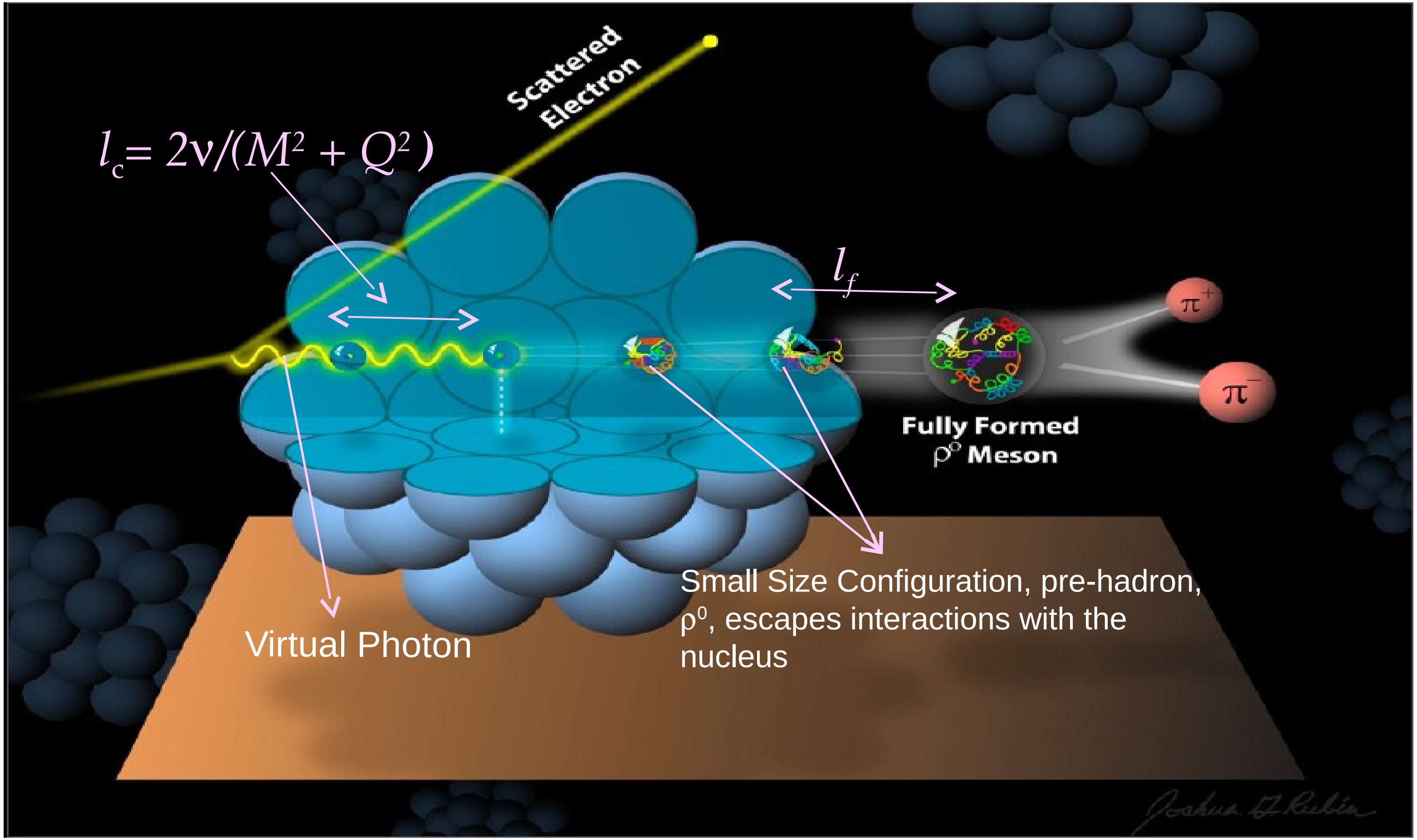


B. Clasie *et al.* PRL 90 (2007), X. Qian *et al.*, PI

The π^+ CT measurements will be extended to Q^2 of about 10 $(GeV/c)^2$ using an 11 GeV beam energy and the Hall-C two-arm spectrometer.



Diffractive ρ^0 Leptoproduction

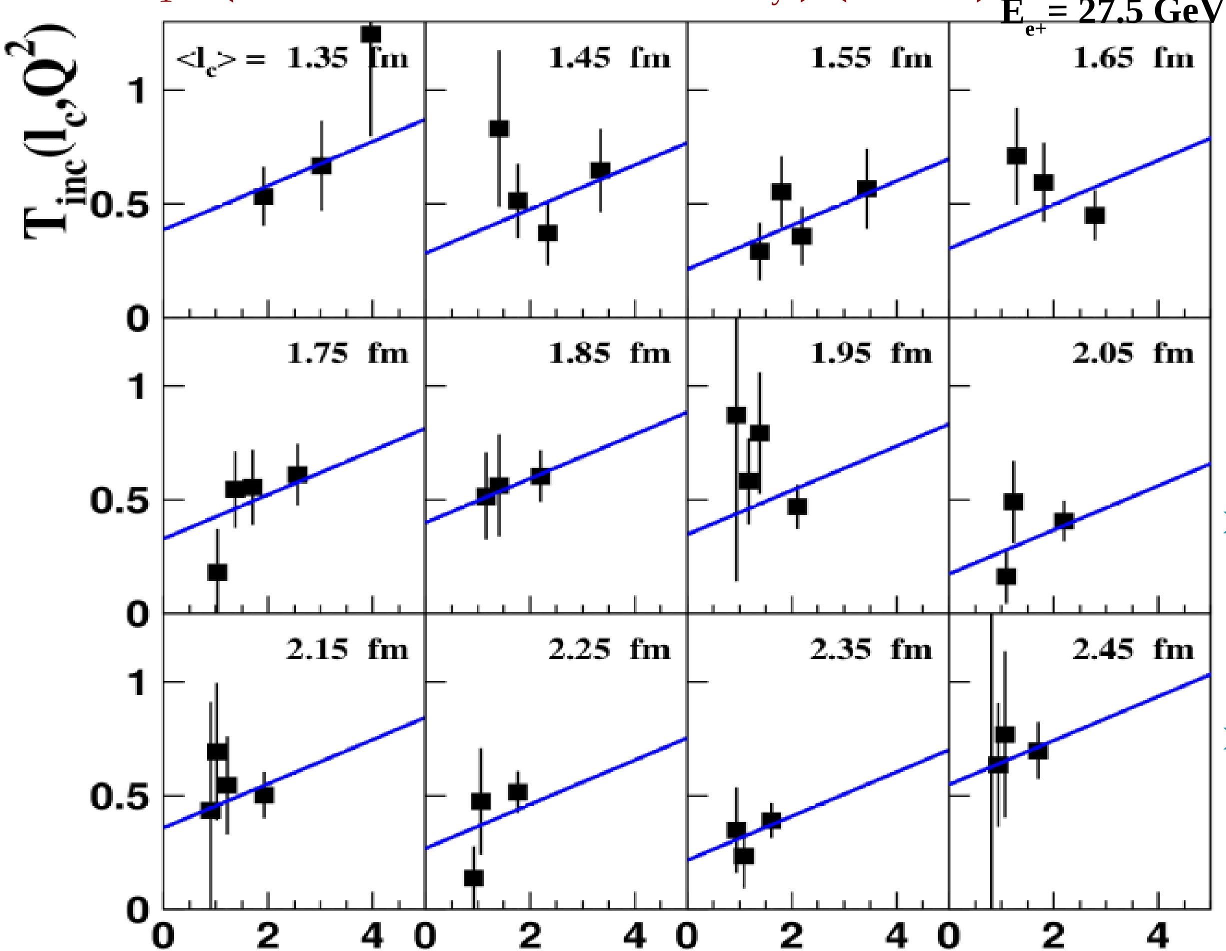


- Coherence length, l_c: the lifetime of the **qq-bar** pair.
- Formation time, l_f: the SSC time evolution to on-shell ρ^0 meson.

Exclusive ρ^0 Leptoproduction: Hermes

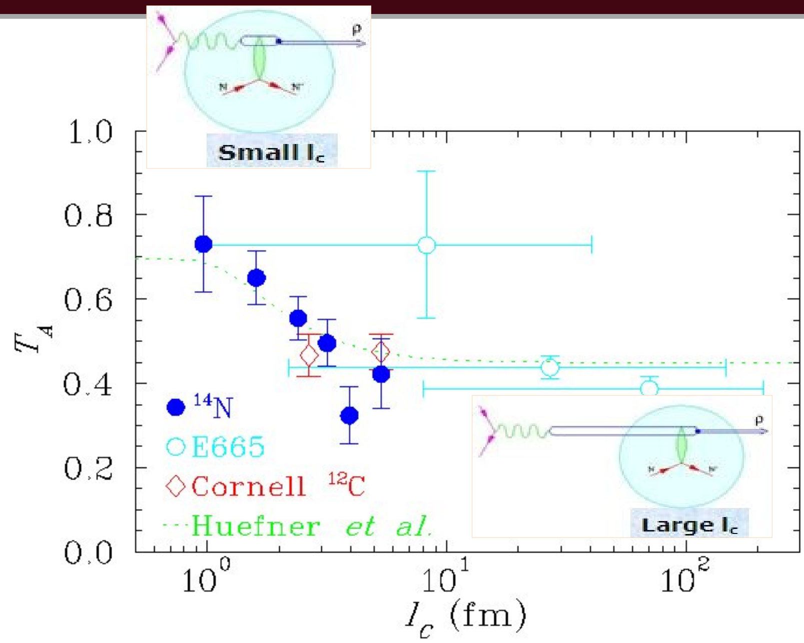
- HERMES ^{14}N Data: $T_{inc}(l_c, Q^2) = P_0 + P_1 Q^2$

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



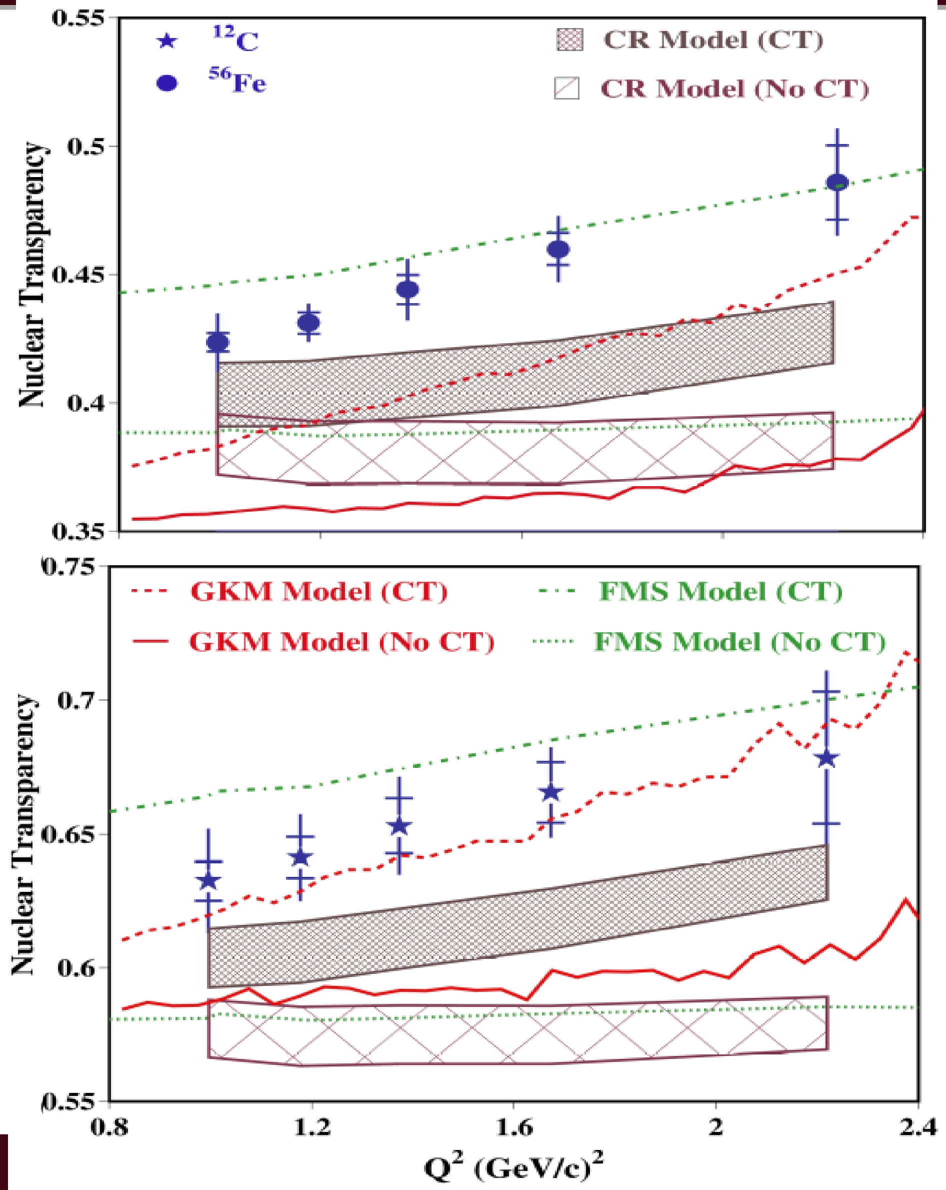
Airapetian *et al.*, PRL 90 (2003)

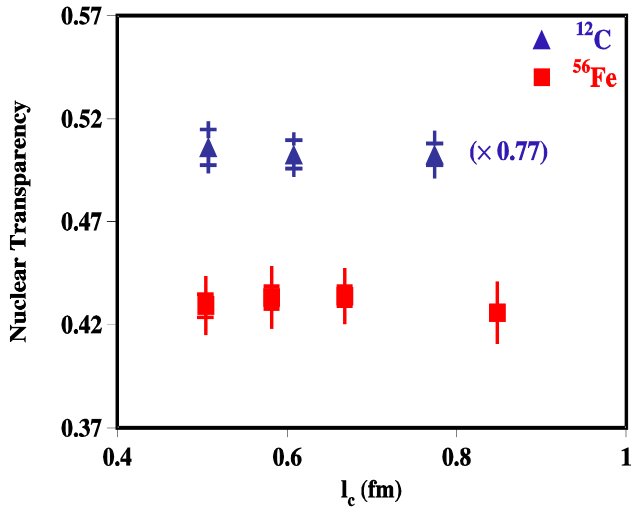
Consistent with CT predictions of Kopeliovich *et al.*



- 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.

CLAS6 ρ^0 CT Results





No l_c dependence observed

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

- **FMS**: semi-classical Glauber formalism based on quantum diffusion model (QDM).
- Dashed-dotted curve includes CT effects, FSIs and ρ^0 decay.

Frankfurt, Miller & Strikman, PRC 78 (2008) & Private communication

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

Gallmeister, Kaskulov & Mosel, PRC 83 (2011)

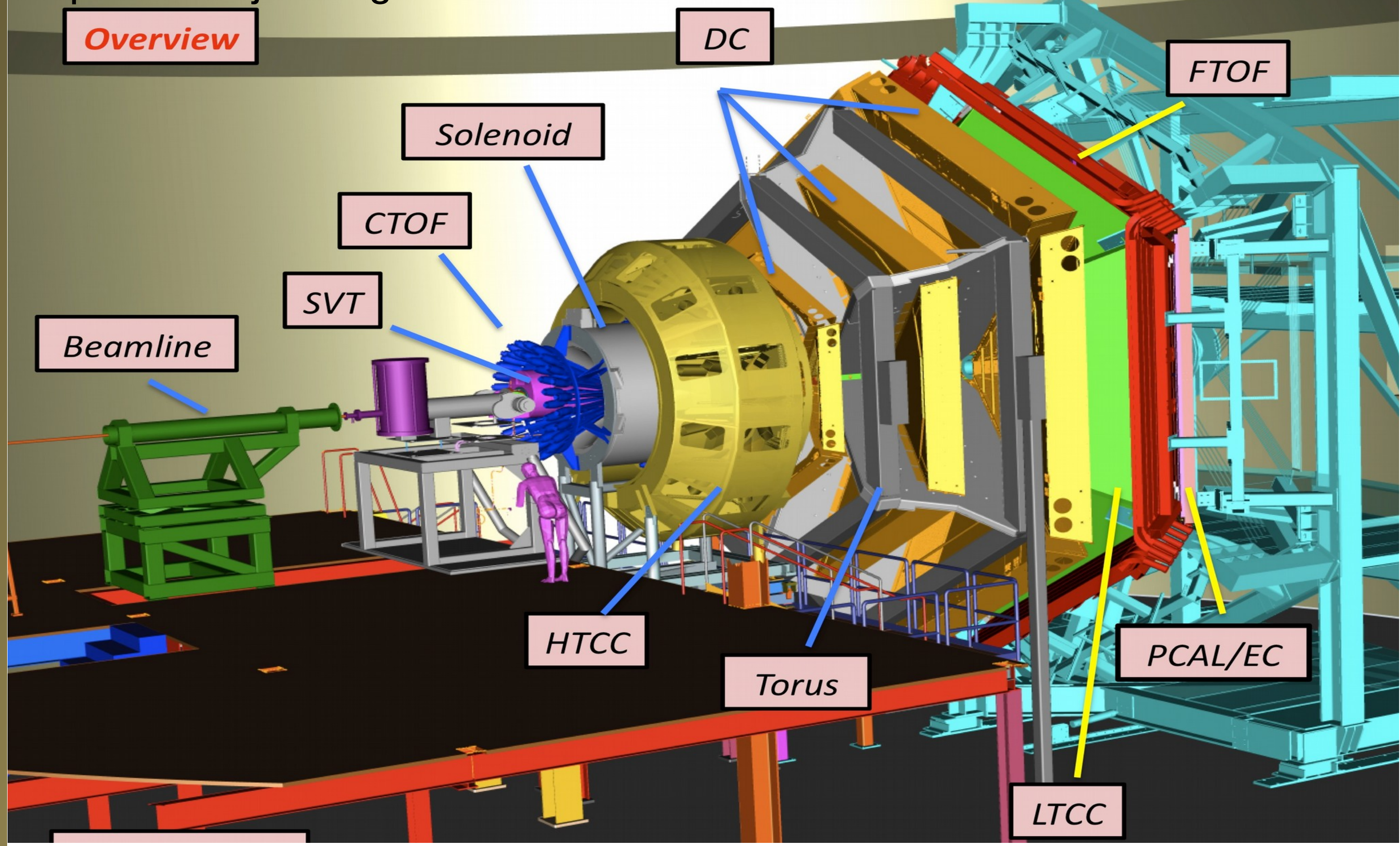
- **CR**: relativistic multiple scattering Glauber approximation.
- Hatched-band includes CT effects based on QDM.

W. Cosyn, and J. Ryckebusch PRC 87 (2013)

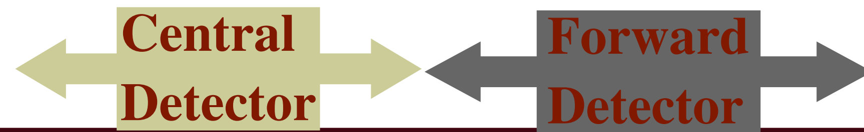
CLAS12 ρ^0 CT Experiment @ JLab

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

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

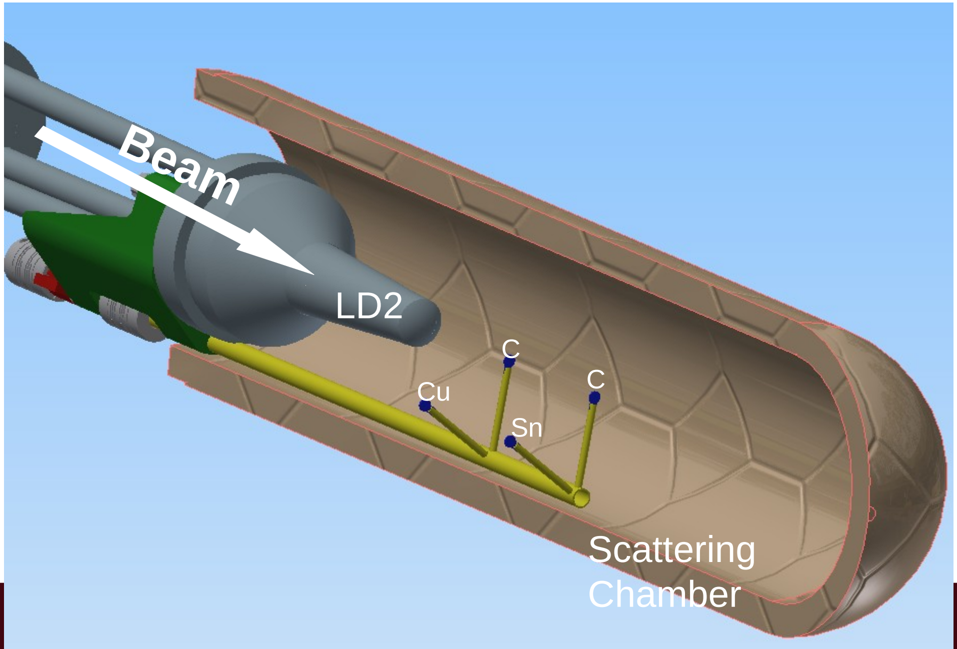


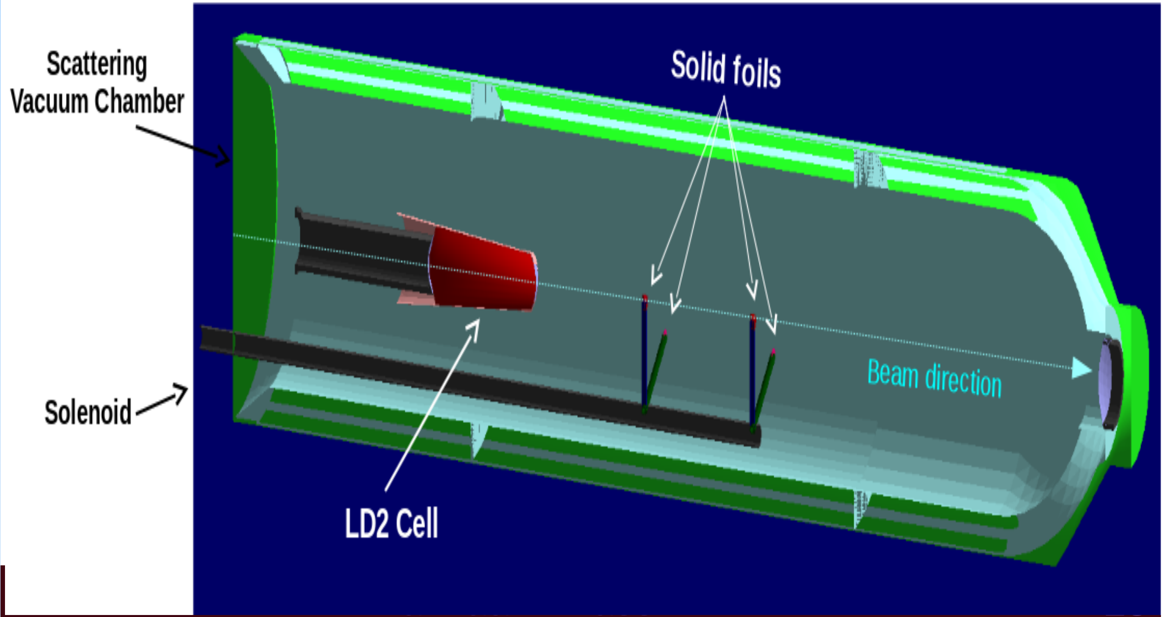
~ 111832 readout channels



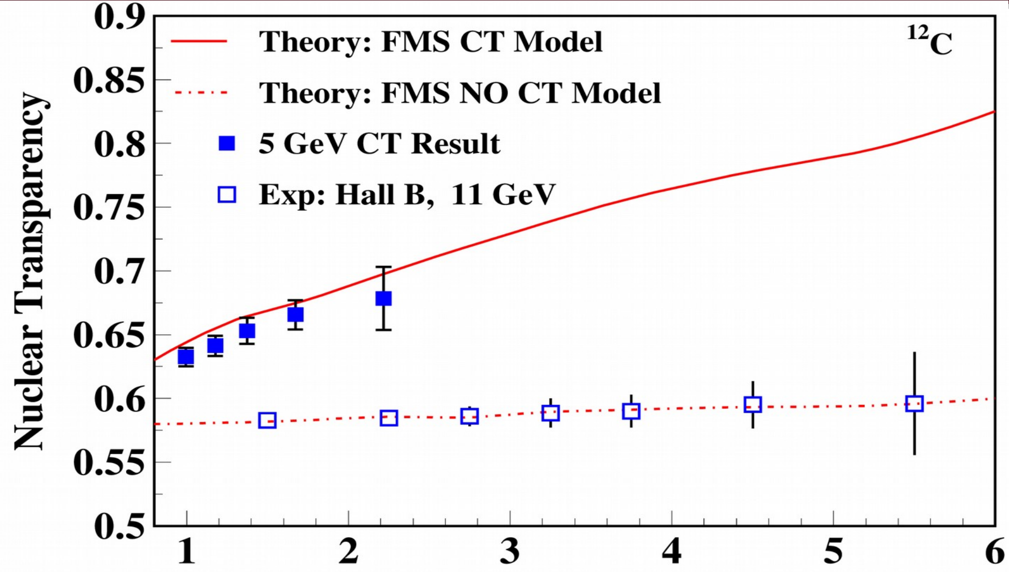
CLAS12 ρ^0 CT Experiment: Nuclear-target Flag Assembly

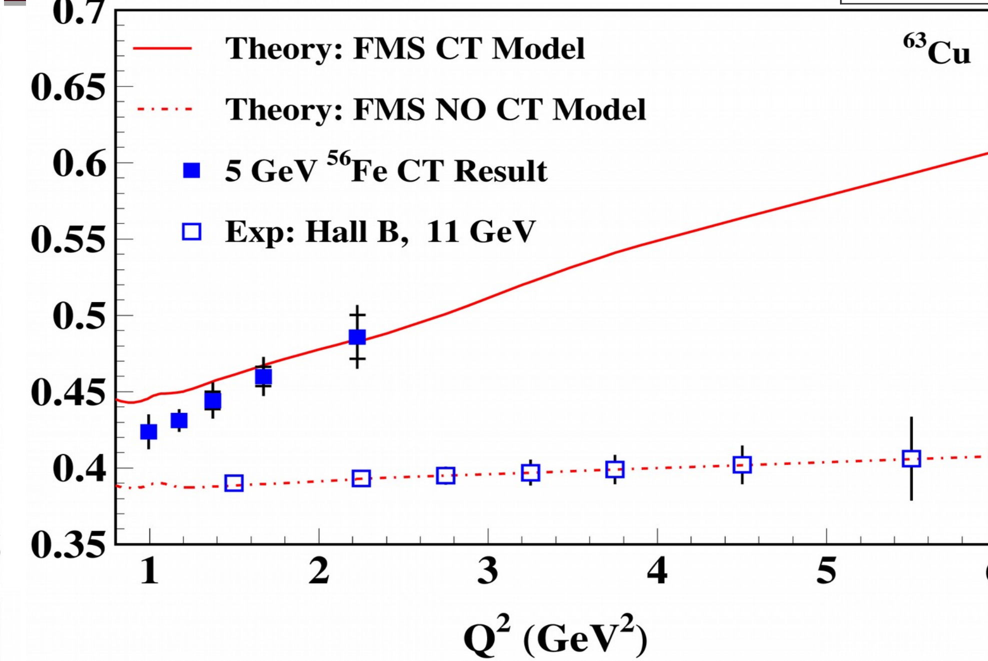
- Standard LD2 cell,
- Foils of 4 mm diameter are mounted on the same shaft and rotate together with a stepper motor,
- 5 cm separation between LD2 cell downstream window and the upstream foil,
- 5 cm spacing between target foils,
- Entire target assembly can be moved along the beamline to center the D2 cell on the solenoid magnet, or center the foils on the solenoid magnet.

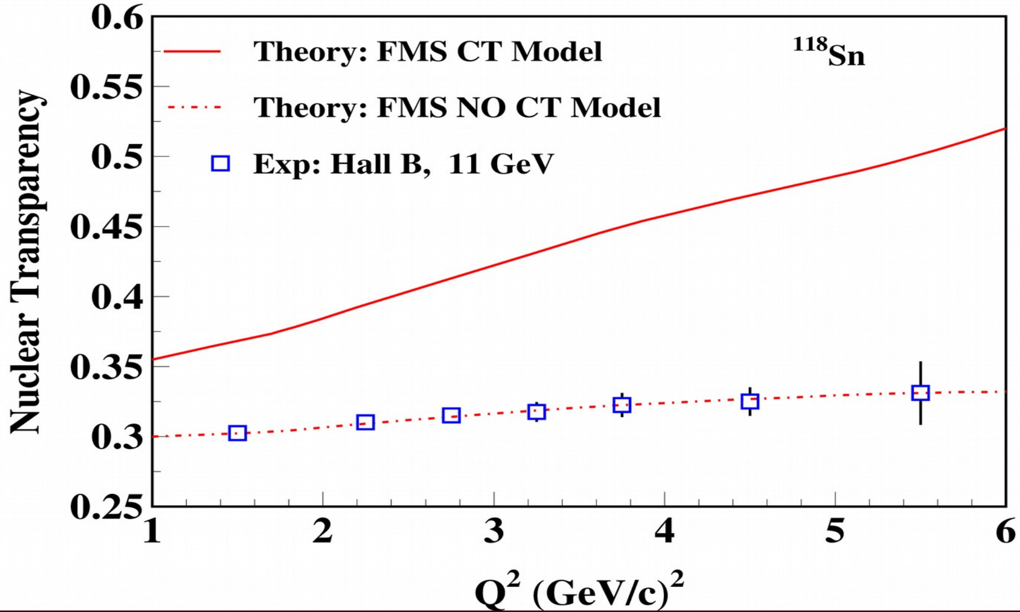


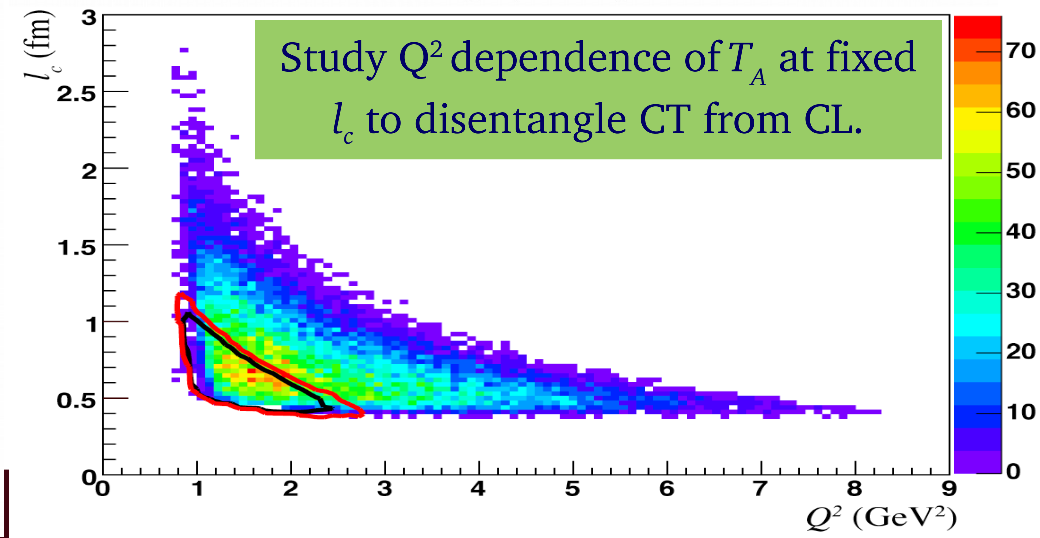


CLAS12 ρ^0 CT Projections: One l_c bin









Summary and Outlook

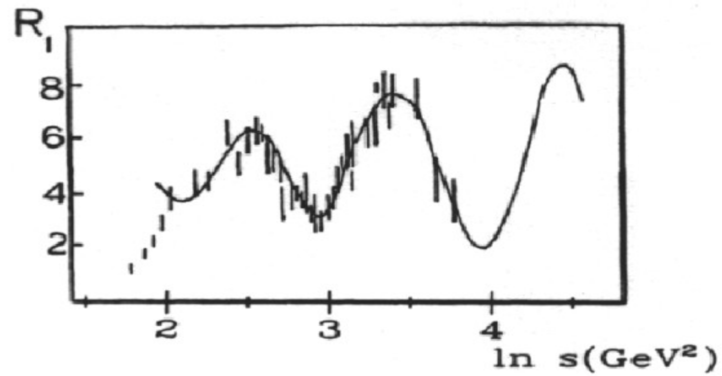
- Strong evidence for the onset of CT in ρ^0 electroproduction off nuclei: CLAS6 5 GeV dataset showed 11±2.3% (12.5±4.1%) decrease in the absorption of ρ^0 in ^{56}Fe (^{12}C).
- The early onset of CT in ρ^0 electroproduction ($Q^2 \approx$ 1 GeV/c^2) compared to pion channel ($Q^2 \approx$ 3 GeV/c^2) suggests that the diffractive meson production is optimum in creating small size configurations.
- At intermediate energies, CT provides unique probe of the space-time evolution of special configurations of the hadron wave function.
- Upcoming CLAS12 measurement will allow to disentangle different CT effects (SSC creation, its formation, and interaction with the nuclear medium).
- Study of high-energy measurements at J-PARC or DIS eA, pA or AA at an EIC and LHC and RHIC should shed more light on CT effects for various production channels and help resolve the proton-CT puzzle *(see the interesting agenda)!*

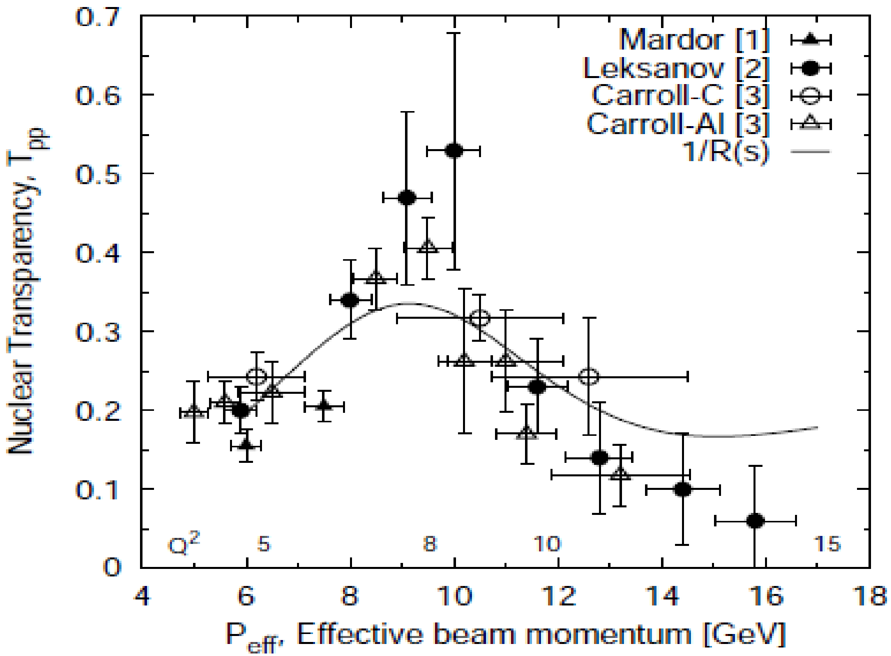
This work is supported in part by the US DOE contract # DE-FG02-07ER41528

Backup

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

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





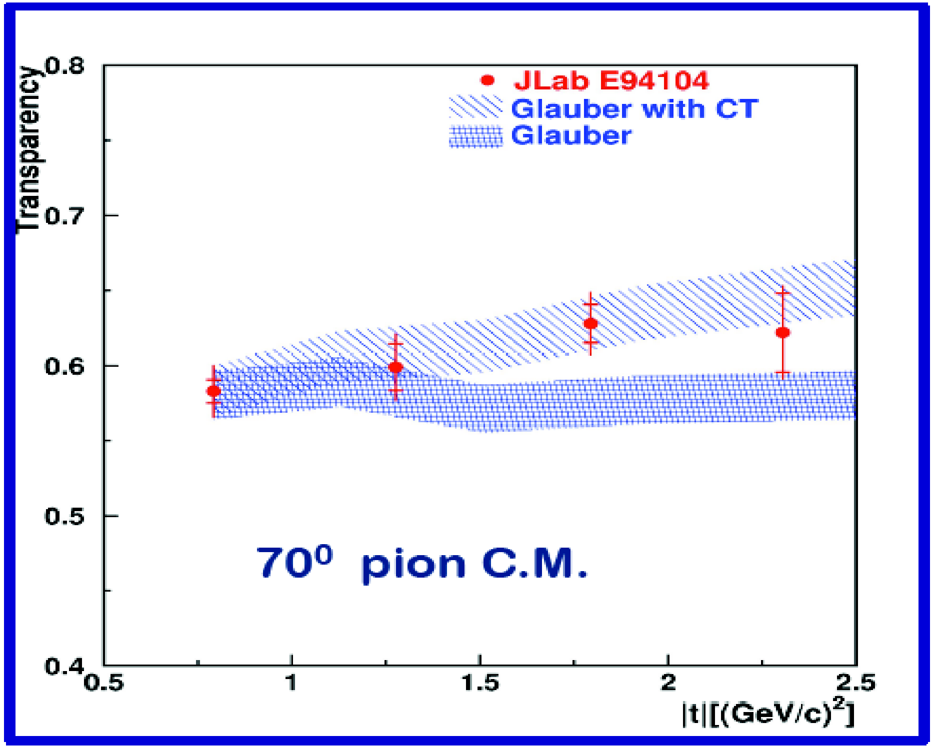
A. Leksanov *et al.* PRL 2001

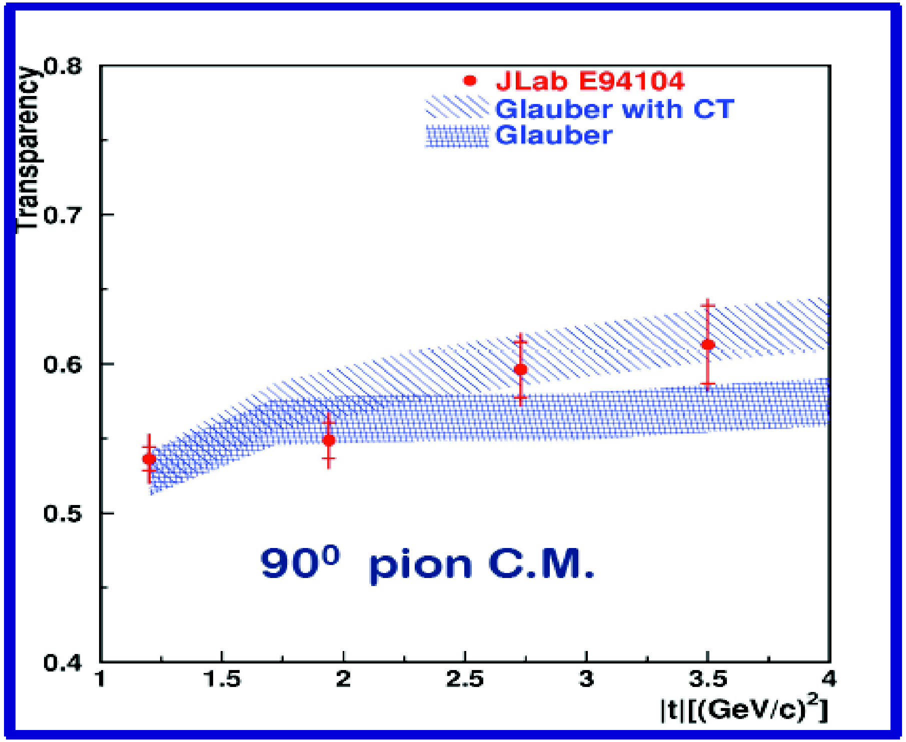
- Initial rise in transparency at low momentum is consistent with CT predictions.
- Subsequent drop at high momentum was explained by
  - Ralston and Pire as a nuclear filtering of soft amplitudes arising from higher order radiative processes (Landshoff mechanism).
  - Brodsky and De Teramond as a threshold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

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

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

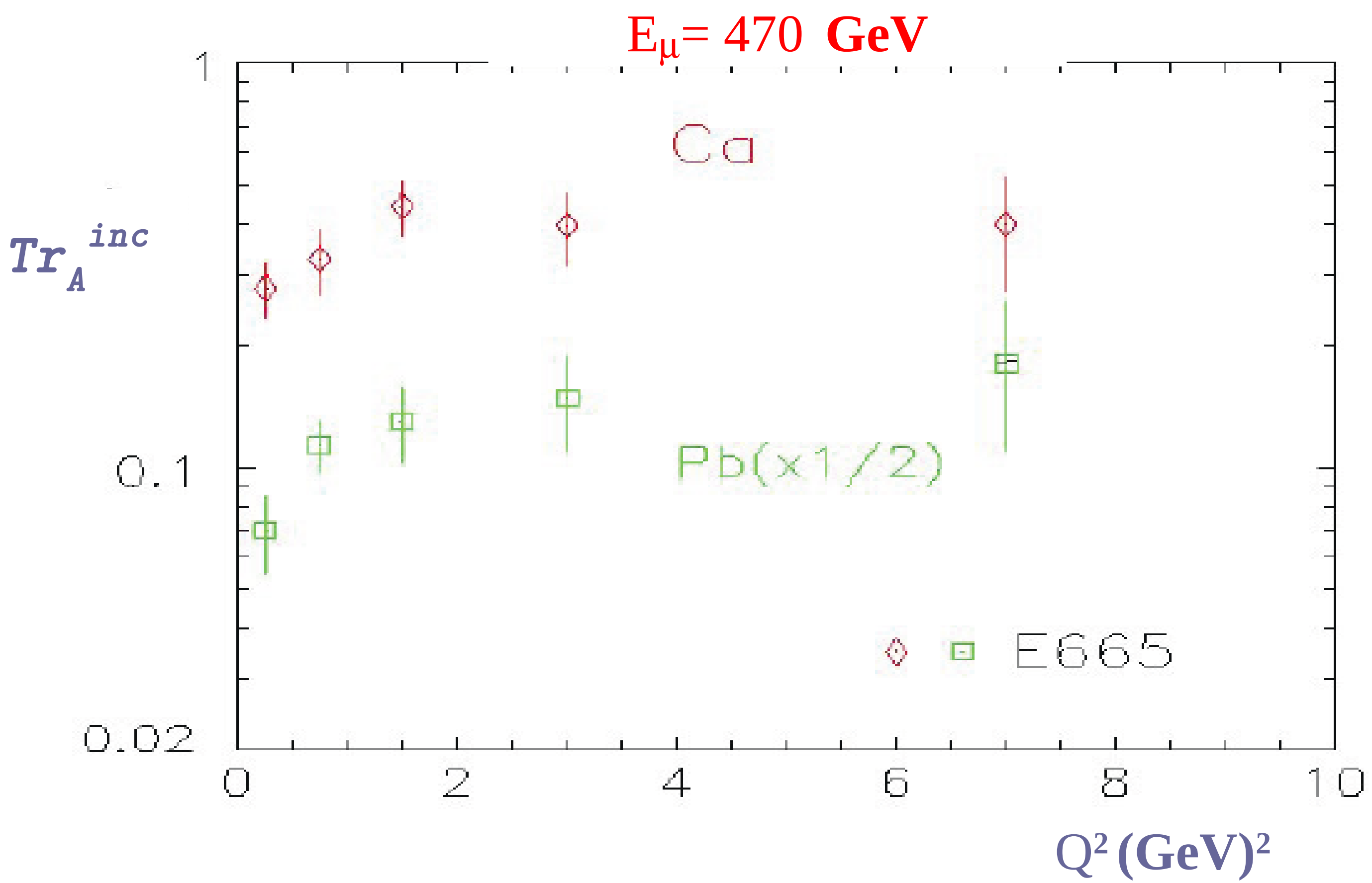
$$(\gamma + {}^4\mathrm{He} \longrightarrow \pi^- + p + X)\ /\ (\gamma + D \longrightarrow \pi^- + p + p)$$





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

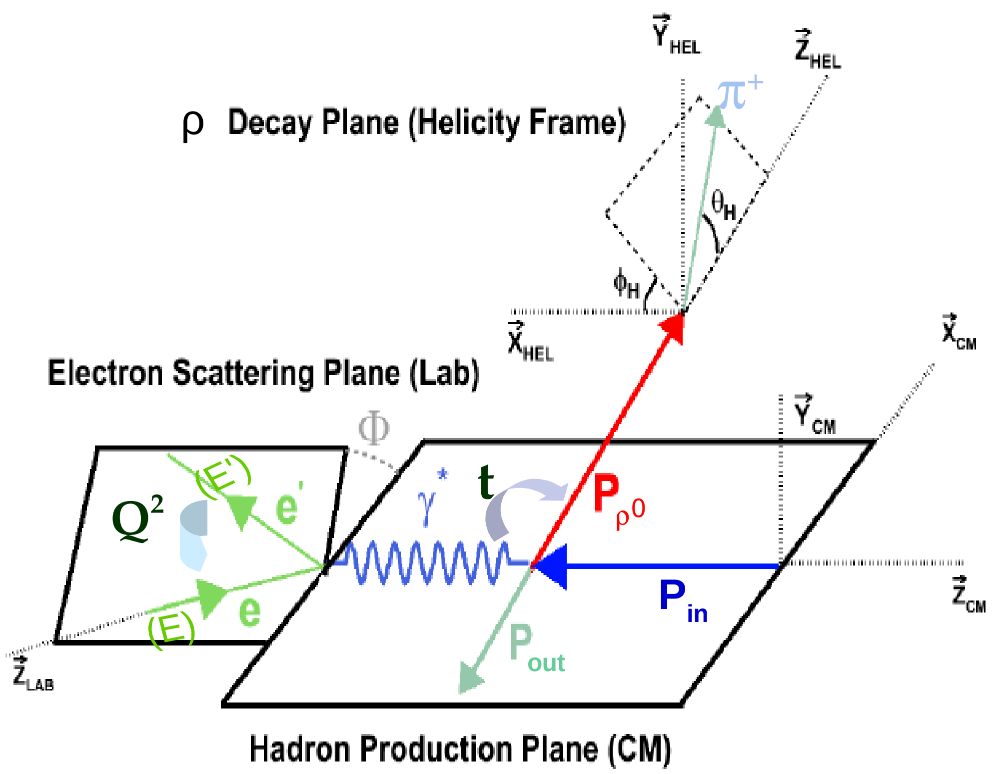
Exclusive ρ^0 Leptoproduction: FNAL 665



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

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

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

Simple Breit-Wigner

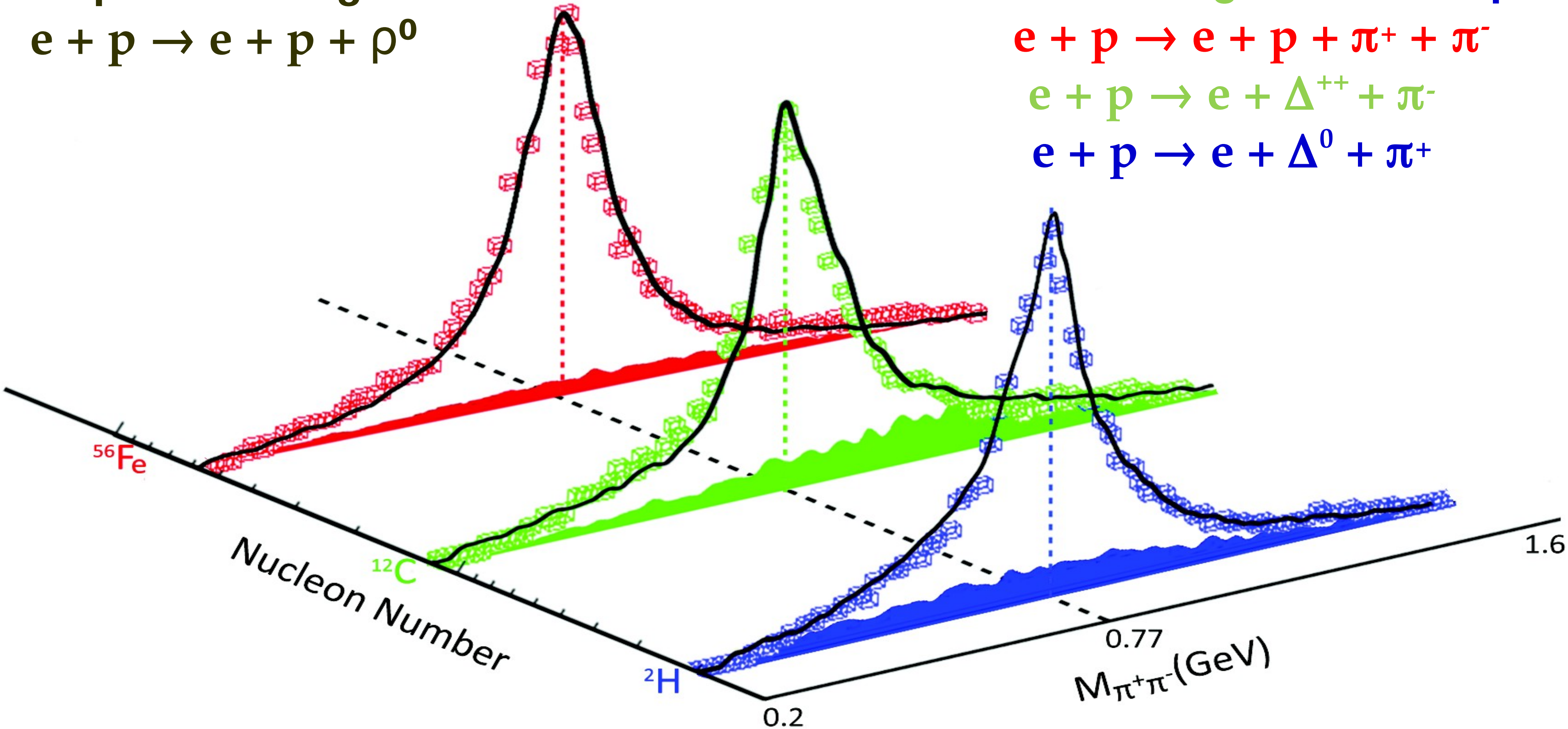
$e + p \rightarrow e + p + \rho^0$

Simulated Background's Shapes

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

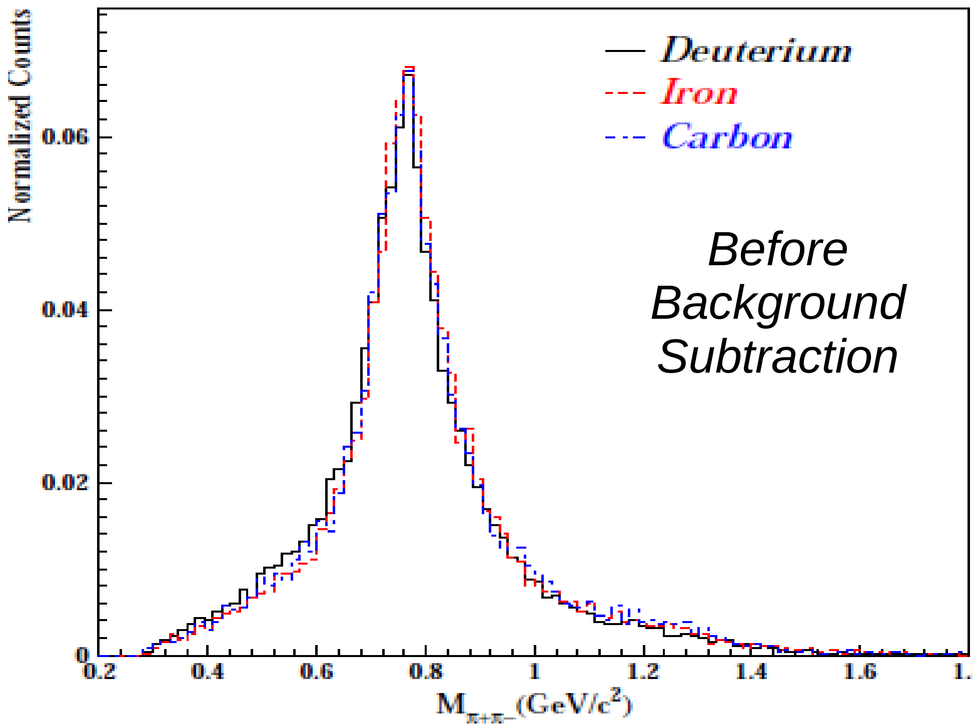
$e + p \rightarrow e + \Delta^{++} + \pi^-$

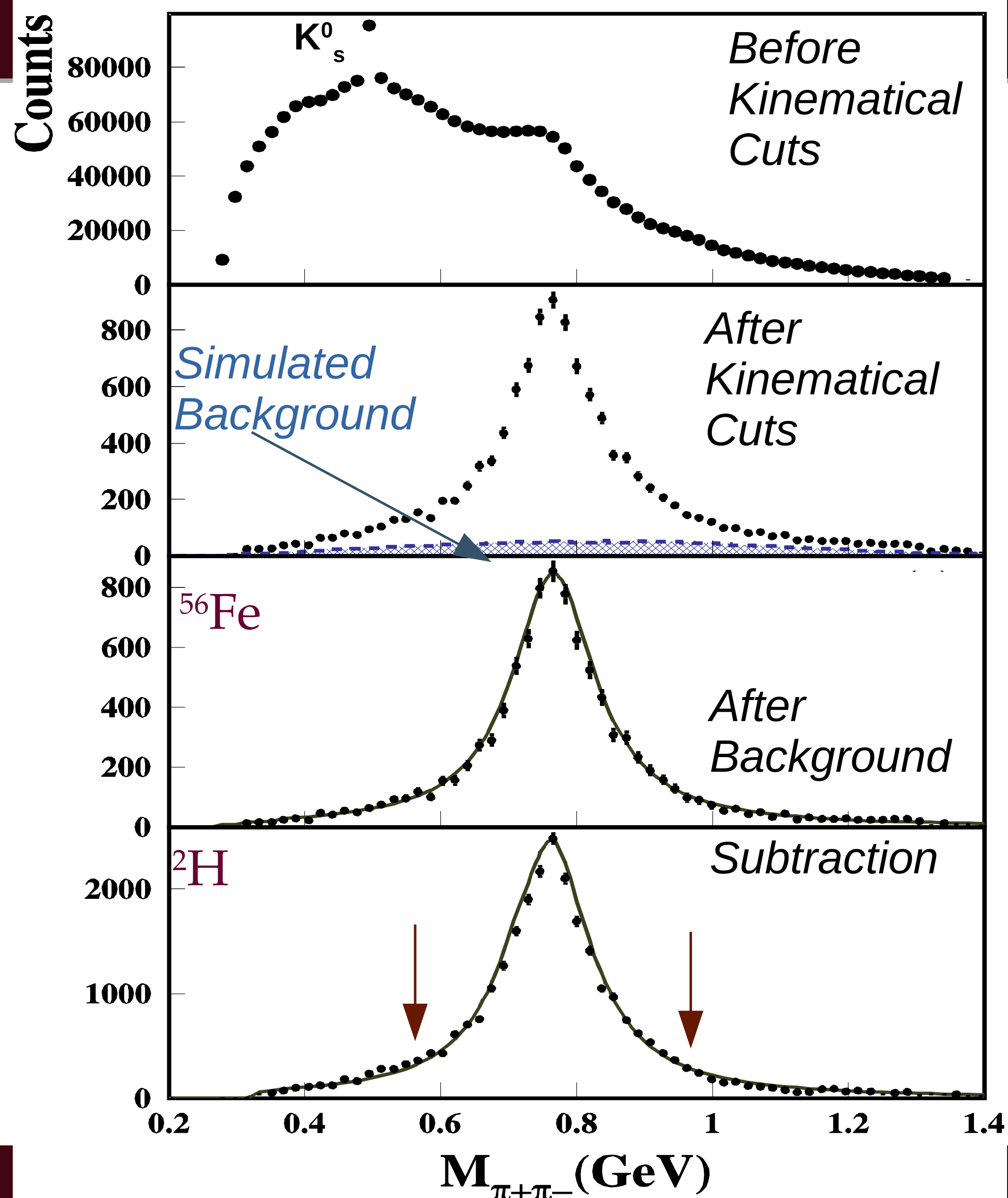
$e + p \rightarrow e + \Delta^0 + \pi^+$



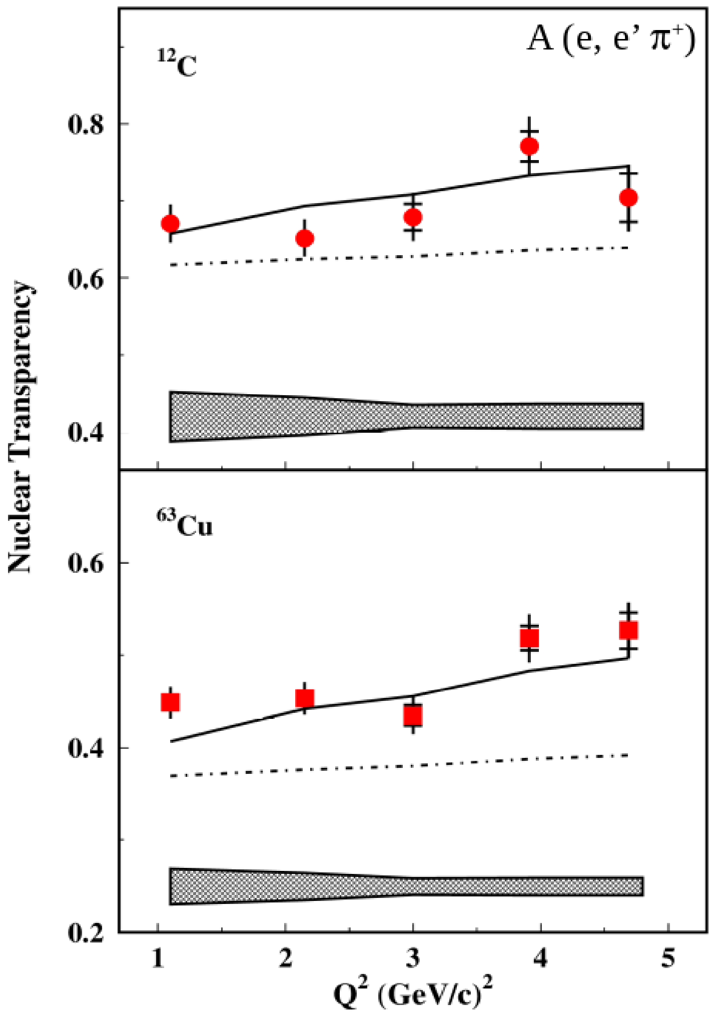
Two Pions Invariant Mass

After
Kinematical Cuts

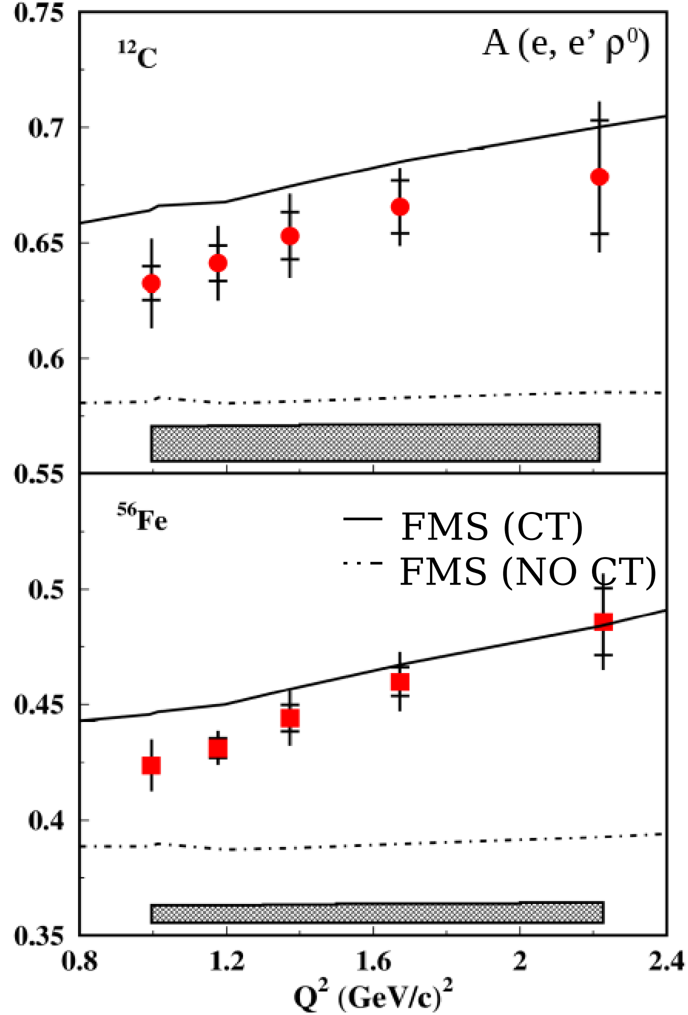




JLab CT Results at 6 GeV Era

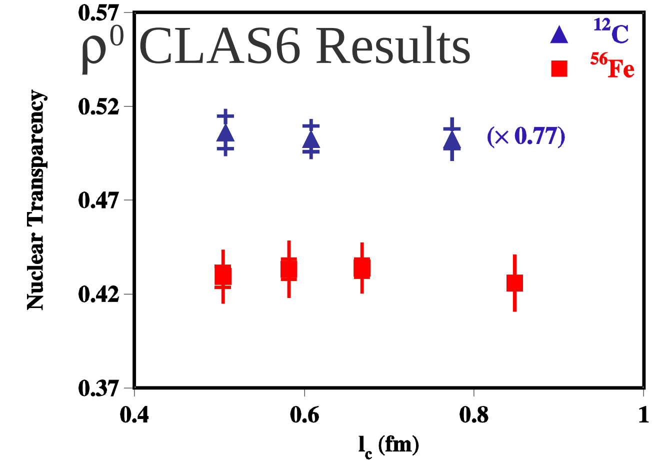


B. Clasie *et al.* PRL 90, 10001 (2007)
Larson, Miller, and M. Strikman, PRC 74 (2006)

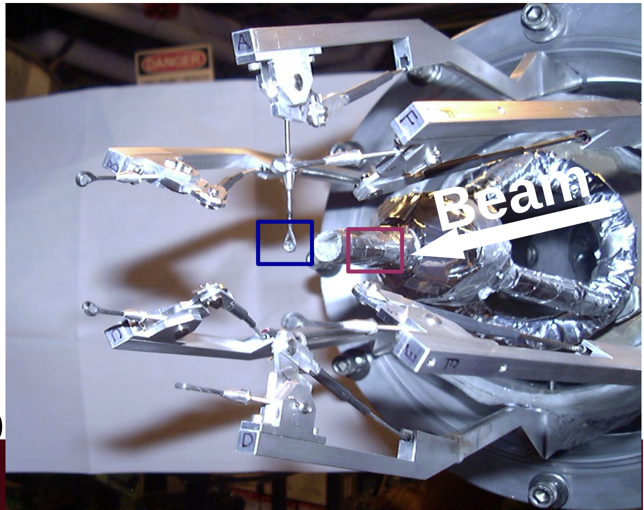


L. El Fassi *et al.*, PLB 712 (2012)
Frankfurt, Miller & Strikman, PRC 78 (2008)

No l_c dependence observed



Target Assembly for CLAS6 ρ^0 Experiment



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.
- SSC expansion time with FMS model were found to be between 1.1 fm and 2.4 fm for CLAS6 ρ^0 momenta between 2 and 4.3 GeV.

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

- GKM model is based on coupled-channel semi-classical Giessen-Boltzmann Uehling-Uhlenbeck (GiBUU) 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 FSIs, 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): $\gamma^* N \rightarrow V N$,
- $M(\gamma^* N \rightarrow V N) = \langle V | \sigma(q\bar{q}) | \gamma^* \rangle$.

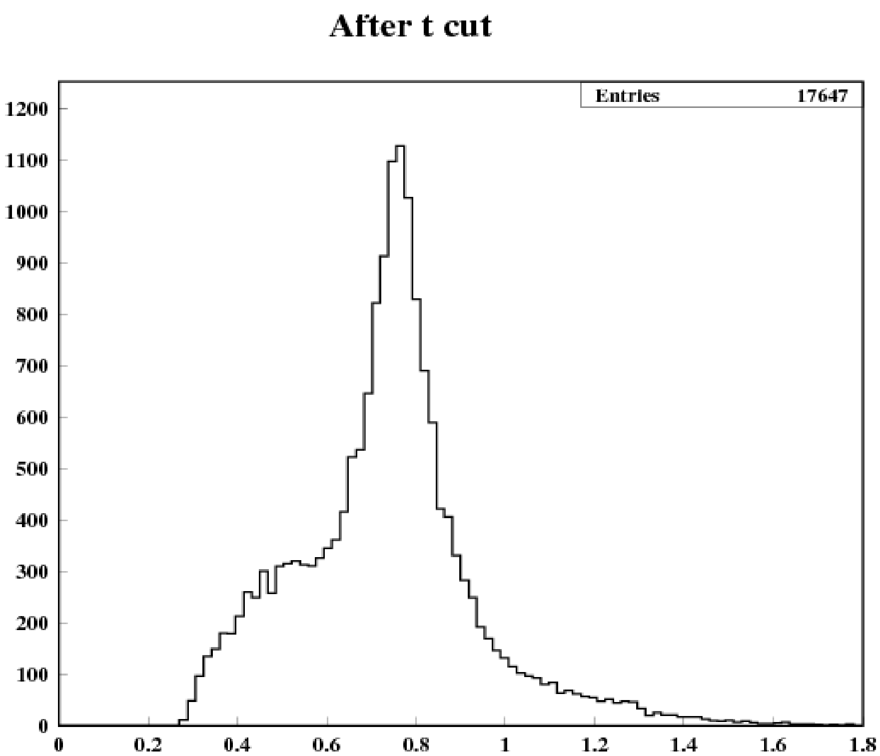
  - ✔ s(qq-bar): universal flavor independent dipole cross section for qq-bar interaction with a nucleon fitted to the proton structure function data over a large range of x_B and Q^2.
  - ✔ Ψ_{γ^*}: LC wave function for qq-bar fluctuation of the virtual photon.
  - ✔ Ψ_v: LC wave function for the vector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

Hall-B Target Assembly Advantage

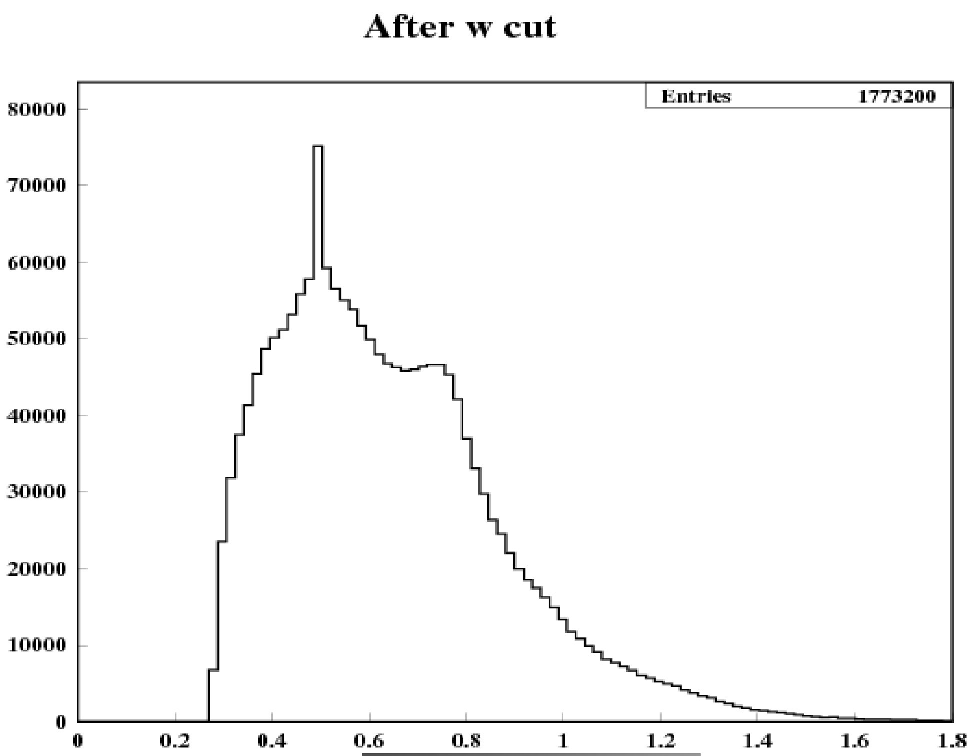
- Take liquid and solid targets data in similar vertex position which will minimize the acceptance correction,
- Reduce the amount of collected deuterium data as one set can be used with all nuclear targets to extract the physics results,
- Can accommodate several thinner solid targets, allowing to take full luminosity even on heavy targets.

ρ^0 Invariant Mass from 5 GeV D2+Fe dataset

Iron



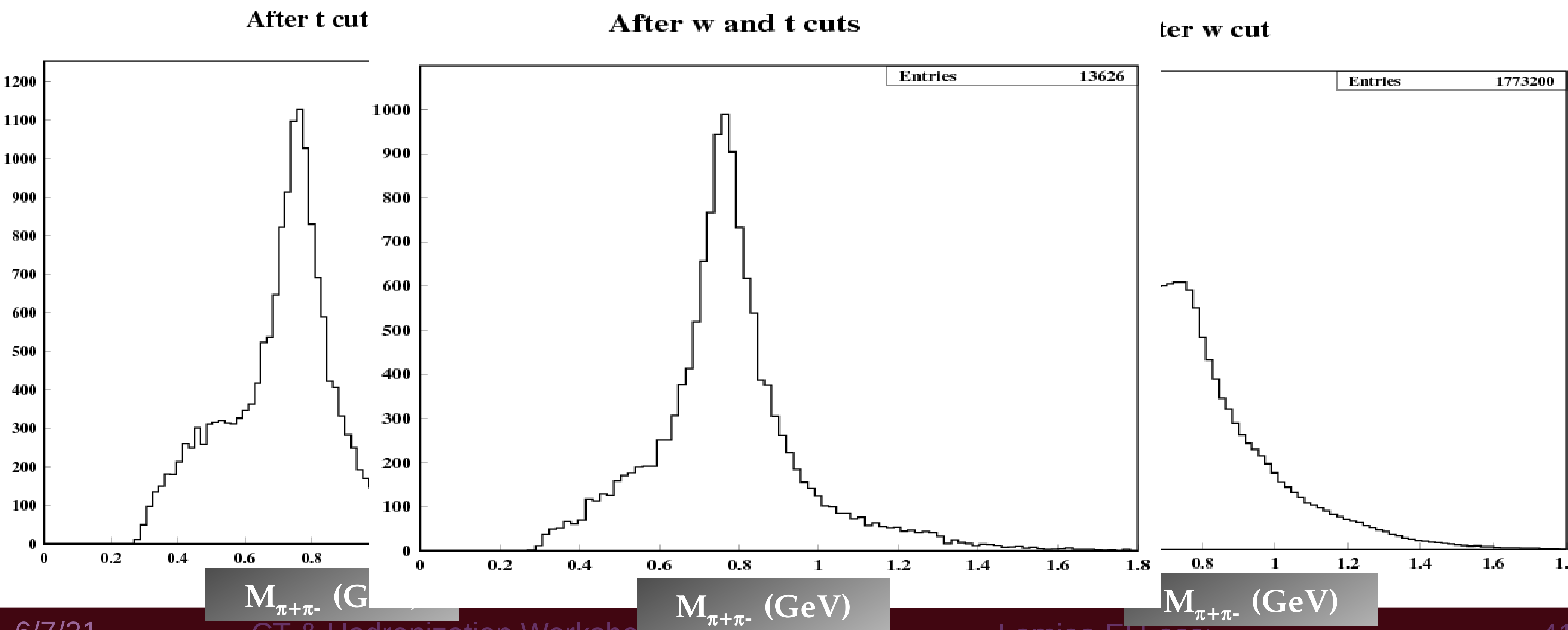
$M_{\pi+\pi-}$ (GeV)



$M_{\pi+\pi-}$ (GeV)

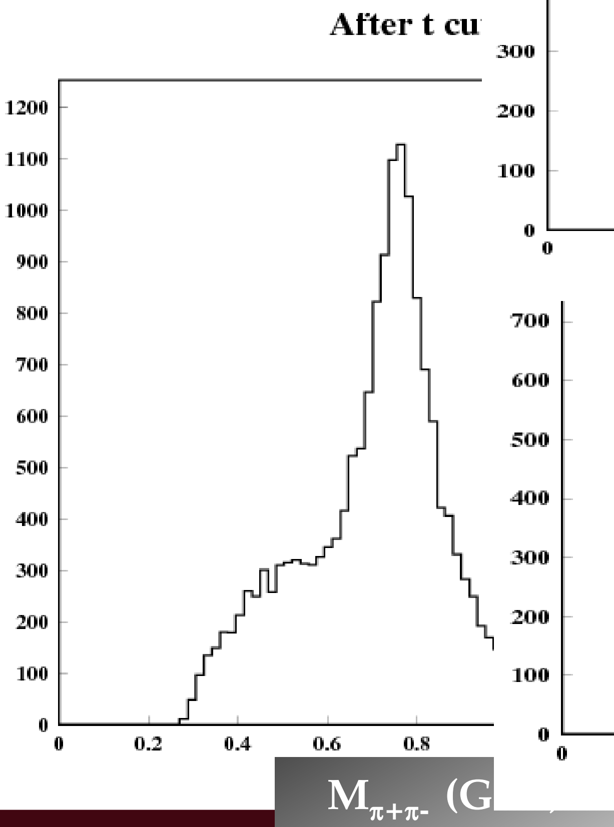
ρ^0 Invariant Mass from 5 GeV D2+Fe dataset

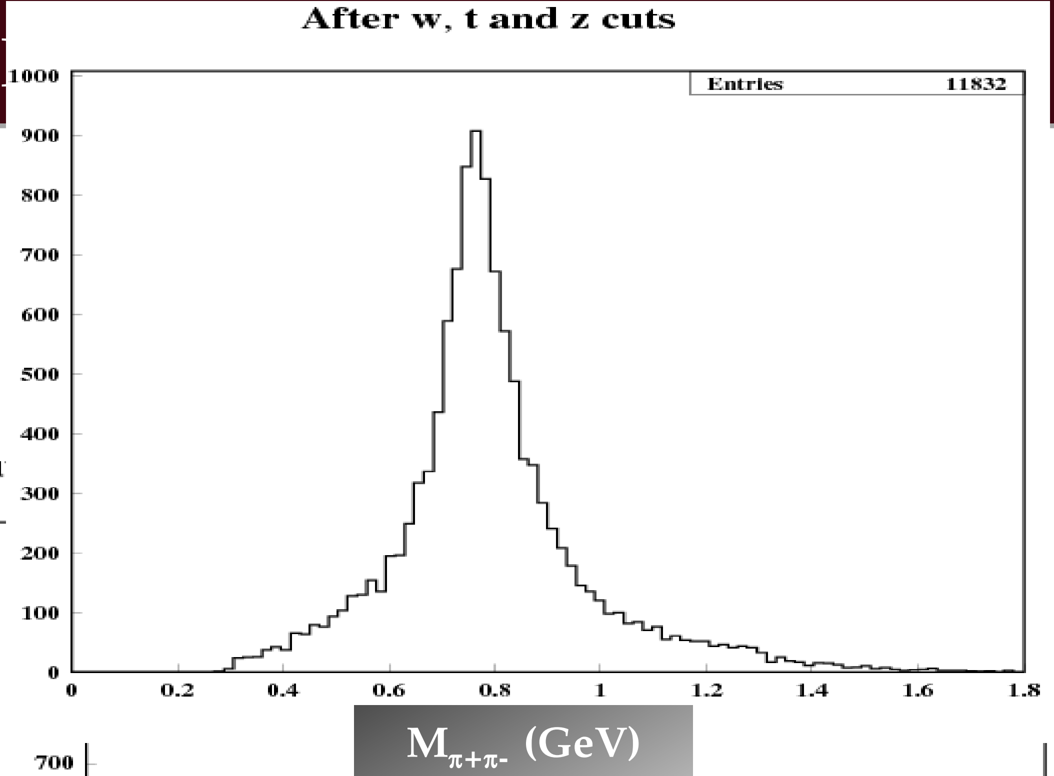
Iron

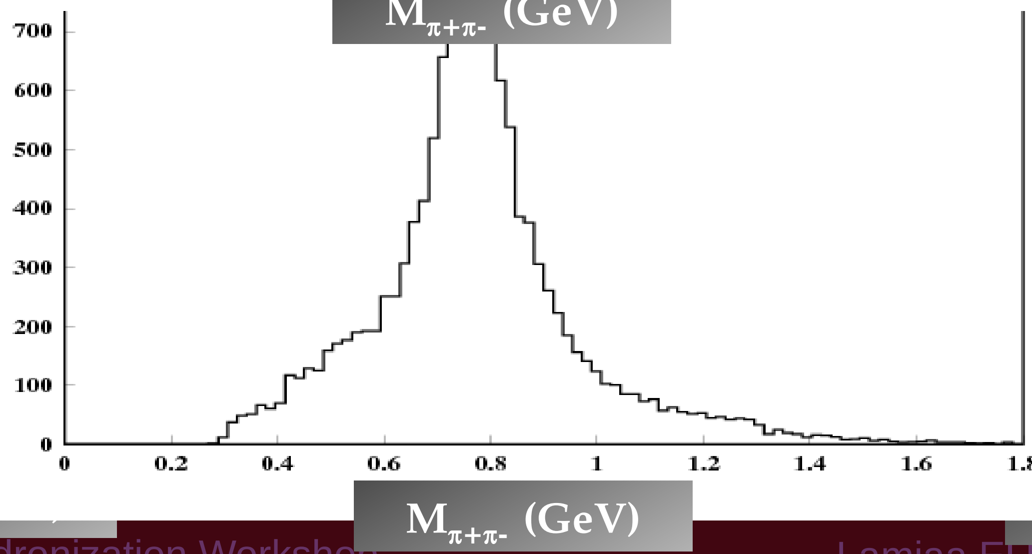


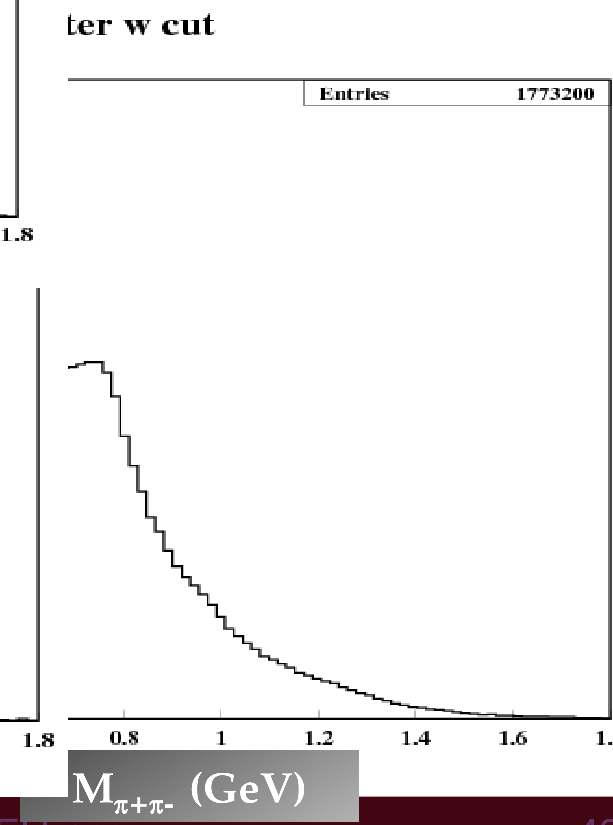
ρ^0 Invariant

Iron



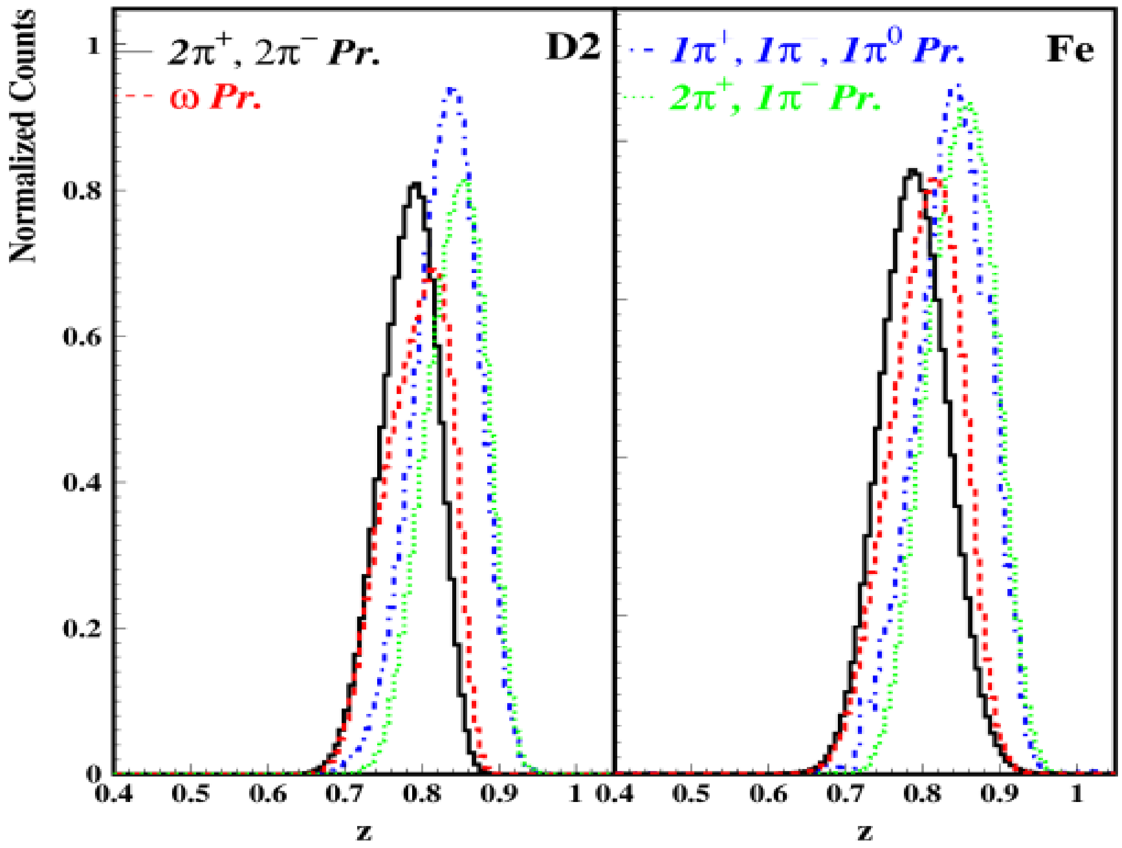






Multi-pions Processes

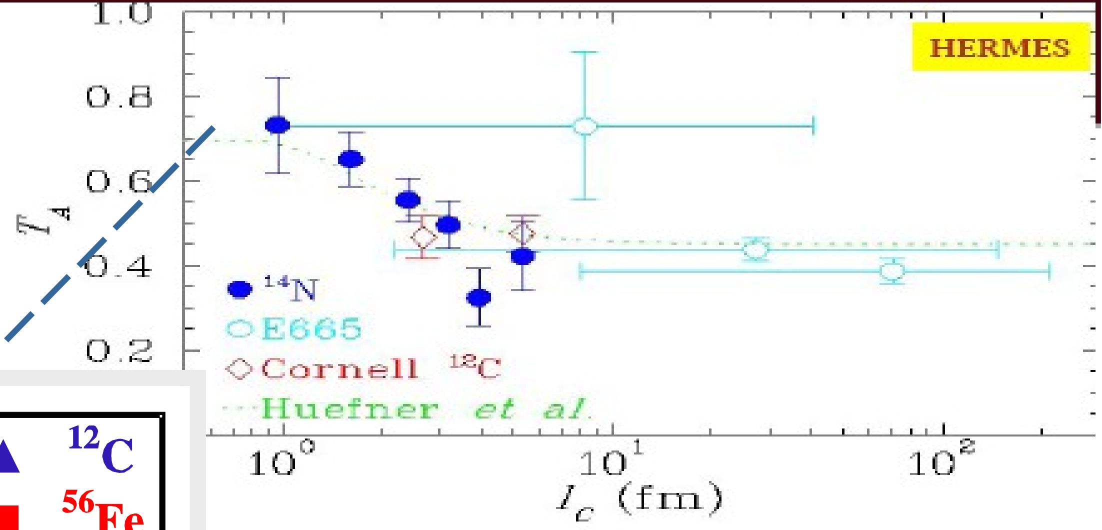
- $\mathbf{Z_h \geq 0.9}$ is effective in removing muti-pions final state contribution.

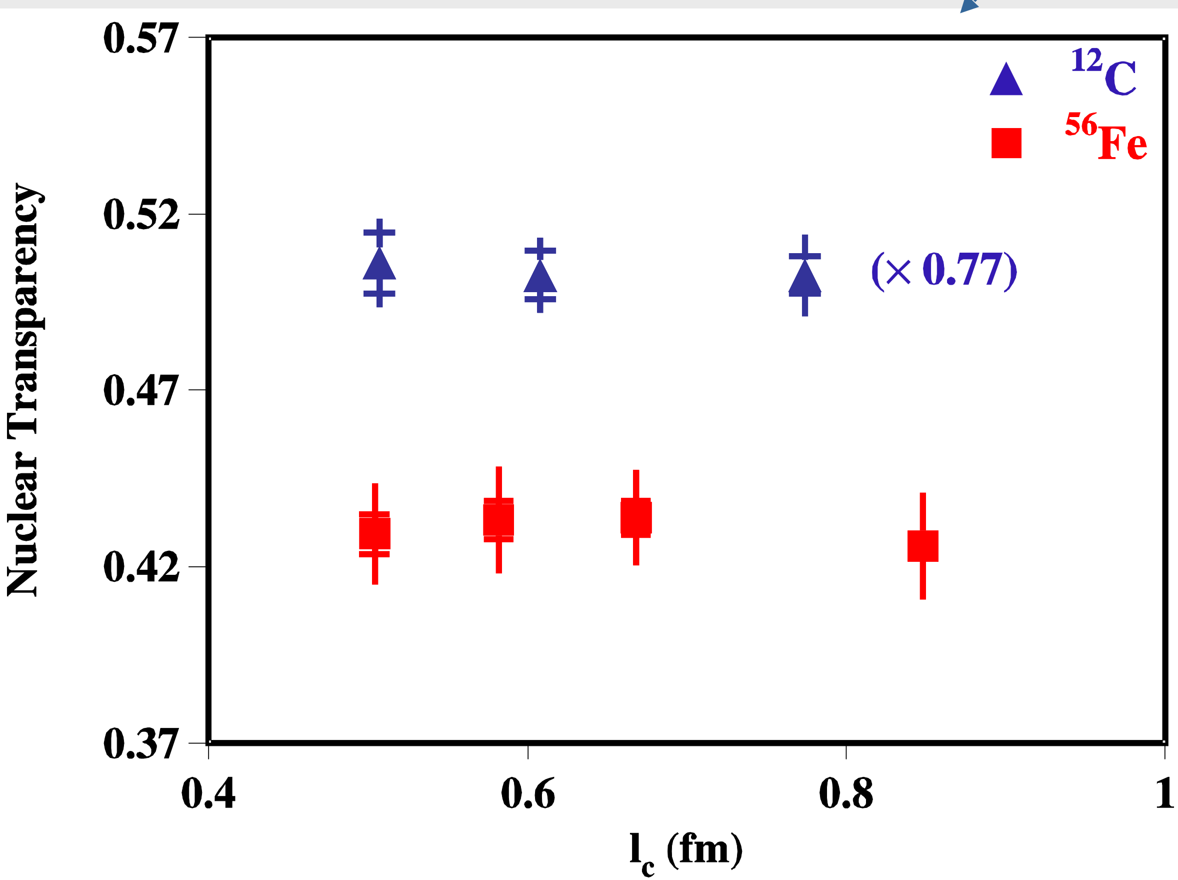


l_c Dependence on T_A

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

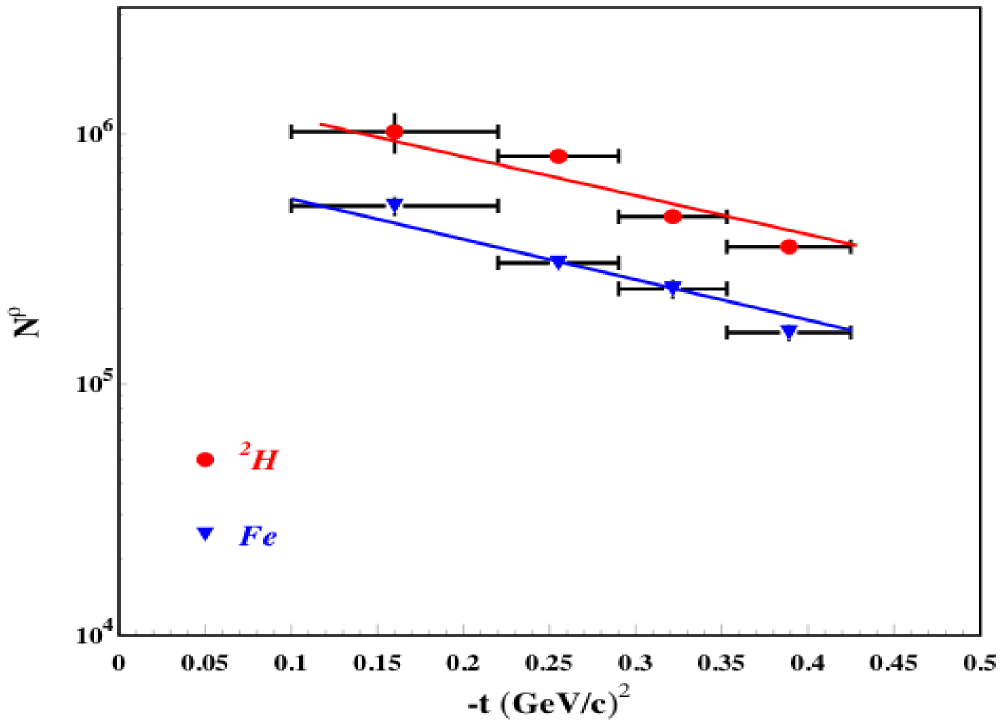
ρ^0 CT slopes from linear fit of Q^2 dependence, $T_A = a\,Q^2 + b$

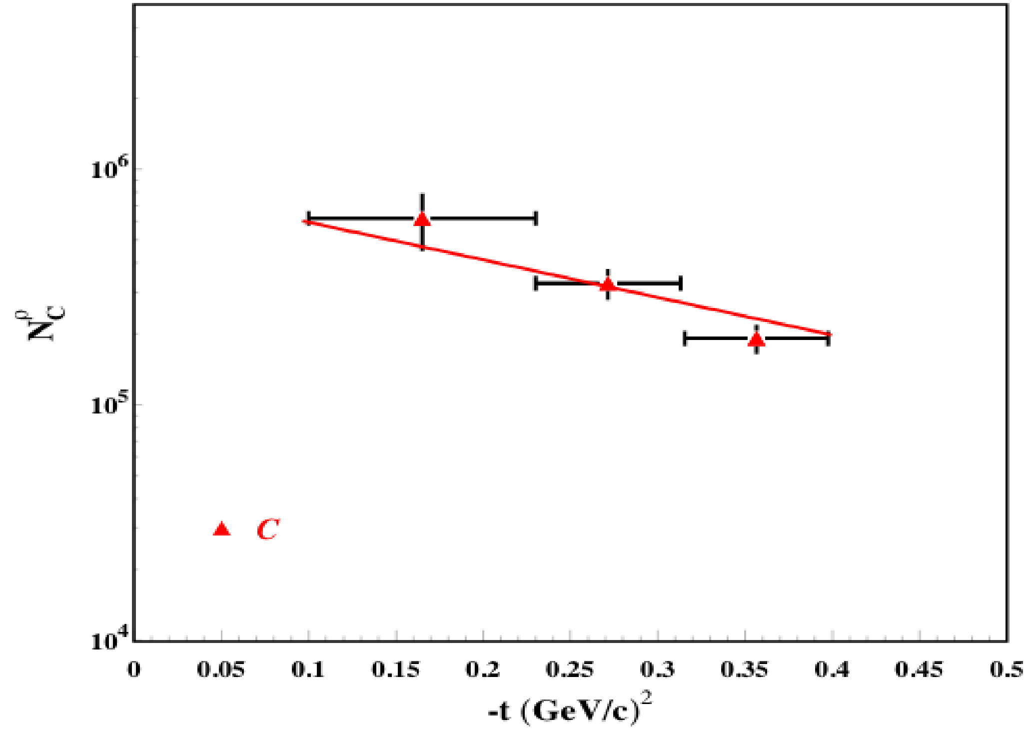
Targets / Models	Carbon slopes (GeV^{-2})	Iron 5 GeV slopes (GeV^{-2})	Iron 4 GeV slopes (GeV^{-2})
FMS	0.029	0.032	0.033
GKM	0.06	0.047	-
KNS	0.06	0.047	-
CR	$0.026_{\text{Upper Limit}}$ $0.027_{\text{Lower Limit}}$	$0.02_{\text{Upper Limit}}$ $0.021_{\text{Lower Limit}}$	$0.027_{\text{Upper Limit}}$ $0.029_{\text{Lower Limit}}$
CLAS Data	$0.044 \pm 0.015_{stat} \pm 0.019_{syst}$	$0.053 \pm 0.008_{stat} \pm 0.013_{syst}$	$0.037 \pm 0.015_{stat} \pm 0.027_{syst}$

- KNS: Light Cone QCD Formalism

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

t Slopes





Ae^{bt} fit $b(^2H) = 3.58 \pm 0.5$ GeV^{-2}
$b(C) = 3.67 \pm 0.8$ GeV^{-2}
$b(Fe) = 3.72 \pm 0.6$ 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
$b = 2.63 \pm 0.44$ GeV^{-2}

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