RUTGERS
THE STATE UNIVERSITY OF NEW JERSEY

Overview of Color Transparency Measurements

CIPANP, May 29th, 2012

Lamiaa El Fassi
Rutgers University

(On behalf of CLAS Collaboration)

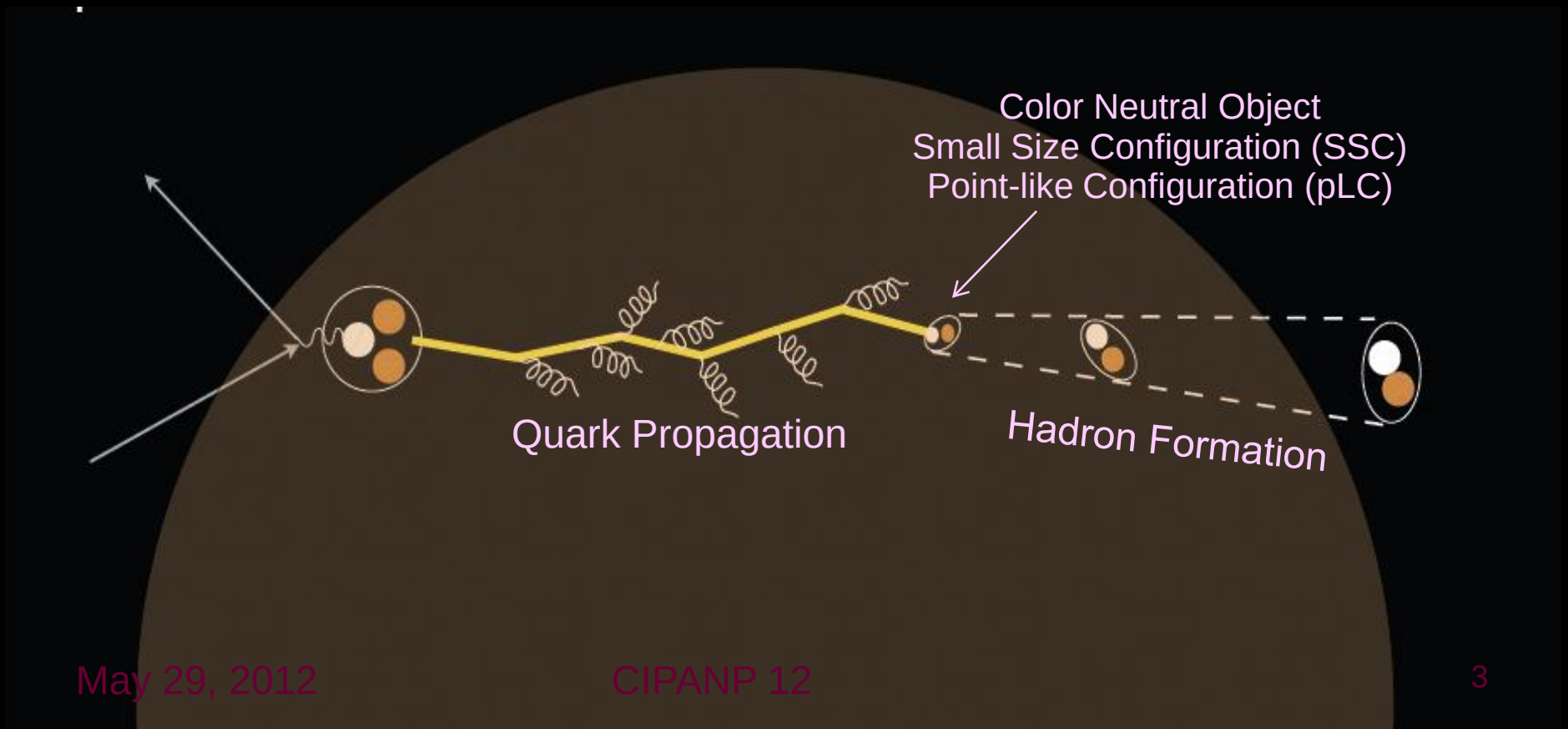
Outline

- Introduction
- Overview of previous Color Transparency (CT) measurements
- Newest JLab ρ^0 CT results
- Summary and Outlook

Introduction

Study of hard interactions in nuclei gives information about the time evolution of the produced states, and investigates the properties of the nucleus itself.

P. Hoyer, arXiv:hep-ph/9510394v1



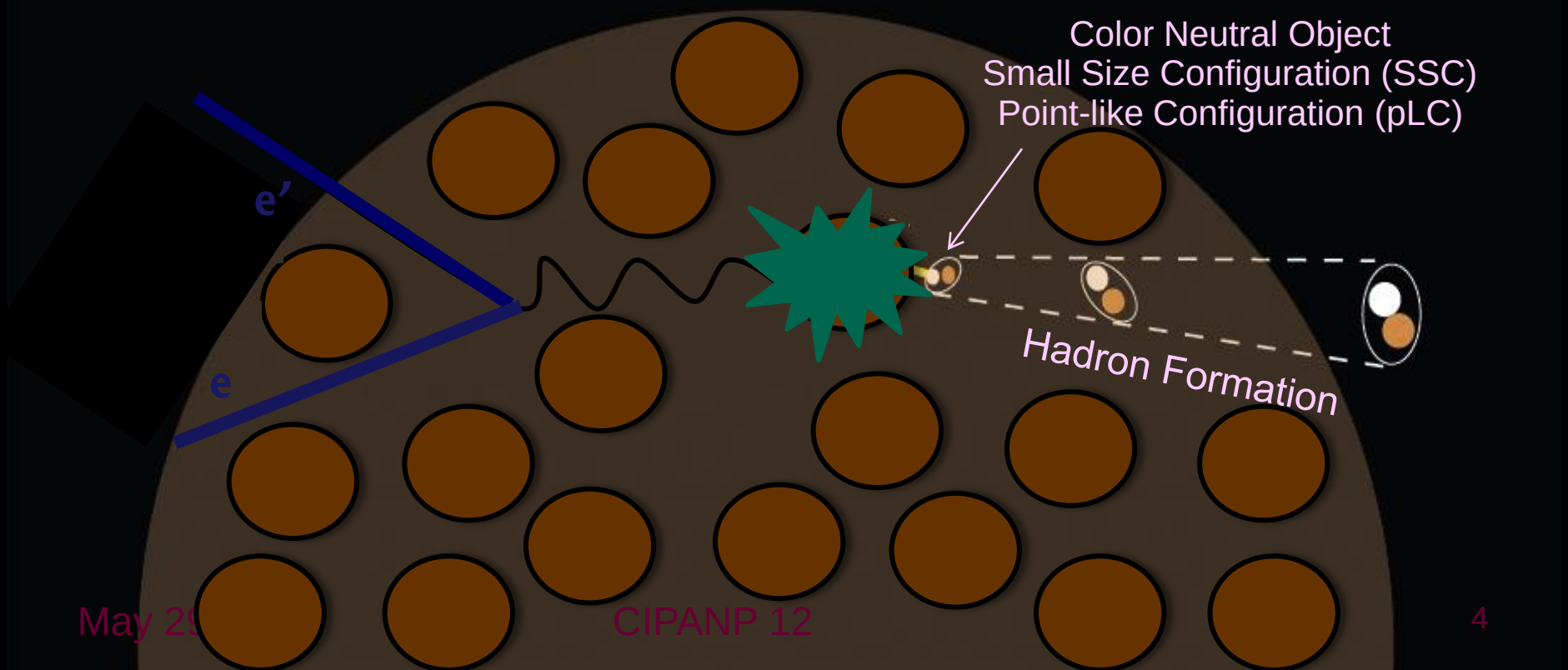
Introduction

Study of hard interactions in nuclei gives information about the time evolution of the produced states, and investigates the properties of the nucleus itself.

P. Hoyer, arXiv:hep-ph/9510394v1

Color Transparency is the proposal that under certain circumstances the strong interactions can be controlled and in some cases reduced in magnitude.

P. Jain et al. Phys. Reports 271 (1996)



CT Basics: Survival of the smallest

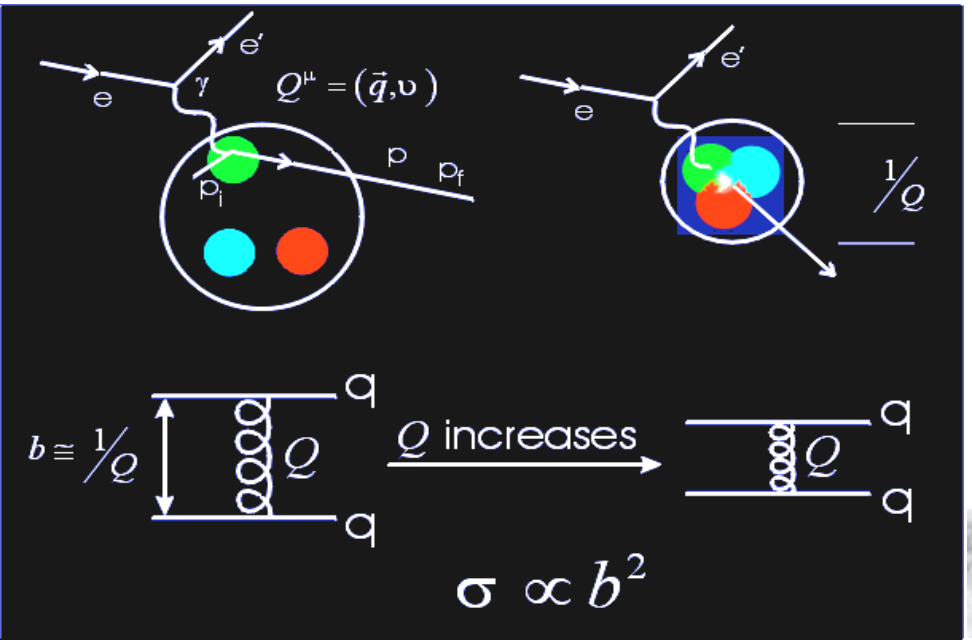
- **Creation of Small Size Configuration (SSC)**

  via hard and exclusive reactions.

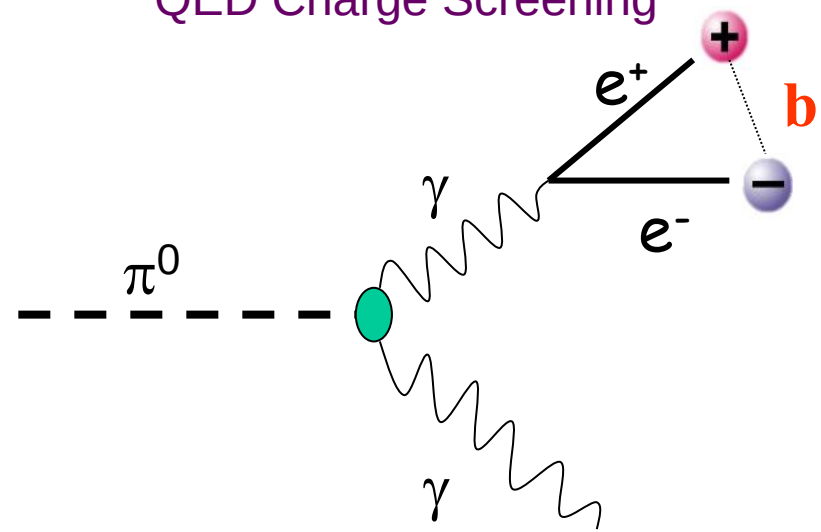
CT Basics: Survival of the smallest

- **Creation of Small Size Configuration (SSC)** via hard and exclusive reactions
- **SSC experiences reduced attenuation before evolving to normal hadron.**

QCD Color Screening



QED Charge Screening



200 GeV π⁰ emulsion produced in cosmic rays (Perkins 1955)

- In QCD the color field of a color neutral object vanishes as the size of the object is reduced.
- The interaction cross-section has a dipole form $\sigma \cong b^2$.

CT Basics: Survival of the smallest

- **Creation of Small Size Configuration (SSC)**

  via hard and exclusive reactions.

- **SSC experiences reduced attenuation before evolving to normal hadron.**

- **The distance over which a SSC expands to its free size is at least as large as the nuclear radius.**

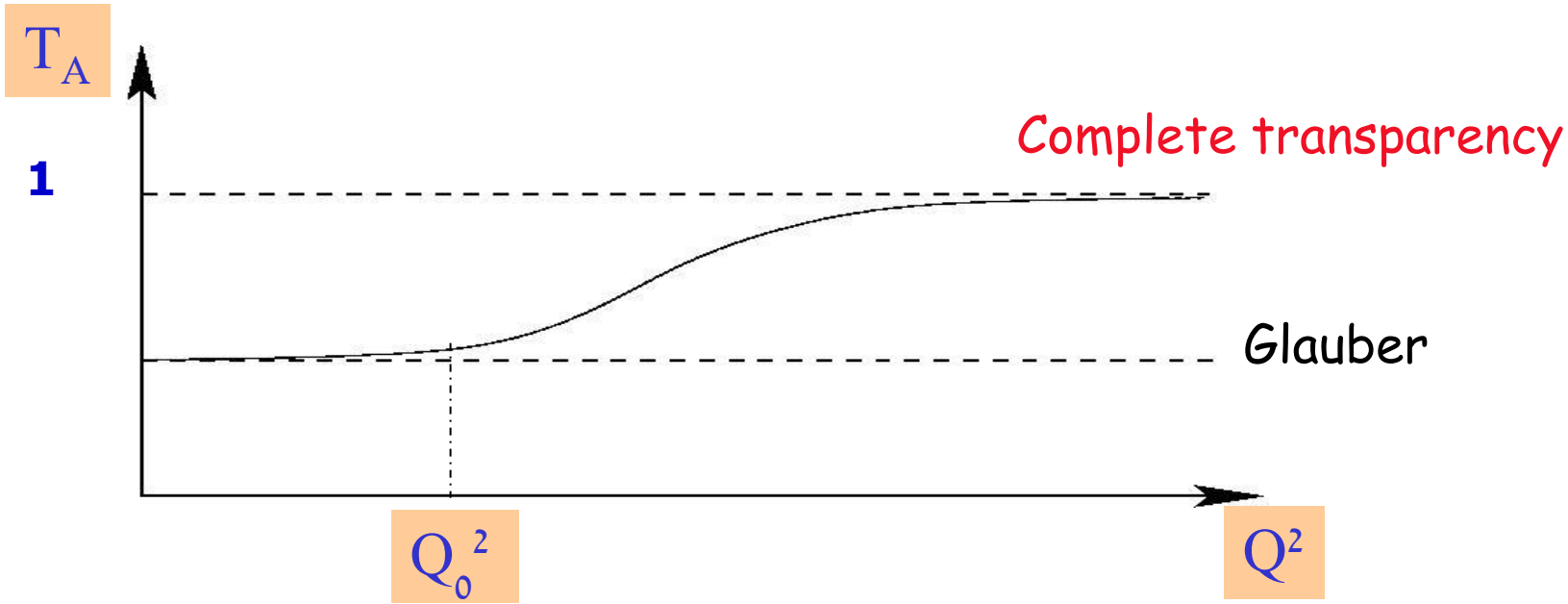
Introduction

The signature of Color Transparency is the increase of the medium "nuclear" Transparency T_A as a function of the momentum transfer

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

σ_A is the nuclear cross section

σ_N is the free (nucleon) cross section



Experimental Status

Baryon

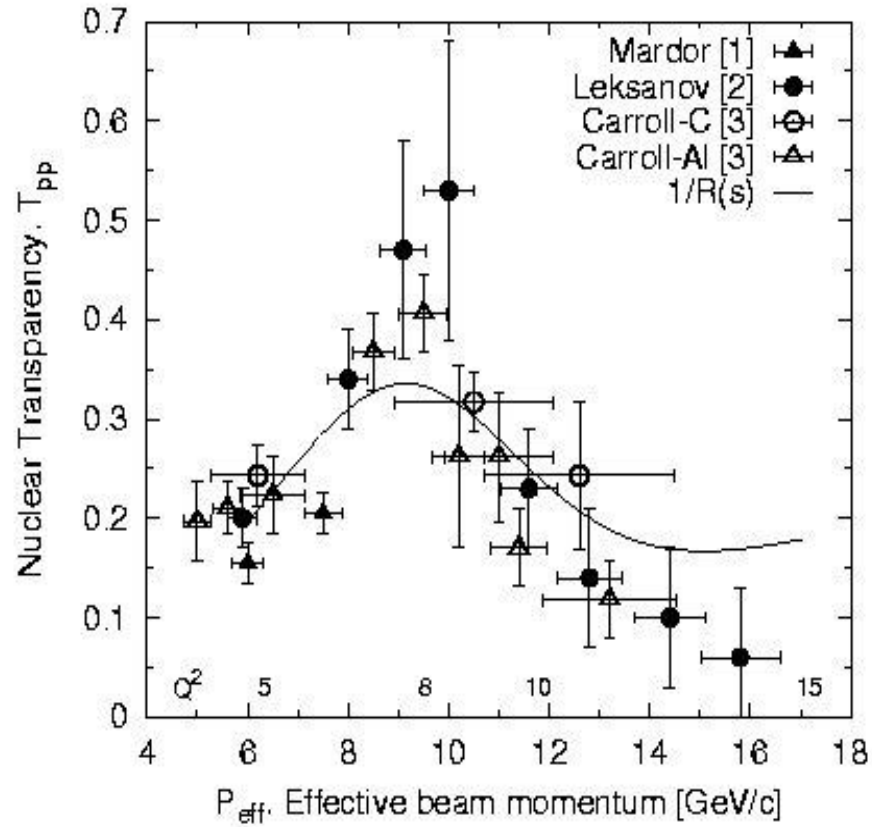
- A(p, 2p) BNL
- A(e, e'p) SLAC & JLab

Meson

- A(π,di-jet) FNAL
- A(γ, πp) JLab
- A(e, e'π) Jlab
- A(μ, μ'ρ) FNAL
- A(e, e'ρ) DESY & JLab

Quasi-elastic A(p,2p) : BNL E834 and E850

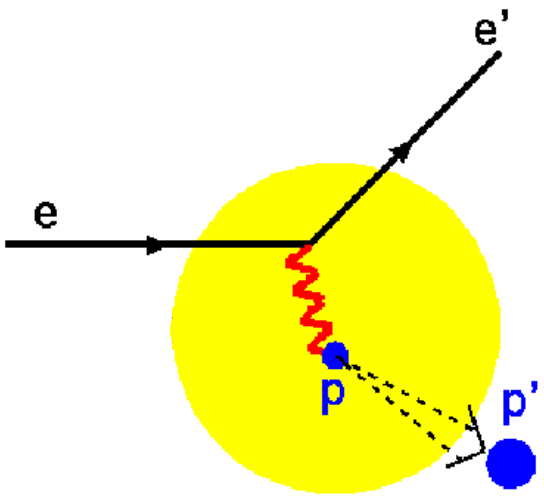
$$\frac{d\sigma}{dt_{pp}}(\theta = 90^{o}_{c.m.}) = R(s)s^{-10}$$

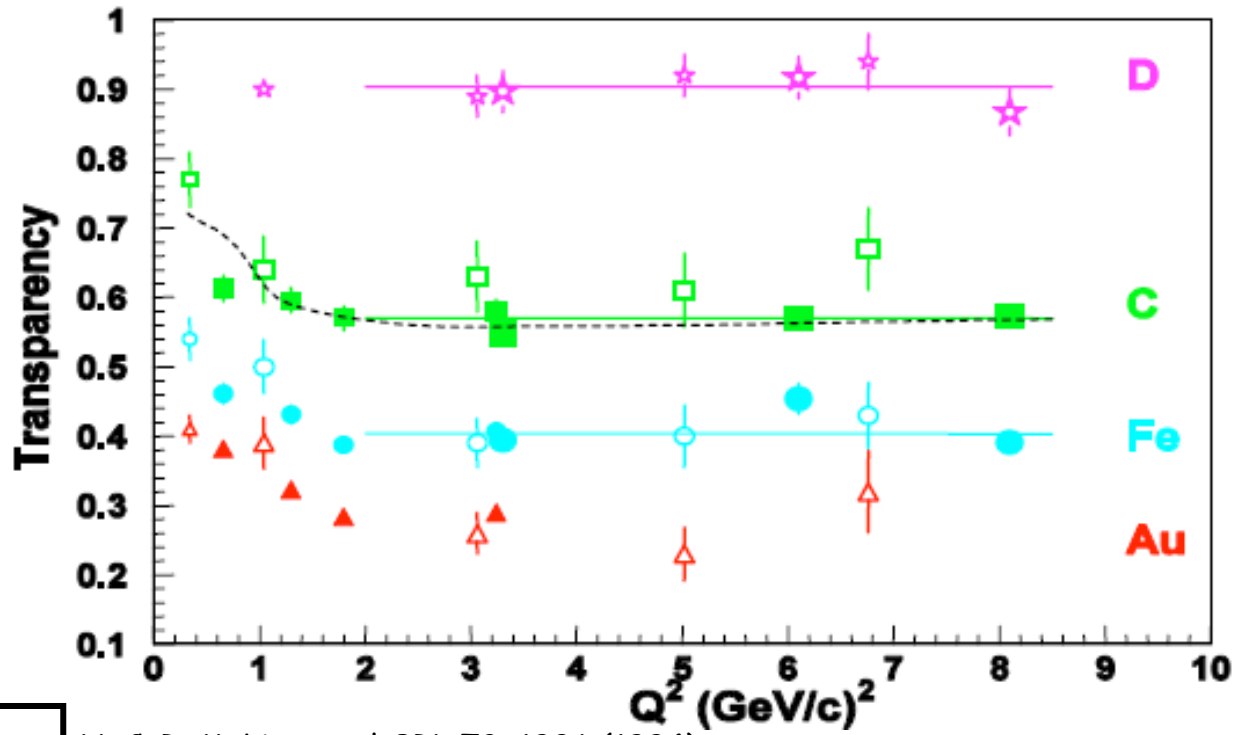


A. Leksanov et al. PRL 2001

- 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) states.

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





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

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)

Solid Pts – JLab
Open Pts -- other

Conventional Nuclear Physics Calculation by Pandharipande et al. gives good description

(qqq) versus (q,q-bar) systems

- Small size is more probable in 2 quark system such as pions, rho mesons than in protons.

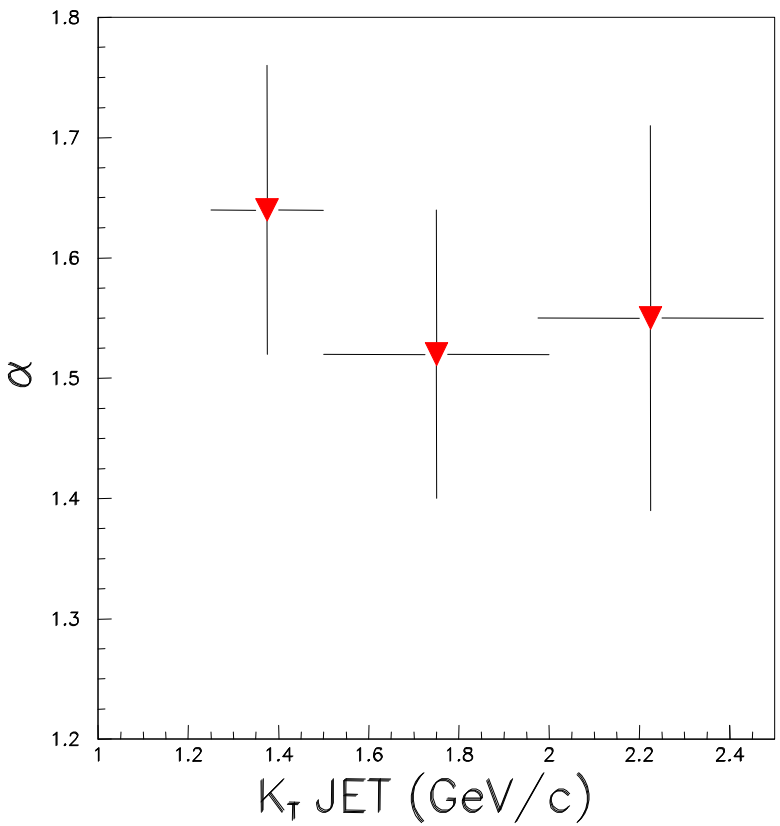
B. Blattel et al., PRL 70, 896 (1993)

- Onset of CT expected at lower Q^2 in (q,q-bar) system.

- Onset of CT related to onset of factorization required for access to GPDs in deep exclusive (q,q-bar) production.

Strikman, Frankfurt, Miller and Sargsian

A(π, dijet) data from FNAL



Coherent π^+ diffractive dissociation with 500 GeV/c pions on Pt and C.

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

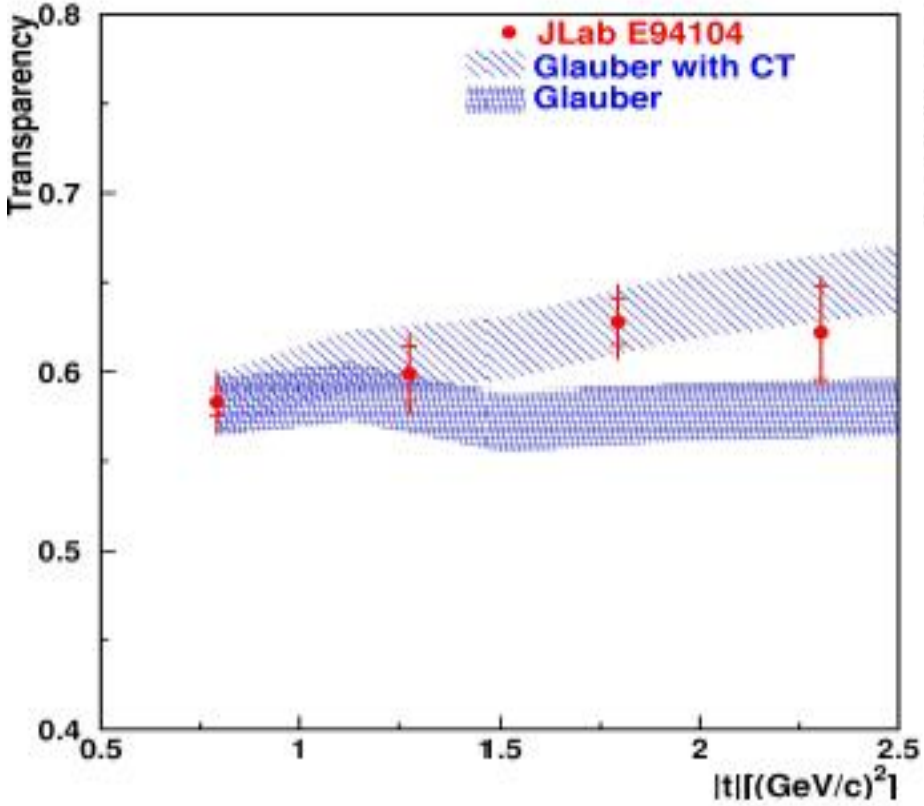
$\alpha > 0.76$ from pion-nucleus total cross-section.

Aitala et al., PRL 86 4773 (2001)

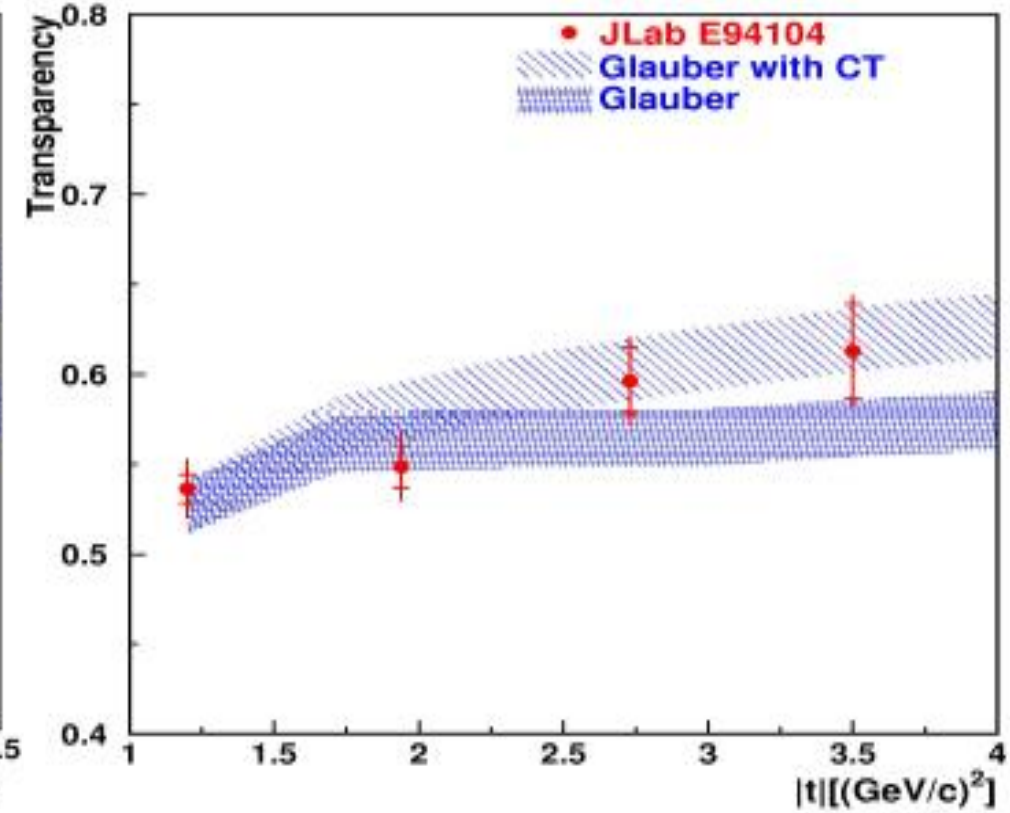
L. L. Frankfurt, G. A. Miller, and M. Strikman, Found. Of Phys. 30 (2000) 533

Pion Photo-production γ n -> π^- p in ^{4}He

$$\theta^{\pi}_{CM} = 70^\circ$$

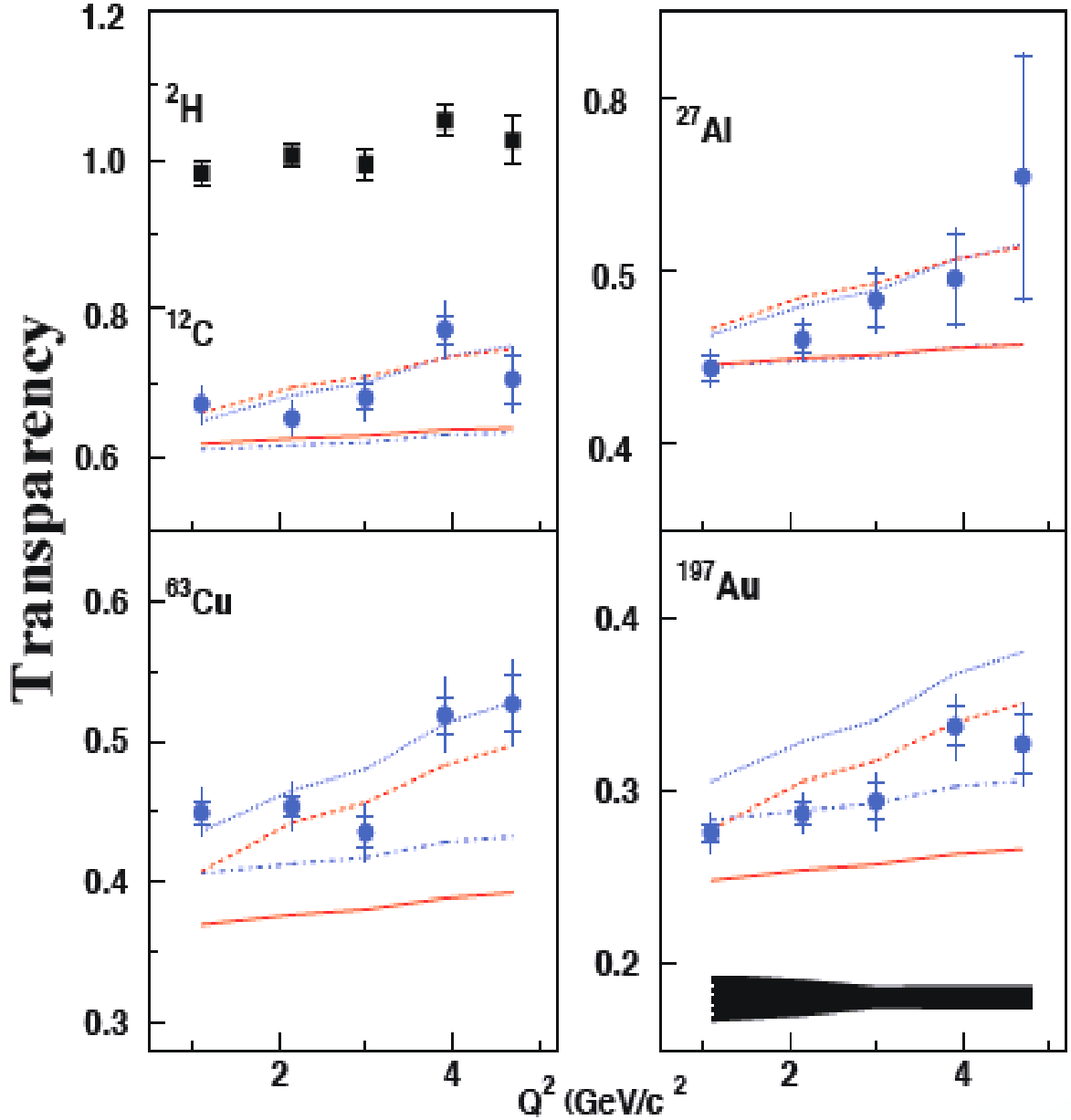


$$\theta^{\pi}_{CM} = 90^\circ$$



D. Dutta et al. PRC 2003

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



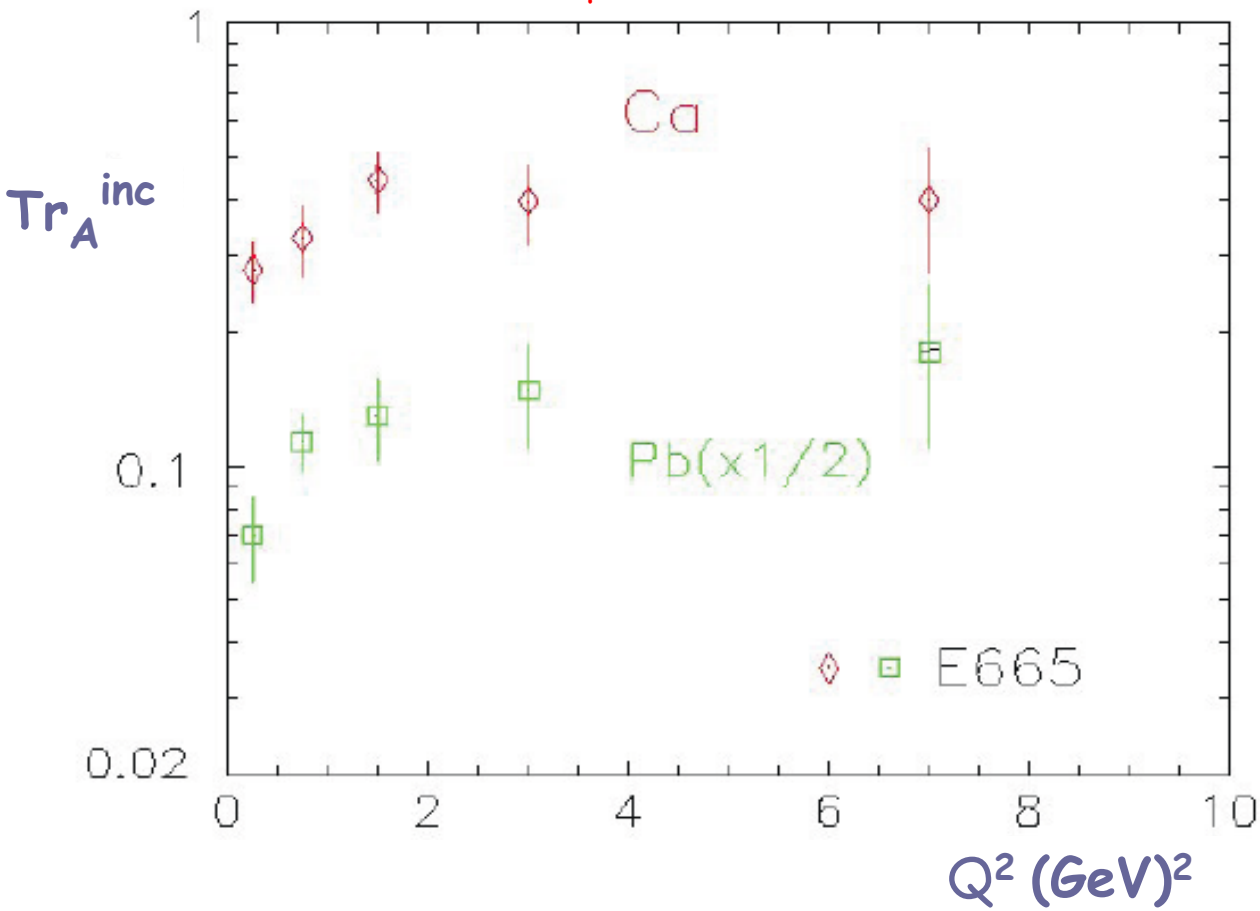
B. Clasie et al. PRL 2007

These measurements will be extended to Q^2 of about 10 $(GeV/c)^2$ after the JLab 12 GeV upgrade

Exclusive ρ^0 leptoproduction: FNAL E665

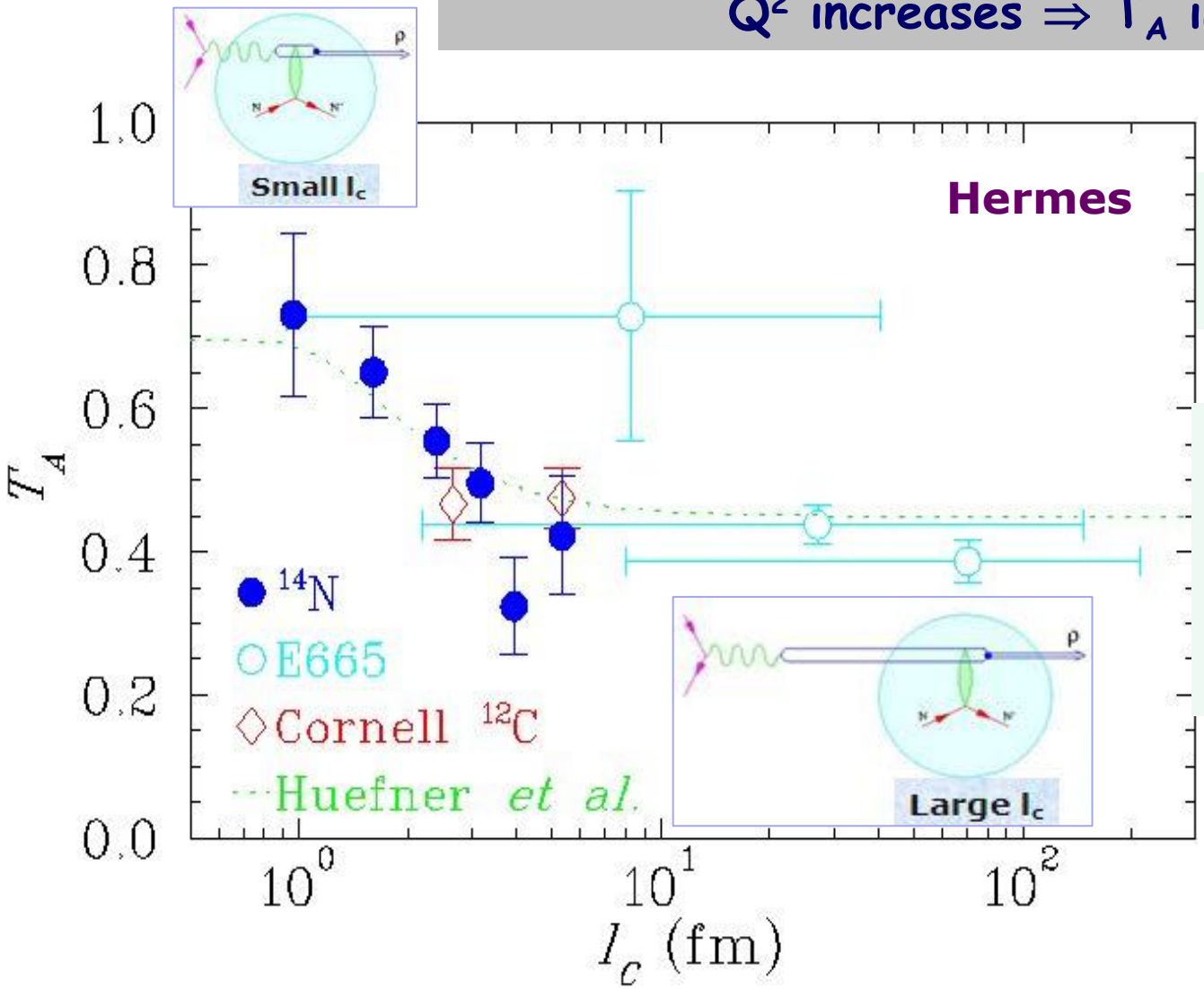
Adams et al. PRL74, 1525 (1995)

E_μ= 470 GeV



What could imitate CT signal?

Coherence length effect (CL) can mimic CT signal
Q^2 increases $\Rightarrow$ T_A increases



Coherence Length

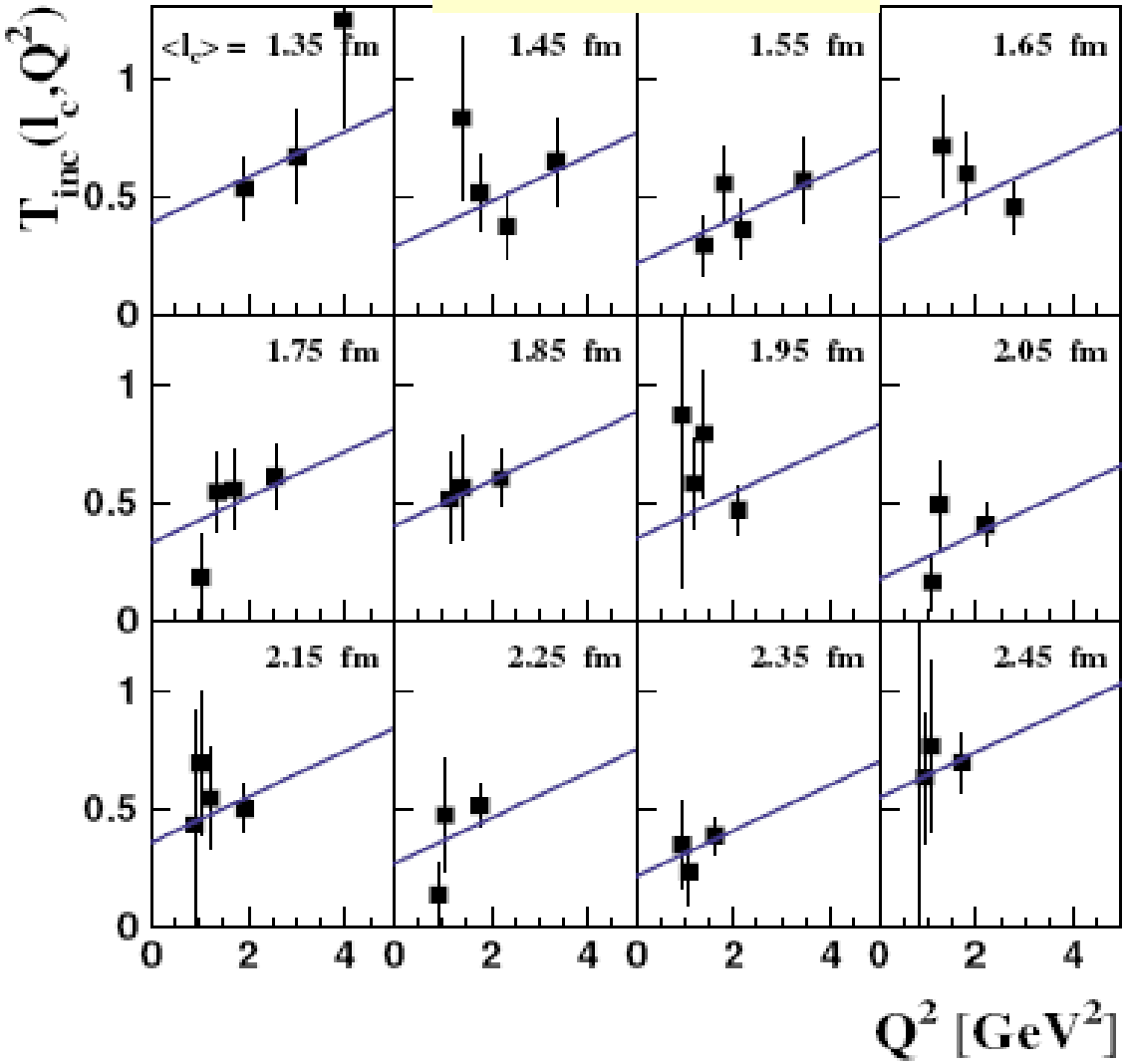
$l_c = 2\nu/(M^2 + Q^2)$

- To exclude CL, the Q^2 dependence of T_A must be measured at small or fixed l_c.

Exclusive ρ^0 leptoproduction: HERMES

Airapetian et al. PRL 90 (2003) 052501

E_{e+}= 27.5 GeV

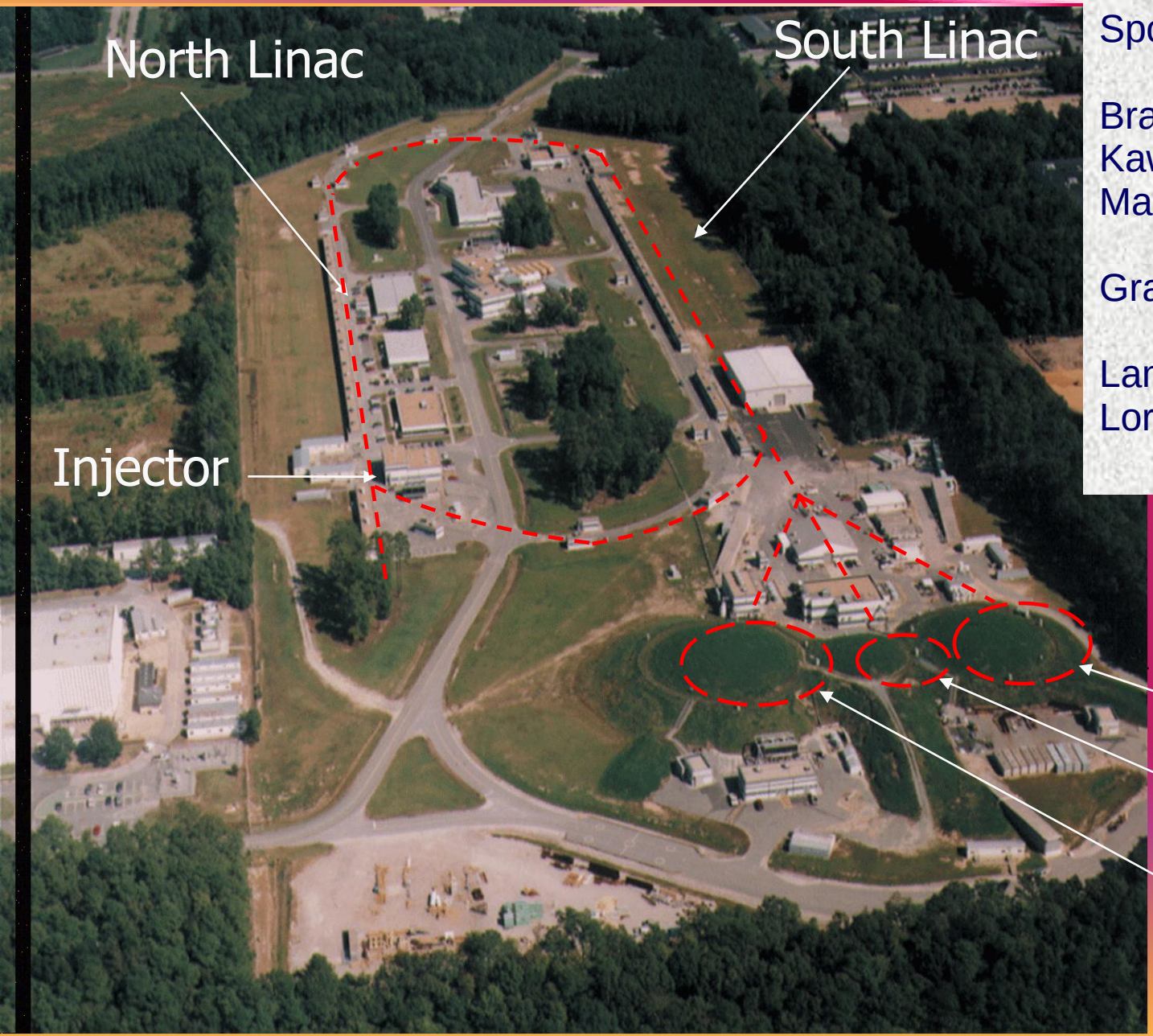


HERMES ^{14}N Data:

$T_{inc}(l_c,Q^2) = P_0 + P_1 Q^2$

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

JLab: Exclusive Diffractive ρ^0 Electro-production
Winter 2004



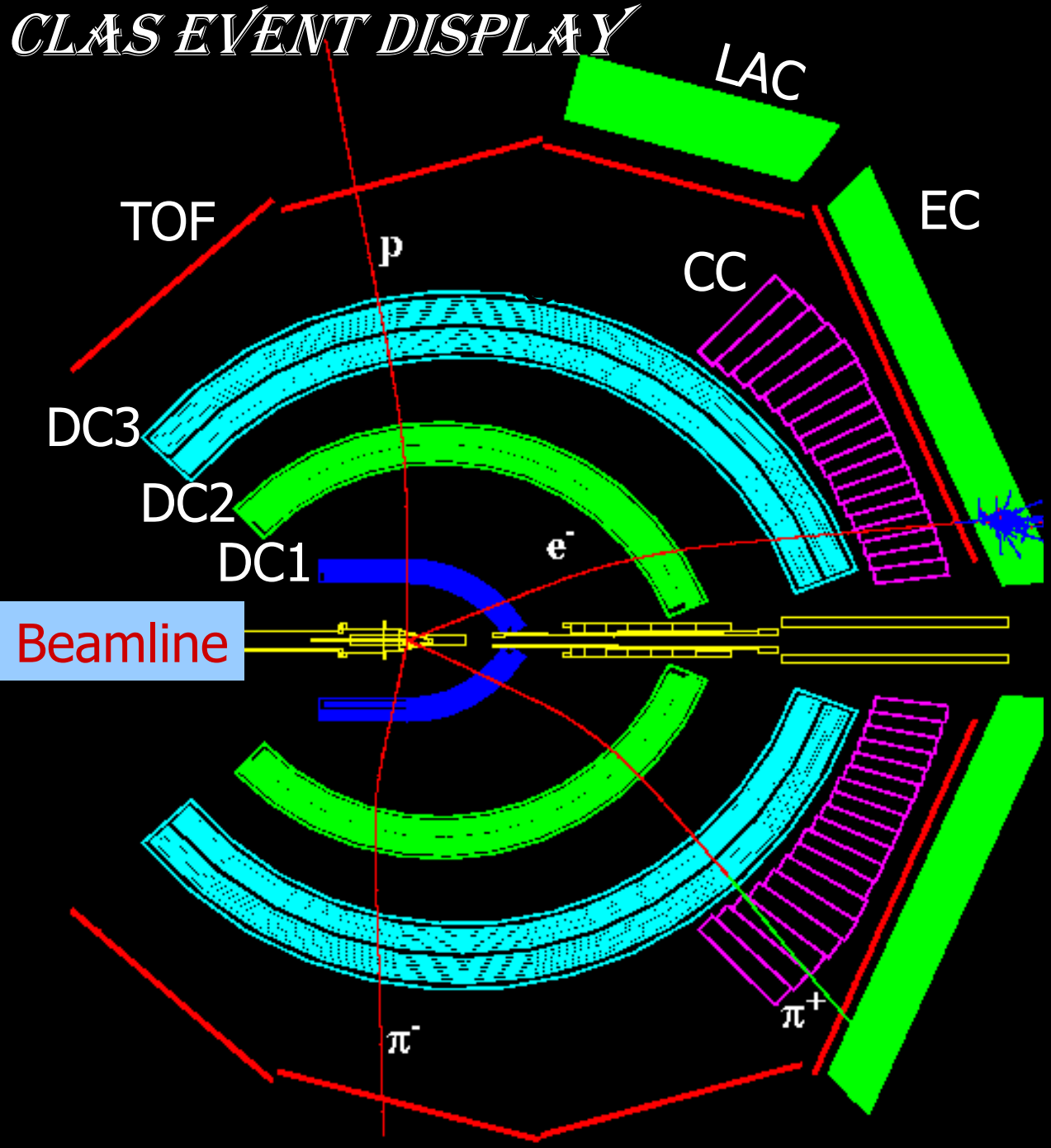
Spokespersons:

Brahim Mustapha (ANL)
Kawtar Hafidi (ANL)
Maurik Holtrop (UNH)

Graduate Students:

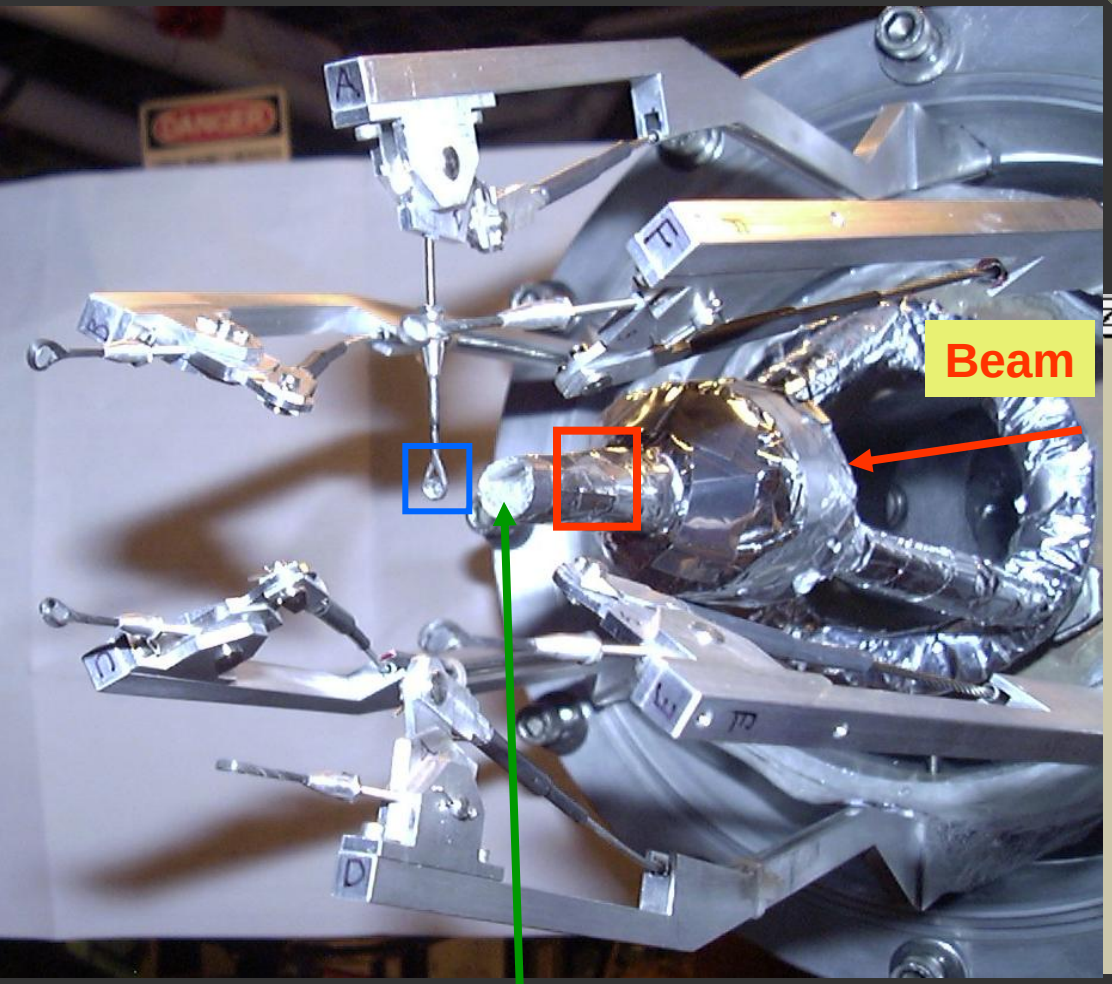
Lamiaa El Fassi (ANL)
Lorenzo Zana (UNH)

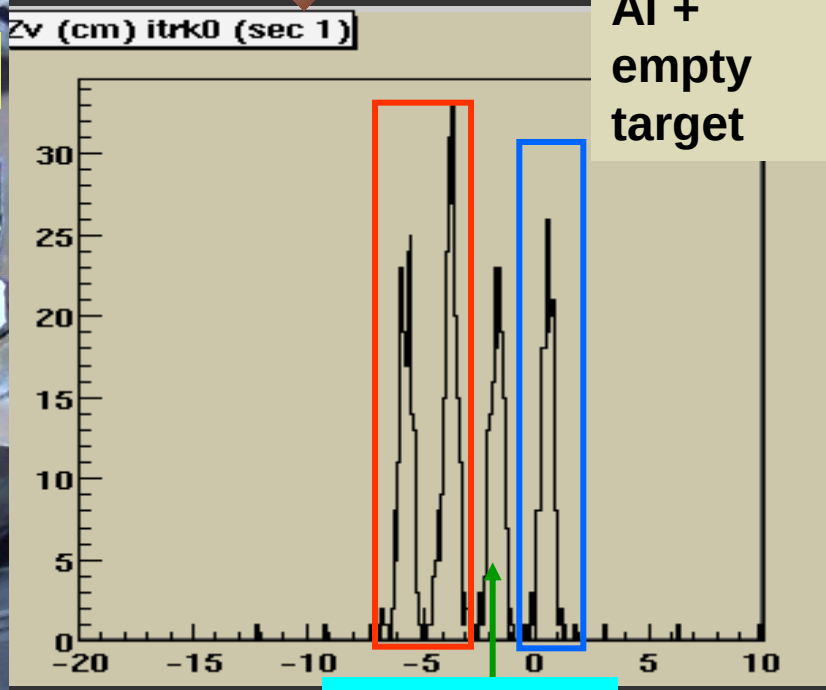
CLAS EVENT DISPLAY



- Charged particle angles
  8° - 144°
- Neutral particle angles
  8° - 70°
- Momentum resolution
  ~0.5% (charged)
- Angular resolution
  ~0.5 mr (charged)
- Identification of
  p, π^+/π^-, K^+/K^-, e^-/e^+

EG2 Targets

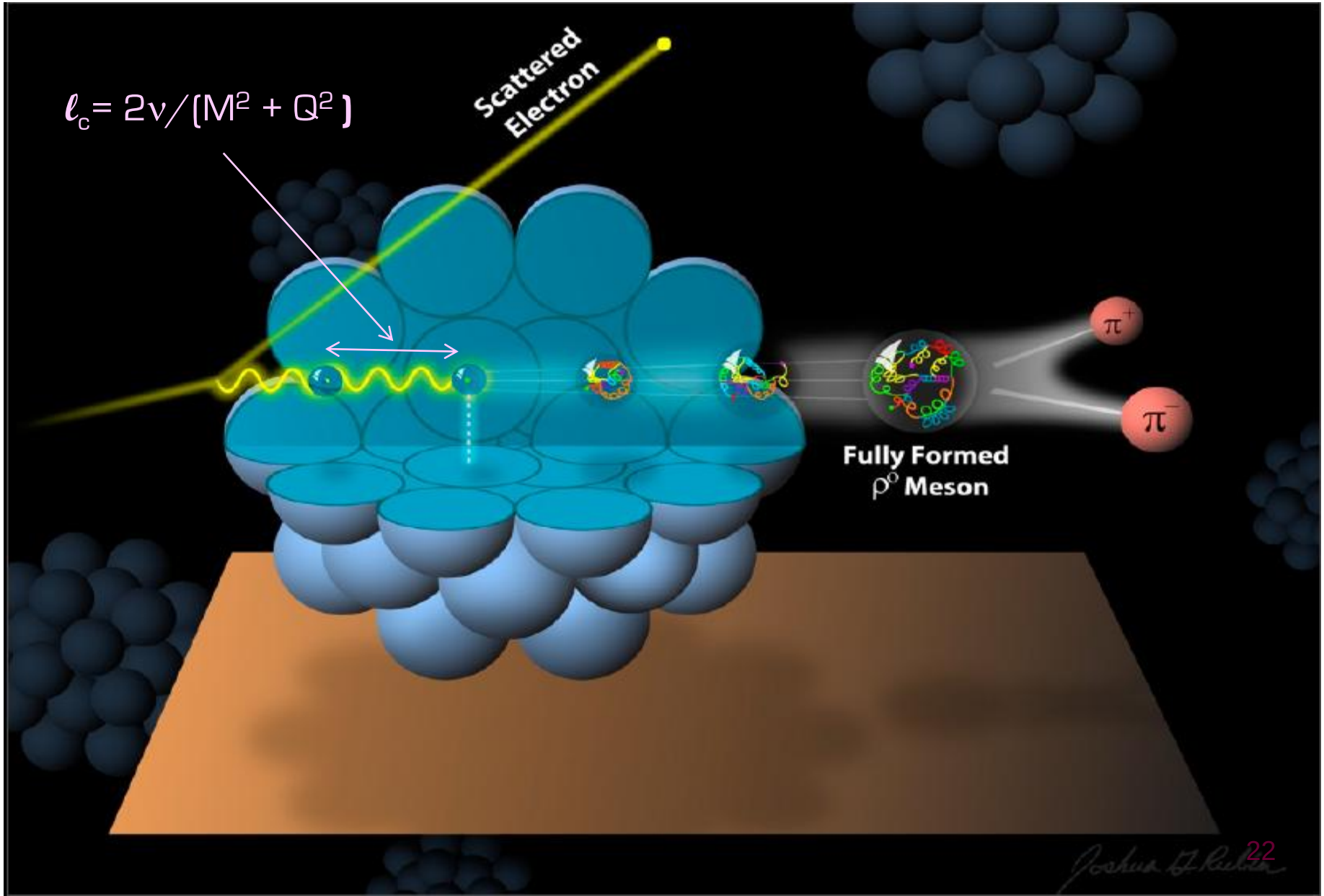




Al + empty target

Reference Foil

Exclusive Diffractive ρ^0 production off Nuclei



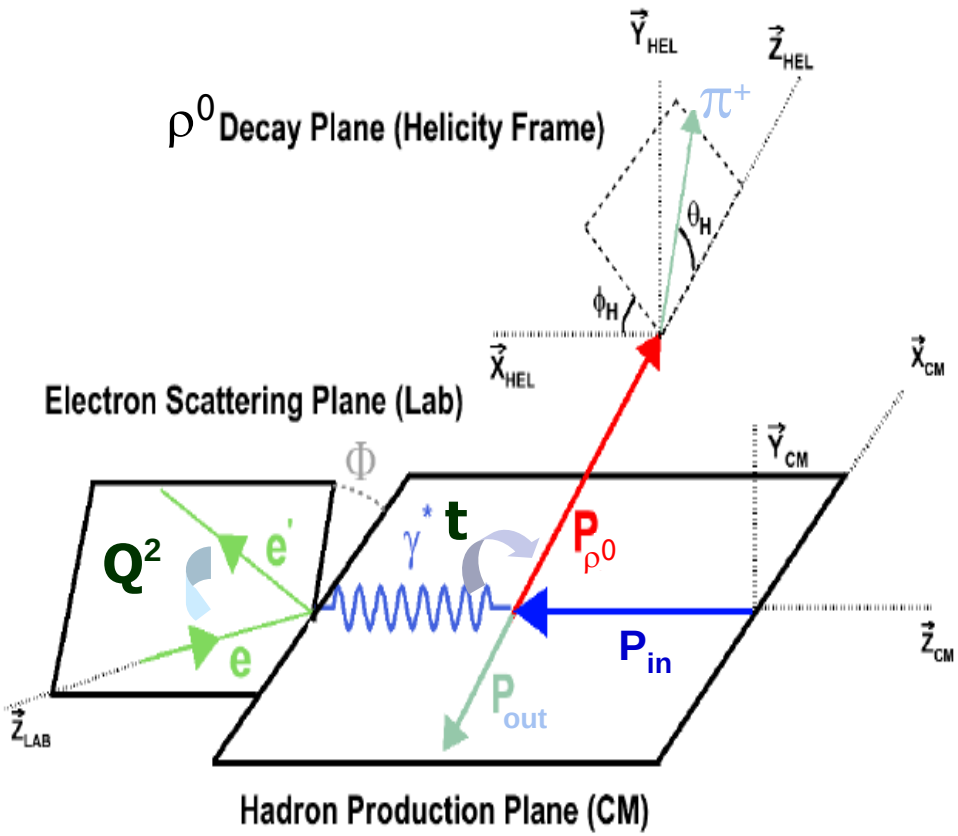
Kinematics

$\nu = e - e'$

$Q^2 = -(P^\mu_e - P^\mu_{e'})^2 \cong 4\, e\, e' \sin^2(\theta/2)$

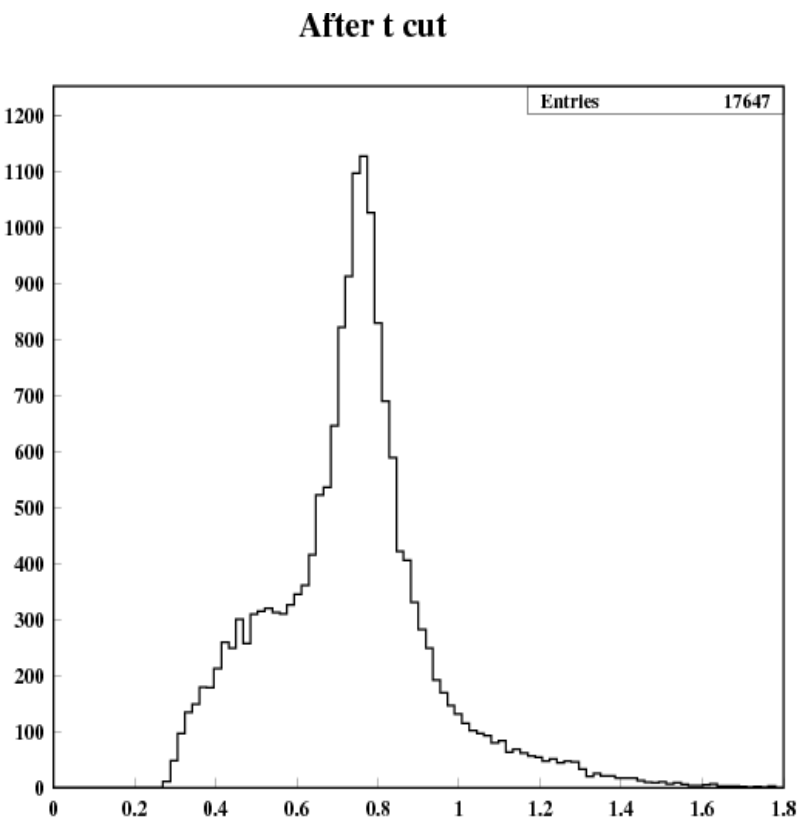
$t = (P^\mu_{\gamma^*} - P^\mu_\rho)^2$

$W^2 = (P^\mu_{in} + P^\mu_{\gamma^*})^2 = -Q^2 + M_p^2 + 2M_p\nu$

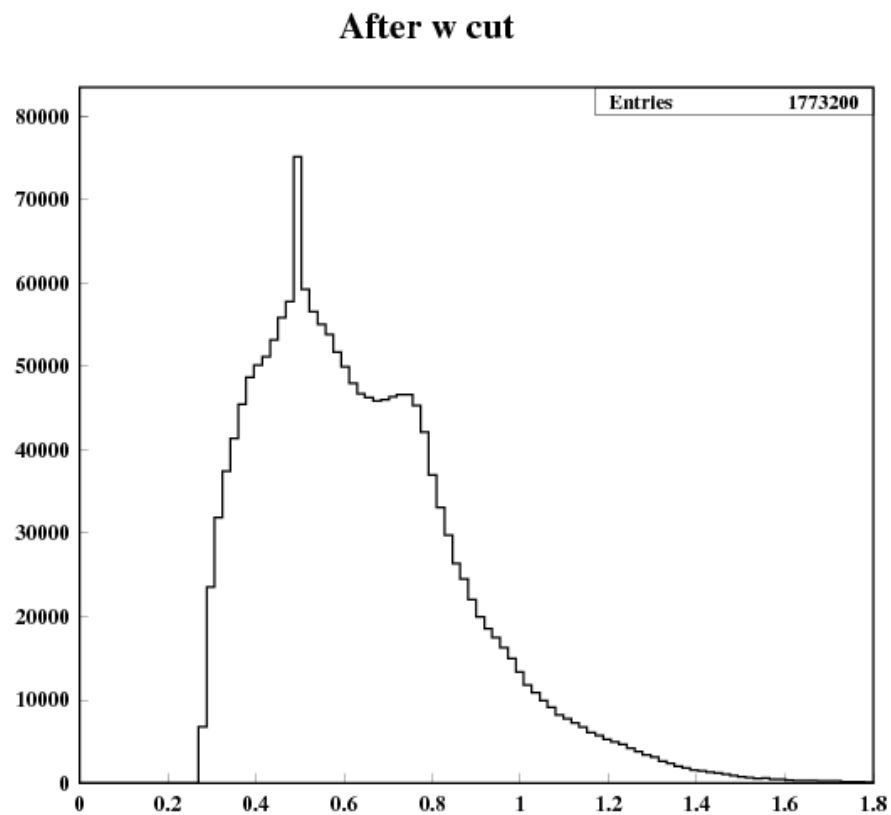


- $W \geq 2$ GeV
  $\Rightarrow$ avoid resonance region
- $t \geq -0.4$ GeV^2
  $\Rightarrow$ select diffractive process
- $t < -0.1$ GeV^2
  $\Rightarrow$ exlude coherent production
- $Z_h = E_h/\nu \geq 0.9$
  $\Rightarrow$ select elastic channel

Iron

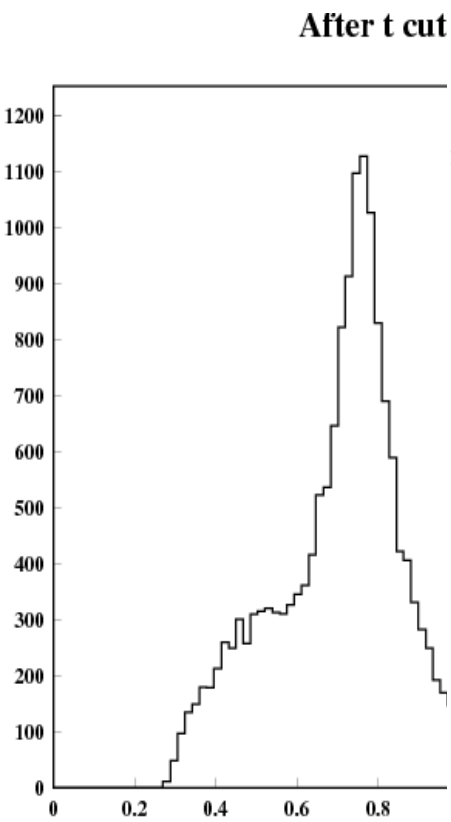


$M_{\pi+\pi-}$ (GeV)

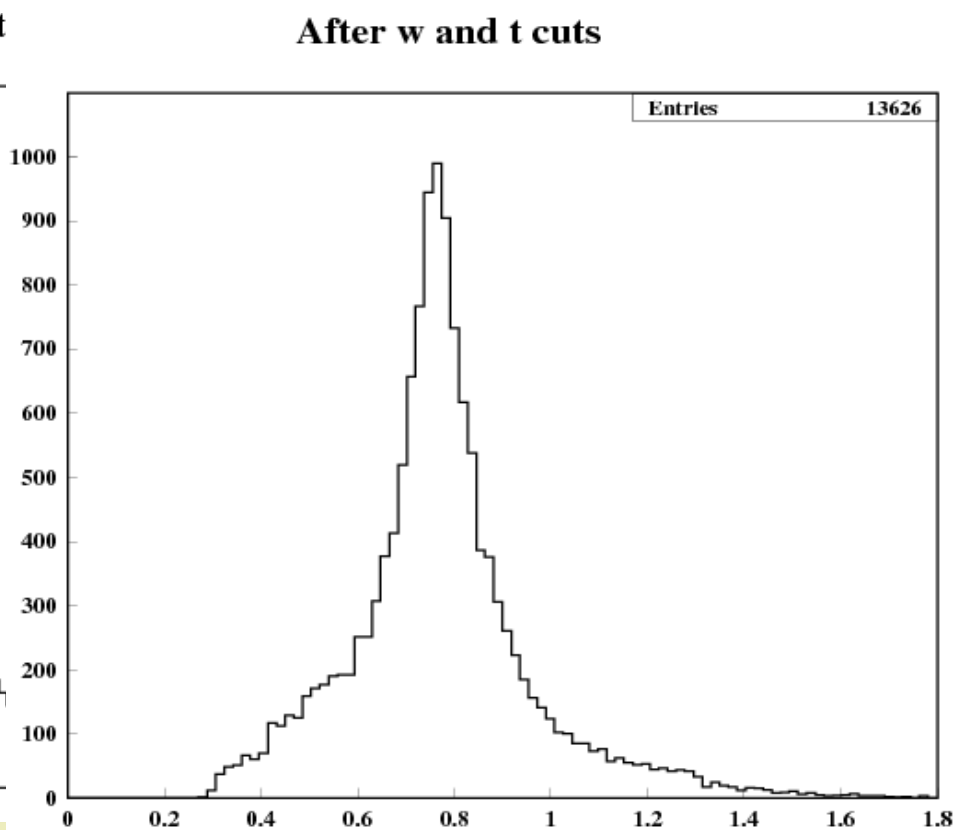


$M_{\pi+\pi-}$ (GeV)

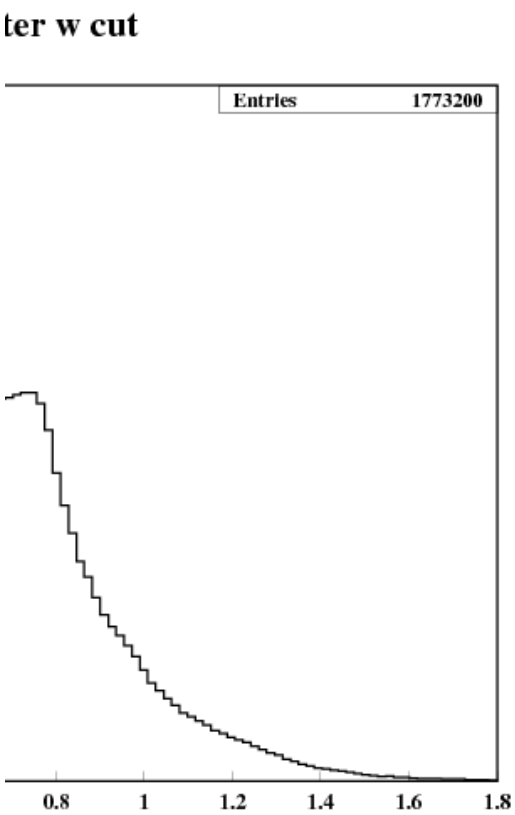
Iron



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

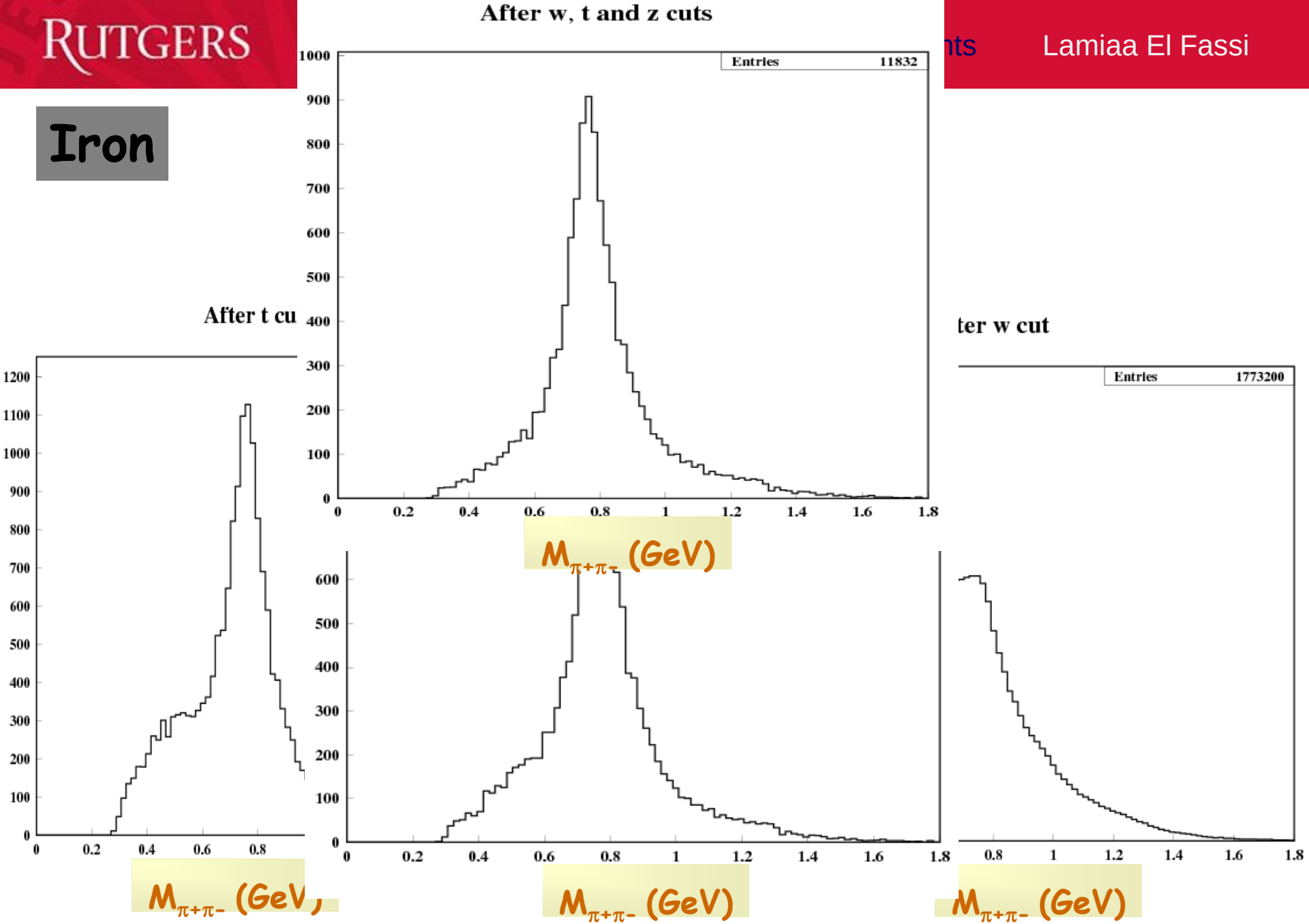


$M_{\pi+\pi-}$ (GeV)



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

Iron


After w, t and z cuts
Entries 11832
After t cu
ter w cut
Entries 1773200
$M_{\pi+\pi-}$ (GeV)
$M_{\pi+\pi-}$ (GeV)
$M_{\pi+\pi-}$ (GeV)
$M_{\pi+\pi-}$ (GeV)

Two pions invariant mass

Simple Breit-Wigner:

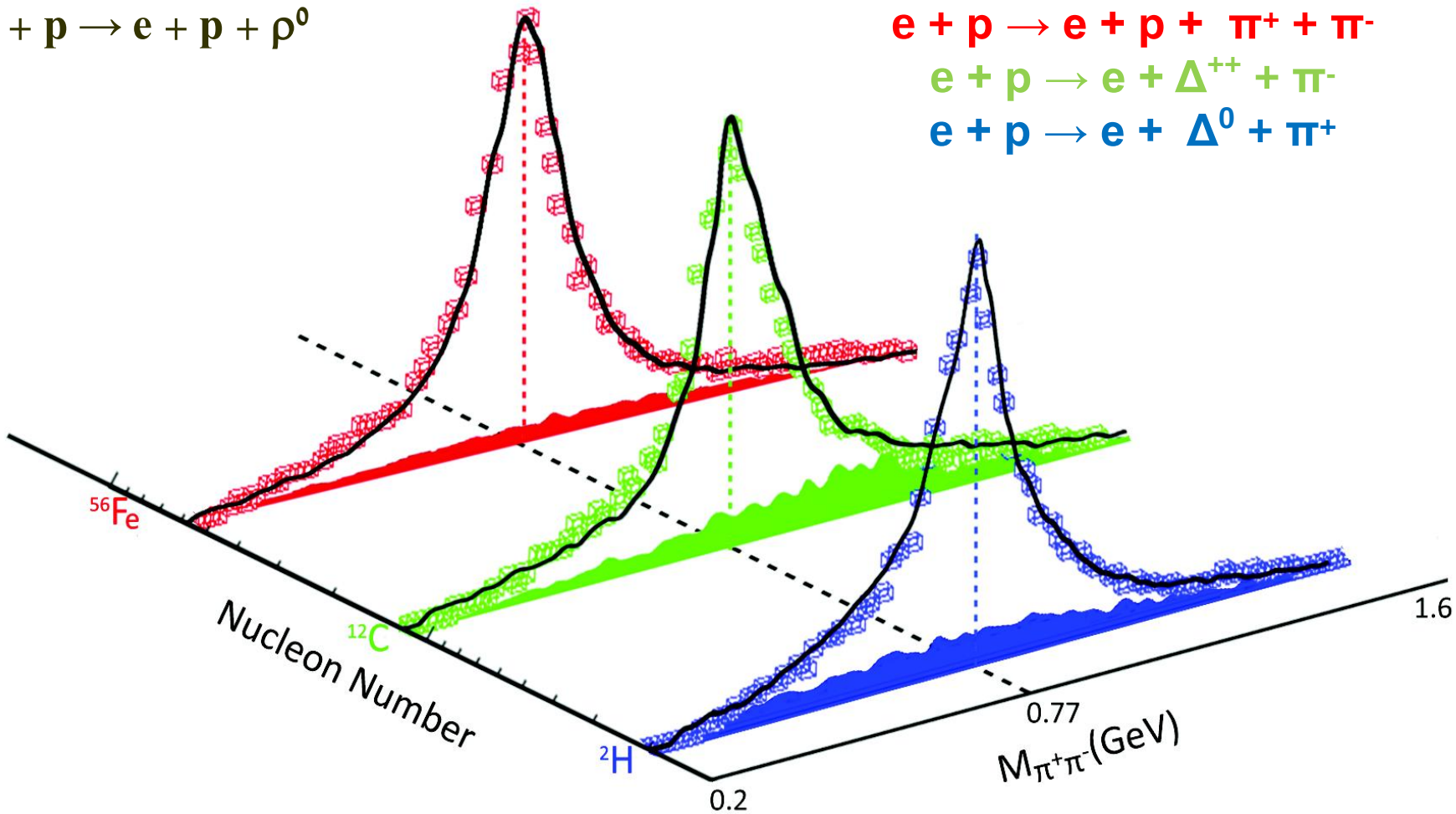
$e + p \rightarrow e + p + \rho^0$

Simulated Background's Shapes:

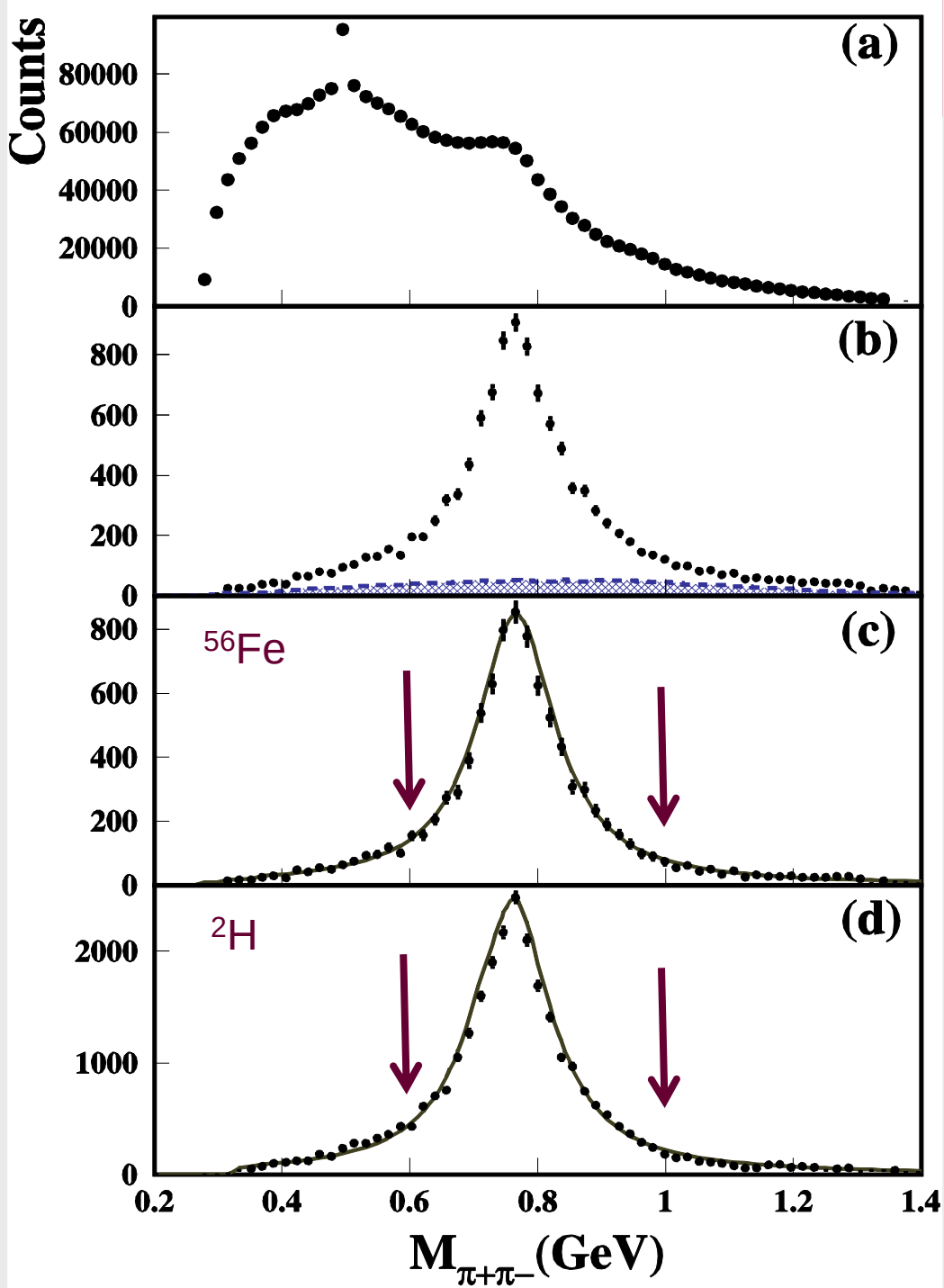
$e + p \rightarrow e + p + \pi^+ + \pi^-$

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

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



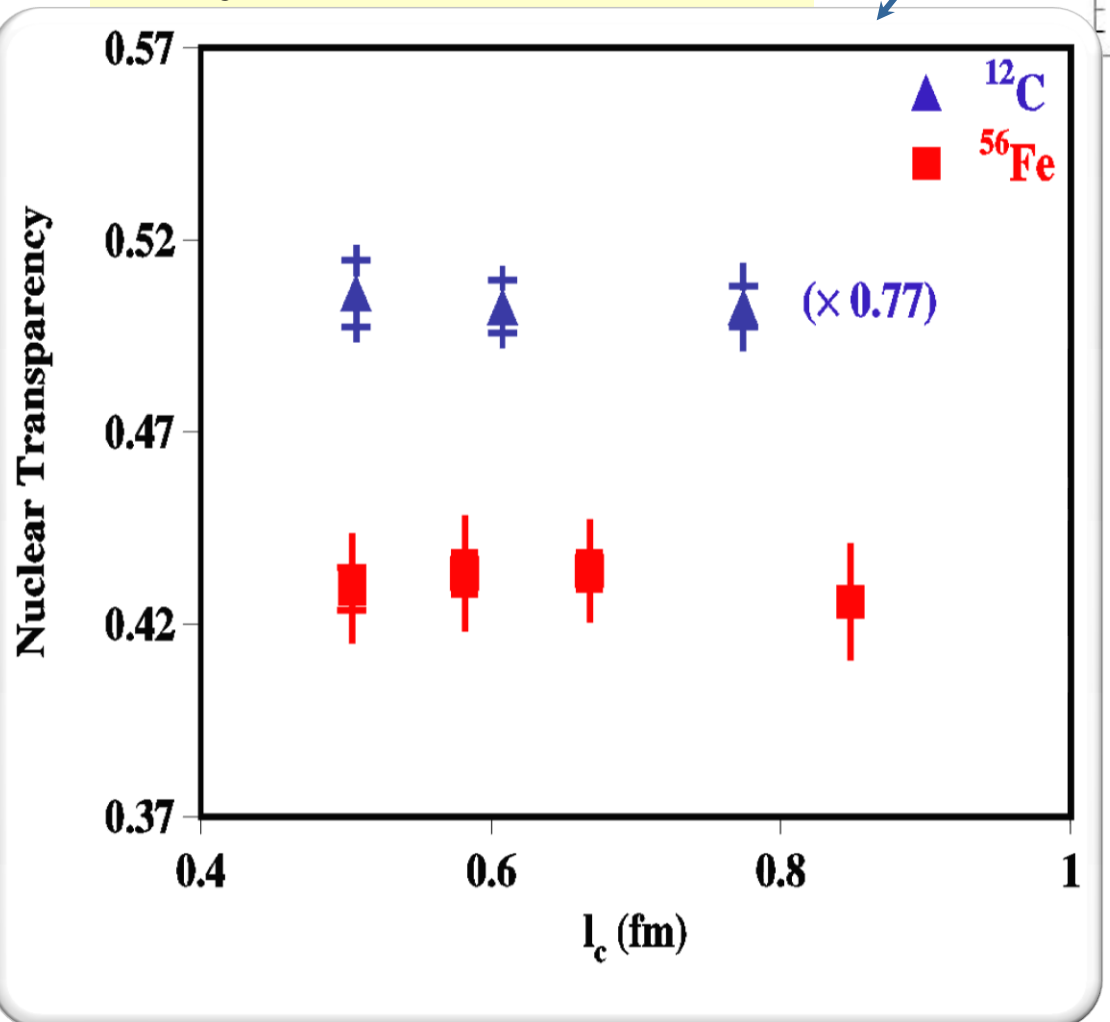
Lamiaa El Fassi

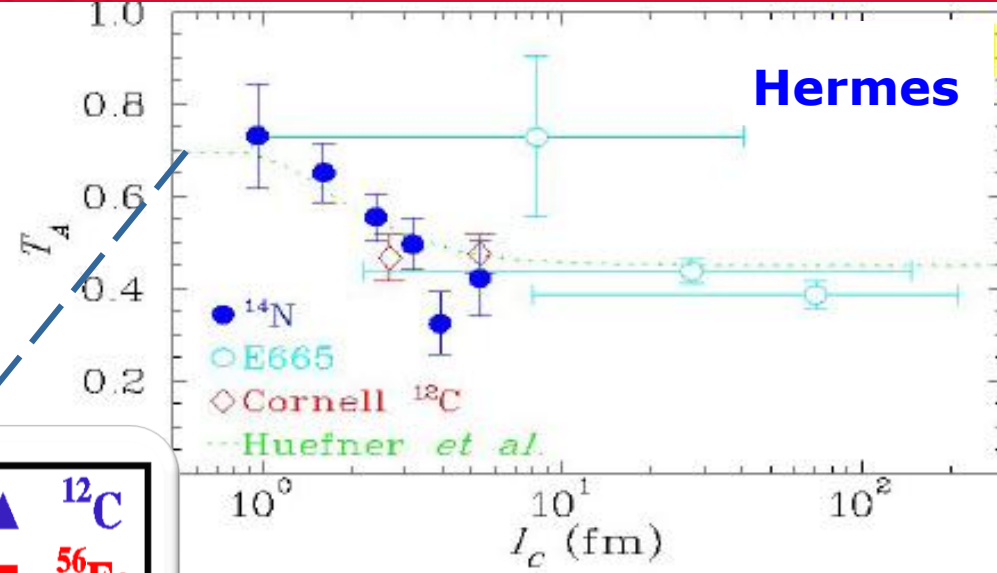


l_c Dependence on T_A

Coherence Length

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





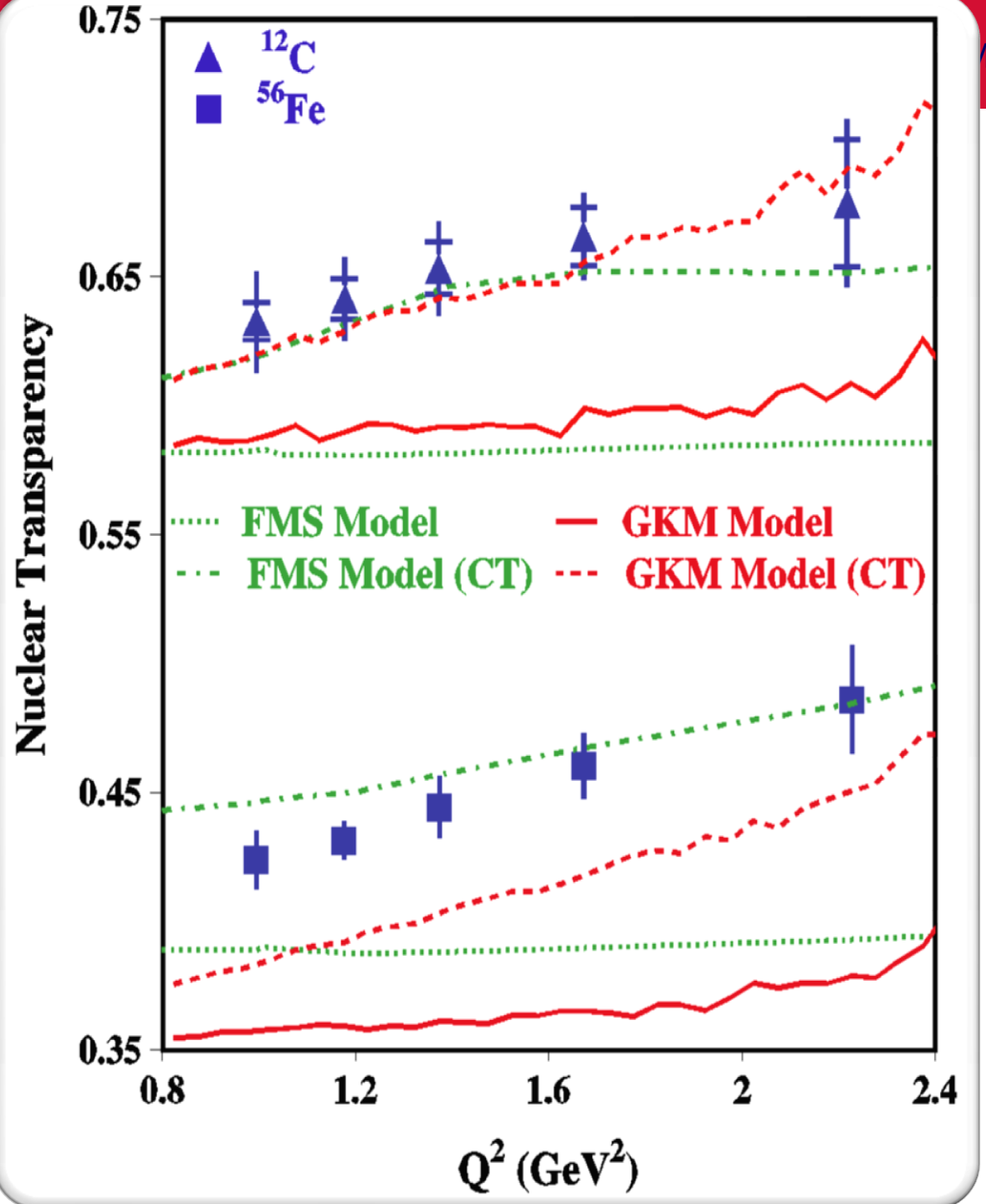
Nuclear Transparency

$T^{\rho}_A = N^{\rho}_A / N^{\rho}_D \times (\rho_D \times t_D) / (\rho_A \times t_A)$

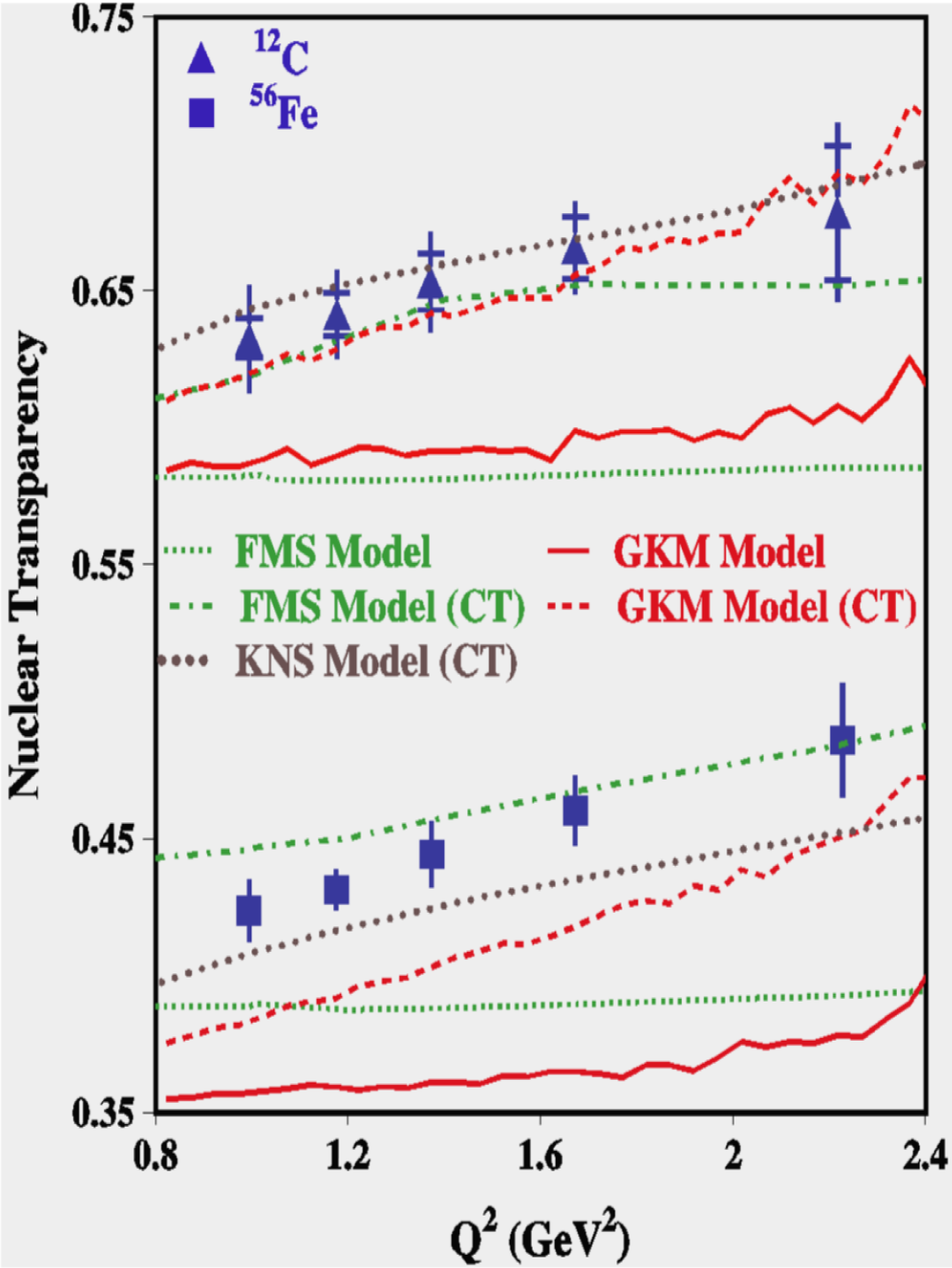
- ρ_D and ρ_A are the target densities
- t_A is a solid target thickness
- t_D= 2 cm is the liquid target length

L. El Fassi et al. PLB 712, 2012

ρ^0 CT Results: Iron & Carbon data



L. El Fassi et al. PLB 712, 2012



ρ^0 CT Results: Iron & Carbon data

- **FMS: Glauber model based on multiple diffusion scattering formalism.**

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

- **GKM: Transport Model (GiBUU)**

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

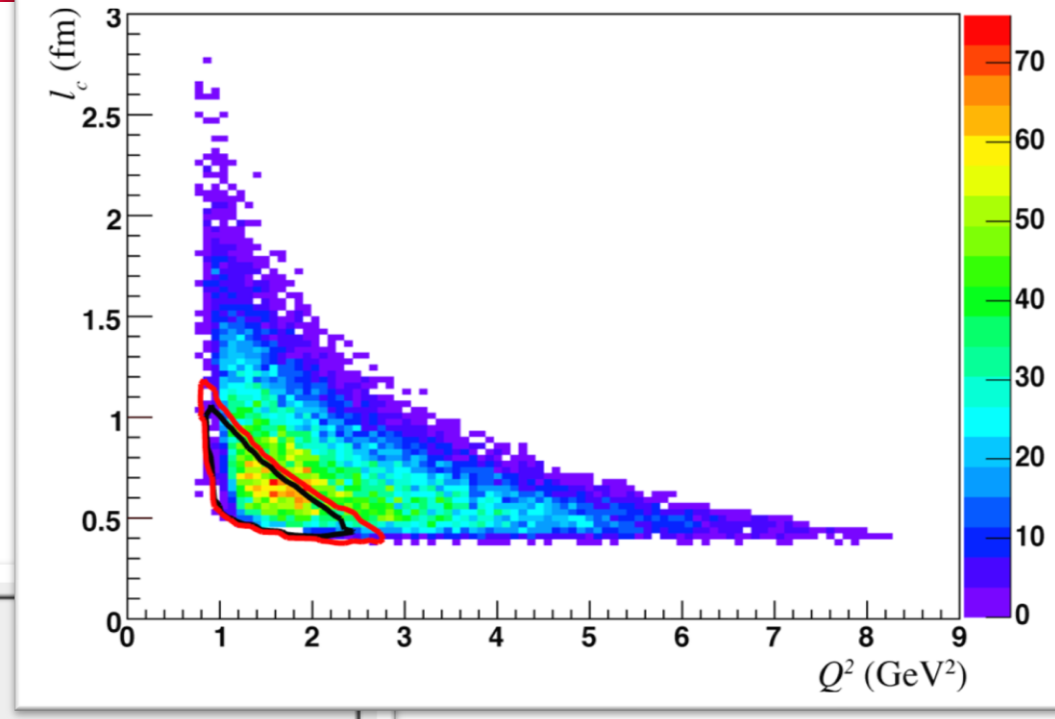
- **KNS: Light Cone QCD Formalism**

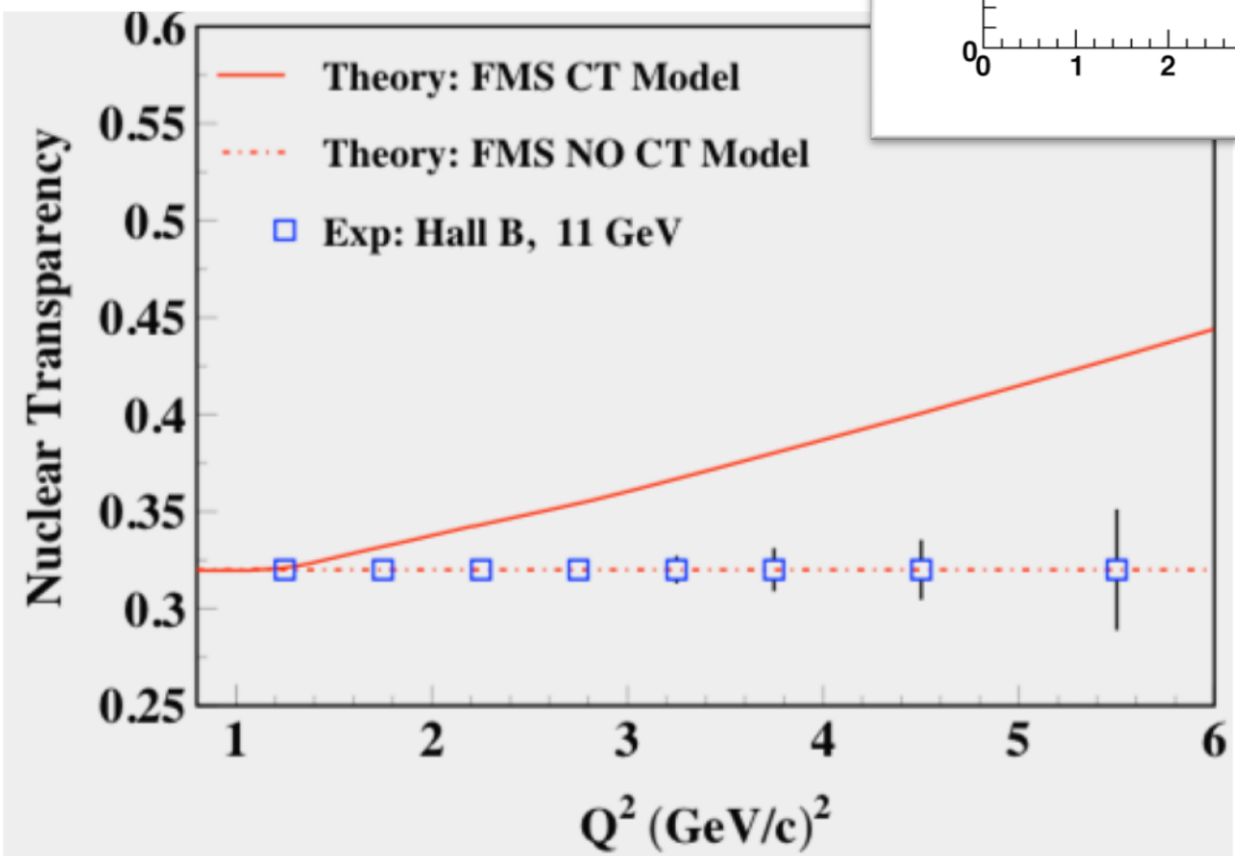
  Kopeliovich, Nemchik & Schmidt, PRC 76, 015205 (2007) & Private communication.

ρ^0 CT slopes

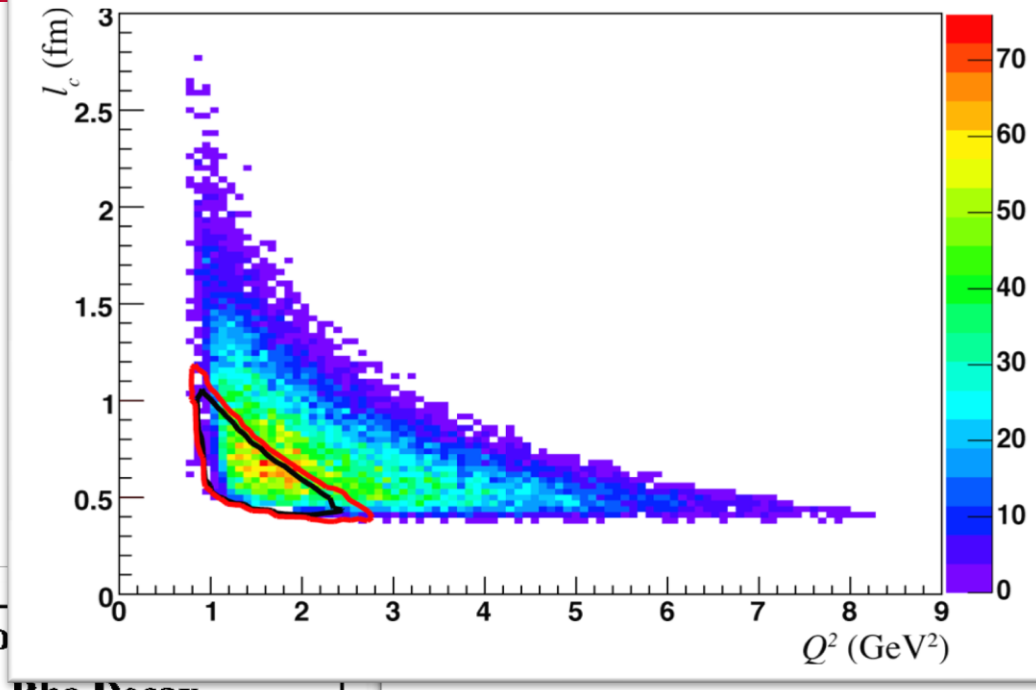
Target slopes (GeV^{-2})	Carbon	Iron
FMS	0.025	0.032
GKM	0.06	0.056
KNS	0.06	0.045
CLAS Data	0.044±0.015±0.019	0.053±0.008±0.013

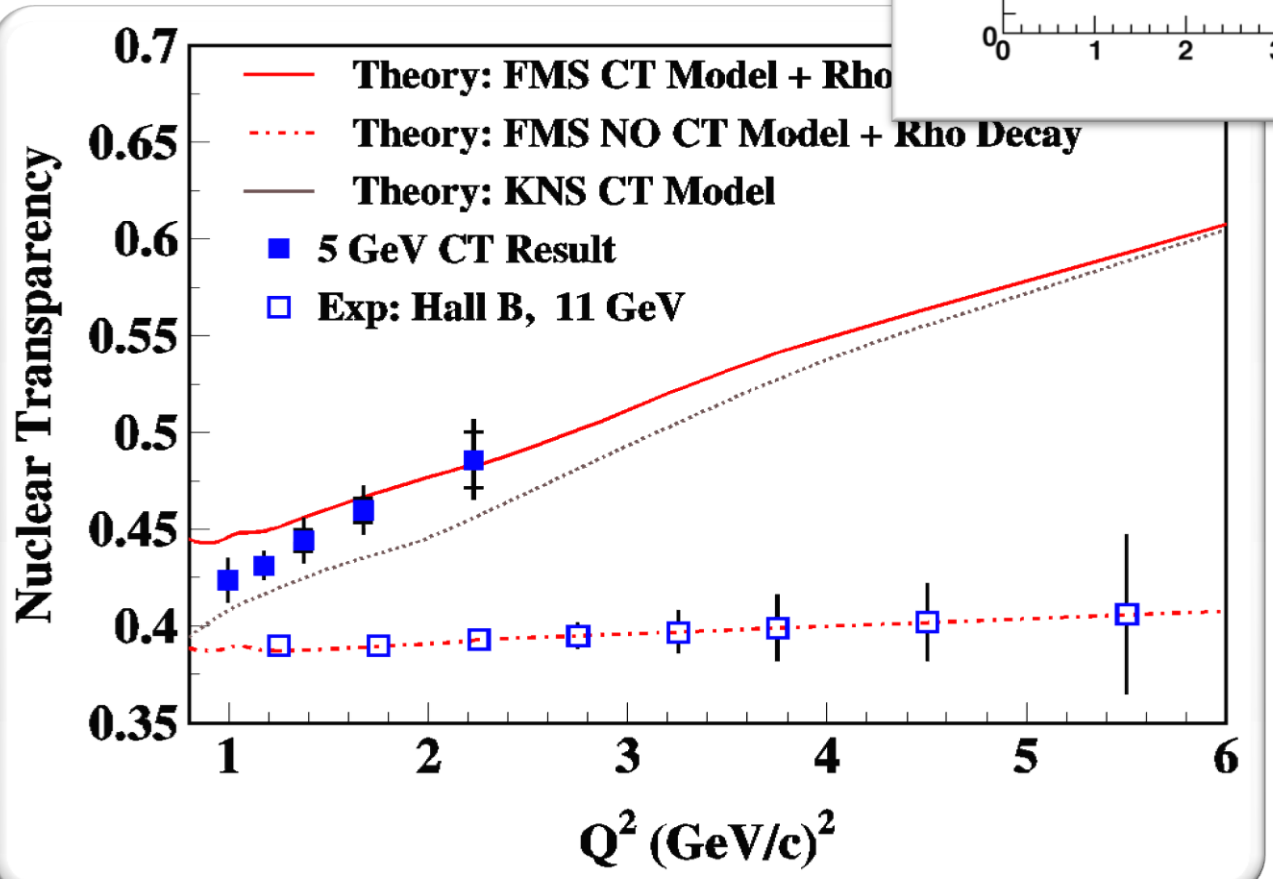
JLab 12 GeV ρ^0 electroproduction measurements C, Fe and Sn





JLab 12 GeV ρ^0 electroproduction measurements C, Fe and Sn





Summary and Outlook

- Strong evidence for the onset of Color Transparency using ρ electro-production off nuclei at JLab (11 ± 2.3% (12.5 ± 4.1%) decrease in the absorption of ρ in iron (carbon))
- SSC expansion time with FMS model were found to be between 1.1 and 2.4 fm for ρ momenta between 2 and 4.3 GeV
- At intermediate energies, CT provides unique probe of the space-time evolution of special configurations of the hadron wave function
- Using the upgraded JLab 12 GeV, we plan to disentangle different CT effects (SSC creation, its formation and interaction with the nuclear medium)

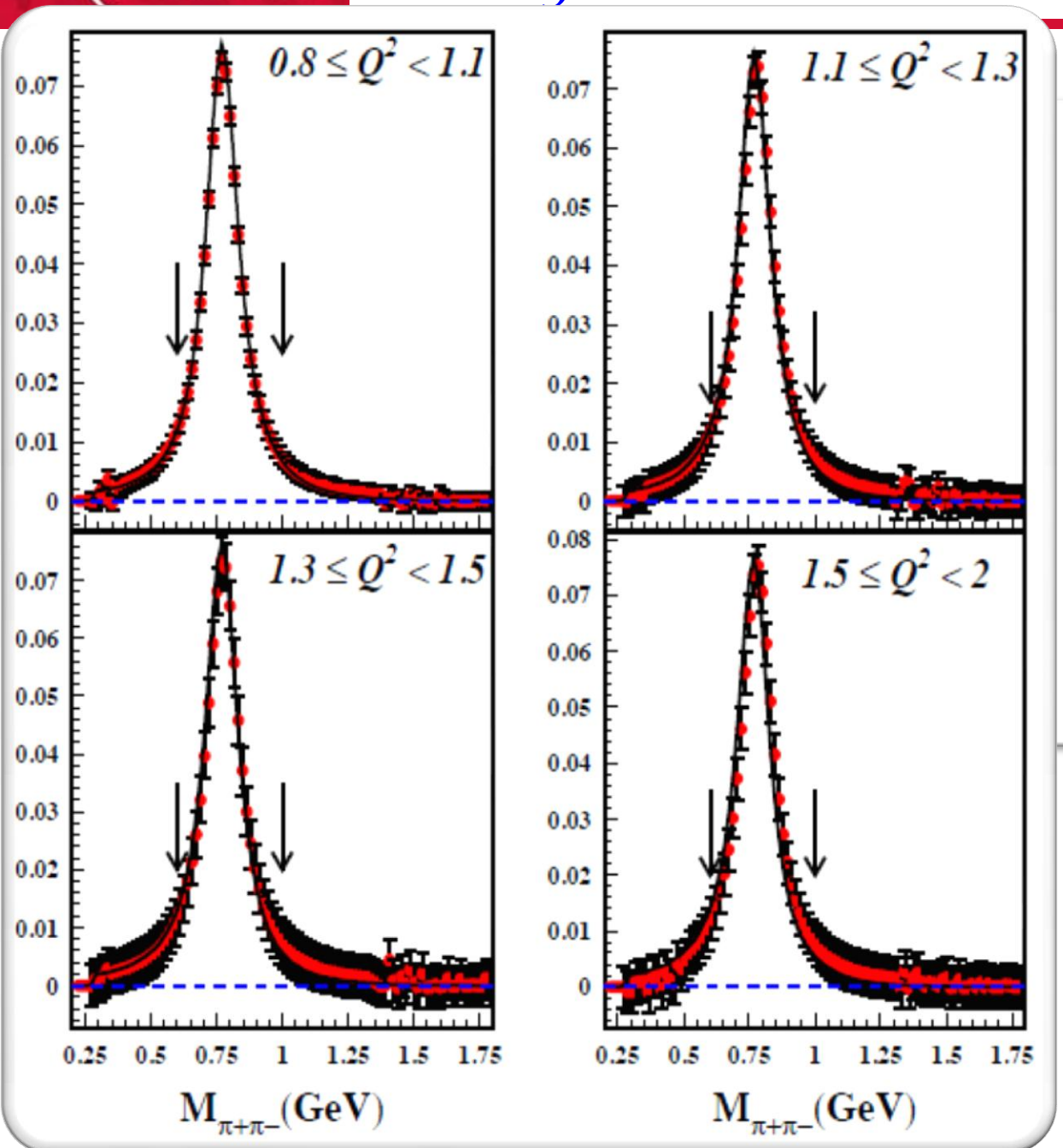
Acknowledgements

- Kawtar Hafidi (ANL)
- Brahim Mustapha (ANL)

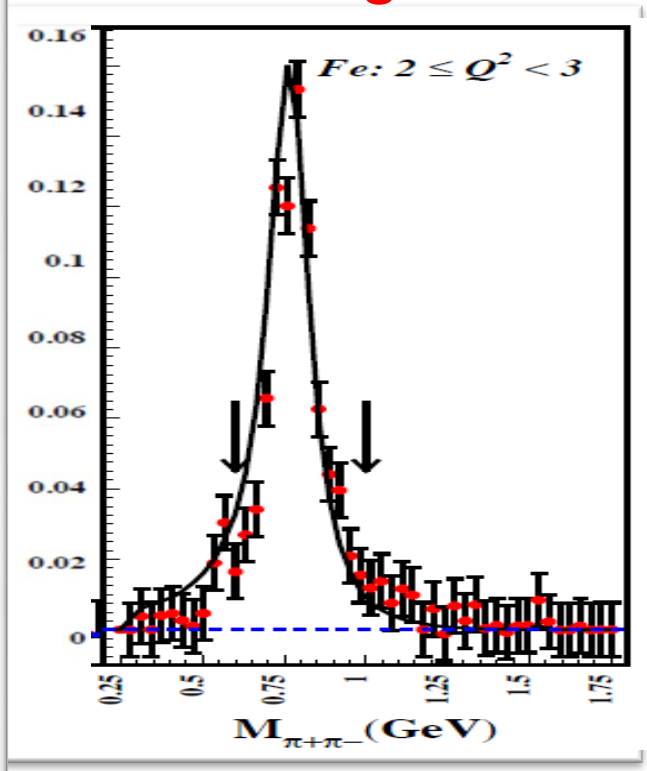
- Lorenzo Zana (UNH/Syracause University)
- Maurik Holtrop (UNH)
- William Brooks (JLab/UFTSM)
- Hayk Hakobyan (JLab/Yervan/UFTSM)
- ANL Medium Energy Group
- CLAS Collaboration

Backup Slides

Two pions invariant mass

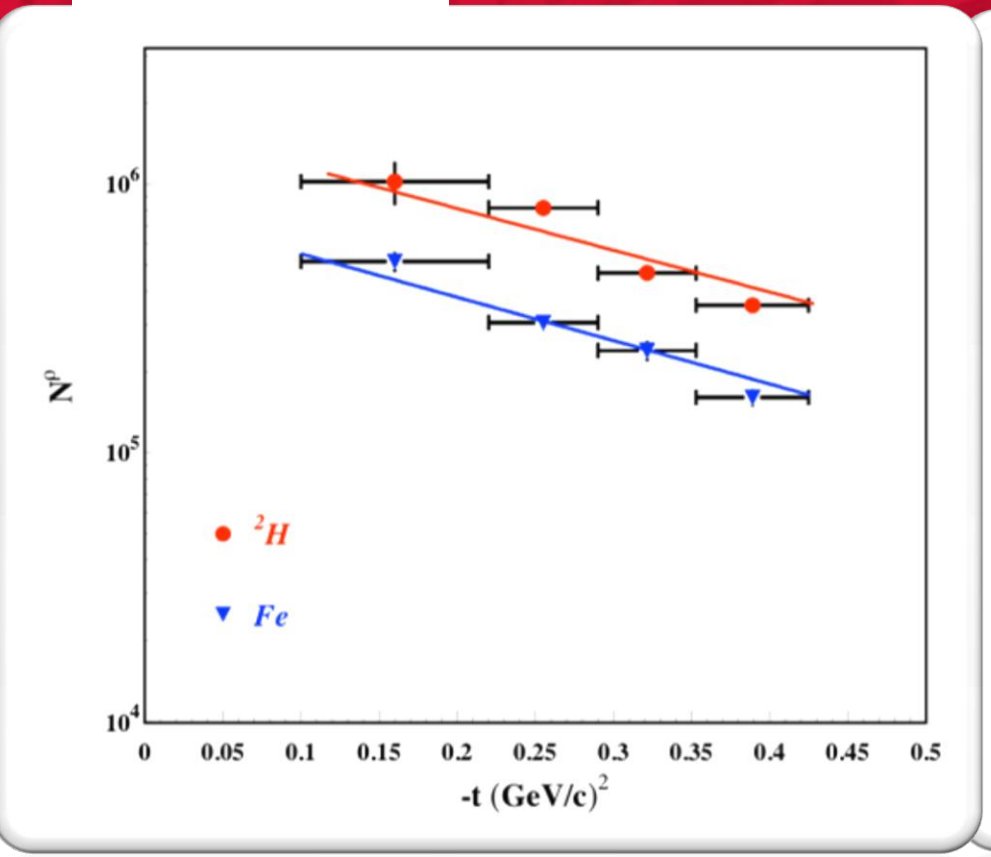


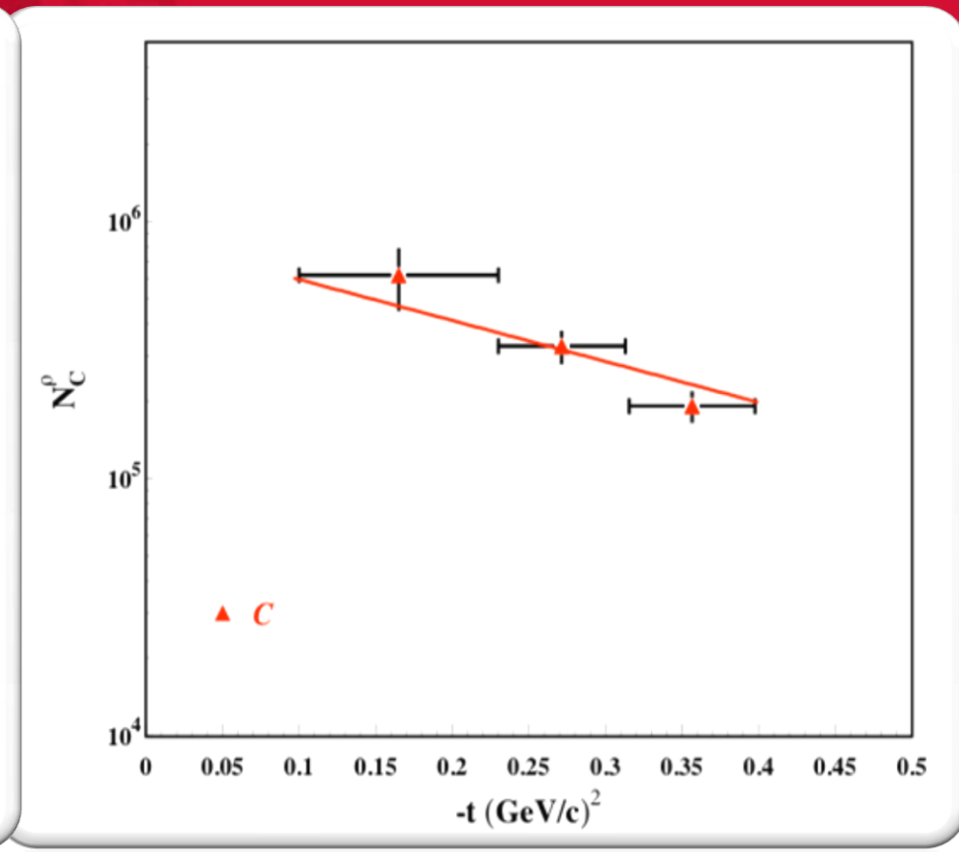
Iron target



Acceptance corrected invariant mass

t slopes





Ae^{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}

Systematic error budget

Systematic Uncertainty of Nuclear Transparency of Iron																														
Systematic Effect	Kinematical cuts					Acceptance correction					Background subtraction					Radiative corrections					Fermi motion					Target				
Q^2 Bins	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Normalization	0.1					0.8					0.5					0.3					1					1.75				
Point-to-point	1.1	1.3	0.4	-	1.1	1.6	-	1.7	1.6	1.5	1.3	0.2	1.6	1.5	1.7	1	0.5	-	1	1.8	0.1	0.05	0.03	0.08	-	-	-	-	-	-

Systematic Uncertainty of Nuclear Transparency of Carbon																														
Systematic Effect	Kinematical cuts					Acceptance correction					Background subtraction					Radiative corrections					Fermi motion					Target				
Q^2 Bins	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Normalization	0.49					0.89					1.1					0.47					1					1.75				
Point-to-point	1	1.25	-	1.18	2.6	1.34	1.31	1.82	0.95	-	-	0.82	0.37	1.11	1.17	2.34	1.13	1.39	-	1.37	0.1	0.05	0.03	0.08	-	-	-	-	-	-

Total Systematic Uncertainties of Nuclear Transparency										
Targets	Iron Case					Carbon Case				
Q^2 bins	1st bin	2nd bin	3rd bin	4th bin	5th bin	1st bin	2nd bin	3rd bin	4th bin	5th bin
Point-to-point	2.5	1.4	2.4	2.4	3.1	2.87	2.22	2.32	1.88	3.16
Normalization	2.1					2.4				

Theoretical Prediction of CT
Frankfurt, Miller & Strikman, PRC 78 (2008)

- Model (FMS) 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

Theoretical Prediction of CT

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

- Model (GKM) 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 a PLC. 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.

Theoretical Prediction of CT
Kopeliovich et al., PRC 65 (2002) 035201

- **Model based on light-cone (LC) approach**
- **LC dipole phenomenology for elastic production of vector meson (VM) $\gamma^*N \rightarrow VN$**

- $M(\gamma^*N \rightarrow VN) = \langle V|\sigma(qq\text{-bar})|\gamma^*\rangle$

- 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