Study of Color Transparency in Exclusive Vector Meson Electroproduction off Nuclei

CLAS Collaboration Meeting
March 9th, 2018

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(for the EG2 run-group)

MISSISSIPPI STATE UNIVERSITY™

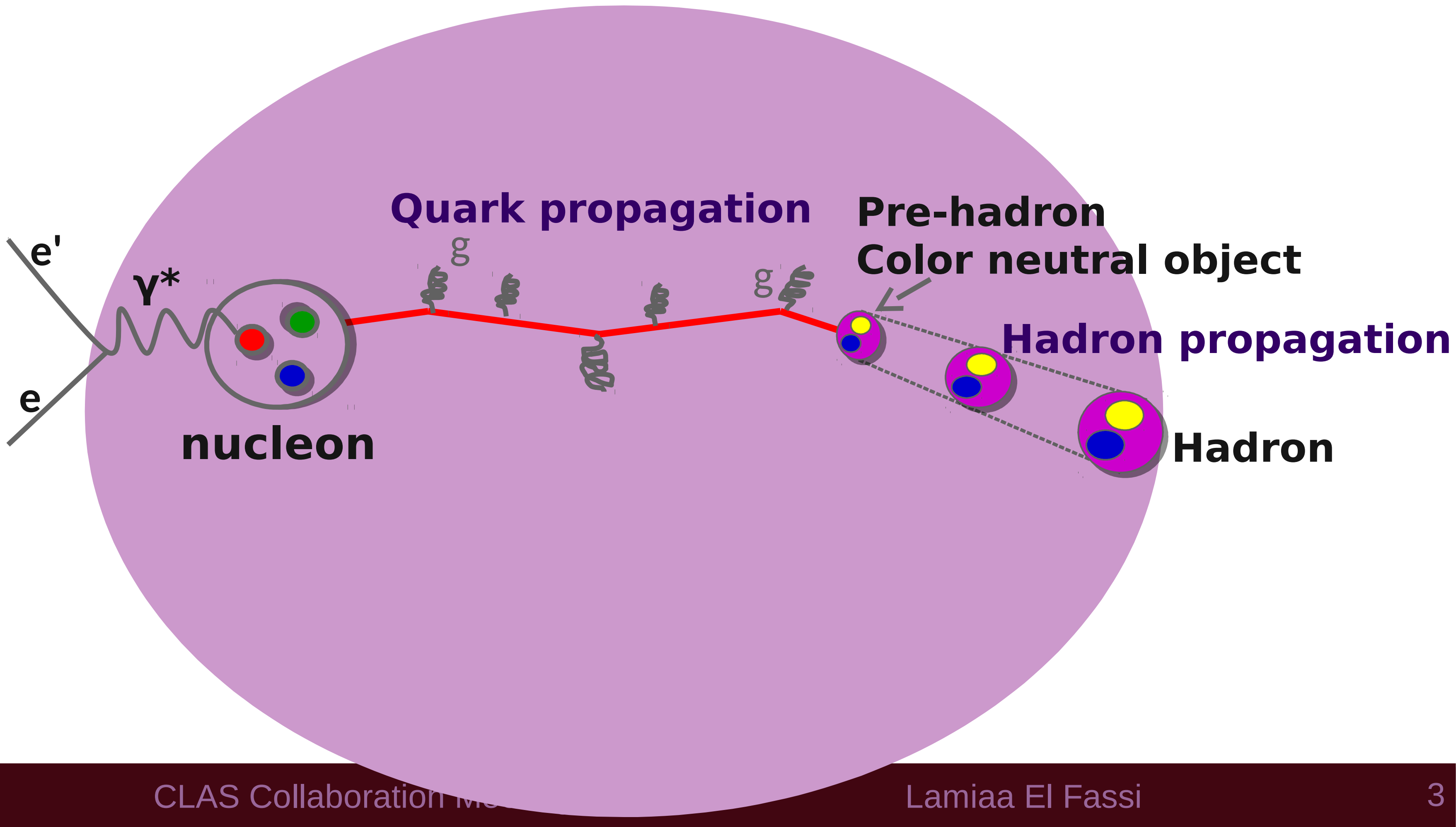
CEBAF Large Acceptance Spectrometer

Outline

- Brief introduction
- Highlight of CT experimental studies
    - Past and future CLAS experiment
- Summary and Outlook

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

- Study hard processes in nuclei to probe the QCD confinement dynamics:
  - Color propagation and fragmentation - **Hadronization process**



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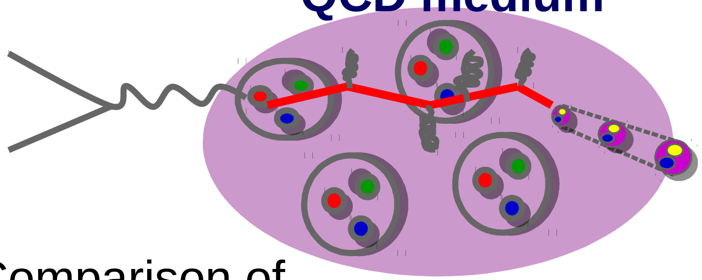
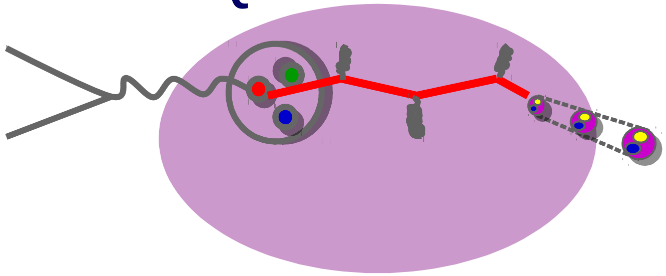
“QCD medium”



Comparison of leads to extraction of hadronization time-scales

“QCD vacuum”



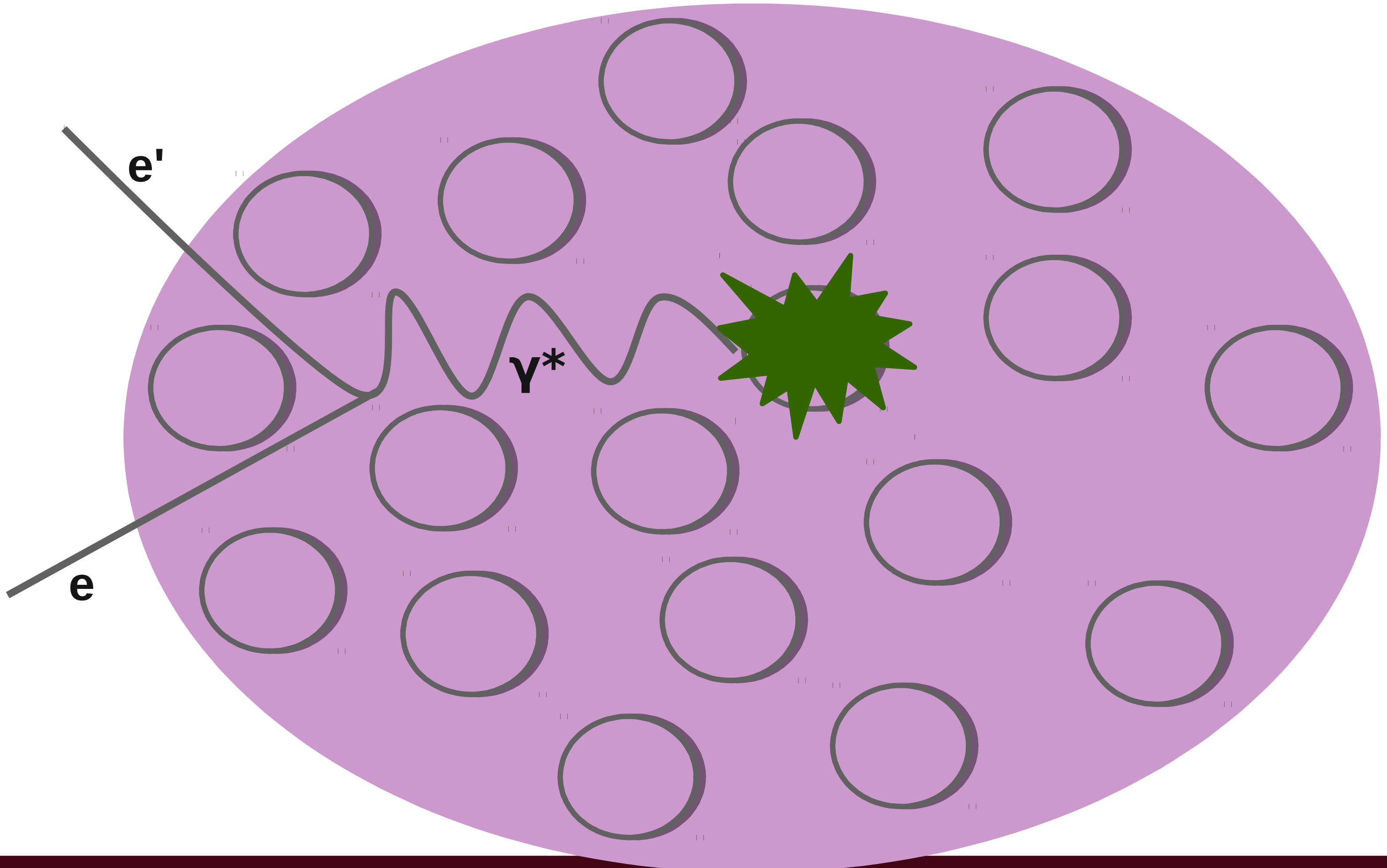
&

in-medium stimulated effects such as

- Parton energy loss,
- Hadron attenuation

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

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



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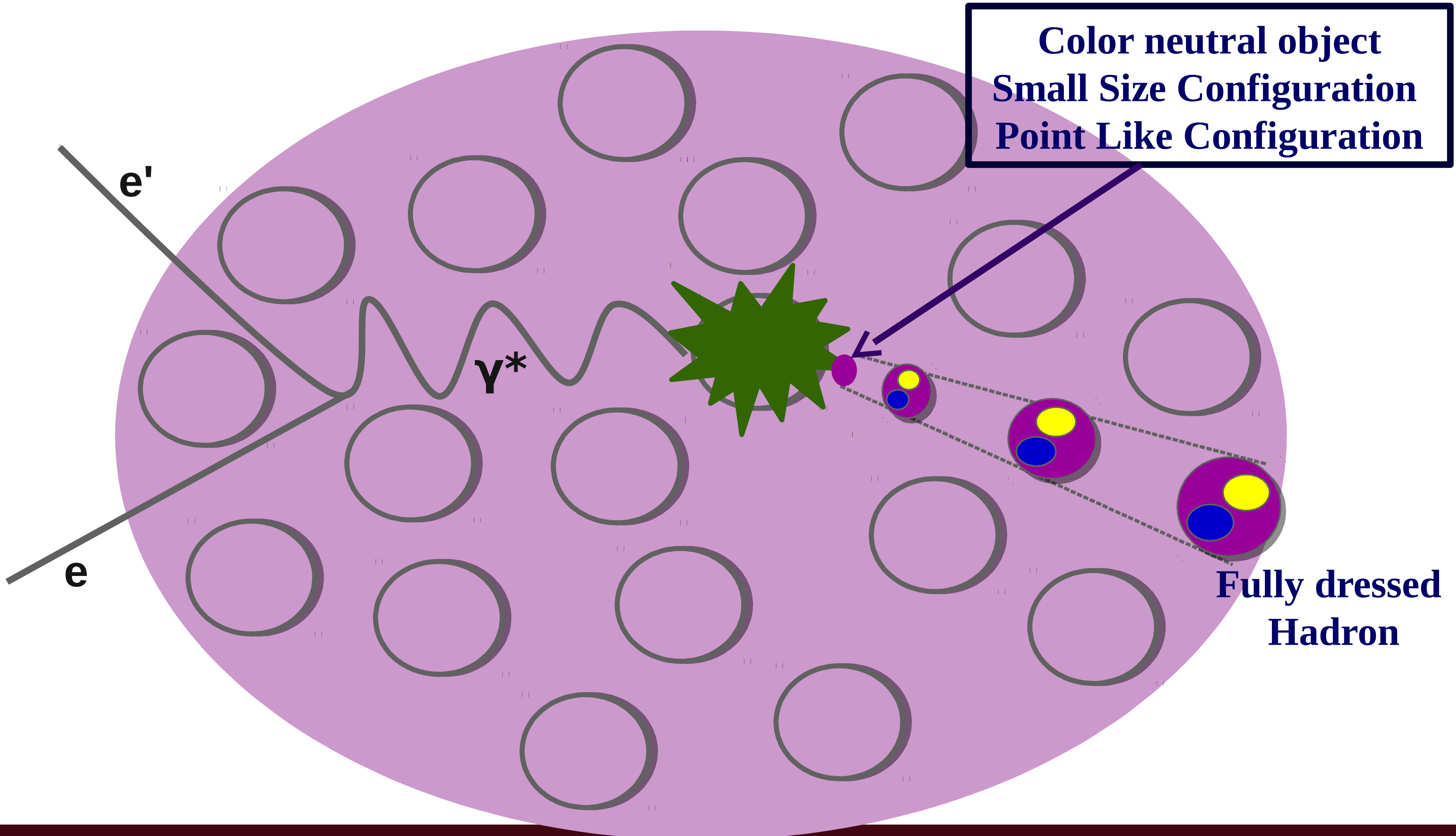
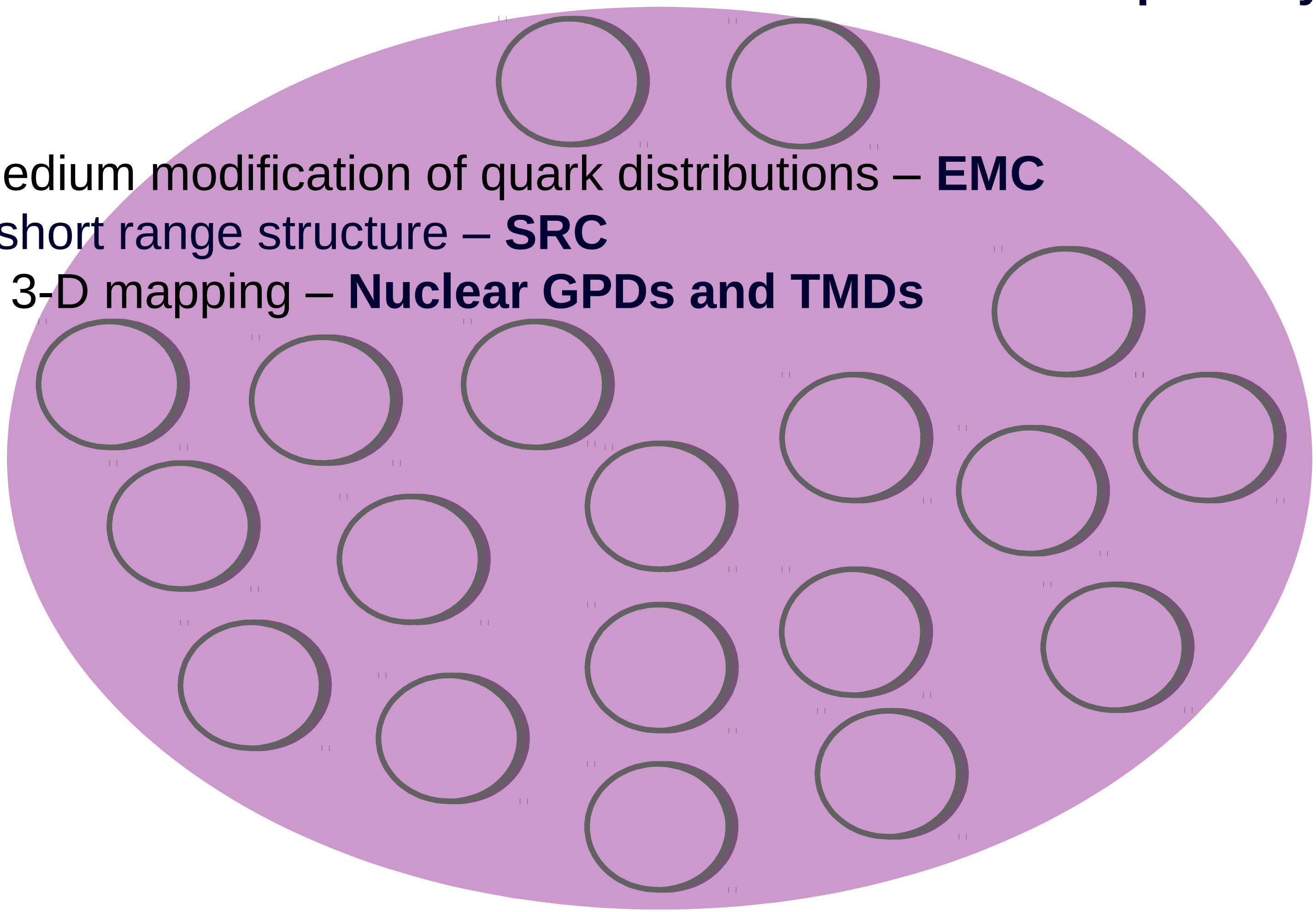


Hard Probe .vs. Medium

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



- Study medium modification of quark distributions – **EMC**
- Access short range structure – **SRC**
- Perform 3-D mapping – **Nuclear GPDs and TMDs**

CT Basics: The Survival of the Smallest !

- Creation of small size configuration (SSC) in hard and exclusive reactions,

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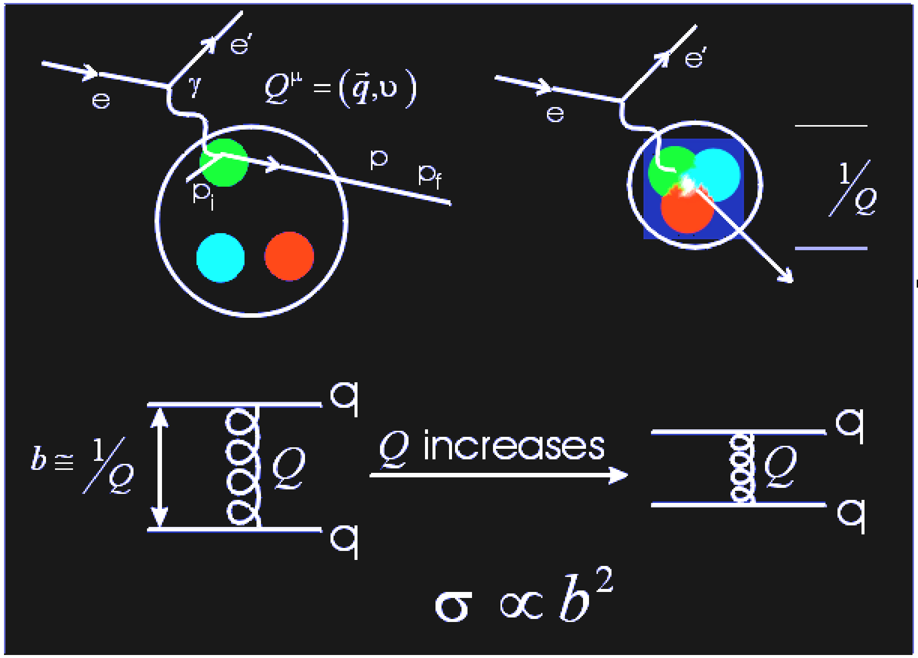
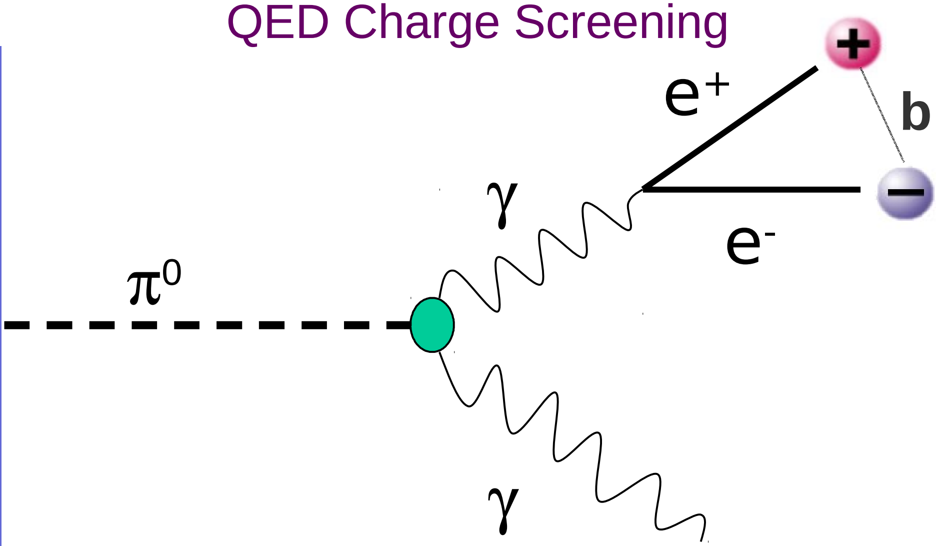
QCD Color Screening



QED Charge Screening



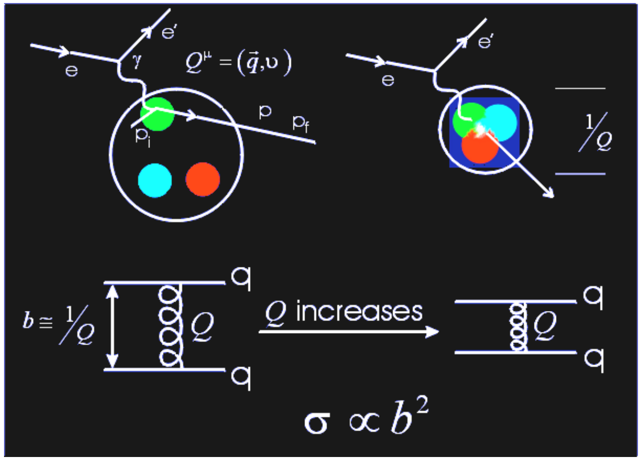
200 GeV π^0 emulsion produced in cosmic rays (Perkins 1955)

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

CT Basics: The Survival of the Smallest!

- Creation of Small Size Configuration (SSC) in hard and exclusive reactions,
- SSC experiences reduced attenuation before evolving to the fully dressed hadron.

QCD Color Screening



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

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

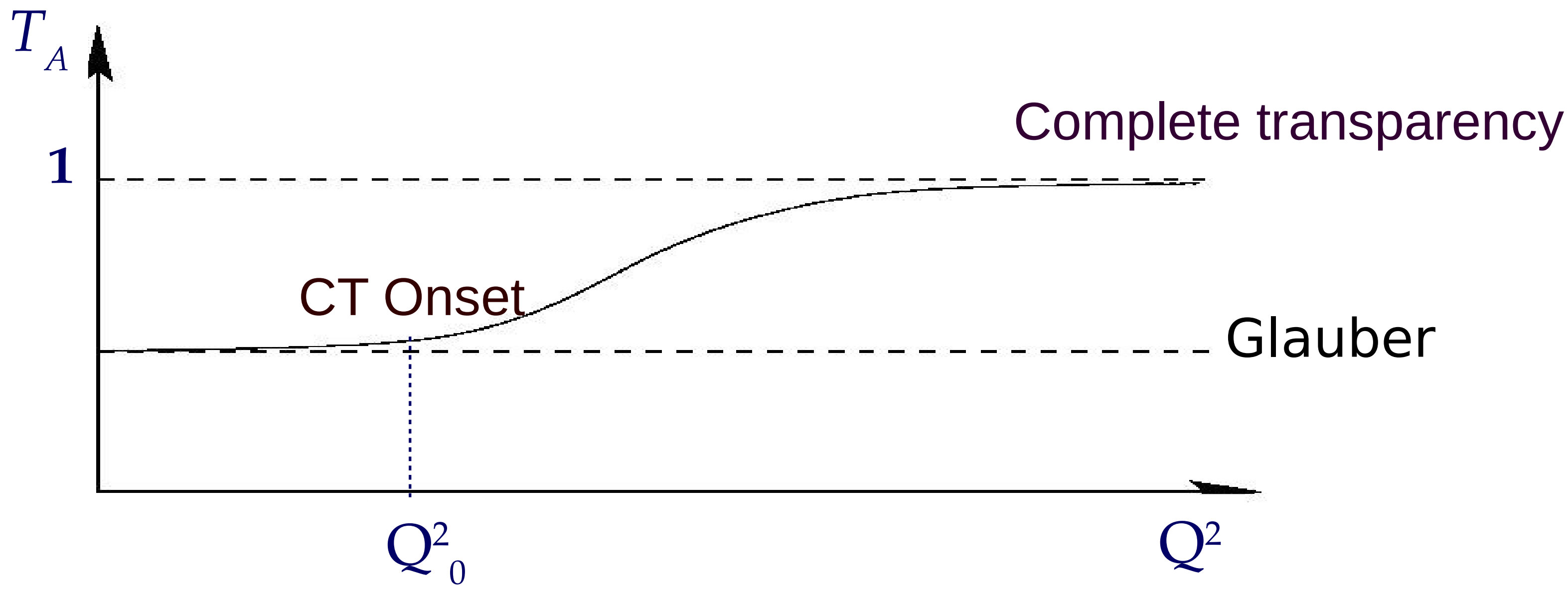
CT Signature

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

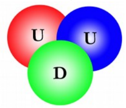
$$T_A = \frac{\sigma_A}{A\,\sigma_N}$$

σ_A is the nuclear cross section

σ_N is the free (nucleon) cross section



Baryon



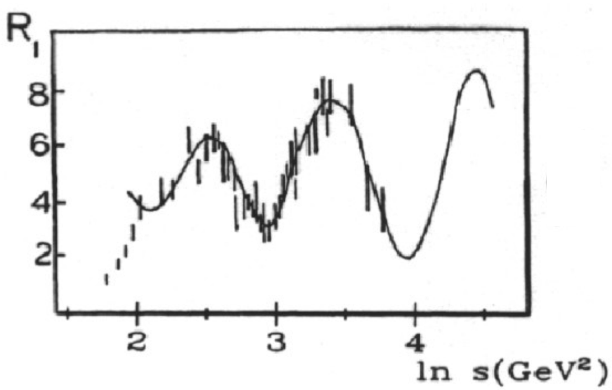
- A(p, 2p) BNL
- A(e, e′p) SLAC and JLab

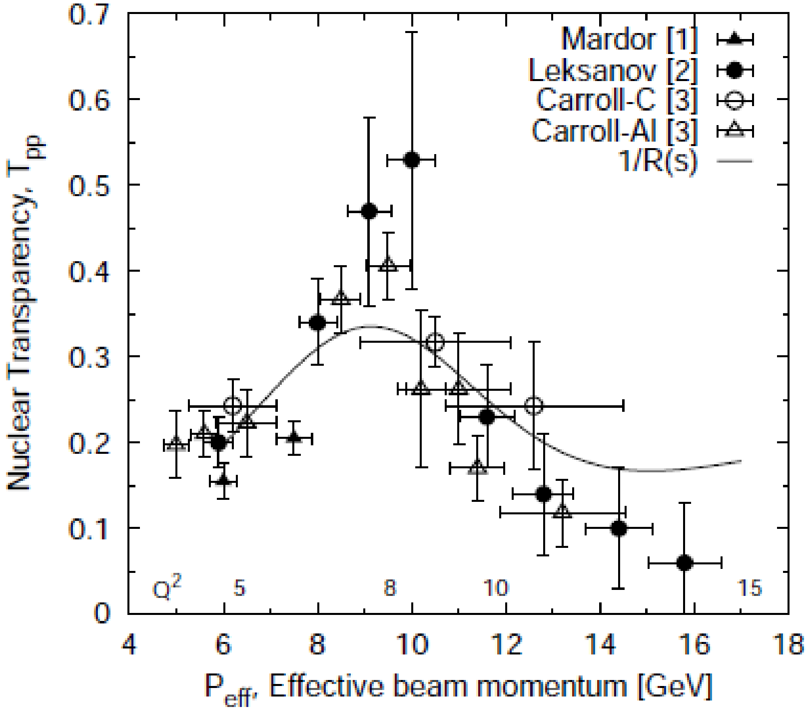
Meson

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

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

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



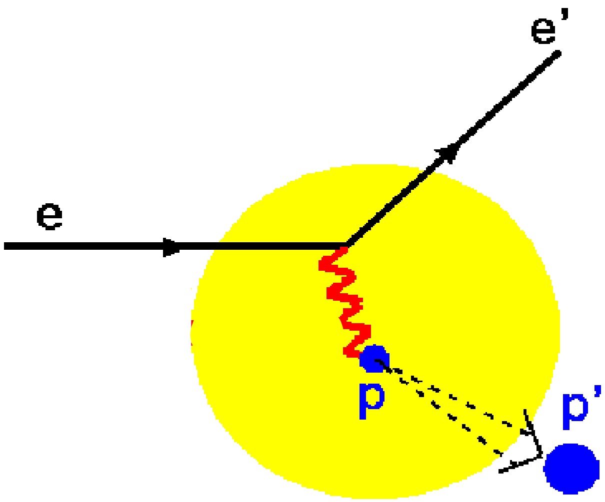


A. Leksanov et al. PRL 87 (2001)
J. L. S. Aclander et al., PRC 70 (2004)

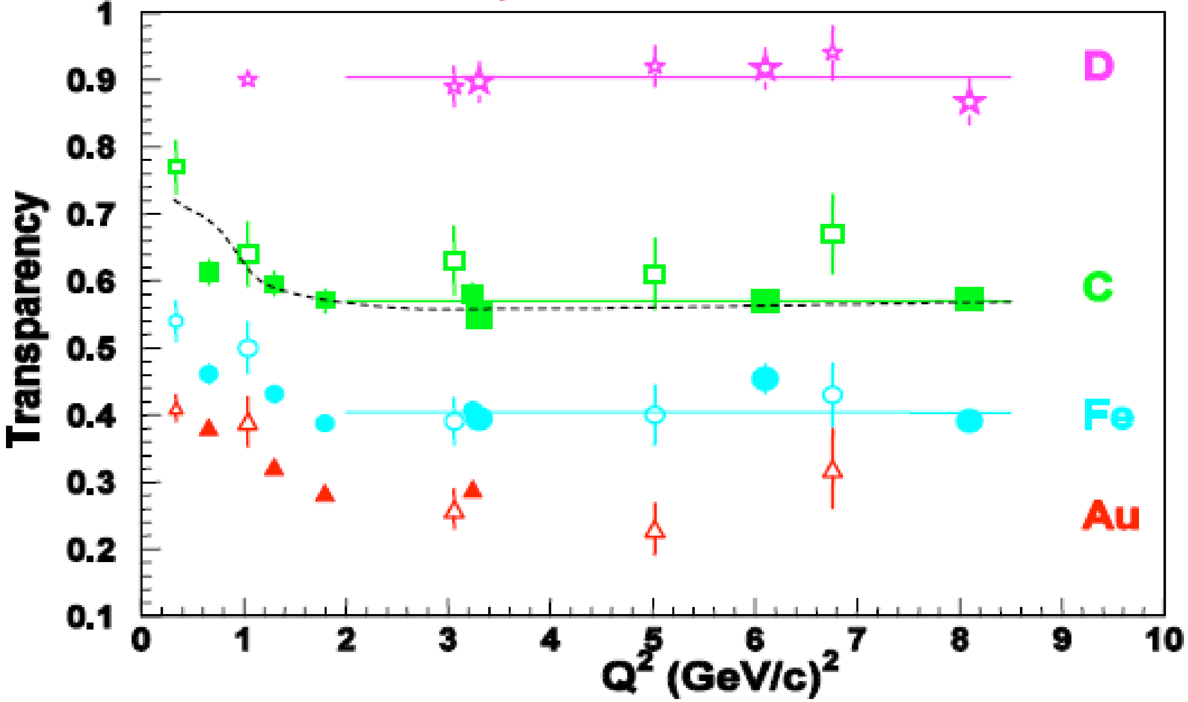
- Initial rise in transparency at low momentum is consistent with CT predictions.
- Subsequent drop at high momentum was explained by:
  - Ralston and Pire as a nuclear filtering of soft amplitudes arising from higher order radiative processes (Landshoff mechanism)
  - Brodsky and De Teramond as a threshold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



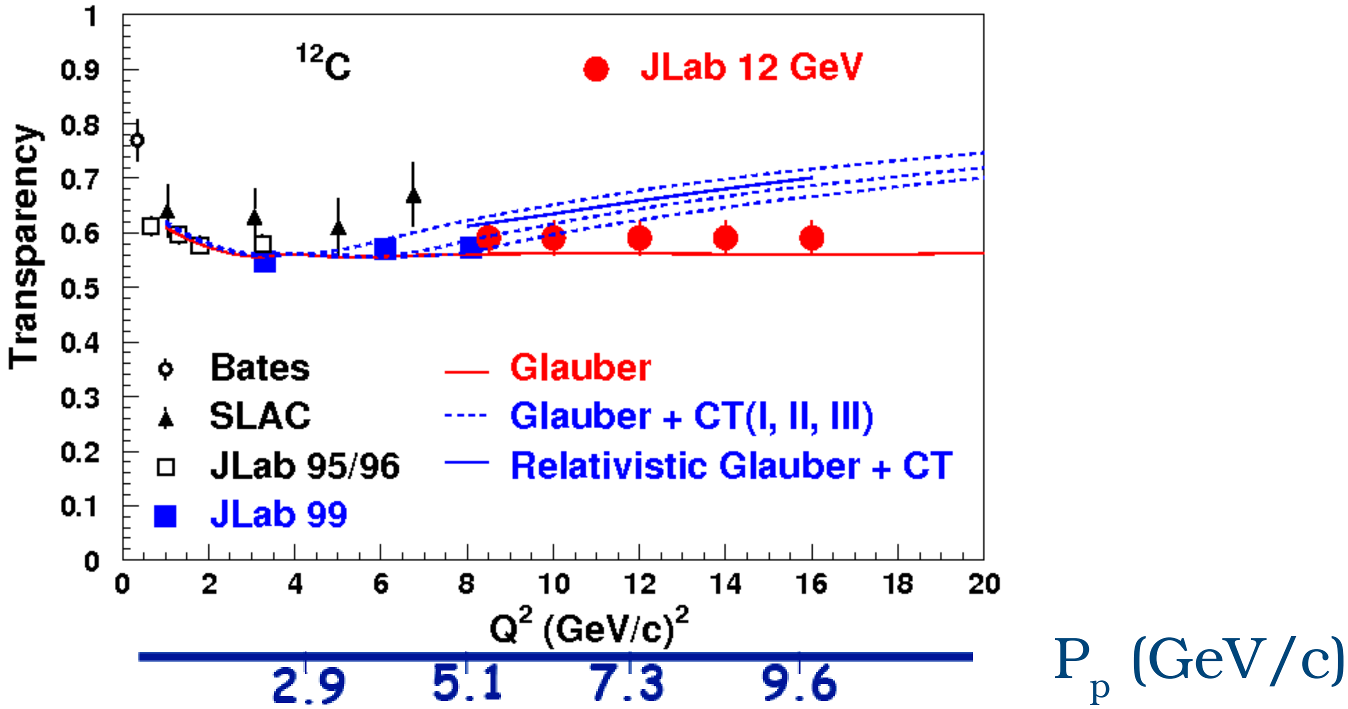
Solid Pts – JLab   Open Pts -- other



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)

11 GeV JLab A(e, e'p) Experiment: Just completed data-taking

- Experiment E12-06-107: Spokespersons - D. Dutta & R. Ent
- Ran only A(e,e'p) portion of the experiment - 3.5 days @ 8.8 GeV & 6.5 days @ 11 GeV beam energy (total 10 days).
- Measure the A(e,e'p) proton knockout cross sections to extract the proton nuclear transparency for 5 Q^2 bins (8, 10, 12, 14 & 16.4 $(GeV/c)^2$).
- Help interpret the rise seen in the BNL A(p, 2p) data at P_p = 6 – 9.5 GeV/c.
- Search for the onset of CT in three quarks system.



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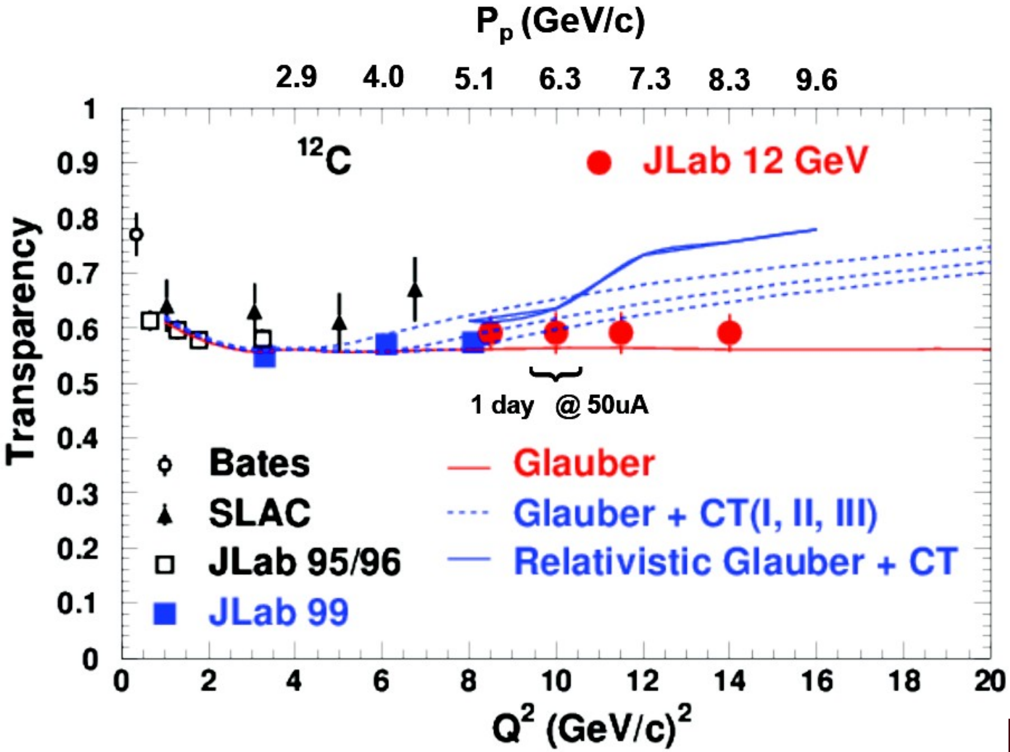

- 4 Q^2 points are completed.
- Need 1 day at high currents to complete the highest Q^2 point.

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.**

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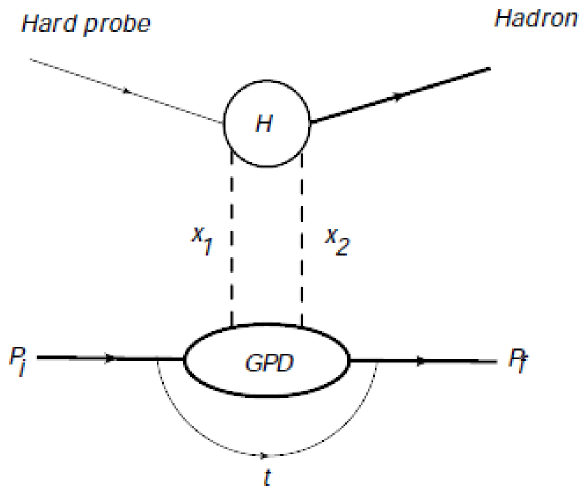
- **Onset of CT is expected at lower Q^2 in qq-bar system.**

- **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.

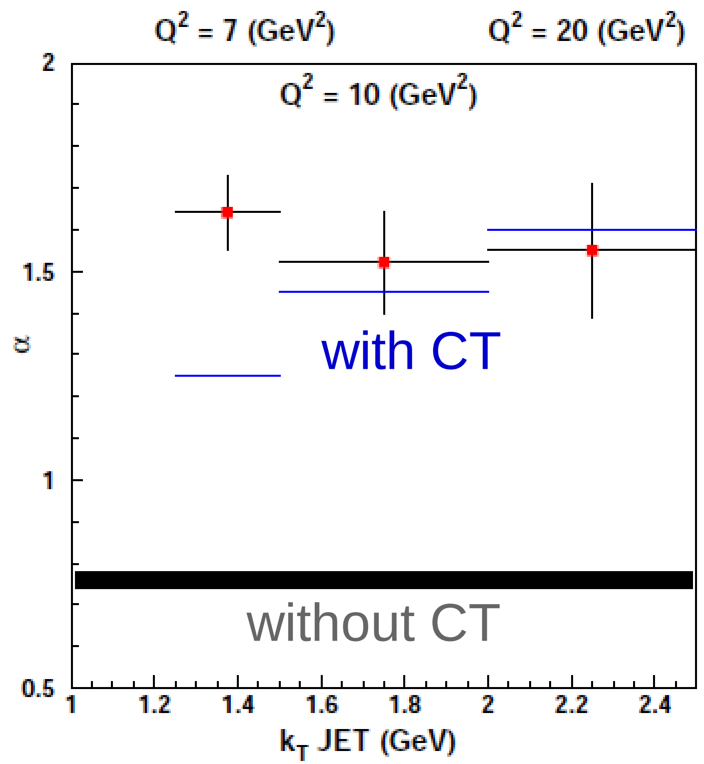
Collins, Frankfurt, Miller, Sargsian and Strikman



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

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)

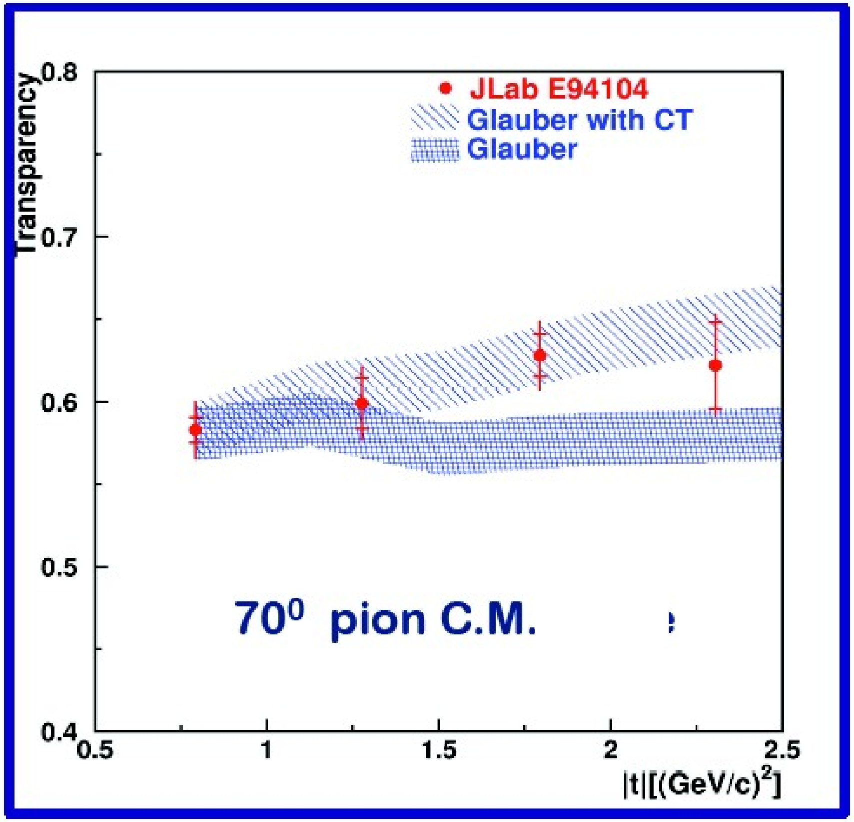


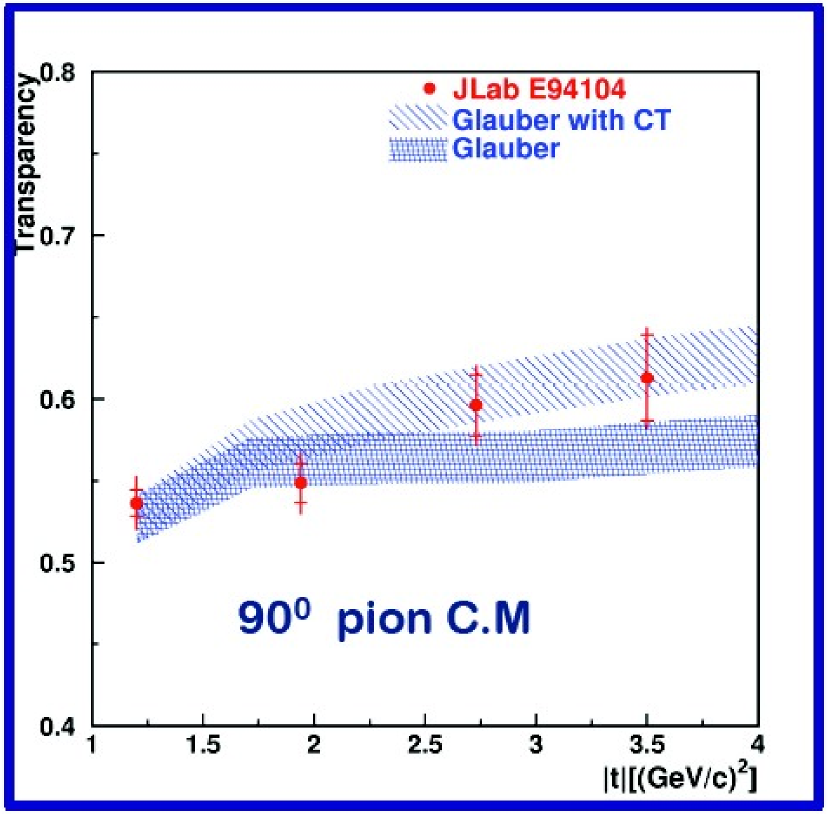
Aitala et al., PRL 86, 4773 (2001)

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 $1\sigma(2\sigma)$ for $70^o(90^o)$ pion center-of-mass (CM) angle.

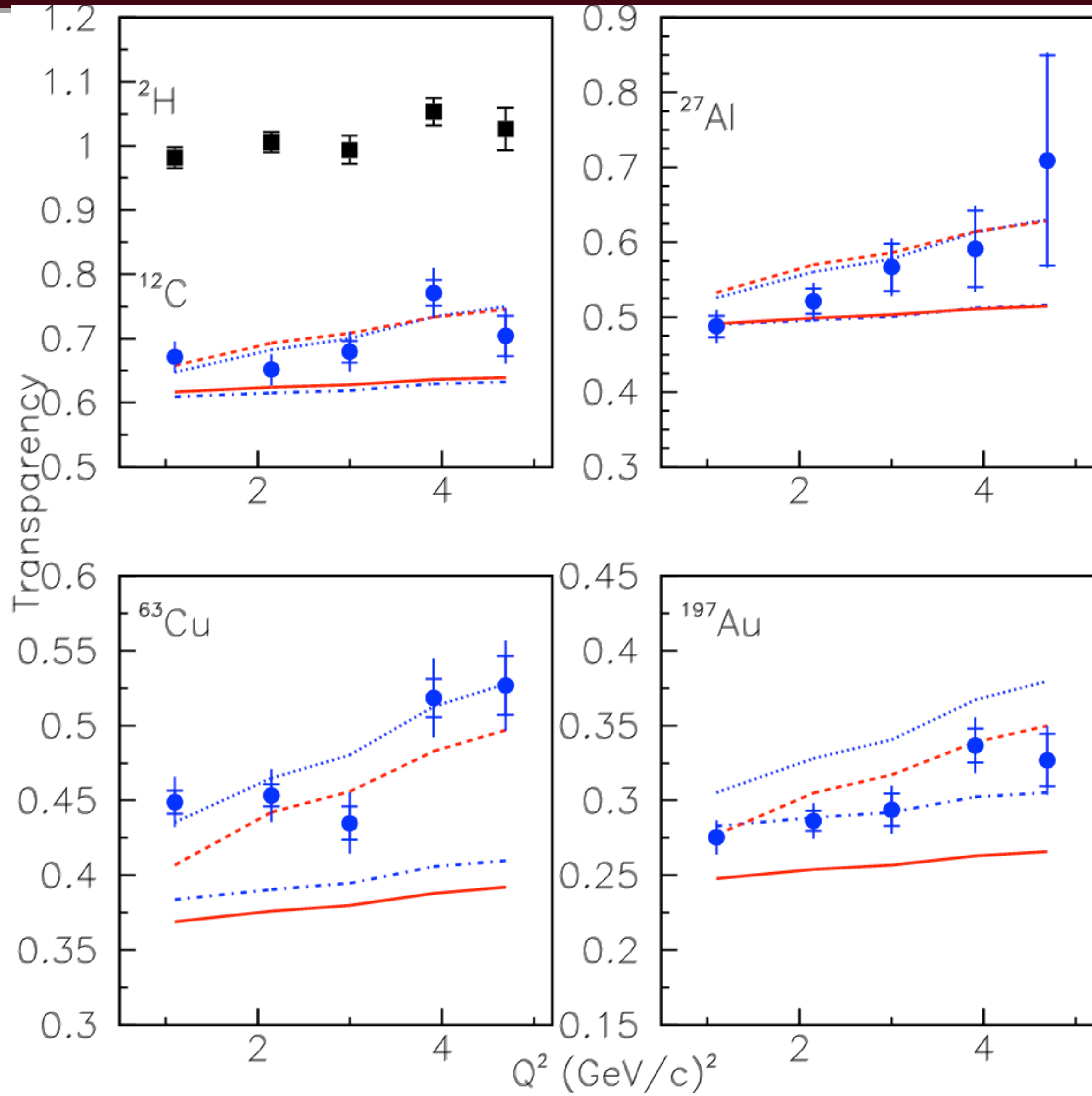
$$(\gamma + {}^4\mathrm{He} \rightarrow \pi^- + p + X)\ /\ (\gamma + D \rightarrow \pi^- + p + p)$$





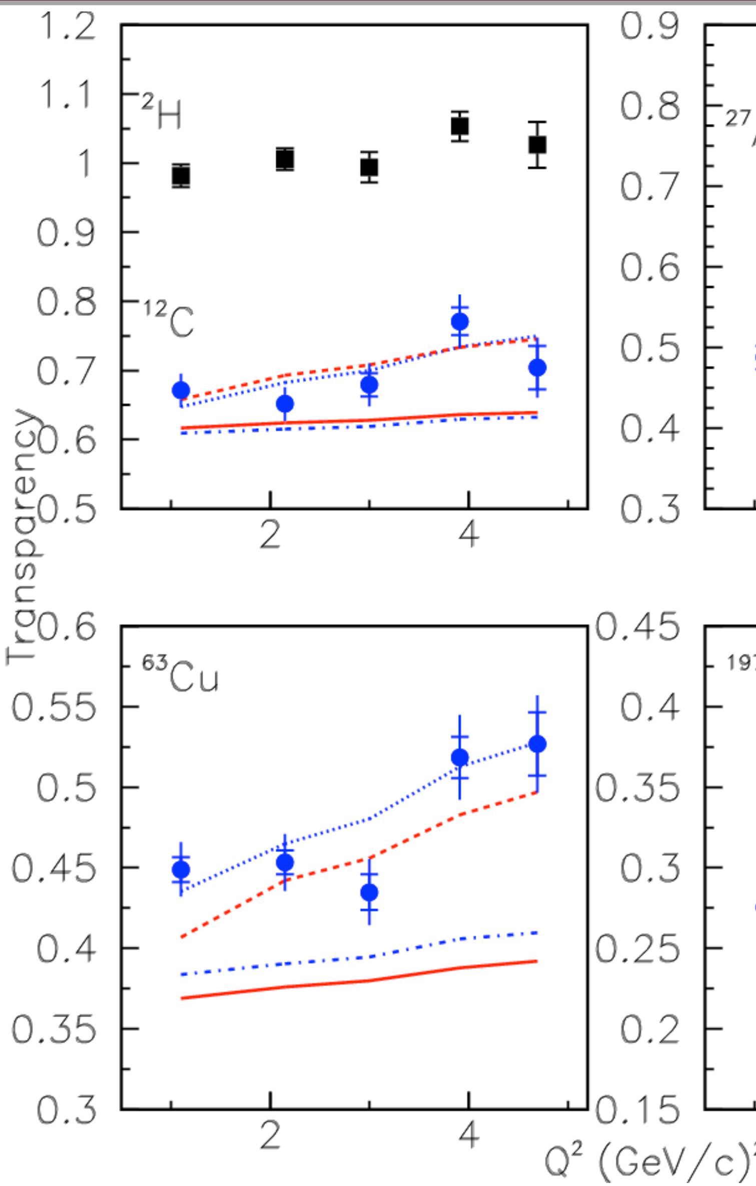
Dutta et al. PRC 68, 021001R (2003)
Gao et al. PRC 54, 2779 (1996)

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

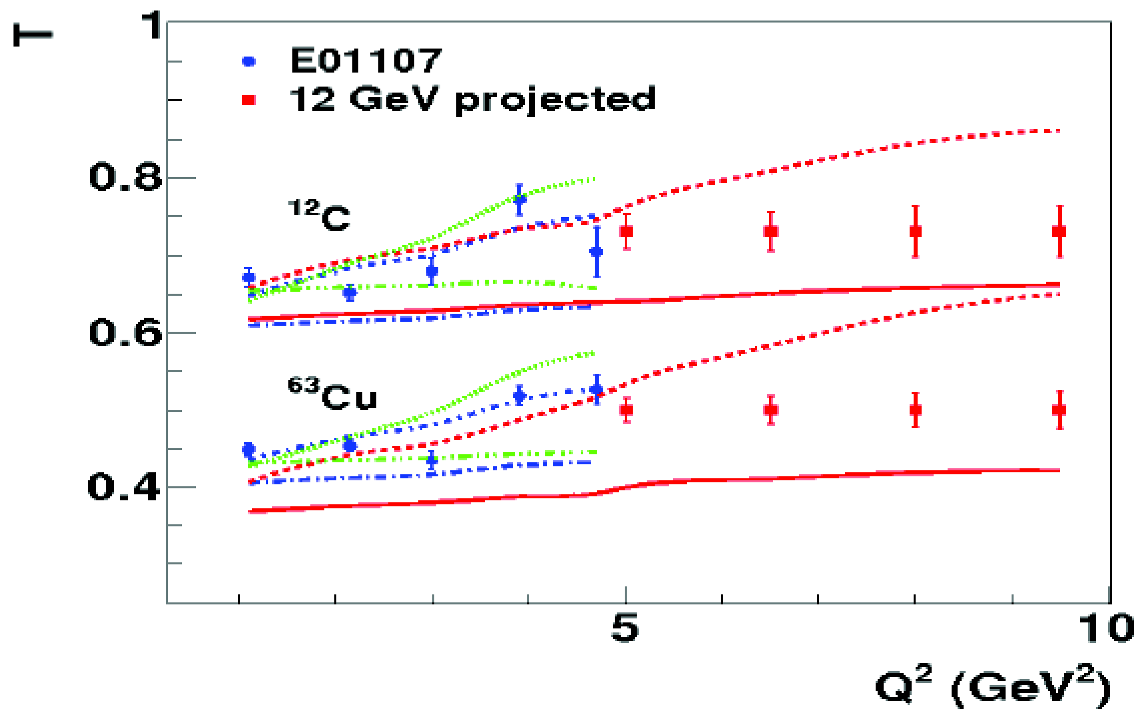


B. Clasie et al. PRL 90, 10001 (2007), X. Qian et al., PRC 81, 055209 (2010)

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

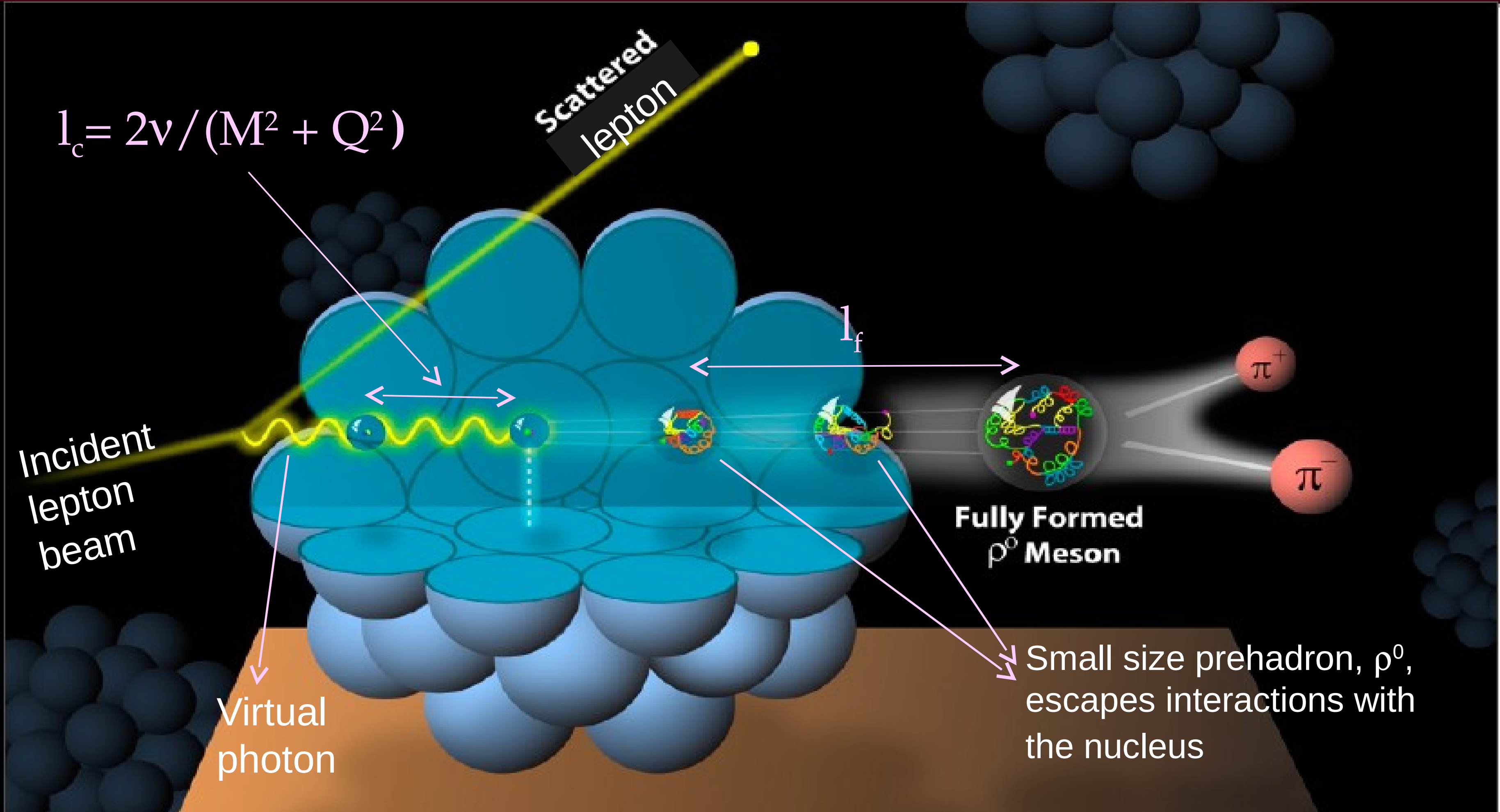


These measurements will be extended to Q^2 of about 10 $(GeV/c)^2$ in Hall-C @ 11 GeV beam energy



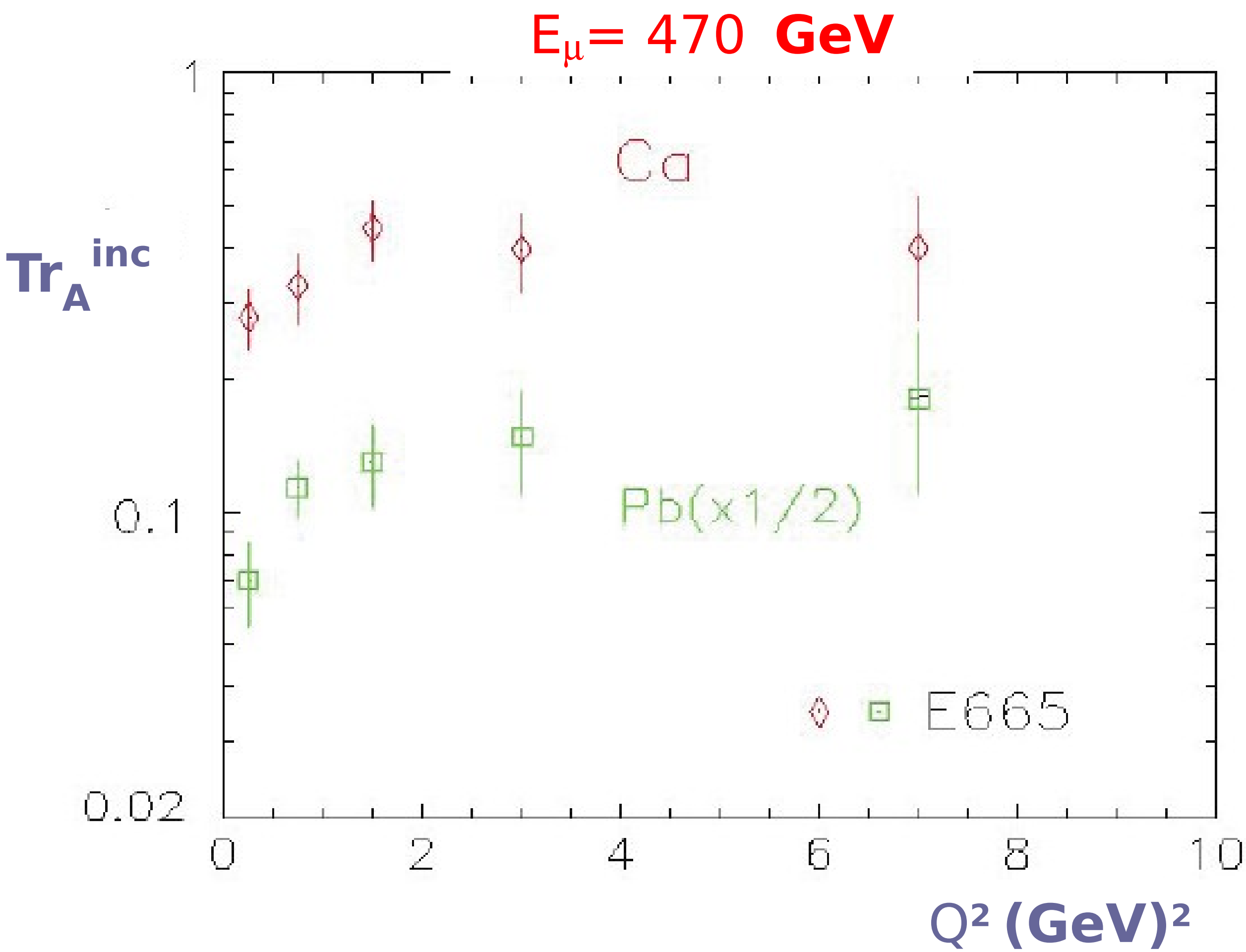
B. Clasie et al. PRL 90, 10001 (2007), X

Exclusive Incoherent ρ^0 Leptoproduction



- Coherence length, l_c, is the lifetime of the **qq-bar** pair.
- Formation length, l_f, is the lifetime of the small size configuration before evolving to a full ρ^0 meson.

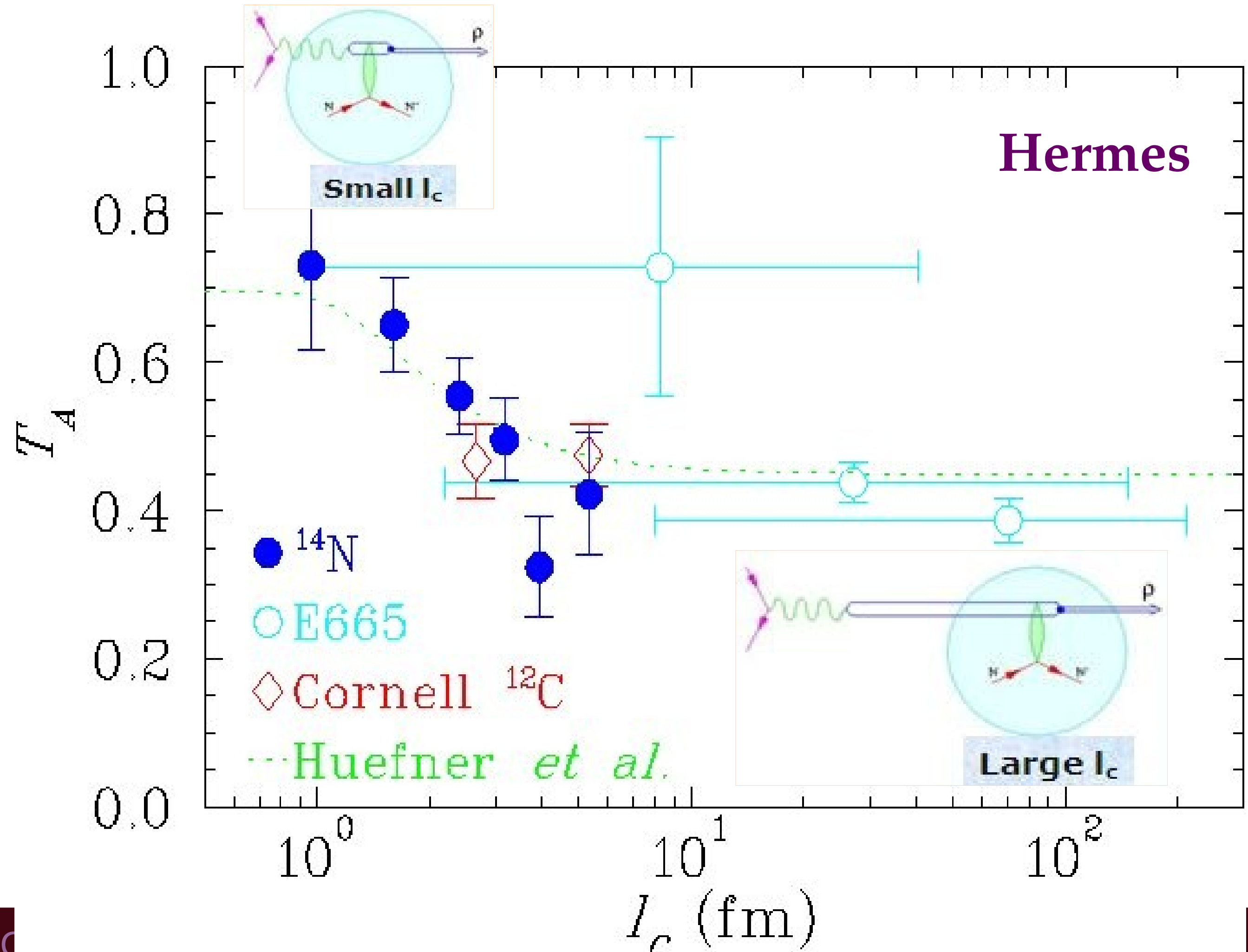
Exclusive ρ^0 Leptoproduction: FNAL 665



Adams et al. PRL 74, 1525 (1995)

Coherence length (CL) effect could mimic CT signal?

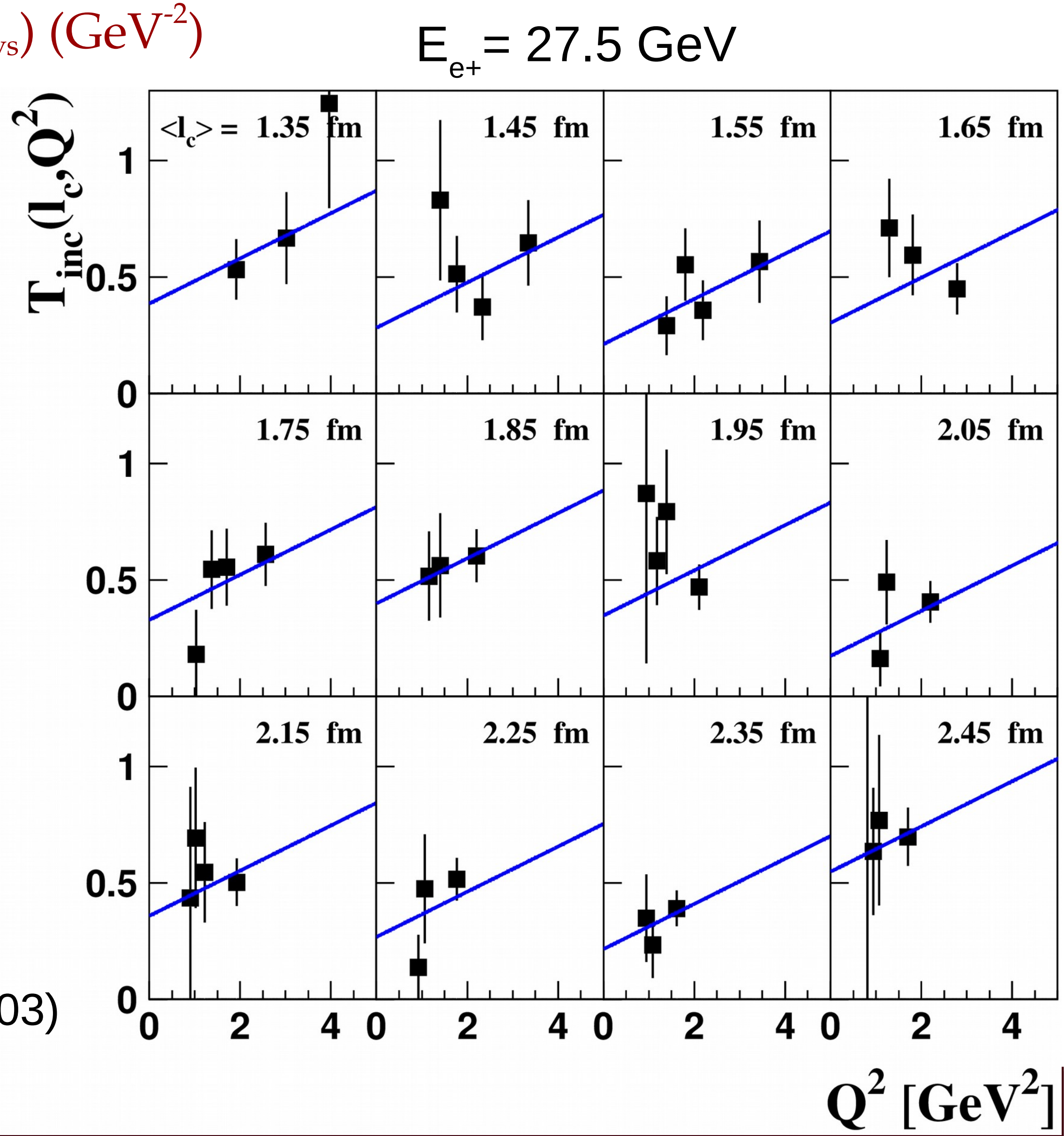
- CT signature is the rise of T_A with Q^2, however, as $l_c = 2\nu/(M^2 + Q^2)$, the CL effect leads also to T_A increase with Q^2.
- **To exclude CL, the Q^2 dependence of T_A must be measured at small or fixed l_c.**



Exclusive ρ^0 Leptoproduction: Hermes

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

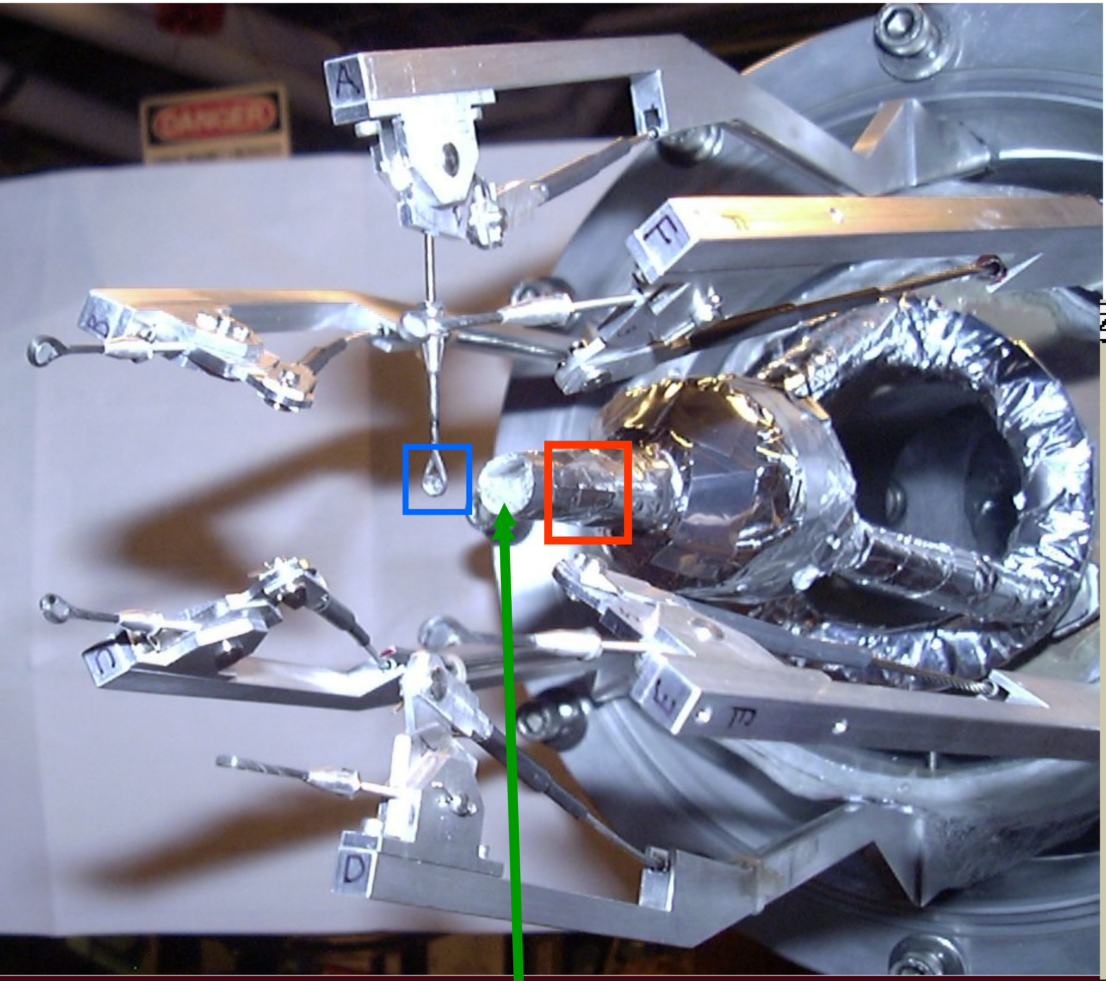
  $P_1 = (0.089 \pm 0.046_{stat} \pm 0.008_{sys})\ (\mathrm{GeV}^{-2})$

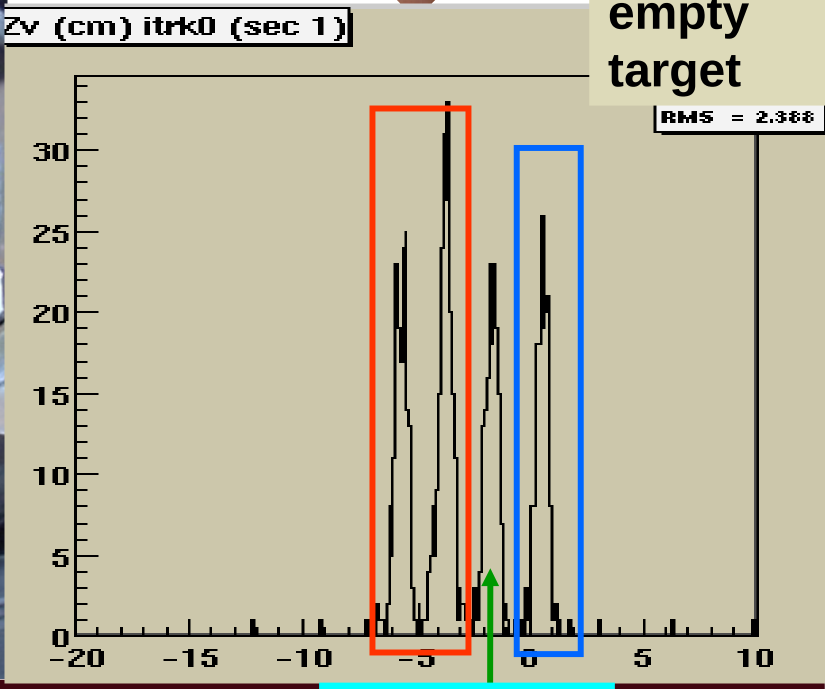


Airapetian et al. PRL 90, 052501 (2003)

Exclusive Diffractive ρ⁰ Electro-production

EG2 run-group targets

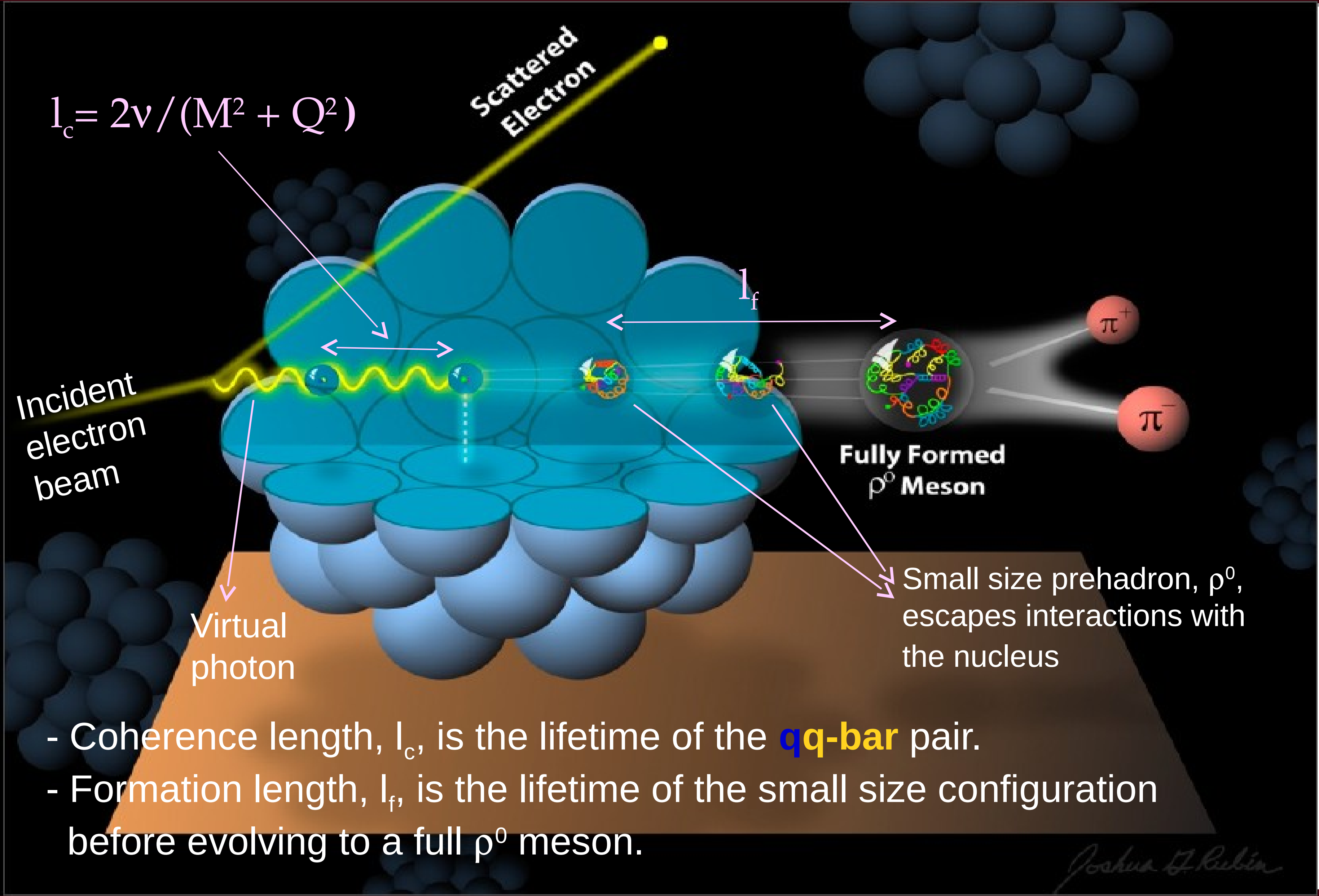




Al + empty target

Reference Foil

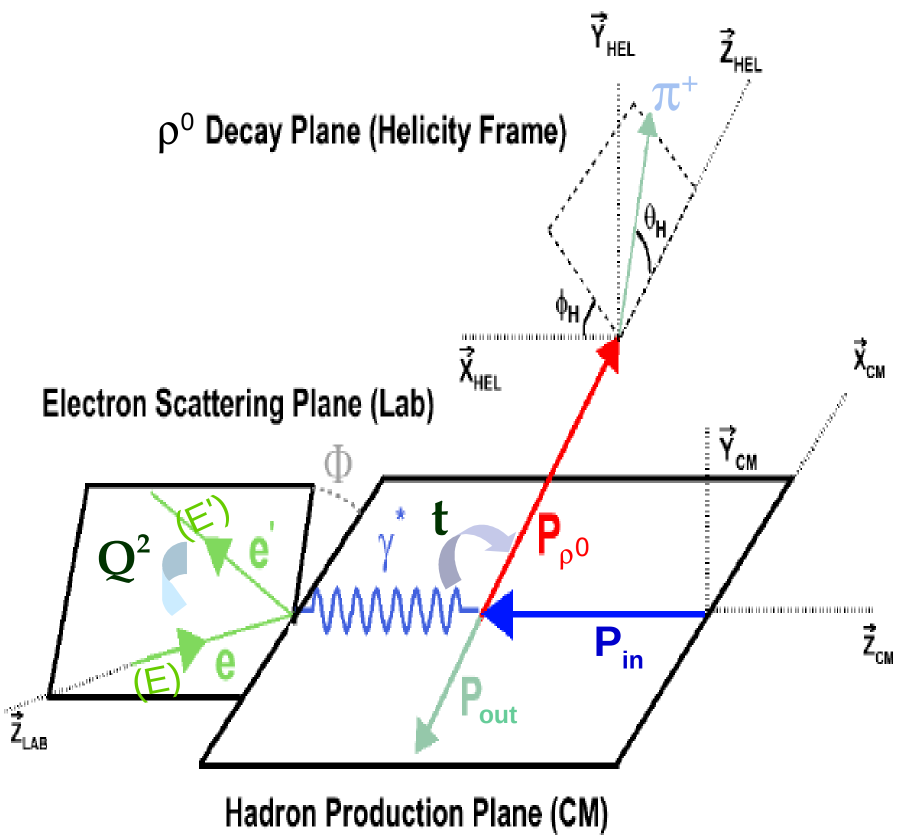
CT study using 4 & 5 beam energies @ CLAS



- Coherence length, l_c, is the lifetime of the **qq-bar** pair.
- Formation length, l_f, is the lifetime of the small size configuration before evolving to a full ρ^0 meson.

ρ^0 Electro-production Kinematics

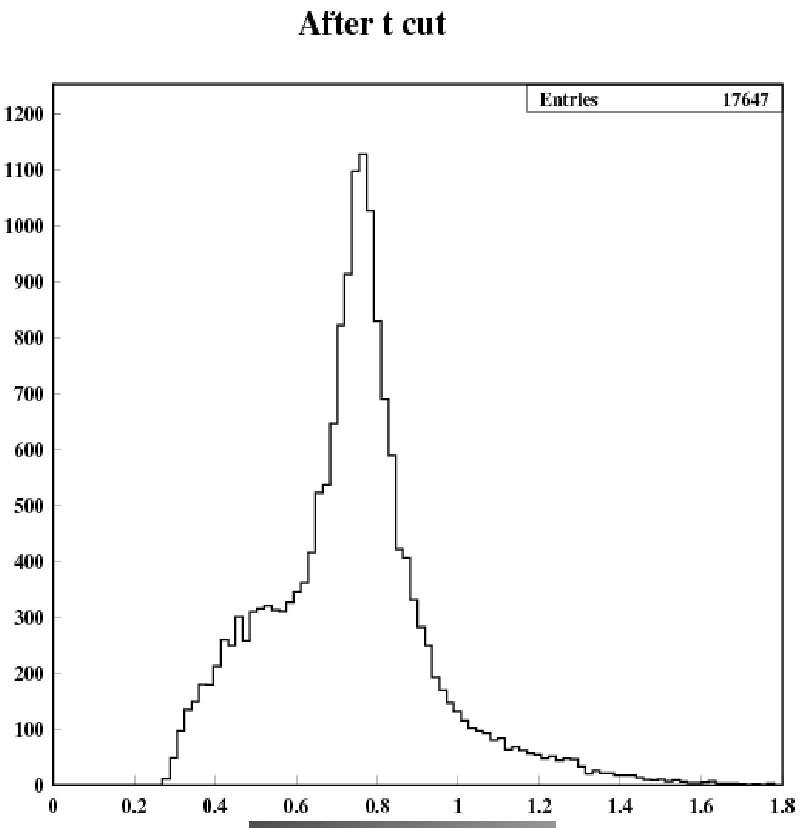
- $\nu = E - E'$: virtual photon (γ^*) energy in the Lab frame,
- $Q^2 = -(P^\mu_e - P^\mu_{e'})^2 = 4\, E\, E' \sin^2(\theta/2)$: photon virtuality,
- $t = (P^\mu_{\gamma^*} - P^\mu_\rho)^2$: momentum transfer square,
- $W^2 = (P^\mu_{in} + P^\mu_{\gamma^*})^2 = -Q^2 + M_p^2 + 2M_p\nu$: invariant mass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



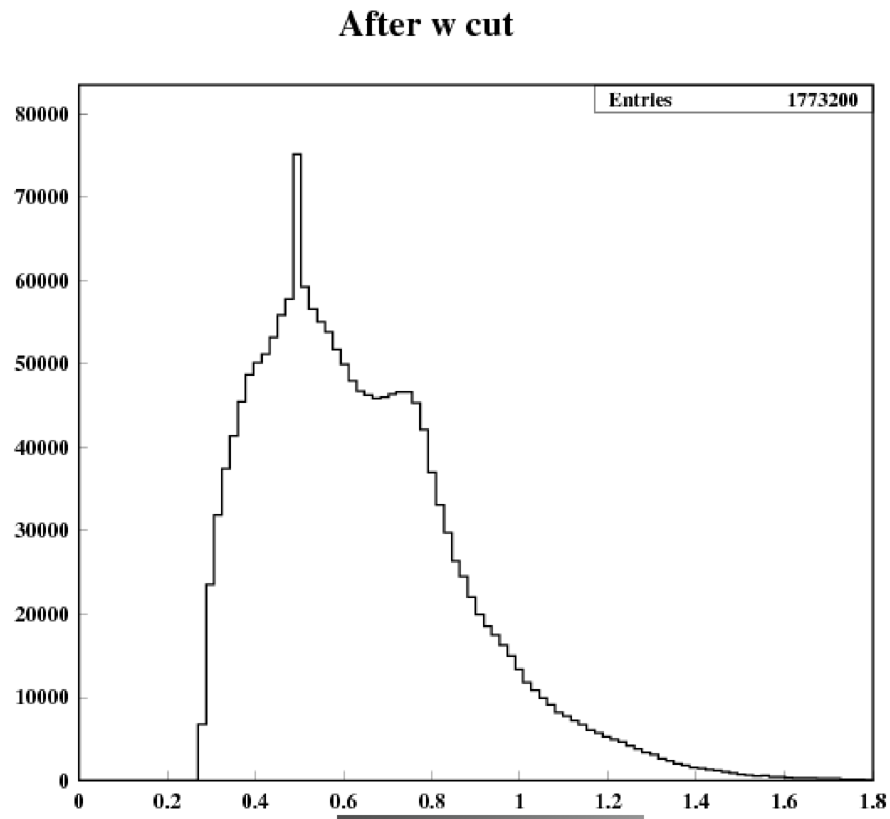
- **W ≥ 2 GeV**
  ⇒ avoid resonance region
- **-t < 0.4 GeV²**
  ⇒ select diffractive process
- **-t > 0.1 GeV²**
  ⇒ exclude coherent production
- $Z_h = E_h/\nu \geq 0.9$
  ⇒ select elastic or exclusive channel

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

Iron



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



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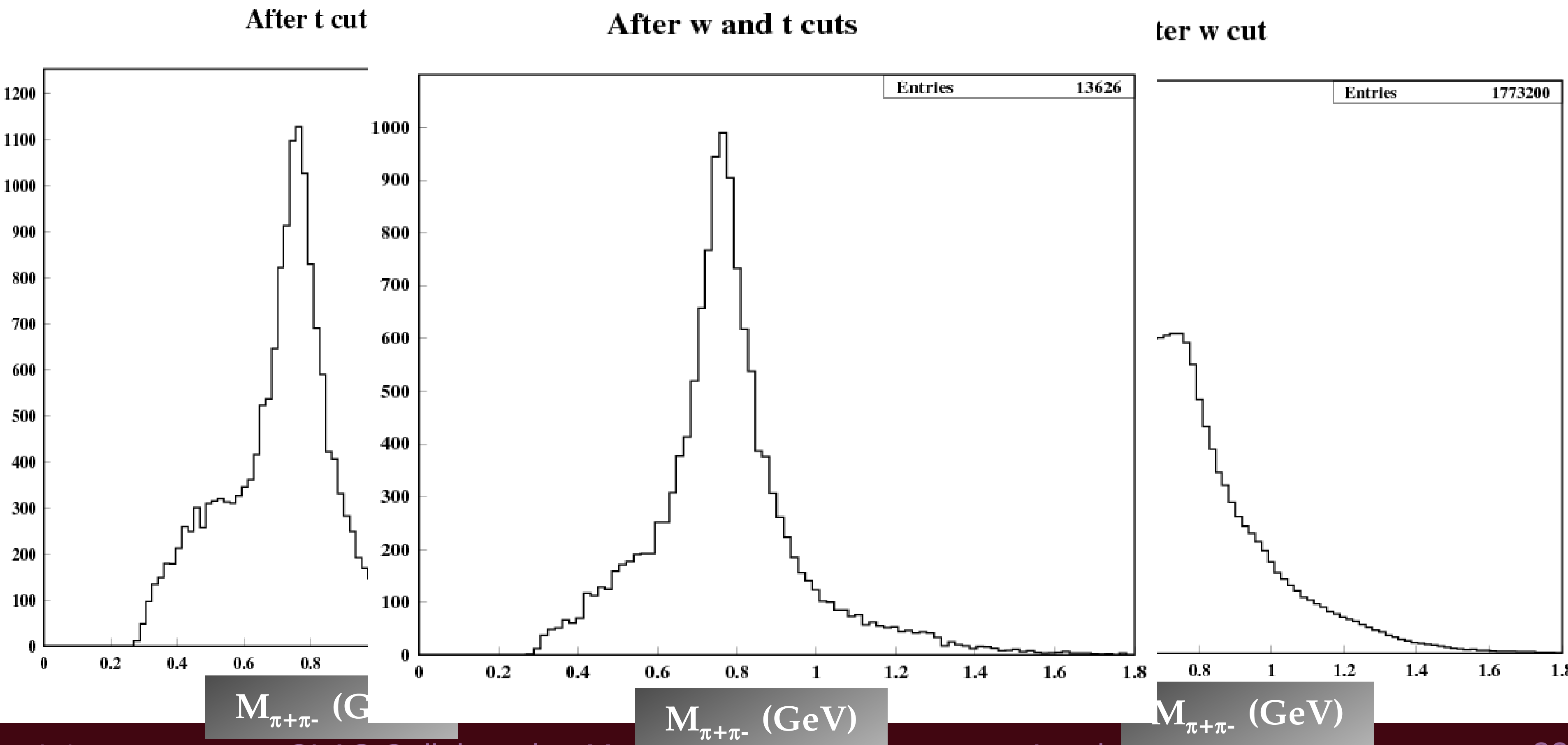
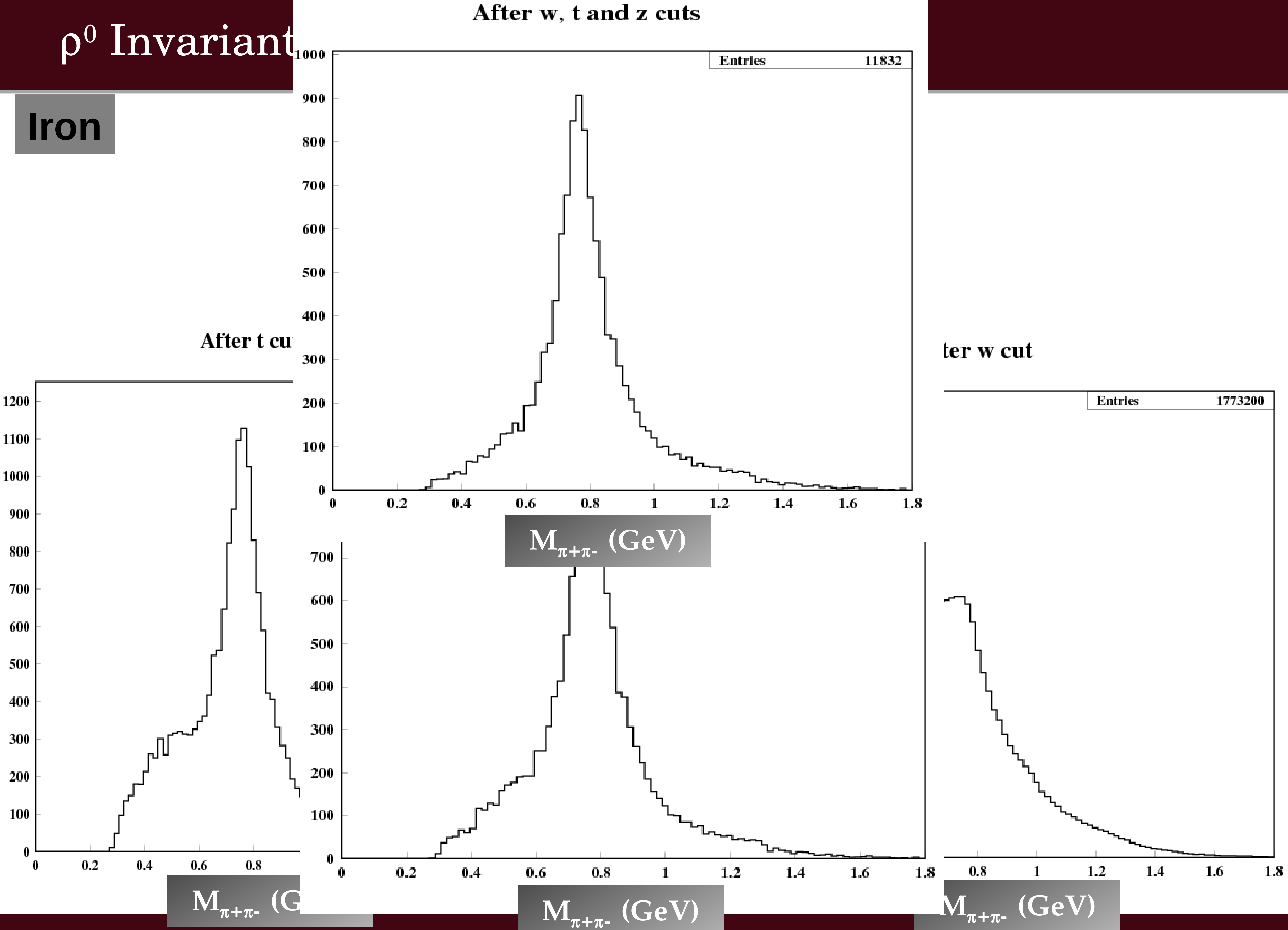


ρ^0 Invariant

Iron



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

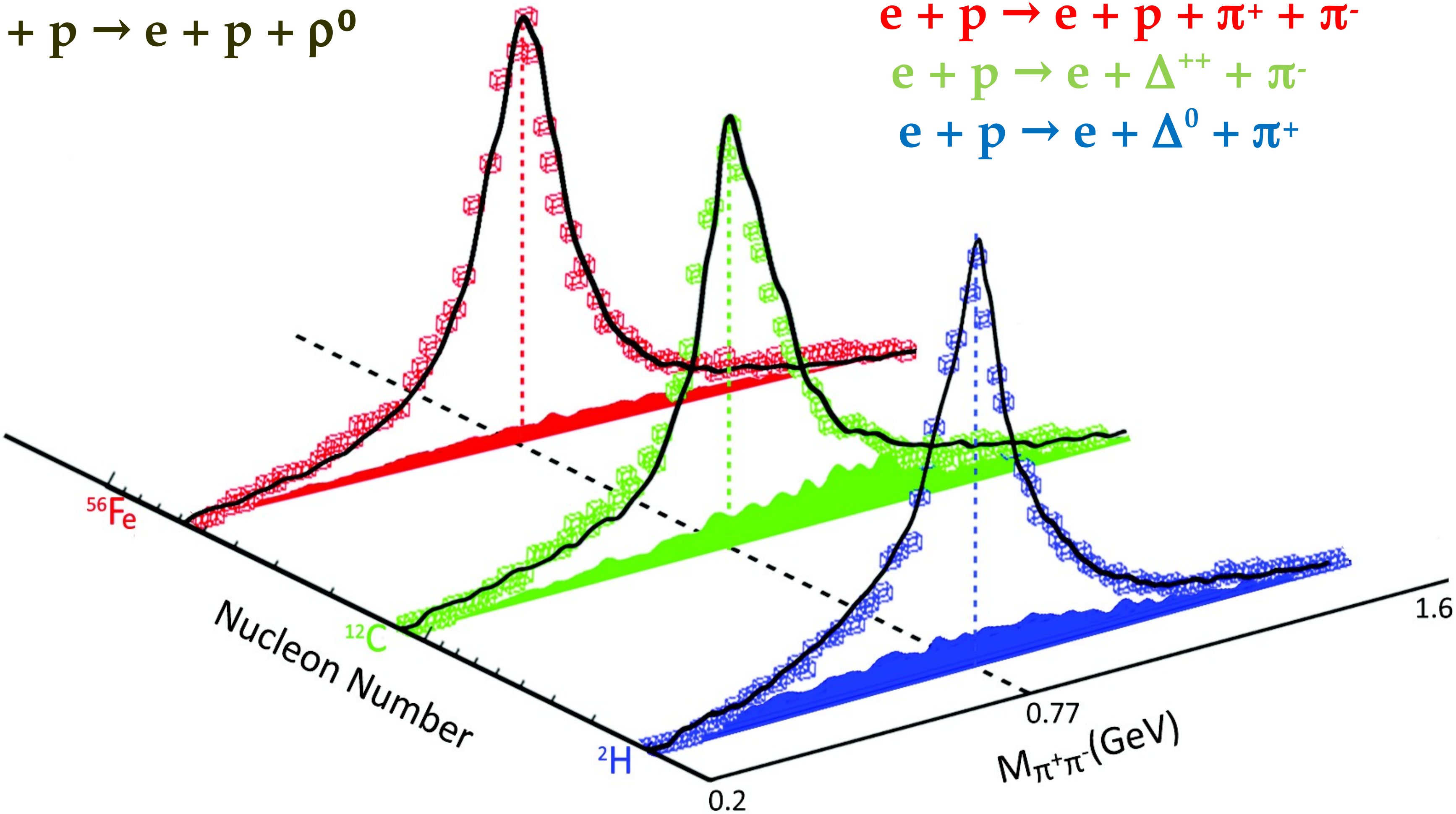
$e + p \rightarrow e + p + \rho^0$

Simulated Background's Shapes

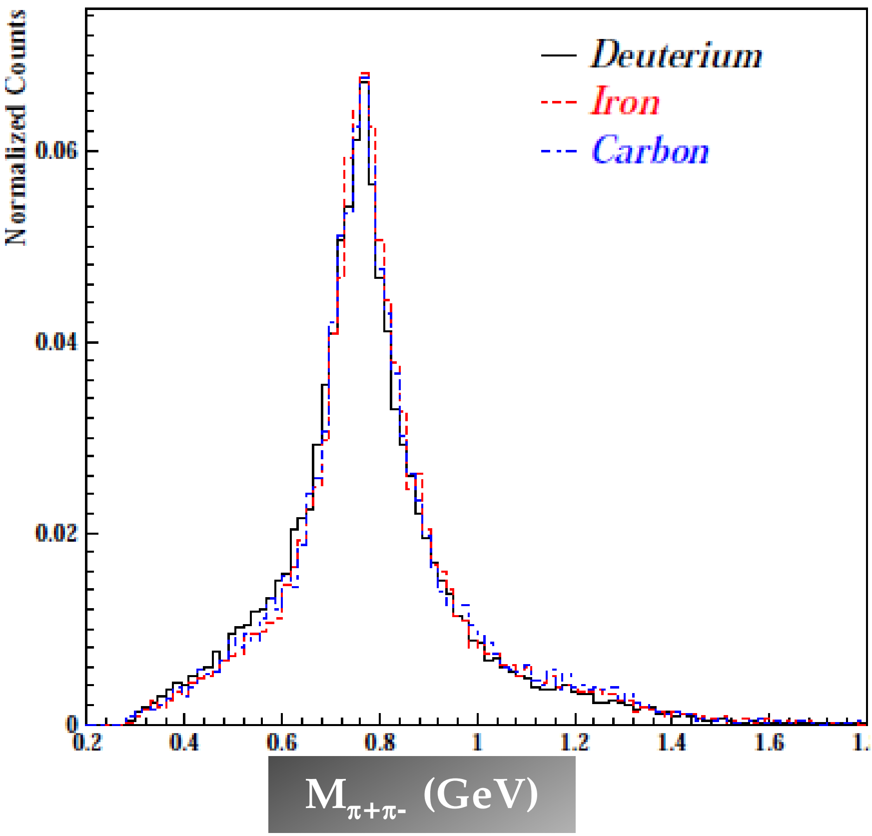
$e + p \rightarrow e + p + \pi^+ + \pi^-$

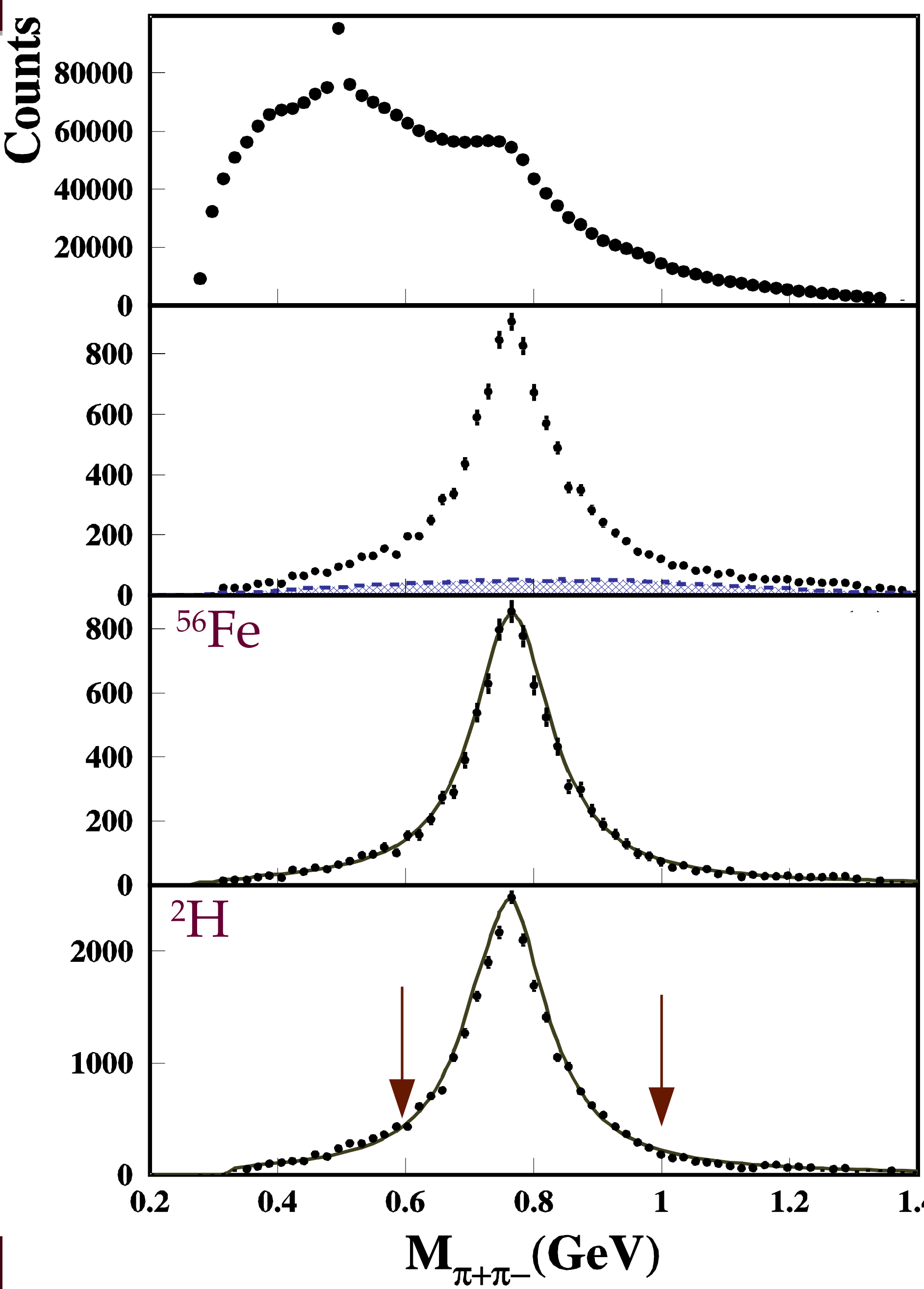
$e + p \rightarrow e + \Delta^{++} + \pi^-$

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



Two pions invariant mass

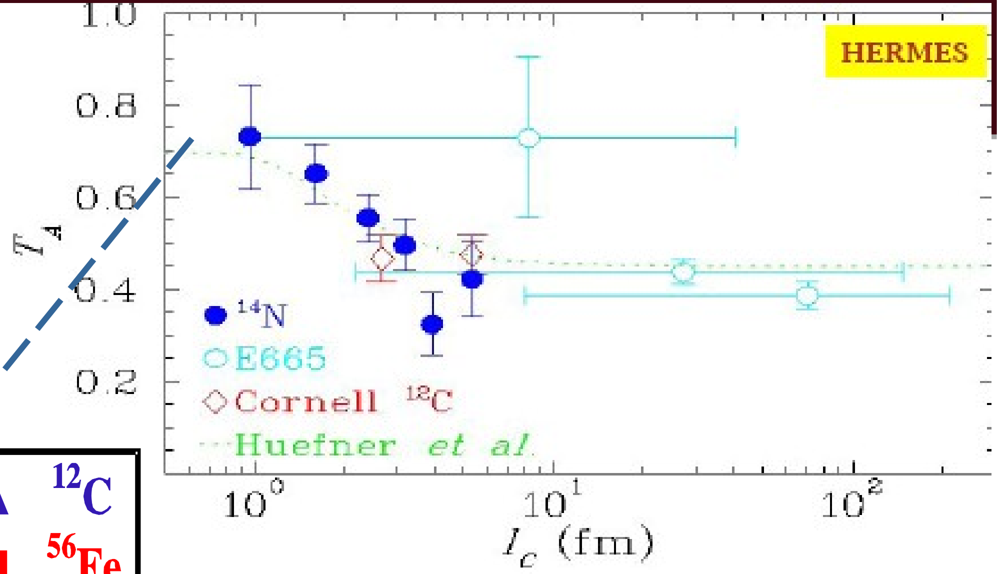


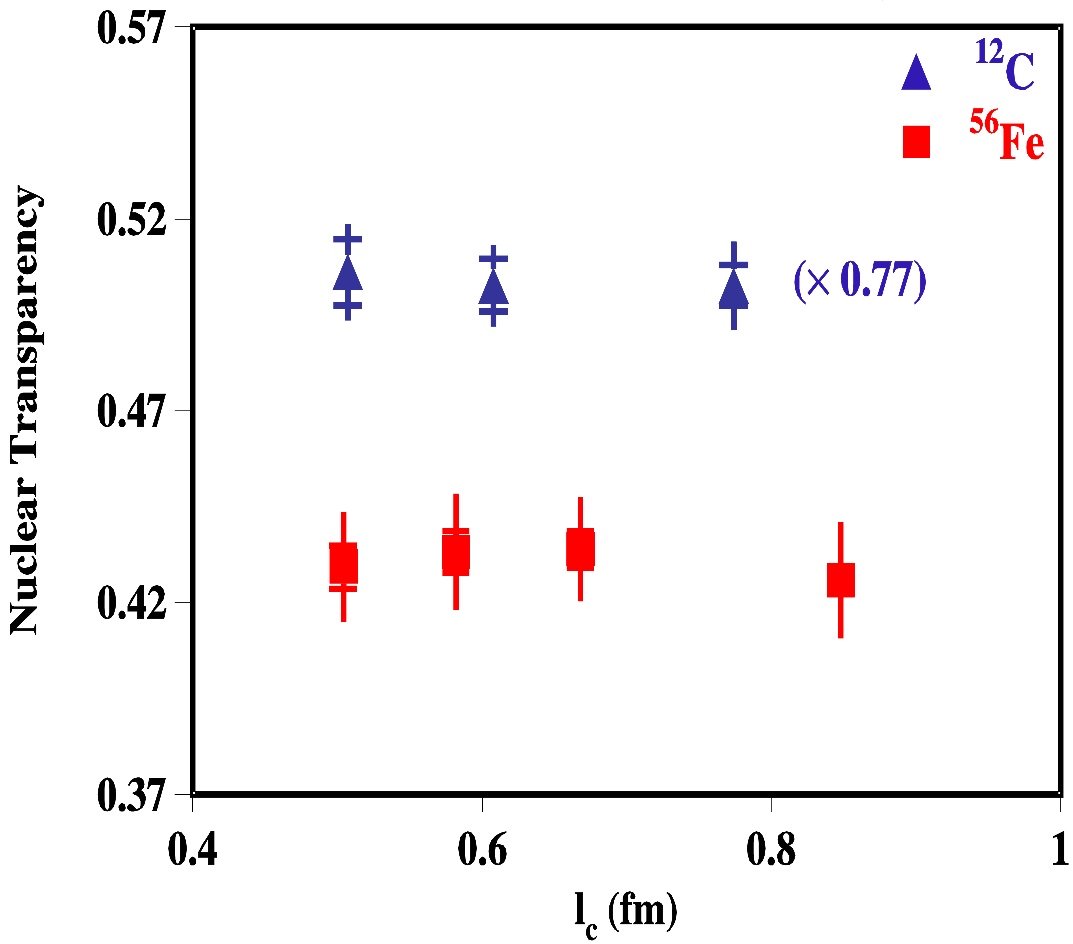


l_c Dependence of T_A

Coherence Length

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





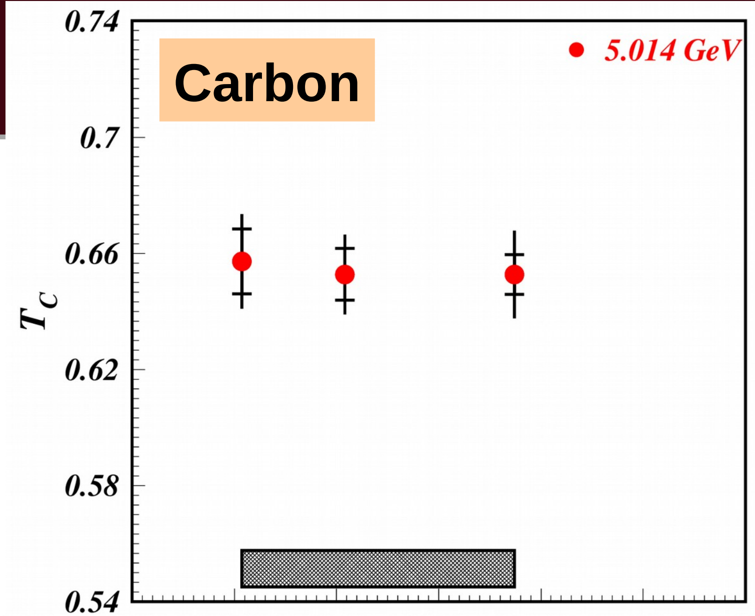
Nuclear Transparency

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

- 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

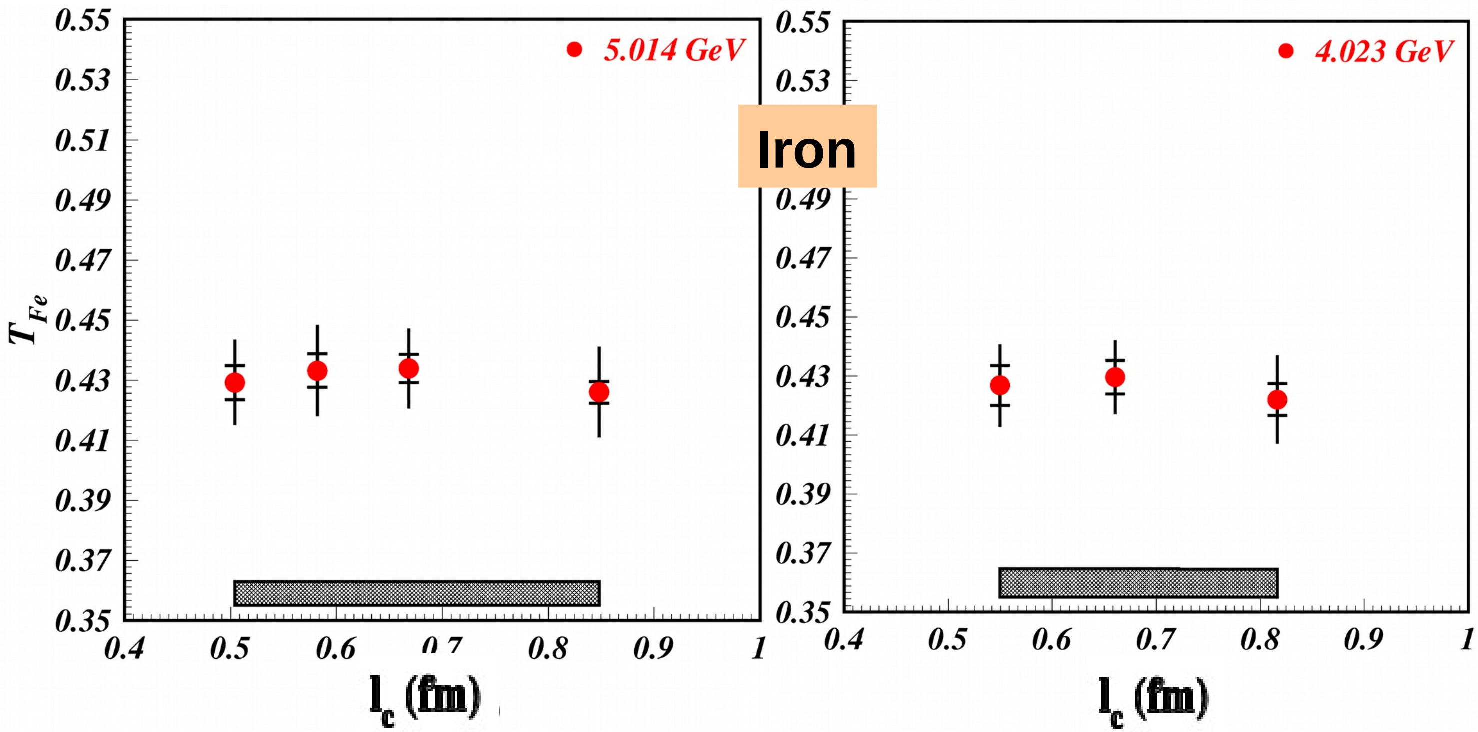
l_c Dependence of T_A of EG2 datasets



Nuclear Transparency

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

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



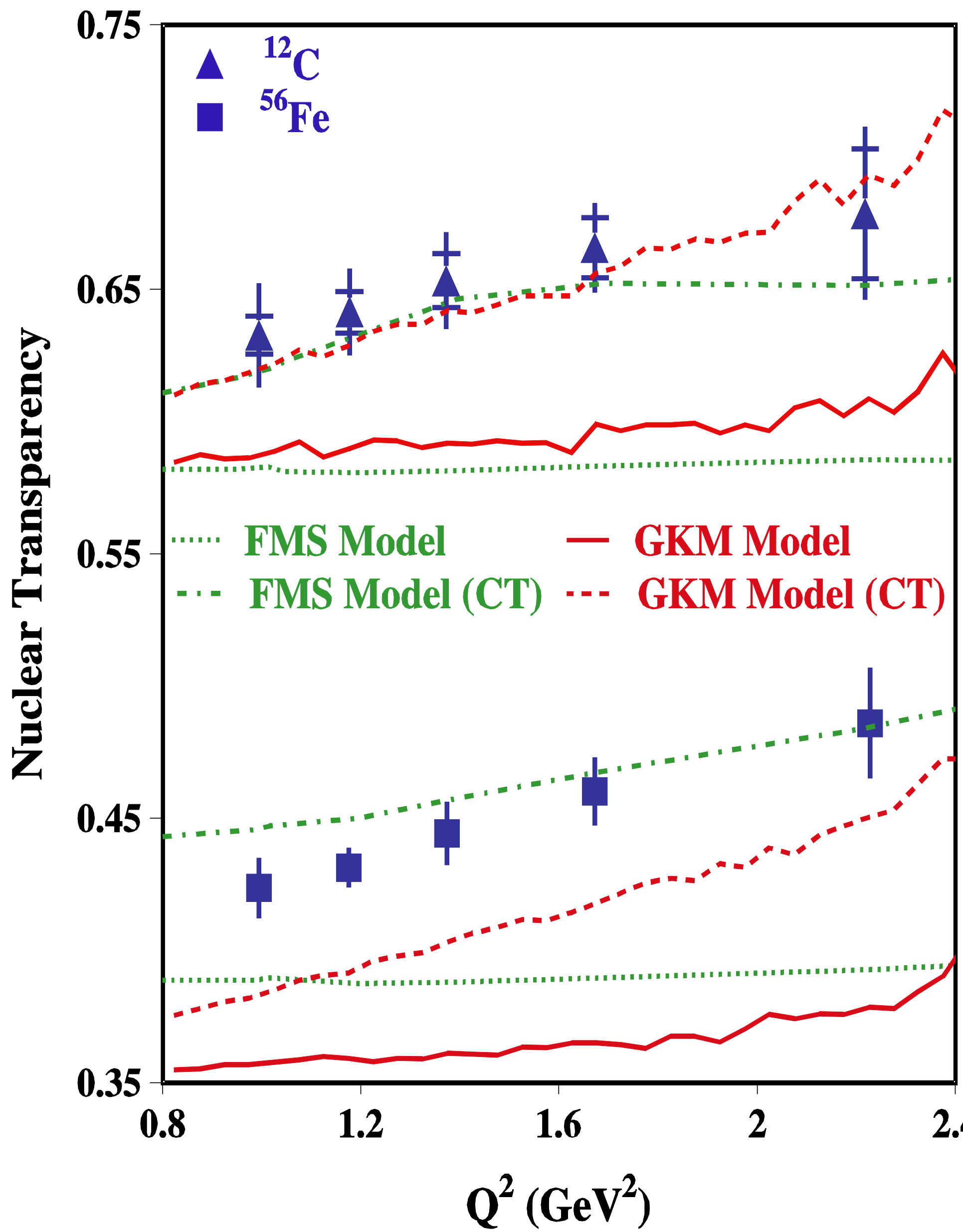
ρ^0 CT Results for 5 GeV Iron & Carbon datasets

- **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 communication

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

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



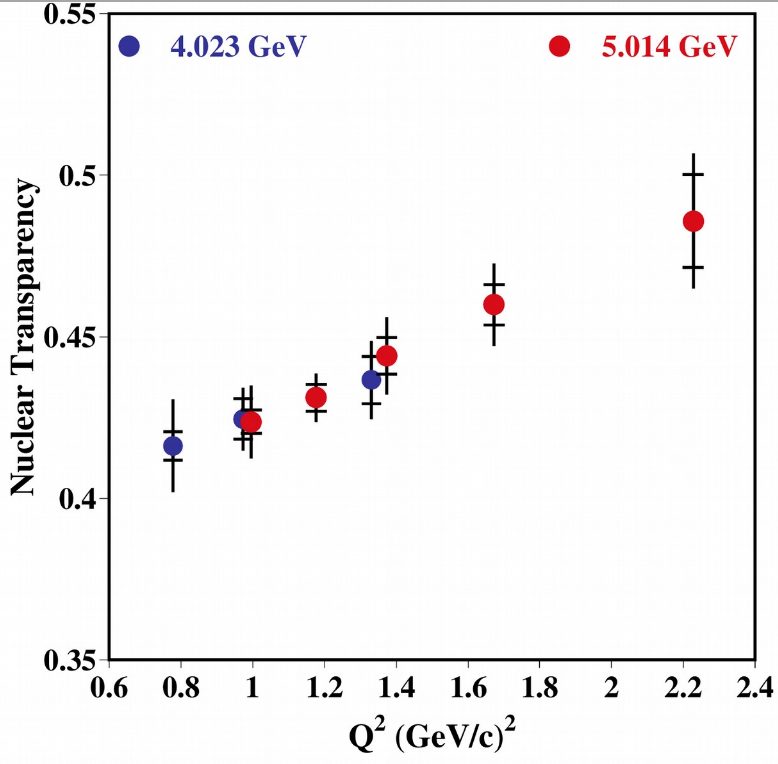
L. El Fassi et al. PLB 712, 2012

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

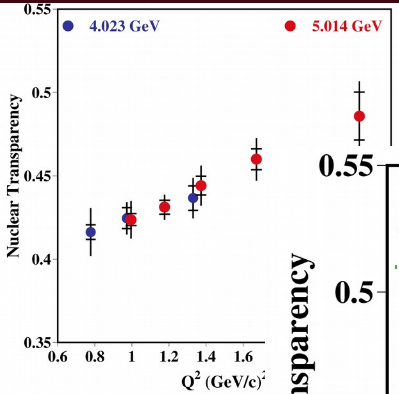
Targets / Models	Carbon slopes (GeV^{-2})	Iron slopes (GeV^{-2})
FMS	**0.029**	**0.032**
GKM	**0.06**	**0.047**
KNS	**0.06**	**0.047**
CLAS Data	**0.044±0.015±0.019**	**0.053±0.008±0.013**

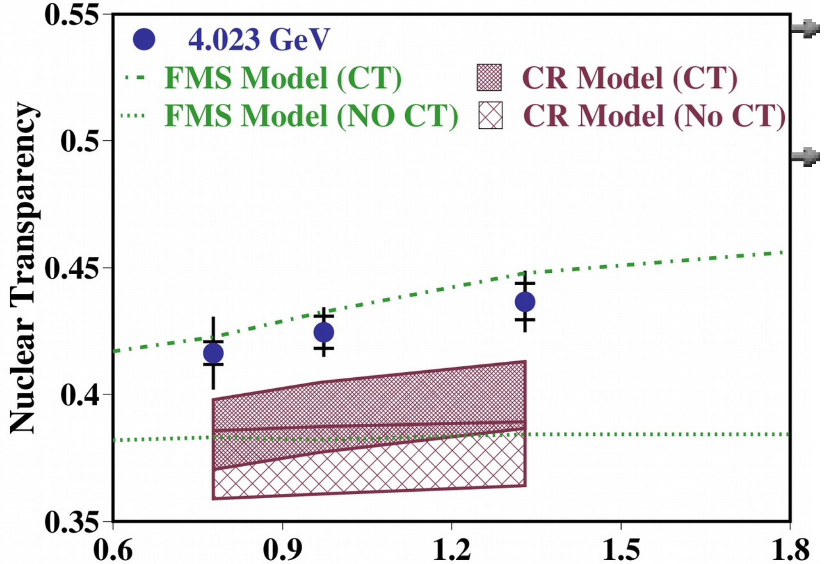
- KNS: Light Cone QCD Formalism
  Kopeliovich, Nemchik & Schmidt, PRC 76, 015205 (2007).

CT Results for 4 & 5 GeV EG2 data



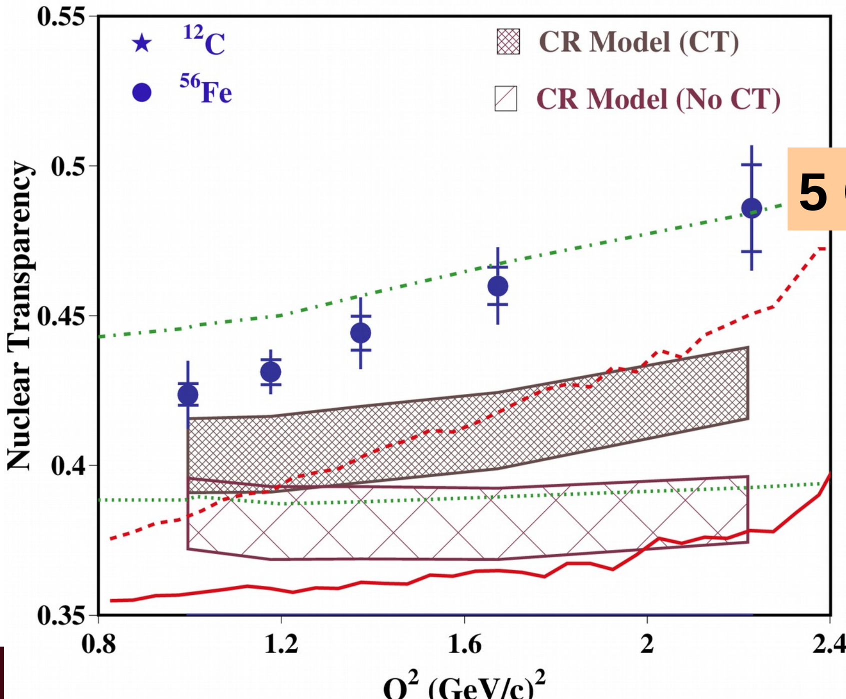
CT Results for 4 & 5 GeV EG2 data



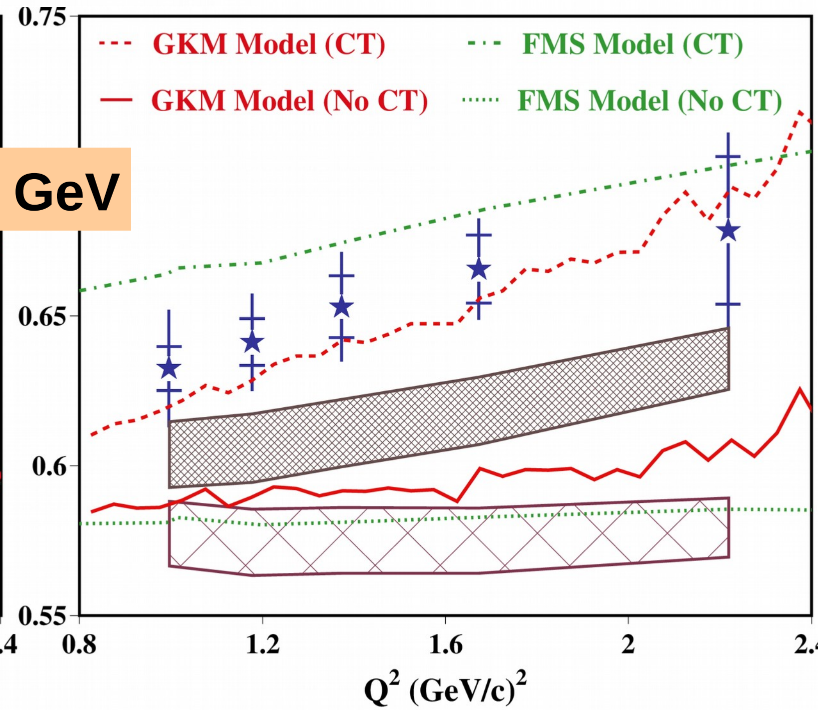


- **CR**: relativistic multiple scattering Glauber approximation.
- Hatched-band includes CT effects based on quantum diffusion model.

W. Cosyn, and J. Ryckebusch PRC 87, 06460 (2013)



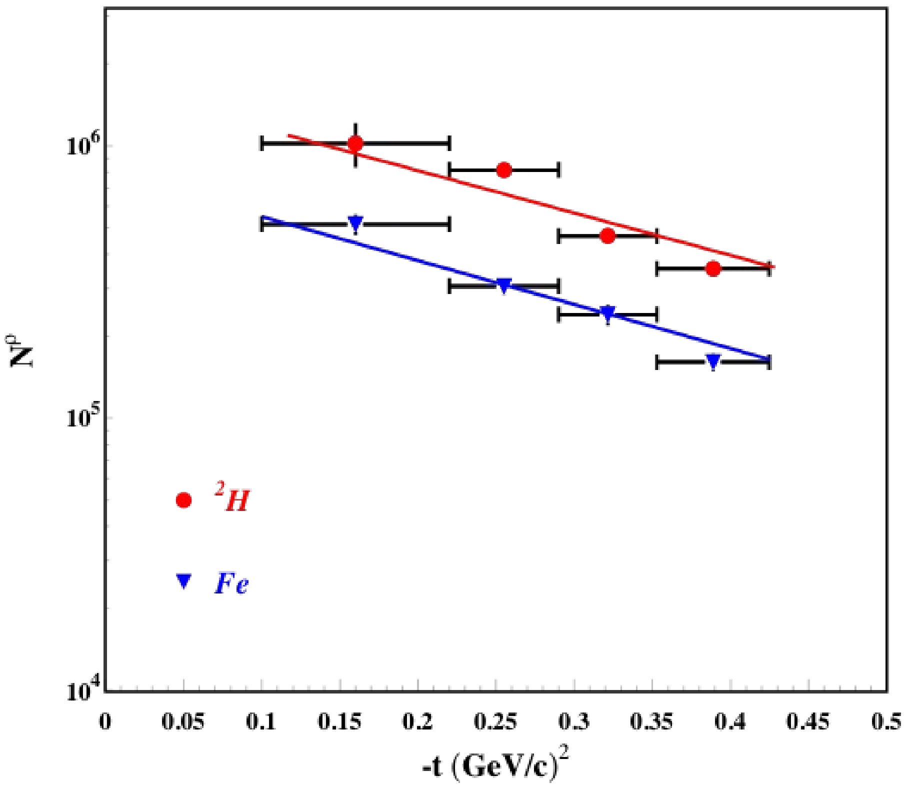
5 GeV

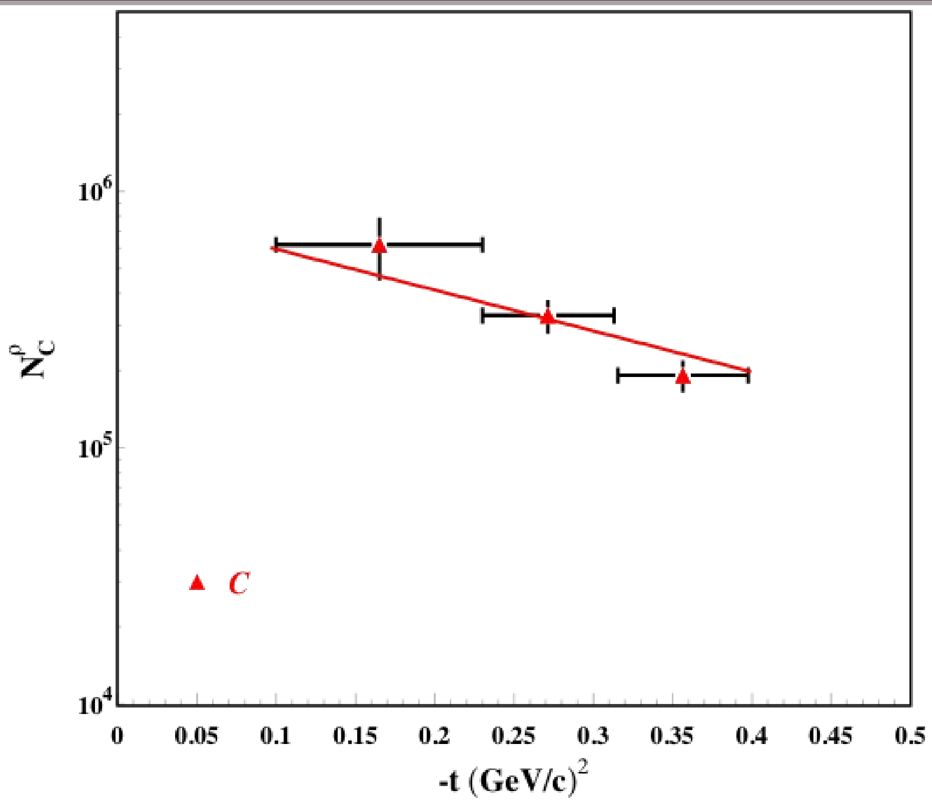


CT slopes from linear fit of Q^2 dependence, $T_A = a\, Q^2 + b$

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** Upper Limit **0.027** Lower Limit	**0.02** Upper Limit **0.021** Lower Limit	**0.027** Upper Limit **0.029** Lower Limit
CLAS Data	**0.044±0.015±0.019**	**0.053±0.008±0.013**	**0.037±0.015±0.027**

t Slopes





Ae^{-bt} fit b(^{2}H) = 3.58 ± 0.5 GeV^{-2}

b(C) = 3.67 ± 0.8 GeV^{-2}

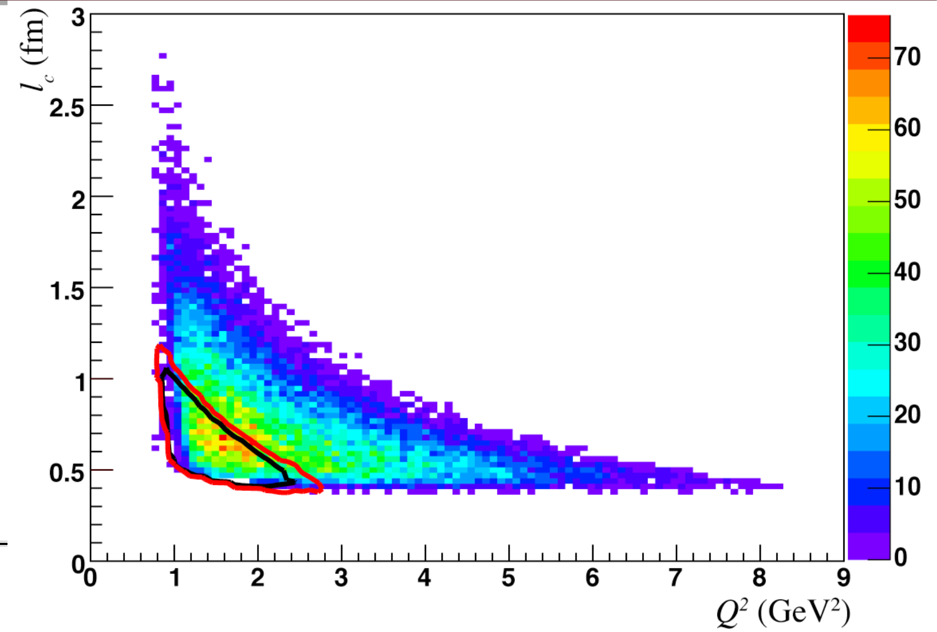
b(Fe) = 3.72 ± 0.6 GeV^{-2}

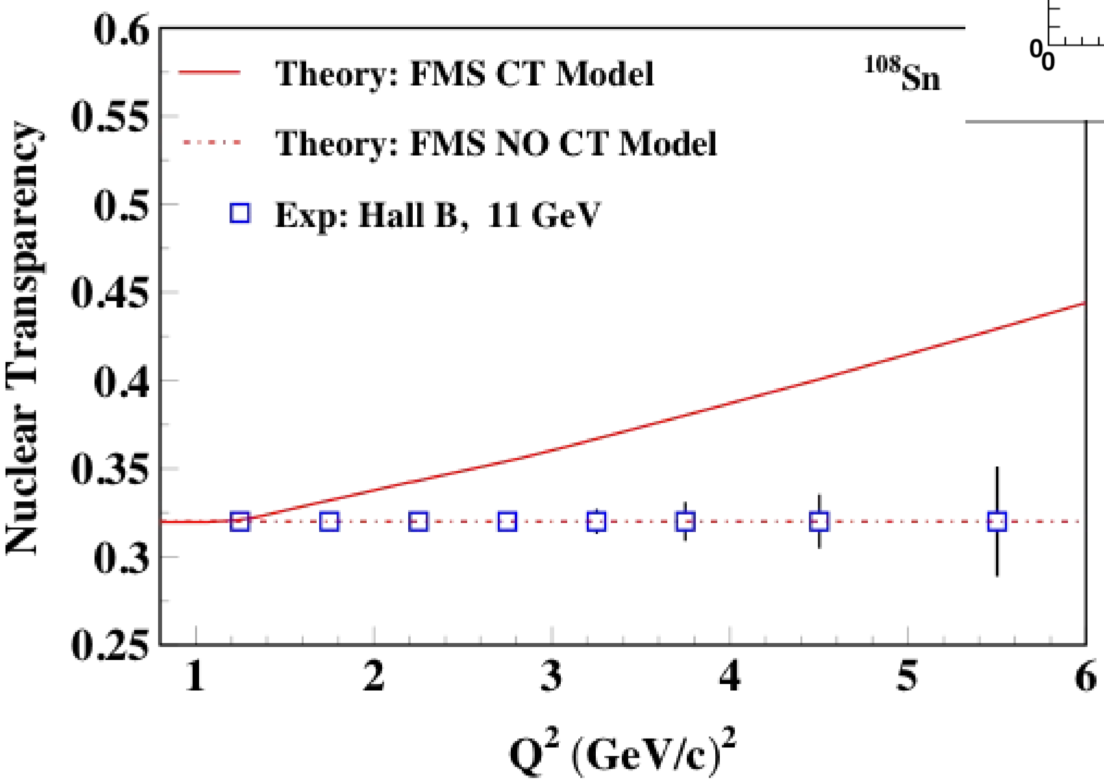
CLAS proton data

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

$2.4 < W < 2.8$ GeV

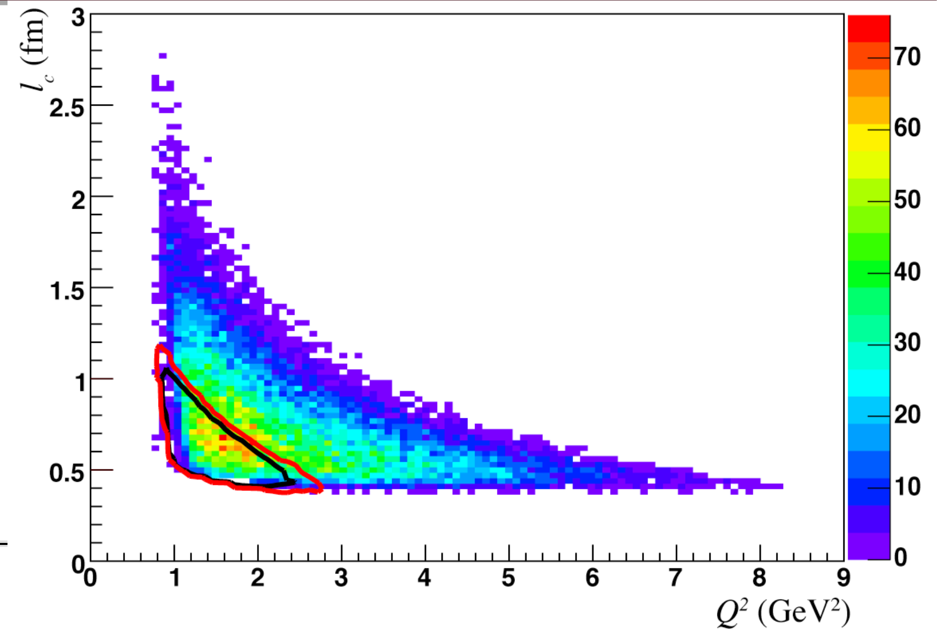
b = 2.63 ± 0.44 GeV^{-2}

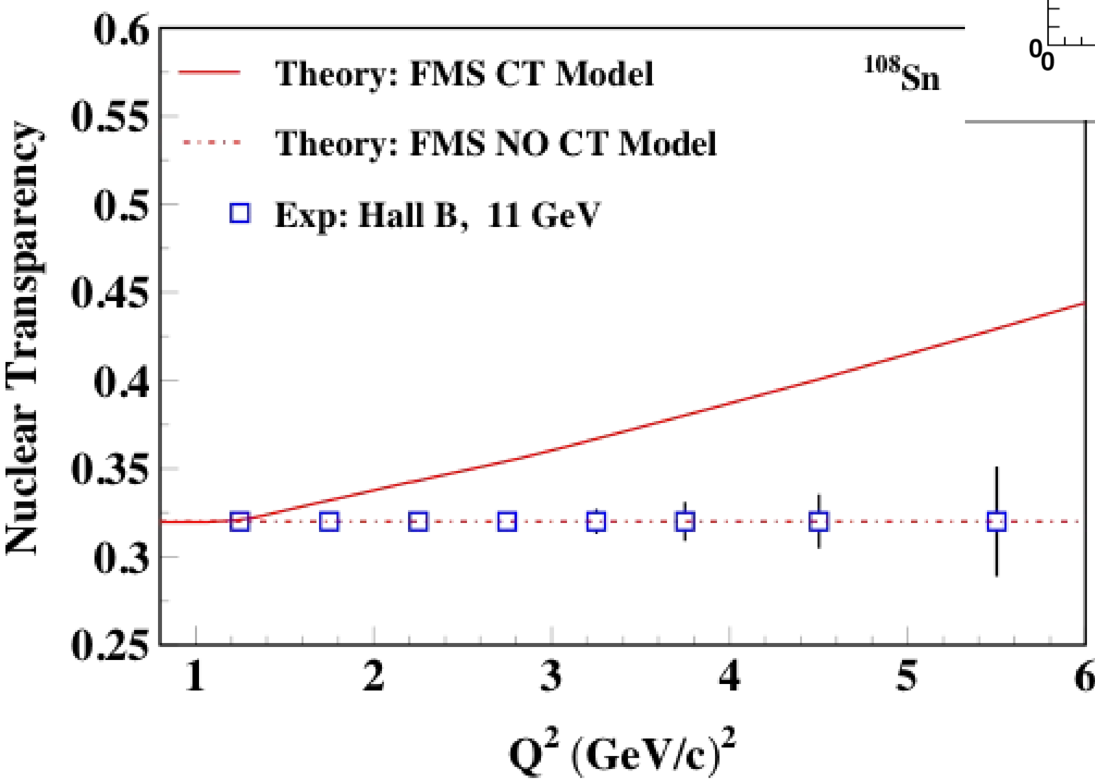

l_c (fm)
3
2.5
2
1.5
1
0.5
0
0
1
2
3
4
5
6
7
8
9
Q^2 (GeV^2)
70
60
50
40
30
20
10
0


Theory: FMS CT Model
Theory: FMS NO CT Model
Exp: Hall B, 11 GeV
^{108}Sn
Nuclear Transparency
0.6
0.55
0.5
0.45
0.4
0.35
0.3
0.25
1
2
3
4
5
6
Q^2 (GeV/c)^2

CLAS12 ρ^0 CT measurements in C, ~~Fe~~ and Sn

- Will use Copper ($^{63}_{29}Cu$) instead of $^{56}_{26}Fe$ as Fe can't be used with the high solenoid field!





Summary and Outlook

- Strong evidence for the onset of CT using ρ^0 electroproduction off nuclei especially for 5 GeV dataset - 11 ± 2.3% (12.5 ± 4.1%) decrease in the absorption of ρ^0 in iron (carbon).

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

- Upcoming CLAS12 measurement will allow to disentangle different CT effects (SSC creation, its formation and interaction with the nuclear medium).

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- Upcoming CLAS12 measurement will allow to disentangle different CT effects (SSC creation, its formation and interaction with the nuclear medium).

- Partial beam-time request for CLAS12 CT experiment (7 PAC days) was approved to be part of RG-B!

Backup Slides

Systematic uncertainties budget

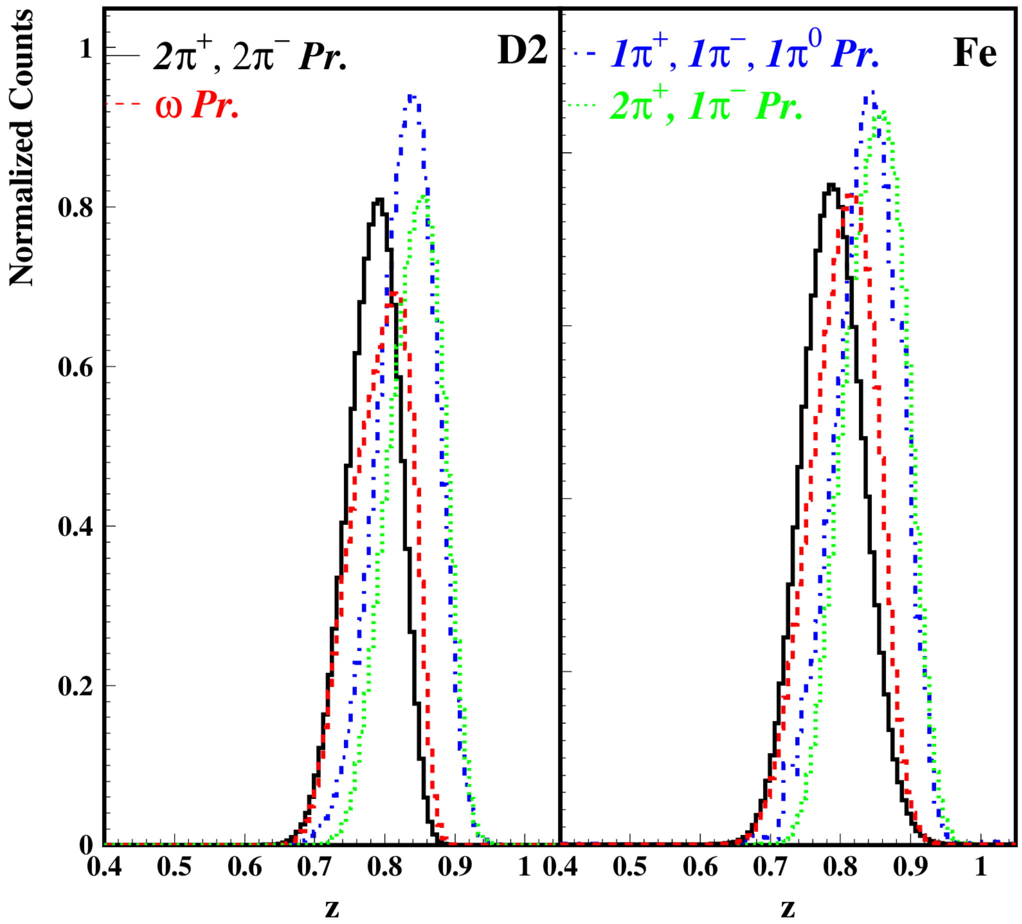
Systematic Uncertainty of Nuclear Transparency of Iron																														
Systematic Effect	Kinematical cuts					Acceptance correction					Background subtraction					Radiative corrections					Fermi motion					Target				
Q^2 Bins	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Normalization	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				

Multi-pions Processes

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



Two pions Invariant Mass

5 GeV Iron dataset