

# QCD Signature in Nuclei: Hadronization and Color Transparency Studies with CLAS-6/12

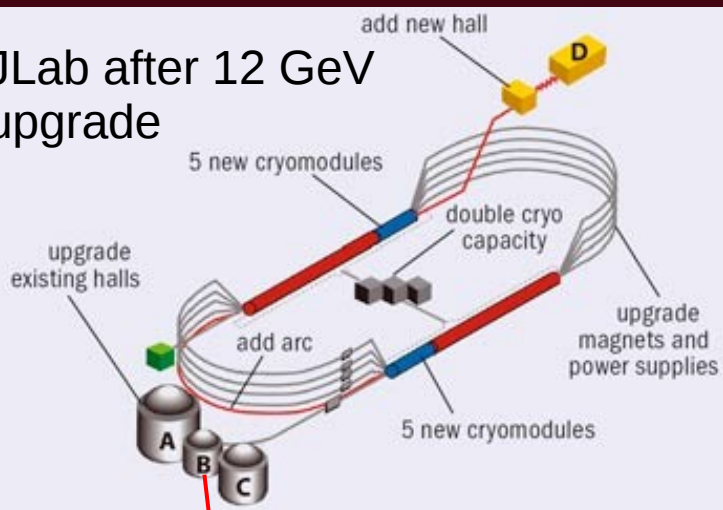
EIC User Group Meeting 2018  
July 31<sup>st</sup>, 2018

Lamiaa El Fassi  
Mississippi State University  
(for the EG2 and CLAS Collaborations)

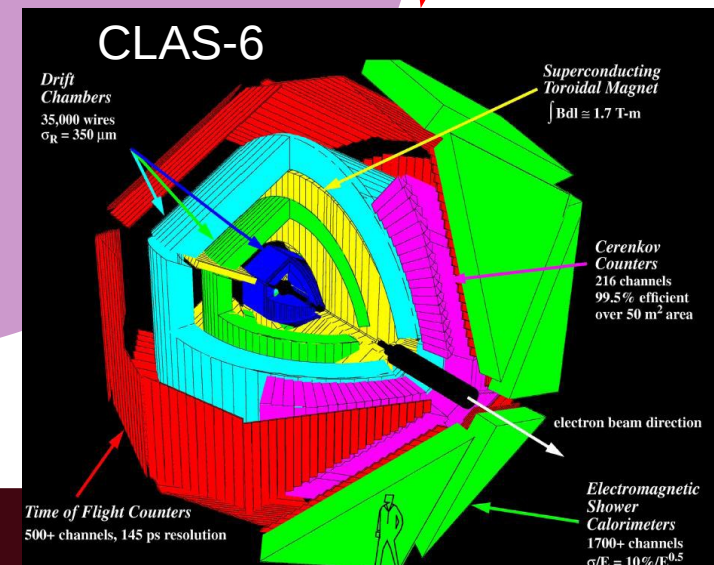
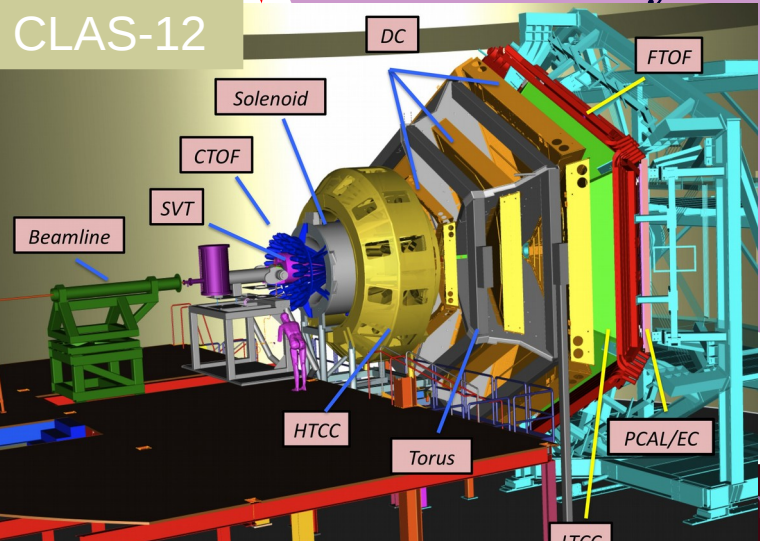


- Brief introduction
- Highlight of CT and CP experimental studies
  - Past and future CLAS-6/12 experiment
- Summary and Outlook

# JLab after 12 GeV upgrade

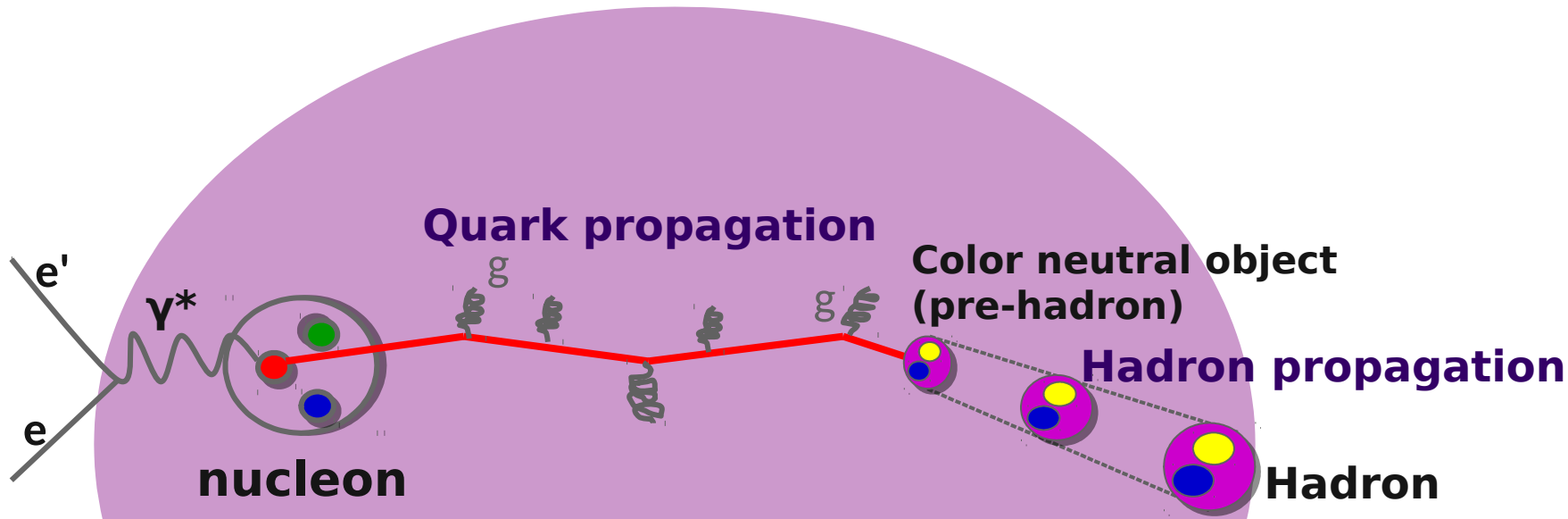


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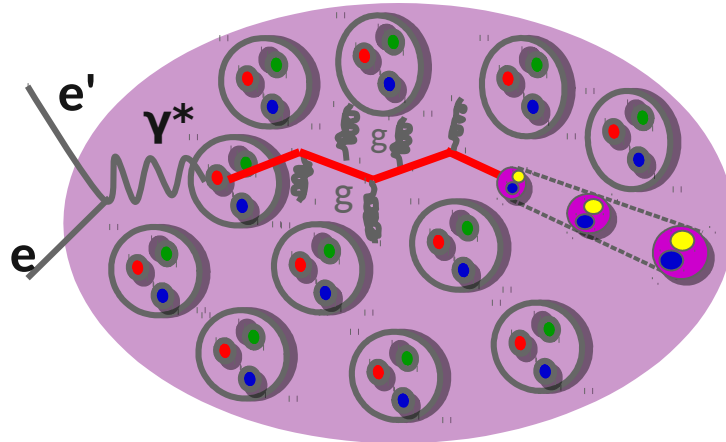
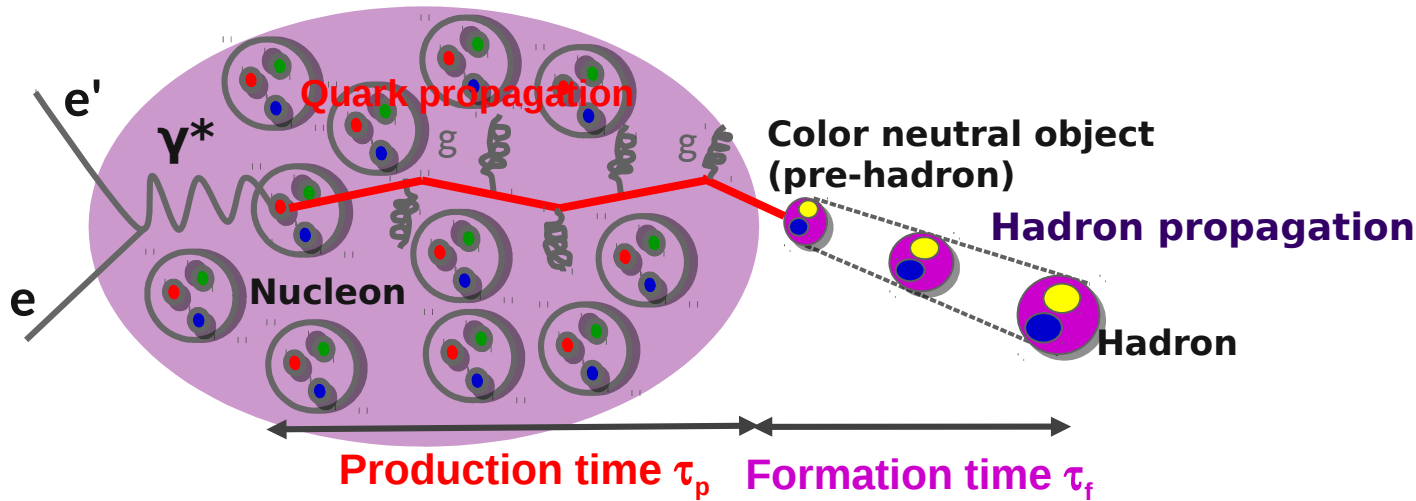
# How does the colored bare, **quark**, evolves to a fully dressed hadron?

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



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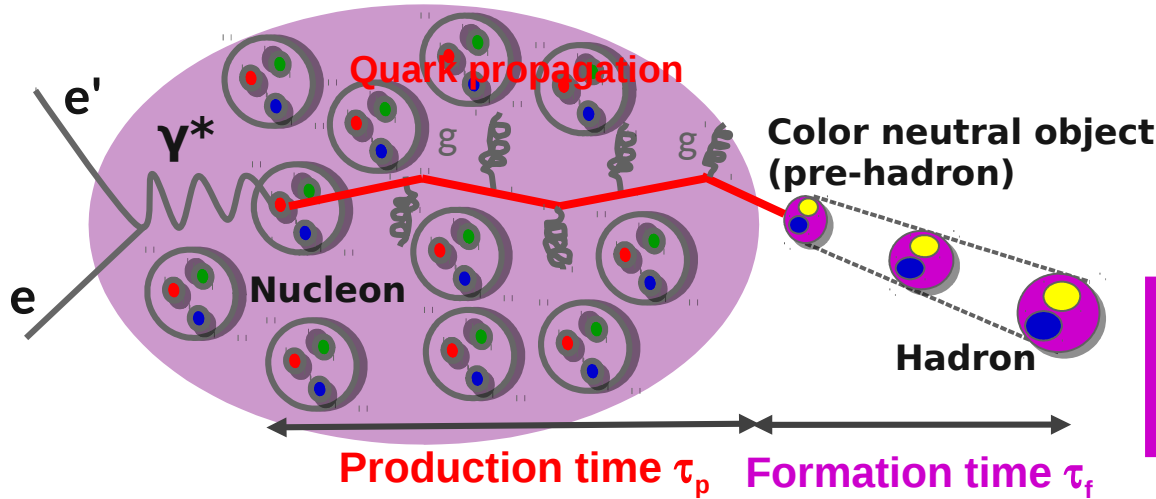
Use semi-inclusive deep inelastic scattering (SIDIS) to access hadronization time-scales:

**Production time  $\tau_p$** : Time spent by a deconfined quark to neutralize its color charge.

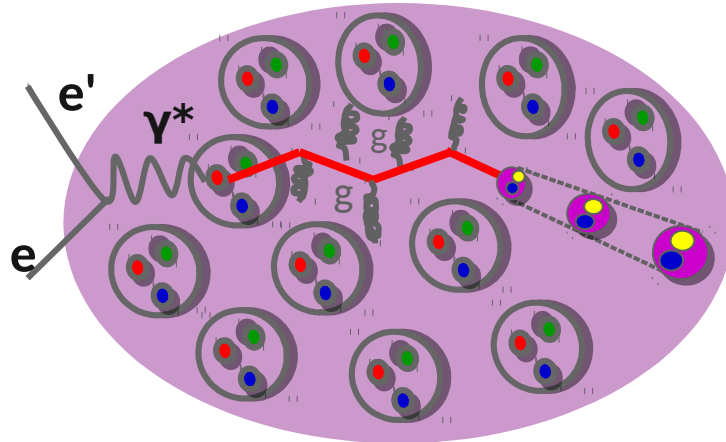
**Formation time  $\tau_f$** : Time required to form a regular hadron (h).

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Hadron formation outside the medium dominates at high energies



Hadron formation inside the medium manifests at low energies

Use semi-inclusive deep inelastic scattering (SIDIS) to access hadronization time-scales:

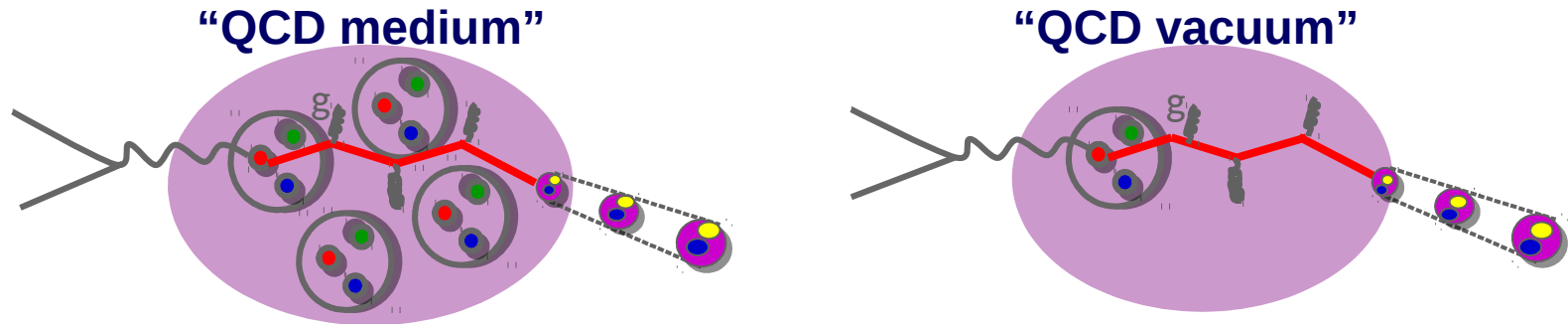
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## Comparison of



leads to extraction of hadronization time-scales

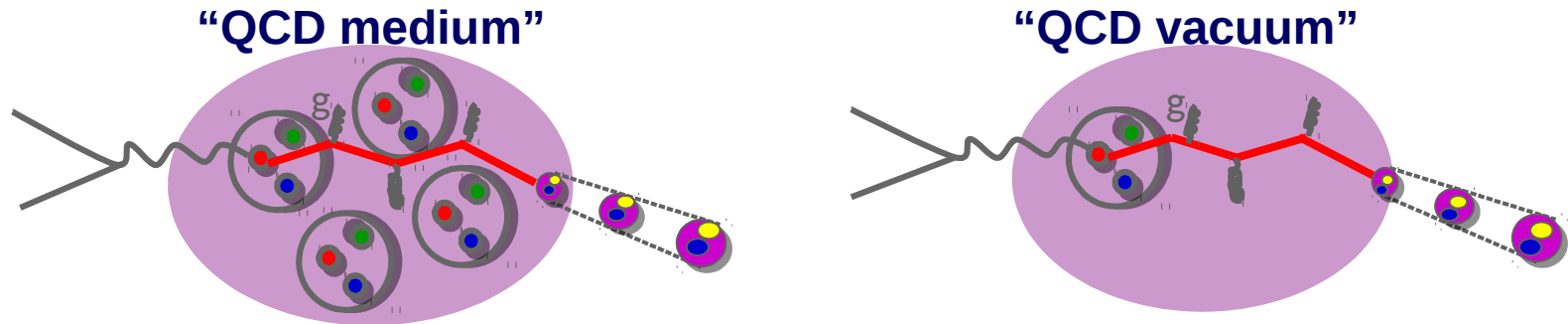
**Production time  $\tau_p$** : Time spent by a deconfined quark to neutralize its color charge.  
Stimulated by a medium-energy loss via a gluon emission.  
➡ Transverse momentum ( $p_T$ ) broadening.

**Formation time  $\tau_f$** : Time required to form a regular hadron (h).  
Signaled by interactions with known hadron cross sections.  
➡ Hadron attenuation via the extraction of hadron multiplicity ratios.

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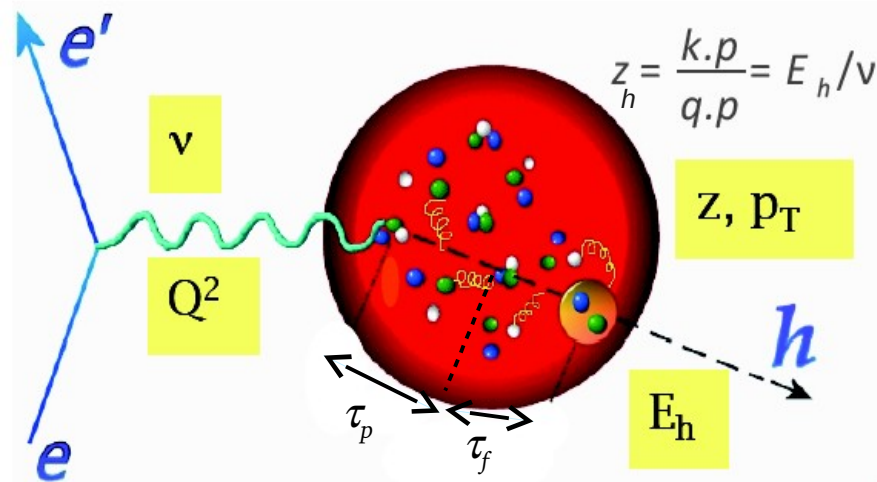
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See Jianwei Qiu and Will Brooks talks for complementary overviews of these studies



# Color Propagation SIDIS Kinematics



## Variables:

$v$  : Electron energy loss,

$\equiv$  Initial energy of a struck quark

$Q^2$ : Four-momentum transferred,

$\sim 1/(\text{spatial resolution})$  of the probe

$y : v/E_{\text{beam}}$ , Electron energy fraction transferred to a struck quark,

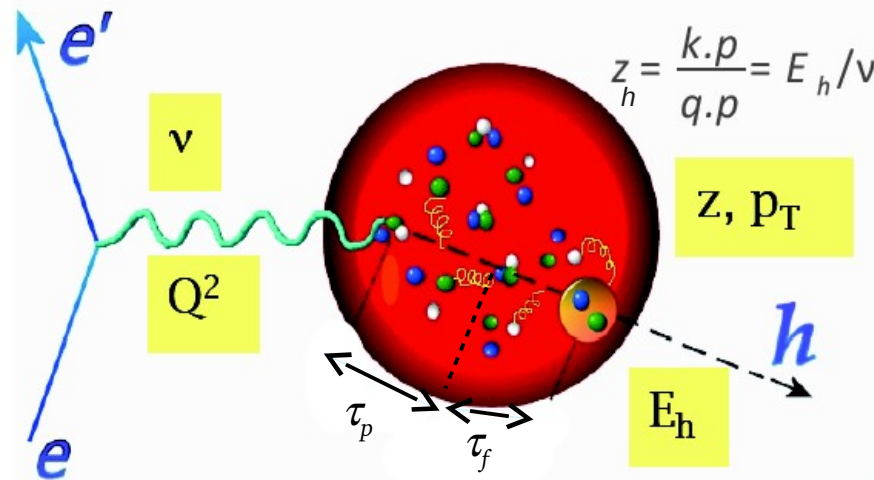
$W : \sqrt{M_n^2 + 2vM_n - Q^2}$  w/.  $M_n$  is a nucleon mass, is the mass of the total hadronic final state,

$z_h$ : Fraction of the struck quark's initial energy carried by the formed hadron ( $0 < z_h < 1$ )

$p_T$ : Hadron momentum transverse to a virtual photon direction.

$x_F : \frac{P_L}{P_L^{\text{max}}}$ , Feynman variable, a fraction of the maximum longitudinal momentum carried by the observed hadron.

# Color Propagation SIDIS Kinematics



## Kinematical cuts:

$Q^2$ : Four-momentum transfer,

$> 1$ , to probe the intrinsic structure of nucleons,

$y : v/E_h$ , Electron energy fraction transferred to a struck quark,

$< 0.85$ , to reduce the size of the radiative effects on multiplicity ratios

$W : \sqrt{M_n^2 + 2vM_n - Q^2}$  w/.  $M_n$  is a nucleon mass, is the mass of the total hadronic final state,

$> 2$ , to avoid a contamination from the resonance region

$x_F$ : Fraction of the maximum longitudinal momentum carried by the observed hadron.

$> 0$ , selects the current fragmentation region.

$< 0$ , selects the backward (target-remnant) fragmentation region.

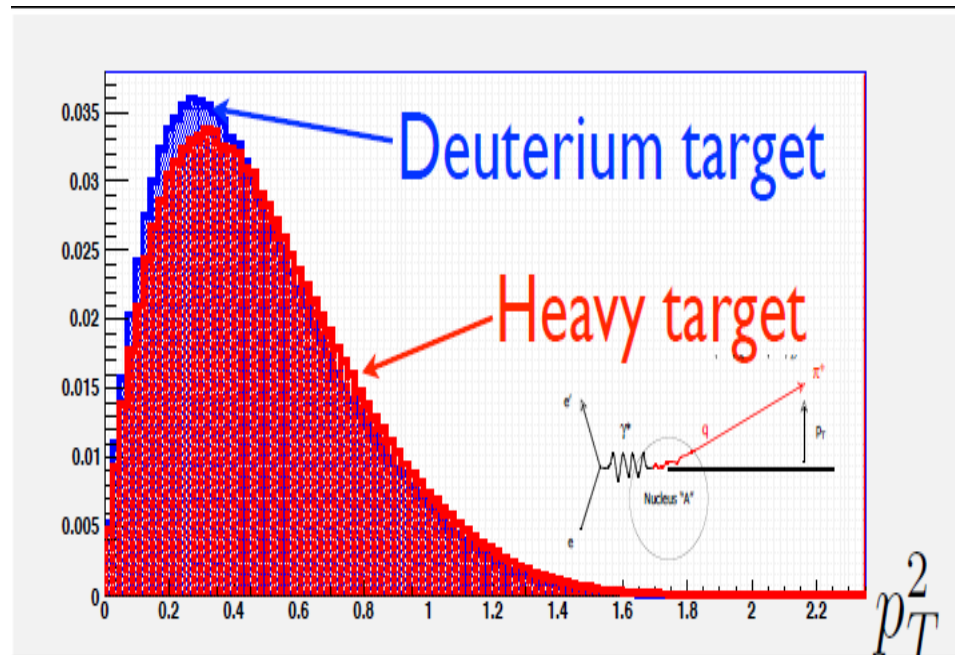
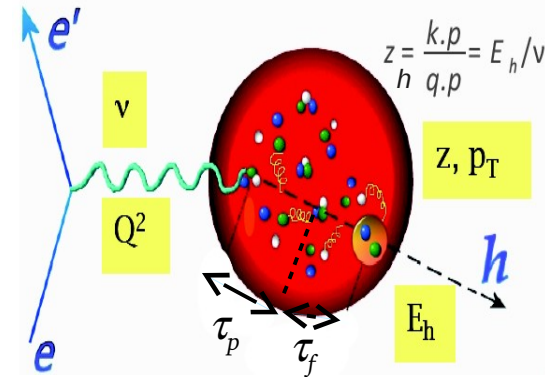
# Color Propagation Study: Experimental Observables

## Transverse momentum broadening

$$\Delta P_T^2 = \langle P_T^2 \rangle_A - \langle P_T^2 \rangle_D$$



Allow access to  $\tau_p$  via production of different hadrons and quark's flavor



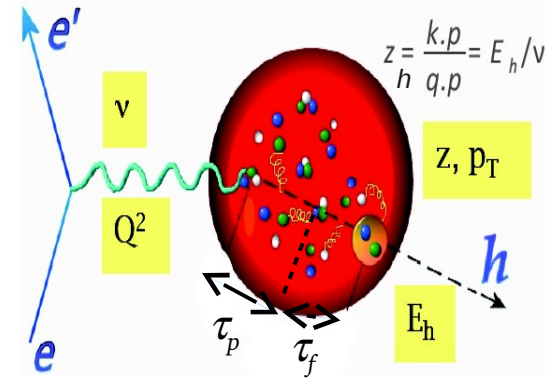
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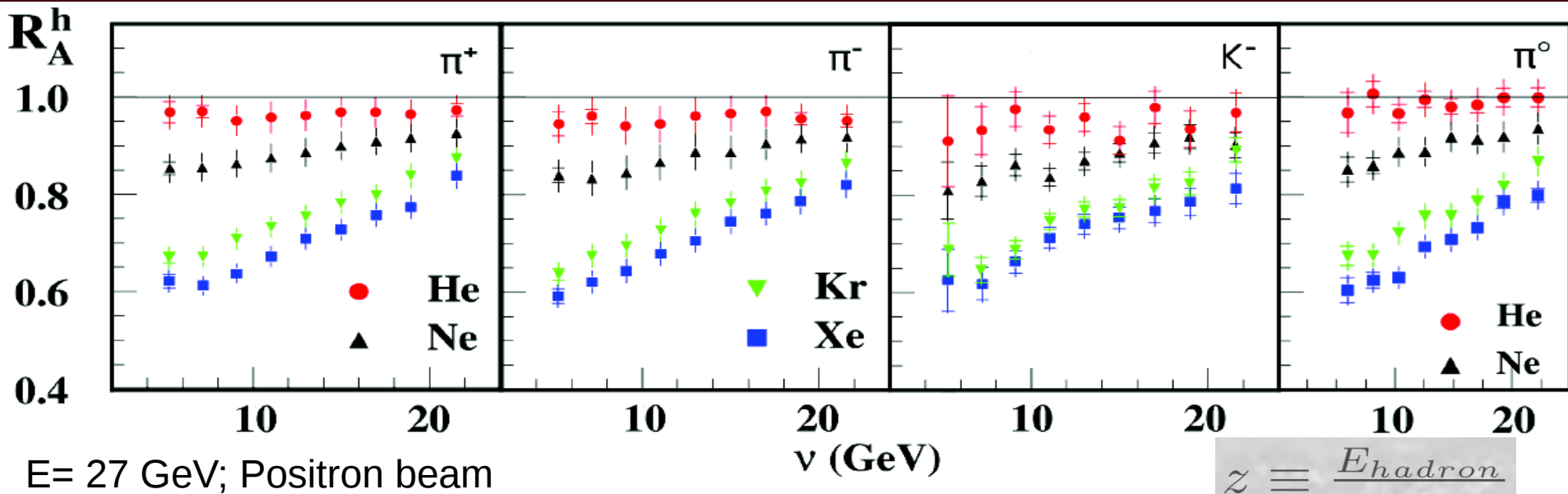
## Hadron Multiplicity Ratio

$$R_M^h(z, \nu, p_T^2, Q^2) = \frac{\left\{ \frac{N_h^{DIS}(z, \nu, p_T^2, Q^2)}{N_e^{DIS}(\nu, Q^2)} \right\}_A}{\left\{ \frac{N_h^{DIS}(z, \nu, p_T^2, Q^2)}{N_e^{DIS}(\nu, Q^2)} \right\}_D}$$

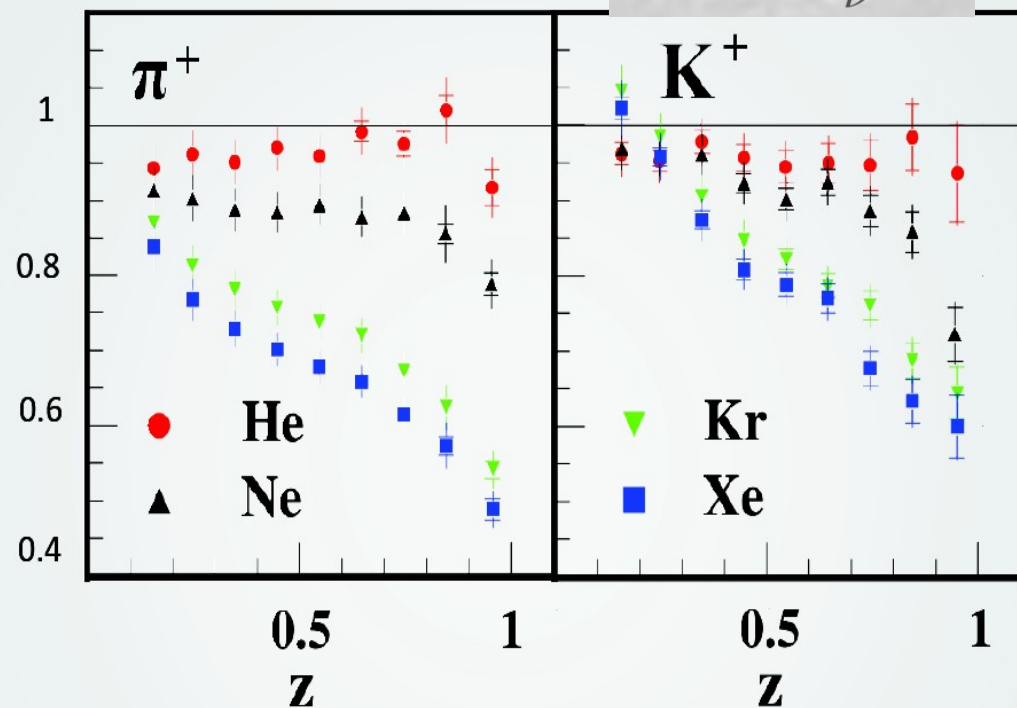


Access  $\tau_f$  after the extraction of  $\tau_p$  and  $R_M^h$

# CLAS-6 CP Study Motivation: Hermes Multiplicity Ratios

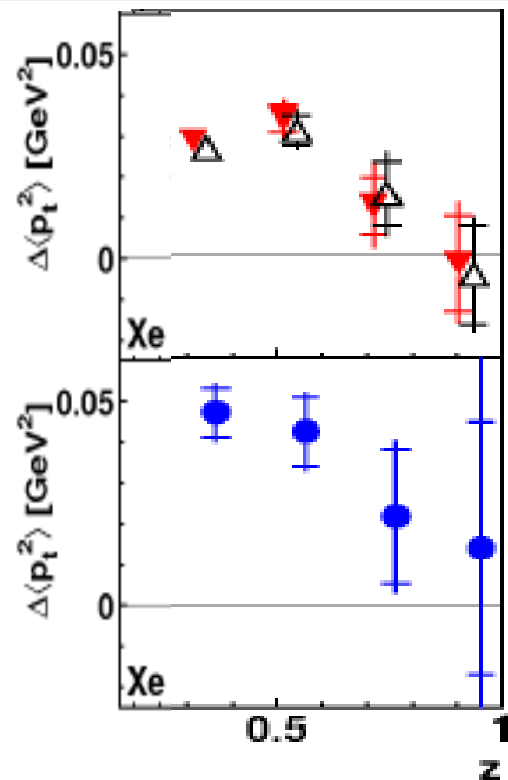
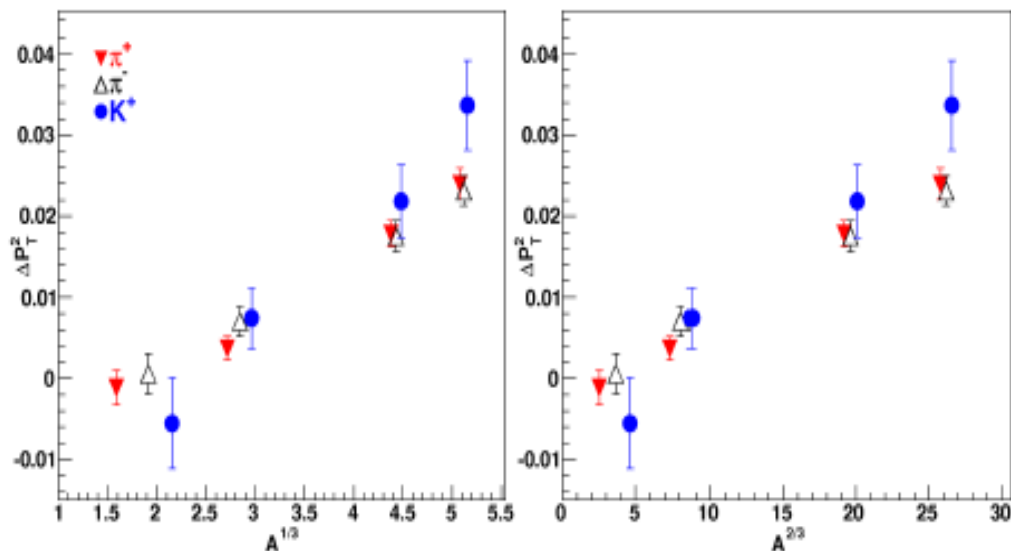


- All pion's flavors and  $K^-$  experience similar attenuation.
- $K^+$  is less attenuated compared to  $\pi^+$  most likely due to a contamination from  $\pi + p \rightarrow \Lambda + K$  (B. Kopeliovich *et al.*) from the target fragmentation.



# CLAS-6 CP Motivation: Hermes Transverse Momentum Broadening

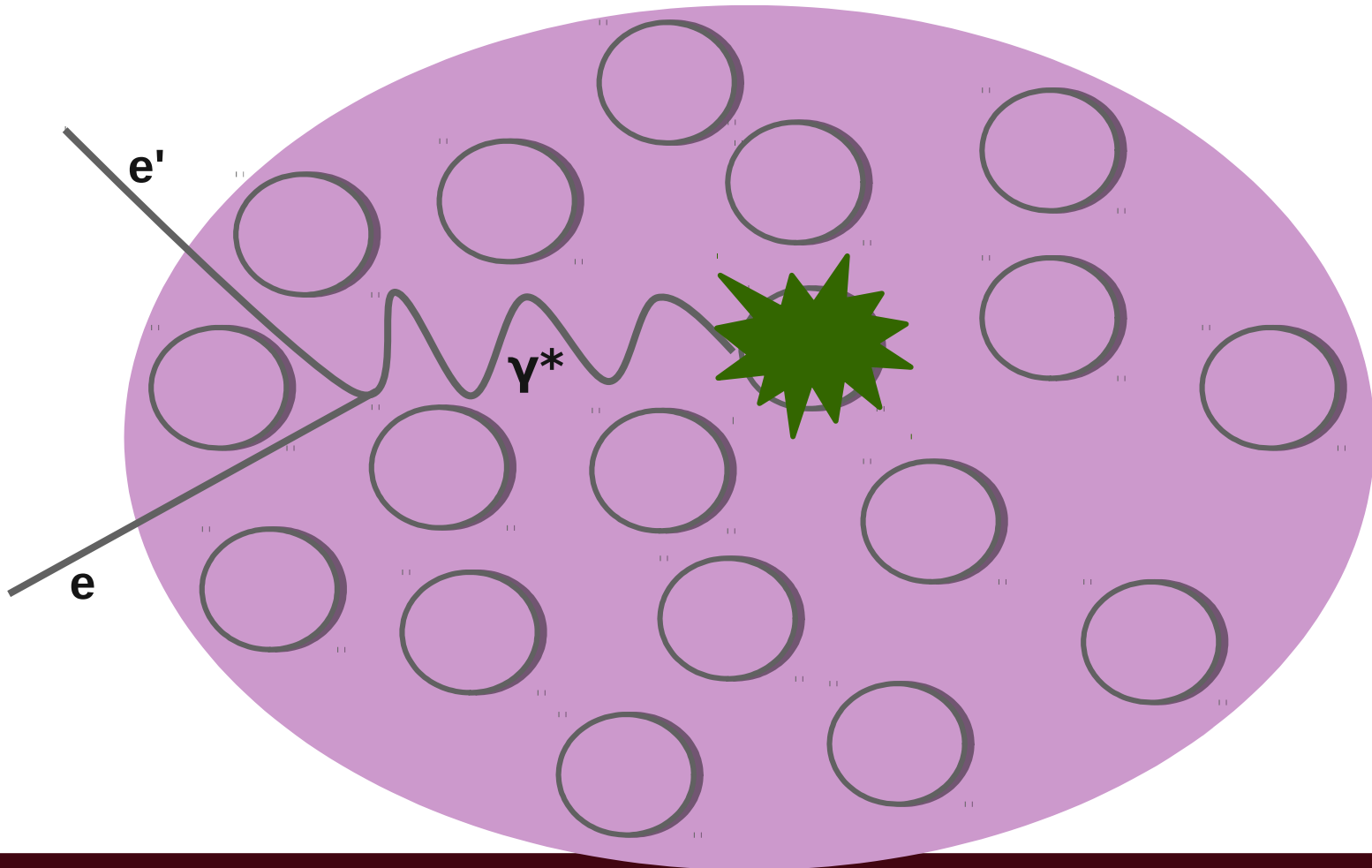
$E = 27$  GeV; Positron beam



- Reduced broadening at high  $z$  favors no prehadron interaction,
- Different  $K^+ p_T$  broadening behavior compared to pions  $\implies$  Flavor dependence?
- Perturbative QCD description of  $p_T$  broadening:  $\Delta p_T^2 \propto \frac{dE}{dx}$  while  $\Delta p_T^2 \propto L$  &  $dE \propto L^2$
- A similar dependence of  $\Delta p_T^2$  on  $A^{1/3}$  &  $A^{2/3}$ ?  $\implies$  More data are needed!

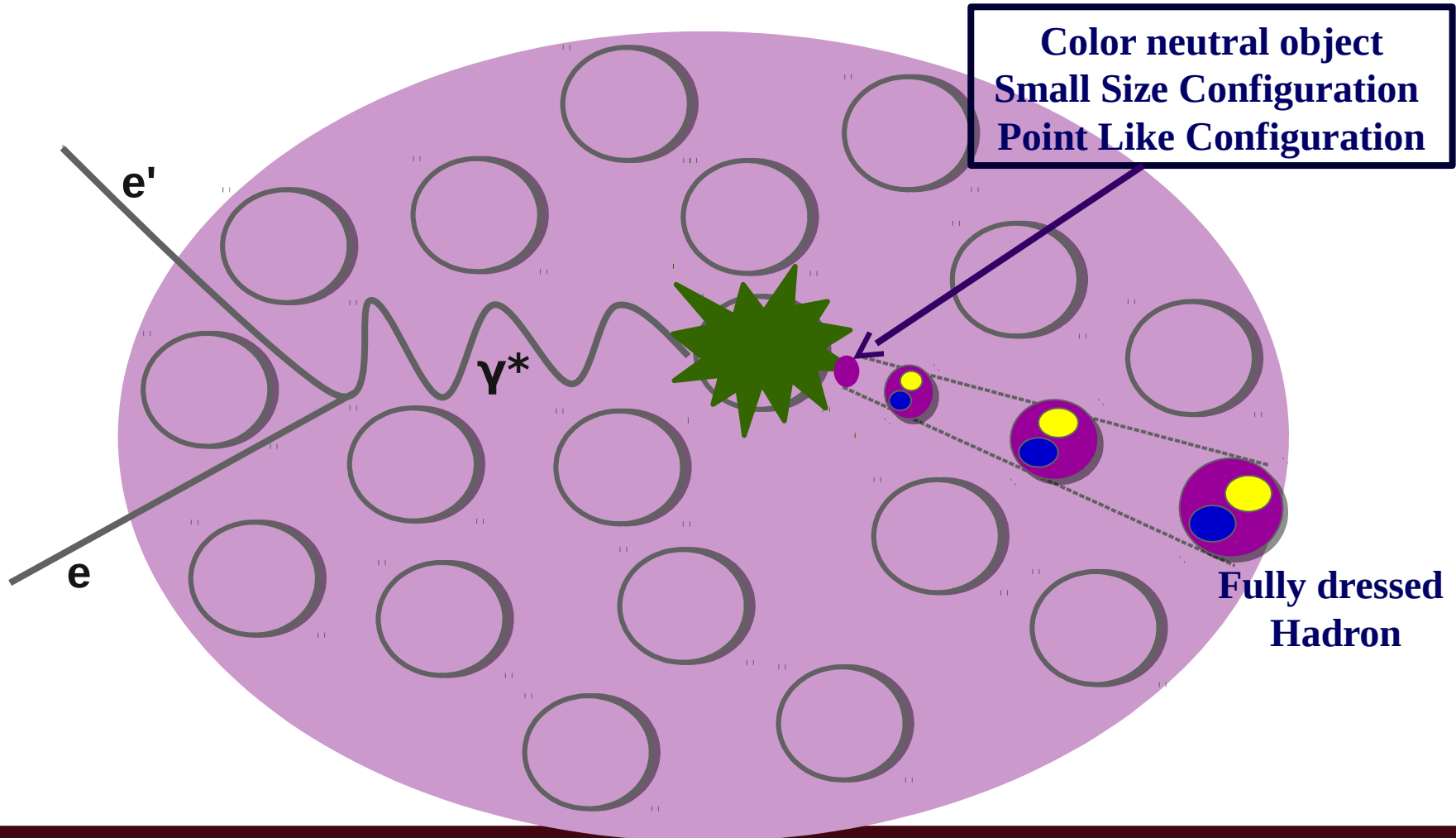
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- Study hard processes in nuclei to probe the QCD confinement dynamics:
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  - > Creation and evolution of small size hadrons - **color transparency (CT)**



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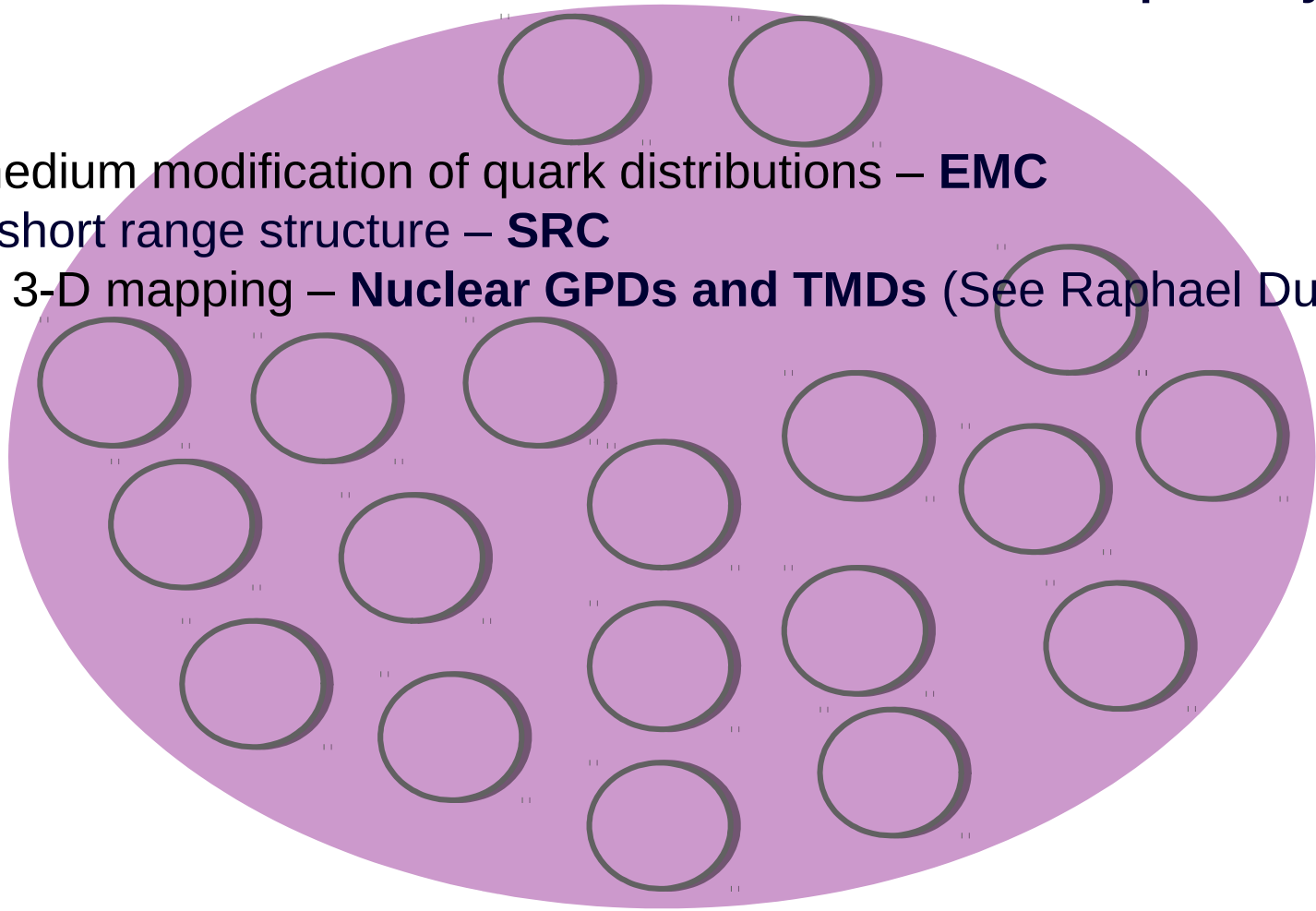
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# Hard Probe .vs. Medium

- 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** (See Raphael Dupre talk)



# CT Basics: The Survival of the Smallest !

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

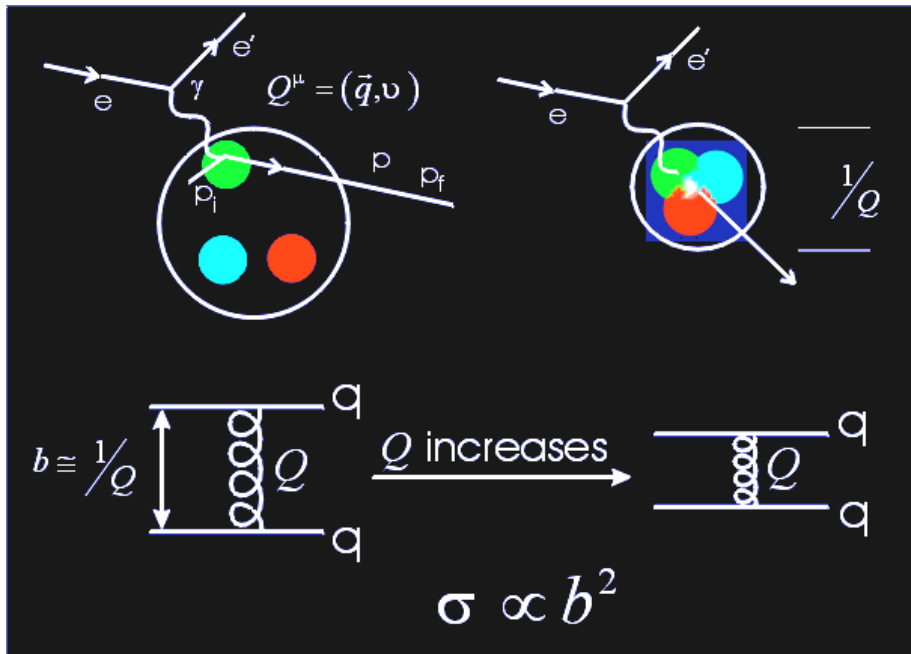
# CT Basics: The Survival of the Smallest!

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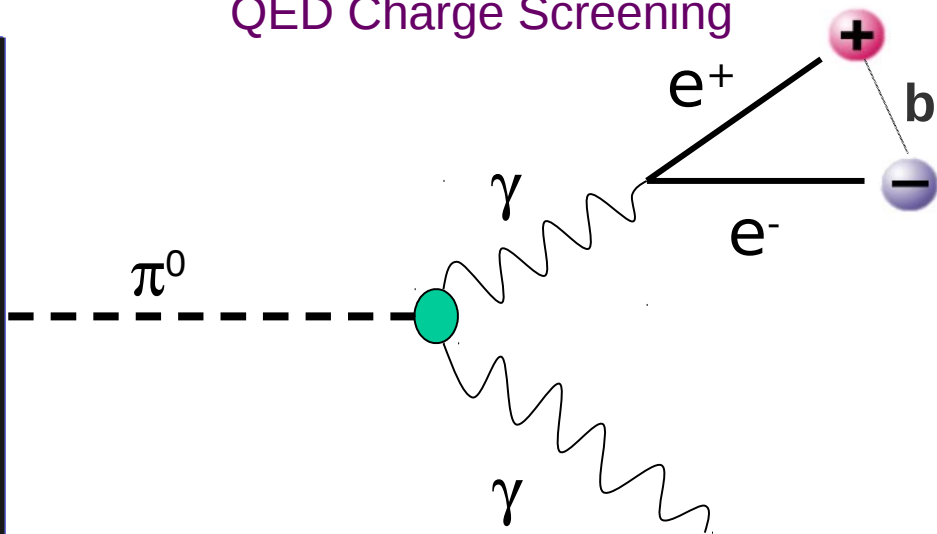
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## QCD Color Screening



## QED Charge Screening



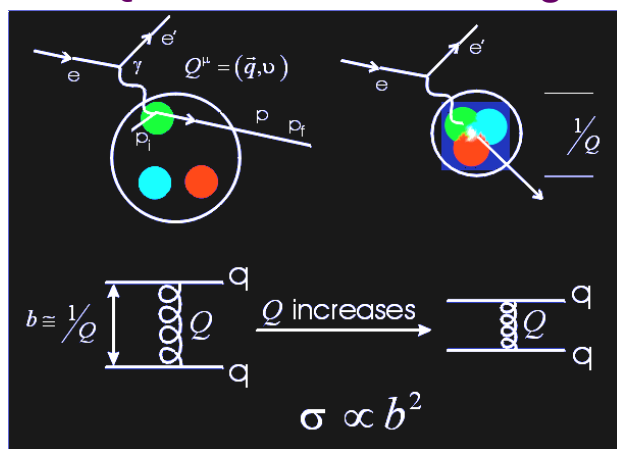
200 GeV  $\pi^0$  emulsion produced in cosmic rays (Perkins 1955)

➤ 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.

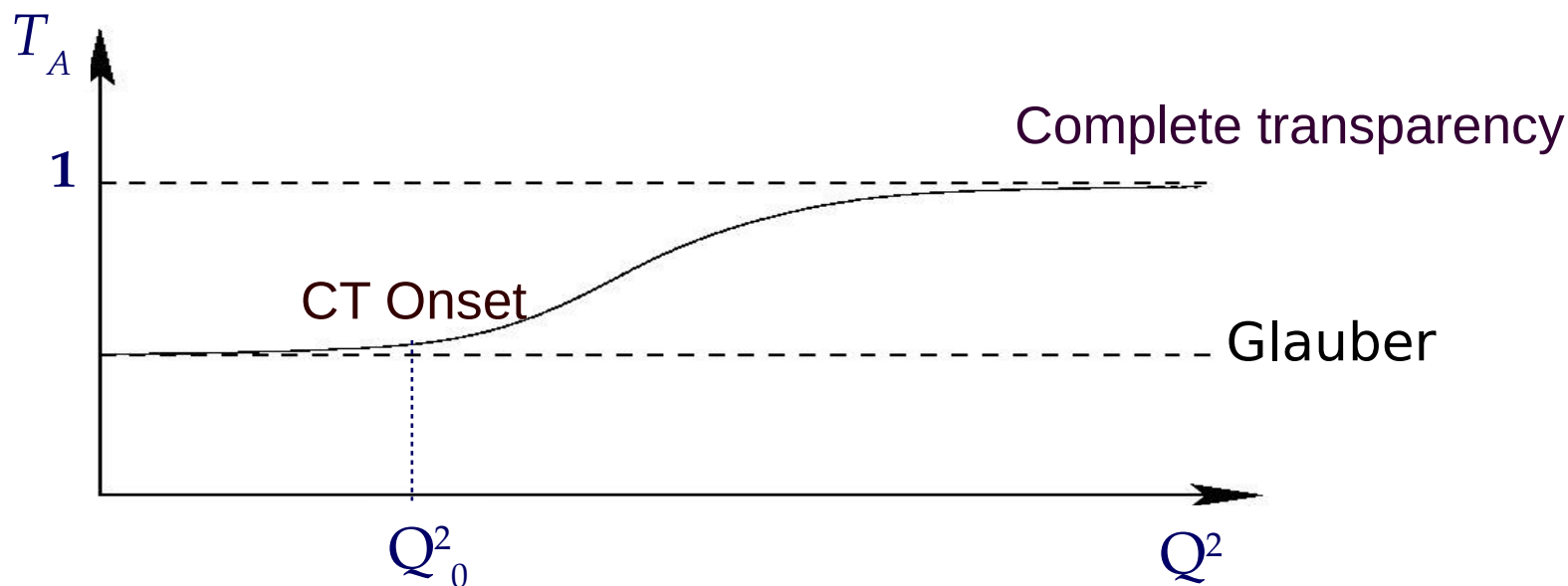
# CT Signature

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

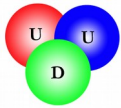
$$T_A = \frac{\sigma_A}{A \sigma_N}$$

$\sigma_A$  is the nuclear cross section

$\sigma_N$  is the free (nucleon) cross section



## Baryon



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

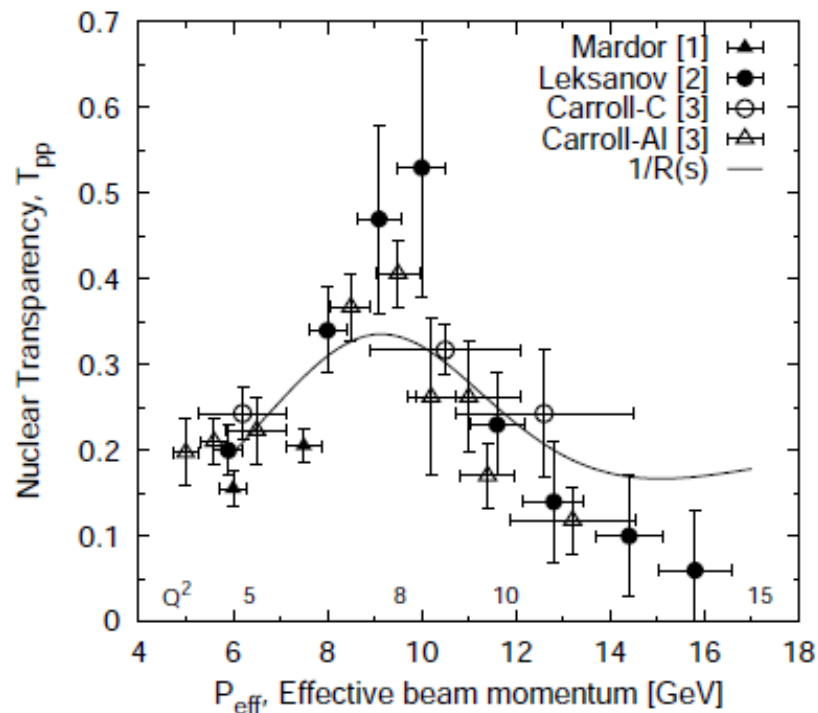
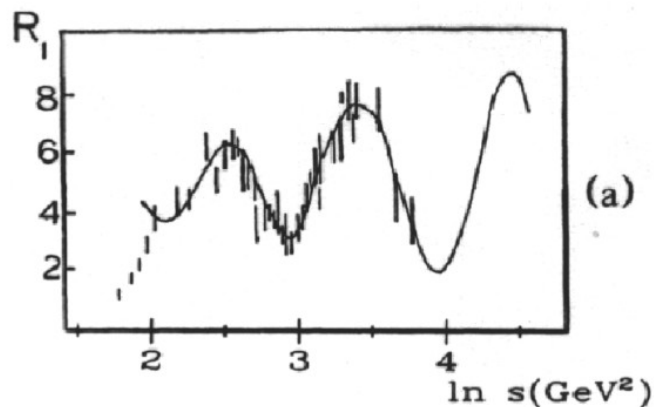
## Meson



- $A(\pi, \text{di-jet})$  FNAL
- $A(\gamma, \pi^- p)$  JLab
- $A(e, e'\pi^+)$  JLab
- $A(e, e'\rho^0)$  DESY & JLab

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

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



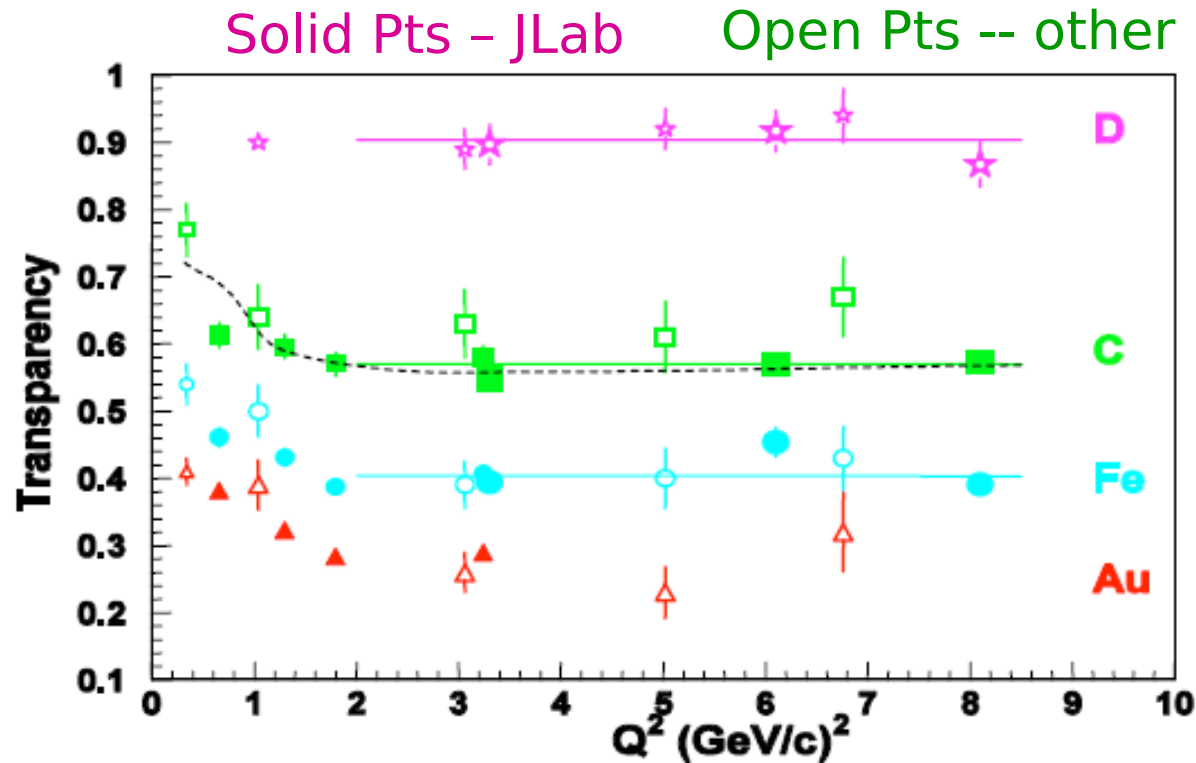
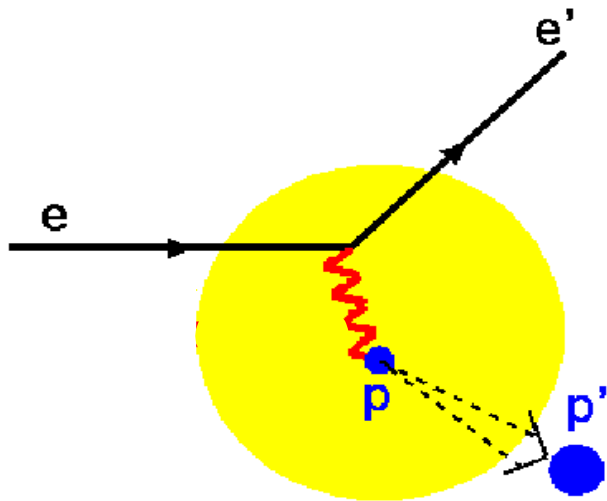
A. Leksanov et al. PRL 2001

- 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  $\chi^2 / \text{ndf} \approx 1$ .
- Conventional Nuclear Physics Calculation by Pandharipande et al. gives a good description.



N. C. R. Makins et al. PRL 72, 1986 (1994)

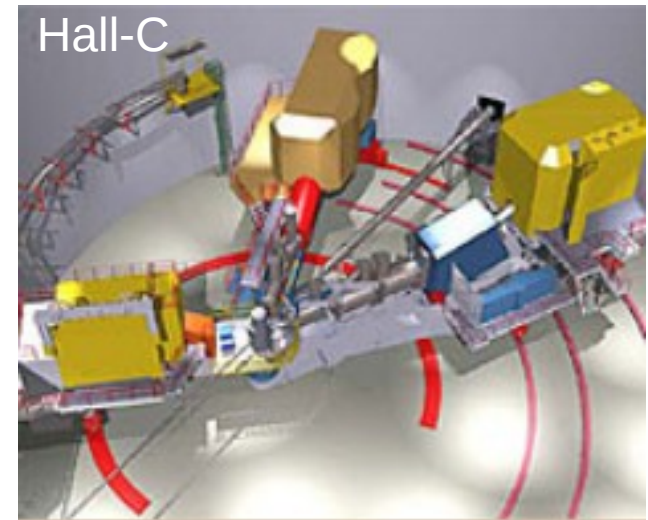
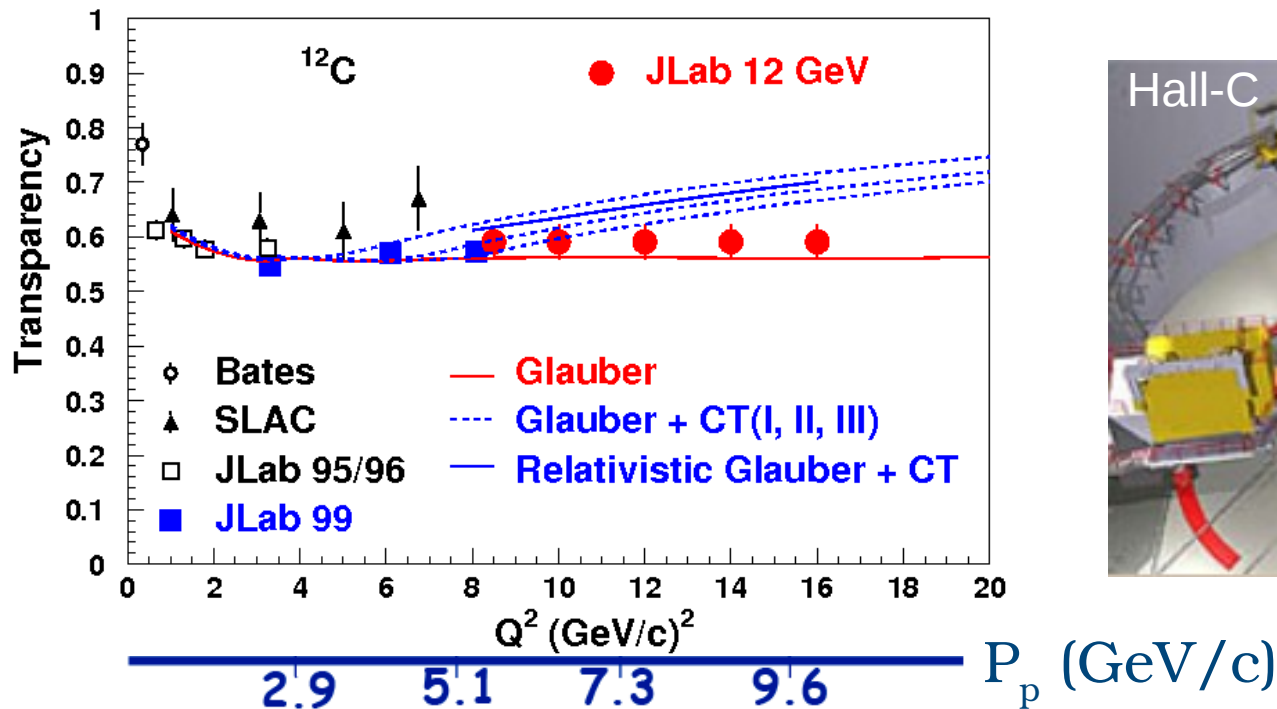
G. Garino et al. PRC 45, 780 (1992)

D. Abbott et al. PRL 80, 5072 (1998)

K. Garrow et al. PRC 66, 044613 (2002)

# 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)<sup>2</sup>).
- 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 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, 896 (1993)

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

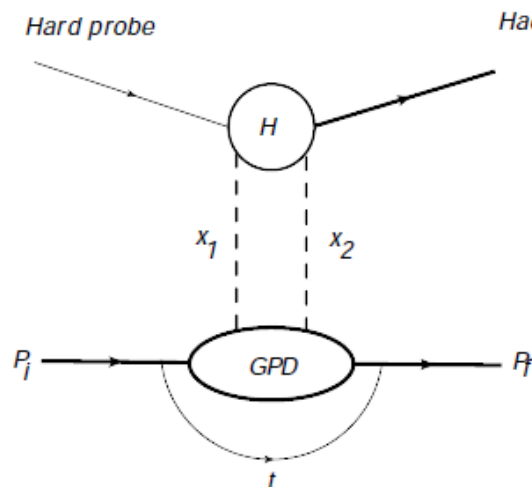
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- Onset of **CT** is expected at lower  $Q^2$  in **qq-bar** system.
- Onset of **CT** is crucial to test the validity of the **factorization theorem** (GPDs framework), and determine **its onset** for exclusive meson production in deep inelastic scattering.

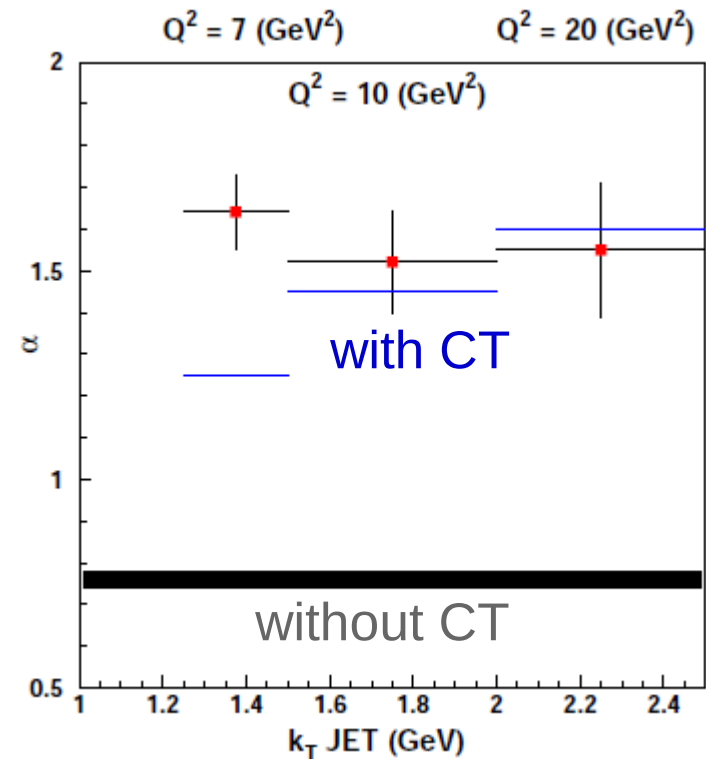
Collins, Frankfurt, Miller, Sargsian and Strikman



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

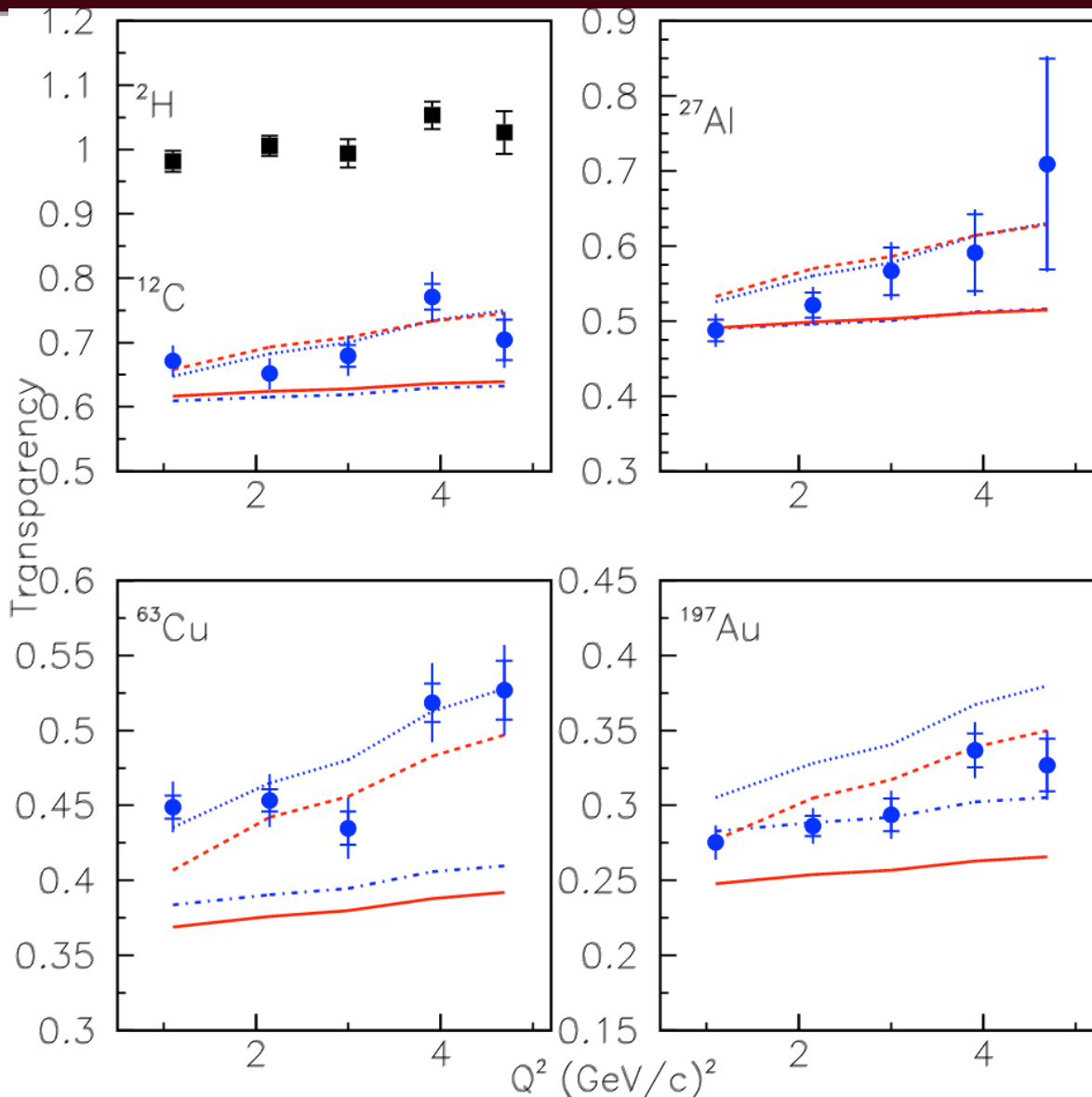
# $A(\pi, \text{dijet})$ data from FNAL

- Coherent  $\pi^+$  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)



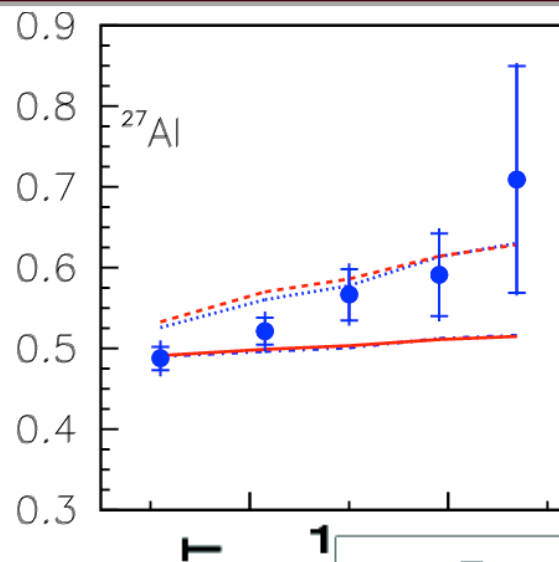
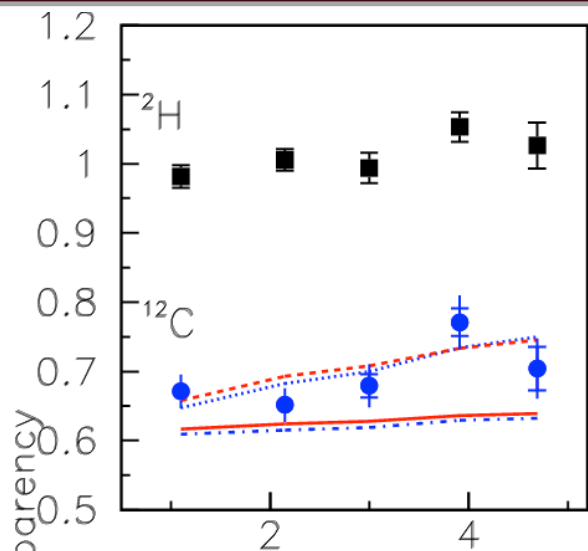
Aitala et al., PRL 86, 4773 (2001)

# Pion Electroproduction $A(e, e' \pi^+)$ at JLab

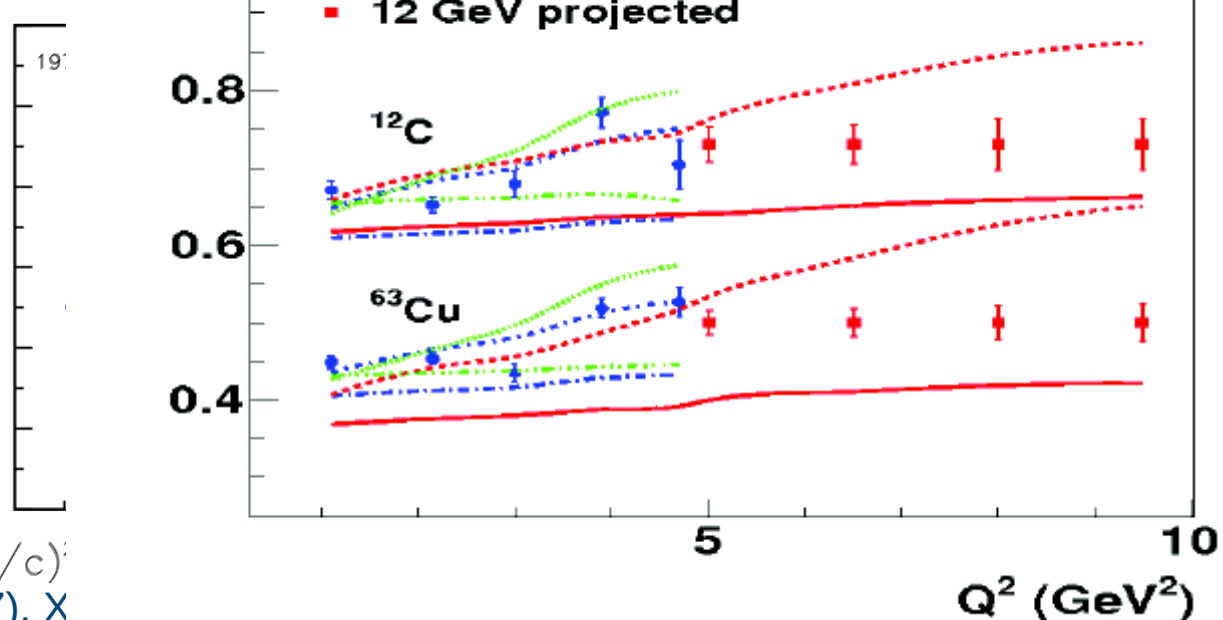
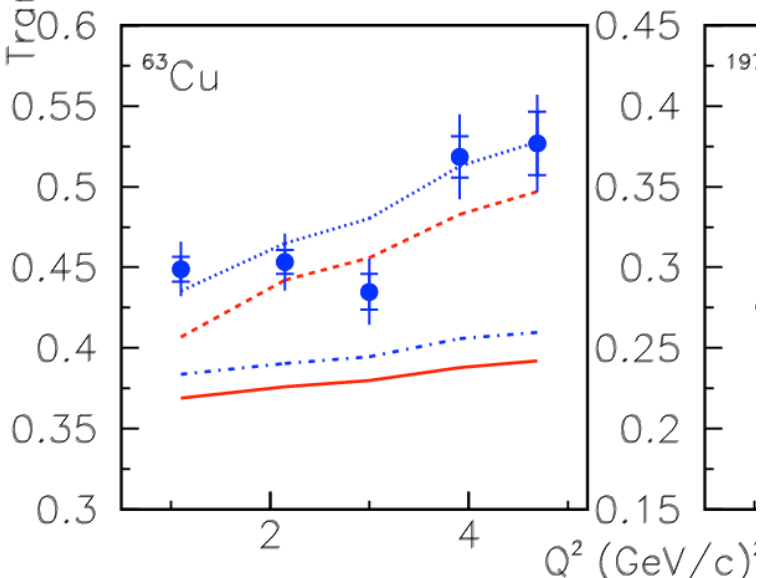


B. Clasie et al. PRL 90, 10001 (2007), X. Qian et al., PRC 81, 055209 (2010)

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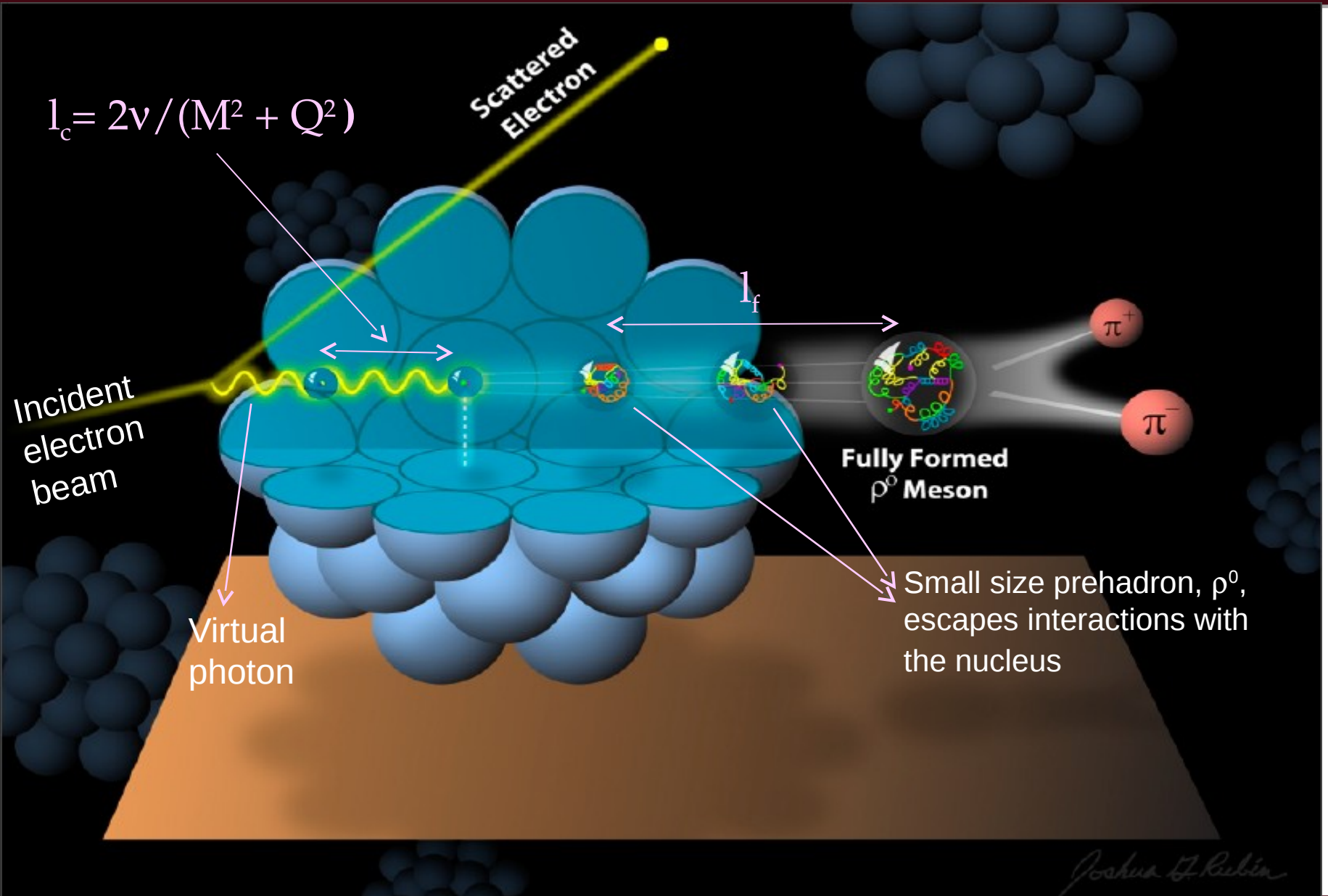


These measurements will be extended to  $Q^2$  of about  $10 \text{ (GeV/c)}^2$  in Hall-C @ 11 GeV beam energy



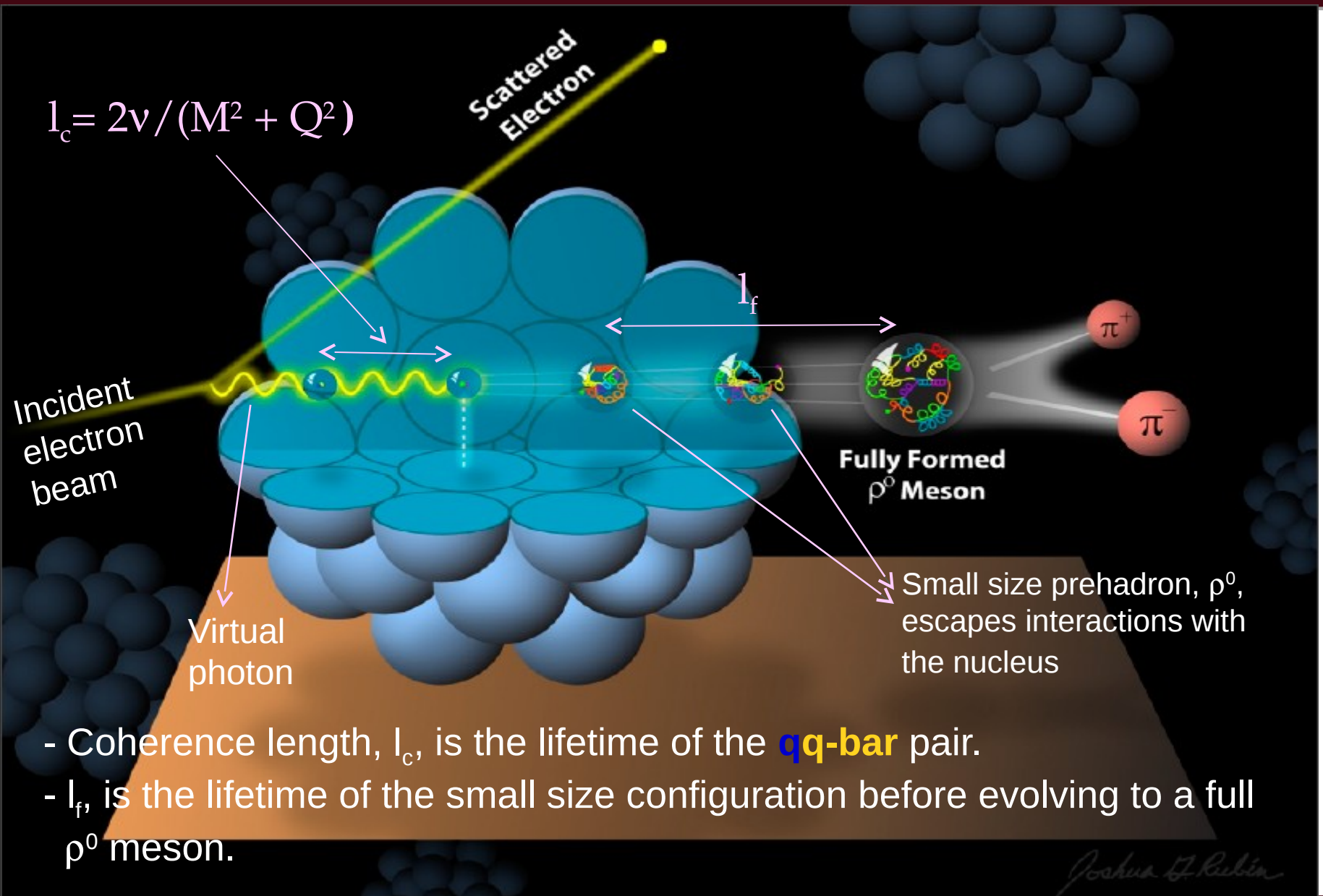
B. Clasie et al. PRL 90, 10001 (2007), X

# Exclusive $\rho^0$ leptonproduction

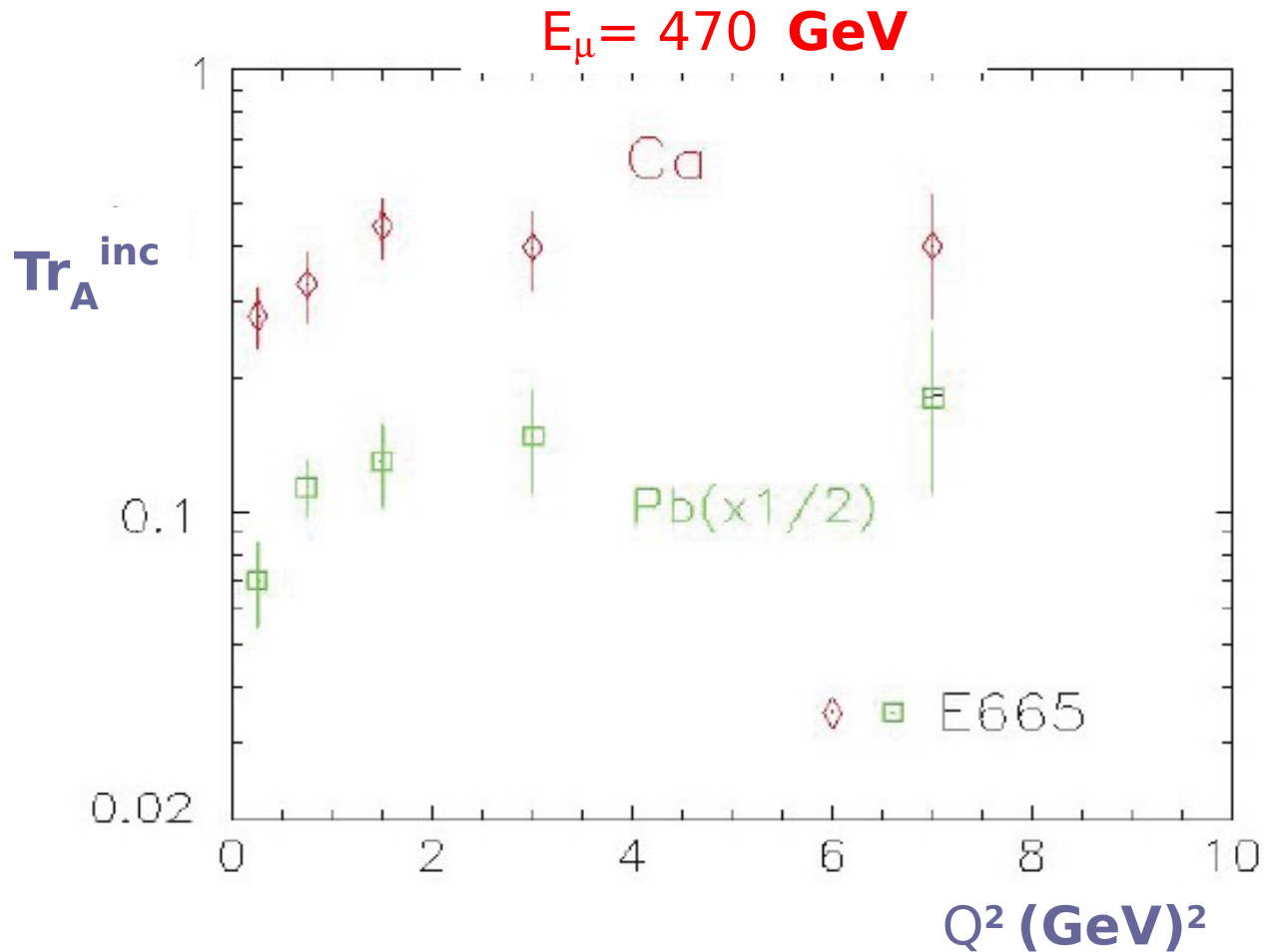




# Exclusive $\rho^0$ leptonproduction



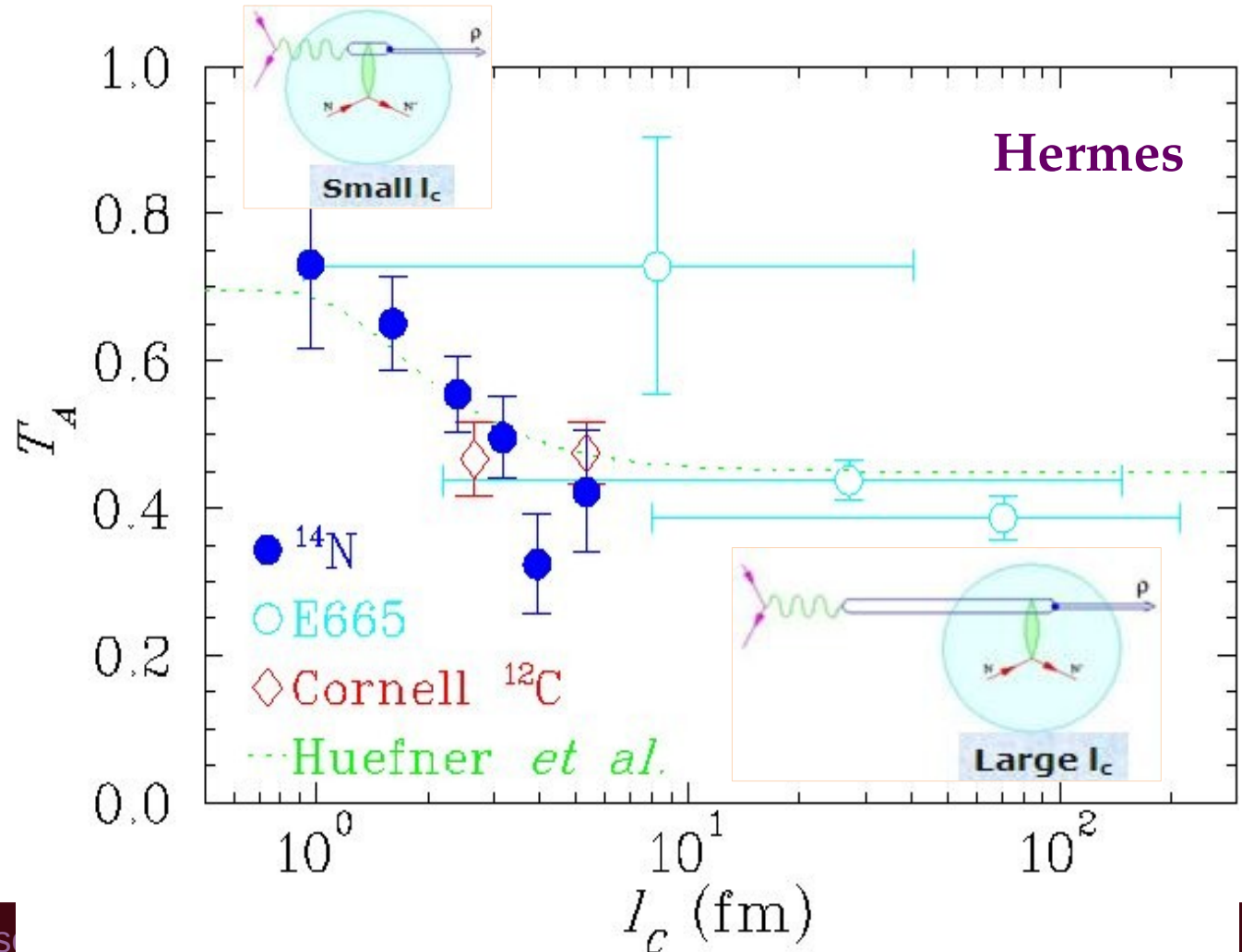
# Exclusive $\rho^0$ leptonproduction: FNAL E665



Adams et al. PRL 74, 1525 (1995)

# Coherence length effect (CL) could mimic CT signal?

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

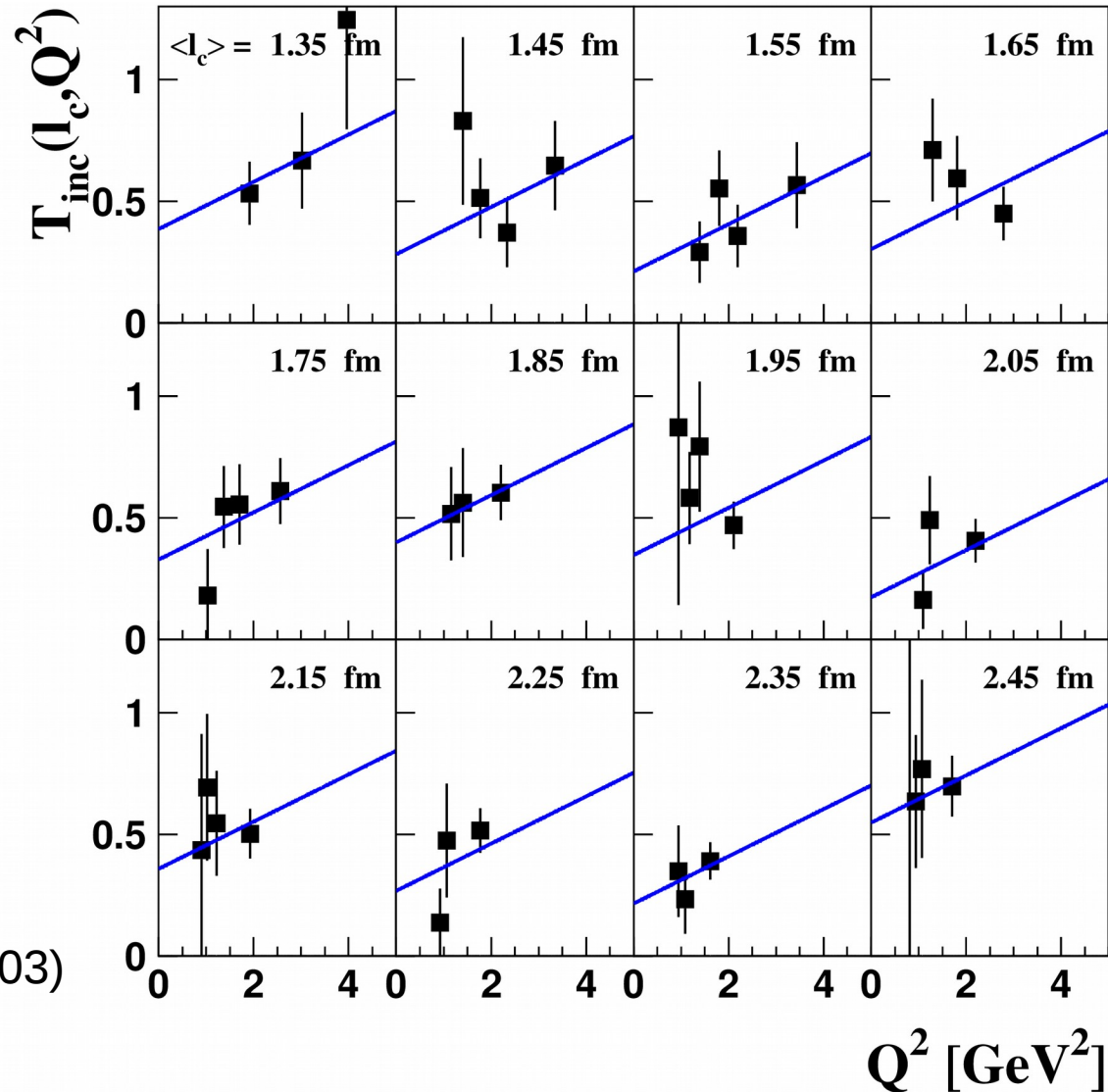


# Exclusive $\rho^0$ leptonproduction: Hermes

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

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

$E_{e^+} = 27.5 \text{ GeV}$



Airapetian et al. PRL 90, 052501 (2003)

# CLAS-6/12 CT and CP Collaboration

K. Joo (U. Connecticut)

K. Kicks (Ohio U.)

**K. Hafidi**, Sereres Johnston and **B. Mustapha** (ANL)

**L. El Fassi**, Latiful Kabir and Shirsendu Nanda (Miss State U.)

**M. Holtrop** and **L. Zana** (U. New Hampshire)

**R. Dupre** (IPN-Orsay)

**W. K. Brooks**, A. El Alaoui, **H. Hakobyan**, **T. Mineeva** and **Orlando Soto** (UTFSM)

L. Weinstein (Old Dominion Univ.)

J. Gilfoyle (U. Richmond)

I. Niculescu and G. Niculescu (James Madison Univ.)

M. Wood (Canesius College)

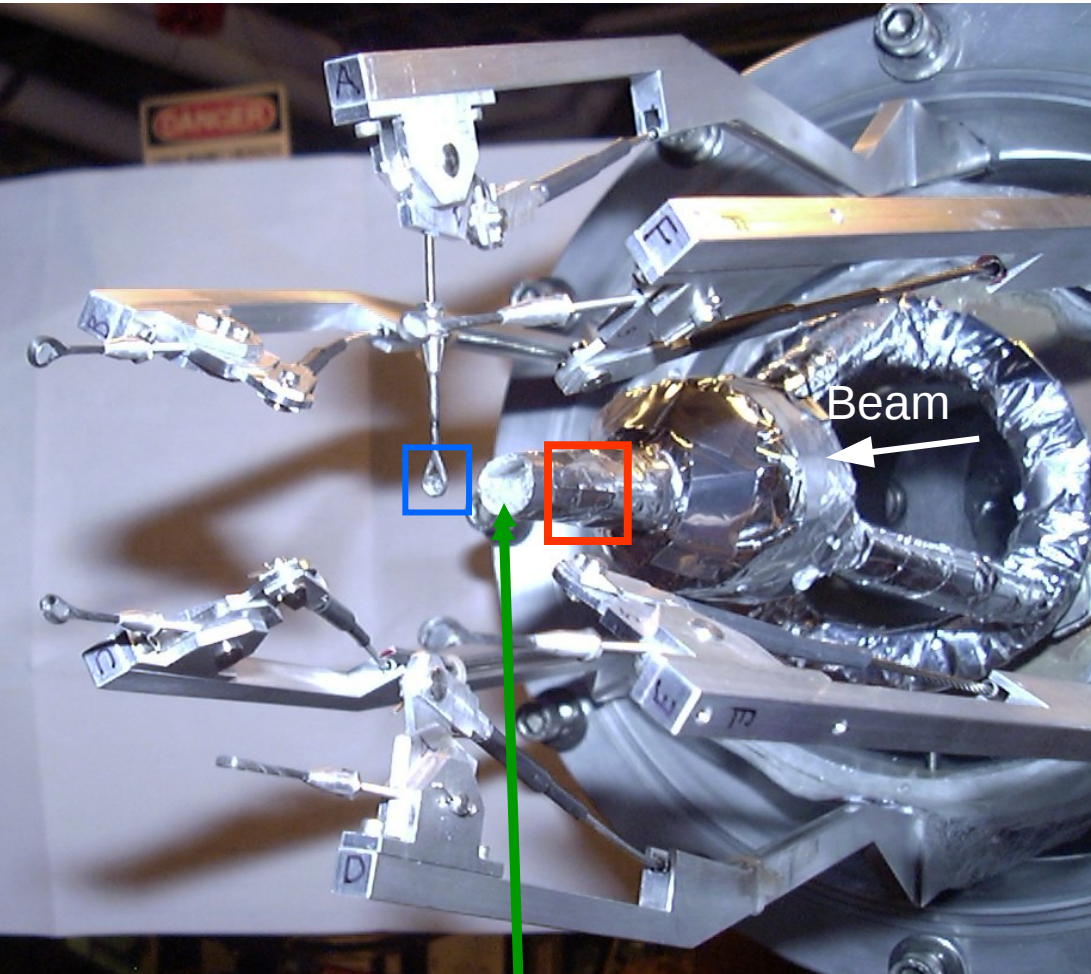
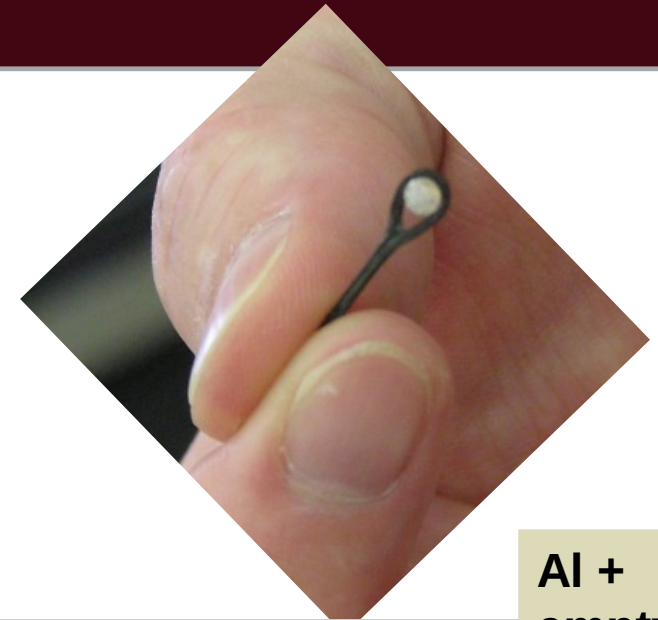
**○** CLAS-6 CT or CP experiment Spokespersons

CLAS-12 CT and/or CP experiment Spokespersons

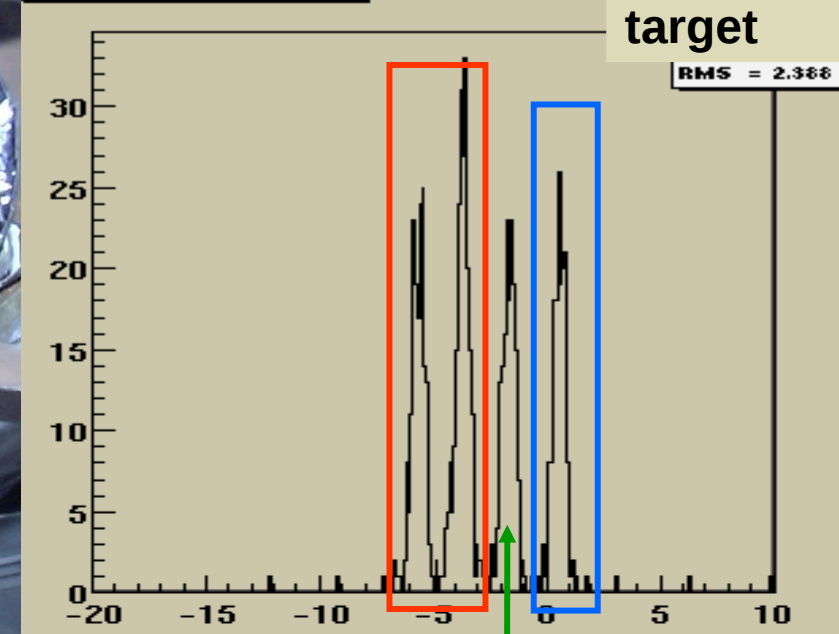
**○** Former CLAS-6 CT or CP Graduate Students

# CLAS-6 CT and CP Experiments

## EG2 run-group targets



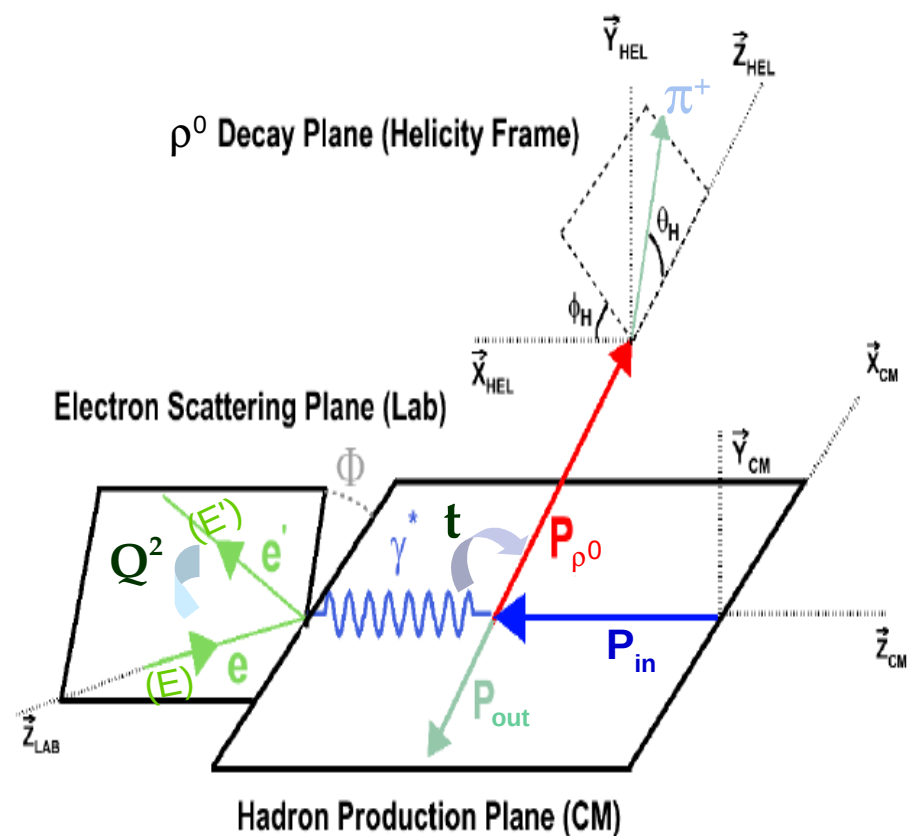
Zv (cm) itrk0 (sec 1)



Reference Foil

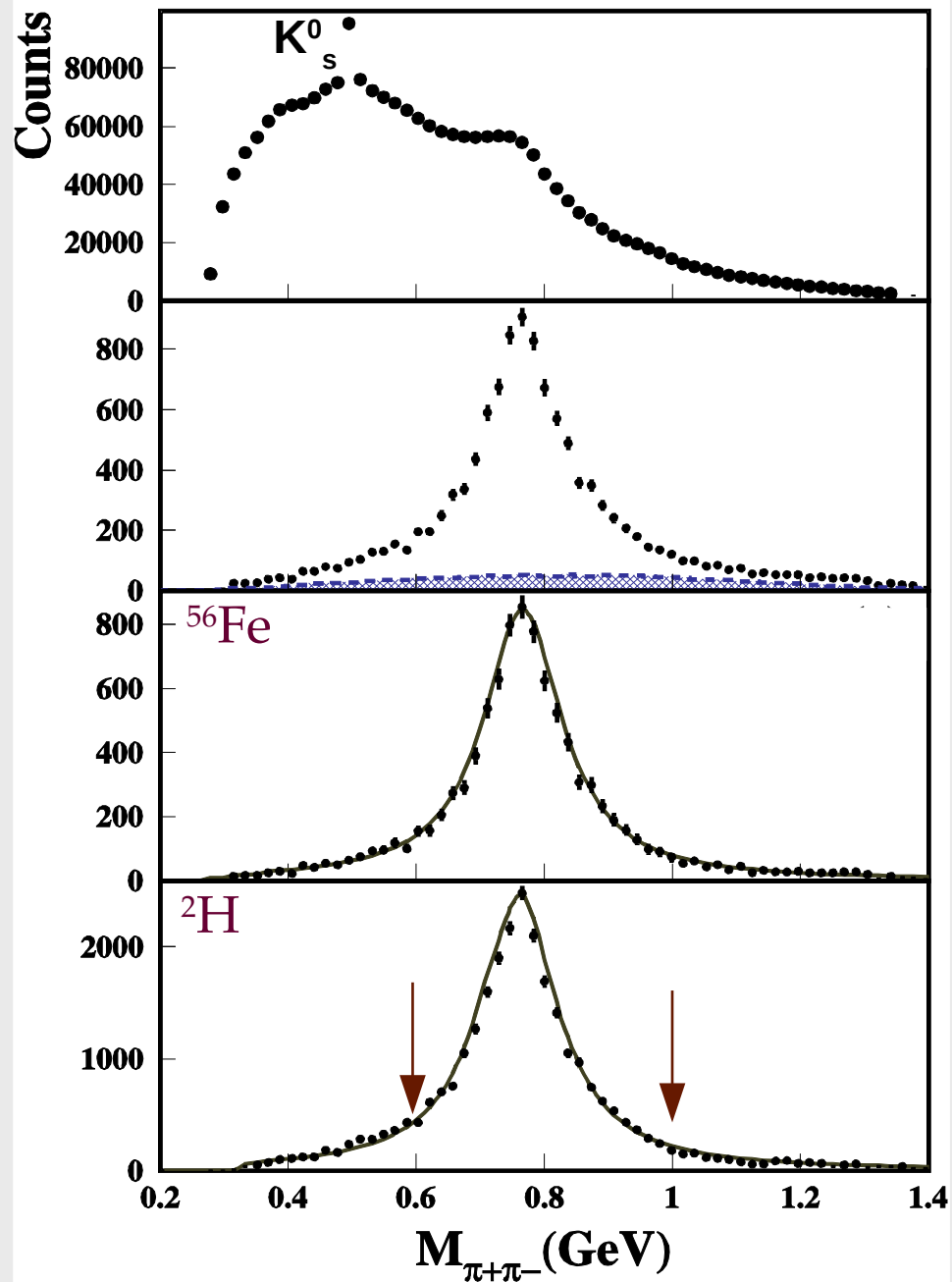
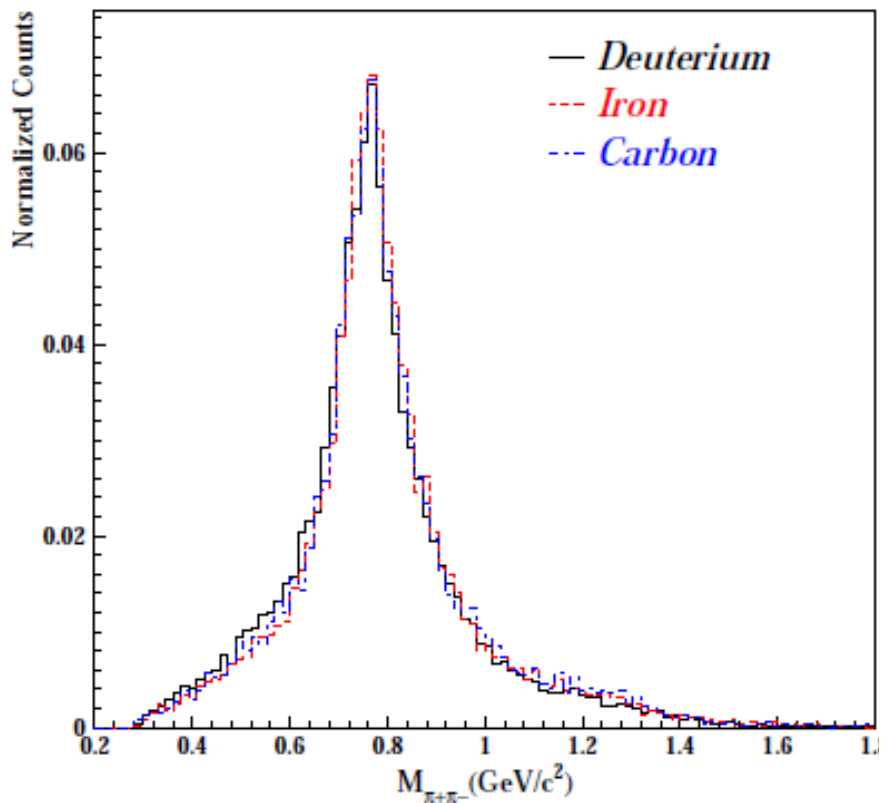
# $\rho^0$ Electro-production Kinematics

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



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

# Two pions invariant mass

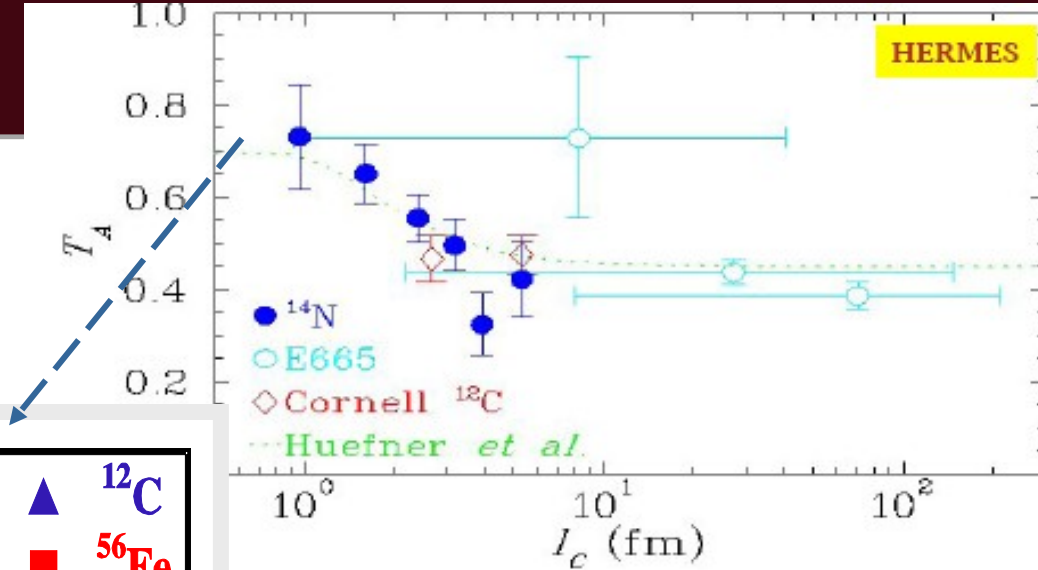
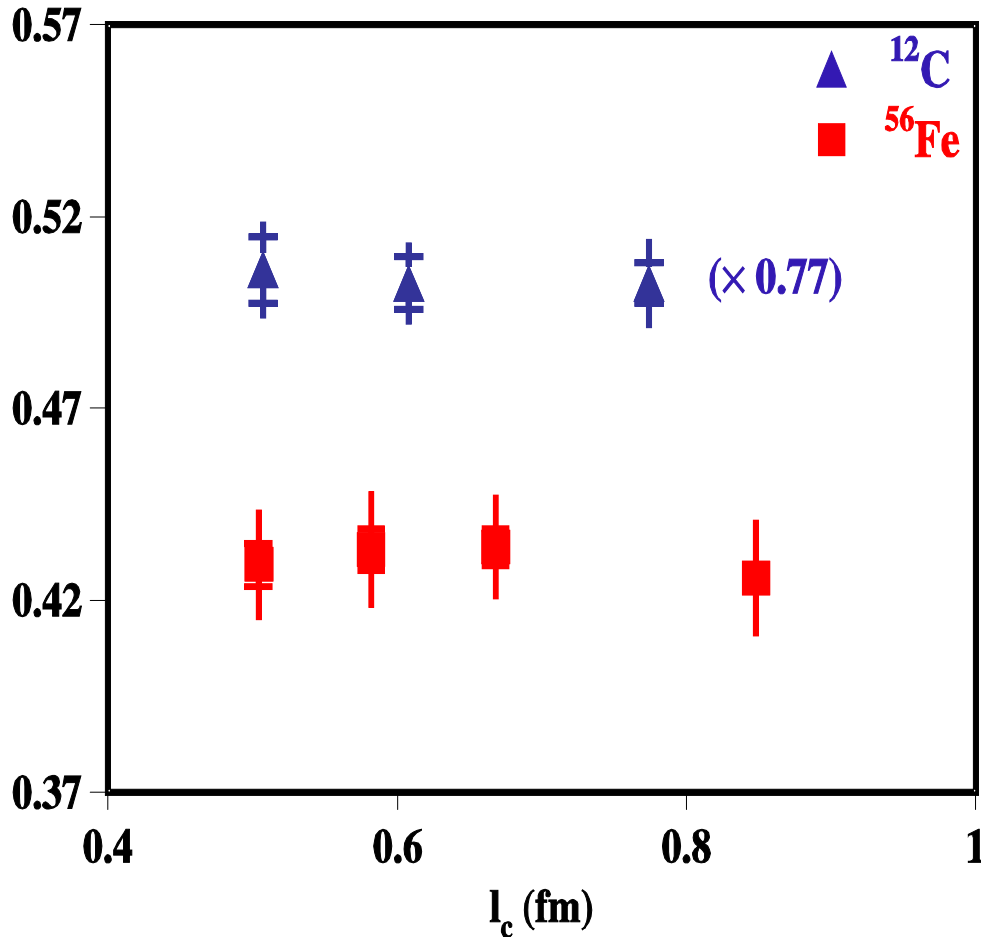




# $l_c$ Dependence on $T_A$

Coherence Length

$$l_c = 2v / (M^2 + Q^2)$$



## Nuclear Transparency

$$T_A^p = N_A^p / N_D^p \times (\rho_D \times t_D) / (\rho_A \times t_A)$$

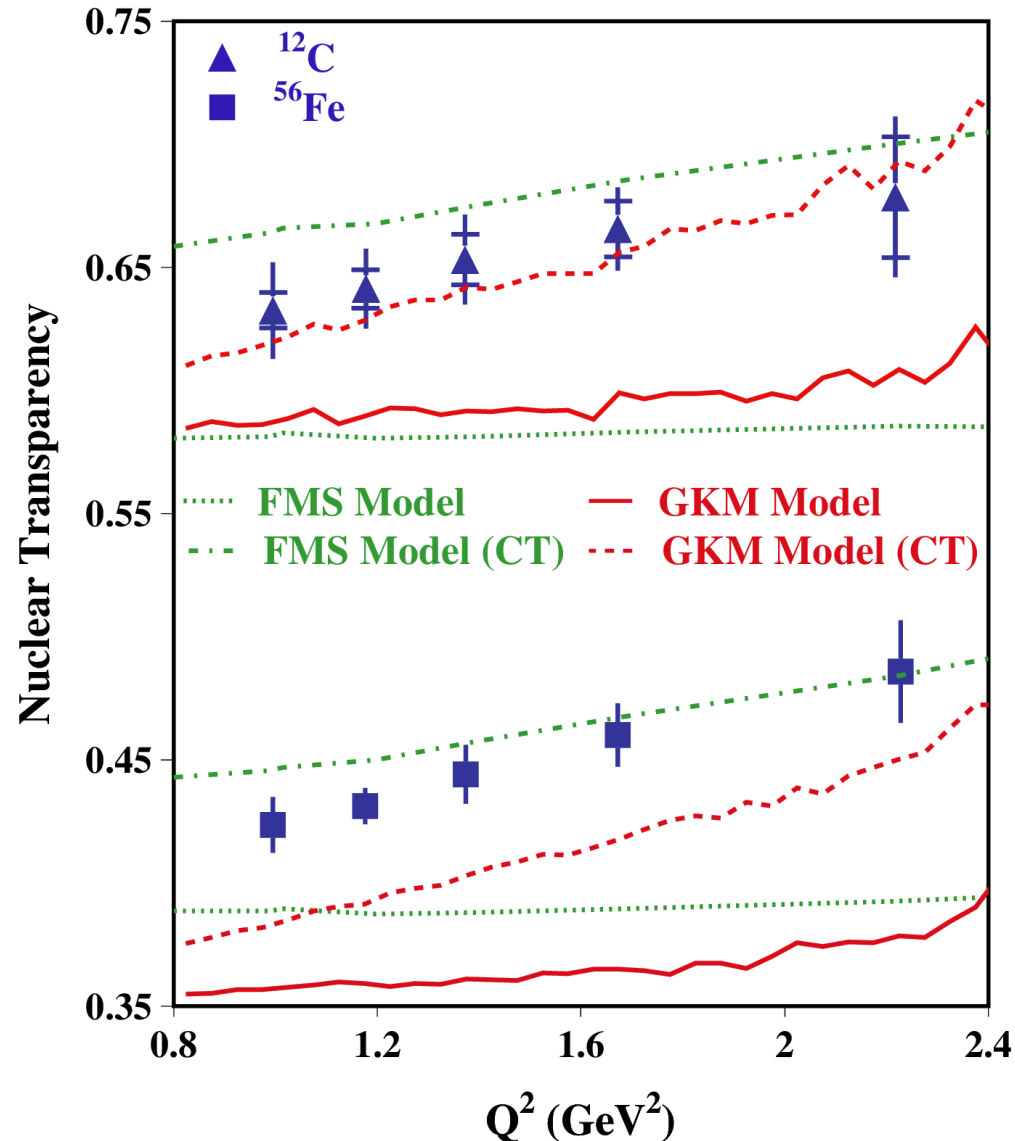
- $\rho_D$  and  $\rho_A$  are target's densities
- $t_A$  is the solid target thickness
- $t_D = 2$  cm, liquid target length

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

# $\rho^0$ 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  $\rho^0$  decay.  
Frankfurt, Miller & Strikman, PRC 78 (08)  
& Private communication

- **GKM**: Transport Model (GiBUU)
- dashed curve includes CT effects for  $\rho^0$  produced in DIS regime only!  
Gallmeister, Kaskulov & Mosel, PRC 83, 015201 (2011)



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

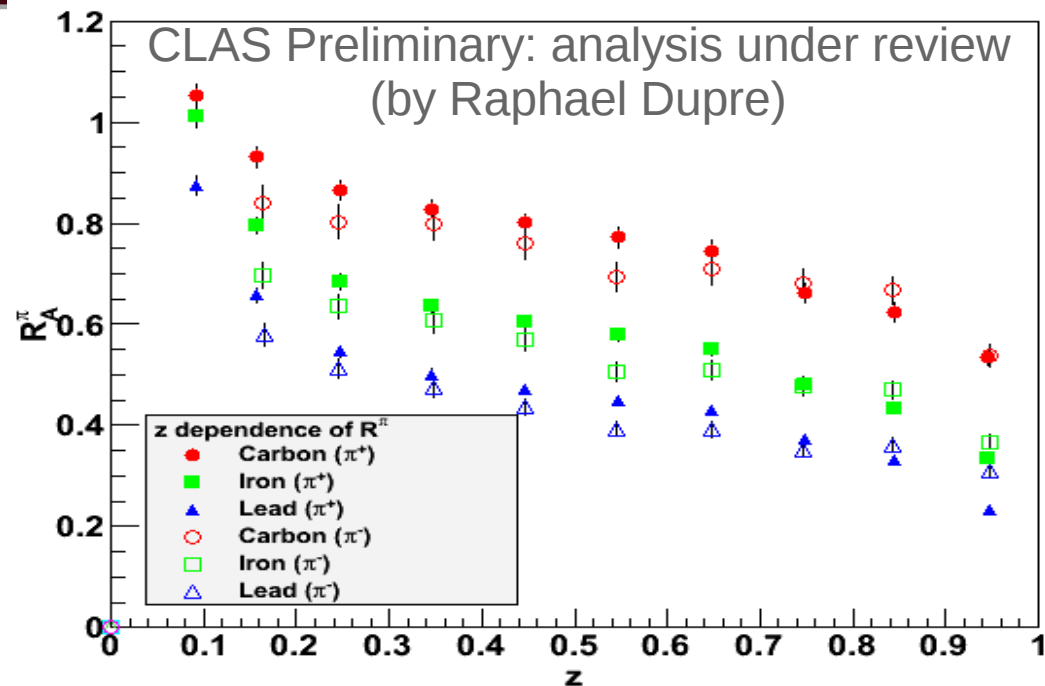
$\rho^0$  CT slopes from linear fit of  $Q^2$  dependence,  $T_A = a Q^2 + b$

Targets / Models	Carbon slopes (GeV <sup>-2</sup> )	Iron slopes (GeV <sup>-2</sup> )
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

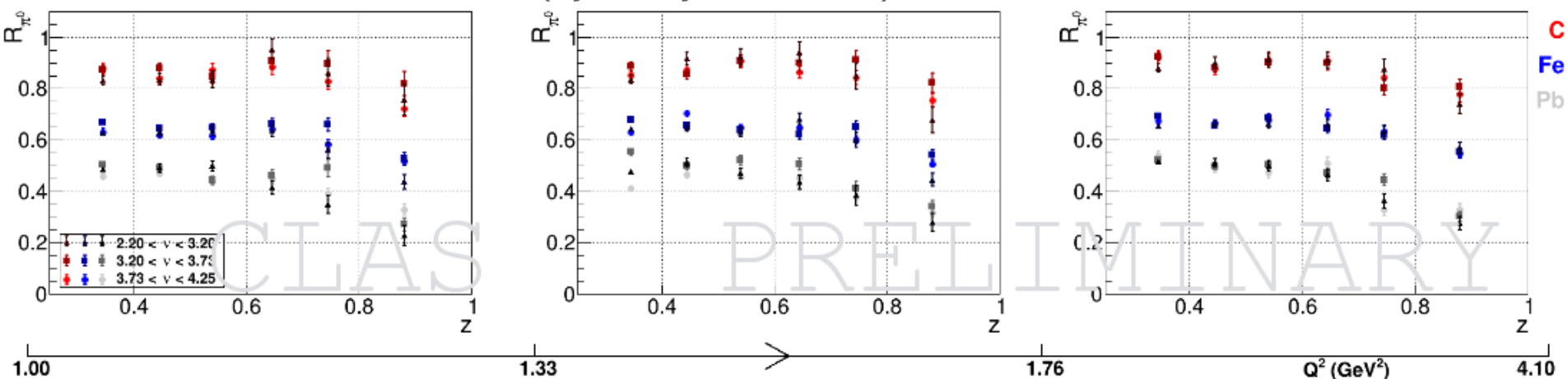
Kopeliovich, Nemchik & Schmidt, PRC 76, 015205 (2007)  
& Private communication

# 5 GeV CLAS-6 Hadronization Results: Meson Channels



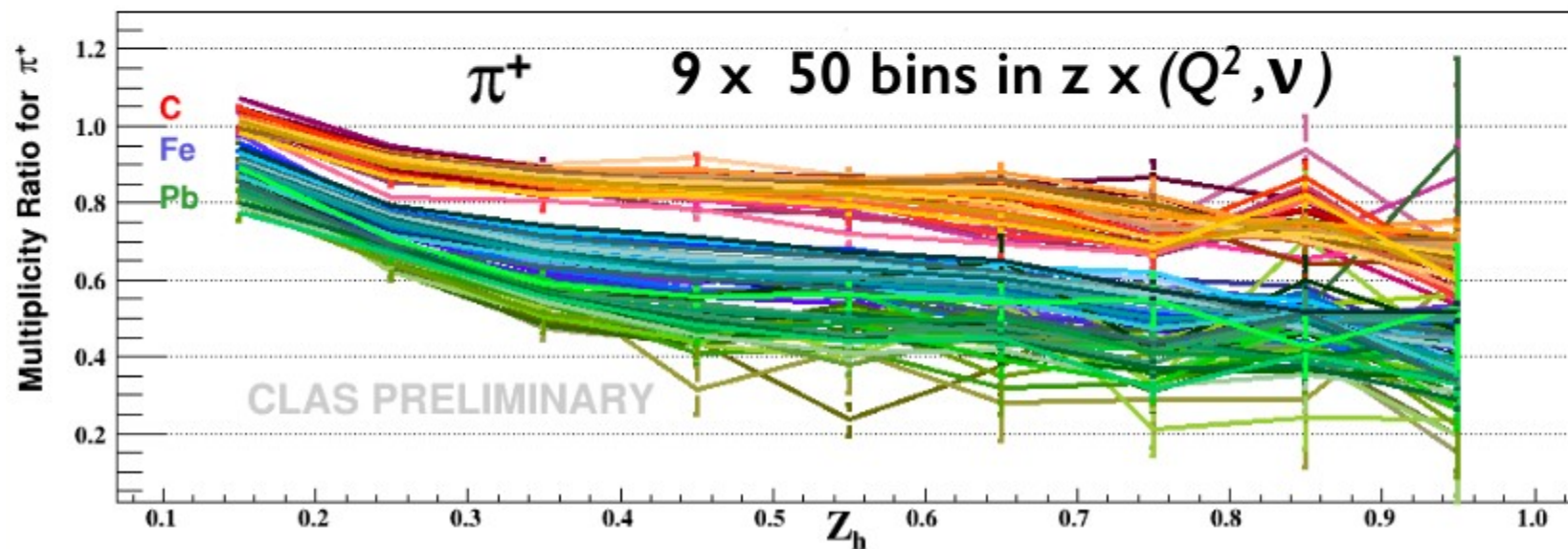
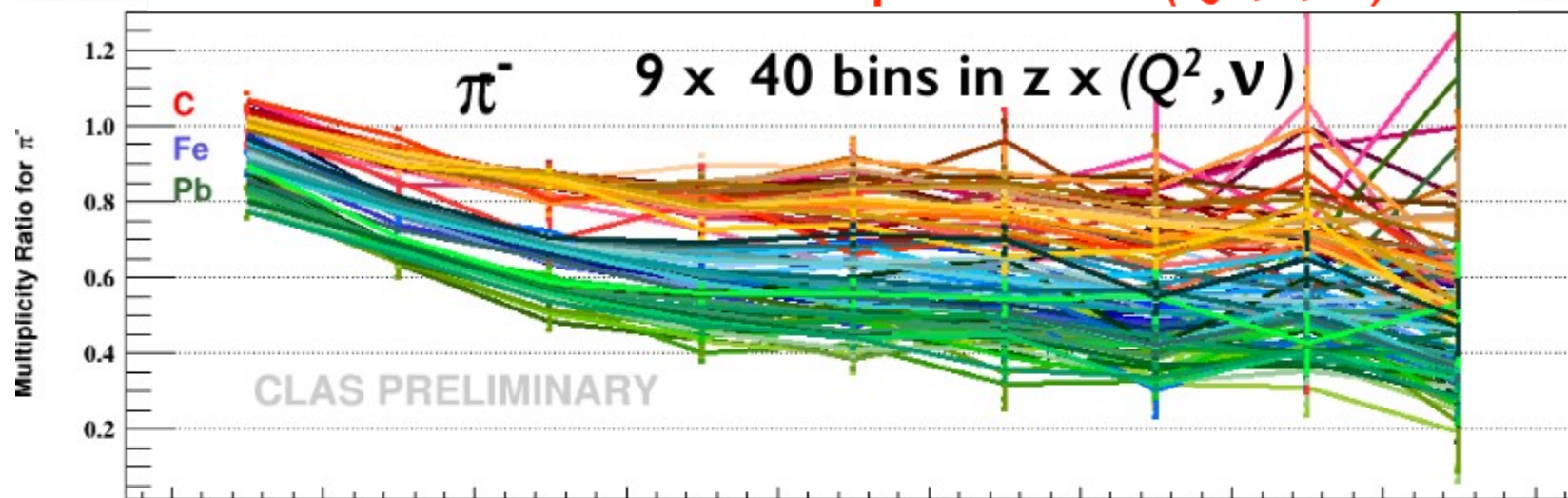
- 3-dimensional CLAS-6 multiplicity ratios, fully corrected for radiative processes and acceptance, normalized to target thicknesses; C, Fe, Pb.
- Similar behavior for  $\pi^0$  (Taisiya's thesis results; under review),  $\pi^+$  (Hayk's thesis) and  $K^0$  (A. Daniel, Ken Hicks *et al.*; published!)
- Consistent with Hermes results!

Example of 3-D  $\pi^0$  multiplicity ratios  
(by Taisiya Mineeva)

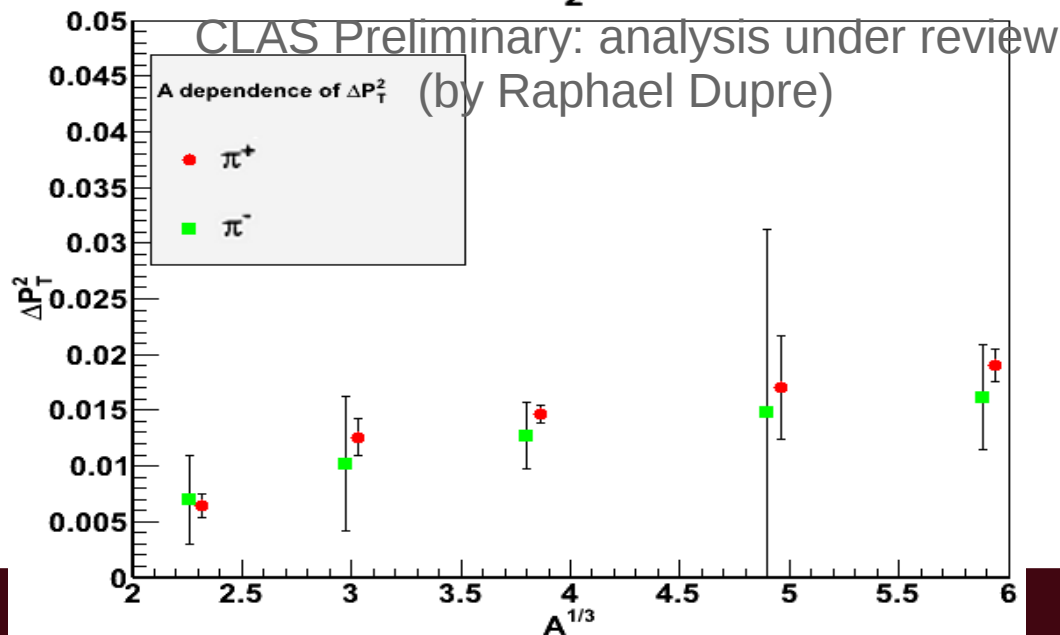
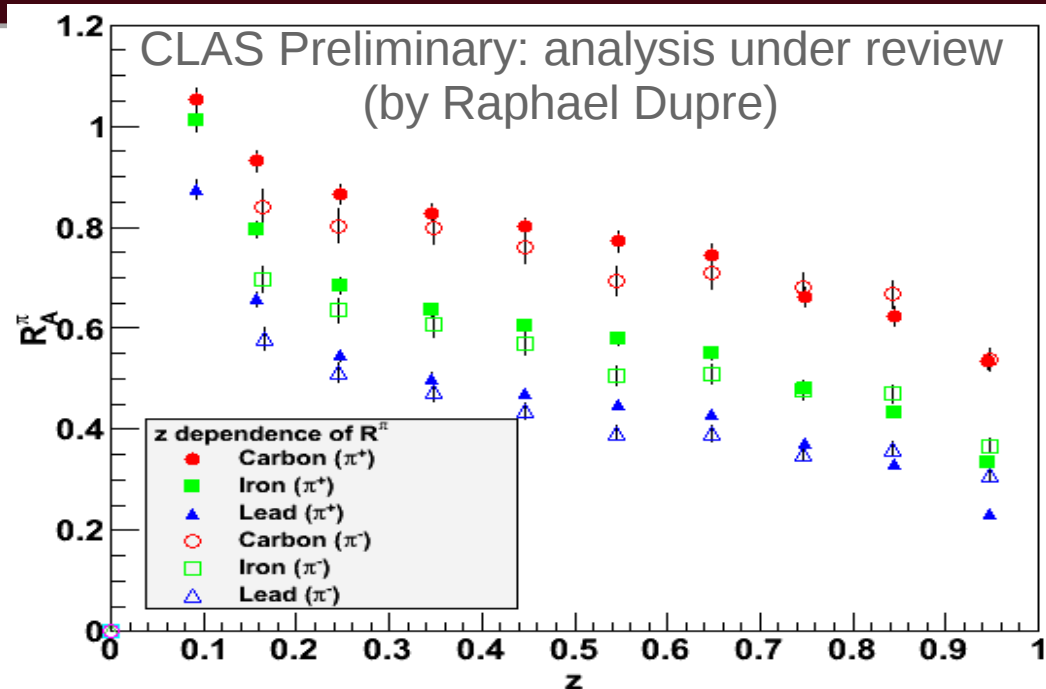


# 5 GeV CLAS-6 Hadronization Results: Meson Channels

## 3D $\pi^+$ and $\pi^-$ Multiplicities $R_\pi(Q^2, \nu, z)$



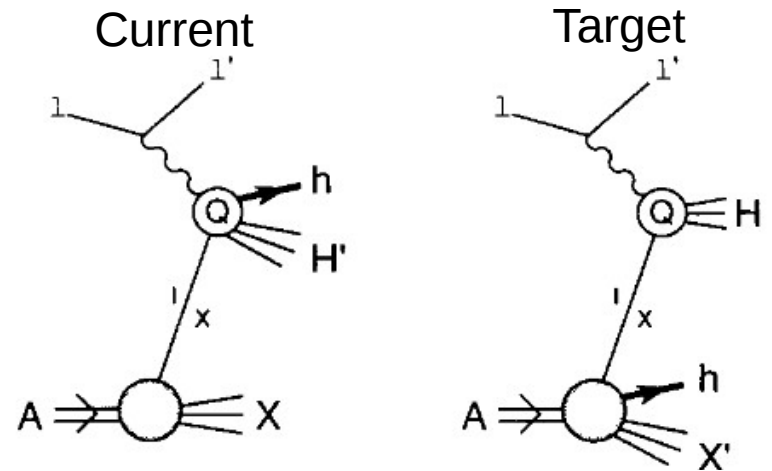
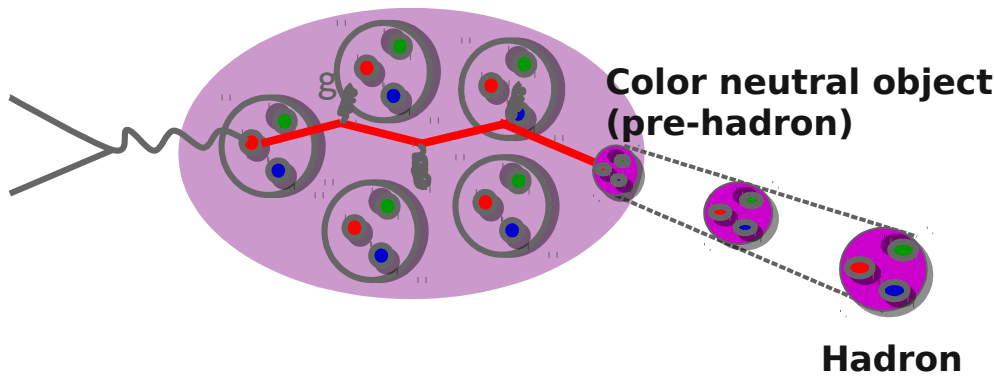
# 5 GeV CLAS-6 Hadronization Results: Meson Channels



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- Similar behavior for  $\pi^0$  (Taisiya's thesis results; under review),  $\pi^+$  (Hayk's thesis) and  $K^0$  (A. Daniel, Ken Hicks *et al.*; published!)
- Consistent with Hermes results!
- CLAS-6 transverse momentum broadening results for charged pions shows a similar behavior (a slight shift was added for a clarity!).
- Saturation behavior for large nuclei.

# 5 GeV CLAS-6 Hadronization Results: Baryon Channel

- First time ever to study the hadronization process of  $\Lambda^0$  hyperon and probe the forward (current) and backward (target) fragmentation regions.



Phys. Let. B 323 (1994) 201-211, Trentadue and Veneziano

# 5 GeV CLAS-6 Hadronization Results: Baryon Channel

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D2/Fe/C/Pb: DIS  $\Lambda^0$

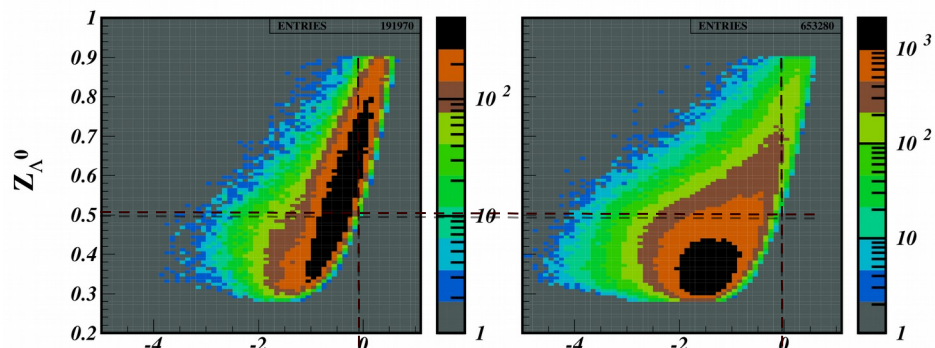


Fig. 1. D2:  $X_F$

Fig. 2. Fe:  $X_F$

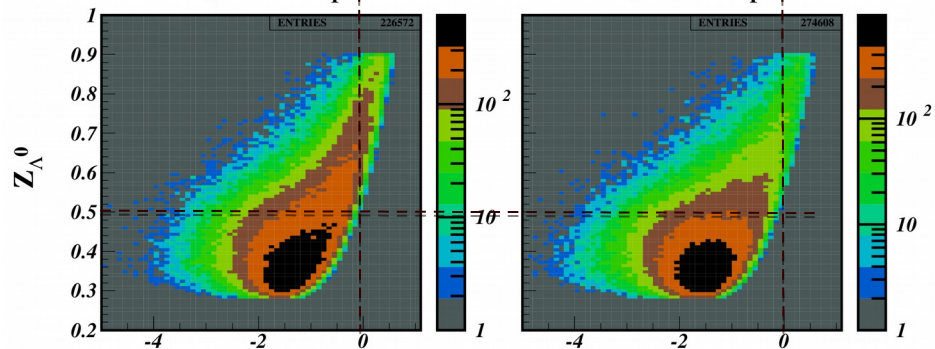
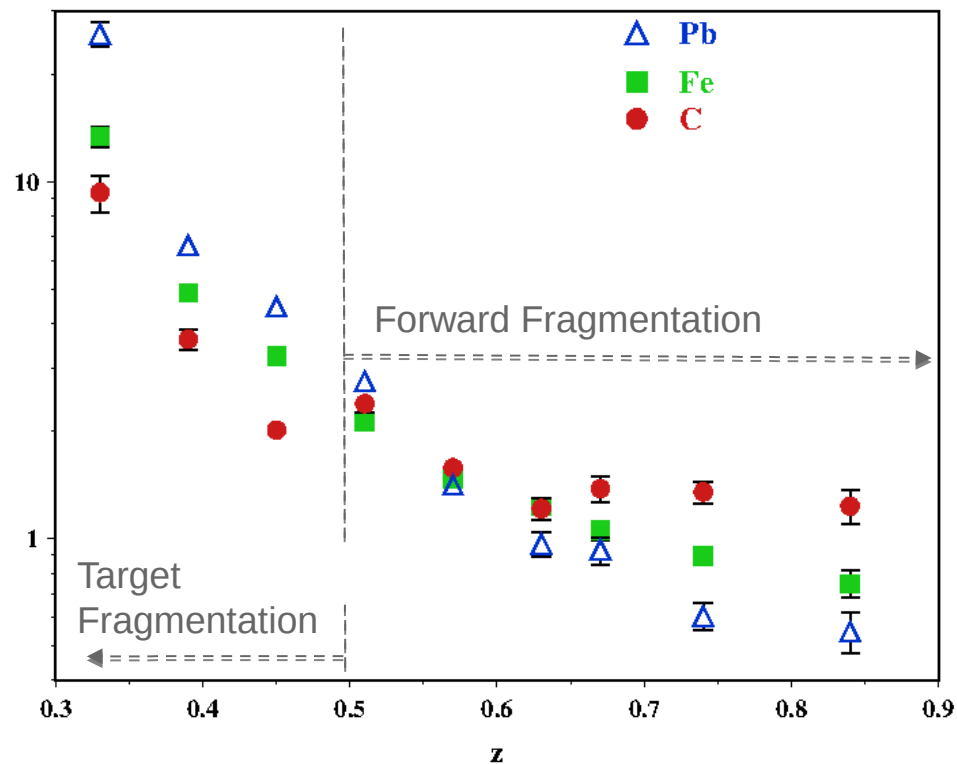


Fig. 3. C:  $X_F$

Fig. 4. Pb:  $X_F$

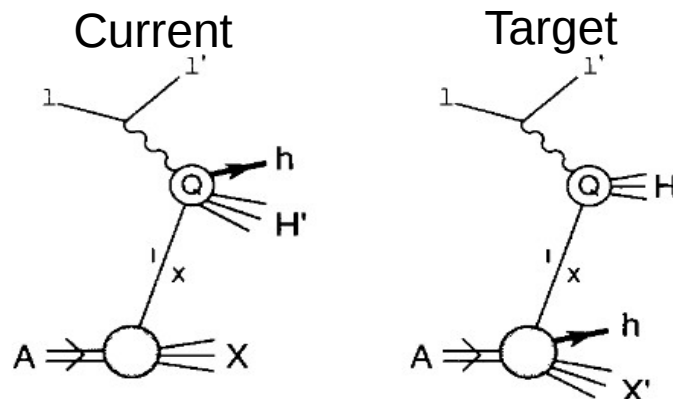
CLAS Preliminary: raw multiplicity ratio





# 5 GeV CLAS-6 Hadronization Results: Baryon Channel

- First time ever to study the hadronization process of  $\Lambda^0$  hyperon and probe the forward (current) and backward (target) fragmentation regions.

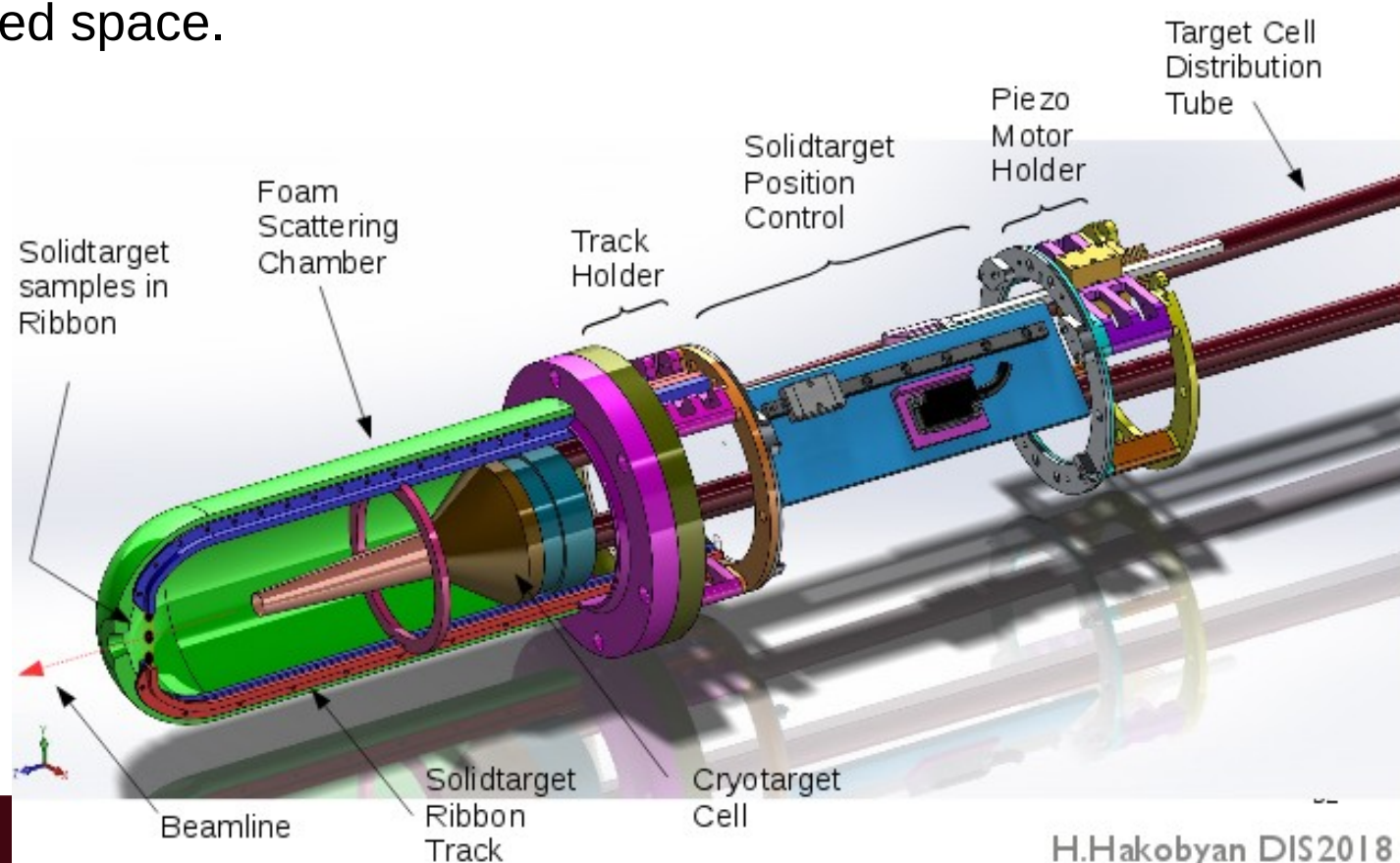


Phys. Let. B 323 (1994) 201-211  
Trentadue and Veneziano

- Aim to study also the other universal functions known as the fracture functions that encode the information on both the parton participating on the hard scattering and the fragmentation of the spectator system into the observed hadron.

Federico Alberto Ceccopieri and Davide Mancusi, Eur. Phys. J.C 73, 2013

- Dual target is currently under construction in UFTSM, Chile!
- Will operate under extreme conditions:
  - High vacuum ( $6 \times 10^{-6}$  mbar),
  - Magnetic field (5 Tesla),
  - Cryotarget at 30 °K,
  - Radiation hardness,
  - Reduced space.



# DIS channels: *stable* hadrons, accessible with 11 GeV JLab experiment PR12-06-117

Actively underway with existing 5 GeV data

<i>meson</i>	$c\tau$	mass	flavor content	<i>baryon</i>	$c\tau$	mass	flavor content
$\pi^0$	25 nm	0.13	$u\bar{u}d\bar{d}$	$p$	stable	0.94	ud
$\pi^+, \pi^-$	7.8 m	0.14	$u\bar{d}, d\bar{u}$	$\bar{p}$	stable	0.94	$\bar{u}\bar{d}$
$\eta$	170 pm	0.55	$u\bar{u}d\bar{d}s\bar{s}$	$\Lambda$	79 mm	1.1	uds
$\omega$	23 fm	0.78	$u\bar{u}d\bar{d}s\bar{s}$	$\Lambda(1520)$	13 fm	1.5	uds
$\eta'$	0.98 pm	0.96	$u\bar{u}d\bar{d}s\bar{s}$	$\Sigma^+$	24 mm	1.2	us
$\phi$	44 fm	1.0	$u\bar{u}d\bar{d}s\bar{s}$	$\Sigma^-$	44 mm	1.2	ds
$f_1$	8 fm	1.3	$u\bar{u}d\bar{d}s\bar{s}$	$\Sigma^0$	22 pm	1.2	uds
$K^0$	27 mm	0.50	$d\bar{s}$	$\Xi^0$	87 mm	1.3	us
$K^+, K^-$	3.7 m	0.49	$\bar{u}s, \bar{d}s$	$\Xi^-$	49 mm	1.3	ds

# DIS channels: *stable* hadrons, accessible with 11 GeV JLab experiment PR12-06-117

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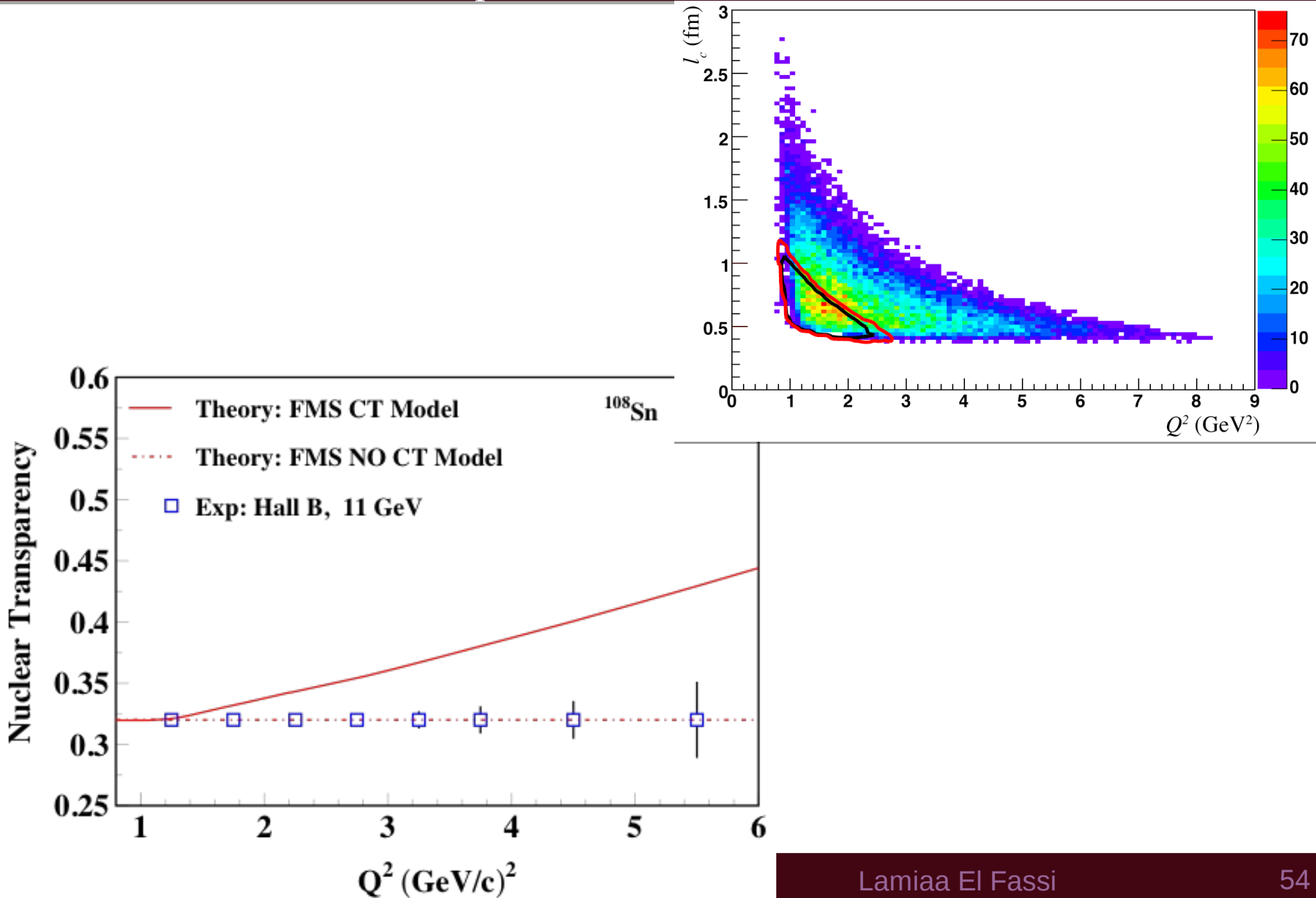
<i>meson</i>	$c\tau$	mass	flavor content	<i>baryon</i>	$c\tau$	mass	flavor content
$\pi^0$	25 nm	0.13	$\bar{u}d\bar{d}$	$p$	stable	0.94	$ud$

- Span a wider range of nuclei masses  $\implies$  Better understanding of the A dependence,
  - Study the production of a variety of hadrons  $\implies$  Improve our understanding of hadron's formation mechanism,
  - Cover much larger kinematical coverage,
  - 10 times higher luminosity compared to CLAS-6 (1000 higher than Hermes),
- $\implies$  Determines the two hadronization time-scales and constrain the existing theoretical models with the correct production picture!

$K^0$	27 mm	0.50	$\bar{d}s$	$E^0$	87 mm	1.3	us
$K^+, K^-$	3.7 m	0.49	$\bar{u}s, \bar{u}\bar{s}$	$E^-$	49 mm	1.3	ds

# CLAS-12 CT Measurement with C, Cu and Sn, unfortunately no Fe

## Experiment PR12-06-106

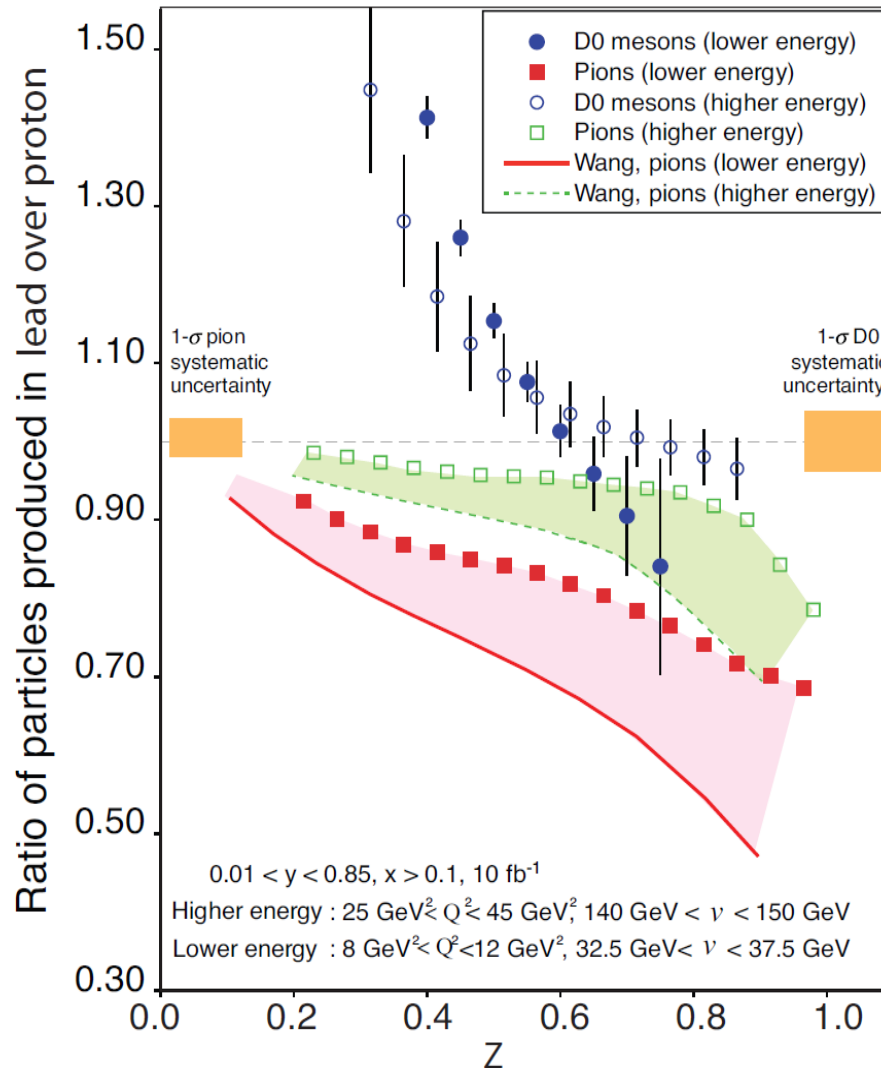


# Summary and Outlook

- Strong evidence for the onset of CT using  $\rho^0$  electroproduction off nuclei and CLAS-6 5 GeV dataset -  $11 \pm 2.3\%$  ( $12.5 \pm 4.1\%$ ) decrease in the absorption of  $\rho^0$  in iron (carbon).
- SSC expansion time with FMS model were found to be between 1.1 fm and 2.4 fm for  $\rho^0$  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.
- Future CLAS12 measurement will allow to disentangle different CT effects (SSC creation, its formation and interaction with the nuclear medium)
- The hadronization study is a complementary probe of the QCD confinement in cold and hot nuclear matter.
- A detailed comprehension of its mechanism helps constraining the existing theoretical models.
- The future CLAS-12 will provide the multi-dimensional data needed to extract the production and formation time-scales.

# Summary and Outlook

EIC will allow the study of hadronization dynamics of heavy quarks in cold nuclear matter for a comparison with heavy ions collisions' data of RHIC and LHC, and provide a wider kinematics coverage to study the in-medium evolution and parton energy loss.



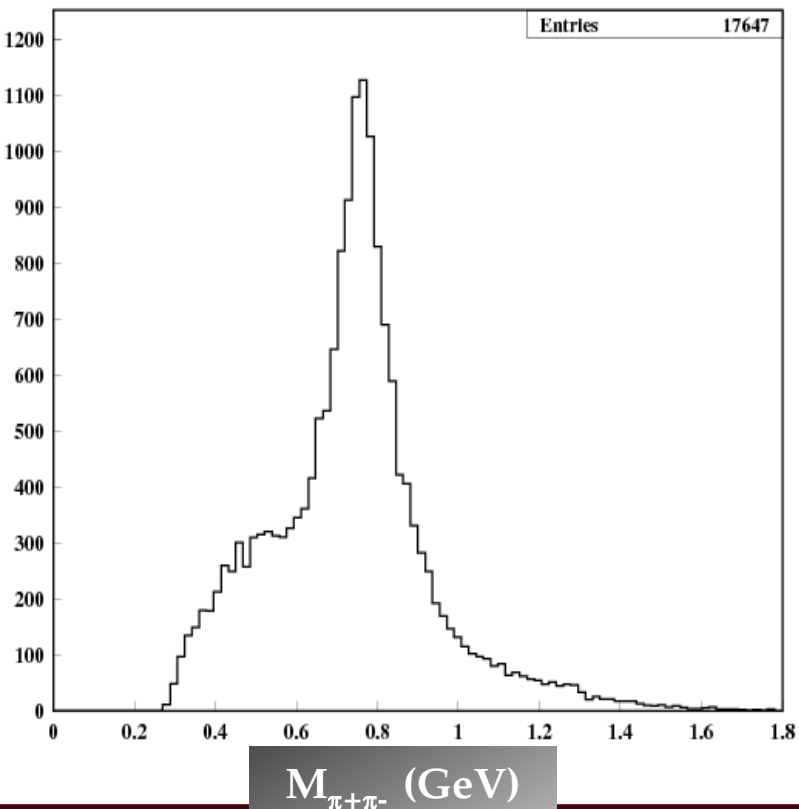
# Backup Slides



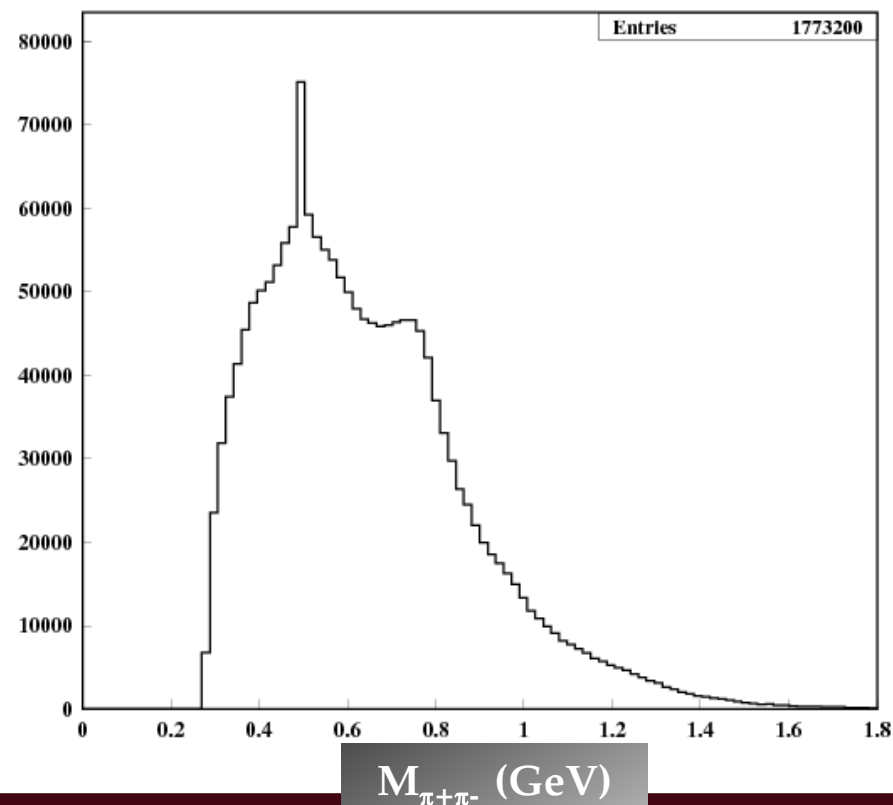
# $\rho^0$ Invariant mass from 5 GeV D2+Fe dataset

Iron

After t cut



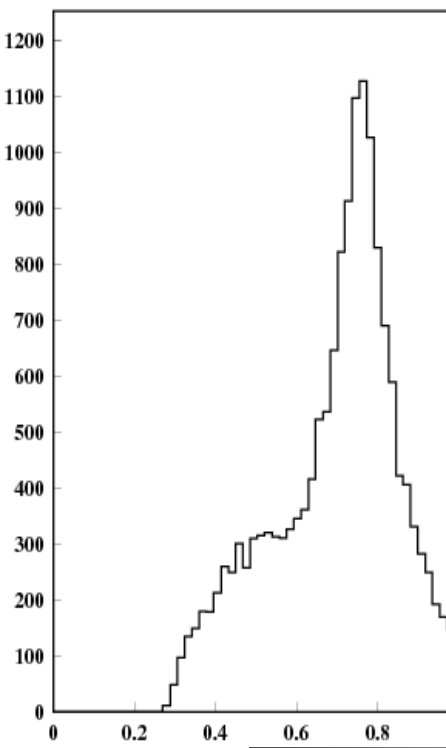
After w cut



# $\rho^0$ Invariant mass from 5 GeV D2+Fe dataset

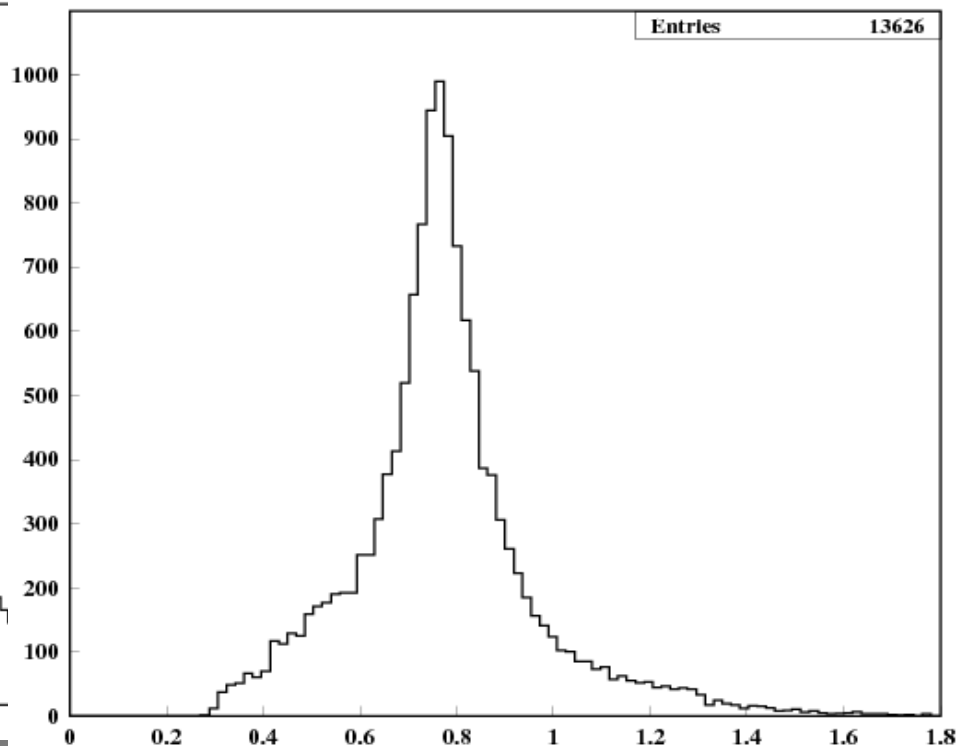
Iron

After t cut



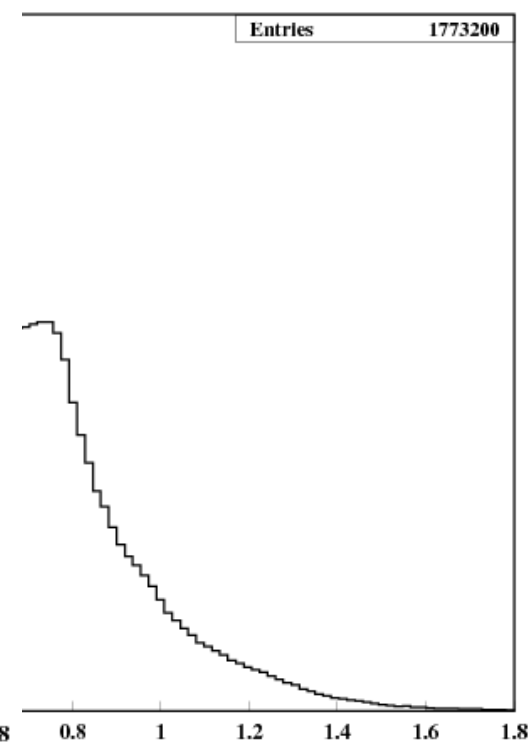
$M_{\pi^+\pi^-}$  (GeV)

After w and t cuts



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

After w cut



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

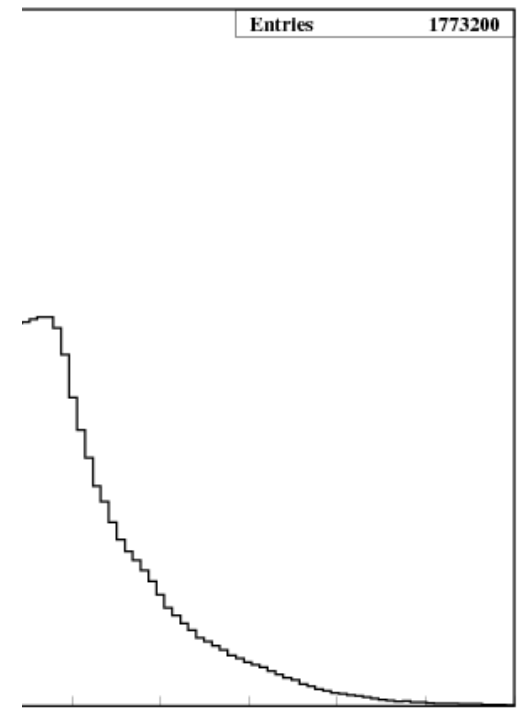
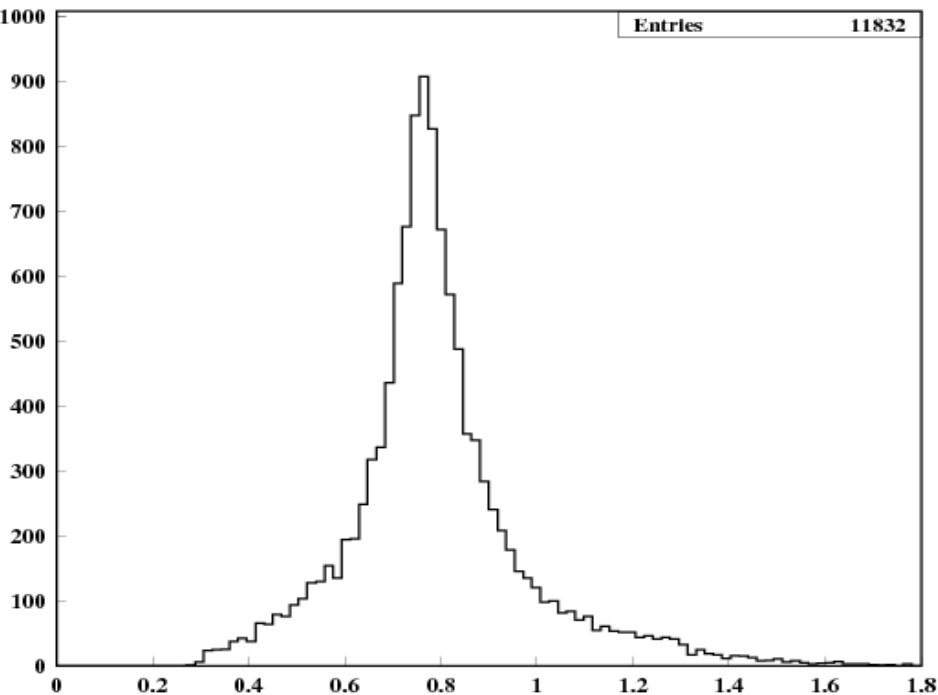
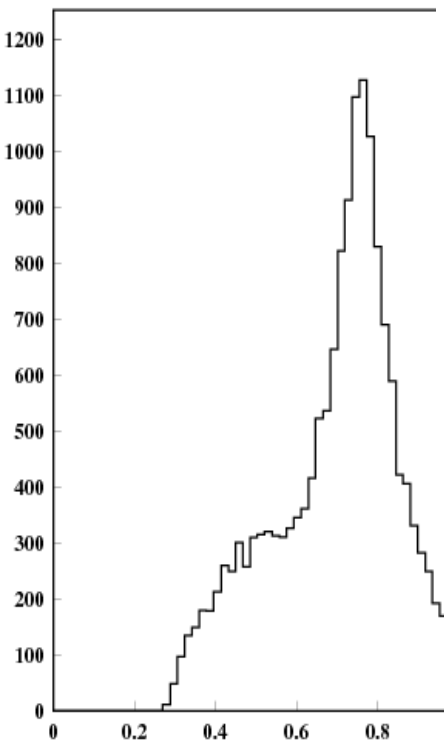
# $\rho^0$ Invariant

Iron

After w, t and z cuts

After t cut

After w cut



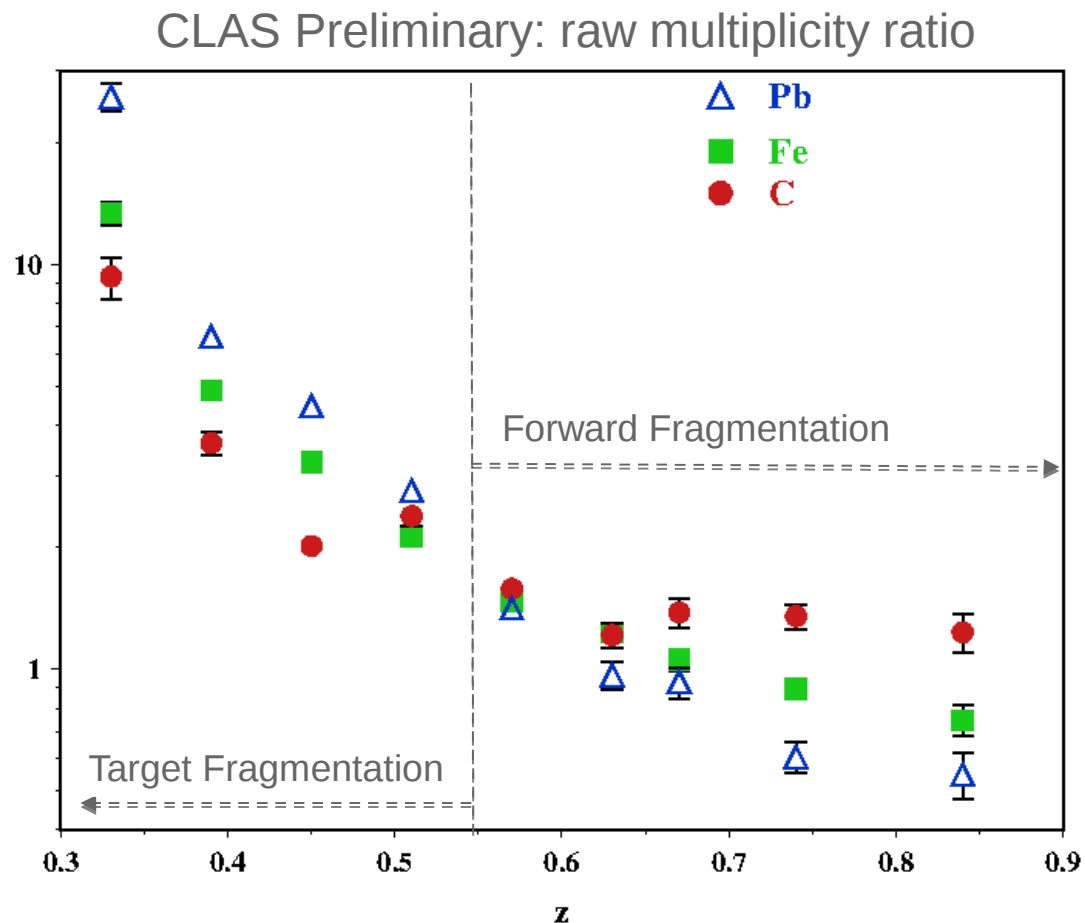
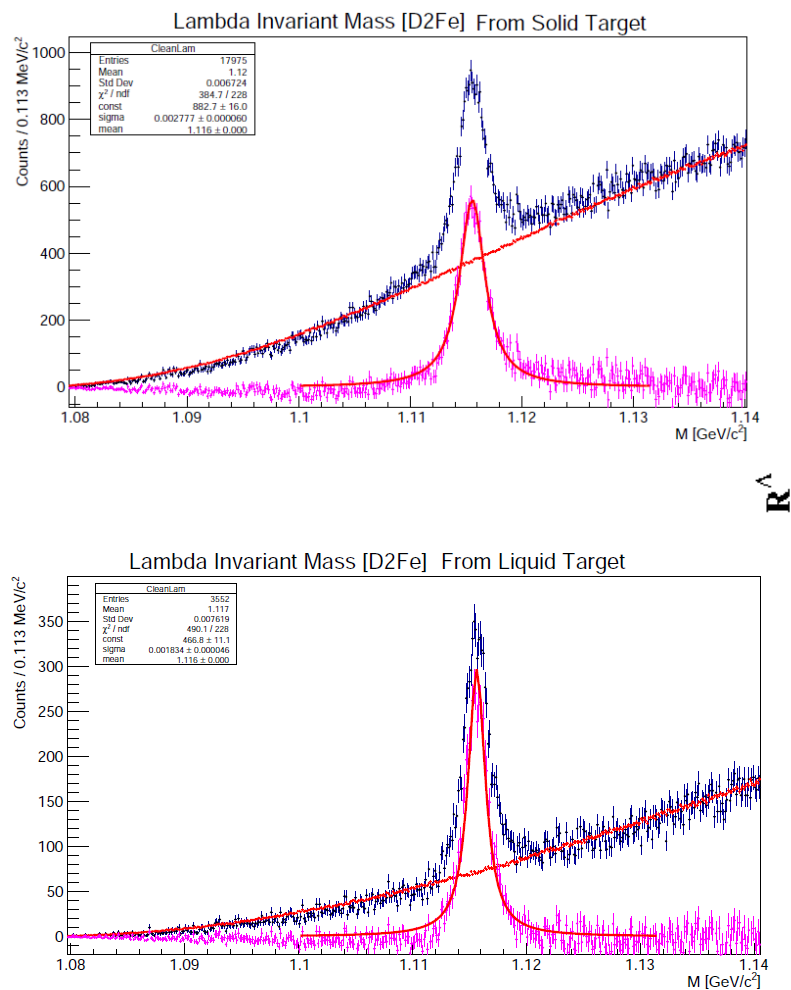
$M_{\pi^+\pi^-}$  (GeV)

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

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

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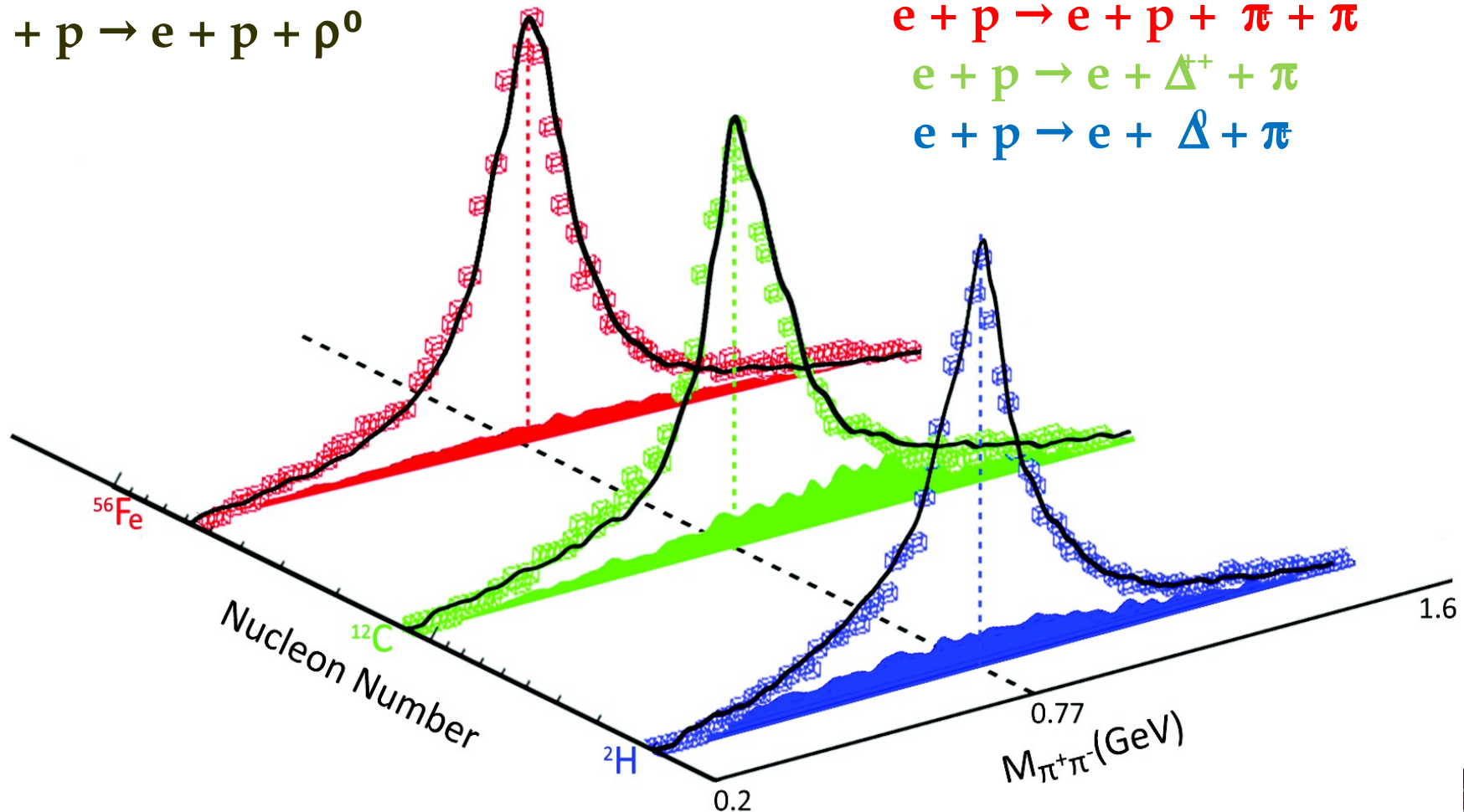
# Two pions invariant mass

- ➔ Our event generator incorporated the measured cross sections for the electroproduction of  $\rho^0$  and main background processes by Cassel et al.  
D. G. Cassel, Phys. Rev. D 24, 2787 (1981)

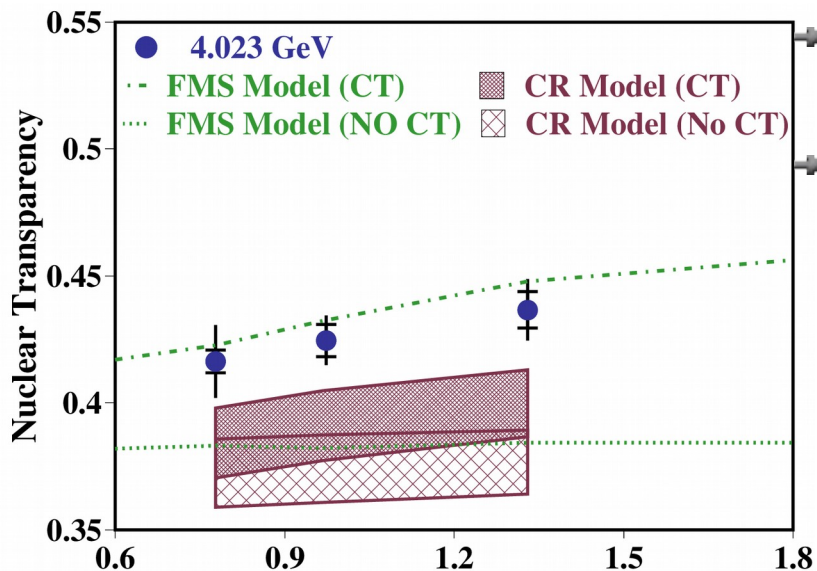
## Simple Breit-Wigner



## Simulated Background's Shapes

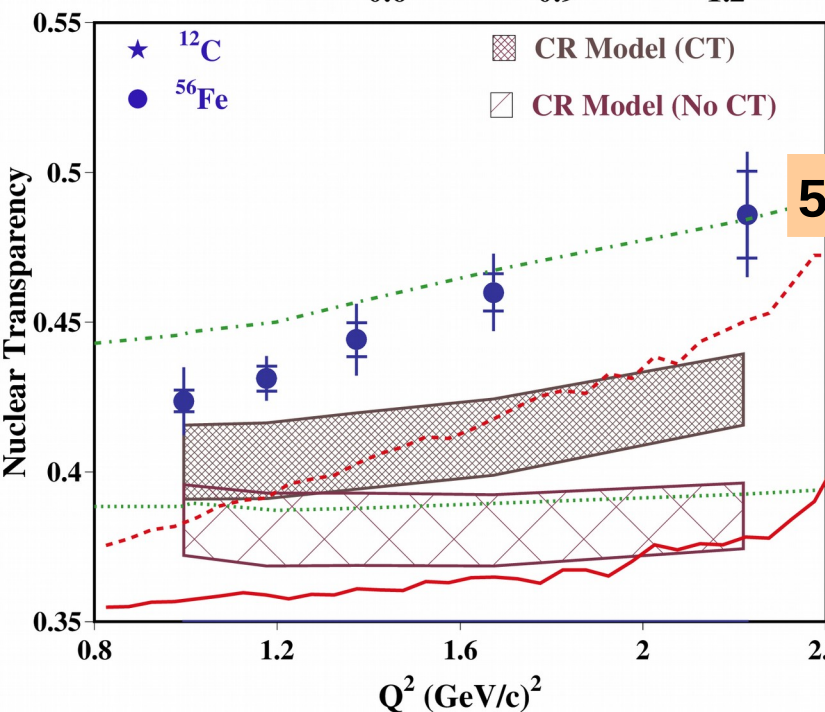


# CLAS-6 CT Results for 4 & 5 GeV EG2 data: Under Review

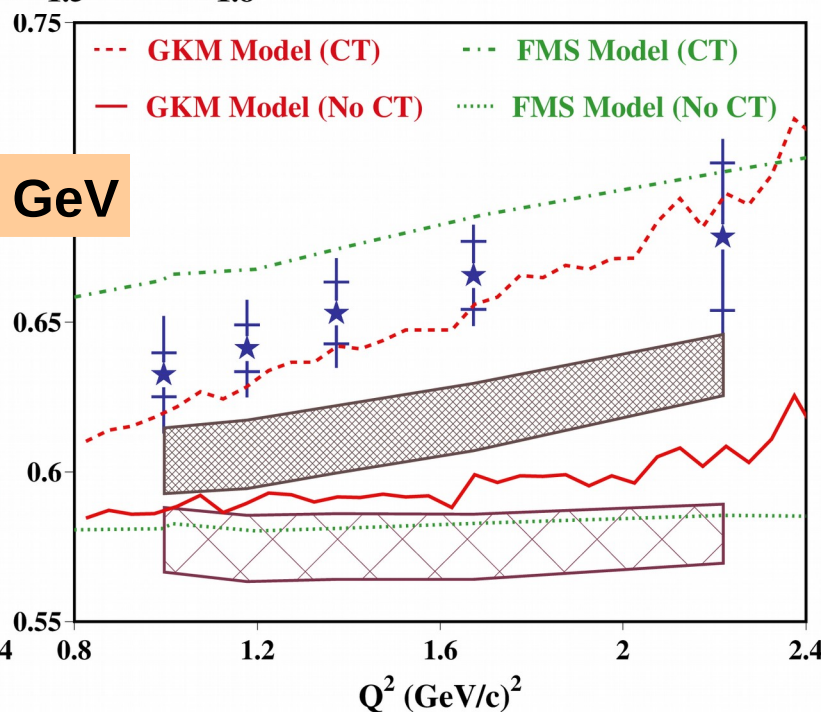


→ **CR**: relativistic multiple scattering Glauber approximation.  
 → Hatched-band includes CT effects based on quantum diffusion model.

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

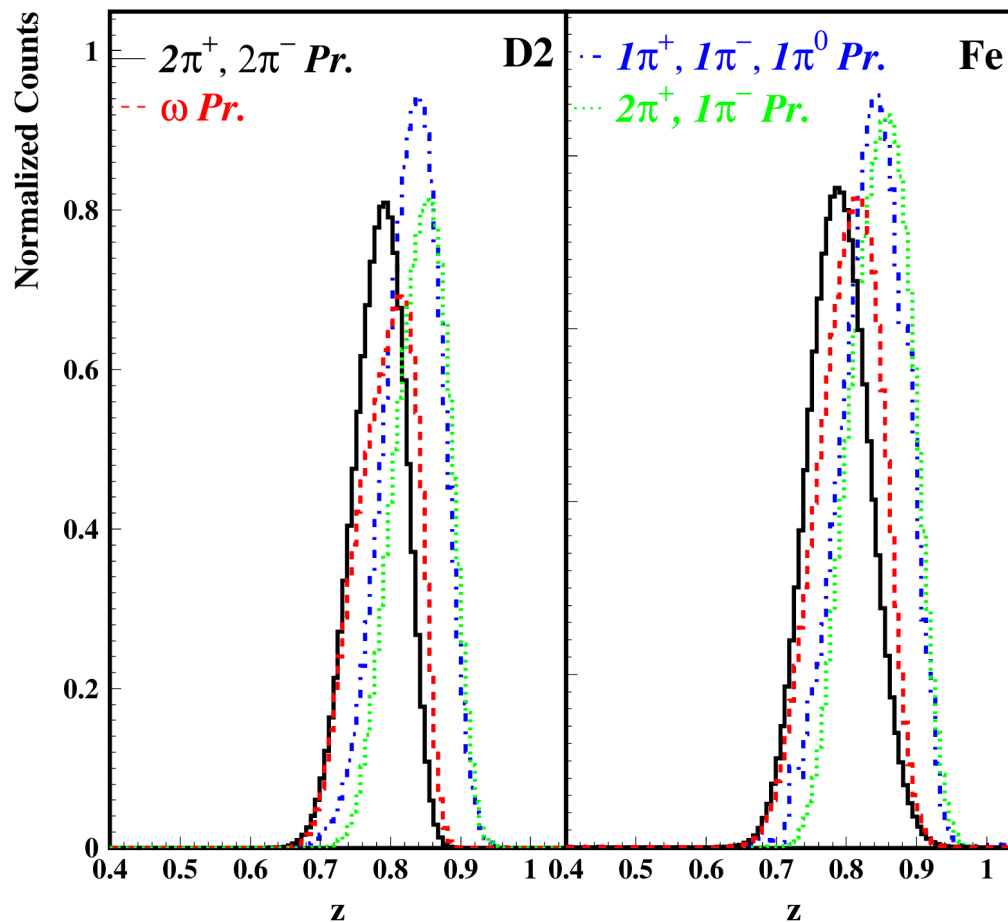


**5 GeV**



# Multi-pions Processes

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



# Two pions Invariant Mass

5 GeV  
Iron dataset

