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

EIC User Group Meeting 2018
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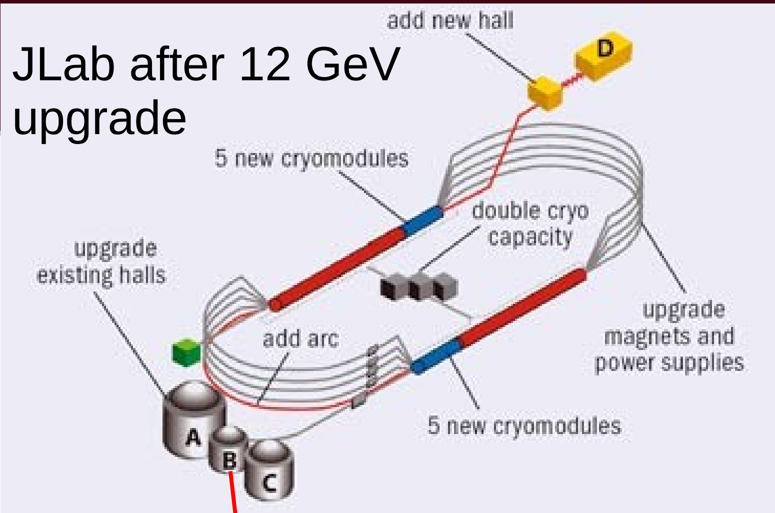
(for the EG2 and CLAS Collaborations)

Outline

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



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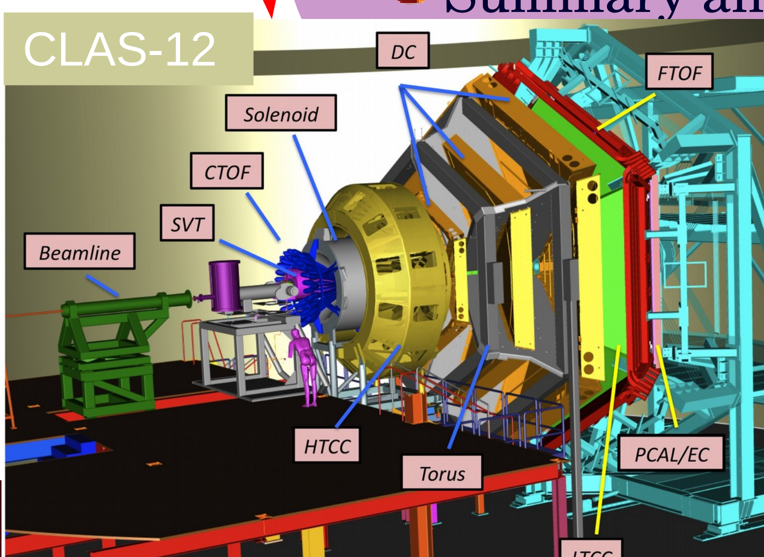

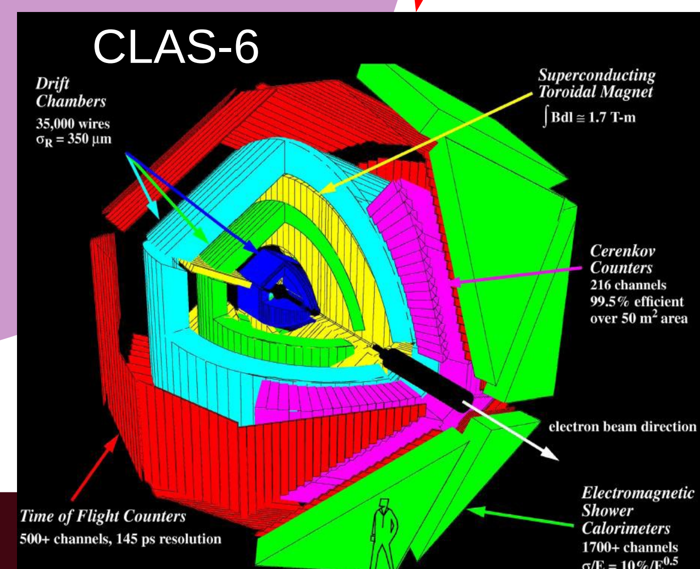

How does the colored bare, quark, evolves to a fully dressed hadron?

- Study hard processes in nuclei to probe the QCD confinement dynamics:
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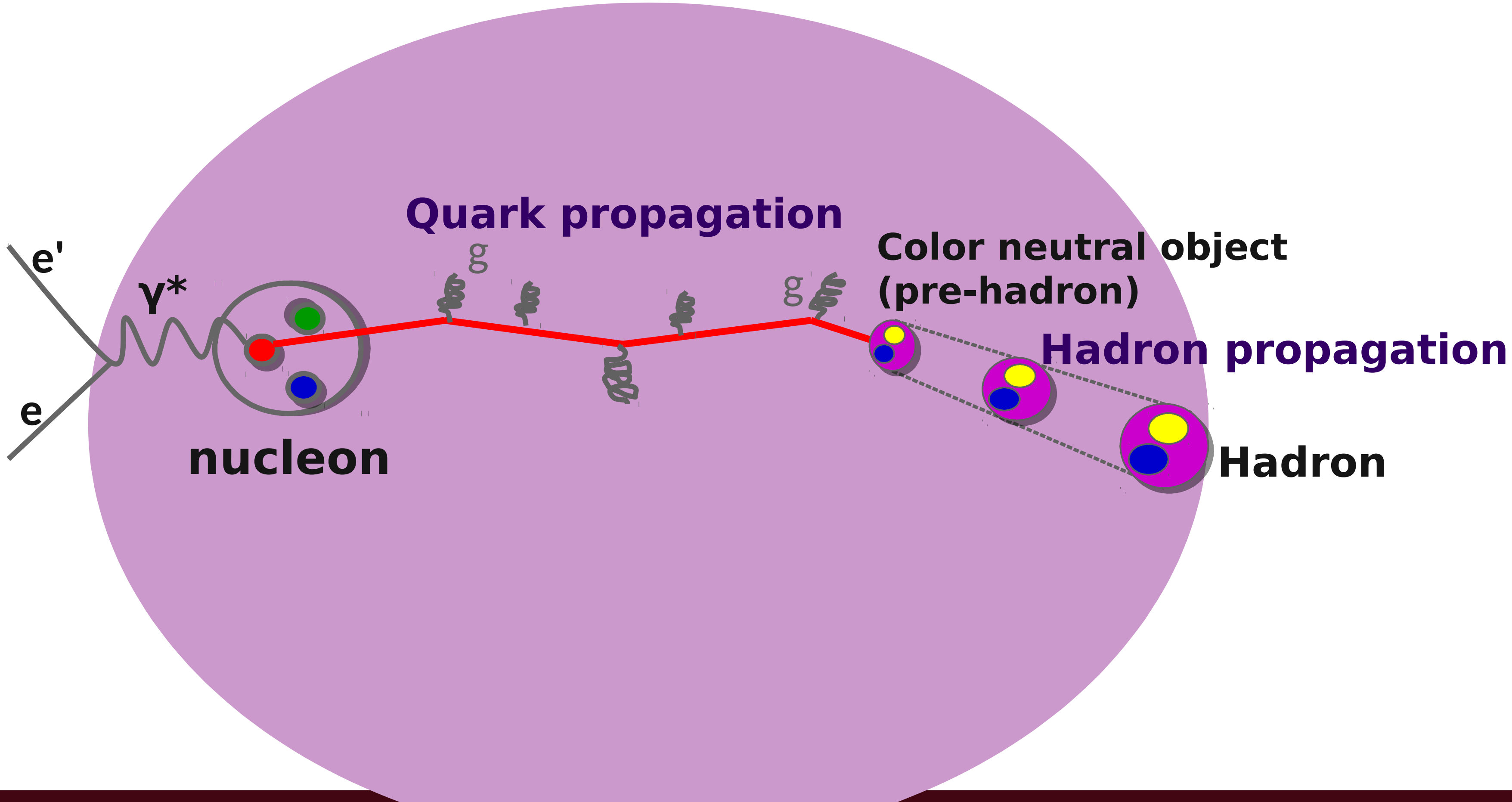

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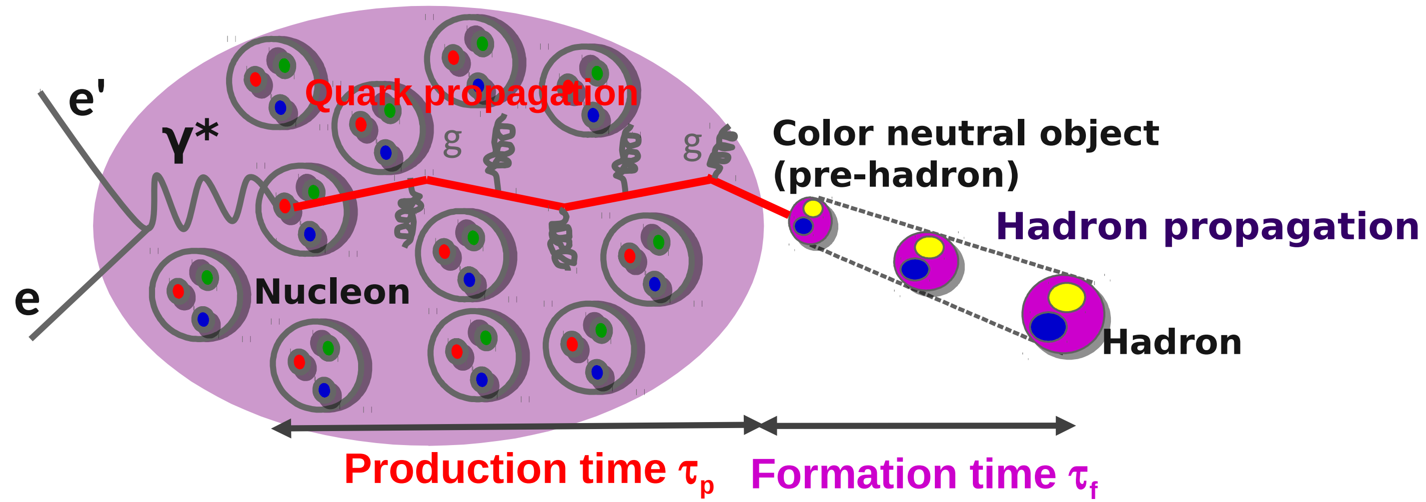

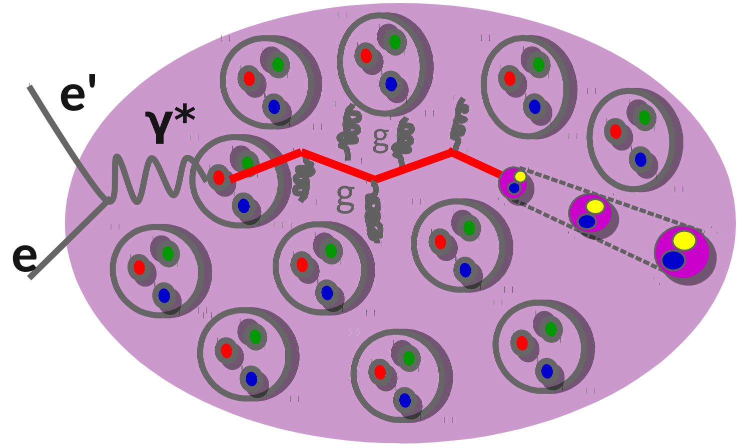

Use semi-inclusive deep inelastic scattering (SIDIS) to access hadronization time-scales:

Production time τ_p: Time spent by a deconfined quark to neutralize its color charge.

Formation time τ_f: Time required to form a regular hadron (h).

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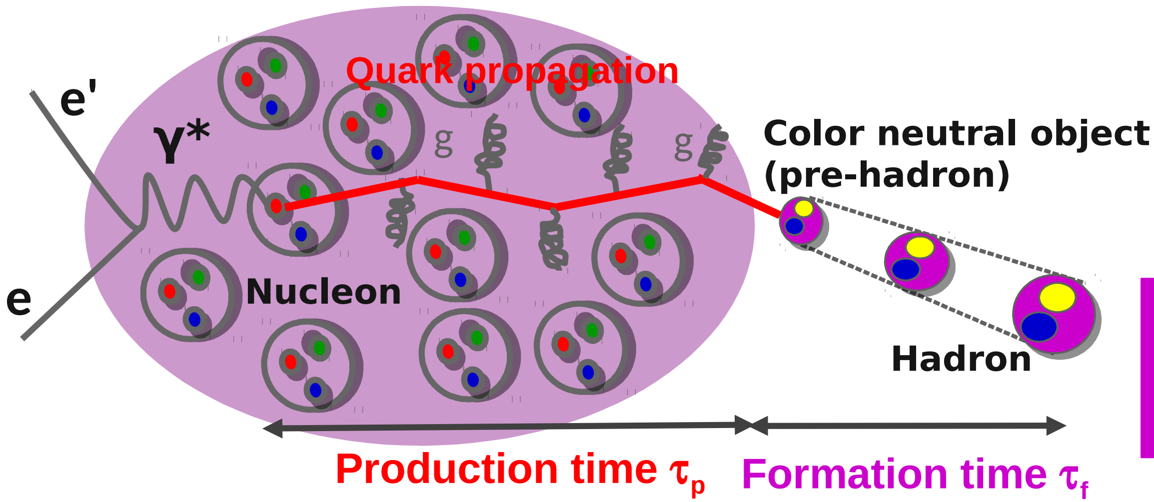
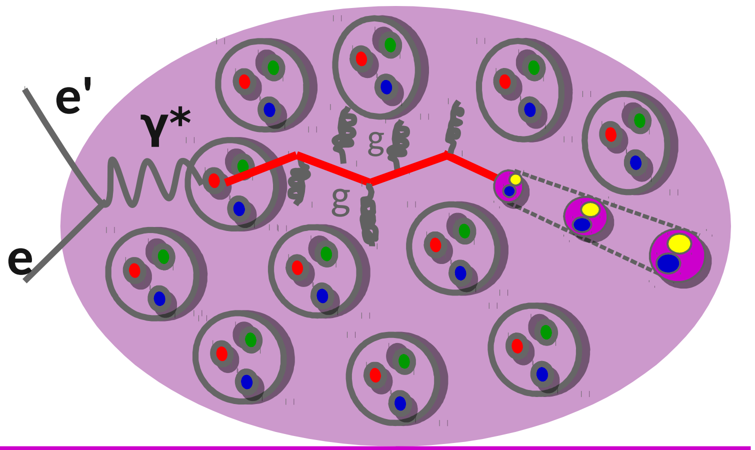


Hadron formation outside the medium dominates at high energies



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Hadron formation inside the medium manifests at low energies

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

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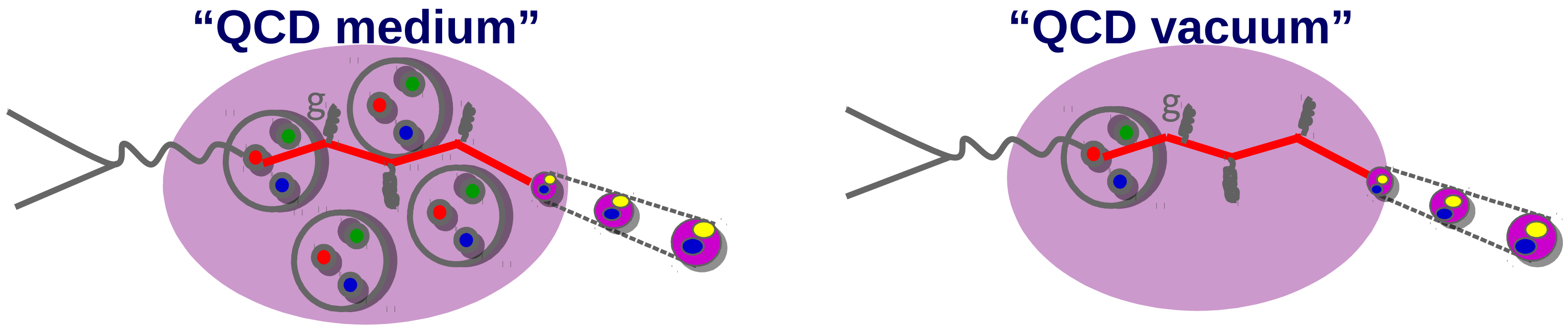
Comparison of



leads to extraction of hadronization time-scales

Production time τ_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 τ_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.

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

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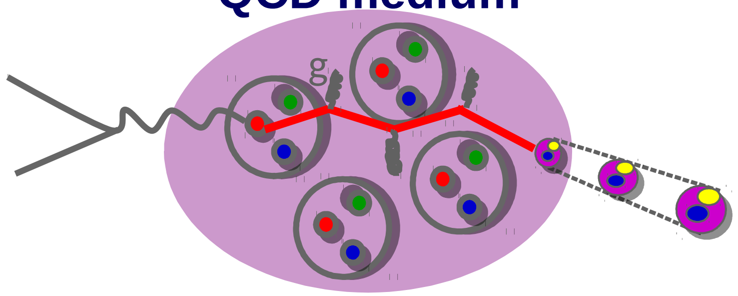
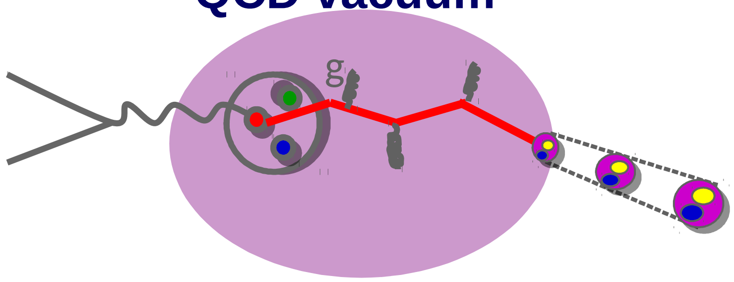
Comparison of

"QCD medium"



"QCD vacuum"



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Production time τ_p: Time spent by a deconfined quark to neutralize its color charge.

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➔ Transverse momentum (p_T) broadening.

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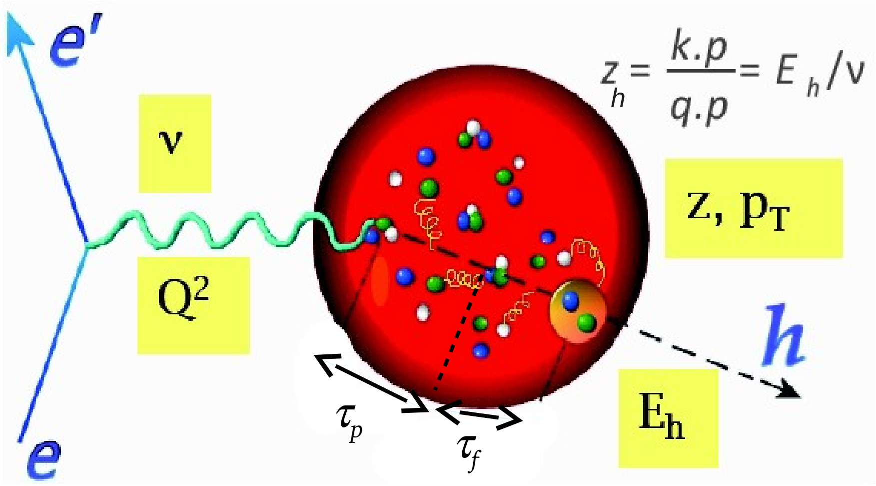
Signaled by interactions with known hadron cross sections.

➔ Hadron attenuation via the extraction of hadron multiplicity ratios.

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

Color Propagation SIDIS Kinematics



Variables:

ν : Electron energy loss,
≡ Initial energy of a struck quark

Q^2: Four-momentum transferred,
~ 1/(spatial resolution) of the probe

y : ν/E_{beam}, Electron energy fraction transferred to a struck quark,

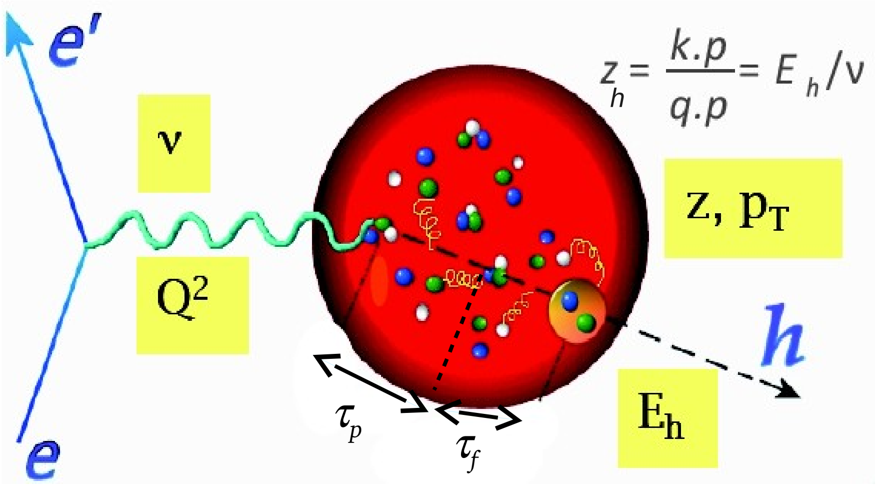
$W : \sqrt{M_n^2 + 2\nu M_n - Q^2}$ *w/. M_n is a nucleon mass*, is the mass of the total hadronic final state,

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: $\frac{P_L}{P_L^{max}}$, *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 : ν/E_h, Electron energy fraction transferred to a struck quark,

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

$W : \sqrt{M_n^2 + 2\nu M_n - Q^2}$ *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

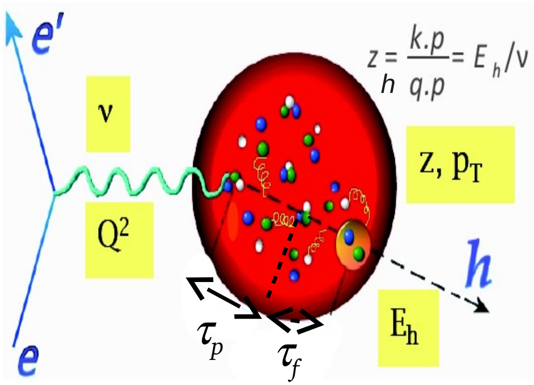
x_F: Fraction of the maximum longitudinal momentum carried by the observed hadron.

> 0, selects the current fragmentation region.

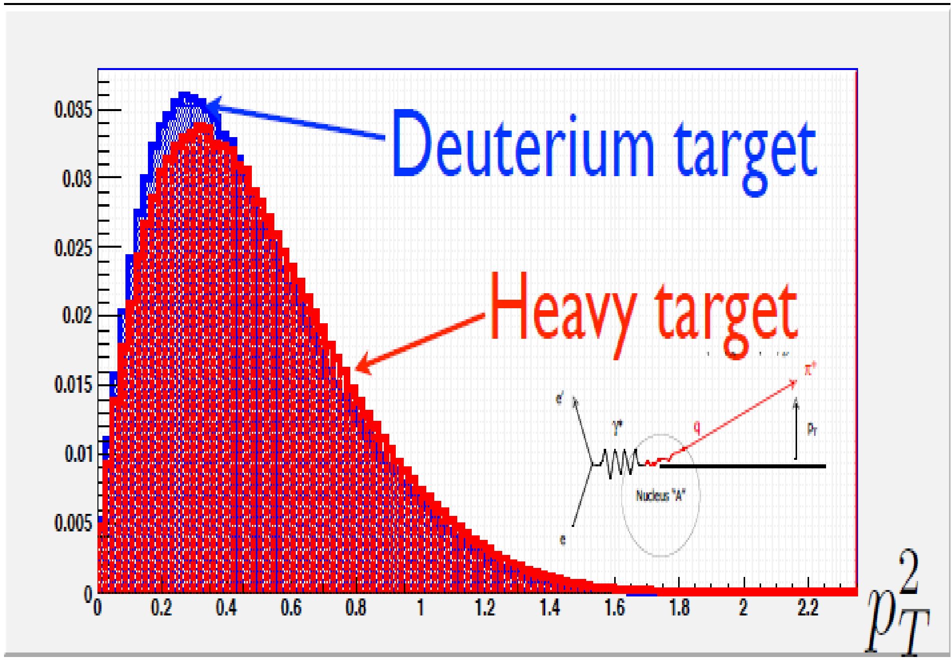
< 0, selects the backward (target-remnant) fragmentation region.

Transverse momentum broadening

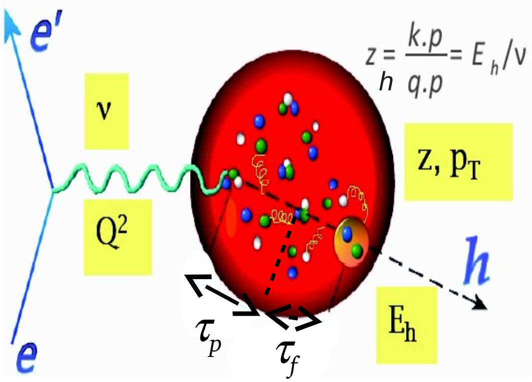
$$\Delta P_T^2 = \langle P_T^2 \rangle_A - \langle P_T^2 \rangle_D$$



Allow access to τ_p via production of different hadrons and quark's flavor



Color Propagation Study: Experimental Observables



Transverse Momentum Broadening

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

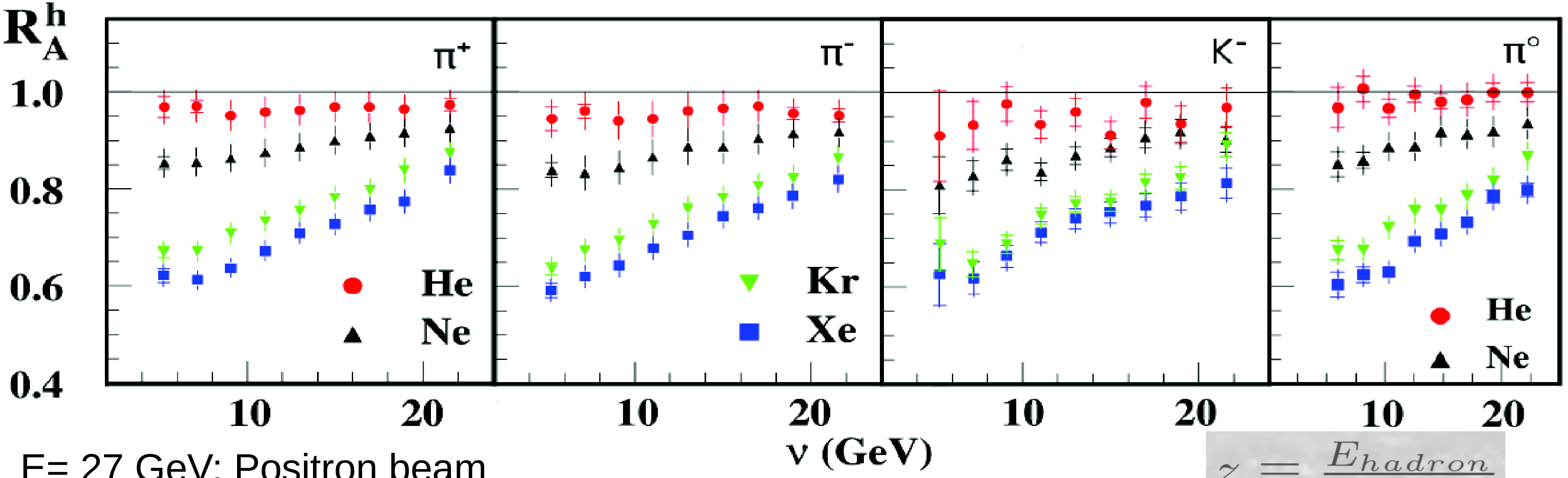
Allow access to τ_p via production of different hadrons and quark's flavor

Hadron Multiplicity Ratio

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

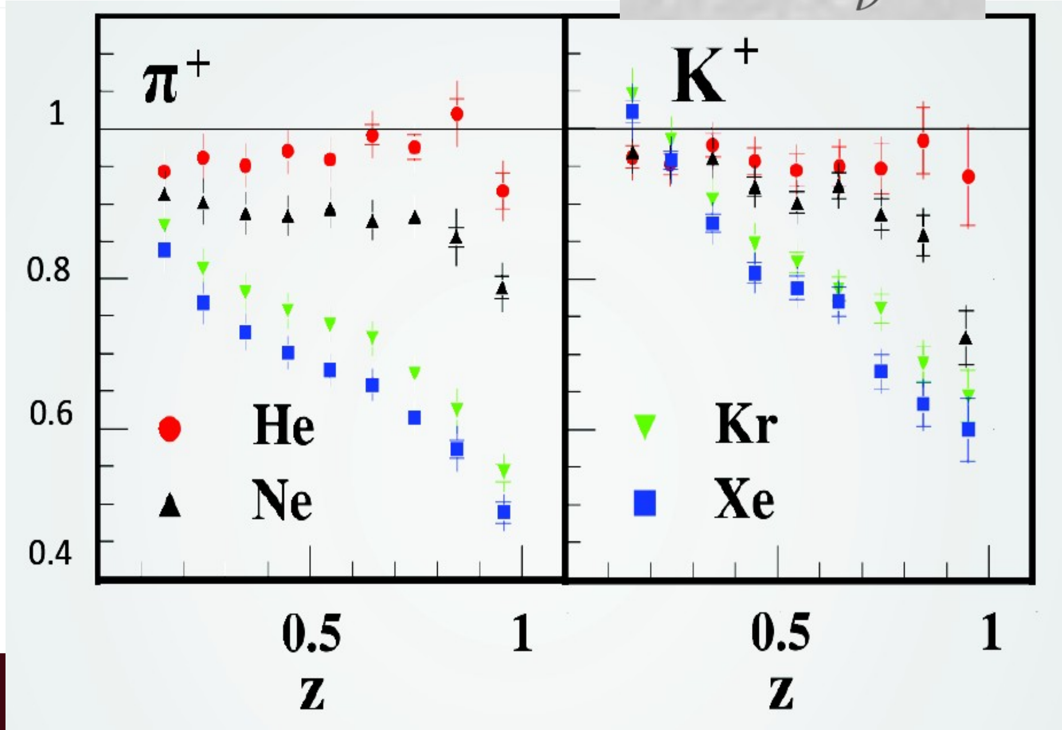
Access τ_f after the extraction of τ_p and R^h_M

CLAS-6 CP Study Motivation: Hermes Multiplicity Ratios



E= 27 GeV; Positron beam

$z \equiv \frac{E_{hadron}}{\nu}$

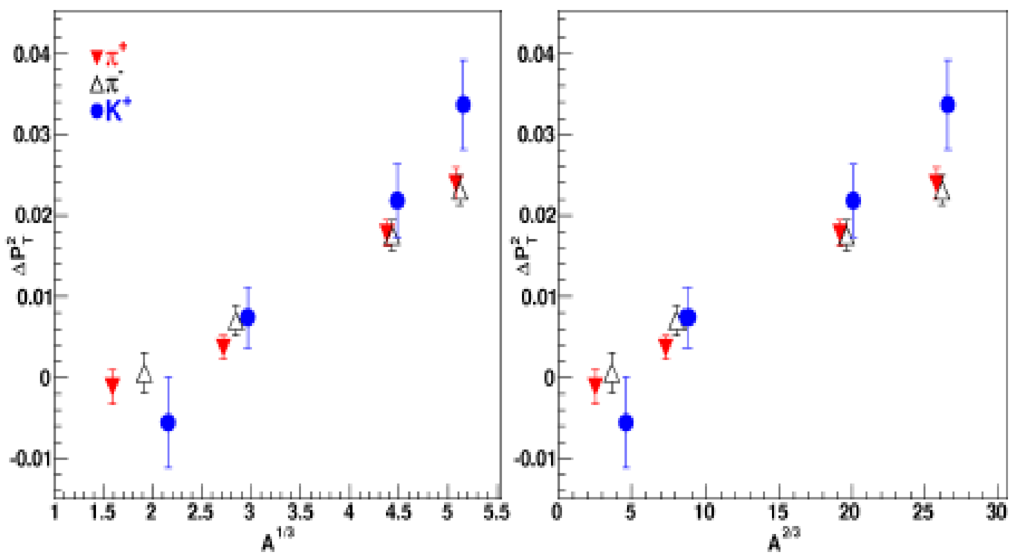


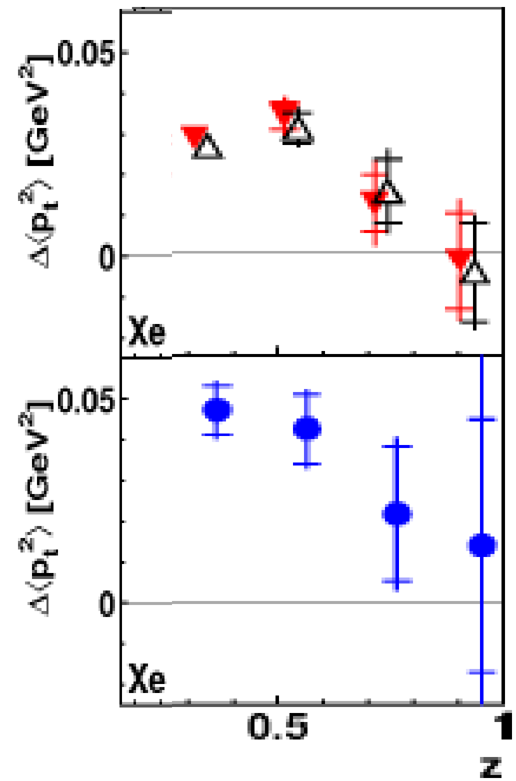
- All pion's flavors and K^- experience similar attenuation.

- K^+ is less attenuated compared to π^+ most likely due to a contamination from $\pi + p \to \Lambda + K$ (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 ⟹ 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 Δp_T^2 *on* $A^{1/3}$ & $A^{2/3}$? ⟹ More data are needed!

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

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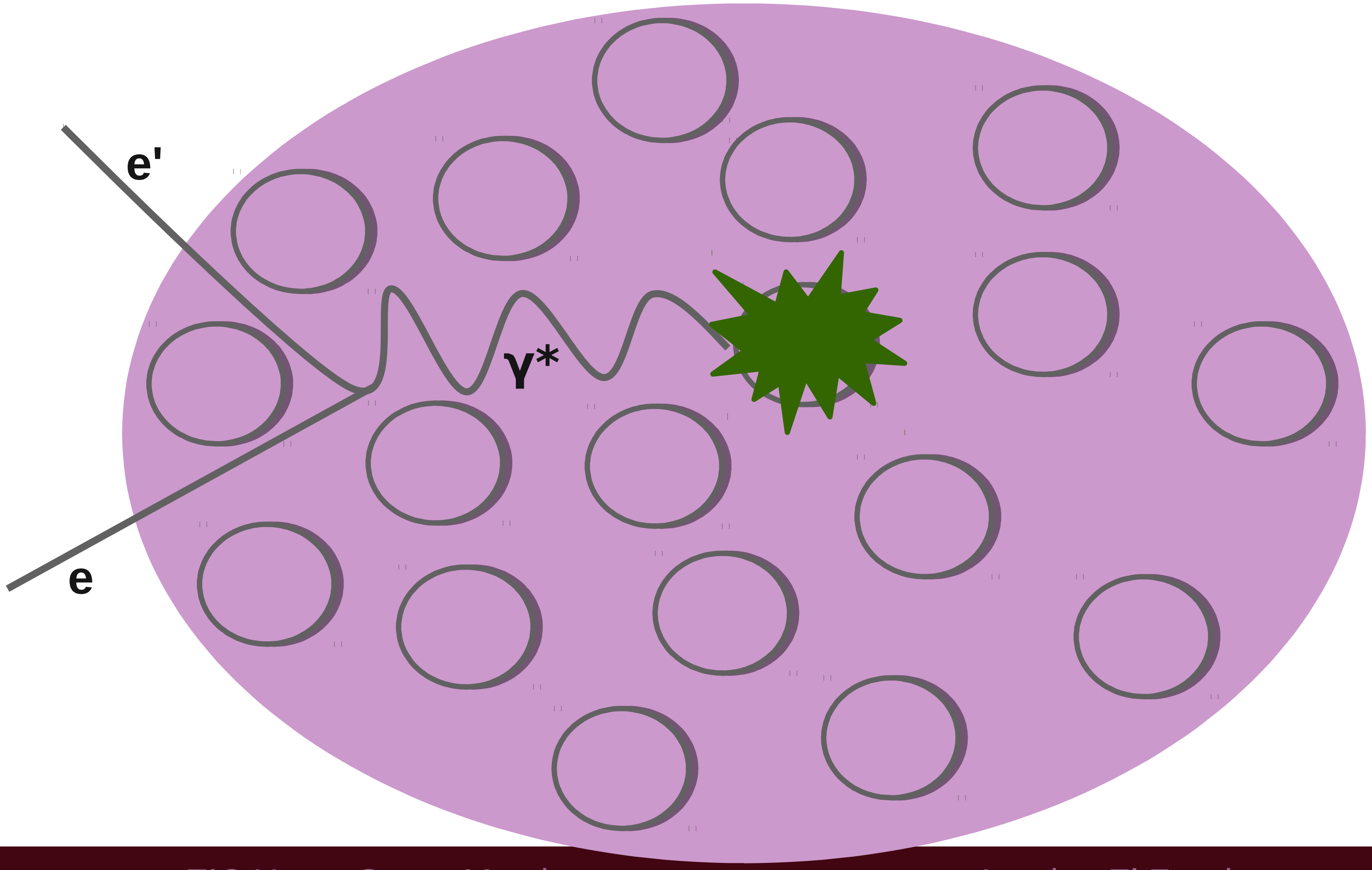
  - Creation and evolution of small size hadrons - **color transparency (CT)**



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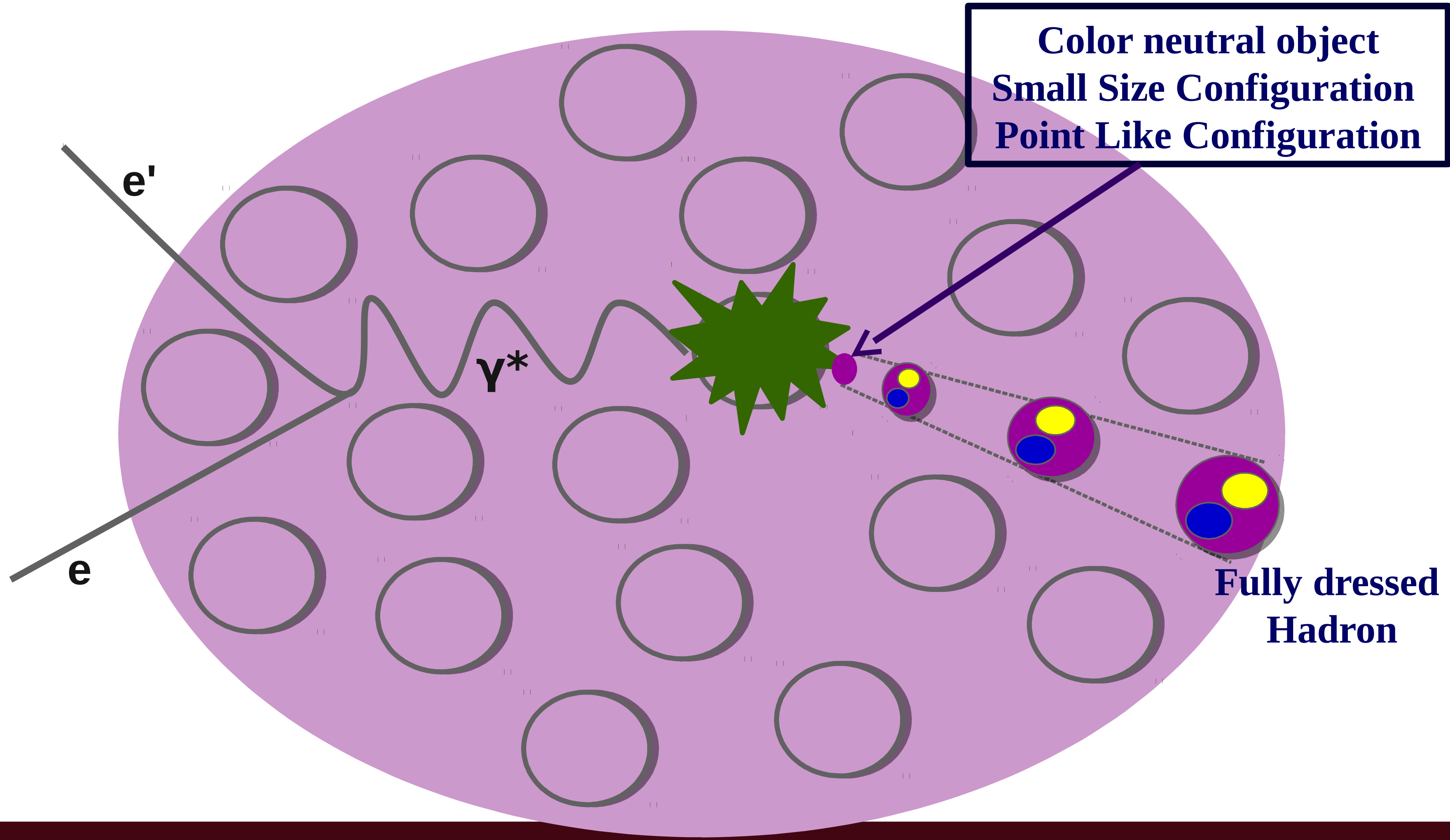

Hard Probe .vs. Medium

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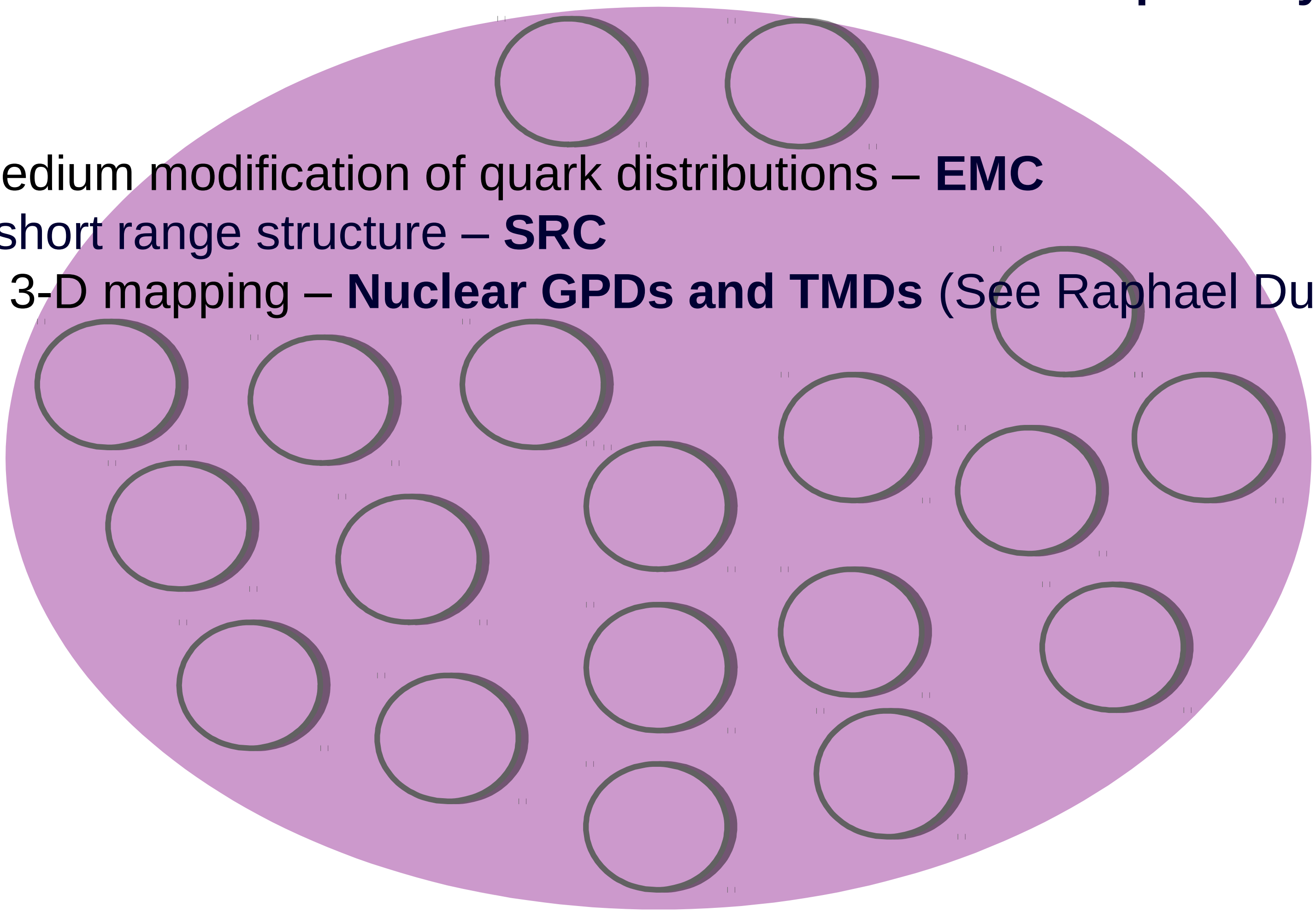

- Study medium modification of quark distributions – **EMC**
- Access short range structure – **SRC**
- Perform 3-D mapping – **Nuclear GPDs and TMDs** (See Raphael Dupre talk)

CT Basics: The Survival of the Smallest !

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

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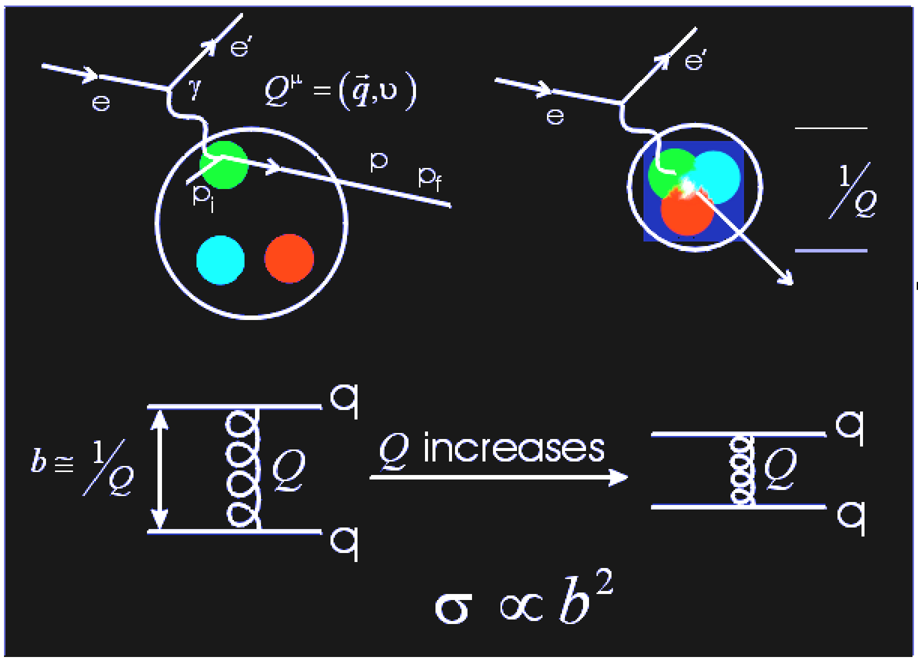
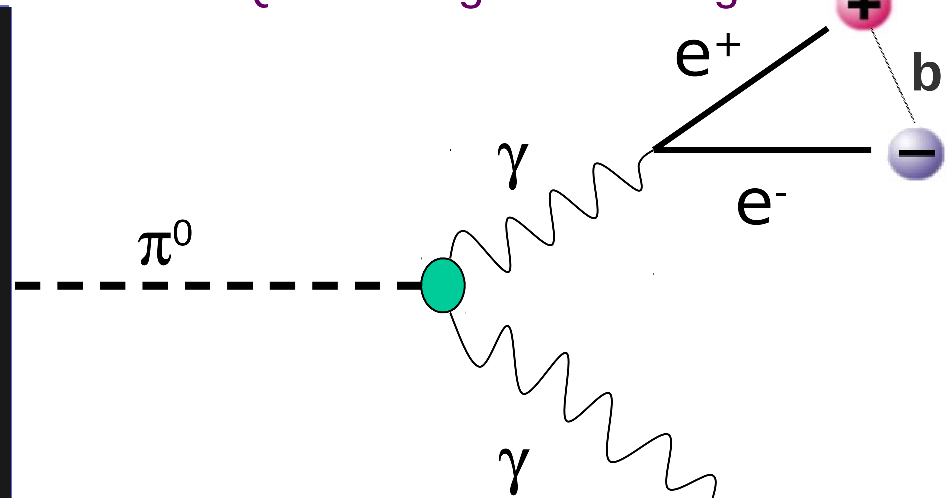
QCD Color Screening



QED Charge Screening



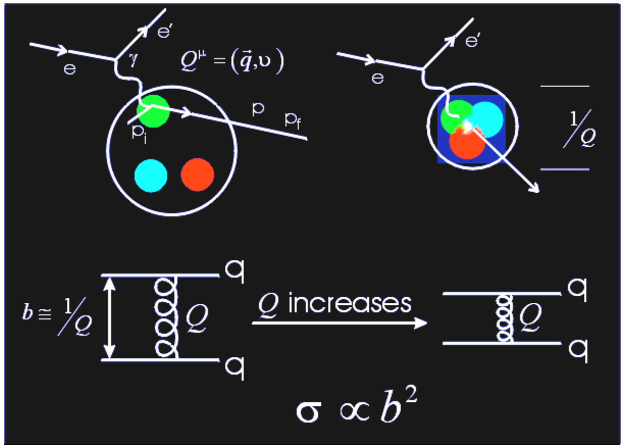
200 GeV π^0 emulsion produced in cosmic rays (Perkins 1955)

- 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.

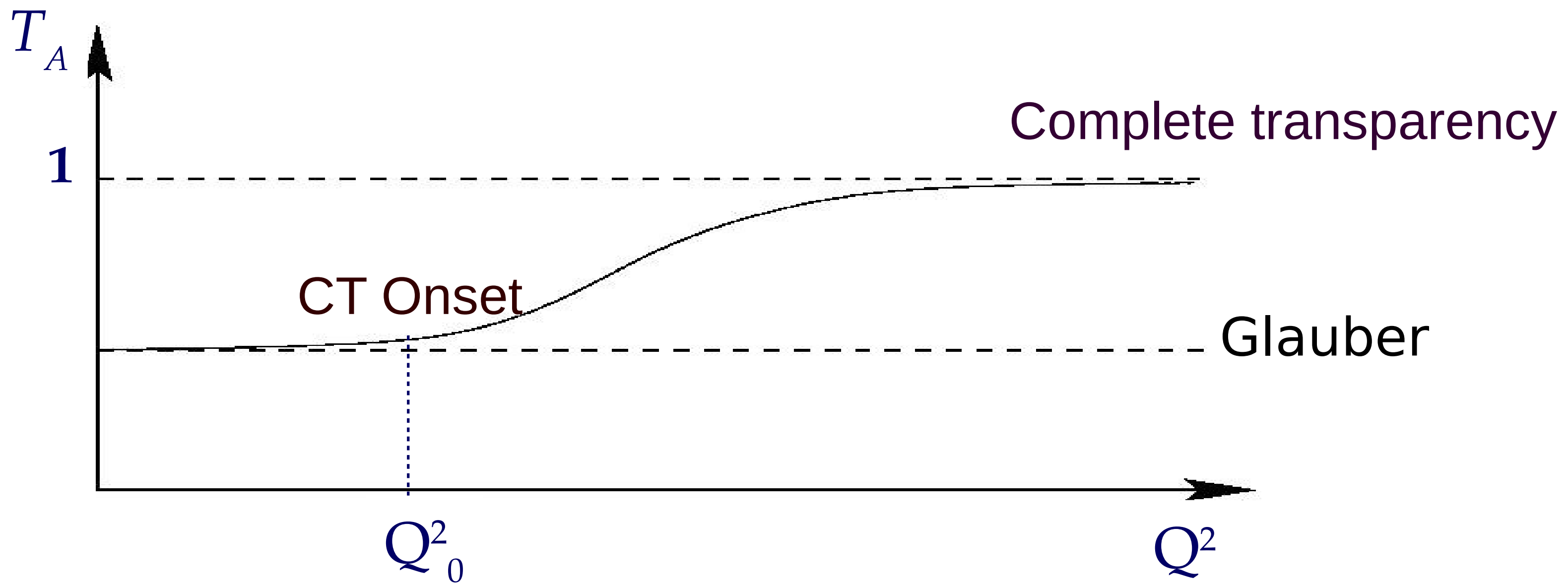
CT Signature

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

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

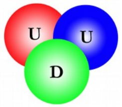
σ_A is the nuclear cross section

σ_N is the free (nucleon) cross section



CT Experimental Studies

Baryon



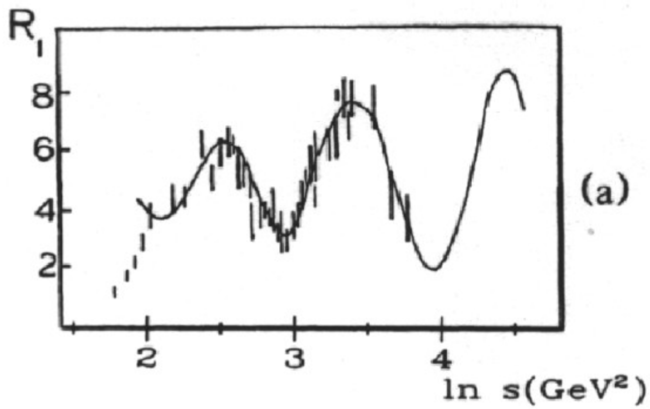
- A(p, 2p) BNL
- A(e, e′p) SLAC and JLab

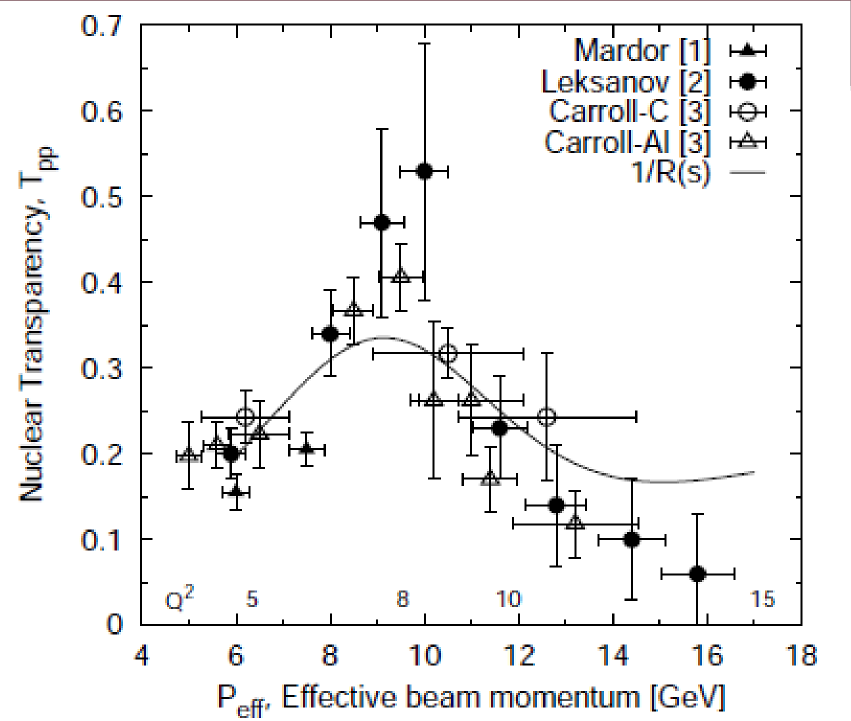
Meson

- 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

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



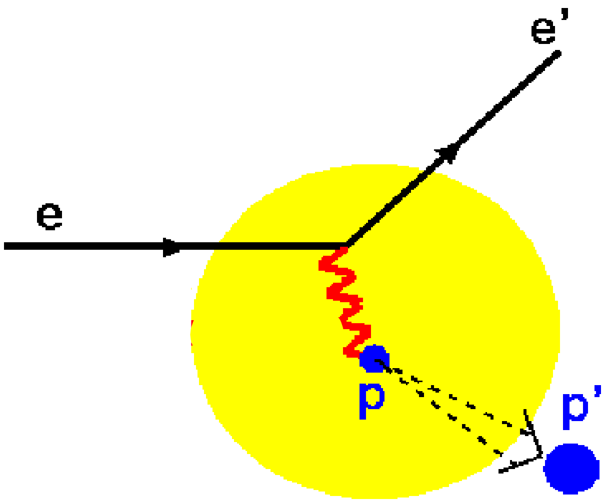


A. Leksanov et al. PRL 2001

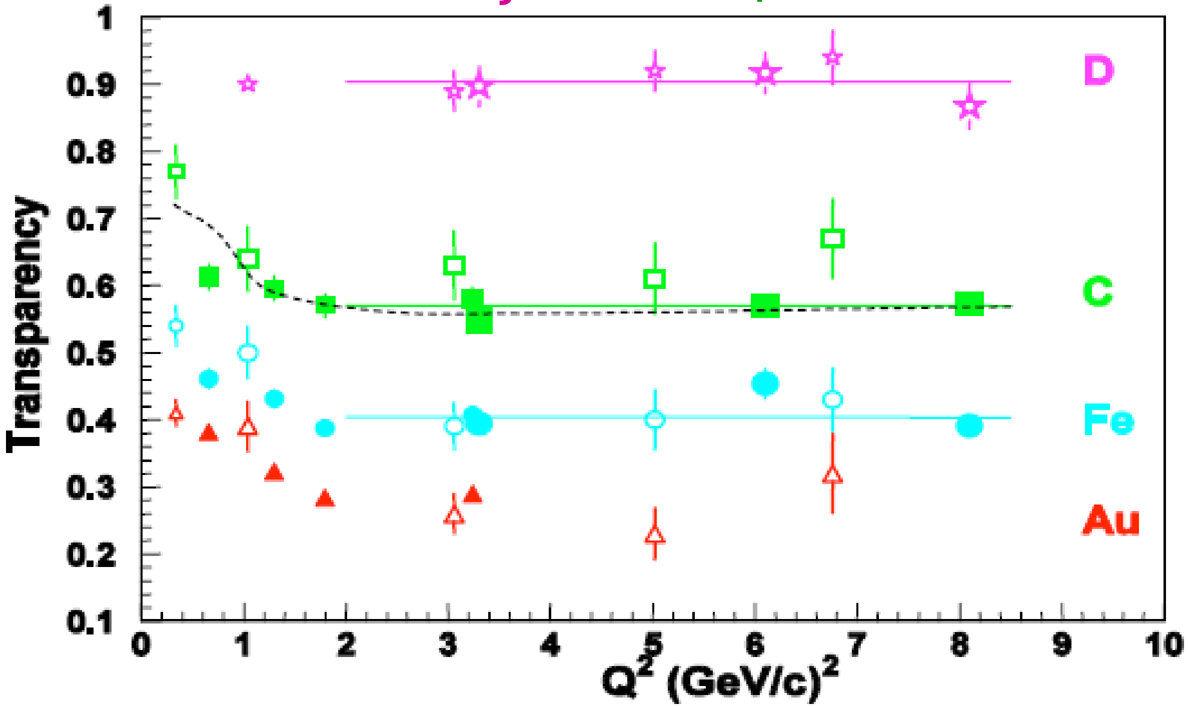
- Initial rise in transparency at low momentum is consistent with CT predictions.
- Subsequent drop at high momentum was explained by:
  - Ralston and Pire as a nuclear filtering of soft amplitudes arising from higher order radiative processes (Landshoff mechanism)
  - Brodsky and De Teramond as a threshold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

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

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



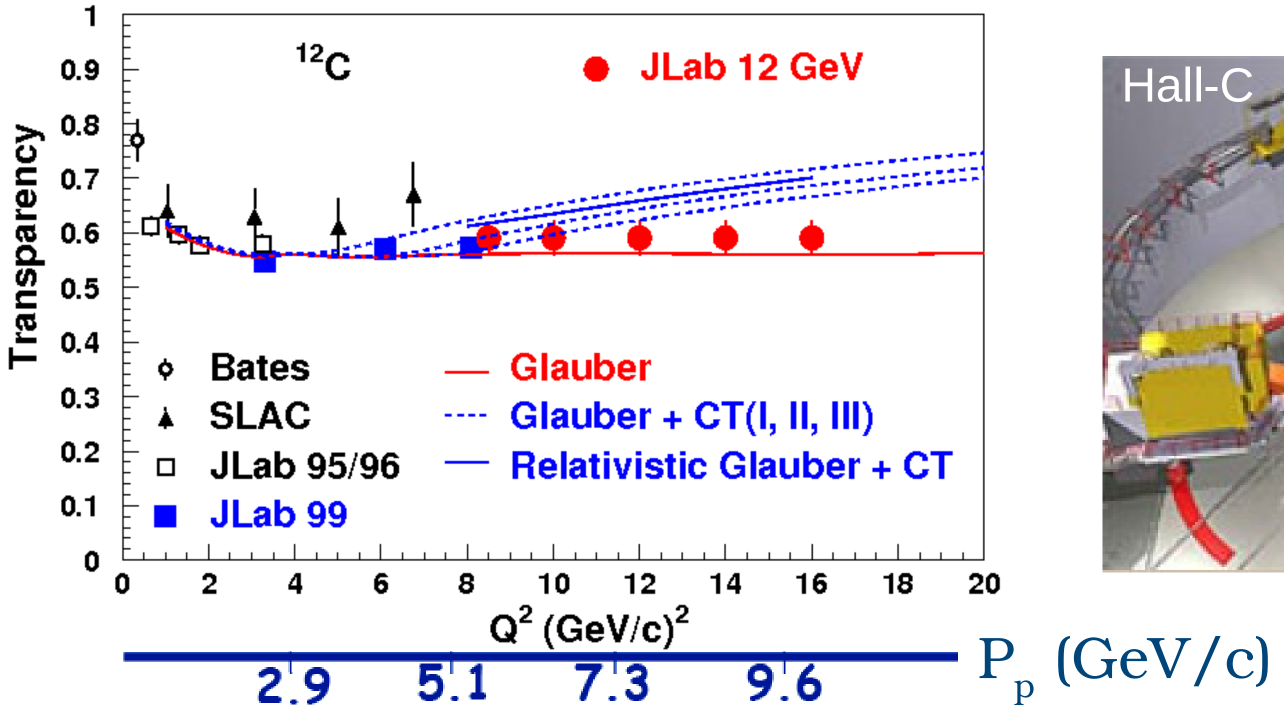
Solid Pts – JLab Open Pts -- other

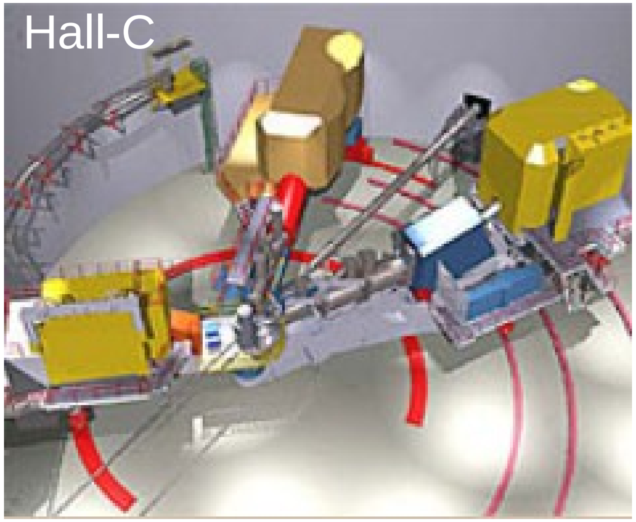


N. C. R. Makins et al. PRL 72, 1986 (1994)
G. Garino et al. PRC 45, 780 (1992)
D. Abbott et al. PRL 80, 5072 (1998)
K. Garrow et al. PRC 66, 044613 (2002)

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 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.**

qqq versus qq-bar systems

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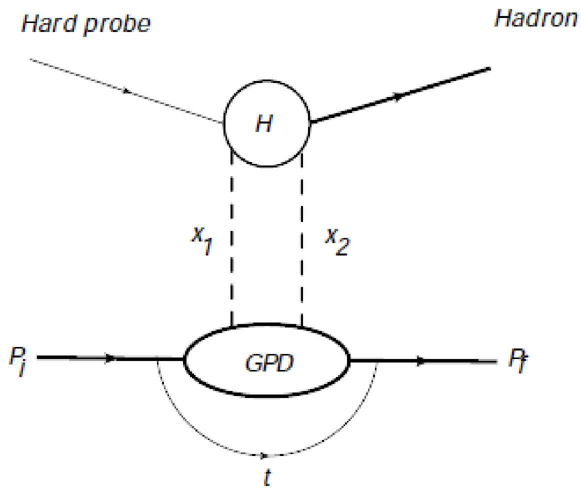
- **Onset of CT is expected at lower Q^2 in qq-bar system.**

- **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.

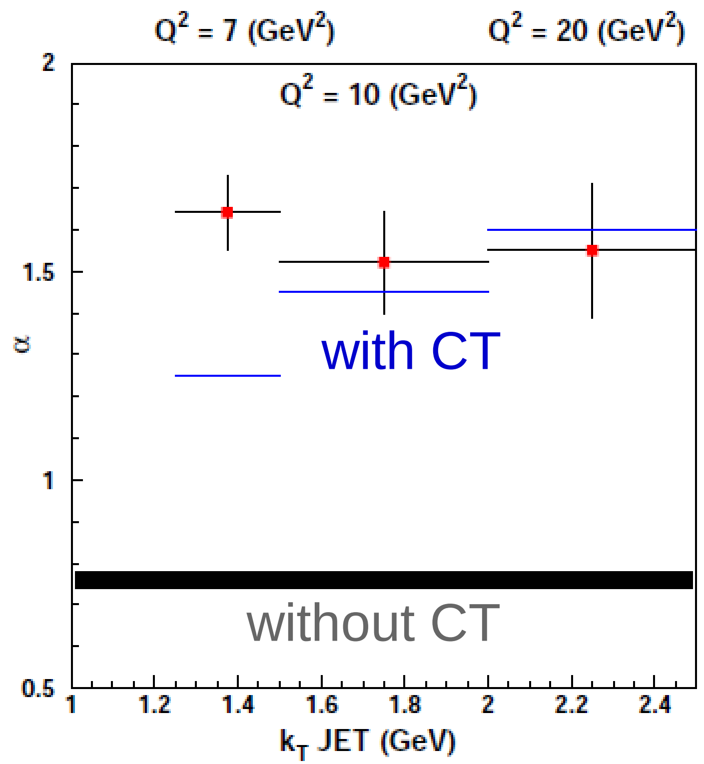
Collins, Frankfurt, Miller, Sargsian and Strikman



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

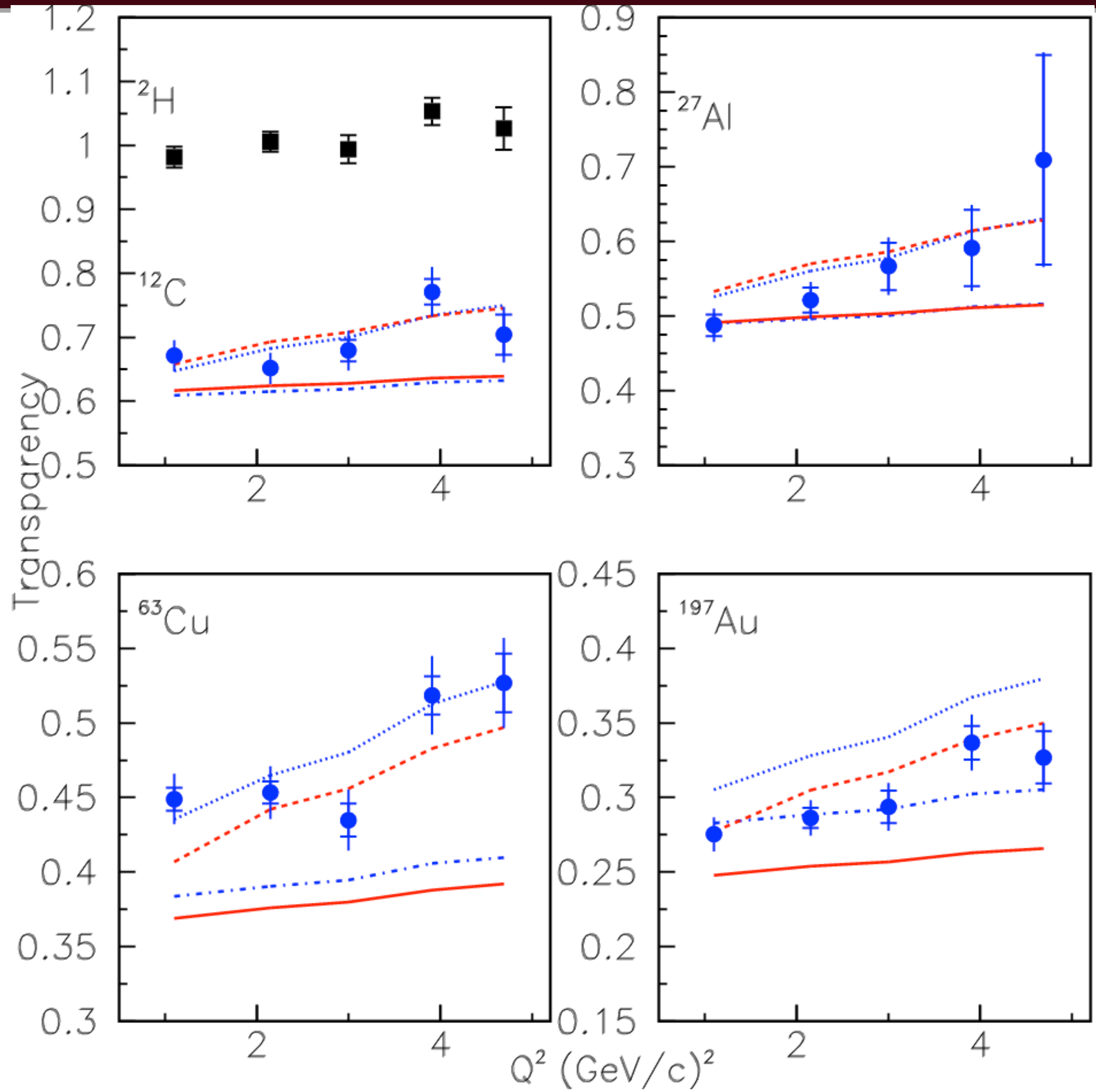
A(π, dijet) data from FNAL

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



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

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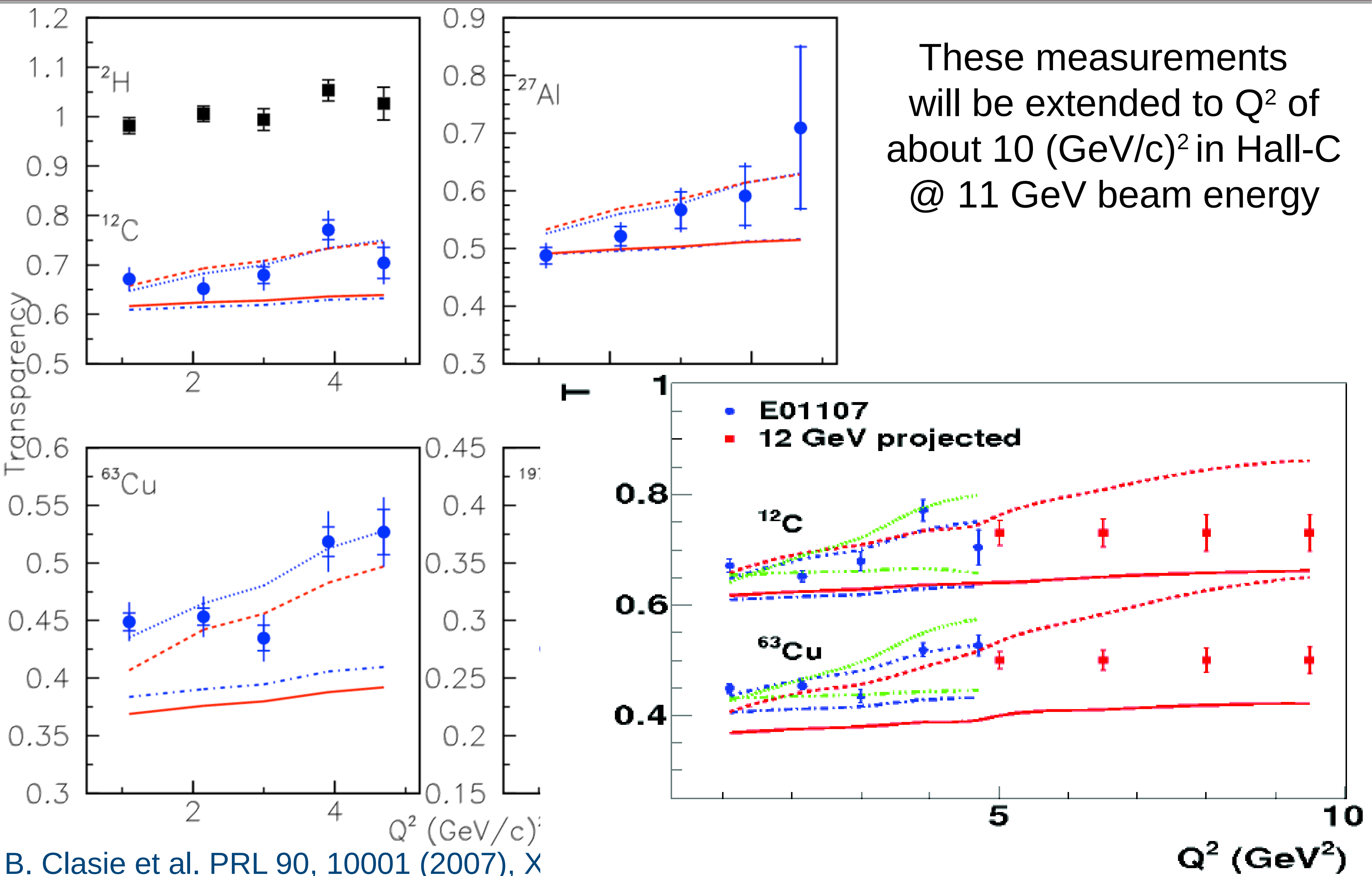
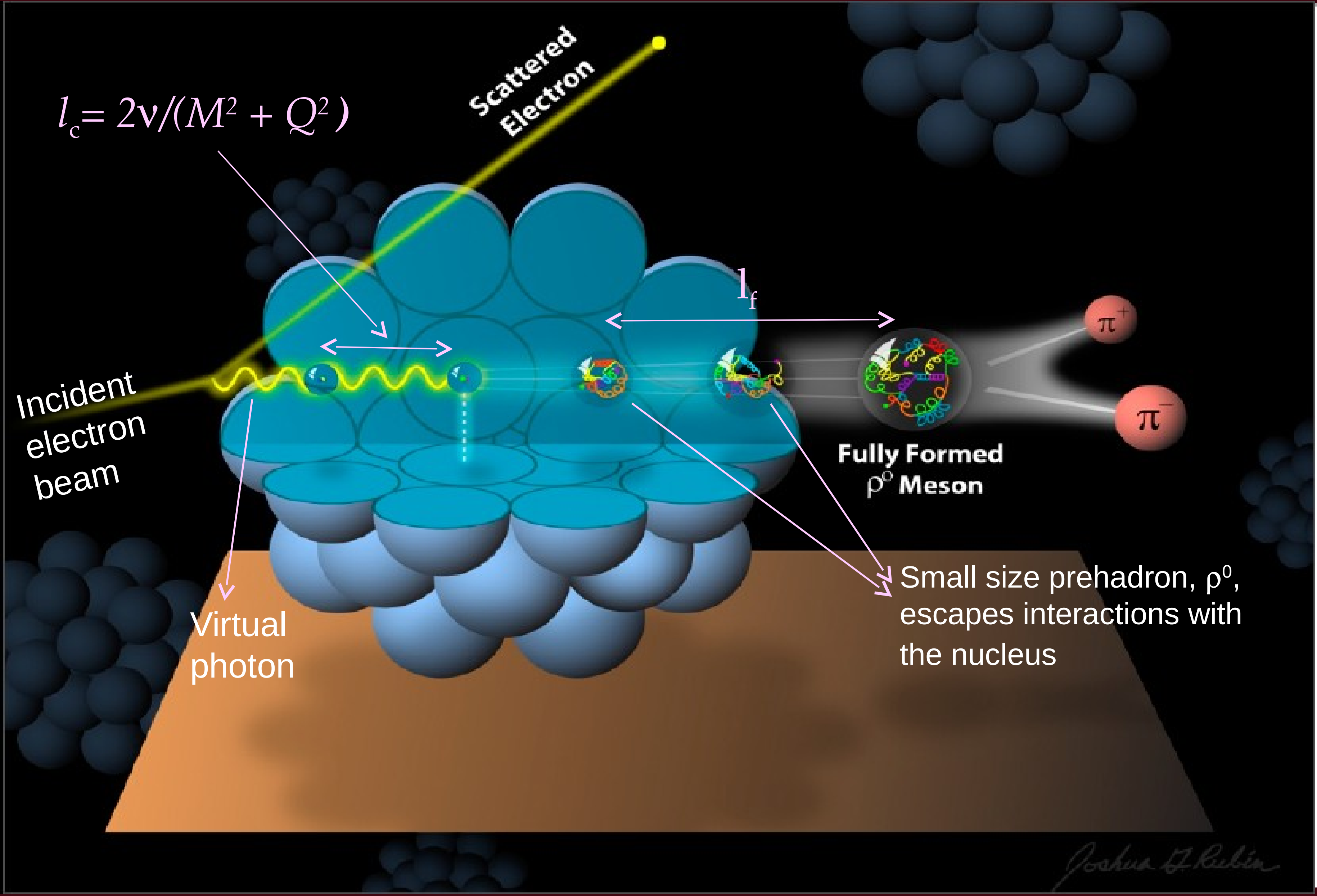


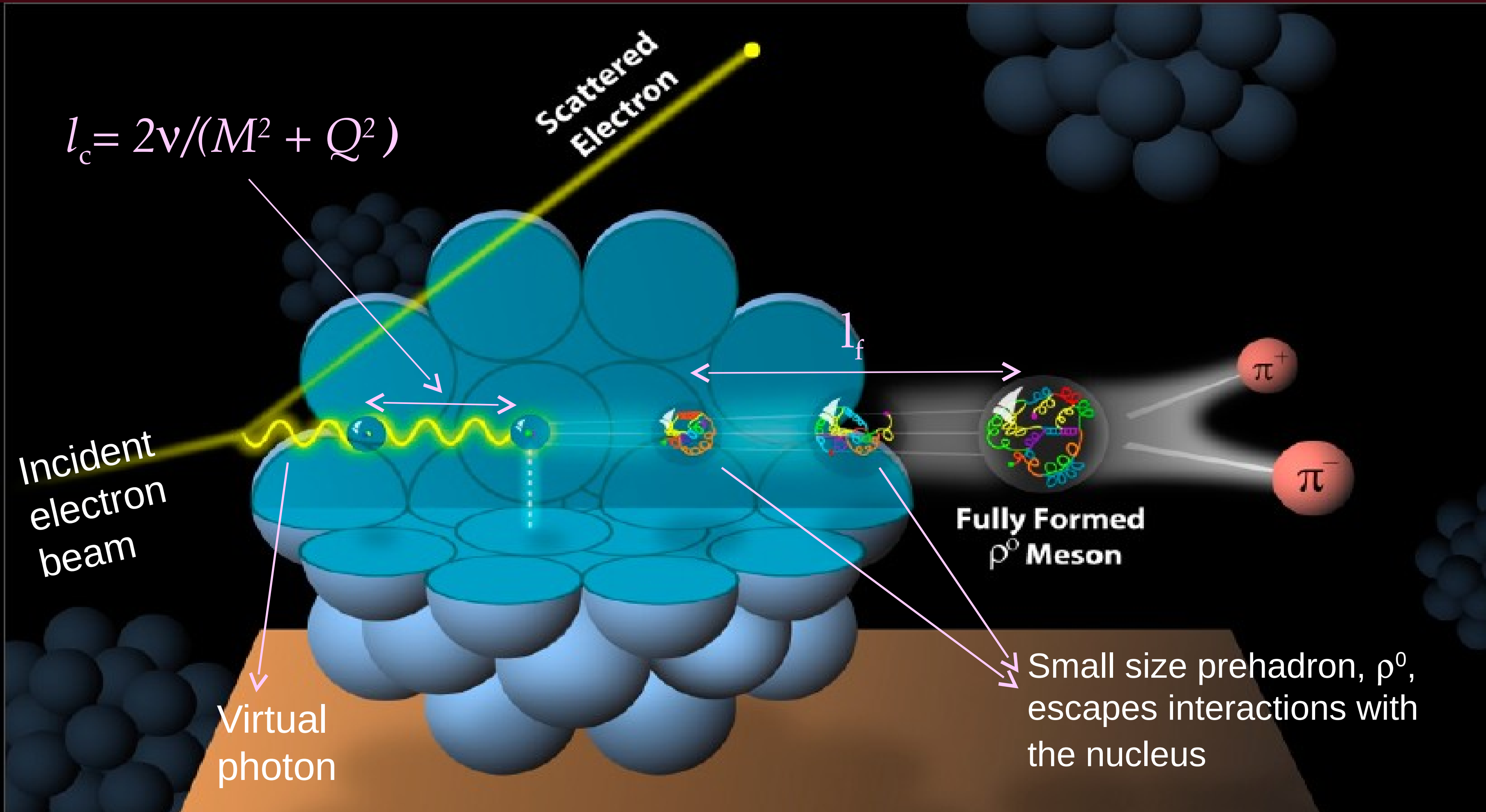
These measurements will be extended to Q^2 of about 10 $(GeV/c)^2$ in Hall-C @ 11 GeV beam energy

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

Exclusive ρ^0 leptoproduction

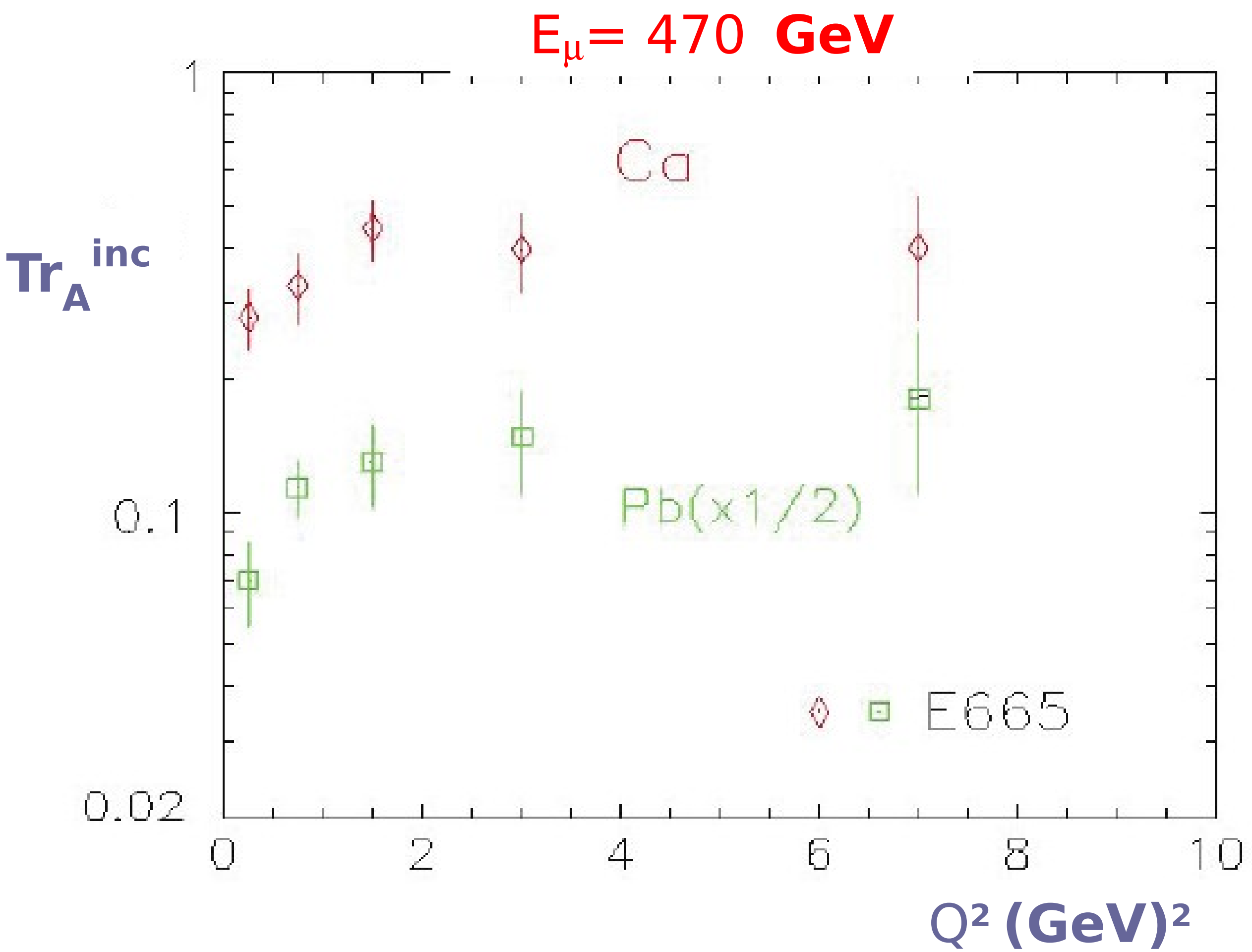


Exclusive ρ^0 leptoproduction



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

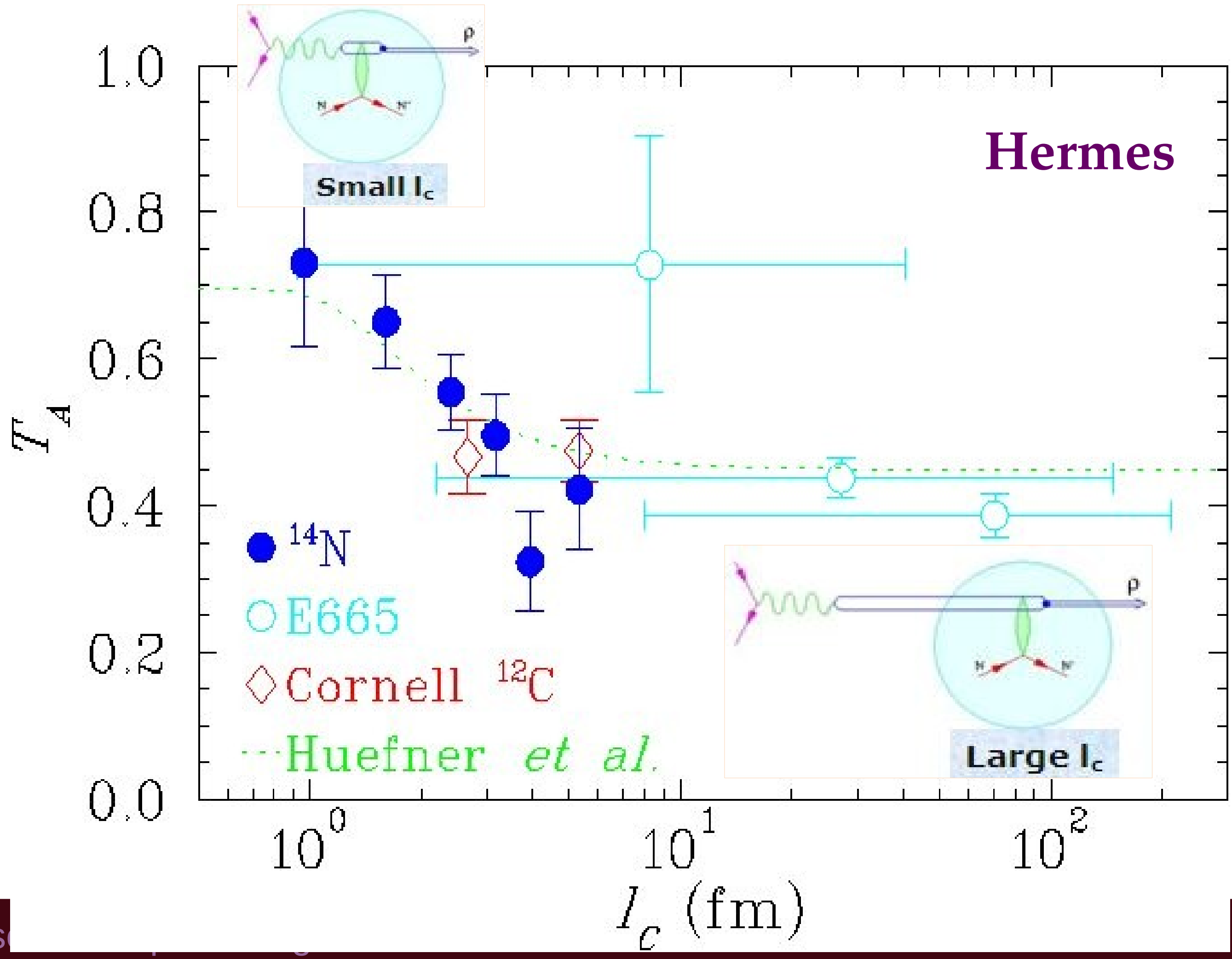
Exclusive ρ^0 leptoproduction: FNAL E665



Adams et al. PRL 74, 1525 (1995)

Coherence length effect (CL) could mimic CT signal?

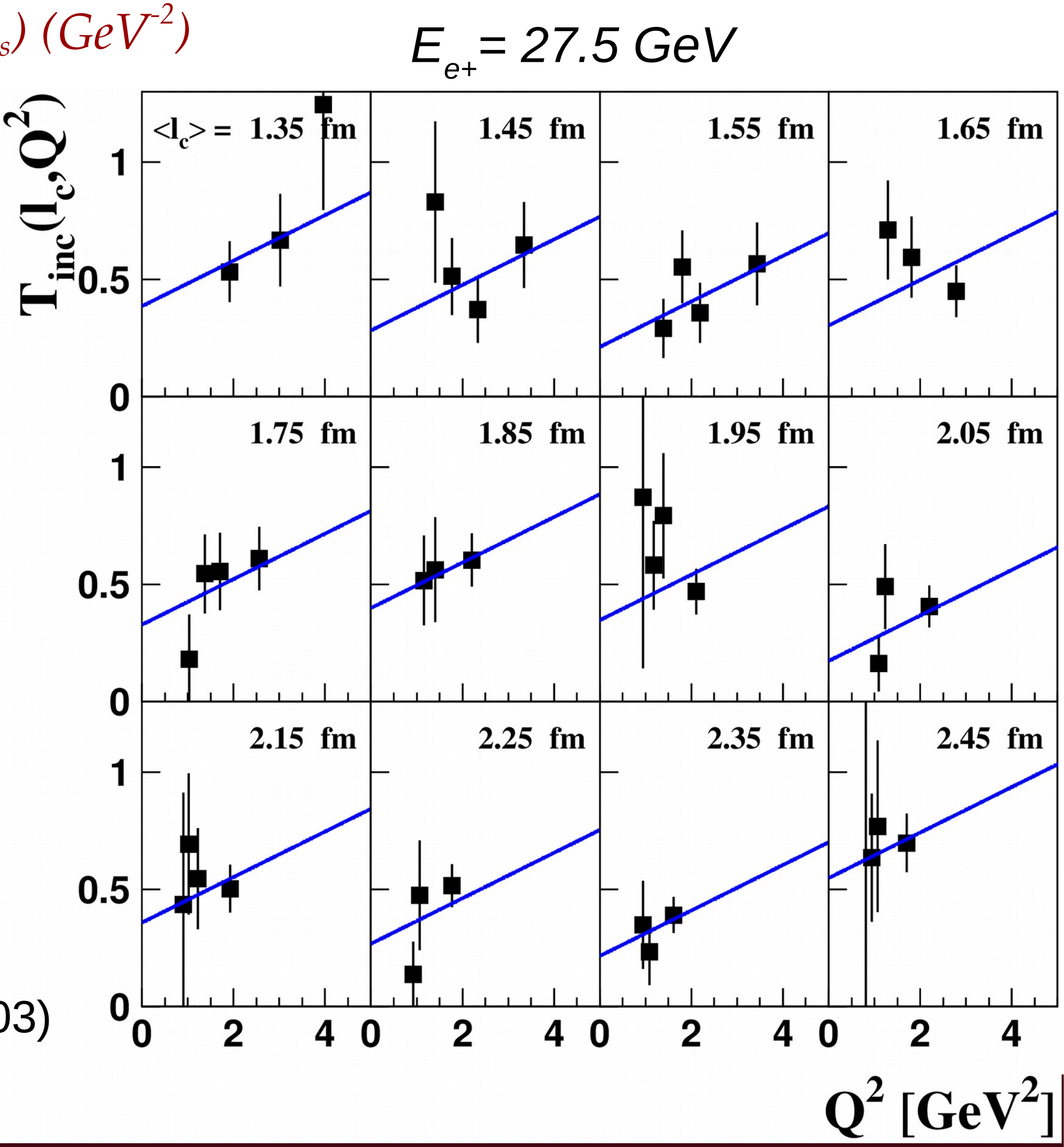
- CT signature is the T_A increase with Q², however, as $l_c = 2\nu/(M^2 + Q^2)$, the CL effect manifests also the T_A increase with Q².
- **To exclude CL, the Q^2 dependence of T_A must be measured at small or fixed l_c.**



Exclusive ρ^0 leptoproduction: Hermes

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

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



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.)

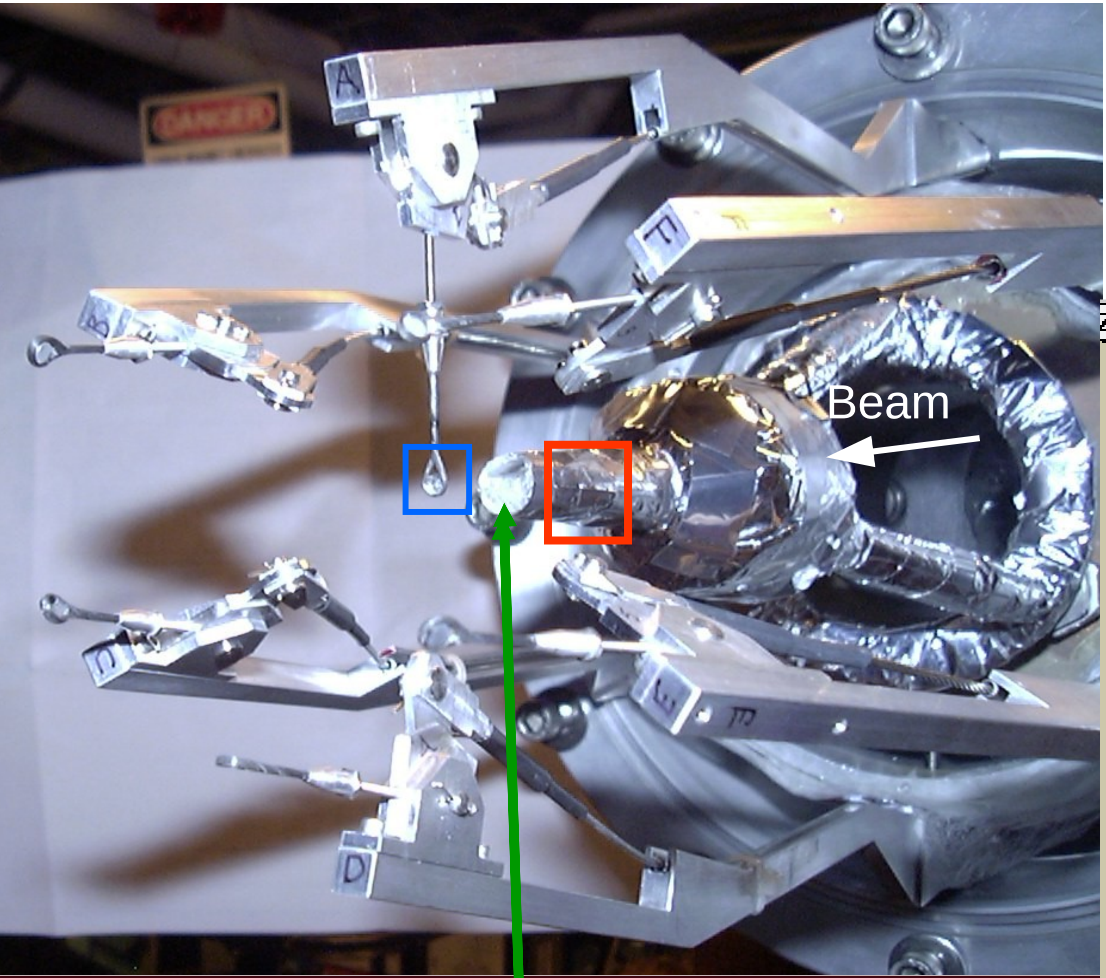
M. Wood (Canesius College)

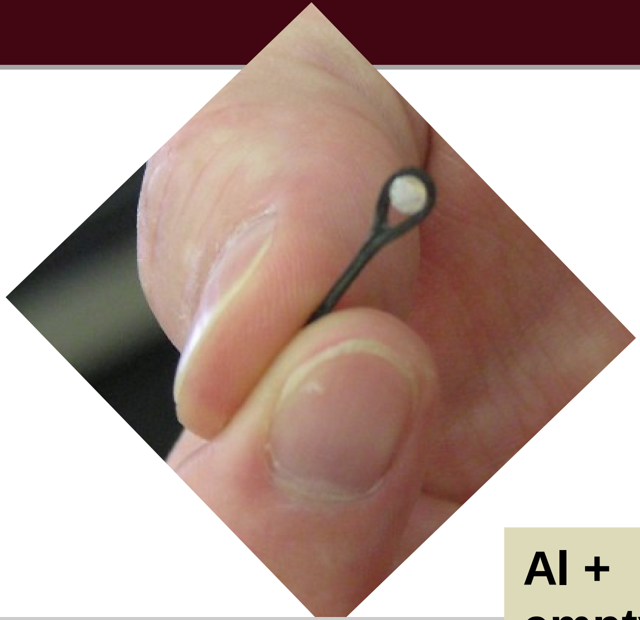
(blue ellipse) CLAS-6 CT or CP experiment Spokespersons

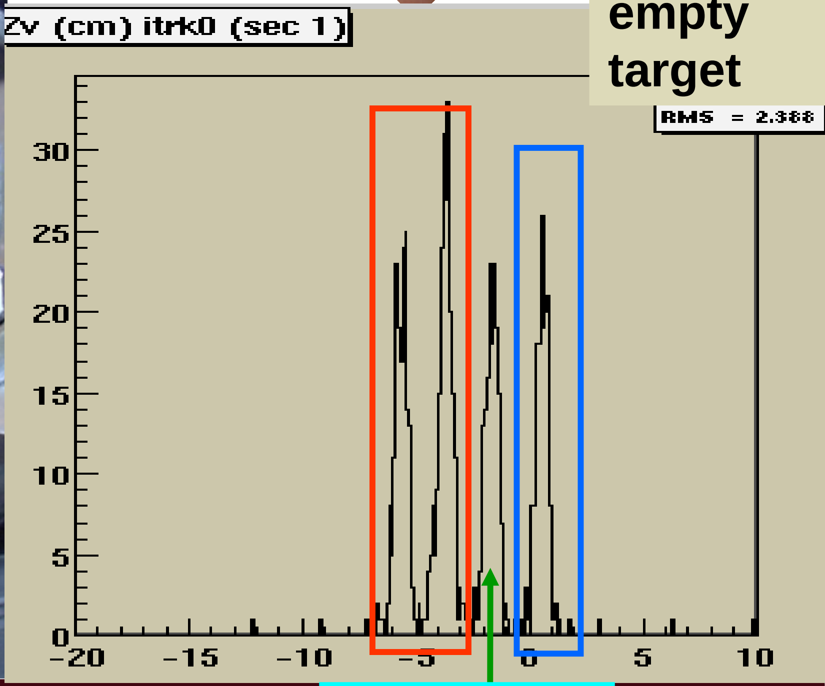
CLAS-12 CT and/or CP experiment Spokespersons

(red ellipse) Former CLAS-6 CT or CP Graduate Students

EG2 run-group targets

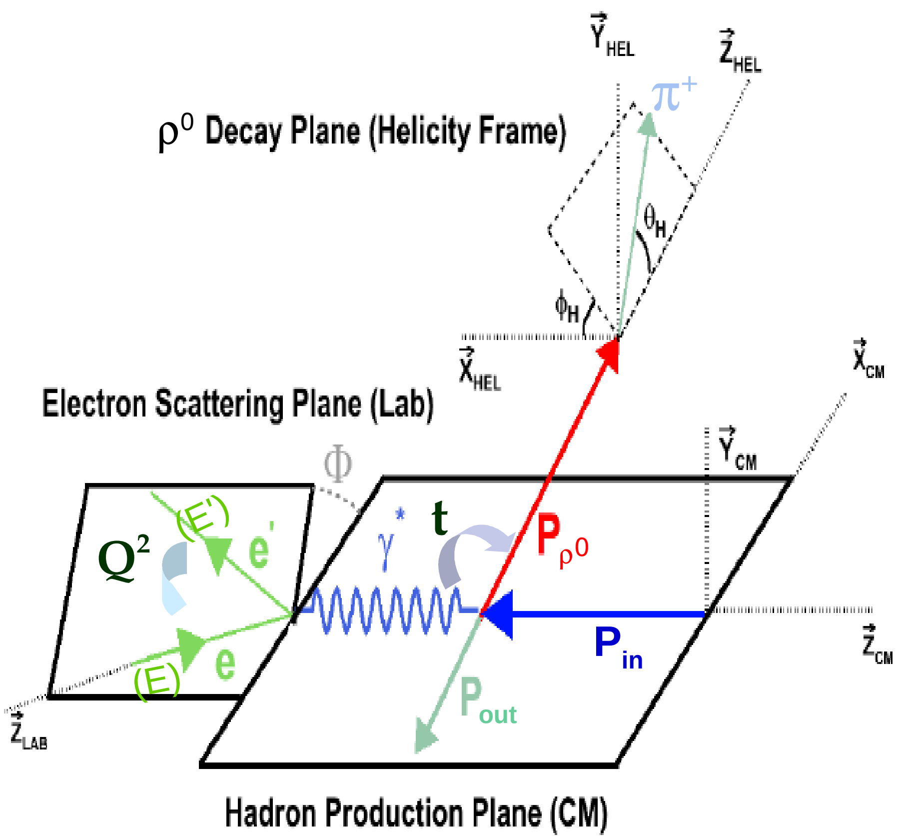






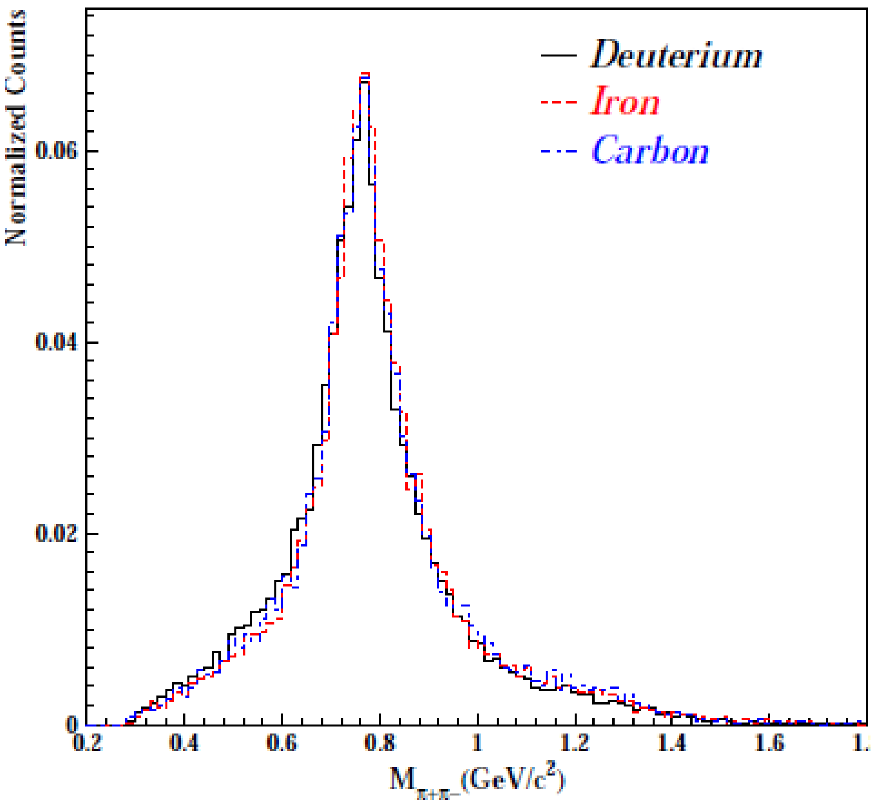
ρ^0 Electro-production Kinematics

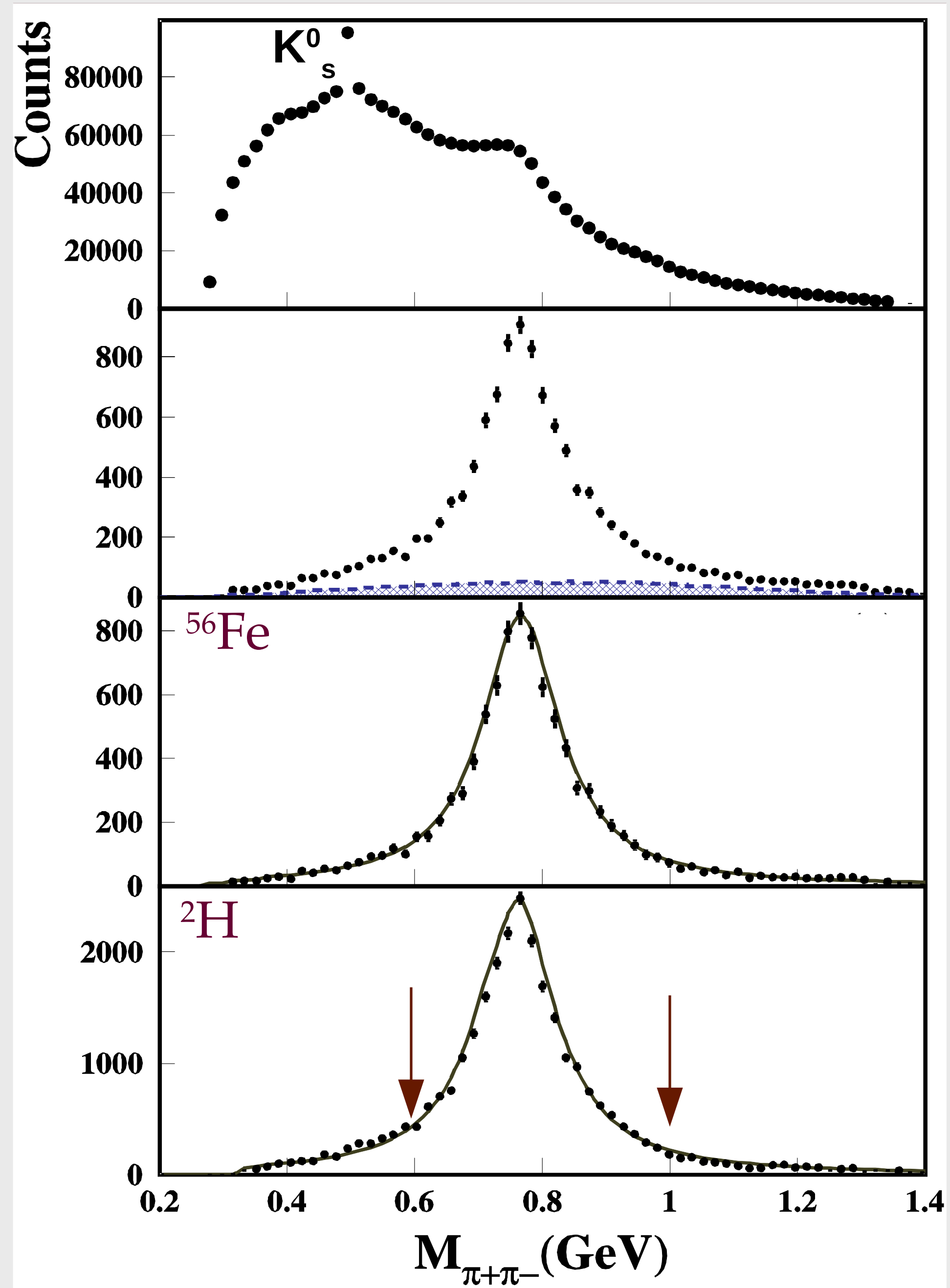
- $\nu = E - E'$: virtual photon (γ^*) energy in the Lab frame,
- $Q^2 = -(P^\mu_e - P^\mu_{e'})^2 = 4\,E\,E'\sin^2(\theta/2)$: photon virtuality,
- $t = (P^\mu_{\gamma^*} - P^\mu_\rho)^2$: momentum transfer square,
- $W^2 = (P^\mu_{in} + P^\mu_{\gamma^*})^2 = -Q^2 + M_p^2 + 2M_p\nu$: invariant mass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

Two pions invariant mass

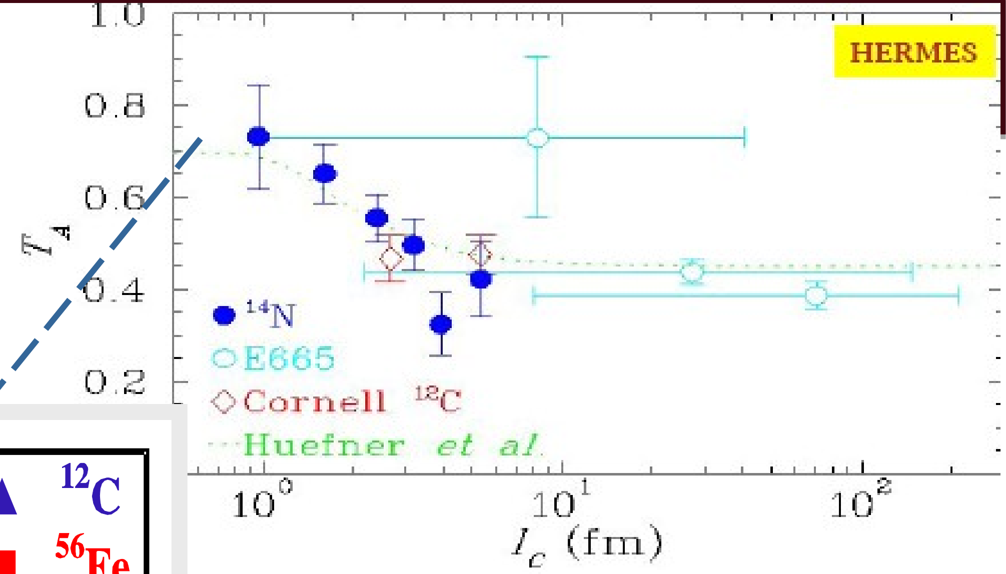


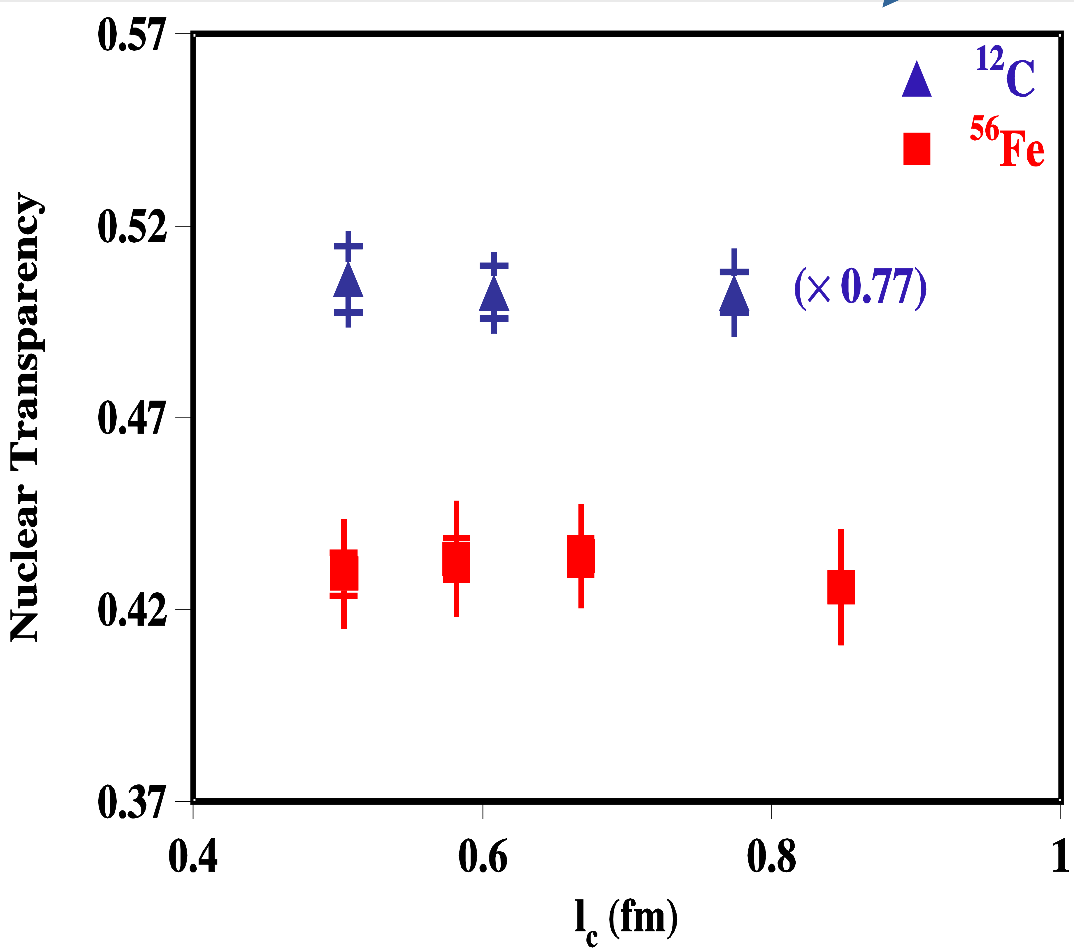


l_c Dependence on T_A

Coherence Length

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





Nuclear Transparency

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

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

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

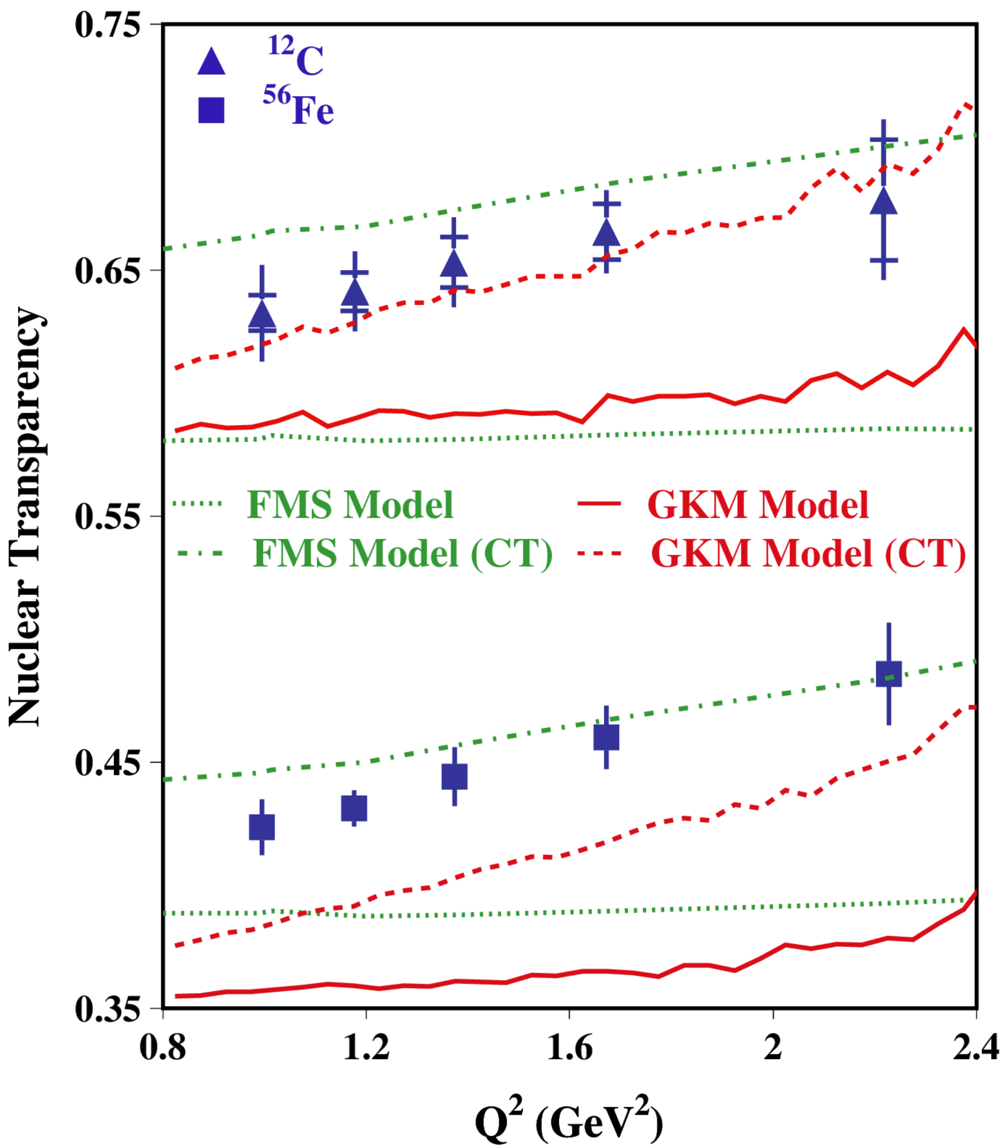
ρ⁰ CT Results for 5 GeV Iron & Carbon data-sets

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

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



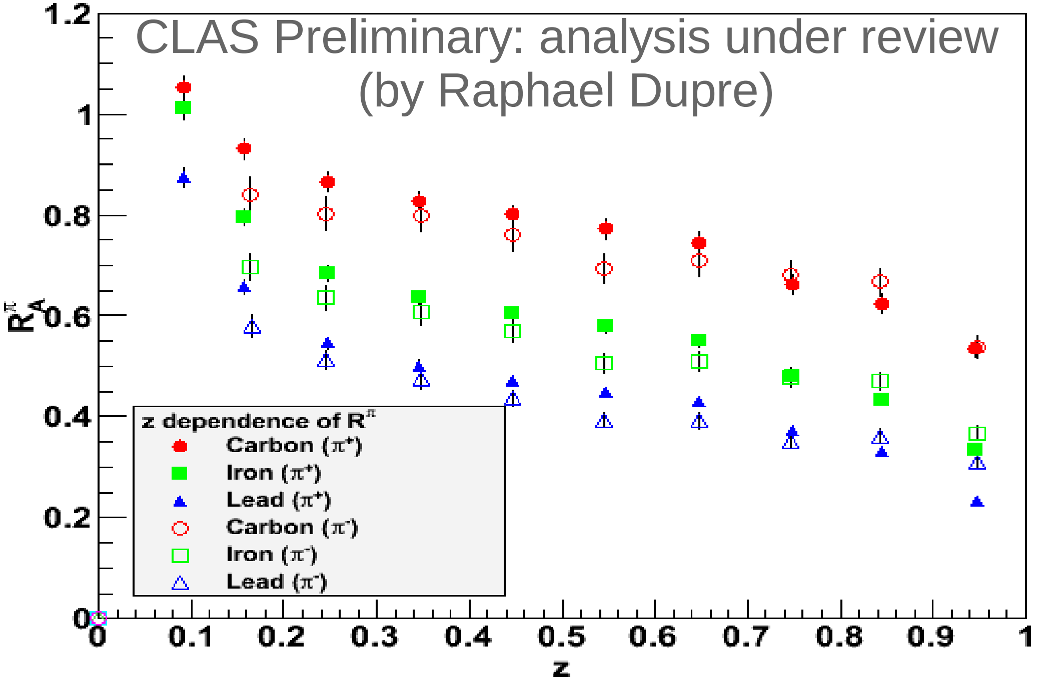
L. El Fassi *et al.* PLB 712, 2012

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

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

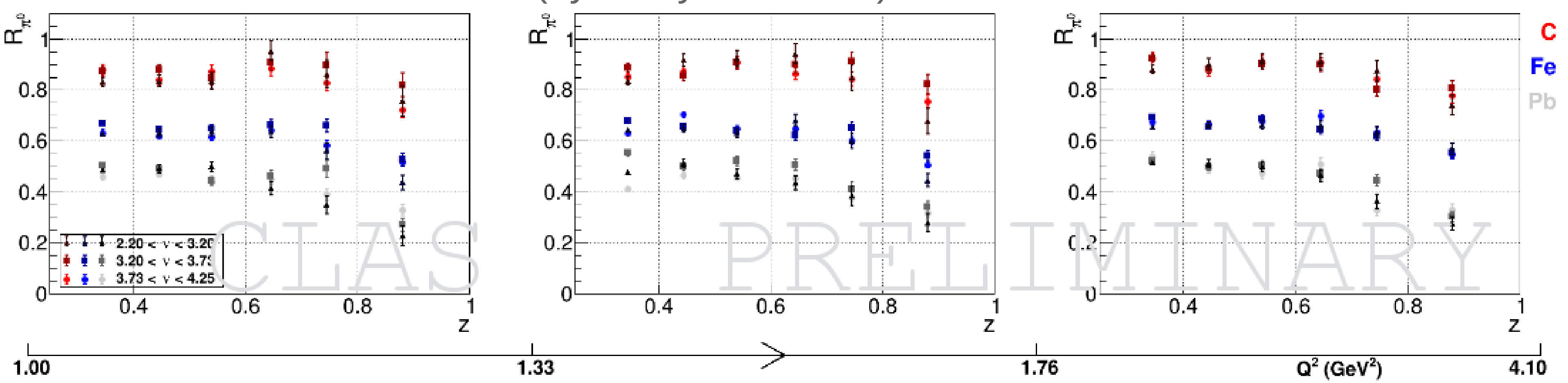
- KNS: Light Cone QCD Formalism
  Kopeliovich, Nemchik & Schmidt, PRC 76, 015205 (2007)
  & Private communication

5 GeV CLAS-6 Hadronization Results: Meson Channels

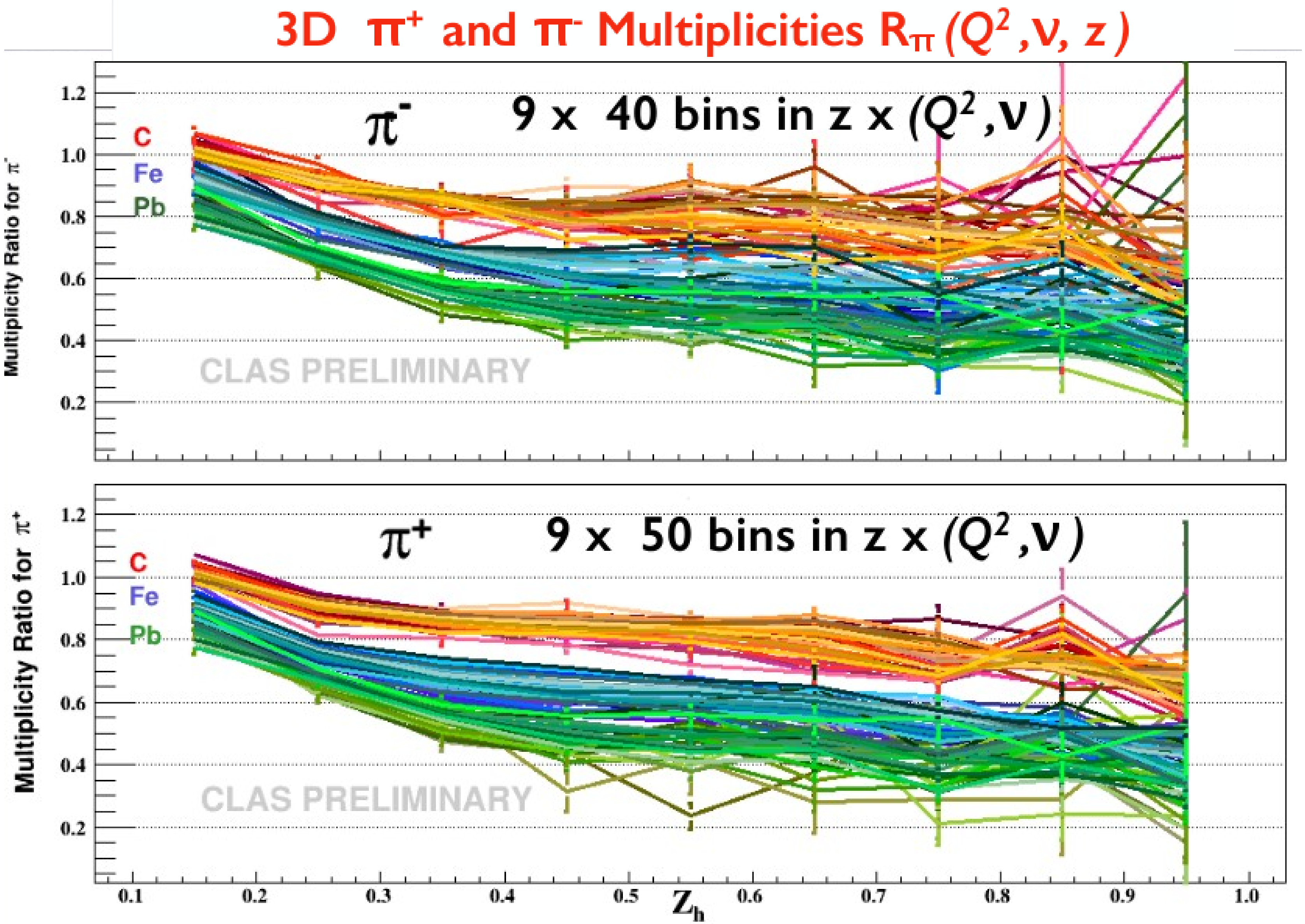


- 3-dimensional CLAS-6 multiplicity ratios, fully corrected for radiative processes and acceptance, normalized to target thicknesses; C, Fe, Pb.
- Similar behavior for π^0 (Taisiya's thesis results; under review), π^+ (Hayk's thesis) and K^0 (A. Daniel, Ken Hicks *et al.*; published!)
- Consistent with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

Example of 3-D π^0 multiplicity ratios
(by Taisiya Mineeva)

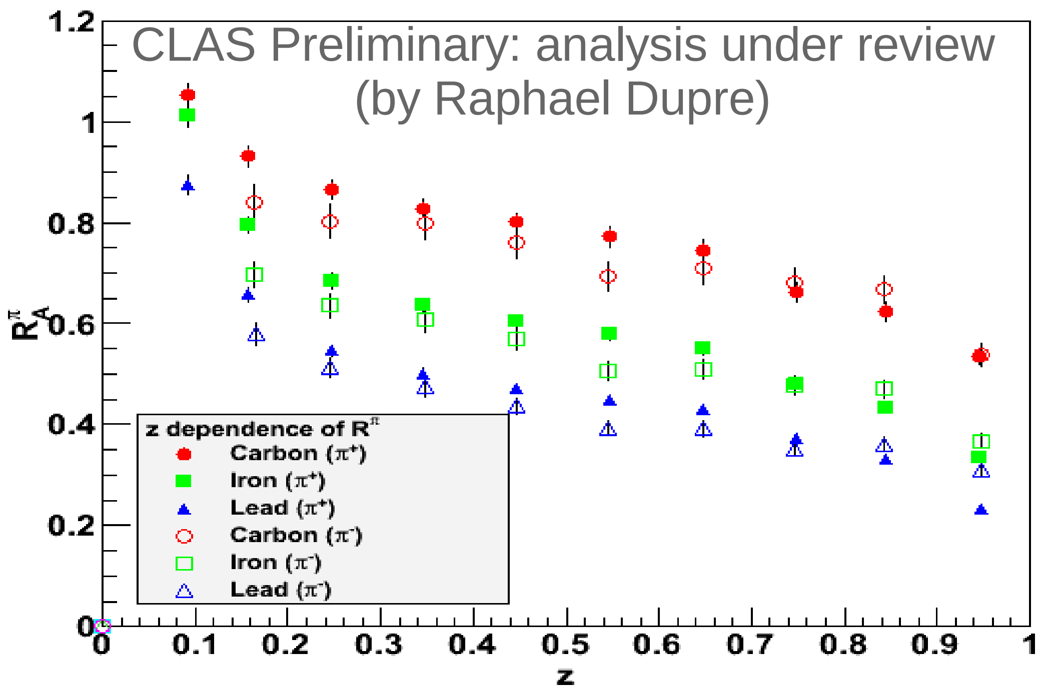


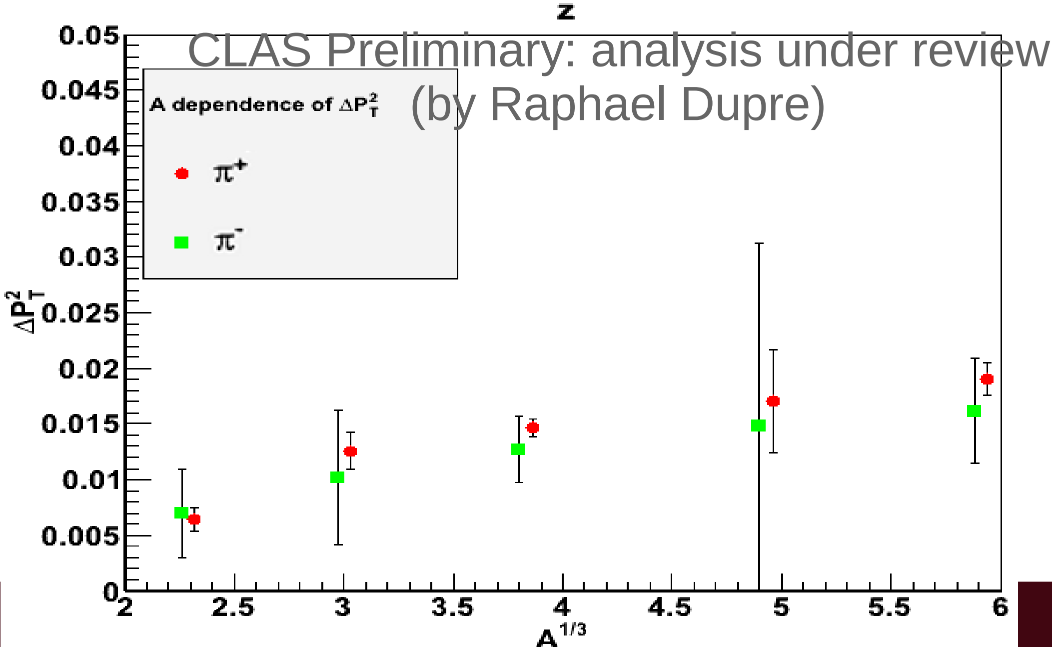
5 GeV CLAS-6 Hadronization Results: Meson Channels



Courtesy to Raphael Dupre, Hayk Hakobyan and Sebastian Moran

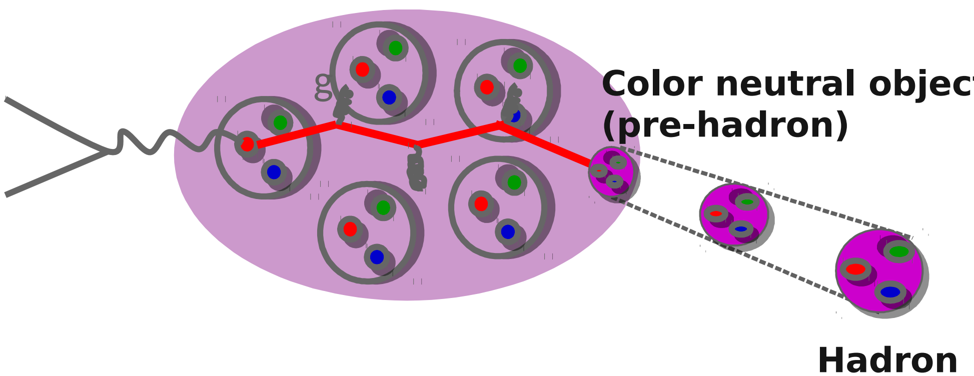
5 GeV CLAS-6 Hadronization Results: Meson Channels

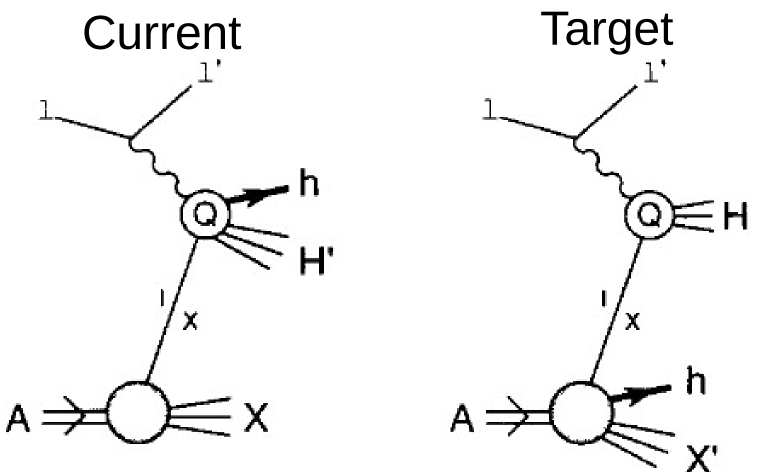




- 3-dimensional CLAS-6 multiplicity ratios, fully corrected for radiative processes and acceptance, normalized to target thicknesses; C, Fe, Pb.
- Similar behavior for π^0 (Taisiya's thesis results; under review), π^+ (Hayk's thesis) and K^0 (A. Daniel, Ken Hicks *et al.*; published!)
- Consistent with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

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

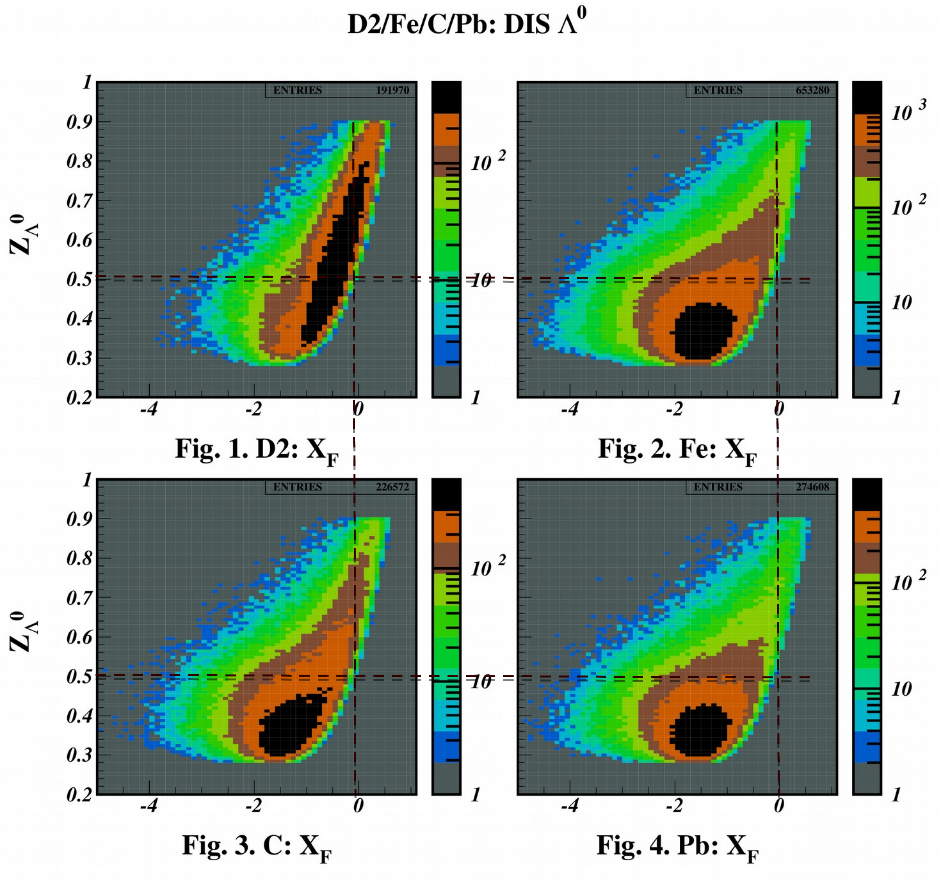




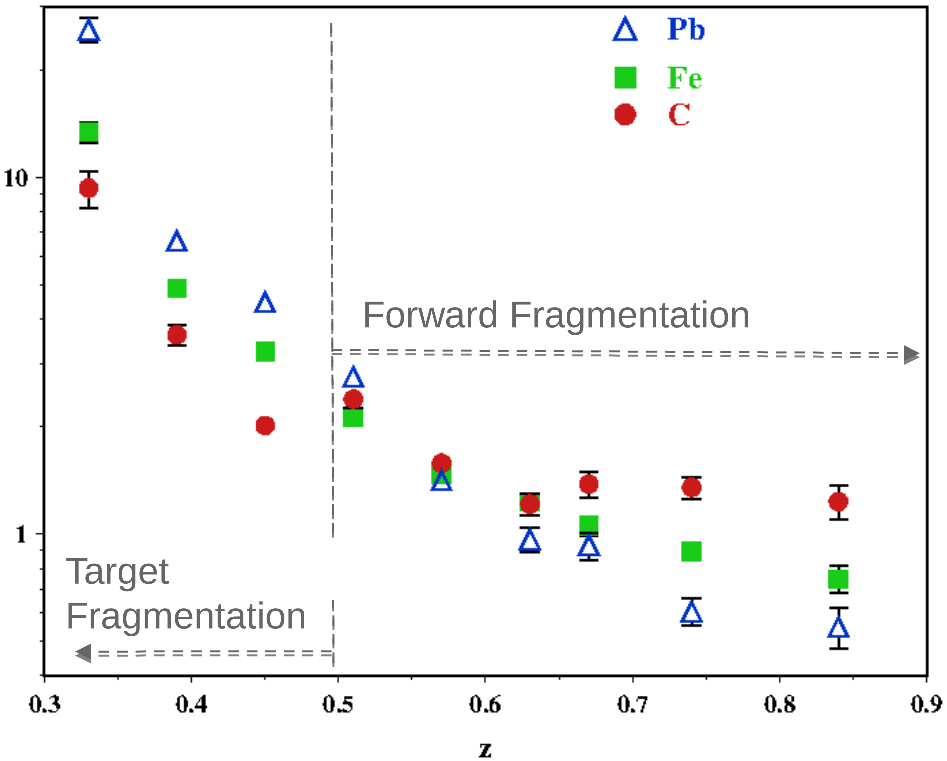
Phys. Let. B 323 (1994) 201-211, Trentadue and Veneziano

5 GeV CLAS-6 Hadronization Results: Baryon Channel

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

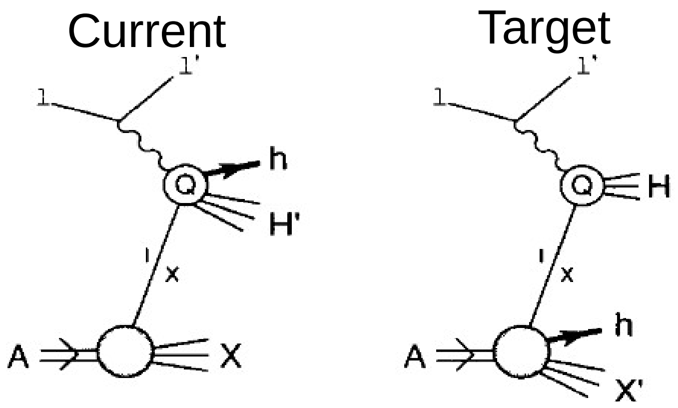


CLAS Preliminary: raw multiplicity ratio



5 GeV CLAS-6 Hadronization Results: Baryon Channel

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



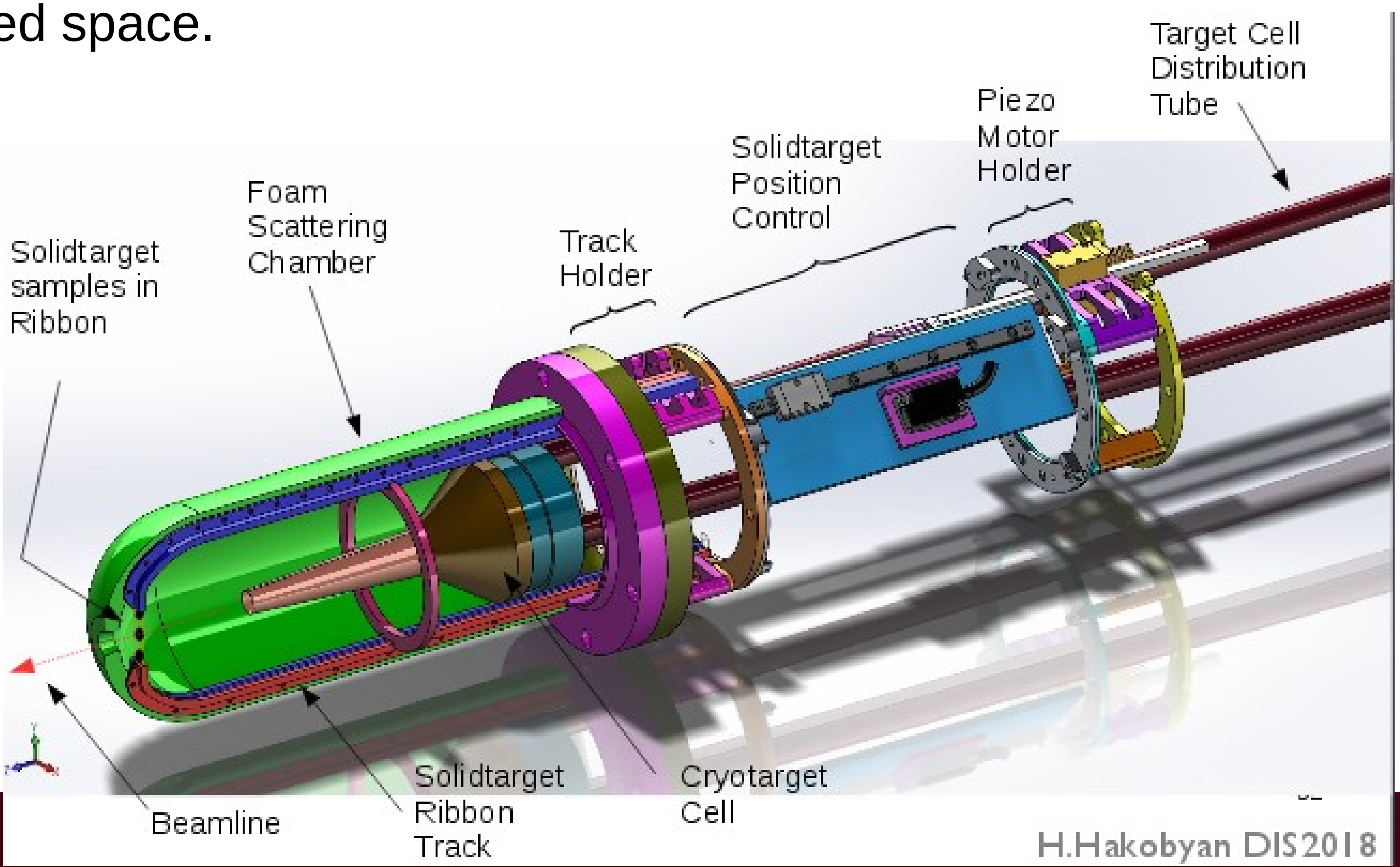
Phys. Let. B 323 (1994) 201-211
Trentadue and Veneziano

- 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

CLAS-12 CT & CP Measurements with C, Cu, Sn and Pb, unfortunately no Fe

- Dual target is currently under construction in UFTSM, Chile!
- Will operate under extreme conditions:
  - High vacuum (6x10E-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

meson	cτ	mass	flavor content
π^0	25 nm	0.13	$u\bar{u}d\bar{d}$
π^+, π^-	7.8 m	0.14	$u\bar{d}$, $d\bar{u}$
η	170 pm	0.55	$u\bar{u}d\bar{d}s\bar{s}$
ω	23 fm	0.78	$u\bar{u}d\bar{d}s\bar{s}$
η'	0.98 pm	0.96	$u\bar{u}d\bar{d}s\bar{s}$
ϕ	44 fm	1.0	$u\bar{u}d\bar{d}s\bar{s}$
f1	8 fm	1.3	$u\bar{u}d\bar{d}s\bar{s}$
K^0	27 mm	0.50	$d\bar{s}$
K^+, K^-	3.7 m	0.49	$u\bar{s}$, $\bar{u}s$

baryon	cτ	mass	flavor content
p	stable	0.94	ud
$\bar{p}$	stable	0.94	$\overline{ud}$
Λ	79 mm	1.1	uds
$\Lambda(1520)$	13 fm	1.5	uds
Σ^+	24 mm	1.2	us
Σ^-	44 mm	1.2	ds
Σ^0	22 pm	1.2	uds
Ξ^0	87 mm	1.3	us
Ξ^-	49 mm	1.3	ds

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

Actively underway with existing 5 GeV data

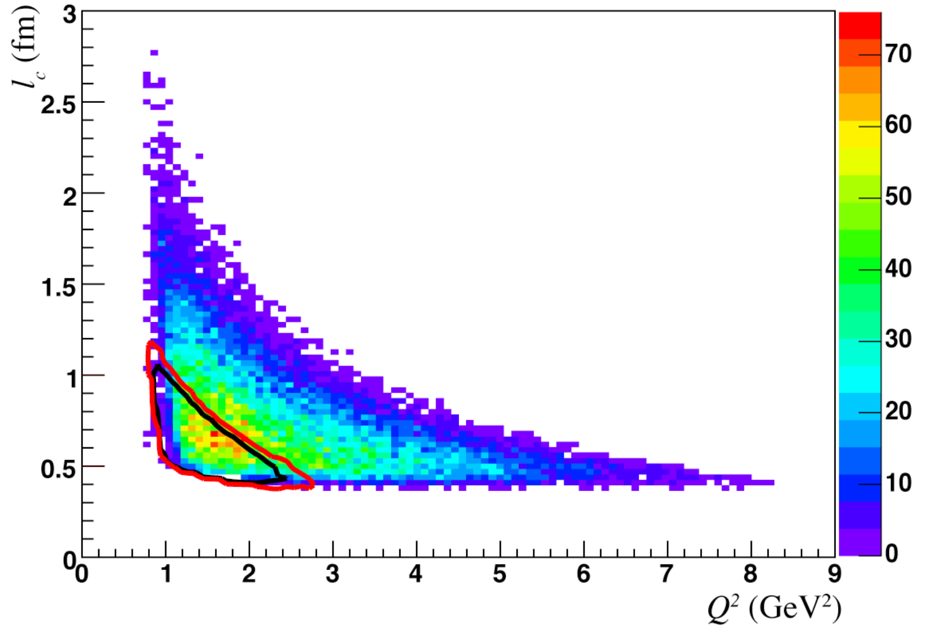
meson	cτ	mass	flavor content
π^0	25 nm	0.13	
K^0	27 mm	0.50	$d\bar{s}$
K^+, K^-	3.7 m	0.49	$u\bar{s}$, $\bar{u}s$

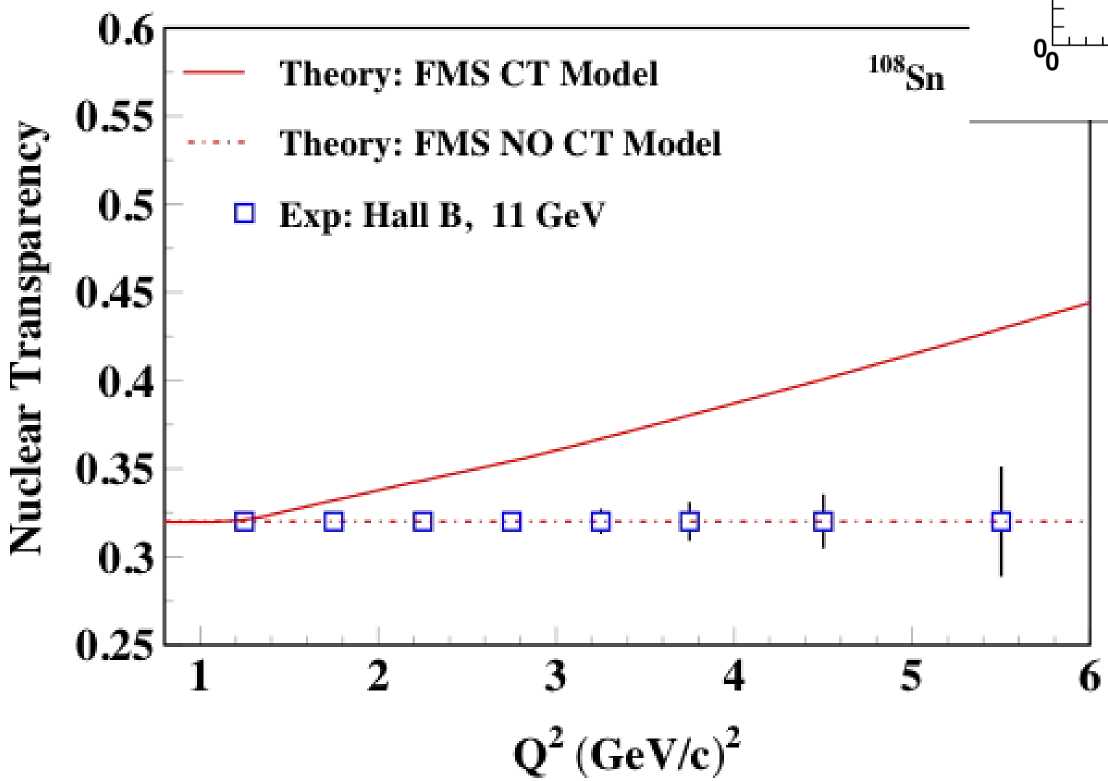
baryon	cτ	mass	flavor content
	stable	0.94	ud
Ξ^0	87 mm	1.3	us
Ξ^-	49 mm	1.3	ds

- Span a wider range of nuclei masses ⟹ Better understanding of the A dependence,
- Study the production of a variety of hadrons ⟹ 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),

⟹ Determines the two hadronization time-scales and constrain the existing theoretical models with the correct production picture!

CLAS-12 CT Measurement with C, Cu and Sn, unfortunately no Fe
Experiment PR12-06-106



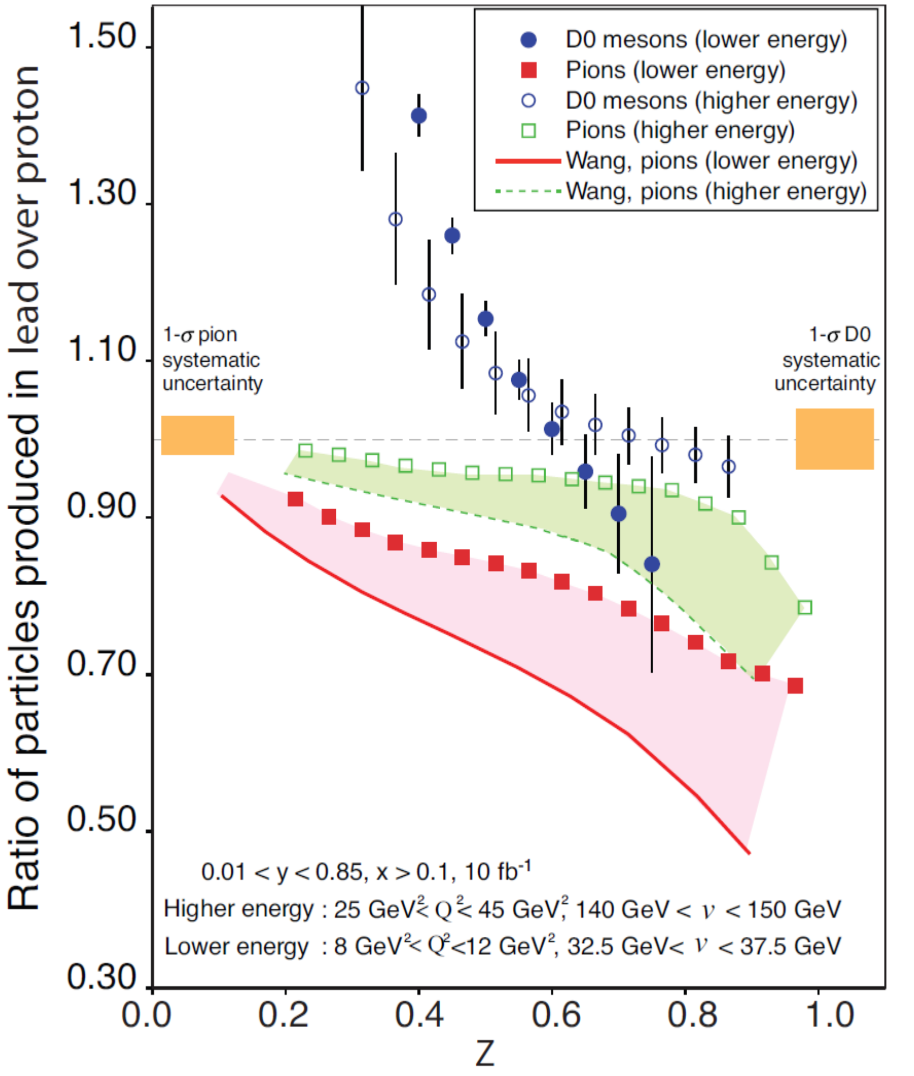


Summary and Outlook

- Strong evidence for the onset of CT using ρ^0 electroproduction off nuclei and CLAS-6 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.
- 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

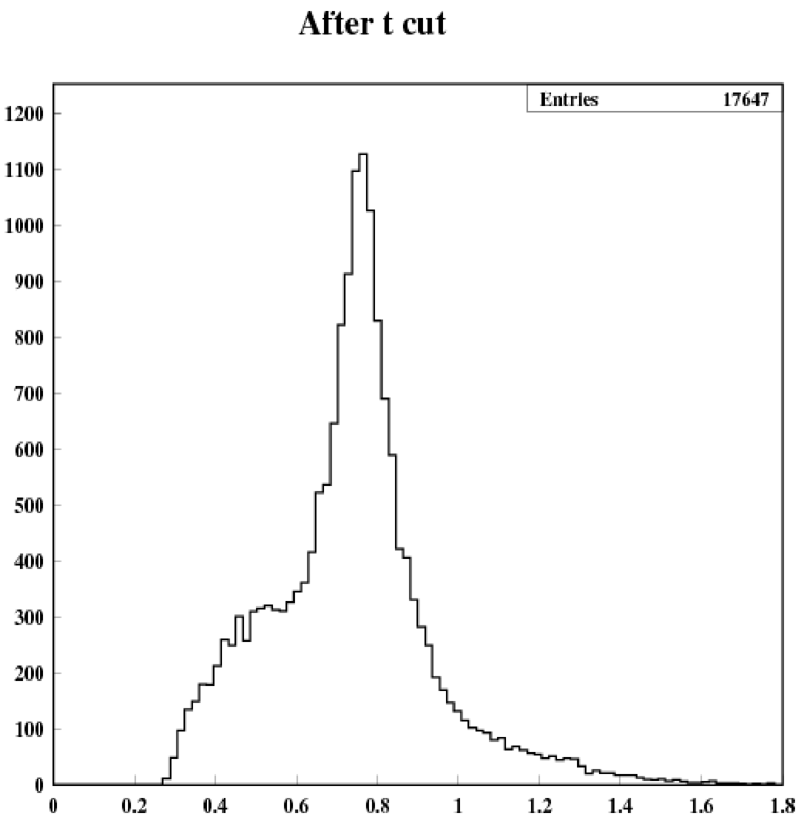
- EIC will allow the study of hadronization dynamics of heavy quarks in cold nuclear matter for a comparison with heavy ions collisions' data of RHIC and LHC, and provide a wider kinematics coverage to study the in-medium evolution and parton energy loss.



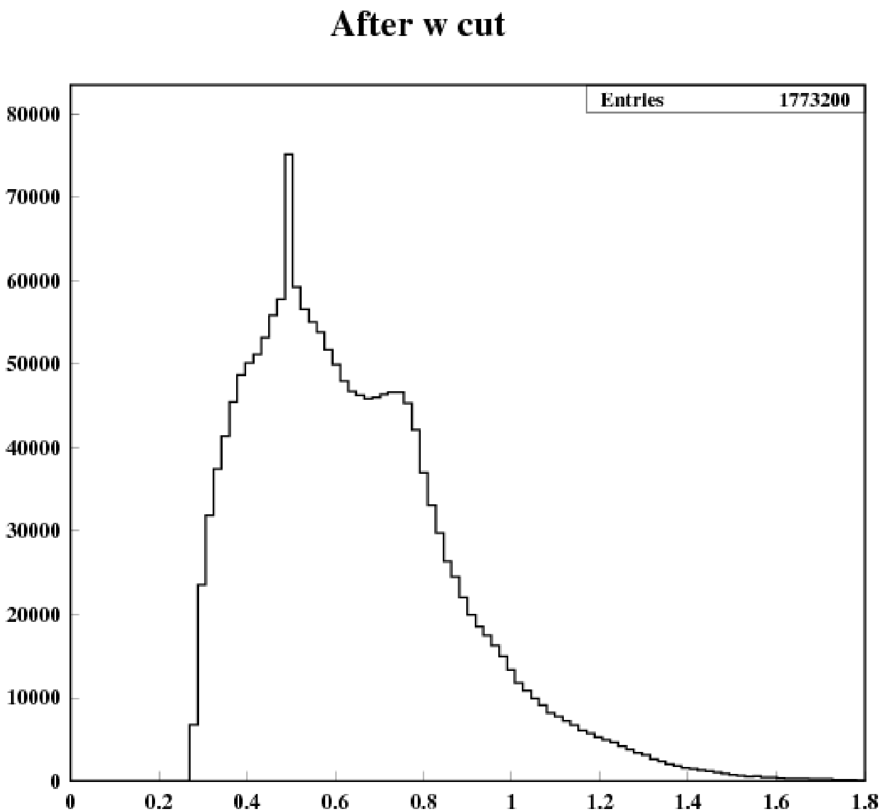
Backup Slides

ρ⁰ Invariant mass from 5 GeV D2+Fe dataset

Iron



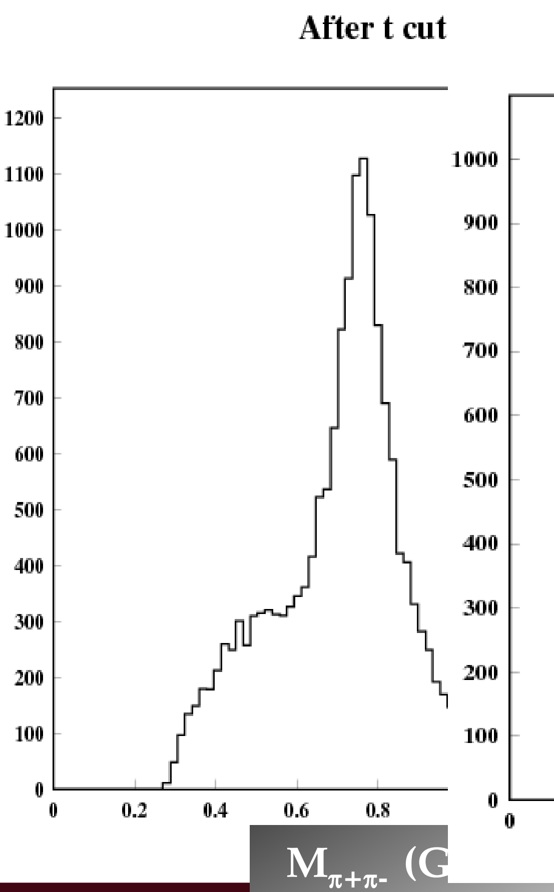
$M_{\pi+\pi-}$ (GeV)

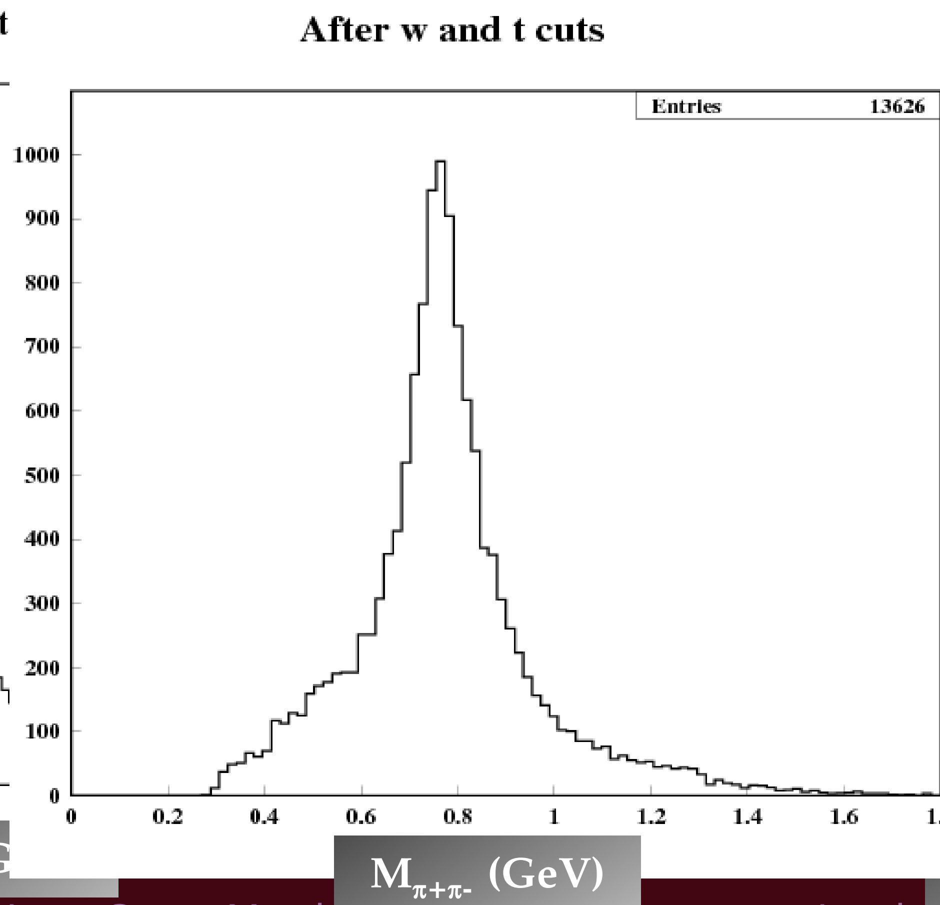


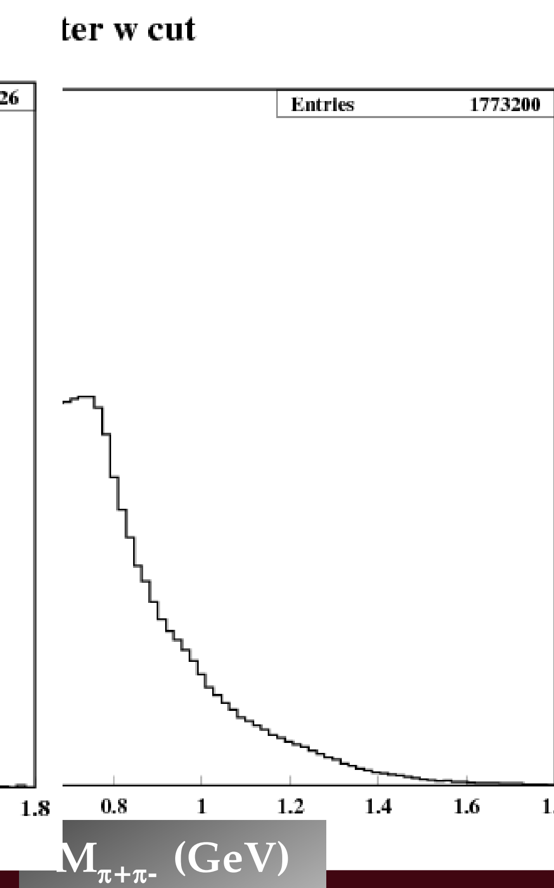
$M_{\pi+\pi-}$ (GeV)

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

Iron

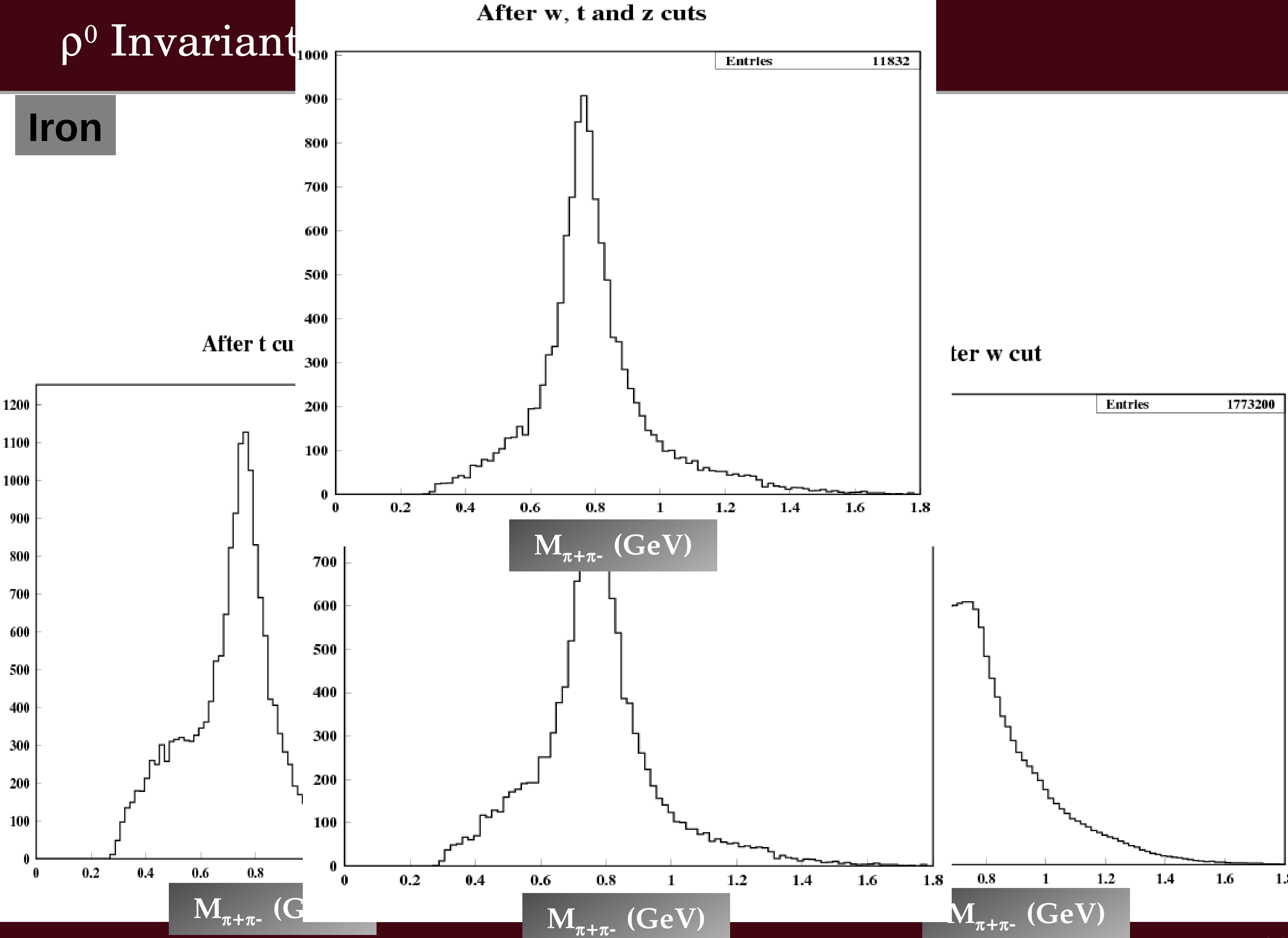






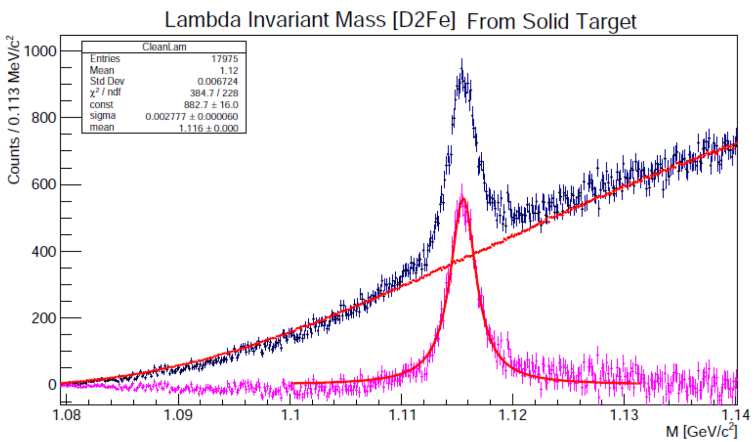
ρ^0 Invariant

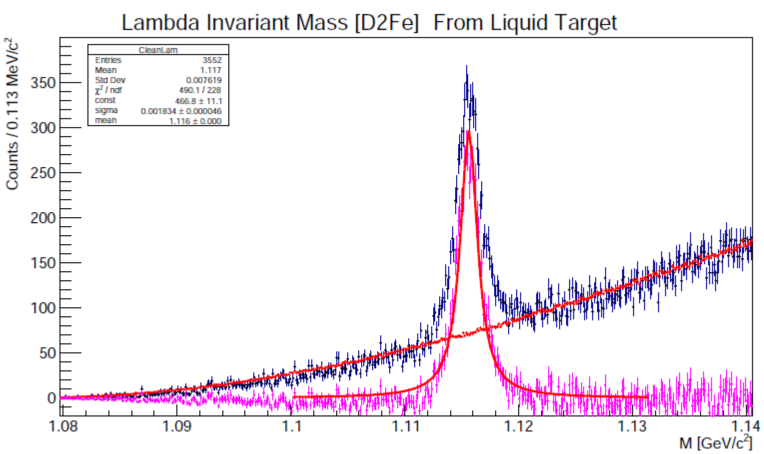
Iron

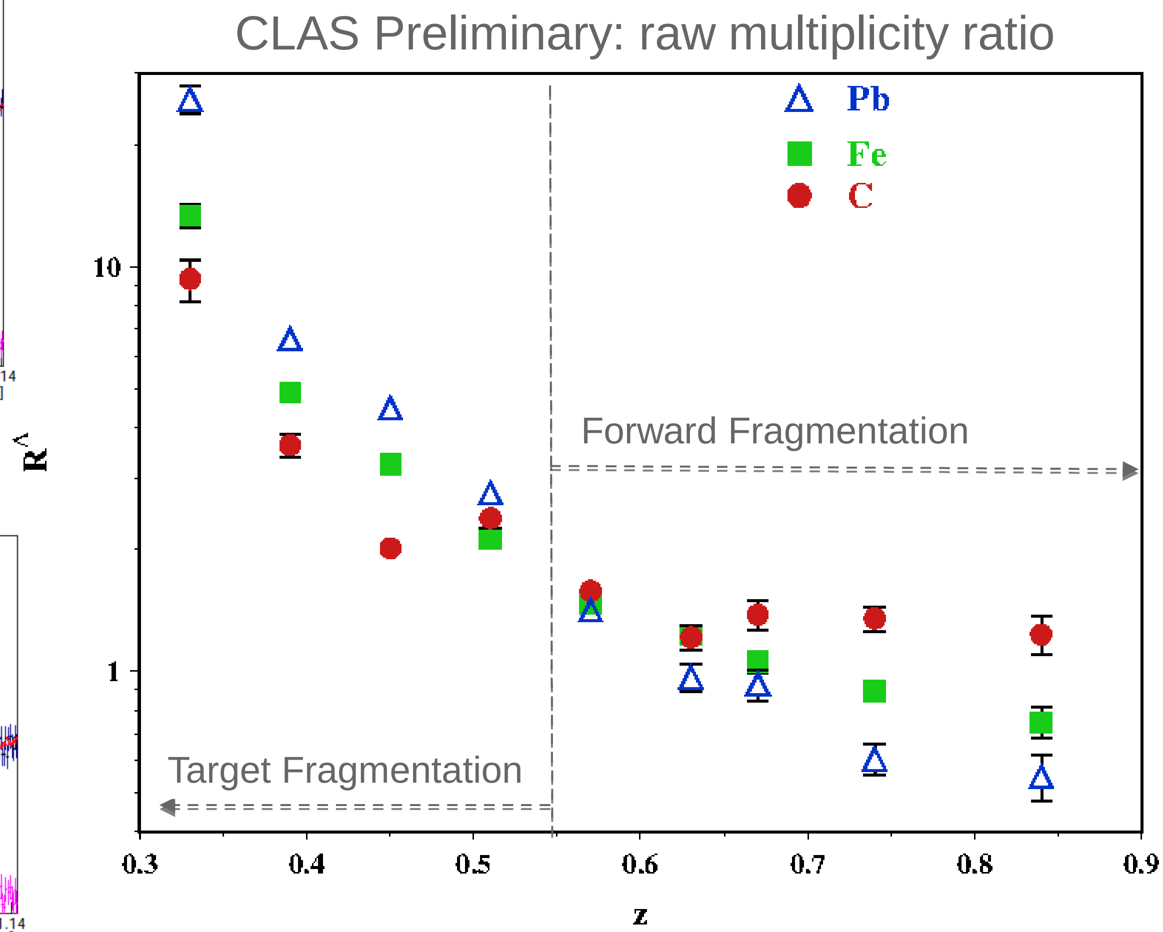


5 GeV CLAS-6 Hadronization Results: Baryon Channel

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







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

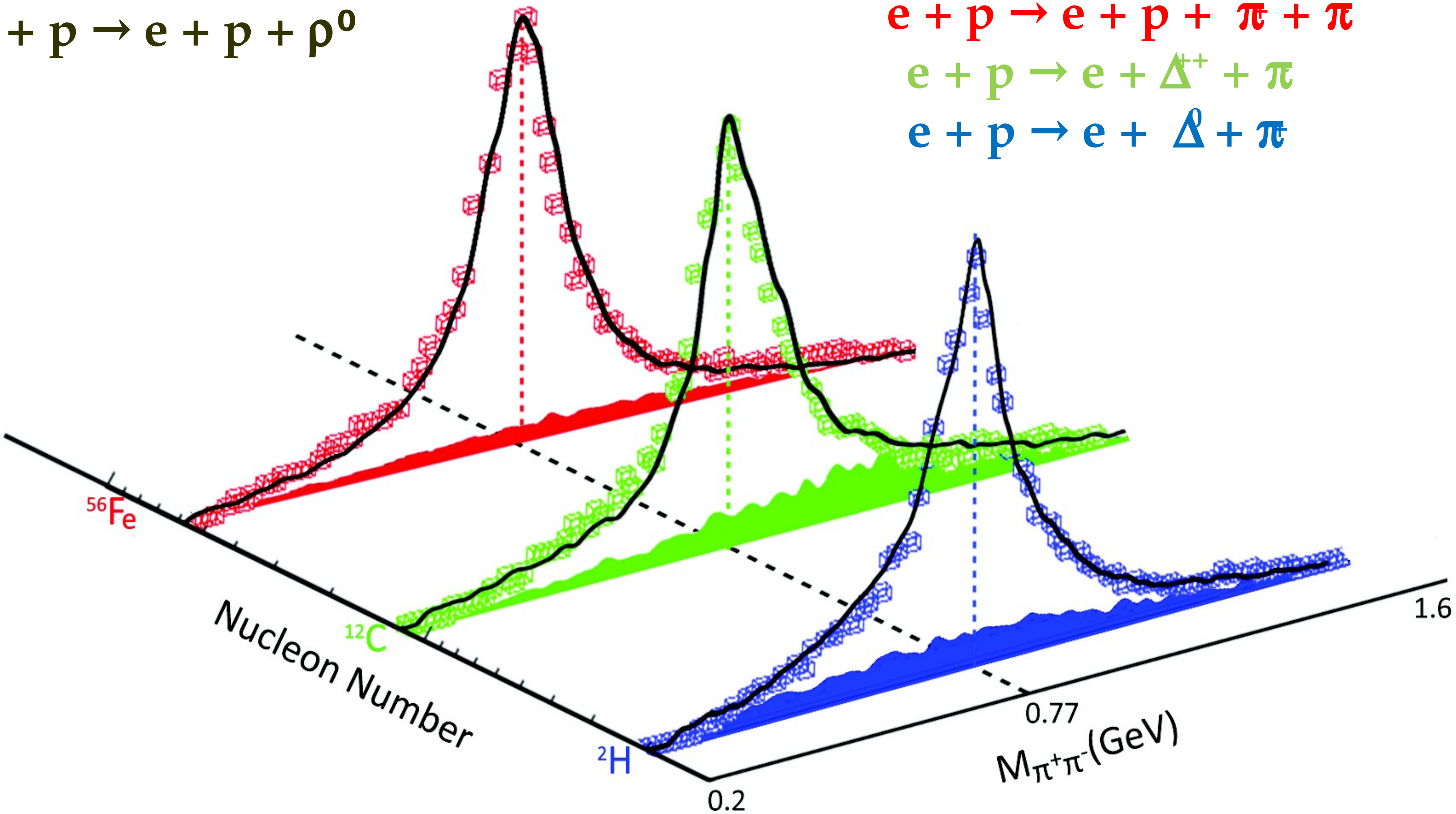
$e + p \rightarrow e + p + \rho^0$

Simulated Background's Shapes

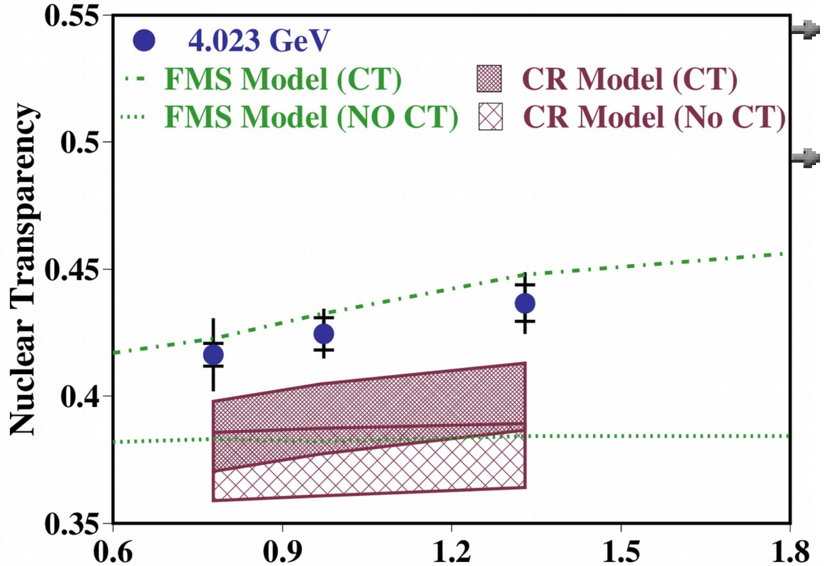
$e + p \rightarrow e + p + \pi + \pi$

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

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

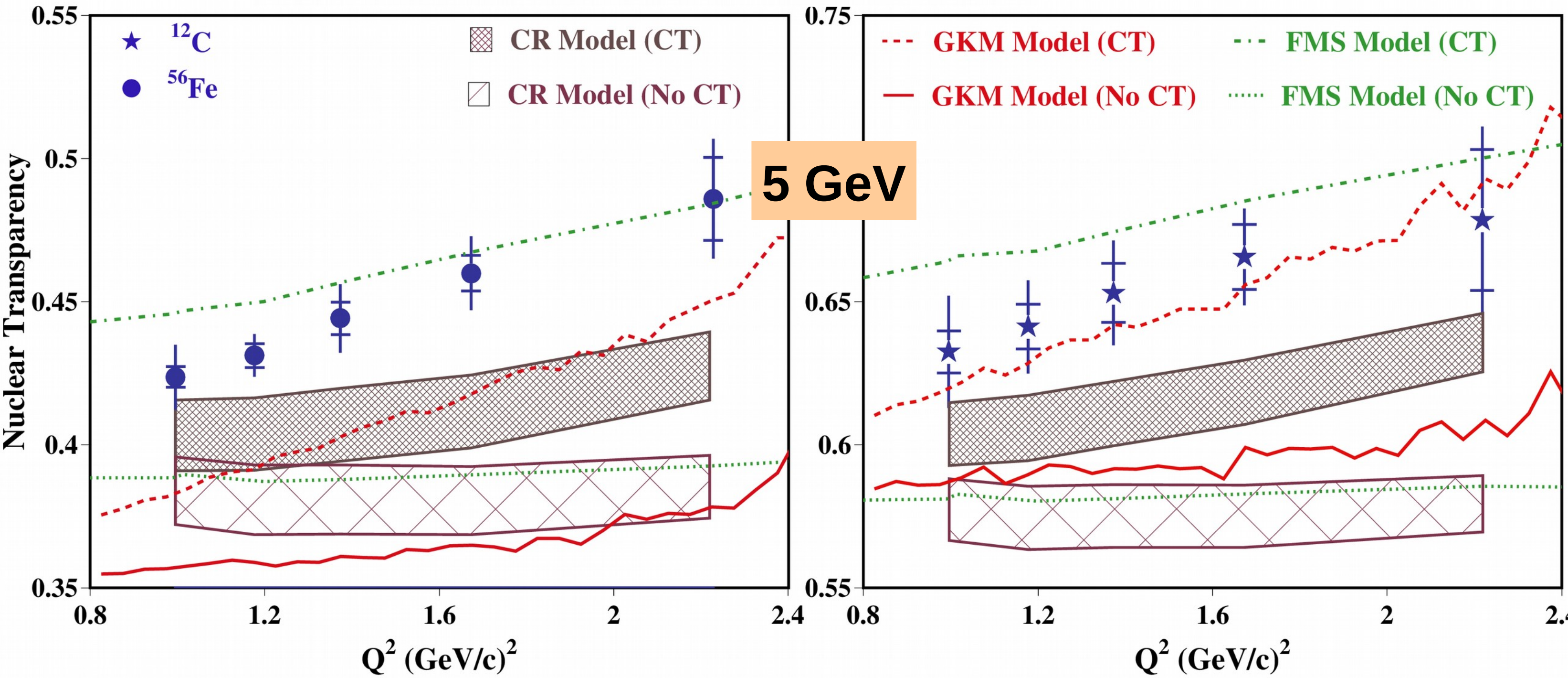


CLAS-6 CT Results for 4 & 5 GeV EG2 data: Under Review



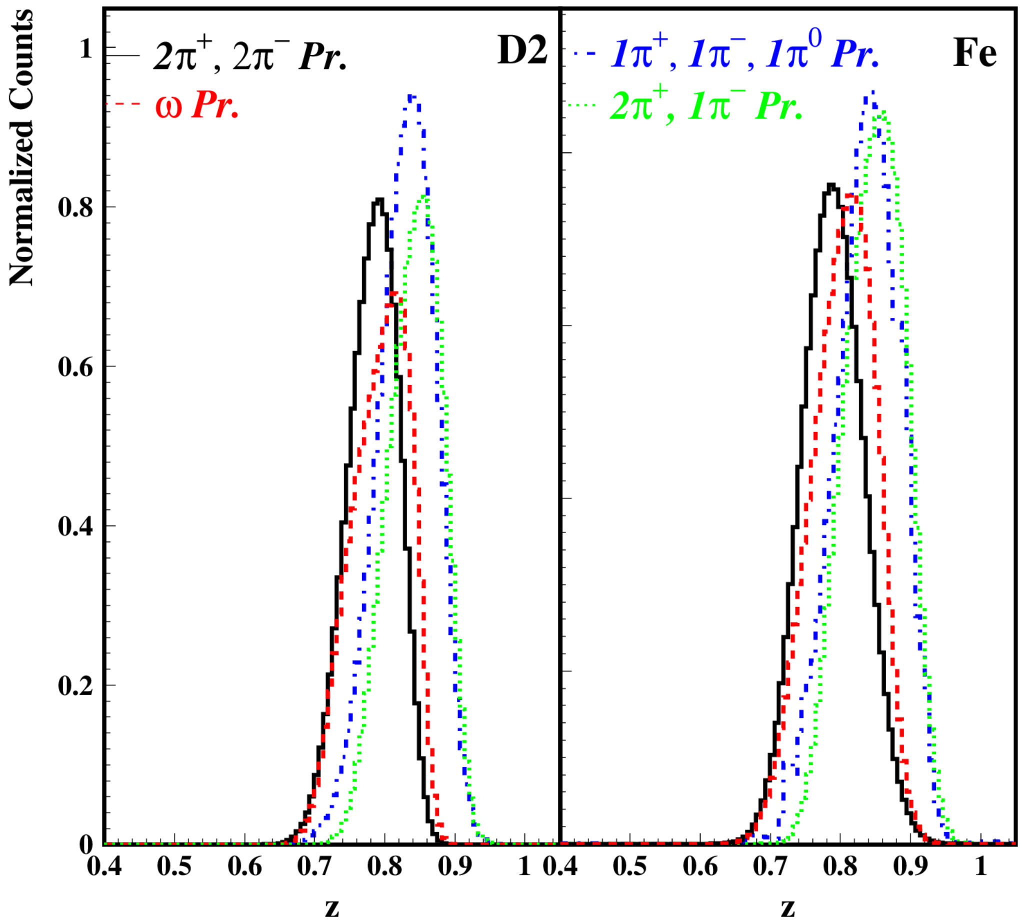
- **CR**: relativistic multiple scattering Glauber approximation.
- Hatched-band includes CT effects based on quantum diffusion model.

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



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