Hadronization and Color Transparency Studies at JLab

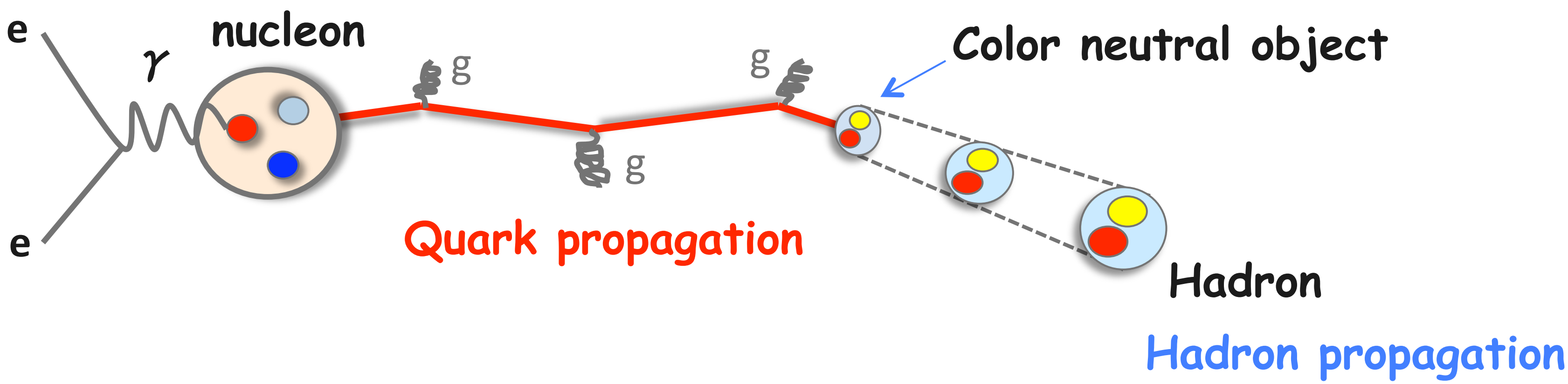
The Physics of pA Collisions at RHIC, BNL

Monday January 7th, 2013

Kawtar Hafidi

Part 1 - Hadronization

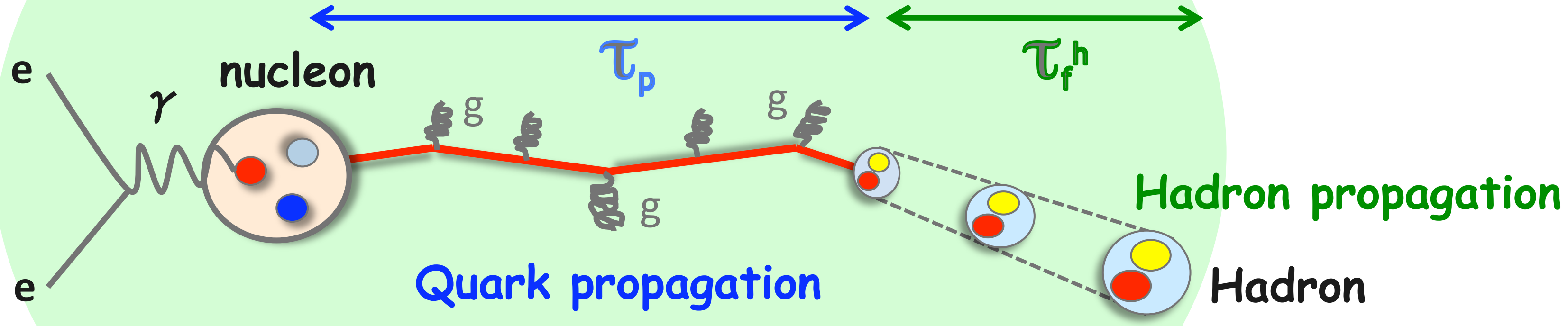
How do quarks transform “hadronize” into hadrons?



- Color charges cannot be separated by much more than 1 fm, since light quarks easily pop up from the vacuum
- Taking into account Lorentz dilation, the proper time scales for hadronization in the Lab frame become few fm
- However our detectors are placed distances 10^{15} times further away from the origin compared to the hadronization length

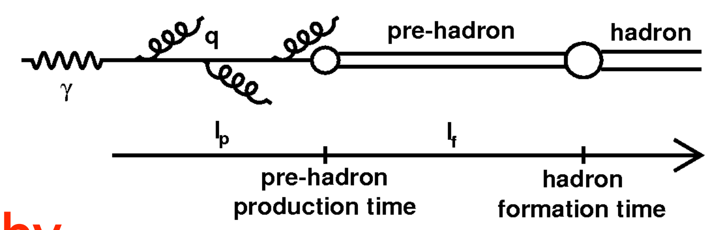
Hadronization in Nuclei

Nuclei provide a unique opportunity as detectors at a tiny distance within the range of hadronization process and perform direct measurements. These are the multiple scattering centers separated by only 1 – 2 fm

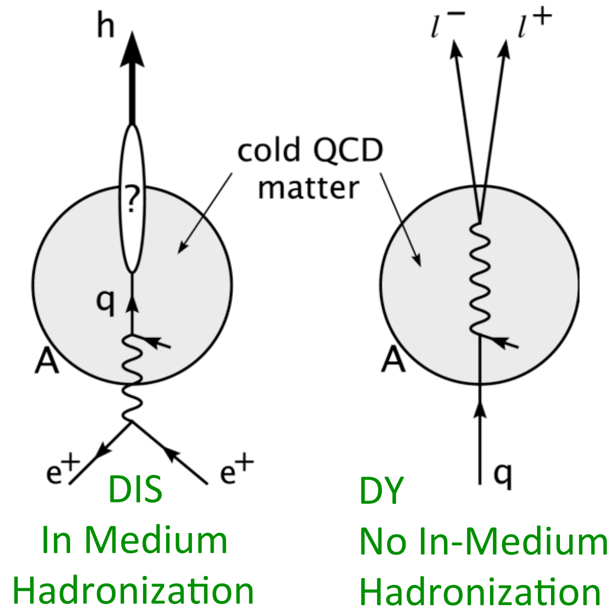


- What is the interaction of the struck quark before it neutralizes its color?
- What is the lifetime of an energetic free quark τ_p?
- How long does it take to form the color field of a hadron τ_f?
- What is the dynamic leading to color confinement?

Motivation

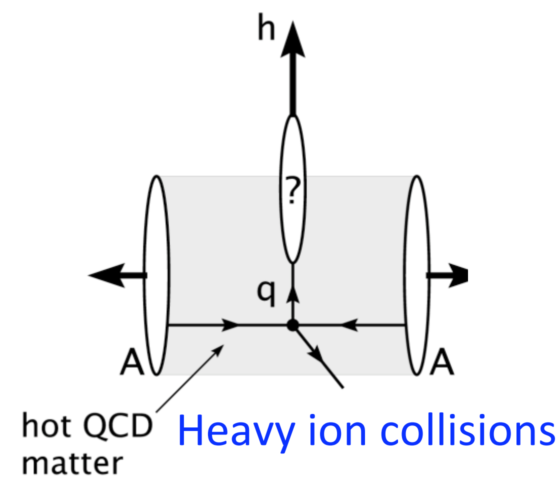


- Understand the Hadronization process by
  - Measuring the characteristic times
  - Measuring quark energy loss
  - Measuring hadron attenuation



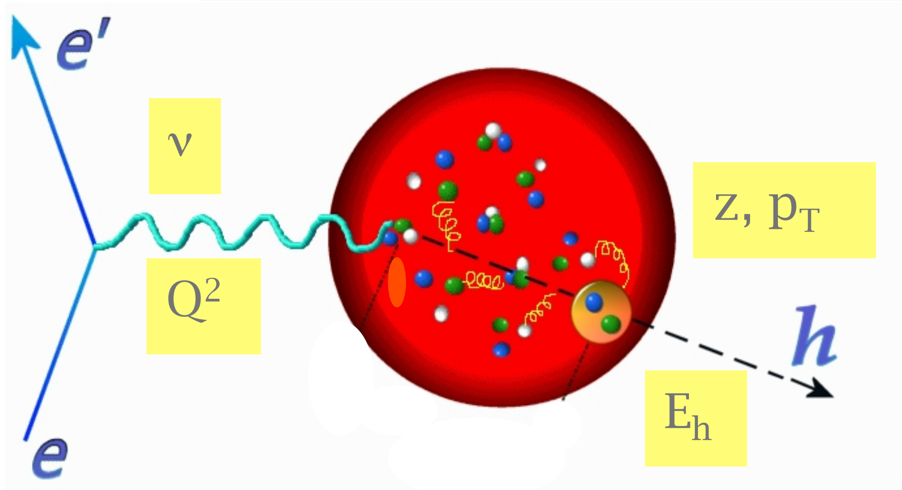
- Characterization of the QCD medium
  - Testing and calibrating theoretical tools used to determine the properties of Quark–Gluon Plasma

- Reduce systematic effects when attenuation needs to be corrected for
  - Neutrino experiments since they use nuclear targets



Experimental techniques

$$z = \frac{k.p}{q.p} = E_h/\nu$$



- Identify quark propagation phase by measuring p_T broadening
- Identify hadron formation phase by measuring hadron attenuation
- Extract characteristic times and reaction mechanisms using the variation of these observables with the nuclear size

Observables

- Multiplicity ratio → Characterizes the attenuation (1− R)

$$R_A^h(Q^2, x_{Bj}, z, P_T) = \frac{N_A^h(Q^2, x_{Bj}, z, P_T)/N_A^e(Q^2, x_{Bj})}{N_D^h(Q^2, x_{Bj}, z, P_T)/N_D^e(Q^2, x_{Bj})}$$

- Transverse momentum broadening → Characterizes the modification of the P_t spectrum

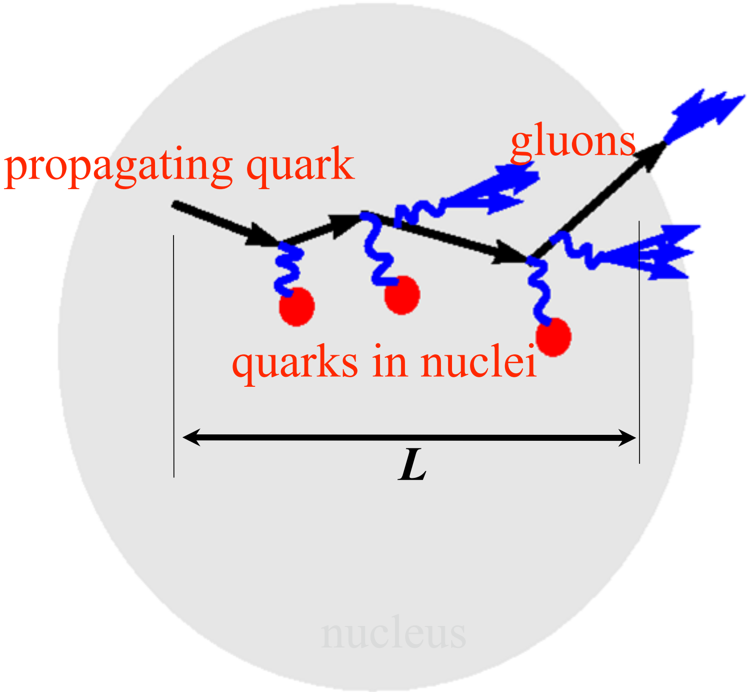
$$\Delta P_T^2 = \langle P_T^2 \rangle_A - \langle P_T^2 \rangle_D$$

- These are normalized to deuterium to reduce isospin effects
  → Other nuclei might be used for normalization as well

p_T Broadening and Quark Energy Loss

Quarks lose energy by gluon emission as they propagate

- In vacuum
- Even more within a medium



- This energy loss is manifested by Δp_T^2
- Δp_T^2 is a signature of the production time l_p
- $\Delta E \sim L$ dominates in QED
- $\Delta E \sim L^2$ dominates in QCD?

$$dE/dx \approx \frac{\alpha_s}{\pi} N_c \langle p_T^2 \rangle_L$$

Medium-stimulated loss calculation by BDMPS

$$l_p \approx \frac{\nu(1-z)}{dE/dx}$$

Experimental effort

Semi-inclusive deep inelastic scattering on nuclei

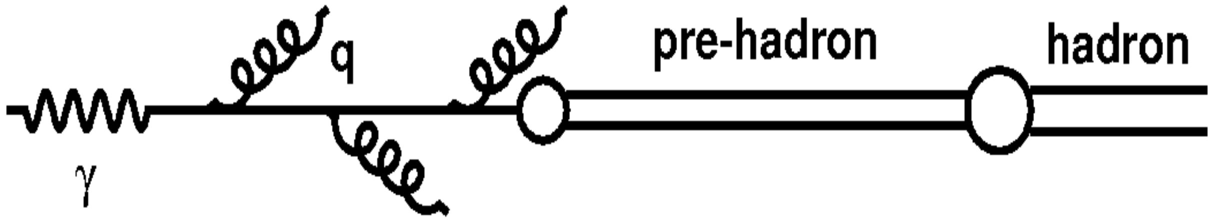
- 1970's SLAC eA → e'Xh, energy transfer ~35-145 GeV
- 1990's CERN EMC μA → μ'Xh, energy transfer ~35-145 GeV
- 1990's WA21/59 (4- 64 GeV) ν beam on Ne target
- 2000's HERA HERMES $e^+A \rightarrow e^{+\prime}Xh$, 12 and 26 GeV beam
- 2000's Jefferson Lab Hall C and CLAS, eA → e'Xh, 5 GeV beam

Drell-Yan reaction

- 1980's CERN SPS NA-10 spectrometer: $pA \rightarrow X\mu^+\mu^-$, 140 and 280 GeV beam
- 1990's Fermilab $pA \rightarrow X\mu^+\mu^-$, 800 GeV beam

International, multi-institutional quest for 30 years, but most progress since 2000

Models



- Which process dominates? Parton energy loss or Hadron absorption?

- Are fragmentation functions modified in the nuclear medium?

Several models exists with different answers to these questions

→ Pure parton energy loss or hadron absorption models

→ Mixed models

Selected Models

- Gluon Bremsstrahlung **Model** *(B. Kopeliovich, J. Nemchik E. Predazzi, A. Hayashigaki)*

  Gluon radiation + hadronization model

- Twist-4 pQCD **Model** *(X.-N. Wang, E. Wang, X. Guo, J. Osborne)*

  Medium-induced gluon radiation only

- Rescaling **Models** *(A. Accardi, H. Pirner, V. Muccifora)*

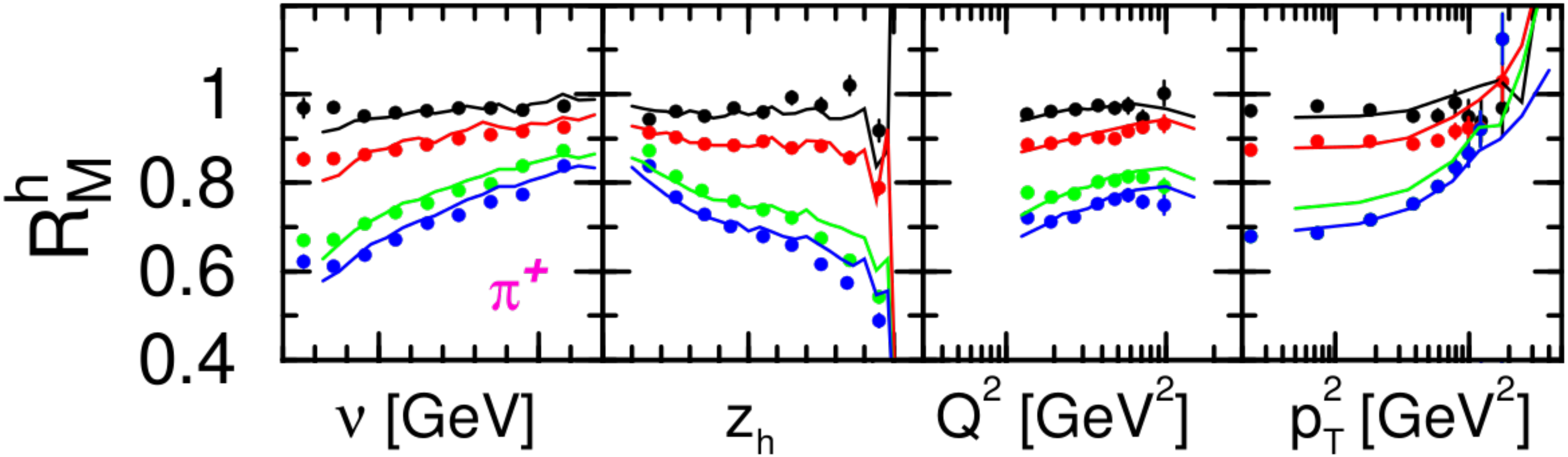
  Gluon emission, partial deconfinement, nuclear absorption

- PYTHIA-BUU Coupled Channel **Model** *(T. Falter, W. Cassing, K. Gallmeister, U. Mosel)*

  Fundamental interaction + coupled channel nuclear final state interaction

The general picture

$$\tau_p \approx \frac{\nu z}{Q^2}(1-z)$$

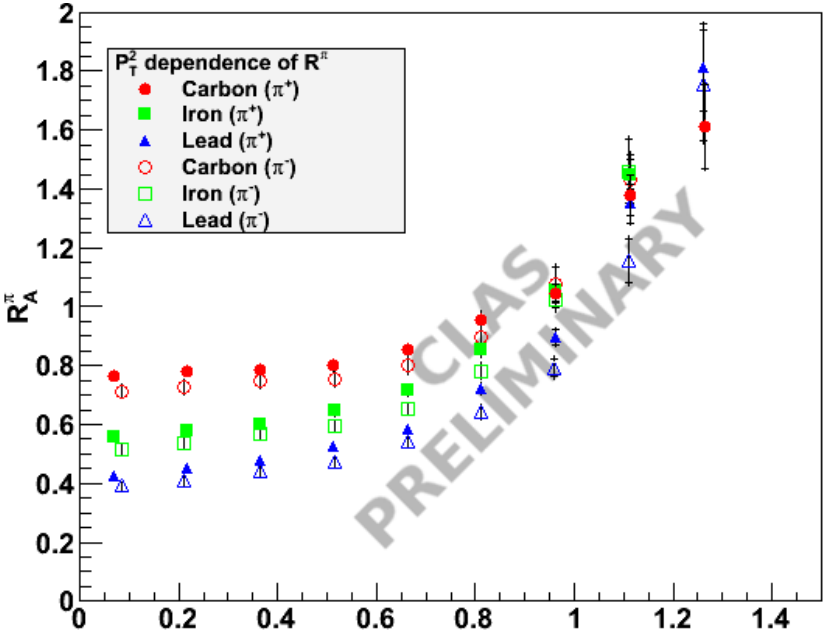


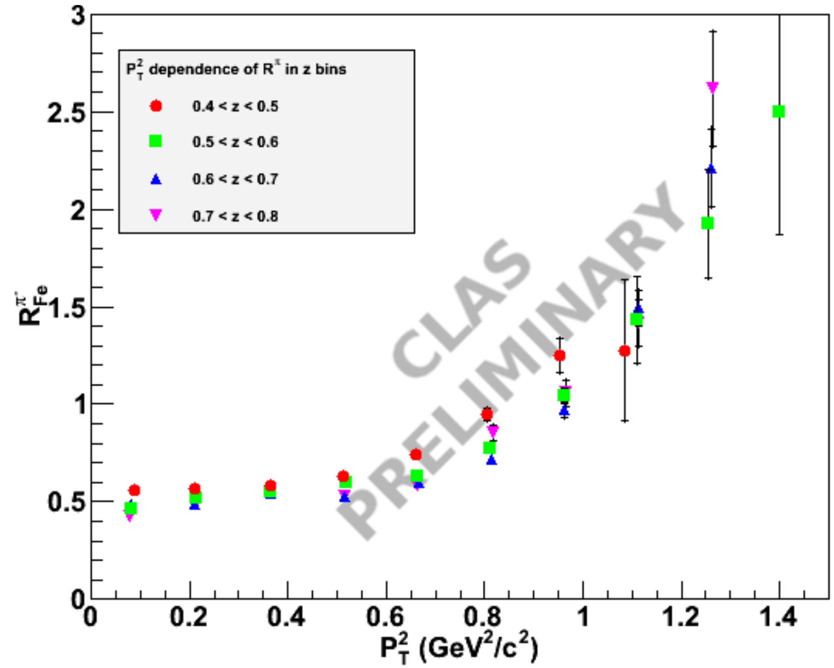
HERMES Data compared to GIBUU model

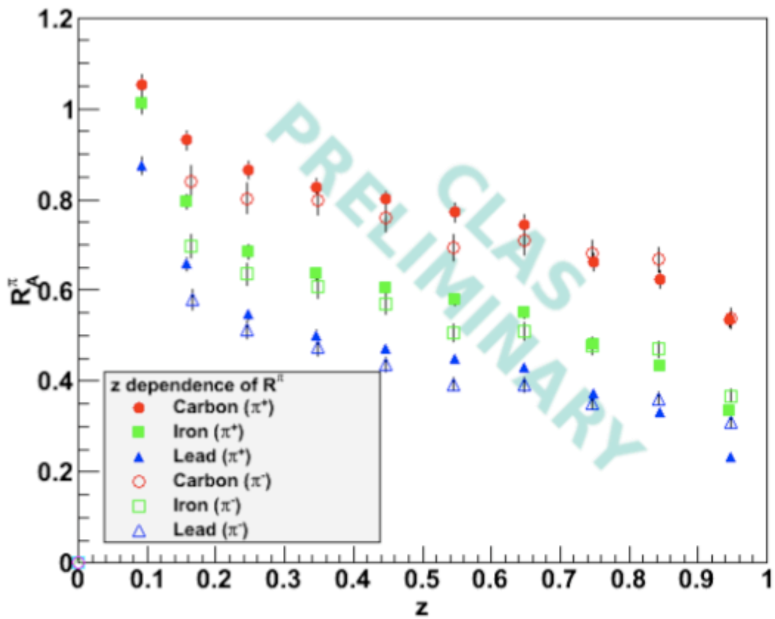
He, Ne, Kr, Xe

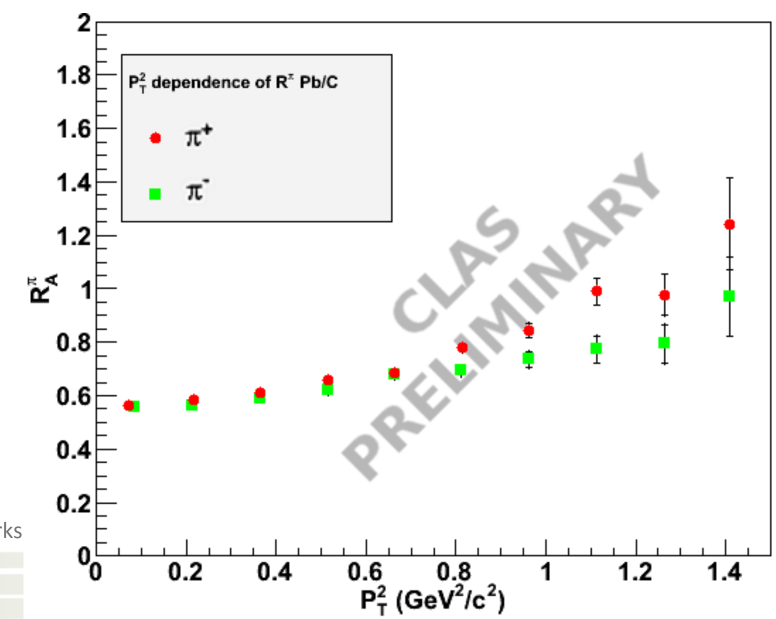
- Increase with ν
- Decrease with z
- Slight increase with Q^2
- Strong increase with P_T

CLAS preliminary

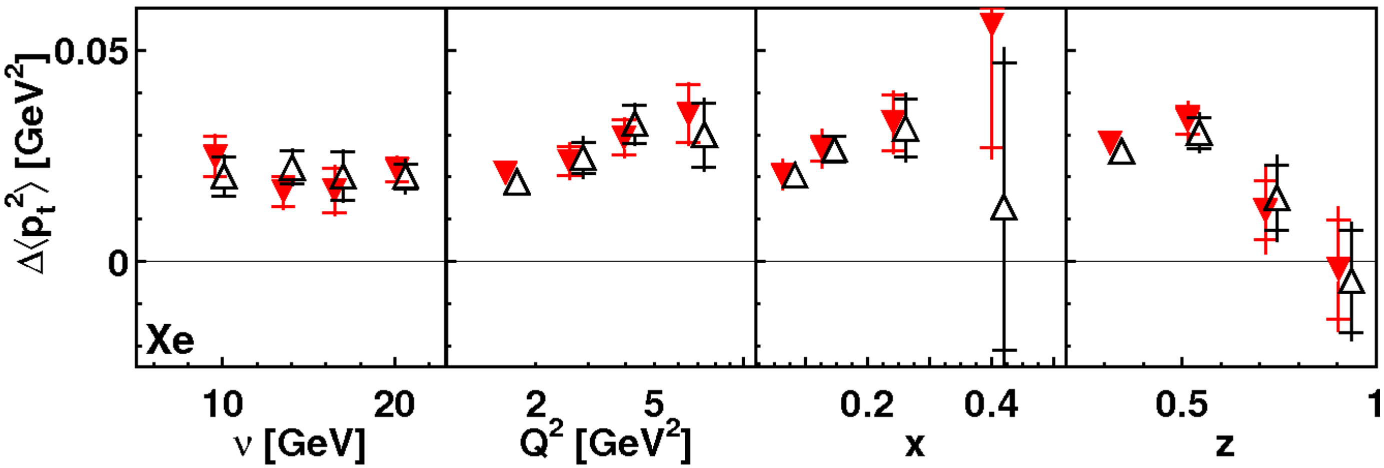




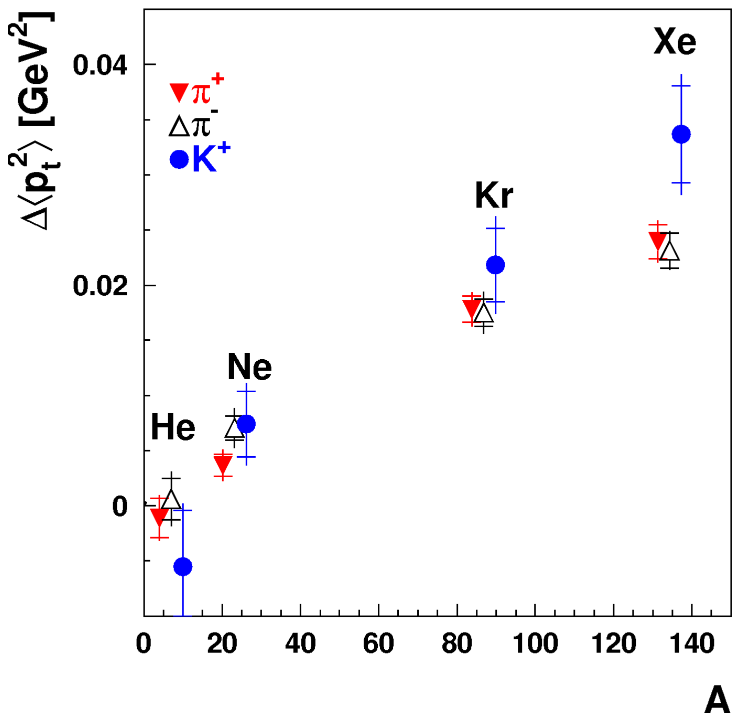




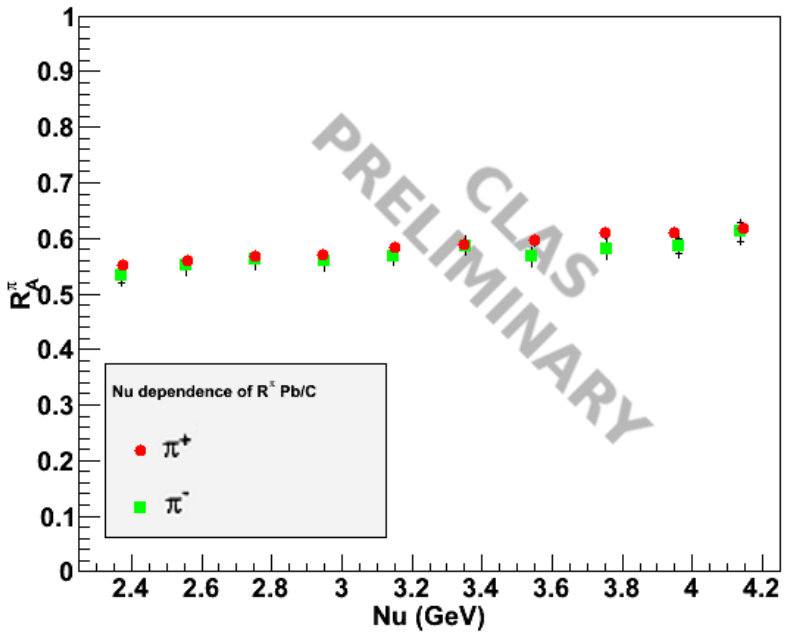
HERMES ΔP_t^2 Results

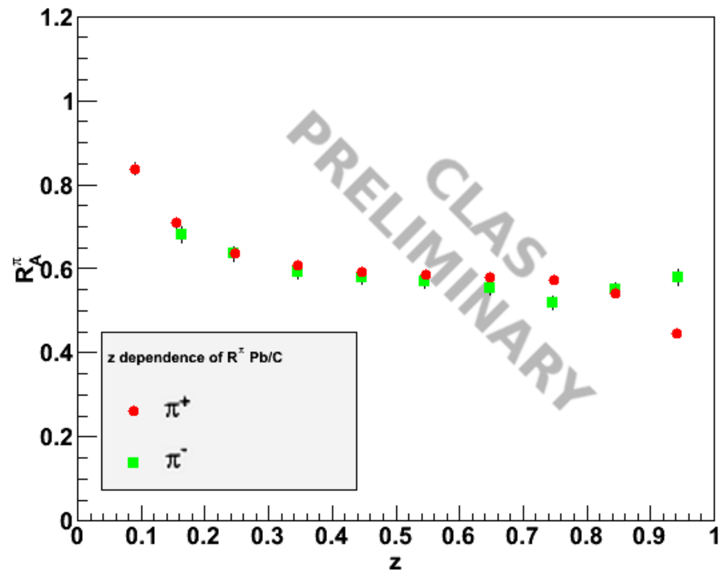


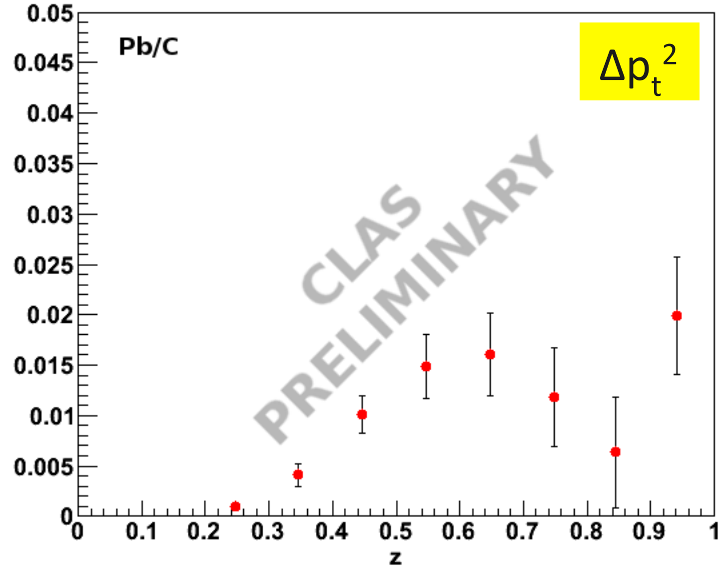
- No broadening at high *z*
  - → No effect at the partonic level
- Increase with Q^2
  - → Predicted in the framework of parton energy loss
- Dependence in A not conclusive
  - → Compatible with $A^{1/3}$ and $A^{2/3}$
- Different behavior for kaons?



CLAS Preliminary Results: Pb/C

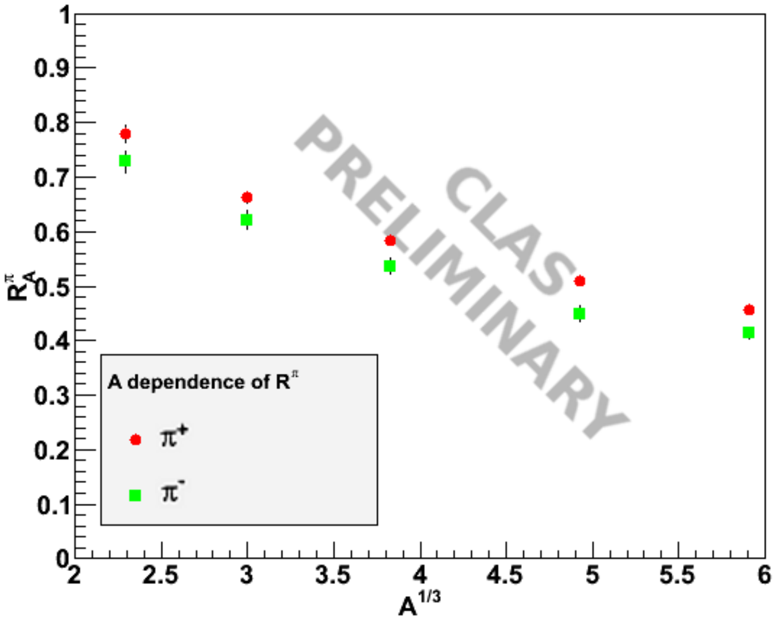


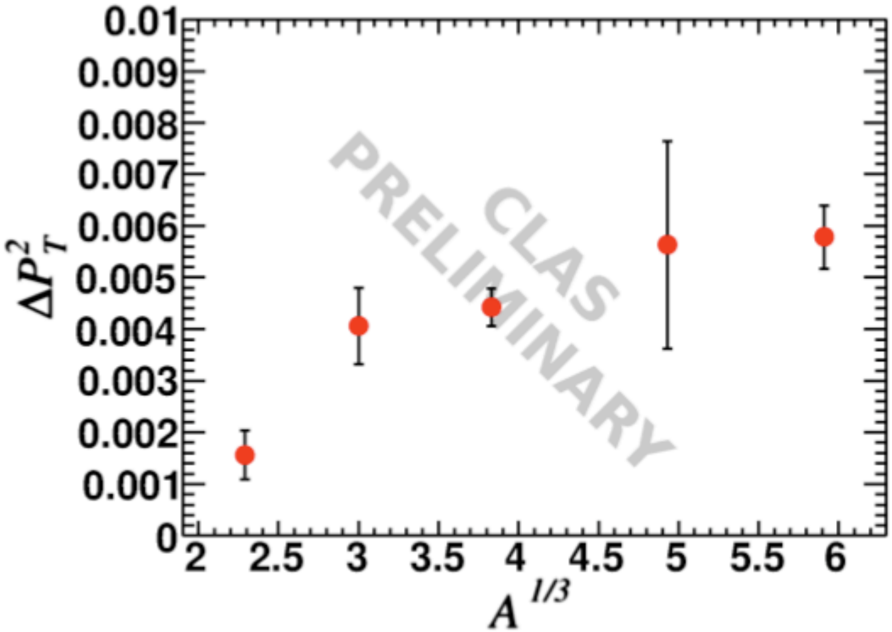




- Reproduce the ratios of HERMES
  - → ν slope similar to HERMES
  - → z Slope not as pronounced as in HERMES (?)
- Results for Δp_t^2 compatible with HERMES

CLAS Preliminary Results : A Dependence

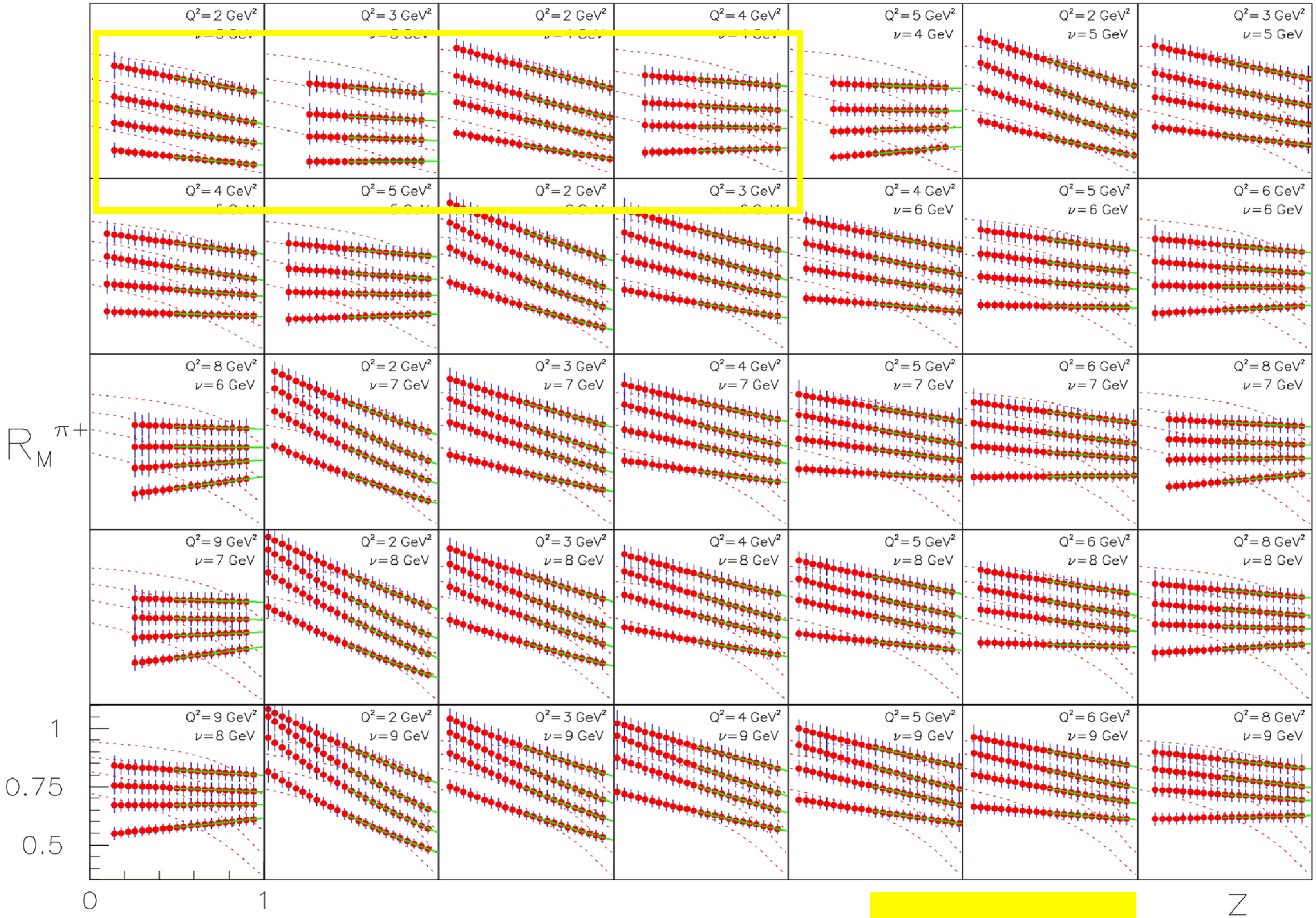




- Nuclear effect saturates at high A – Does not follow $A^{1/3}$ or $A^{2/3}$
  → Can be resolved within parton energy loss picture with small production time
- Multiplicity ratio and P_t broadening follow the same trend
  → Originates from the same process ?

Examples of Experimental Data and Theoretical Predictions

12 GeV Anticipated Data



E12-06-117

Summary of Part 1

- Hadronization is a fundamental process of QCD
  → Link between perturbative and non-perturbative domains
  → A way to probe nuclear media, either cold or hot
  → Helpful for other experiments

- Past results gave the global picture of hadronization in medium
  → Effect of the various kinematic variables understood
  → Recent results provides multi-dimensional binning

- Multi-dimensional analysis is crucial to constrain existing models
  → CLAS12 experiment (E-12-06-117) will provide such high statistics data in the right kinematic range

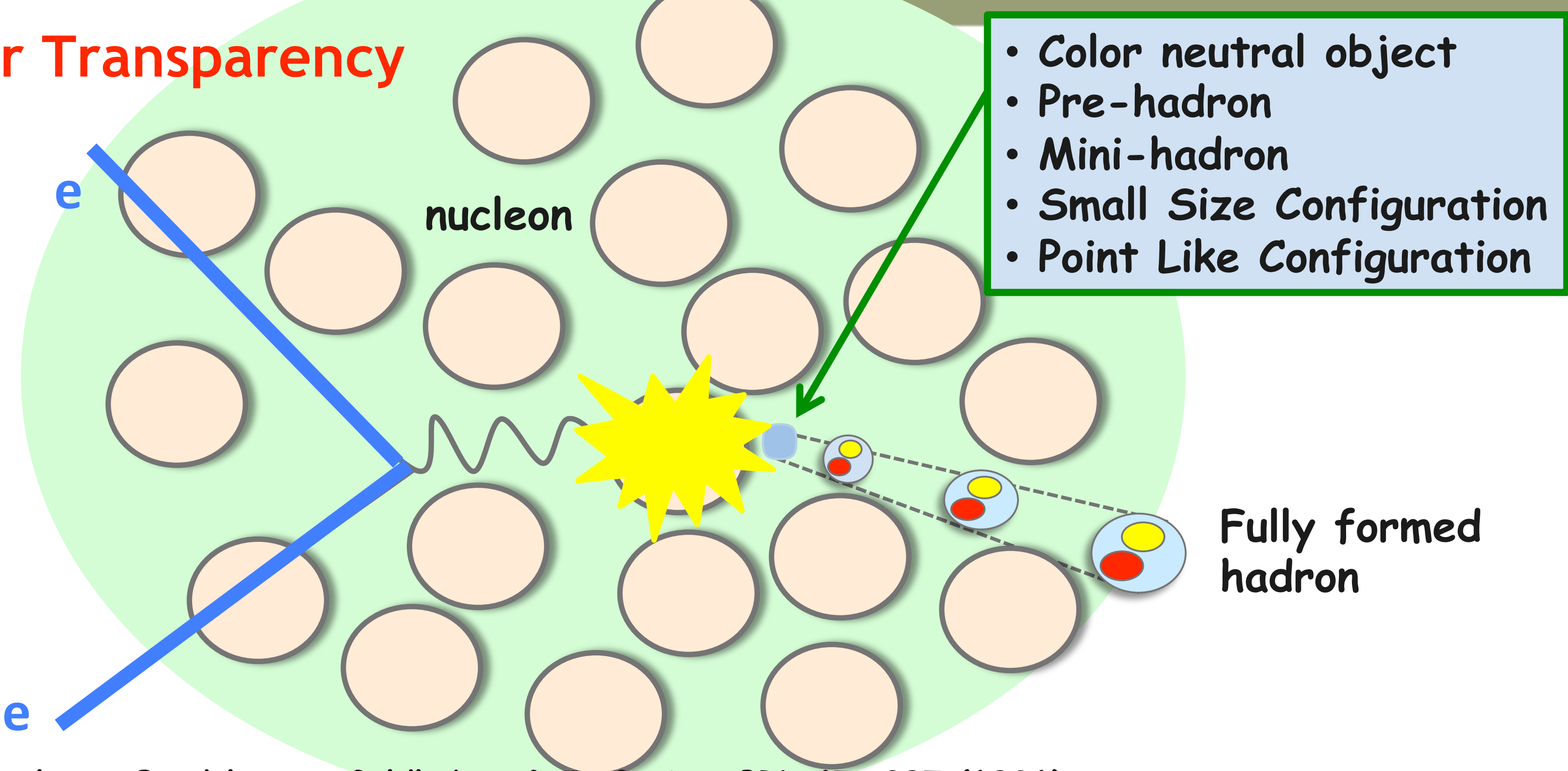
Future prospects for Hadronization studies

- FNAL: E906 Drell-Yan at 120 GeV
  - ✓ Lower energy run will significantly simplify dE/dx extraction and remove ambiguity between shadowing and energy loss
- LHC Nuclear data
- RHIC upgrades
- JLab 12 GeV upgrade – CLAS12 in Hall B
  - ✓ 10 times more luminosity than CLAS and 1000 times more than HERMES
  - ✓ Improved particle identification
  - ✓ Access to higher masses
  - ✓ Much larger kinematical range

❑ **Future electron-ion collider (Heavy quarks measurements)**

Part 2 - Color Transparency

Color Transparency



G. Bertsch, S. Brodsky, A. Goldhaber & J. Gunion, PRL 47, 297 (1981)
A. Zamolodchikov, B. Kopeliovich and L. Lapidus, Pis'ma Zh.Teor. Fiz (1981);SPJETP Lett. (1981).
S. Brodsky & A. Mueller, Phys. Lett. B206, 685 (1988)

◆ QCD predicts the existence of hadron-like configuration which under specific conditions, will pass through nuclear matter with dramatically reduced interaction

◆ These configurations are of small size and their interactions with the nucleus are suppressed because of the small spatial extent of their color field

The 3 Pillars of Color Transparency "CT"

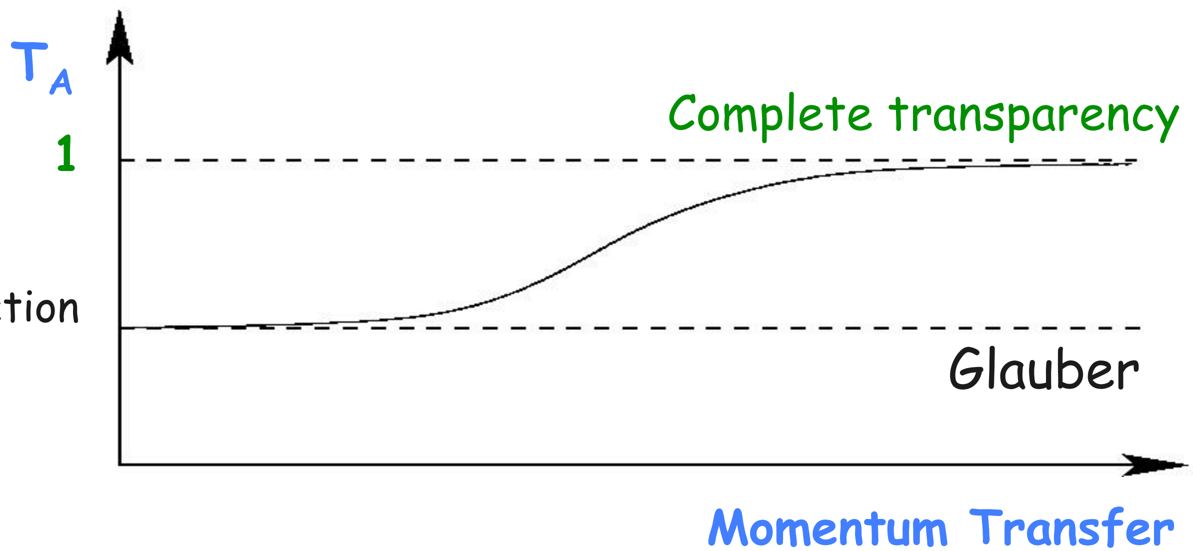
- ✓ Creation of Small Size Configurations (SSC)
- ✓ SSC experiences reduced interaction with the medium
- ✓ SSC does not evolve rapidly as it propagates out of the nucleus

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

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

σ_N is the free (nucleon) cross section

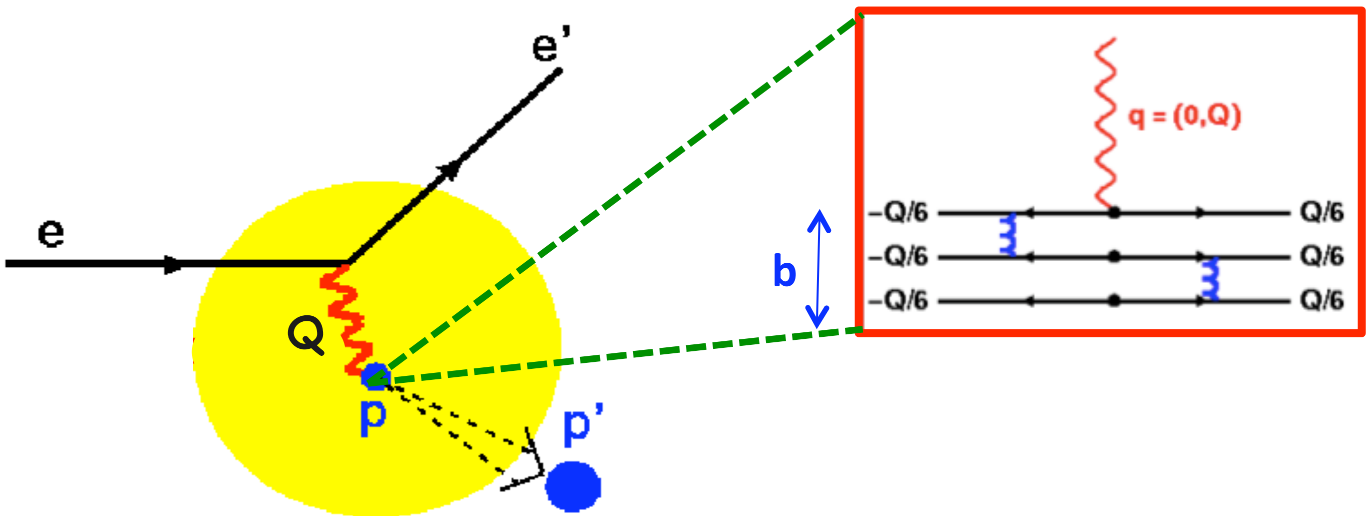
σ_A is the nuclear cross section



The power of hard exclusive reactions in CT studies

Hard exclusive processes play a key role in QCD

- They allow the studies of quark and gluons scattering and their formation into hadrons at the amplitude level
- They depend in detail on the composition of the hadron wave functions themselves

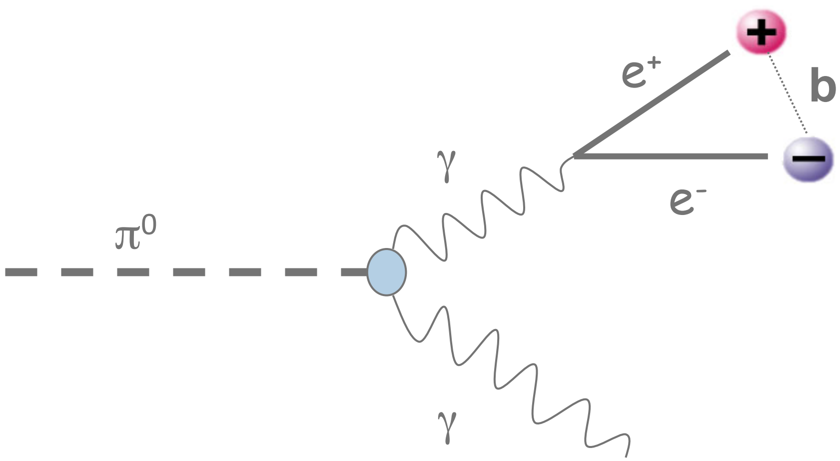


Lowest order elastic Scattering shown in the Breit frame where the proton momentum is changed in sign not magnitude and no energy is been exchanged

- For the reaction to be elastic, all partons in the proton wave function have to be located within the same transverse interval $b \leq 1/Q$
- At large Q^2, the transverse size of the ejectile can be much smaller than the equilibrium radius of the proton

Pillar # 2: Color screening: the SSC experiences reduced attenuation

In QCD the color field of a color neutral object vanishes with decreasing size of the object



200 GeV π^0 produced in cosmic rays

- Consequence of charge screening in QED were observed by Perkins in 1955
- The ionization produced by the pair was small near the decay point, increasing with distance from vertex
- It was quickly interpreted by Chudakov (1955) in the framework of QED: A pair of oppositely charged particles interacts in the medium with a dipole cross-section proportional to b^2

- In Perturbative QCD two-gluon exchange is believed to be the dominant scattering mechanism

- The SSC-nucleon cross section is $\sigma_{SSC,N} \approx \sigma_{h,N} \dfrac{b^2}{R_h^2}$, R_h is the hadron radius

Pillar # 3: Lifetime of Small-Size-Configuration

Naïve parton model:

- Quarks expand back to their usual separation at the speed of light

$\tau \approx R_h/c$ (with time dilation it becomes $E_h * \tau / M_h$)

- If the hadron is a nucleon $R_h \approx 0.8$ fm, probability of SSC escaping the nucleus is significant even for modest values of Lorentz factor

More realistic "quantum diffusion" model:

- the expansion takes a total time of $1/(E_{h*} - E_h)$, where E_{h*} is the energy of the typical intermediate state
- The key point is that the SSC is not the ground state of the free hadron Hamiltonian

Medium Energy search for Color Transparency

Baryons

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

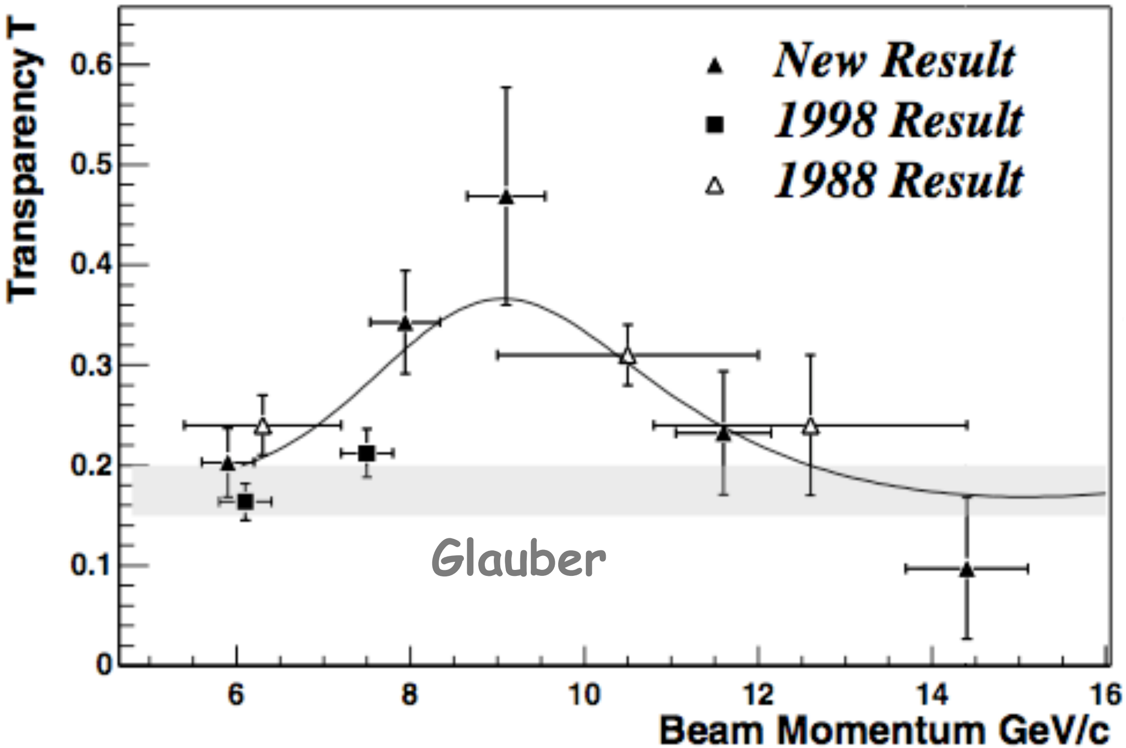
Mesons

- A(γ, πp) JLab
- A(e, e'π) JLab
- A(e, e'ρ) Fermilab, DESY and JLab

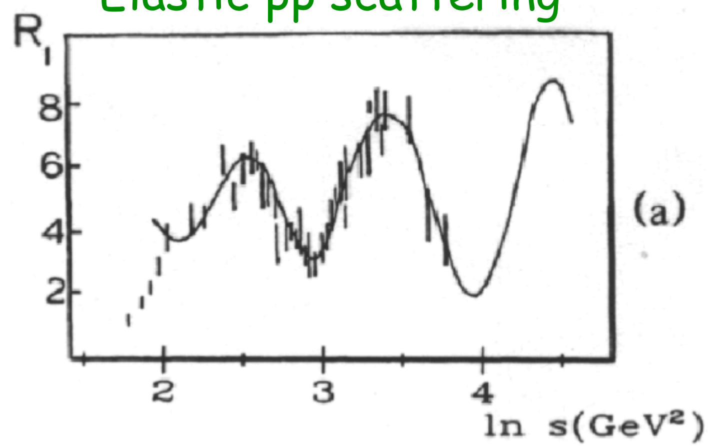
Color Transparency in C(p, 2p) reaction

$$R_1 \propto s^{10} \frac{d\sigma}{dt}$$

A. Leksanov et al. PRL 2001

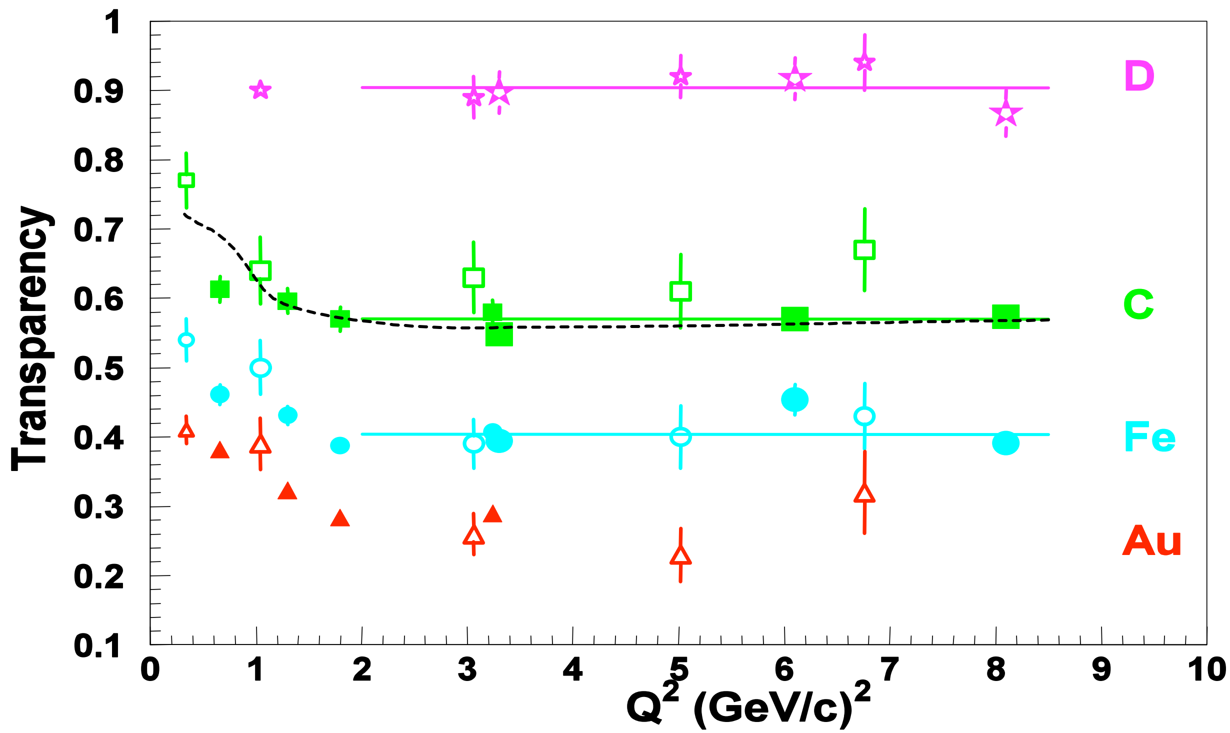


Elastic pp scattering



- The increase at low momentum cannot be taken as an unambiguous signal of CT
- Results explained in terms of nuclear filtering (J. Ralston PRL 1988) or the crossing of the open charm threshold (S. Brodsky PRL 1988)

Search for Color Transparency in A(e, e'p) reaction



N. C. R. Makins et al. PRL 72, 1986 (1994)
G. Garino et al. PRC 45, 780 (1992)

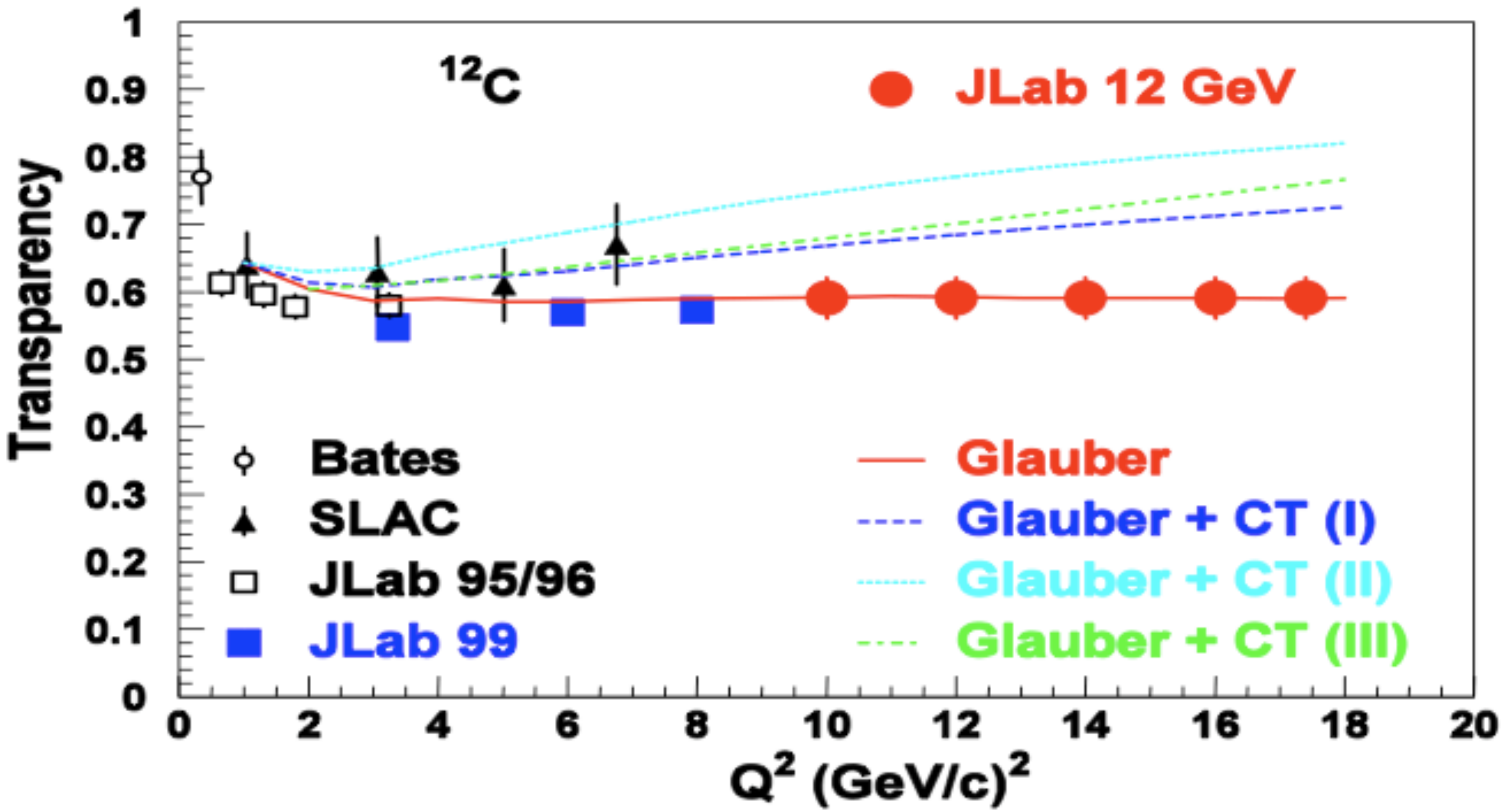
D. Abbott et al. PRL 80, 5072 (1998)
K. Garrow et al. PRC 66, 044613 (2002)

Solid Pts – JLab
Open Pts -- other

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

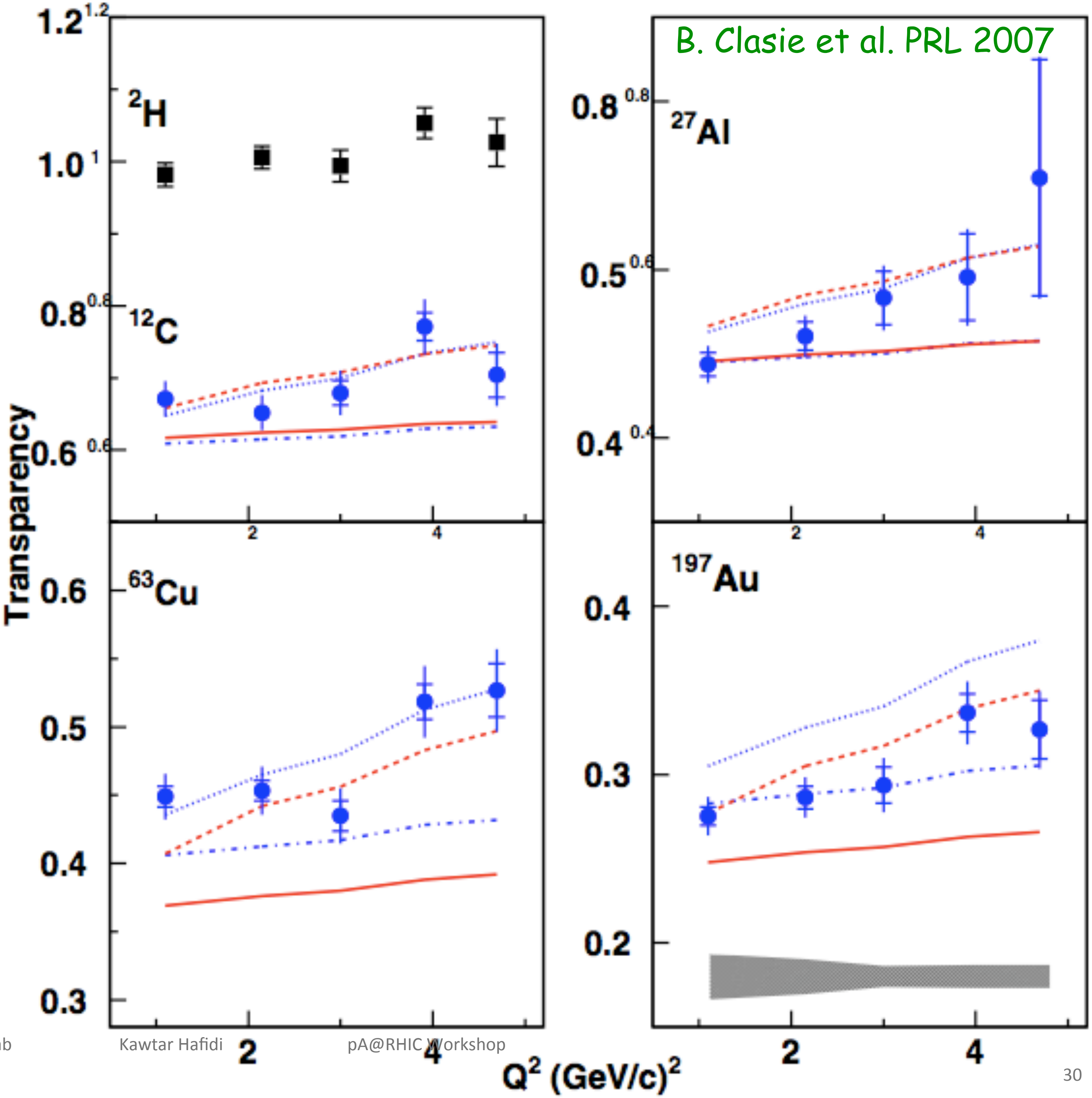
Conventional Nuclear Physics "Glauber" Calculation gives good** description
(V. Pandharipande and S. Pieper PRC 1992)

A(e, e'p) @ JLab 12 GeV

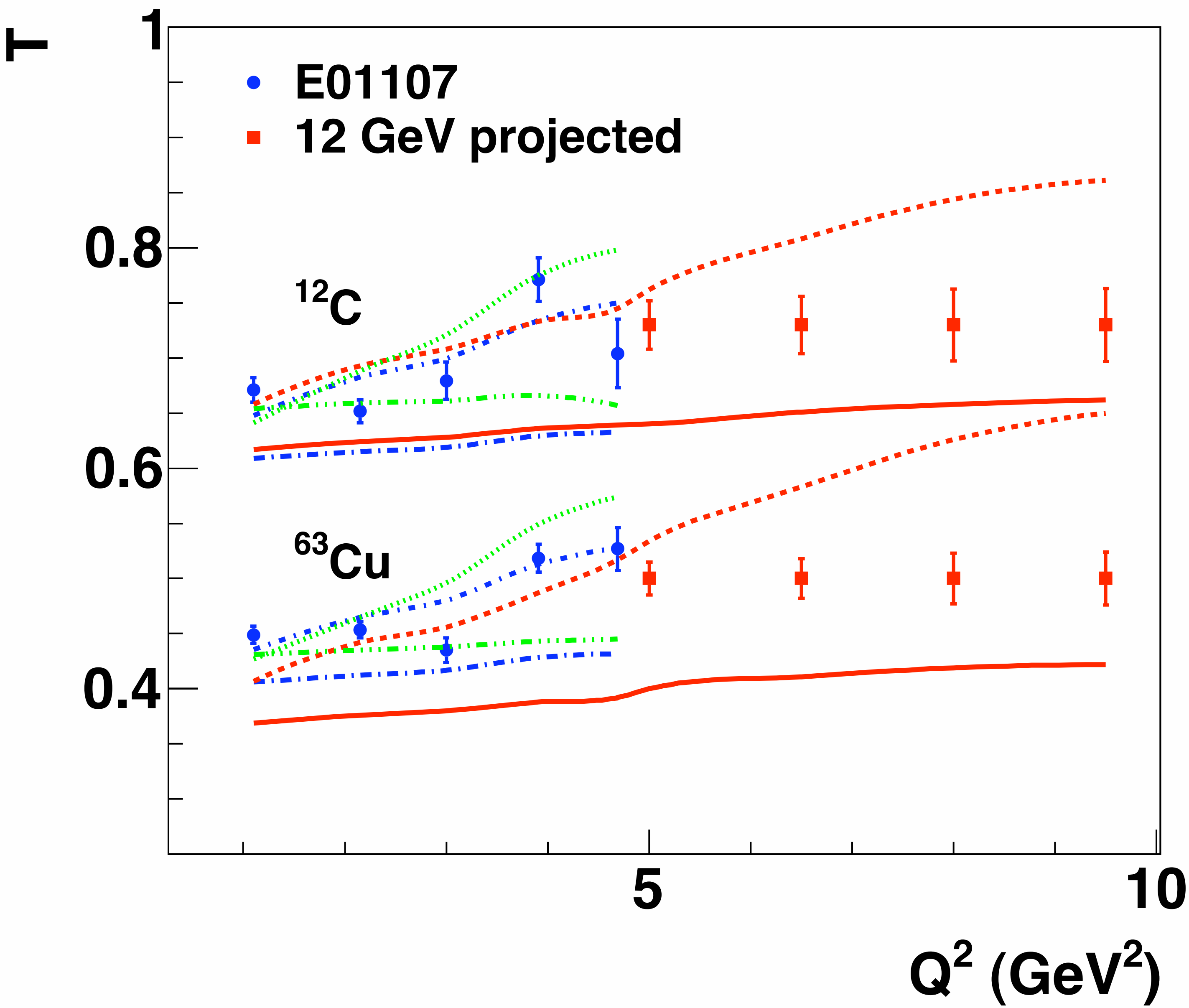


Search for Color Transparency in A(e, e'π) reaction

Extensions of these measurements to Q^2 of about 10 $(GeV/c)^2$ are planned for JLab 12 GeV upgrade

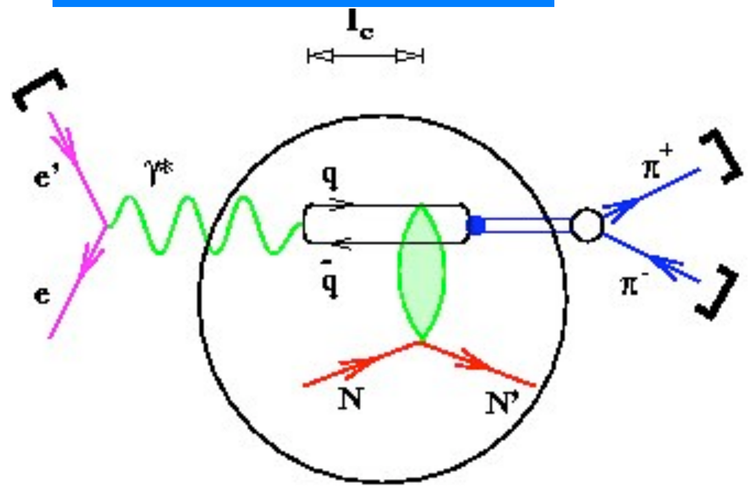


A(e, e'π) projections for JLab 12 GeV



ρ^0 electroproduction on nuclei

$$e + N \rightarrow e' + N + \rho^0$$



Detected particles are :

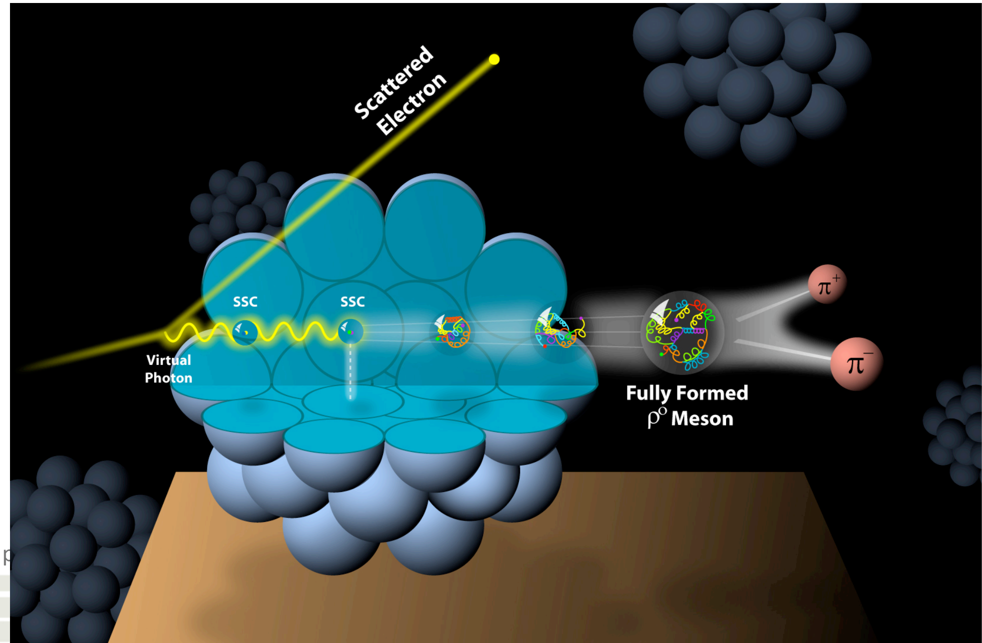
Scattered electron and the π^+ and π^- from ρ^0 decay

Finite propagation distance (lifetime) l_c for the (q q-bar) virtual state

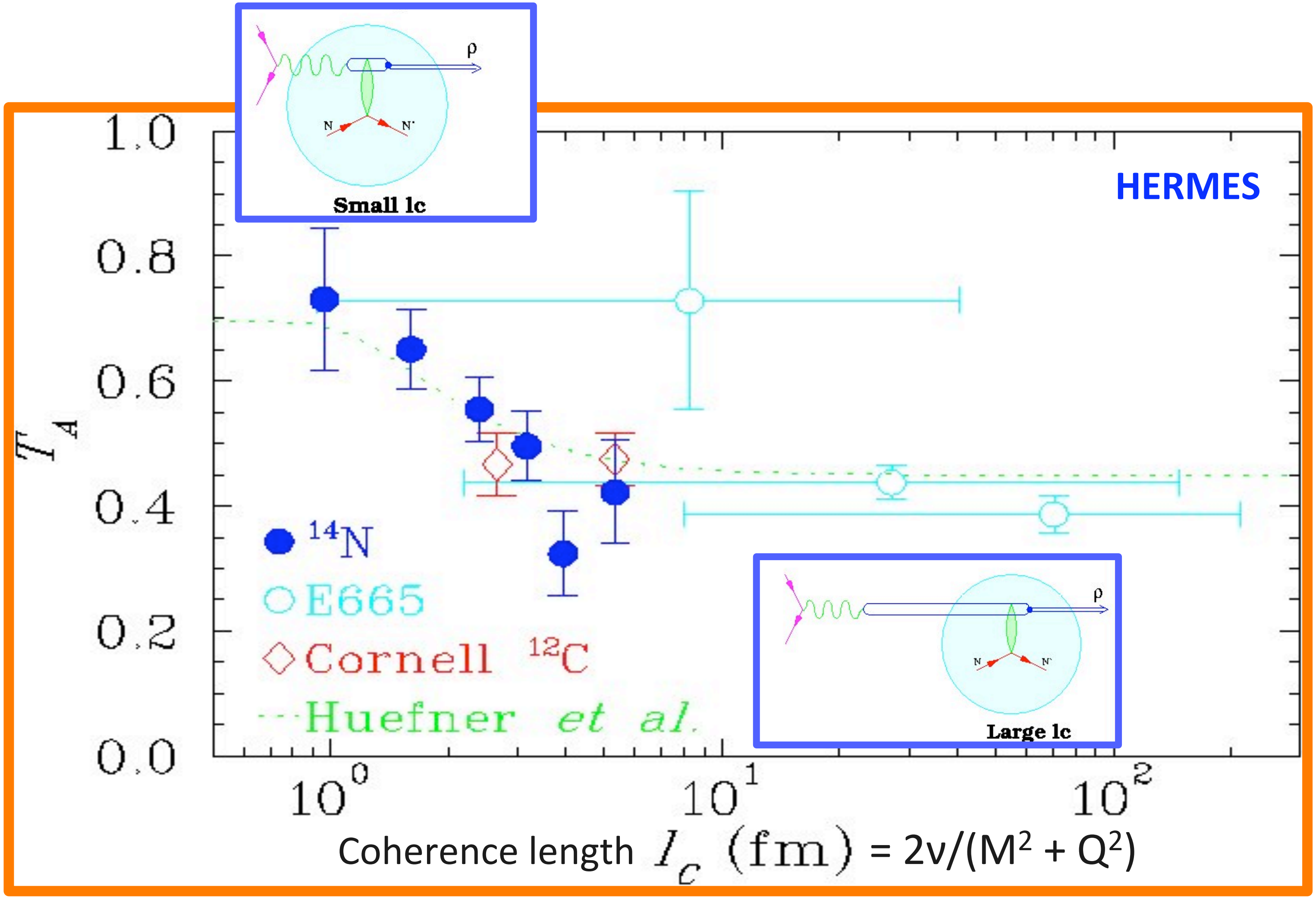
$$l_c = 2\nu/(M^2 + Q^2)$$

M is the mass of the vector meson

ν is the energy transferred by the electron



CT Signature is the rising of the nuclear transparency with Q^2. However …



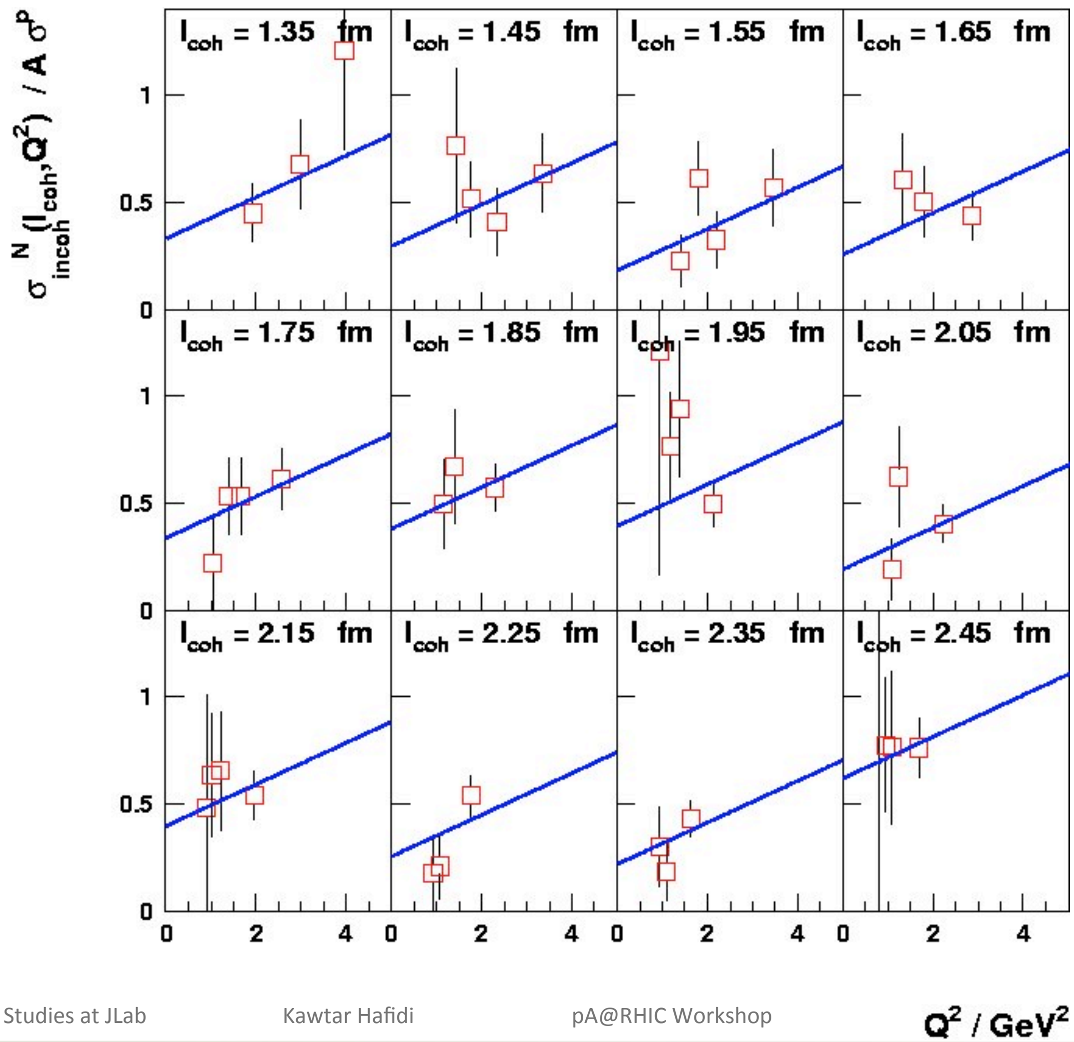
HERMES experiment at fixed coherence length

HERMES Nitrogen data : $T_A = P_0 + P_2 Q^2$

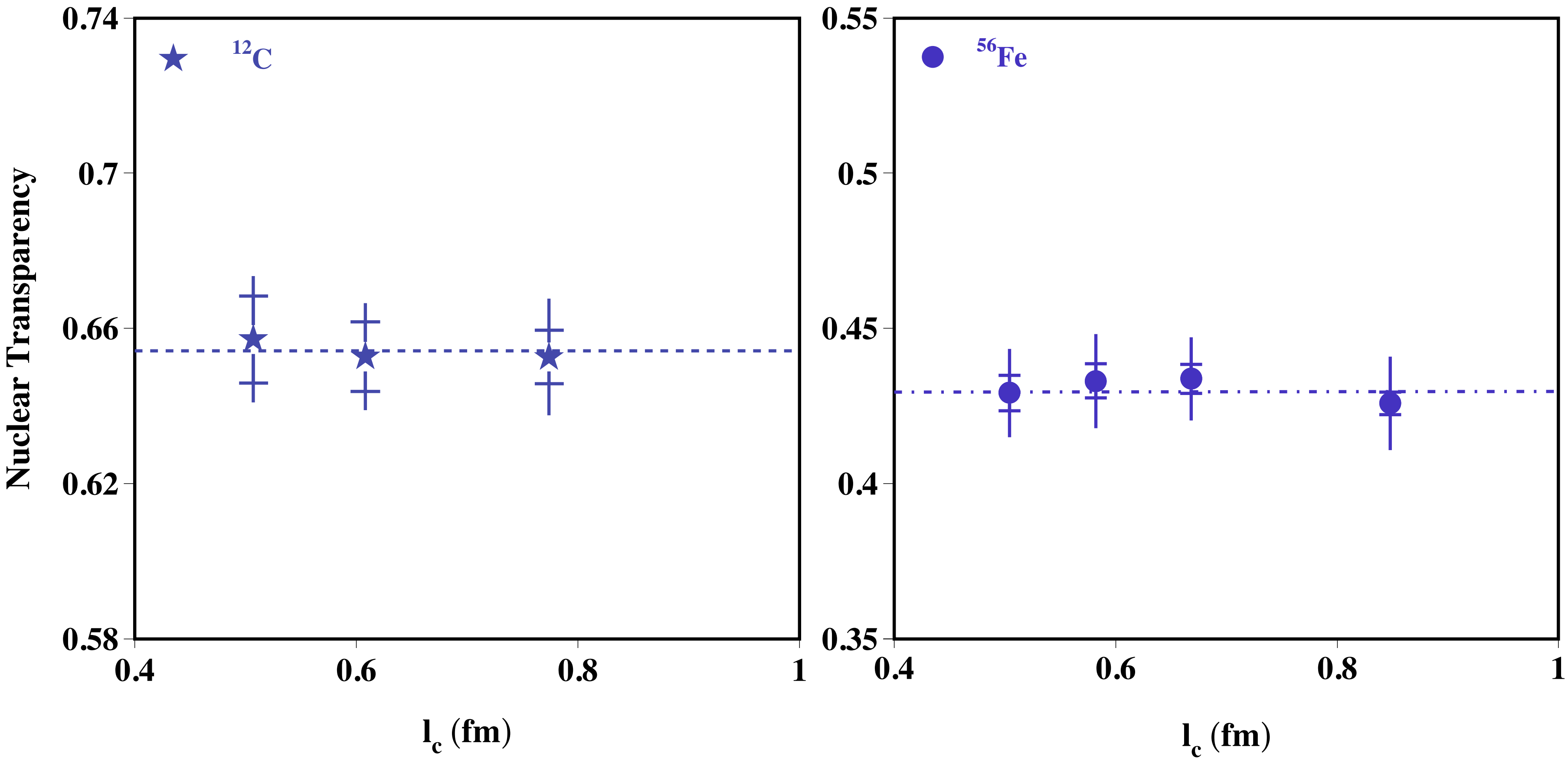
$P_2 = (0.097 \pm 0.048_{stat} \pm 0.008_{syst})\ GeV^{-2}$

Phys. Rev. Lett. 90 (2003) 052501

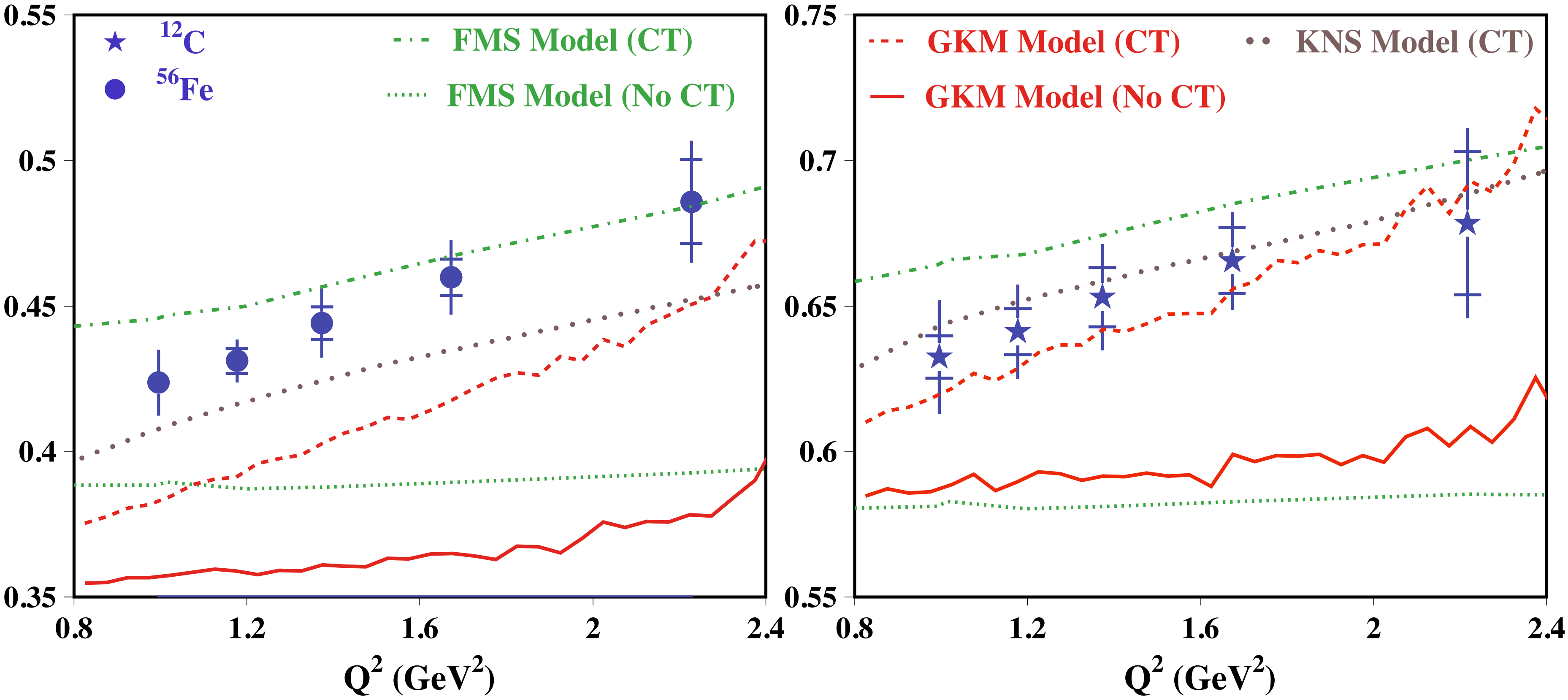
27 GeV positron beam



Nuclear Transparency vs. coherence length



Nuclear Transparency vs. Q^2

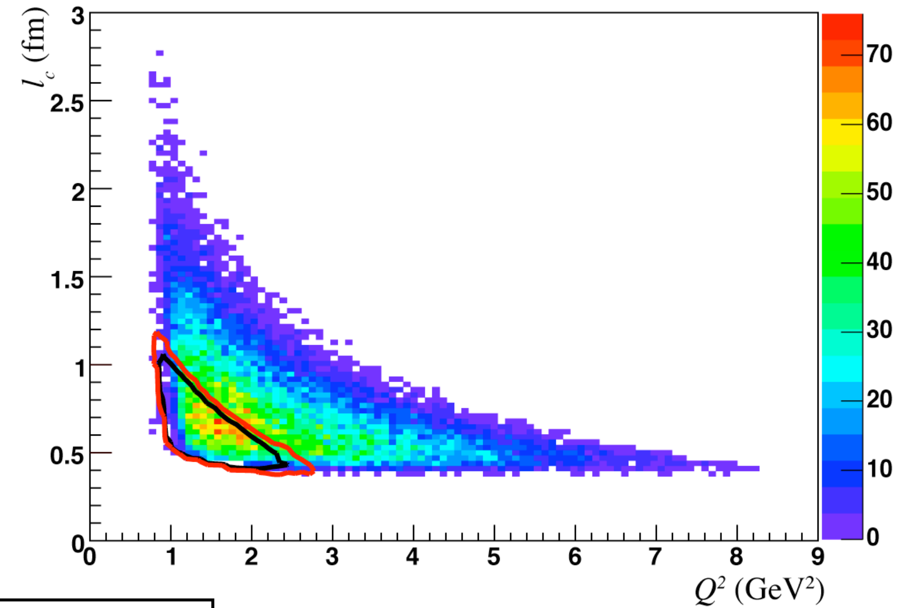


FMS (Glauber Model): Frankfurt, Miller & Strikman, PRC 78, 015208 (2008)

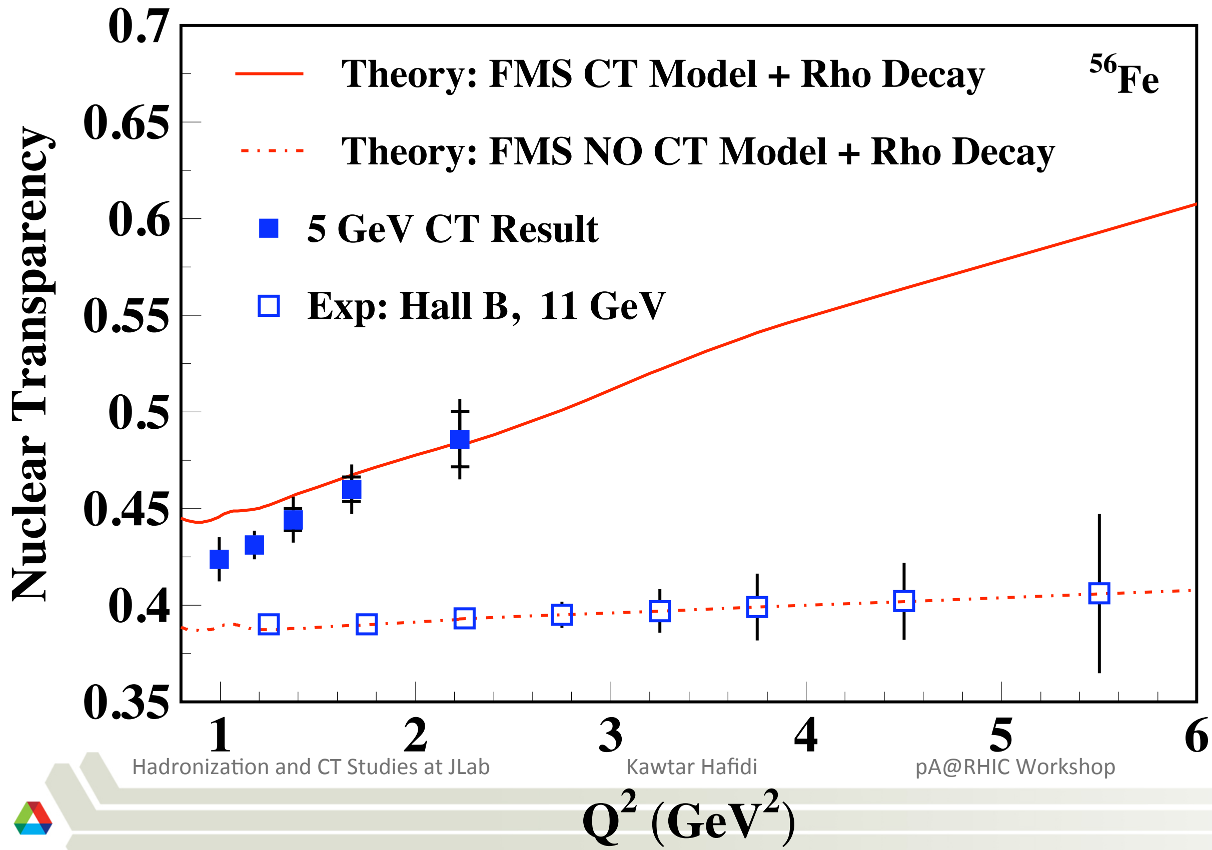
GKM (Transport Model): Gallmeister, Kaskulov & Mosel, PRC **83, 015201 (2011)**

KNS (LC QCD Model): Kopeliovich, Nemchik & Schmidt, PRC **76, 015205 (2007)**

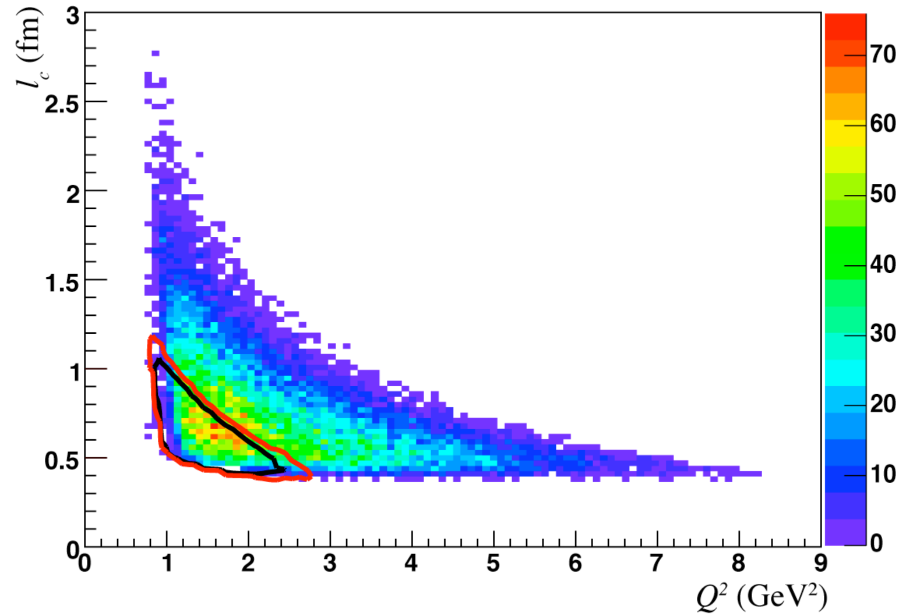
JLab 12 GeV ρ^0 electroproduction measurements
C, Fe and Sn



E12-06-106

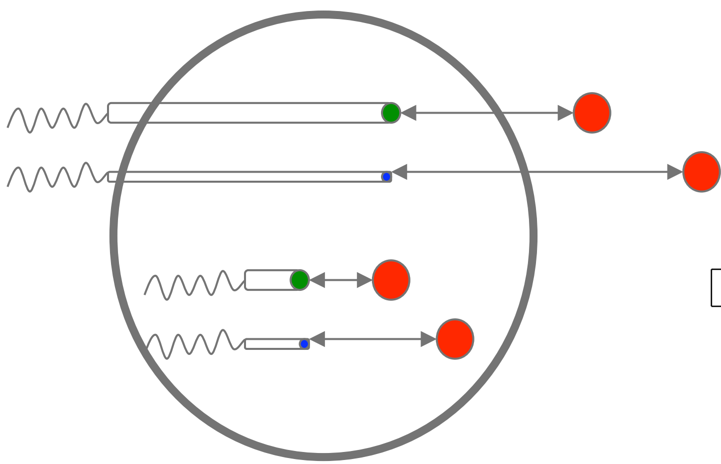


SSC vs. formation effects



Long l_c and fixed

Q^2 increases $\Rightarrow$ T_A increases because the mean transverse separation of the {q,q-bar} fluctuation decreases

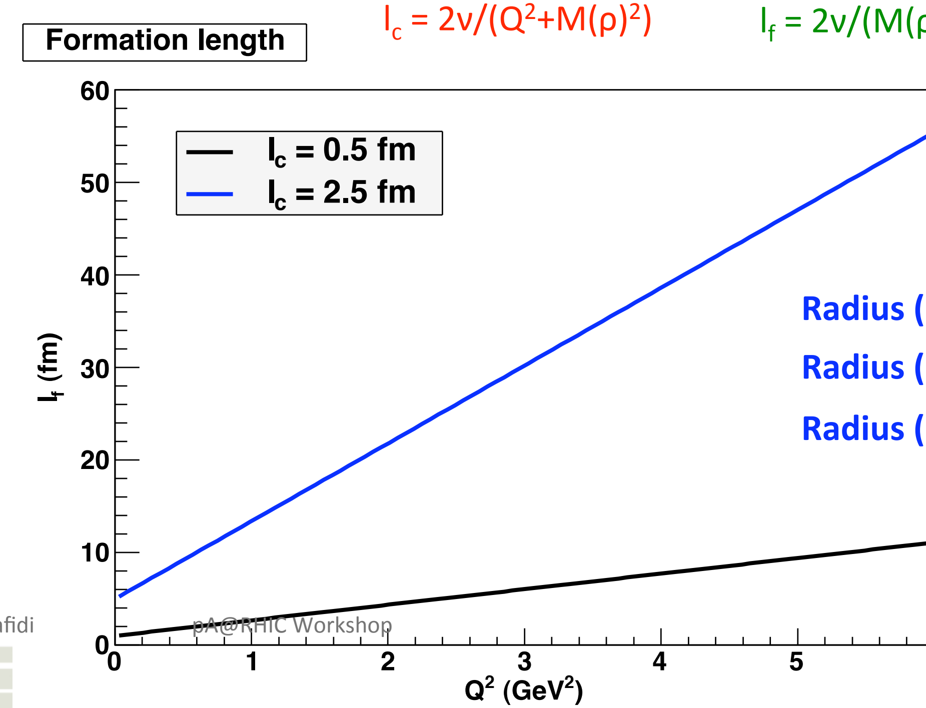


Coherence length

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

Formation length

$l_f = 2\nu/(M(\rho')^2 - M(\rho)^2)$



Radius (C) = 2.7 fm

Radius (Fe) = 4.6 fm

Radius (Sn) = 5.7 fm

l_c small and fixed (@ low Q^2 $l_f \sim l_c$)

Q^2 increases $\Rightarrow$ l_f increases

$\Rightarrow$ CT increases for two reasons:

$\Rightarrow$ transverse separation and l_f effects

Summary part 2

- Strong evidence for the onset of Color Transparency using ρ and pion electroproduction off nuclei at JLab (11 ± 2.3% decrease in the absorption of ρ in iron)

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

- At intermediate energies, CT provides unique probe of the space-time evolution of special configurations of the hadron wave function

- Using the upgraded JLab 12 GeV, we plan to disentangle different CT effects (SSC creation, its formation and interaction with the nuclear medium)