QCD Processes in Nuclear Matter at Jefferson Lab

Jerry Gilfoyle for the CLAS Collaboration

University of Richmond

- Introduction
- Jefferson Lab: Accelerator and End Stations.
- Overview of Program
- Selected Topics
- The Future
- Concluding Remarks

RICHMOND

Jefferson Lab
Thomas Jefferson National Accelerator Facility

What Questions are We Asking?

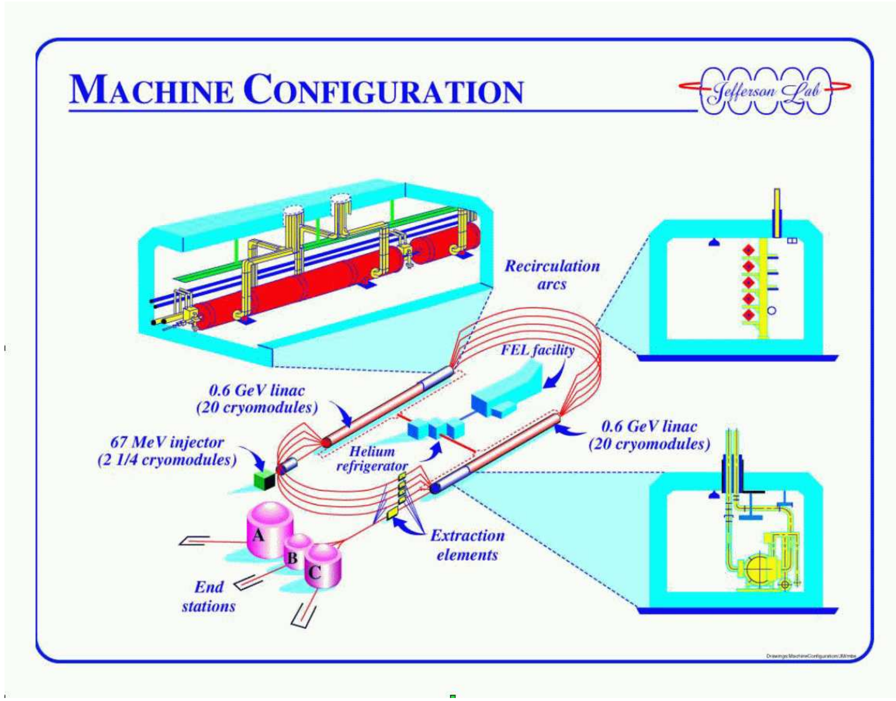
- What are the phases of strongly interacting matter, and what roles do they play in the cosmos?
- What does QCD predict for the properties of strongly interacting matter?
- What governs the transition of quarks and gluons into pions and nucleons?
- What is the role of gluons and gluon self-interactions in nucleons and nuclei?

The Frontiers of Nuclear Science, A Long Range Plan, The DOE/NSF Nuclear Science Advisory Committee, December, 2007.

Similar raised questions in *NuPECC Long Range Plan 2004.*

The Continuous Electron Beam Accelerator Facility at JLab

View of site in Newport News, Va.

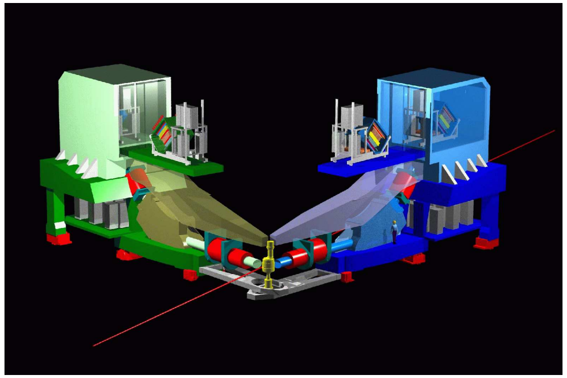


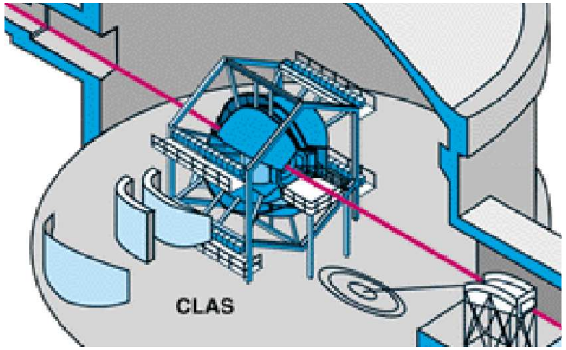
Schematic of accelerator and components.

Superconducting Electron Accelerator (338 cavities), 100% duty cycle, $I_{max} = 200\,\mu A$, $E_{max} = 6\,GeV$, $\Delta E/E = 10^{-4}$, $P_e > 80\%$, 1500 physicists, over 30 countries, operational since end of 1997.

The JLab End Stations

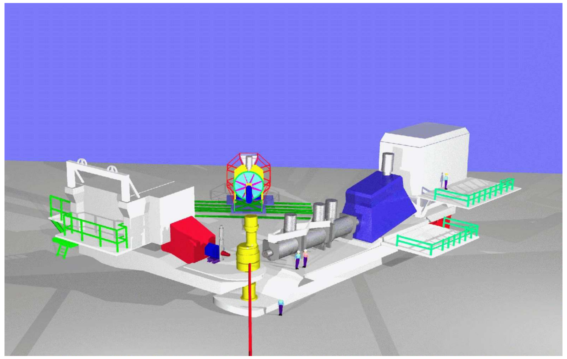
Hall A - Two identical, high-resolution spectrometers ($\Delta p/p < 2 \times 10^{-4}$); luminosity $\approx 10^{38}\ cm^{-2}s^{-1}$.





Hall B - The CLAS, nearly 4-π-acceptance spectrometer based on a toroidal magnet ($\Delta p/p = 0.5\%$); luminosity $\approx 10^{34}\ cm^{-2}s^{-1}$.

Hall C - Moderate-resolution (10^{-3}), 7-GeV/c High-Momentum Spectrometer (HMS) and the large-acceptance Short-Orbit Spectrometer (SOS) and additional detectors.



Overview of the Program

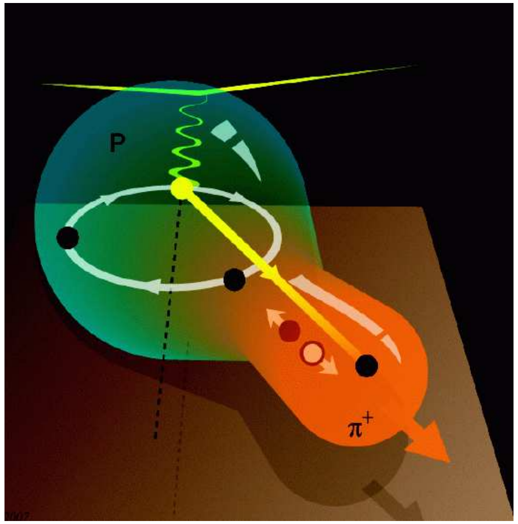
1. Hypernuclei.

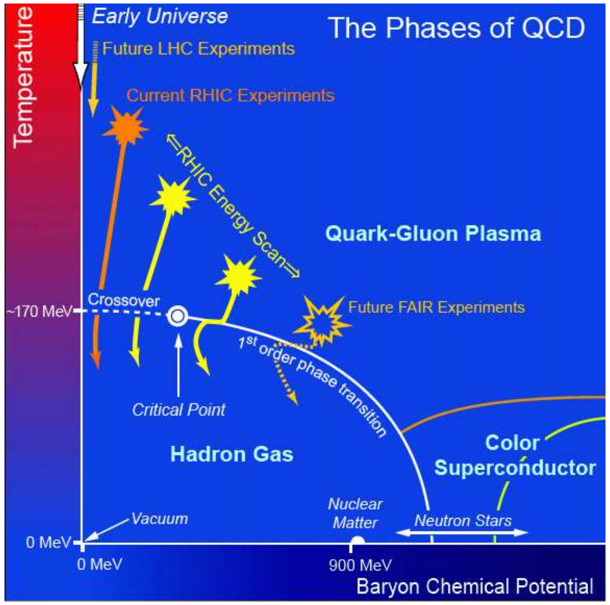
2. Short-Range Correlations

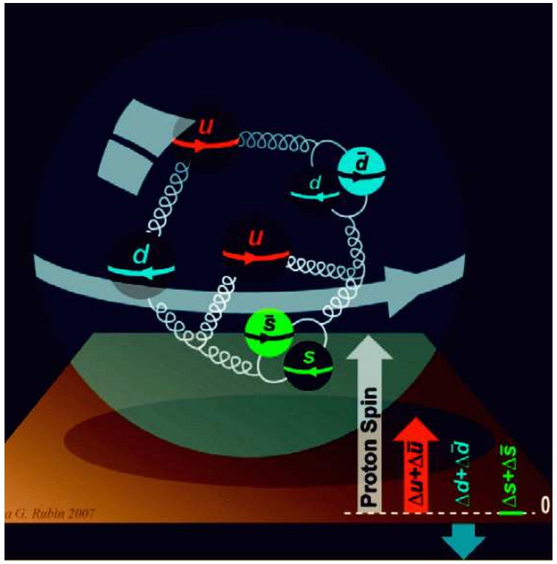
3. Medium Modifications of Hadronic Properties.

4. Color Transparency

5. Quark Propagation and Hadron Formation.



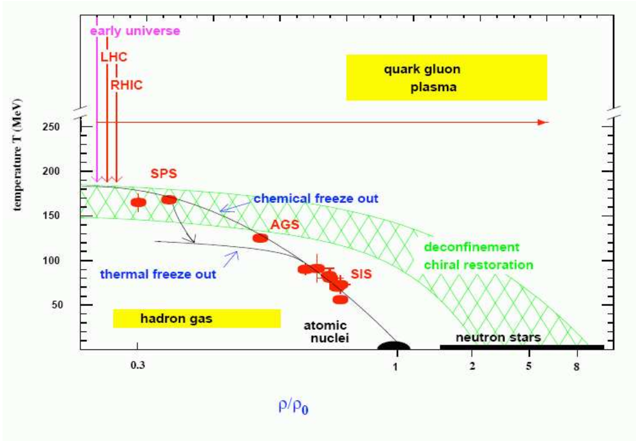




Hypernuclear Spectroscopy at JLab

Physics Motivation:

- A strange ($S = -1$) impurity (Λ) is inserted in the nucleus using the $(e, e'K^+)$ reaction.
- The Λ is not Pauli-blocked and can occupy deeply bound states.
- Probes the nuclear structure, the $\Lambda - N$ interaction, hyperon decay, high-density, low-T states.



Second generation experiments:

The Future:

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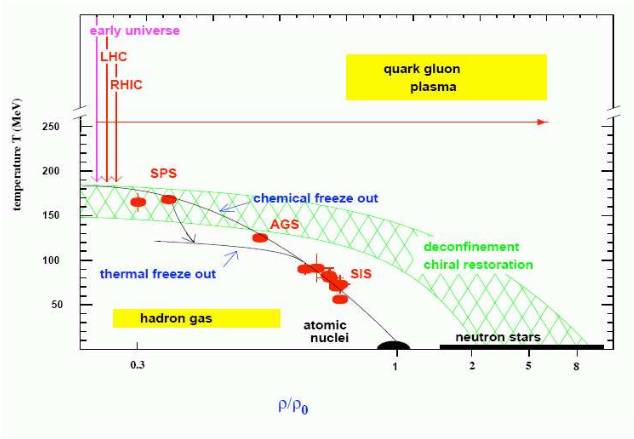
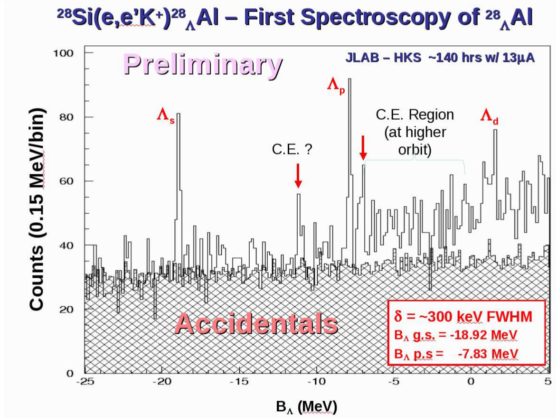
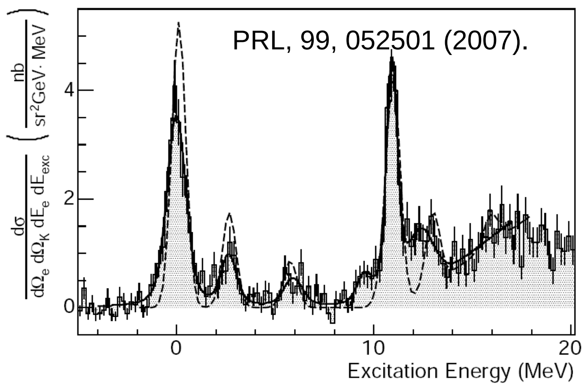


Second generation experiments:

- E01-011 (Hall C) using High-resolution Kaon Spectrometer (HKS) (L.Tang).



- E94-107 in Hall A with new septum magnets and RICH detector achieves $\Delta E \approx 700\ keV$ (FWHM).
- Good agreement of major states with SLA model (T.Mizutani, *et al.*, PRC 58, 75 (1998)), but core-excited (CE) states are unexplained.



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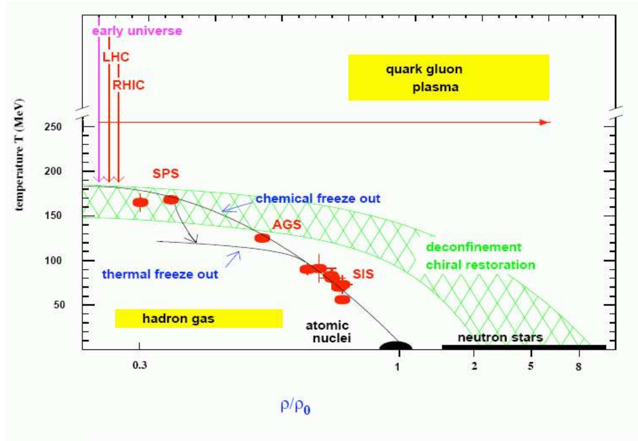

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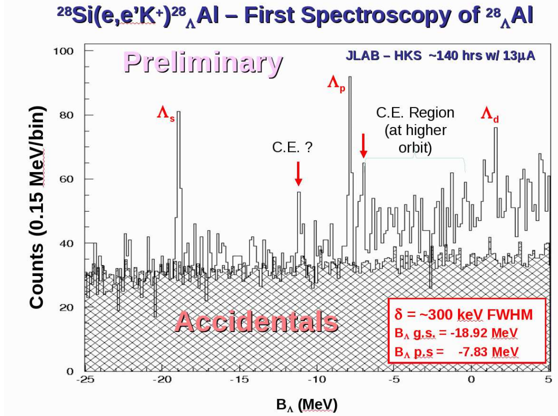

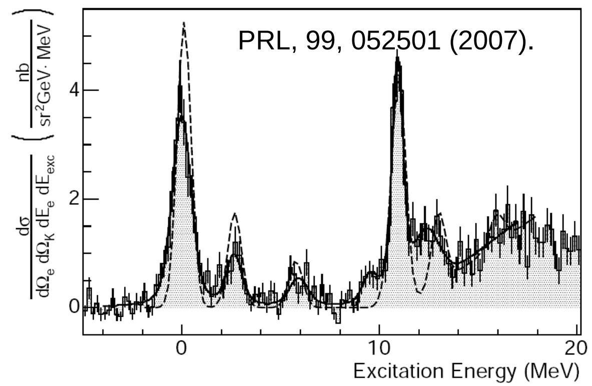

The Future:

- Third generation E05-115 is scheduled for 2009 in Hall C.
- Uses HKS and new High-resolution electron spectrometer.

Short-Range Correlations in Nuclei

Physics Motivation:

- SRC probe the high-momentum components of the nuclear wave function and cold, dense nuclear matter.
- This cold, dense region is a laboratory to study the NN force at short range and probe the physics of neutron stars.

Scaling in (e, e') with CLAS

Next-Generation Exclusive Reactions

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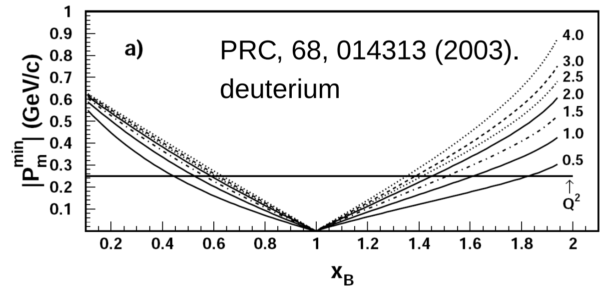
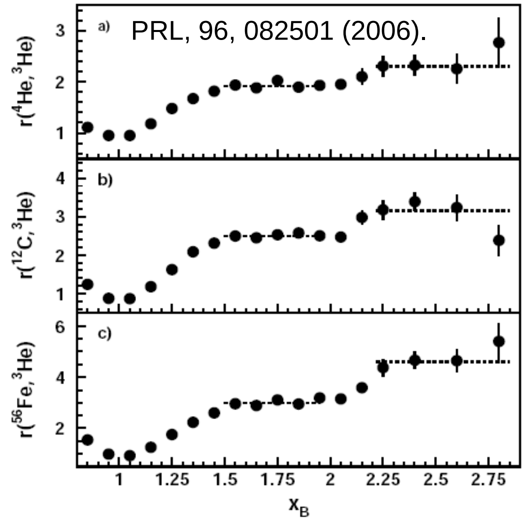


Scaling in (e, e') with CLAS

- Use broad kinematic coverage to isolate the SRCs.
- Extract the ratio of the cross section in a nucleus to the cross section in ${}^3\mathrm{He}$ to minimize FSI.
- A large fraction (20%) of all nucleons exist in correlated pairs.



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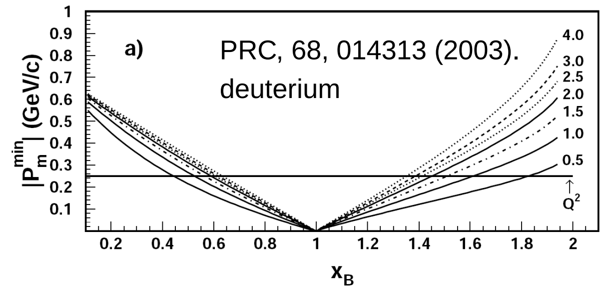

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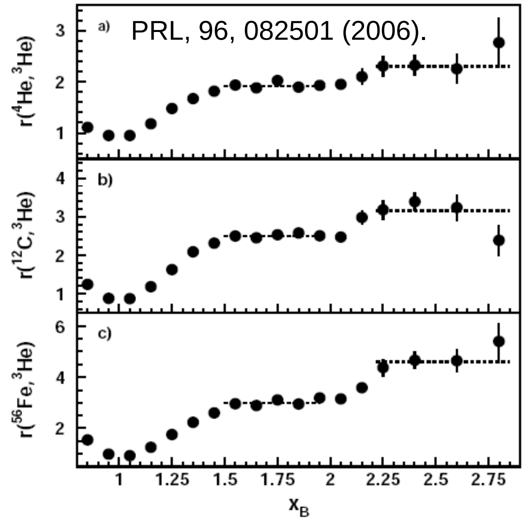
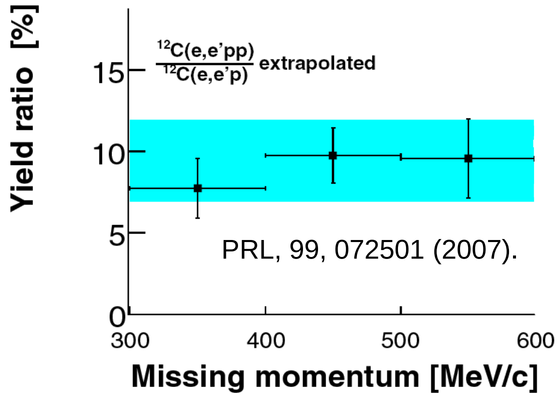


Next-Generation Exclusive Reactions

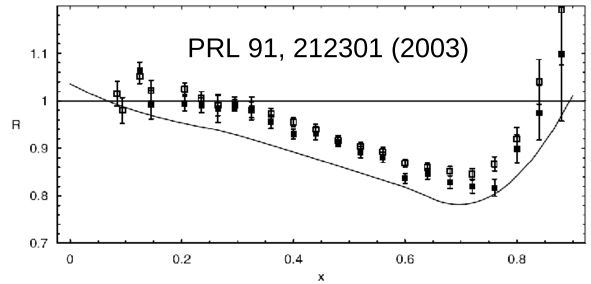
- Use Hall A and BigBite to measure $(e, e'p)$ and $(e, e'pp)$. The ratio will give you the proportion of pp pairs in the SRCs.
- It's small, less than 10%, the signature of the repulsive part of the tensor nuclear force.



Medium Modifications of Hadronic Properties

Motivation:

- Hadrons change when embedded in a nucleus (EMC effect). →
- Changes expected to masses, polarization observables, *etc.*



Proton Spin Observables:

ρ^0 meson photoproduction:

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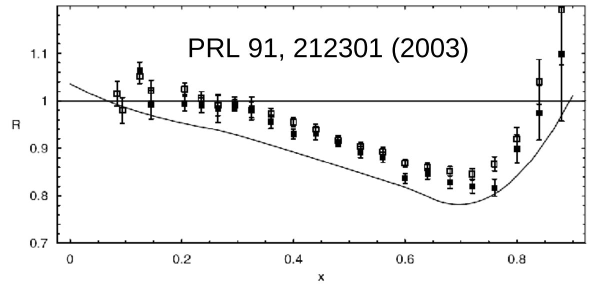
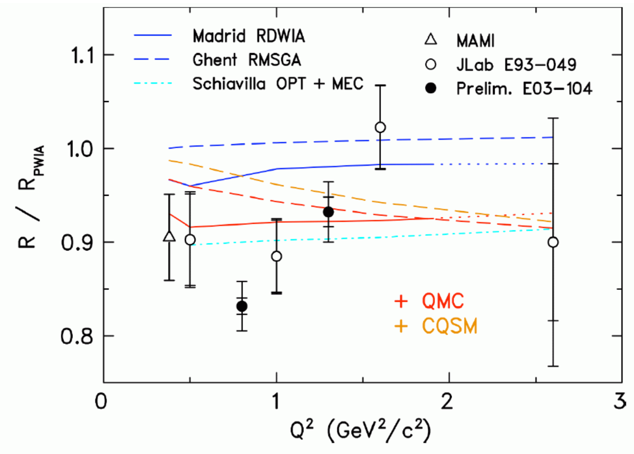


Proton Spin Observables:

- Polarization transfer on the proton related to G_E/G_M.
- Polarization transfer in $^4\mathrm{He}(\tilde{\mathrm{e}}, \mathrm{e}'\tilde{\mathrm{p}})^3\mathrm{H}$ in Hall A to extract $(P'_x/P'_z)_{^4\mathrm{He}}/(P'_x/P'_z)_{^1\mathrm{H}}$ ($^4\mathrm{He}$ nucleus is dense and tractable).
- Preliminary results of E03-104 not consistent with previously successful models. (S.Strauch)



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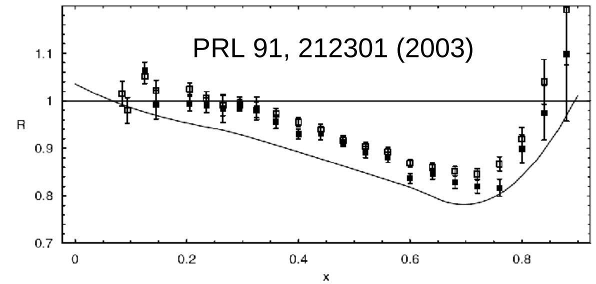

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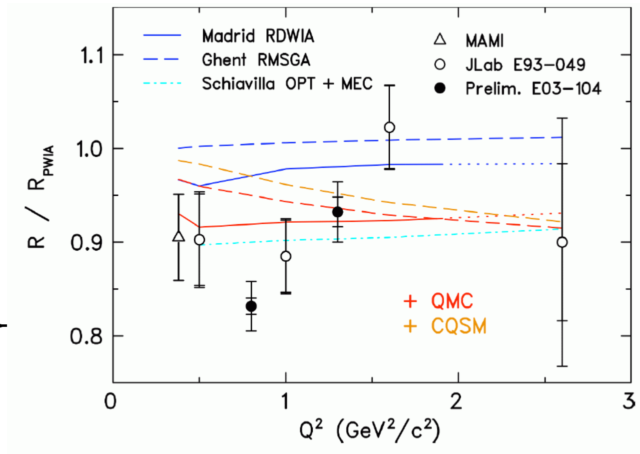
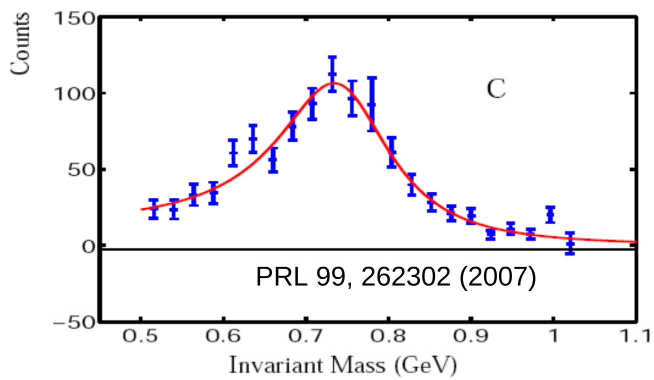


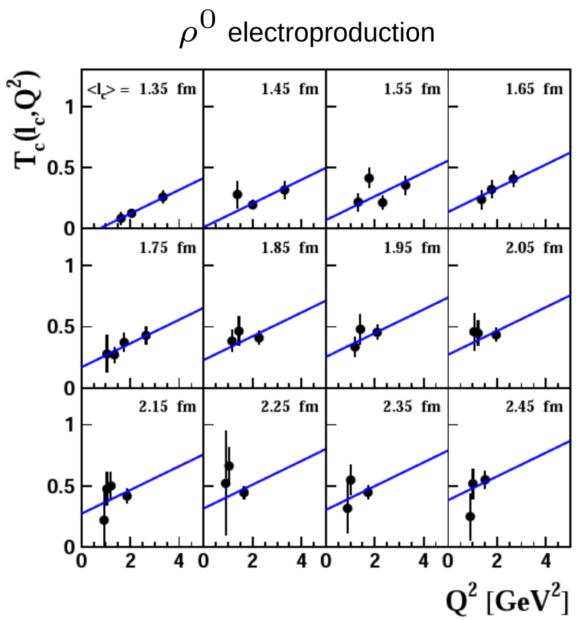
ρ^0 meson photoproduction:

- Hadronic mass shifts predicted at normal nuclear densities and $T = 0$ are observed in some experiments (CERN/NA45 and KEK).
- Photoproduce the vector mesons (ρ, ω, ϕ) and detect them via e^+e^- decay in the CLAS detector in Hall B (e^+e^- less sensitive to FSI).
- Mass shifts small consistent with zero!



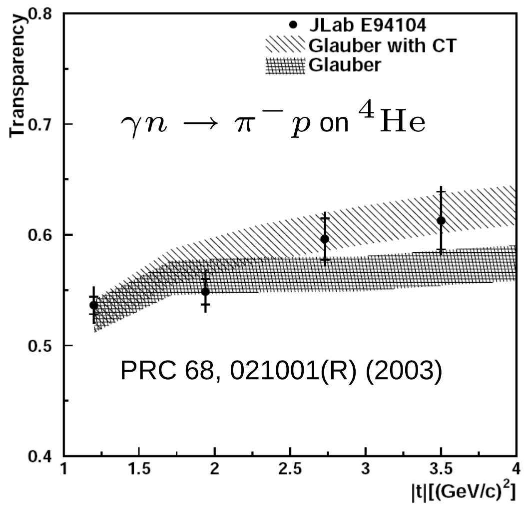
Color Transparency

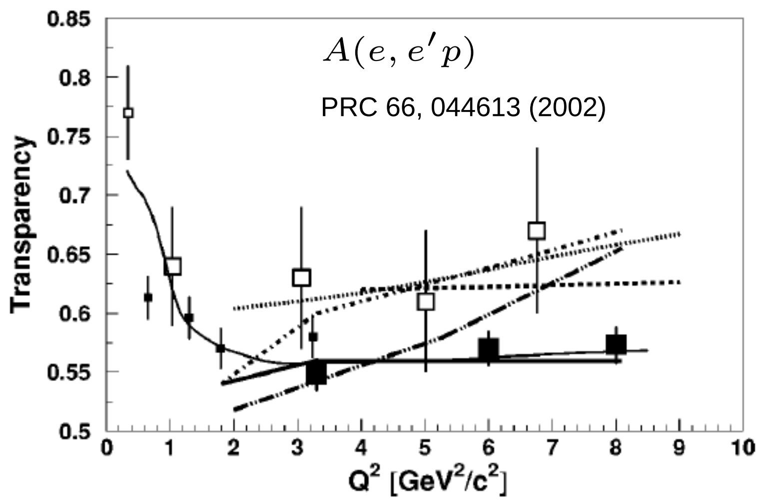
- Small, point-like, color-neutral, hadron formed inside a nucleus and passes through with little interaction.
- Central (and surprising!) prediction of QCD.
- Signature of transition from hadronic to quark-gluon description of nuclei.
- More recently, necessary condition for factorization of meson electroproduction and extraction of generalized parton distributions.
- Observed at 'high' momentum and/or energy transfer.



PRL 90, 052501 (2003)

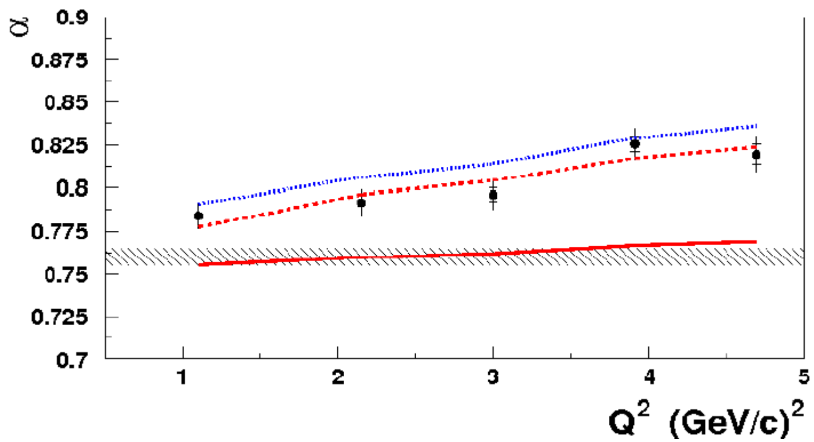
$$T_A = \sigma_A/(A\sigma_N)$$

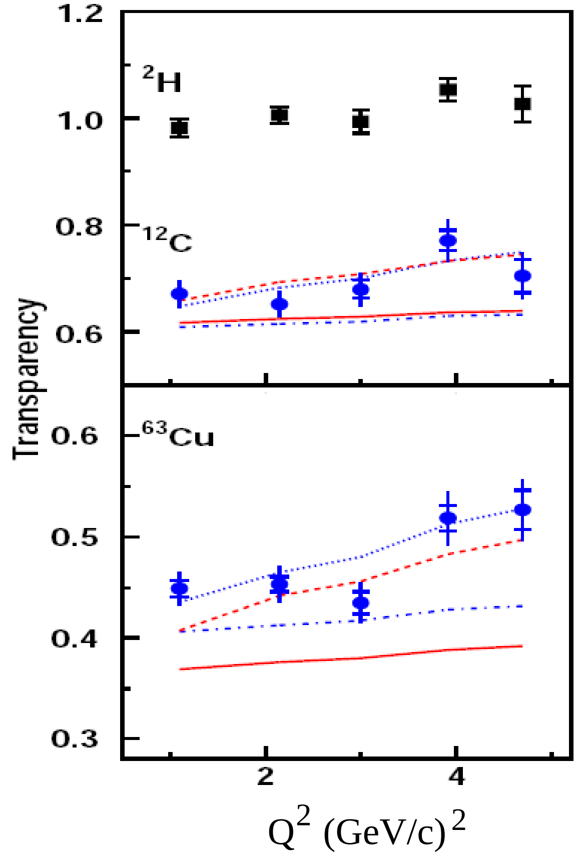




Seeking Color Transparency - Recent JLab Hall-C Results

- Measure in Hall C $A(e,e'\pi^+)$ on $^2\mathrm{H}$, $^{12}\mathrm{C}$, $^{27}\mathrm{Al}$, $^{63}\mathrm{Cu}$, and $^{197}\mathrm{Au}$ for $Q^2 = 1.1 - 4.7\ (\mathrm{GeV/c})^2$
- Use multi-pion simulation to set missing mass cut and correct for Fermi motion, Pauli blocking, off-shell properties, and acceptance.
- Compared results with Glauber and Glauber+CT.
- Observe modest rise in Q^2 and dependence on A. The parameter α comes from a fit to $T_A = A^{\alpha-1}$ at fixed Q^2.



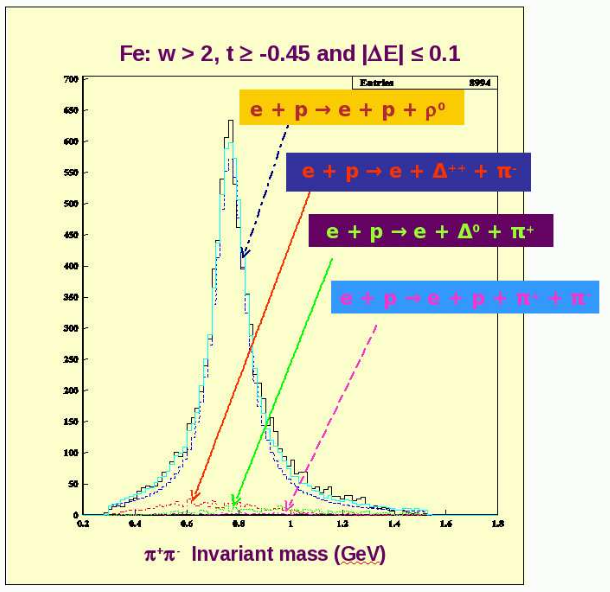


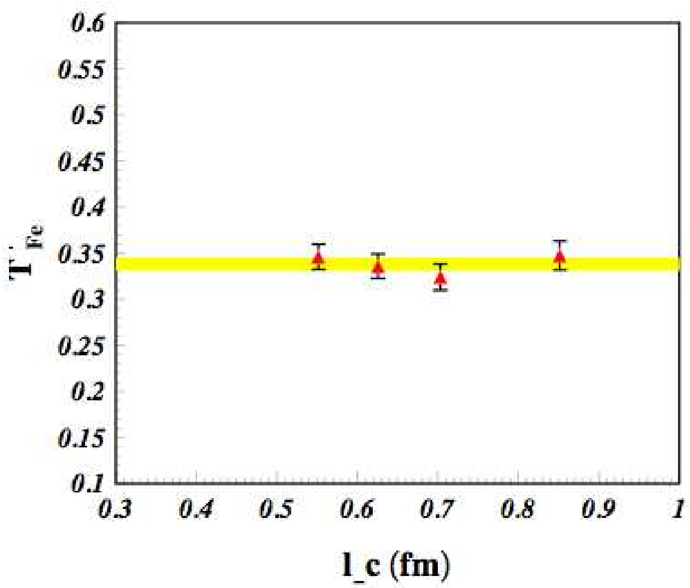
PRL 99, 242502 (2007)

Seeking Color Transparency - Preliminary JLab Hall B Results

- Measure in the Hall B CLAS $A(e, e'\rho^0)$ via $\pi^+\pi^-$ decay of the ρ on ^{2}H, ^{12}C, and ^{56}Fe for $Q^2 = 1 - 2\ (\mathrm{GeV/c})^2$
- Cuts: $\Delta W \geq 2\ GeV$ (avoid resonance region), $0.1 \leq -t \leq 0.4\ GeV/c$ (diffractive processes), $Z > 0.9$ (exclusive processes).
- Apply corrections for pion absorption, radiative corrections, and acceptance, using GENOVA MC with cross sections added for background from delta and pion production.
- Coherence length under control. Results imminent (K.Hafidi).

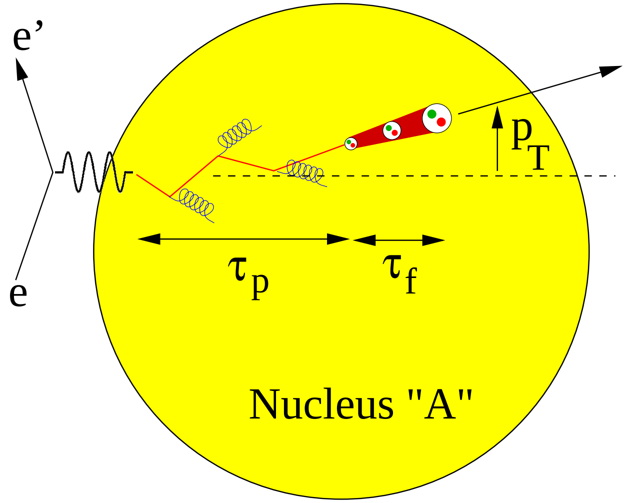
Observation of CT still problematic, but should become clear with JLab 12-GeV Upgrade.





Quark Propagation and Hadron Formation

- Probe space-time properties of hadronization in nuclear DIS.
- Struck quark is deconfined and loses energy by multiple scattering and/or gluonic radiation (production time τ_p).
- The quark is finally 'dressed' to form a hadron (formation time τ_f).

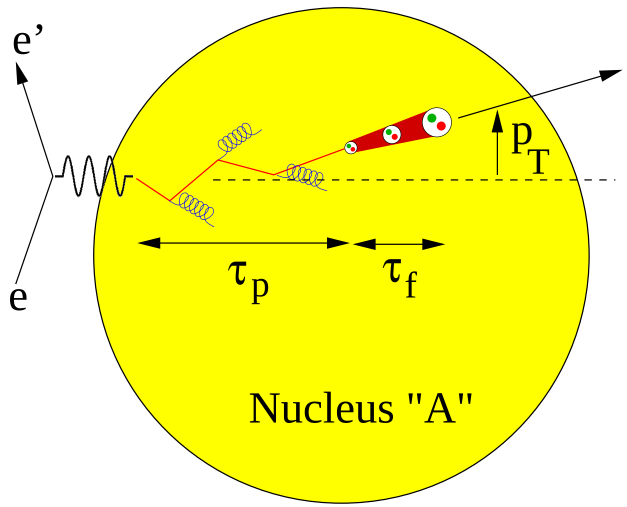


- Direct confrontation of QCD and confinement in the nuclear environment.

- How long can a light quark be deconfined?
- How long does it take to form the color field of a hadron?

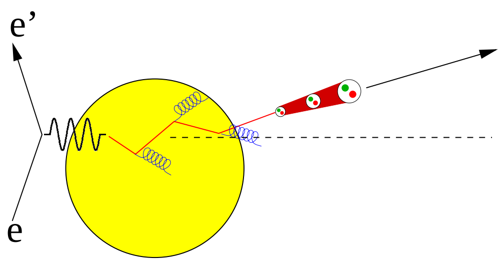
Extracting Production Times (τ_p)

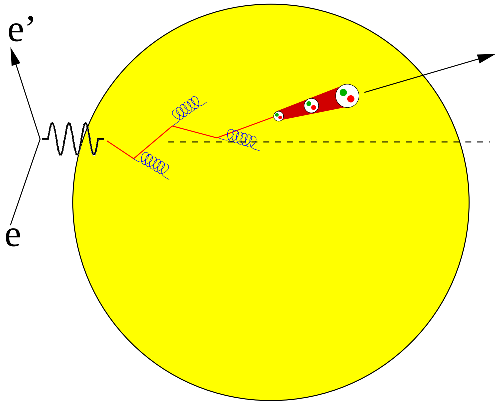
- Transverse momentum distribution (p_T) of deconfined quark gets wider from gluonic radiation.



$$\Delta p_T^2 = \langle p_T^2 \rangle_A^{DIS} - \langle p_T^2 \rangle_D^{DIS}$$

- Nuclear dimensions are well-matched to be a 'filter' for measuring τ_p and τ_f.
- Extract partonic energy loss $\frac{dE}{dx} \propto \langle p_T^2 \rangle$.
- Δp_T^2 mostly accumulates during production time.
- Saturation of Δp_T^2 is a sign that the maximum production time has been reached $\longrightarrow$ extract τ_p.

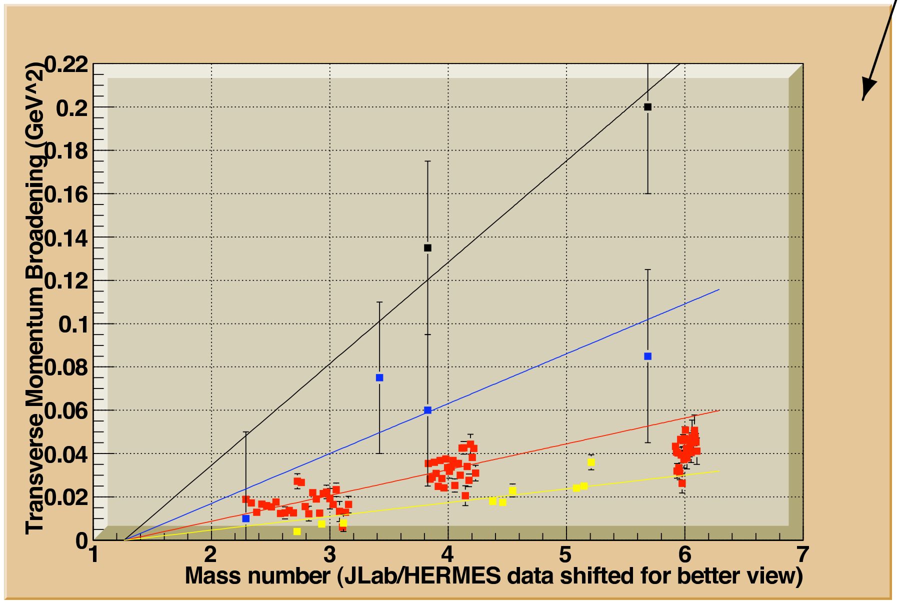


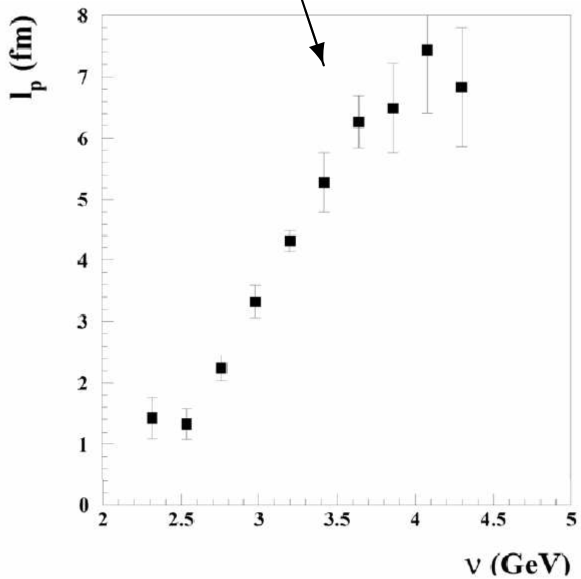


Preliminary JLab Results on Production Times (τ_p)

Transverse Momentum Broadening

- Good statistics in over 50 bins in $z = E_h/\nu$, $\nu = E - E'$, Q^2, and p_T for each of π^+, π^0, K^0, and Λ.
- Results from Fermi Lab Drell-Yan experiments (E772(blue), E866(black), and HERMES(yellow)) and results for Δp_T^2 for CLAS E5 (W.Brooks) - saturation of Δp_T^2!
- Extraction of production time based on Kopeliovich, *et al.* (hep-ph/0608044).

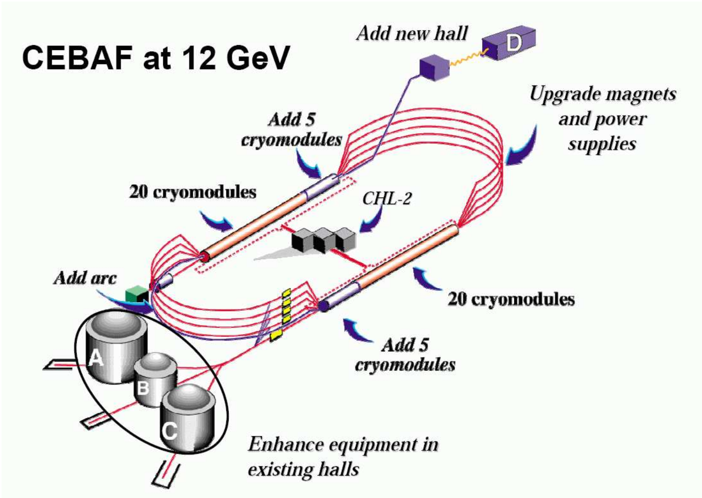




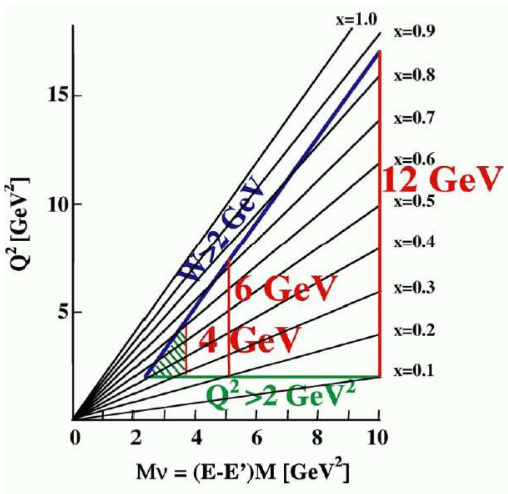
$A^{1/3}$

JLab 12-GeV Upgrade

- The electron beam energy at JLab (CEBAF) will be doubled from 6 GeV to 12 GeV.
- Halls A, B and C will be upgraded to accommodate the new physics opportunities.
- A new hall (Hall D) will house a large-acceptance detector built around a solenoidal magnet for photon beam experiments.
- All of the physics discussed here will be extended to 12 GeV.
- Specific proposals have already been approved for running during the first five years to study hadronization (PR12-06-117 and PR12-07-101), color transparency (PR12-06-106 and PR12-06-107), and SRC (PR12-06-105).



See Talk 138 by A.Lung



Conclusions

- JLab has developed a rich, diverse program to challenge QCD with new data in the nuclear environment.
  - High-resolution, observations of core-excited states in hypernuclei.
  - Isospin structure of nucleons in correlated pairs in nuclei.
  - Mass shift of the ρ^0 mass in nuclei is small while change in polarization is significant.
  - Transparency measured as a function of Q^2 for several channels and possible signal seen for the onset of color transparency.
  - Evidence for the saturation of Δp_T^2 in nuclei leading to the extraction of the production time of deconfined quarks in nuclei.
- Bright future with the 12-GeV Upgrade.

Apologies to those I missed.

Jefferson Lab
Thomas Jefferson National Accelerator Facility

Additional Slides

What is the Mission of Jefferson Lab?

Nuclear Physics in the US is focused on

1. QCD and understanding the early universe, confinement, gluons, and nucleon structure.
2. Nuclear structure and the evolution of the cosmos.
3. New Standard Model of fundamental interactions, the origins of matter, and the properties of nuclei and neutrinos.

The Frontiers of Nuclear Science, A Long Range Plan, The DOE/NSF Nuclear Science Advisory Committee, December, 2007.

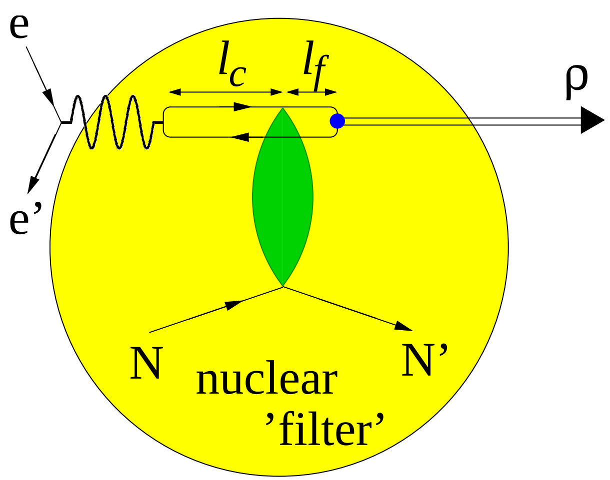
In the EU

1. Understanding the properties of nucleons and their interactions in terms of QCD
2. Modifications of hadron properties in nuclei.
3. Quark energy loss in matter.
4. Color transparency.
5. Implantation of strange quarks in nuclei as structure probes.

NuPECC Long Range Plan 2004, edited by H. Muhsin, *et al.*, European Science Foundation, April, 2004.

Seeking Color Transparency - 1

- Use meson electroproduction in nuclei.
  - PLC more probable for small, $q\bar{q}$ configurations than 3-quark baryons.
  - Coherence length is $l_c = 2\nu/(M^2 + Q^2)$ where ν is the energy transfer and M is the meson mass. Variations can mimic CT.
  - Formation length l_f is the distance of PLC will travel before evolving into a full-sized hadron.
  - If l_f is longer than nuclear size, meson gets out.

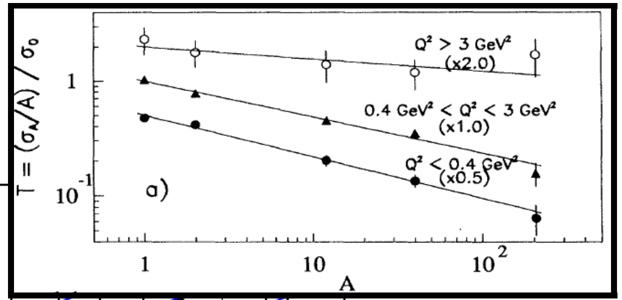


- Method
  - Main observable is the transparency $T_A = \frac{\sigma_A}{A\sigma_N}$ where σ_A is the cross section on nucleus of mass A and σ_N is the free nucleon cross section.
  - If l_c is fixed, non-CT Glauber calculations are constant with Q^2. The signature of CT is an increasing T_A with Q^2.
  - If l_c and Q^2 are fixed, then T_A should decrease with A.

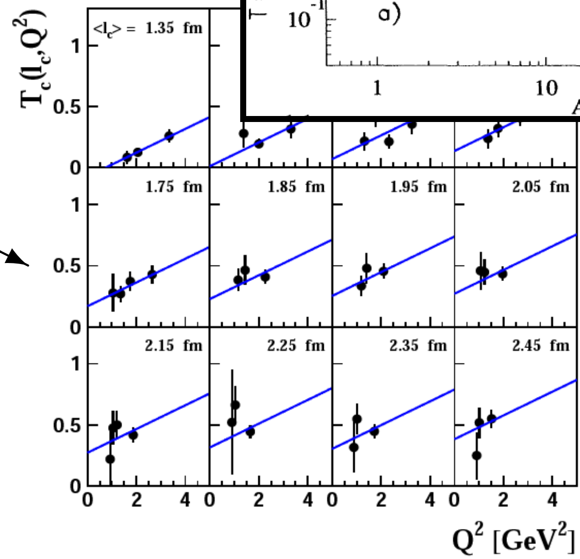
Seeking Color Transparency - Status

At high Q^2 and/or ν.

- Observed in ρ_0 production at Fermi Lab E665 (PRL 74, 1525 (1995)).

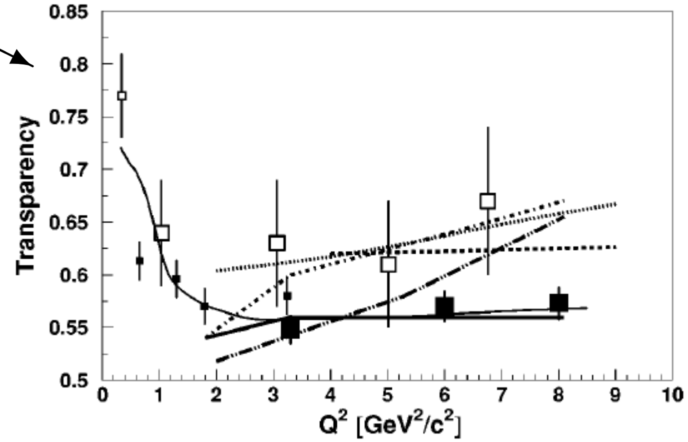


- ρ^0 production at HERMES (PRL 90, 052501 (2003)).

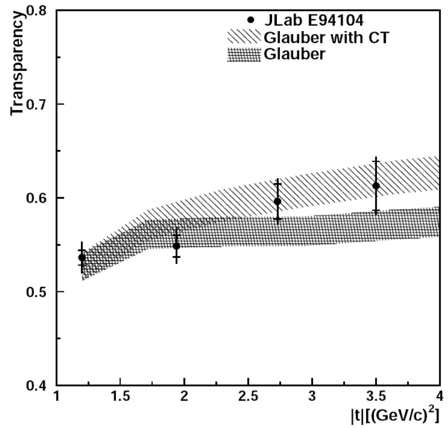


At moderate Q^2 and/or ν.

- Hall C $A(e,e'p)$ (PRC 66, 044613 (2002)) - little or no CT.



- Hall A $^4He(\gamma,\pi^- p)$ (PRC 68, 021001(R) (2003)) - small increase in transparency with Q^2.



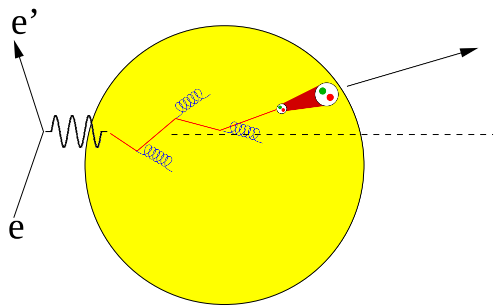
Extracting Formation Times (τ_f)

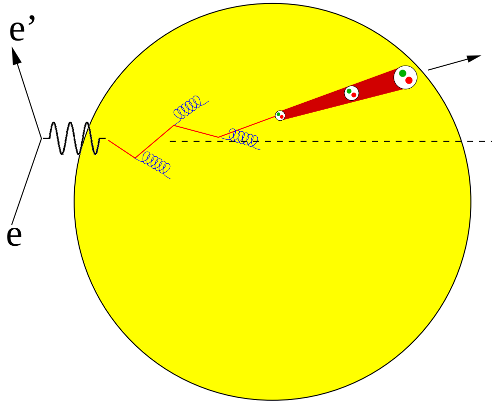
- Hadron attenuation

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

- Use results on τ_p and extract $\tau_f(\nu, z, Q^2, p_T)$ for different species.

$$\nu = E - E'$$
$$z = E_h/\nu$$





- Pioneering experiments performed at HERMES at 27.6 GeV (five publications).
- JLab measurement in CLAS (EG2 running period)
  - Carbon, iron, lead, hydrogen, and deuterium targets, higher luminosity.
  - $E = 5.0\,\mathrm{GeV}$, $Q^2 = 1.0 - 2.5\,(\mathrm{GeV/c})^2$, $\nu = 2.6 - 4.2\,\mathrm{GeV}$.

Preliminary JLab Results on Formation Times (τ_f)

Hadron Attenuation

- Two competing approaching to extracting the formation time rely on partonic energy loss and hadron/pre-hadron interactions remain unresolved.
- More CLAS results on the way!.