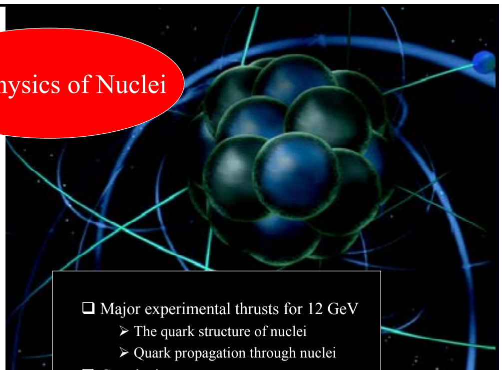


The Physics of Nuclei

- ❑ Major experimental thrusts for 12 GeV
  - ➢ The quark structure of nuclei
  - ➢ Quark propagation through nuclei
- ❑ Conclusions
- ❑ One-page summary sheets

The 12 GeV Program for the Physics of Nuclei

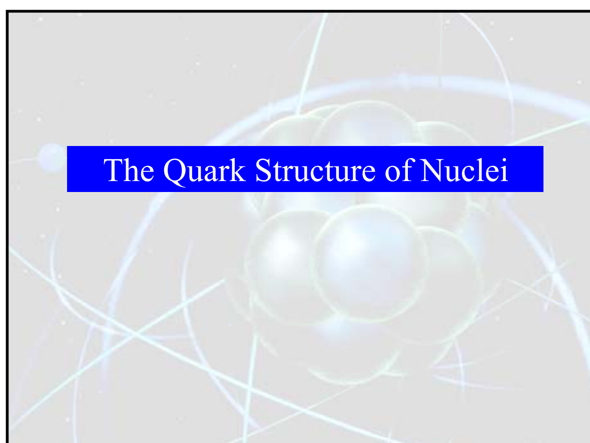
- ❑ The quark structure of nuclei
- ❑ Quark propagation through nuclei
- ❑ Color transparency
- ❑ Universal scaling behavior
- ❑ Threshold J/Ψ photoproduction on nuclei
- ❑ Short-range correlations and cold dense matter
- ❑ Few-body form factors

Nucleons and Pions or Quarks and Gluons?

- ❑ From a field theoretic perspective, nuclei are a separate solution of QCD Lagrangian
  - ➢ Not a simple convolution of free nucleon structure with Fermi motion
- ❑ 'Point nucleons moving non-relativistically in a mean field' describes lowest energy states of light nuclei very well
  - ➢ But description ***must*** fail at small distances
- ❑ In nuclear deep-inelastic scattering, we look directly at the ***quark structure of nuclei***

This is new science, and largely unexplored territory

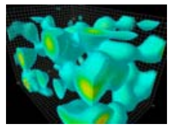
New experimental capabilities to attack long-standing physics issues



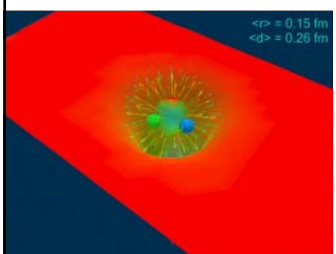
The Quark Structure of Nuclei

The QCD Lagrangian and Nuclear "Medium Modifications"

The QCD vacuum



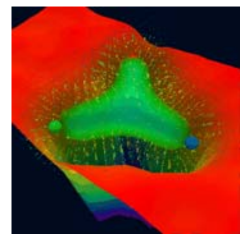
Long-distance gluonic fluctuations



Lattice calculation demonstrates *reduction of chiral condensate* $\langle q\bar{q}\rangle$ of QCD vacuum in presence of hadronic matter

Leinweber, Signal et al.

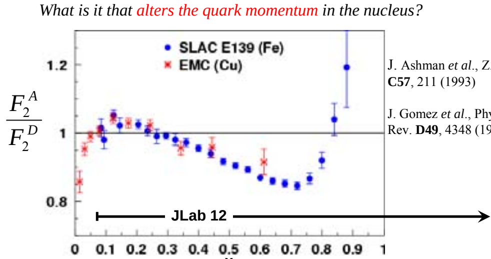
Does the quark structure of a nucleon get modified by the suppressed QCD vacuum fluctuations in a nucleus?



Quark Structure of Nuclei: Origin of the EMC Effect

- ❑ Observation that structure functions are altered in nuclei stunned much of the HEP community 23 years ago
- ❑ ~1000 papers on the topic; the best models explain the curve by change of nucleon structure, BUT more data are needed to *uniquely* identify the origin

What is it that alters the quark momentum in the nucleus?



J. Ashman *et al*., Z. Phys. **C57**, 211 (1993)

J. Gomez *et al*., Phys. Rev. **D49**, 4348 (1994)

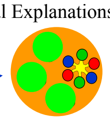
Unpacking the EMC effect

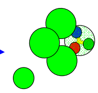
- ❑ With 12 GeV, we have a variety of tools to unravel the EMC effect:
  - ➢ Parton model ideas are valid over fairly wide kinematic range
  - ➢ High luminosity
  - ➢ High polarization
- ❑ New experiments, including several major programs:
  - ➢ Precision study of A-dependence; x>1; valence vs. sea
  - ➢ $g_{1A}(x)$ "Polarized EMC effect" – influence of nucleus on spin
  - ➢ Flavor-tagged polarized structure functions $\Delta u_A(x_A)$ and $\Delta d_A(x_A)$
  - ➢ x dependence of axial-vector current in nuclei (can study via parity violation)
  - ➢ Nucleon-tagged structure functions from ^{2}H and ^{3}He with recoil detector
  - ➢ Study x-dependence of exclusive channels on light nuclei, sum up to EMC

EMC Effect - Theoretical Explanations

Quark picture

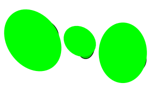
- ❑ Multi-quark cluster models
  - ➢ Nucleus contains multinucleon clusters (e.g., 6-quark bag)
- ❑ Dynamical rescaling
  - ➢ Confinement radius larger due to proximity to other nucleons

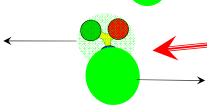




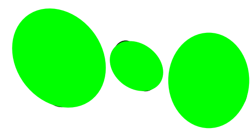
Hadron picture

- ❑ Nuclear binding
  - ➢ Effects due to Fermi motion and nuclear binding energy, including virtual pion exchange
- ❑ Short range correlations
  - ➢ High momentum components in nucleon wave function





What is the role of binding energy in the EMC effect?
What is the role of Fermi momentum (at high x)?
Do virtual pions play any role at all?

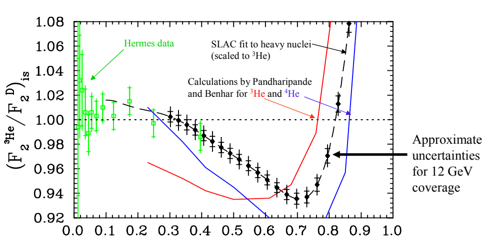


EMC Effect in ^{3}He and ^{4}He

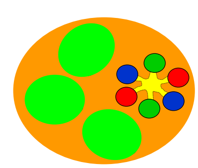
❑ Current data do not differentiate between A-dependence or ρ-dependence.

❑ Can do exact few-body calculations, and high-precision measurement

❑ Fill in high-x region – transition from rescaling to Fermi motion?

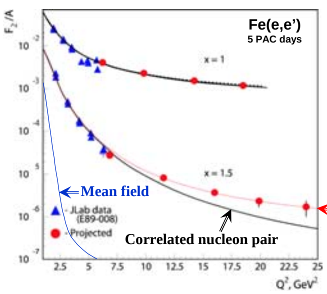


Do multi-quark clusters exist in the nuclear wavefunction?
Do they contribute significantly to the EMC effect?

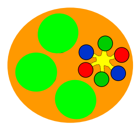


How to answer: tag overlapping nucleons…

Multi-quark clusters are accessible at large x (>>1) and high Q^2

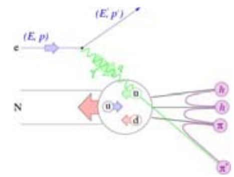


12 GeV gives access to the high-x, high-Q^2 kinematics needed to find multi-quark clusters



Six-quark bag
(4.5% of wave function)

Reminder: semi-inclusive DIS



Detect a final state hadron in addition to scattered electron

Can 'tag' the flavor of the struck quark by measuring the hadrons produced: 'flavor tagging'

Cross section ~ $\sum_{q,\bar{q}} q(x) \cdot D_{q \to h}(z)$

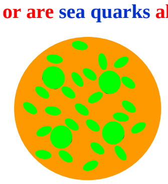
$$z = \frac{E_{hadron}}{\nu}$$

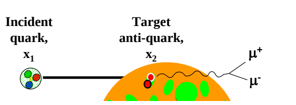
Transverse momentum p_T **= hadron momentum component transverse to virtual photon**

Full cross section is a function of ν, Q^2, z, p_T, and ϕ

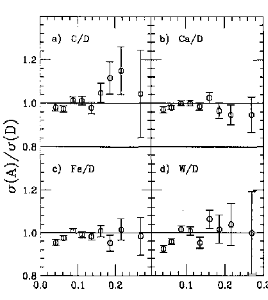
Nuclear fragmentation functions will be discussed in detail in second half of talk, needed here for extraction of $q_A(x)$

Is the EMC effect a valence quark phenomenon, or are sea quarks also involved?



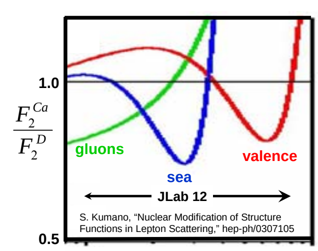


Drell-Yan data from Fermilab, showing no clear excess of anti-quarks in nuclei

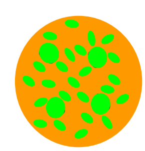


Flavor-tagged EMC Effect

- Sea and valence expected to be quite different according to *calculations*



- Global **fit** of electron and muon DIS experiments and Drell-Yan data



- Semi-inclusive measurements: detect π^+, π^-, (K^+, K^-), do flavor decomposition to extract sea and valence quark distributions using Ca(e,e'h).

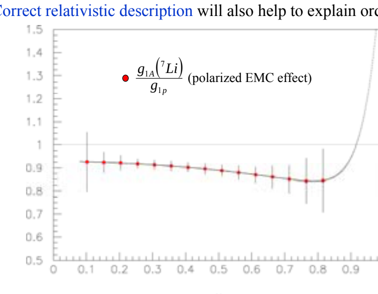
What is the role of relativity in the description of the EMC effect?
What can we learn from spin?

Surprises:
23 years ago – EMC effect
17 years ago – the 'spin crisis'
will there be another 'spin crisis' in nuclei?

- Quantum field theory for nuclei:
  - Large (300-400 MeV) Lorentz scalar and vector fields required
  - Binding energies arise from cancellations of these large fields
  - Relativity an *essential component*
- Quark-Meson Coupling model:
  - Lower Dirac component of confined light quark modified most by the scalar field
- How to probe the lower component further? *SPIN!*

$g_{1A}(x)$ – "Polarized EMC Effect"

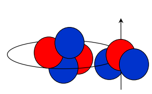
- Spin-dependent parton distribution functions for nuclei essentially unknown
- Can take advantage of modern technology for polarized solid targets to perform systematic studies – Dynamic Nuclear Polarization
- Correct relativistic description will also help to explain ordinary EMC effect



Curve follows calculation by W. Bentz, I. Cloet, A. W. Thomas

$g_1(A)$ – "Polarized EMC Effect" – Some Solid Target Possibilities

Nuclide	Compound	Polarization (%)
^{6}Li	^{6}LiD	45
^{7}Li	**^{7}LiD**	**90**
^{11}B	$C_2N_2BH_{13}$	75
^{13}C	$^{13}C_4H_9OH$	65
^{19}F	LiF	90

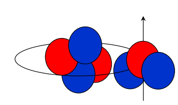


Proton embedded in 7Li with over 50% polarization!

$g_1(A)$ – "Polarized EMC Effect" – ^{7}Li as Target

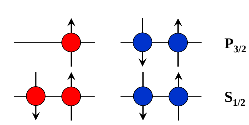
Shell model: 1 unpaired proton, 2 paired neutrons in $P_{3/2}$, closed $S_{1/2}$ shell.
Cluster model: triton + alpha

^{7}Li polarization: 90%



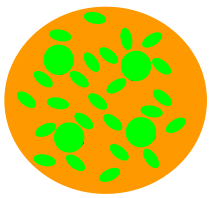
Nucleon polarization calculations:
Cluster model: 57%
GFMC: 59%

59% x 90% = 53%



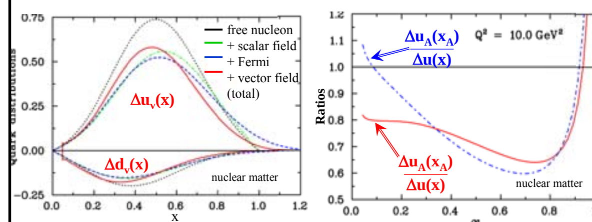
Proton embedded in ^{7}Li with over 50% polarization!

Can we go further in understanding relativistic effects and the role of quark flavor?
How much of the spin is carried by the valence quarks?
Is there a nuclear ‘spin crisis’ too?

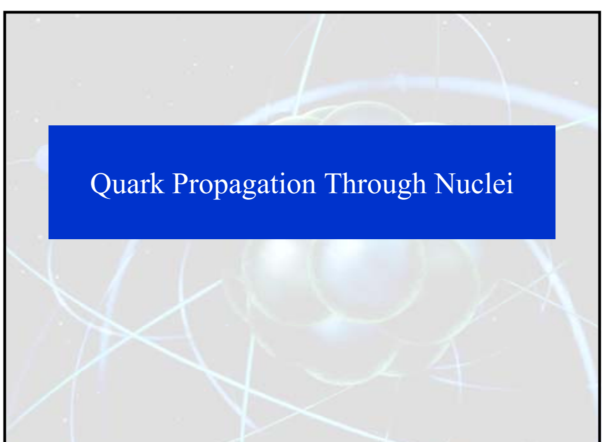


“Polarized EMC Effect” – Flavor Tagging

- Can perform semi-inclusive DIS on sequence of polarized targets, measuring π^+ and π^-, decompose to extract $\Delta u_A(x_A)$, $\Delta d_A(x_A)$.
- Challenging measurement, but have *new tools:*
  - High polarization for a wide variety of targets
  - Large acceptance detectors to constrain systematic errors and tune models

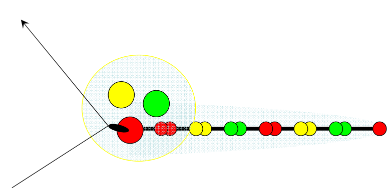


W. Bentz, I. Cloet, A. W. Thomas

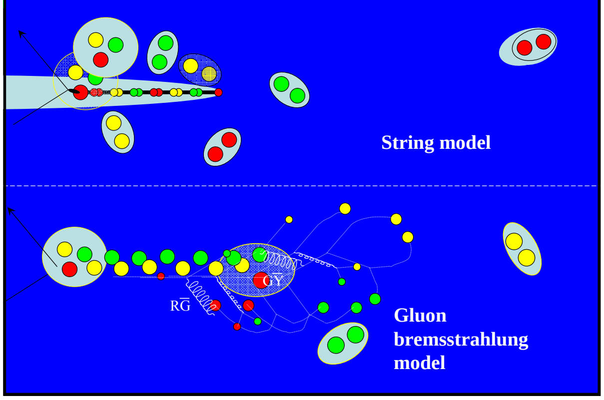


Quark Propagation Through Nuclei

How do energetic quarks transform into hadrons?
How quickly does it happen?
What are the mechanisms?

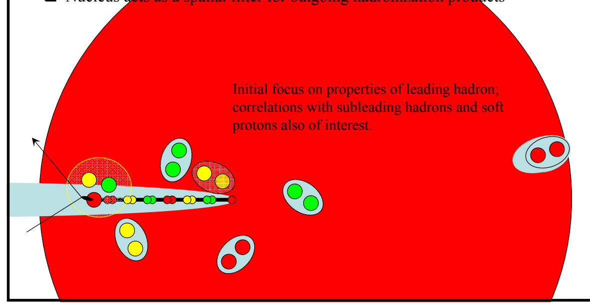


Two Possible Hadronization Mechanisms



Nuclear Deep Inelastic Scattering and Hadronization

- We can learn about hadronization distance scales and reaction mechanisms from semi-inclusive nuclear DIS
- Nucleus acts as a spatial filter for outgoing hadronization products



Observables – Hadronic Multiplicity Ratio

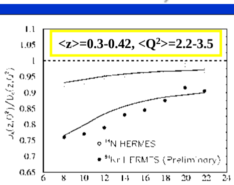
(≈ medium-modified fragmentation function)

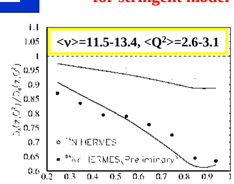
$$R_M^h(z,\nu) = \frac{\left\{\frac{N_h(z,\nu)}{N_e(\nu)}\right\}_A}{\left\{\frac{N_h(z,\nu)}{N_e(\nu)}\right\}_D} = \frac{\left[\frac{\sum_f e_f^2 q_f(x) D_f^h(z)}{\sum_f e_f^2 q_f(x)}\right]_A}{\left[\frac{\sum_f e_f^2 q_f(x) D_f^h(z)}{\sum_f e_f^2 q_f(x)}\right]_D}$$

In general, $R_M^h(z,\nu,p_T^2,Q^2,\phi)$

Significant dependence of R on z, ν, p_T^2, A

Must **measure multi-variable dependence for stringent model tests!**





HERMES Data

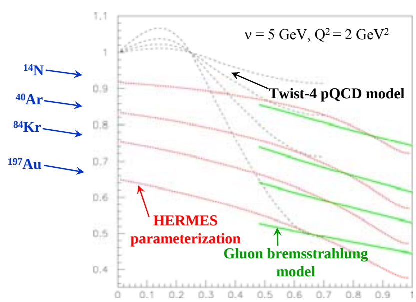
- Mostly 27 GeV positron beam, some 12 GeV beam
- Targets include D, He, N, Kr, Xe
- Excellent PID (RICH) except for early nitrogen targets
  - identify $\pi^{+/-/o}$, $K^{+/-}$, proton and antiproton
- Pioneering measurements of high quality, however
  - Limited luminosity, gas targets → can only do 1-D binning, lower Q^2, A<140

With JLab at 12 GeV, will have:

nearly three orders of magnitude more luminosity:
→ do multi-dimensional binning
→ reach high Q^2
→ study multi-particle correlations

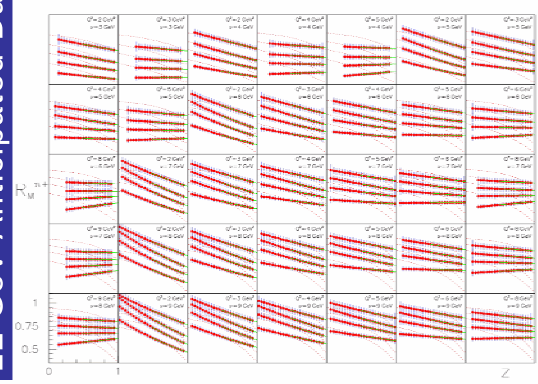
capability of solid targets:
→ study largest nuclei

Model Descriptions



12 GeV Anticipated Data

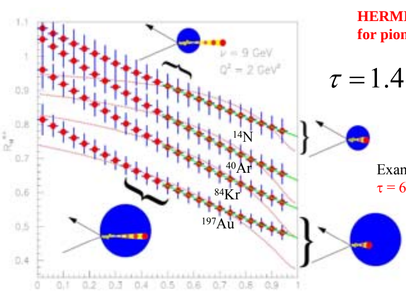
Examples of Experimental Data and Theoretical Predictions



Each point is differential in Q^2, ν, z, and A; all are acquired simultaneously

Interpretation of Hadronic Multiplicity Ratio

(concrete example in hadronization picture)



HERMES parameterization for pion formation length:

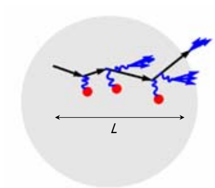
$$\tau = 1.4 \cdot \nu \cdot (1 - z)\ fm$$

Example: z = 0.5, ν = 9 GeV,
τ = 6.3 fm, ~ radius Pb

Accessible Hadrons (12 GeV)

hadron	$c\tau$	mass (GeV)	flavor content	detection channel	production rate per 1k DIS events
π^0	25 nm	0.13	$u\bar{u}d\bar{d}$	$\gamma\gamma$	1100
π^+	7.8 m	0.14	$u\bar{d}$	direct	1000
π^-	7.8 m	0.14	$d\bar{u}$	direct	1000
η	0.17 nm	0.55	$u\bar{u}d\bar{d}s\bar{s}$	$\gamma\gamma$	120
ω	23 fm	0.78	$u\bar{u}d\bar{d}s\bar{s}$	$\pi^+\pi^-\pi^0$	170
η'	0.98 pm	0.96	$u\bar{u}d\bar{d}s\bar{s}$	$\pi^+\pi^-\eta$	27
ϕ	44 fm	1.0	$u\bar{u}d\bar{d}s\bar{s}$	K^+K^-	0.8
K^+	3.7 m	0.49	$u\bar{s}$	direct	75
K^-	3.7 m	0.49	$\bar{u}s$	direct	25
K^0	27 mm	0.50	$d\bar{s}$	$\pi^+\pi^-$	42
p	stable	0.94	ud	direct	1100
$\bar{p}$	stable	0.94	$\bar{u}\bar{d}$	direct	3
Λ	79 mm	1.1	uds	$p\pi^-$	72
$\Lambda(1520)$	13 fm	1.5	uds	$p\pi^-$	-
Σ^+	24 mm	1.2	us	$p\pi^0$	6
Σ^0	22 pm	1.2	uds	$\Lambda\gamma$	11
Ξ^0	87 mm	1.3	us	$\Lambda\pi^0$	0.6
Ξ^-	49 mm	1.3	ds	$\Lambda\pi^-$	0.9

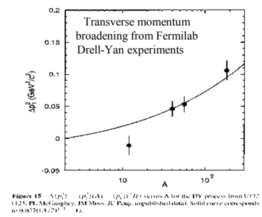
How much energy do energetic quarks lose by gluon emission in propagating through nuclei?



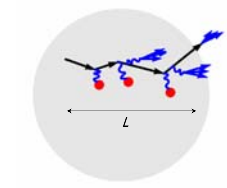
Photon bremsstrahlung a fundamental process in QED

Gluon bremsstrahlung a fundamental process in QCD

but confinement radically changes the way it works…



Quark energy loss from p_T broadening



- Struck quark emits gluons in vacuum because of confinement
- Medium stimulates *additional* gluon radiation
- Multiple scattering creates p_T broadening proportional to quark energy loss:

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

- Measure p_T broadening, infer energy loss, over wide range of kinematics

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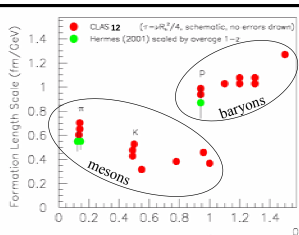
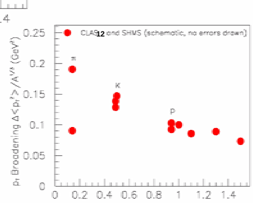
12 GeV Anticipated Data

Schematic Examples of Analysis Results



- Formation lengths for a wide variety of hadrons using data from CLAS12 and SHMS



- Transverse momentum broadening for a number of hadrons using data from CLAS12 and SHMS, for a particular Q^2, ν.

Conclusions

In the first five years, we will:

- Deliver a new understanding of the origin of the EMC effect with a series of measurements elucidating
  - valence and sea contributions
  - spin dependence and the role of relativity
  - existence of multi-quark clusters
  - density dependence
  - role of Fermi momentum
- Deliver a new understanding of hadronization mechanisms and distance scales by deriving multi-variable formation lengths for many hadron species
- Thoroughly explore quark energy loss in-medium

Conclusions

With 12 GeV, poised to make a brilliant contribution to our understanding of the Physics of Nuclei:

- Ideally equipped to solve the 23-year-old problem of the EMC effect
- Ideal energy range to study quark propagation through nuclei, with orders of magnitude more luminosity than previously possible

No other laboratory can address these important problems

Summaries

Quark Structure of Nuclei – Summary Sheet

What are the issues?	What causes the EMC effect, i.e., what is it that affects how quarks are distributed in nuclei? What are the roles of multi-quark clusters, relativity, binding effects, and valence/sea?
How does the upgrade address the issues?	Reach high x (>>1) and Q^2 for inclusive measurements; get much higher luminosity for semi-inclusive measurements.
Which issues are not addressed?	Particle ID is limited for semi-inclusive measurements with large acceptance.
What must be measured to get to the science?	Precision inclusive measurements (Hall C); precision semi-inclusive and polarized measurements (Hall B); F_2 and hadronic multiplicity ratio R_M^h for a series of nuclei
What is critical to get to the science?	New SHMS, fully instrumented; new magnets, cerenkov counter, and forward detector components of *CLAS12*
What are the high priority items?	To take enough data with enough new information content to be able to eliminate incorrect models for the EMC effect.
What will be learned in first 5 years?	Origin of EMC effect, and its dependence on new variables such as density and polarization.

Quark Propagation through Nuclei – Summary Sheet

What are the issues?	What are the mechanisms and distance scales of hadronization? How large is medium-stimulated quark energy loss?
How does the upgrade address the issues?	Reach wide range of Q^2 and ν, z and p_T; increased luminosity for studying multi-variable dependence and complex final states.
Which issues are not addressed?	Particle ID limited for semi-inclusive measurements with large acceptance.
What must be measured to get to the science?	Precision semi-inclusive and polarized measurements; hadronic multiplicity ratio R_M^h and p_T broadening for a series of nuclei.
What is critical to get to the science?	New magnets, cerenkov counter, and forward detector components of *CLAS12*. HMS & SHMS (kaon identification).
What are the high priority items?	To take enough data with enough new information content to be able to eliminate incorrect models for hadronization.
What will be learned in first 5 years?	Mechanisms of hadronization; multi-variable hadron formation lengths; a determination of quark energy loss in-medium.

The JLab Nuclear Physics Program for 12 GeV

(from the PN12 workshop)

The Emergence of Nuclei from QCD

- ❑ Fundamental Nature of Hadron-Hadron Interactions
- ❑ Short-Range Structure of Nuclei
- ❑ Medium Modifications
- ❑ Scaling Laws and Conformal Symmetries

Fundamental QCD Processes in the Nuclear Arena

- ❑ Hadronization in the Nuclear Medium
- ❑ Hadron-Hadron Interactions in Nuclei

Inclusive and Semi-inclusive Electron Scattering

❑ Inclusive electron scattering - only detect scattered electron (e+H→e'):

$$\frac{d^2\sigma}{dxdQ^2} = \frac{4\pi\alpha^2}{Q^4}\left[\left(1-y-\frac{Mxy}{2E}\right)\frac{F_2(x,Q^2)}{x} + y^2 F_1(x,Q^2)\right]$$

Parton distribution functions: $F_2 = x\sum_i e_i^2 q_i(x), \quad F_1 = \frac{1}{2x}F_2$

$$\{\ x = Q^2/(2P\cdot q) = Q^2/(2M\nu), \quad y = P\cdot q/(P\cdot k) = \nu/E\ \}$$

❑ Semi-inclusive electron scattering – detect additional hadron (e+H→e'+h):

$$\frac{d^3\sigma}{dxdydz} = \frac{8\pi\alpha^2 ME}{Q^4}\left[xy^2 H_1 + (1-y)H_2\right] \qquad \{\ z = E_h/\nu\ \}$$

Fragmentation functions:

$$H_2(x,z) = \sum_i e_i^2 x\left[q_{i/H}(x)D_{h/i}(z)\right], \quad H_1 = \frac{1}{2x}H_2$$

In nuclei: EMC effect $\Rightarrow F_2 \Rightarrow q_i(x)$***; quark propagation*** $\Rightarrow H_2 \Rightarrow D_{h/i}(z)$