Hadrons in the Nuclear Medium

some highlights

Goal: Use the nuclear environment to study exotic hadronic configurations - nature of confinement/ QCD in the non-perturbative regime

Matter at High Densities
- Modification to hadron structure in nuclei
- High density configurations in nuclei

Color Transparency
- A(e,e'p) - nuclear transparency
- Rescattering measurements
- Meson electro(photo)-production

J/ψ Production in Nuclei
- Interaction of intrinsically small QCD bound state

Jeffylab-12

"Beam in 2009 or it's free"

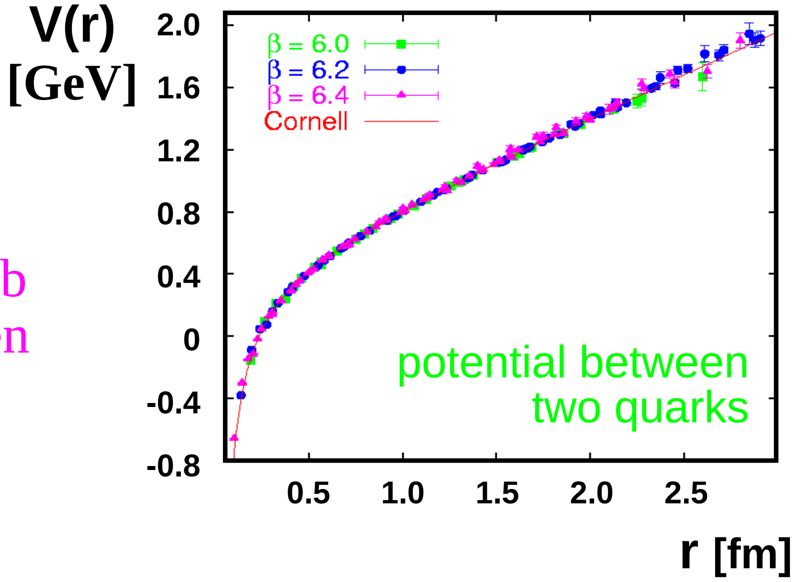
Two "Realms" of Nuclear Physics

QCD land: quarks + gluons + color

Strongly attractive at all distances:

1 GeV/cm = 18 tons

>10^{12} times the coulomb attraction in hydrogen

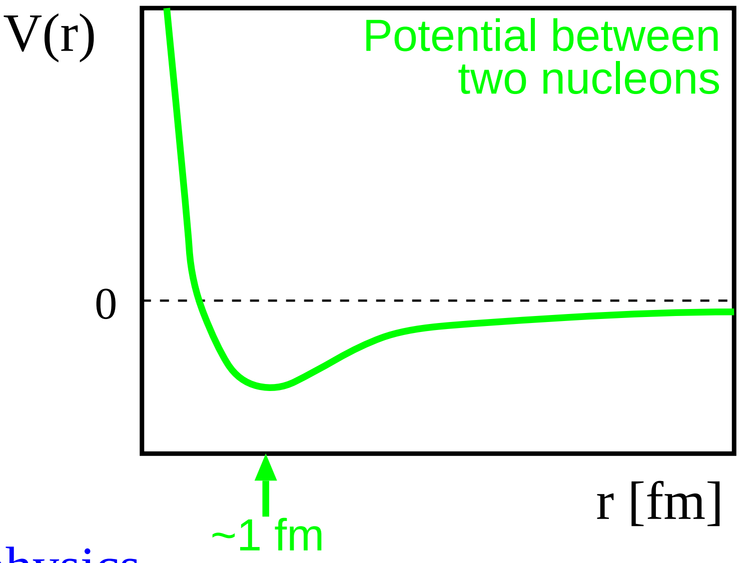


"Real world": nucleons + mesons + interaction

Matter consists of colorless bound states of QCD

Quark interactions cancel at large distances, making the interactions of hadrons finite.

Don’t observe quarks, gluons, or color in traditional nuclear physics



Both regions are well understood, but there is no roadmap from QCD-land to the real world

QCD calculations of hadronic structure are extremely limited

- Lattice for heavy mesons, Dyson-Schwinger equations
- Far from being able to calculate structure and interactions of nucleons and nuclei

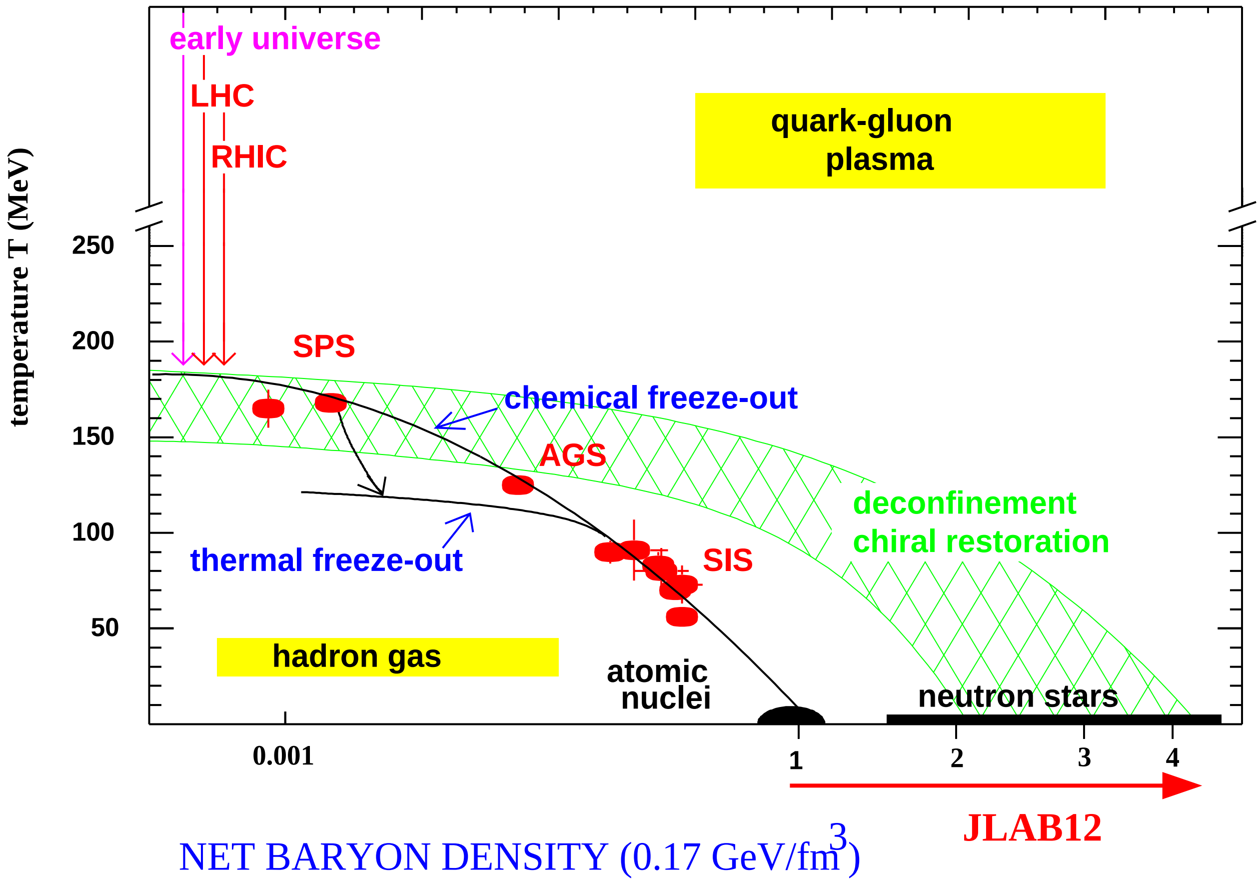
Experimentally:

- Most data is for real world states - bound states of QCD where the underlying degrees of freedom are not visible
- Structure functions give us ’end result’ of confinement
- *Need data that connects QCD-land to the real world*

In nuclei, there are unique opportunities to study exotic states of matter

- Modified structure - new bound states of QCD to study
- Modified interactions of these exotic bound states

Phase Transition at High Densities



We do see density-dependent effects in nuclear structure

EMC effect: $F_2(A)/F_2(D)$ - varies with A (or $<\rho_A>$)

Nucleon form factor: G_E^p/G_M^p reduced in ^{4}He?

We ***know*** that a nucleus is not just a collection of nucleons

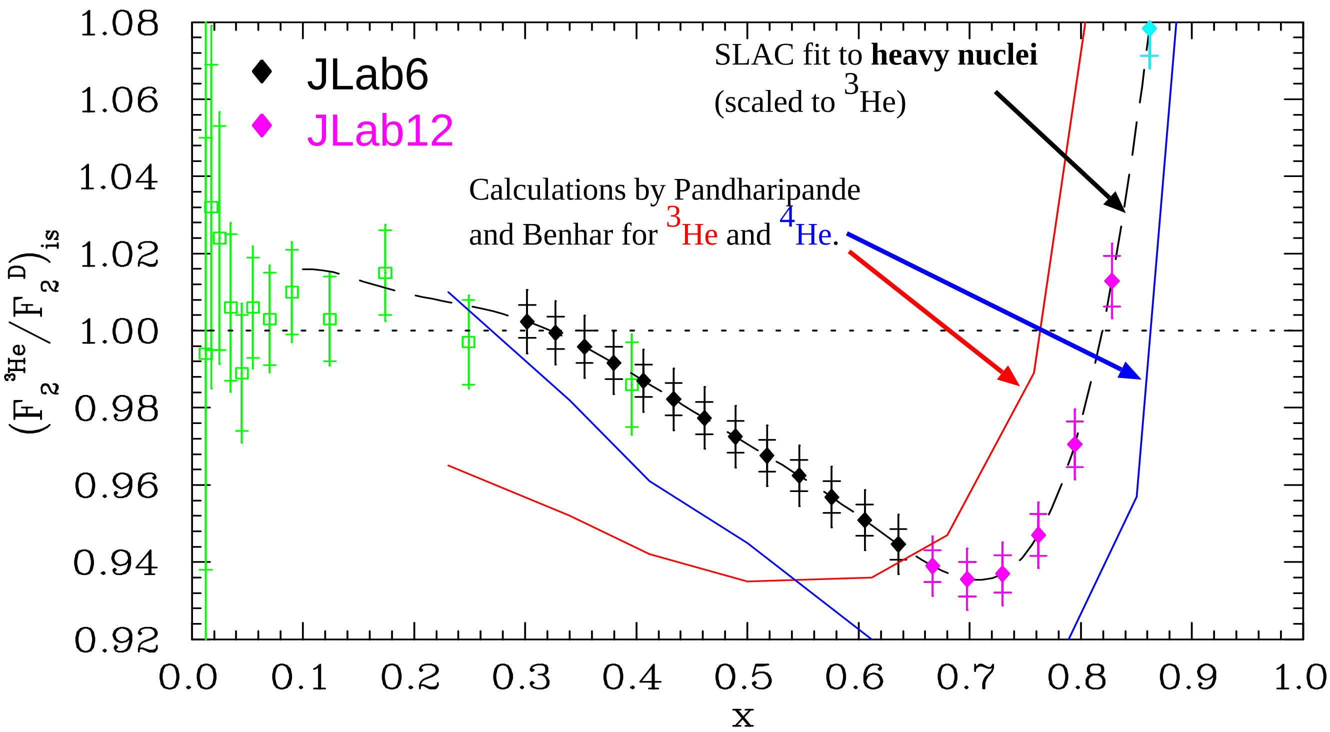
We cannot fully explain the observed deviations

EMC effect

$F_2(A)/F_2(D)$ - Vary with A or $<\rho_A>$?

x-dependence same for all nuclei?

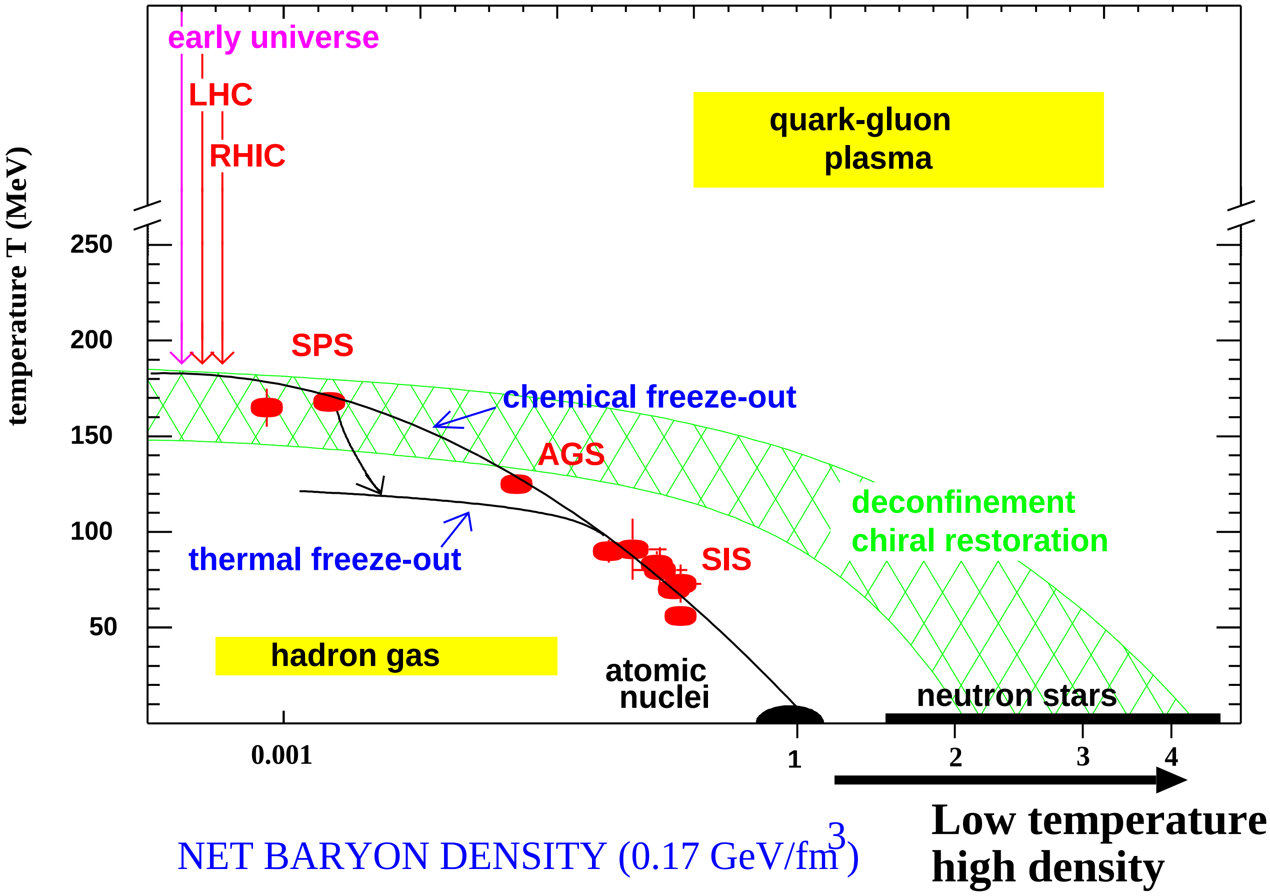
Data on light nuclei will help determine the A-dependence
The shape in light nuclei will test the existing models



Measurements on light nuclei over a large x range will:

- **Determine if effect depends on A or ρ**
- **Allow us to evaluate models of EMC effect**
- **Help determine nuclear effects in deuterium**

Phase Transition at High Densities



Average nuclear densities are well below phase transition

Short range correlations provide a small high-density component in nuclei

- * This may be origin of EMC effect, medium modifications
- * We can try to isolate SRCs to probe high density matter

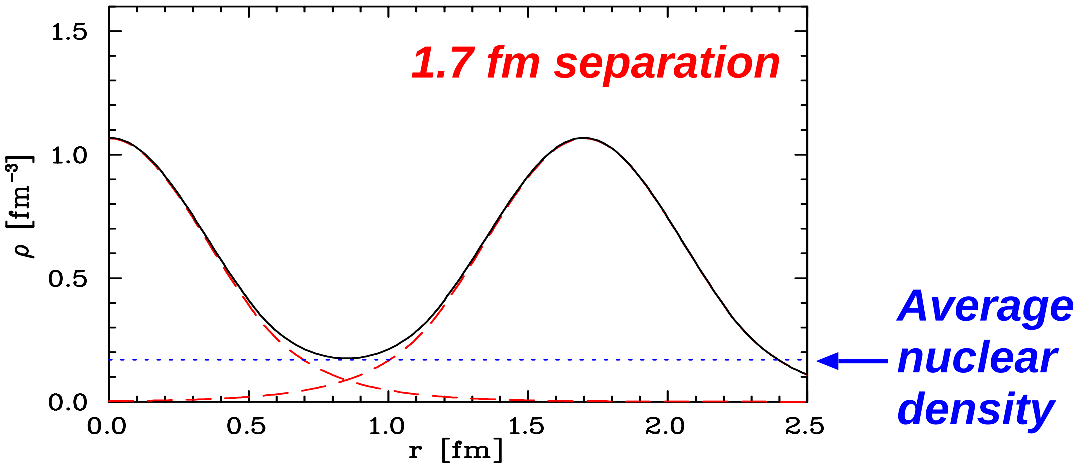
  QCD in intermediate region

  Cold, dense matter relevent to astrophysics

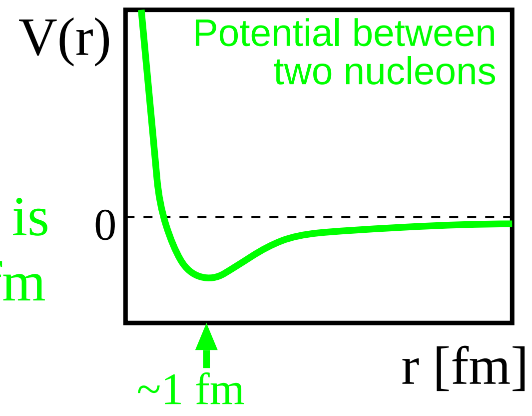
High Density Configurations

Nucleons are already closely packed in nuclei

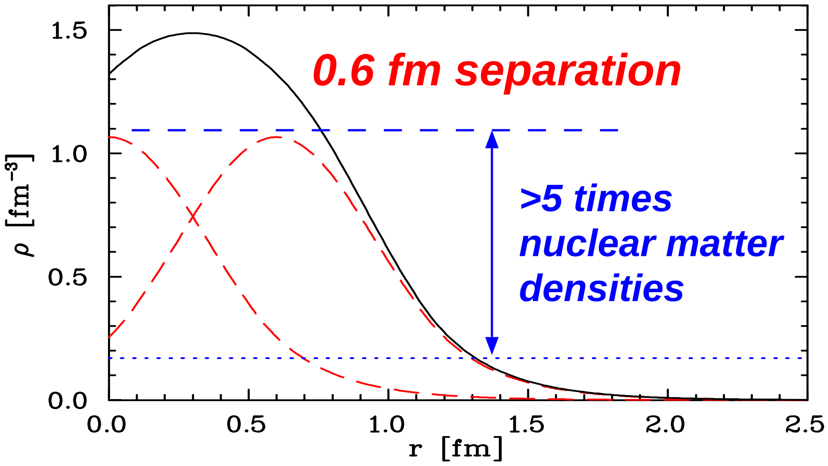
separation ~1.7 fm in heavy nuclei
nucleon charge radius ~ 0.86 fm



Nucleon separation is only limited by the short range repulsive core



Repulsive core is 1 GeV at ~0.4 fm



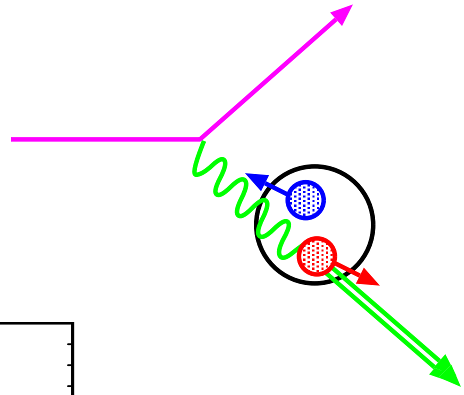
Tagged EMC Effect in Deuterium

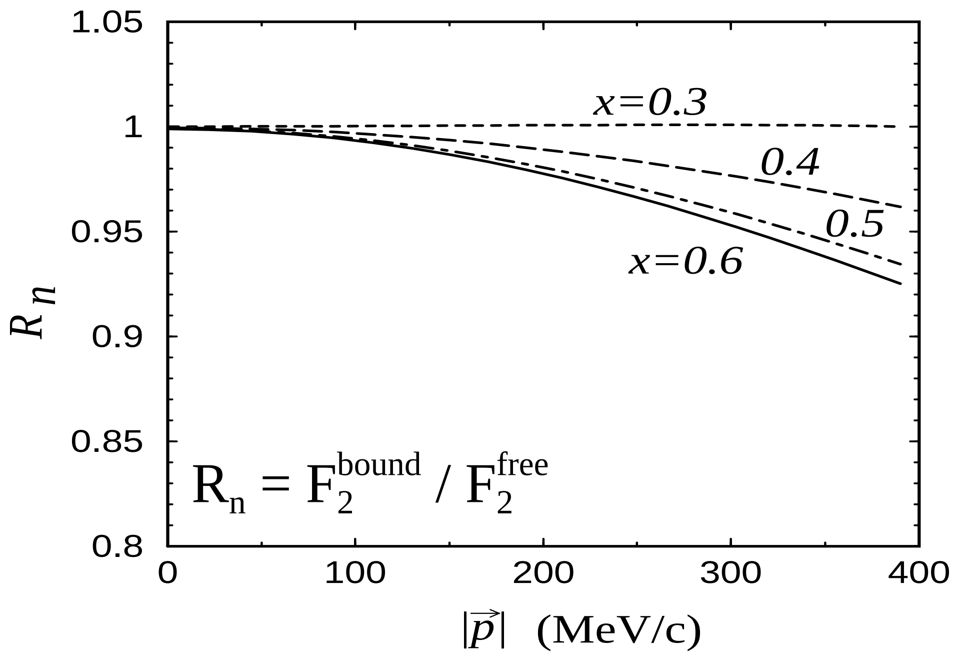
EMC effect: modified structure in a nucleus

Tagged EMC effect: modified structure in a short range correlation

'tag' spectator proton to measure:

$F_2^n(P_S^{large}) / F_2^n(P_S^{small})$

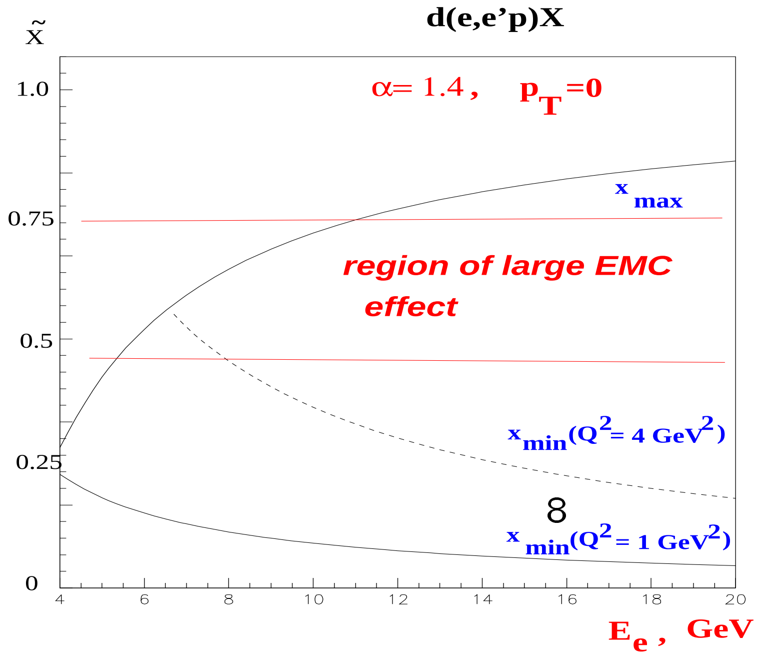




Small P_S --> ~free neutron

Large P_S --> Isolate SRCs (high-density configuration)

d(e,e'p_S) with CLAS

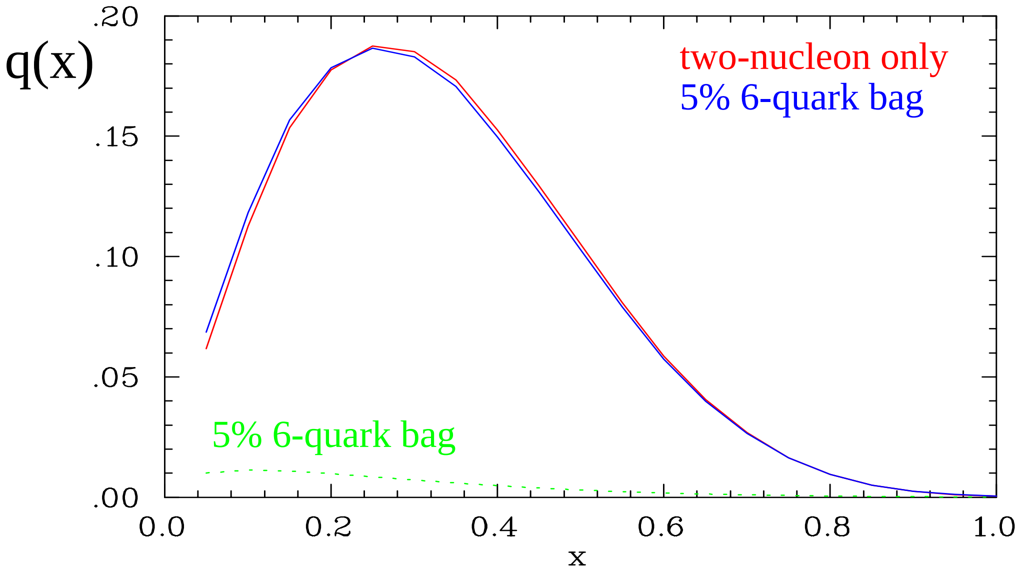


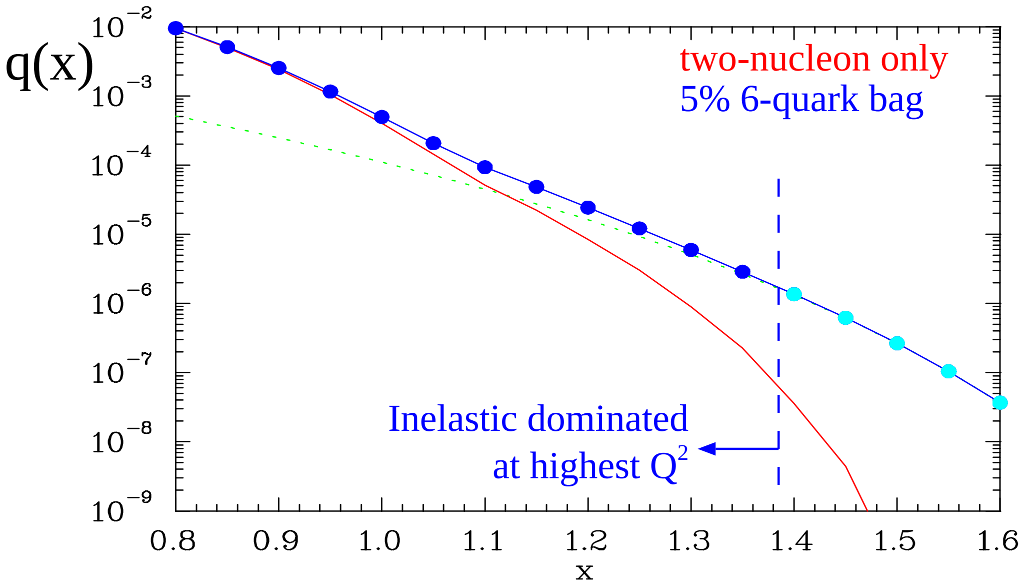
Deeply Inelastic Scattering at $x_B>1$

Quark distributions of high-density configurations in nuclei (SRCs)

x	Q^2_{max}
1.0	18 GeV^2
1.2	21 GeV^2
1.4	19 GeV^2
1.6	15 GeV^2

Comparison of nucleon-only quark distributions to 5% admixture of 6q:





$q(x) \sim x^{\alpha}\,(2-x)^{\beta}$

P. Mulders and A. W. Thomas, PRL 52, 1199(1984)

Clear signature of exotic states in nuclei

Deuteron provides cleanest signature

May have larger signals from heavy nuclei, but need to combine with studies of multi-nucleon correlations

Nuclear Matter at High Density

Extensions of measurements of the EMC effect

- Nucleus is ***not*** just a collection of nucleons
- Origin still not completely understood: two-body effect?
- Extend measurements to high x, low A
- Hall C or Hall A

New way to measure EMC effect

- Tag high-momentum spectator to isolate high density SRCs,
- Low-momentum spectator to isolate almost free nucleons
- Hall B: use CLAS to tag high-p spectators
  independent low-p tagger (BONUS)

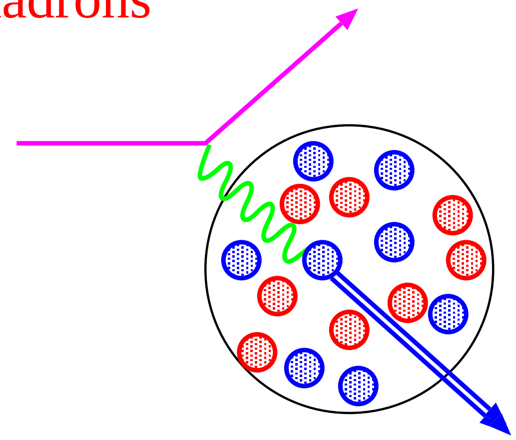
Probe structure of high-density configurations

- Measure distribution of superfast quarks (DIS at x>1)
- Probe internal structure of high density configuration
- Look for exotic states of matter at high density
- Hall A or Hall C:
  - Hall A has larger solid angle
  - Hall C has greater momentum range, resolution

Color Transparency

Interactions of exotic (small-sized) QCD bound states
Probes color degrees of freedom in hadrons

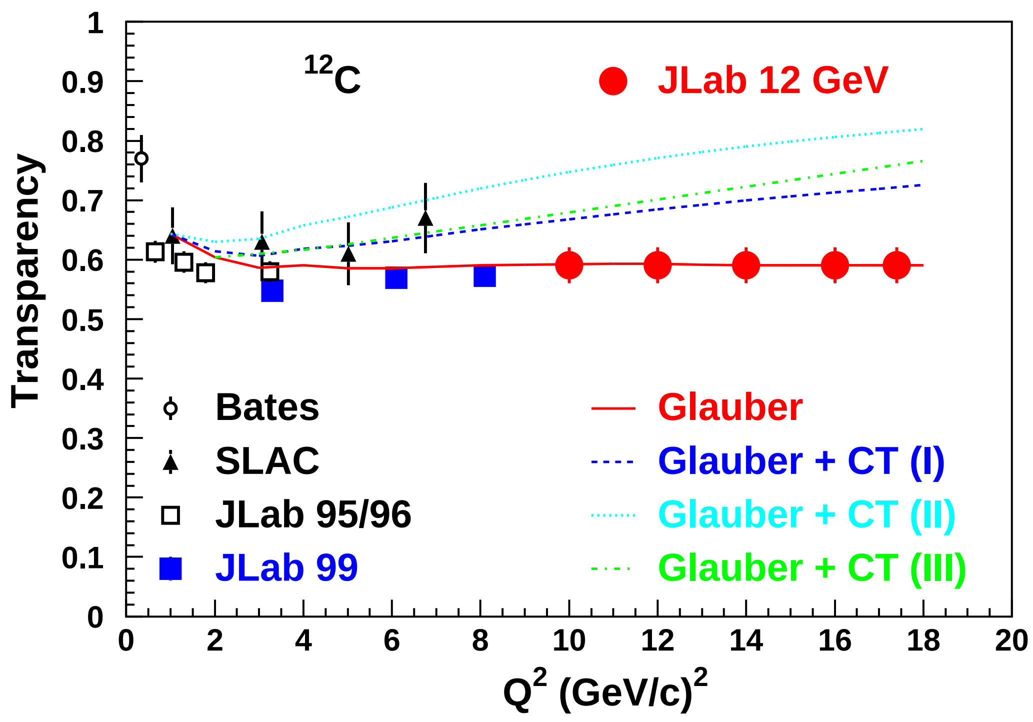
Can be measured directly
in quasielastic A(e,e'p)



Need highest possible Q^2

-Struck nucleon must form
Point-Like Configuration (PLC)

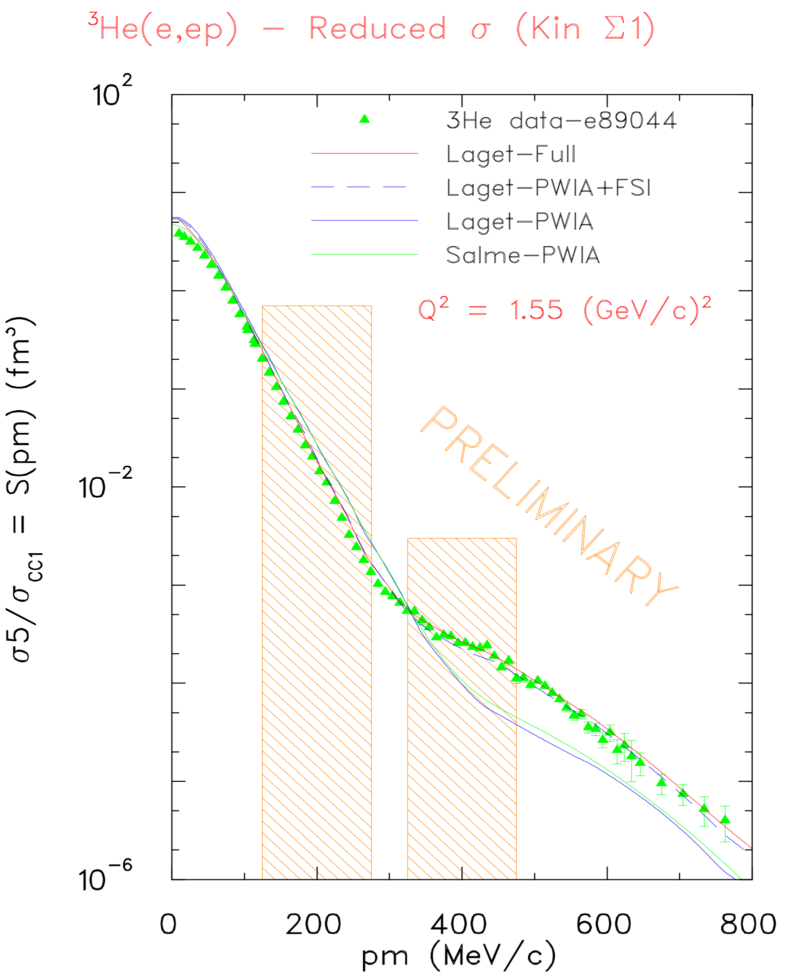
-Want 'slow' evolution of PLC back to proton



+ Relatively clean signal

+ ***Must*** see CT for Q^2~12 GeV^2 if Brookhaven (p,2p) data explained by CT

Can also look for CT in rescattering rather than attenuation

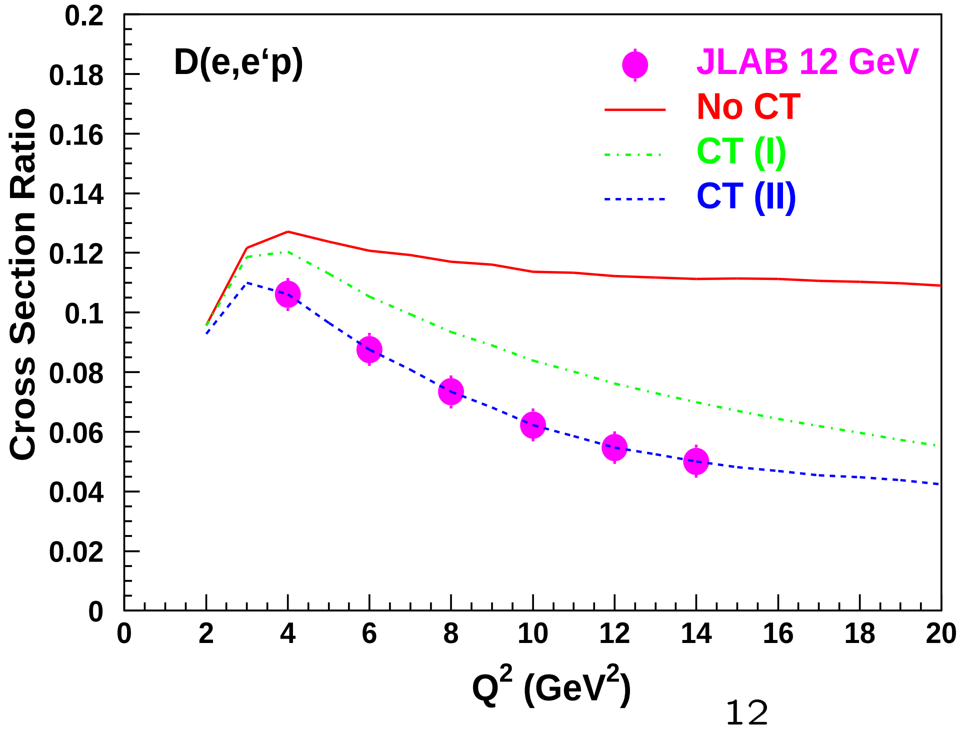


Without rescattering, A(e,e'p) maps out spectral function

Rescattering dominates for large missing momentum

+ Larger signal

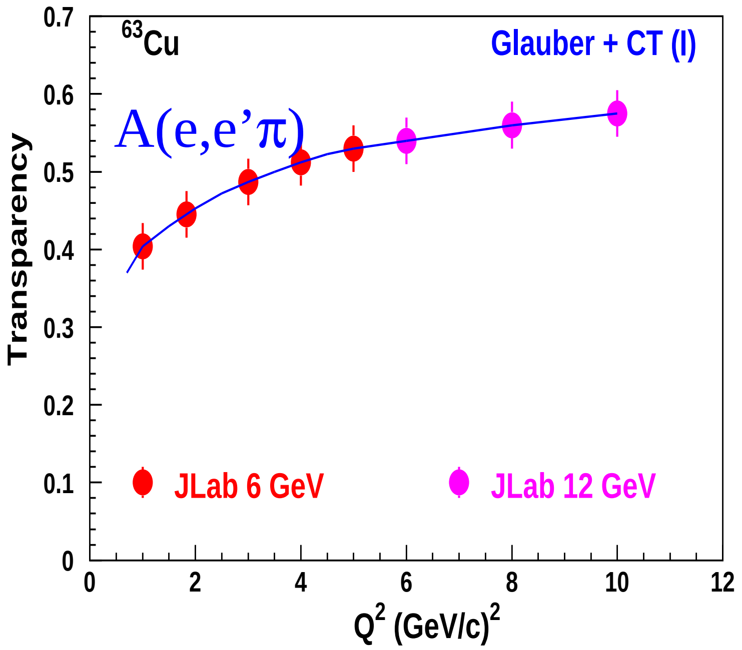
+ Insensitive to PLC evolution

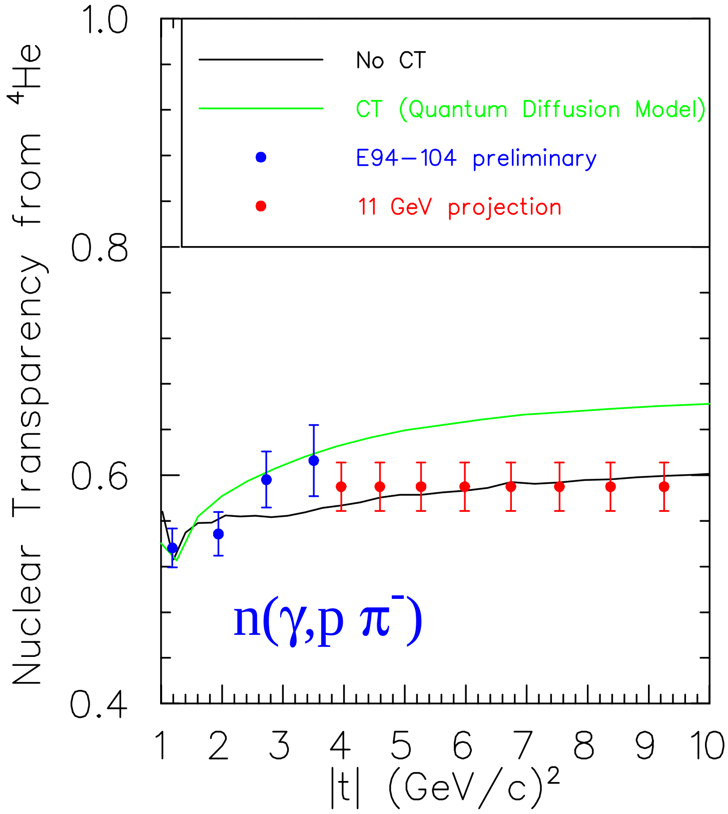


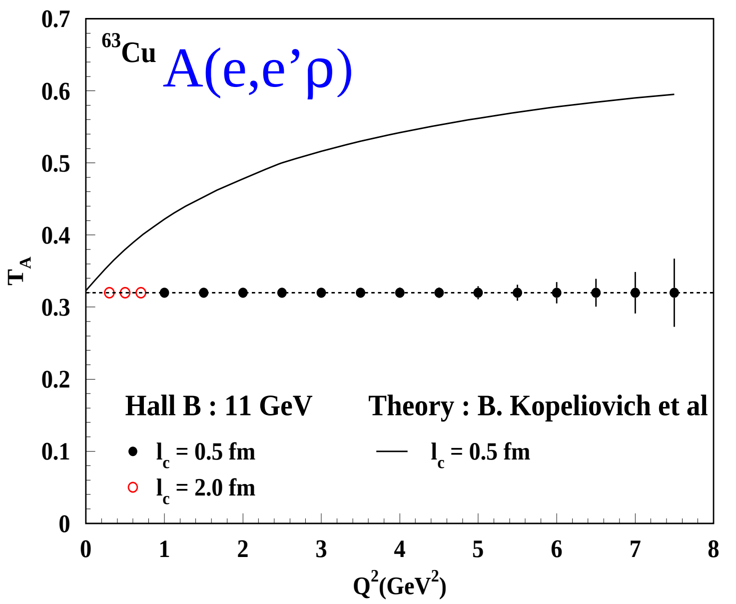
Color Transparency in Meson Production

For two-quark system, formation of PLC should be easier

Direct measurements of meson production





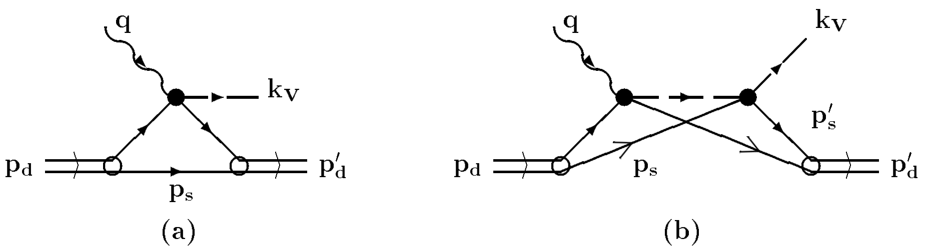


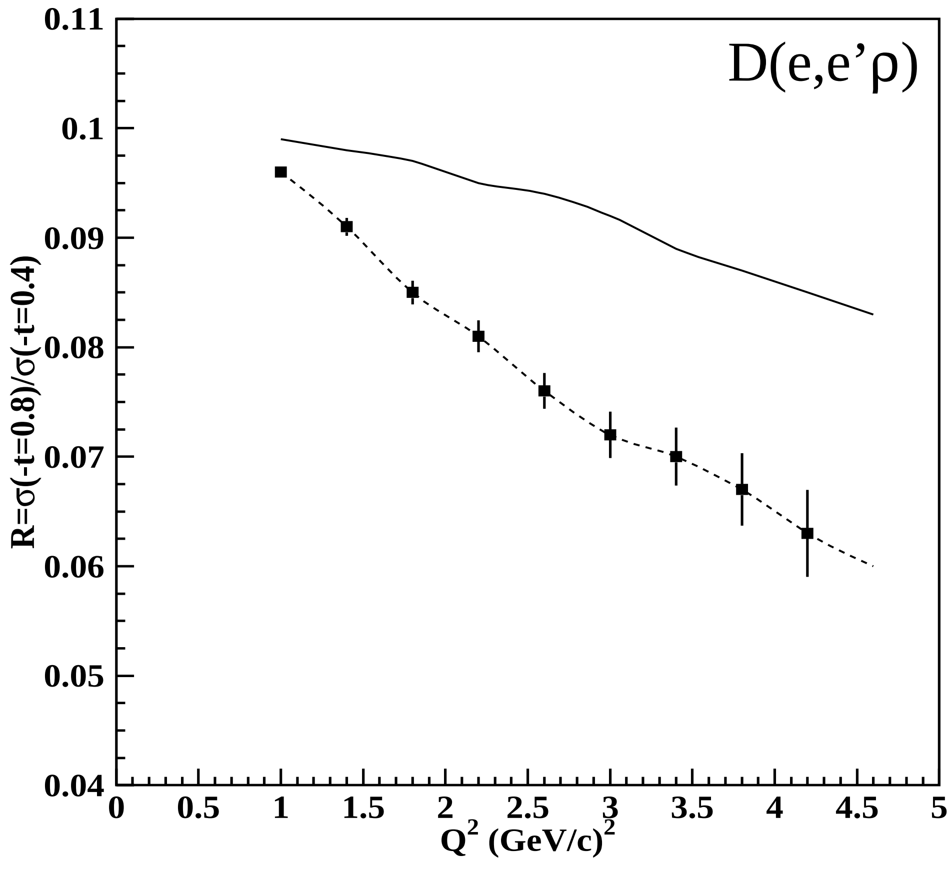
+ Expect PLC formation at lower Q^2

+ Larger signal at moderate Q^2

CT in Meson electroproduction (rescattering)

Meson --> PLC formation is easier
Rescattering --> ~independent of PLC evolution





Combining the different types of CT measurements,
we can try to disentangle the relevent effects:
PLC formation, PLC evolution, Color degrees of freedom

Color Transparency

qqq - Unique to QCD

PLC is not formed (or short lived) at Q^2=8 GeV^2

$q\bar{q}$ - Similar to QED

Expect formation of PLC at lower Q^2

Rescattering measurements (low A) only sensitive to PLC evolution for ~1 fm

Direct A(e,e'p) CT measurements:

Direct test of Brookhaven (p,2p) signal for Q^2>12 GeV^2

Need luminosity and large momentum: Hall C up to 18 GeV^2
Hall A up to 10 GeV^2

A(e,e'p) rescattering measurements:

Need luminosity and large momentum: Hall C up to 14 GeV^2
Hall A up to 10 GeV^2

Direct A(e,e'π) measurements:

Need luminosity and large momentum: Hall C up to 14 GeV^2
Hall A up to 8 GeV^2

Direct pion photo-production:

Want to exceed charm and J/ψ threshold (s ~ 15 and 16 GeV^2)

Need luminosity and large momentum: Hall C up to s=23 GeV^2
Hall A up to s=15 GeV^2

Direct or rescattering A(e,e'ρ^0) measurements:

Reconstruction of rho-meson --> Hall B

J/ψ production

The J/ψ is an unusual particle

- Intrinsically small size c-$\bar{c}$ pair
  - Unusual bound state of QCD
  - Small size --> weaker interaction
    color Van der Waals interaction

- Virtually no charm quarks in nucleons
  - Quark exchange supressed
  - 2-gluon exchange dominates - sensitive to short range effects (e.g.hidden color)

- Exotic effects have been observed at charm threshold
  - Source of 'CT' signature in Brookhaven (p,2p) data?
  - Large asymmetry in double-polarized proton-proton scattering

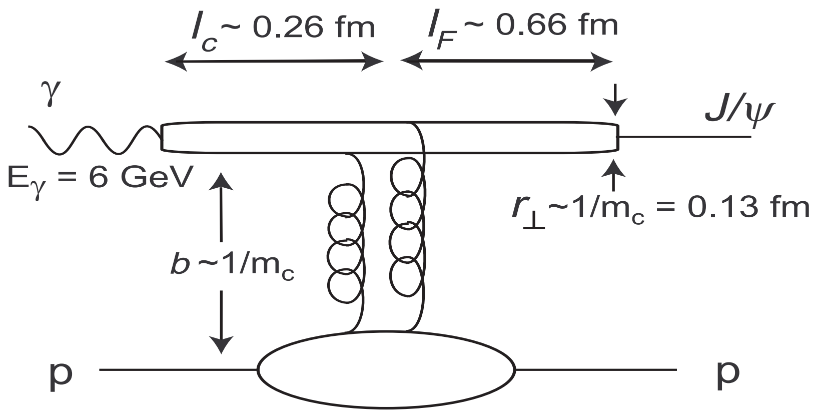
- Important signature of Quark-Gluon plasma

J/ψ production in Nuclei

Small size --> weaker interaction
color Van der Waals interaction

Measure J/ψ production for various nuclei

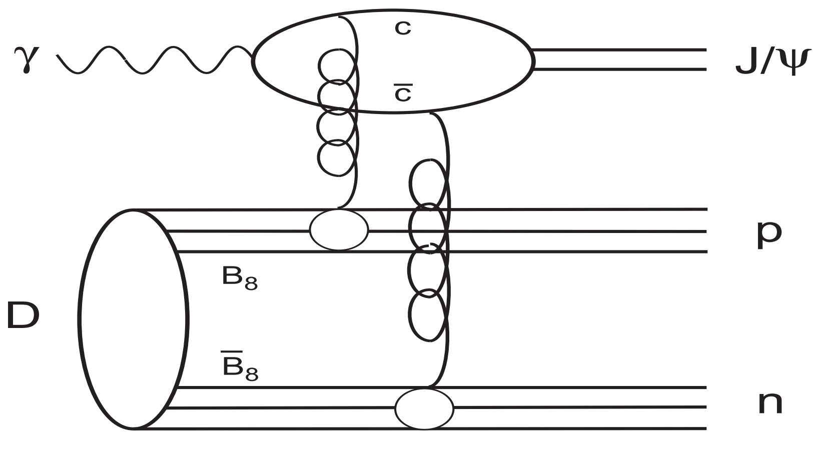
Attenuation --> ψ-N cross section



Small size --> sensitive to short distance effects

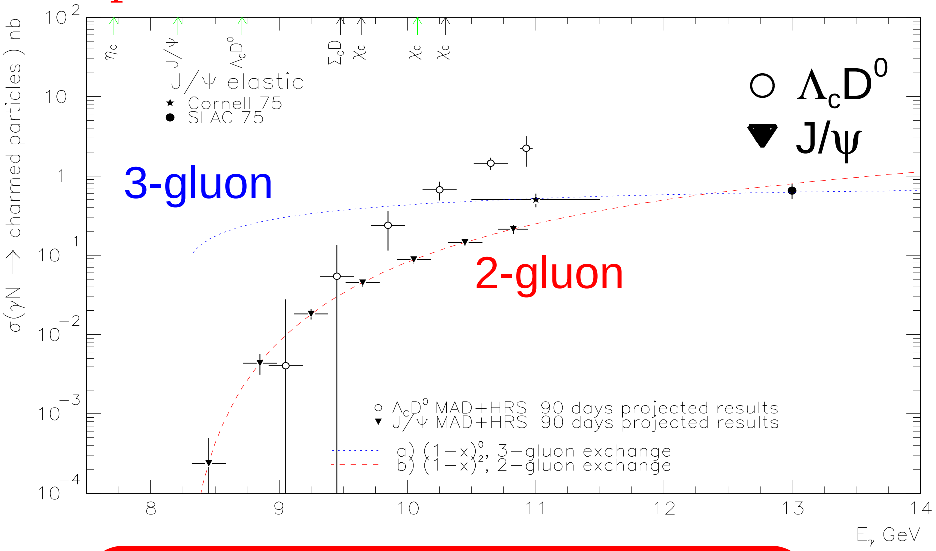
Observe in sub-threshold production from SRC

Probe 'hidden color' in nucleus



J/ψ Production Cross Section

- Study reaction mechanism
- Input for measurements in nuclei



Hall A, 90 days, MAD+HRS
Hall D, 300 days

Sub-threshold J/ψ production

- Probe short range effects, hidden color

6 GeV can (will) be done in Hall C
>6 GeV, Halls A or C

A-dependence of J/ψ Production

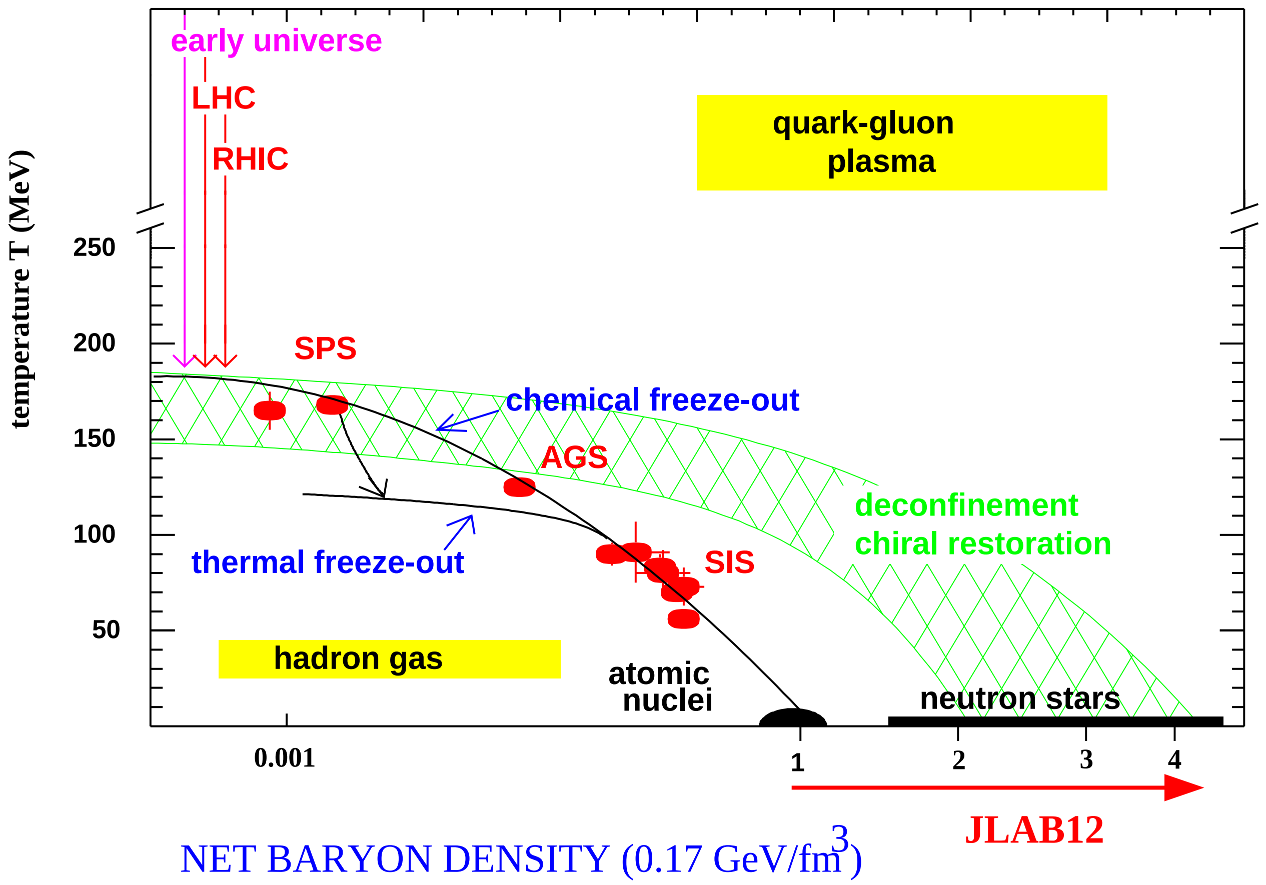
- Extract ψ-N cross section to <20%
- Study color Van der Waals force
- Input to heavy ion physics

Hall A (HRS+MAD)

Larger program of Charm physics

- Some may be possible with HRS+MAD
- More possibilities with dedicated calorimeter

Studies of QCD in Nuclei



Traditional measurements of hadron structure give us the end-result of confinement

Experiments in nuclei open up unique new windows on:

- -Matter at high density
- -Effect of color degrees of freedom (CT, hidden color)
- -Structure of exotic bound states of QCD

This physics has applications to other areas of research:

- -Complements RHIC/LHC studies of QCD at high temperature
- -J/ψ production and attenuation are input to QGP searches
- -Cold, dense matter important for neutron stars/astrophysics