The Nucleus As A QCD Laboratory

G. A. Miller, U. W. Seattle

Outline

QCD View of the Nucleus- made of nucleons

QCD View of Nucleon (structure & shape)-

bound nucleon ≠ free nucleon-not much

EMC effect & Drell Yan DY

Conventional hadron dynamics fails EMC/DY

nuclear modification of nucleon verified

3 models and consequences

Discovery of color transparency(CT) and observation of small size components in pions in the coherent diffraction: $\pi + A \rightarrow jet_1 + jet_2 + A$

Lessons for CT in π and ρ production

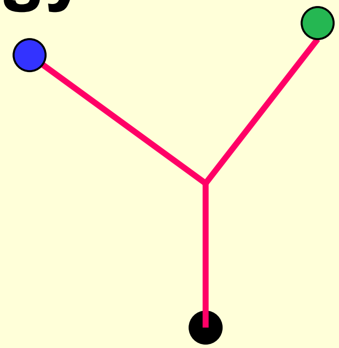
Why is the nucleus the way it is?

- $M(A) = Z\,M_p + N\,M_n$ 0.1% accuracy
- nucleus is made of nucleons
- QCD says quarks and gluons

Puzzle – why?

Strong coupling QCD- SCQCD (Kogut & Susskind) GAMiller PRC39,1563

Leading term - gluon electric field energy~L length of flux line



inert color singlets at rest- small corrections yield Fermi motion, int’s

Finding corrections due to quarks, gluons vital

QCD view of the nucleon

- **vacuum is bubbling cauldron of q $\bar{q}$ pairs**
- **nucleon is color singlet of quarks, gluons**
- **many configurations**
- **size: sometimes small, mostly average, sometimes HUGE**
- **Point Like Configs. PLC don't interact**
- **use nucleus to observe, change fluctuations**

Phenomenological view of nucleon- need relativistic model of free wave function

- 3 quark anti-symmetric
- relative variables, frame independent
- eigenstate of spin operator- rotational invariant
- reduces to non-relativistic if $m \to \infty$

$\Psi = \Phi(M_0^2) u(p_1) u(p_2) u(p_3 = K) \psi(s_i, t_i)$ Terentev, Coester

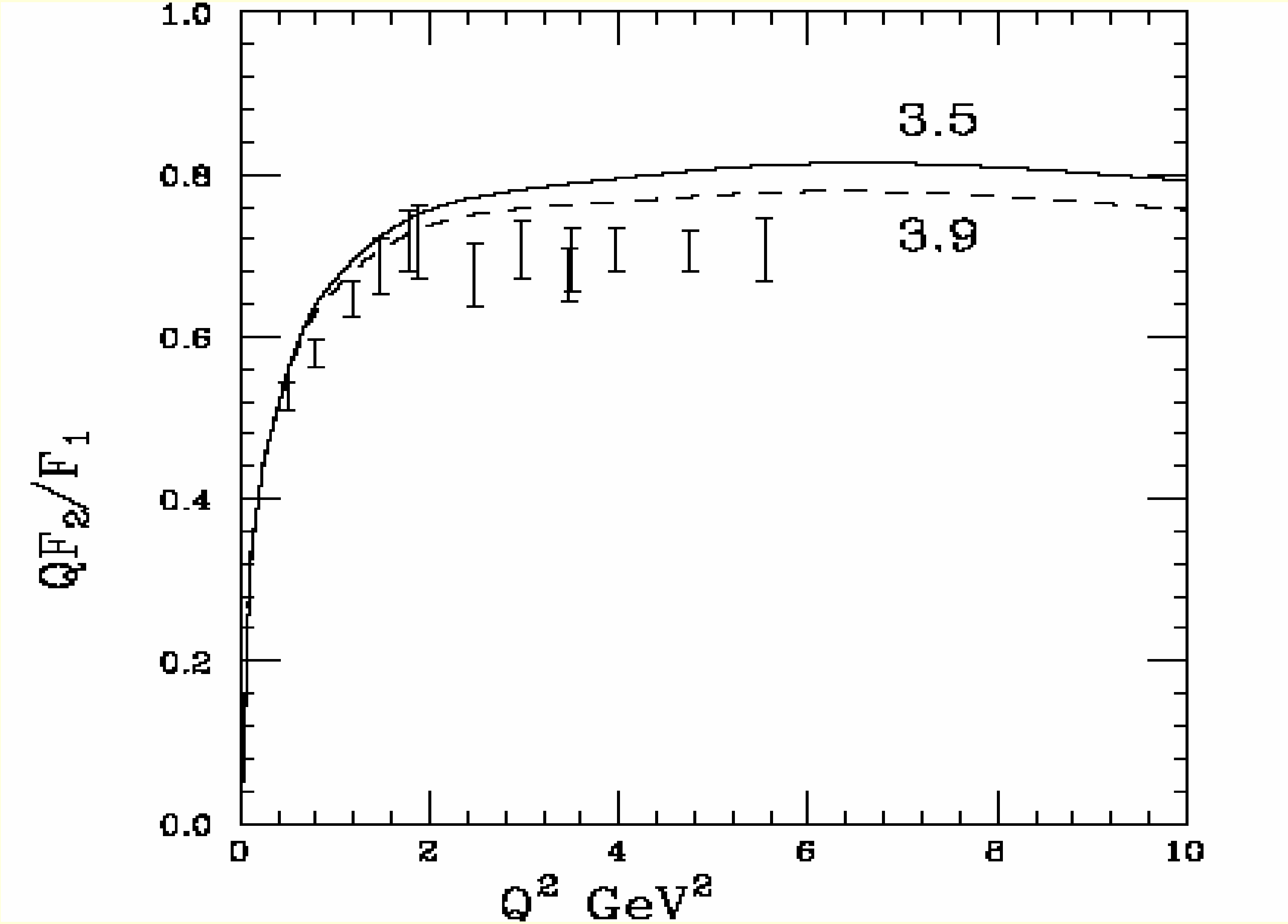
spatial dist DIRAC SPINORS spin-ispin color amp

Schlumpf Mom space wf $\Phi(M_0) = N/(M_0^2 + \beta^2)^\gamma$

$\beta = 0.607$GeV $\gamma = 3.5$ $m = 0.267$ GeV

$M_0^2 = s(p_1, p_2, p_3)$

Ratio: Pauli/Dirac form factors calculation '95 data 2000



Relativistic Explanation-Proton

J^+ acts on third quark, other two have 0 spin

$$u(K,s) = \begin{pmatrix} (E(K)+m)|s\rangle \\ \boldsymbol{\sigma}\cdot\mathbf{K}|s\rangle \end{pmatrix}$$

$\boldsymbol{\sigma}_y|s\rangle$: quark spin $\neq$ proton ang mom

lower components $\equiv L_z \neq 0$

In calculating overlap, K is of order Q

→ Q $F_2/F_1 \approx$ constant

Spin-dependent density

- **Spin dependent densities**

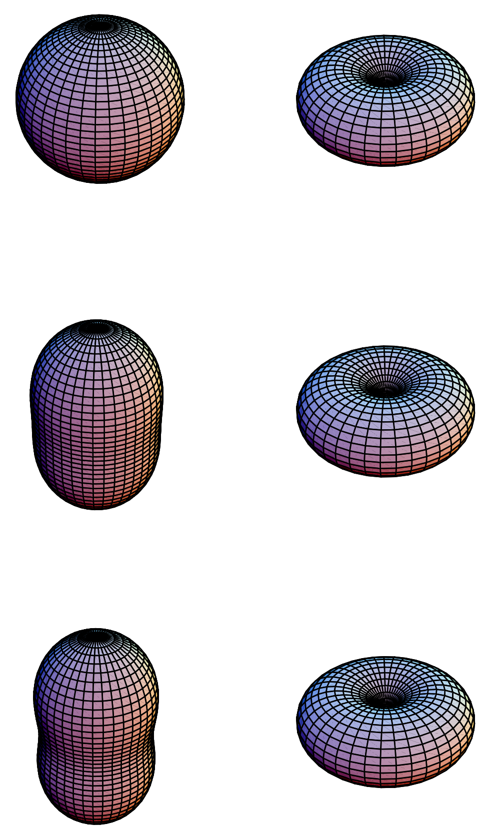
  probability that quark has given momentum K and spin in direction n

$$\hat{\rho}(\mathbf{K},\mathbf{n}) = \int \frac{d^3r}{(2\pi)^3} e^{i\mathbf{K}\cdot\mathbf{r}} \bar{\psi}(\mathbf{r}) \frac{\widehat{Q}}{e} (\gamma^0 + \boldsymbol{\gamma}\cdot\mathbf{n}\gamma_5)\psi(\mathbf{0})$$

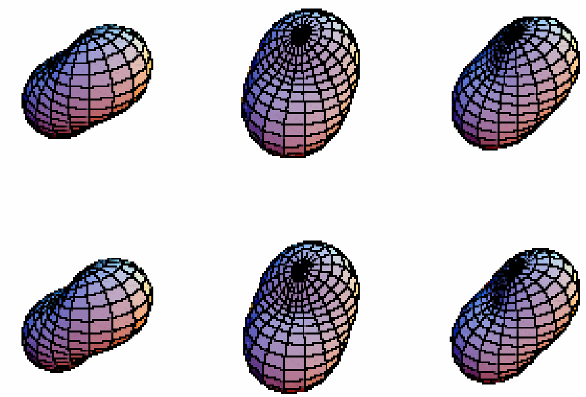
take matrix elements in proton at rest

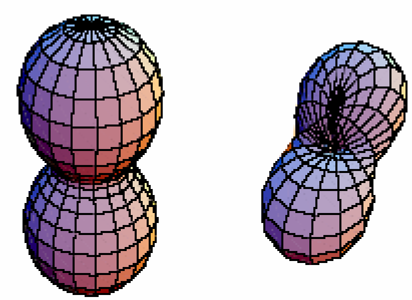
Shapes of the proton

n parallel **-n parallel**



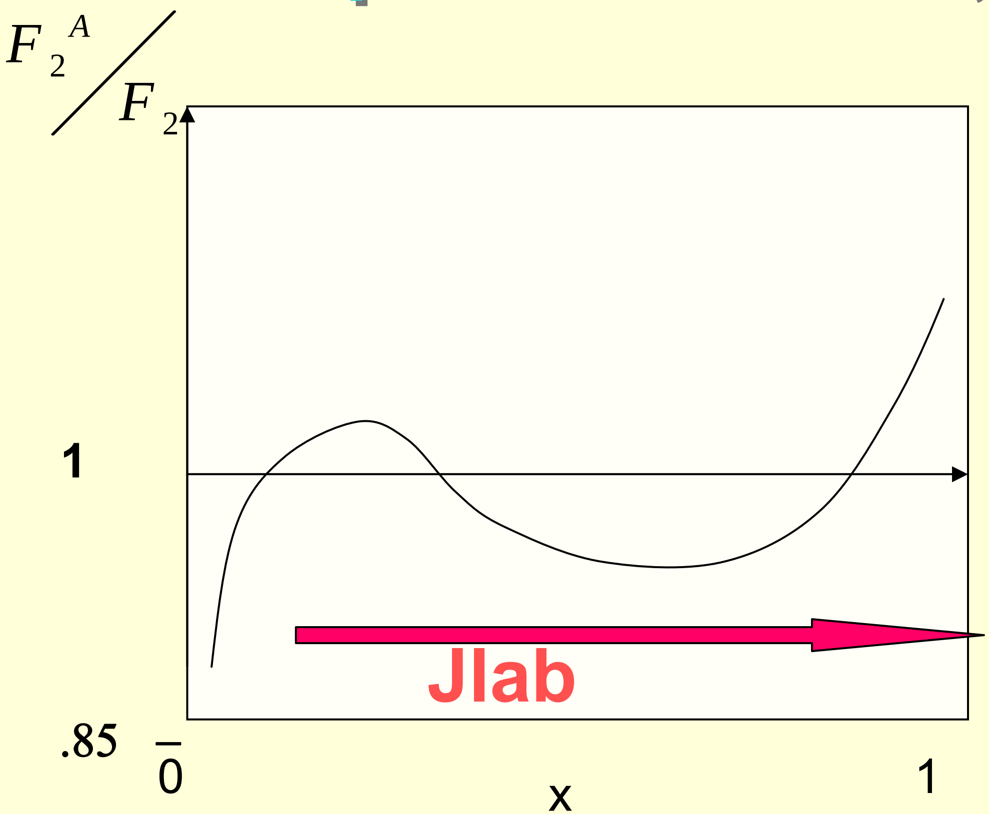
n out





lattice calculations- Negele looking

Deep Inelastic **Nuclear** Scattering Experiments EMC,SLAC,NMC



$$\frac{F_2^A(x)}{AF_2^N(x)} = 1 + g_{F_2}(x)\mathcal{G}(A)$$

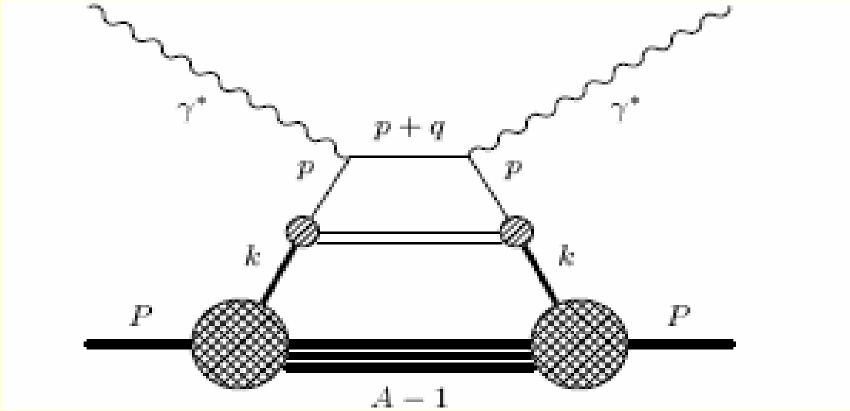
Chen Detmold '05

Bruell

Nucleon structure is modified: valence quark momentum depleted, sea or gluon enhanced. **How do quarks work in a nucleus?**

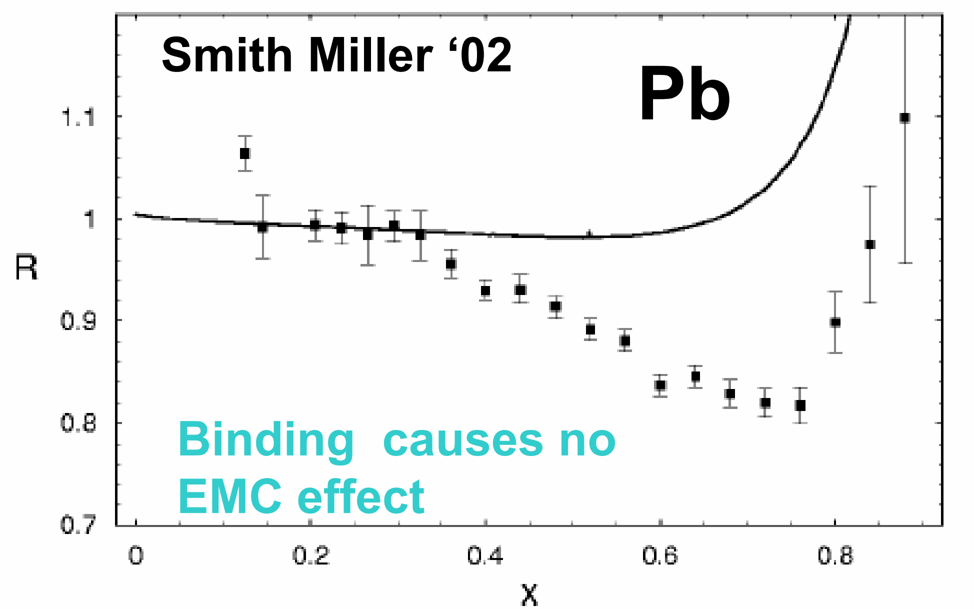
EMC – "Everyone's Model is Cool (1985)

Deep Inelastic scattering from nuclei-nucleons only free structure function



$$\frac{F_{2A}(x_A)}{A} = \int_{x_A}^{A} dy f_N(y) F_{2N}(x_A/y)$$

$y = A\, k^+/P^+$



SLAC-E139

- Hugenholz van Hove theorem nuclear stability implies (in rest frame) $P^+ = P^- = M_A$
- $P^+ = A(M_N - 8\text{ MeV})$
- average nucleon $k^+ = M_N - 8$ MeV, y → 1

$F_{2A}/A \sim F_{2N}$ no EMC effect

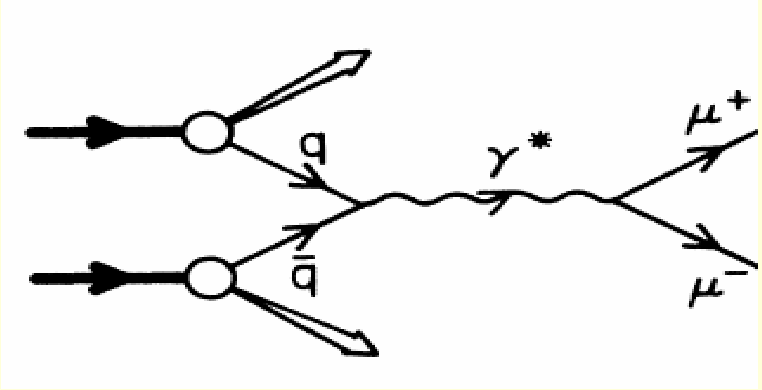
Nucleons and pions

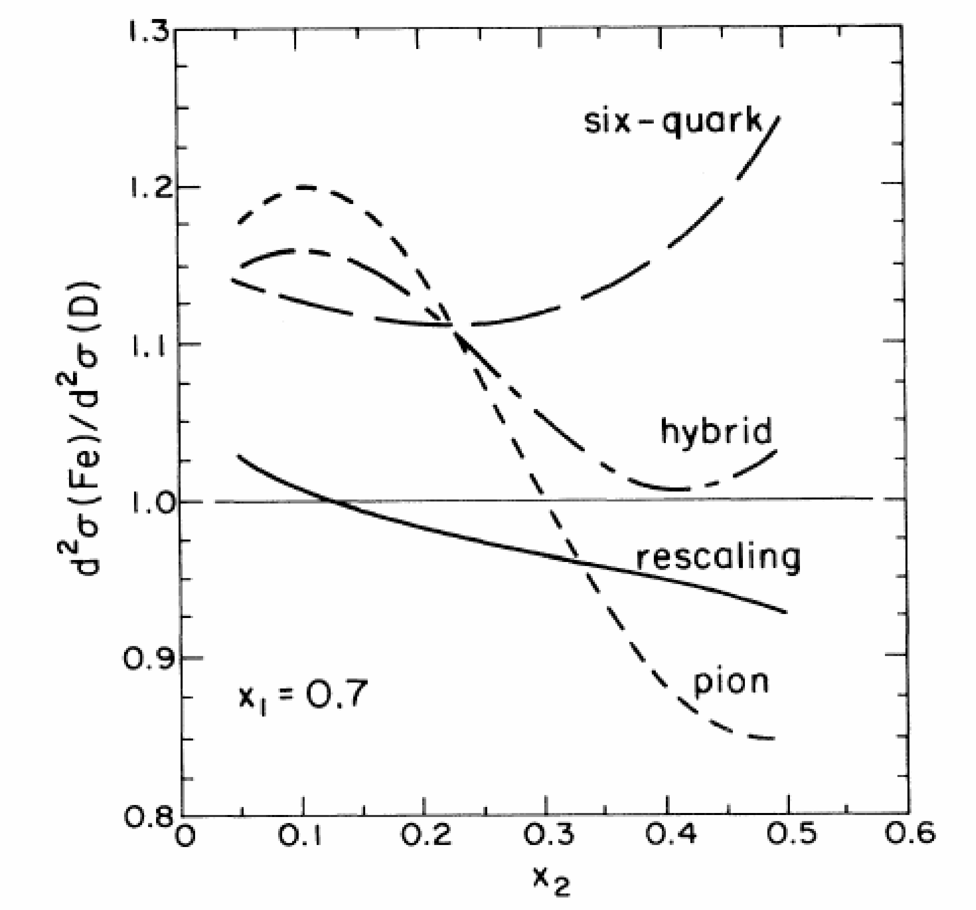
$P_A^+ = P_N^+ + P_\pi^+ = M_A$

$P_\pi^+ / M_A = .04$, explain EMC

try Drell-Yan, **Bickerstaff, Birse, Miller 84**

proton(x_1) nucleus(x_2)



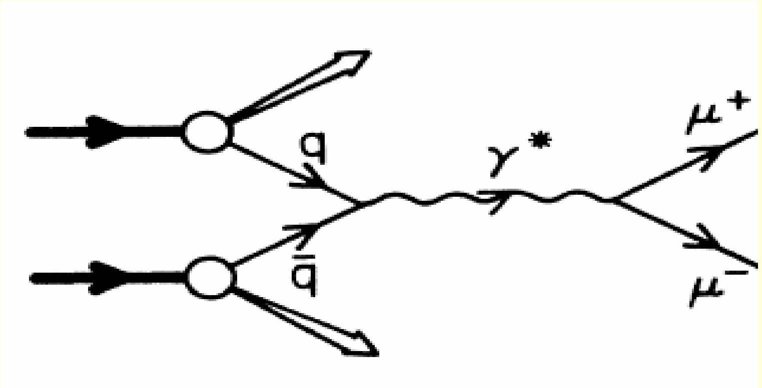


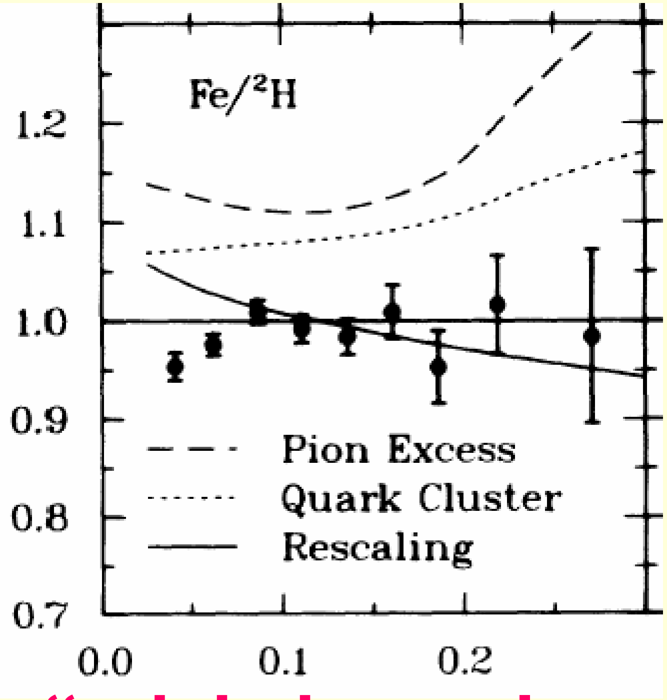
Nucleons and pions

$P_A^+ = P_N^+ + P_\pi^+ = M_A$

$P_\pi^+ / M_A = .04$, explain EMC

Drell-Yan, E772





No one's model is cool

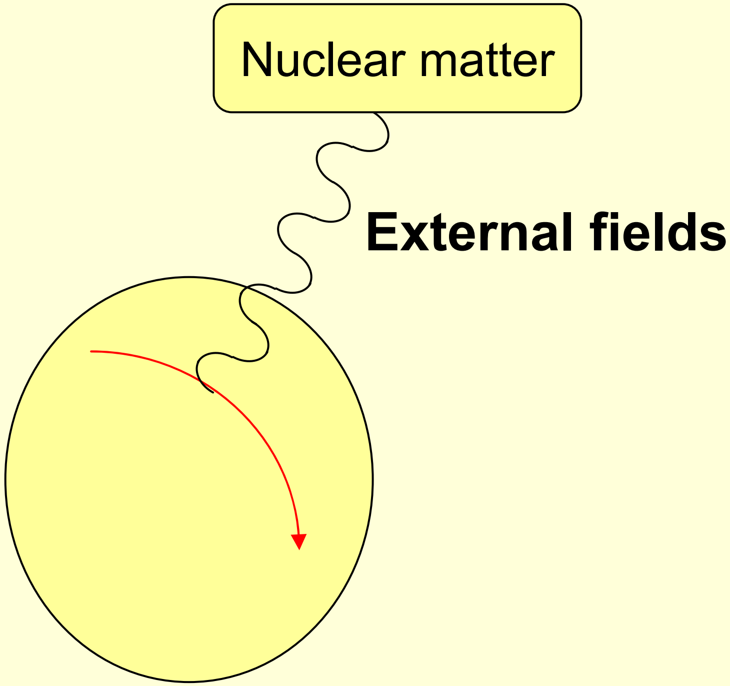
π fails

Bertsch, Frankfurt, Strikman "crisis in nuclear theory" conventional physics does not work

Conventional n
does not expla

- **It's ~ easy to explain one or the other**
- **Intrinsic structure of nucleon is changed**
- **start with models-requirements**
- **Model free distributions (valence, sea, support)**
- **Consistency with nuclear properties**
- **Describe deep inelastic and di-muon production data- valence plus sea**
- **Predict new phenomena based on medium modified nucleons**

Nucleon in medium- 3 models



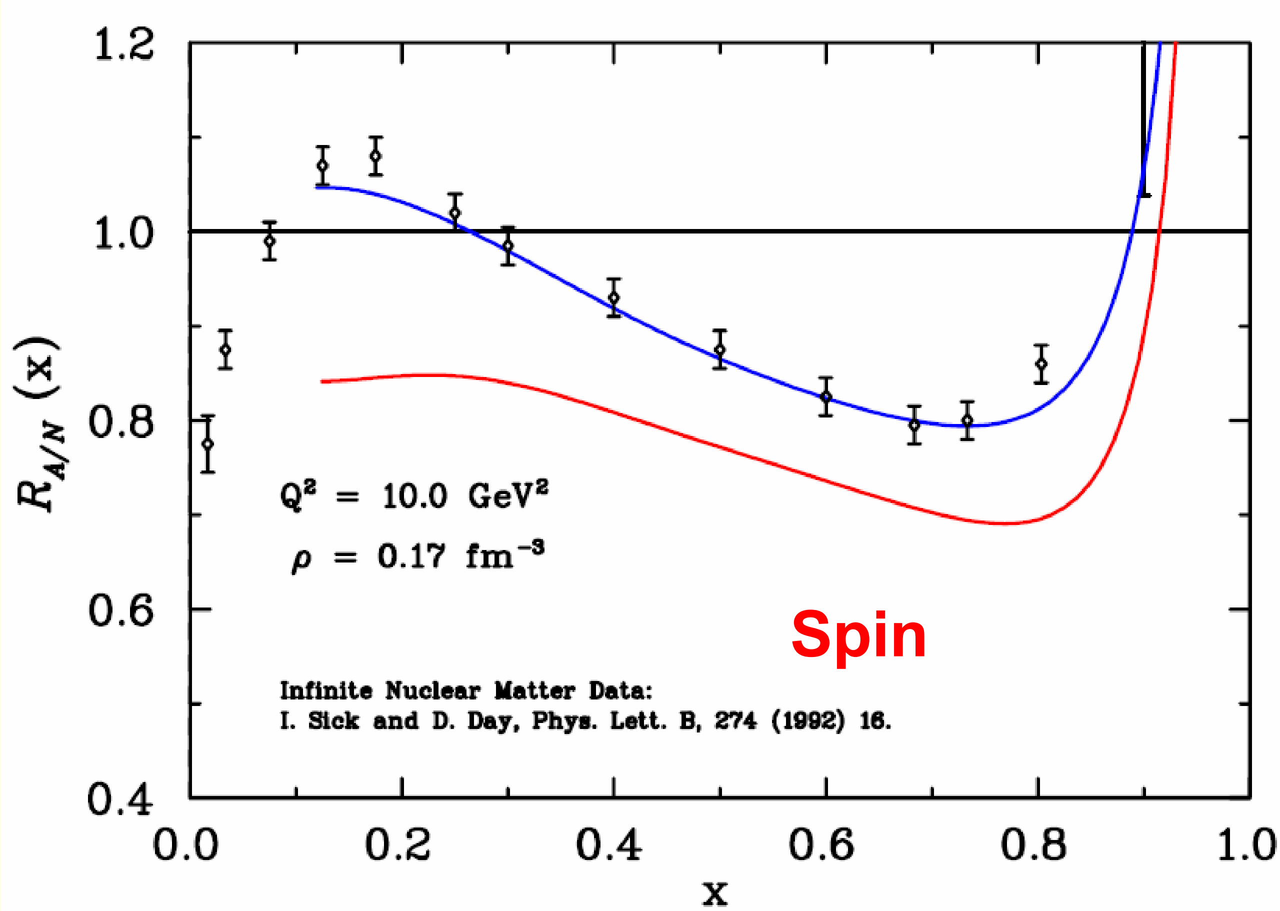
1. QMC- quarks in nucleons (MIT bag, NJL) exchange mesons with nuclear medium
2. CQSM- quarks in nucleons (soliton) exchange infinite pairs of pions, vector mesons with nuclear medium, sea
3. Suppression of point-like-configurations
   Frankfurt, Strikman

Spin experiments enhance EMC?

- g_{1n}, g_{1p} in nuclei   Bentz, Cloet, Thomas

ratio of g_1 medium to free

Infinite Nuclear Matter



Quark Soliton Model –

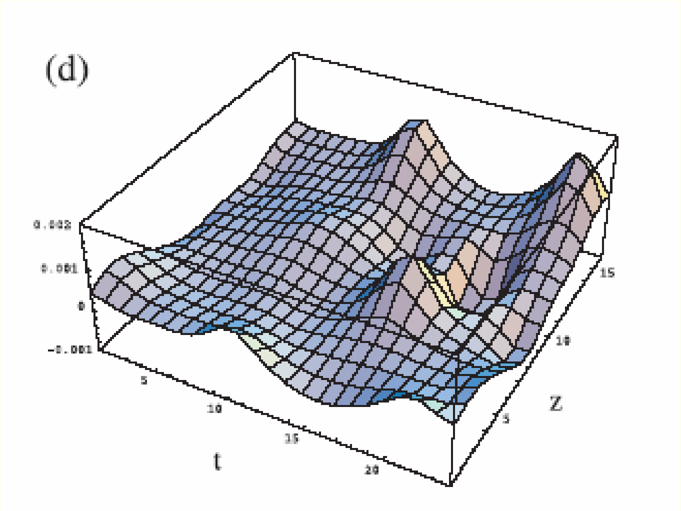
Diakonov, Petrov, Polykov, Gamberg, Weigel

- Instanton dominated vacuum
- quarks with spontaneously generated masses interact with pions

$$\mathcal{L}_{\rm eff} = \bar{q}\;\left[i\partial\!\!\!/ - M\exp(i\,\gamma_5\,\pi^A\lambda^A/F_\pi)\right]\;q,$$

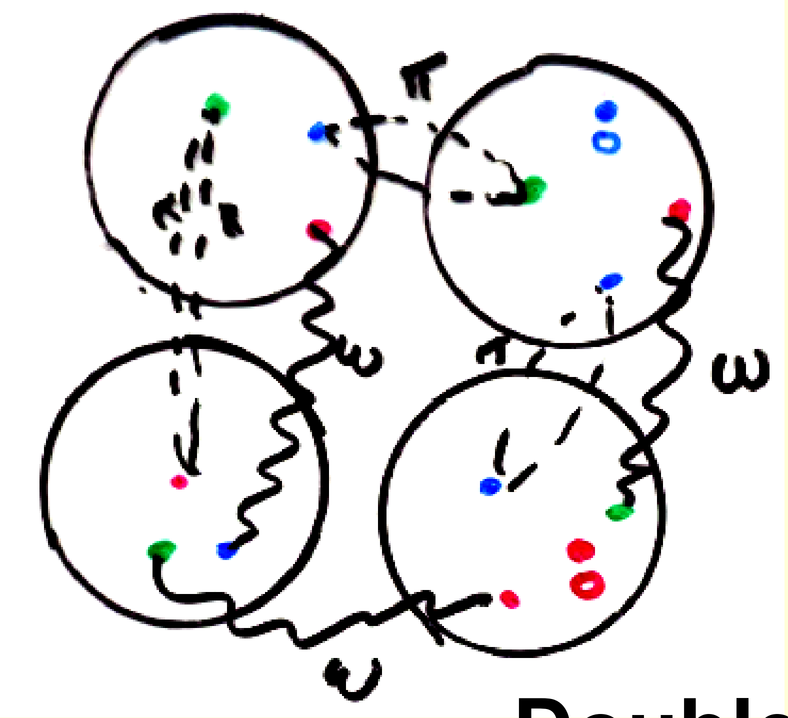
- Nucleon is soliton in pion field π(r)
- M=420 MeV
- good nucleon properties, distribution functions rest and infinite momentum frames

Negele et al hep-lat/9810053 topological charge density



Chiral Quark Soliton Model of Nucleus-

Smith, Miller



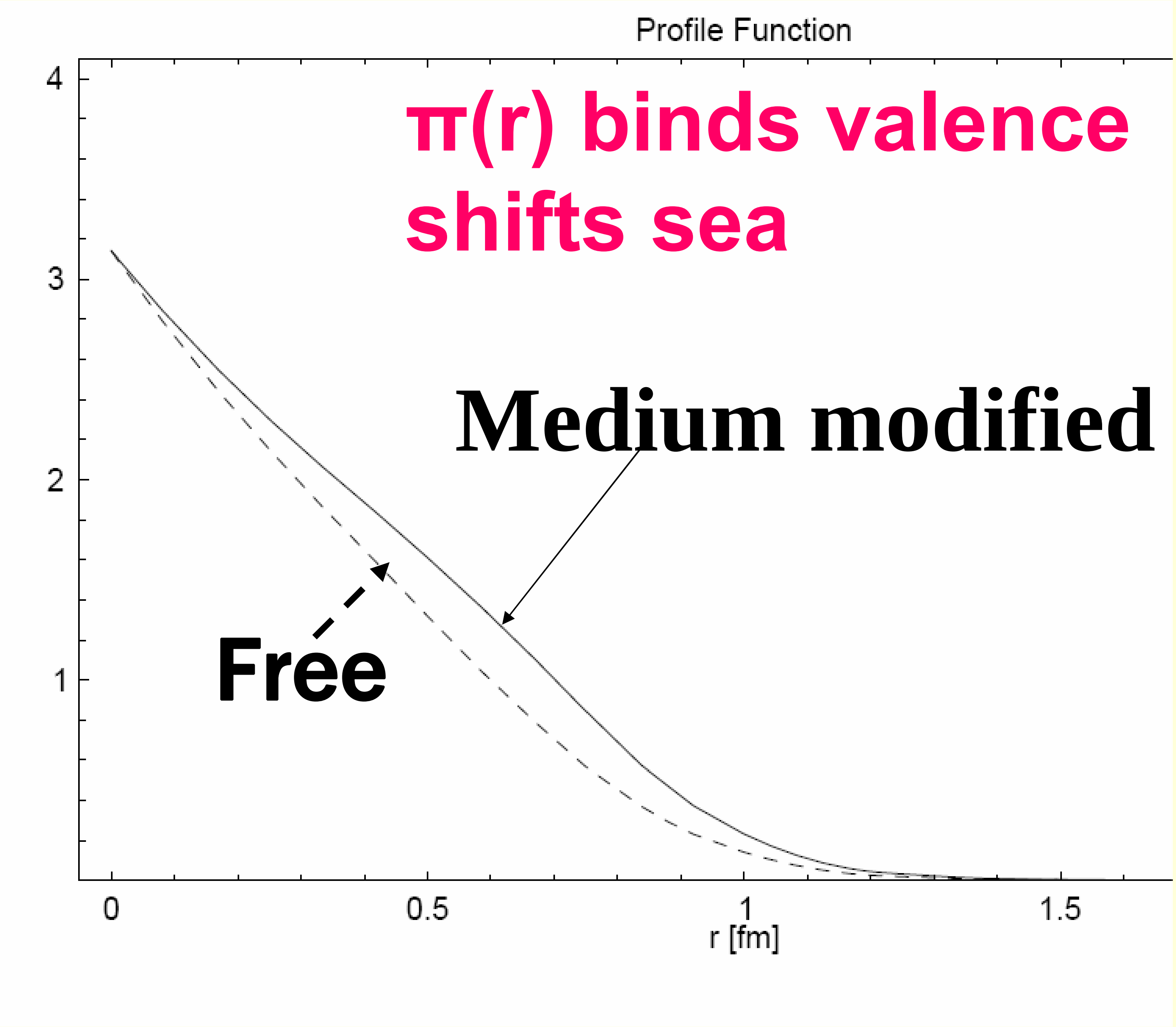
2 π exchange – attraction

ω (vector meson) exchange - repulsion

Double self consistency

profile function and k_f →

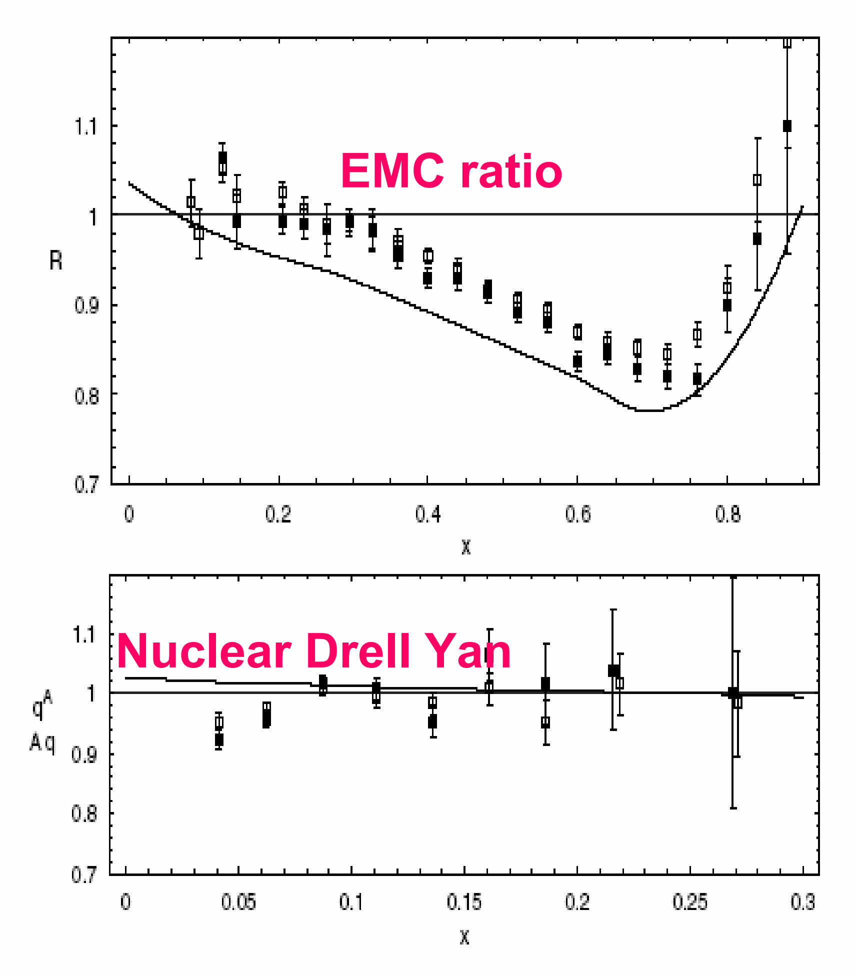
good nuclear saturation

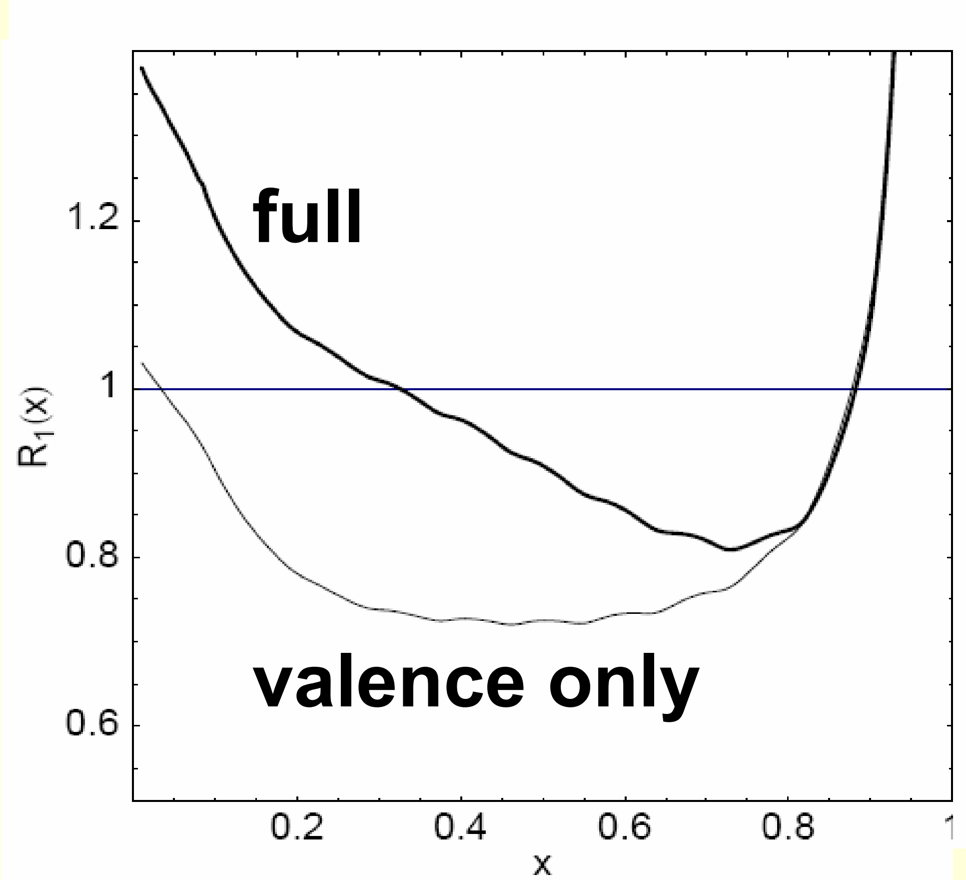


Profile Function
π(r) binds valence shifts sea
Medium modified
Free
0
1
2
3
4
0.5
1.5
r [fm]

Results Smith & Miller '03,04,05

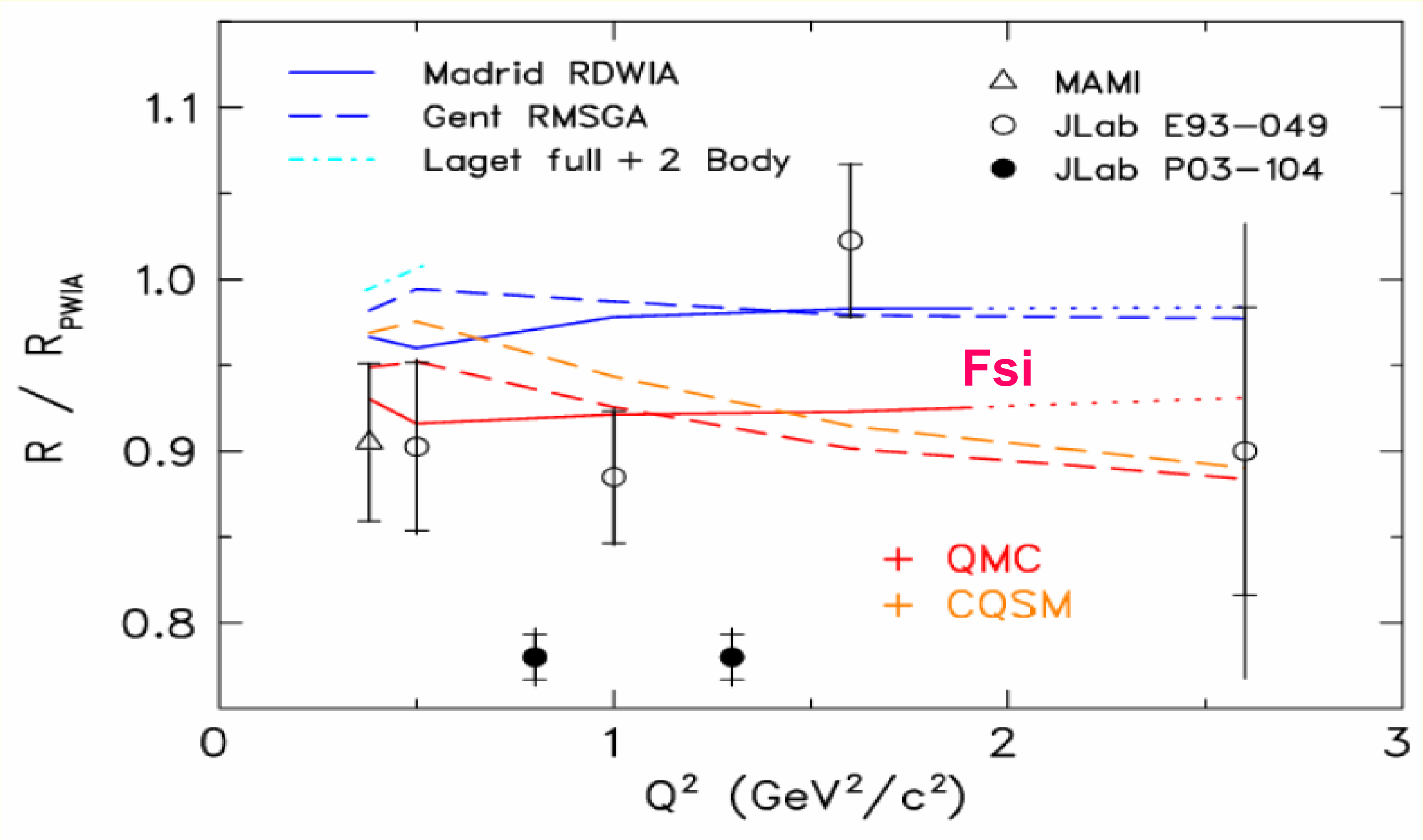
g_1 ratio



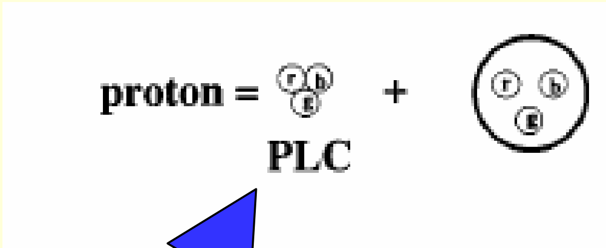


sea is not much modified

Polarization transfer in ^{4}He(e,e'p) Nucleon form factors in medium – G_E/G_M ratios Strauch

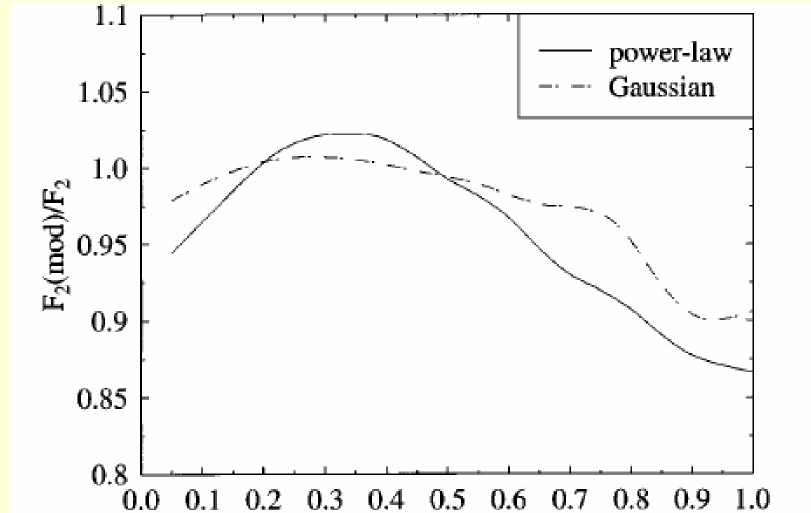


Suppression of Point Like Configurations

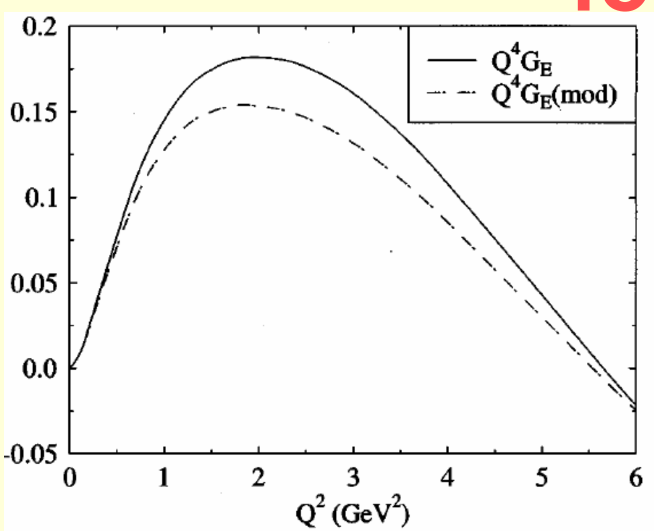


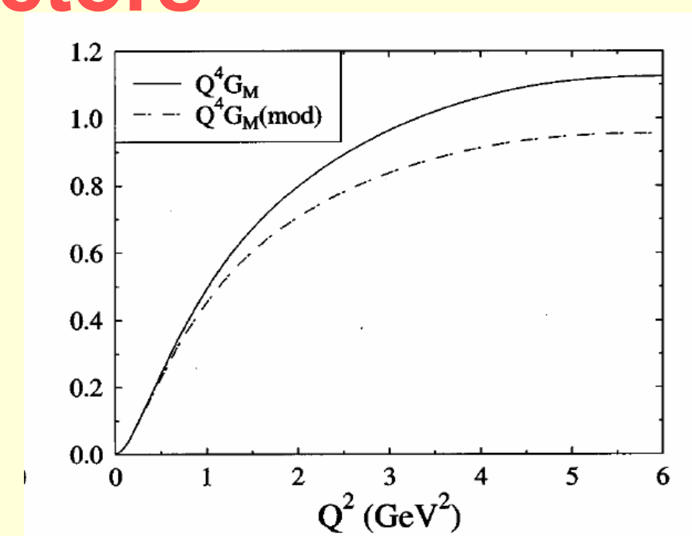
suppressed

DIS



form factors

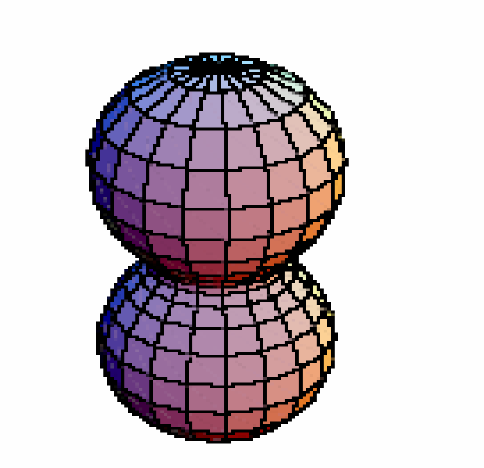




Medium modified form factors - Challenge:

- Should be there in any model- how to really nail it experimentally ???

  high accuracy data, independent assessment of FSI



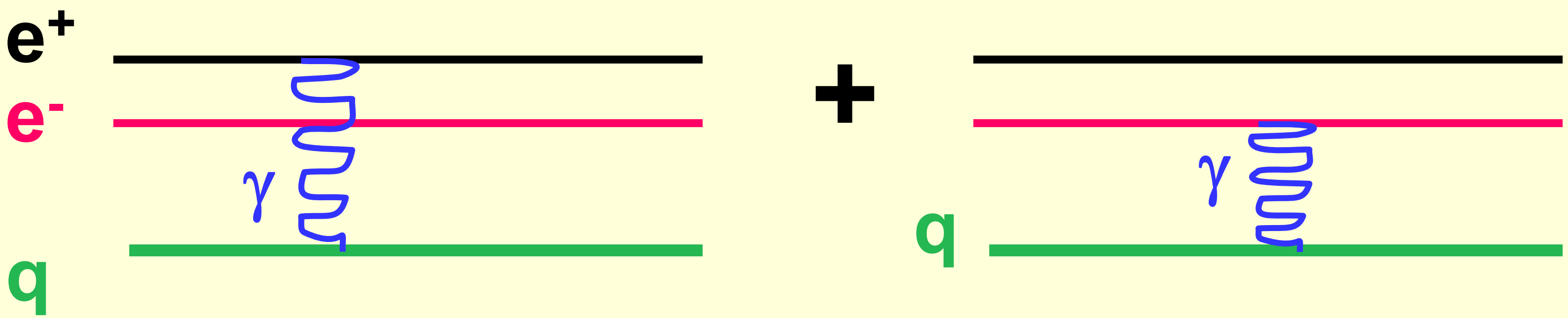
Suppression of PLC in reactions – Color Transparency

Reduced initial, final state interactions in high Q^2 quasielastic nuclear reactions (p,pp),(e,e'p), (e,e',π), (π +A →jet +jet +A, FermiLab)

WHY?

1. high Q^2 hadronic exclusive reactions proceed by PLC formation-Brodsky, Mueller '82
2. PLC have small scattering amplitudes-gluon emission amplitudes cancel- coherent
3. PLC expands as it moves
   Jennings & Miller '90,'91

Charge neutrality and coherence



Same final state exclusive:

$V = e\,q/r_+ - e\,q/r_- = e\,q\,(r_- - r_+)\,/\,(r_+\,r_-)$ dipole

COHERENCE –does your experiment maintain coherence?

Strong int'n- two gluon exchange → dipole2

inclusive - square amplitudes first then add,

no cancellation

Gluonic strong interaction

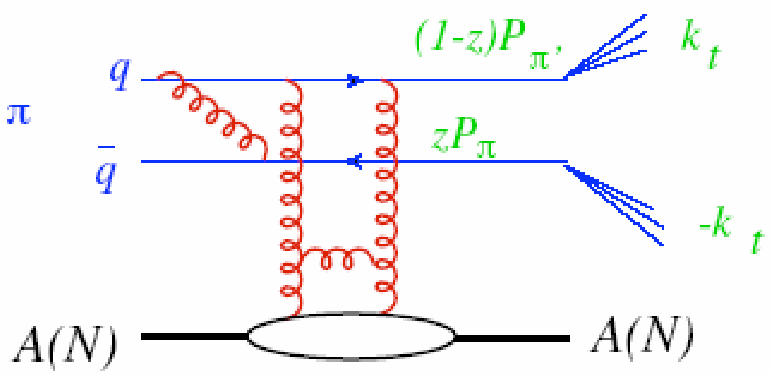
$\sigma = C\ d^2$

λ/d^2 ~ sometimes called Q^2_{eff}

$\pi + N(A) \to$ "2 high p_t jets" $+ N(A)$

Mechanism: Pion approaches the target in a frozen small size $q\bar{q}$ configuration and scatters elastically via interaction with $G_{target}(x, Q^2)$.

- First attempt of the theoretical analysis of πN process - Randa 80 - power law dependence of p_t of the jet (wrong power)
- First attempt of the theoretical analysis of πA process - Brodsky et al 81 - exponential suppression of p_t spectra, weak A dependence ($A^{1/3}$)
- pQCD analysis - Frankfurt, Miller, MS 93; elaborated arguments related to factorization 2003



a dominant term

1993 predictions Frankfurt, Miller, Strikman

M(A) =A $e^{t\,R(A)}$ M(N) , σ(A)~$A^{4/3}$ + O(1/k^2) ~$A^{1.55}$

$$\frac{d\sigma(z)}{dz} \propto \phi_\pi^2(z) \approx z^2(1-z)^2 \text{ where } z = E_{jet_1}/E_\pi.$$

k_t dependence: $\frac{d\sigma}{d^2k_t} \propto \frac{1}{k_t^n}, n \approx 8$ for $x \sim 0.02$

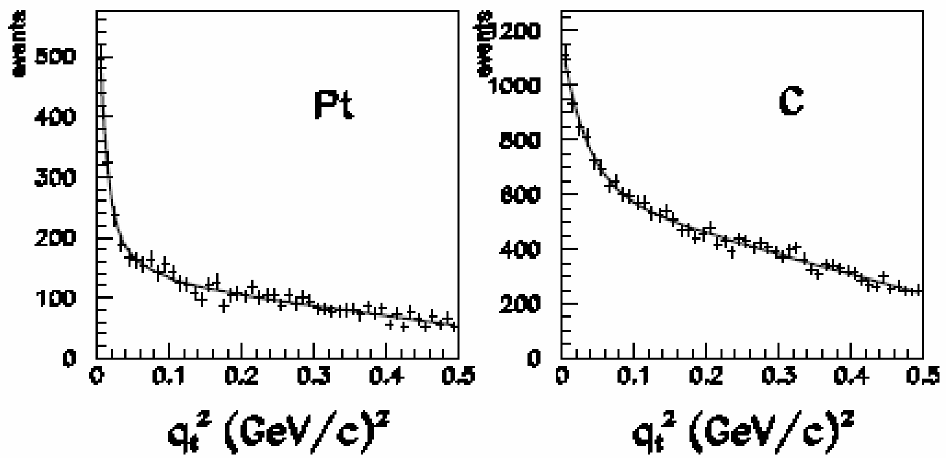
k_t>1.5 GeV/c

Naive expectation M(A)~ $A^{1/3}$ (nuclear path length), inelastic diffraction FMS93: M(A)~ $A^{.7}$

E791 results

The E-791 (FNAL) data $E^{\pi}_{inc} = 500 GeV$ (D.Ashery et al, PRL 2000)

♡ Coherent peak is well resolved:



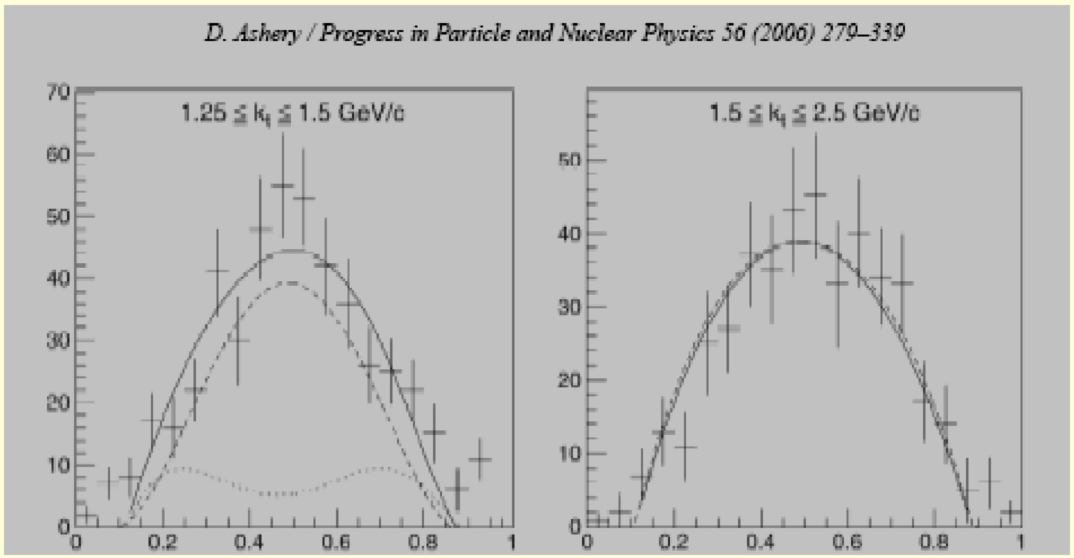
♡♡ Observed A-dependence $A^{1.61 \pm 0.08}$ $[C \rightarrow Pt]$

FMS prediction $A^{1.54}$ $[C \rightarrow Pt]$ for large k_t & extra small enhancement for intermediate k_t.

For soft diffraction the Pt/C ratio is $\sim$ 7 times smaller!!

More E791

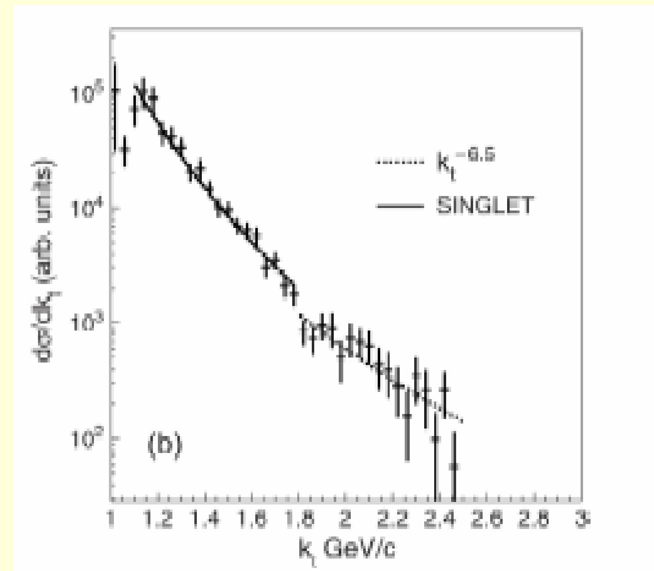
z dependence



z z

Consistent with $(z(1-z))^2$

k_t dependence



$d\sigma/dk_t \sim k_t^{-7}$ theory

E791 summary

- Color transparency discovered
- seen clearly for k_t=1.8,2.3 GeV/c
- corresponds to Q^2=3.2, 5.3 GeV^2
- p_π is large –no expansion
- small effects at Jlab6 should be strong signals at Jlab12

Color Transparency in π reactions

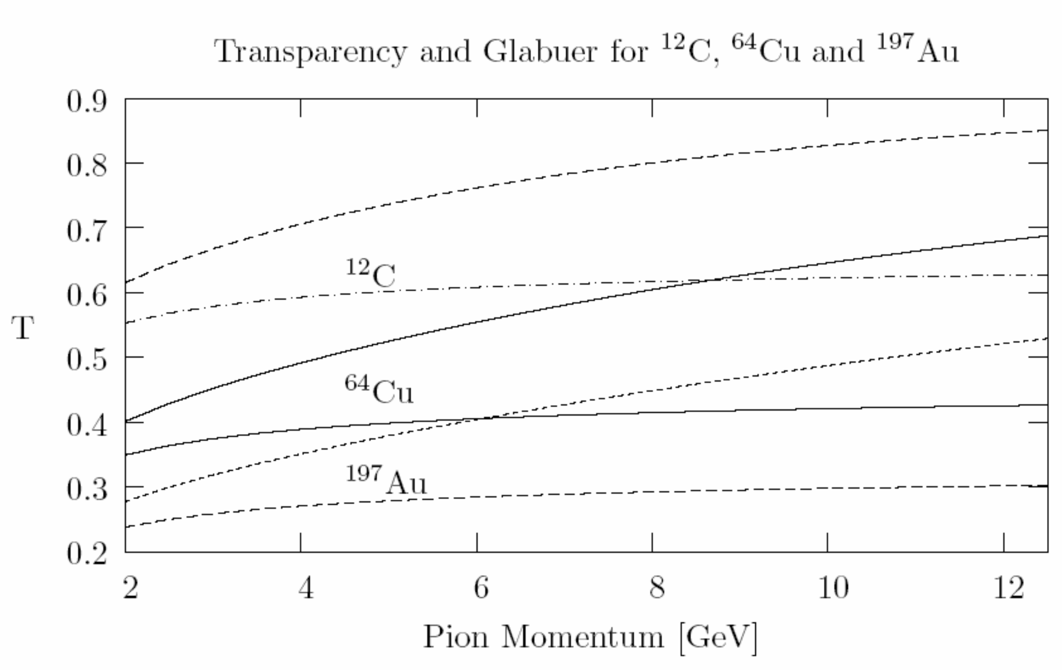
- (e,e’ π) – hope to make pionic PLC
- normal sized pion does not interact with PLC hadron-chiral transparency

  PRC 55,909 (97) Lee + FMS
- consequence: point like “ρ” configurations do not decay to two π

Pion color transparency Jlab 6,12

(e,e’, π): γ^* makes pion PLC (expands)

E01-107



Larson, Miller, Strikman ’06

Good at 6 (theory ~ data), better at 12

Summary

- nucleon structure is modified by nucleus
- minimum model requirements- EMC, DY, nuclear saturation
- predict new phenomena
- needed –experimental tests –form factors in medium, (eA →e’ X N) spectator tag BONUS
- color transparency for mesons!

Remainder are spares

QCD view of Nucleus?

- Kinetic energy via meson cloud flux tube breaks

- Interactions by meson exchange

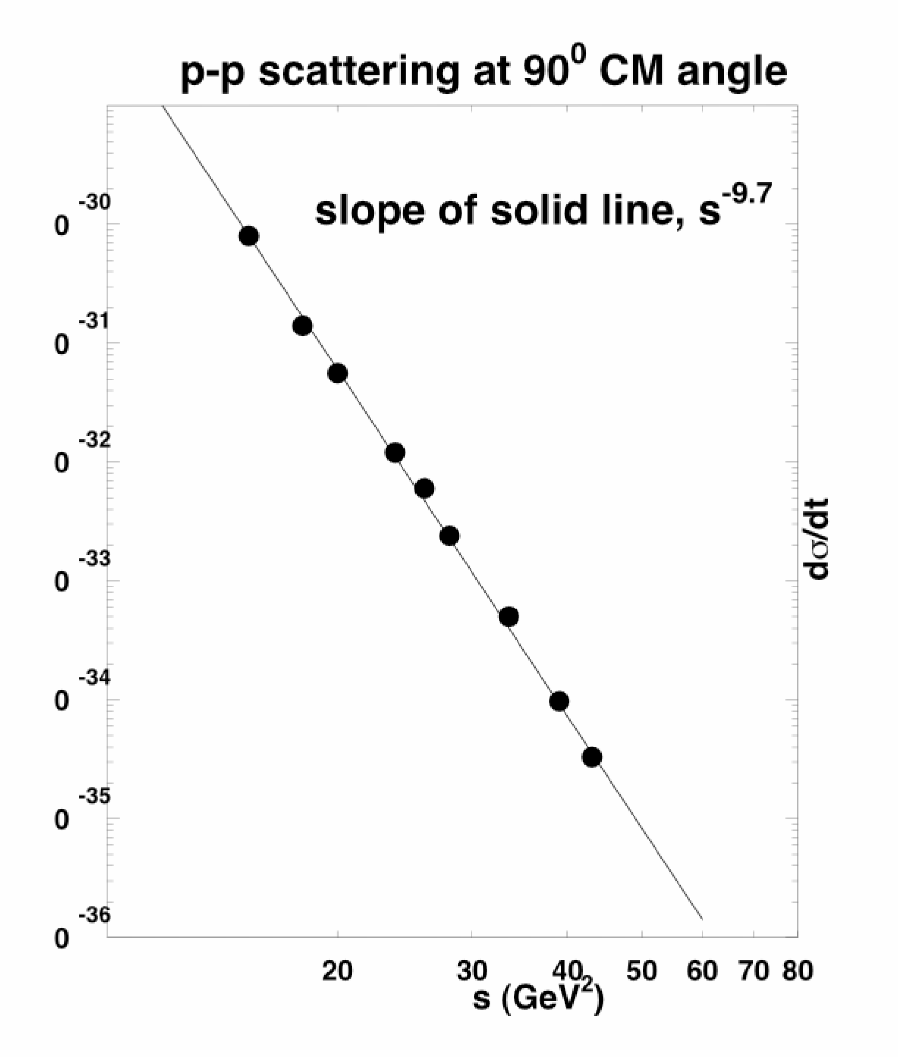
confinement, flux string, color singlet clusters

leading order: inert nucleons sit

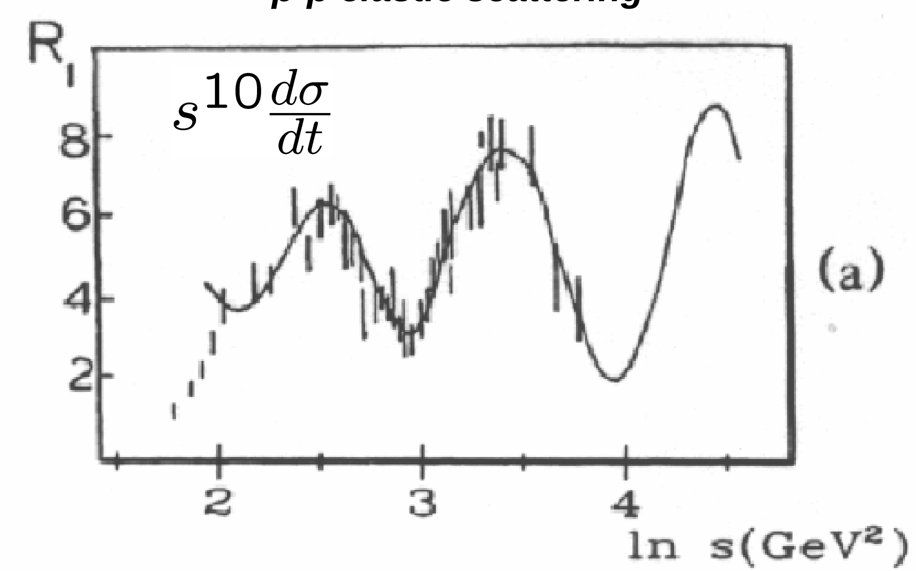
SCQCD → meson exchange model of nuclei, GAM PRC39,1563

quark, gluon effects hard to find, but vital

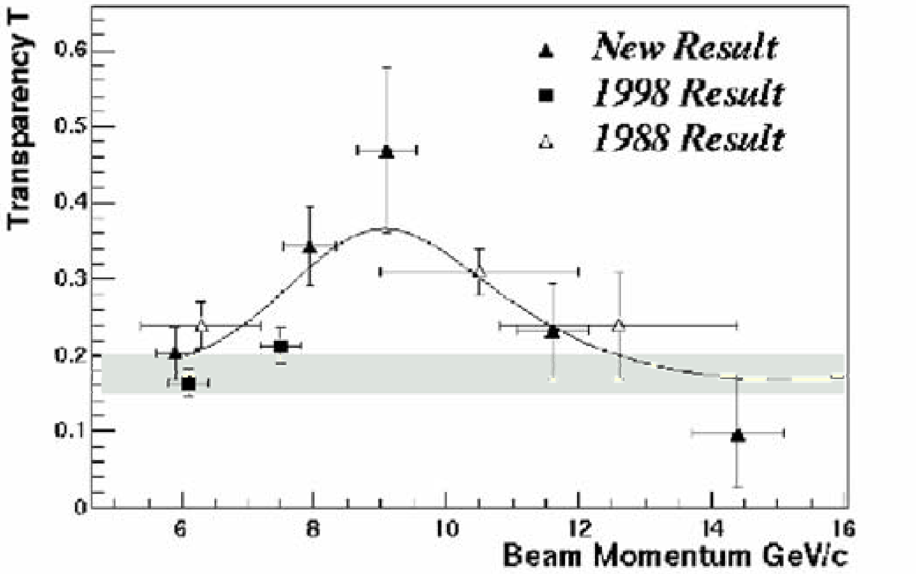
QCD Oscillations and Nuclear Filtering



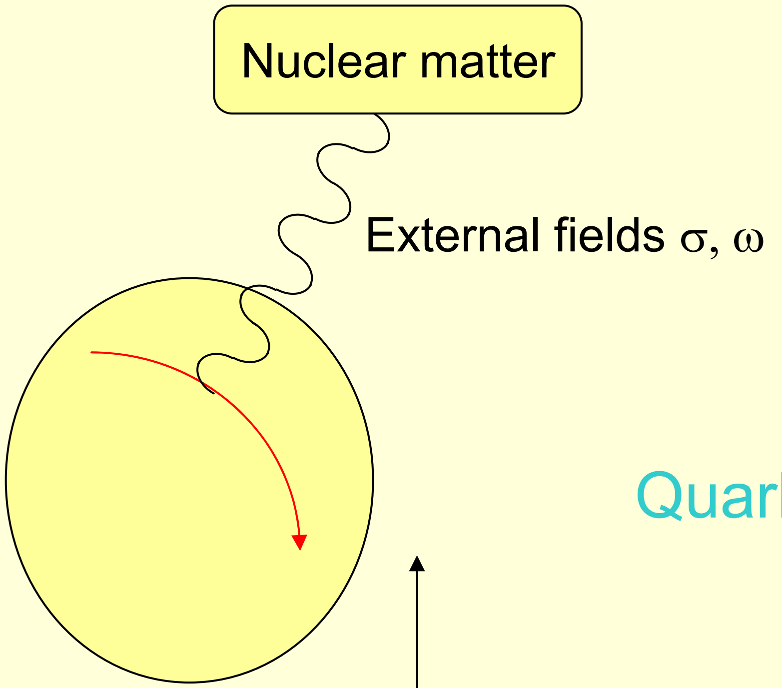
p-p elastic scattering



BNL A(p,2p)



Quark Meson Coupling Model – Guichon, Thomas, Saito plus more

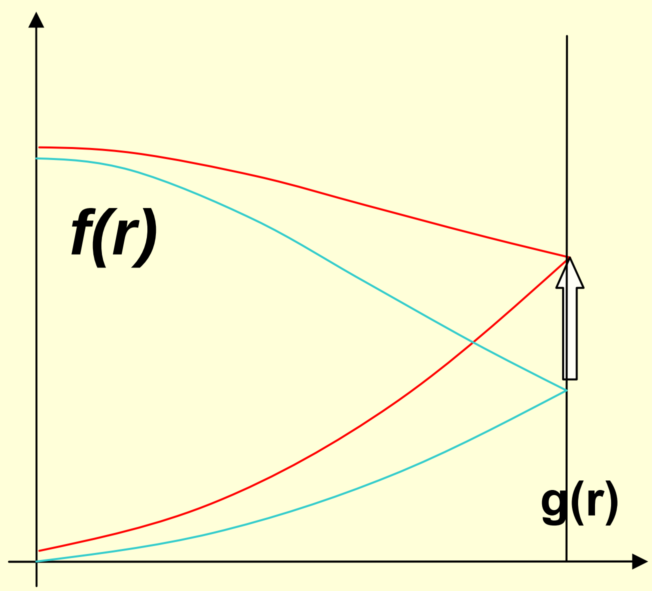


m_q ▸ $m_q - g_\sigma\, \sigma$ (attraction)

E_q ▸ $E_q\ + g_\omega\, \omega$ (repulsion)

Quark field

$$\psi_q(x) = e^{iE_q t}\begin{pmatrix} f(r) \\ i\vec{\sigma}.\hat{r}\, g(r) \end{pmatrix}\chi_{1/2}$$

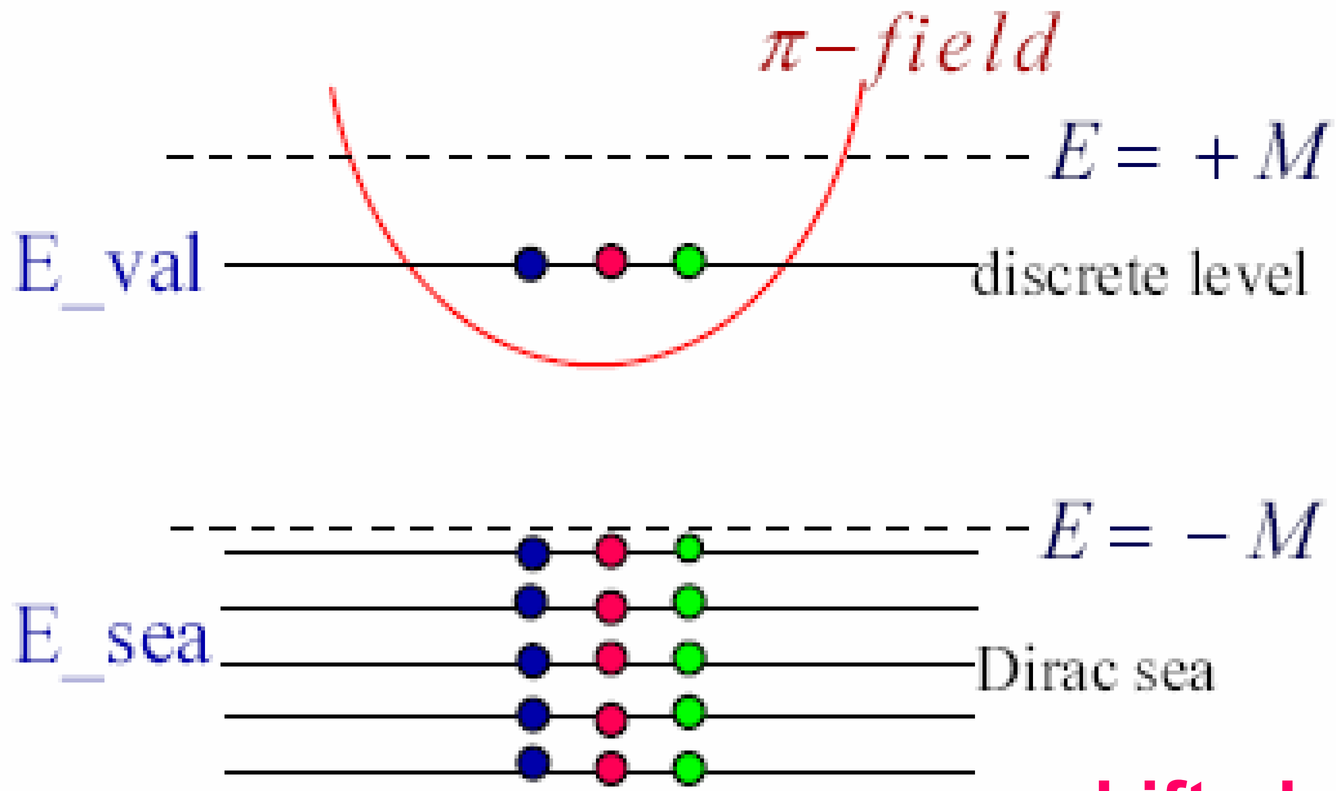


scalar field effect, lower component loc enhanced

Single nucleon modification by nuclei

- Does it make sense?
- Neutron in nucleus is modified, lifetime changed from 15 minutes to forever
- Binding changes energy denominator, suppresses $|pe\gamma\rangle$ component
- Change energy denominator change wave fun
- Strong fields polarize nucleons- analog of Stark effect, induces dipole moment of atom
- Nuclei: no direction - monopole polarization

Quark energy levels in π field



shifted

Enhancing EMC-spin independent

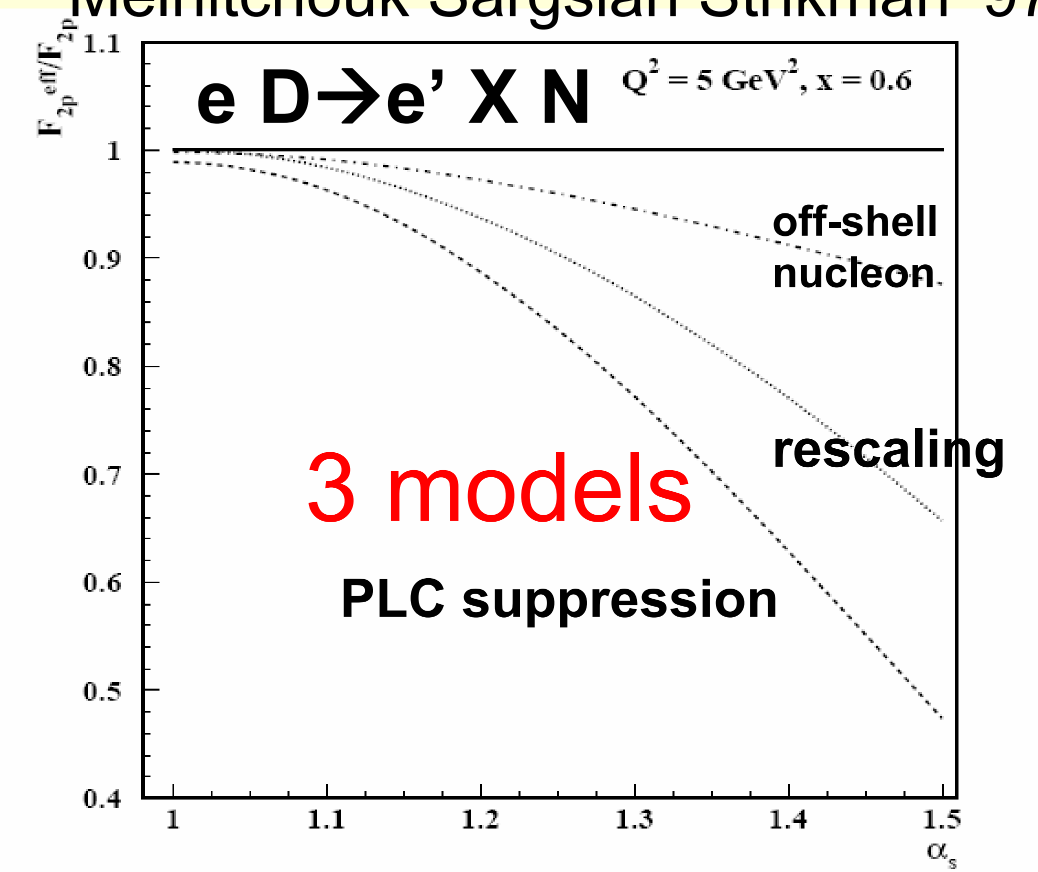
- Tagged structure functions (measurement of a nucleon from the target fragmentation region in coincidence with the outgoing electron) with the goal of directly observing the presence of non-nucleonic degrees of freedom in droplets of superdense matter.

Ratio
bound to free F_2

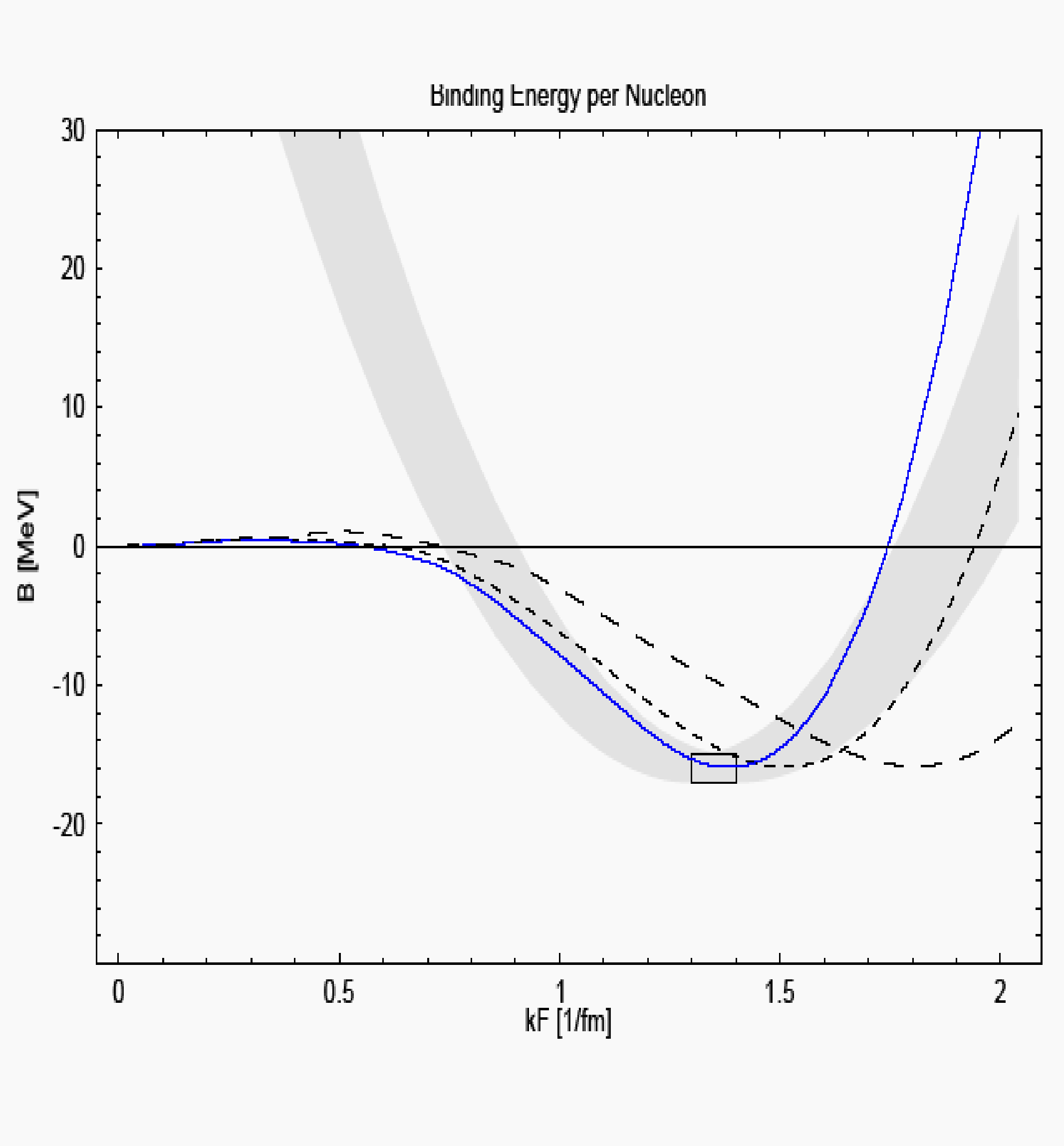
$$\alpha_s = \frac{E_s - p_z^s}{M}$$

BoNuS expt Jlab- n/p sf

Melnitchouk Sargsian Strikman '97



Results –Nuclear Matter

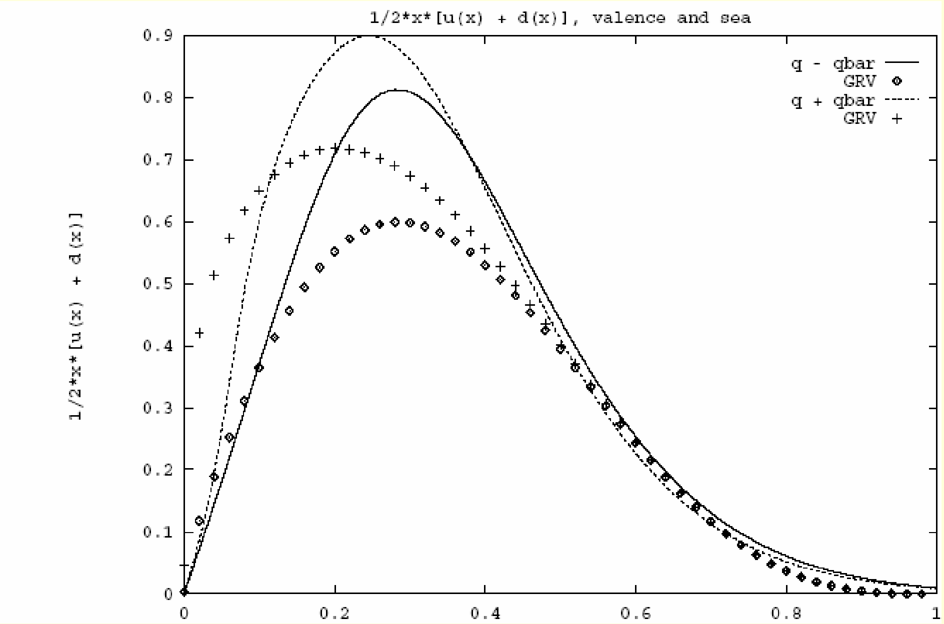


Smith-Miller

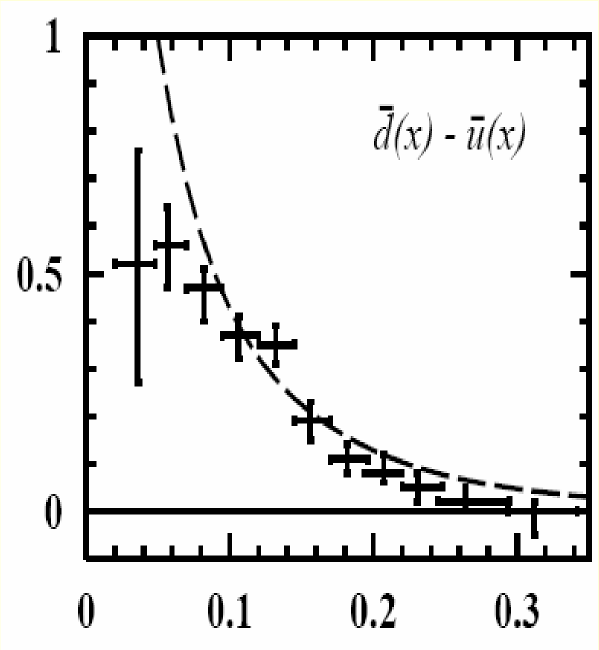
$-\langle\bar{\psi}\psi\rangle_0^{1/3}$ [MeV]	$g_v^2/4\pi$	k_F [fm^{-1}]	K [MeV]
225	7.22	1.81	291.7
210	8.96	1.51	312.5
200	10.55	1.38	348.5
-	10.47	1.42	560

Quark Soliton Model

- **Twist-2 pdfs (low scale Λ=600 MeV UV cutoff) - gluon's carry 30 % momentum, sea**
- **QCD evolve to higher Q^2**
- **Sum rules, support and positivity**
- **Pdfs:rest and infinite momentum frames**

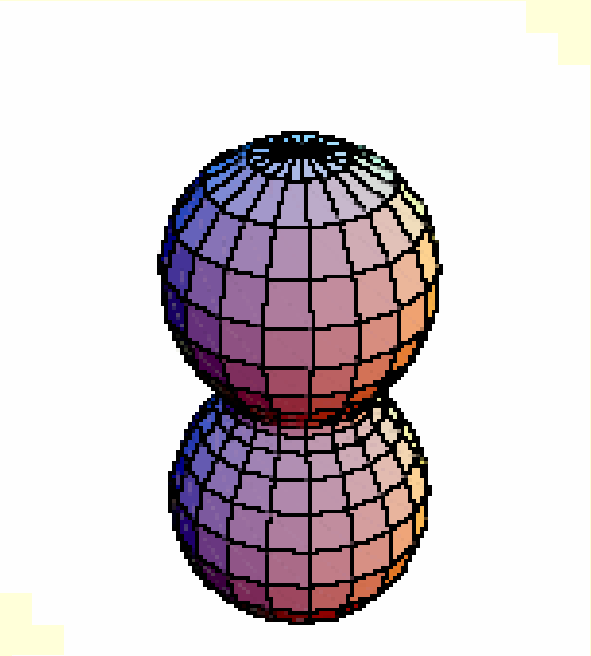


DPP

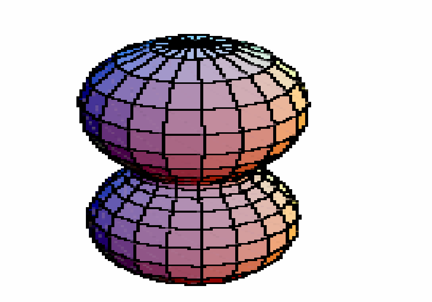


Closer look needed! Lower components LoC

- LoC account for QF_2/F_1
- LoC gives non-spherical shape of proton

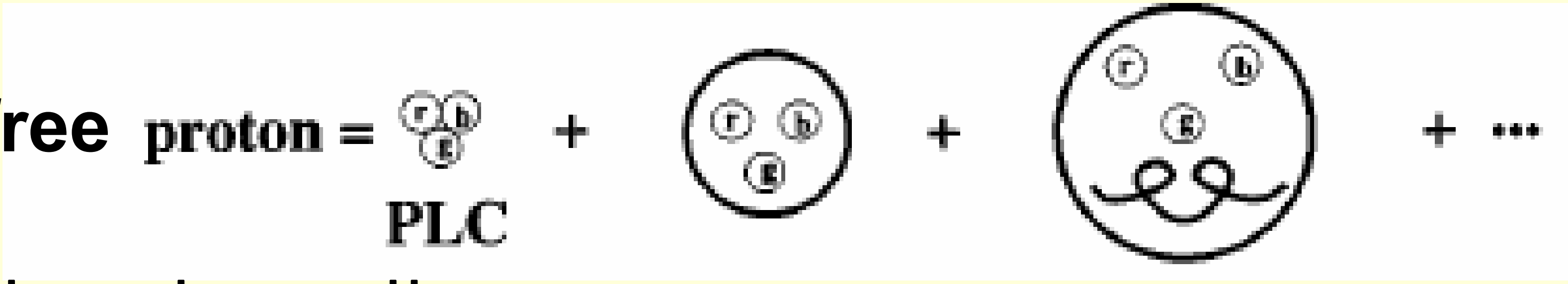


- Medium modifies LoC
- Medium modifies shape



Challenge to experiment- measure either

Suppression of Point Like Configurations- Frankfurt, Strikman

free 

place in medium:

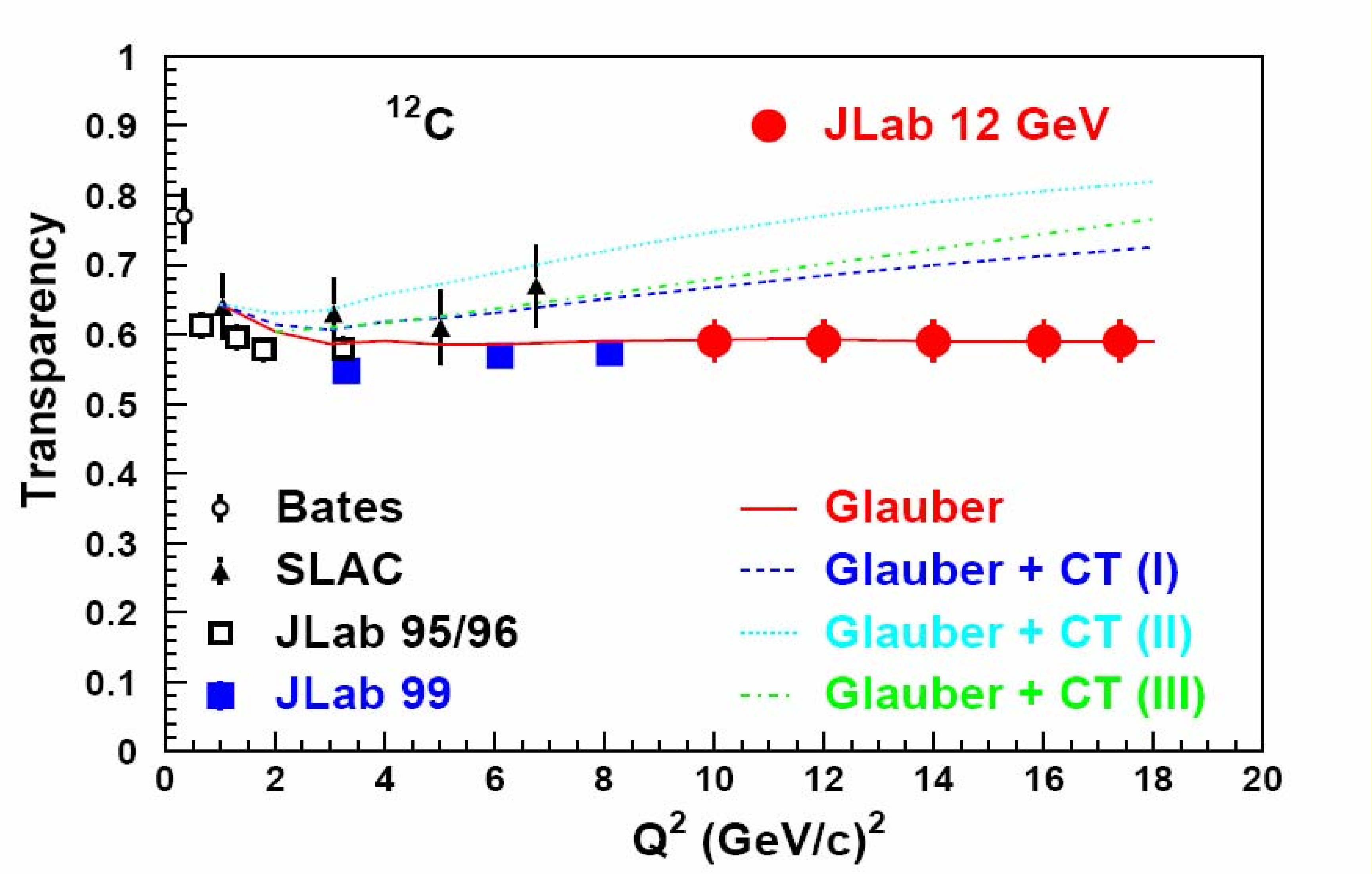
normal size components attracted energy goes down

PLC does not interact- color screening

energy denominator increased, PLC suppressed

quarks lose momentum in medium

Color transparency in (e,e'p) enhancement



Color transparency in double scattering- suppression