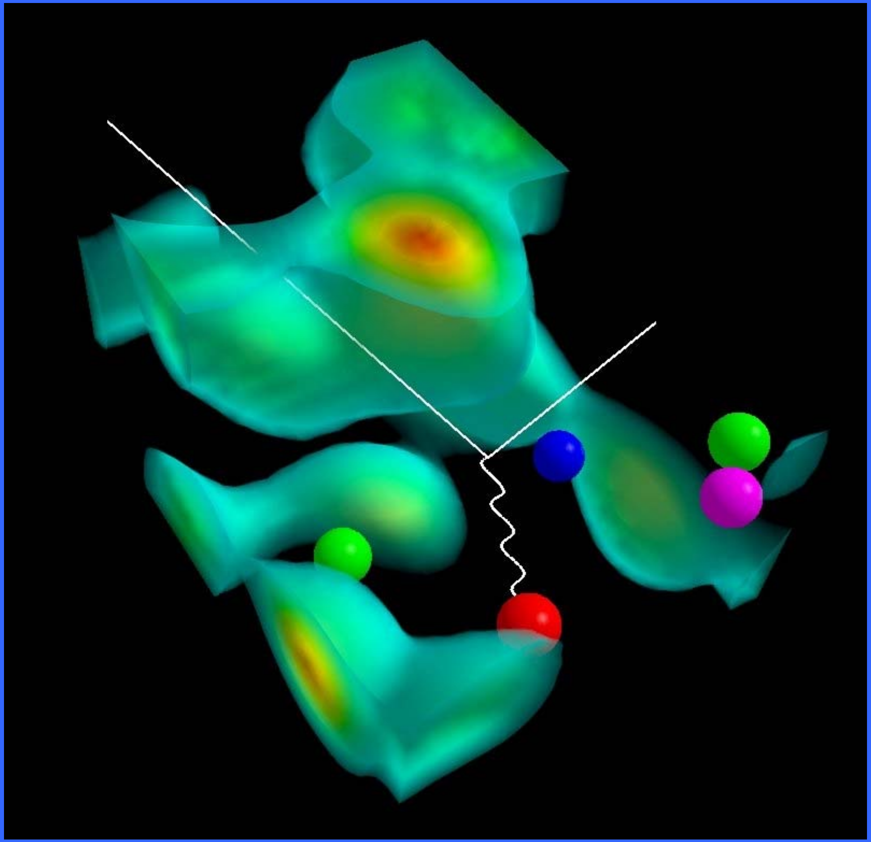
The QCD Many-Body Problem and 12 GeV Electrons



Anthony W. Thomas

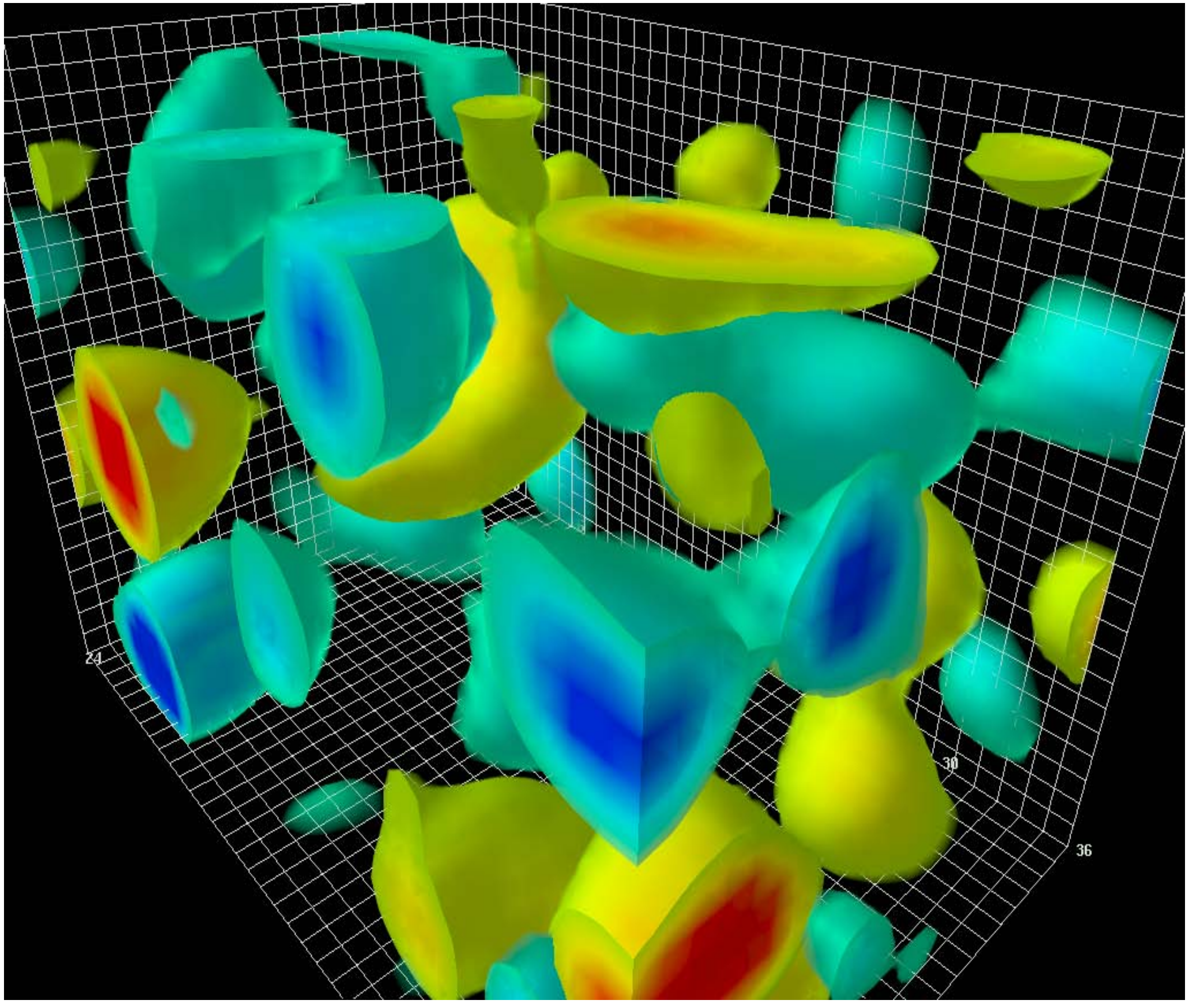
Workshop on Nuclear Physics at 12 GeV

Jlab : Nov 4, 2004

Outline

- The QCD vacuum
- Quarks to Nucleons and Excited States
- Things we know about NN forces and nuclei…
- Inevitable consequences and important links…
- Form factors, PDFs, GPDs, etc.…
- What needs measuring?

Topology of QCD Vacuum



Leinweber: see CSSM web pages

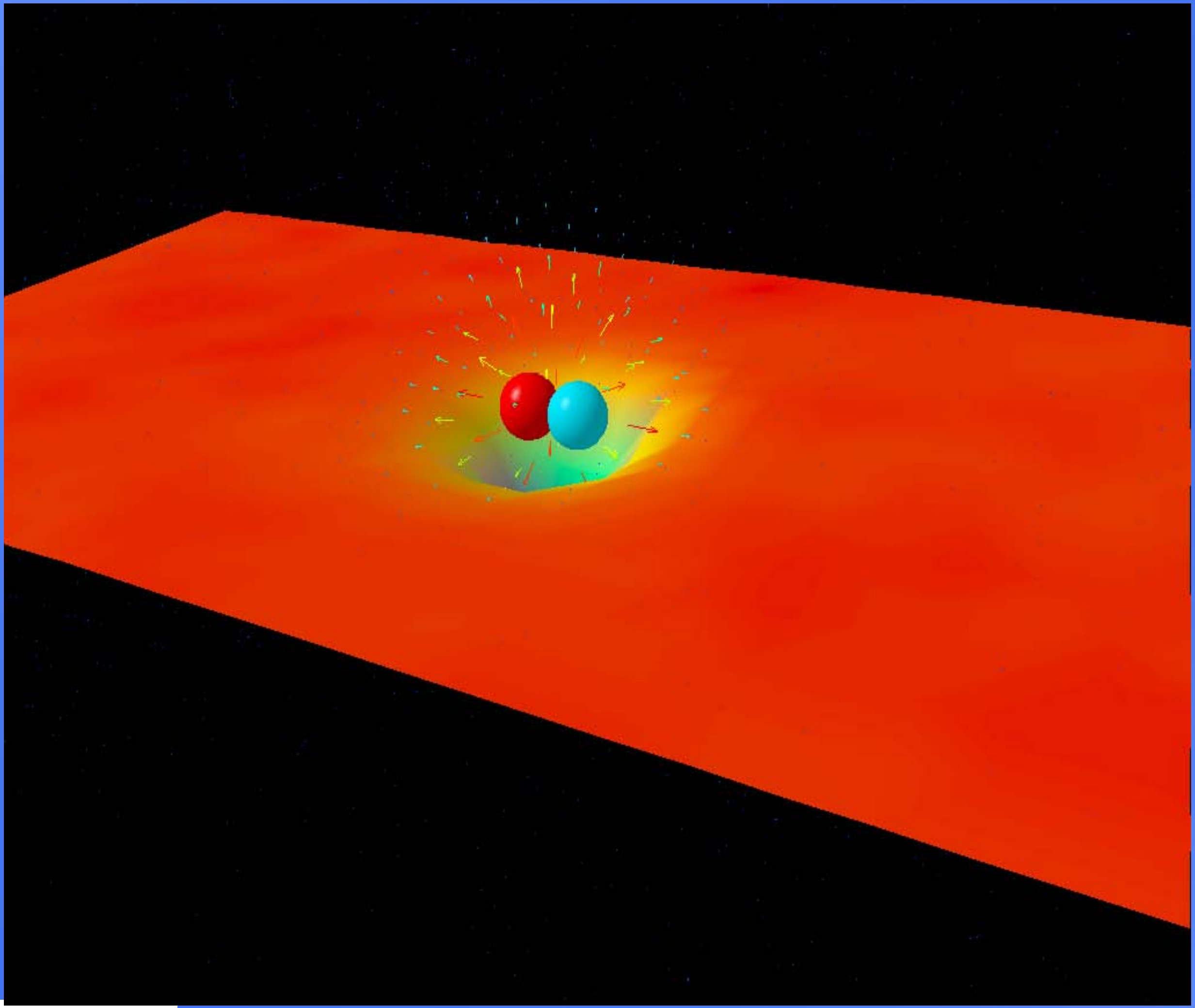
Powerful New Qualitative Insights from Lattice Simulations

D sum rules :

$$\left\langle 0 \left| \frac{\alpha_s}{\pi} G^i_{\mu\nu} G_i^{\mu\nu} \right| 0 \right\rangle = \left\langle 0 \left| \frac{2\alpha_s}{\pi} (B^2 - E^2) \right| 0 \right\rangle = (350 \pm 30 \text{ MeV})^4,$$

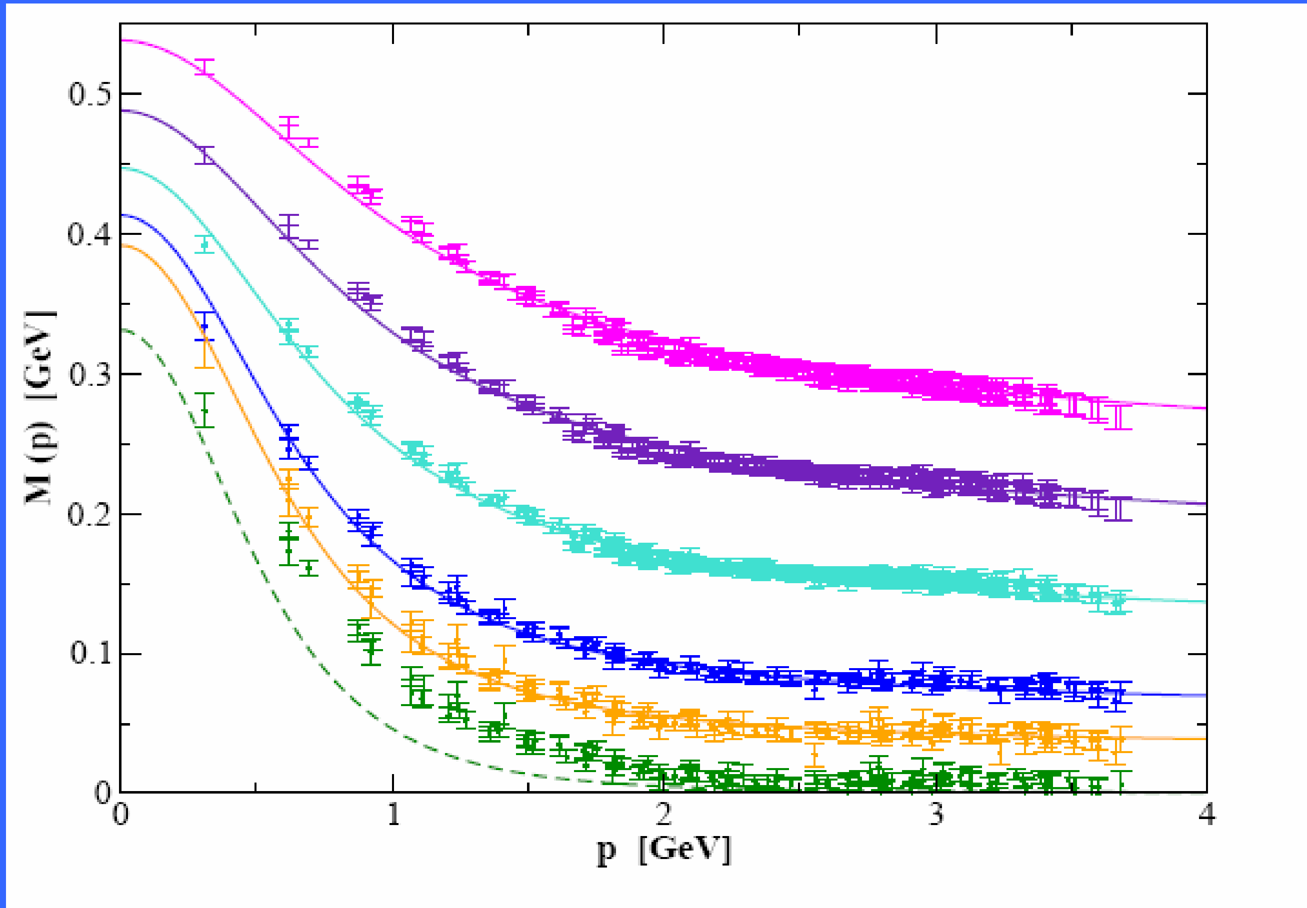
- Non-trivial topological structure of vacuum linked to dynamical chiral symmetry breaking
- There are regions of positive and negative topological charge
- BUT they clearly are NOT spherical
- NOR are they weakly interacting!

"String"



Lasscock, Leinweber, Thomas & Williams

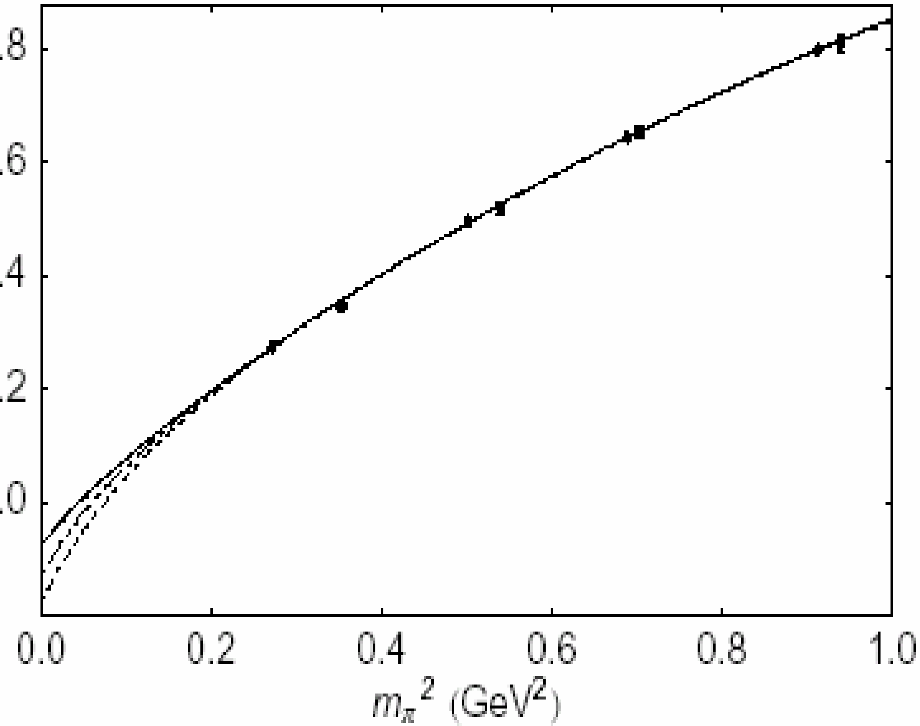
Dynamical Mass of Quark in Vacuum



DSE : Bhagwat et al., Phys Rev C68 (2003) 015203

Lattice: Bowman et al., N. P. Proc. Suppl. 119 (2003) 323.

Coefficients Known – e.g. for the nucleon



FRR give same answer to <<1% systematic error!

Regulator	LNA m_N	NLNA m_N
Dim. Reg.	0.784	0.884 ± 0.103
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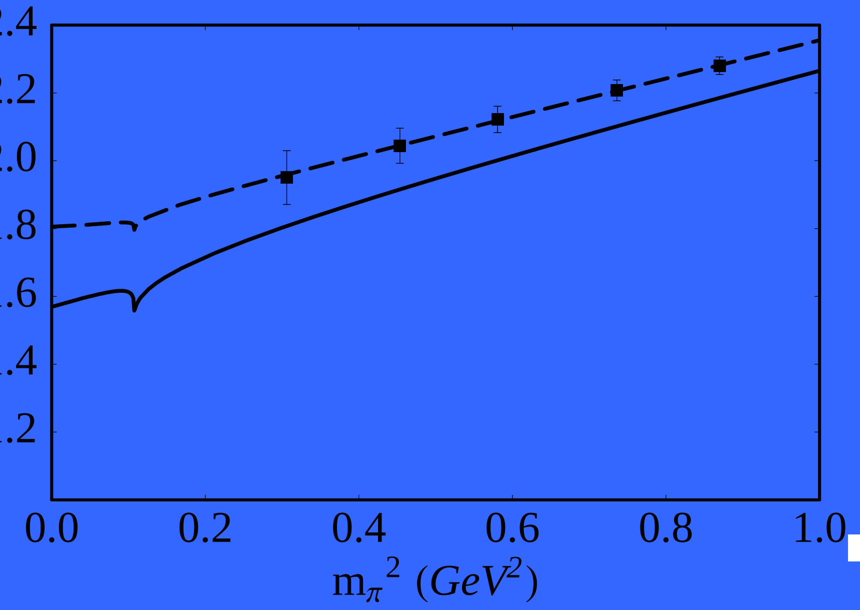
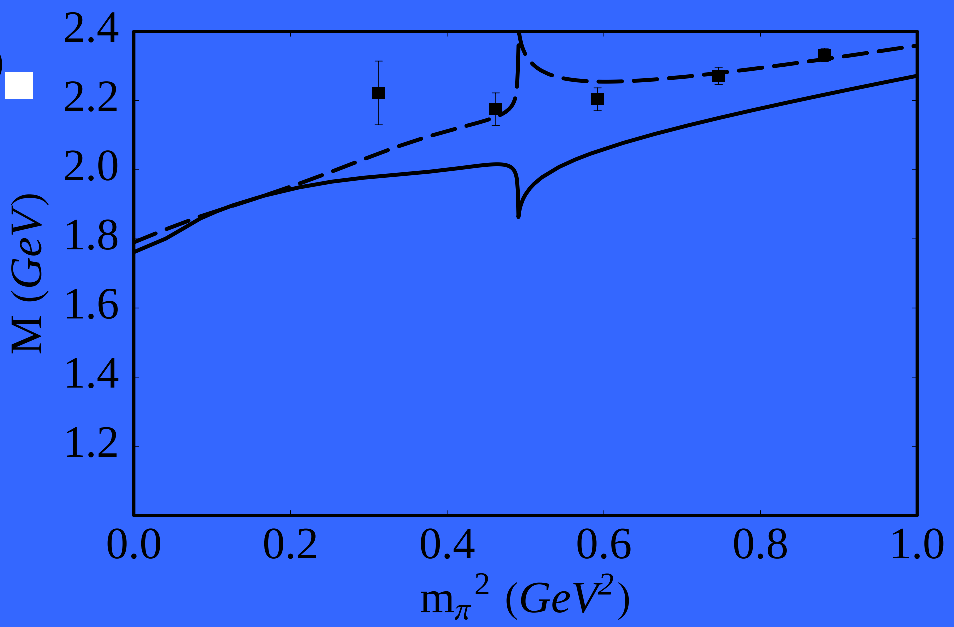
einweber et al., PRL 92 (2004) 242002

Excited States are more Difficult



N(1520) 3/2⁻



N(1650) ½⁻

Crouch et al., QQCD unquenched using chiral coefficients from quark model of Capstick

Quark Condensate in Medium

$$\langle \bar{u}u \rangle = \langle \bar{d}d \rangle = \langle \bar{s}s \rangle = -(225 \pm 25 \text{ MeV})^3$$

at a renormalization scale of about 1 GeV.

σ commutator measures chiral symmetry breaking
¼ valence + pion cloud +
volume * (difference of condensate in & out of N)

and last term is as big as 20 MeV (or more)
i.e. presence of nucleon "cleans out" vacuum to some extent

Hence: Model independent LO term for in-medium condensate

$$\frac{Q(\rho_B)}{Q_0} \simeq 1 - \frac{\sigma_N}{f_\pi^2 m_\pi^2} \rho_B$$

BUT this has no new physics at all!

What do we know about Nuclear Environment?

Walecka et al., (QHD): Lorentz structure of attraction and repulsion is crucial (σ and ω respectively)

NOT arbitrary – inspired by Paris potential, built on dispersion relations) I=0, $J^{\pi} = 0^{+}$ channel dominates intermediate range attraction

(origin two-pion ¼ σ exchange)

Modern version: Machleidt et al., RBHF) g_{σ} σ ¼ 400 MeV

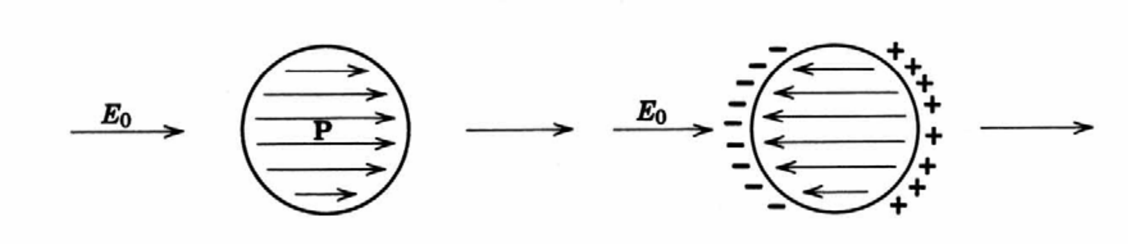
i.e. There are strong (» 0.4 M_N) Lorentz scalar fields in nuclei……..

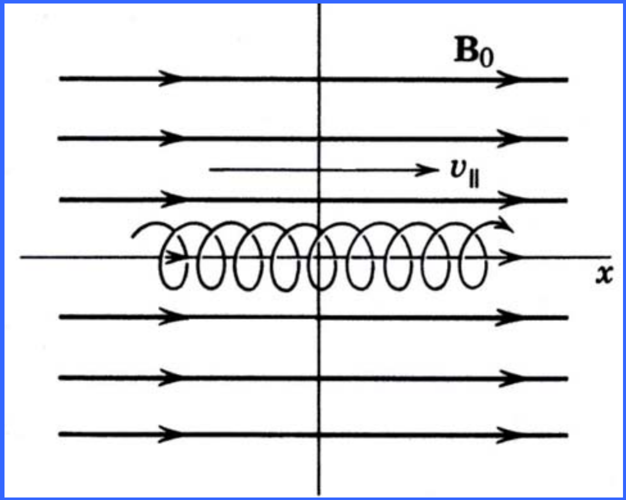
so what?

What happens if we put an atom in a strong electric field?

Jackson)

atom has a polarizability: internal structure is arranged in response to plied field





///’ly in applied magnetic field (indeed, in super strong field -e.g. n-star surface atoms & molecules essentially linear!)

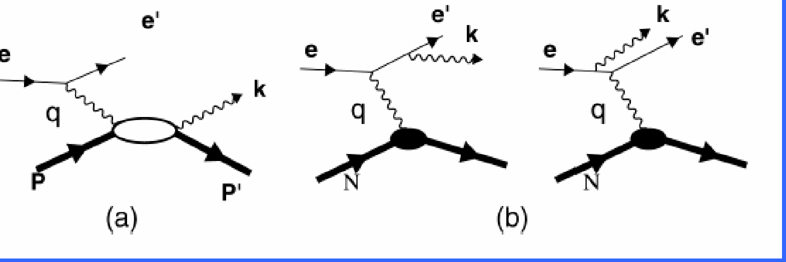
# of Nucleon are Measured

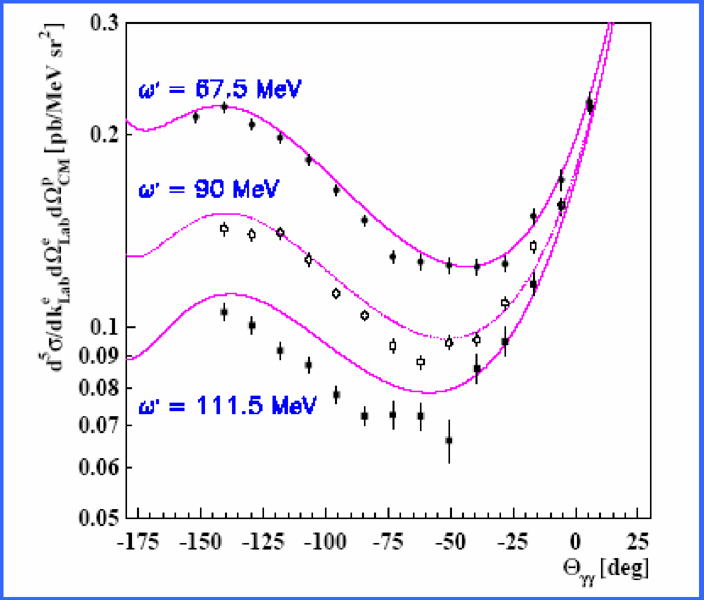
e.g. Compton scattering:

$$4\pi\,\alpha_E = 2\sum_{I\neq N}\frac{|\langle I|d_z|N\rangle|^2}{E_I - E_N}$$

$$\begin{aligned}\alpha_E^p &= (12.1 \pm 1.3)\cdot 10^{-4}\,\mathrm{fm}^3,\\ \beta_M^p &= (2.1 \mp 1.3)\cdot 10^{-4}\,\mathrm{fm}^3.\end{aligned}$$

Also Virtual Compton Scattering) GPs





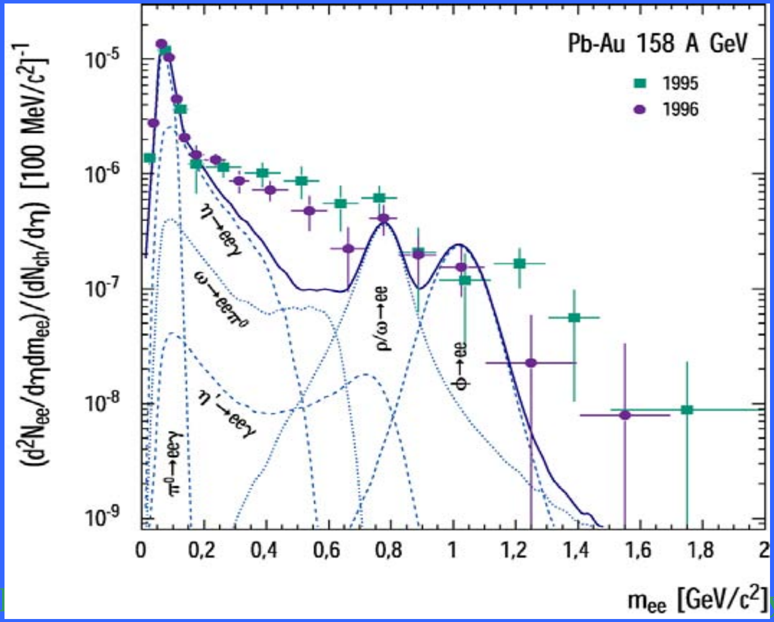
So what?

toms respond to external E and B fields

ucleons respond to external E and B fields

UT it is unthinkable that nucleons respond to
arge scalar fields known to exist in-medium??

or some reason change of hadron mass m ! m*
s accepted widely BUT it is unthinkable that any other property
might change



?

"Fundamental Question is then "What is the Scalar Polarizability of the Nucleon?"

Nucleon response to a chiral invariant scalar field
Is then a nucleon property of great interest…

$$M^*(\vec{R}) = M - g_\sigma \sigma(\vec{R}) + \frac{d}{2}\left(g_\sigma \sigma(\vec{R})\right)^2$$

lon-linear dependence ´ scalar polarizability
d ¼ 0.22 R in original QMC (MIT bag)

Indeed, in nuclear matter at mean-field level, this is the ONLY place the response of the internal structure of the nucleon enters.

ORIGIN ….

$$[i\gamma^\mu \partial_\mu - (m_q - g_\sigma{}^q \bar{\sigma}) - \gamma^0 g_\omega{}^q \bar{\omega}]\psi = 0$$

Source changes: $\int_{Bag} d\vec{r}\,\bar{\psi}(\vec{r})\psi(\vec{r})$

SELF-CONSISTENCY

and hence mean scalar field changes…

and hence quark wave function changes….

THIS PROVIDES A NATURAL SATURATION MECHANISM
(VERY EFFICIENT BECAUSE QUARKS ARE ALMOST MASSLESS)

source is suppressed as mean scalar field increases
(i.e. as density increases

in Lattice QCD ?

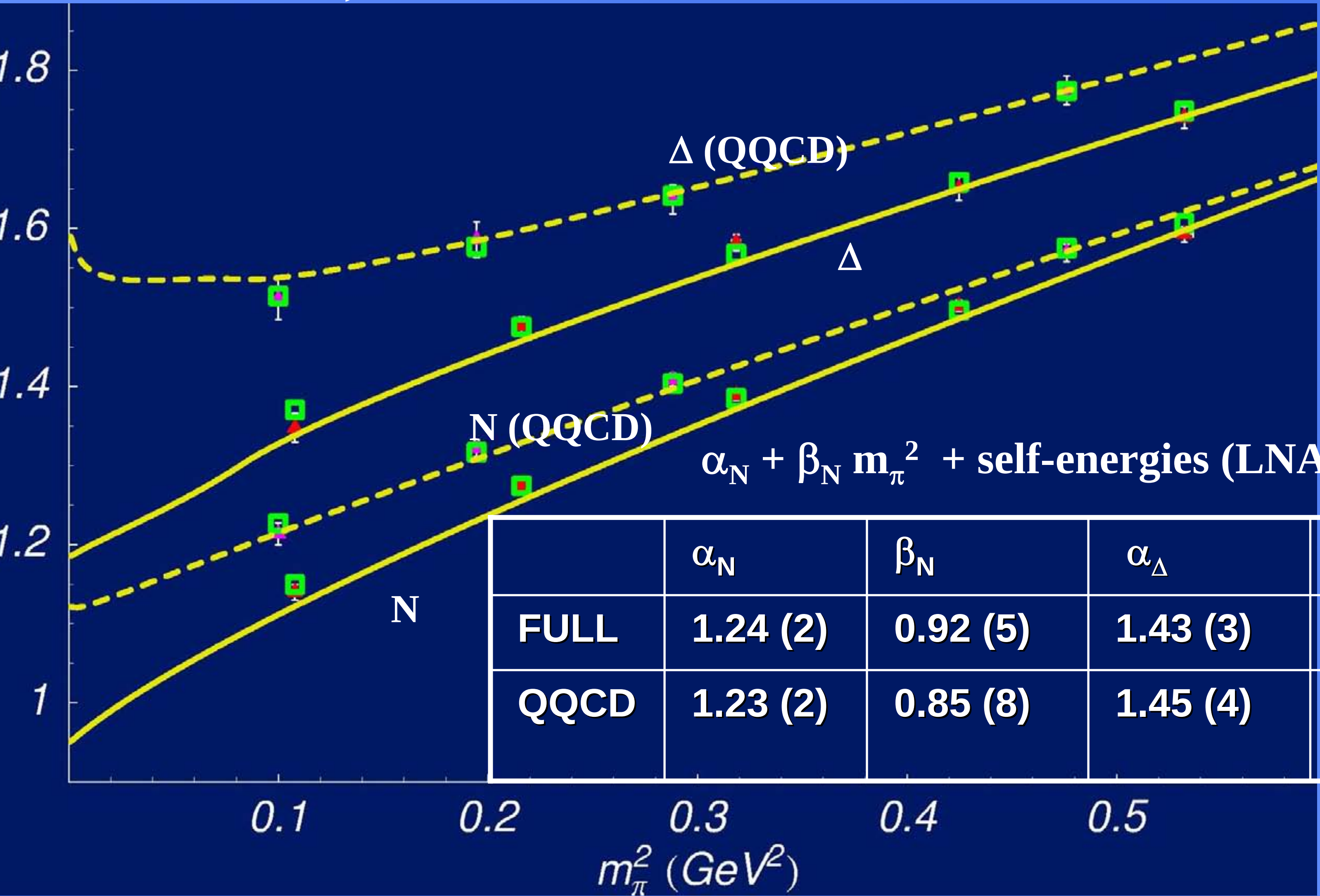
- IF we can, then in a real sense we would be linking nuclear structure to QCD itself, because scalar polarizability is sufficient in simplest, relativistic mean field theory to produce saturation

- Ideas on this just published: the trick is to apply a <u>chiral invariant</u> scalar field

18th Nishinomiya Symposium: nucl-th/0411014

•Green boxes: fit evaluating σ's on <u>same finite grid as lattice</u>

•Lines are exact, continuum results

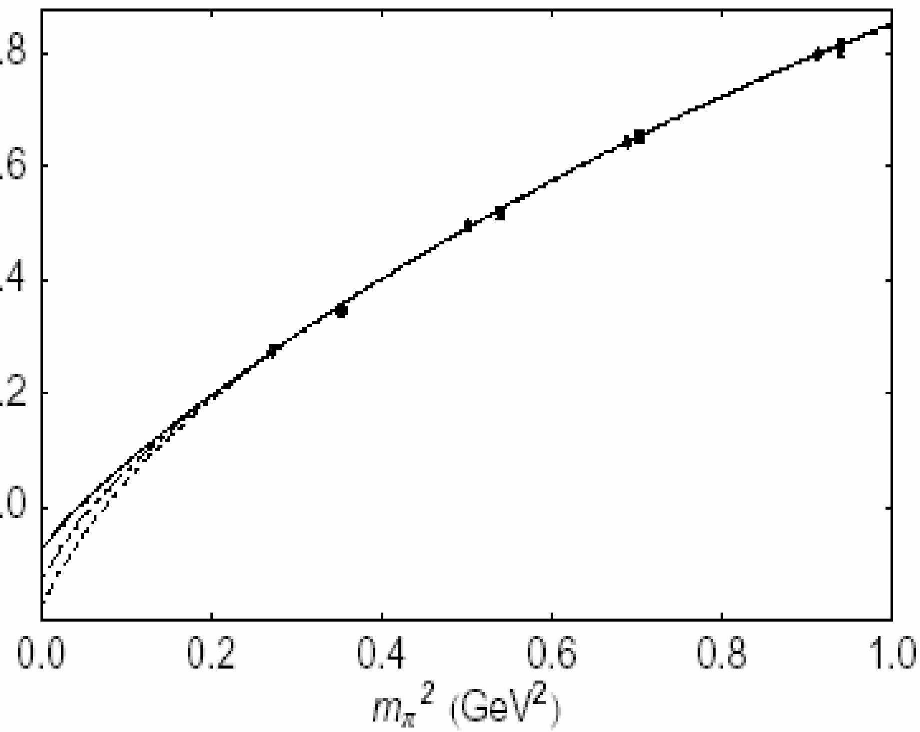


$\alpha_N + \beta_N m_\pi^2$ + self-energies (LNA+NLNA)

	α_N	β_N	α_Δ	β_Δ
FULL	1.24 (2)	0.92 (5)	1.43 (3)	0.75 (8)
QQCD	1.23 (2)	0.85 (8)	1.45 (4)	0.71 (11)

Young *et al.*, hep-lat/0111041; Phys. Rev. D66 (2002) 094507

Coefficients Known – e.g. for the nucleon



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einweber et al., PRL 92 (2004) 242002

Invariant Scalar Field

i.e. Change m_q BUT <u>not</u> mass of pionic fluctations

BUT study of chiral extrapolation of M_N and M_Δ (in QQCD and full QCD) can do this now !

$$M_N^* = a_0 + a_2\, m_\pi^2 + a_4\, m_\pi^4 + \text{self-energy}(m_\pi^{phys},\Lambda)$$

χ PT) m_π^2 ¼ $4\, m_q + 20\, m_q^2$, and in mean field m_q ! $m_q - g_\sigma^q\, \sigma$

positive

HENCE: $M_N^* = M_N - (4\, a_2\, g_\sigma^q)\, \sigma + (20\, a_2 + 16\, a_4)\, g_\sigma^{q\,2}\, \sigma^2$

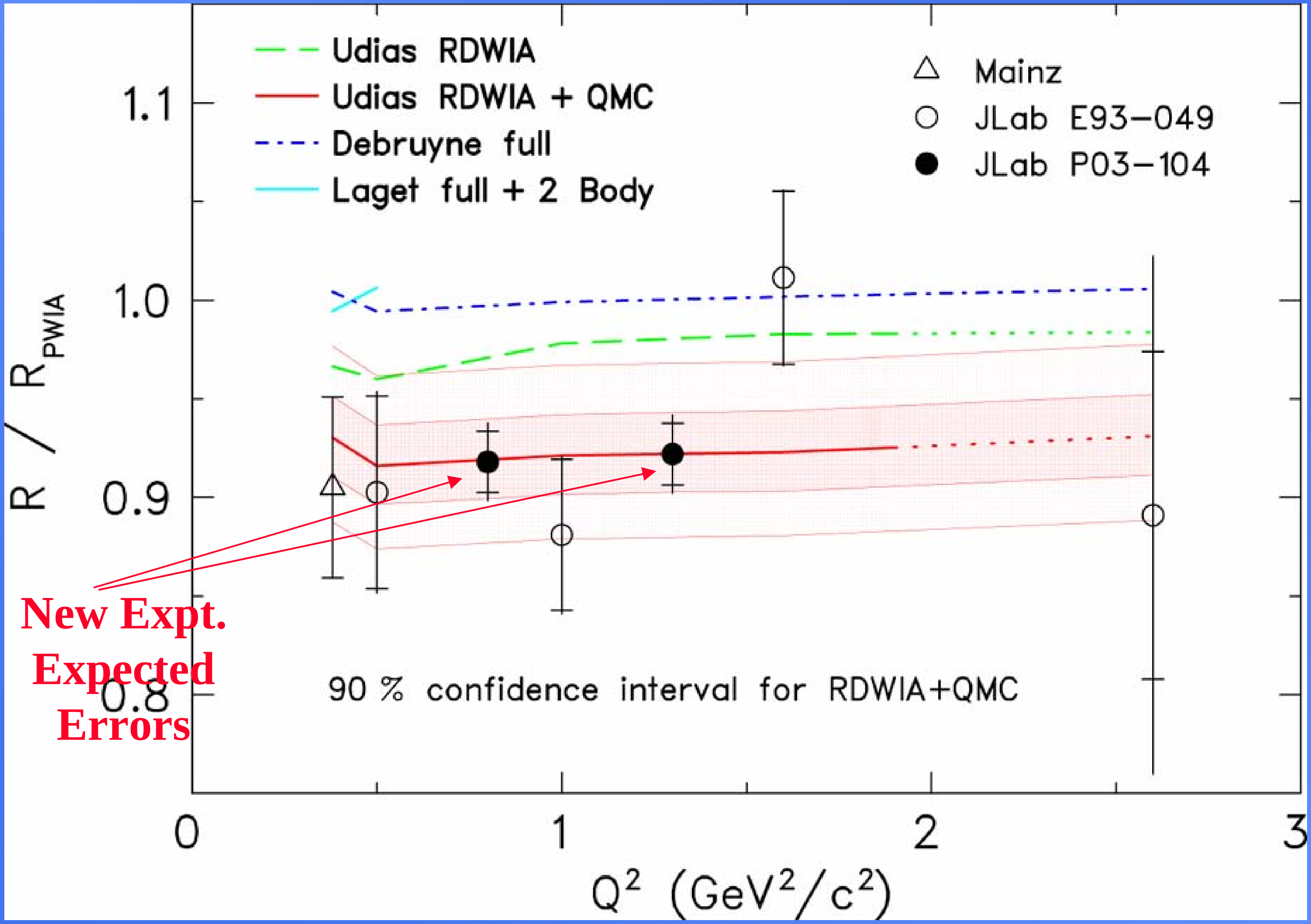
¼ $M_N - g_\sigma\, (1 - g_\sigma\, \sigma)\, \sigma$

Coefficient ~ unity if units GeV) 10-20% + at ρ_0 … as in QMC!

Other Consequences

- Form factors: $G_{E, M, A}$
- Parton Distribution Functions
- Generalized Parton Distribution Functions
- more masses…..

Jefferson Lab & Mainz



Parton Distribution Functions of Nuclei

or those old enough to remember there were
wo responses to 1983 EMC discovery

) Complete shock

) So what : no reason for $f_{q/N}(z) = p_- \int \frac{dw^-}{2\pi} e^{ip_- z w^-} < N, p \left| \bar{\psi}(0) \gamma^+ \psi\left(w^-\right) \right| N, p >$

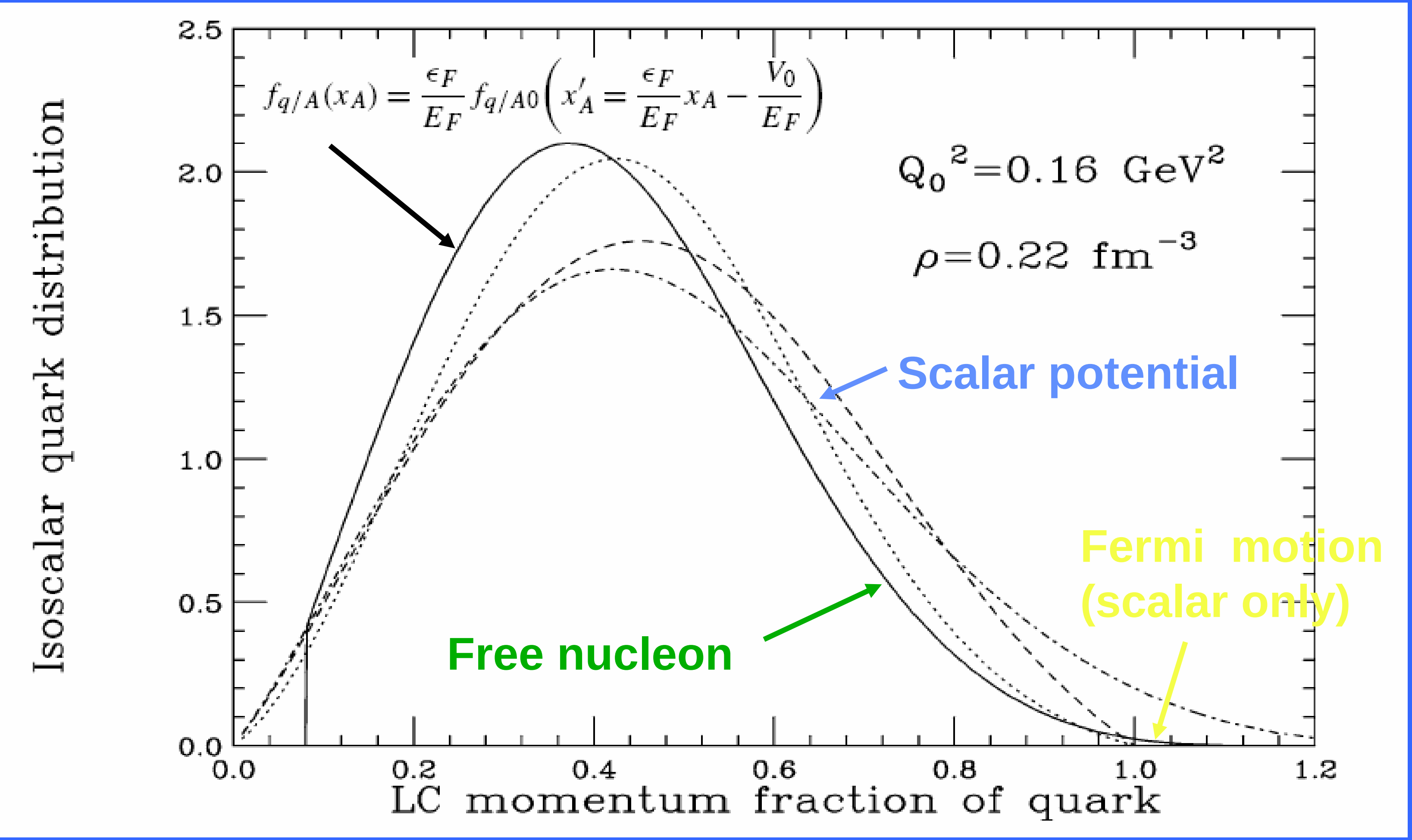
to be related to $f_{q/A}(y_A) = \frac{P_-}{A^2} \int \frac{dw^-}{2\pi} e^{iP_- y_A w^- / A} < A, P \left| \bar{\psi}\ (0) \gamma^+ \psi\left(w^-\right) \right| A, P >$

They are two different eigenstates of QCD Hamiltonian…

END of STORY !

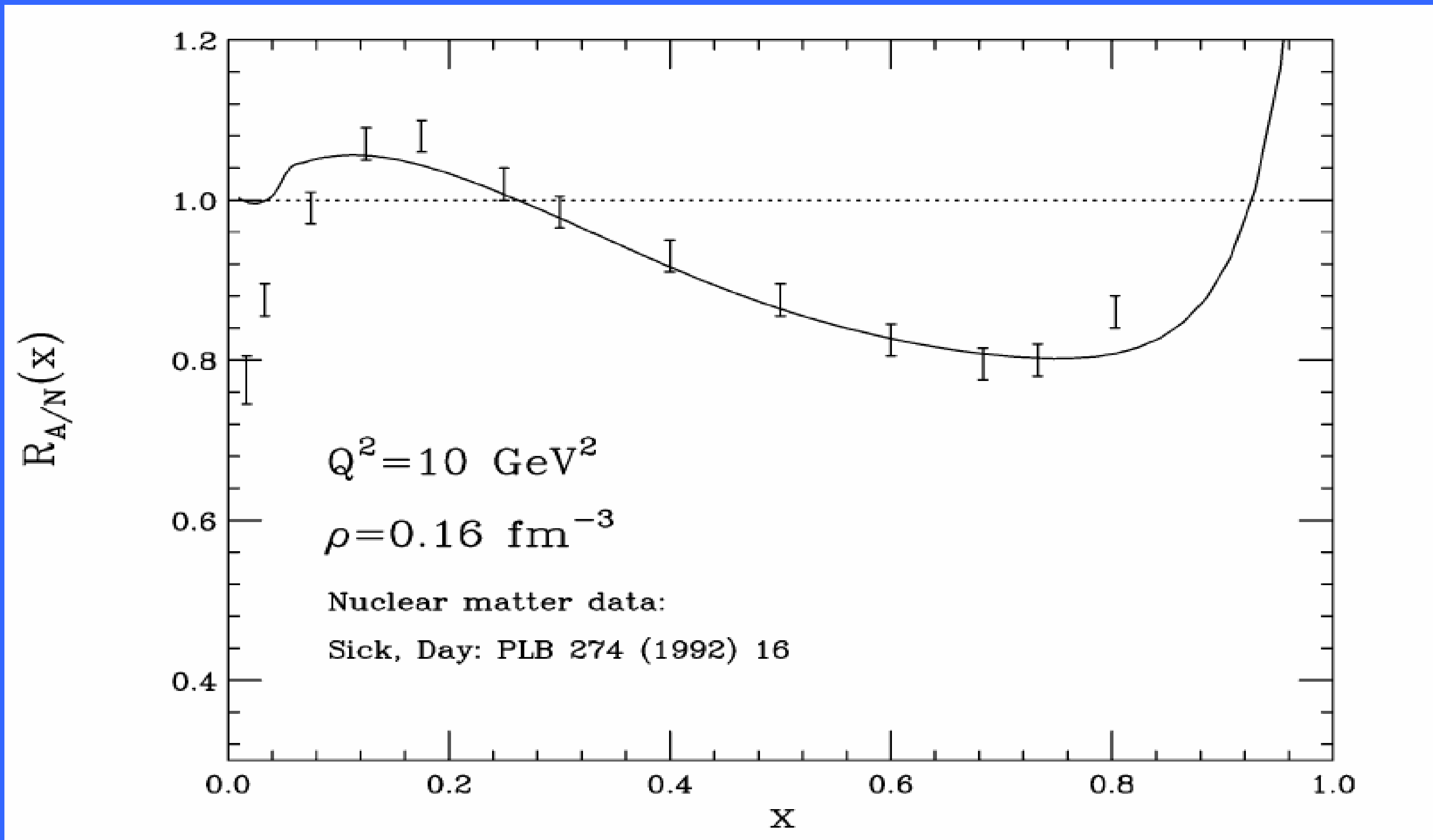
i.e. NO derivation at all, within QCD (THE theory of the strong interaction) of a convolution of nucleon motion with free structure function!

Change of Nucleon PDF In-Medium



Mineo et al., N P A735 (2004) 482

EMC Ratio for Infinite Nuclear Matter



Data of Sick et al. for nuclear matter: Phys Lett B274 (1992) 16

But really puzzling!!!

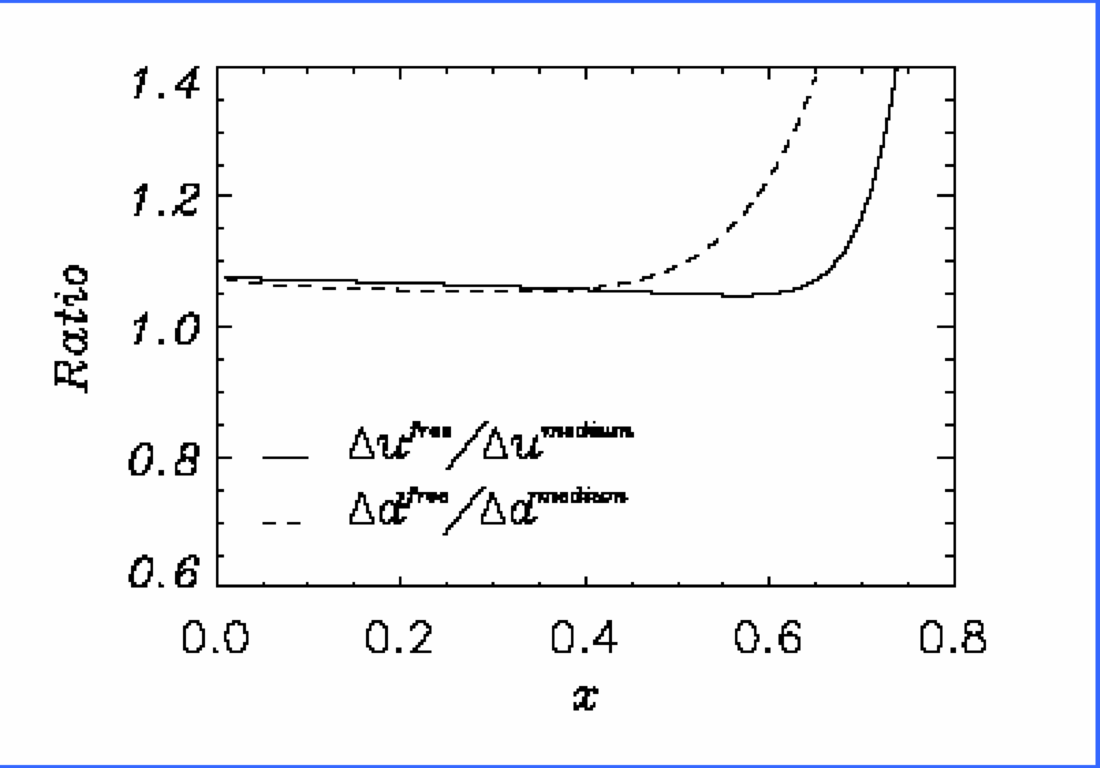
- 1983: major surprise that nuclear structure function is not equal to nucleon.
- 1988: major surprise for spin structure function of the proton

WHY HAS THE OBVIOUS NEVER BEEN DONE??

Indeed, SLAC uses ^{6}Li as a polarized neutron target assuming there is NO EMC spin effect!

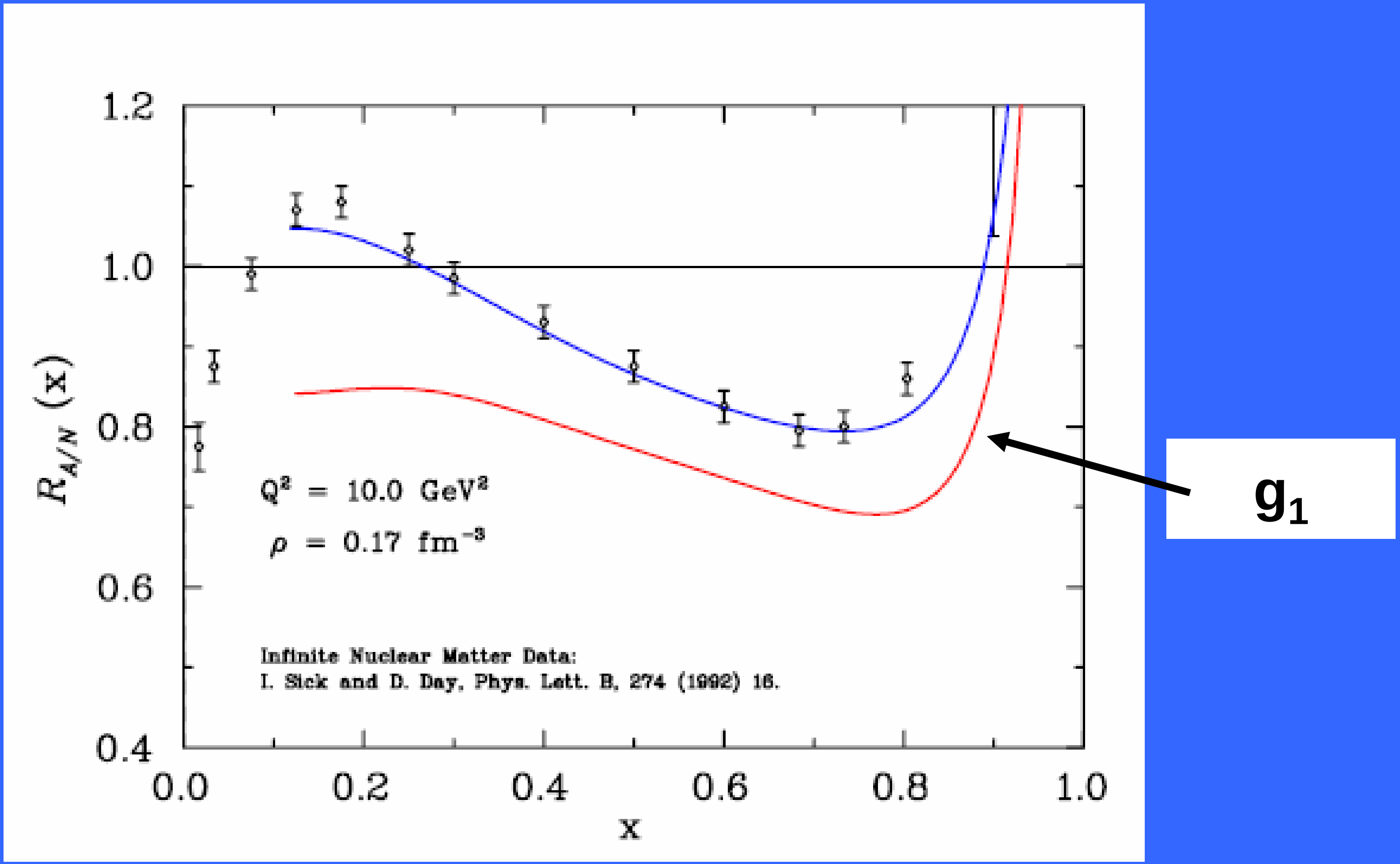
Predicted "EMC" Effect Bigger for Spin

First "estimate" in ^{3}He of medium effects in spin dependent PDFs in QMC model



Steffens et al., Phys.Lett.B447 (1999) 233

QMC-like Model (NJL with Confinement)



Cloet, Bentz, Thomas, this meeting

Other Experimental Issues

- Large x: Multi-quarks/hidden color
  Short Range Correlations

- Small x: is nuclear sea anywhere close to the sea of the free nucleon? Flavor and spin dependence…..
  (for theorists: role of scalar and vector potentials)
  SEMI-INCLUSIVE DIS WILL BE CRUCIAL!

- Nuclear dependence of higher twist (e.g. VMD corrections) – different for EM, CC & NC !
  (complements work at Fermilab with ν)

- Ambitious: How do GPD’s change in-medium?

- More masses….

in Matter – Complements GSI Project

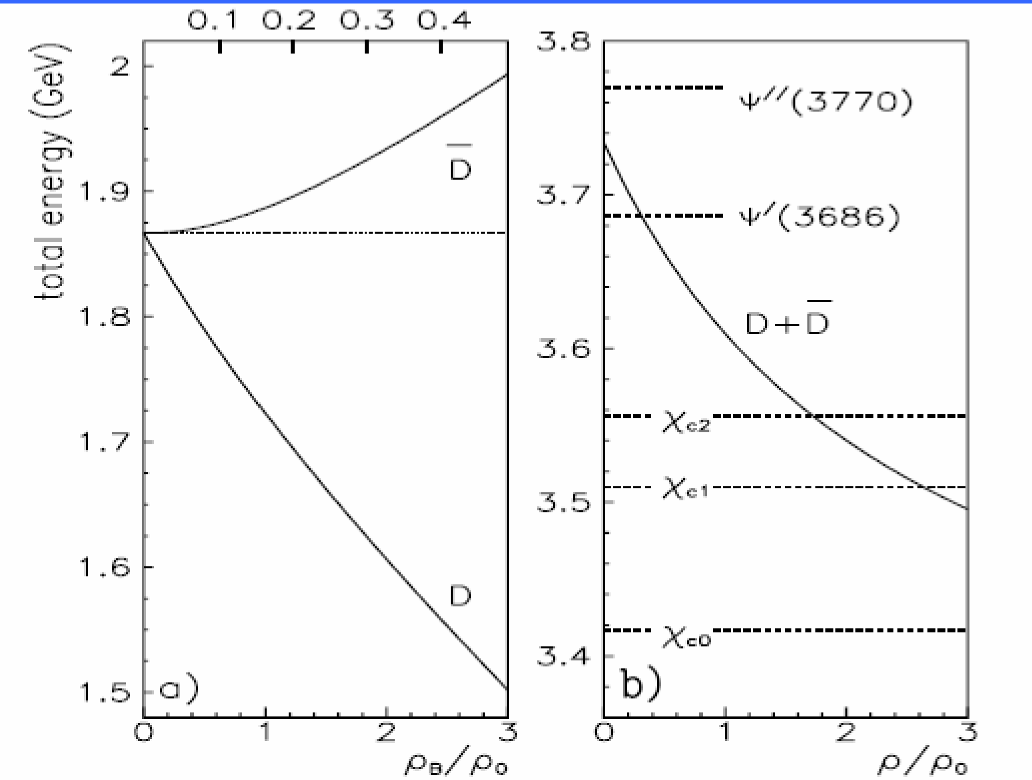


Fig. 1. a) The in-medium mass of D- and $\bar{D}$-mesons as a function of nuclear density ρ/ρ_0, with $\rho_0 = 0.16\,\mathrm{fm}^{-3}$ and the $D\bar{D}$ mass splitting (upper axis). b) The solid line shows the overall $D\bar{D}$ mass as a function of density. The dashed lines

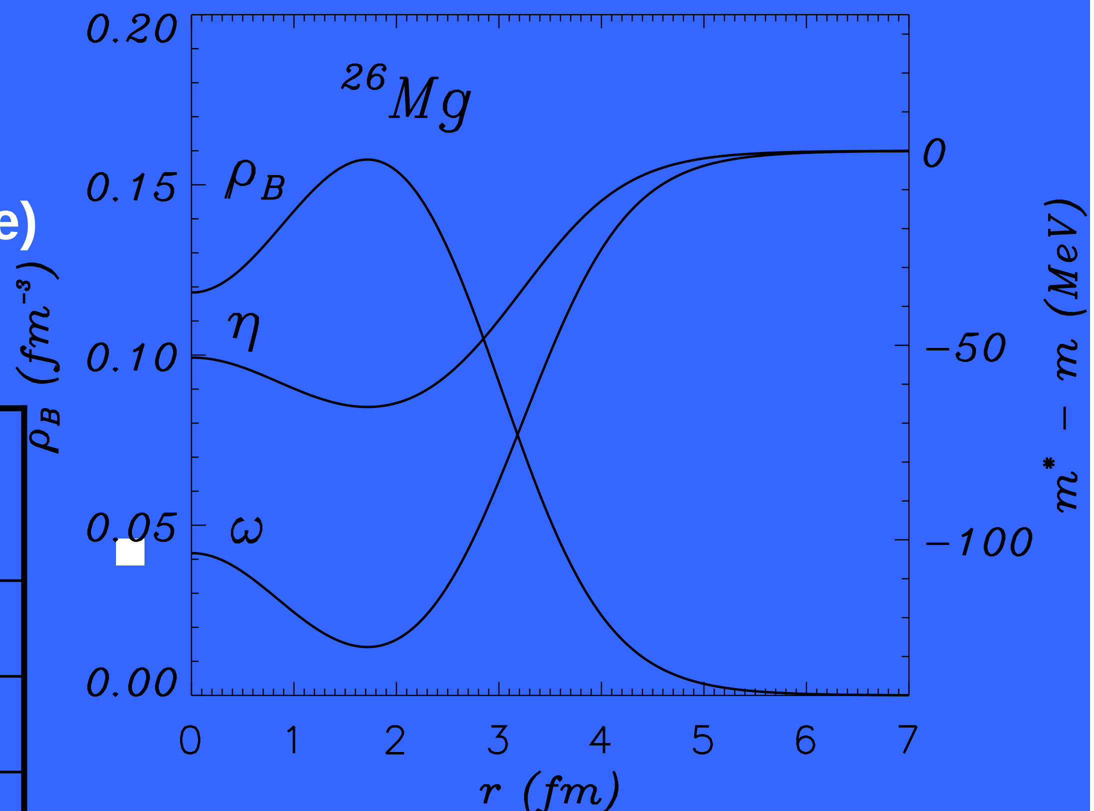
Enhance intrinsic charm in nuclei?

Sibirtsev, Eur. Phys. J. A18 (2003) 475

Binding of Other Mesons in Nuclei

action: e.g. $^{27}Al\ (d,^{3}He)\ ^{26}Mg_{\omega}$
ero recoil momentum possible)

Aω		ε MeV	Γ MeV
He	1s	-56	25
B	1s	-81	29
Mg	1s	-100	31
	1p	-79	29
	2s	-43	25



Again GSI experiment but recall Lolos et al. for ρ in He at INS Tokyo

Big Picture

- QCD) phase transition at high density (and T)
- Is dense matter (n-star) nuclear/strange/QM/superconducting QM/color cond.?
- Changes at low density are precursors of what happens under more extreme conditions
- Crucial part of our understanding of these phenomena
- Theoretical and experimental studies of these kinds are the only systematic way to move up

DON'T ASK YOU WILL NOT FIND!