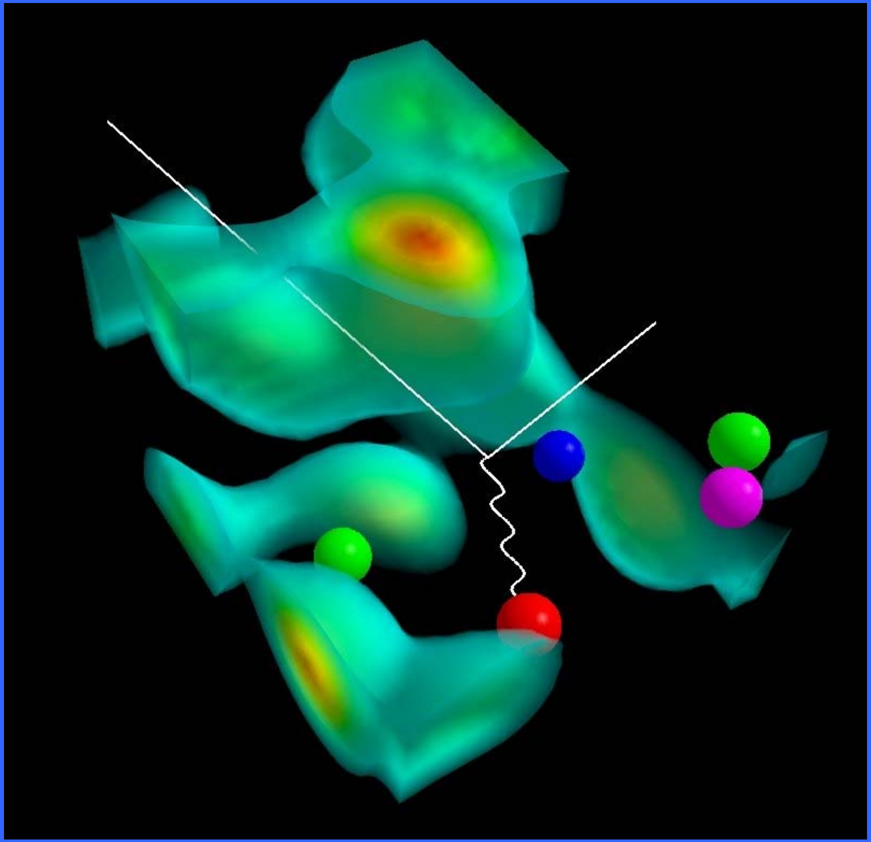
The Origin of Nuclear Forces: QCD and the Structure of Hadrons



Anthony W. Thomas

GRC: Today's Frontiers in Nuclear Physics

Bates College : July 10th, 2005

Special Mentions……

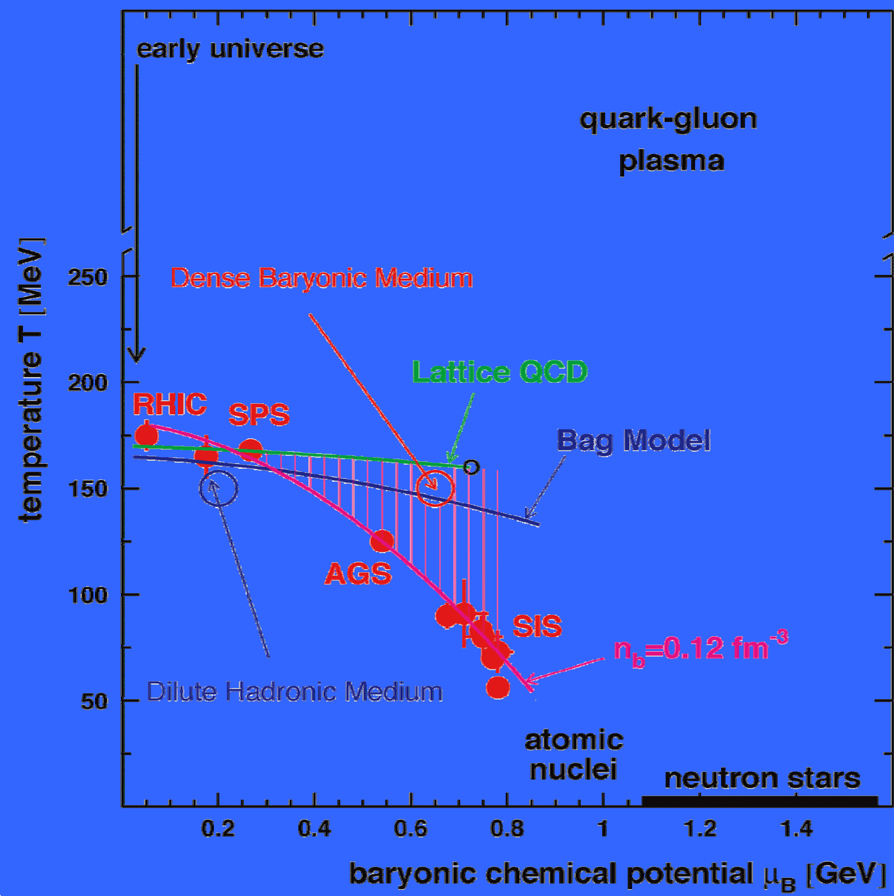
Outline

- The QCD vacuum
- Quarks to Hadrons
- Things we know about NN forces and nuclei…
- Inevitable consequences and important links…
- Nuclei emerging from QCD
- What needs measuring?

Major Challenges for Nuclear Physics

- Origin of Nuclear Saturation

- EOS … as $\rho\uparrow$; as $T\uparrow$
  as $S\uparrow$; as $N\text{-}Z\uparrow$



- Phase Transition to:
  - quark matter (QM), superconducting QM, strange condensate
  - related to nuclear astrophysics; n-stars….

QCD and the Origin of Mass

	u	+	u	+	d	=	proton
mass:	0.003	+	0.003	+	0.006	≠	0.938

HOW does the rest of the proton mass arise?

Quark Condensate In-Medium

Free space:

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

at a renormalization scale of about 1 GeV.

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

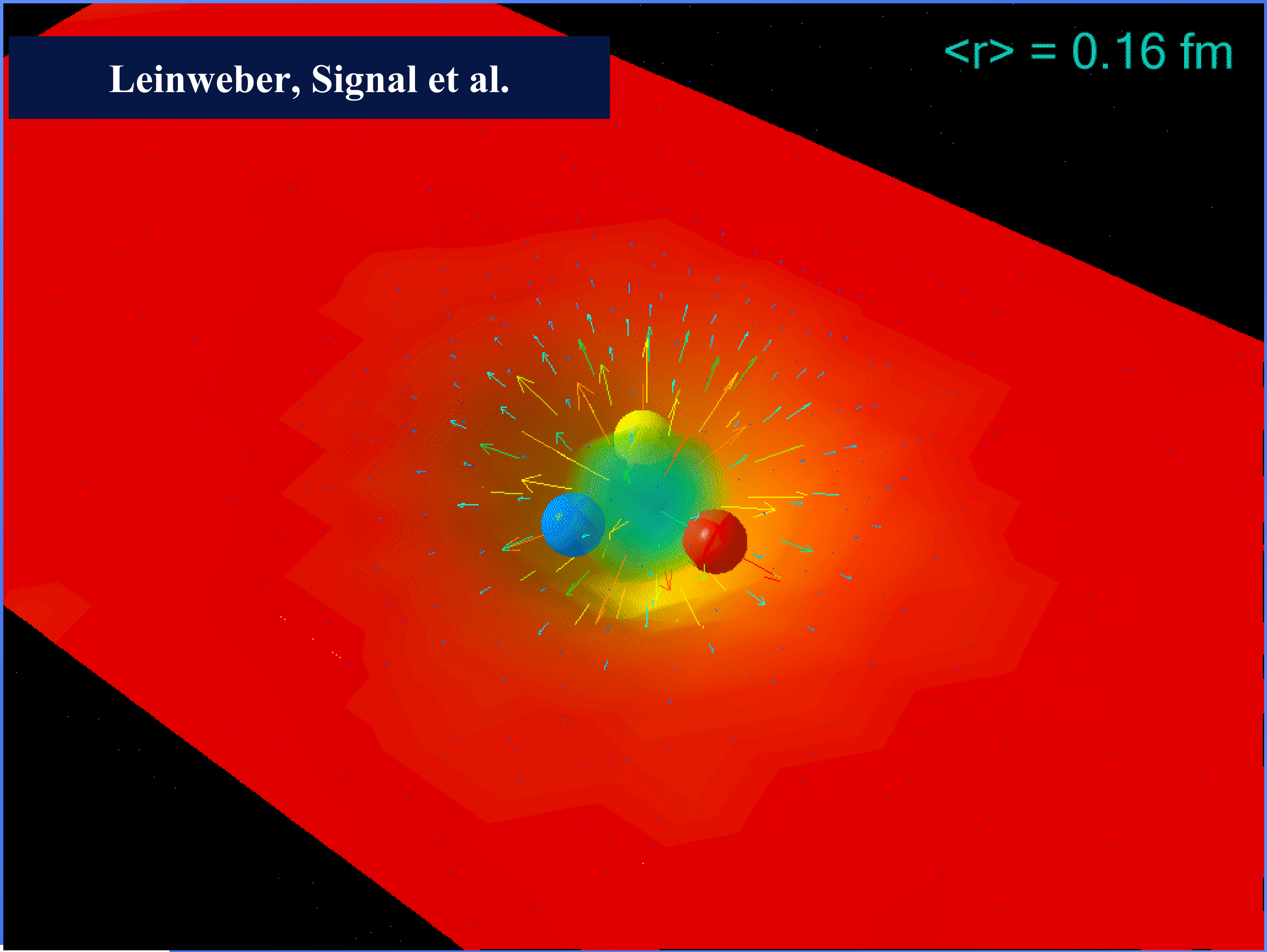
and last term is as big as 20 MeV (or more)
i.e. presence of nucleon "cleans out" vacuum to some extent

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!

Lattice QCD Simulation of Vacuum Structure



Strangeness Widely Believed to Play a Major Role – Does It?

- As much as 100 to 300 MeV of proton mass:

$$M_N = \langle N(P)| -\frac{9\,\alpha_s}{4\pi}\,\mathrm{Tr}(G_{\mu\nu}G^{\mu\nu}) + m_u\bar{\psi}_u\psi_u + m_d\bar{\psi}_d\psi_d + m_s\bar{\psi}_s\psi_s|N(P)\rangle$$

$$\Delta M_N^{s-\mathrm{quarks}} = \frac{y m_s}{m_u + m_d}\sigma_N$$

y=0.2 $\pm$ 0.2

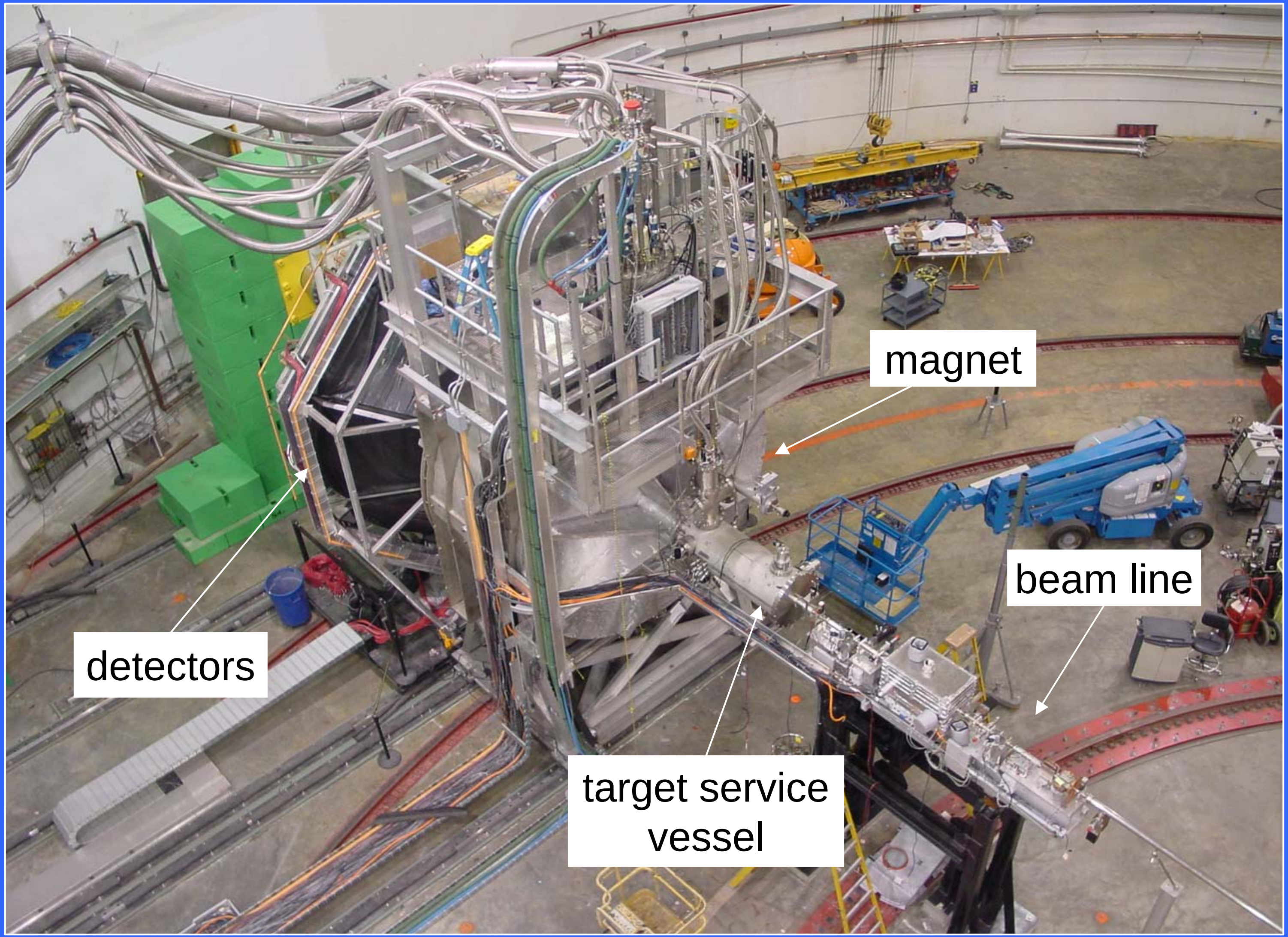
45 $\pm$ 8 MeV (or 70?)

Hence 110 $\pm$ 110 MeV (increasing to 180 for higher σ_N)

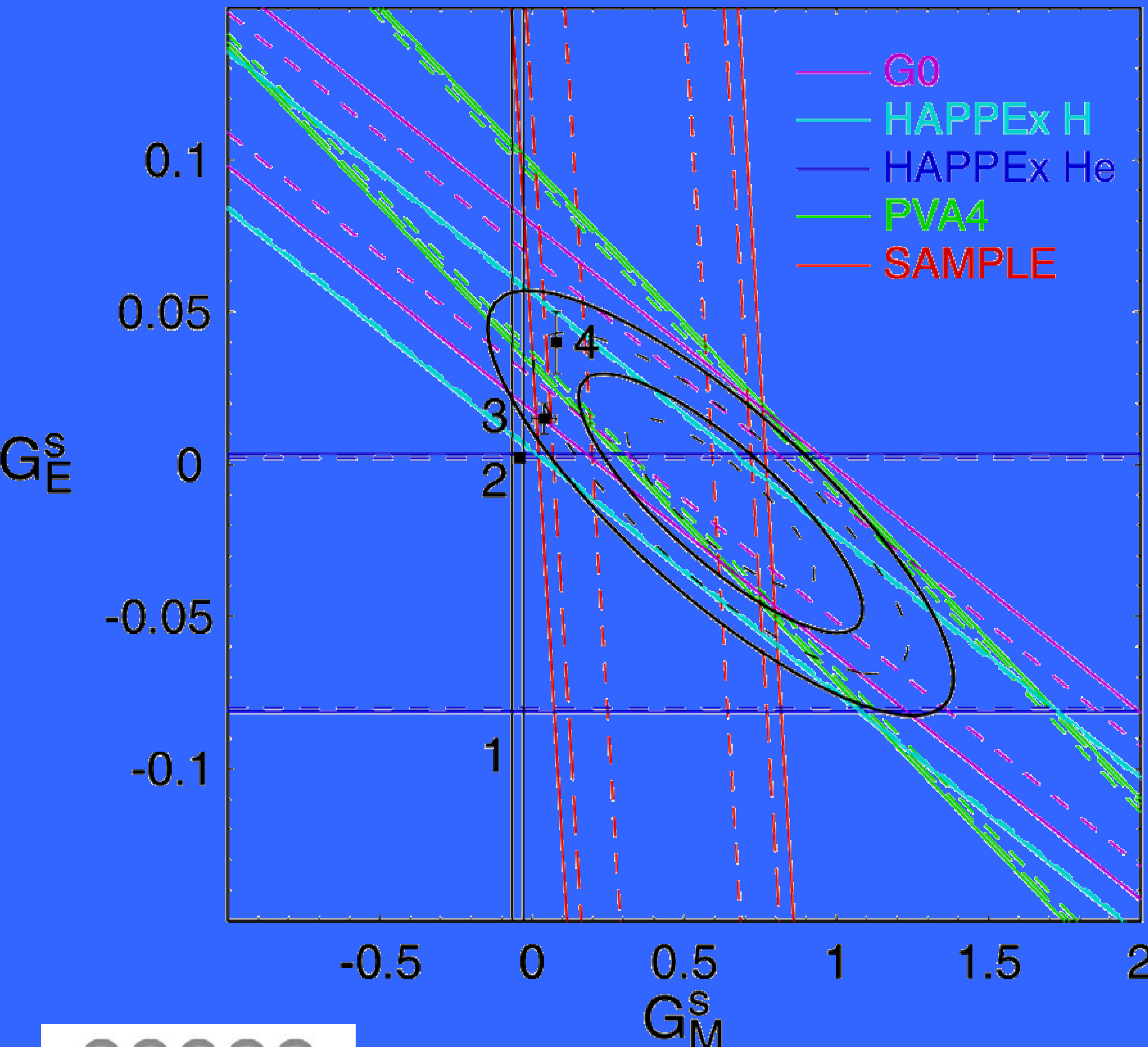
- Through proton spin crisis:
  As much as 10% of the spin of the proton

- HOW MUCH OF THE MAGNETIC FORM FACTOR?

G0 Experiment at Jefferson Lab



World Data @ $Q^2 = 0.1$ GeV^2



$G_E^s = -0.013 \pm 0.028$

$G_M^s = +0.62 \pm 0.31$

$\pm 0.62 \; 2\sigma$

<u>Contours</u>

----- 1σ, 2σ

—— 68.3, 95.5% CL

<u>Theories</u>

1. Leinweber, et al. PRL **94** (05) 212001
2. Lyubovitskij, et al. PRC **66** (02) 055204
3. Lewis, et al. PRD **67** (03) 013003
4. Silva, et al. PRD **65** (01) 014016

Significance & Comparison with Lattice QCD

- Size and sign of the strange magnetic moment is astonishing!

- Experimental isoscalar nucleon moment is 0.88 μ_N

  c.f. this result which is (Beck) - 0.54 μ_N : i.e. - 60% !!

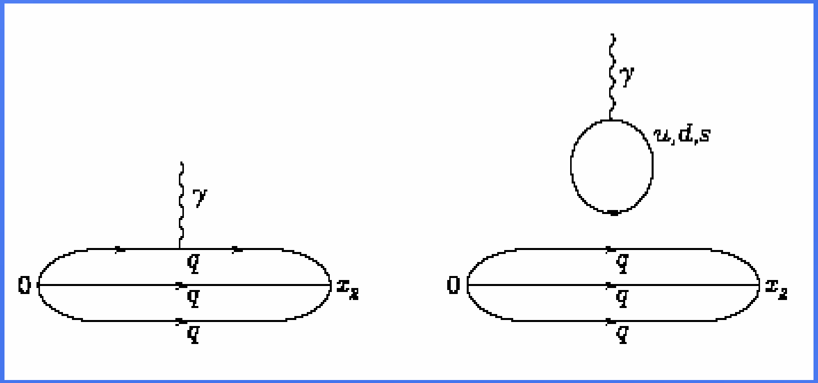
- Also remarkable versus lattice QCD which gives

  $+0.03 \pm 0.01\ \mu_N$ (Leinweber et al., PRL 94 (2005) 212001)

- Sign would require violation of universality of

  valence quark moments by $\sim$ 70% !

Magnetic Moments within QCD



CS

$p = 2/3\ u^p - 1/3\ d^p + O_N$

$n = -1/3\ u^p + 2/3\ d^p + O_N$

$\Rightarrow$ $2p + n = u^p + 3\ O_N$

(and $p + 2n = d^p + 3\ O_N$)

$\Sigma^+ = 2/3\ u^\Sigma - 1/3\ s^\Sigma + O_\Sigma$

$\Sigma^- = -1/3\ u^\Sigma - 1/3\ s^\Sigma + O_\Sigma$

$\Rightarrow$ $\Sigma^+ - \Sigma^- = u^\Sigma$

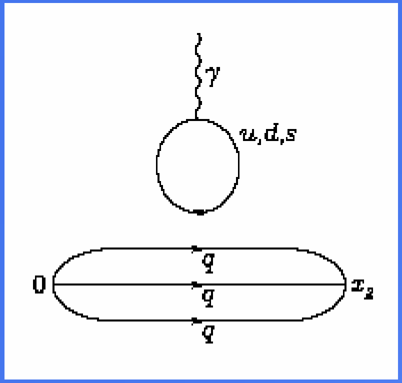
HENCE: $O_N = 1/3\ [\ 2p + n - (\ u^p / u^\Sigma\ )\ (\Sigma^+ - \Sigma^-)\ ]$

Just these ratios from Lattice QCD

OR $O_N = 1/3\ [\ n + 2p - (\ u^n / u^\Xi\ )\ (\Xi^0 - \Xi^-)\ ]$

Constraint from Charge Symmetry

$$
\begin{aligned}
O_N &= \frac{2}{3}\,{}^{\ell}G_M^u - \frac{1}{3}\,{}^{\ell}G_M^d - \frac{1}{3}\,{}^{\ell}G_M^s \\
&= \frac{1}{3}\left({}^{\ell}G_M^d - {}^{\ell}G_M^s\right)\,, \\
&= \frac{{}^{\ell}G_M^s}{3}\left(\frac{1 - {}^{\ell}R_d^s}{{}^{\ell}R_d^s}\right)\,,
\end{aligned}
$$

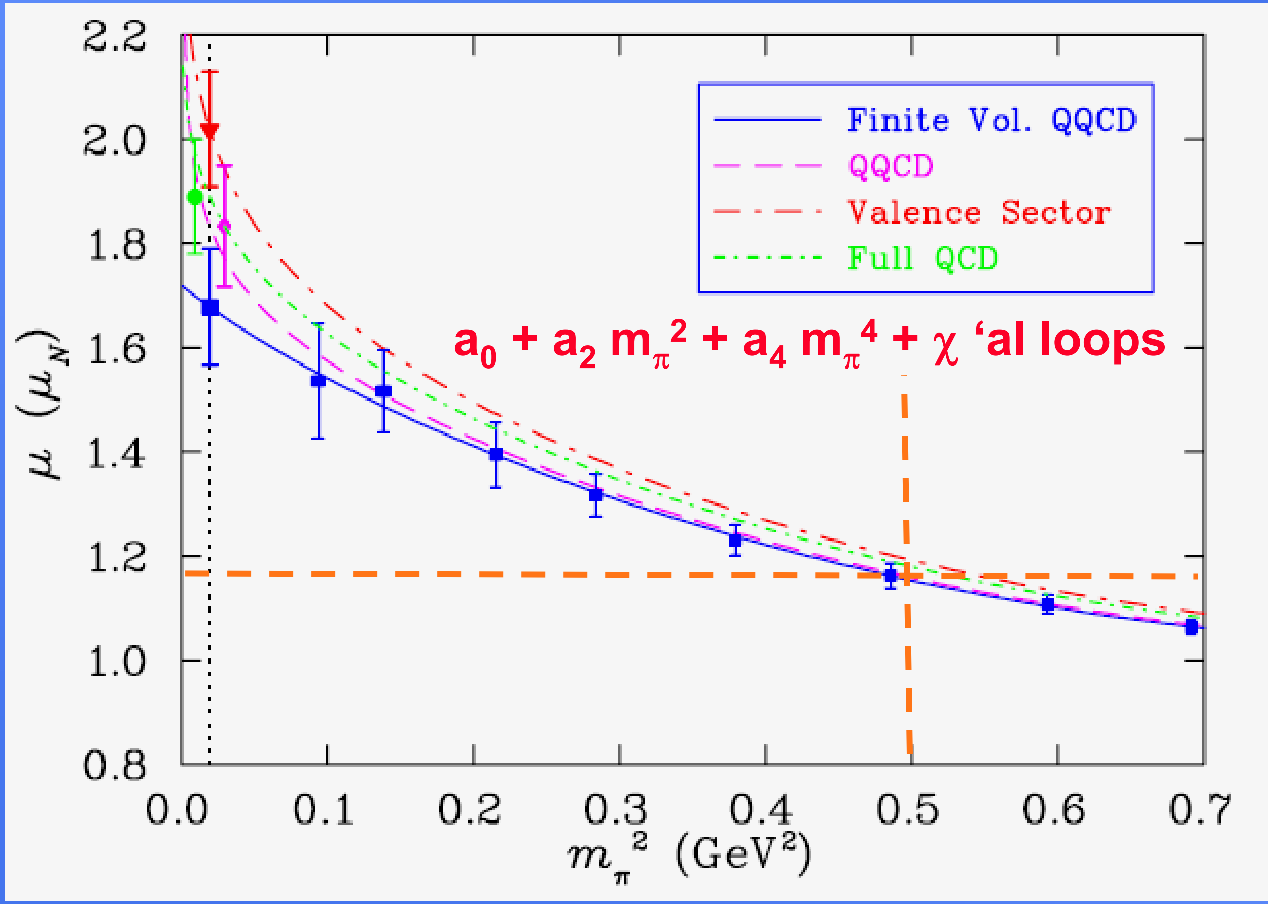


$$
G_M^s = \left(\frac{{}^{\ell}R_d^s}{1 - {}^{\ell}R_d^s}\right)\left[3.673 - \frac{u_p}{u_{\Sigma^+}}\,(3.618)\right]
$$

$$
G_M^s = \left(\frac{{}^{\ell}R_d^s}{1 - {}^{\ell}R_d^s}\right)\left[-1.033 - \frac{u_n}{u_{\Xi^0}}\,(-0.599)\right]
$$

Leinweber and Thomas, Phys. Rev. D62 (2000) 07505.

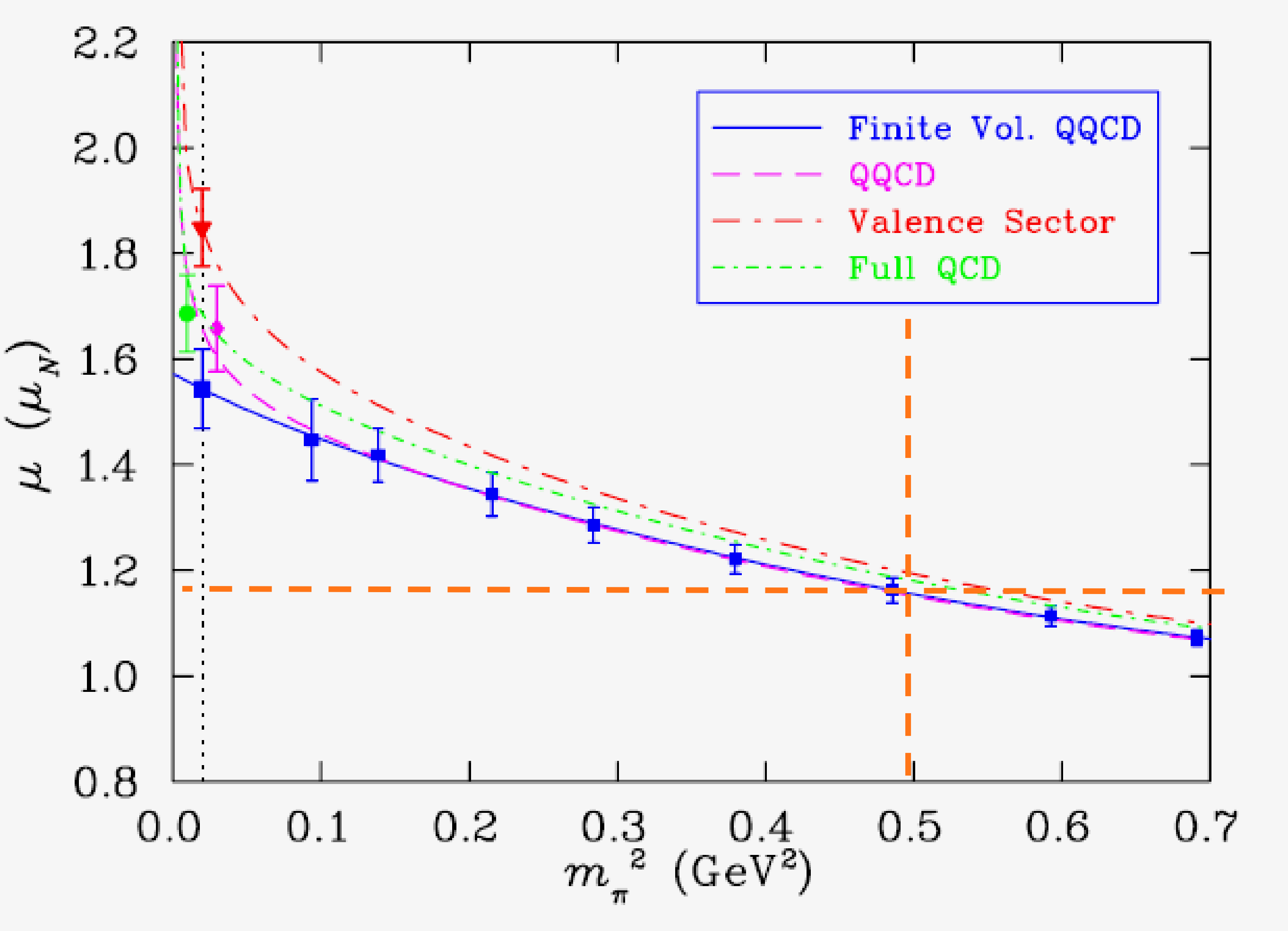
$u^p_{valence}$: QQCD Data Corrected for Full QCD Chiral Coeff's



c.f. CQM 2/3 940/540 ~ 1.18

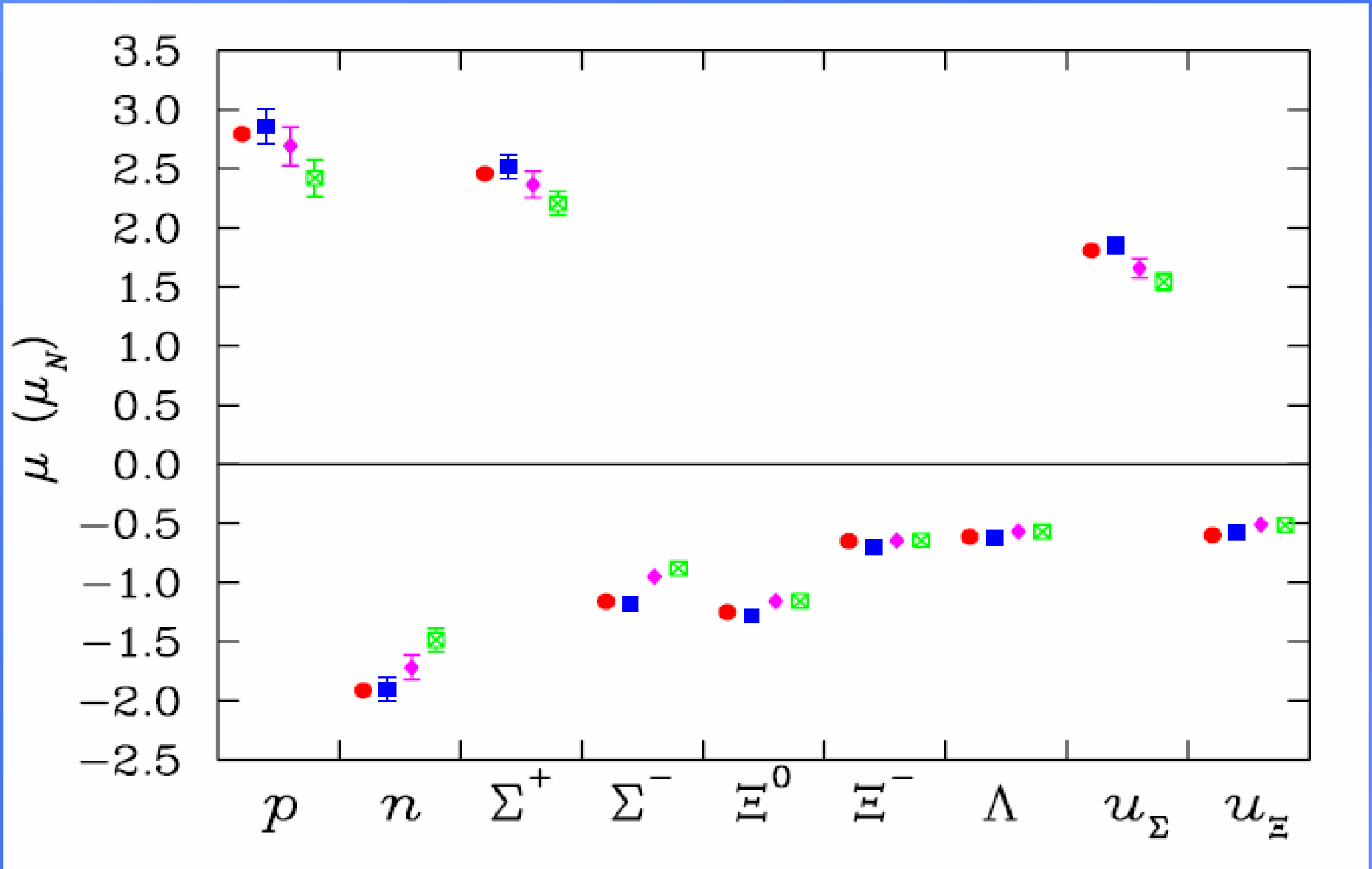
New lattice data from Zanotti et al. ; Chiral analysis Leinweber et al.

u^{Σ} valence



Universal Here!

Check: Octet Magnetic Moments



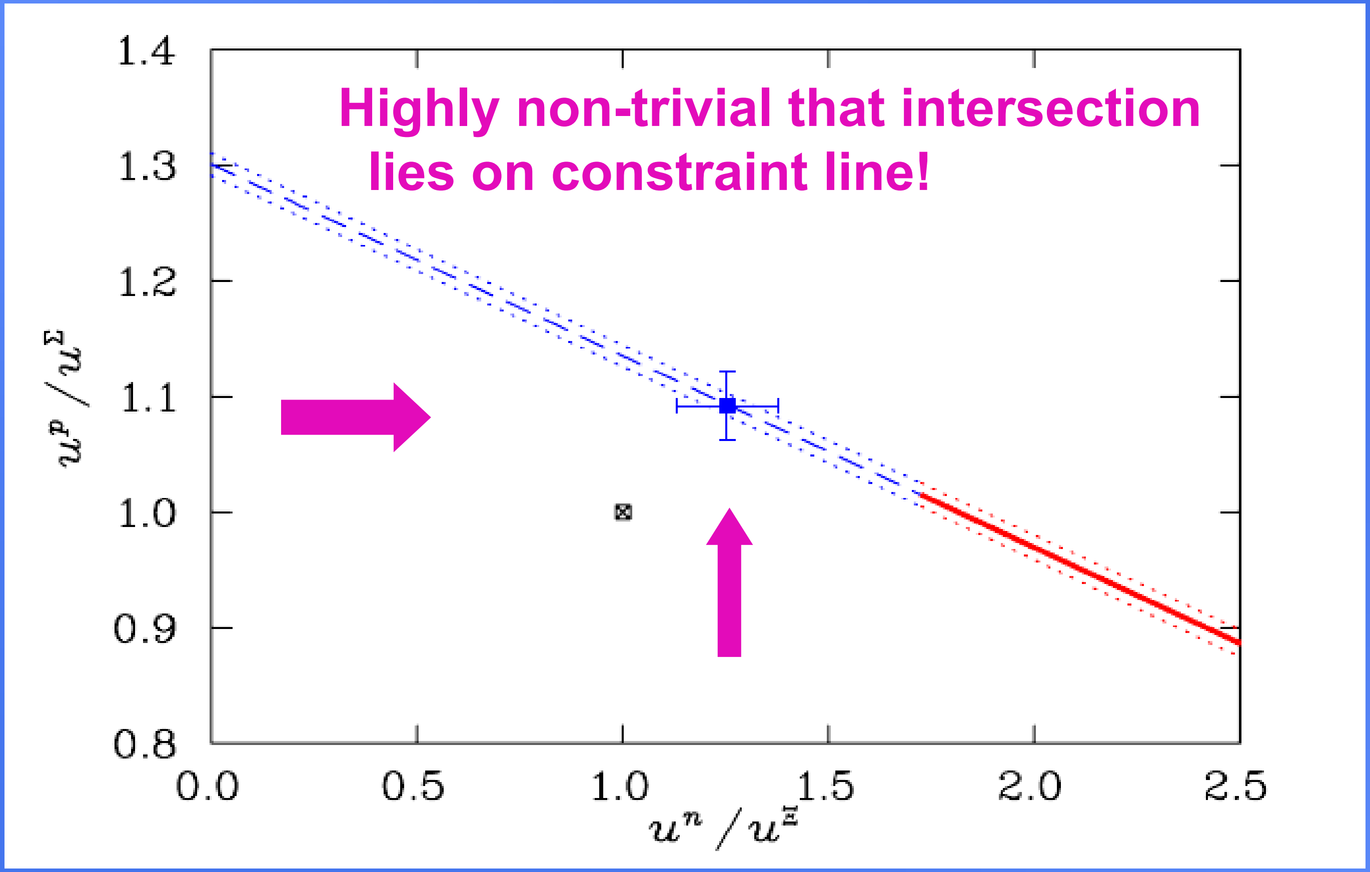
Leinweber et al., hep-lat/0406002

State of the ART Magnetic Moments

	QQCD	Valence	Full QCD	Expt.
p	2.69 (16)	2.94 (15)	2.86 (15)	2.79
n	-1.72 (10)	-1.83 (10)	-1.91 (10)	-1.91
Σ^+	2.37 (11)	2.61 (10)	2.52 (10)	2.46 (10)
Σ^-	-0.95 (05)	-1.08 (05)	-1.17 (05)	-1.16 (03)
Λ	-0.57 (03)	-0.61 (03)	-0.63 (03)	-0.613 (4)
Ξ^0	-1.16 (04)	-1.26 (04)	-1.28 (04)	-1.25 (01)
Ξ^-	-0.65 (02)	-0.68 (02)	-0.70 (02)	-0.651 (03)
u^p	1.66 (08)	1.85 (07)	1.85 (07)	1.81 (06)
u^Ξ	-0.51 (04)	-0.58 (04)	-0.58 (04)	-0.60 (01)

Accurate Final Result for G_M^s

1.10±0.03



1.25±0.12

Yields : $G_M^s = -0.046 \pm 0.019\ \mu_N$

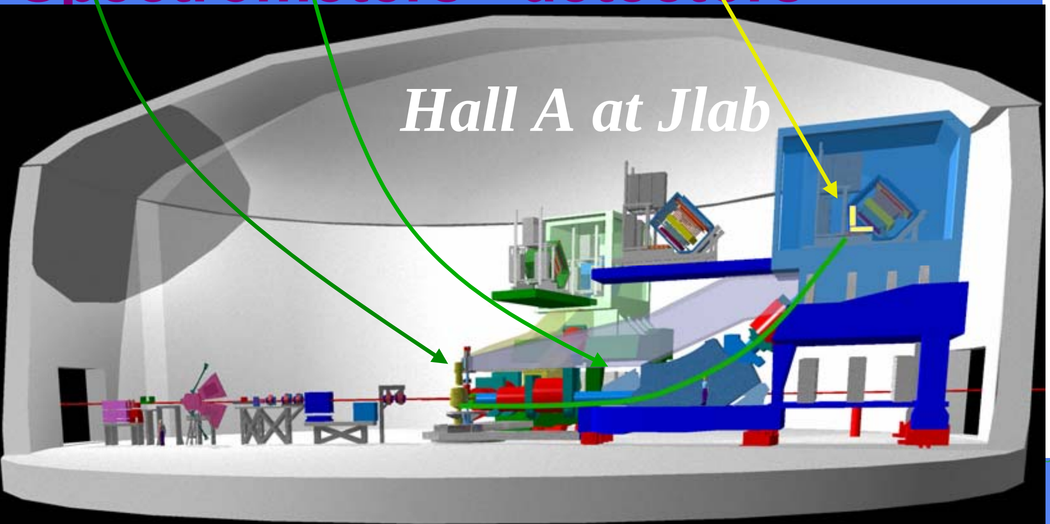
Leinweber et al., (PRL June ’05) hep-lat/0406002

Parity Violating Studies on ^{1}H and ^{4}He

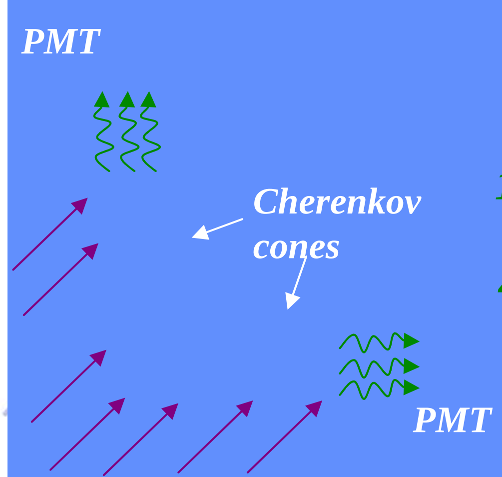
3 GeV beam in Hall A $\theta_{lab} \sim 6°$ $Q^2 \sim 0.1\ (GeV/c)^2$

target	A_{PV} $G^s = 0$ (ppm)	Stat. Error (ppm)	Syst. Error (ppm)	sensitivity
^{1}H	-1.6	0.08	0.04	$\delta(G^s_E + 0.08 G^s_M) = 0.010$
^{4}He	+7.8	0.18	0.18	$\delta(G^s_E) = 0.015$

Septum magnets (not shown)
High Resolution Spectrometers detectors



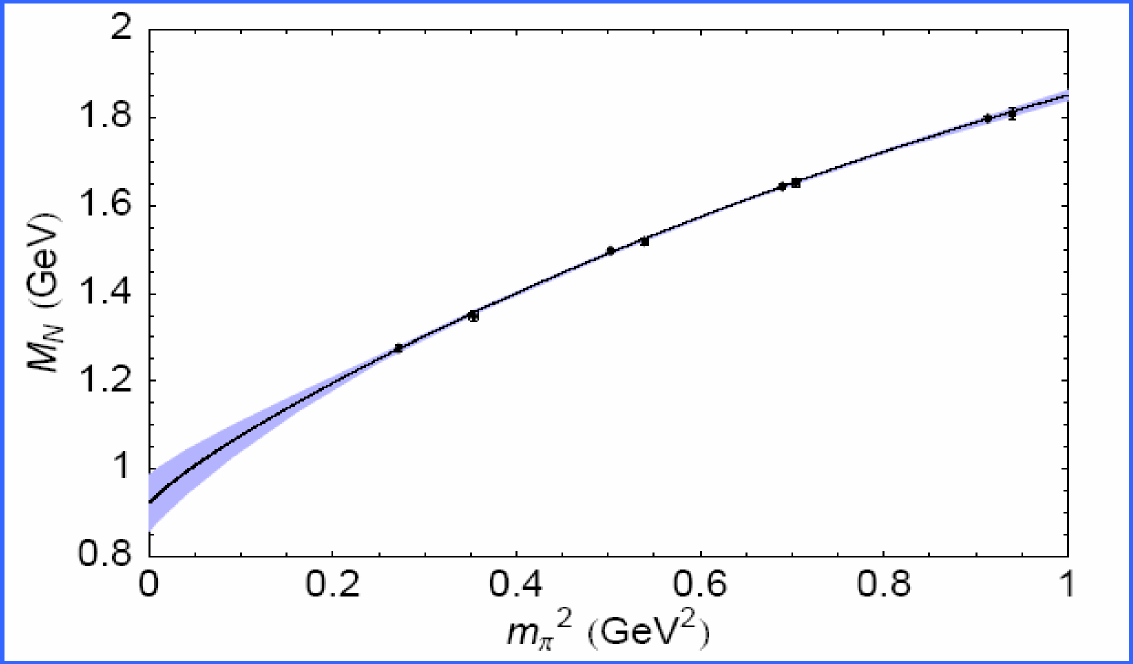
Brass-Quartz integrating detector



Elastic Rate:
^{1}H: 120 MHz
^{4}He: 12 MHz

Background ≤ 3%

χ'al Extrapolation Under Control when Coefficients Known – e.g. for the nucleon

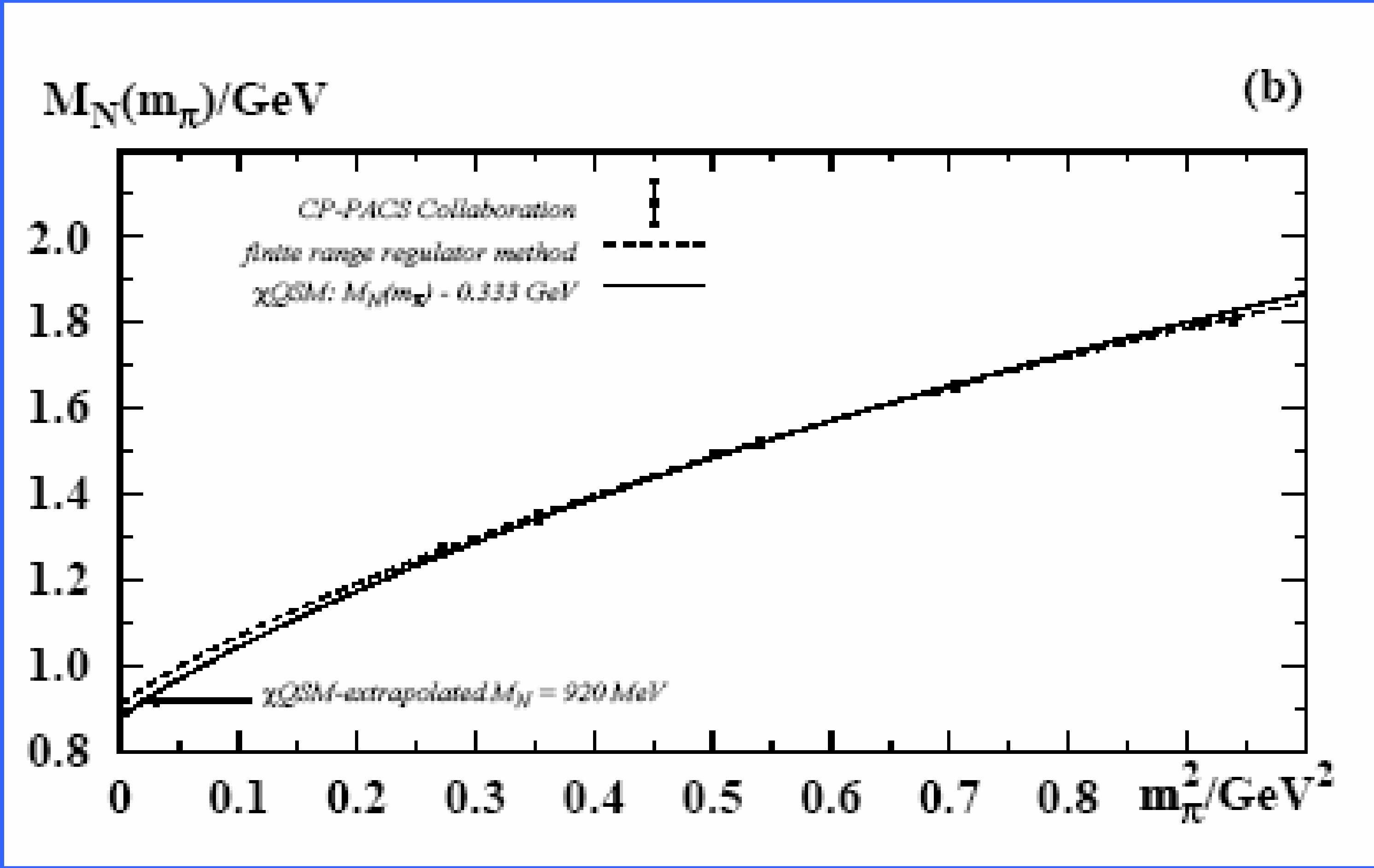


FRR give same answer to <<1% systematic error!

	Bare Coefficients				Renormalized Coefficients			
Regulator	a_0^Λ	a_2^Λ	a_4^Λ	Λ	c_0	c_2	c_4	m_N
Monopole	1.74	1.64	−0.49	0.5	0.923(65)	2.45(33)	20.5(15)	0.960(58)
Dipole	1.30	1.54	−0.49	0.8	0.922(65)	2.49(33)	18.9(15)	0.959(58)
Gaussian	1.17	1.48	−0.50	0.6	0.923(65)	2.48(33)	18.3(15)	0.960(58)
Sharp cutoff	1.06	1.47	−0.55	0.4	0.923(65)	2.61(33)	15.3(8)	0.961(58)
Dim. Reg. (BP)	0.79	4.15	+8.92	–	0.875(56)	3.14(25)	7.2(8)	0.923(51)

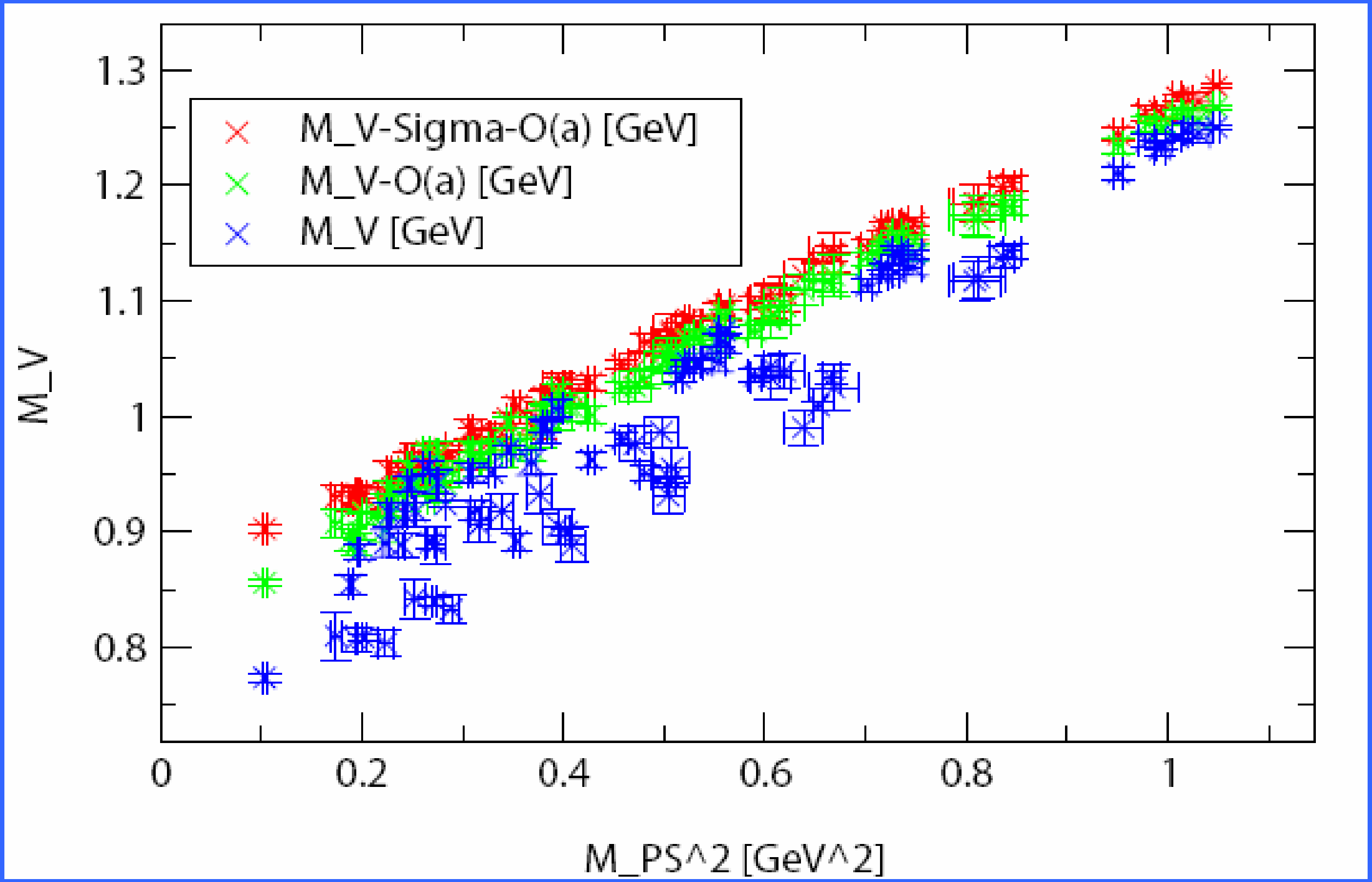
Leinweber et al., PRL 92 (2004) 242002

Comparison with χ QSM



Goeke *et al.*, hep-lat/0505010

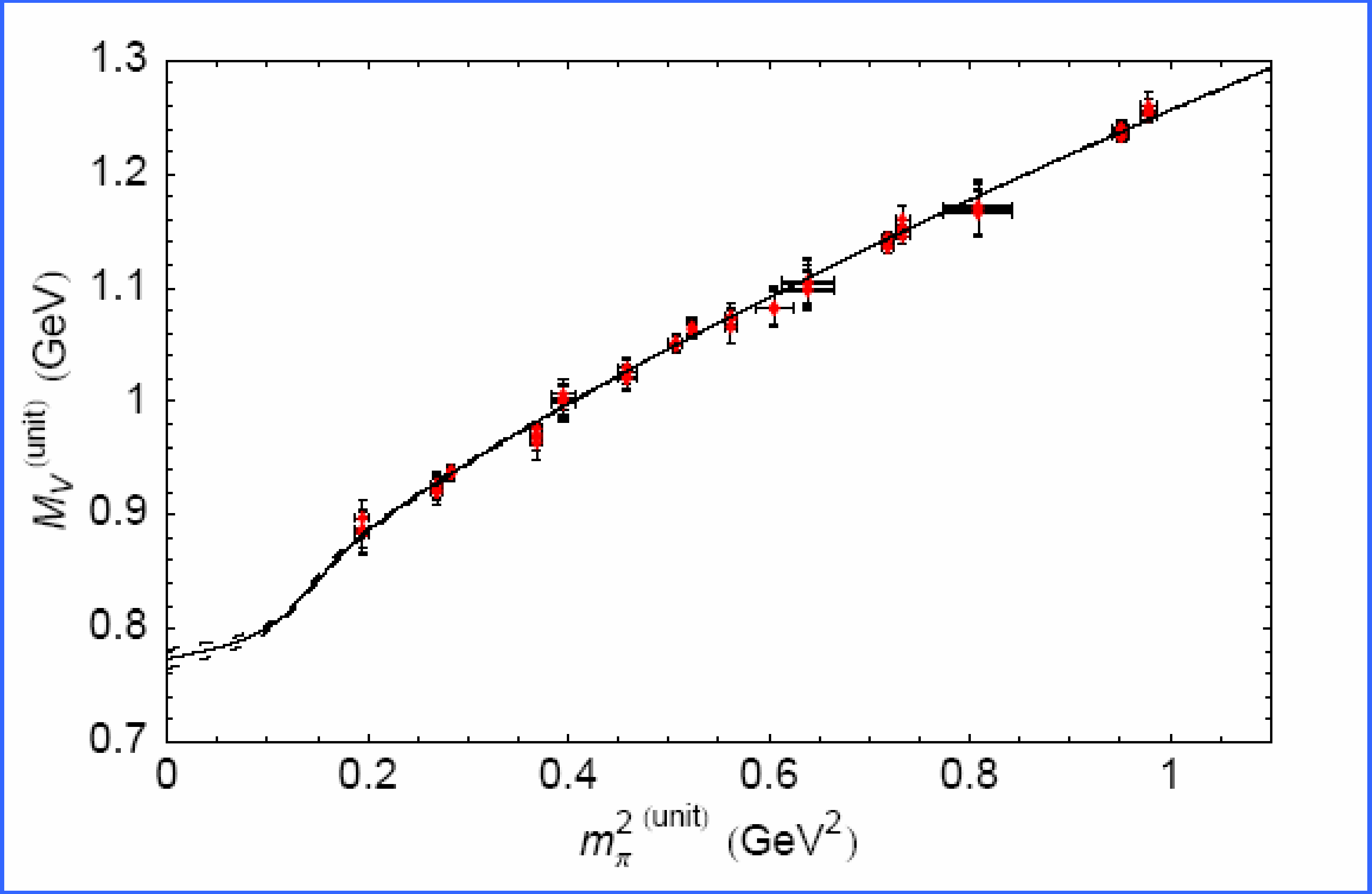
Analysis of pQQCD ρ data from CP PACS



$$\sqrt{(M_V^{deg})^2 - \Sigma_{TOT}} = (a_0^{cont} + X_1 a + X_2 a^2) + a_2 (M_{PS}^{deg})^2 + a_4 (M_{PS}^{deg})^4 + a_6 (M_{PS}^{deg})^6$$

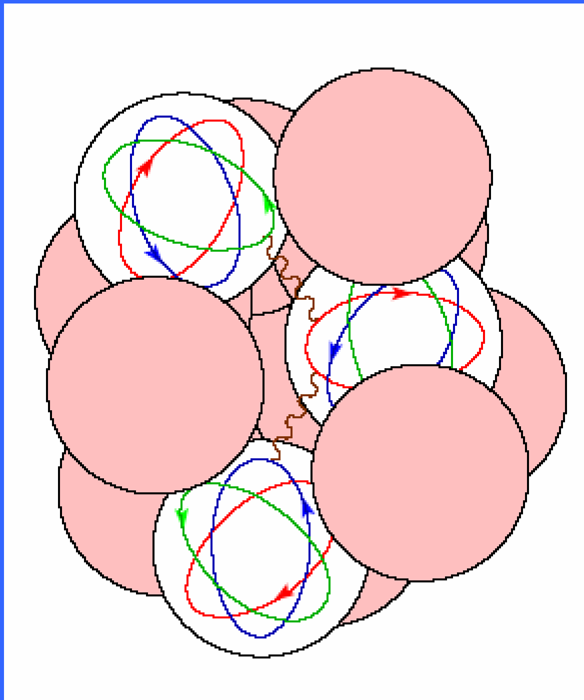
Infinite Volume Unitary Results

All 80 data points drop onto single, well defined curve



Allton, Young *et al.*, hep-lat/0504022

Nuclear Structure in Terms of QCD



Aim for :

- New physical insight into nuclear structure
- e.g. new mechanism for nuclear saturation!
- Precursors of the deconfinement transition?
- Guidance as to signals of deconfinement transition
- Signals of chiral restoration as density rises….
- **Changes in hadron properties in-medium !**

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 $\Rightarrow$ I=0, $J^{\pi} = 0^{+}$ channel dominates intermediate range attraction
  (origin two-pion $\approx \sigma$ exchange)

- Modern version: Machleidt et al., RBHF $\Rightarrow g_{\sigma}\, \sigma \approx 400$ MeV

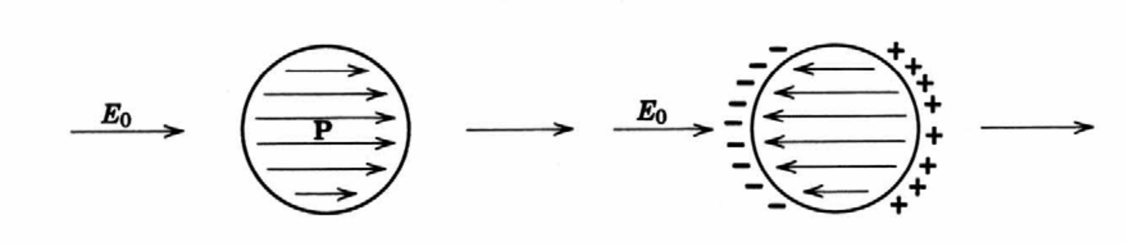
i.e. There are strong ($\sim 0.4\ M_N$) Lorentz scalar fields in nuclei……..

so what?

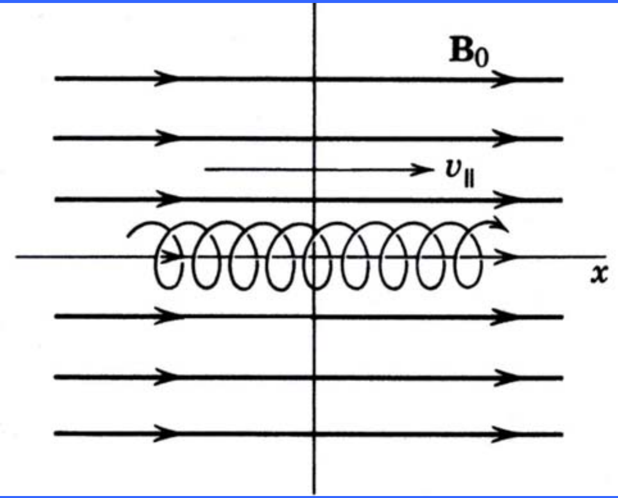
What happens if we put an atom in a strong electric field?

Jackson ⇒

i.e. atom has a polarizability: its internal structure is rearranged in response to applied field



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



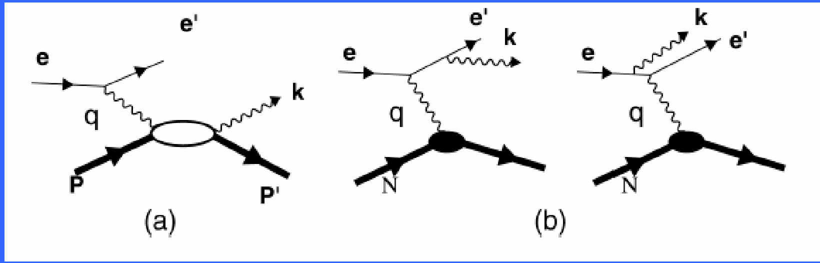
Electric & Magnetic Polarizabilities of Nucleon are Measured

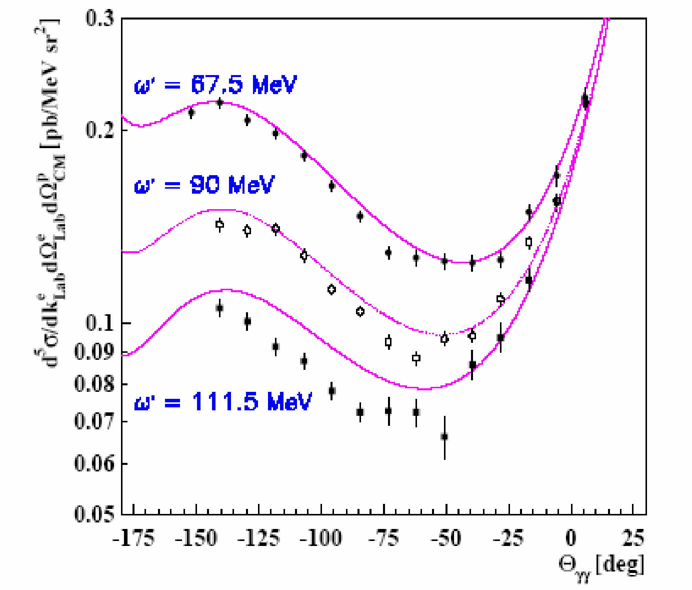
e.g. Compton scattering:

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

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

Also Virtual Compton Scattering ⇒ GPs



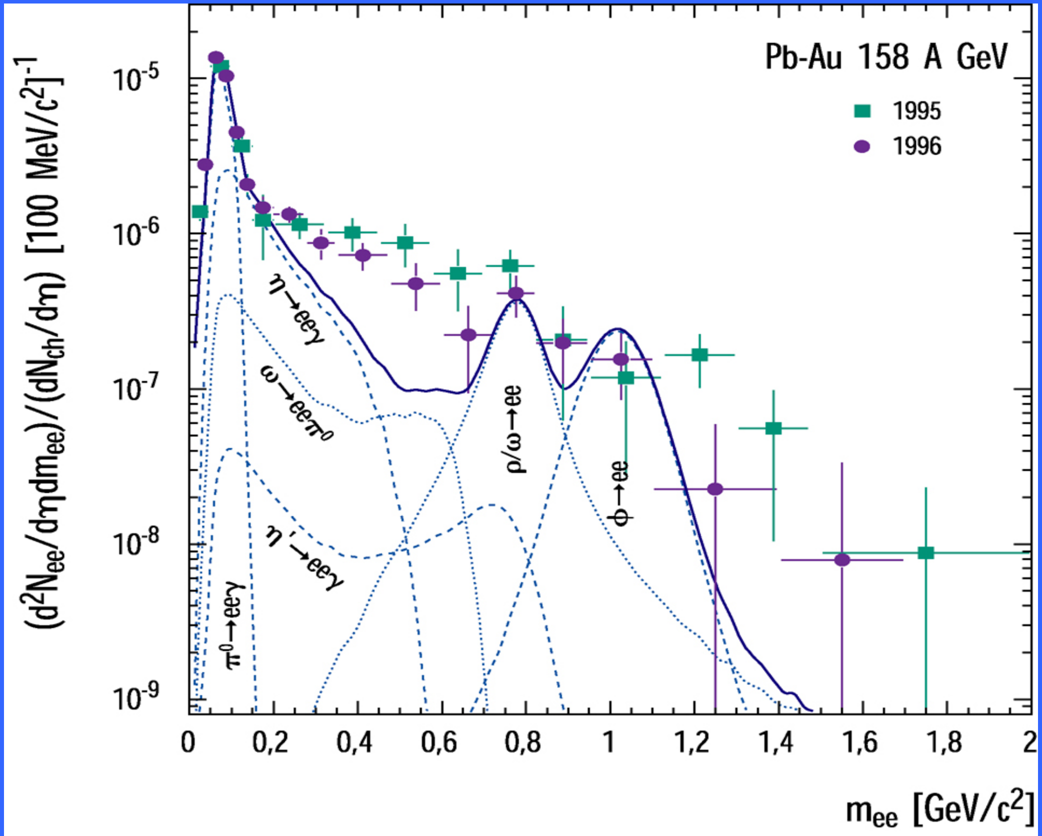


So what?

- Atoms respond to external E and B fields

- Nucleons respond to external E and B fields

- Nucleons must respond large scalar fields in-medium !
  (scalar polarizability)

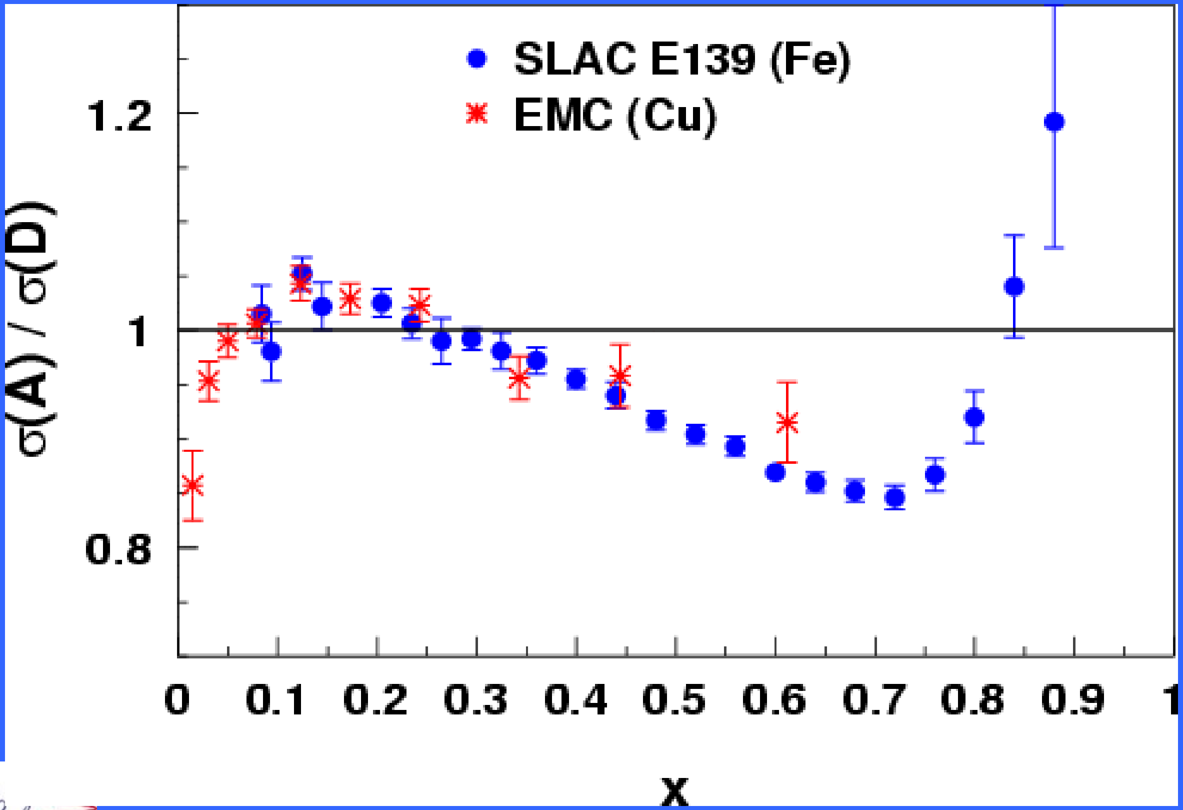


- Change of hadron mass $m \to m^*$ is accepted and studied

What about other properties?

Classic Illustration: The EMC effect

- Observation stunned and electrified the HEP community 20 years ago
- Nearly one thousand papers have been generated…..
- 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)

Parton Distribution Functions of Nuclei

For those old enough to remember there were two responses to 1983 EMC discovery

a) Complete shock

b) 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!

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

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

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

Non-linear dependence ≡ scalar polarizability

d ≈ 0.22 R in original QMC (MIT bag)

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

Quark-Meson Coupling Model: QMC*

Intermediate step to full quark-gluon theory of ∞ nuclear matter

- Use successful model of hadron structure : MIT Bag
- Couple scalar (σ: 0^+) and vector (ω: 1^-) mesons to confined quarks
- Confined quarks generate mean scalar and vector fields
- Scalar field changes confined quark wave function

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

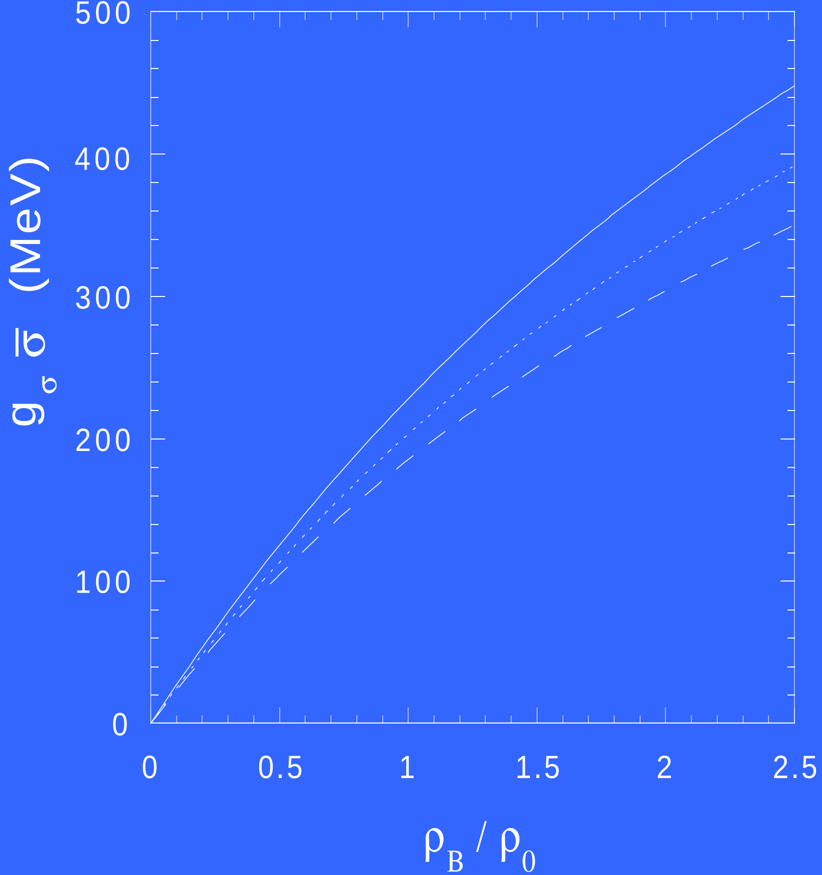
- This changes source……

*Guichon, Phys. Lett. B200 (1988) 235; Saito & Thomas, Phys. Lett. B327 (1994) 9

Review: Saito et al., hep-ph/0506314

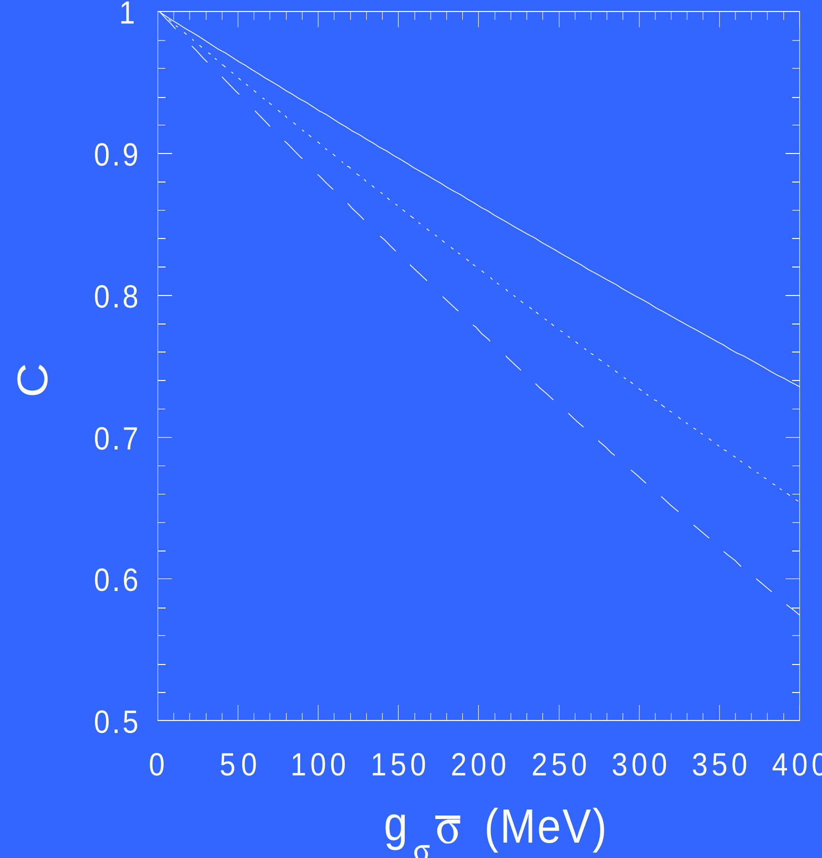
Numerical Results

Scalar mean-field $\sim$ 1/3rd of QHD



Decrease of $g_\sigma(\sigma)$ as density ↑

(effect of scalar polarizability)



QMC: Generalization to Finite Nuclei*

*Guichon, Saito, Rodionov & Thomas: Nucl. Phys. A601 (1996) 349

- Use Born-Oppenheimer approximation…
  i.e. assume internal "nucleon" structure
  adjusts to local mean scalar field

$\Rightarrow$ 3% accuracy in typical nuclei

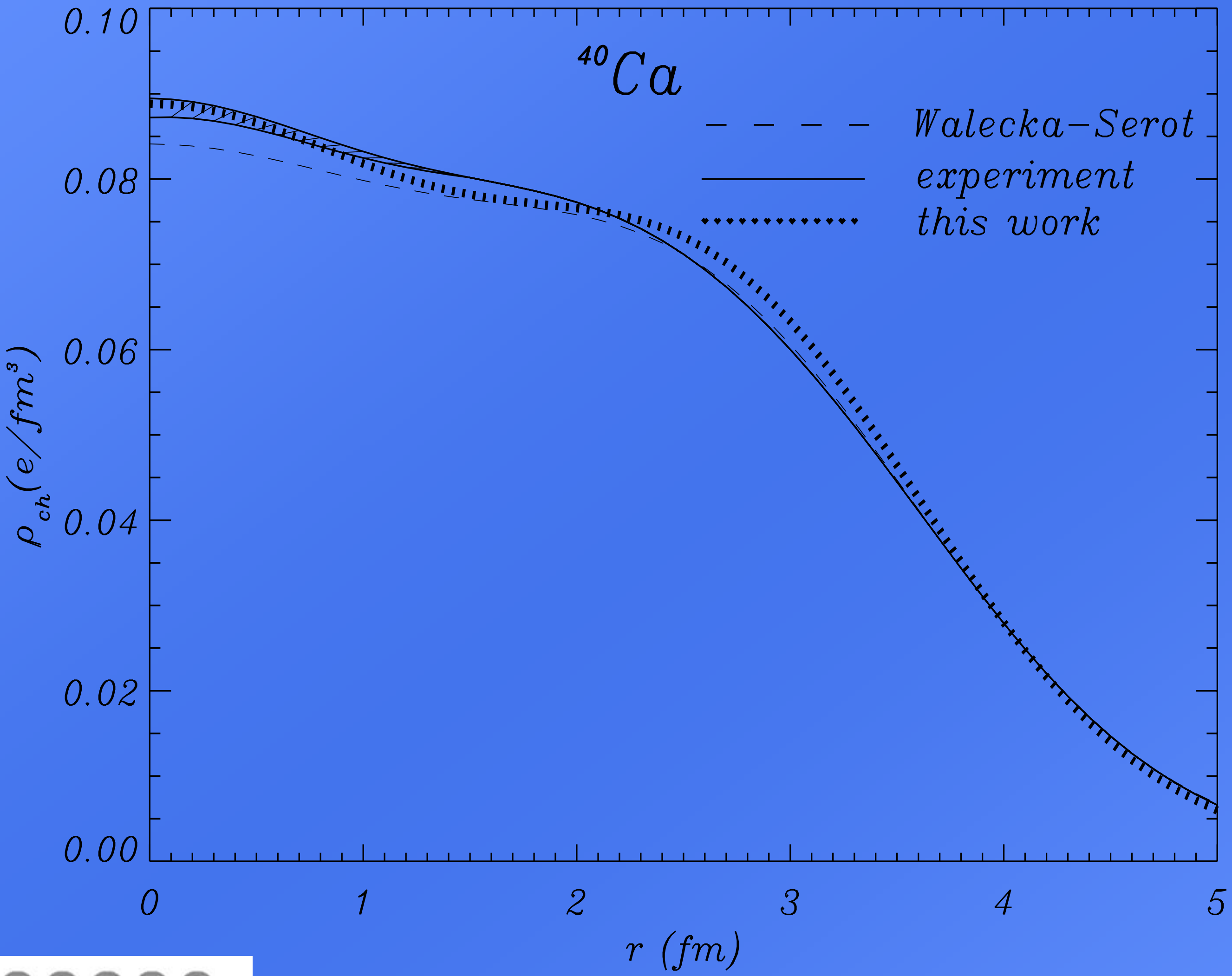
- I KNOW OF NO OTHER WAY TO DERIVE EXISTENCE OF NUCLEI WITHIN QCD

$\Rightarrow$ *CHANGE IN PARADIGM*

- everyone has heard of <u>shell model</u>

BUT: what occupies shell model orbits are NOT free nucleons

Application of QMC to Nuclear Density



Guichon, Saito, Rodionov & Thomas, Nucl. Phys. A601 (1996) 349

Linking QMC to Familiar Nuclear Theory

- Since early 70's tremendous amount of work in nuclear theory is based upon effective force
- Used for everything from nuclear astrophysics to collective excitations of nuclei
- Skyrme Force: Vautherin and Brink
- Systematic phenomenology analogous to phase shifts connecting data and deeper derivation of NN force

P. Guichon and A.W. Thomas, Phys. Rev. Lett. 93, 132502 (2004)

Effective Interaction is of Skyrme III Type :

$$V = t_3 \sum_{i<j<k} \delta(\vec{R}_{ij})\delta(\vec{R}_{jk}) + t_0 \sum_{i<j} (1 + x_0 P_\sigma)\delta(\vec{R}_{ij})$$

$$+ \frac{1}{4} t_2 \overleftarrow{\nabla}_{ij} . \delta(\vec{R}_{ij}) \vec{\nabla}_{ij} - \frac{1}{8} t_1 \left[\delta(\vec{R}_{ij}) \vec{\nabla}_{ij}^2 + \overleftarrow{\nabla}_{ij}^2 \delta(\vec{R}_{ij}) \right]$$

$$+ \frac{i}{4} W_0 (\vec{\sigma}_i + \vec{\sigma}_j) . \overleftarrow{\nabla}_{ij} \times \delta(\vec{R}_{ij}) \vec{\nabla}_{ij},$$

and from comparison with QMC ⇒

$$t_0 = -G_\sigma + G_\omega - \frac{G_\rho}{4},$$

$$t_3 = 3 d G_\sigma^2,$$

$$x_0 = -\frac{G_\rho}{2 t_0}.$$

Comparison Between Skyrme III and QMC

	QMC	QMC	SkIII	QMC(N=3)
$m_\sigma (MeV)$	500	600		600
$t_0 (MeV\ fm^3)$	-1071	-1082	-1129	-1047
x_0	0.89	0.59	0.45	0.61
$t_3 (MeV\ fm^6)$	16620	14926	14000	12996
M_{eff}/M	.915	.814	.763	.821
$5t_2 - 9t_1 (MeV\ fm^5)$	-7622	-4330	-4030	-4036
$W_0 (MeV\ fm^5)$	118	97	120	91

$$\frac{M_{eff}}{M} = \left(1 + \frac{(3t_1 + 5t_2) M \rho_0}{8}\right)^{-1}$$

Great Start: What’s Next

- Remove zero-range approximation
- Derive density-dependent forms
- Add the pion
- Derive Λ N, Σ N, Λ Λ … effective forces in-medium with no additional free parameters!
- Hence attack dense hadronic matter, n-stars, transition from NM to QM or SQM with more confidence

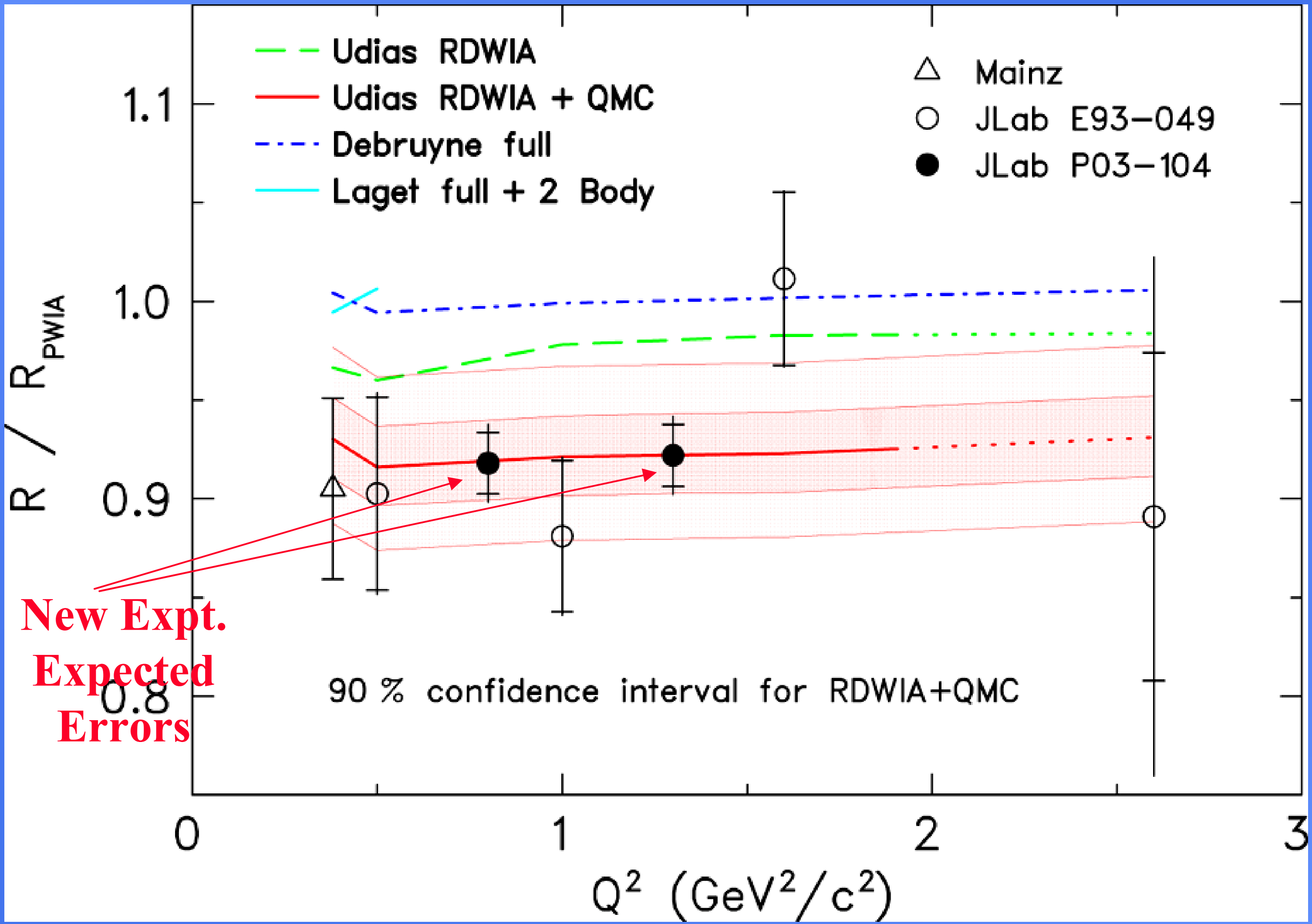
Experimental consequences

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

e.g. Experiments on both ρ and ω in
finite nuclei* show predicted mass shifts
Further tests planned for η and η'

*Trnka et al., PRL 94 (2005) 192303
Huber et al., PR C68 (2003) 065202

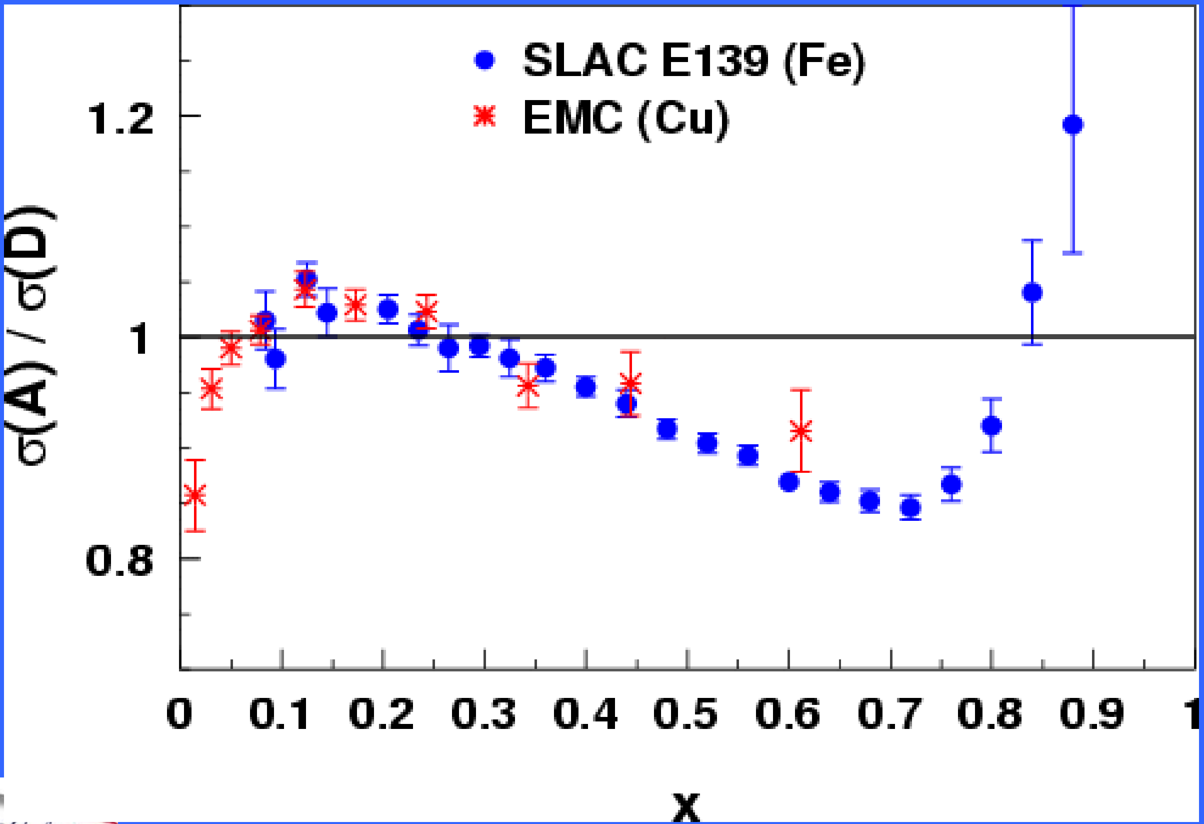
Jefferson Lab & Mainz



Properties of quark systems in-medium: Origin of the EMC effect

- Observation that structure functions are altered in nuclei stunned and electrified much of the HEP community 30 years ago

- 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)

Quark Model of QMC type: NJL with Confinement & Saturation of Nuclear Matter

- Similar to QMC of Guichon and collaborators
- Advantage that NJL is completely covariant
- Confinement modeled through "proper time regularization*" (Ebert et al., Phys Lett 388 (1996) 154)
- Saturation of nuclear matter as consequence of scalar polarizability of nucleon (response of light quarks to an applied scalar field)

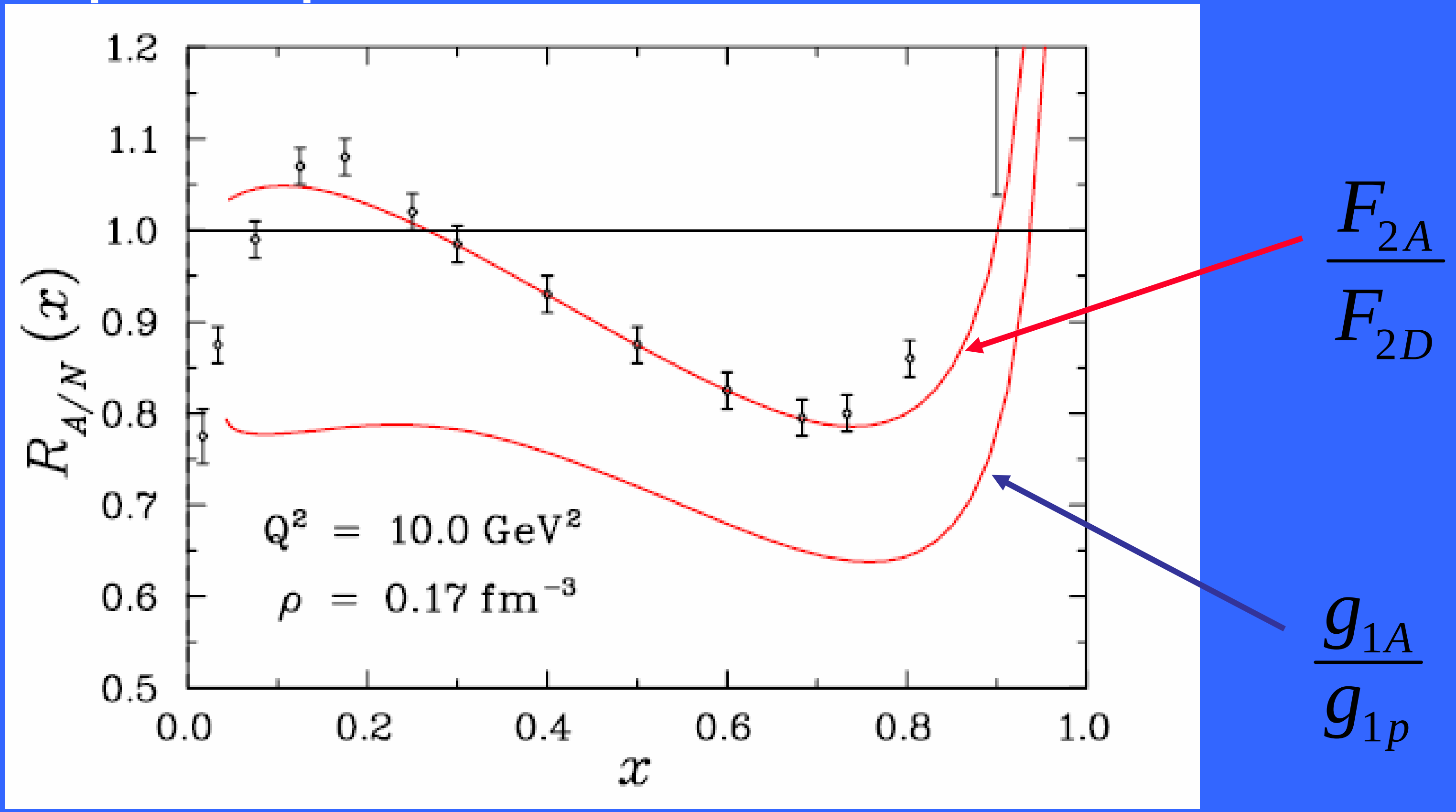
Mineo et al., Nucl Phys A735 (2004) 482

* After Feynman parameters and Wick rotation: $$\frac{1}{A^n} \rightarrow \frac{1}{(n-1)!}\int_{1/\Lambda_{IR}^2}^{1/\Lambda_{IR}^2} d\tau \tau^{n-1} e^{-\tau A} \quad (n \geq 1)$$

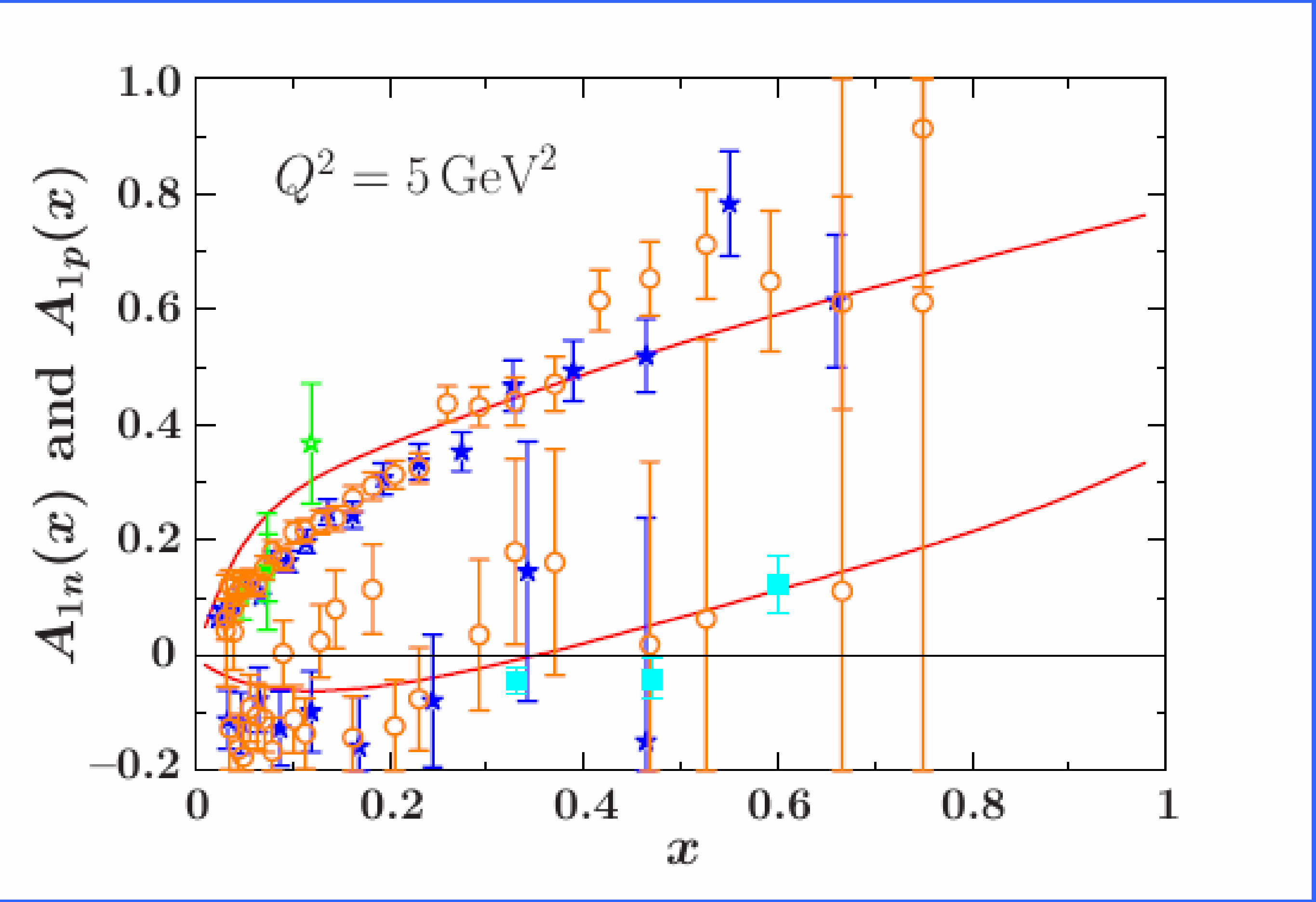
$g_1(A)$ – "Polarized EMC Effect"

- New calculations indicate larger effect for polarized structure than unpolarized: scalar field modifies lower cpts of Dirac wave function

   (Cloet, Bentz, AWT, Phys Rev Lett, to appear: nucl-th/0504019)
- Spin-dependent parton distribution functions for nuclei unknown

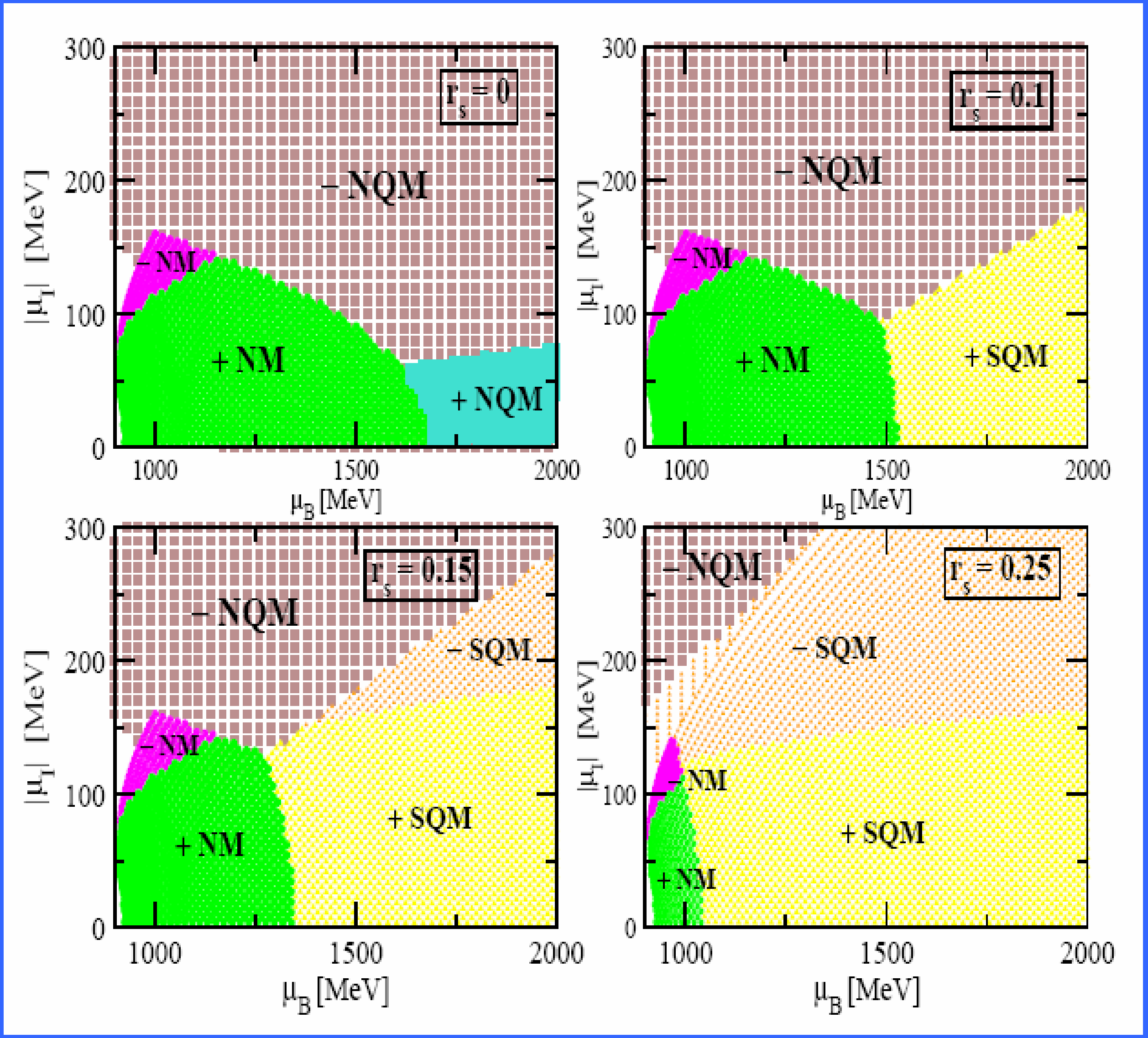


Proton and Neutron Asymmetry



Cloet, Bentz, AWT, (Phys Lett, to appear) hep-ph/0504229

Covariant, NJL model with confinement and QMC mechanism for saturation of nuclear matter



Lawley, Bentz,AWT, nucl-th/0504020

Conclusion

- Quark level approach to nuclear structure leads naturally to effective force of Skyrme type
- Numerical agreement between QMC and Skyrme III ~10%
- Key ingredient is <u>scalar polarizability</u> of nucleon
- Dramatic change to how we view shell model
- Experimental consequences just now being explored

and…. lattice QCD naturally yields scalar polarizability of correct sign and magnitude (Nishinomiya, to be published)

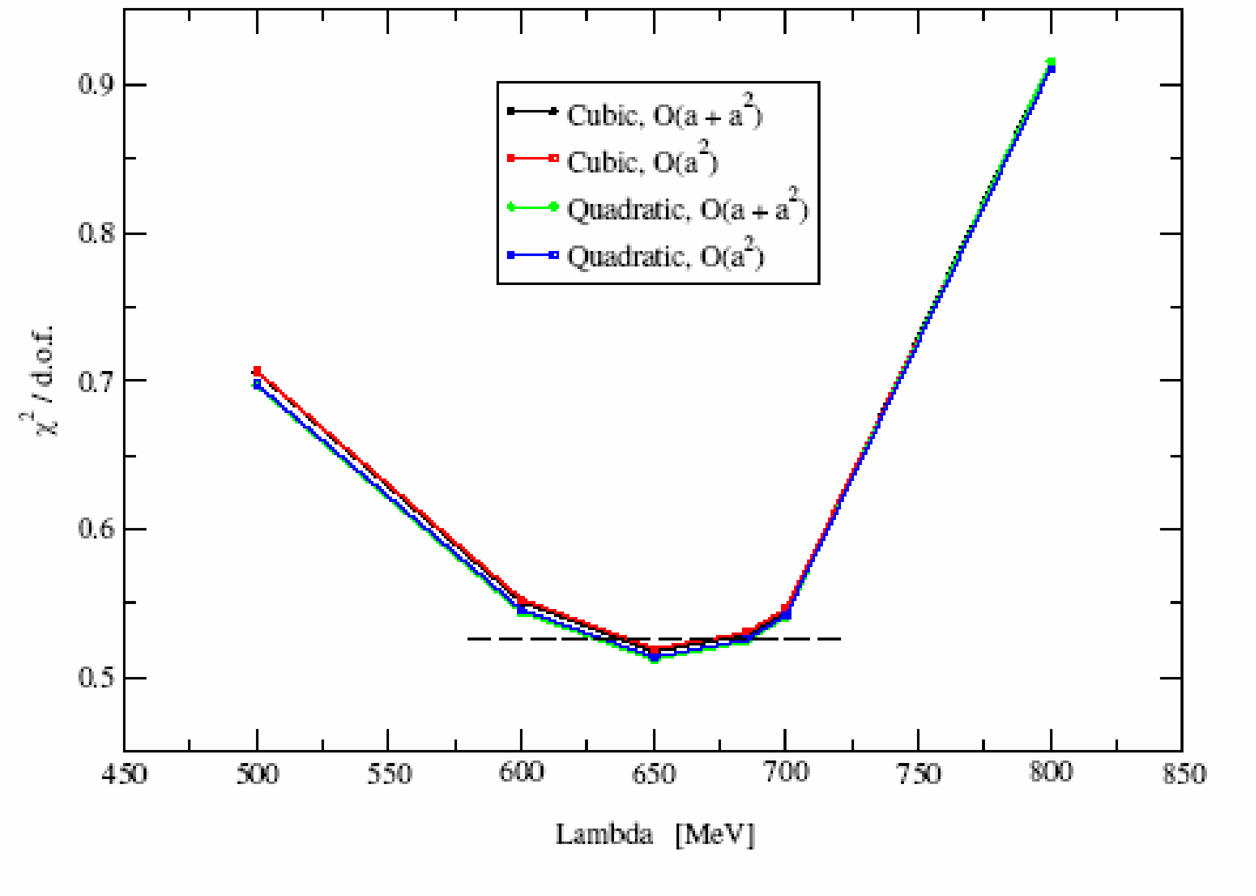
Big Picture

- QCD $\Rightarrow$ phase transition at high density (and T)
- Is dense matter (n-star) nuclear/strange/QM/superconducting QM/color condensate?
- 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 make progress

Rapid Convergence from LNA to NLNA

Regulator	LNA m_N	NLNA m_N
Dim. regulator	0.784	0.884 ± 0.103
Dim. regulator (BP)	0.784	0.923 ± 0.103
Sharp cutoff	0.968	0.961 ± 0.116
Monopole	0.964	0.960 ± 0.116
Dipole	0.963	0.959 ± 0.116
Gaussian	0.966	0.960 ± 0.116

FRR Mass well determined by data



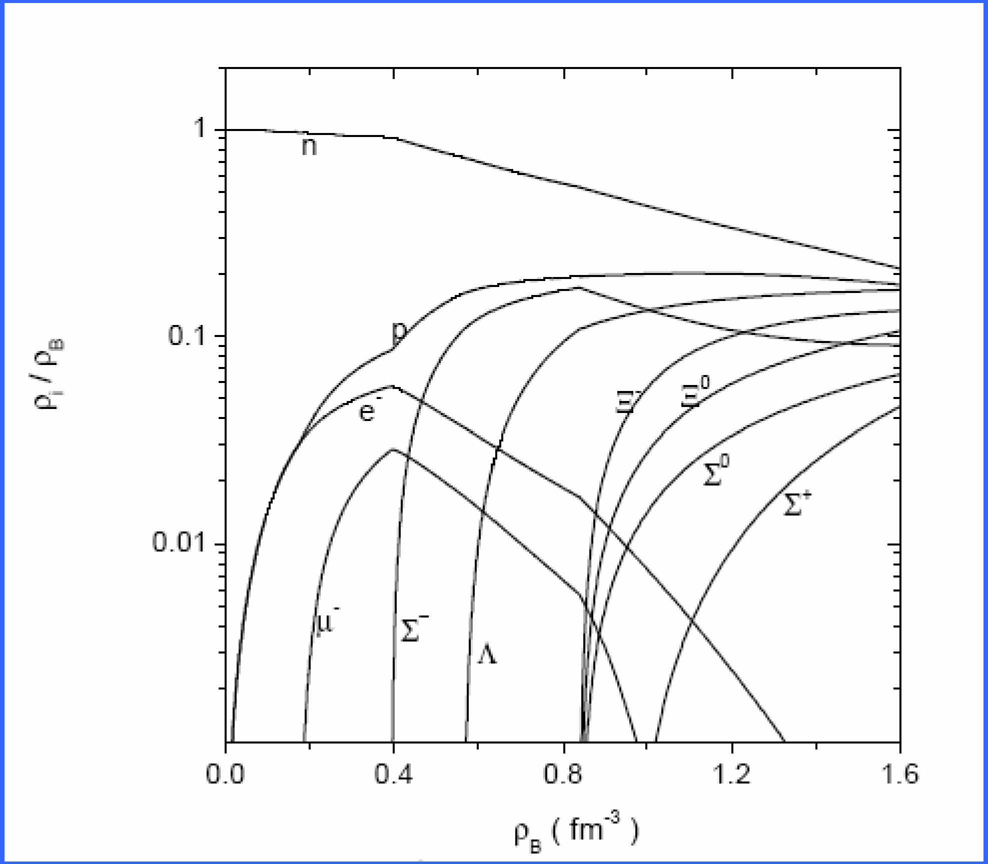
$$\sqrt{(M_V^{deg})^2 - \Sigma_{TOT}} = (a_0^{cont} + X_1 a + X_2 a^2) + a_2 (M_{PS}^{deg})^2 + a_4 (M_{PS}^{deg})^4 + a_6 (M_{PS}^{deg})^6$$

Neutron Star Composition

Hyperons enter at just 2-3 ρ_0

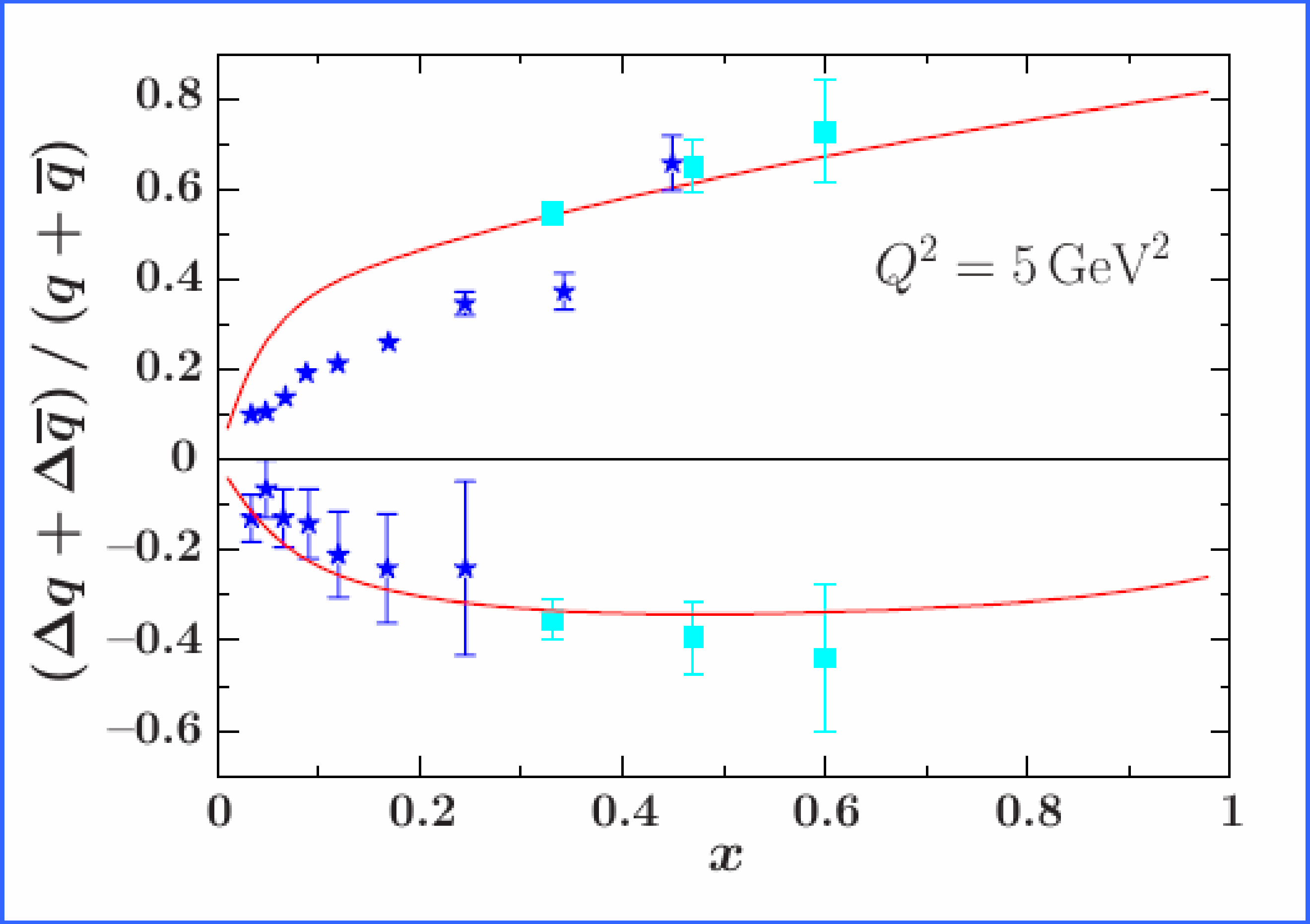
Hence need effective Σ-N and Λ-N forces in this density region!

Hypernuclear data is important input – but not enough



Wang, Lawley et al., nucl-th/0506014

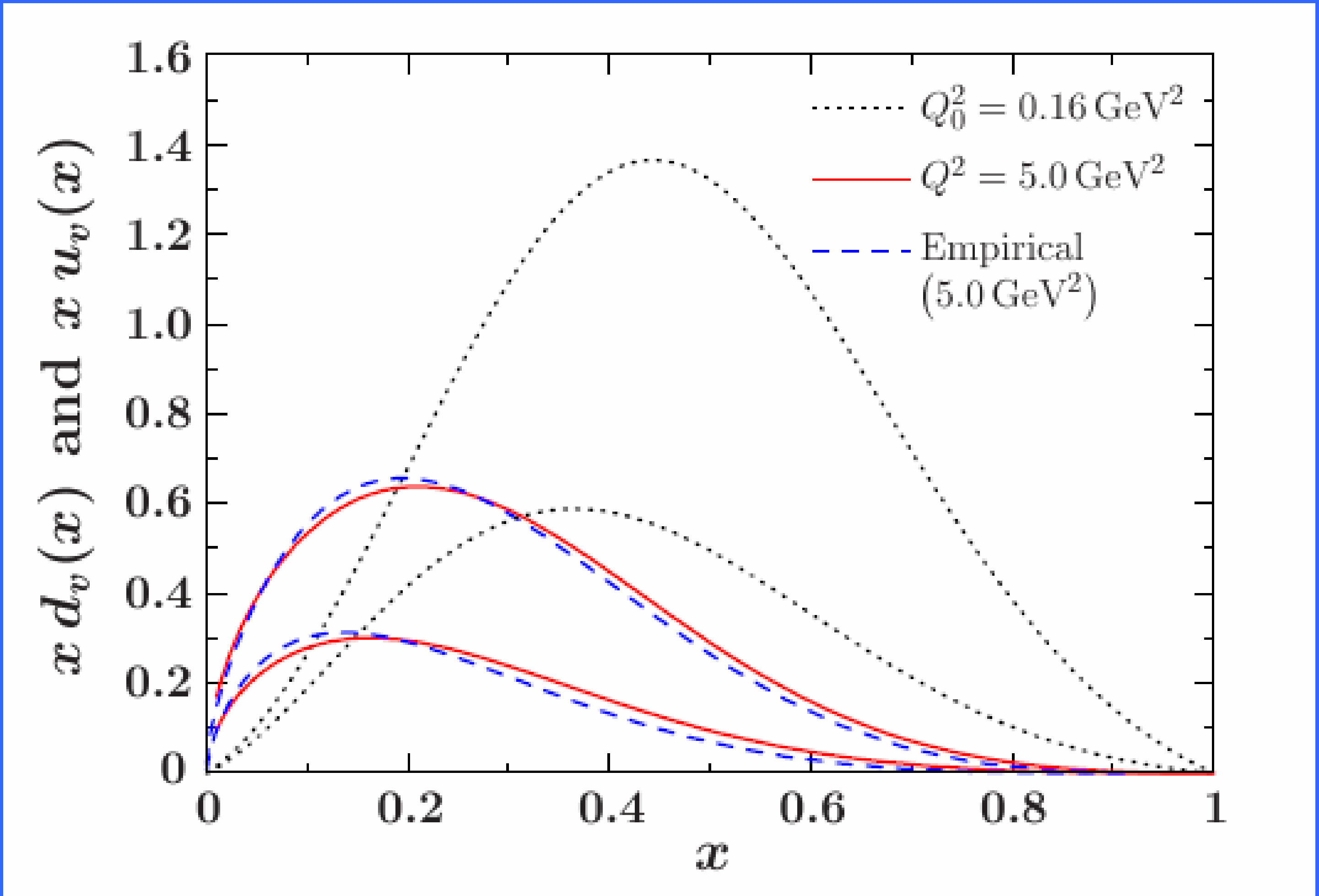
Spin Dependent PDFs



Data: Hermes & JLab

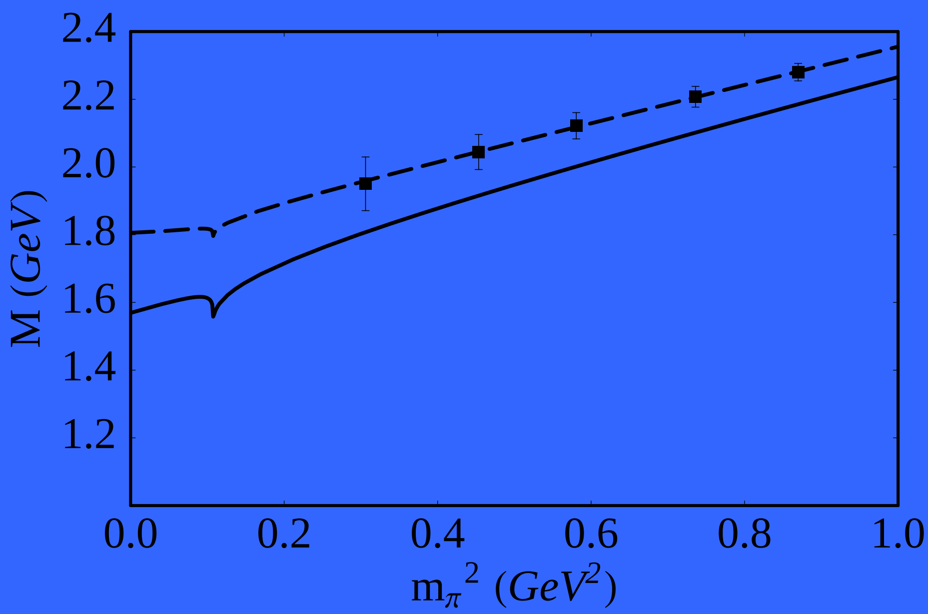
Cloet, Bentz, AWT, hep-ph/0504229

Free Spin Independent PDFs



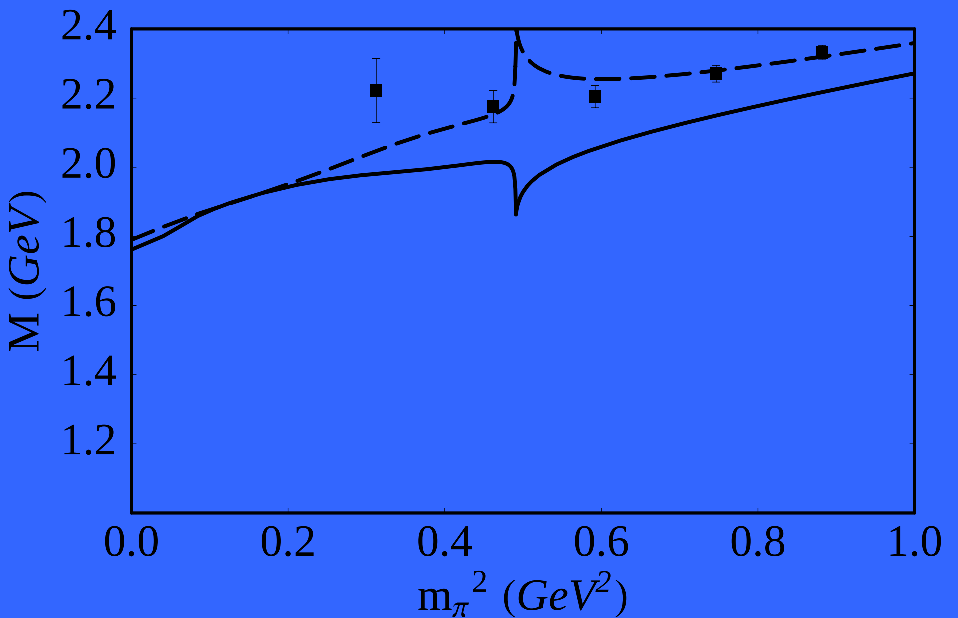
Cloet, Bentz, AWT, hep-ph/0504229

Excited States are more Difficult



N(1520) 3/2⁻

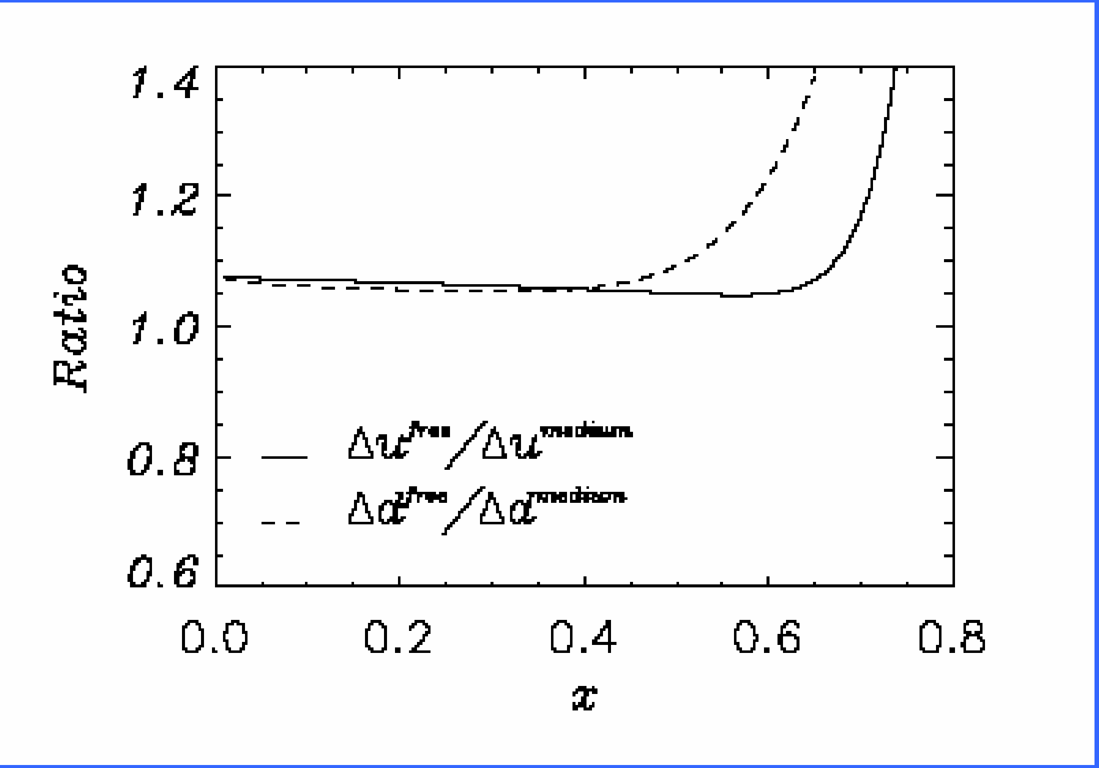
N(1650) ½⁻



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

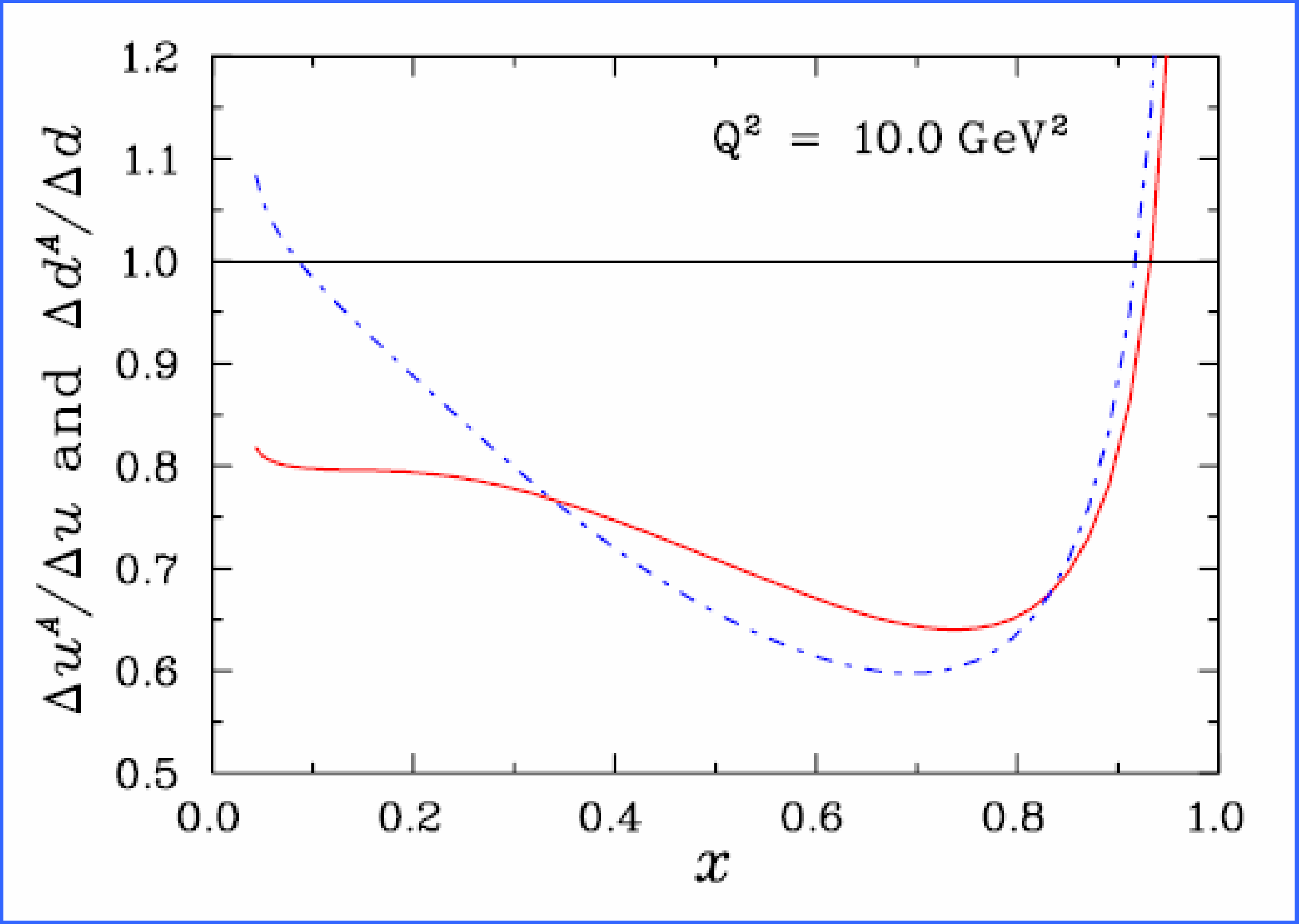
Predicted "EMC" Effect Bigger for Spin

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



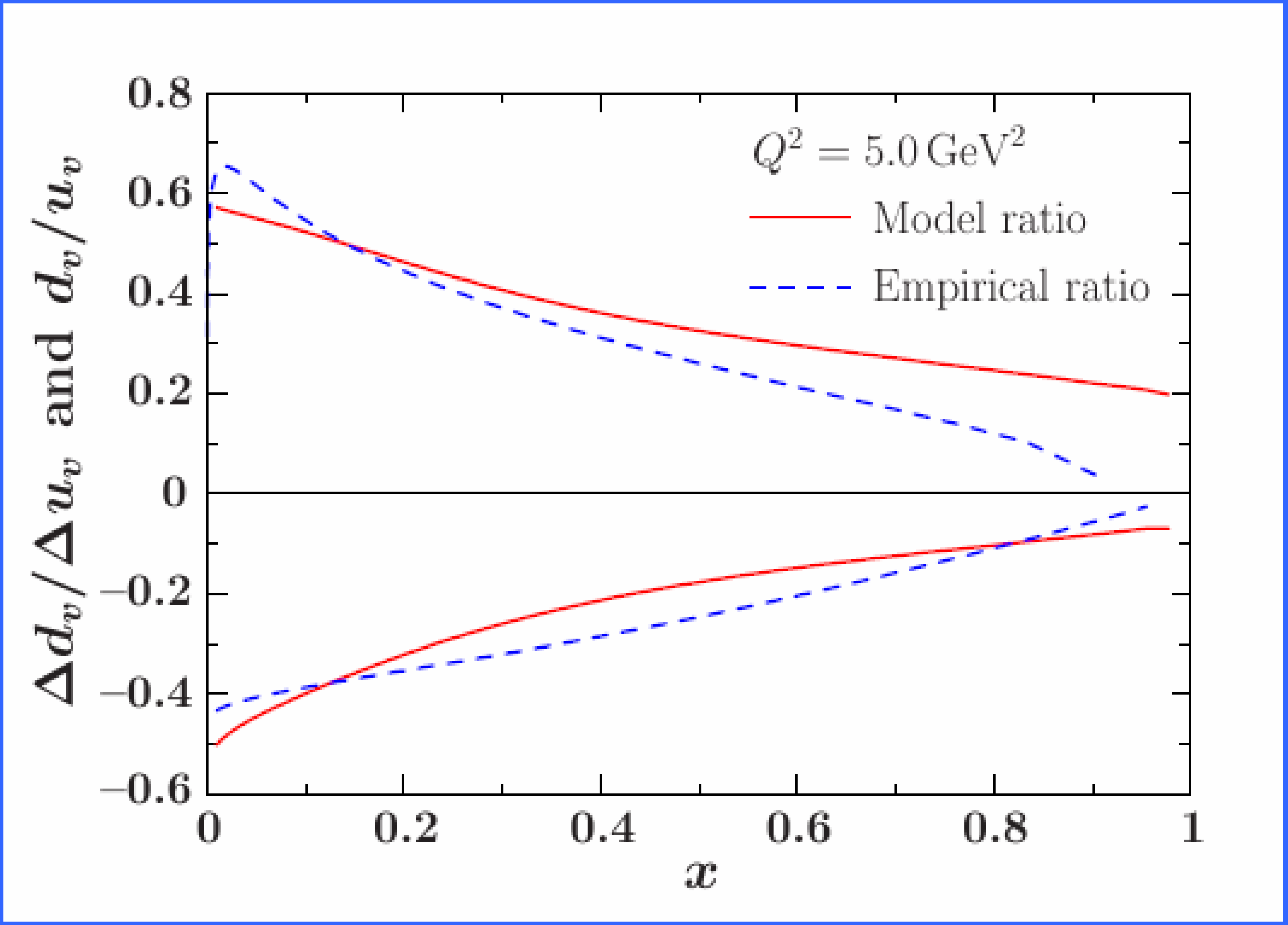
Steffens et al., Phys.Lett.B447 (1999) 233

Flavor Dependence of EMC Effect



Cloet, Bentz, AWT, nucl-th/0504019

Flavor Dependence of PDFs



Cloet, Bentz, AWT, hep-ph/0504229