# Nucleon Structure in QCD

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Hall C Meeting
Aug 19, 2004

# Outline

- How to model hadron structure…..

  in a manner consistent with non-perturbative QCD

- Lattice QCD :

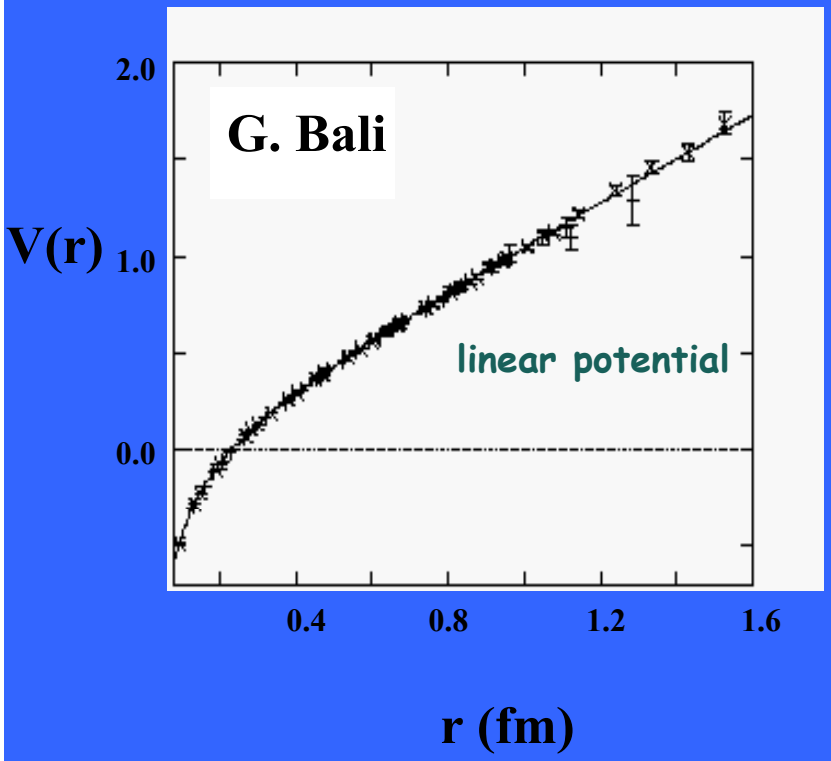
  there are no problems, only new opportunities!

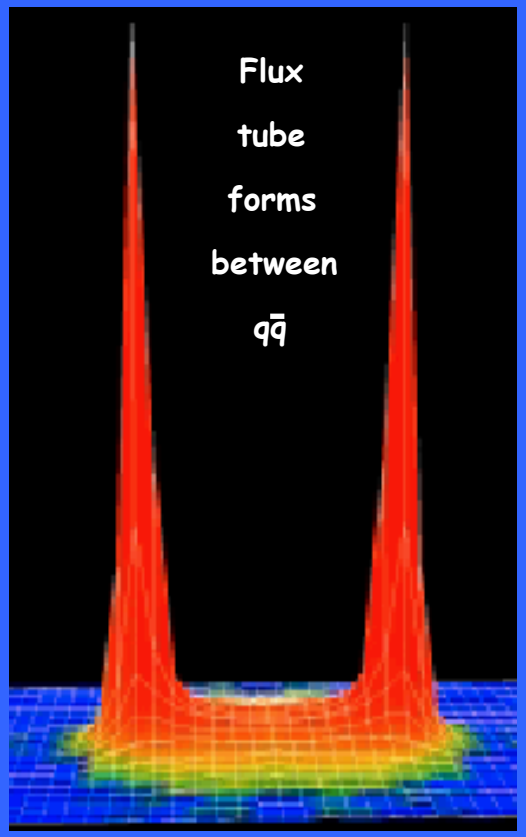
  (and, by the way, some things CAN be calculated ACCURATELY)

- How to build nuclei in QCD….

  Why continue to live in the 20th Century?

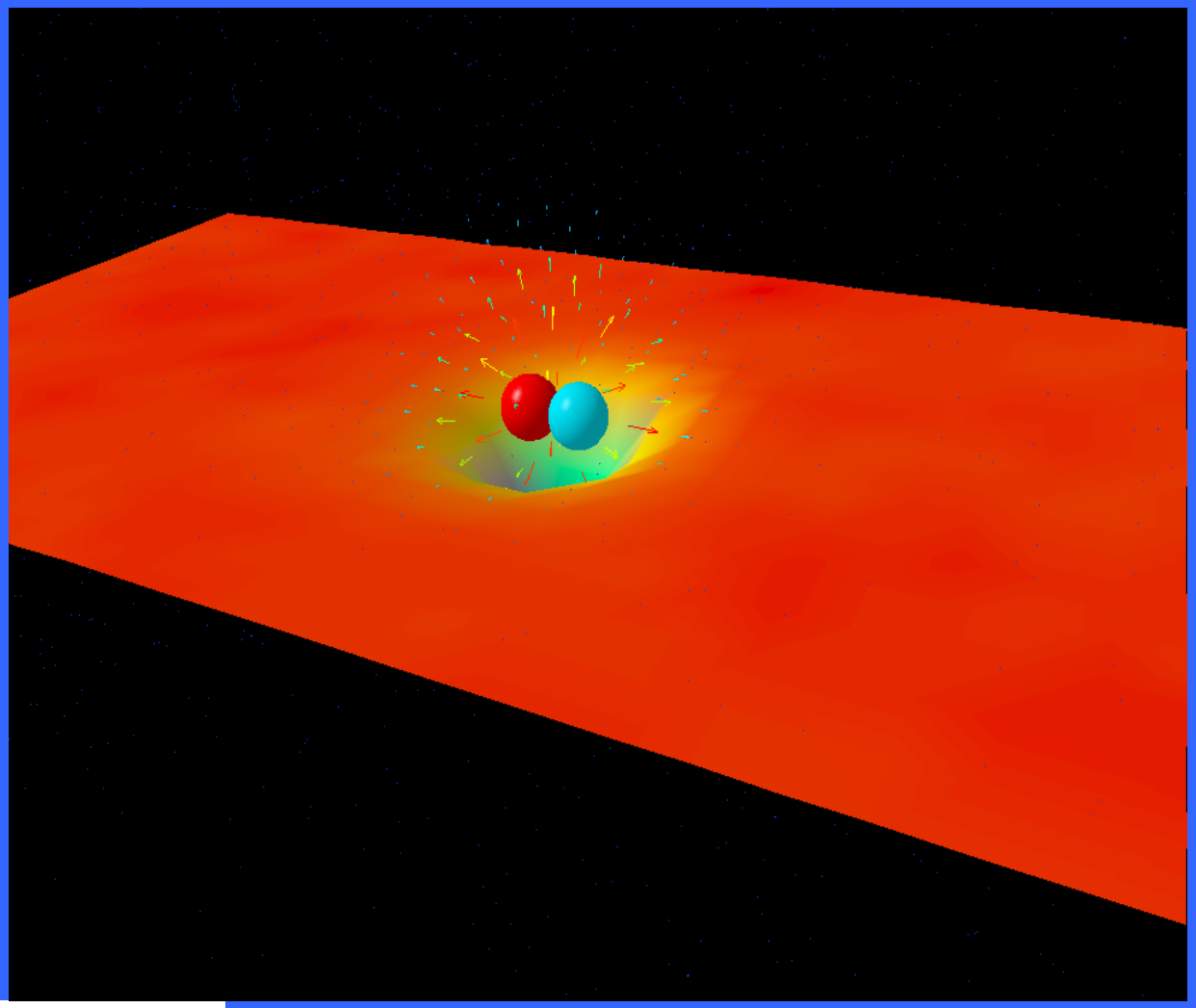
# Heavy Valence Quarks




- BUT dominated by short-distance fluctuations
- No idea of what happens for light quarks!

# Quark-Anti-Quark Flux Tube: “String”



Lasscock, Leinweber, Thomas & Williams

# Unavoidable Problem

♦ Lattice QCD currently limited to $m_q$ > 30-50 MeV

Time to decrease $m_\pi$ by factor of 2 : $2^7$ » 100

♦ NEED perhaps 500 Teraflops to get to 5 MeV !

Furthermore EFT implies <u>ALL hadronic properties</u> are non-analytic functions of $m_q$ ……..

HENCE: NO simple power series expansion about $m_q = 0$
: NO simple chiral extrapolation

) need EFT ($\chi$ PT)

# Truly Effective Field Theory

- Set some mass scale, $\Lambda$ , above which EFT does NOT contain relevant physics.

- LePage : "it makes little sense to [increase $\Lambda$ ] above the range" in which we understand the physics, because the "structure [seen] there is almost certainly wrong".

- Choose a physically reasonable $\Lambda$ and let other parameters "run with $\Lambda$" to eliminate dependence on it as far as possible.

# Natural Cut-off Scale for $\chi$PT

- Usually think of $\Lambda\chi_{SB}$ » $4\pi f_\pi$ » 1 GeV as the scale….

BUT: There is another SCALE in the problem
- not natural in (e.g.) <u>dim-regulated</u> $\chi$PT

$\Lambda$ ~ 1 / Size of Source of Goldstone Bosons
~ 400 – 500 MeV

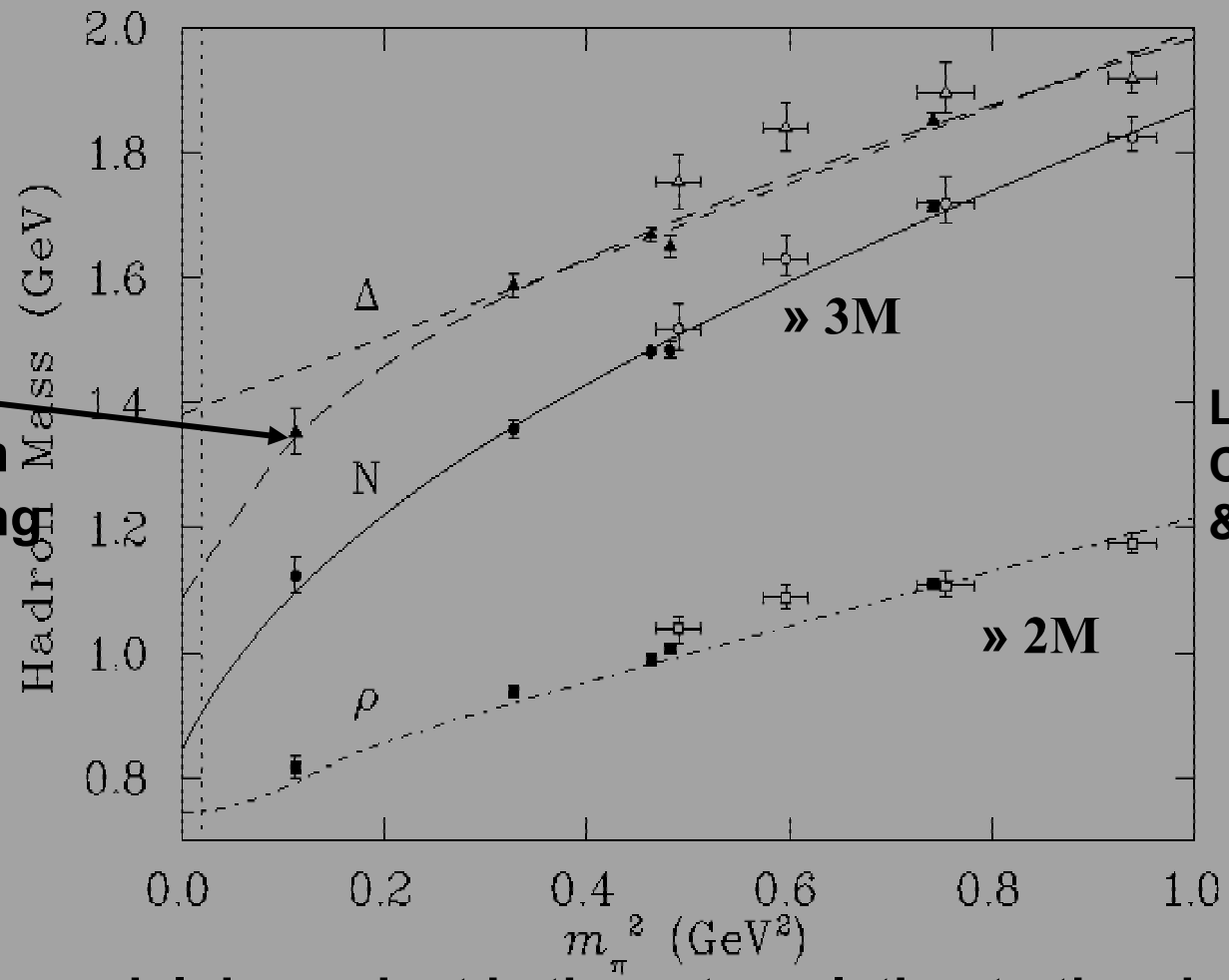
- <u>Above this scale</u>, $m_\pi$ > 0.5 GeV, <u>we probe physics of internal structure of hadrons</u>, i.e. non-perturbative QCD : outside scope of EFT

- There pion sits <u>inside</u> quark and gluon core and <u>pion loops are strongly suppressed</u> ) new degree of freedom emerges: "Constituent Quark" !

# Behaviour of Hadron Masses with $m_\pi$

From: Leinweber *et al.*, Phys. Rev., D61 (2000) 074502

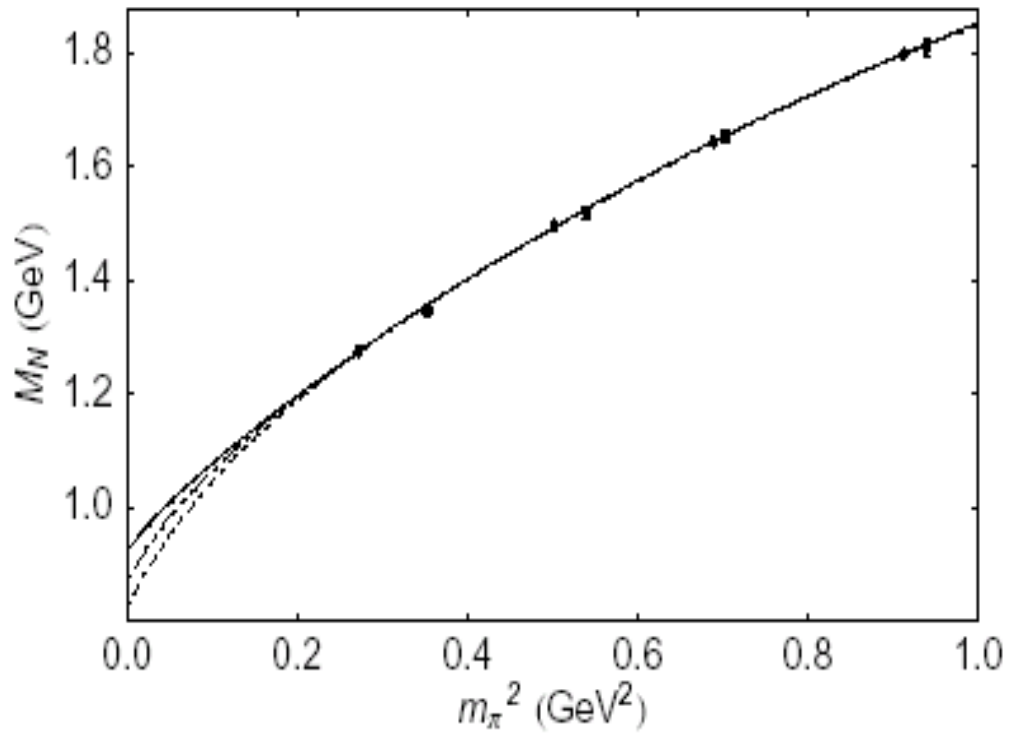
Point of inflection at opening of N $\pi$ channel




Lattice data from CP-PACS & UKQCD

BUT how <u>model dependent</u> is the extrapolation to the physical point?

# χ'al Extrapolation Under Control when 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 | $0.884 \pm 0.103$ |
| Dim. Reg. (BP) | 0.784 | $0.923 \pm 0.103$ |
| Sharp cutoff | 0.968 | $0.961 \pm 0.116$ |
| Monopole | 0.964 | $0.960 \pm 0.116$ |
| Dipole | 0.963 | $0.959 \pm 0.116$ |
| Gaussian | 0.966 | $0.960 \pm 0.116$ |

**Leinweber et al., PRL 92 (2004) 242002**

# Not a Problem but a Bonus!

Hadron properties

't Hooft: extremely valuable constraints (Jenkins, this meeting)

$N_C$

3

1

Physical region
$m_q$ » 5 MeV

$m_q$

Adds a third dimension to our knowledge of QCD



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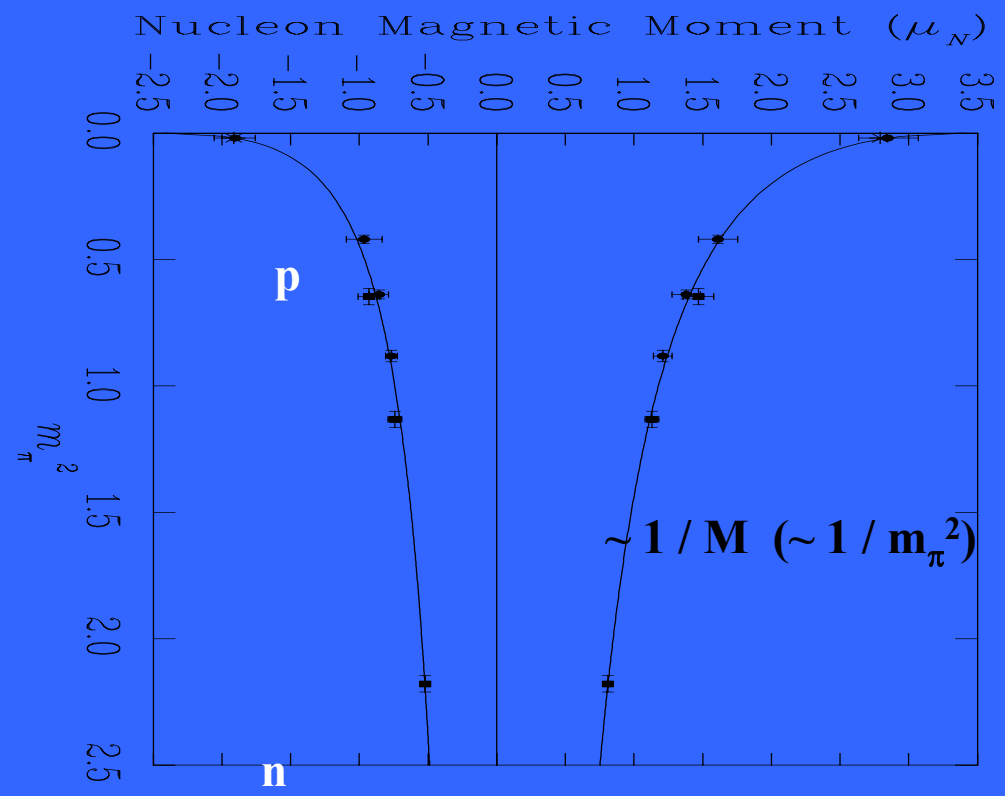
# Early Lattice Work on $\mu_p$ and $\mu_n$

$\mu_{p(n)} = \mu_0 / (1 \pm \alpha / \mu_0\ m_\pi + \beta\ m_\pi^2)$ : fit $\mu_0$ and $\beta$ to lattice data.

Thus: $\mu_p = \mu_0 - \alpha\ m_\pi + \ldots\ldots$ ; $\alpha = 4.4\ \mu_N$-GeV$^{-1}$ (from $\chi$ PT)




**At physical quark mass:**

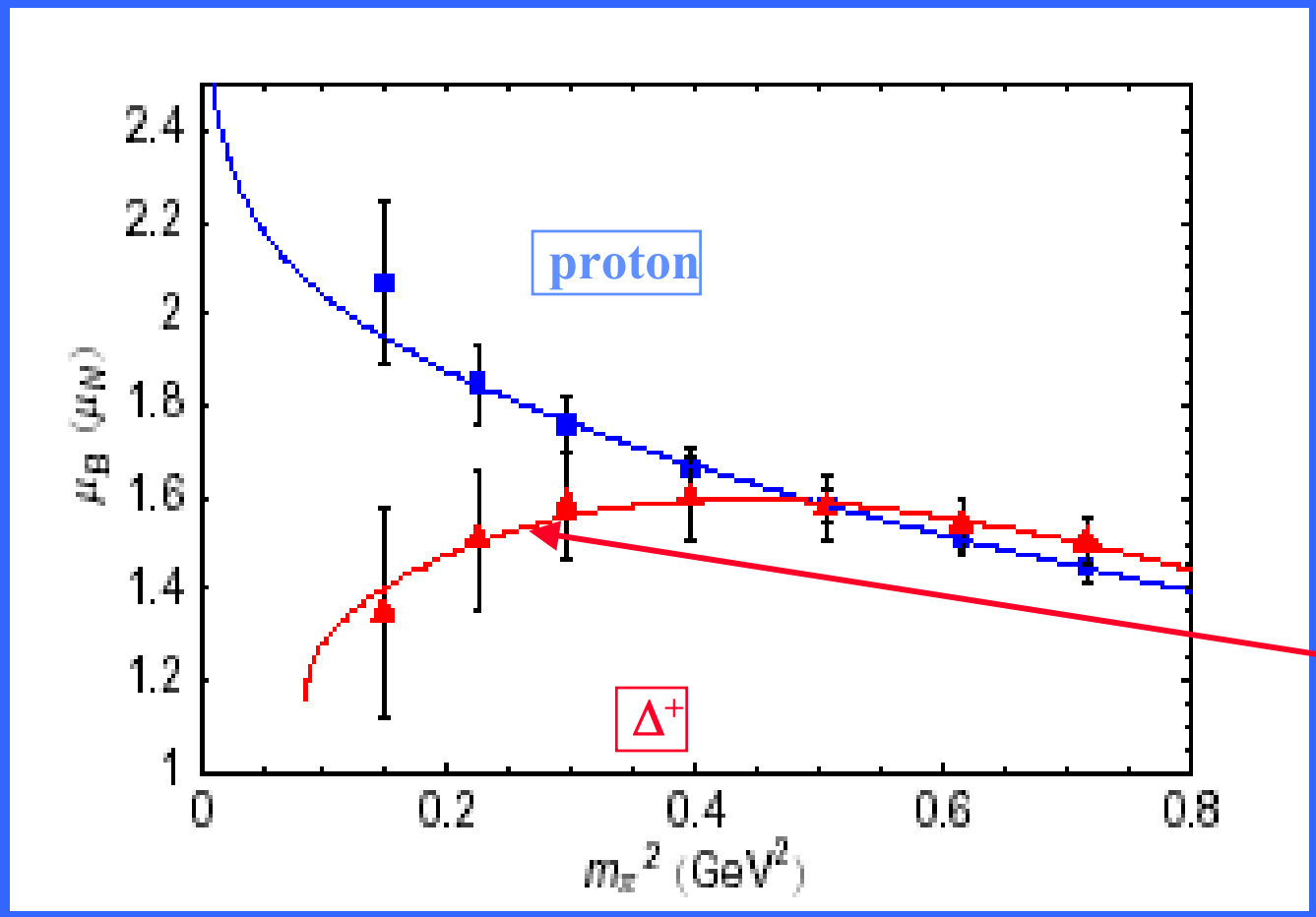
$\mu_p = 2.85 \pm 0.22\ \mu_N$

$\mu_n = -1.90 \pm 0.15\ \mu_N$

(purely statistical errors)

(Leinweber et al., Phys. Rev. D60 (1999) 034014;
/// Hemmert & Weise: nucl-th/0204005 and Pascalutsa, Holstein… 2004)

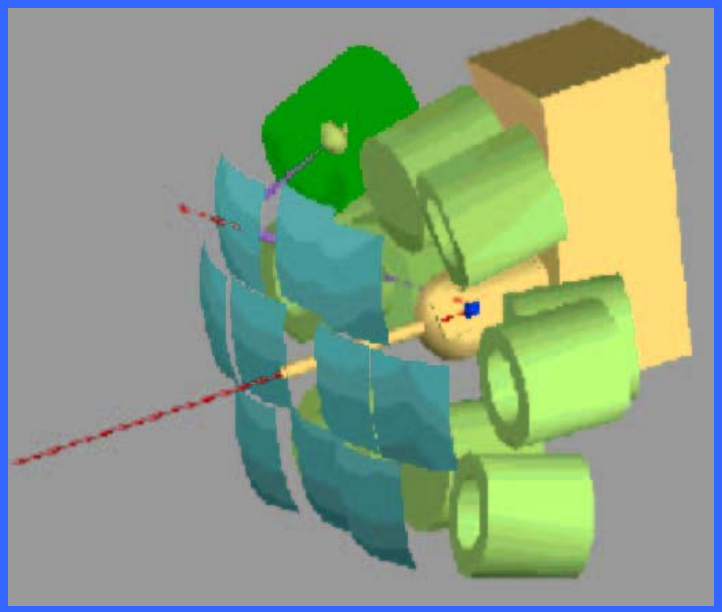
# Strong Evidence for QQCD Chiral Behaviour



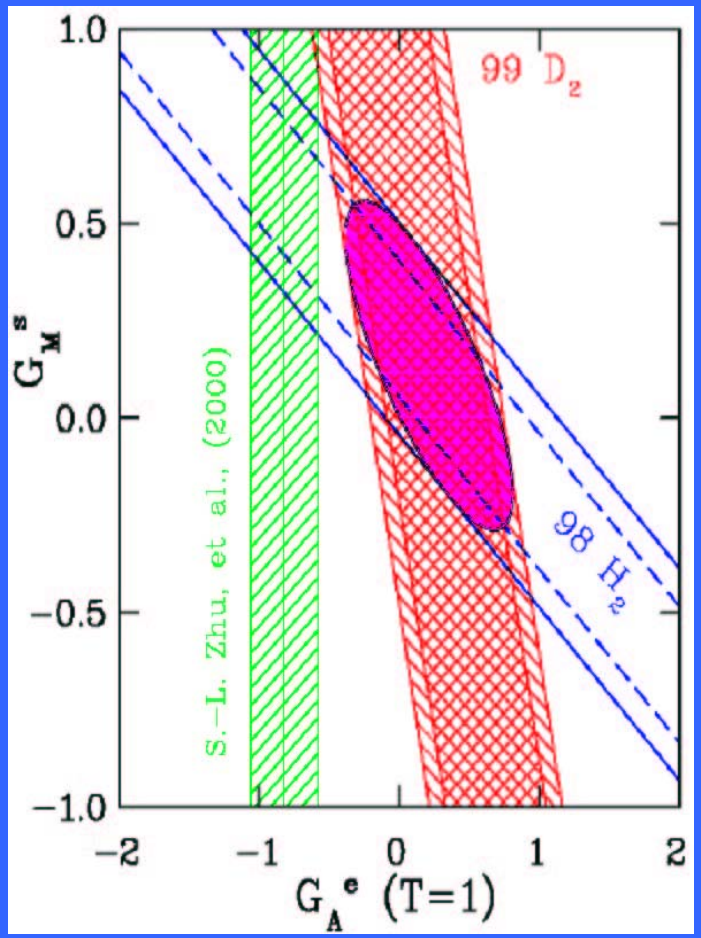

Δ! N π ! Δ
opposite
Sign in QQCD

**New data Zanotti et al. (CSSM): 1 Teraflop, FLIC action (nucl-th/0308083)**

# $G_M^s$ measurement



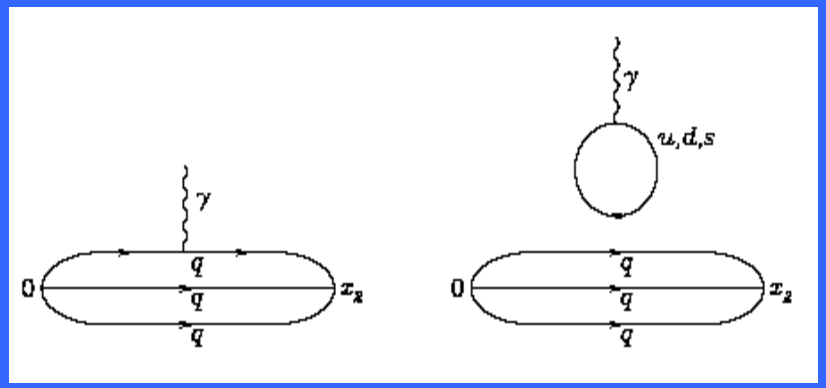
**Initial results:**




**Latest from SAMPLE )**
**Spayde et al., nucl-ex/0312016:**
**0.37 § 0.20 § 0.26 § 0.07 $\mu_N$**

**Theory ahead of experiment for a change….**

# Lattice View of Magnetic Moments with Charge Symmetry




CS

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

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

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

$$(\text{and } p + 2n = d^p + 3\, O_N)$$

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

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

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

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

Just these ratios from Lattice QCD

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



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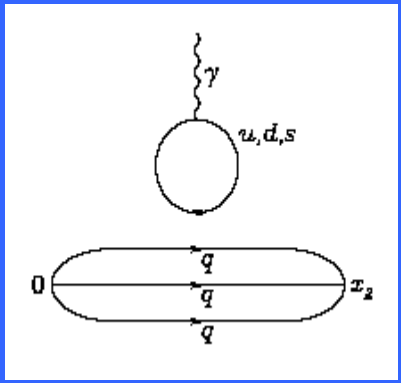
# Constraint from Charge Symmetry

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

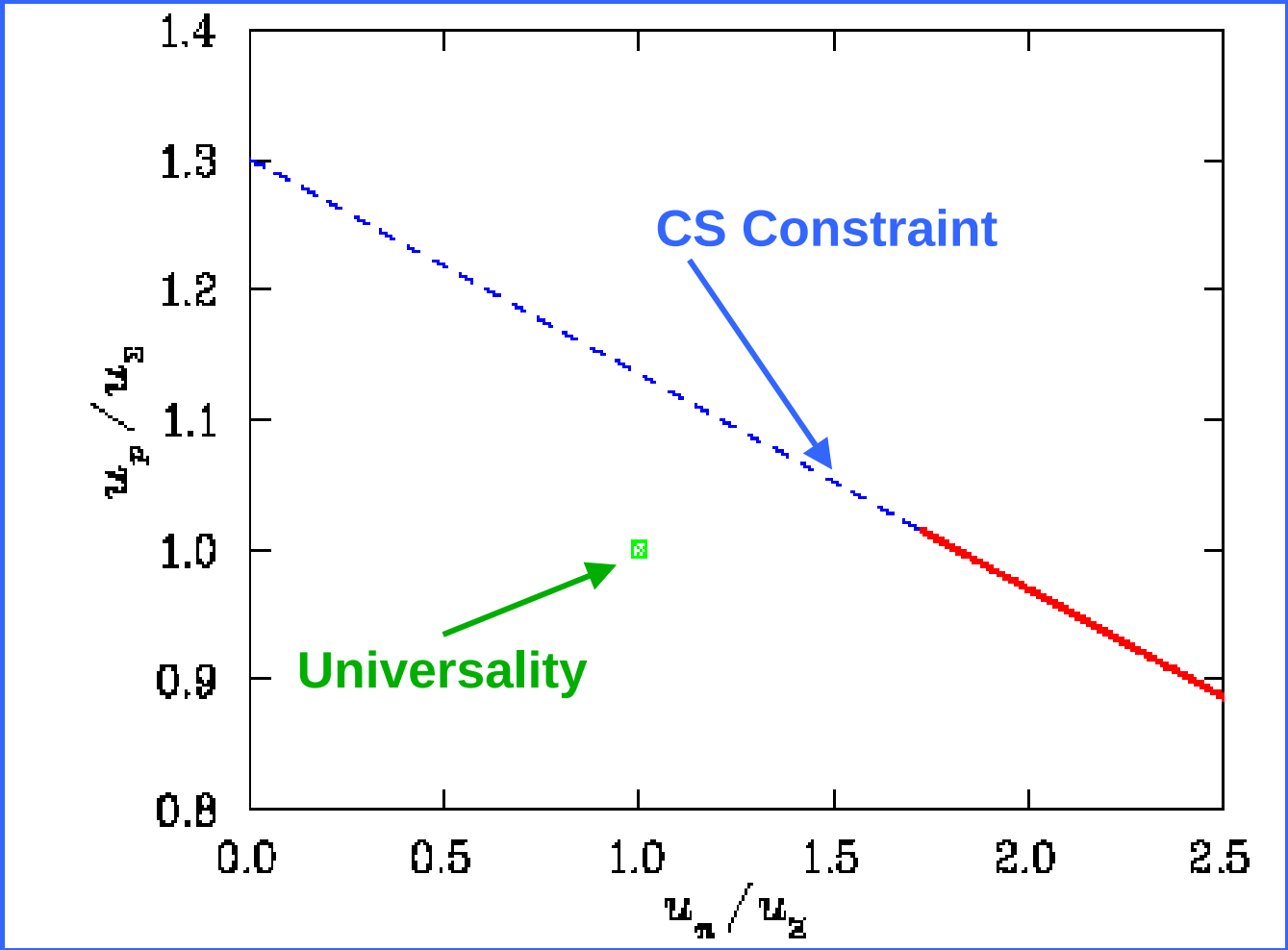



$$
G_M^s = \left(\frac{{}^{\ell}R_d^s}{1-{}^{\ell}R_d^s}\right)\left[3.673 - \frac{u_p}{u_{\Sigma^+}}\,(3.618)\right]
$$

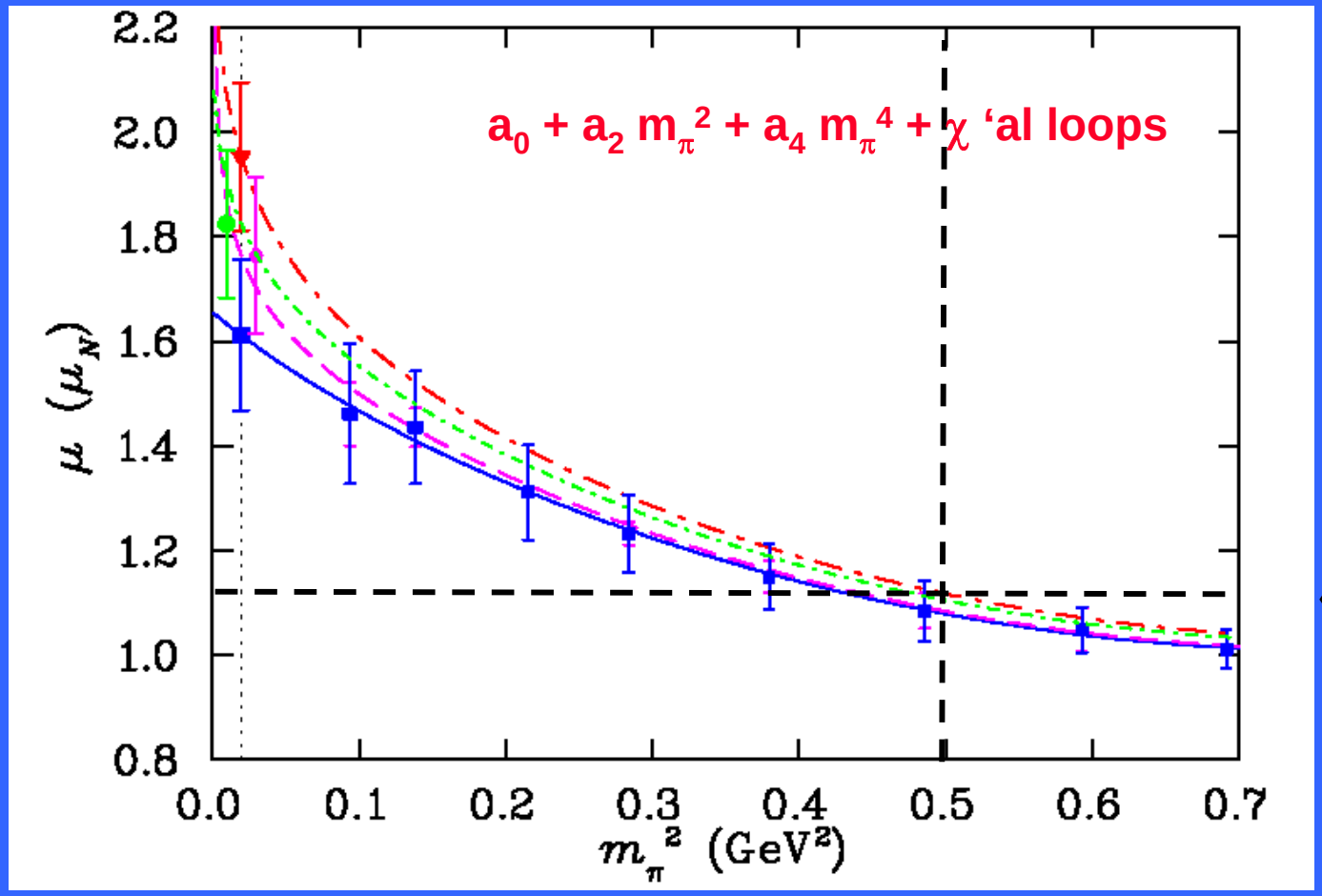
$$
G_M^s = \left(\frac{{}^{\ell}R_d^s}{1-{}^{\ell}R_d^s}\right)\left[-1.033 - \frac{u_n}{u_{\Xi^0}}\,(-0.599)\right]
$$

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

# Equate: Must Have Environment Dependence !



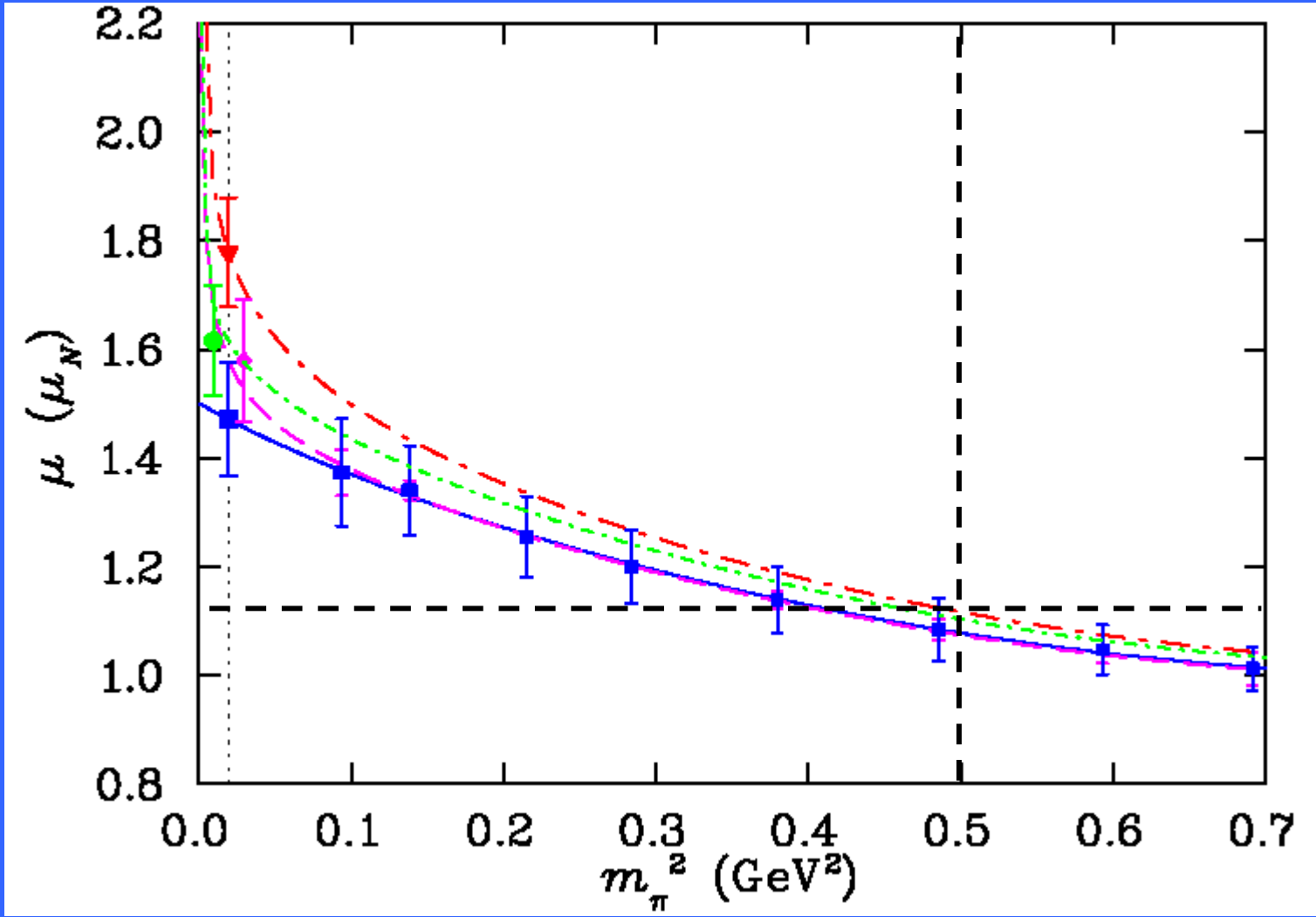
# $u^p_{valence}$ : QQCD Data Corrected for Full QCD Chiral Coeff's




c.f. CQM
2/3 940/540
» 1.16

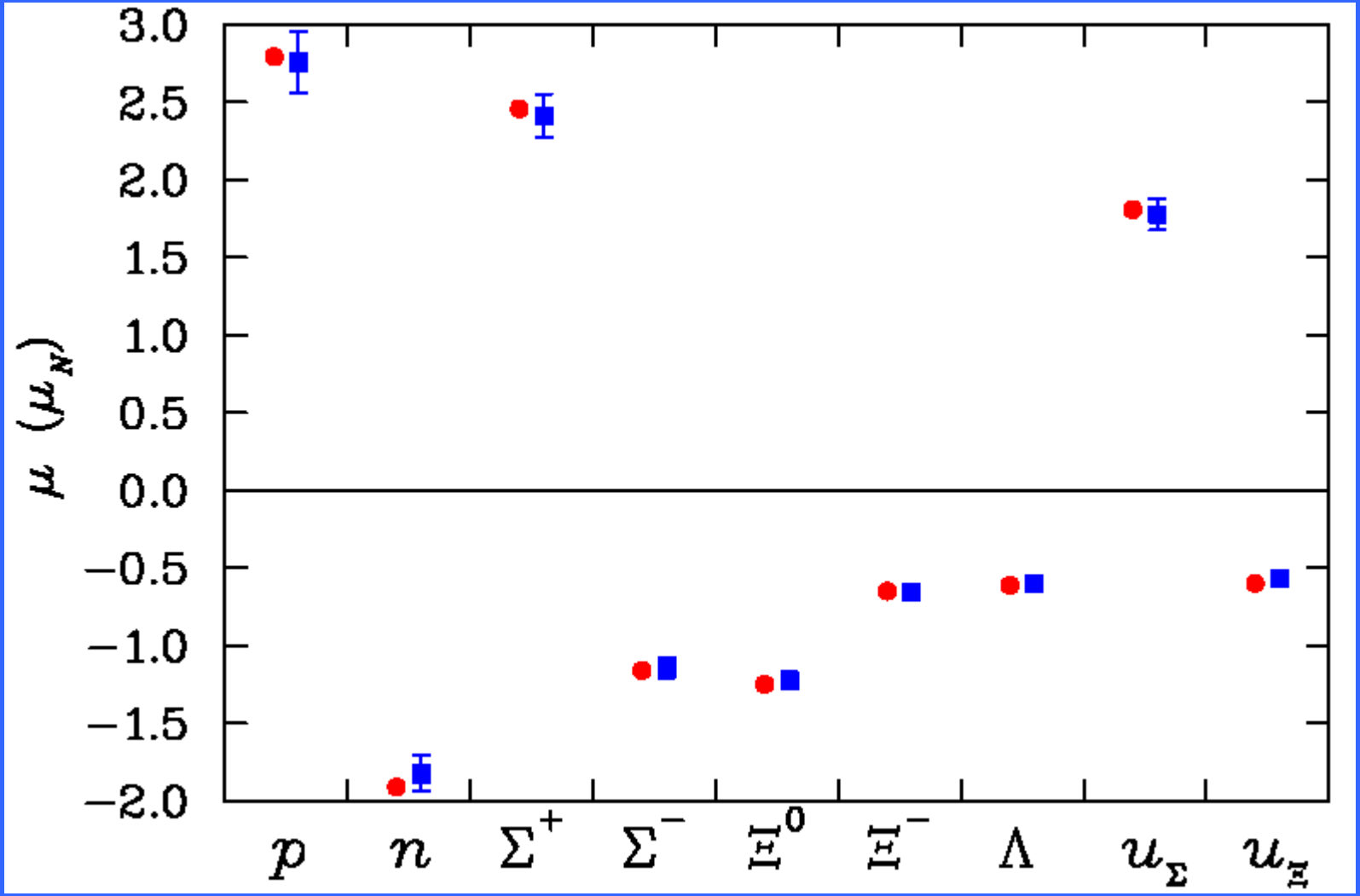
New lattice data from Zanotti et al. ; Chiral analysis Leinweber et al.

# $u^{\Sigma}_{valence}$




**Universal Here!**

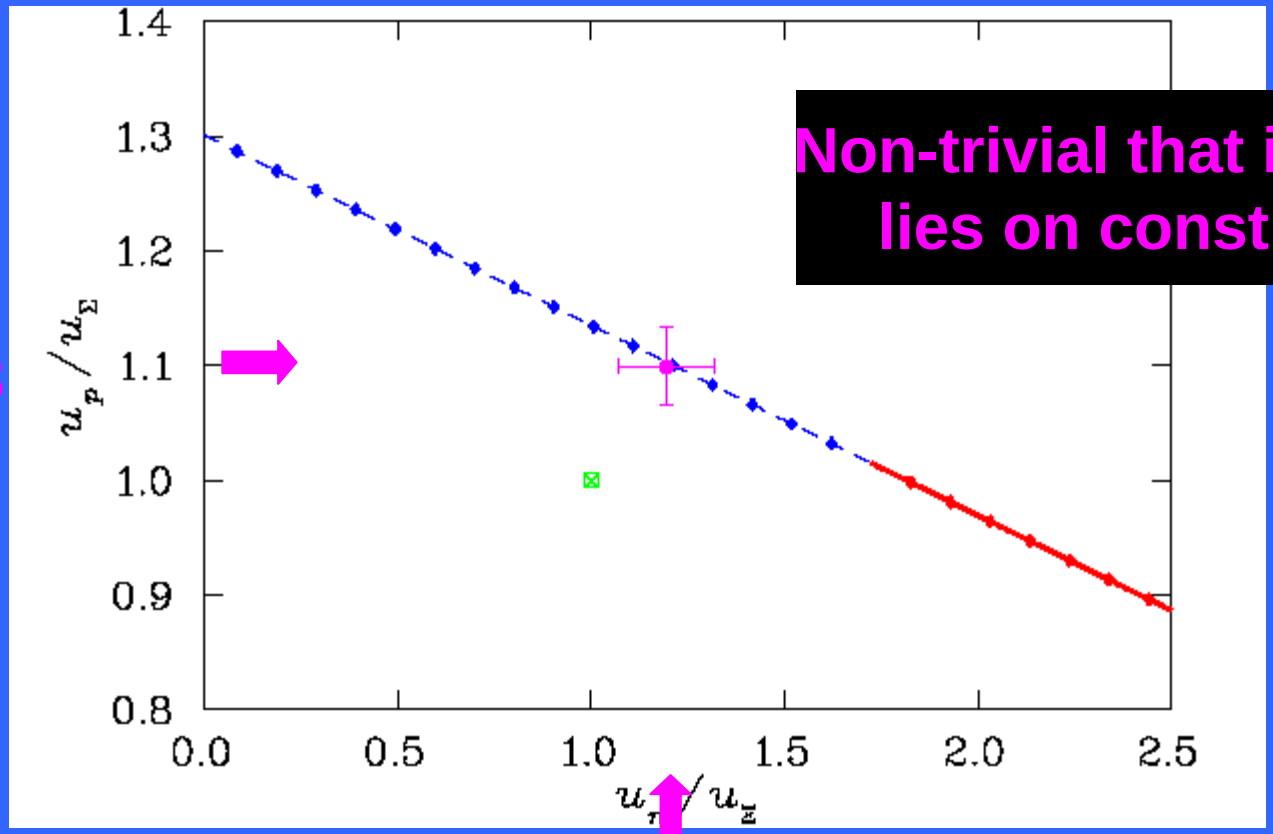
# Check: Octet Magnetic Moments




**Leinweber et al., hep-lat/0406002**

# Accurate Final Result for $G_M^s$

1.10±0.03




**Non-trivial that intersection lies on constraint line!**

1.19±0.12

**Dots are $G_M^s$ in steps of 0.01 $\mu_N$**

**Hence $G_M^s = -0.051 \pm 0.021\ \mu_N$**

**Leinweber et al., hep-lat/0406002**

# Combine with Happex to Extract Strangeness Charge Radius

$G_E^s + 0.39\, G_M^s = 0.025 \pm 0.020 \pm 0.014$ at 0.4 GeV$^2$
(HAPPEX)

Plus lattice calculation of $G_M^s$ and assumed dipole form

$\Rightarrow$ $\langle r^2 \rangle_s = -0.021 \pm 0.015\ \mathrm{fm}^2$

c.f. $\langle r^2 \rangle = -0.113\ \mathrm{fm}^2$ in case of the neutron

# Summary

- New QQCD data to very low $m_\pi$ now available
- Chiral corrections under control
- Magnetic moments of Octet Baryons in excellent agreement with data
- $G_M^s$ = -0.051 § 0.021 $\mu_N$ : from CS constraints (for once theory ahead of experiment!)
- Universality of quark moments broken (at physical light quark masses) by 10% for u in p ($\Sigma^+$ ) and 20% for u in n ($\Xi^0$ )
- BUT universality restored at larger quark mass: $m_q$ » $m_s$

# A New Approach to the Constituent Quark Model

**BUT having seen, FROM non-perturbative QCD, that :**

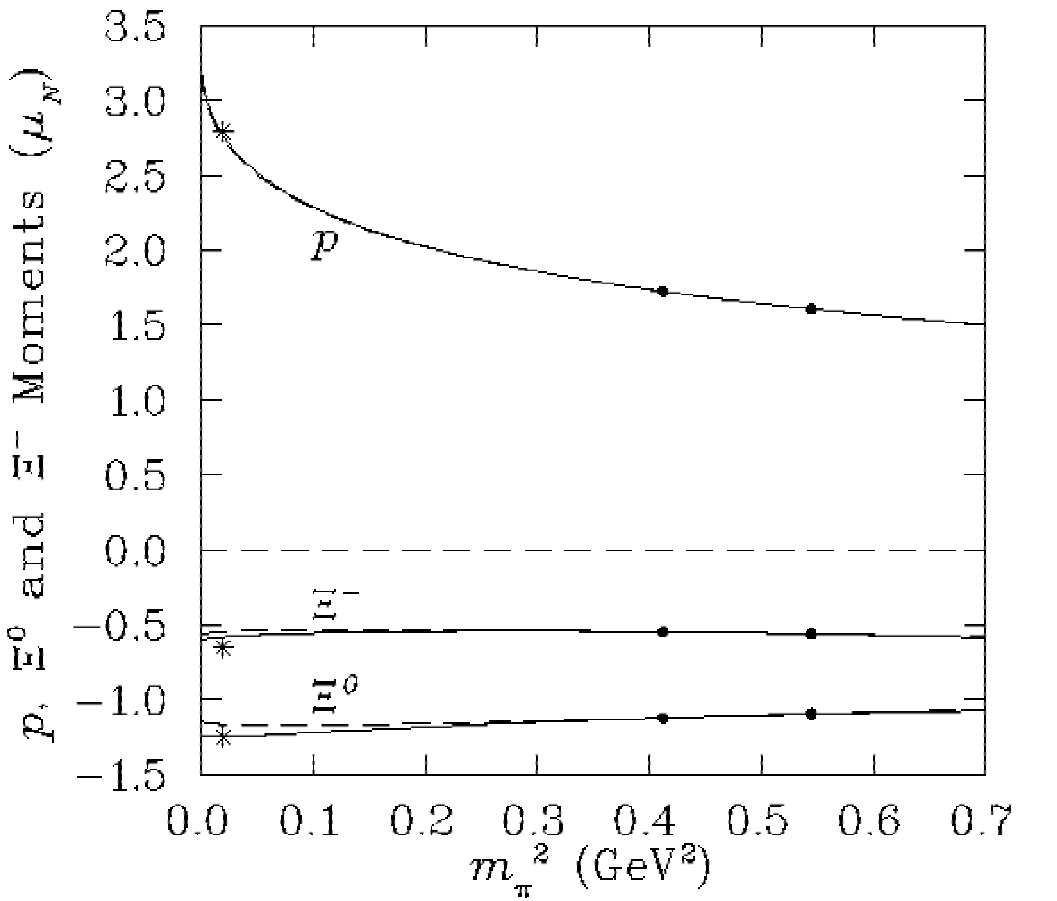
- **magnetic moments**
- **charge radii**
- **moments of PDFs**
- **masses**

**behave like CQM for $m_q$ > 50-60 MeV ($m_\pi$ > 0.5 GeV) ) this is the mass range in which to build a constituent quark model……..**

**Then make comparison with experimental data after chiral extrapolation**

# Chiral Extrapolation from CQM

- Calculate CQM magnetic moments at M (strange) +/- 20 MeV (use exact SU(6) symmetry)
- Use Pade approximant to extrapolate to physical quark mass




Cloet et al., Phys. Rev. C65 (2002) 062201

# QCD Inspired Models of Dense Matter

**Hope for :**

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

# 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

# QMC-2

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

**and hence mean scalar field changes…** **SELF-CONSISTENCY**

**and hence quark wave function changes….**

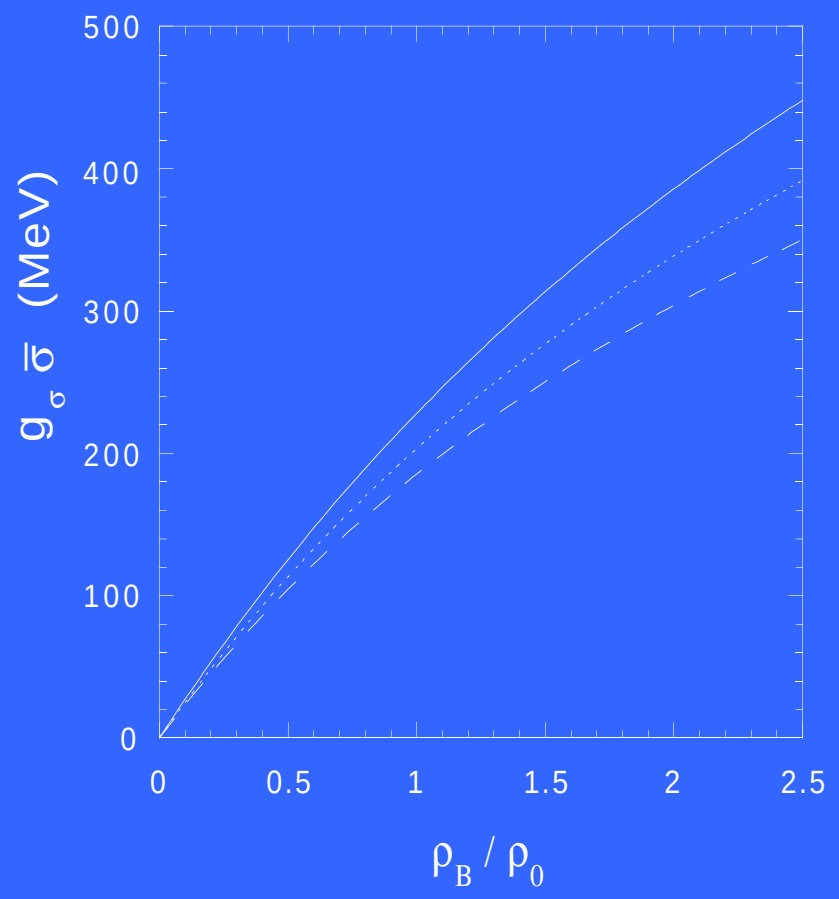
**PROVIDES A NATURAL SATURATION MECHANISM**
**(<u>EFFICIENT BECAUSE QUARKS ARE ALMOST MASSLESS</u>)**

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

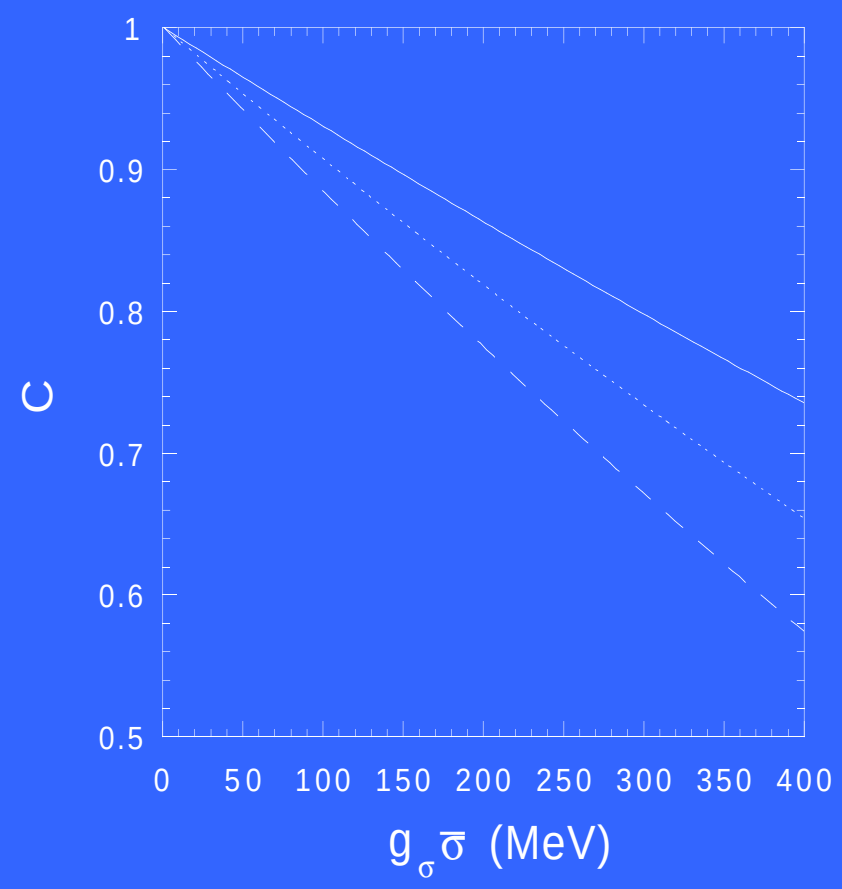
**N.B. Vector field is trivial: just rises linearly with density.**

# Numerical Results

**Scalar mean-field**
**» 1/3rd of QHD**




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



# 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-field

- time to adjust ~ 1 fm/c ) 3% accuracy in typical nuclei

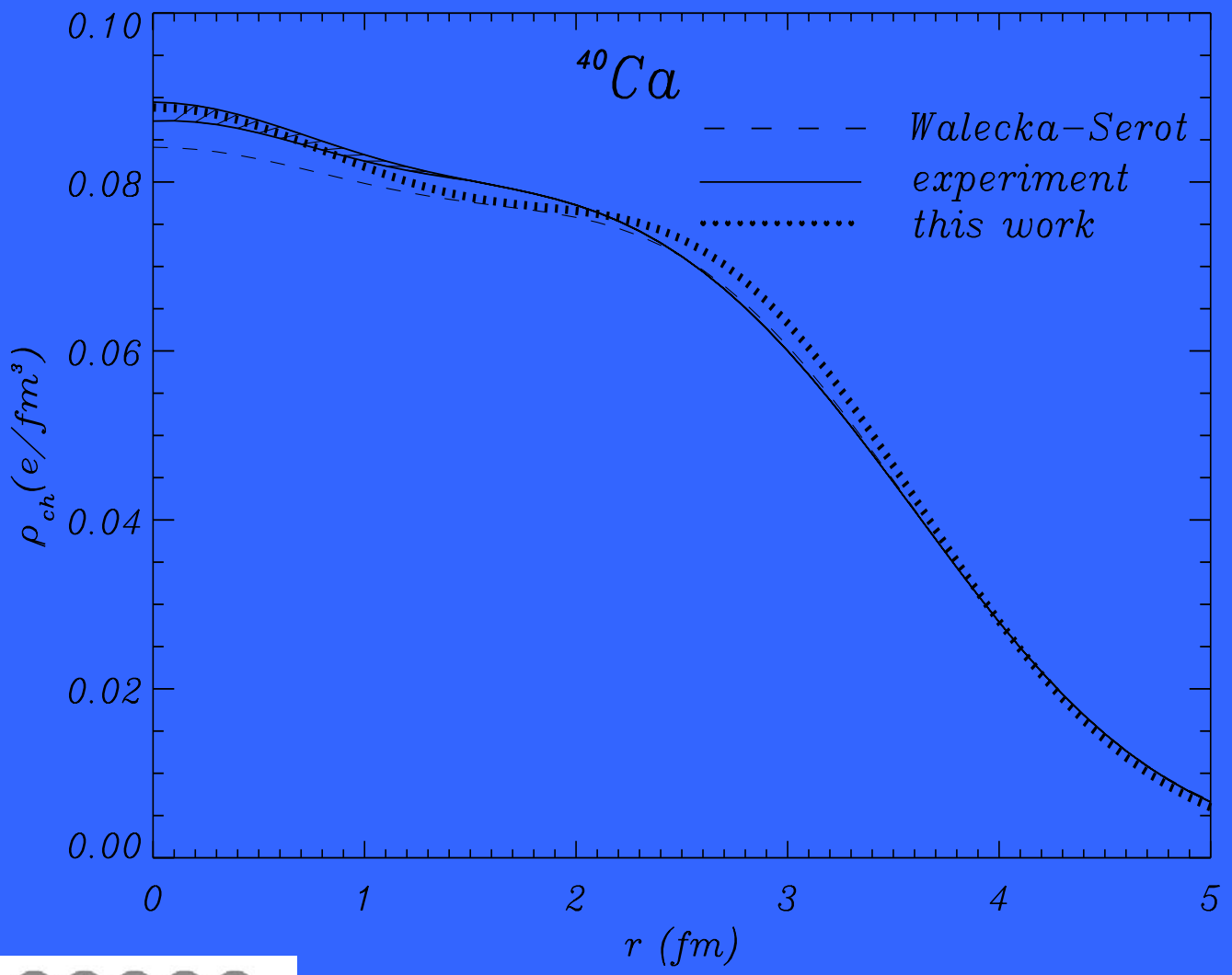
- I KNOW OF NO OTHER WAY TO DERIVE EXISTENCE OF NUCLEI WITHIN QCD

) MAJOR CHANGE IN OUR UNDERSTANDING

- 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**

# Quark Level Description of Finite Nuclei

- **MAJOR CONCEPTUAL CHANGE:**
  **What occupies shell model orbits are nucleon-like quasi-particles**

- **Have: new mass, $M_N^*$; new form factors, etc.**

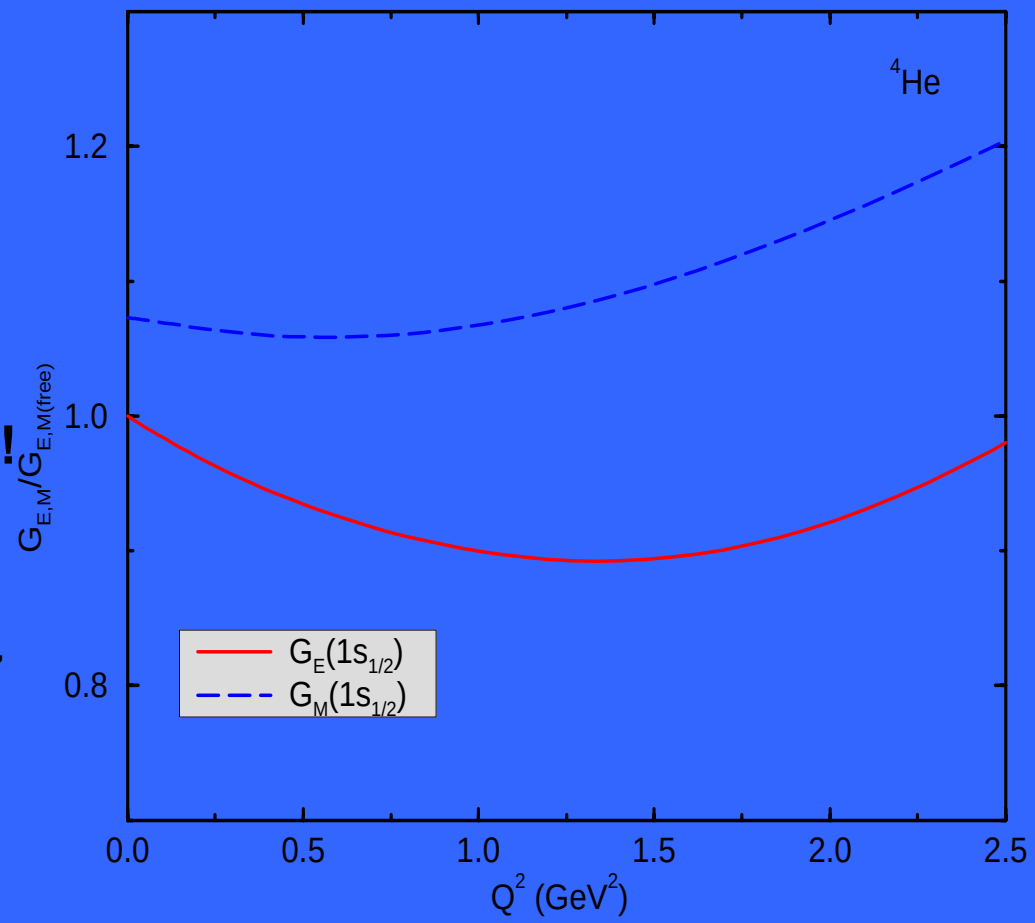
- **EXPERIMENTAL EVIDENCE?**

- **First have to ask the question!**

- **Changes are subtle:**

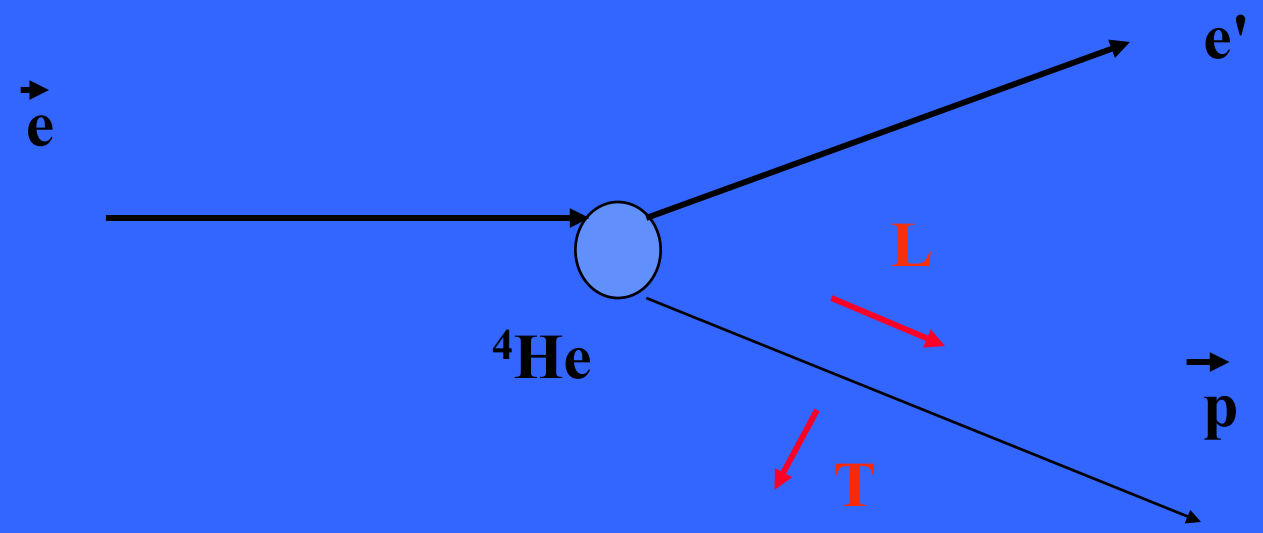
**Lu *et al.*, Phys. Lett. B417 (1998) 217**

***///* results Miller & Smith *(2004)***



# Recent Advance at Mainz & JLab*

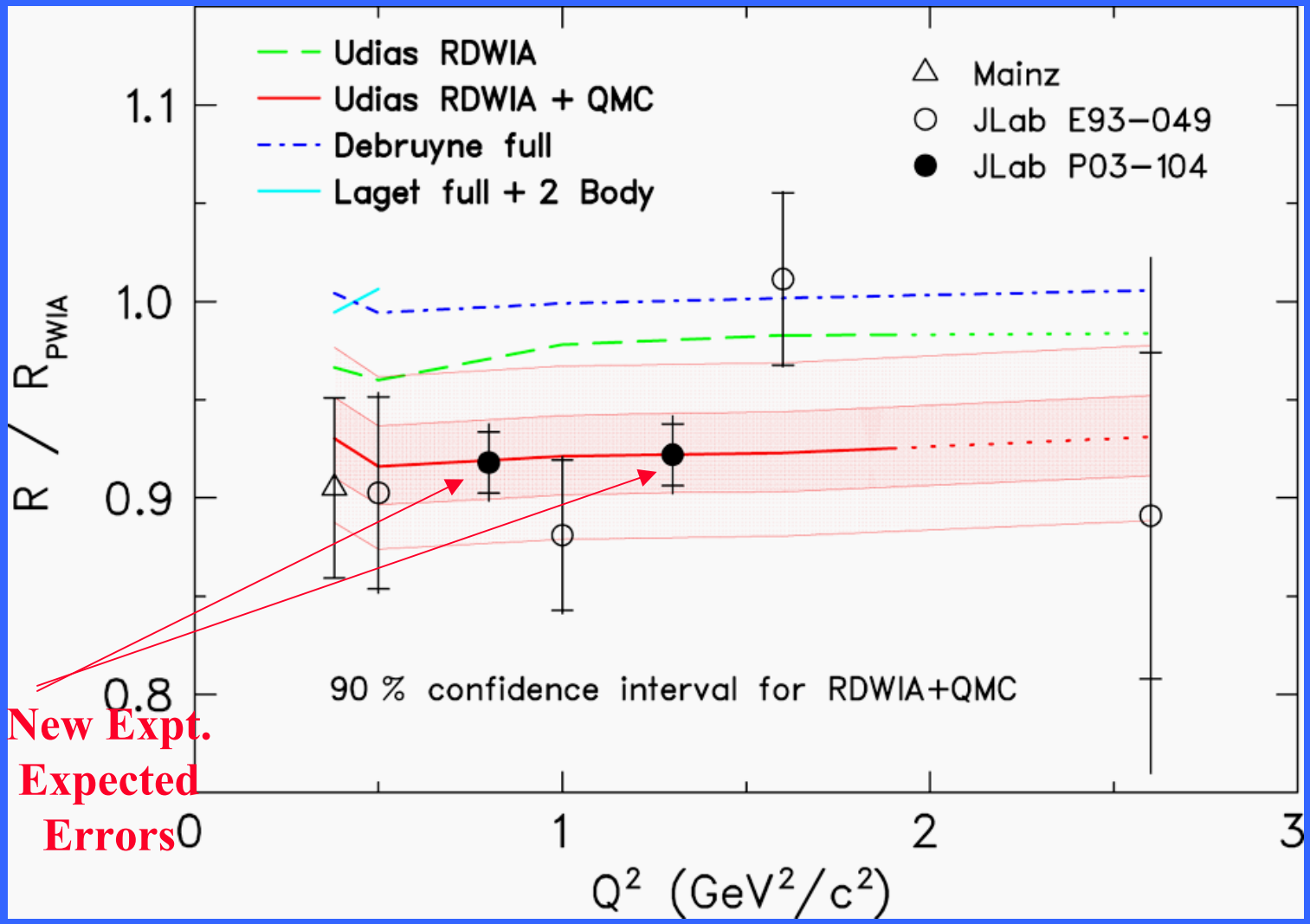
## Capacity to measure polarization in coincidence:




$\sigma_T / \sigma_L$ » $G_E/G_M$ : Compare ratio in $^4$He and in free space

S. Dieterich *et al.* , Phys. Lett. B500 (2001) 47; and JLab report 2002

# Jefferson Lab & Mainz




New Expt. Expected Errors

# Can this apparently orthogonal approach be related to something more traditional?

- Effective forces have been used for many years!
- Vautherin and Brink (early 70's) demonstrated power of Skyrme's ideas
- Density independent effective force, Skyrme III, is still widely used in nuclear structure physics
- In a sense its an interface (like phase shifts in scattering theory) between low energy nuclear data and fundamental theory

# Scalar Polarizability

**In QMC energy of nucleon imbedded in nuclear matter:**

$$E_N(\vec{R}) = \frac{\vec{P}^2}{2M^*(\vec{R})} + M^*(\vec{R}) + g_\omega \omega(\vec{R}) + V_{so}$$

**where:**

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

**Non-linear dependence ´ scalar polarizability**

**d ¼ 0.22 R in original QMC (MIT bag)**



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# Solve Meson Field Equations by Iteration

$$g_\sigma \sigma = G_\sigma \rho_s (1 - d g_\sigma \sigma) + \nabla^2 g_\sigma \sigma / m_\sigma^2$$

$$g_\omega \omega = G_\omega \rho + \nabla^2 g_\omega \omega / m_\omega^2$$

**Keeping leading order terms )**

$$g_\sigma \sigma(\vec{r}) = \frac{G_\sigma}{m_\sigma^2} \nabla^2 \rho + G_\sigma \rho_s + \sum_{k \geq 1} (-d)^k (G_\sigma \rho)^{k+1}$$

$$g_\omega \omega(\vec{r}) = \frac{G_\omega}{m_\omega^2} \nabla^2 \rho + G_\omega \rho$$

**Scalar polarizability leads to higher powers in ρ**

# Use Classical Point-Like Nucleon Density

$$H_{QMC} = \sum_i \left( \frac{\vec{P}_i^2}{2M} + V_{so}(i) \right) + \frac{G_\sigma}{2} \sum_{i \neq j} \frac{\vec{P}_i^2}{M^2} \delta(\vec{R}_{ij})$$

$$+ \frac{G_\omega}{2} \sum_{i \neq j} \left( \delta(\vec{R}_{ij}) + \frac{1}{m_\omega^2} \nabla_i^2 \delta(\vec{R}_{ij}) \right)$$

$$- \frac{G_\sigma}{2} \sum_{i \neq j} \left( \delta(\vec{R}_{ij}) + \frac{1}{m_\sigma^2} \nabla_i^2 \delta(\vec{R}_{ij}) \right)$$

$$+ \frac{dG_\sigma^2}{2} \sum_{i \neq j \neq k} \delta^2(ijk) - \frac{d^2 G_\sigma^3}{2} \sum_{i \neq j \neq k \neq l} \delta^3(ijkl)$$

**we used:** $\rho_s(\vec{r}) = \sum_i (1 - \vec{P}_i^2 / 2M^2) \delta(\vec{r} - \vec{R}_i)$



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# Now Quantize Nucleon Motion & Include ρ - Meson

$$H_{QMC} = \sum_i \frac{\vec{\nabla}_i . \vec{\nabla}_i}{2M} + \frac{G_\sigma}{2M^2} \sum_{i \neq j} \vec{\nabla}_i \delta(\vec{R}_{ij}) . \vec{\nabla}_i$$

$$+ \frac{1}{2} \sum_{i \neq j} \left[ \nabla_i^2 \delta(\vec{R}_{ij}) \right] \left[ \frac{G_\omega}{m_\omega^2} - \frac{G_\sigma}{m_\sigma^2} + \frac{G_\rho}{m_\rho^2} \frac{\vec{\tau}_i . \vec{\tau}_j}{4} \right]$$

$$+ \frac{1}{2} \sum_{i \neq j} \delta(\vec{R}_{ij}) \left[ G_\omega - G_\sigma + G_\rho \frac{\vec{\tau}_i . \vec{\tau}_j}{4} \right]$$

$$+ \frac{dG_\sigma^2}{2} \sum_{i \neq j \neq k} \delta^2(ijk) - \frac{d^2 G_\sigma^3}{2} \sum_{i \neq j \neq k \neq l} \delta^3(ijkl)$$

$$+ \frac{i}{4M^2} \sum_{i \neq j} A_{ij} \vec{\nabla}_i \delta(\vec{R}_{ij}) \times \vec{\nabla}_i . \vec{\sigma}_i$$

**with** $A_{ij} = G_\sigma + (2\mu_s - 1) G_\omega + (2\mu_v - 1) G_\rho \vec{\tau}_i . \vec{\tau}_j / 4$



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# Effective Interaction is of Skyrme III Type :

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

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

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

**and from comparison with QMC )**

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

$$t_3 = 3dG_\sigma^2,$$

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

# Numerical Comparison Remarkably Close

| | 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 | 12513 |
| $3t_1 + 5t_2$(MeV fm$^5$) | 192 | 475 | 710 | 451 |
| $5t_2 - 9t_1$(MeV fm$^5$) | $-7622$ | $-4330$ | $-4030$ | $-4036$ |
| $W_0$(MeV fm$^5$) | 118 | 97 | 120 | 91 |
| $K$(MeV) | 327 | 327 | 355 | 364 |

**Controls nuclear surface thickness**

**Controls nucleon Effective mass**

# Nuclear Structure Functions Revisited

- Are nuclear PDFs really just slightly modified nucleon PDFs??
- Address within a model… BUT not necessarily so bad
- In retrospect some findings turn out to be not so model dependent…
- Models have historically provided insights into non-perturbative QCD and guidance for experiment and lattice QCD

e.g. $\bar{d} \neq \bar{u}$ (1983) ; $s \neq \bar{s}$ (1987);

$\Delta \bar{u} \neq \Delta \bar{d}$ (1991) ; $d^p \neq u^n$ (1992,3) …..

Essential to test

# 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: $\frac{1}{A^n} \rightarrow \frac{1}{(n-1)!}\int_{1/\Lambda_{IR}^2}^{1/\Lambda_{IR}^2} d\tau \tau^{n-1} e^{-\tau A} \quad (n \geq 1)$

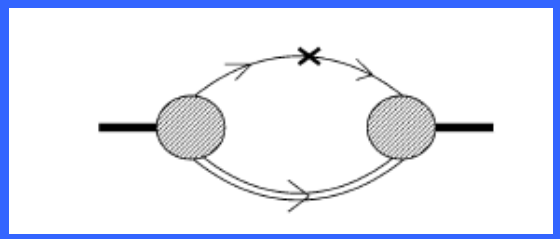
# For the free Nucleon

**We need to evaluate:**

$$f_{q/N}(z) = -i\int \frac{d^4k}{(2\pi)_4}\delta\left(z - \frac{k_-}{p_-}\right) tr\left(\gamma^+ M(p,k)\right),$$

$$M_{\beta\alpha}(p,k) = i\int d^4w e^{ik\cdot w}\left\langle N,p\middle|T\left[\bar{\psi}_\alpha(0)\psi_\beta(w)\right]\middle|N,p\right\rangle$$

**with the result (e.g. hitting quark with spectator di-quark):**



$$f^{(Q)}_{q/N0}(x) = \frac{g_D Z_N}{16\pi^2}(1-x)\int_{1/\Lambda^2_{UV}}^{1/\Lambda^2_{IR}} \frac{d\tau}{\tau} e^{-\tau A\left(x, M_N^2\right)}\left[1 + \tau x\left(\left(M_N + M\right)^2 - M_D^2\right)\right]$$



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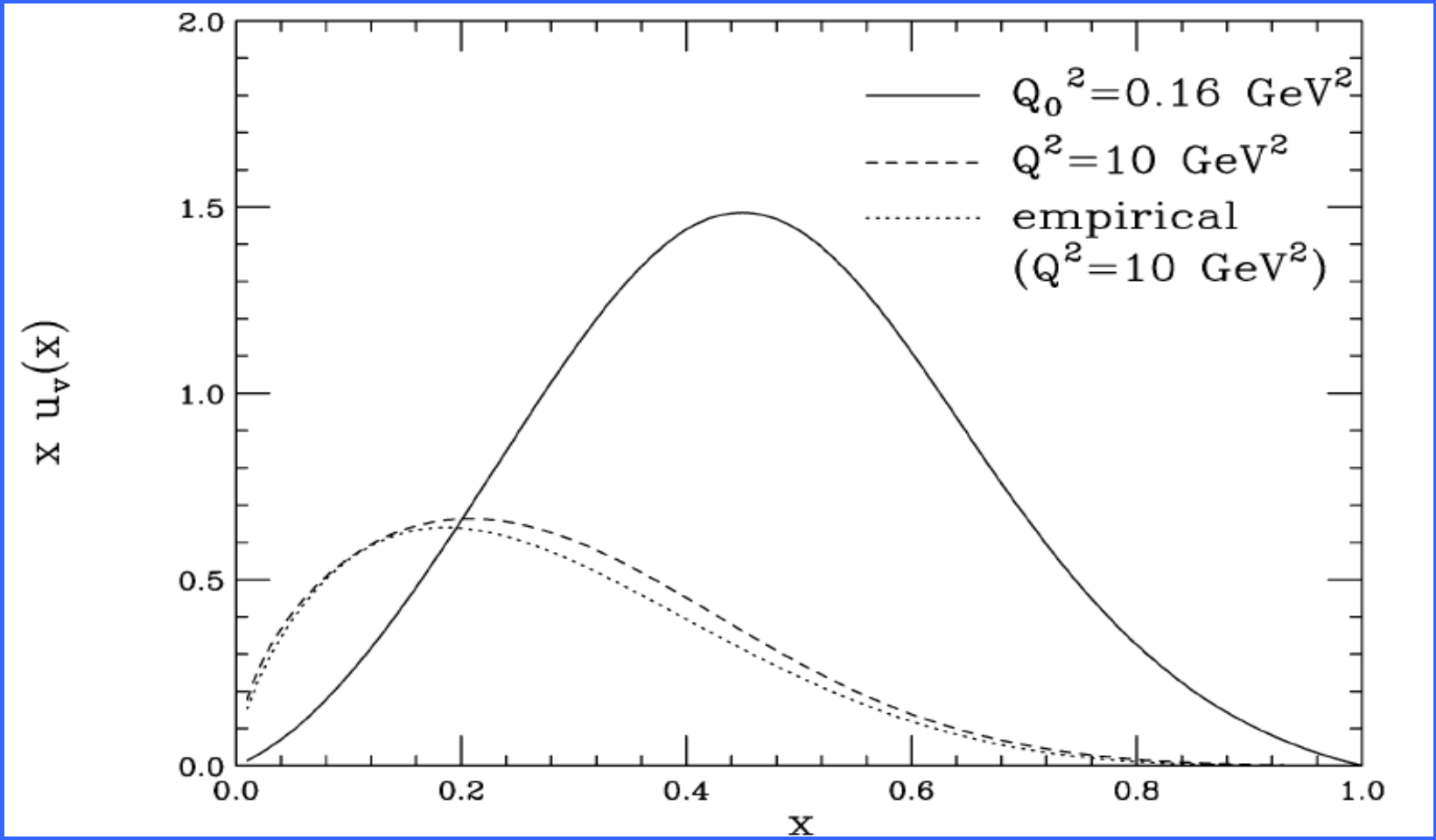
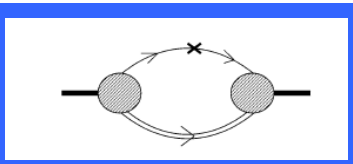
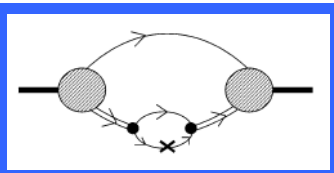
# Free Valence u-quark PDF

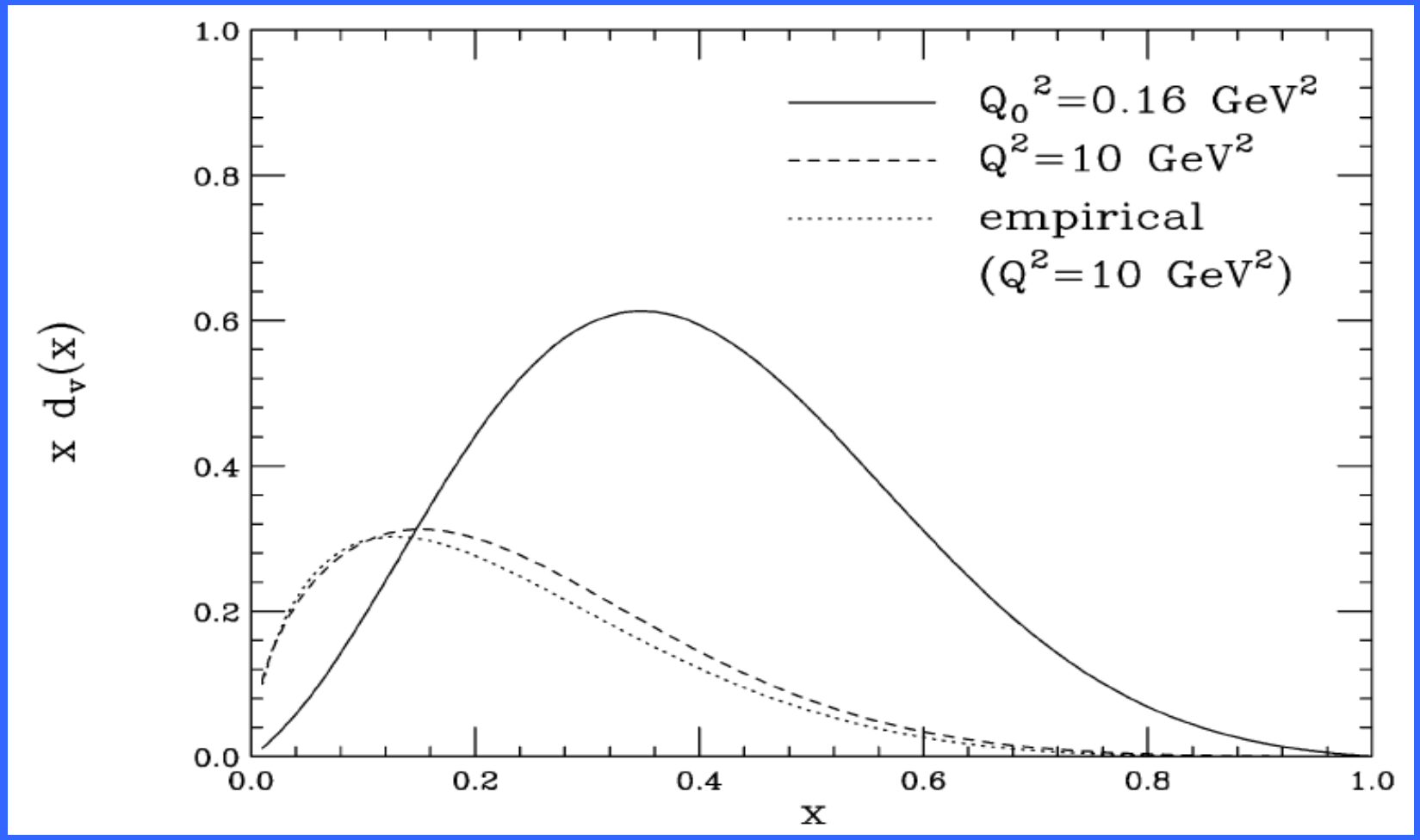


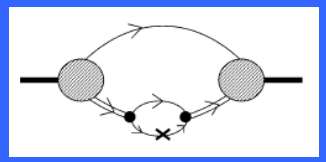
$$u_v(x) = f^{(Q)}_{q/N0}(x) + \frac{1}{2} f^{(D)}_{q/N0}(x)$$



# Free Valence d-quark PDF




$$d_v(x) = \frac{1}{2} f^{(D)}_{q/N0}(x)$$



# Role of Lorentz Vector Potential

( Mineo et al., N P A735 (2004) 482; Steffens et al., hep-ph/0405096)

- While scalar mean-field affects dynamics of nucleon internal structure

- Vector potential is essentially a gauge transformation (i.e. just shifts energy)

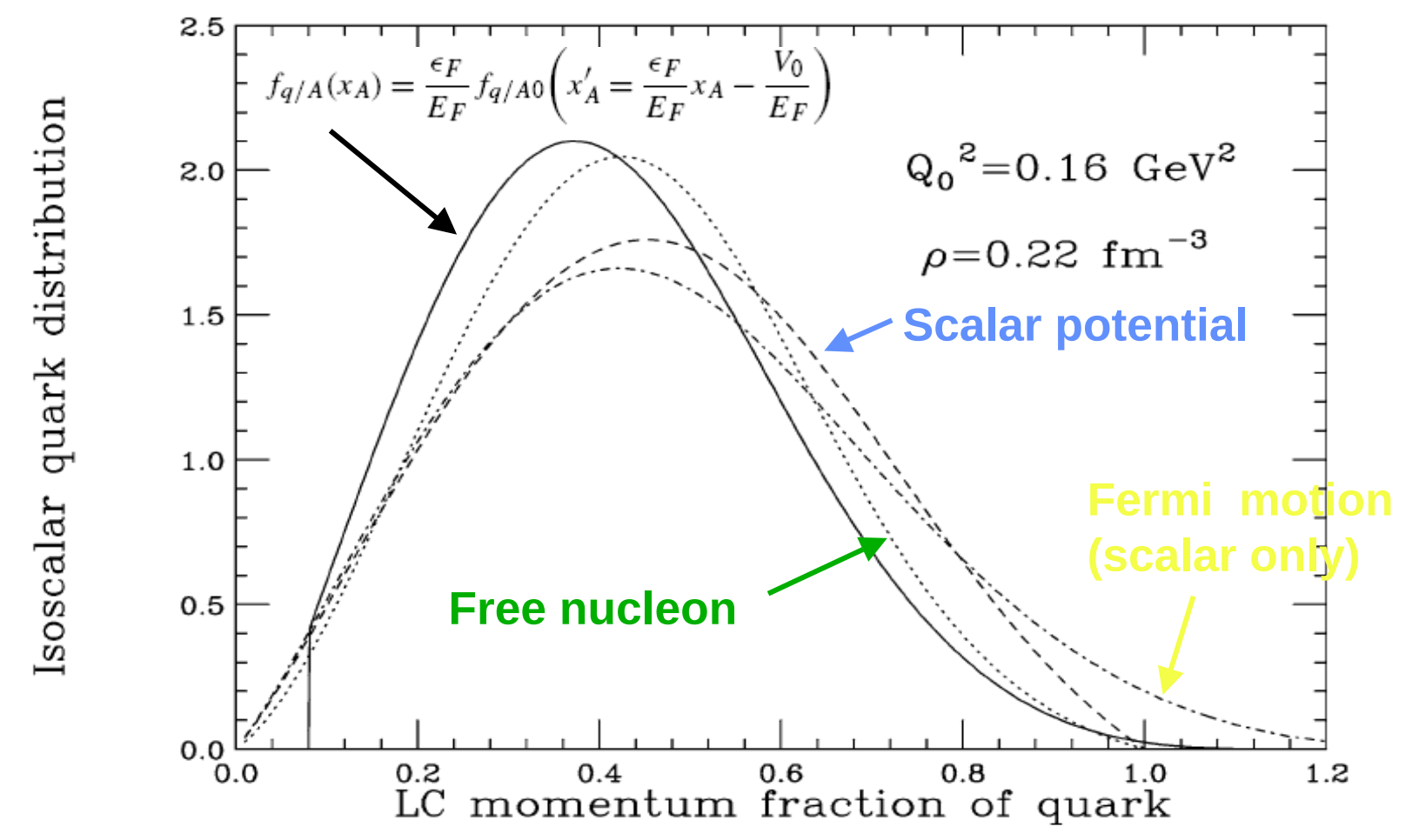
$$\psi(w) = e^{i\hat{P}_q \cdot w}\psi(0)e^{-i\hat{P}_q \cdot w} \qquad \hat{H}_q = \hat{h}_q + V_0\hat{Q}$$

- As a result support of distribution in bound nucleon is changed:

$$\frac{V_-}{p-} < z < 1 - \frac{2V_-}{p-}$$

- $V_-$ is vector potential felt by single quark, which is of order 70 MeV in this model (and QMC)

# Change of Nucleon PDF In-Medium



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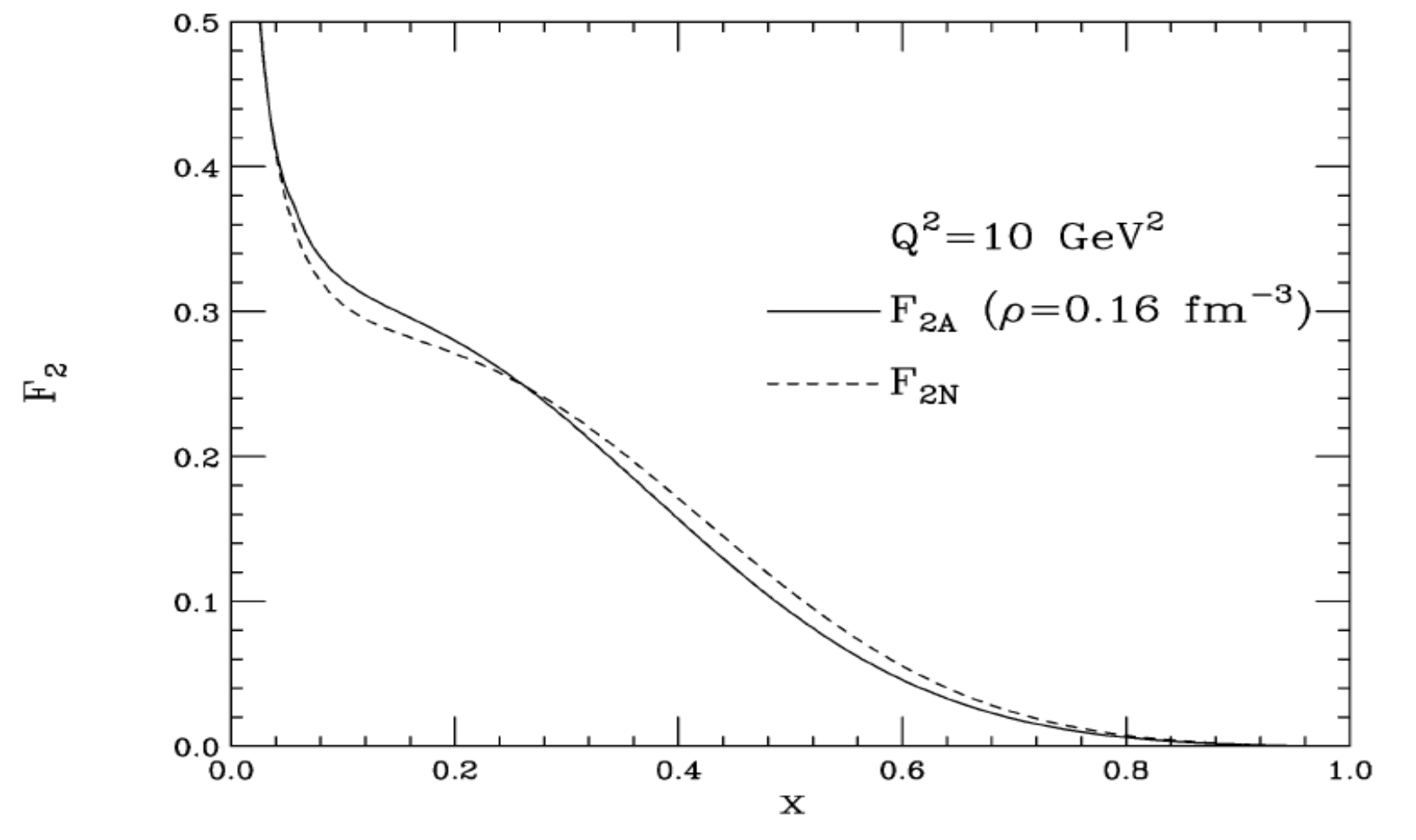
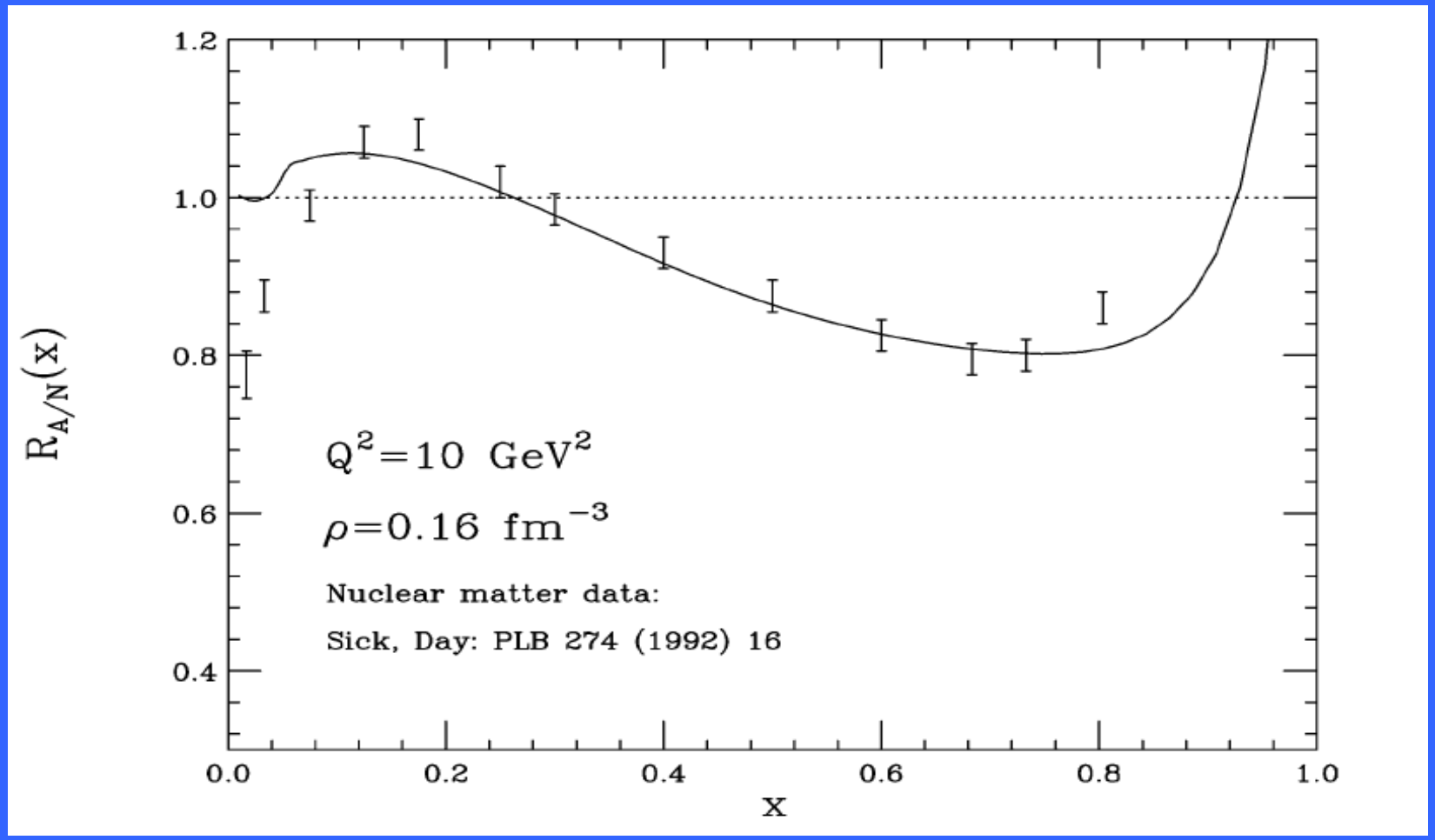
# Comparison of Nucleon and Nuclear SF



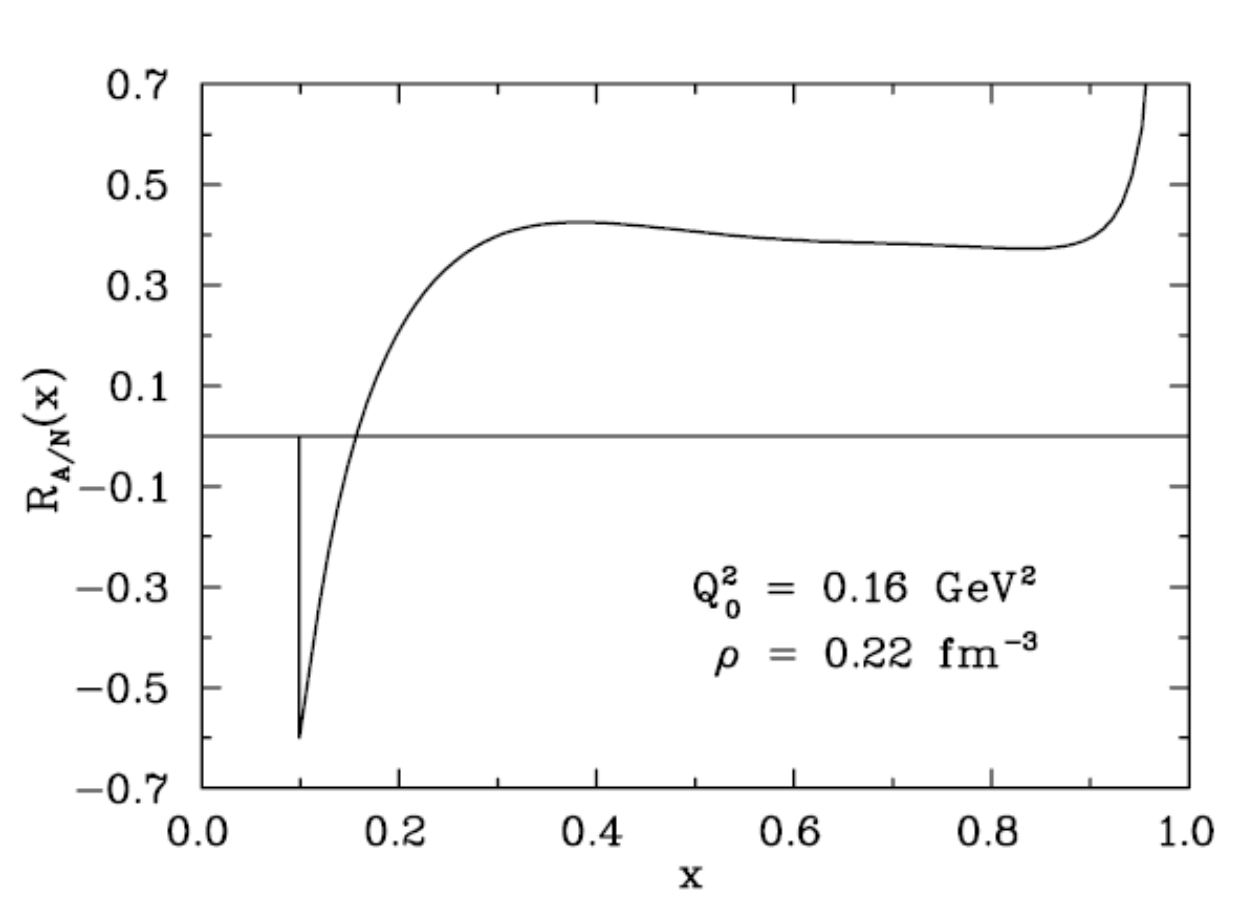
# EMC Ratio for Infinite Nuclear Matter




**Data of Sick et al, Phys Lett B274 (1992) 16**

# Even More Challenging…

**Ratio of $\Delta u_V$ in nuclear matter to that in free space**
**- at quark model scale, no Fermi motion and no vector di-quark, BUT…**




**Bentz, Cloet, Thomas (2004)**

# Conclusions

- Study of hadron properties as function of $m_q$ using data from lattice QCD is extremely valuable…..

  <u>has given major qualitative advance in understanding !</u>

- Inclusion of model independent constraints of $\chi$ PT to get to physical quark mass is essential

- But radius of convergence of traditional (not FRR) $\chi$ P T is too small

# Conclusions…..2

**Nevertheless :**

- **Precisely where divergence occurs, new, simple degree of freedom appears : "constituent quark"**

- **Scale for this transition is set by clear physics : whether $\pi$ -Compton wavelength is larger or smaller than size of pion source**

  **i.e. $m_\pi$ < or > 0.4 – 0.5 GeV**

# Conclusions….3

- **Insight enables: accurate, controlled extrapolation of all hadronic observables….**
  **( e.g. $m_H$ , $\mu_H$ , $\langle r^2 \rangle_{ch}$ , $G_E$, $G_M$, $\langle x^n \rangle$……..)**

- **Suggests new connection between QQCD and QCD**
  **(chiral loops seem to explain whole difference!)**

- **Findings suggest development of new CQM in region where it has a chance to be valid & tests of all quark models!**

# Conclusions…4

- Quark level approach to nuclear structure
  leads naturally to effective force of Skyrme type
  ….WITH 3- and 4-body forces

- 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)

# Special Mentions……