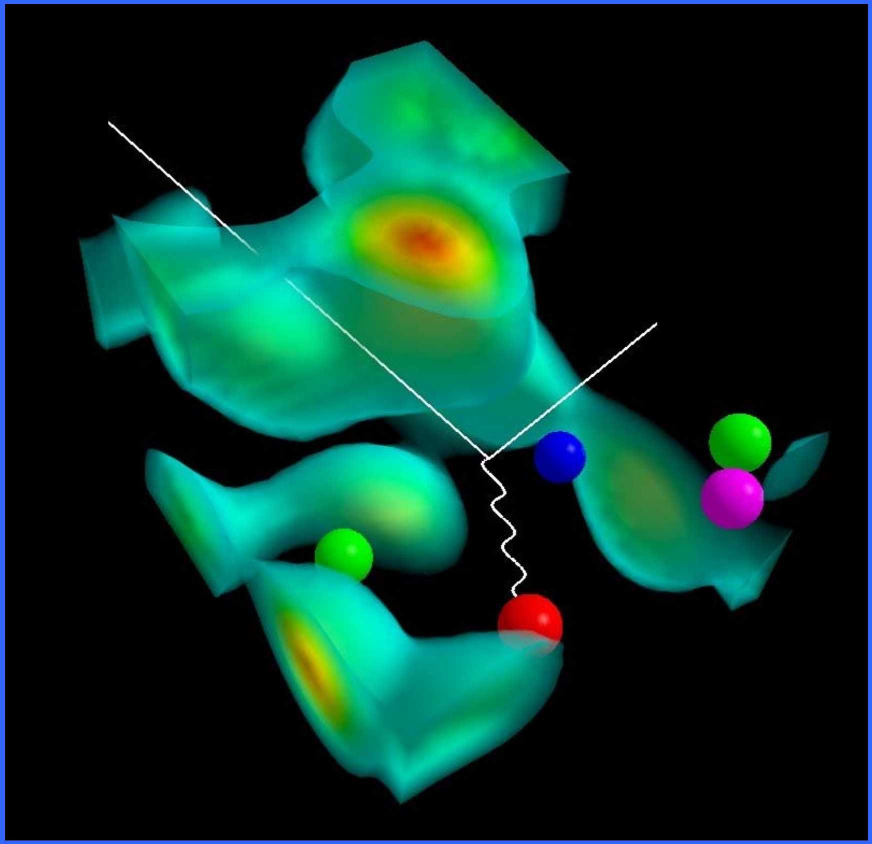
Contribution of Strange Quarks to the Structure of the Nucleon



Wally Melnitchouk (for Anthony W. Thomas)

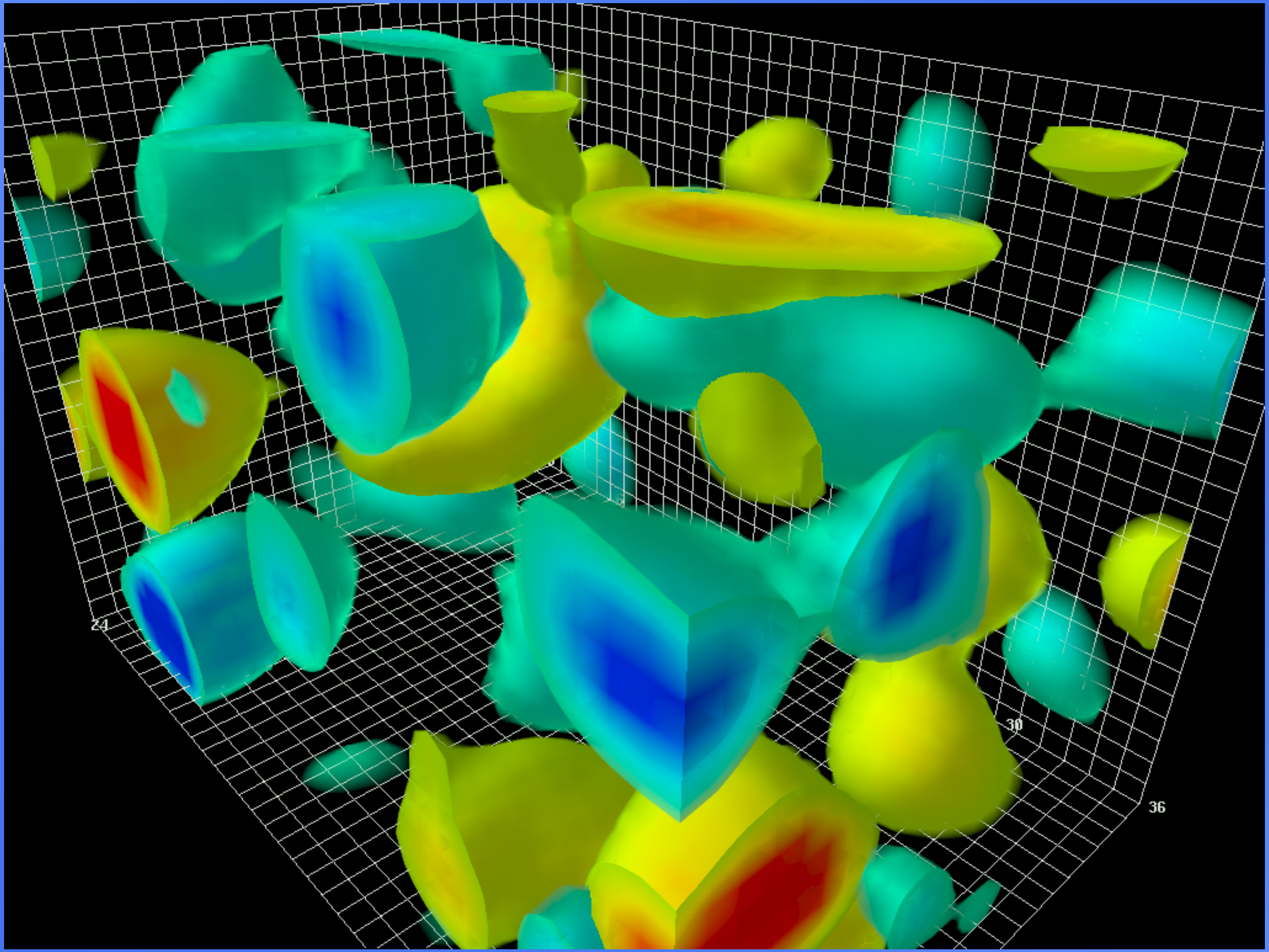
Workshop on Precision Perspectives in Hadronic Physics

ICTP : May 22nd, 2006

Outline

- The QCD Vacuum
- Quarks to Hadrons
- Measurements of Nucleon Form Factors
- A Precise Theoretical Calculation of G_M^s
- Latest Results on Strangeness

Topology of QCD Vacuum



Leinweber: see CSSM web pages

Powerful Qualitative New Insights From Lattice QCD

QCD sum rules :

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

- 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!

Quark Condensate

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

at a renormalization scale of about 1 GeV.

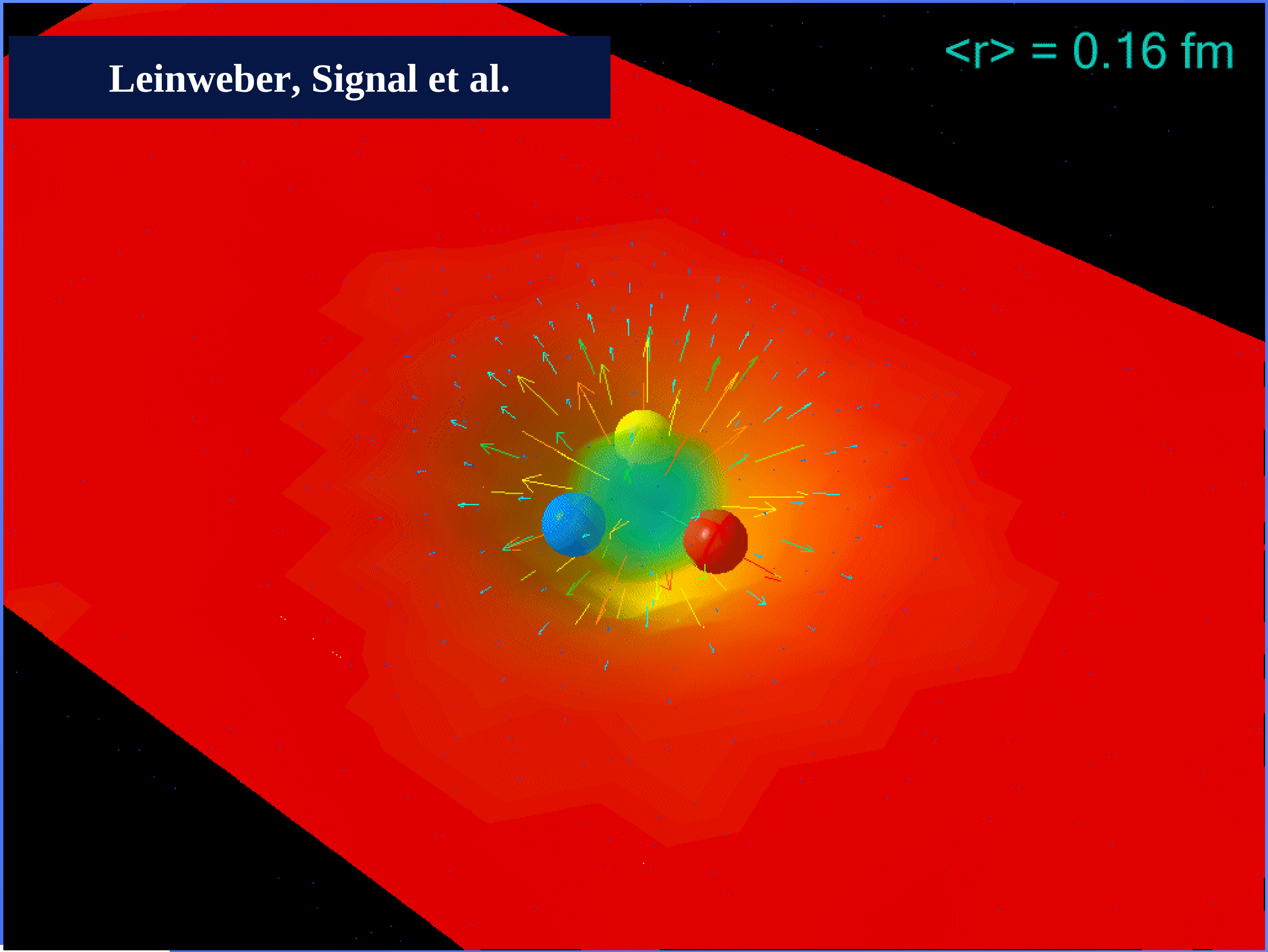
σ commutator measures chiral symmetry breaking

≈ valence + pion cloud
+ volume * (difference of condensate in & out of N)

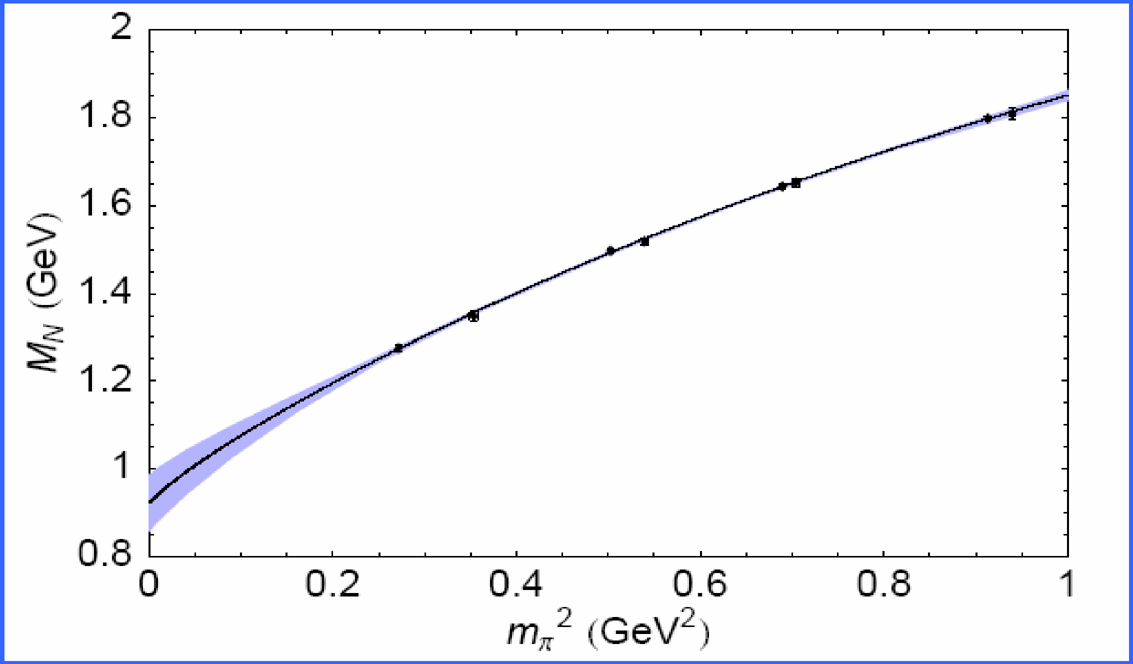
… and last term is as big as 20 MeV (or more)

i.e. presence of nucleon "cleans out" vacuum to some extent

Lattice QCD Simulation of Vacuum Structure



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

Convergence from LNA to NLNA is Rapid – Using Finite Range Regularization

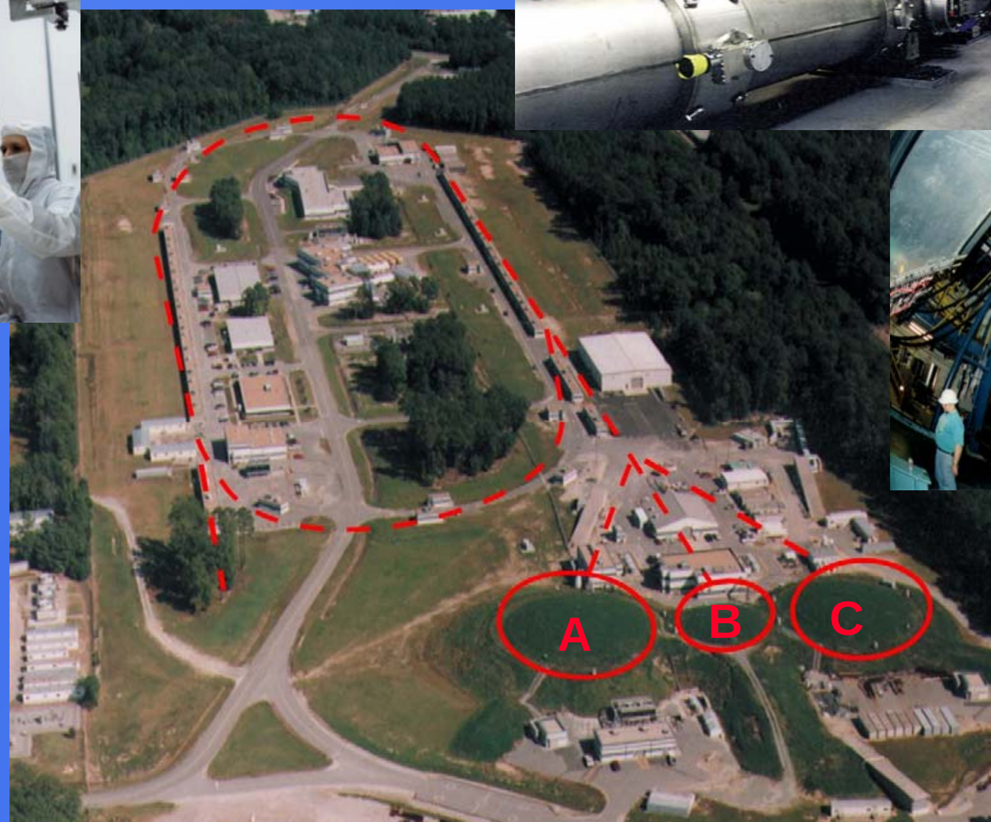
Regulator	LNA	NLNA
Sharp	968	961
Monopole	964	960
Dipole	963	959
Gaussian	960	960
Dim Reg	784	884

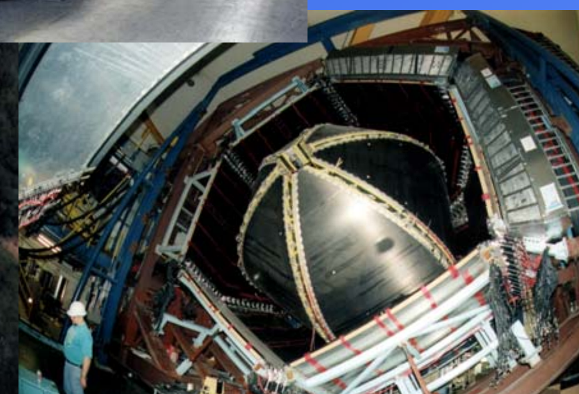
M_N in MeV

JLab: Unique Capabilities for Investigating QCD in the Non-Perturbative Regime

JLab is a world leader in SRF technology: SNS, 12 GeV Upgrade, FEL, RIA, and others in the Office of Science 20-Year Facilities Outlook

Superconducting rf (SRF) technology makes the circulating accelerator feasible



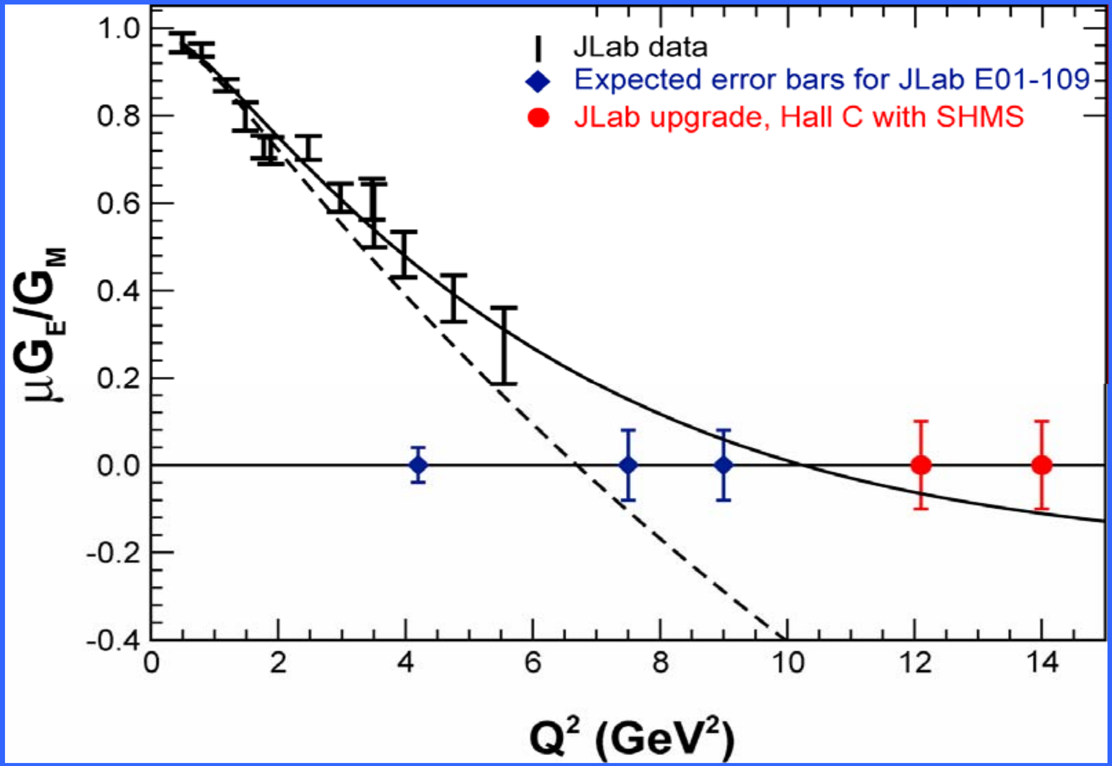


Providing ~2300 international users with a unique electron beam, three experimental halls, and computational and theory support

High luminosity, high resolution detectors in Halls A, B, and C.

Precision Tests of Nucleon Structure

- Astonishing discovery concerning proton electric form factor



- But what about contribution from non-valence quarks

- especially strange quarks ?

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

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

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

y=0.2 ○ 0.2

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

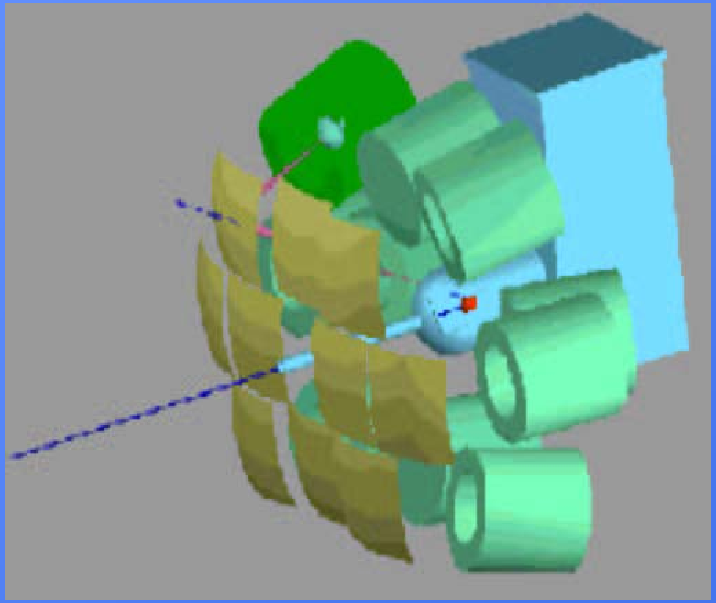
45 ○ 8 MeV (or 70?)

Hence 110 ○ 110 MeV (increasing to 180 for higher σ_N)

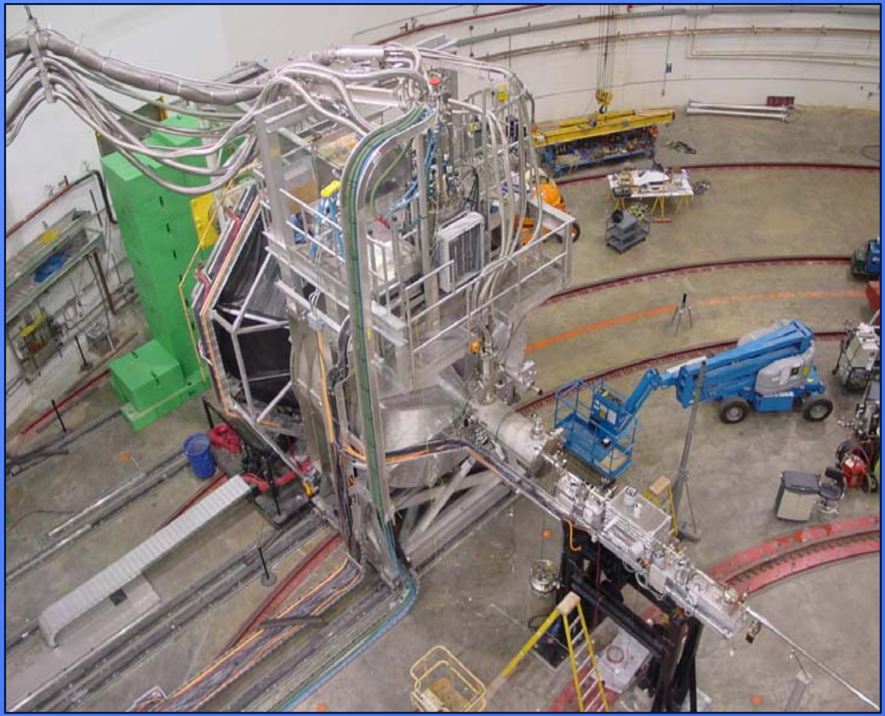
- Through proton spin crisis:
  As much as 10% of the spin of the proton

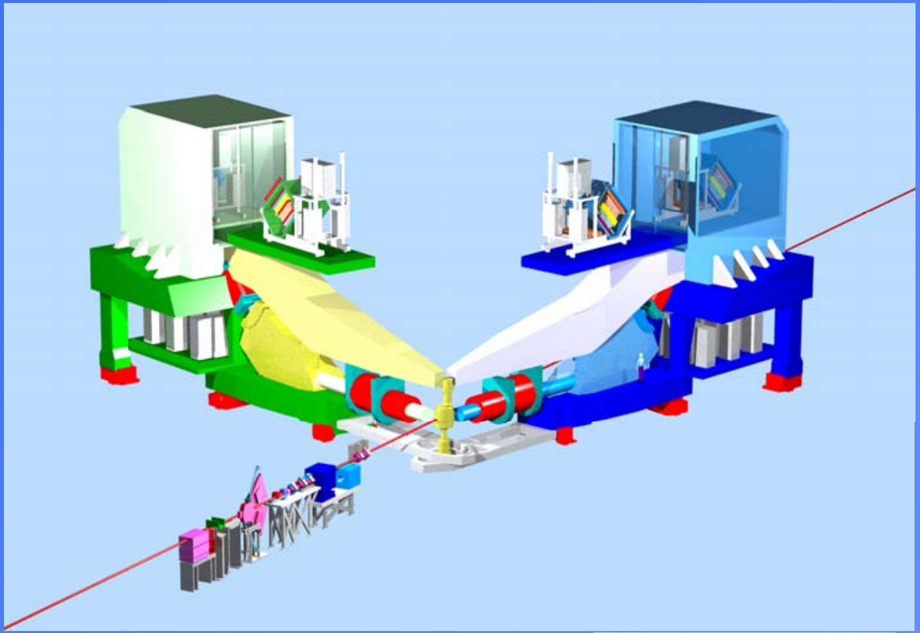
- HOW MUCH OF THE MAGNETIC FORM FACTOR?

MIT-Bates & A4 at Mainz

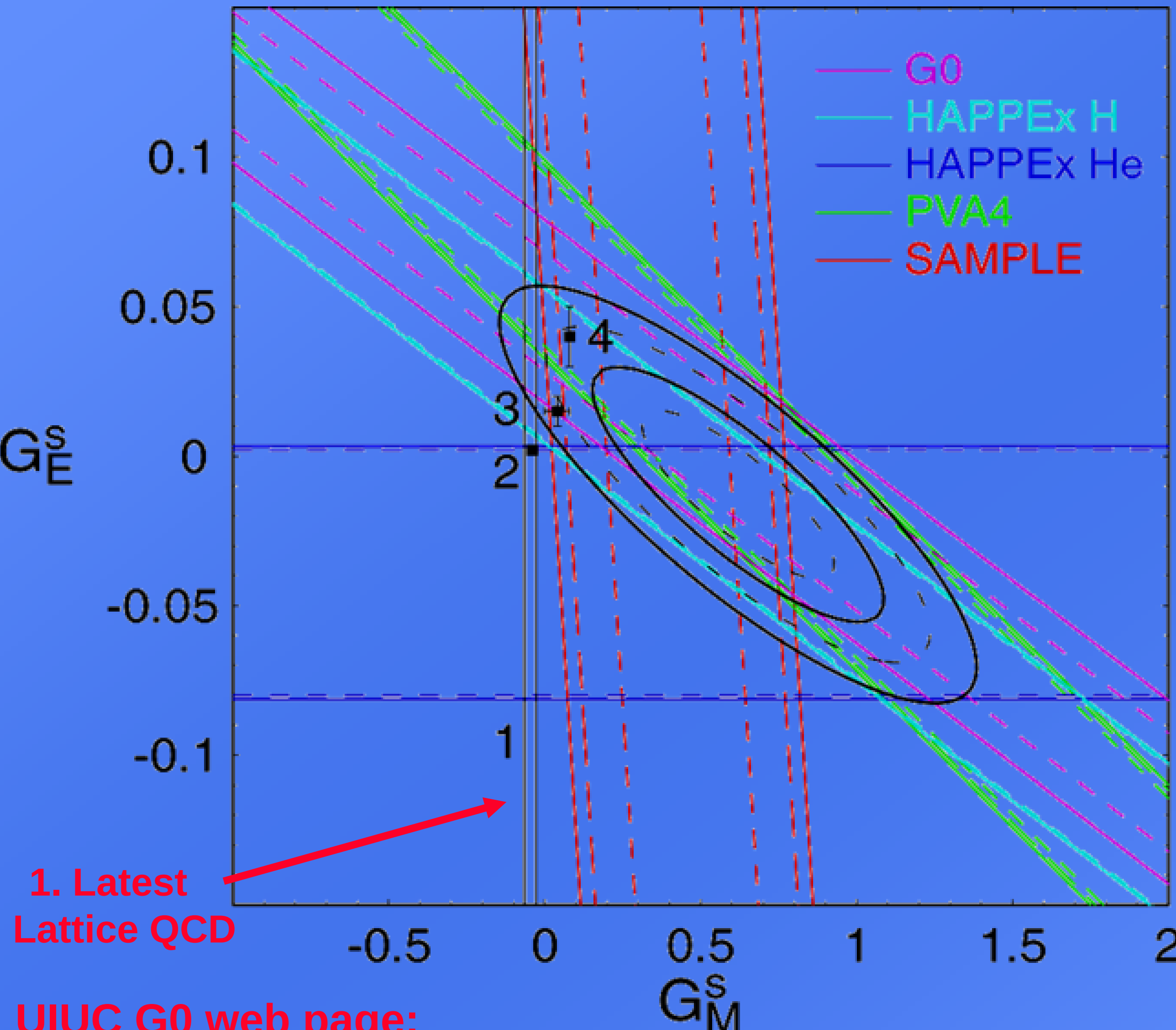


G0 and HAPPEx at JLab





Strange Form Factors at Q^2=0.1GeV^2



$G_E^s = -0.013 \pm 0.028$

$G_M^s = +0.62 \pm 0.31\ \mu_N$

1. Latest Lattice QCD

Theories

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

UIUC G0 web page:

"Excluded at 95.5% confidence level"

http://www.npl.uiuc.edu/exp/G0/Forward

Physical Significance of this Result

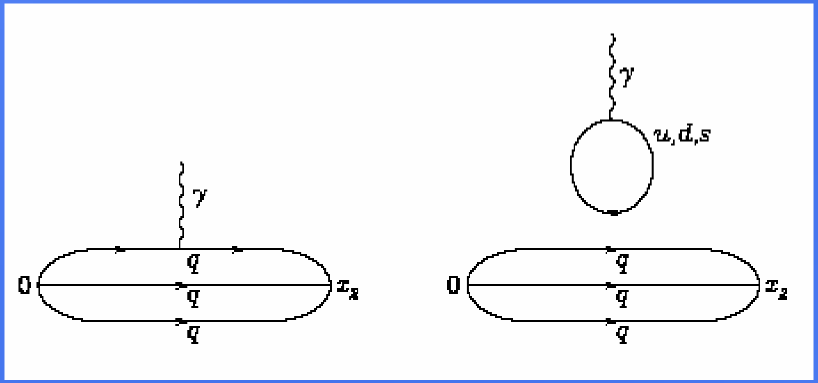
- Size and sign of the strange magnetic moment is <u>astonishing</u>!

- For the deuteron, this result (G0) gives - 0.54 μ_N
  - i.e. - 60% of its experimental magnetic moment!!

- Also remarkable versus lattice QCD which gives
  +0.03 ○ 0.01 μ_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

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

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

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

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

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

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

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

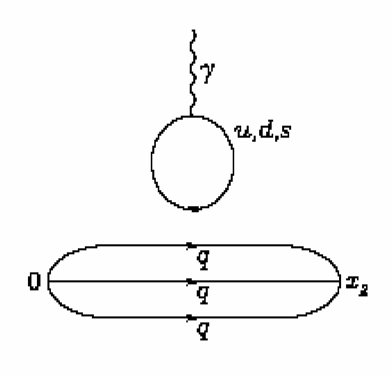
HENCE: $O_N = 1/3\ [\ 2p + n - (\ u^p / u^\Sigma\ )\ (\Sigma^+ - \Sigma^-)\ ]$

Just these ratios from Lattice QCD

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

Constraint from Charge Symmetry

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

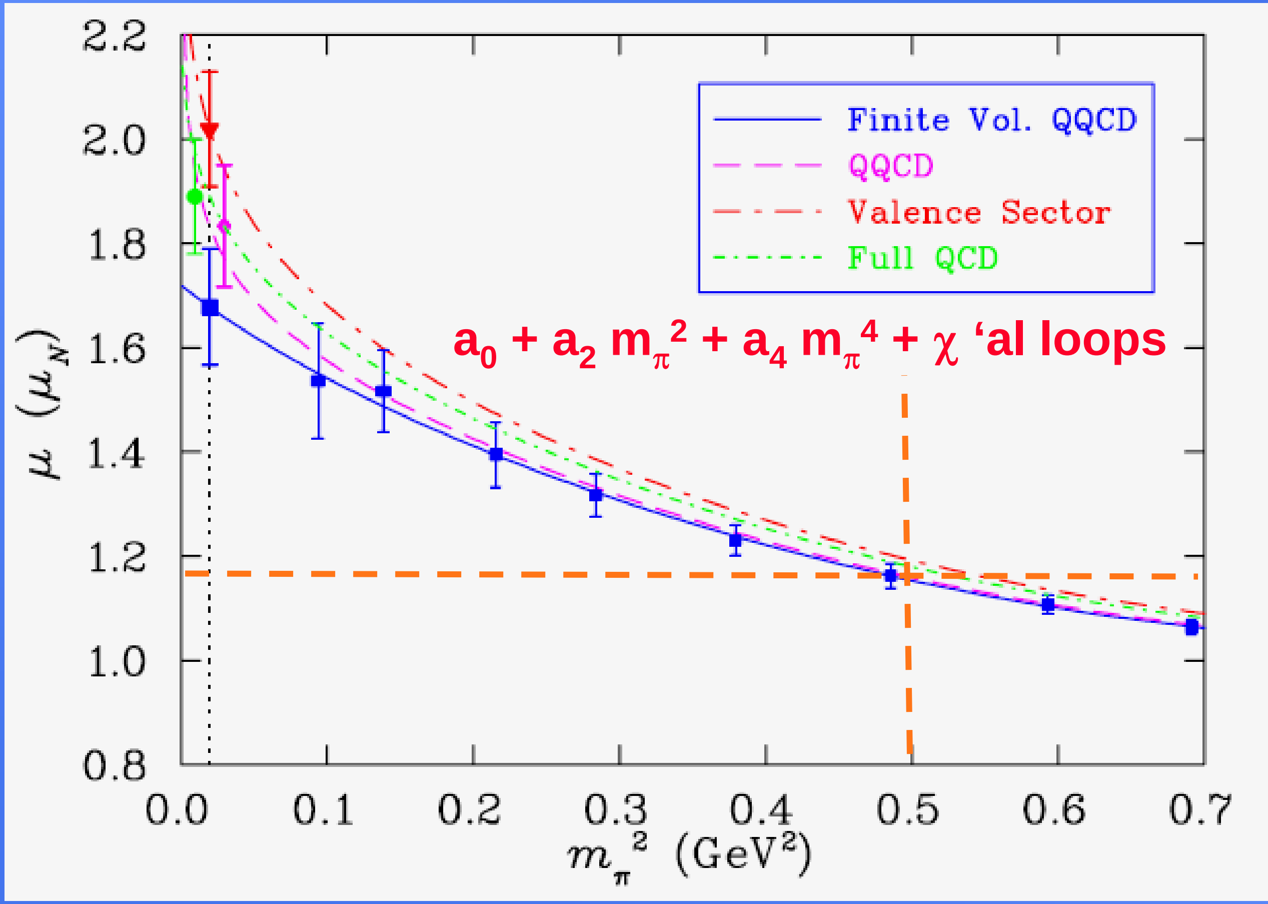


$$G_M^s = \left(\frac{{}^{\ell}R_d^s}{1 - {}^{\ell}R_d^s}\right)\left[3.673 - \frac{u_p}{u_{\Sigma^+}}(3.618)\right]$$

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

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

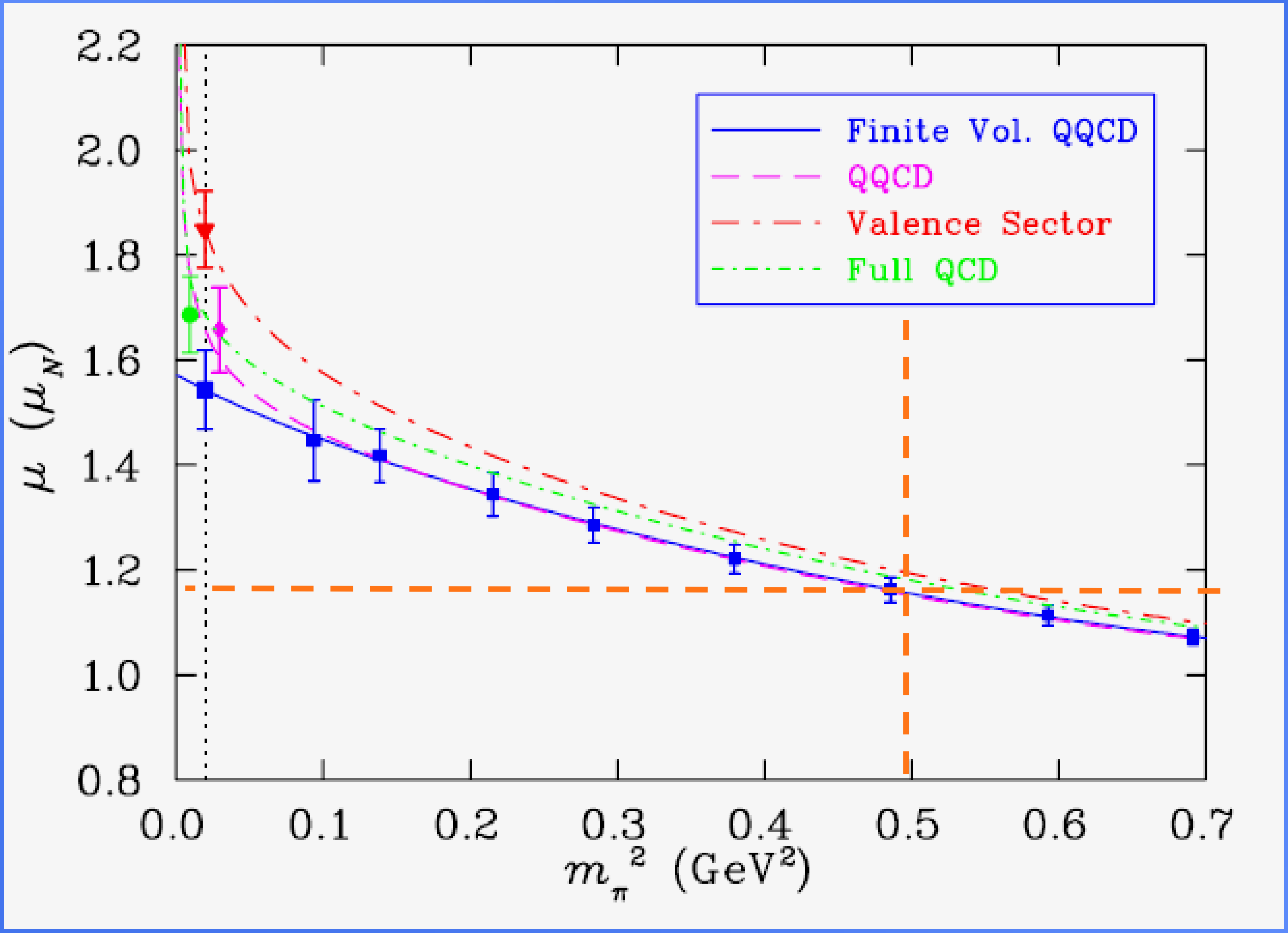
$u^p_{valence}$: QQCD Data Corrected for Full QCD Chiral Coeff's



c.f. CQM
2/3 940/540
♡ 1.18

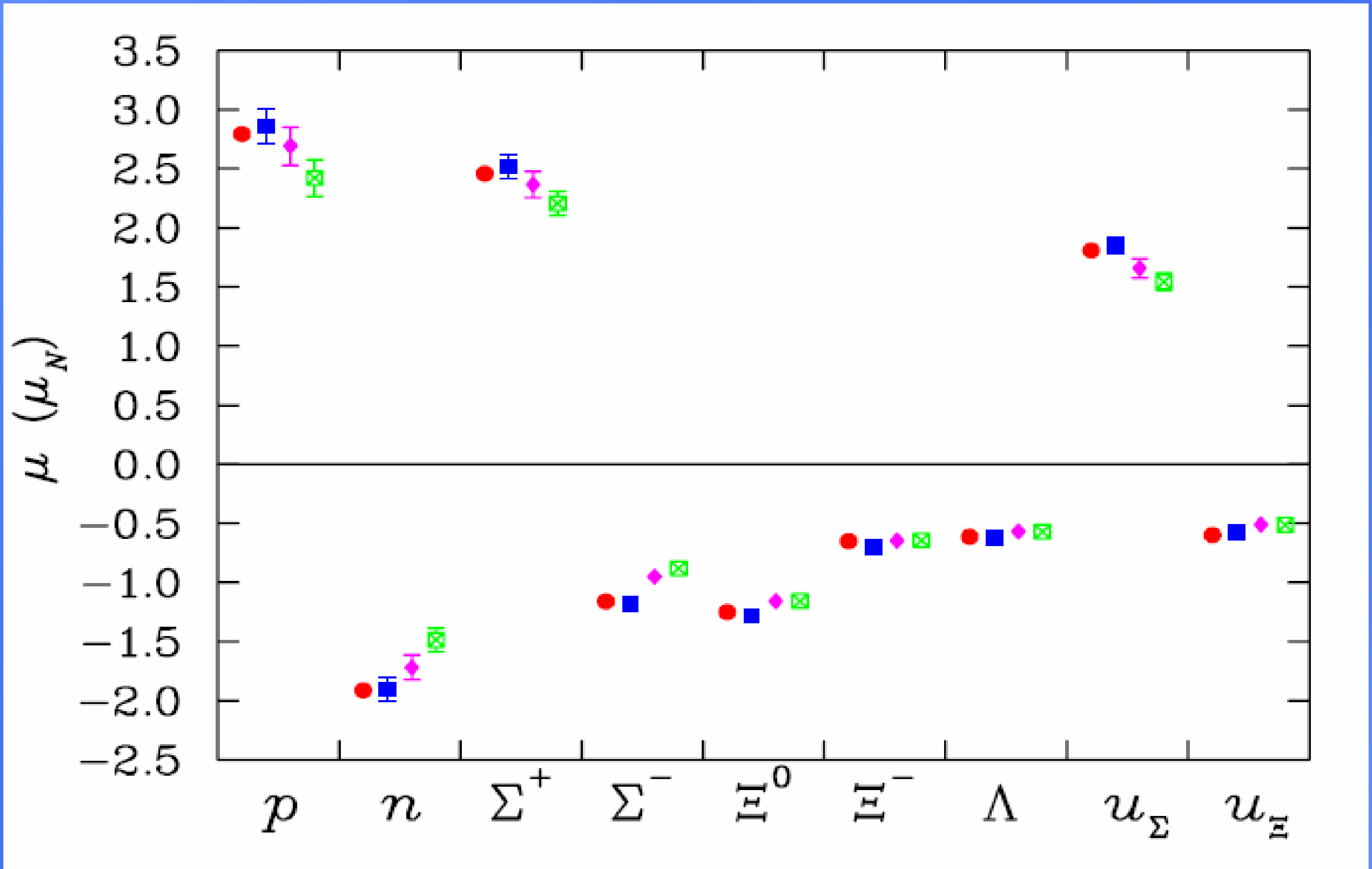
New lattice data from Zanotti et al. ; Chiral analysis Leinweber et al.

u^{Σ} valence



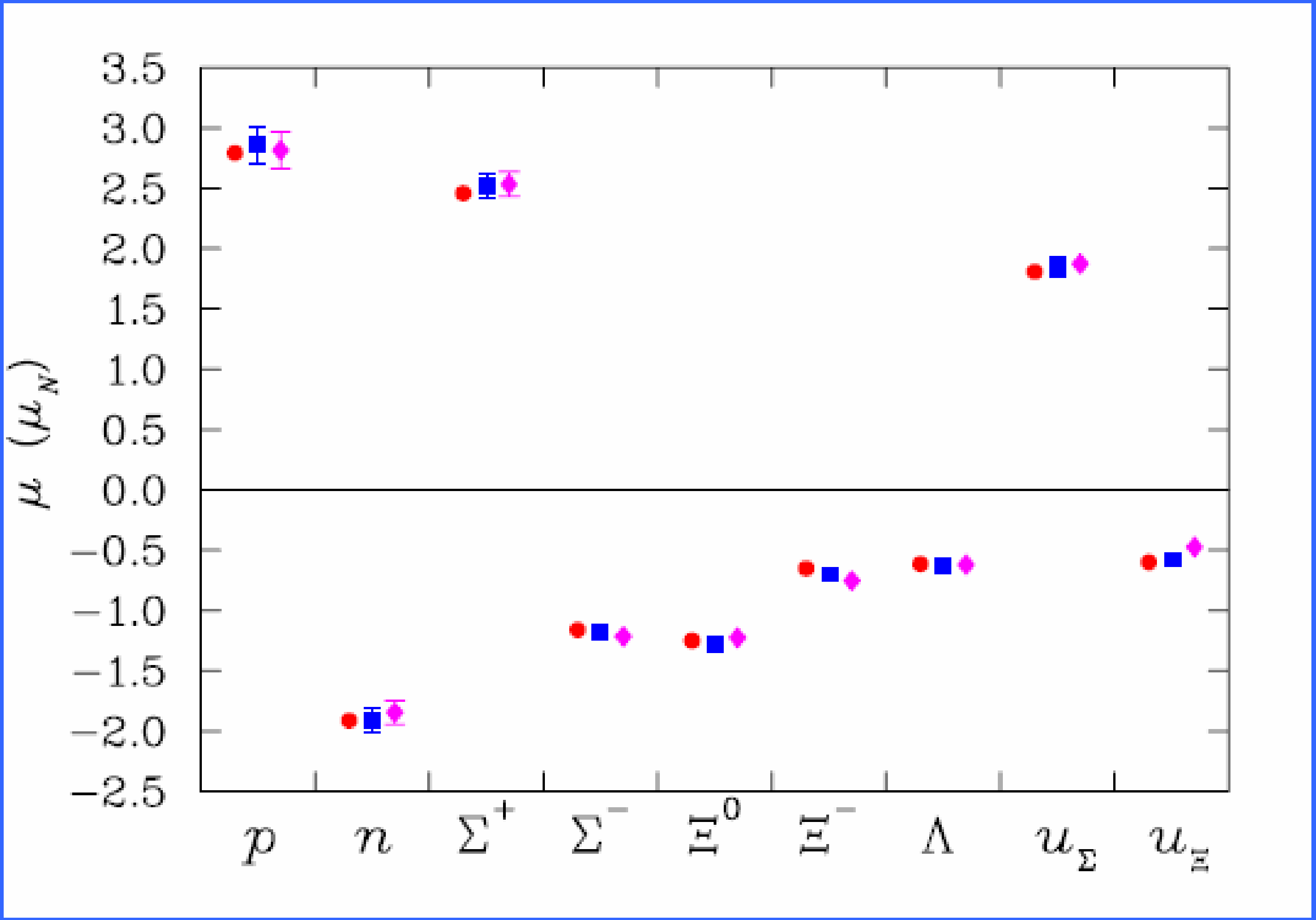
Universal Here!

Check: Octet Magnetic Moments



Leinweber et al., hep-lat/0406002

Convergence LNA to NLNA Again Excellent (Effect of Decuplet)

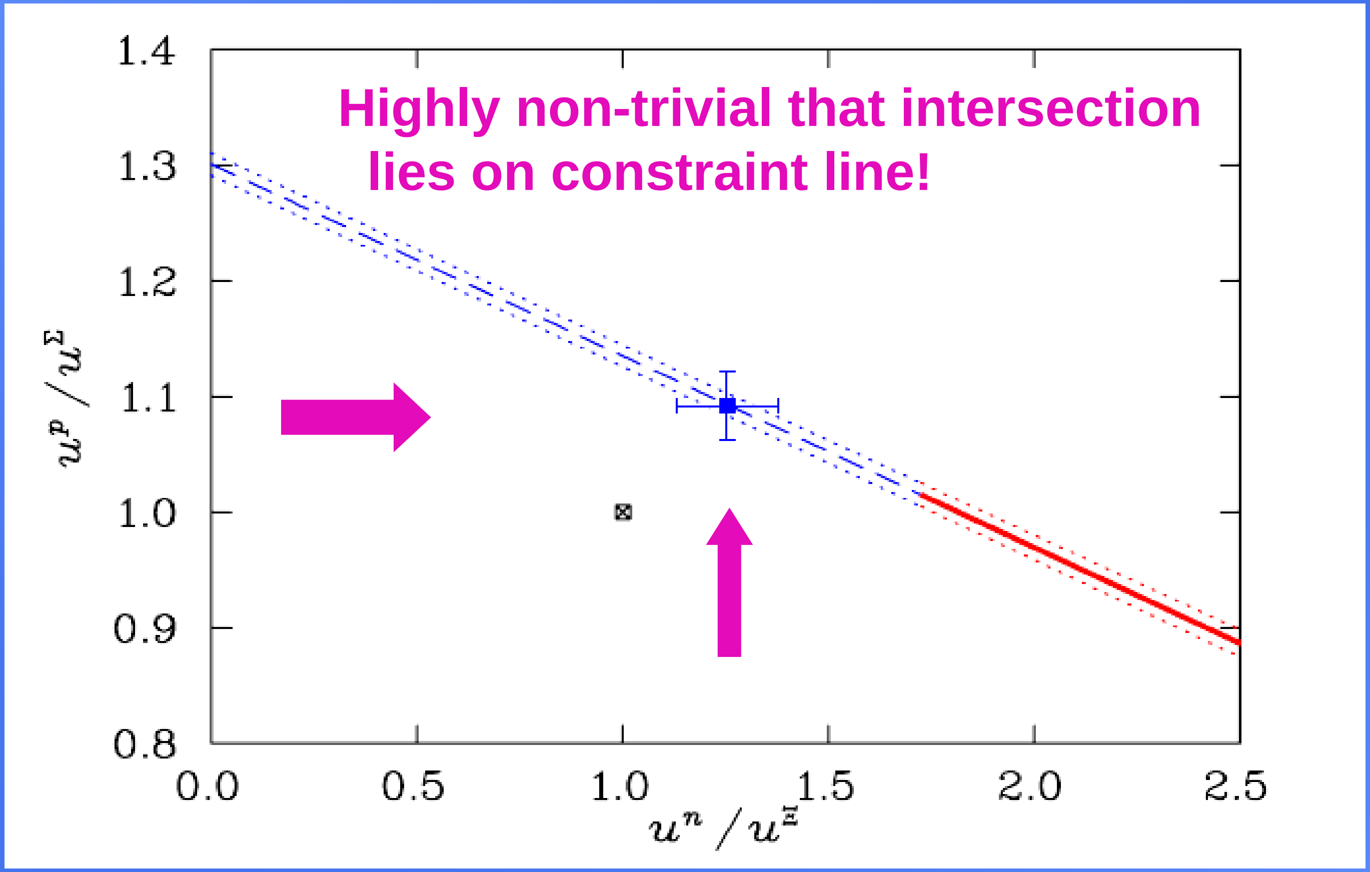


State of the Art Magnetic Moments

	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

G_E^s by same technique (January 2006)

In this case only know Σ^- radius (and p and n)

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

$\langle r^2 \rangle_s$ = 0.000 ⇓↖ 0.006 ⇓↖ 0.007 fm^2 ; 0.002 ⇓↖ 0.004 ⇓↖ 0.004 fm^2

(c.f. using Σ^- : -0.007 ⇓↖ 0.004 ⇓↖ 0.007 ⇓↖ 0.021 fm^2)

$$G_E^s(0.1\,\mathrm{GeV}^2) = +0.001 \pm 0.004 \pm 0.004$$

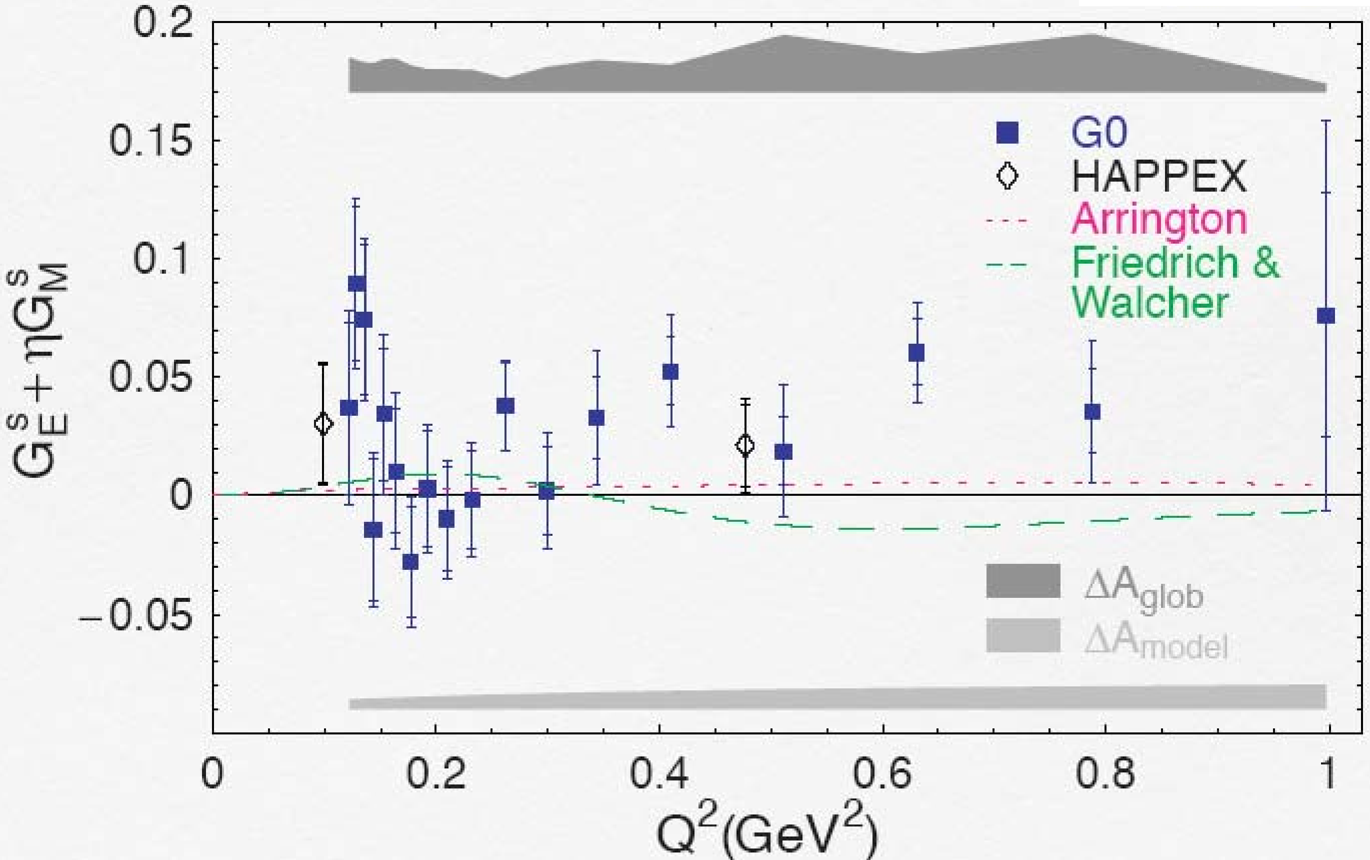
(up to order Q^4)

Note consistency and level of precision!

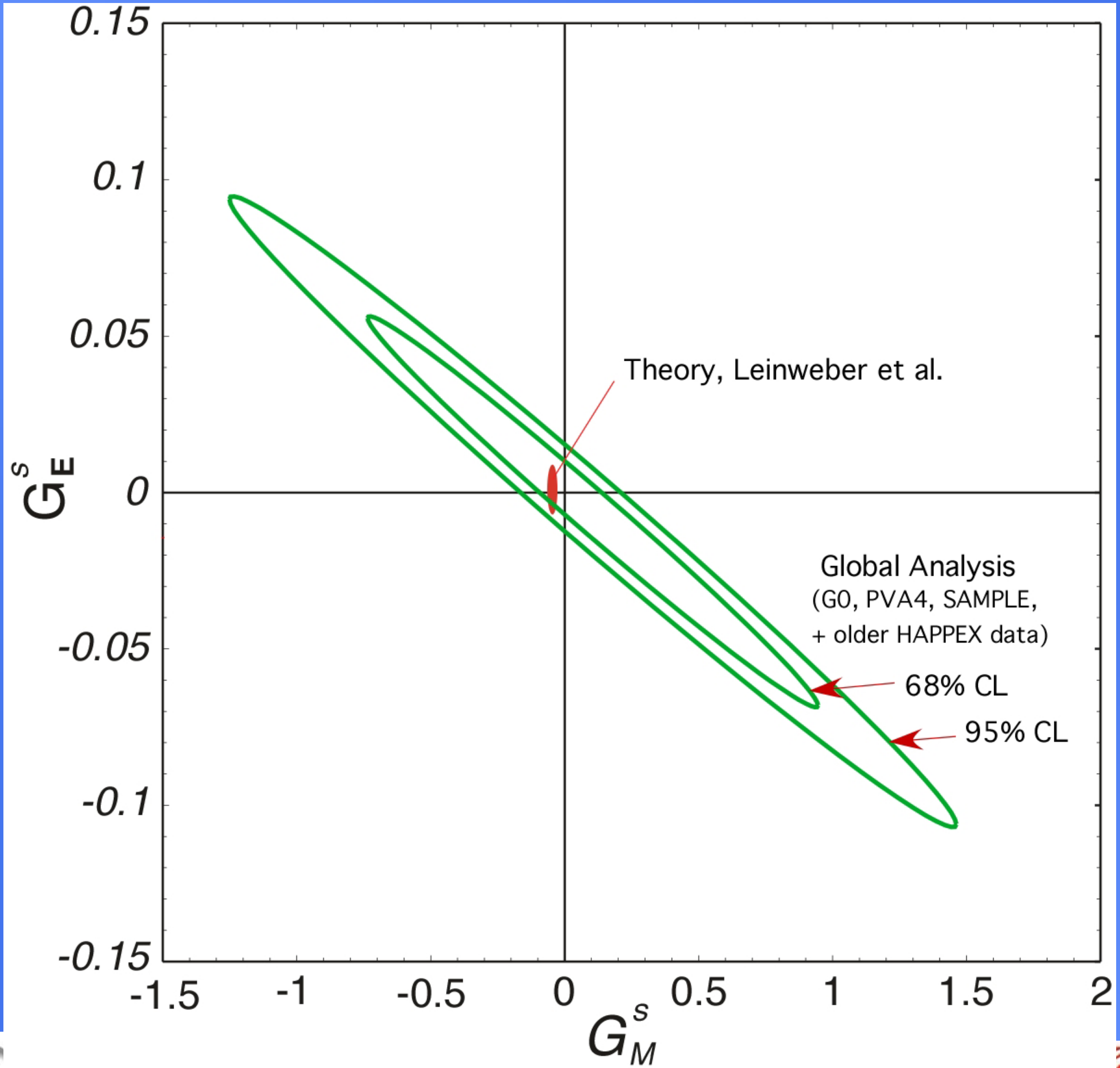
Leinweber, Young et al., hep-lat/0601025: Jan 2006

Ross Young: Why not use ALL the data?

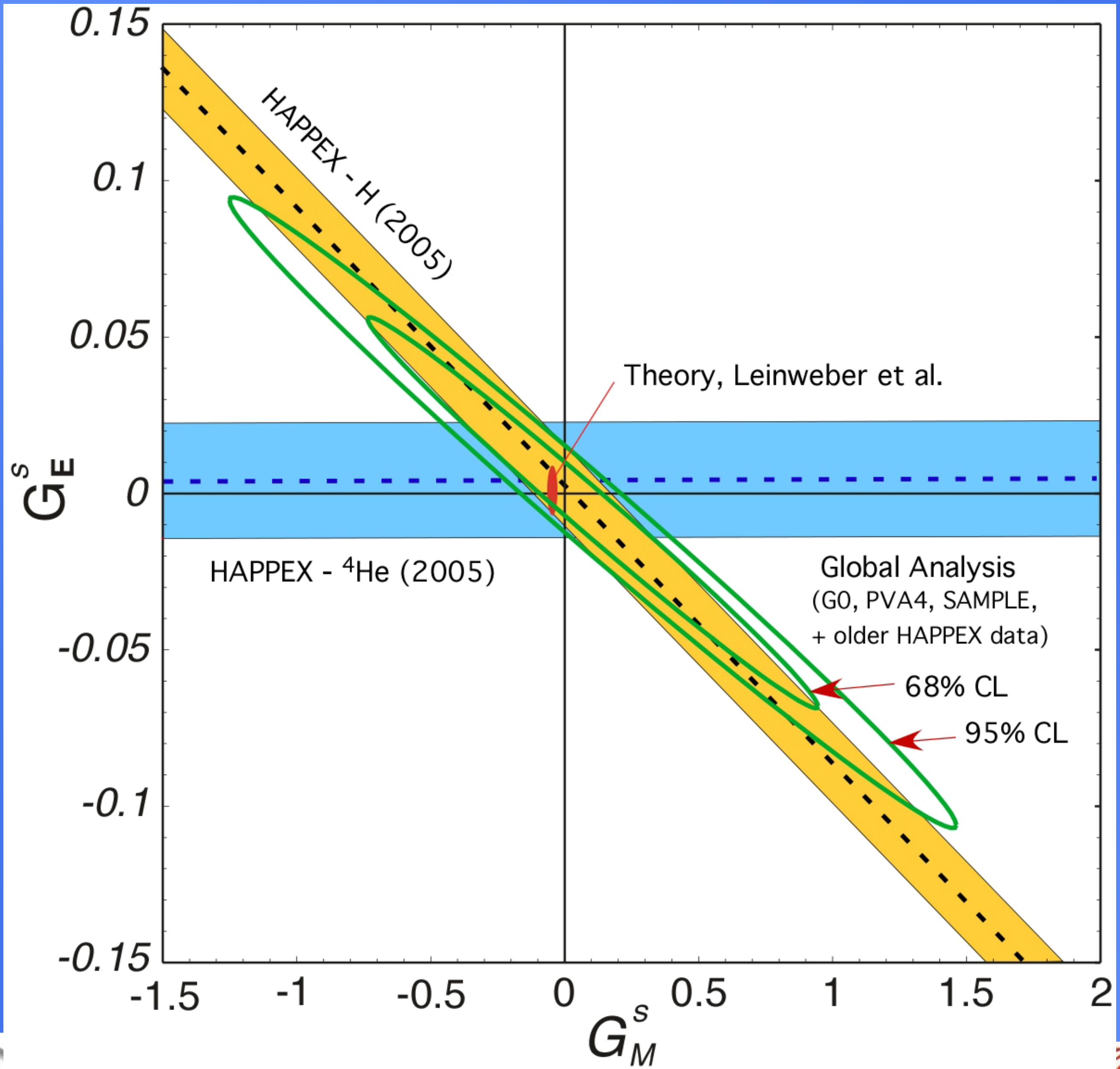
No theoretical constraint (other than charge symmetry); use systematic Taylor expansion of $G_{E,M}^s$ in powers Q^2



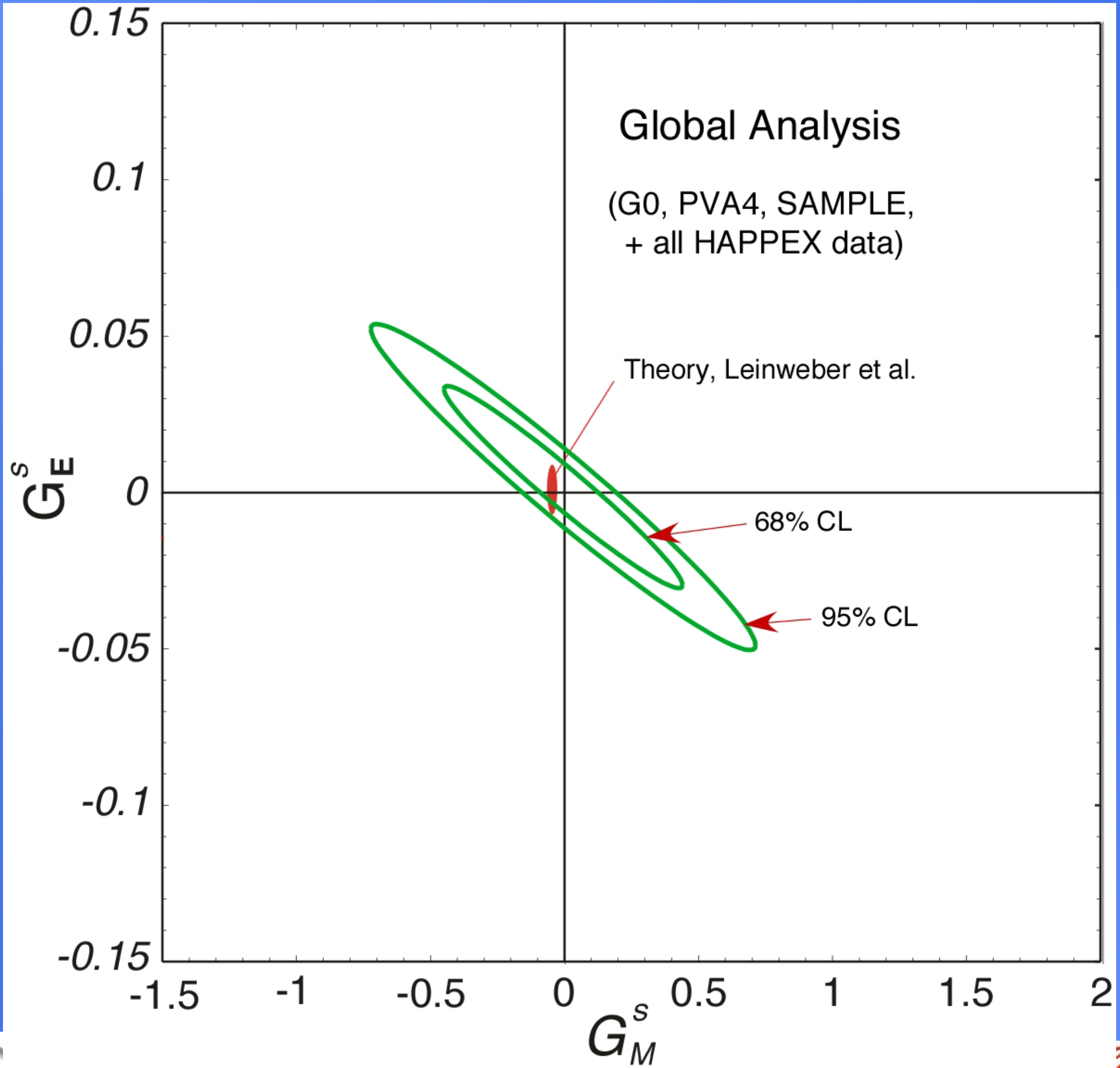
Young, Roche, Carlini, Thomas – nucl-ex/0604010 (pre- latest HAPPEx)



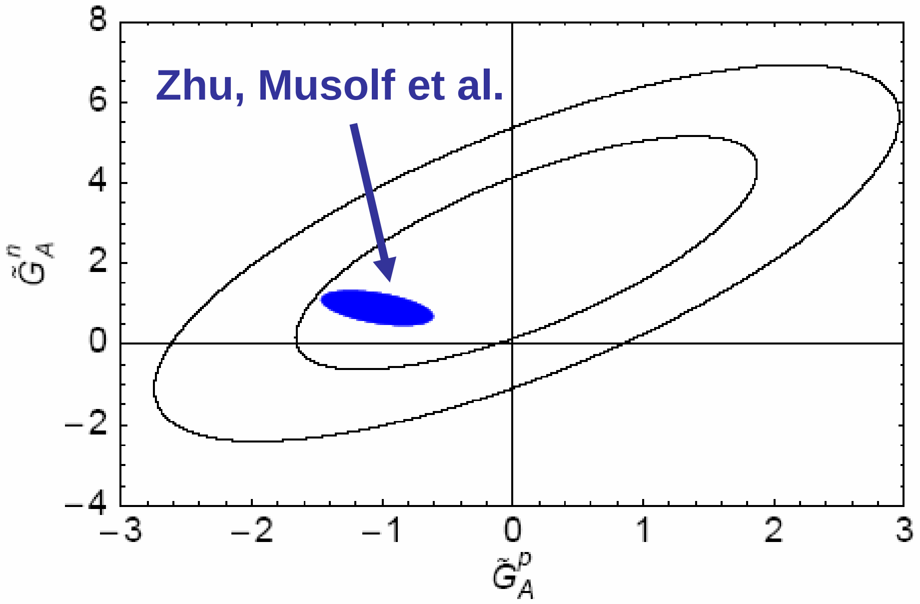
Superimpose NEW HAPPEx Measurement (April 2006)



World data plus new HAPPEx data



Axial Form Factors

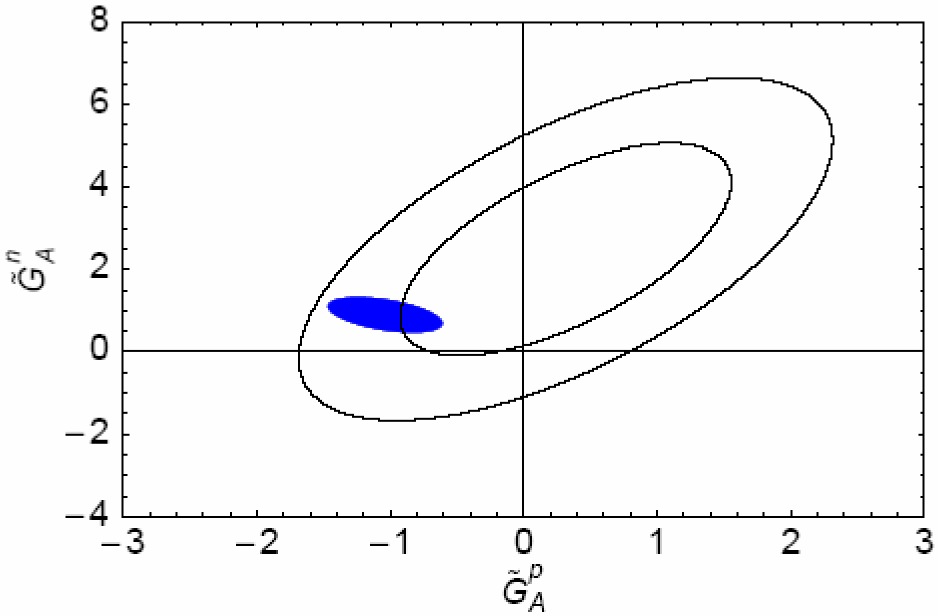


World Data pre-latest HAPPEx

(Young et al., nucl-ex/0604010)

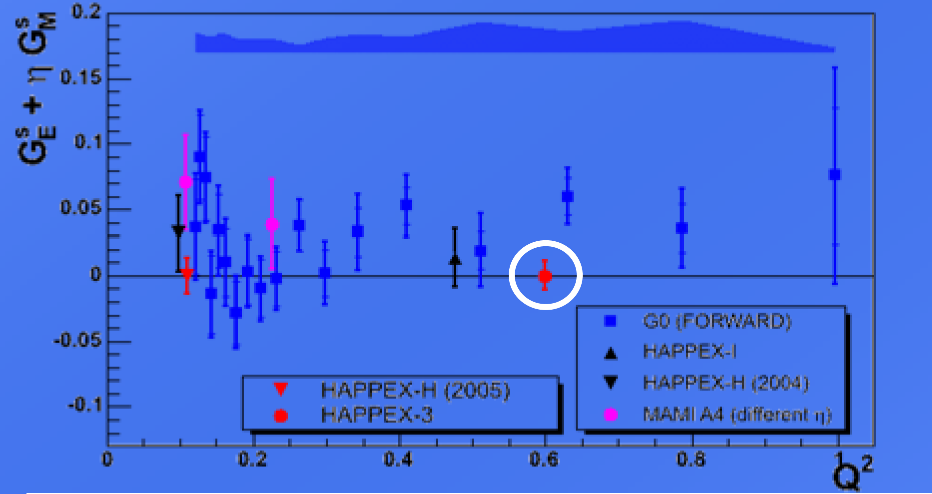
World Data with new HAPPEx

(Young, Roche, Carlini and Thomas, extended analysis)



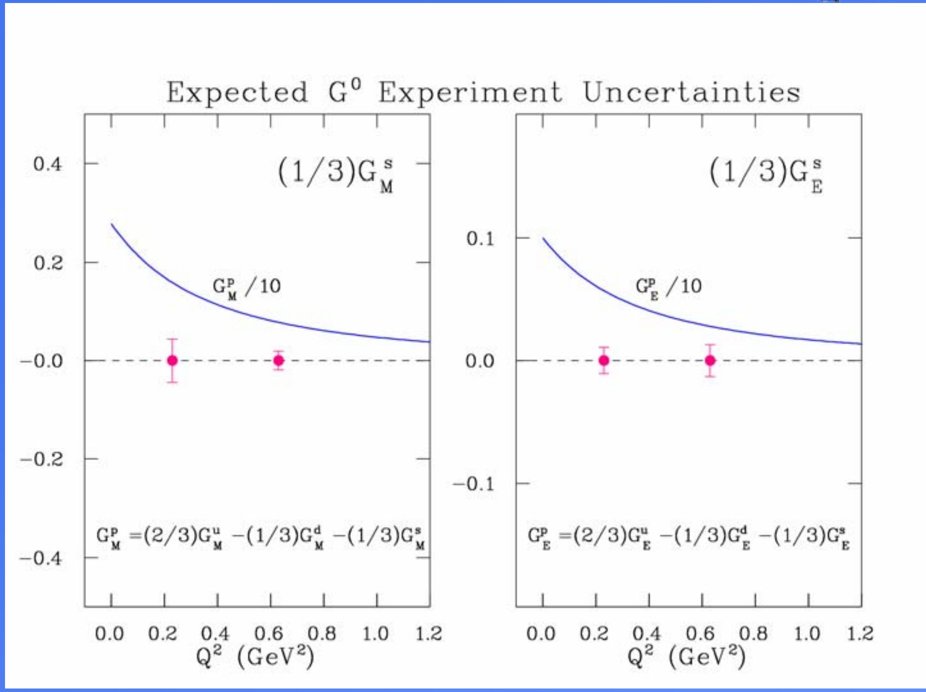
Strange Form Factor Measurements – Future Plans

HAPPEx: "HAPPEx3"
measure $G^s_E + 0.48G^s_M$ with
high precision at Q^2~0.6 GeV^2



G^0: Turn experiment around

- detect electrons at θ = 108°
- add Cerenkov for pion rejection
- measure at Q^2 = .23 and .63 GeV^2
- LH_2 and LD_2 targets



Mainz A4: Turn experiment around

- detect electrons at θ = 145°
- Measure at Q^2 = .23 and .47 GeV^2
- LH_2 and LD_2 targets

from Mark Pitt

Summary

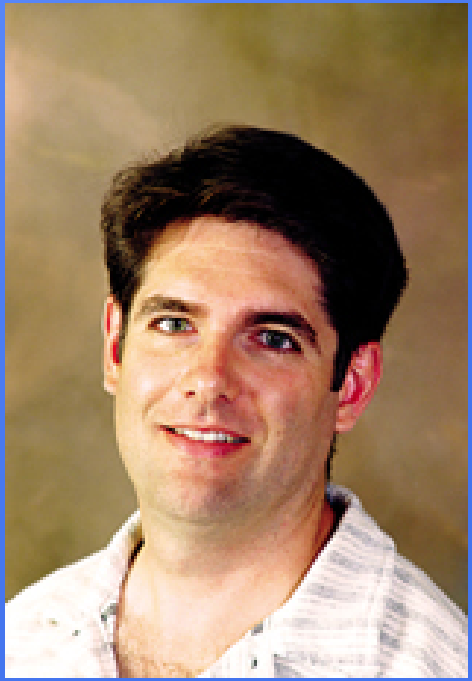
- Beautiful measurements at JLab have defined $G_{E,M}^s$ at $Q^2 = 0.1$ GeV^2 very precisely

- Results agree astonishingly well with modern calculations based on lattice QCD with chiral extrapolation and unquenching using FRR

- Result supports physical picture that s-quark is effectively a HEAVY quark and s-quark fluctuations are strongly suppressed
  - e.g. contribution to nucleon mass $\sim$ 10 MeV

- Useful for lab tests of extra dimensions
  (e.g. Flambaum et al., Phys Rev D – hep-ph/0402098)

Special Mentions……



Derek Leinweber

Ross Young