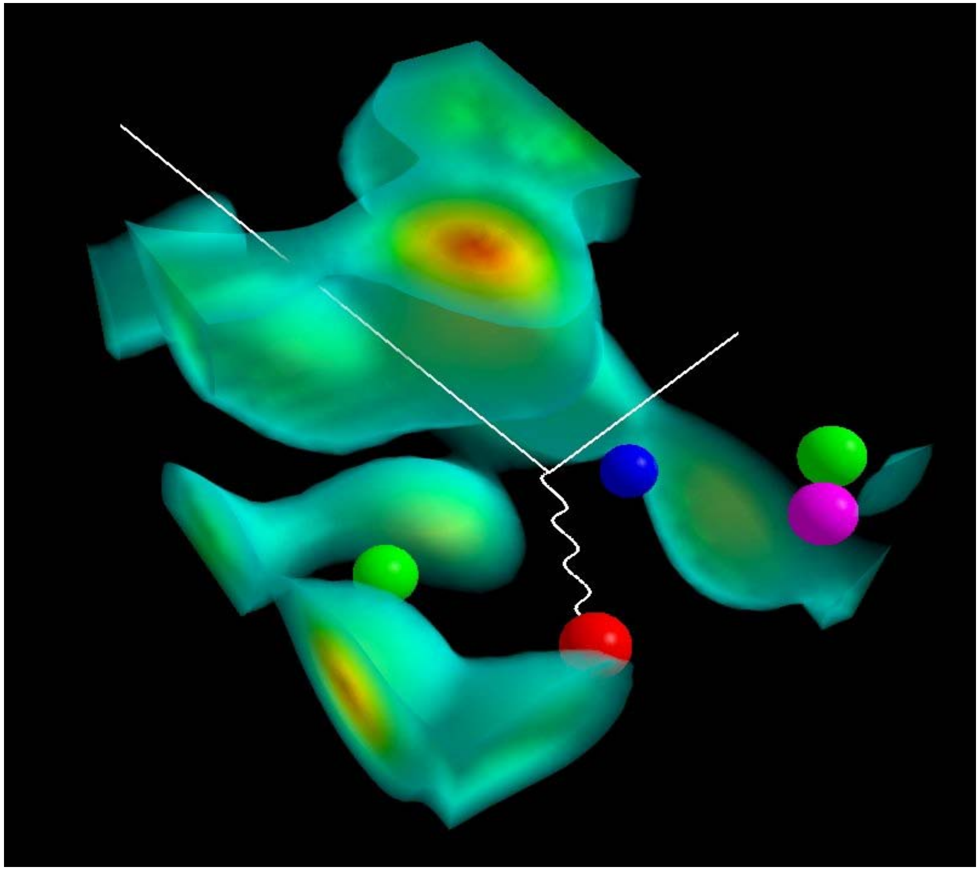
Strangeness in the Nucleon - Introduction

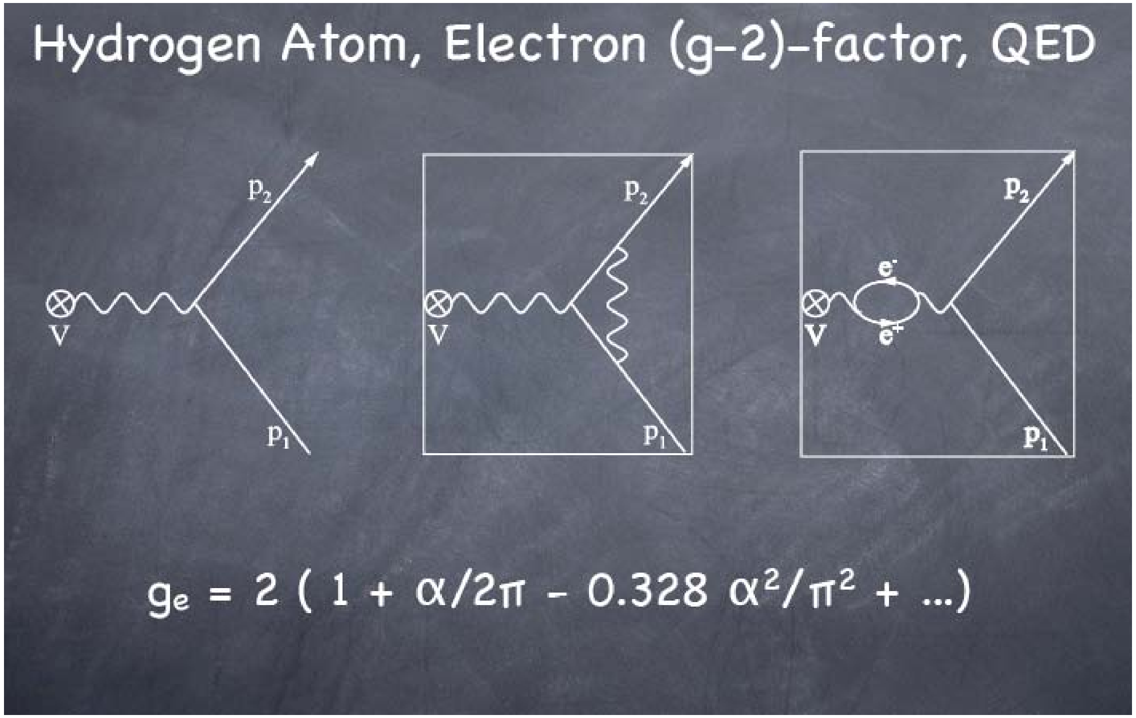


Anthony W. Thomas

CIPANP San Diego : May 30th 2009

Outline

- Strangeness contribution is a vacuum polarization effect, analogous to Lamb shift in QED



- It is a fundamental test of non-perturbative QCD

Outline (cont.)

There have been a number of major steps forward recently, both theory and experiment

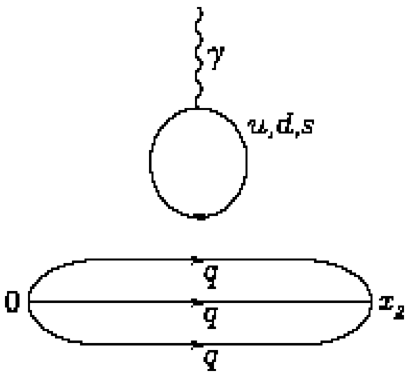
- Contribution to nucleon mass
- Corresponding sigma term (Young, yesterday)

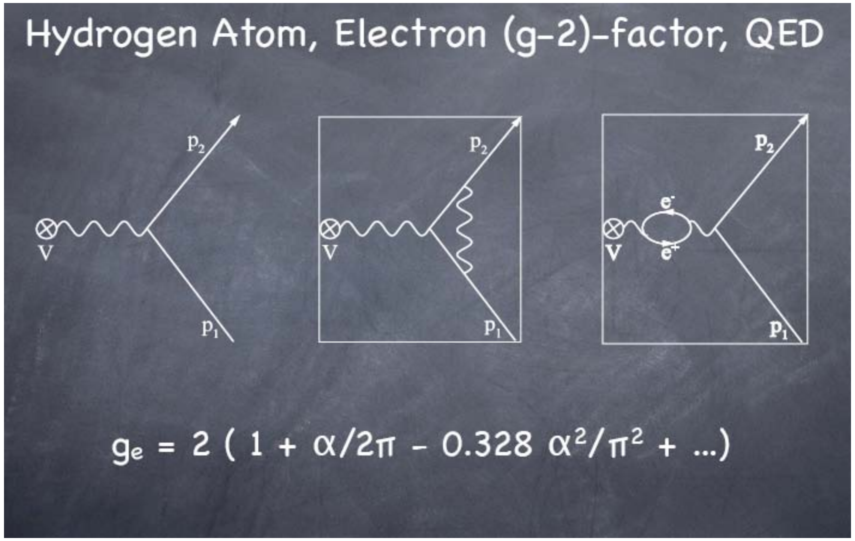
- Calculation of $G_{E,M}^{s}(Q^2)$:
  - Direct: Kentucky (χQCD : K.-F. Liu)
  - Indirect: JLab-Adelaide
- Experimental determination of $G_{E,M}^{s}(Q^2)$
  - G0 (Beise, this session); Mainz PVA4 (arXiv:0903.2733); Happex and Bates
- Agreement between theory and experiment excellent
  - consistent global analysis valuable

Strangeness & Electromagnetic Form Factors

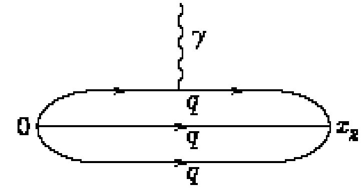
Experiment: Need Parity Violation

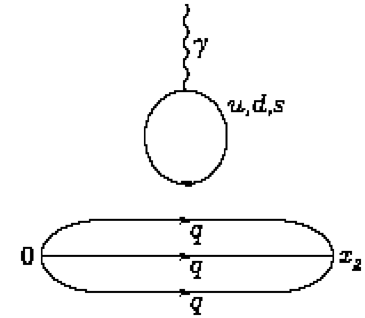
Theory: "Disconnected diagram"





Magnetic Moments within QCD





Leinweber and Thomas, Phys Rev D62 (2000)

CS

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

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

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

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

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

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

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

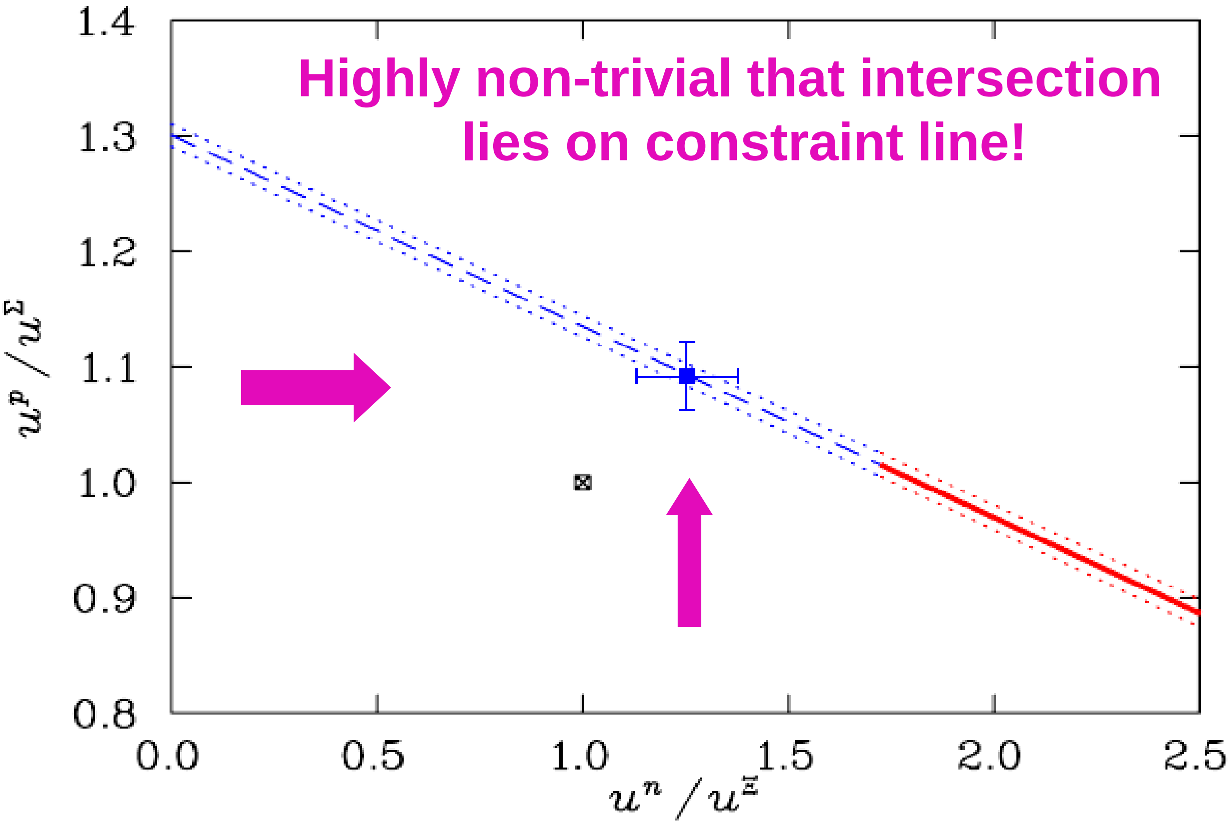
HENCE: $O_N = 1/3\, [\, 2p + n - (\, u^p / u^\Sigma\,)\, (\Sigma^+ - \Sigma^-)\,]$

Just these ratios from Lattice QCD

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

Accurate Final Result for G_M^s

1.10   0.03



1.25   0.12

Yields : G_M^s = -0.046   0.019 μ_N

Leinweber et al., (PRL June '05) 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)

January 2006: G_E^s by same technique

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

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

) $\langle r^2 \rangle_s = 0.000 \pm 0.006 \pm 0.007\ \mathrm{fm}^2$; $0.002 \pm 0.004 \pm 0.004\ \mathrm{fm}^2$

(c.f. using Σ^- : $-0.007 \pm 0.004 \pm 0.007 \pm 0.021\ \mathrm{fm}^2$)

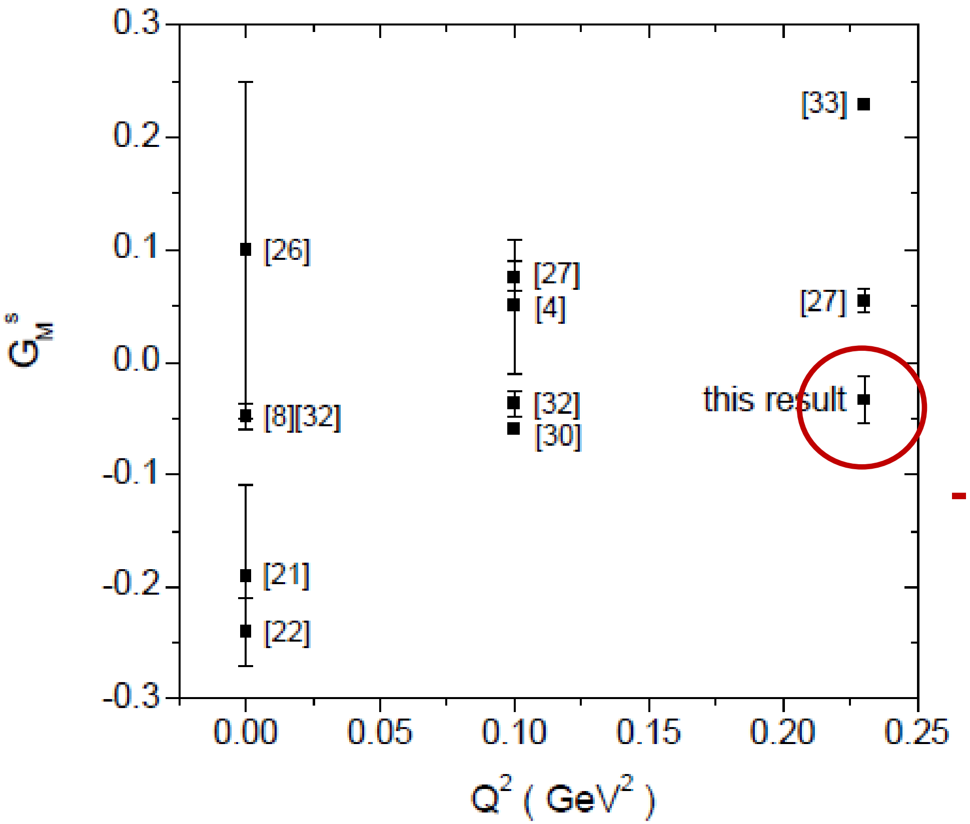
$$G_E^s(0.1\,\mathrm{GeV}^2) = +0.001 \pm 0.004 \pm 0.004$$

(up to order Q^4)

Note consistency and level of precision!

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

Indirect lattice calculation at $Q^2 = 0.23\ \mathrm{GeV}^2$

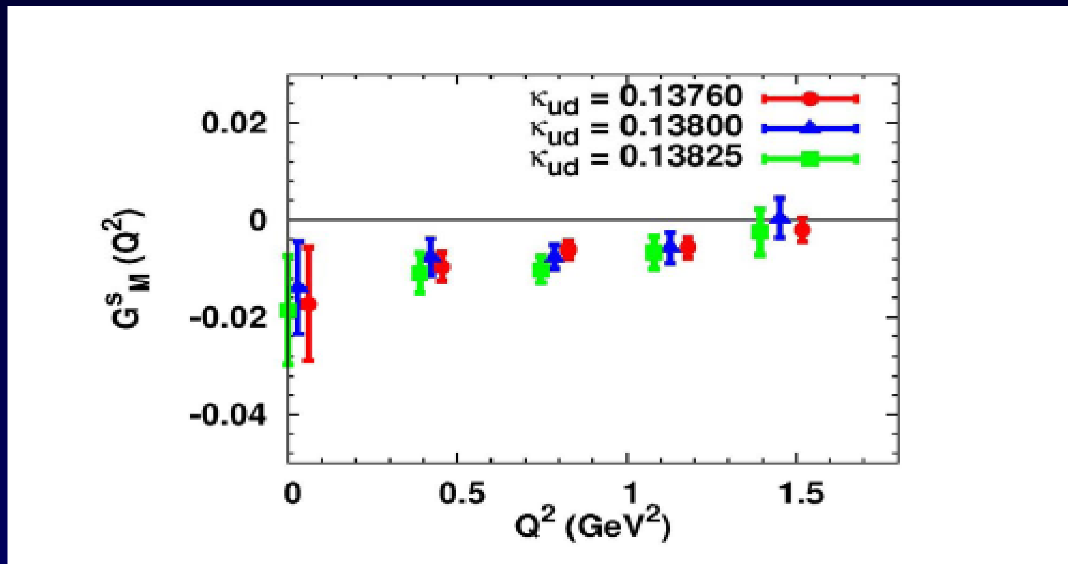


$-0.034 \pm 0.031\ \mu_N$

Wang et al. : arXiv:0807.0944 (PR C in press)

Direct Calculation of $G_M^s(Q^2)$ – K.-F. Liu et al.

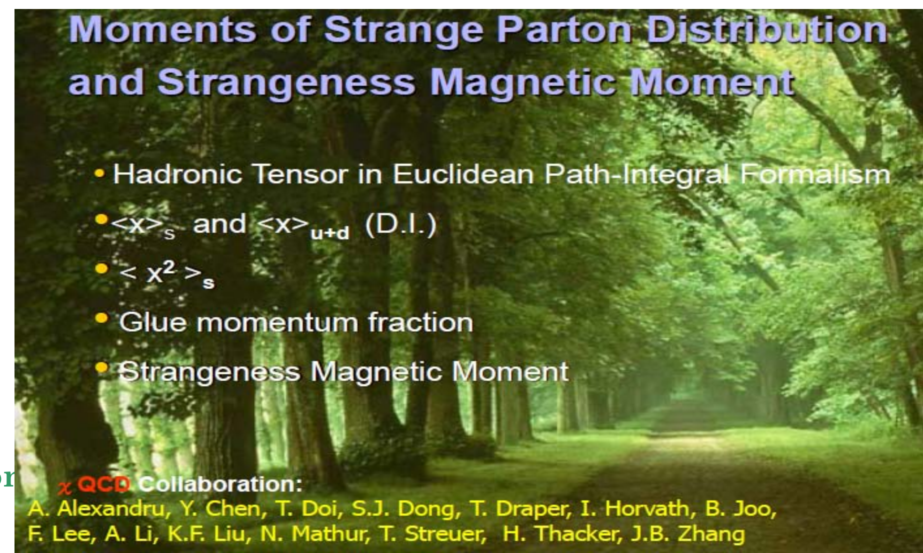
Strangeness Magnetic Form Factors with 3 Quark Masses
(m_π = 0.6, 0.7, 0.8 GeV); T. Doi et al. (χQCD) arXiV:0903.3232



$$G_M^S(Q^2 = 0) = -\,0.017(25)(07)\ \mu_N$$

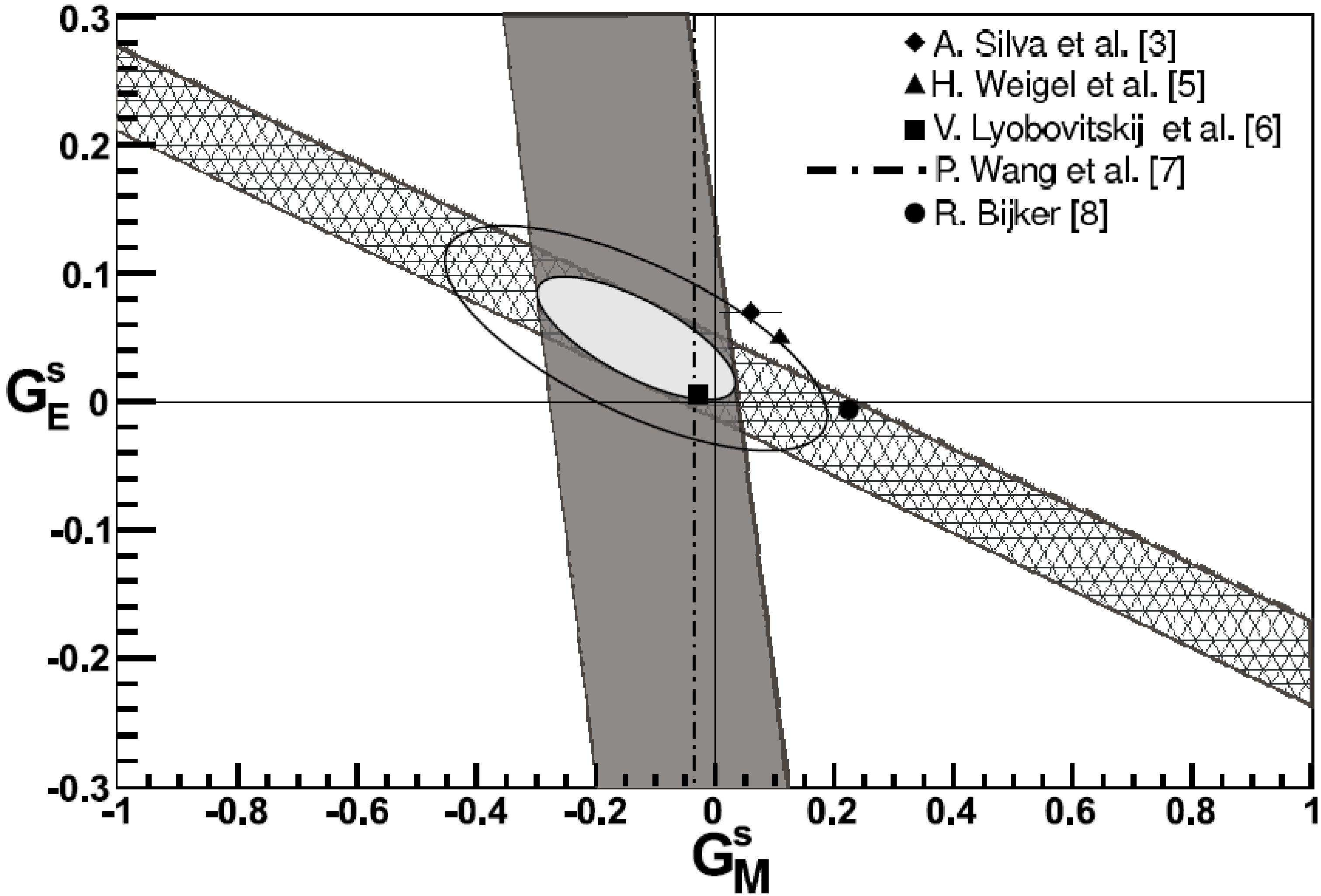
c.f. -0.046 ± 0.019 (Leinweber et al.)

N.B. Expect increase of order 1.8 when light quark mass → physical value with m_s fixed (Wang et al., hep-ph/0701082 :Phys Rev D75, 2008)



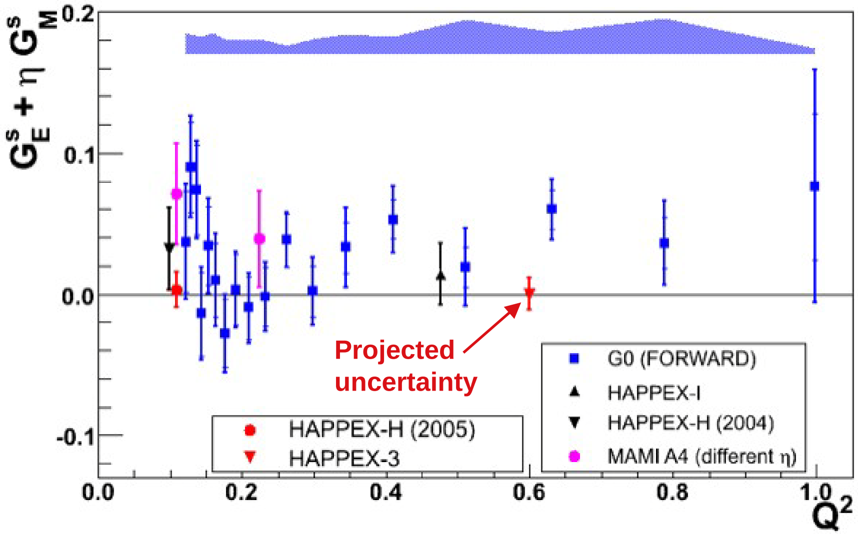
PVA4 2009: $Q^2 = 0.22\ GeV^2$

arXiv: 0903.2733v1

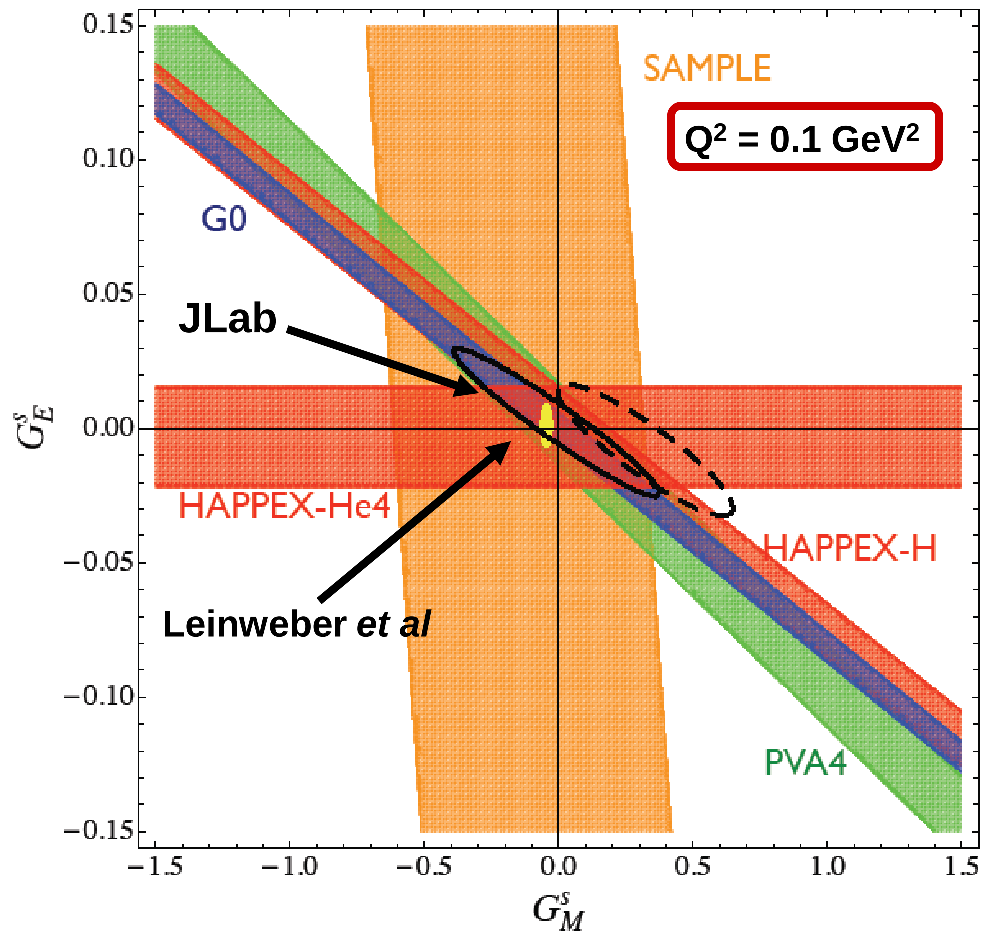


$G_M^s = -0.14 \pm 0.11 \pm 0.11\ \mu_N$; $G_E^s = 0.050 \pm 0.038 \pm 0.019$

Global Analysis of PVES Data



From NSAC Long Range Plan 2007:



- **Proton not all that strange**
- **Separation possible at 0.1 GeV^2**
- **New data coming at 0.23 and 0.6 GeV^2 (PVA4, G0, HAPPEx III)**

Global analysis: Young et al., PRL 99 (2007)122003

“Back of the Envelope” Estimates

Nowhere that current quark masses enter dynamics - always constituent quark masses

- **Hence s-sbar pair costs 1.0-1.1 GeV plus KE**
- **K - Λ costs 0.65 GeV plus KE (and coupling » π N) (K- Σ much smaller) ignore)**
- **Lots of evidence that $P_{\pi N}$ ~ 20%) $P_{K \Lambda}$ ~ 5%**

$$G_M^s \sim -3\, P_{K\Lambda} \;[2/3\,(+0.61 + 1/3) + 1/3(-0.61 + 0)]$$

¼- 0.07 μ_N

Thomas & Young, nucl-th/0509082

Nucleon Mass

- How much do strange quarks contribute to the mass of the nucleon ?

- Typical value is ~ 300 MeV – 1/3rd of M_N

  - e.g. Nelson & Kaplan, 335 ± 132 MeV
    (Phys. Lett. B192, 193 (1987))
  - or 113 ± 108 MeV, Borasoy & Meissner (1997)
    (hep-ph/9711361)

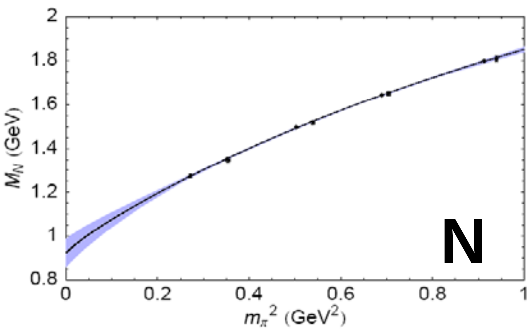
- Of importance for kaon condensation in dense matter

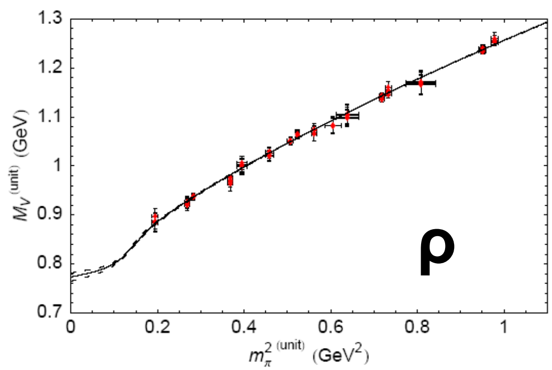
  and in search for dark matter

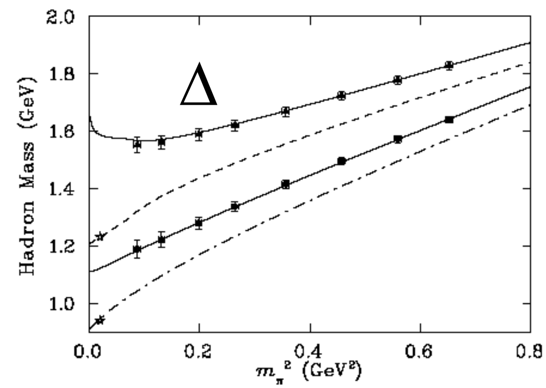
Can now address this issue with lattice QCD data

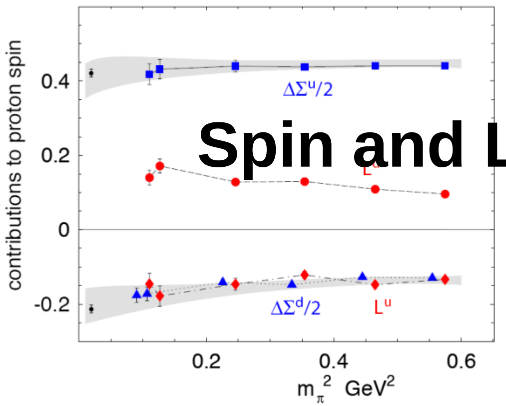
- In fact study available data on whole octet as a function of m_π and m_K
- Data does not lie in "power counting region"
  - hence use finite range regularization (FRR)
- FRR suppresses Goldstone boson loops when Compton wavelength is too small (m_{GB} > 0.4 GeV)

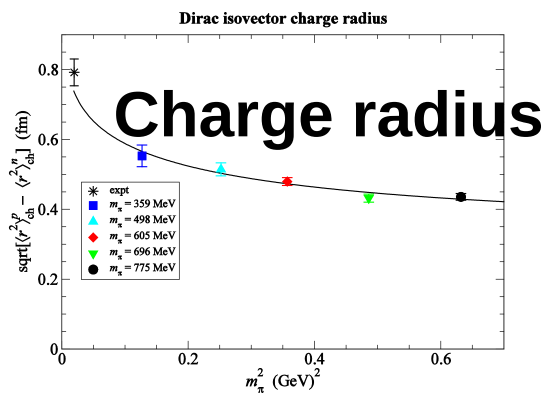
The “big picture”

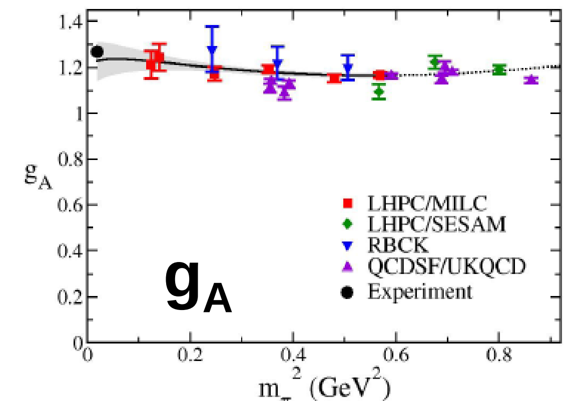


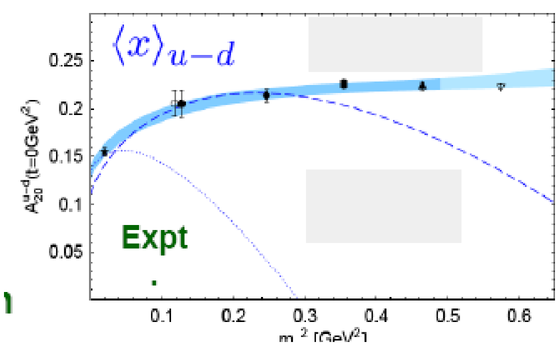












Is it believable that smooth behavior for m_π above 400 MeV is a result of a <u>different</u> accidental cancellation in every case??

$a + b\, m_\pi^2 + c\, m_\pi^3 + d\, m_\pi^4 \ln m_\pi + m_\pi^5 + \ldots$

Octet-baryon masses

- Leading-order expansion O(1)

$$
\begin{aligned}
M_N &= M_0 + 2(\alpha_M + \beta_M)m_q + 2\sigma_M(2m_q + m_s) \\
M_\Lambda &= M_0 + (\alpha_M + 2\beta_M)m_q + \alpha_M m_s + 2\sigma_M(2m_q + m_s) \\
M_\Sigma &= M_0 + \frac{1}{3}(5\alpha_M + 2\beta_M)m_q + \frac{1}{3}(\alpha_M + 4\beta_M)m_s + 2\sigma_M(2m_q + m_s) \\
M_\Xi &= M_0 + \frac{1}{3}(\alpha_M + 4\beta_M)m_q + \frac{1}{3}(5\alpha_M + 2\beta_M)m_s + 2\sigma_M(2m_q + m_s)
\end{aligned}
$$

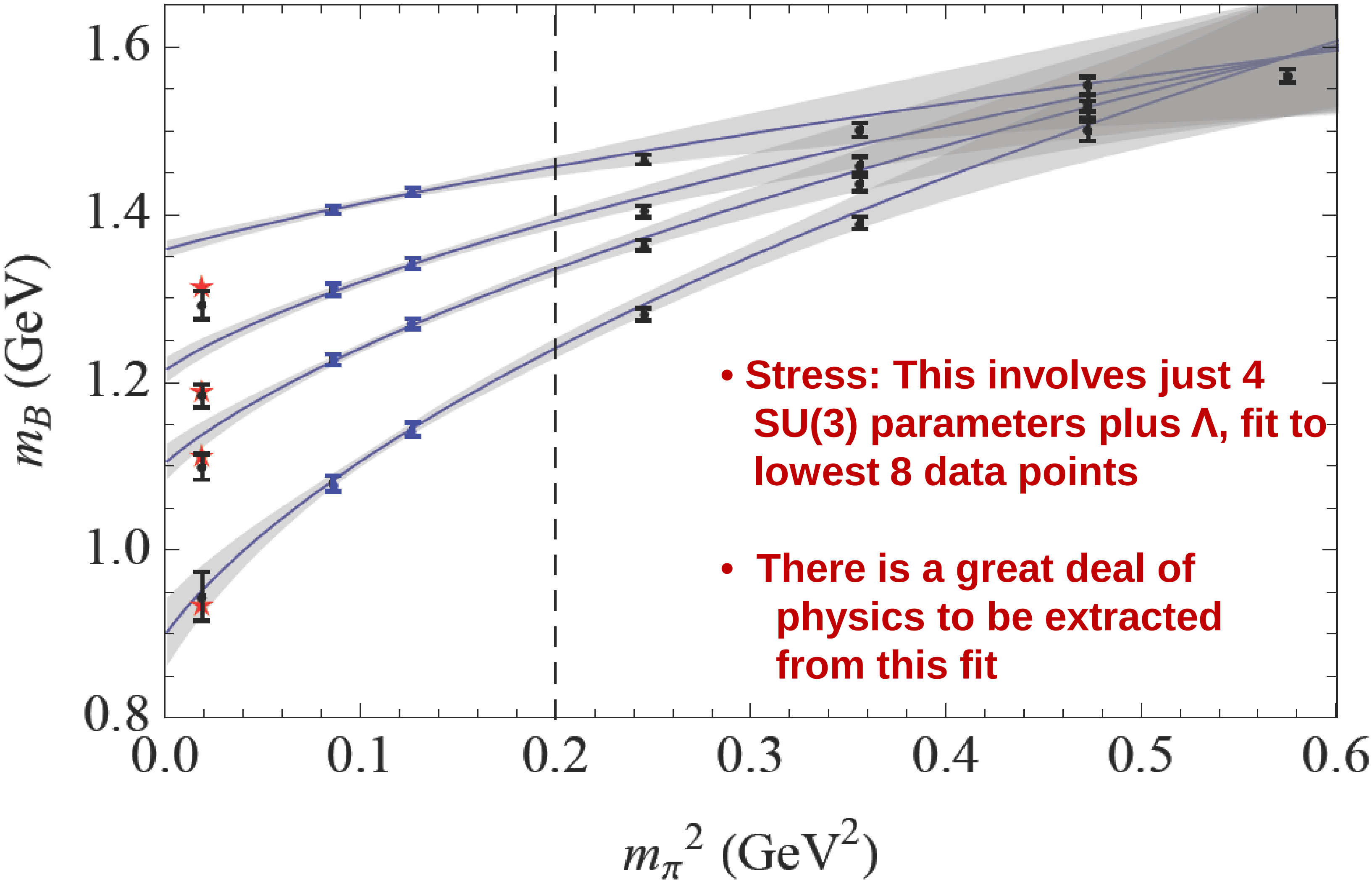
$$m_\pi^2 = 2Bm_q \quad m_K^2 = B(m_q + m_s)$$

$$m_q \to \frac{m_\pi^2}{2B}, \quad m_s \to \frac{2m_K^2 - m_\pi^2}{2B} \qquad \{\alpha, \beta, \sigma\} \to B\{\alpha', \beta', \sigma'\}$$

Fit using SU(3) expansions plus FRR loops (π, η and K)

LHPC Data

(Walker-Loud et al.. arXiv:0806.4549)

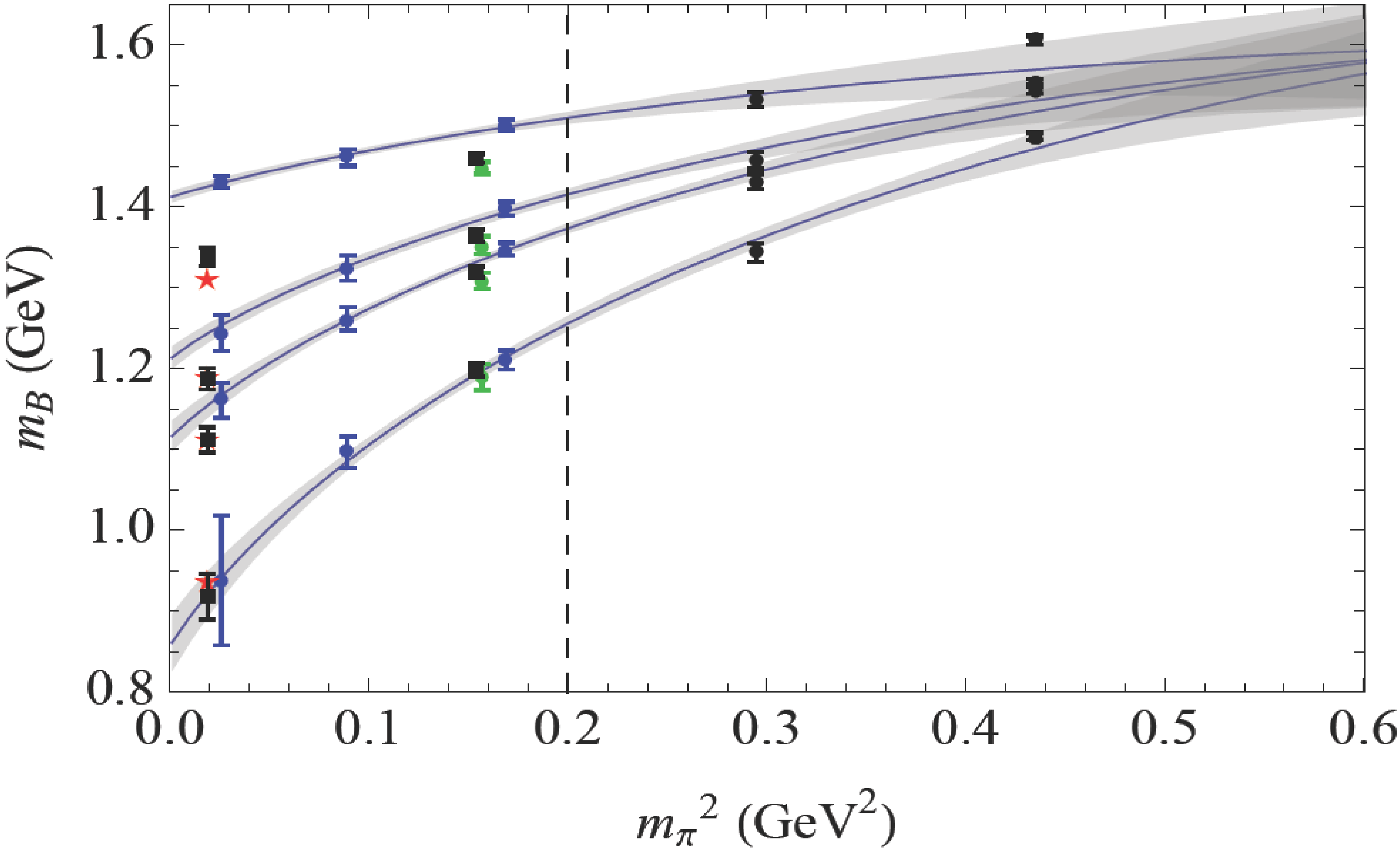


- **Stress: This involves just 4 SU(3) parameters plus Λ, fit to lowest 8 data points**
- **There is a great deal of physics to be extracted from this fit**

Young & Thomas, arXiv:0901.3559 [nucl-th]

PACS-CS Data

(Aoki et al., arXiv:0807.1661[hep-lat])



Young & Thomas, arXiv:0901.3559 [nucl-th]

Summary of Results of Combined Fits
(of 2008 LHPC & PACS-CS data)

B	Mass (GeV)	Expt.	$\bar{\sigma}_{Bl}$	$\bar{\sigma}_{Bs}$
N	0.945(24)(4)(3)	0.939	0.050(9)(1)(3)	0.033(16)(4)(2)
Λ	1.103(13)(9)(3)	1.116	0.028(4)(1)(2)	0.144(15)(10)(2)
Σ	1.182(11)(2)(6)	1.193	0.0212(27)(1)(17)	0.187(15)(3)(4)
Ξ	1.301(12)(9)(1)	1.318	0.0100(10)(0)(4)	0.244(15)(12)(2)

$$\bar{\sigma}_{Bq} = (m_q/M_B)\partial M_B/\partial m_q$$

N. B. Masses are absolute calculations based upon heavy quark potential, which involves no chiral physics

Young & Thomas, arXiv:0901.3559 [nucl-th]

Sigma Commutator

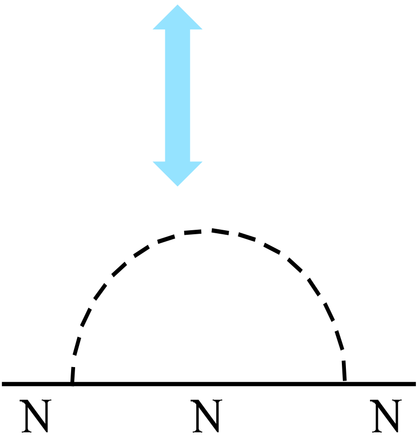
$$\sigma = \langle N \,|\, (m_u + m_d)\,(\bar{u}\,u + \bar{d}\,d)/2 \,|\, N \rangle \equiv m_q\, \partial M_N / \partial m_q$$

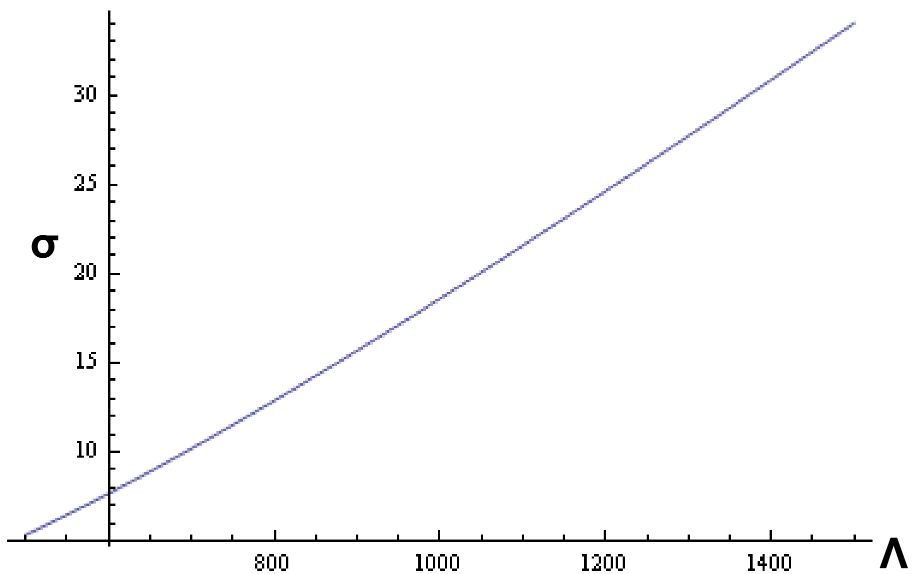
$$= \langle N|[Q_5,[Q_5,H_{QCD}]]|N\rangle$$

$$= \sigma_{val} + \sigma_{sea}$$

LNA

$$\delta\sigma = 35\,\Lambda - 23 + \frac{9.6}{\Lambda} - \frac{3}{\Lambda^2} + \frac{0.8}{\Lambda^3} + \ldots = 18\text{ MeV } (\Lambda = 1\text{GeV})$$





Naïve Expansion Traditionally Used to Extract σ Terms is Hopeless!

- Leading-order expansion $O(1)$

$$
\begin{aligned}
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\end{aligned}
$$

Need $O(m_\pi^6)$ to get accurate light quark σ term

While for strange condensate expansion is useless !

BUT through FRR have closed expression and can evaluate ….

Summary of Results of Combined Fits
(of 2008 LHPC & PACS-CS data)

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$$\bar{\sigma}_{Bq} = (m_q/M_B)\partial M_B/\partial m_q$$

Of particular interest:

σ commutator well determined : $\sigma_{\pi N}$= 47 (9) (1) (3) MeV

and strangeness sigma commutator small

$m_s\, \partial M_N / \partial m_s$ = 31 (15) (4) (2) MeV

NOT several 100 MeV !

Profound Consequences for Dark Matter Searches

Hadronic Uncertainties in the Elastic Scattering of Supersymmetric Dark Matter

John Ellis,[1,*] Keith A. Olive,[2,†] and Christopher Savage[2,‡]

CERN-PH-TH/2008-005
UMN–TH–2631/08
FTPI–MINN–08/02

We find that the spin-independent cross section may vary by almost an order of magnitude for 48 MeV $< \Sigma_{\pi N} <$ 80 MeV, the ± 2-σ range according to the uncertainties in Table I. This uncertainty is already impacting the interpretations of experimental searches for cold dark matter. Propagating the ± 2-σ uncertainties in $\Delta_s^{(p)}$, the next most important parameter, we find a variation by a factor ~ 2 in the spin-dependent cross section. Since the spin-independent cross section may now be on the verge of detectability in certain models, and the uncertainty in the cross section is far greater, *we appeal for a greater, dedicated effort to reduce the experimental uncertainty in the π-nucleon σ term $\Sigma_{\pi N}$*. This quantity is not just an object of curiosity for those interested in the structure of the nucleon and non-perturbative strong-interaction effects: it may also be key to understanding new physics beyond the Standard Model.

spin

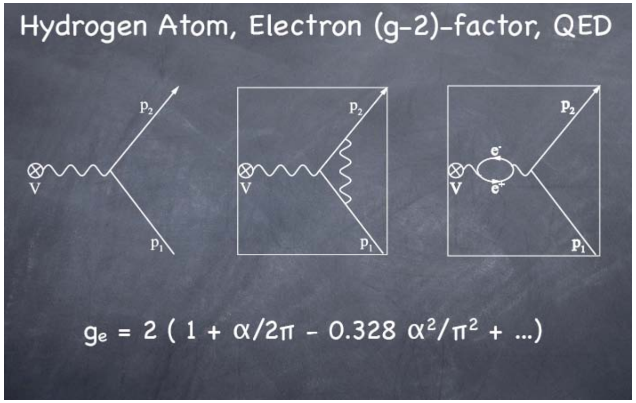
σ terms

$$\mathcal{L} = \alpha_{2i}\bar{\chi}\gamma^{\mu}\gamma^{5}\chi\bar{q}_i\gamma_{\mu}\gamma^{5}q_i + \alpha_{3i}\bar{\chi}\chi\bar{q}_i q_i$$

Neutralino (0.3 GeV / cc :WMAP)

Summary

- Strange content of N small
  — Less than 5% of μ^p and $< r^2 >_{ch}^p$
- Theory agrees well but order of magnitude more accurate
- Major success of QCD : direct insight into
  "disconnected diagrams"
  - analogue of Lamb shift



Summary - 2

- With lattice scale set by heavy quark (non-chiral) physics, agreement with octet masses is good at the 1-2% level!

- Strangeness content (condensate) is roughly an order of magnitude smaller than naively assumed

- Strangeness term usually dominates estimates of dark matter cross section - it should NOT!

Summary - 3

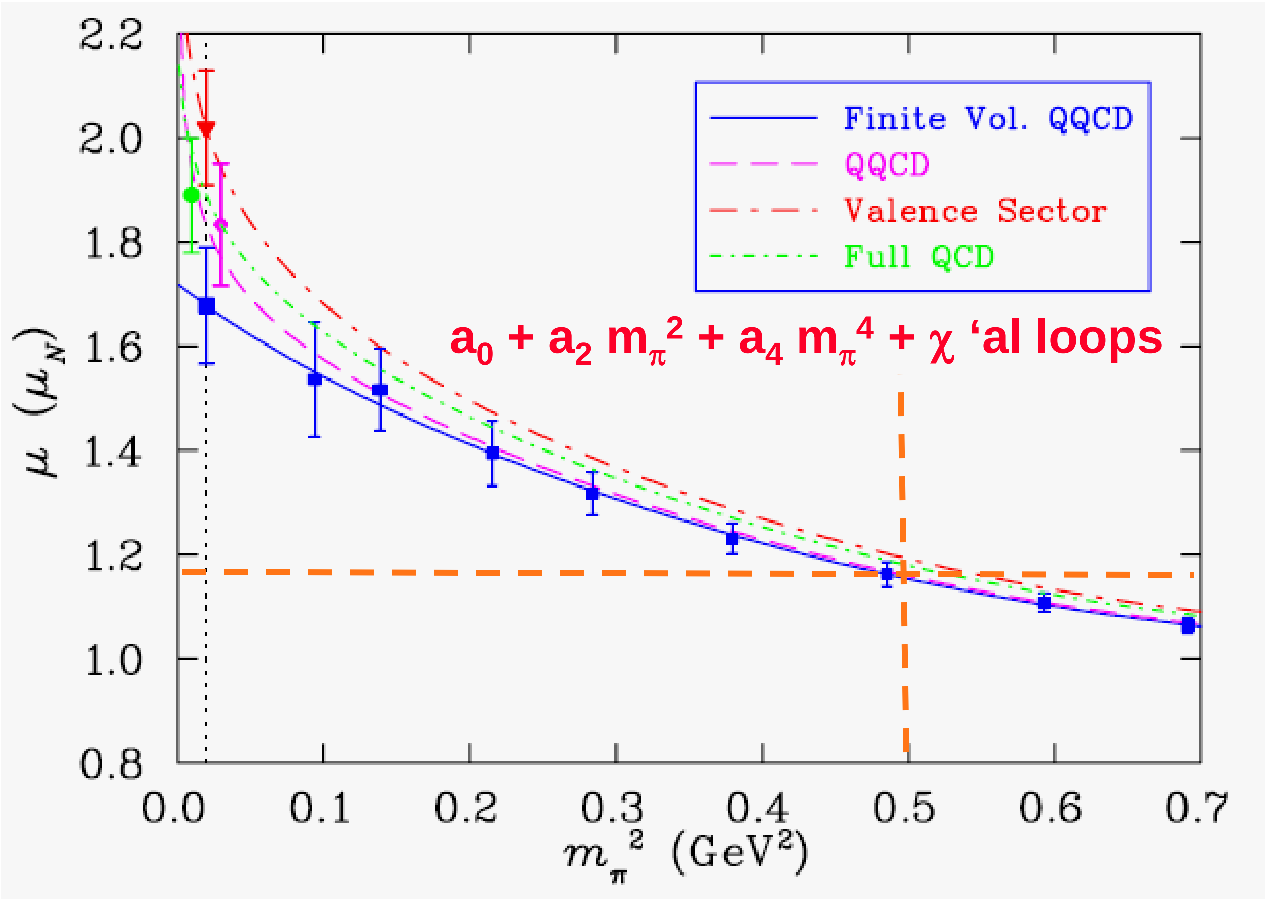
FRR provides a very natural explanation of all of these results

i.e. The contributions of Goldstone boson (π and K and η) degrees of freedom is suppressed once the Compton wavelength is too small (<0.5 fm)

This corresponds to Goldstone boson masses of order 0.4 GeV and higher, which is where the physical K and η are located

Hence their contribution and the role of virtual strange quarks is suppressed

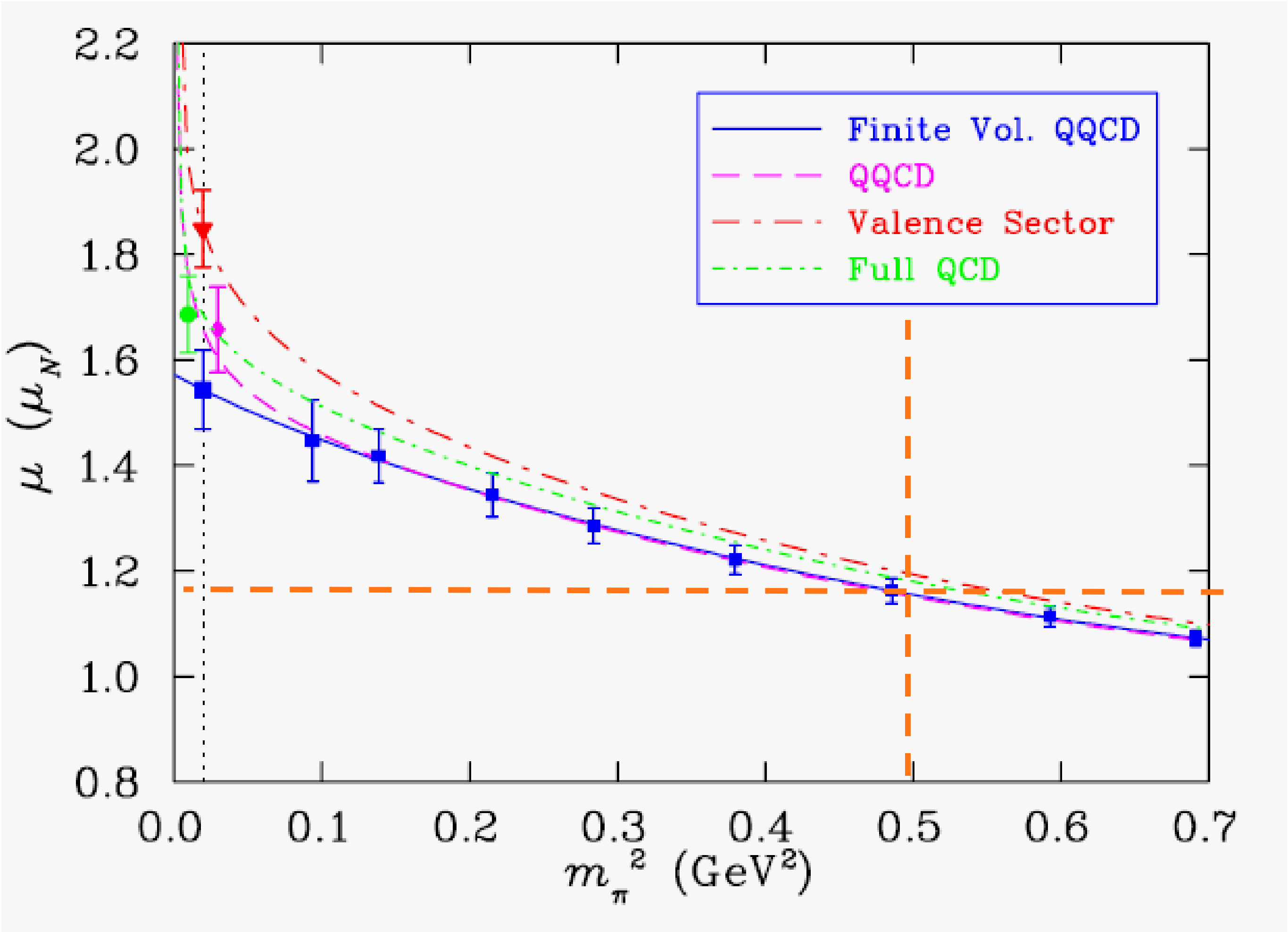
$u^p_{valence}$: QQCD Data Corrected for Full QCD Chiral Coefficients



c.f. CQM
2/3 940/540
» 1.18

Lattice data from Zanotti et al. ; Chiral analysis Leinweber et al.

u^{Σ} valence



Universal Here!

Convergence LNA to NLNA Again Excellent (Effect of Decuplet)