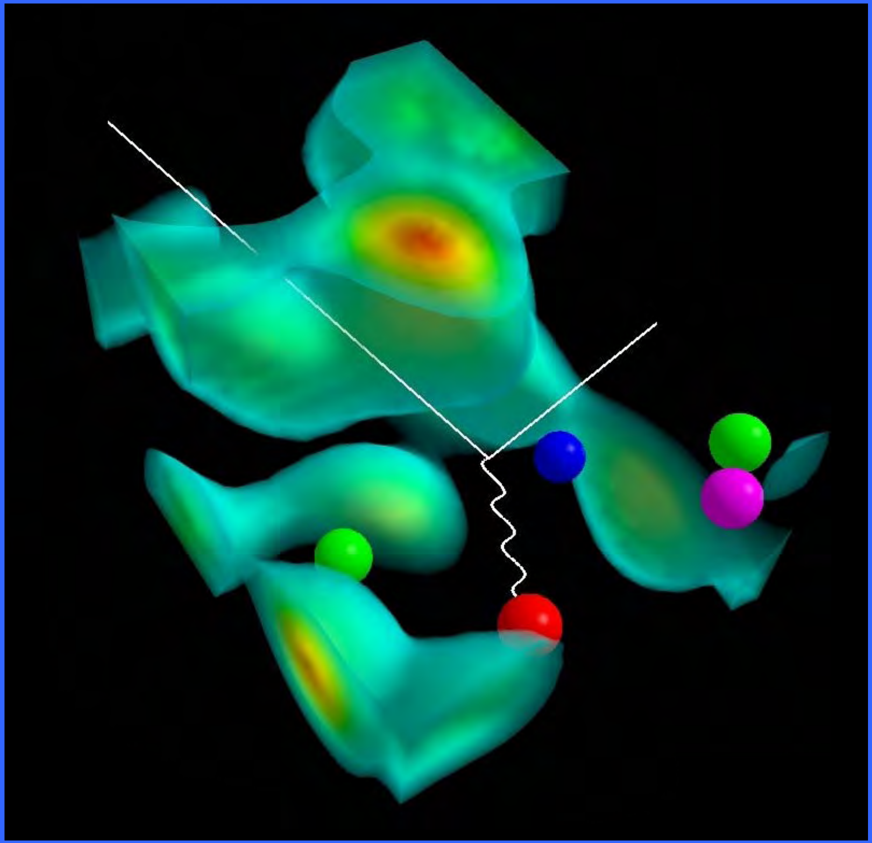
Strangeness Content of the Nucleon



Anthony W. Thomas

ILFTN 2005

Jefferson Lab : October 5th, 2005

Operated by the Southeastern Universities Research Association for the U.S. Department of Energy

Outline

- The QCD Vacuum
- Quarks to Hadrons
- Measurements of Nucleon Form Factors
- Latest Results on Strangeness
- A Precise Theoretical Calculation of G_M^s
- Similar analysis for G_E^s
- What needs measuring?

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 <u>NOT spherical</u>

- <u>NOR</u> 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
¼ valence + pion cloud +
volume * (difference of condensate in & out of N)

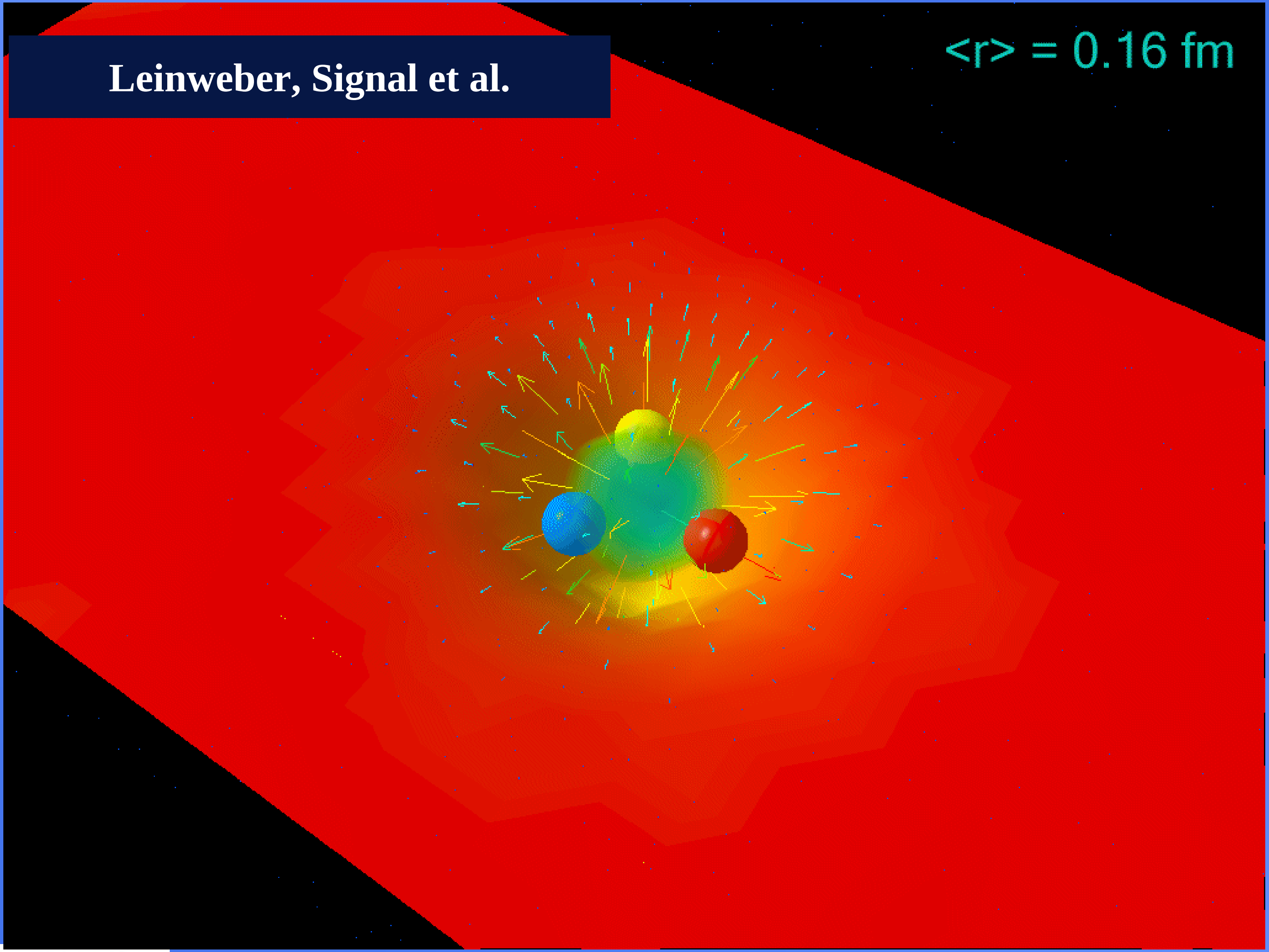
and last term is as big as 20 MeV (or more)
i.e. presence of nucleon "cleans out" vacuum to some extent

Hence: Model independent LO term for in-medium condensate

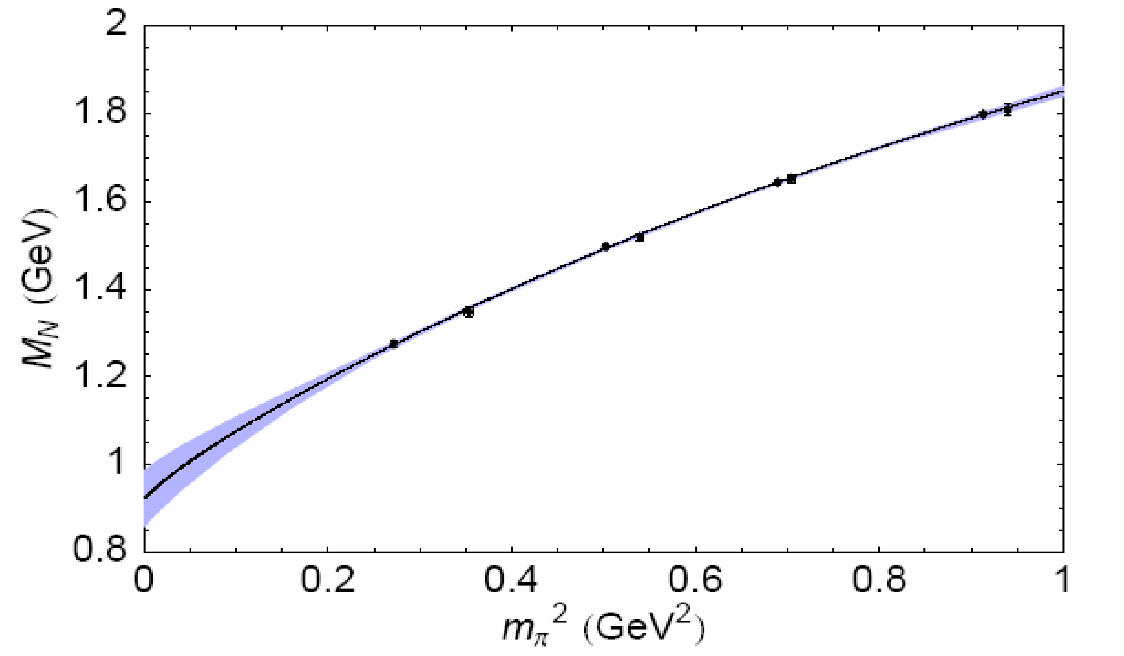
$$\frac{Q(\rho_B)}{Q_0} \simeq 1 - \frac{\sigma_N}{f_\pi^2 m_\pi^2}\rho_B$$

BUT this has no new physics at all!

Lattice QCD Simulation of Vacuum Structure



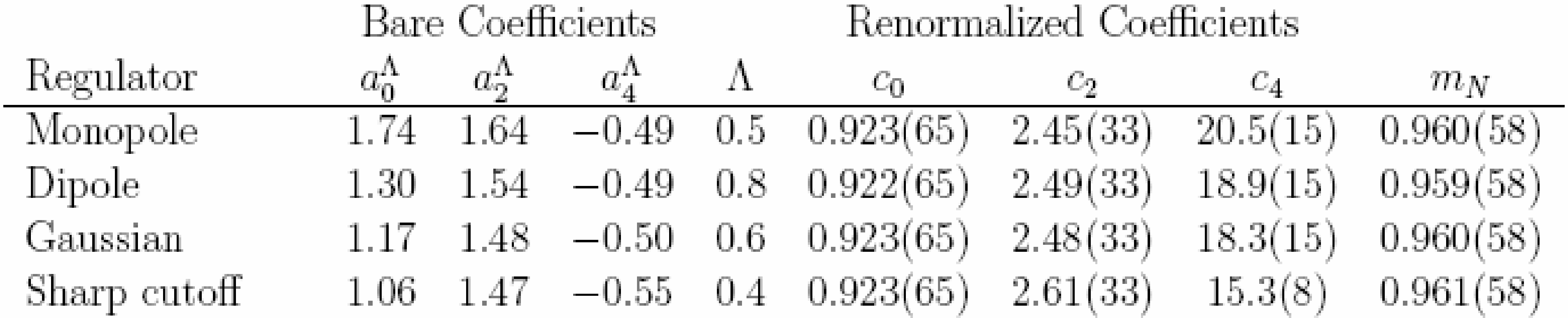
χ’al Extrapolation Under Control when Coefficients Known – e.g. for the nucleon



$M_N = a_0 + a_2 m_\pi^2 + a_4 m_\pi^4 +$ χ ‘al loops

´ $c_0 + c_2 m_\pi^2 + c_{LNA} m_\pi^3 + c_4 m_\pi^4$ +..

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)

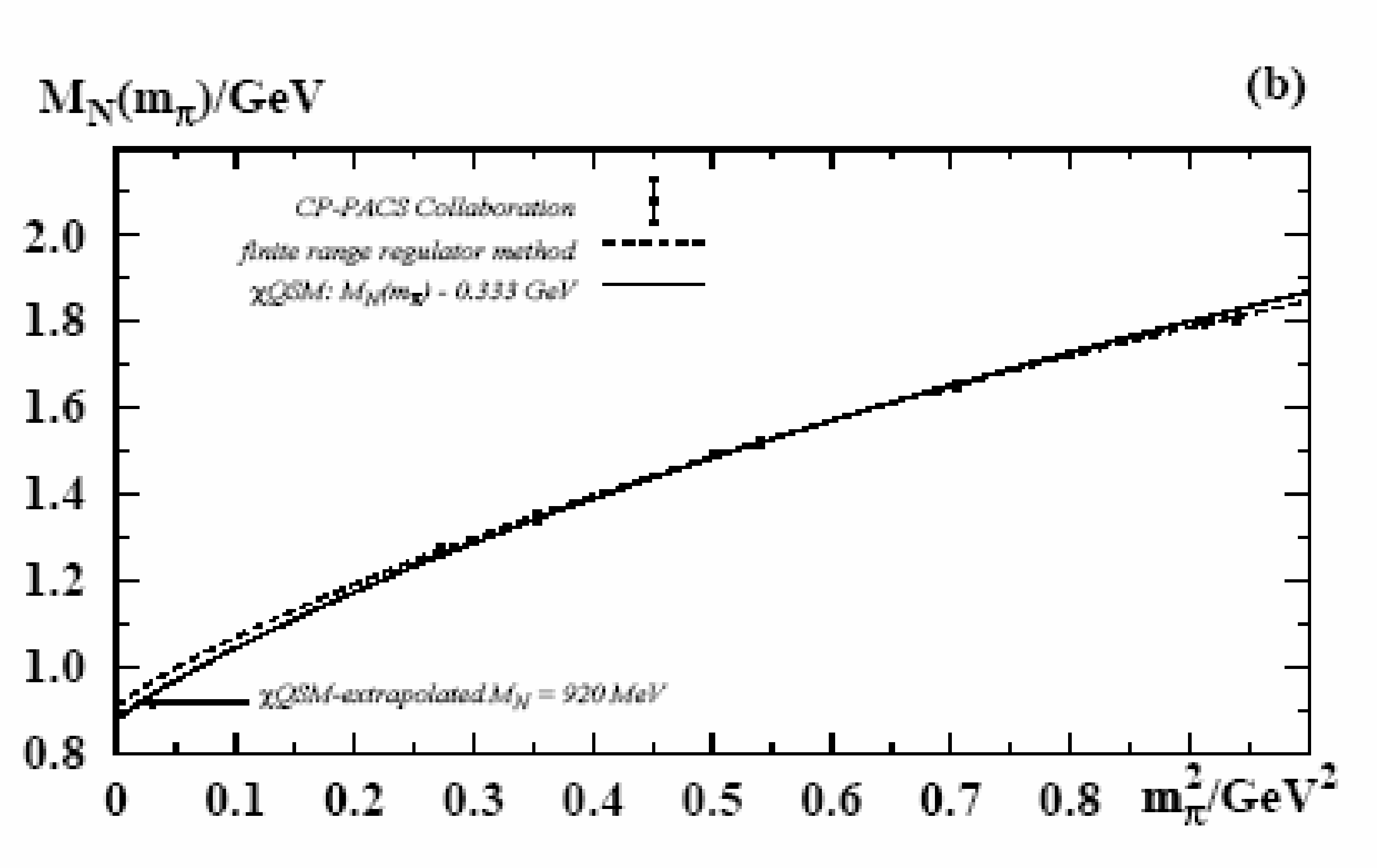
Leinweber et al., PRL 92 (2004) 242002

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

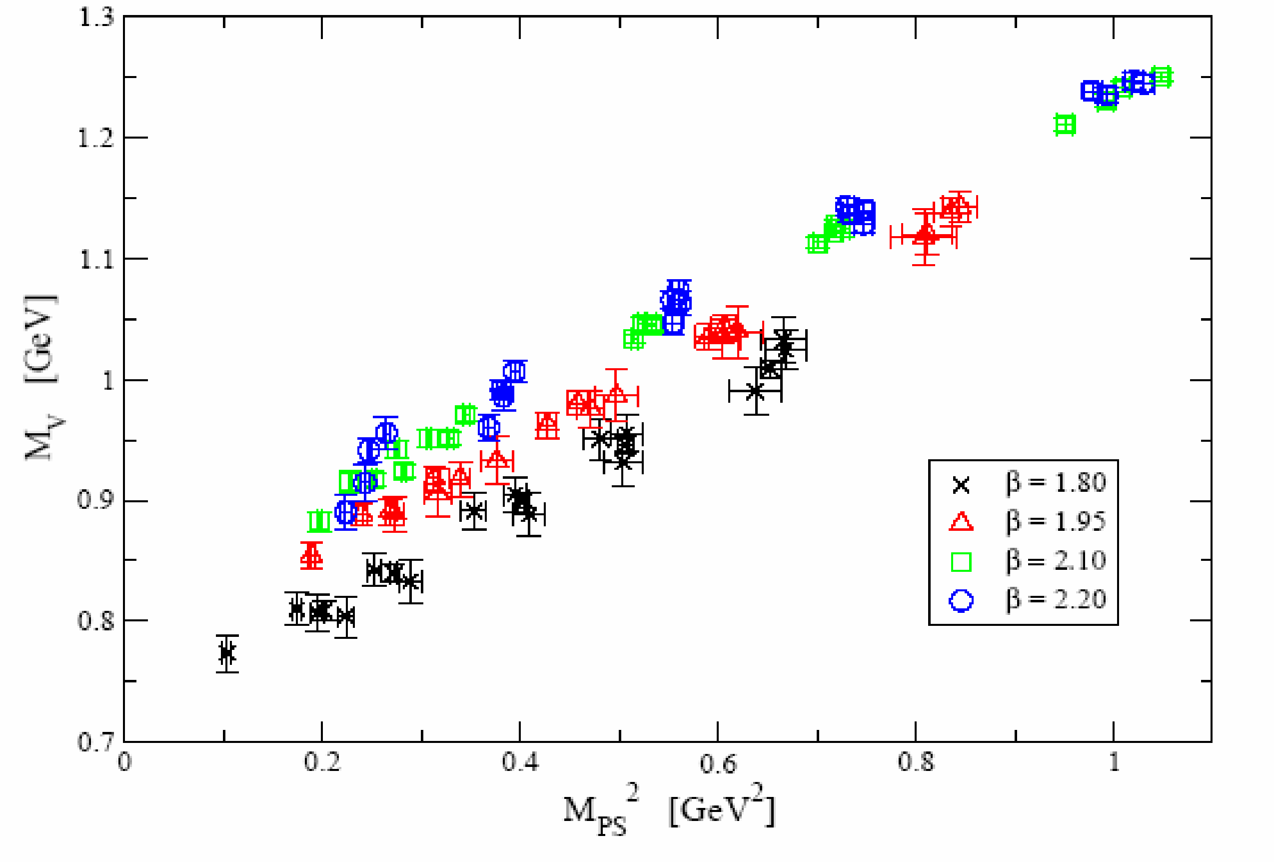
M_N in MeV

Comparison with χ QSM



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

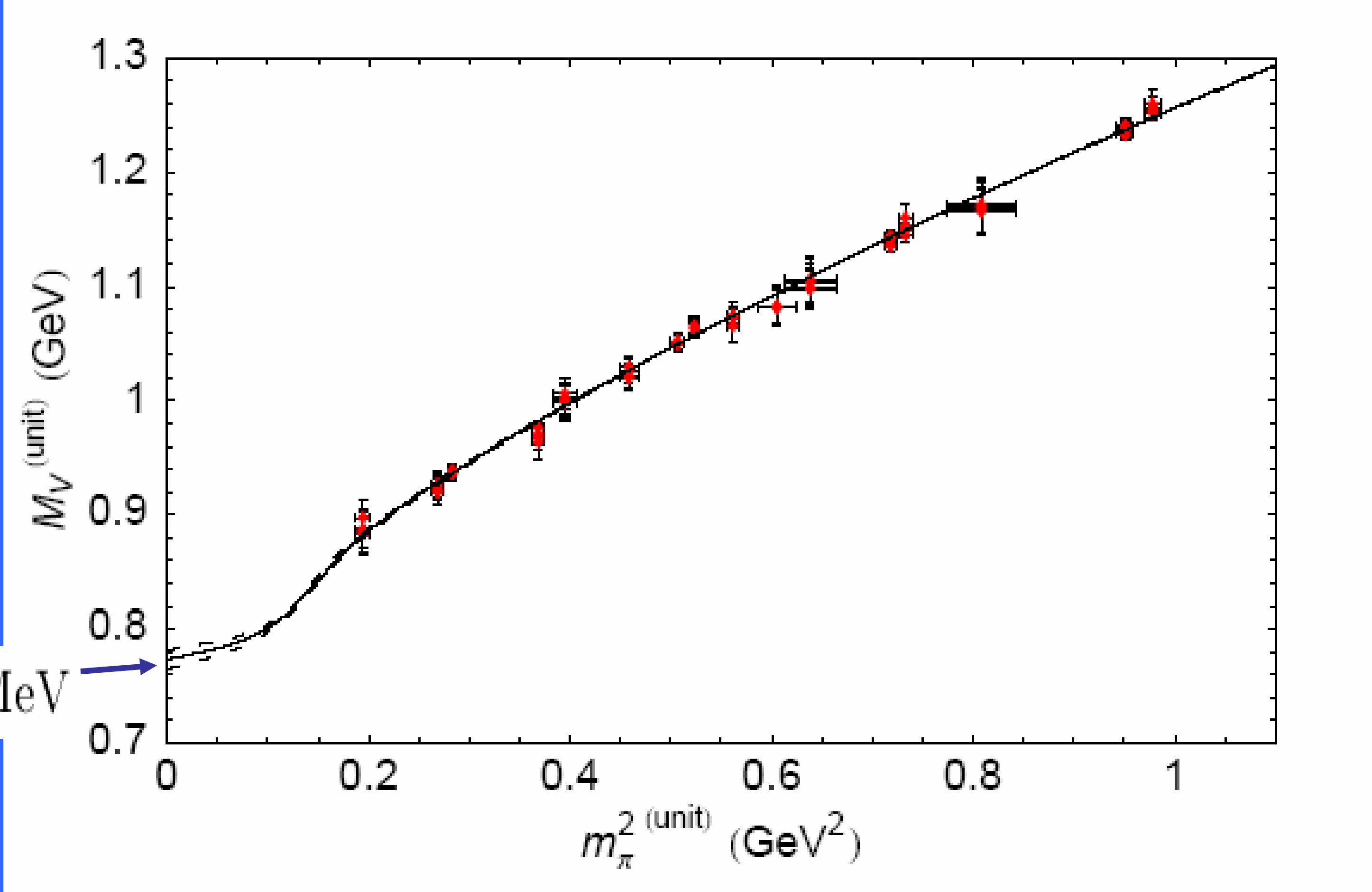
Analysis of pQQCD ρ data from CP PACS



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

Infinite Volume Unitary Results

All 80 data points move onto single, well defined curve



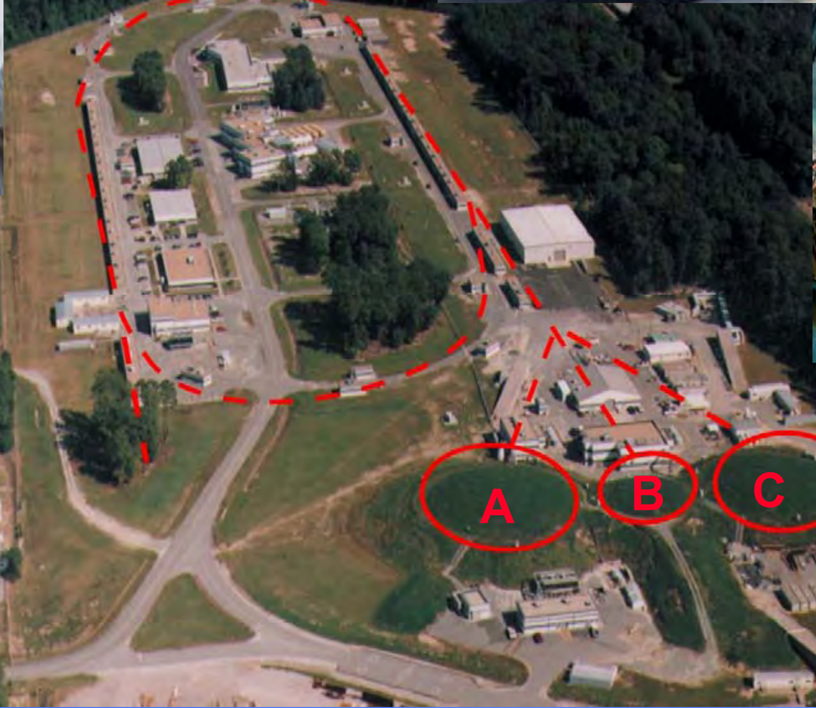
$$M_\rho = 778(4)^{+16+8}_{-6\;-9}\,\mathrm{MeV}$$

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

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

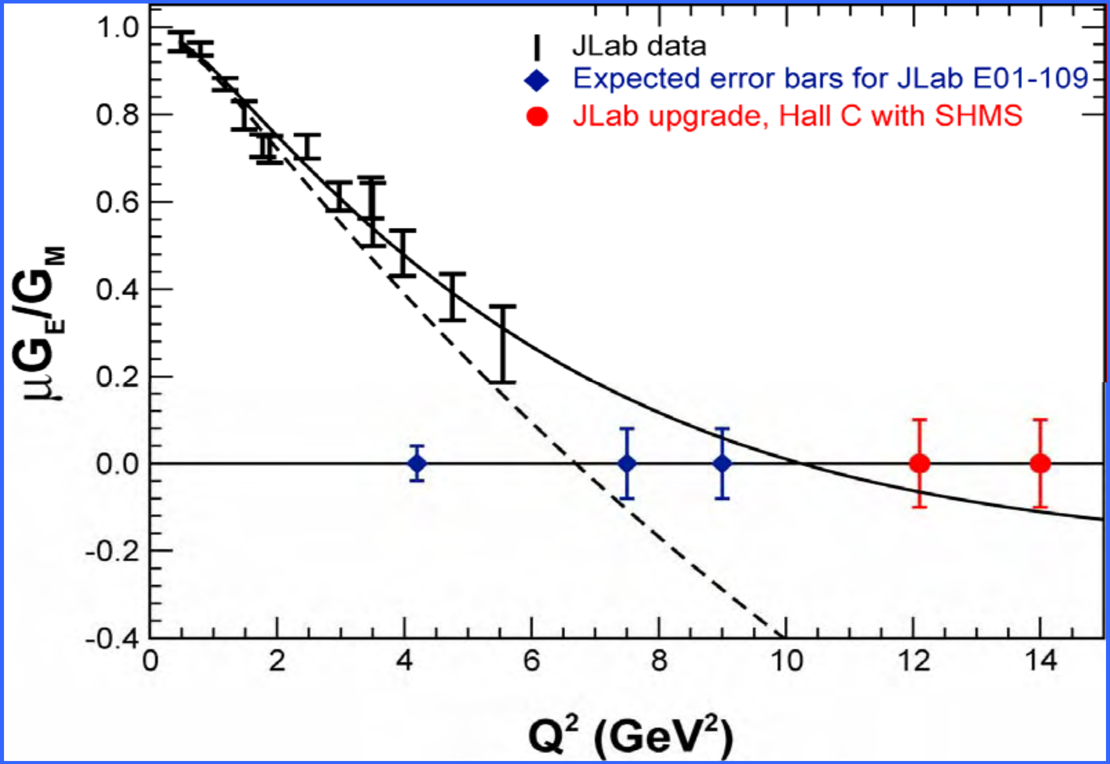


Providing ~2300 international users with a unique electron beam, three experimental halls, and computational and theory support

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

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

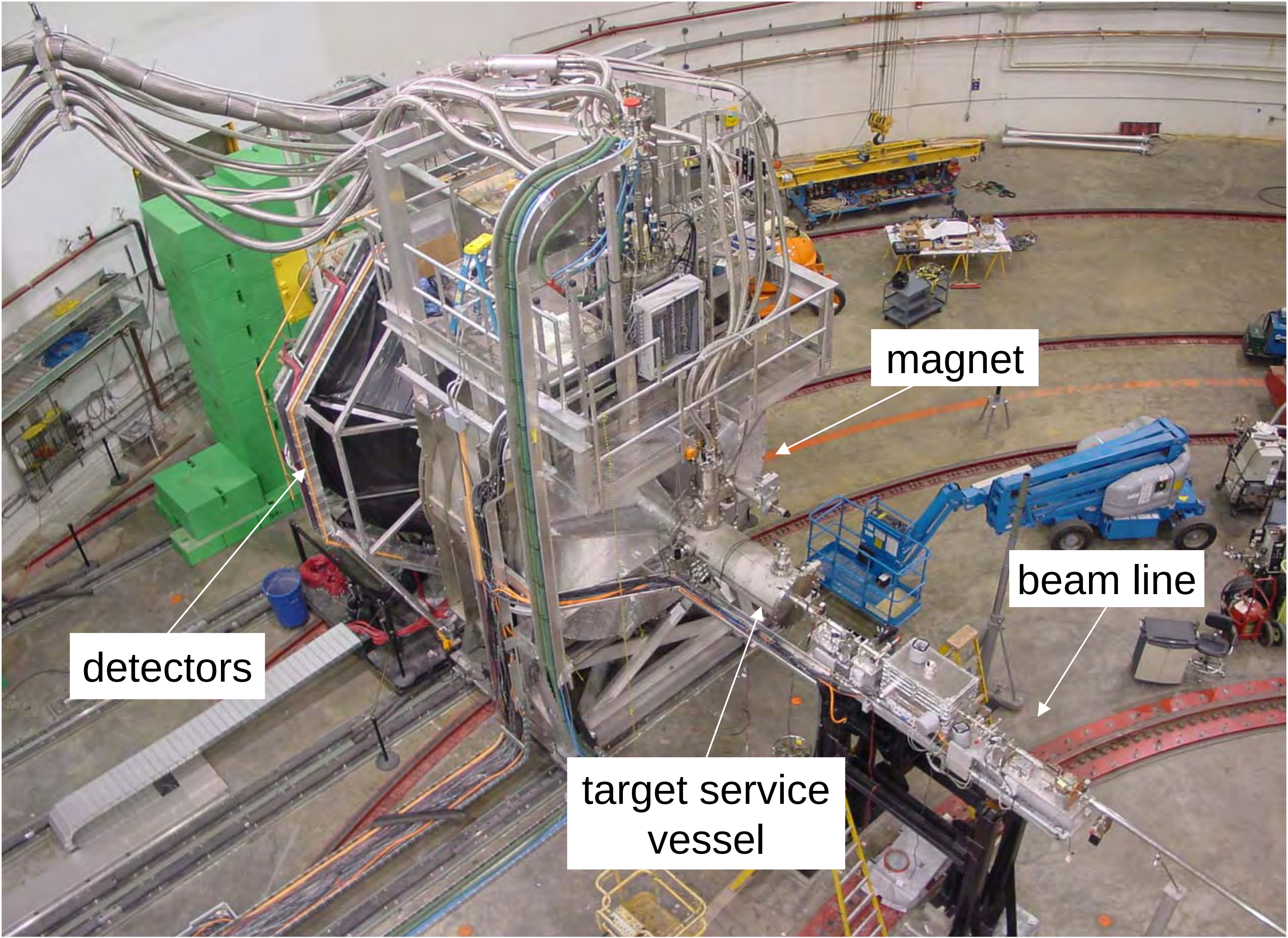
45 § 8 MeV (or 70?)

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

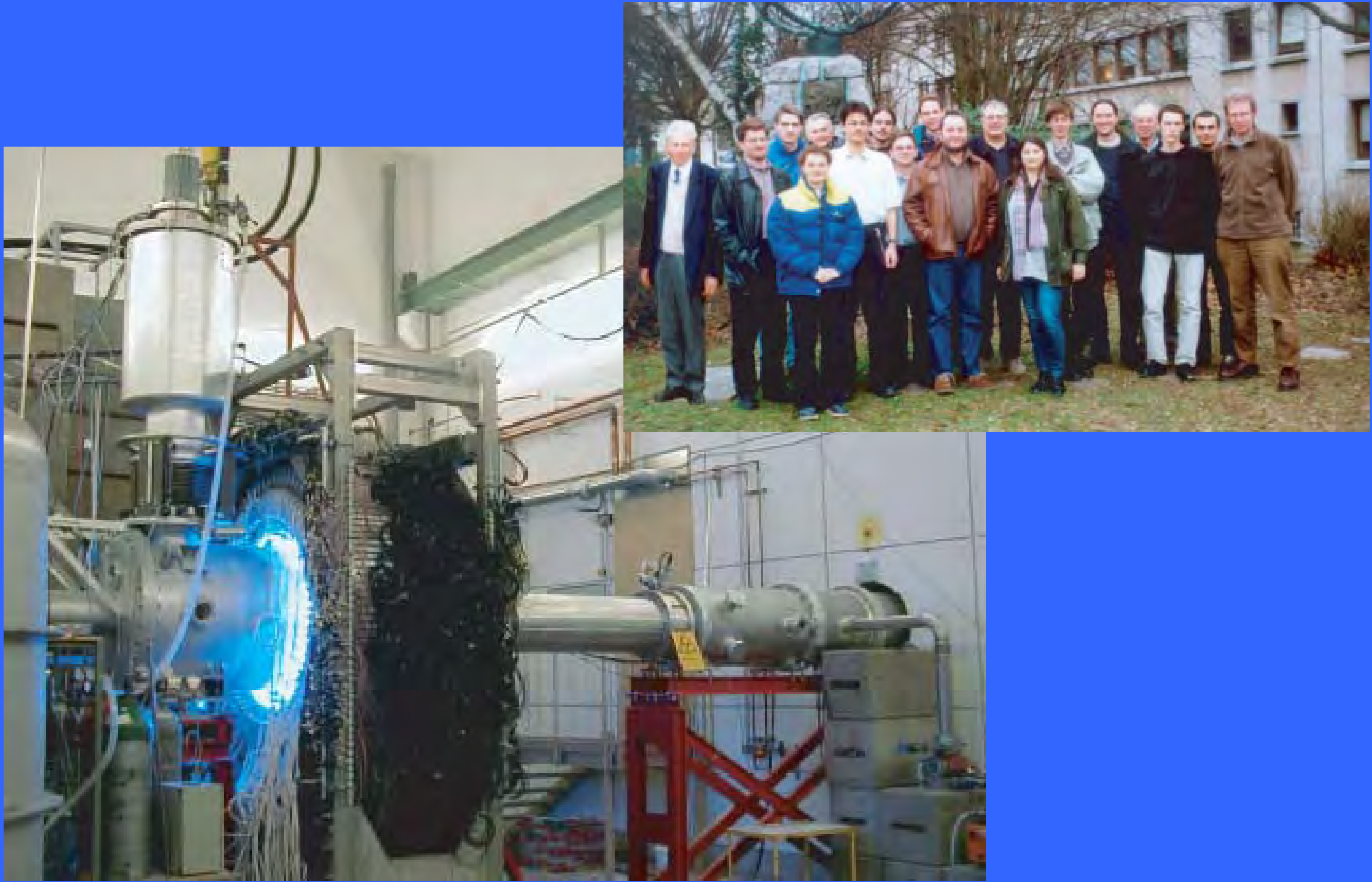
- Through proton spin crisis:
  As much as 10% of the spin of the proton

- HOW MUCH OF THE MAGNETIC FORM FACTOR?

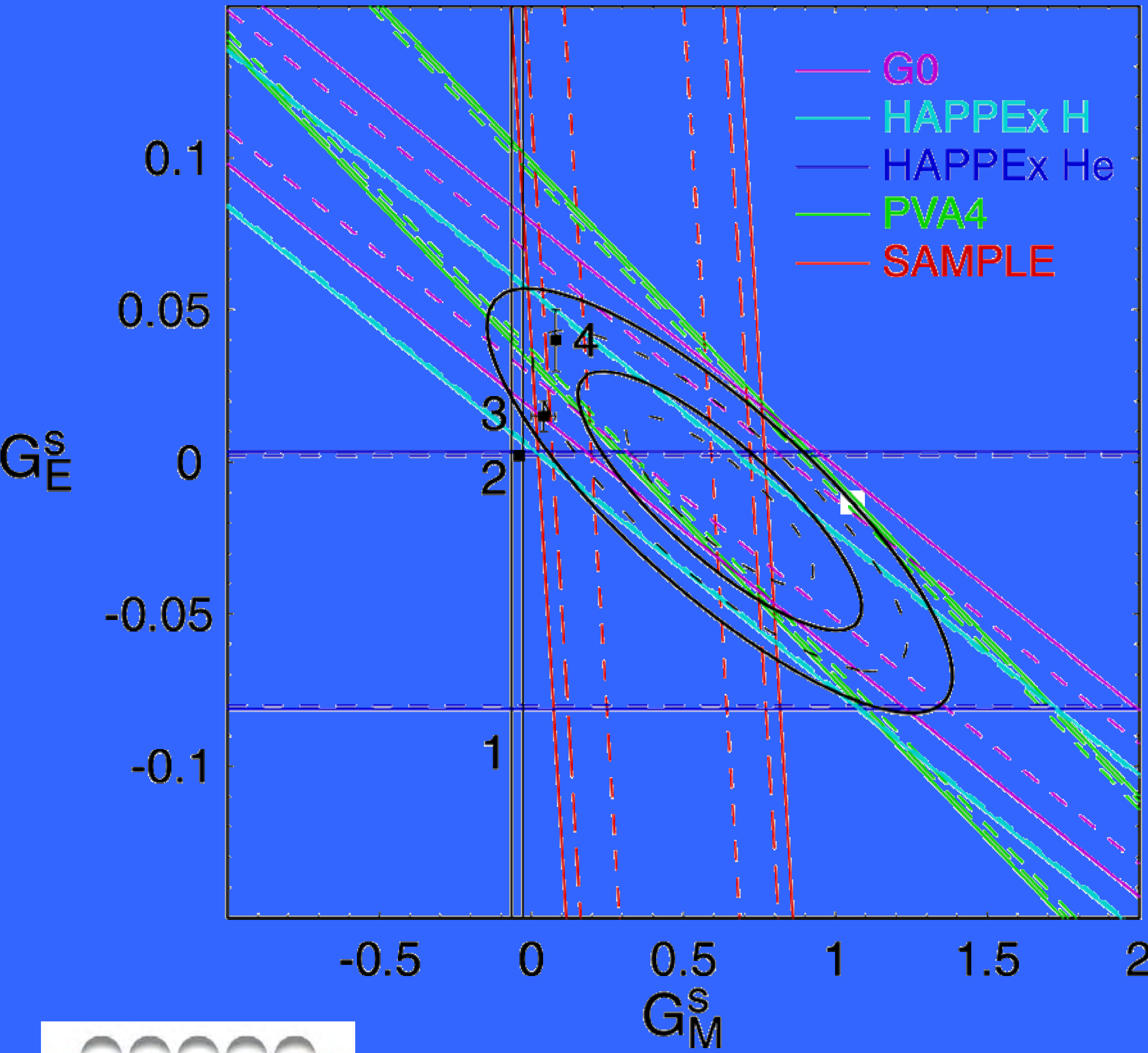
G0 Experiment at Jefferson Lab



A4 at Mainz



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



$G_E^s = -0.013 \pm 0.028$

$G_M^s = +0.62 \pm 0.31$

$\pm 0.62\ 2\sigma$

Contours

----- 1σ, 2σ

—— 68.3, 95.5% CL

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

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

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% !!

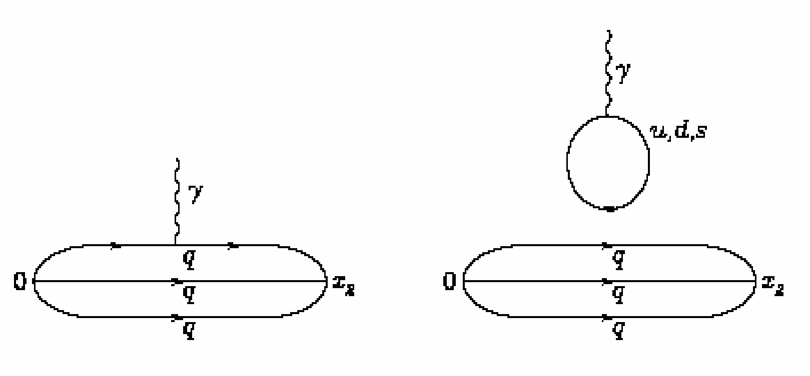
- Also remarkable versus lattice QCD which gives

  +0.03 § 0.01 μ_N (Leinweber et al., PRL 94 (2005) 212001)

- Sign would require violation of universality of

  valence quark moments by » 70% !

Magnetic Moments within QCD



CS

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

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

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

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

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

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

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

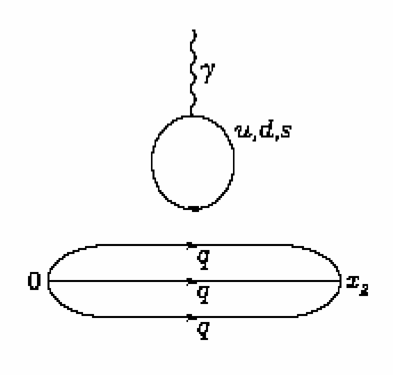
HENCE: $O_N = 1/3\ [\ 2p + n - (\ u^p / u^\Sigma\ )\ (\Sigma^+ - \Sigma^-)\ ]$

Just these ratios from Lattice QCD

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

Constraint from Charge Symmetry

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

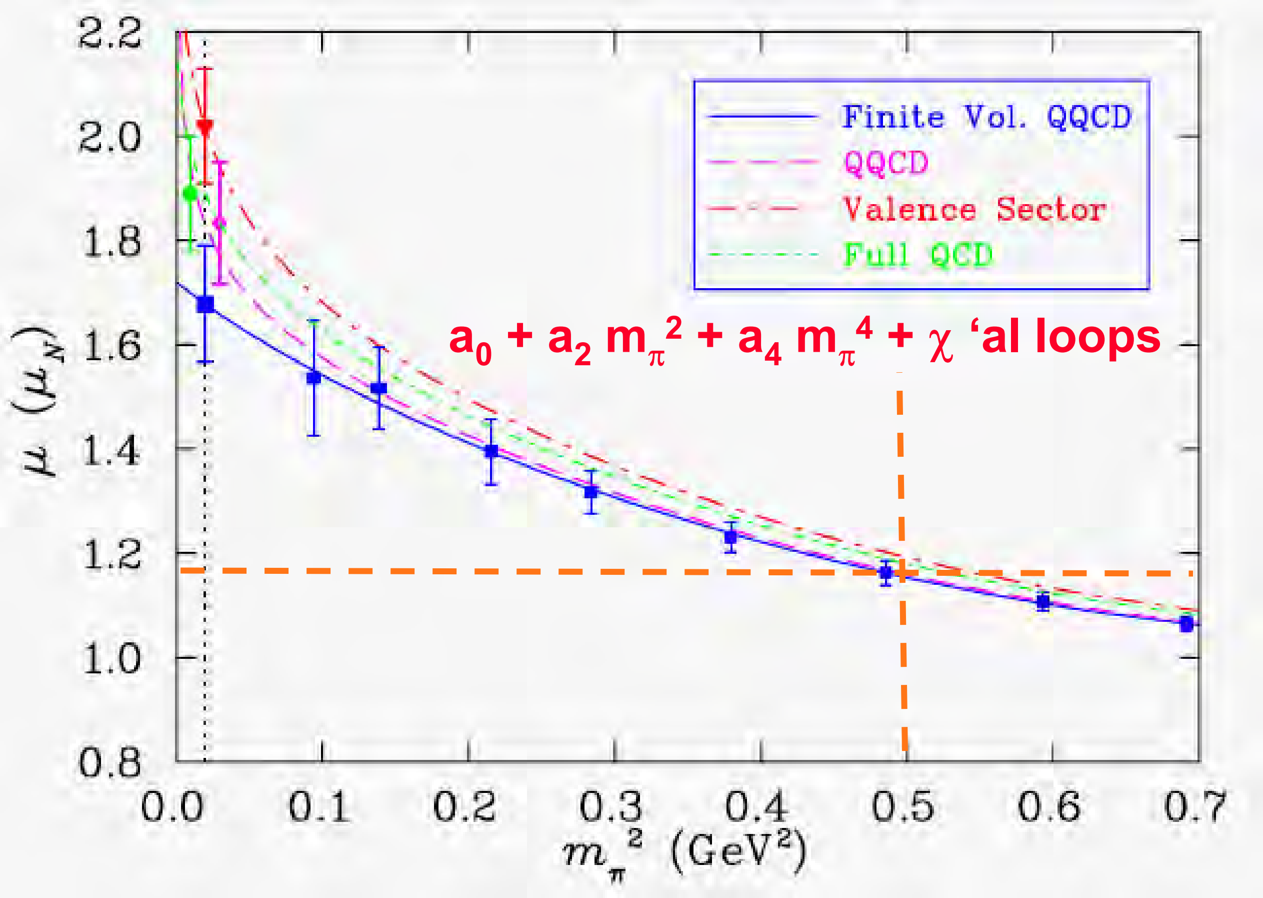


$$G_M^s = \left(\frac{{}^{\ell}R_d^s}{1 - {}^{\ell}R_d^s}\right)\left[3.673 - \frac{u_p}{u_{\Sigma^+}}(3.618)\right]$$

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

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

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

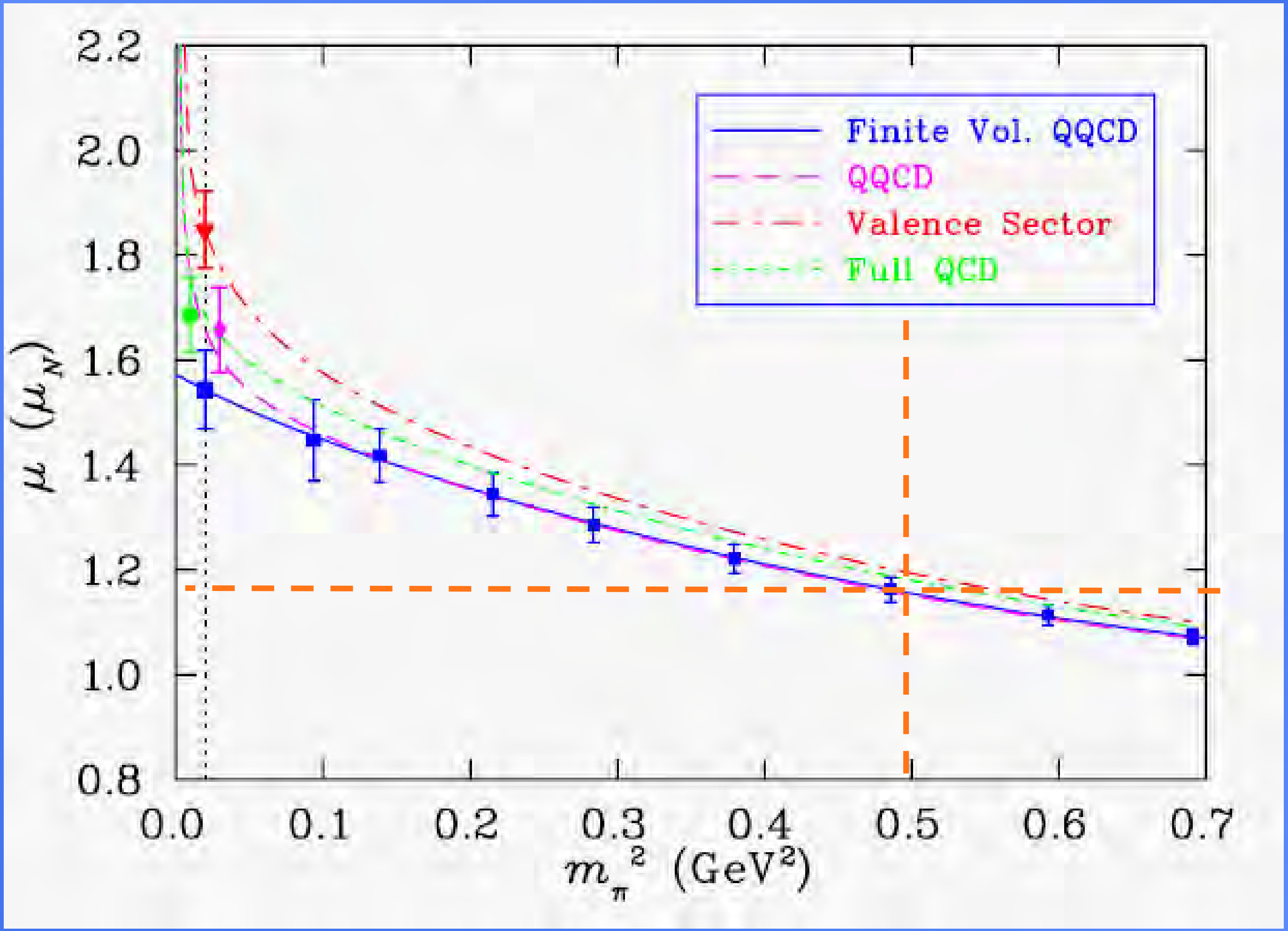


$a_0 + a_2\, m_\pi^2 + a_4\, m_\pi^4 + \chi$ 'al loops

c.f. CQM
2/3 940/540
» 1.18

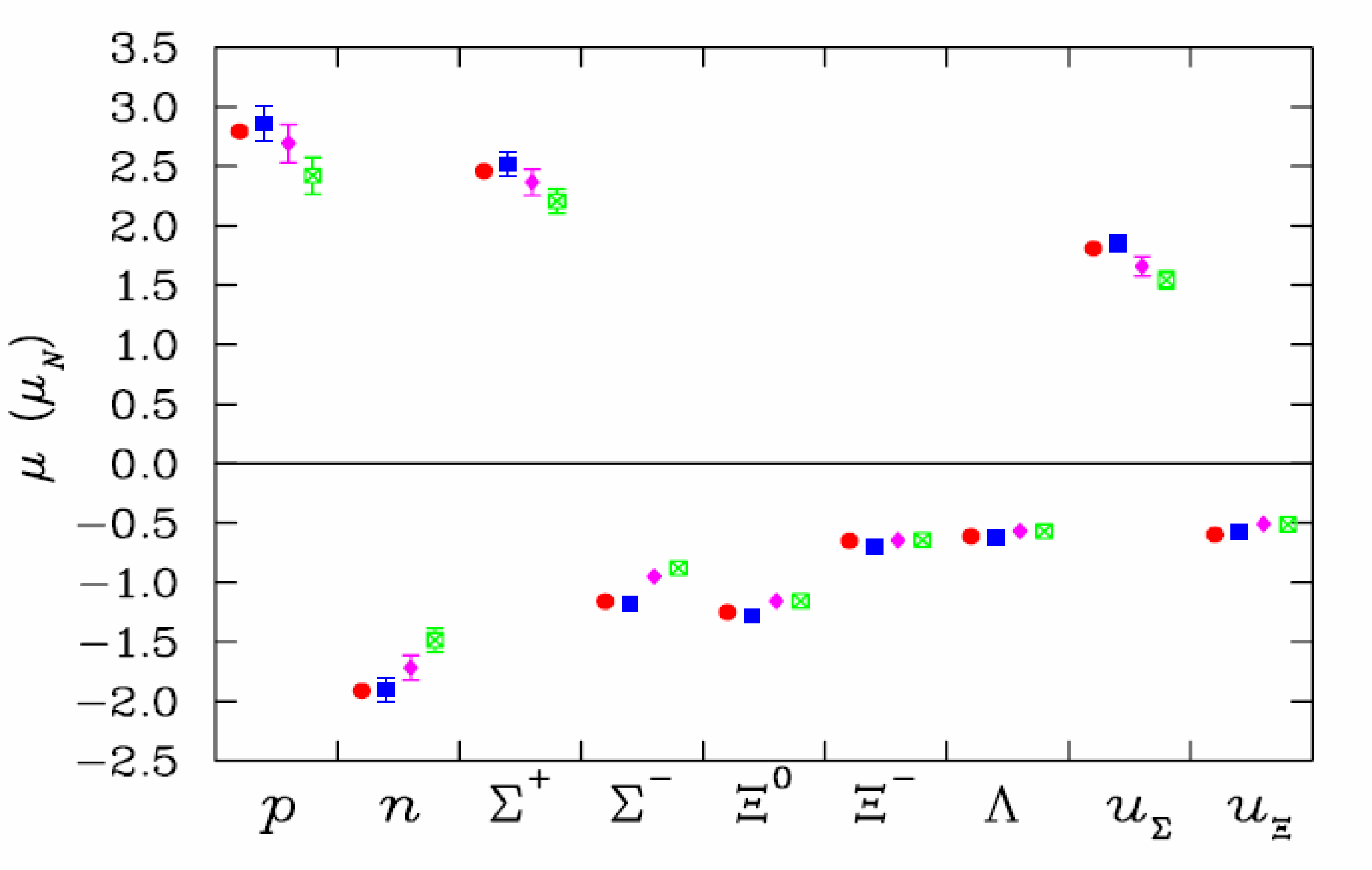
New lattice data from Zanotti et al. ; Chiral analysis Leinweber et al.

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



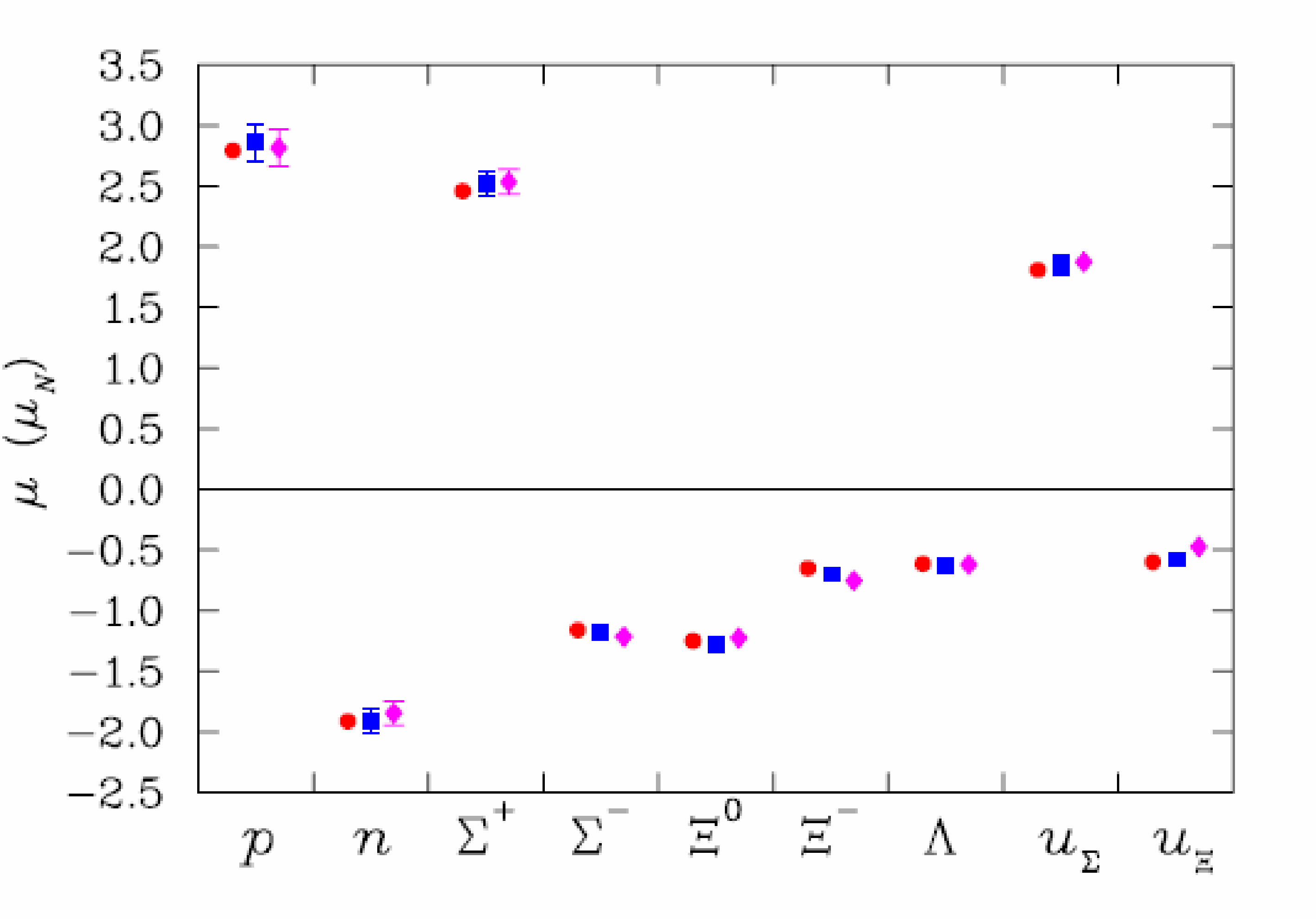
Universal Here!

Check: Octet Magnetic Moments



Leinweber et al., hep-lat/0406002

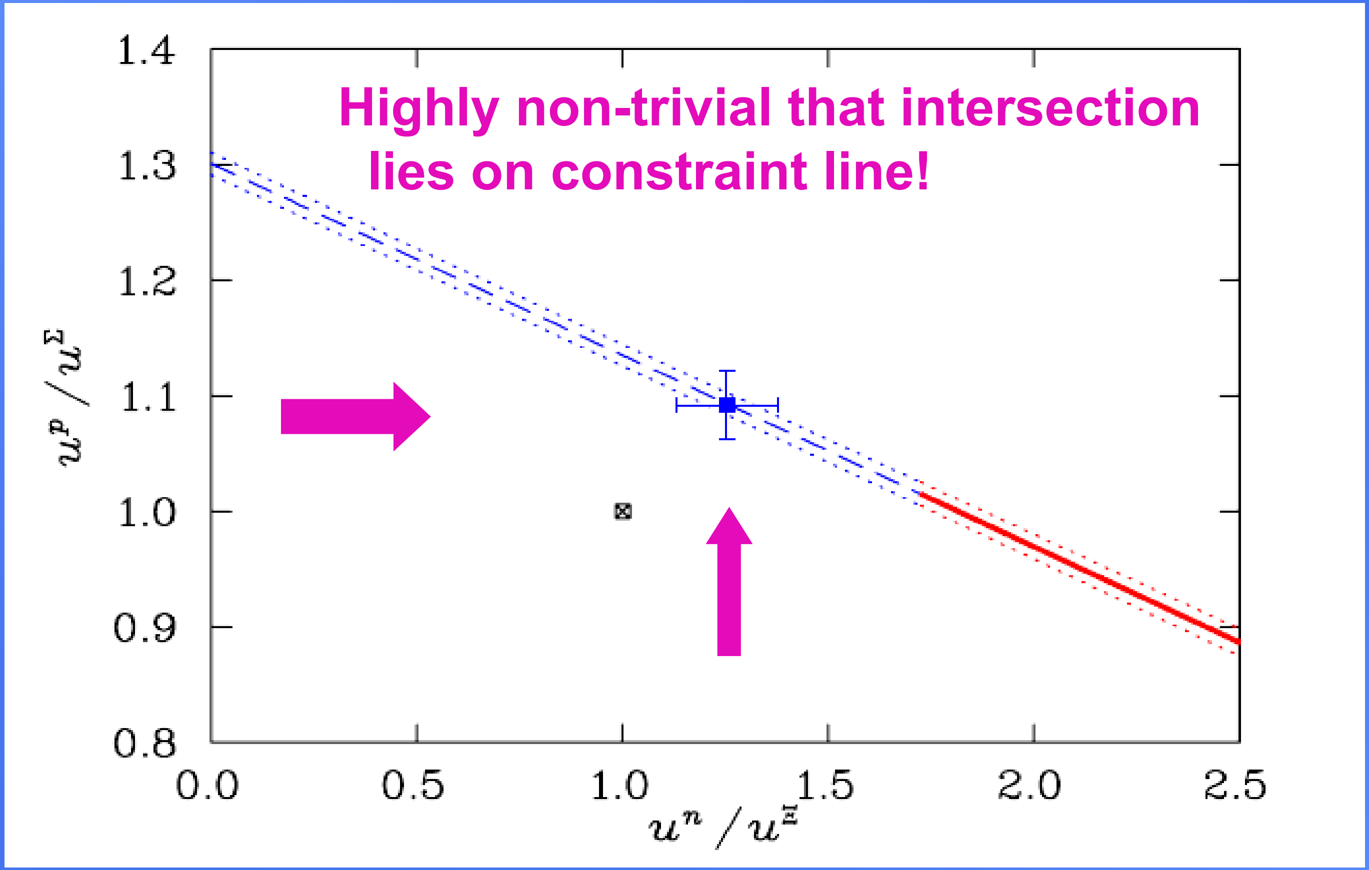
Convergence LNA to NLNA Again Excellent (Effect of Decuplet)



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



Highly non-trivial that intersection lies on constraint line!

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

HAPPEx-II: Parity Violation in H and He

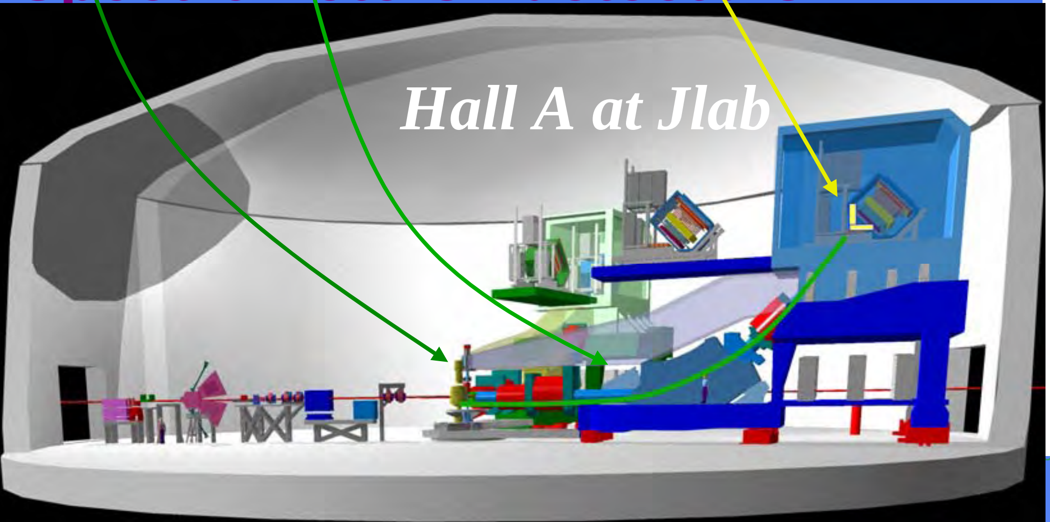
3 GeV beam in Hall A $\theta_{lab} \sim 6^\circ$ $Q^2 \sim 0.1\ (\mathrm{GeV/c})^2$

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

Septum magnets (not shown)

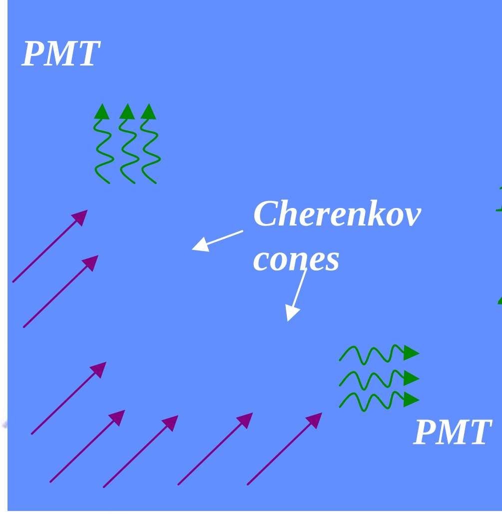
High Resolution Spectrometers

detectors



Hall A at Jlab

Brass-Quartz integrating detector



Elastic Rate:

^{1}H: 120 MHz

^{4}He: 12 MHz

Background ≤ 3%

Charge Radii for the Σ Hyperons

Σ^- mean-square radius has been measured:

$\langle r^2 \rangle_{\Sigma^-}$ = -0.61 § 0.12 § 0.09 fm^2

Σ^+ has not been measured BUT we now have QQCD data on both Σ^+ and Σ^-

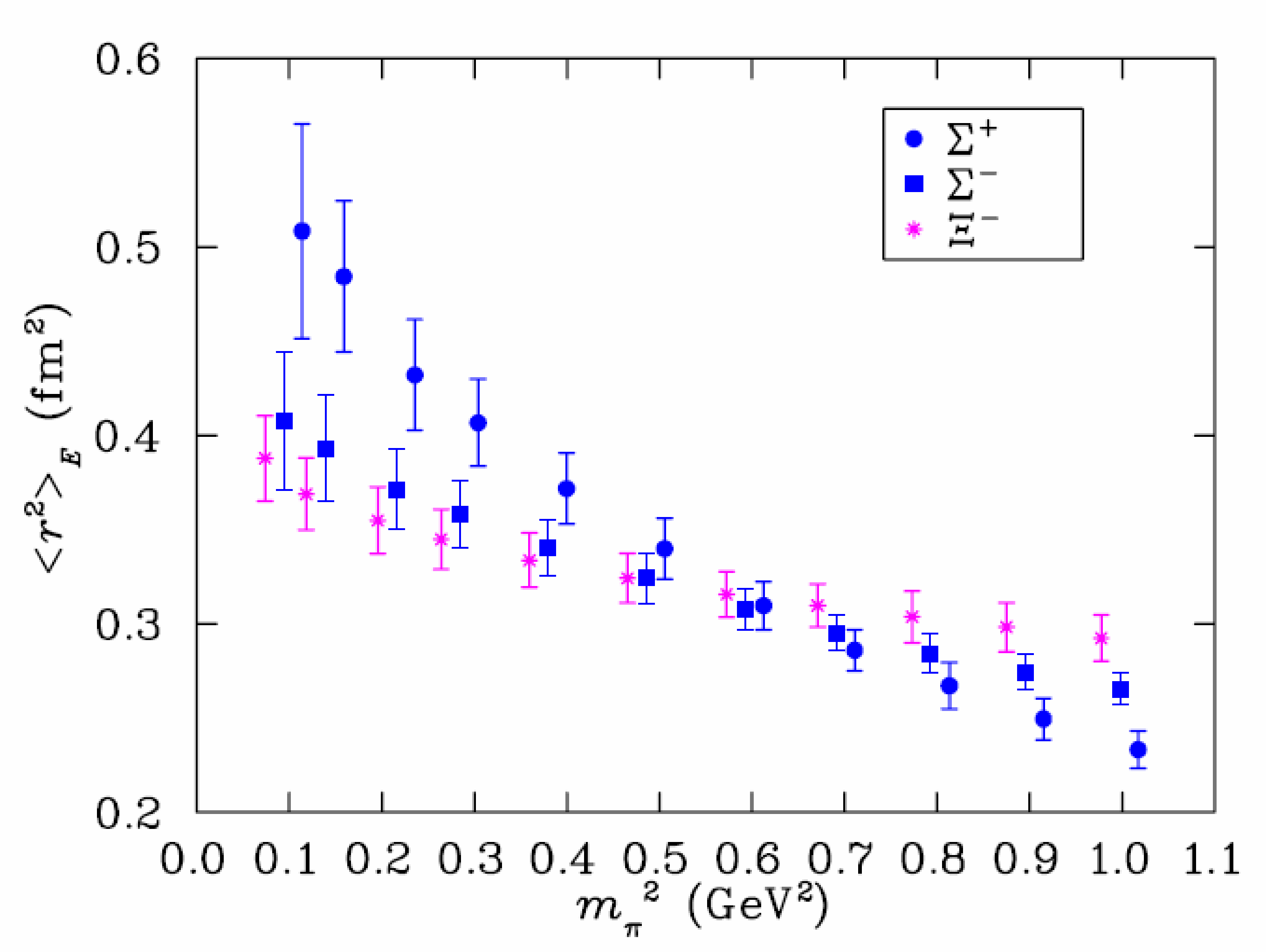
■

The ratio of Σ^+ to Σ^- mean-square charge radii is of order 1.25 (next slide*))
$\langle r^2 \rangle_{\Sigma^+}$ » + 0.76 § 0.15 § 0.11 fm^2

Hence Σ^+ - Σ^- = + 1.37 § 0.19 § 0.14 fm^2

* Error to be determined by jacknife analysis including correlations

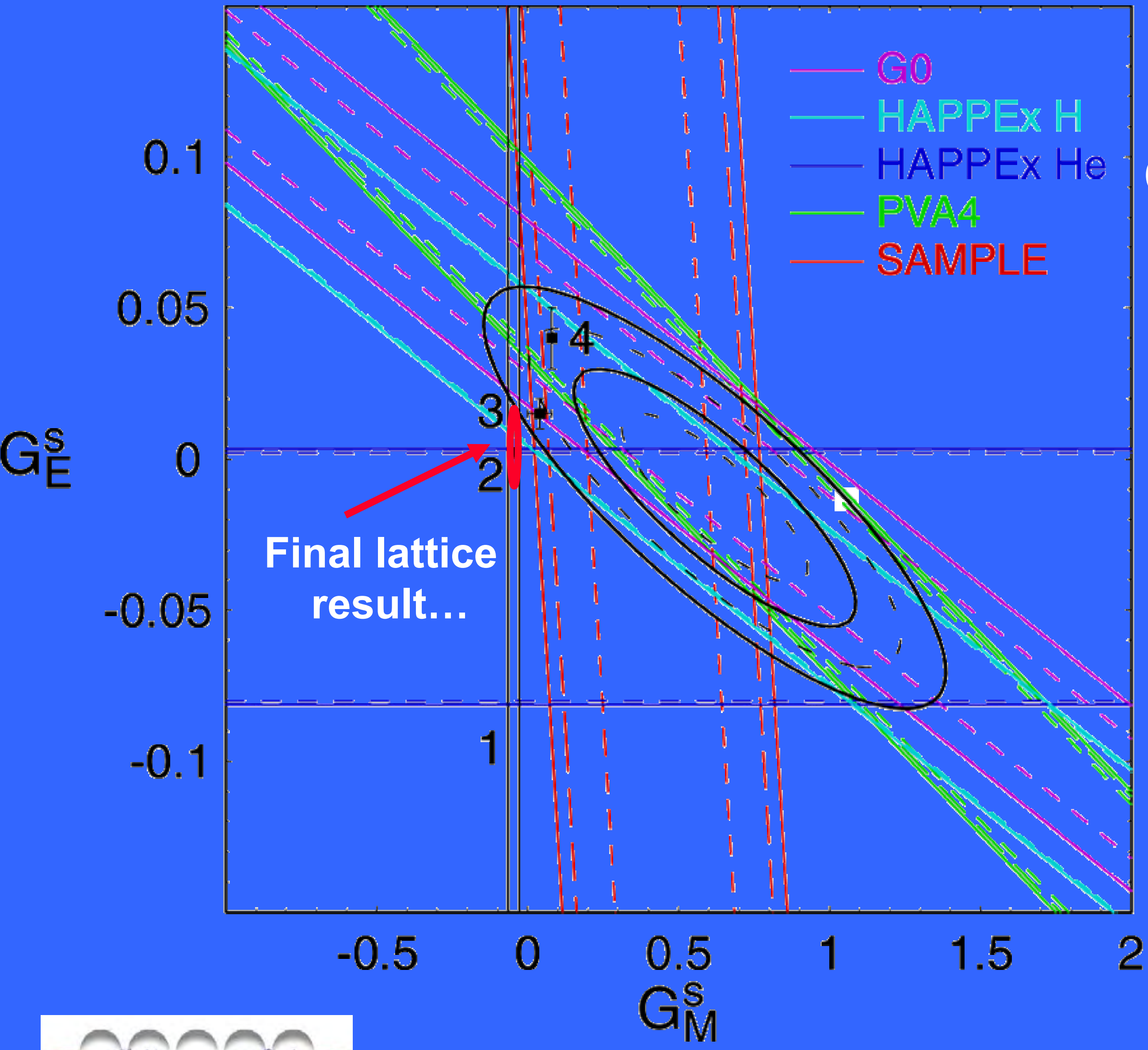
Hyperon Charge Radii



CSSM calculation FLIC fermions

Leinweber, Boinepalli et al.

World Data @ $Q^2 = 0.1\ \text{GeV}^2$



Final lattice result…

$G_E^s = -0.013 \pm 0.028$

$G_M^s = +0.62 \pm 0.31$

($\pm$ 0.62 2σ)

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

“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%

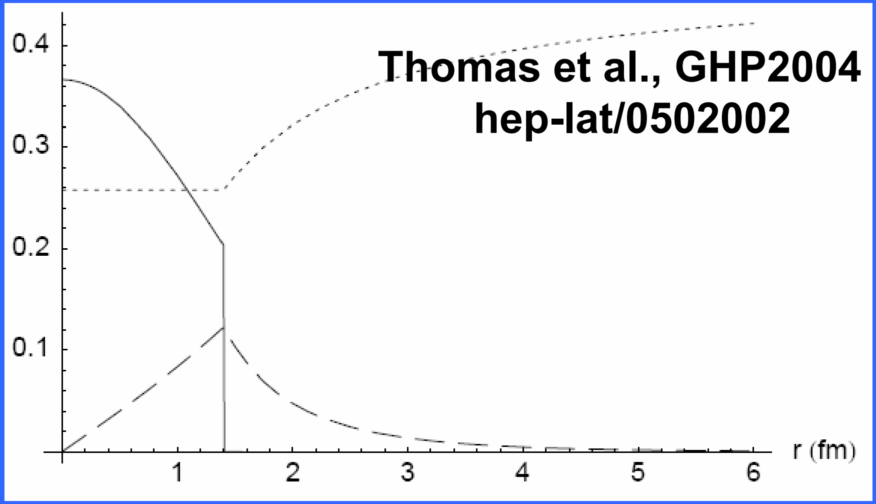
G_M^s ¼ -3 £ $P_{K \Lambda}$ £ [2/3 (+0.61 + 1/3) +1/3(-0.61 + 0)]

¼ -0.067 μ_N

Remarkably close to lattice estimate!

* nucl-th/0509082

Strangeness Radius



Thomas et al., GHP2004
hep-lat/0502002

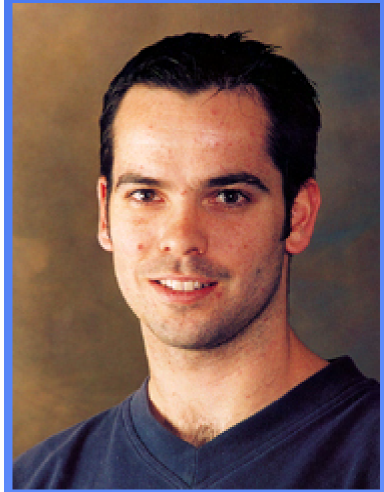
- Meson cloud surface peaked
- Core has mean-square radius » $(0.7\ R)^2$
- Meson cloud » $(R + 0.2)^2$
- Hence: $-3\ \langle r^2\rangle_s$ »

$$-3\ £(+\ 1/3)\ P_{K\ \Lambda}\ [\ -\ 0.49\ R^2\ +\ (R + 0.2)^2\ ]$$

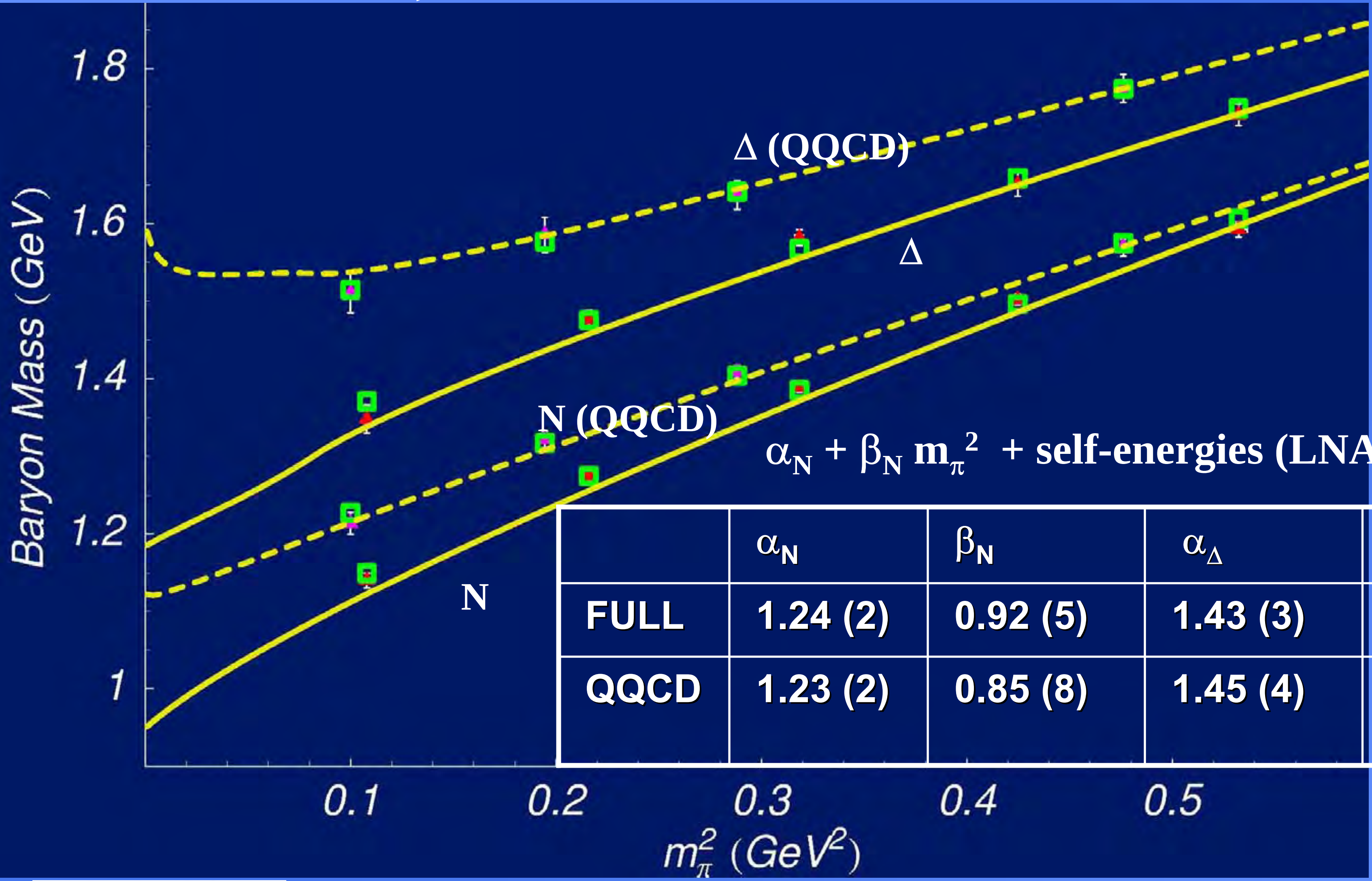
$$\varepsilon\ (-0.02,\ -0.04)\ \mathrm{fm}^2 \text{ for } R\ \varepsilon\ (0.8, 1.0)\ \mathrm{fm}$$

- Hence: $G_E^s\ (0.1\ \mathrm{GeV}^2)$ » $(+0.01,\ +0.02)$

"QUARKS. NEUTRINOS. MESONS. ALL THOSE DAMN PARTICLES YOU CAN'T SEE. THAT'S WHAT DROVE ME TO DRINK. BUT NOW I CAN SEE THEM."



- Lattice data (from **MILC Collaboration**) : red triangles
- Green boxes: fit evaluating σ's on <u>same finite grid as lattice</u>
- Lines are exact, continuum results

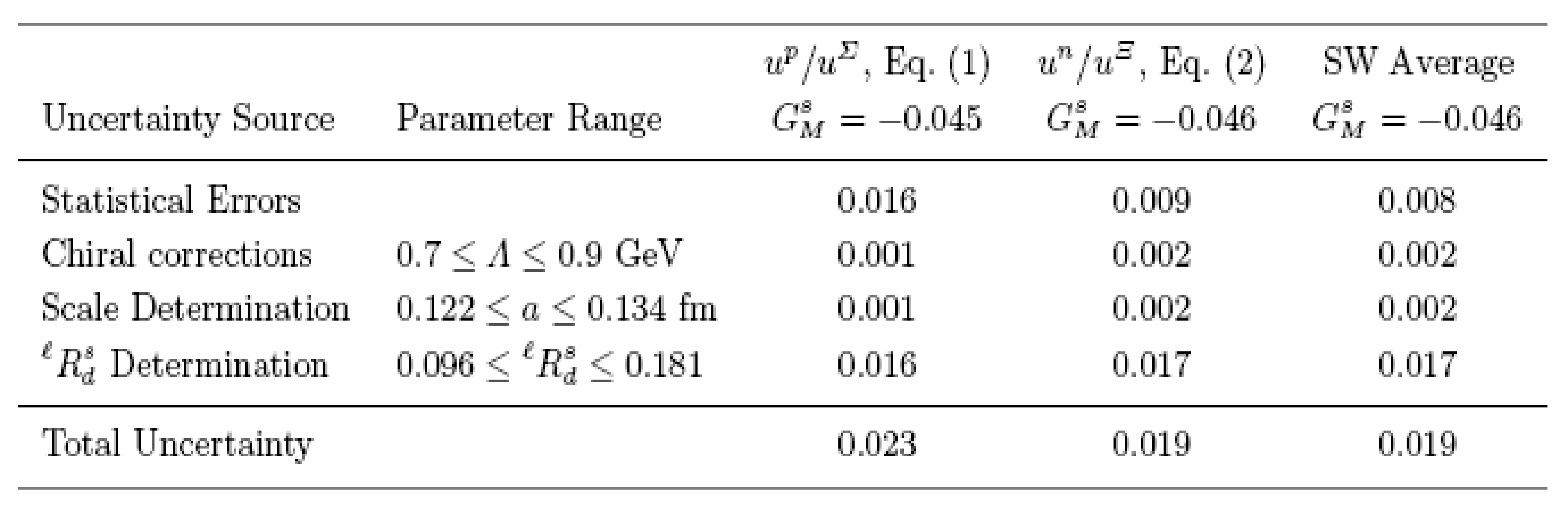


$\alpha_N + \beta_N m_\pi^2$ + self-energies (LNA+NLNA)

	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

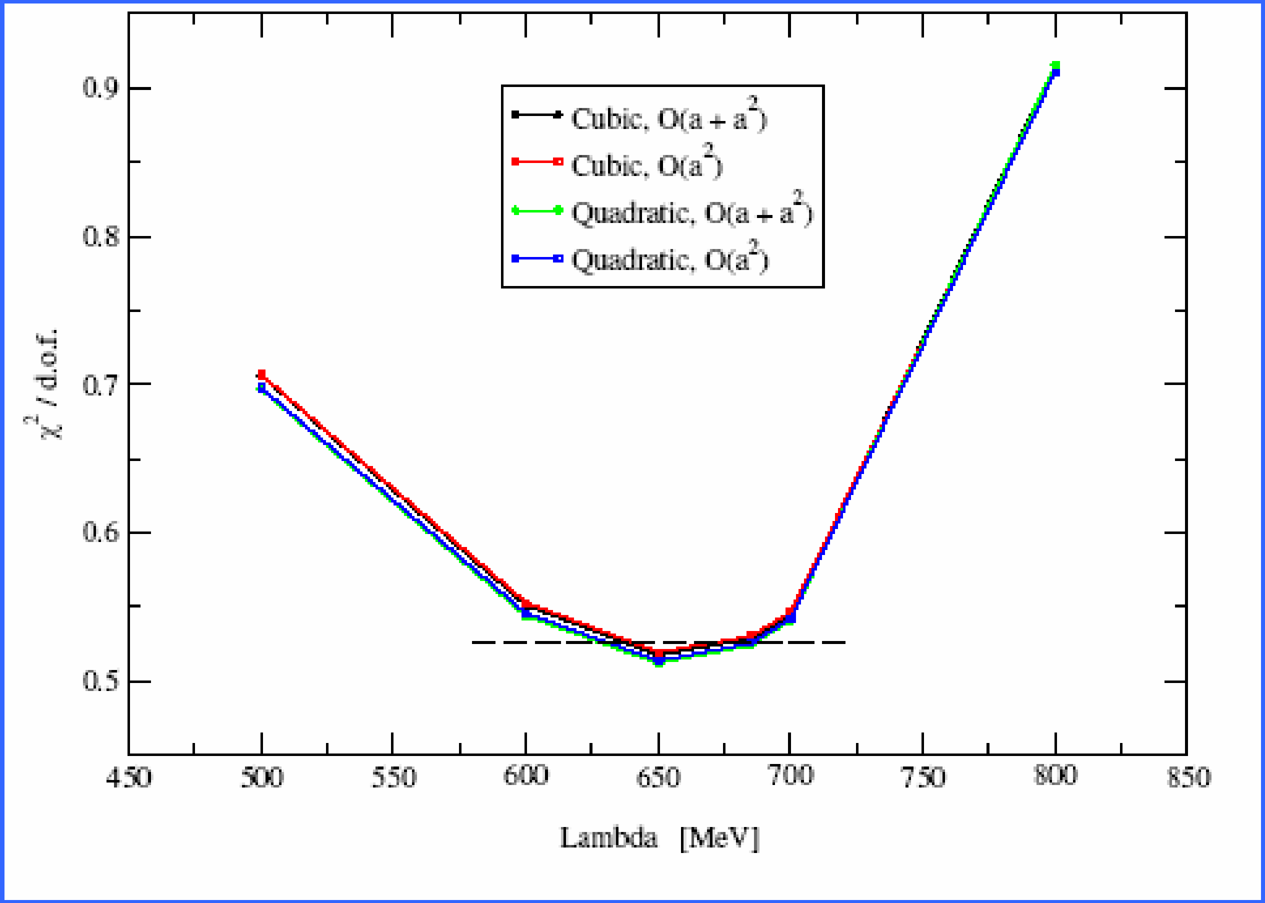
Error Table – Leinweber et al., hep-lat/0502004



Uncertainty Source	Parameter Range	u^p/u^Σ, Eq. (1) $G_M^s = -0.045$	u^n/u^Ξ, Eq. (2) $G_M^s = -0.046$	SW Average $G_M^s = -0.046$
Statistical Errors		0.016	0.009	0.008
Chiral corrections	$0.7 \le \Lambda \le 0.9$ GeV	0.001	0.002	0.002
Scale Determination	$0.122 \le a \le 0.134$ fm	0.001	0.002	0.002
${}^{\ell}R_d^s$ Determination	$0.096 \le {}^{\ell}R_d^s \le 0.181$	0.016	0.017	0.017
Total Uncertainty		0.023	0.019	0.019

Table 1. Sources of uncertainty and their contribution to the strangeness magnetic moment of the nucleon, G_M^s, in units of nuclear magnetons, μ_N. Uncertainties are documented for G_M^s obtained from the valence-quark ratio u^p/u^Σ in Eq. (1), from the valence-quark ratio u^n/u^Ξ in Eq. (2) and from a statistically weighted (SW) average of these two determinations.

FRR Mass well determined by data



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