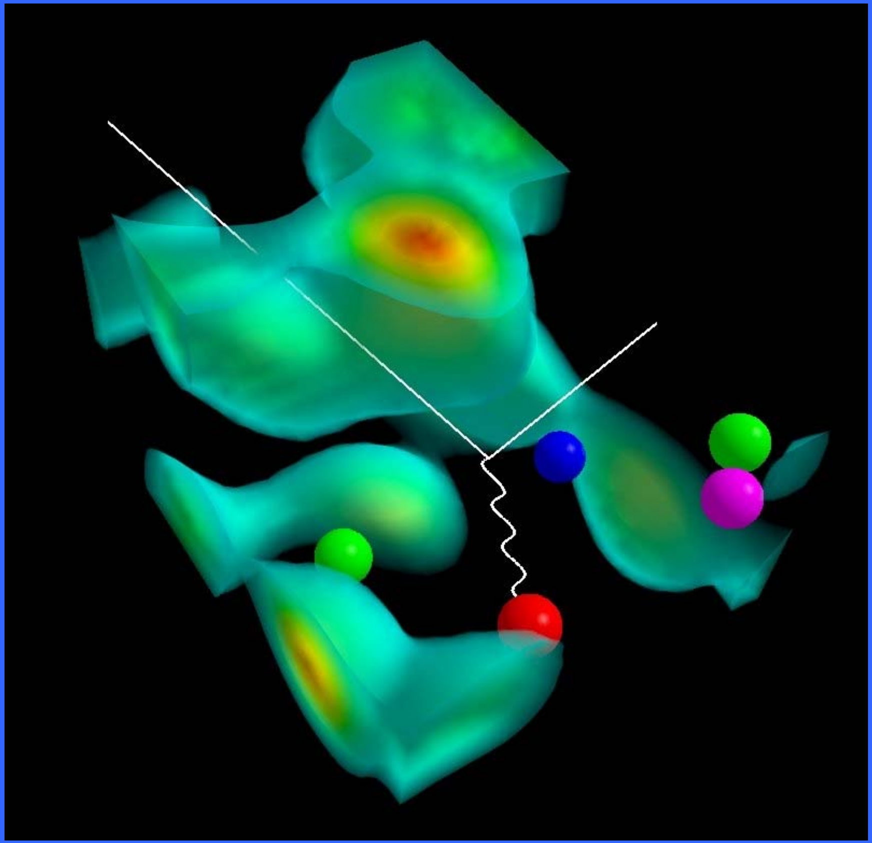
Strangeness Content of the Nucleon



Anthony W. Thomas

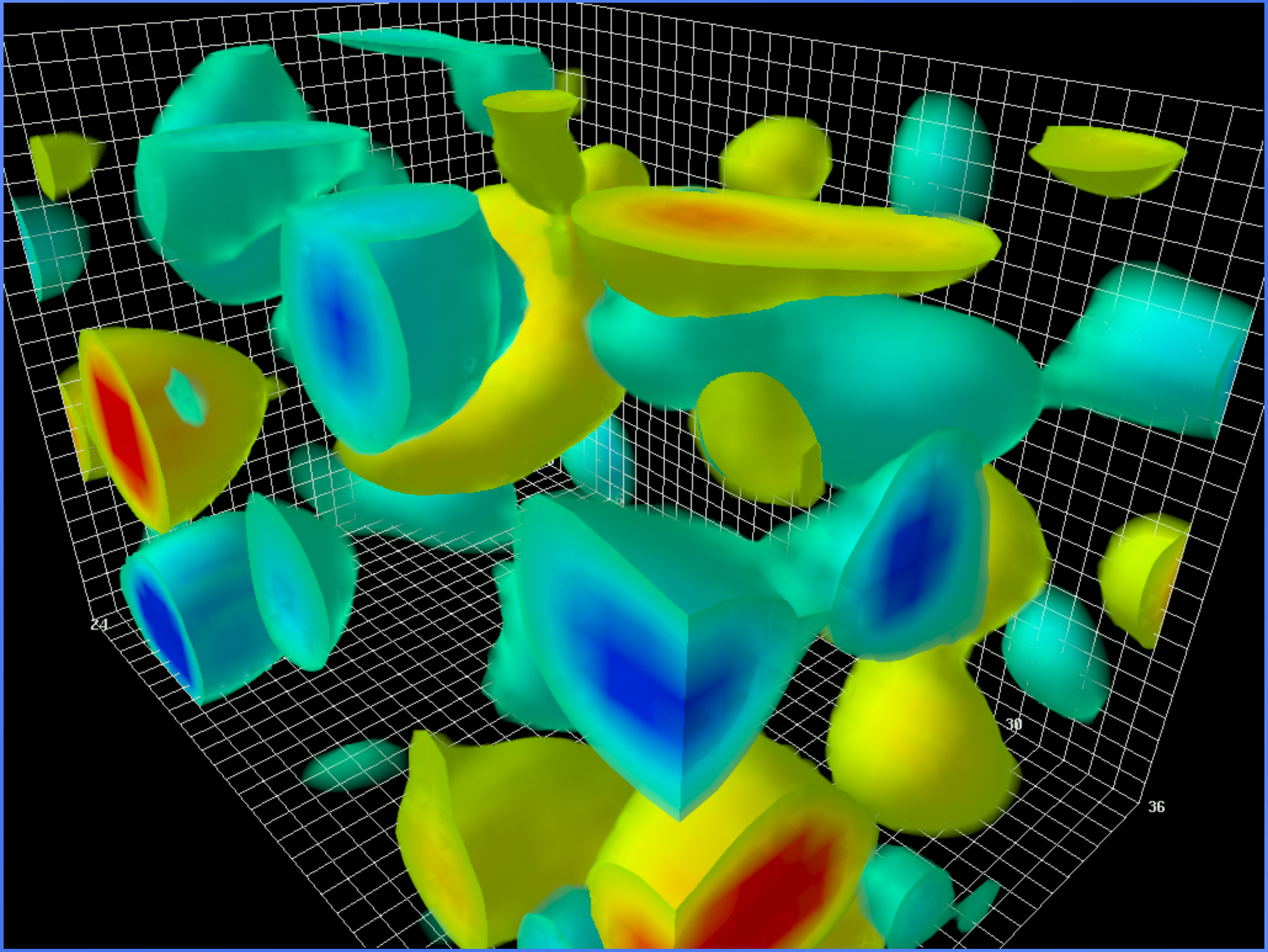
Workshop on Precision ElectroWeak Interactions

College of W&M : August 16th, 2005

Outline

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

Topology of QCD Vacuum



Leinweber: see CSSM web pages

Powerful Qualitative New Insights From Lattice QCD

QCD sum rules :

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

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

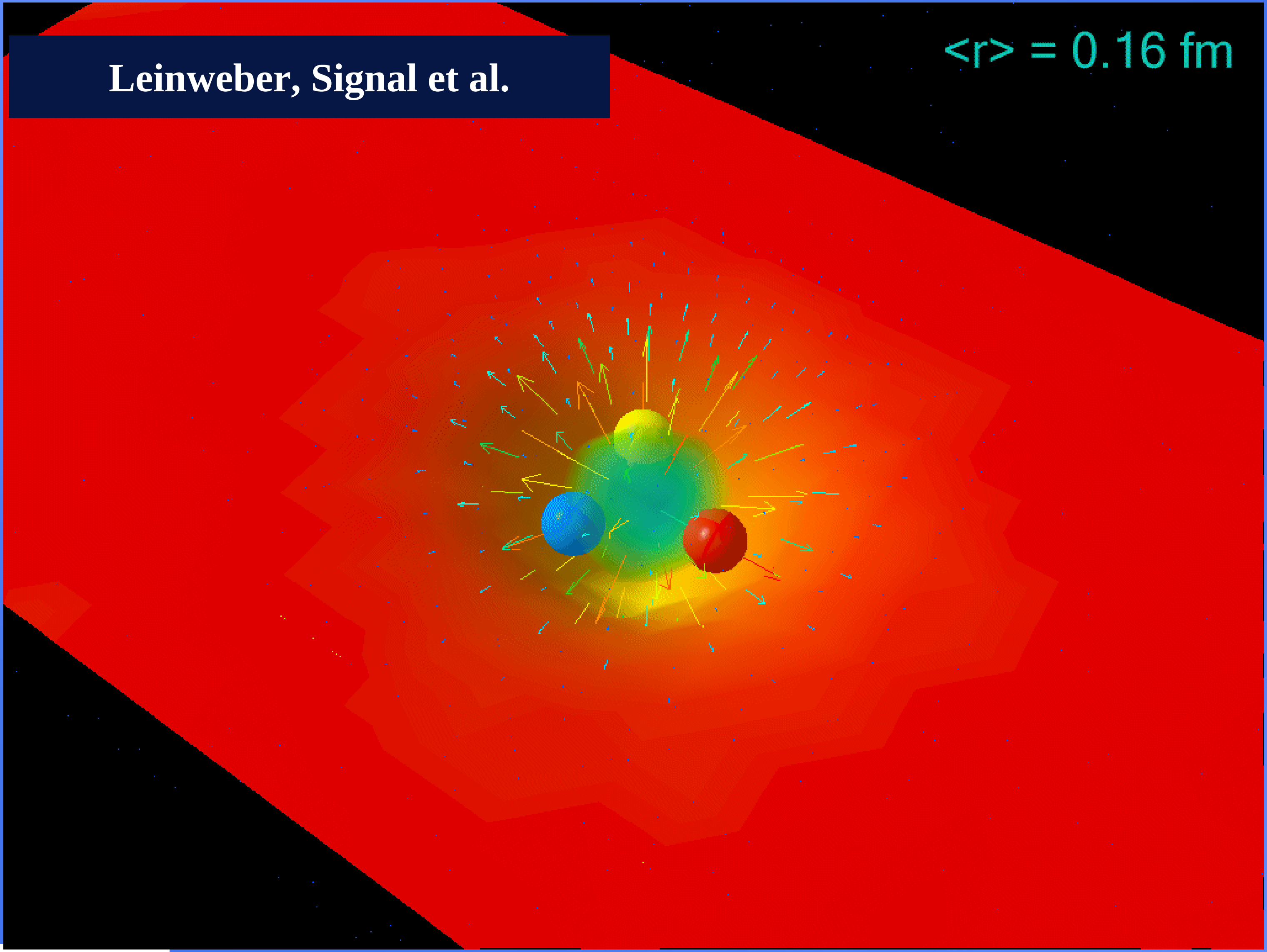
and last term is as big as 20 MeV (or more)
i.e. presence of nucleon "cleans out" vacuum to some extent

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



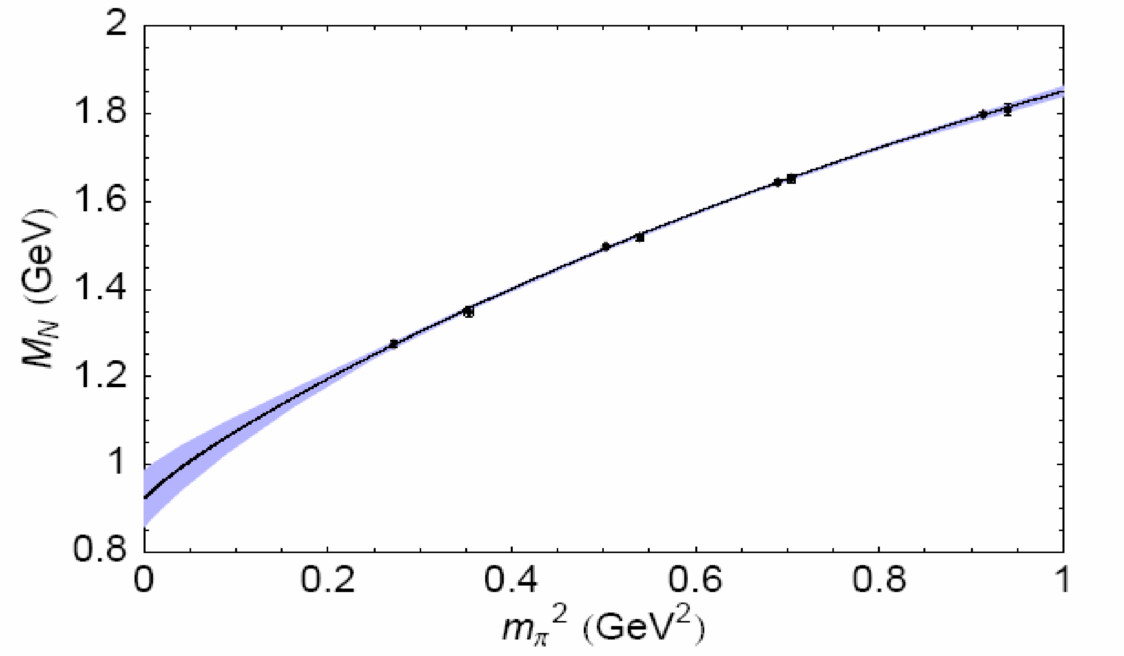
Leinweber, Signal et al.

QCD and the Origin of Mass

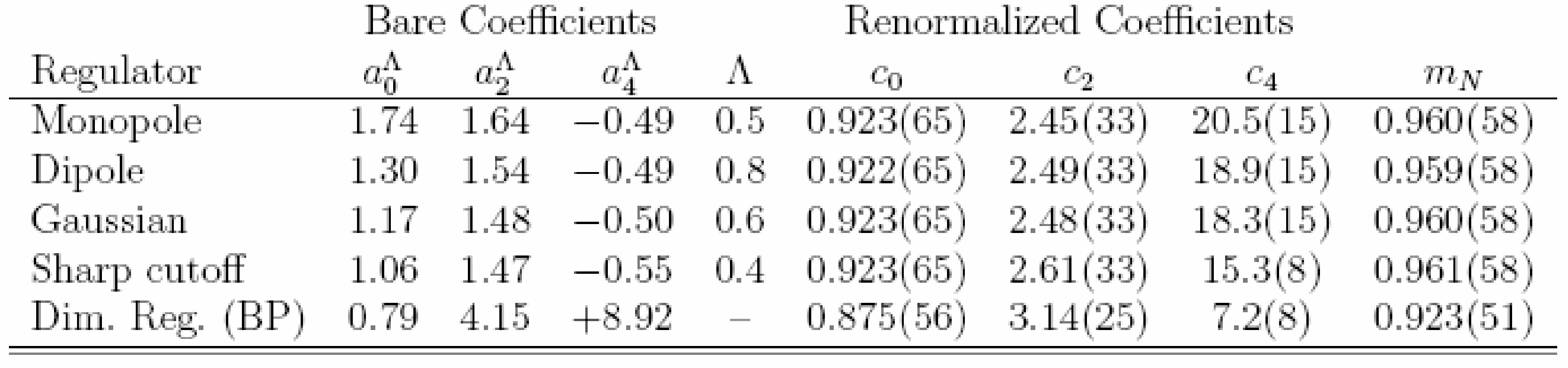
$$\begin{array}{lccccccc} & u & + & u & + & d & = & \text{proton} \\ \text{mass:} & 0.003 & + & 0.003 & + & 0.006 & \neq & 0.938 \end{array}$$

HOW does the rest of the proton mass arise?

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)

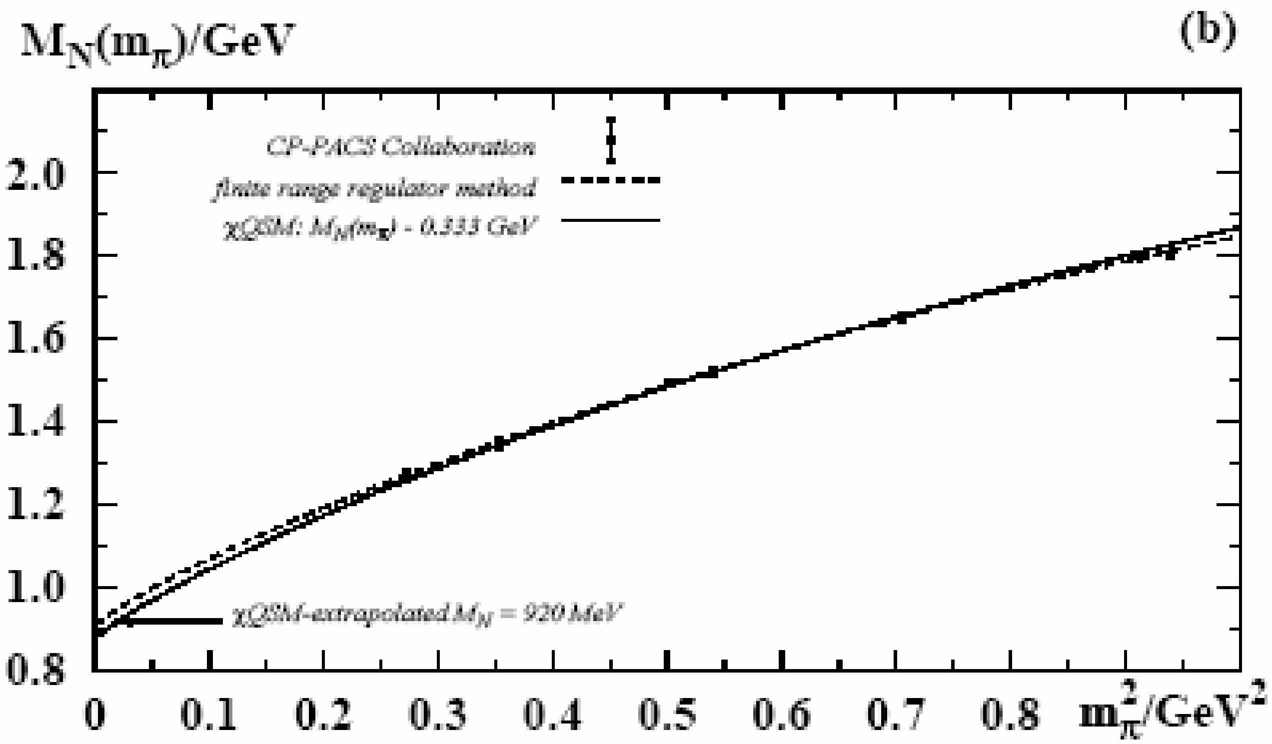
Leinweber et al., PRL 92 (2004) 242002

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

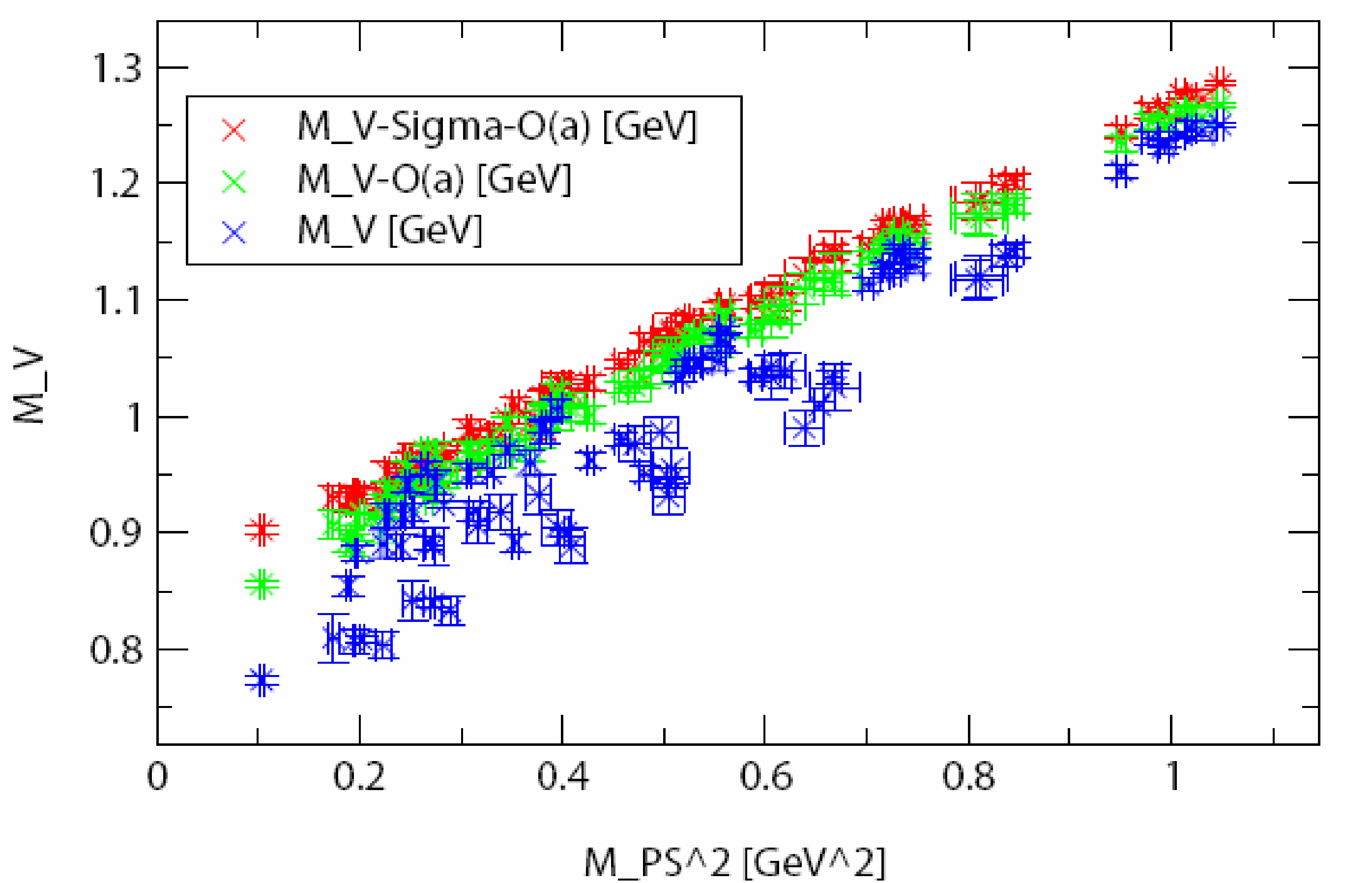
M_N in MeV

Comparison with χ QSM



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

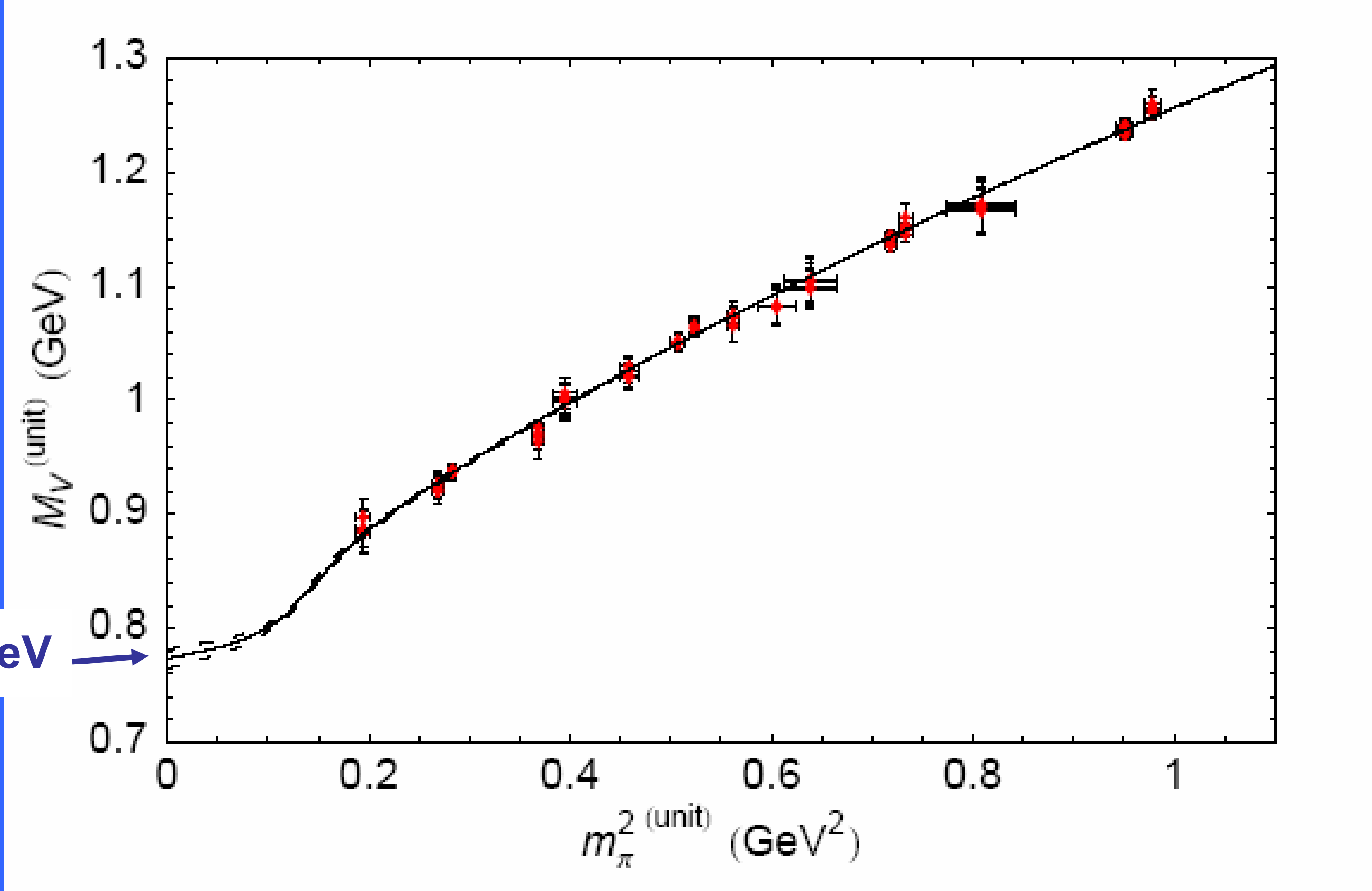
Analysis of pQQCD ρ data from CP PACS



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

Infinite Volume Unitary Results

All 80 data points drop onto single, well defined curve



777 ± 7 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

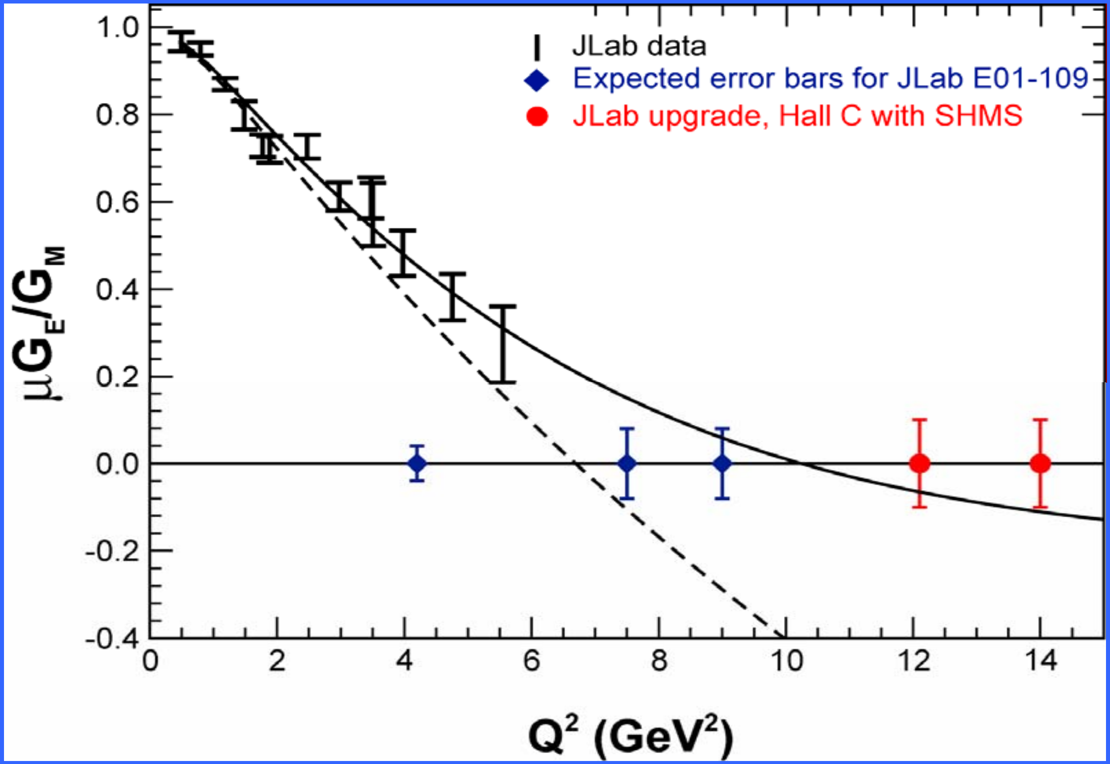
Superconducting rf (SRF) technology makes the circulating accelerator feasible

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:

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

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

y=0.2 ± 0.2

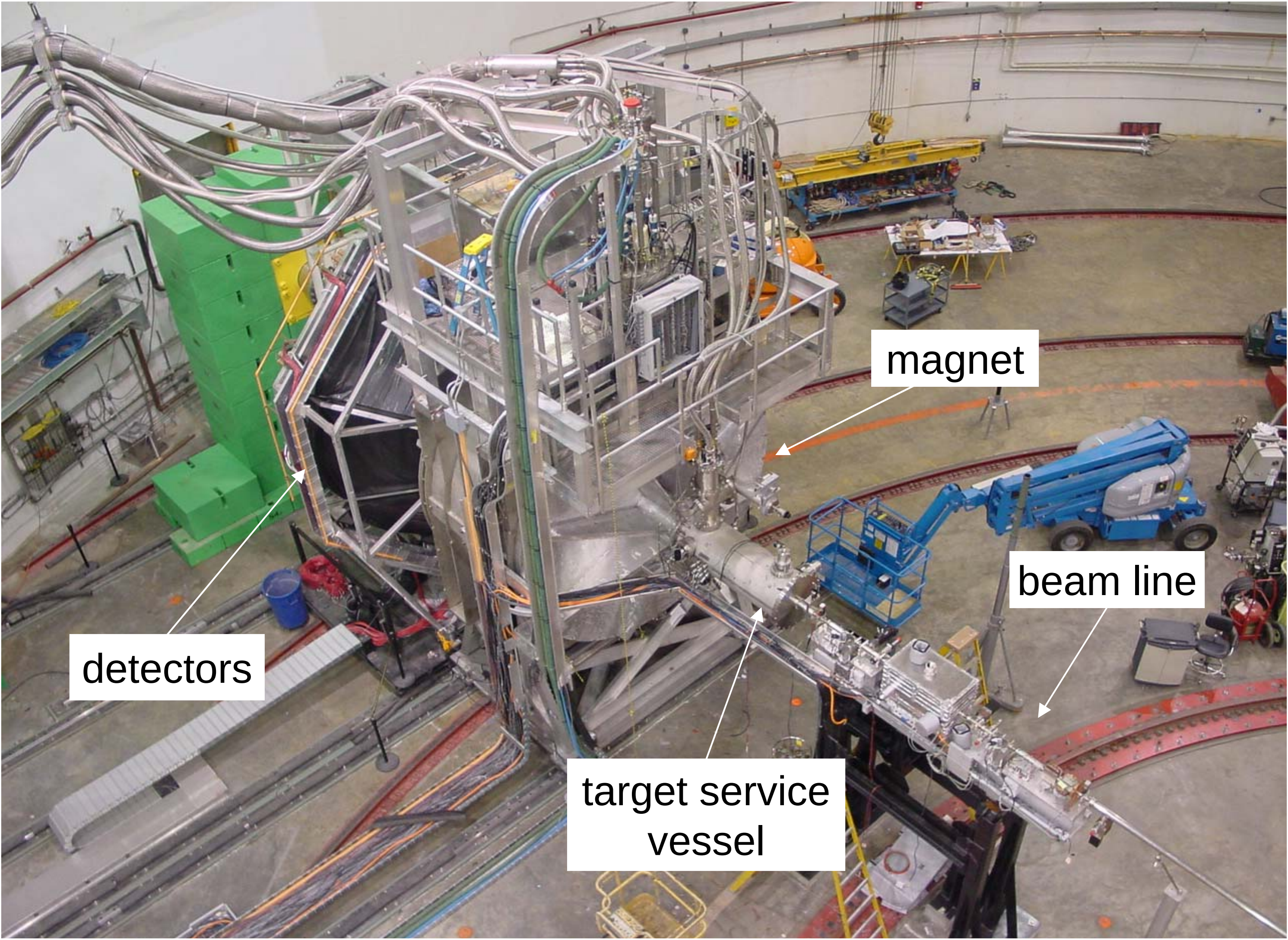
45 ± 8 MeV (or 70?)

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

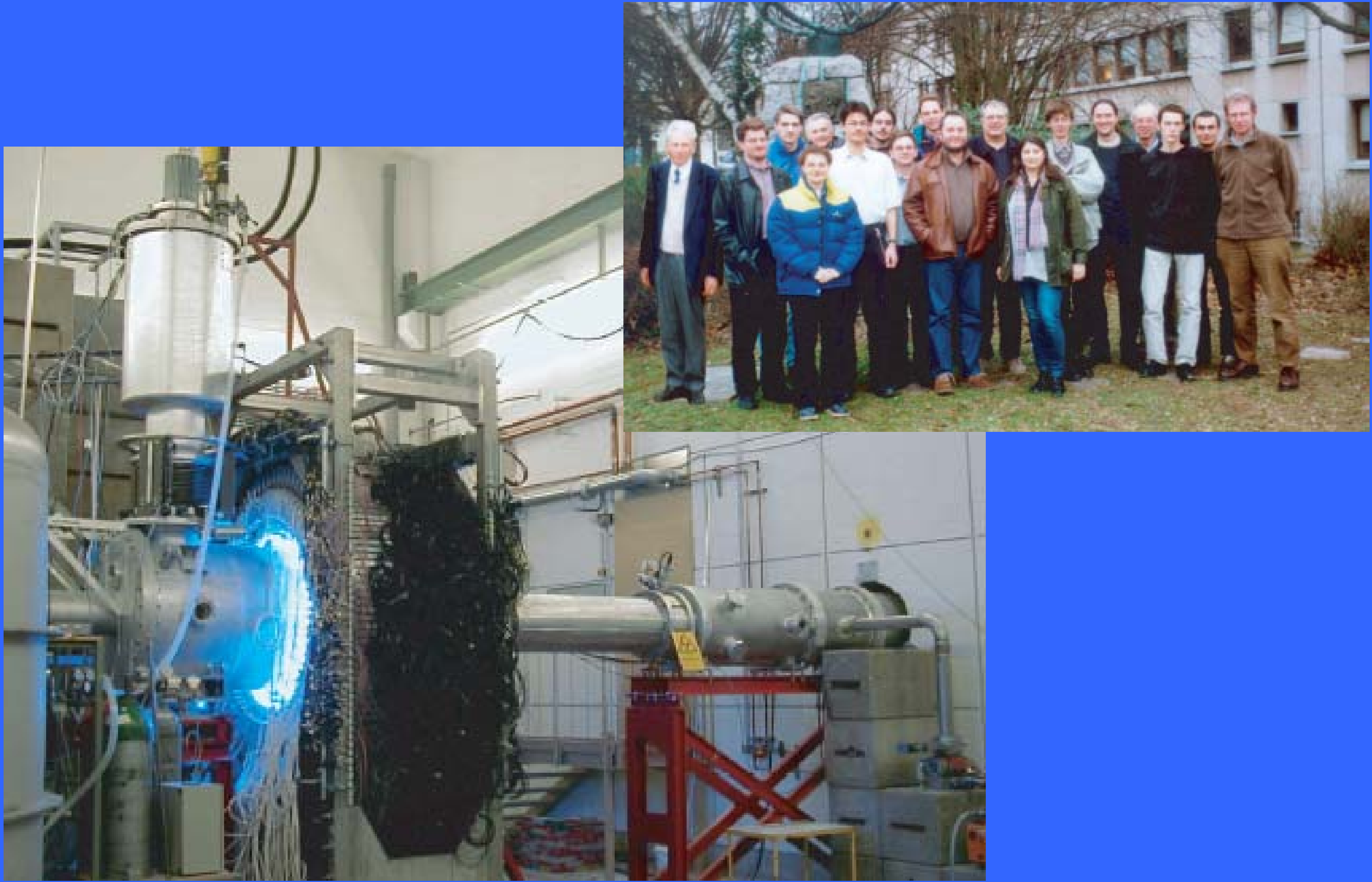
- Through proton spin crisis:
  As much as 10% of the spin of the proton

- HOW MUCH OF THE MAGNETIC FORM FACTOR?

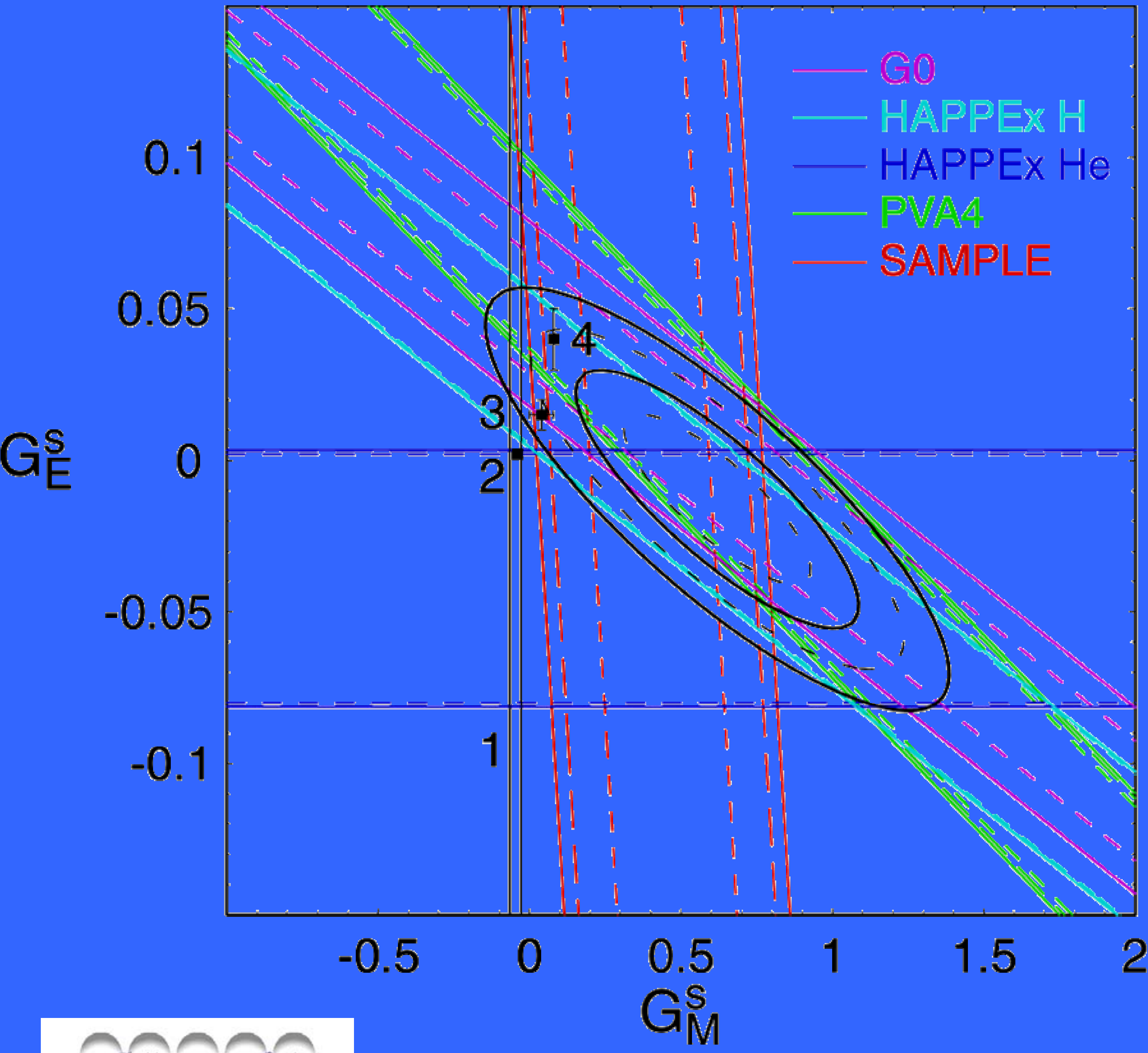
G0 Experiment at Jefferson Lab



A4 at Mainz



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



$G_E^s = -0.013 \pm 0.028$

$G_M^s = +0.62 \pm 0.31$

± 0.62 2σ

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

Simple Fits to World Hydrogen Data

- Fit

$$G_E^s\left(Q^2\right)+\eta\left(Q^2,E_i\right)G_M^s\left(Q^2\right)=$$

$$\frac{4\pi\alpha\sqrt{2}}{G_F Q^2}\,\frac{\varepsilon G_E^{p\,2}+\tau G_M^{p\,2}}{\varepsilon G_E^p\left(1+R_V^{(0)}\right)}\left(A_{phys}-A_{NVS}\left(Q^2,E_i\right)\right)$$

with simple forms for G_E^s , G_M^s

$$G_E^s\left(Q^2\right)=\frac{c_2 Q^4}{1+d_1Q^2+d_2Q^4+d_3Q^6}$$

à la Kelly

$$G_M^s\left(Q^2\right)=\frac{G_M^s\left(Q^2=0\right)}{\left(1+Q^2/\Lambda_M^{s\,2}\right)^2}$$

with

$$G_M^s\left(Q^2=0\right)=0.81$$

from Q^2 = 0.1 GeV^2 plot, dipole ff

“Fit” to World Hydrogen Data

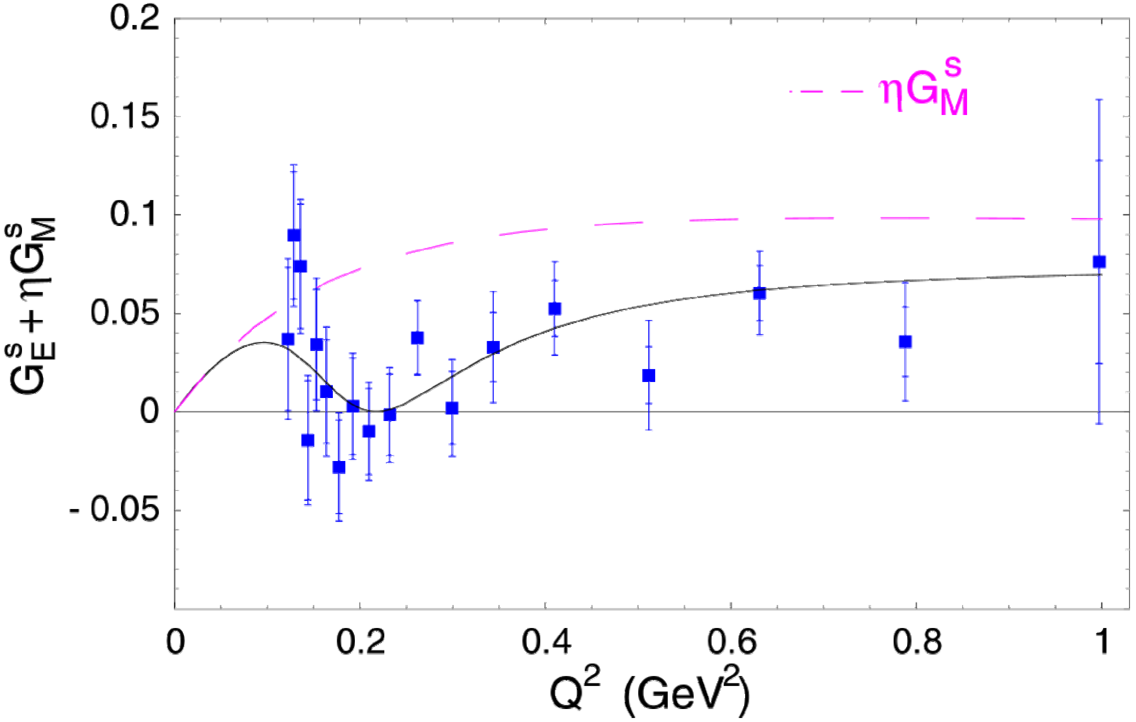
$c_2 = -0.51 \pm 0.25$

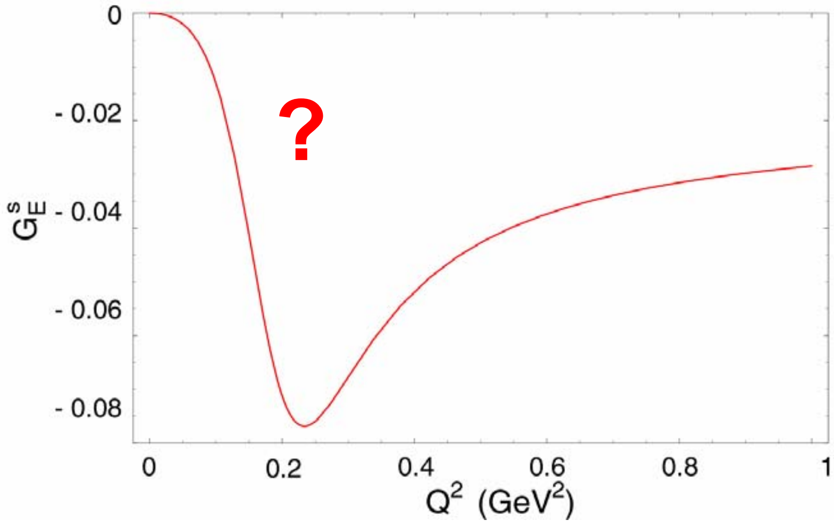
$d_1 = -8.5 \pm 0.9$

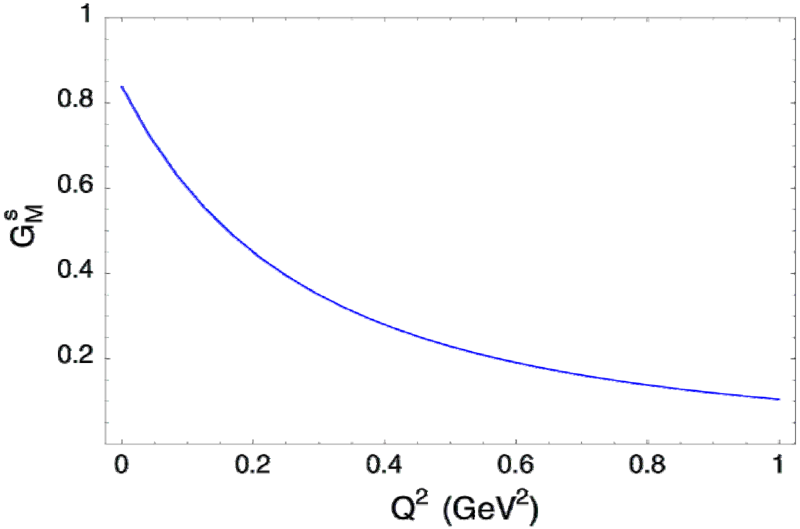
$d_2 = 24 \pm 6$

$d_3 = 1$

$\Lambda_M^{s\,2} = \Lambda^2 / 1.3$







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% !!

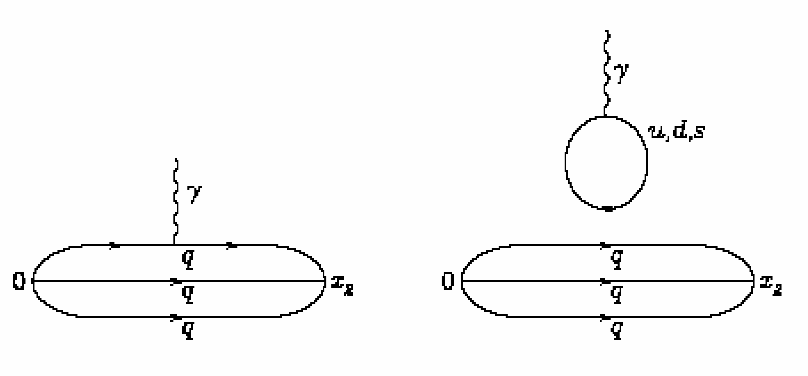
- Also remarkable versus lattice QCD which gives

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

- Sign would require violation of universality of

  valence quark moments by ~ 70% !

Magnetic Moments within QCD



CS

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

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

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

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

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

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

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

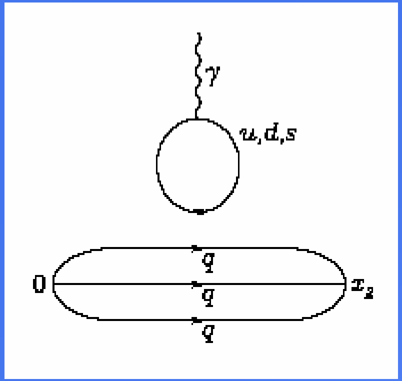
HENCE: $O_N = 1/3\ [\ 2p + n - (\ u^p / u^\Sigma\ )\ (\Sigma^+ - \Sigma^-)\ ]$

Just these ratios from Lattice QCD

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

Constraint from Charge Symmetry

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

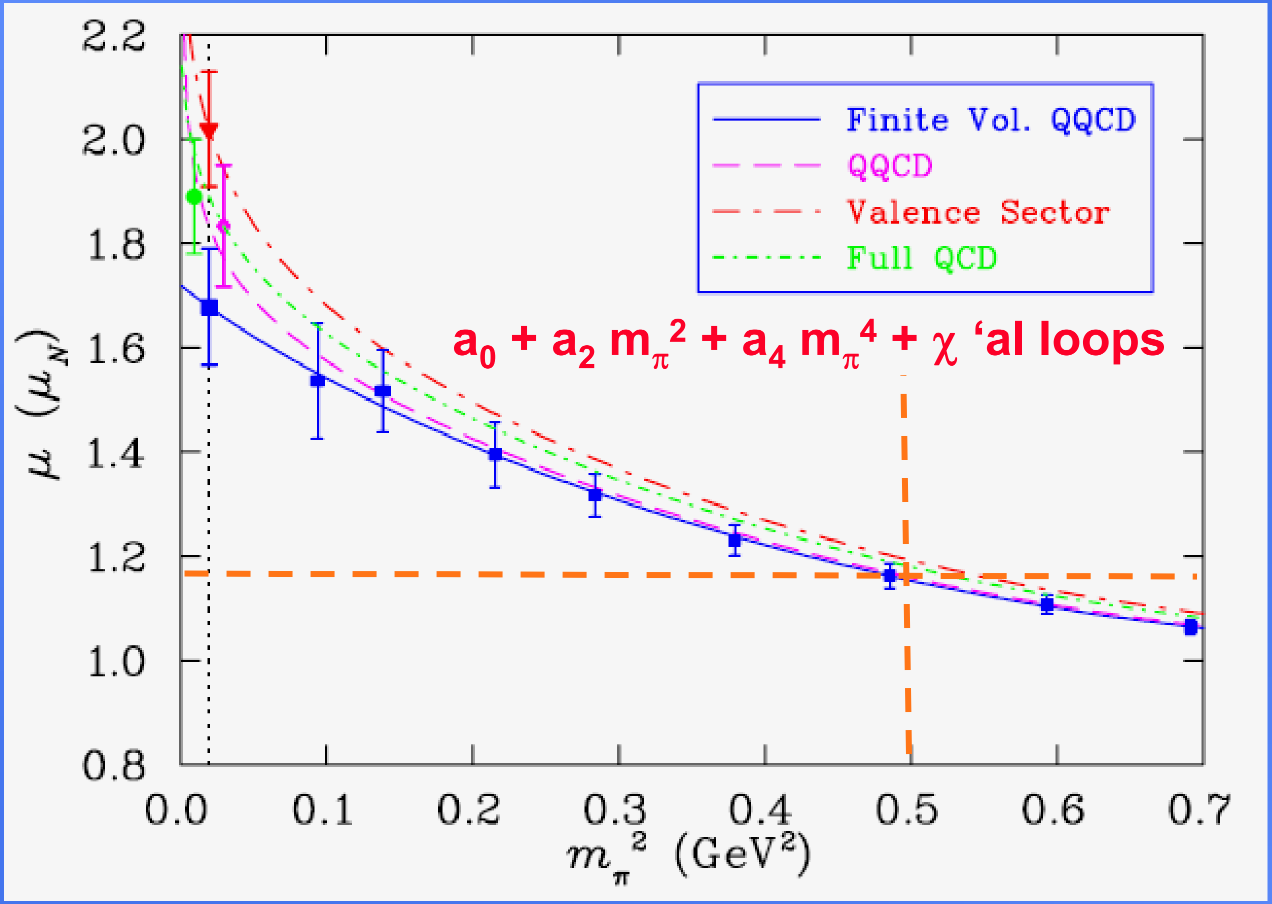


$$G_M^s = \left(\frac{{}^{\ell}R_d^s}{1 - {}^{\ell}R_d^s}\right)\left[3.673 - \frac{u_p}{u_{\Sigma^+}}(3.618)\right]$$

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

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

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

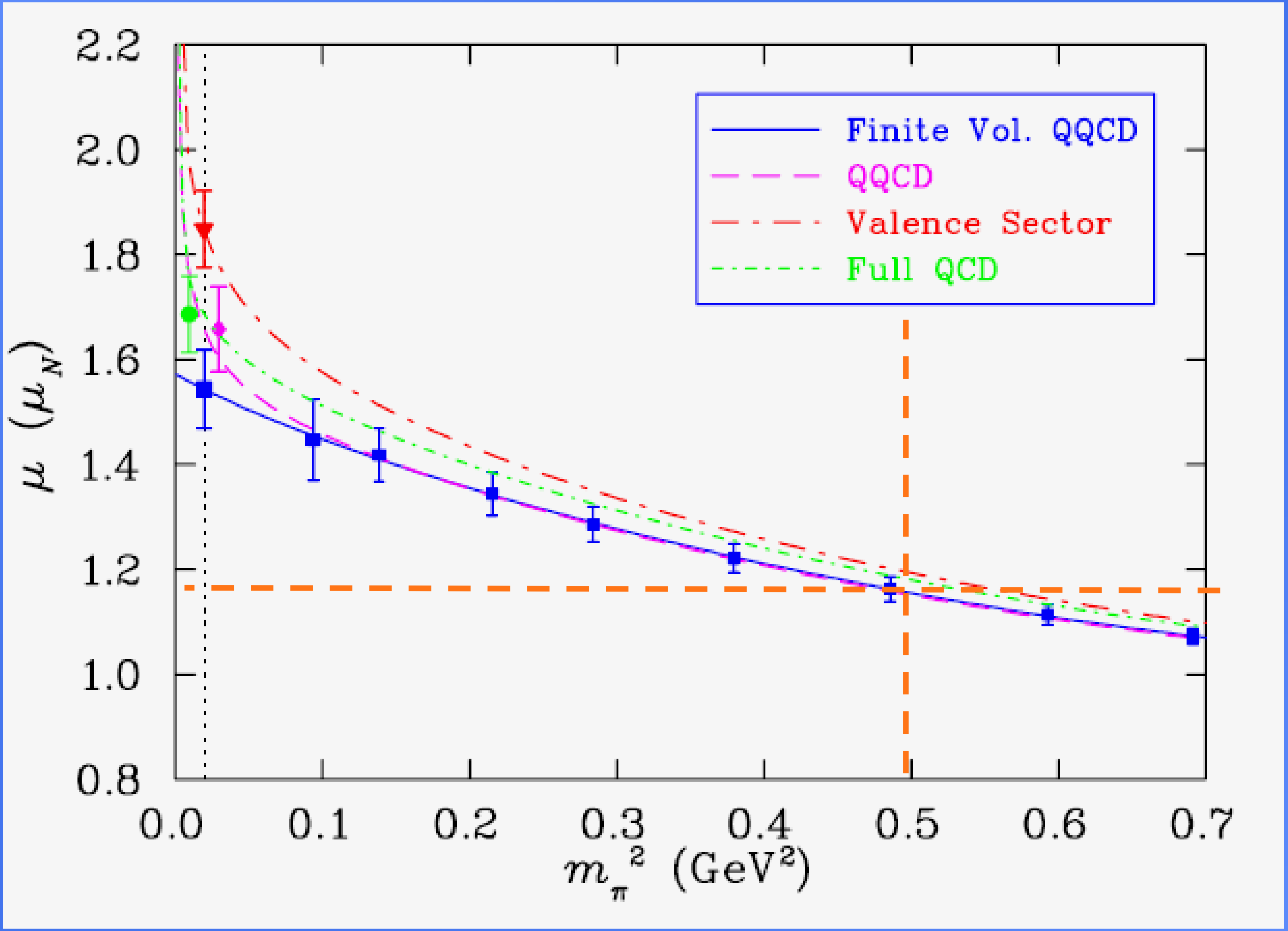


$a_0 + a_2\, m_\pi^{2} + a_4\, m_\pi^{4} + \chi$ 'al loops

c.f. CQM
2/3 940/540
$\sim$ 1.18

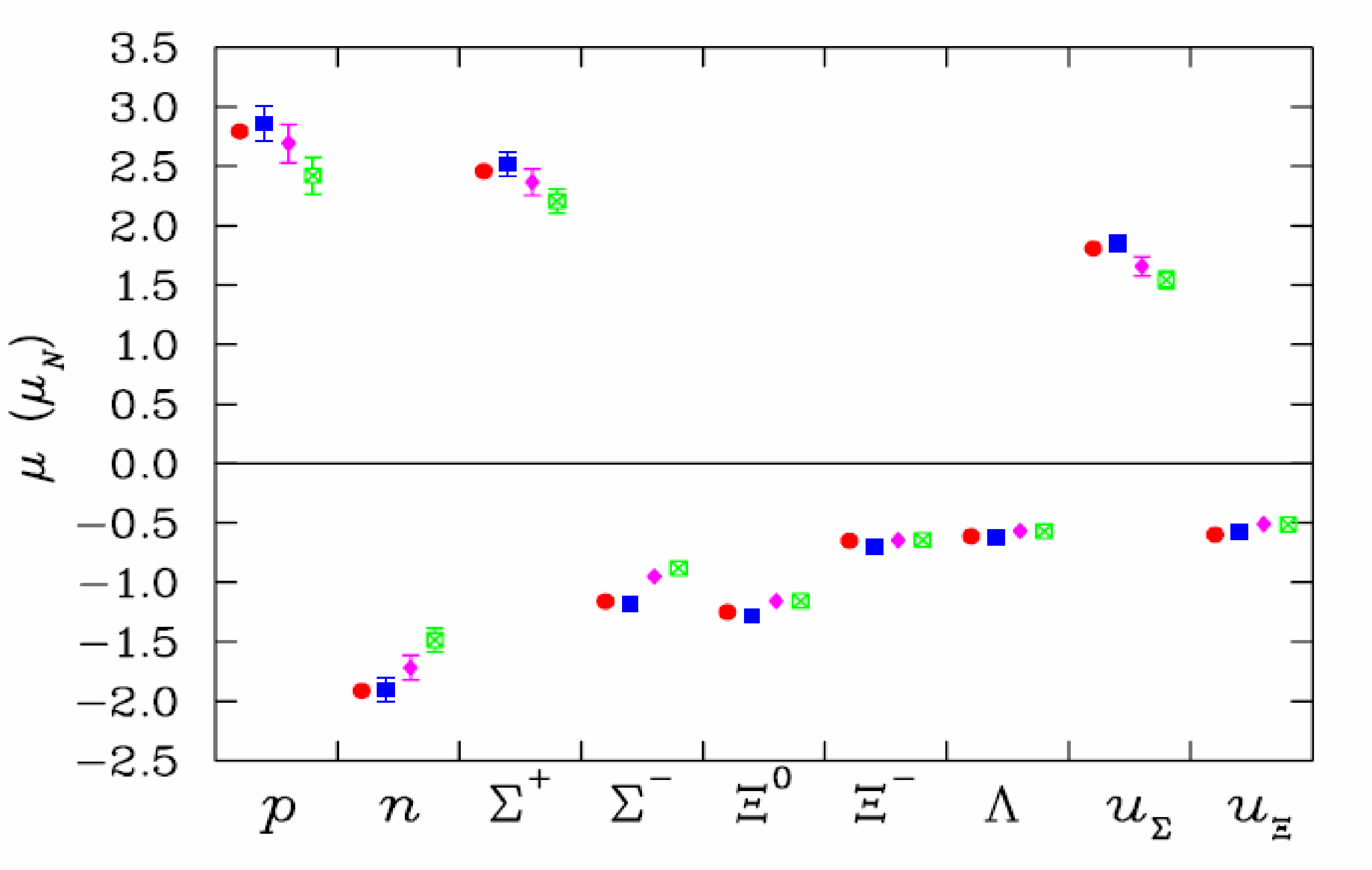
New lattice data from Zanotti et al. ; Chiral analysis Leinweber et al.

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



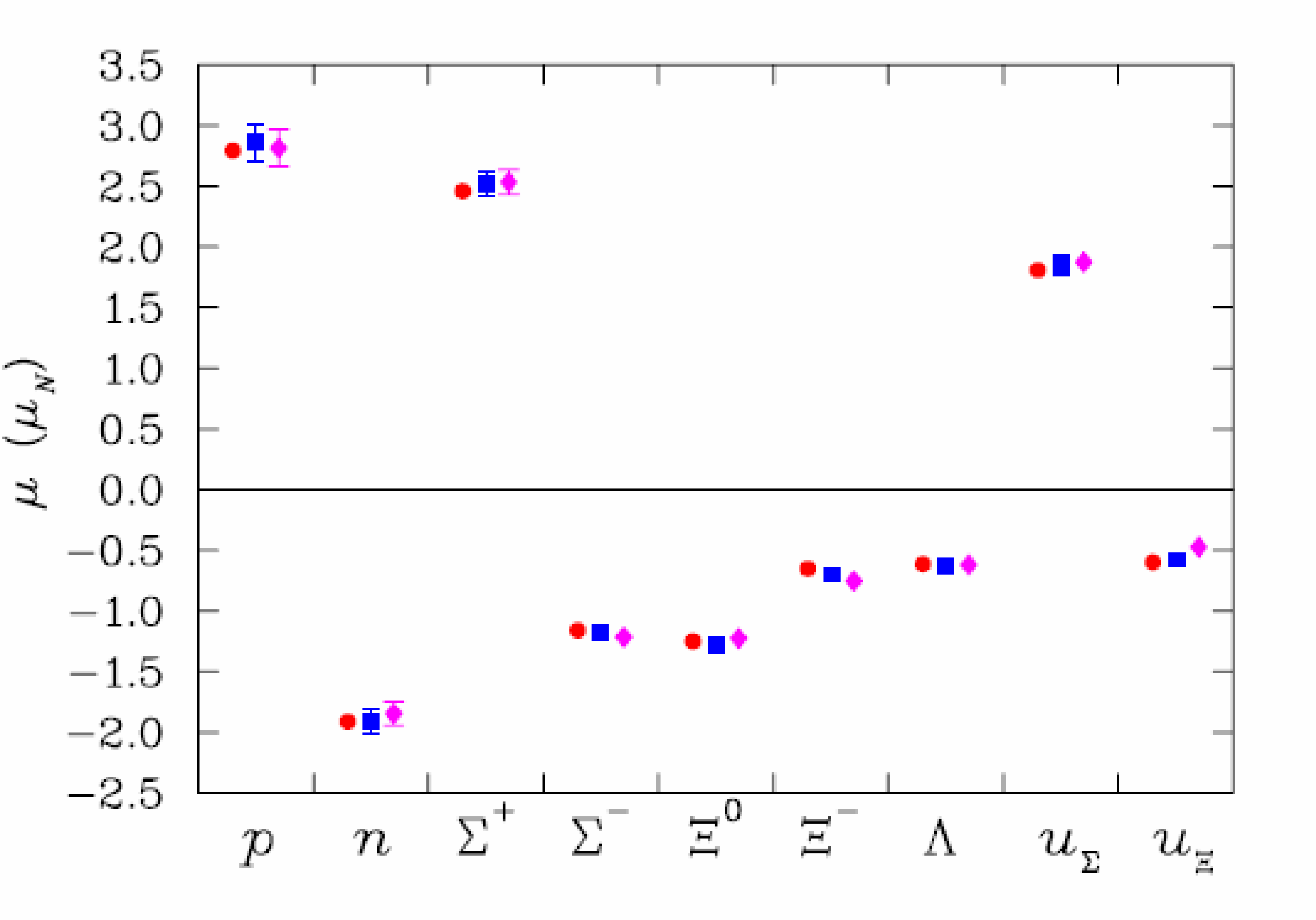
Universal Here!

Check: Octet Magnetic Moments



Leinweber et al., hep-lat/0406002

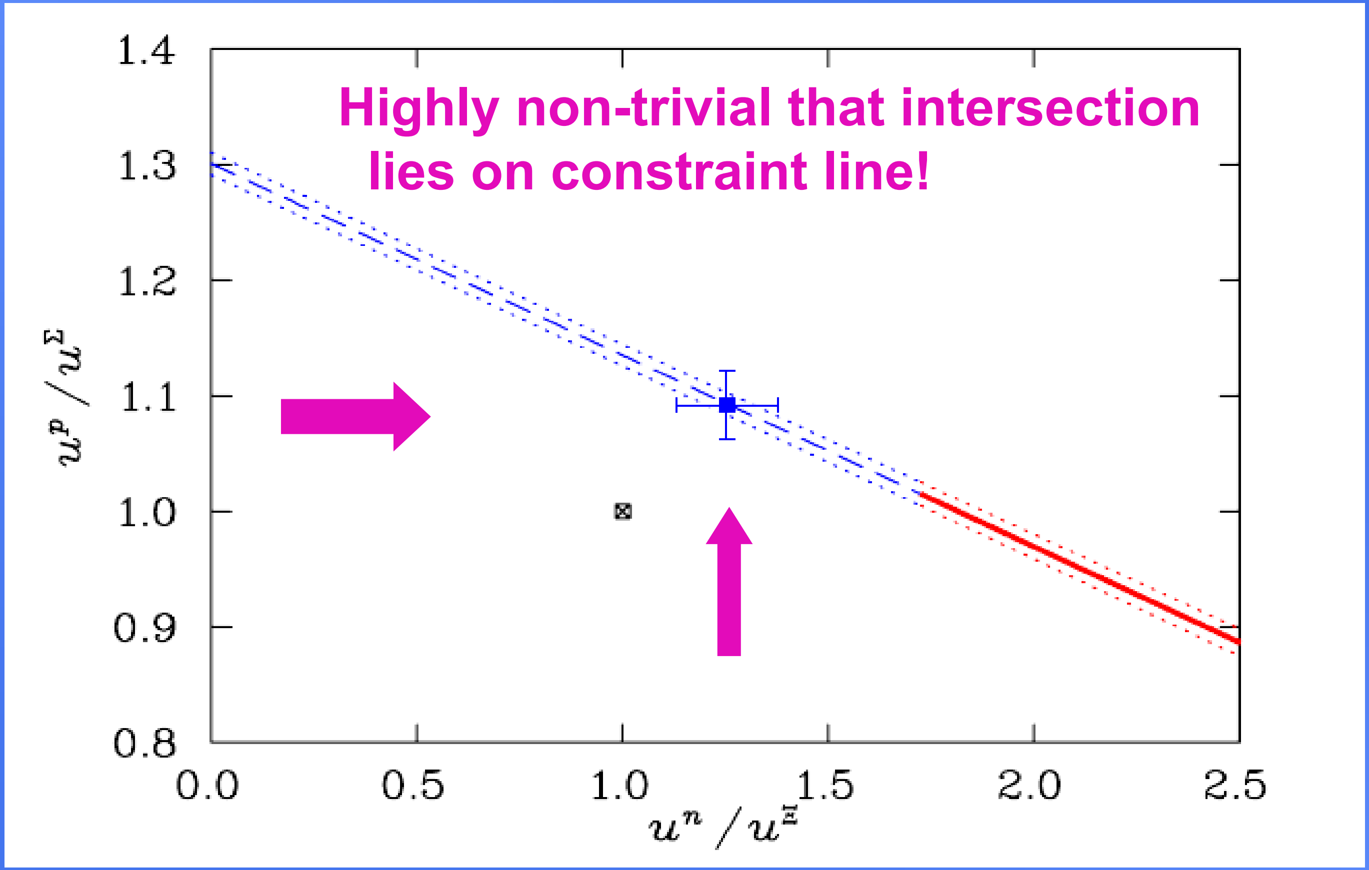
Convergence LNA to NLNA Again Excellent (Effect of Decuplet)



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

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

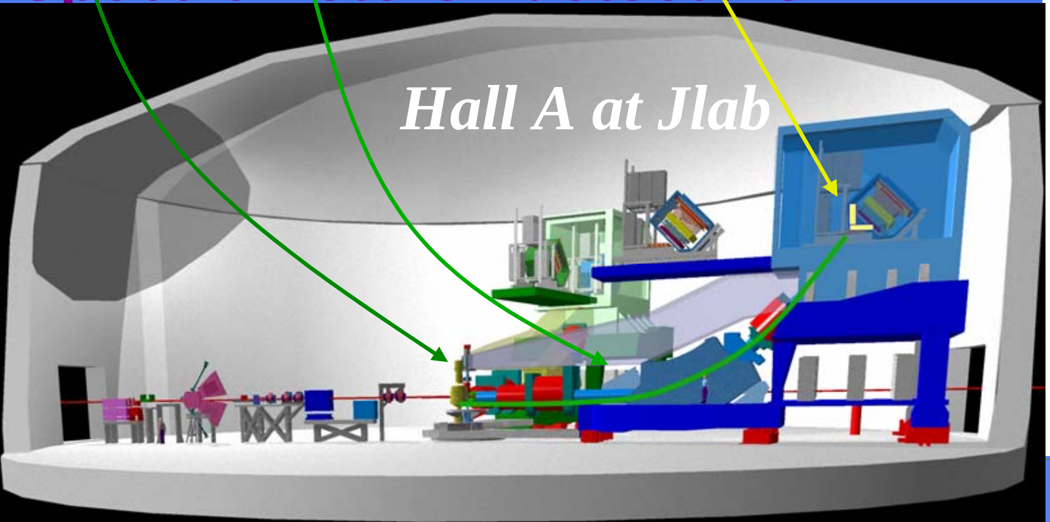
3 GeV beam in Hall A $\theta_{lab} \sim 6°$ $Q^2 \sim 0.1\ (\mathrm{GeV}/c)^2$

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

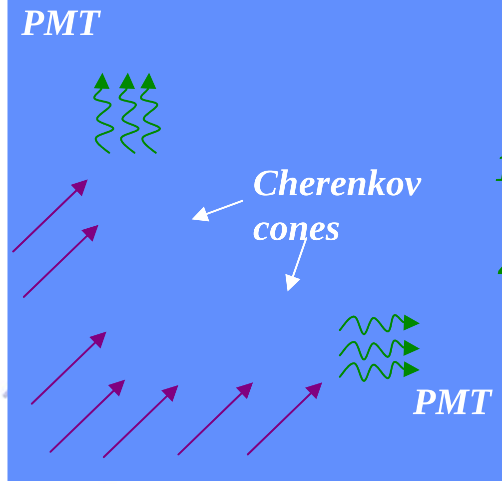
Septum magnets (not shown)

High Resolution Spectrometers

detectors



Brass-Quartz integrating detector



Elastic Rate:

^{1}H: 120 MHz

^{4}He: 12 MHz

Background ≤ 3%

"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 $\sim \pi$ N)
  (K- Σ much smaller $\Rightarrow$ ignore)

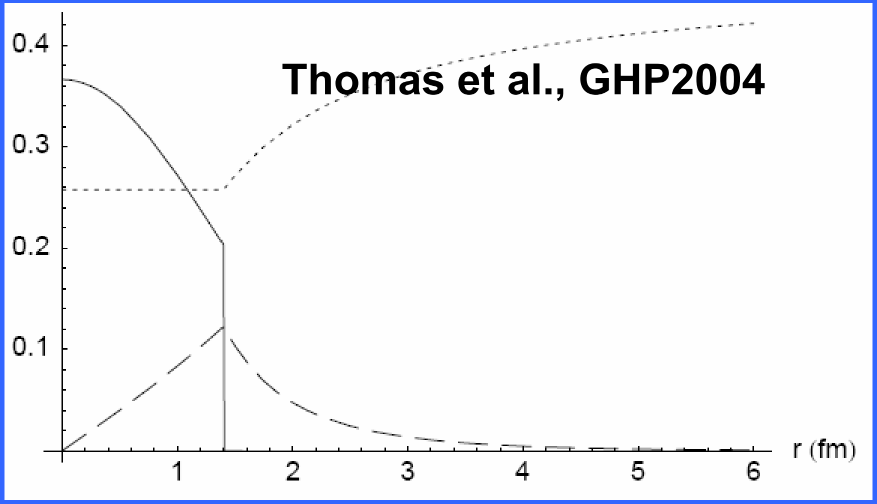
- Lots of evidence that $P_{\pi N} \sim 20\% \Rightarrow P_{K\Lambda} \sim 5\%$

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

$$\approx -0.067\ \mu_N$$

Remarkably close to lattice estimate!

Strangeness Radius



Thomas et al., GHP2004

- Meson cloud surface peaked

- Core has mean-square radius $\sim (0.7\ R)^2$

- Meson cloud $\sim (R + 0.2)^2$

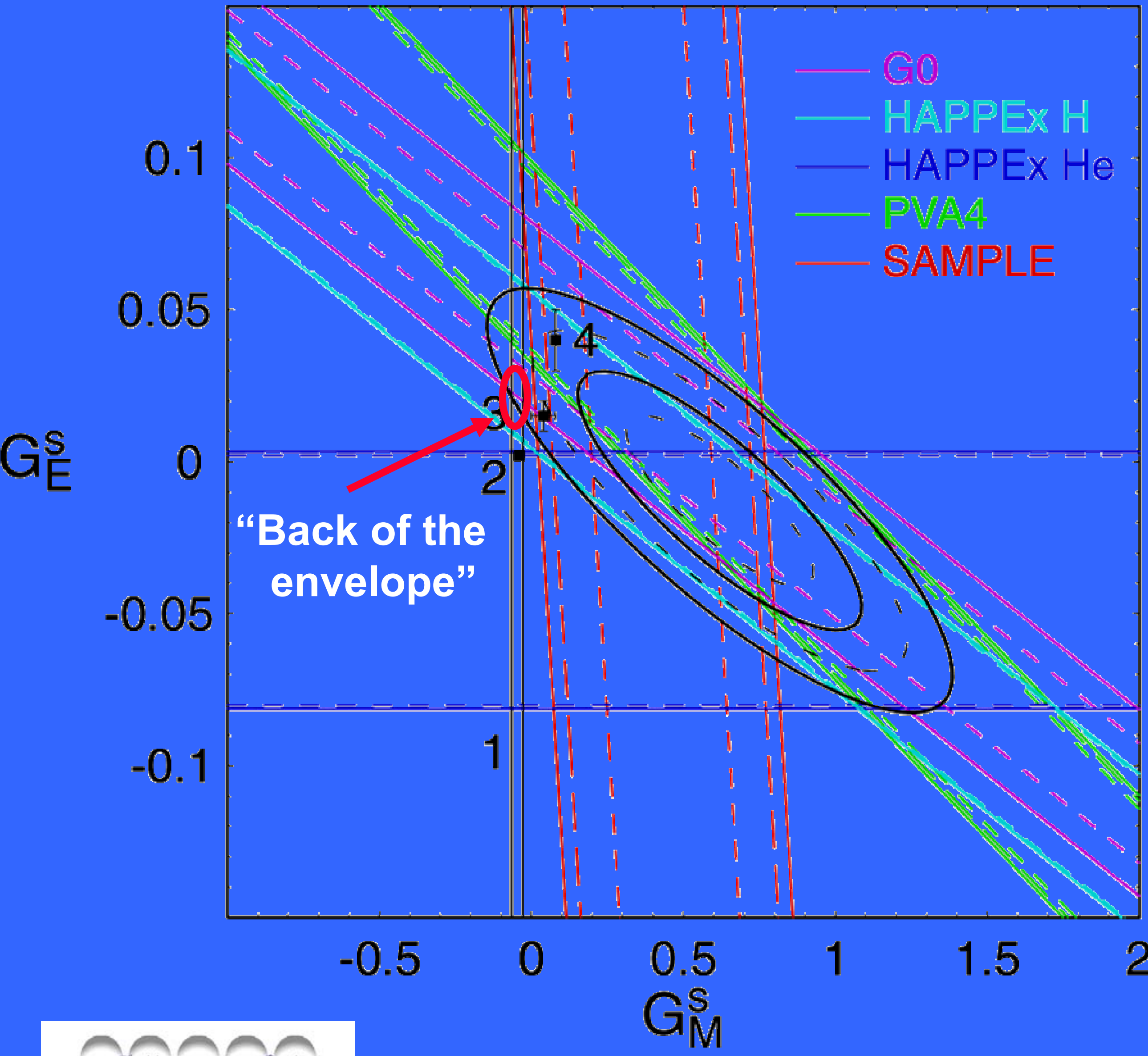
- Hence: $-3 \langle r^2 \rangle_s \sim$

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

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

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

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



"Back of the envelope"

$G_E^s = -0.013 \pm 0.028$

$G_M^s = +0.62 \pm 0.31$

$\pm 0.62\ 2\sigma$

Contours

----- 1σ, 2σ

—— 68.3, 95.5% CL

Theories

1. Leinweber, et al.
   PRL **94** (05) 212001
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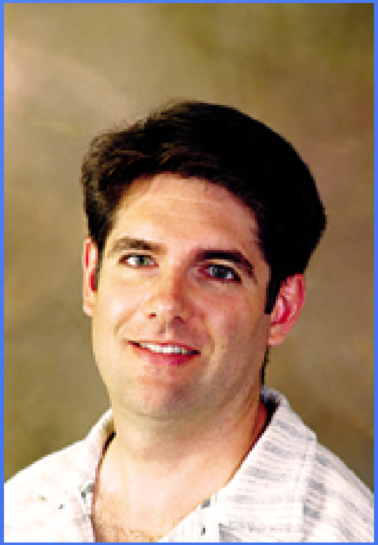
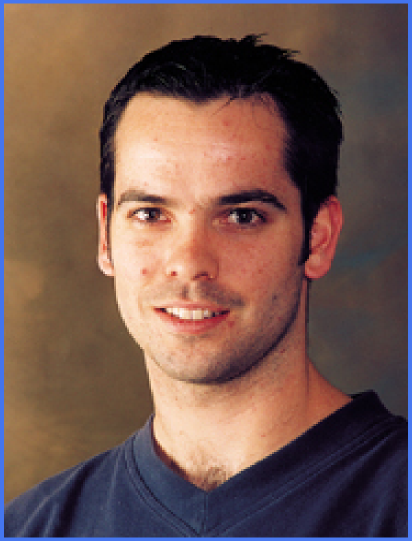
   PRD **67** (03) 013003
4. Silva, et al.
   PRD **65** (01) 014016

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

Special Mentions……



Derek Leinweber

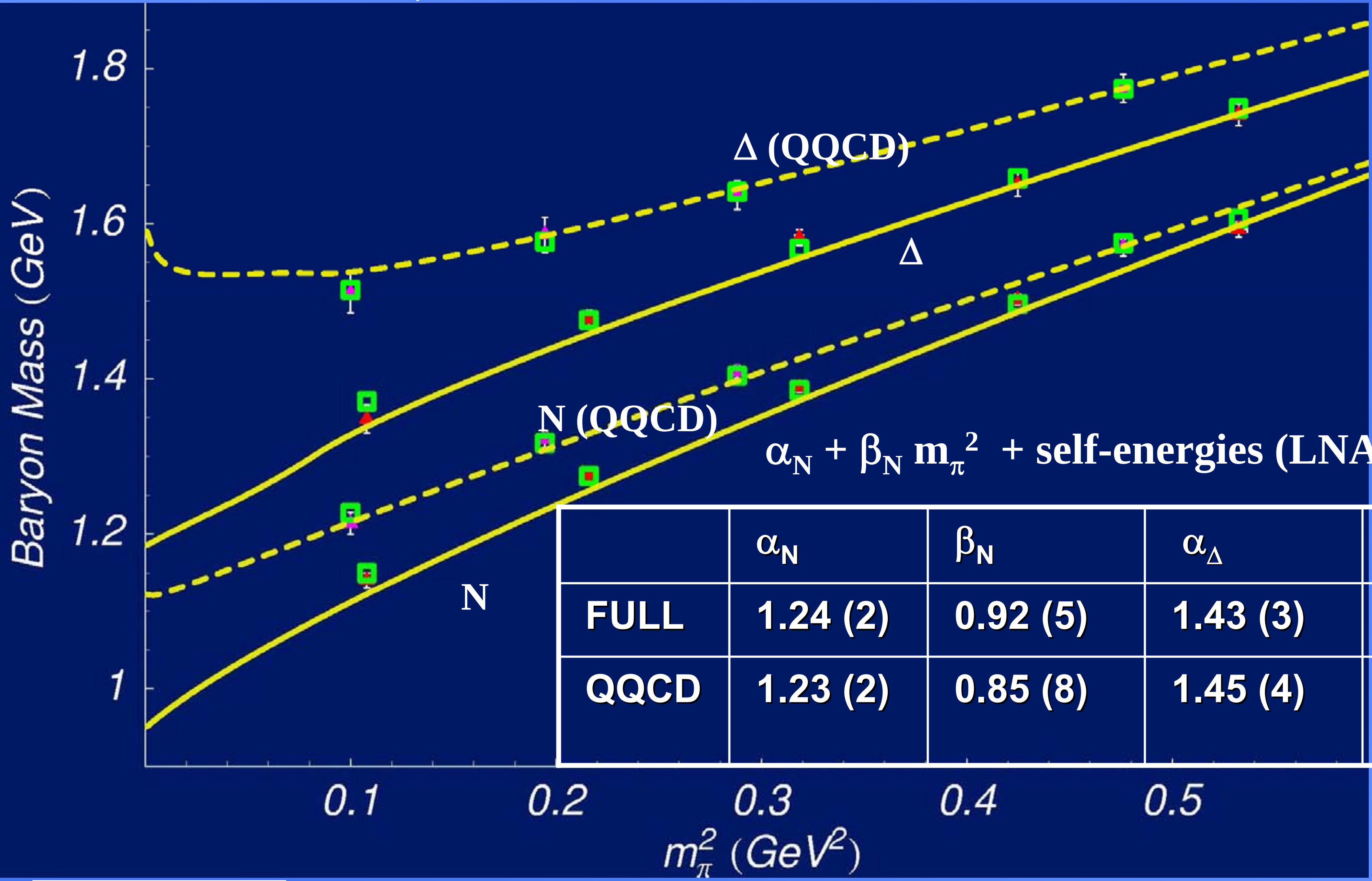


Ross Young

Stewart Wright

"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 same finite grid as lattice
- Lines are exact, continuum results

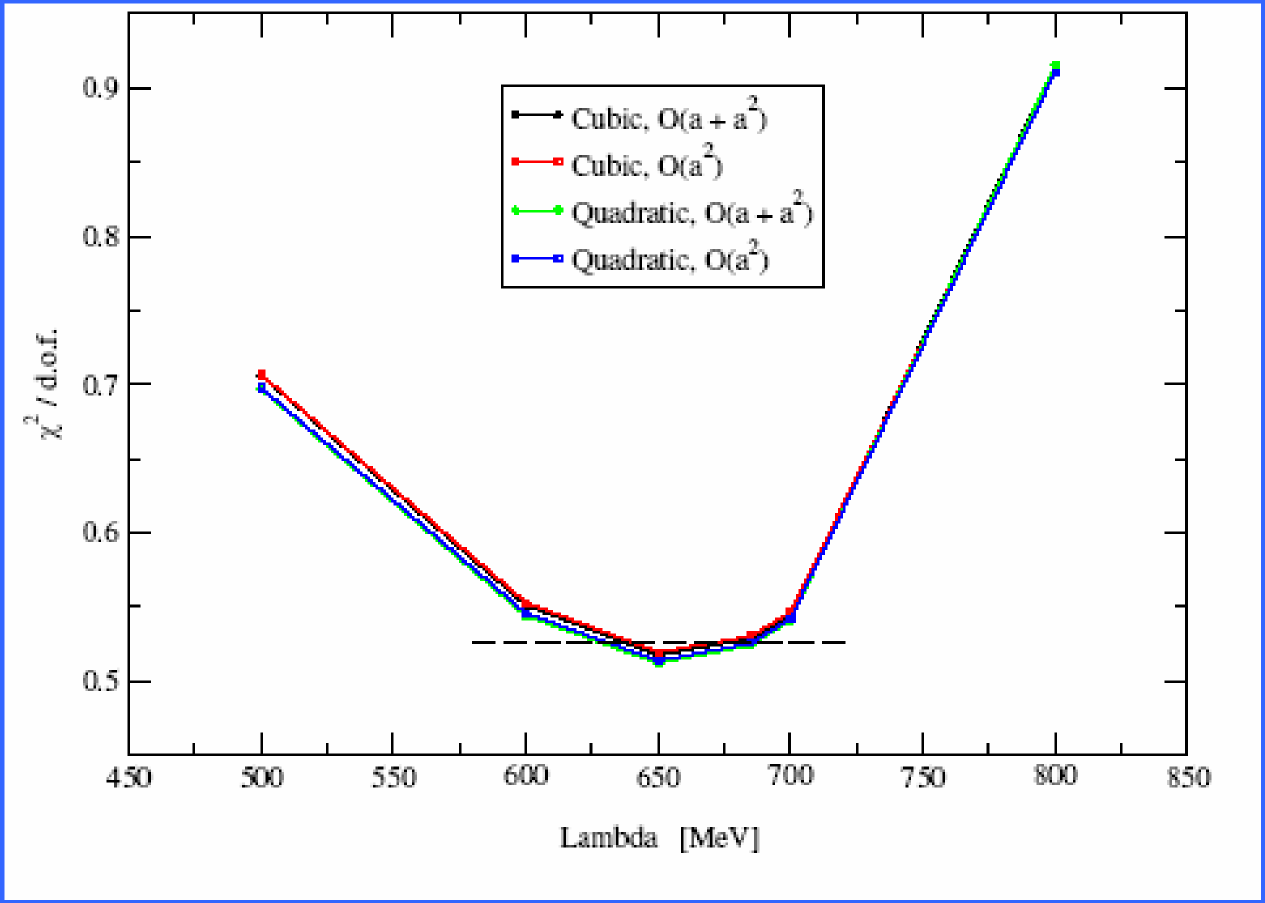


$\alpha_N + \beta_N m_\pi^2$ + self-energies (LNA+NLNA)

	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

FRR Mass well determined by data



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