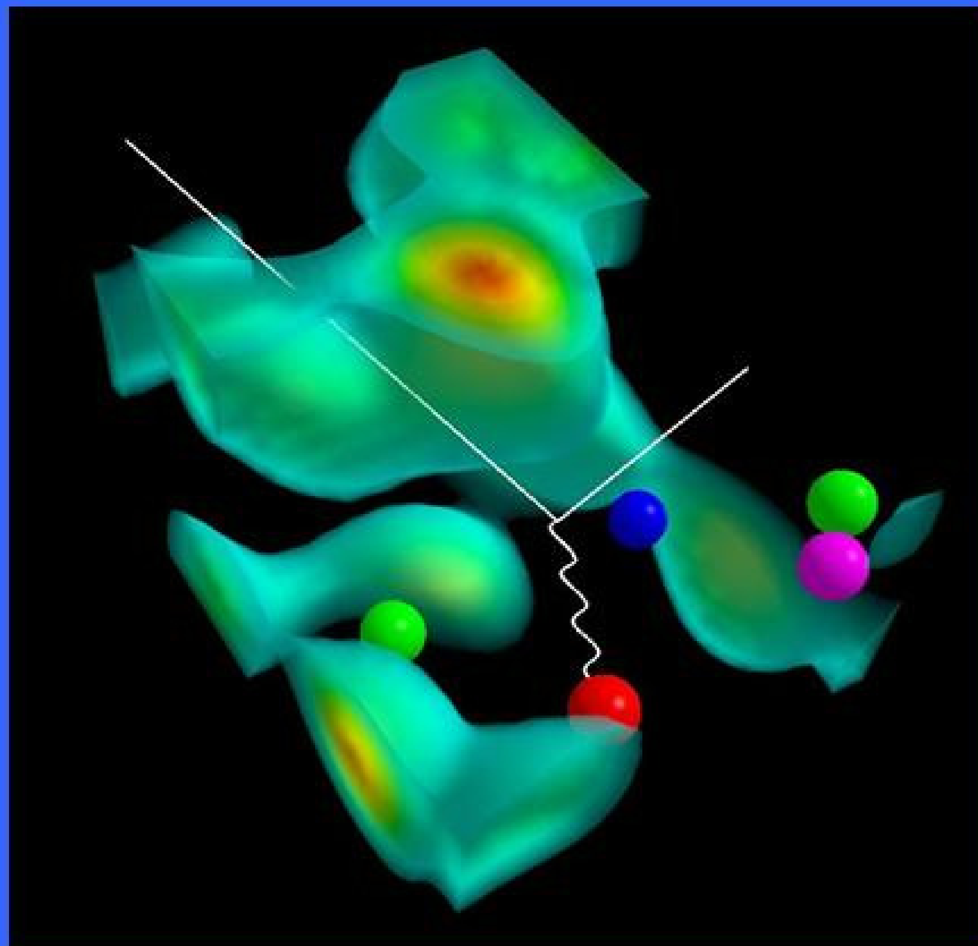
Strangeness Content of the Nucleon



Anthony W. Thomas

Workshop on Precision ElectroWeak Interactions

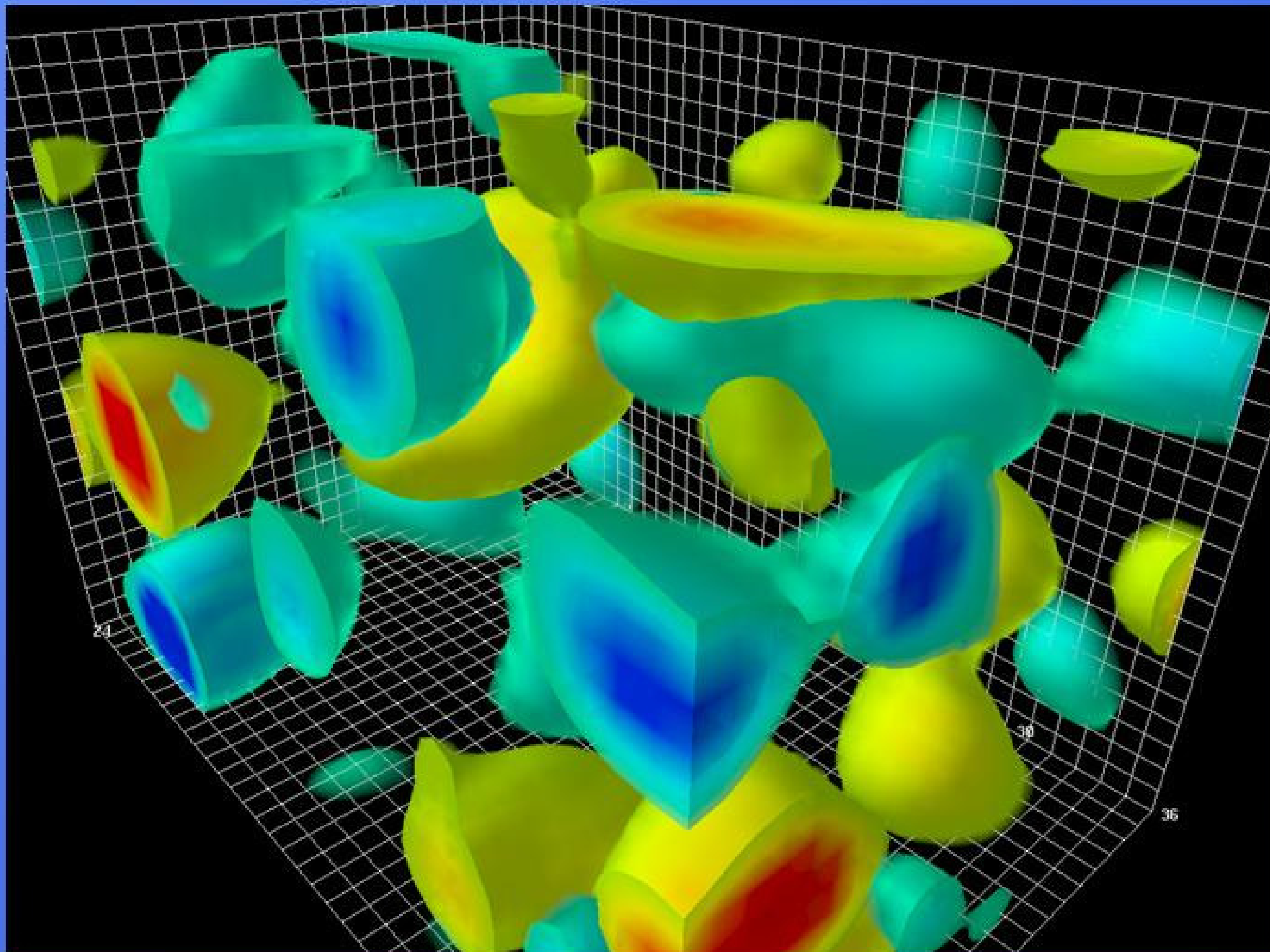
College of W&M : August 16th, 2005

Jefferson Lab
Thomas Jefferson National Accelerator Facility
Operated by the Southeastern Universities Research Association for the U.S. Department of Energy
Office of Science
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
- What needs measuring?

Topology of QCD Vacuum



Leinweber: see CSSM web pages

Powerful Qualitative New Insights From Lattice QCD

QCD sum rules :

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

- 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

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

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)

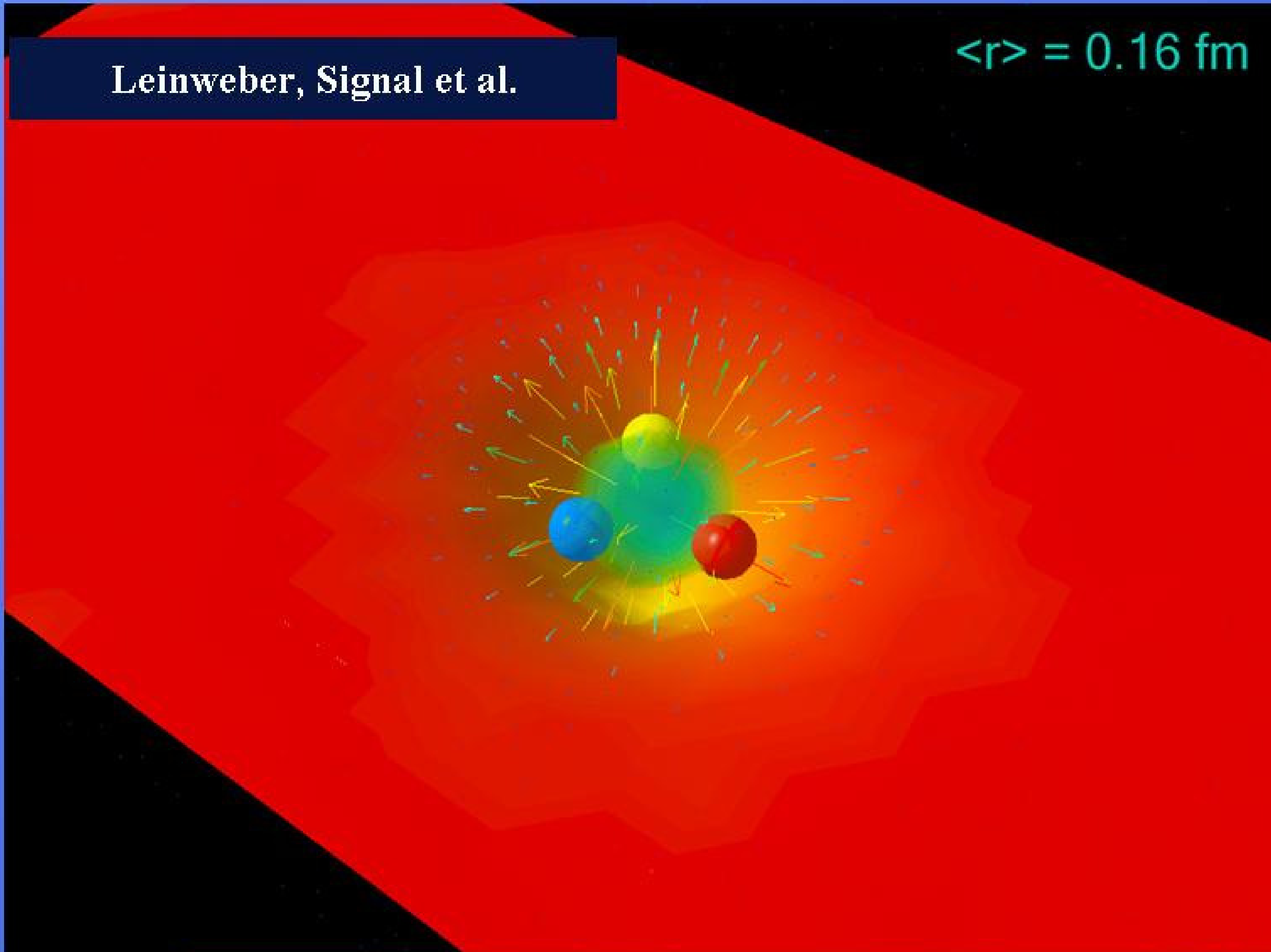
and last term is as big as 20 MeV (or more)
i.e. presence of nucleon "cleans out" vacuum to some extent

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



QCD and the Origin of Mass

	u	+	u	+	d	=	proton
mass:	0.003	+	0.003	+	0.006	$\neq$	0.938

HOW does the rest of the proton mass arise?

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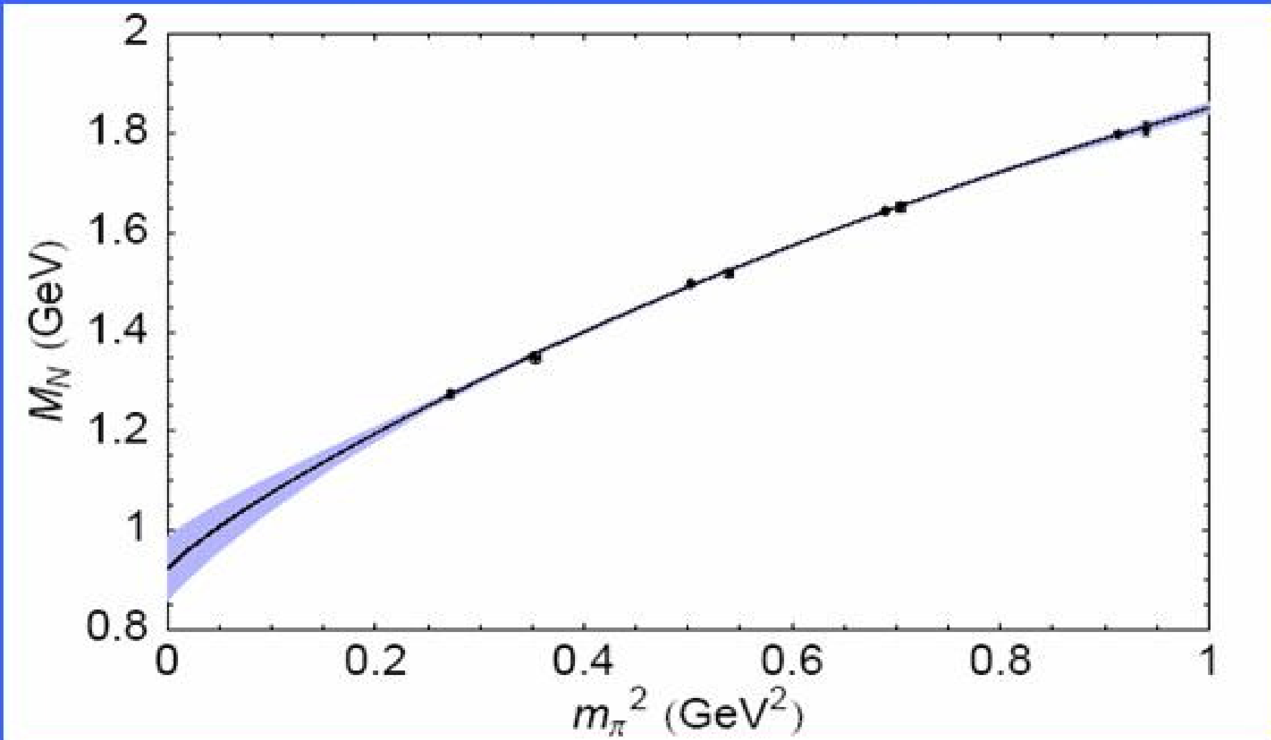
χ'al Extrapolation Under Control when Coefficients Known – e.g. for the nucleon



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)

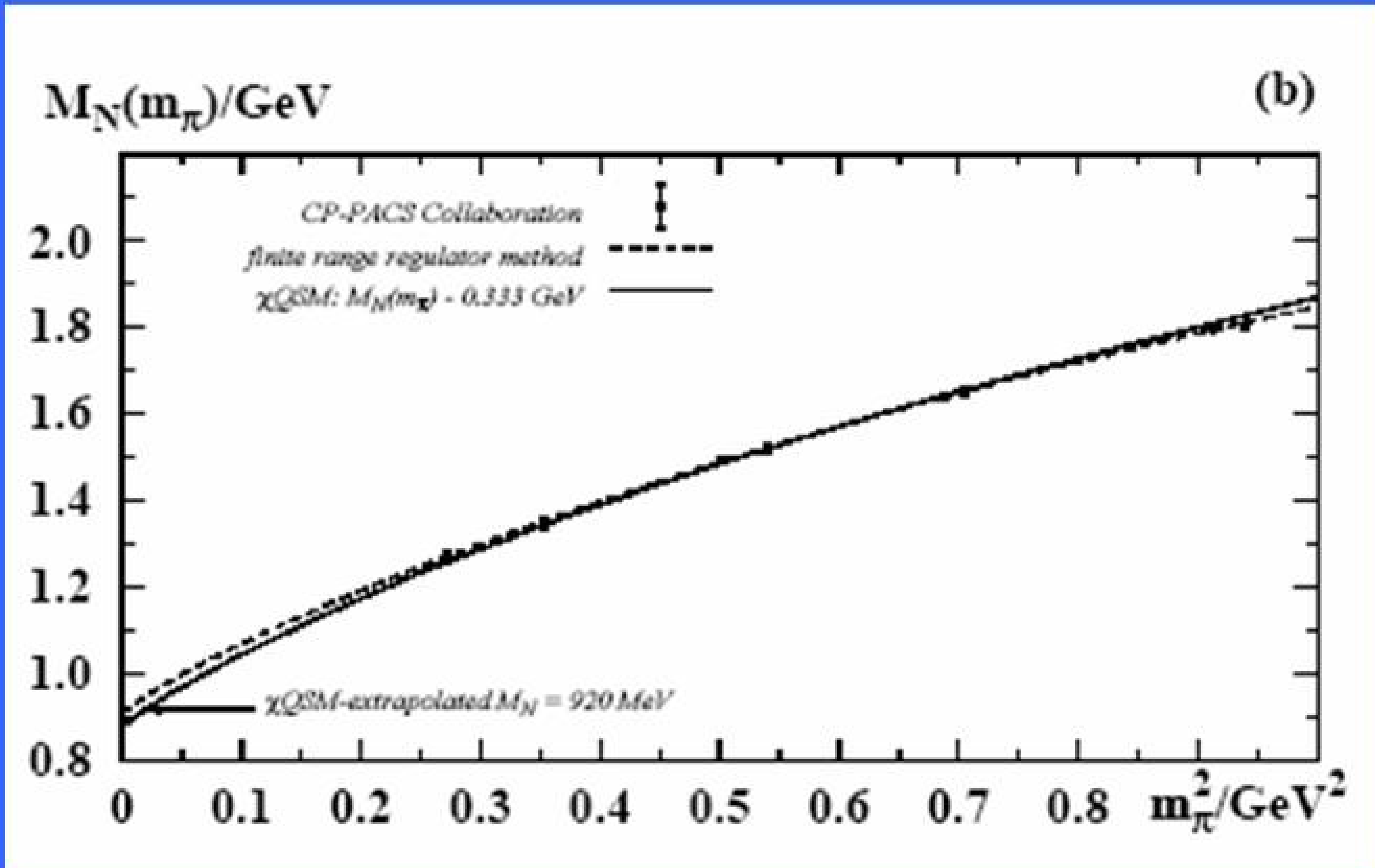
Leinweber et al., PRL 92 (2004) 242002

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

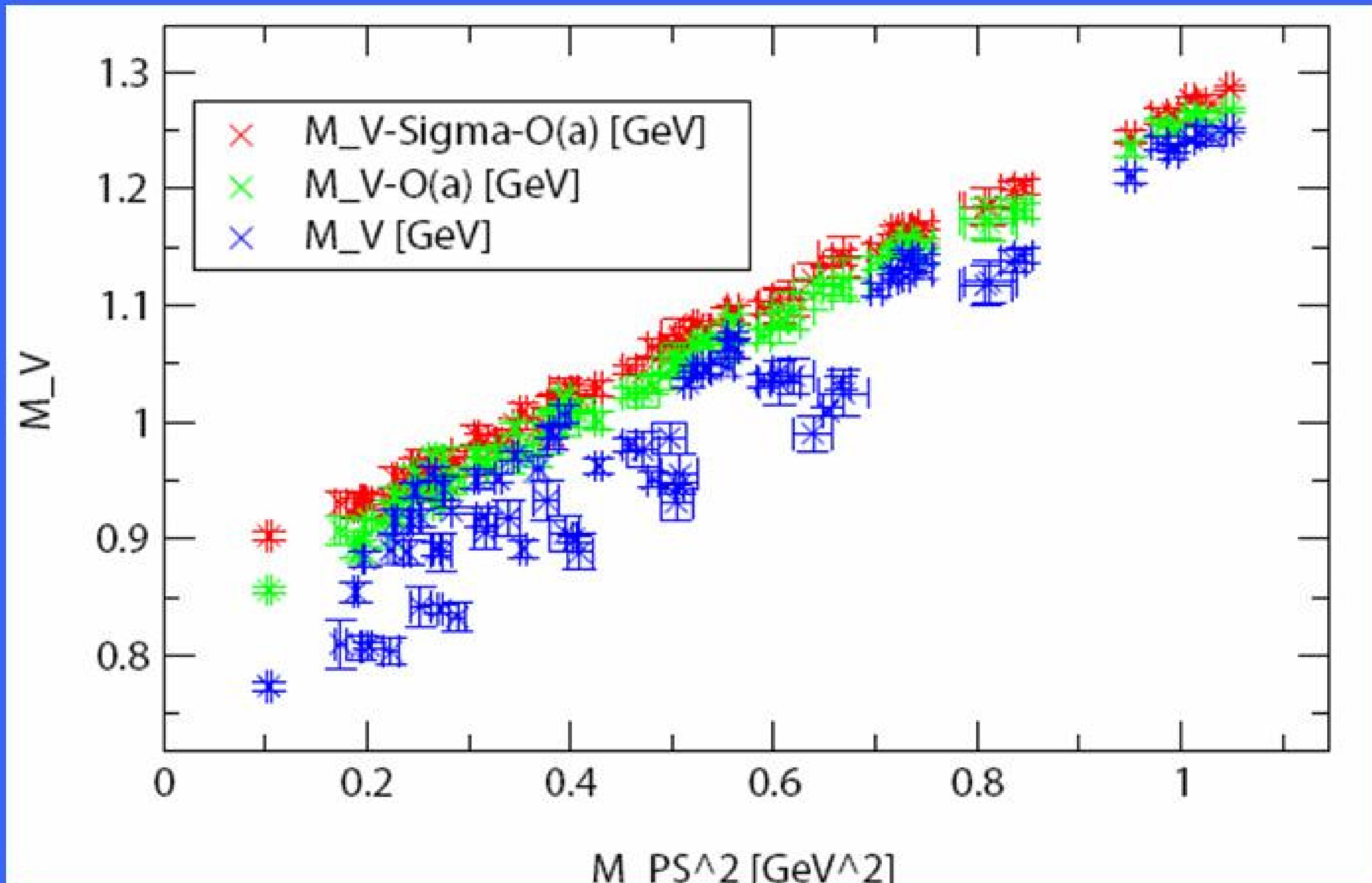
M_N in MeV

Comparison with χ QSM



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

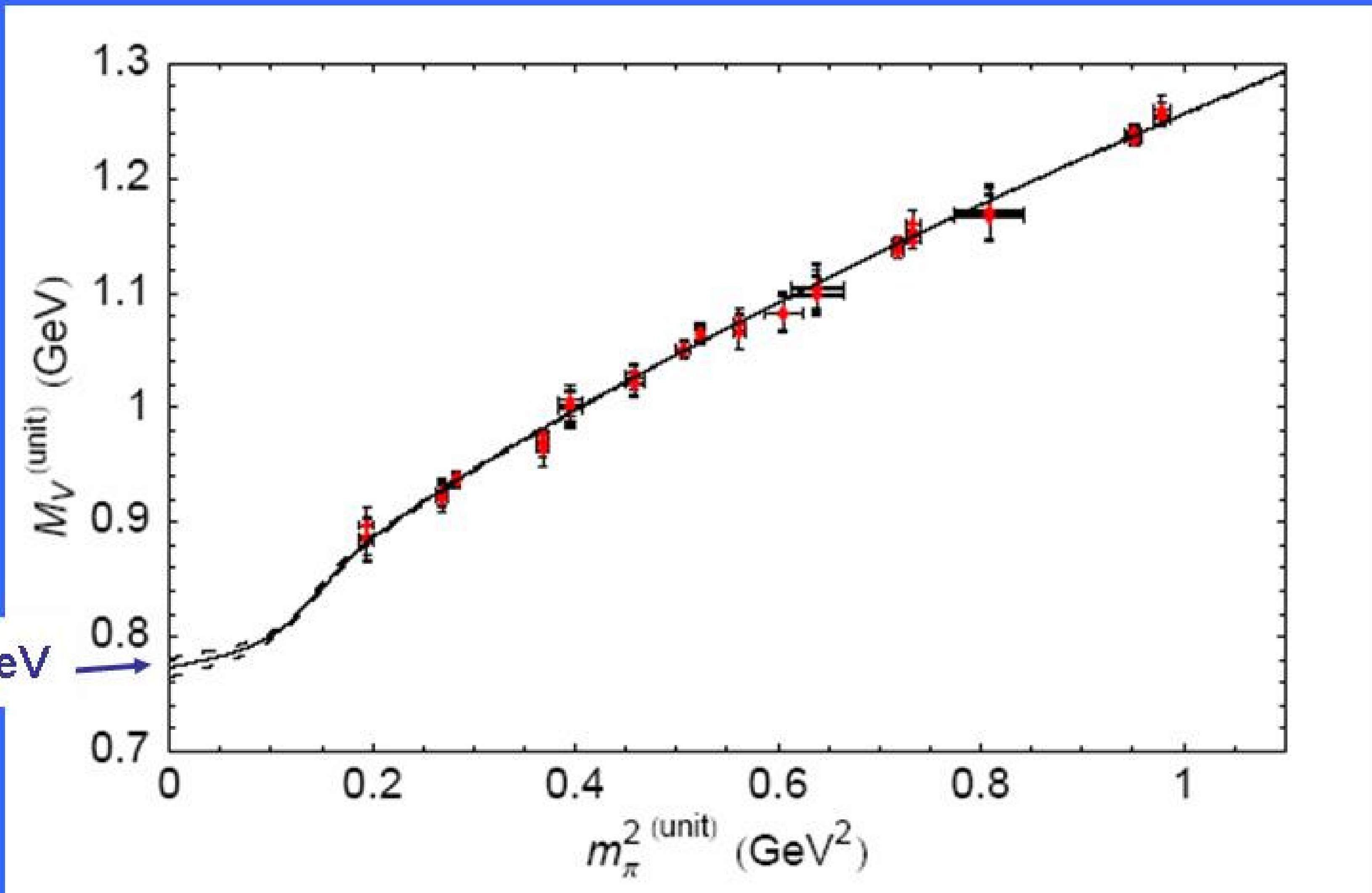
Analysis of pQQCD ρ data from CP PACS



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

Infinite Volume Unitary Results

All 80 data points drop onto single, well defined curve



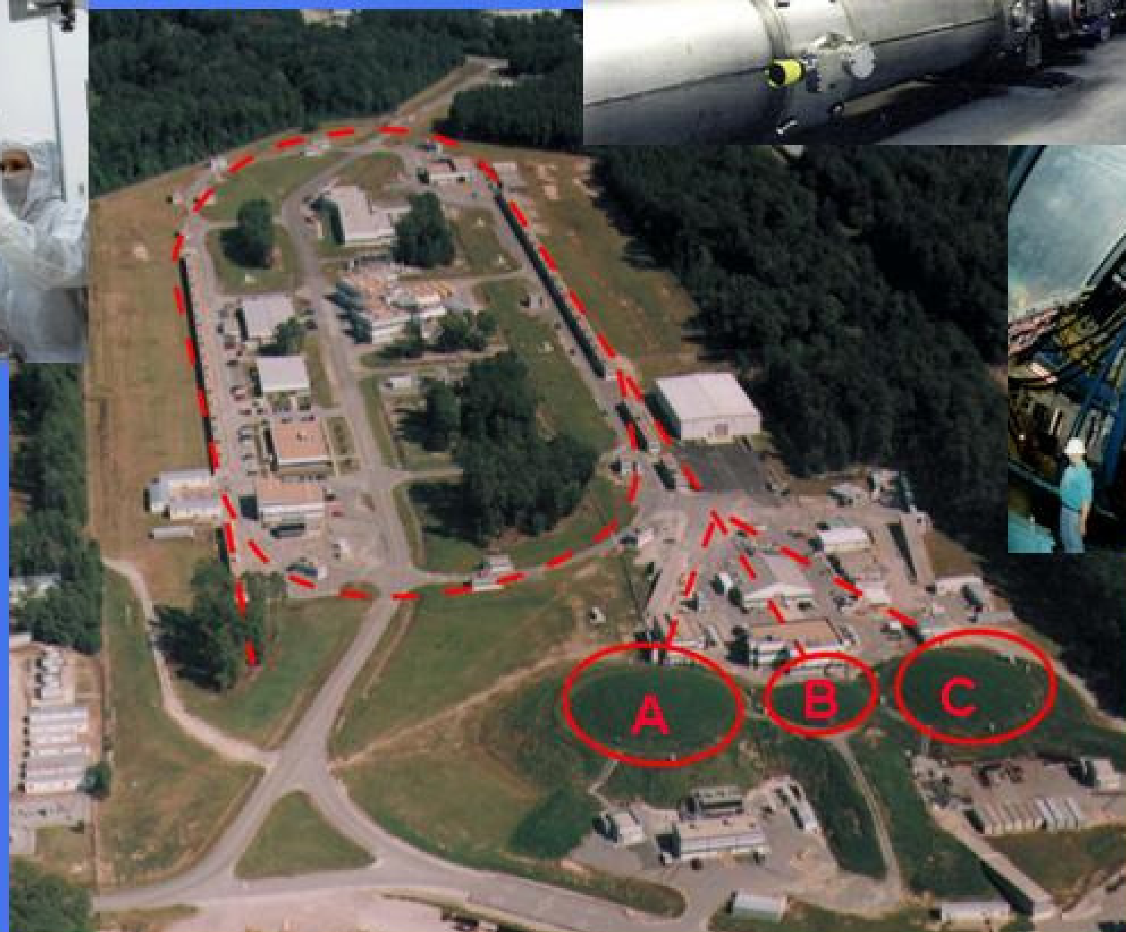
777 § 7 MeV

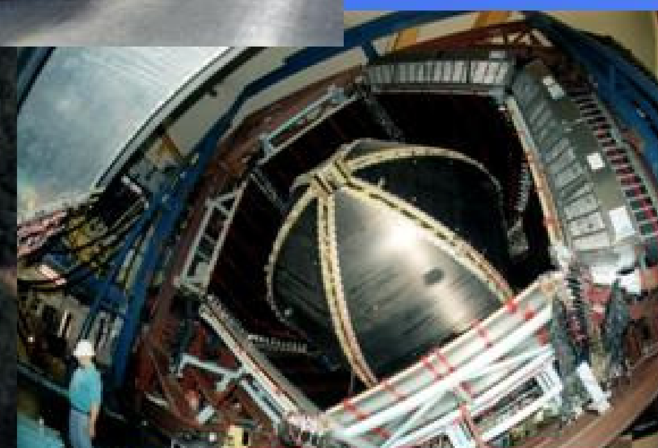
Allton, Young *et al.*, hep-lat/0504022

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



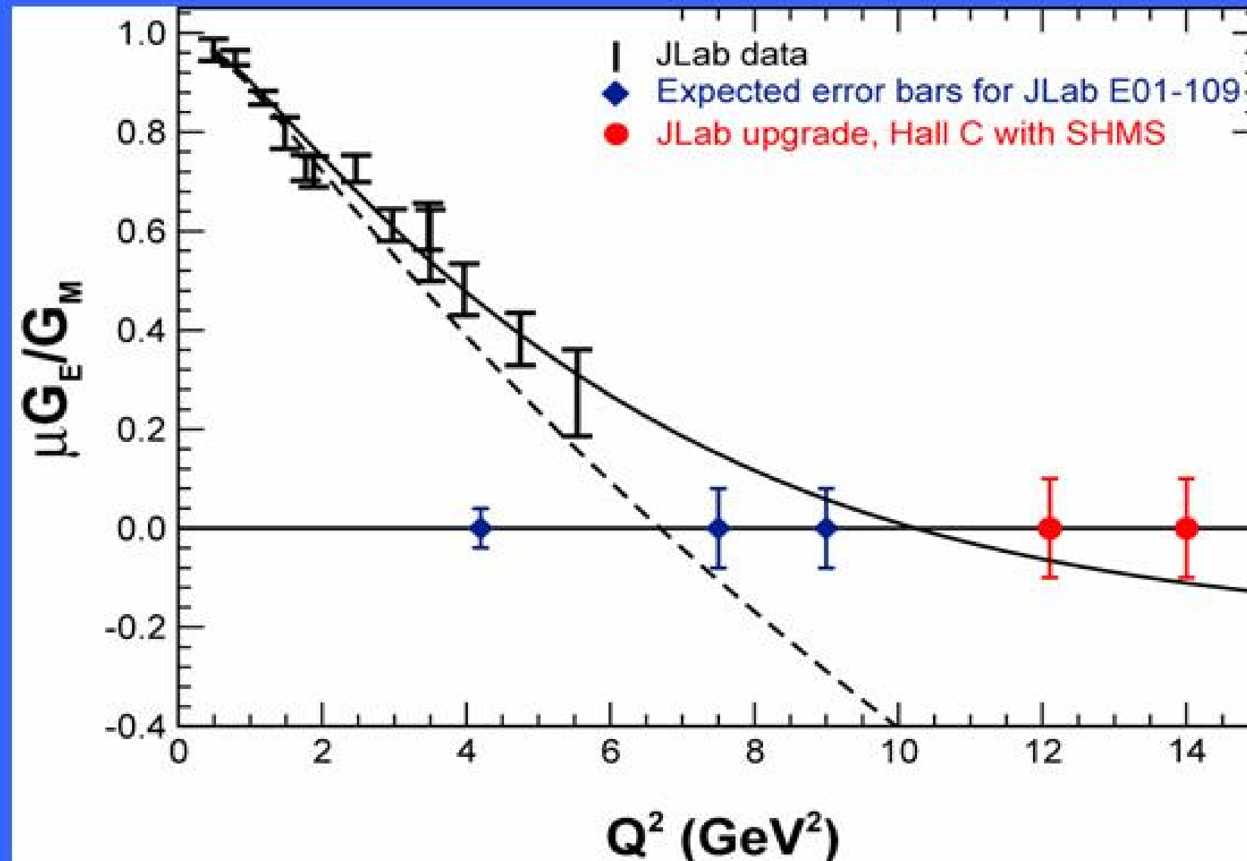


High luminosity, high resolution detectors in Halls A, B, and C.

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

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

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

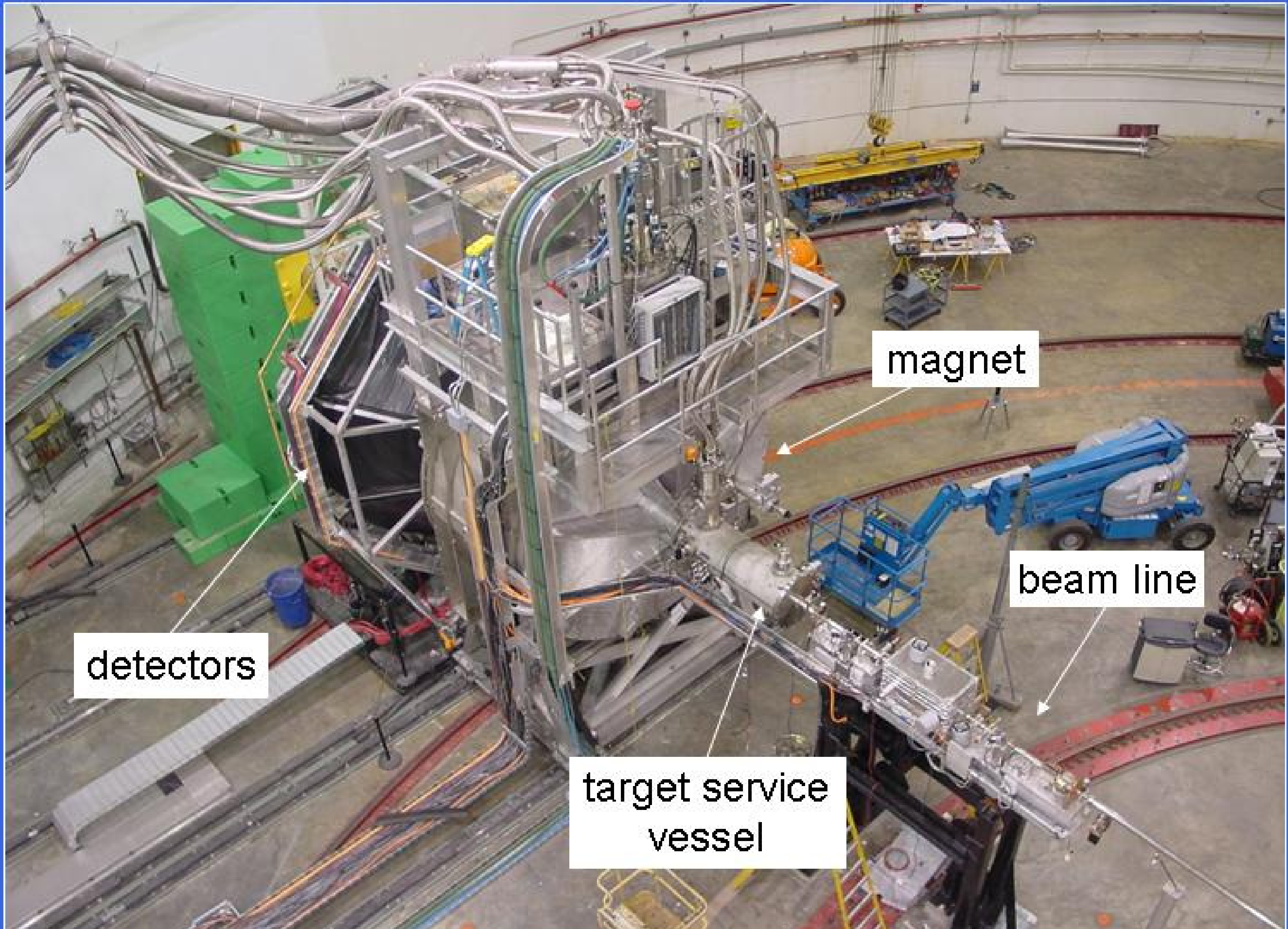
45 § 8 MeV (or 70?)

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

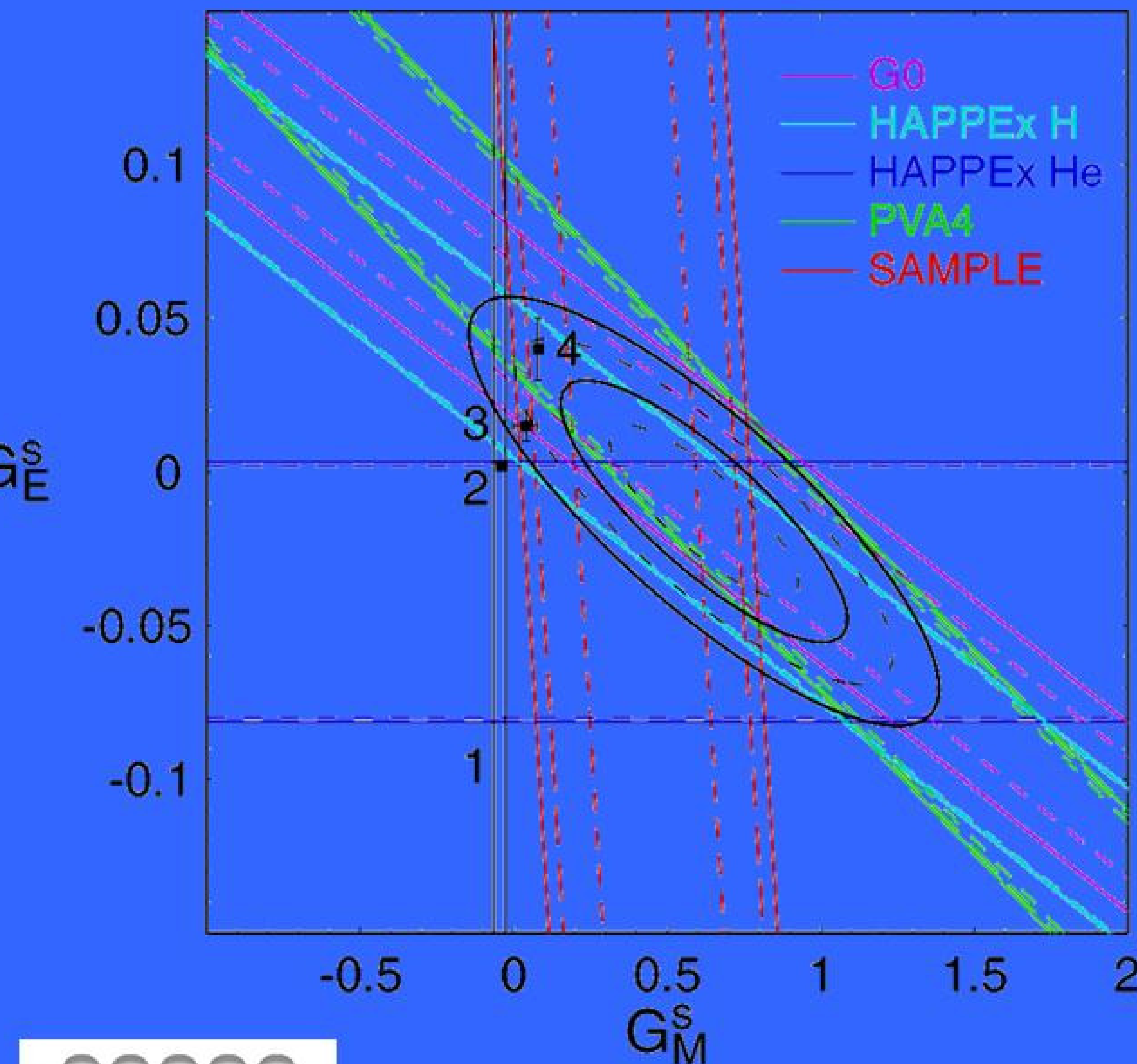
- HOW MUCH OF THE MAGNETIC FORM FACTOR?

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

Operated by the Southeastern Universities Research Association for the U.S. Department of Energy
http://www.npl.uiuc.edu/exp/G0/Forward

Simple Fits to World Hydrogen Data

- Fit

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

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

with simple forms for G_E^s , G_M^s

$$G_E^s(Q^2)=\frac{c_2Q^4}{1+d_1Q^2+d_2Q^4+d_3Q^6}$$

à la Kelly

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

with

$$G_M^s(Q^2=0)=0.81$$

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

"Fit" to World Hydrogen Data

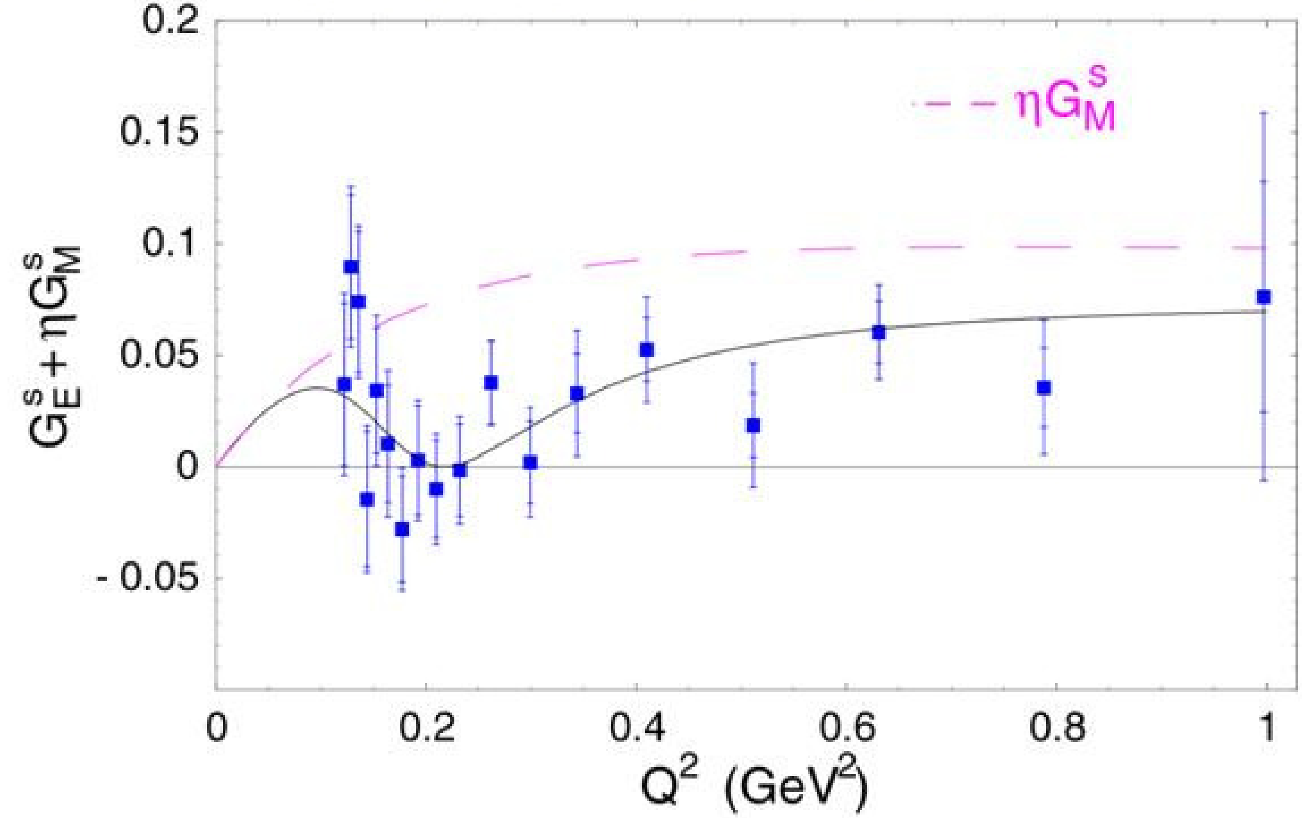
$c_2 = -0.51 \pm 0.25$

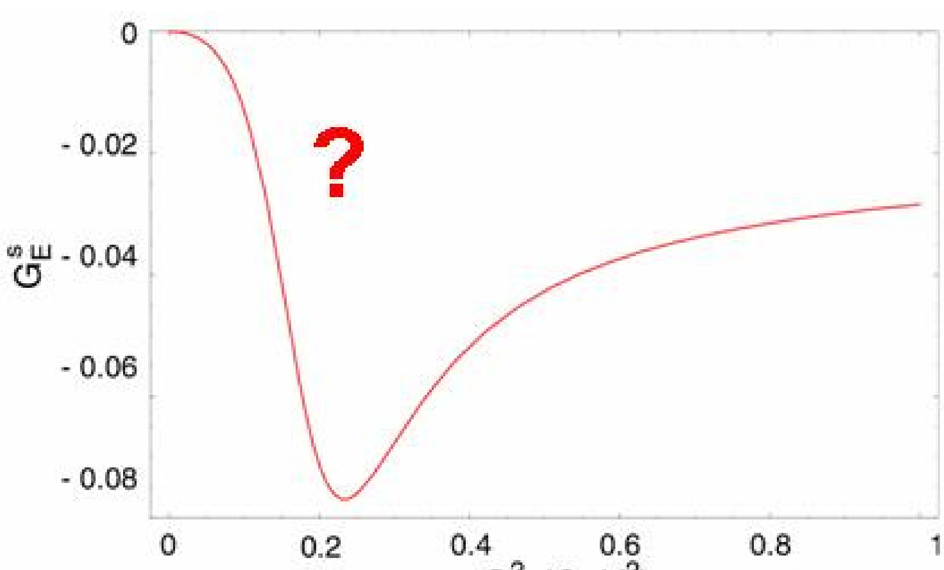
$d_1 = -8.5 \pm 0.9$

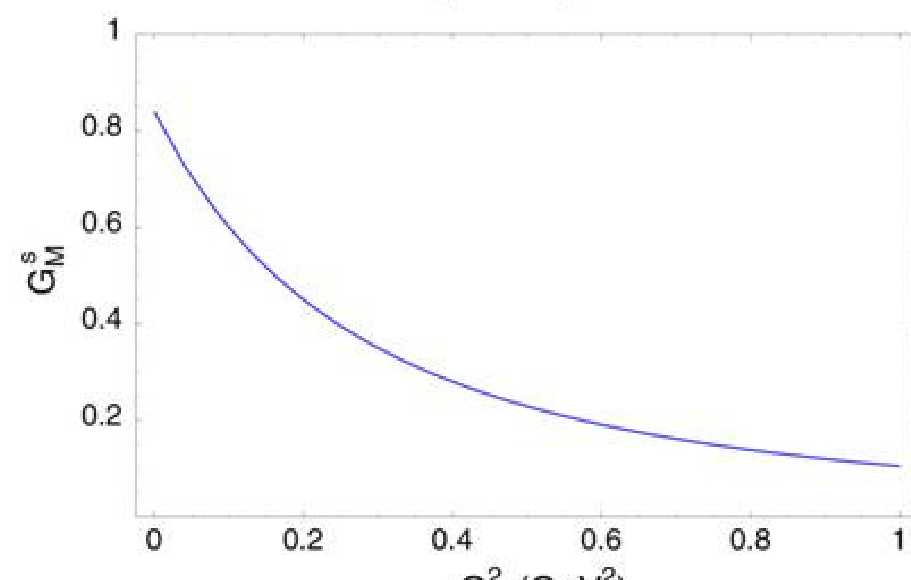
$d_2 = 24 \pm 6$

$d_3 = 1$

${\Lambda^s_M}^2 = \Lambda^2 / 1.3$







Significance & Comparison with Lattice QCD

- Size and sign of the strange magnetic moment is astonishing!

- Experimental <u>isoscalar</u> nucleon moment is 0.88 μ_N

  c.f. this result which is (Beck) - 0.54 μ_N : i.e. - 60% !!

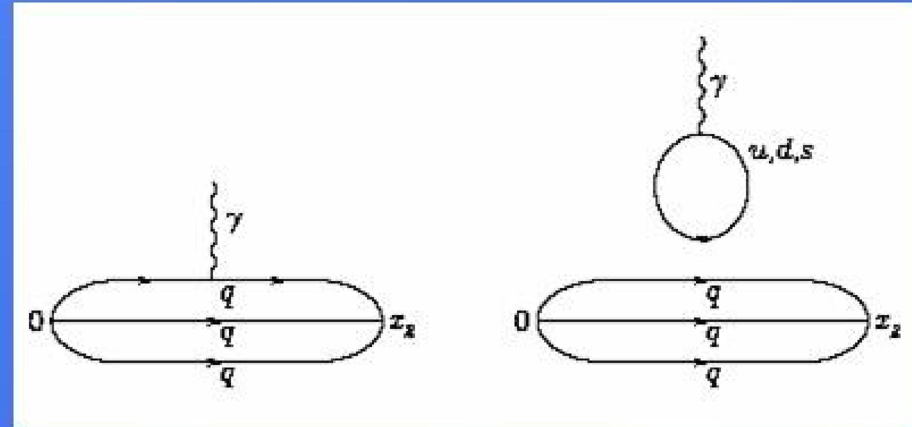
- Also remarkable versus lattice QCD which gives

  +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

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

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

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

(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

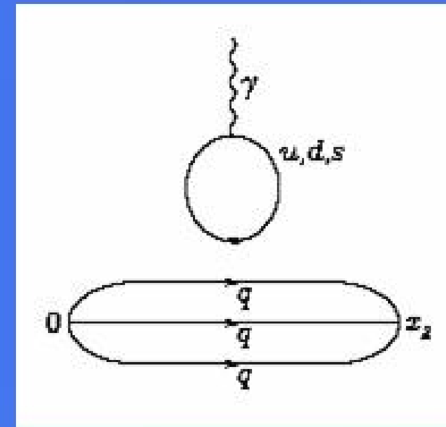
OR $O_N = 1/3\, [\, n + 2p - (u^n / u^\Xi)(\Xi^0 - \Xi^-)\,]$

Constraint from Charge Symmetry

$$O_N = \frac{2}{3}\,{}^{\ell}G_M^u - \frac{1}{3}\,{}^{\ell}G_M^d - \frac{1}{3}\,{}^{\ell}G_M^s$$

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

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

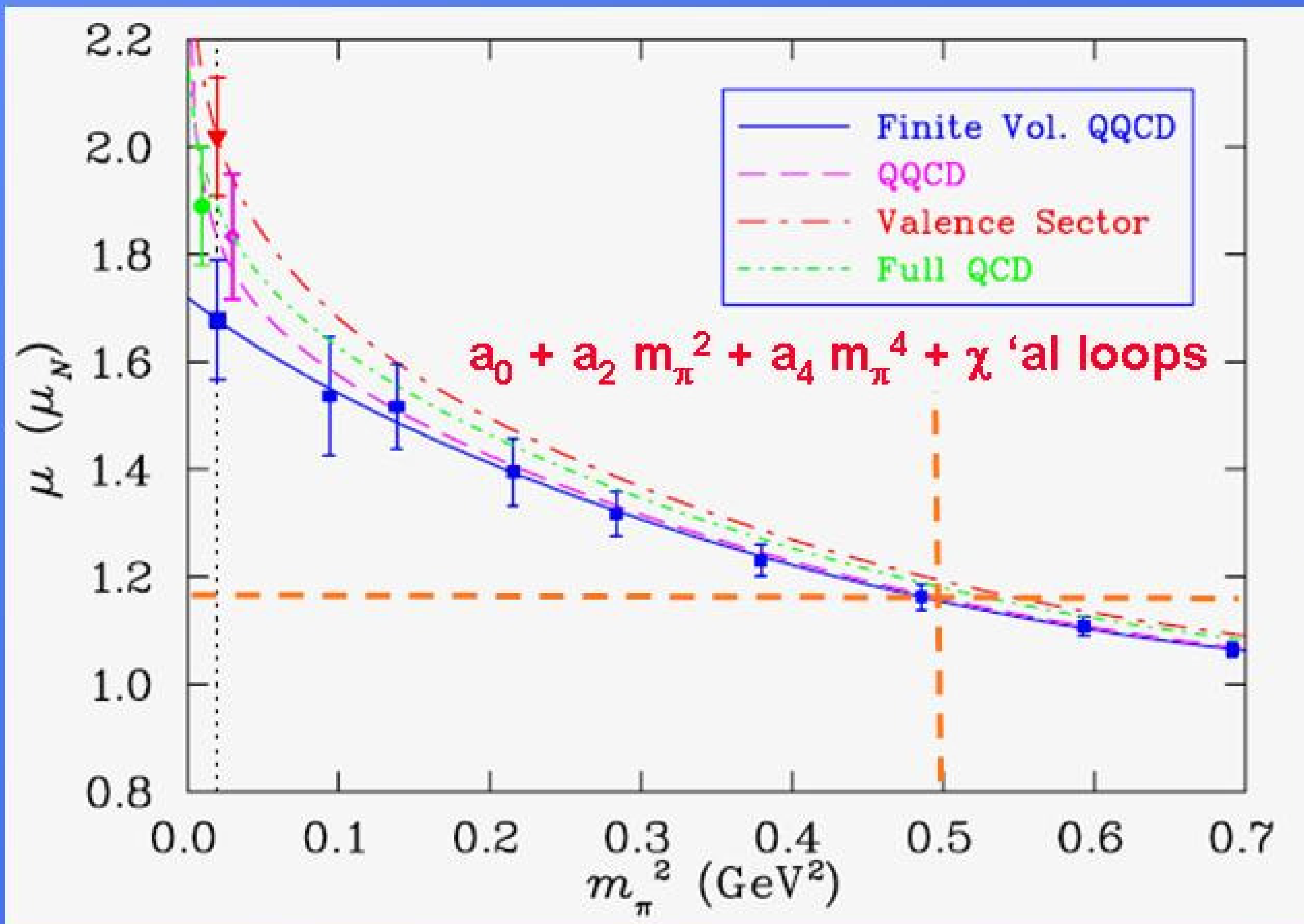


$$G_M^s = \left(\frac{{}^{\ell}R_d^s}{1 - {}^{\ell}R_d^s}\right)\left[3.673 - \frac{u_p}{u_{\Sigma^+}}(3.618)\right]$$

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

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

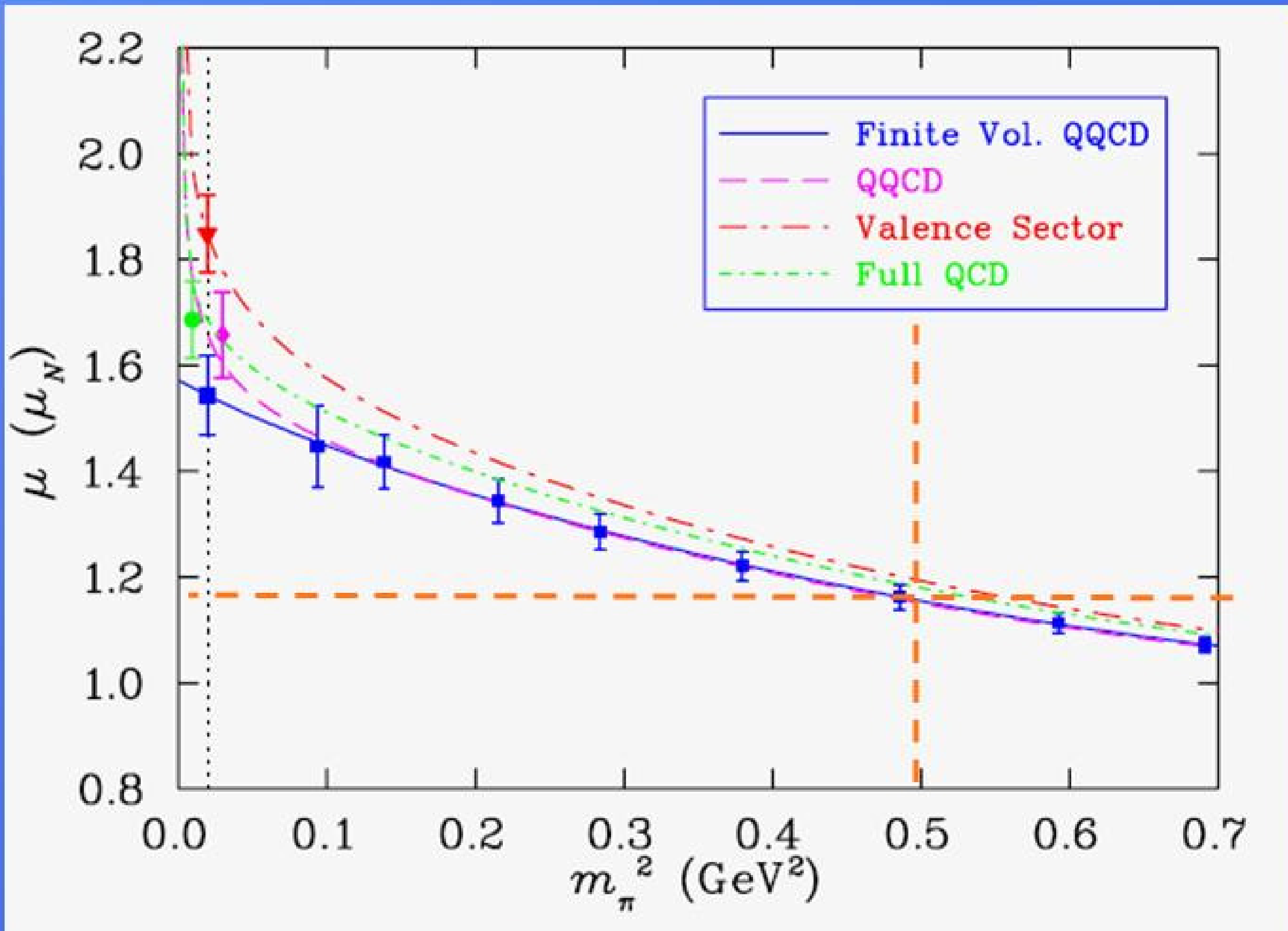
$u^p_{valence}$: QQCD Data Corrected for Full QCD Chiral Coeff's



c.f. CQM
2/3 940/540
» 1.18

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

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



Universa
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