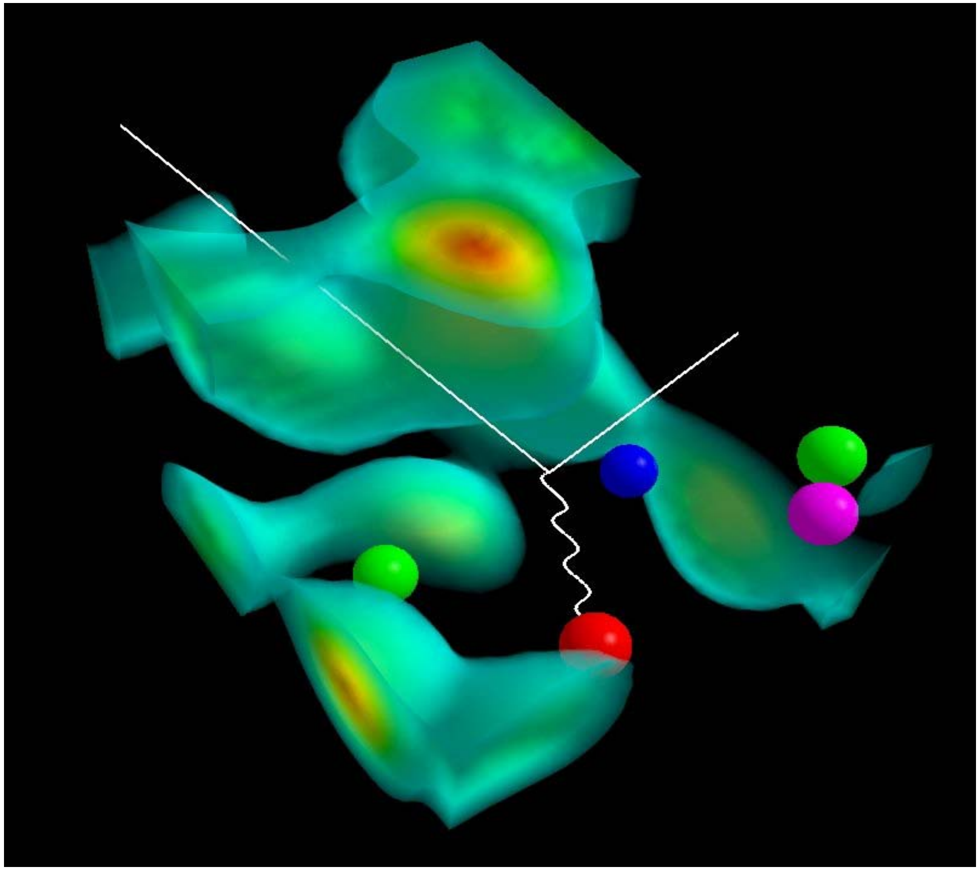
Symmetries & the Search for Physics Beyond The Standard Model



Anthony W. Thomas

4th International Symposium on Symmetries in Subatomic Physics

Taipei : June 2nd 2009

Outline

- Strangeness in the Nucleon

- Parity Violating Electron Scattering

  - testing strangeness
  - testing Electroweak extensions

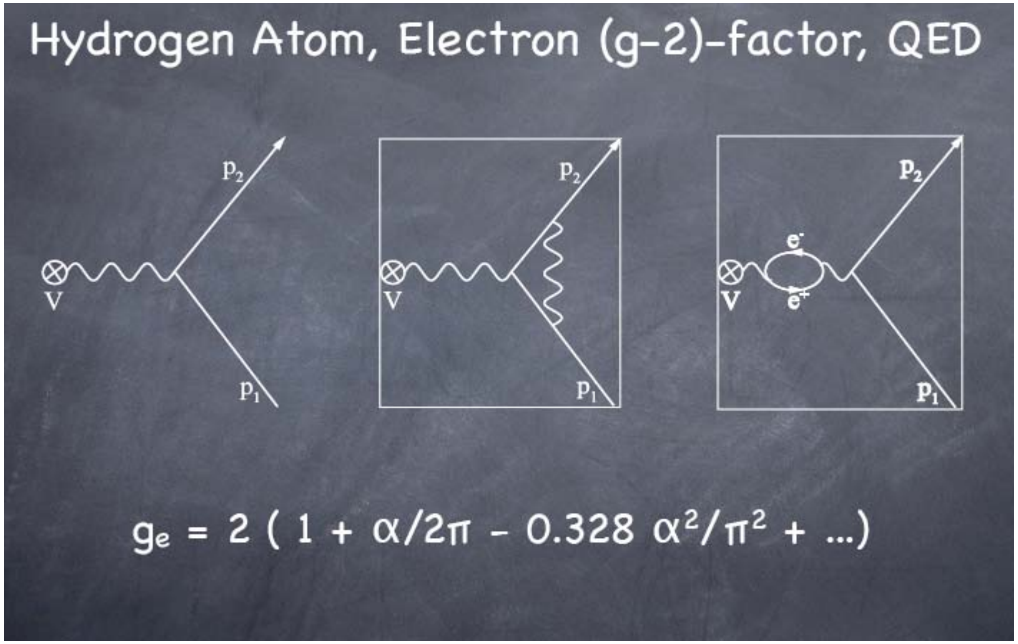
- Dark matter searches

  - σ commutators from lattice QCD

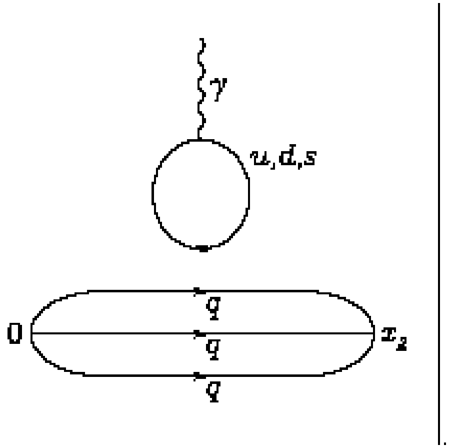
Dedicated to Ernest Henley on his 85th birthday

Testing Non-Perturbative QCD

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


Hydrogen Atom, Electron (g-2)-factor, QED

$$g_e = 2\,(1 + \alpha/2\pi - 0.328\,\alpha^2/\pi^2 + \ldots)$$



- **It is a fundamental test of non-perturbative QCD**

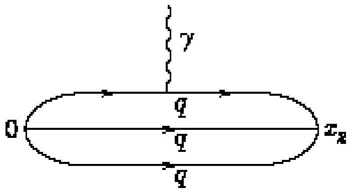
Strange Quarks in QCD

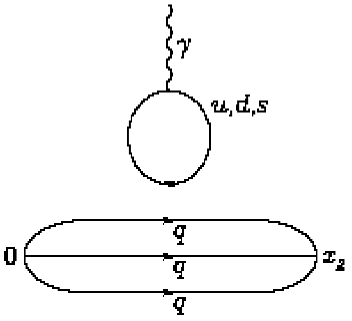
There have been a number of major steps forward recently, both theory and experiment :

- **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, CIPANP); Mainz PVA4 (arXiv:0903.2733); Happex and Bates**
- **Agreement between theory and experiment excellent**
  - **consistent global analysis valuable**

Magnetic Moments within QCD

Leinweber and Thomas, Phys Rev D62 (2000)





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

CS

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

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

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

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

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

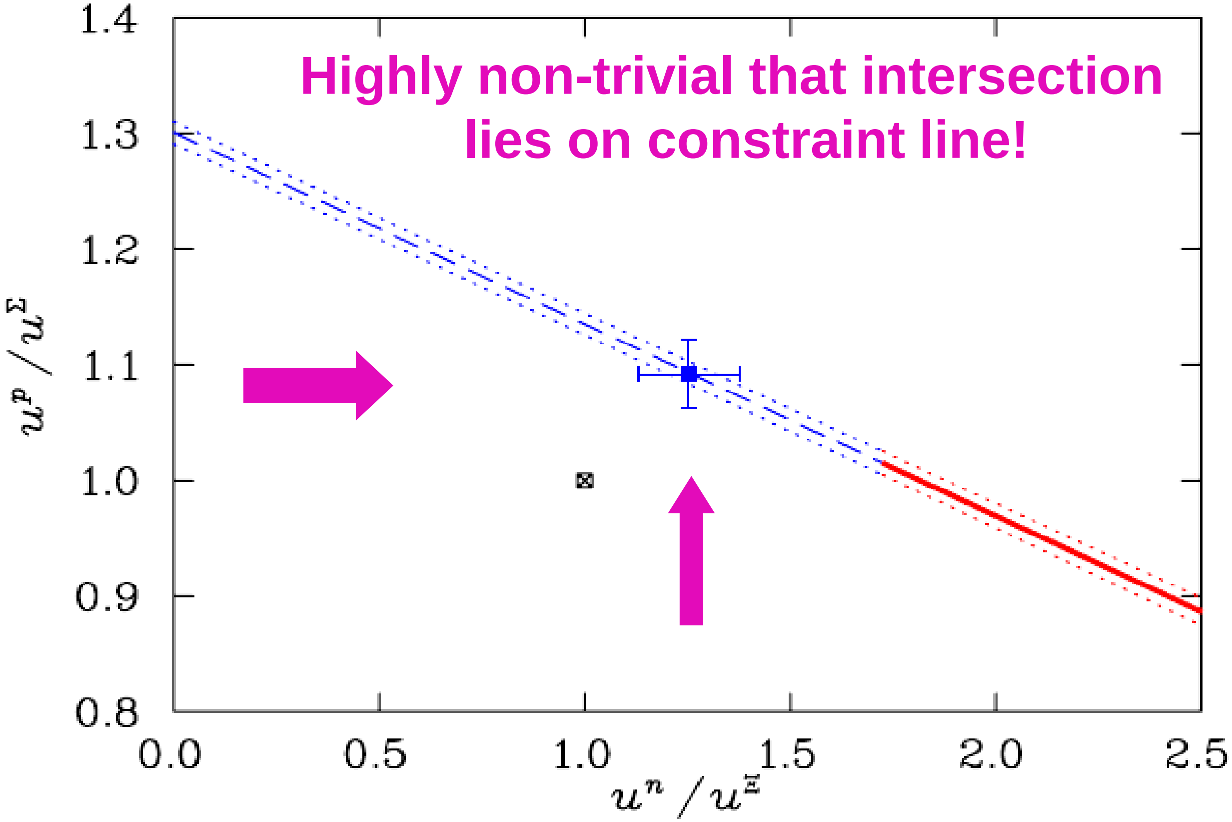
$$\Sigma^+ - \Sigma^- = u^\Sigma$$

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

Just these ratios from Lattice QCD

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

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   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)

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

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

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

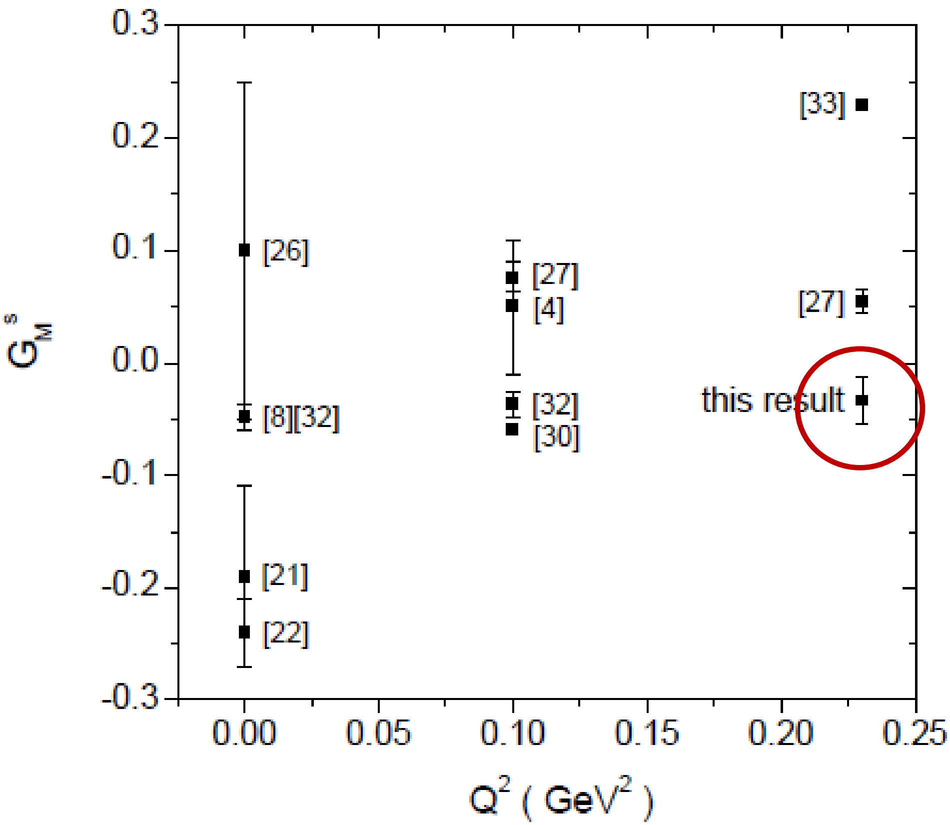
$$G_E^s(0.1\,\mathrm{GeV}^2) = +0.001 \pm 0.004 \pm 0.004$$

(up to order Q^4)

Note consistency and level of precision!

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

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

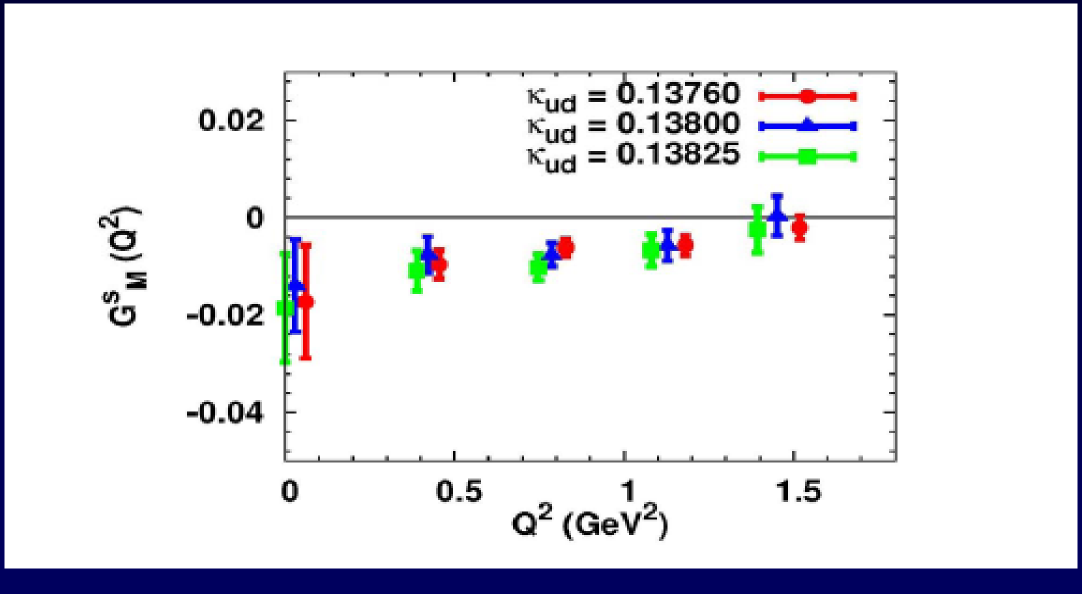


$-0.034 \pm 0.031\ \mu_N$

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

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

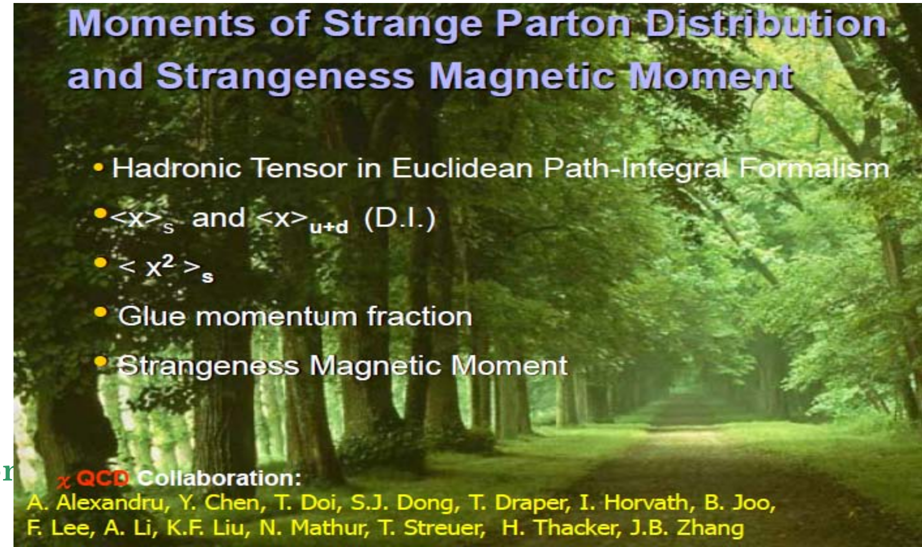
Strangeness Magnetic Form Factors with 3 Quark Masses (m_π = 0.6, 0.7, 0.8 GeV); T. Doi et al. (χQCD) arXiV:0903.3232



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

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

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



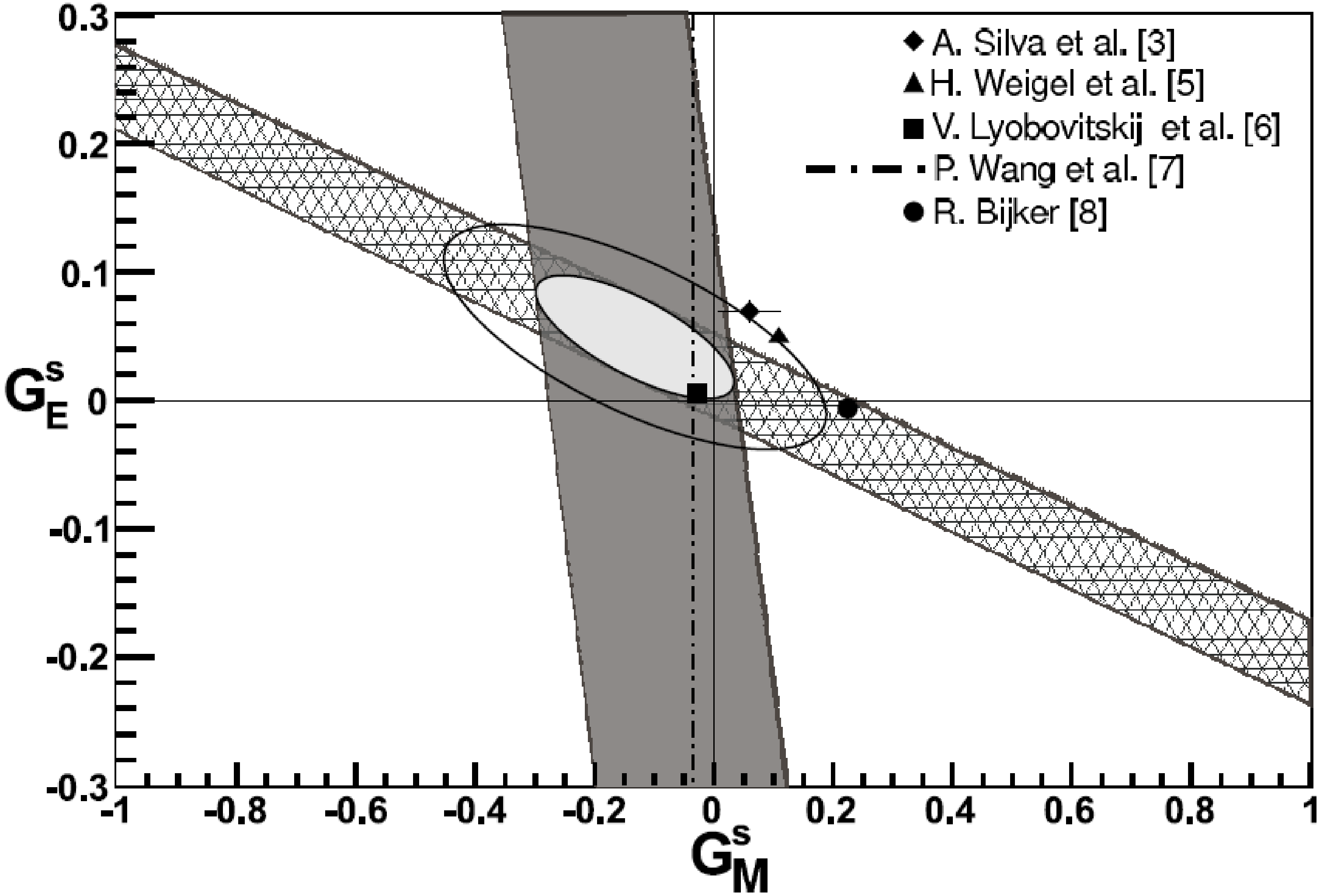
Moments of Strange Parton Distribution and Strangeness Magnetic Moment

- Hadronic Tensor in Euclidean Path-Integral Formalism
- $\langle x \rangle_s$ and $\langle x \rangle_{u+d}$ (D.I.)
- $\langle x^2 \rangle_s$
- Glue momentum fraction
- Strangeness Magnetic Moment

χQCD Collaboration:
A. Alexandru, Y. Chen, T. Doi, S.J. Dong, T. Draper, I. Horvath, B. Joo, F. Lee, A. Li, K.F. Liu, N. Mathur, T. Streuer, H. Thacker, J.B. Zhang

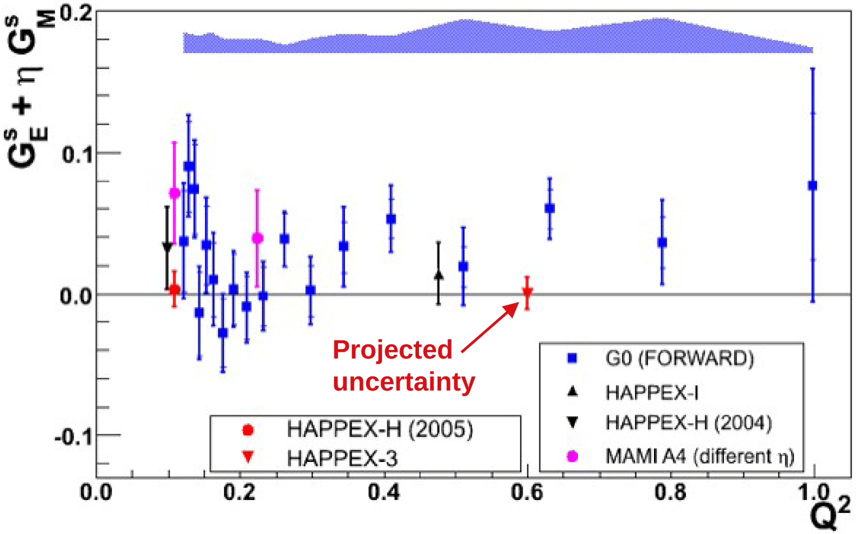
PVA4 Mainz 2009: $Q^2 = 0.22$ GeV^2

arXiv: 0903.2733v1



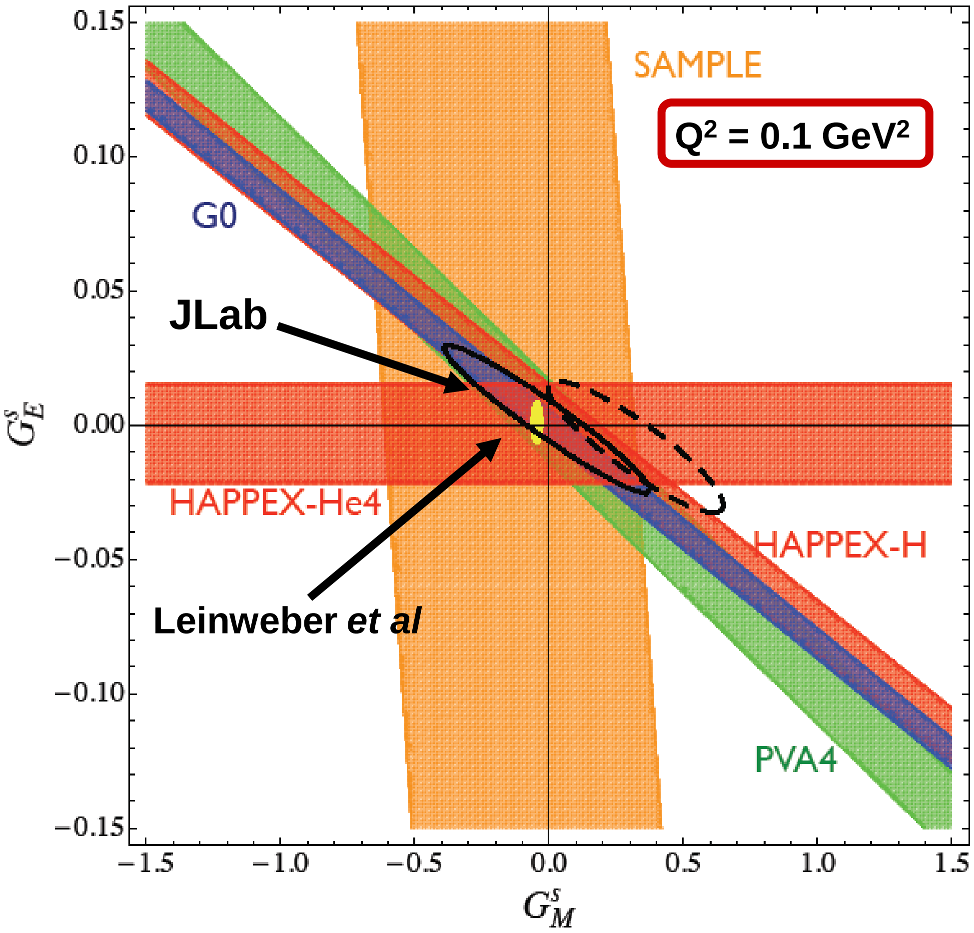
$G_M^s = -0.14 \pm 0.11 \pm 0.11\ \mu_N$; $G_E^s = 0.050 \pm 0.038 \pm 0.019$

Global Analysis of PVES Data



Projected uncertainty

From NSAC Long Range Plan



$Q^2 = 0.1\ \mathrm{GeV}^2$

JLab

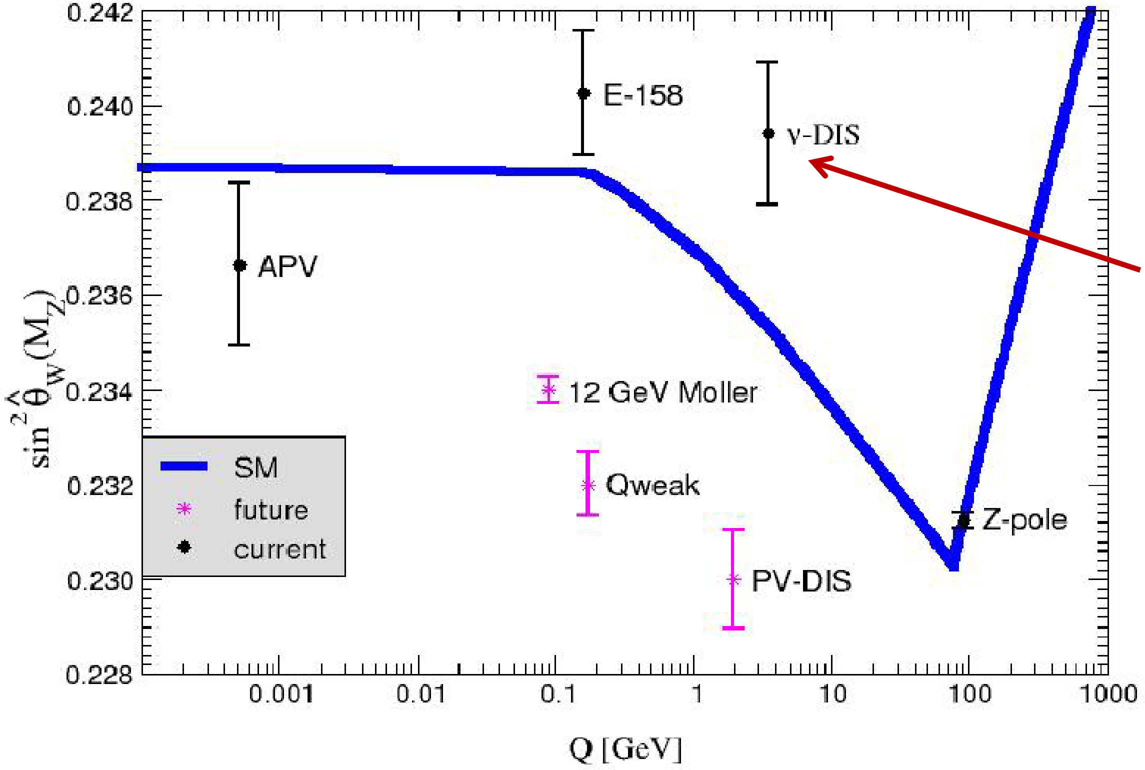
Leinweber *et al*

- **Proton not all that strange**

- **New data not yet included at 0.23 and 0.6 GeV^2 (PVA4 – just out, G0 – final analysis, HAPPEx III – will start this year)**

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

Radiative Corrections as Standard Model Test



N.B. Talk of I. Cloet : discovery of isovector EMC effect provides new “CSV-like “ correction

Analysis of PVES

- Proton target

$$A^{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \left[\frac{-G_F Q^2}{\pi\alpha\sqrt{2}}\right] \frac{\varepsilon G_E^{p\gamma} \boxed{G_E^{pZ}} + \tau G_M^{p\gamma} \boxed{G_M^{pZ}} - \frac{1}{2}(1 - 4\sin^2\theta_W)\varepsilon' G_M^{p\gamma} \boxed{\tilde{G}_A^p}}{\varepsilon (G_E^{p\gamma})^2 + \tau (G_M^{p\gamma})^2}$$

Neutral-weak form factors

Axial form factor

Assume charge symmetry:

$$4G_{E,M}^{pZ} = \underbrace{(1 - 4\sin^2\theta_W)}_{\text{Proton weak charge (tree level)}} G_{E,M}^{p\gamma} - G_{E,M}^{n\gamma} - \underbrace{G_{E,M}^{s}}_{\text{Strangeness}}$$

Use data to constrain the parameters of the electroweak theory

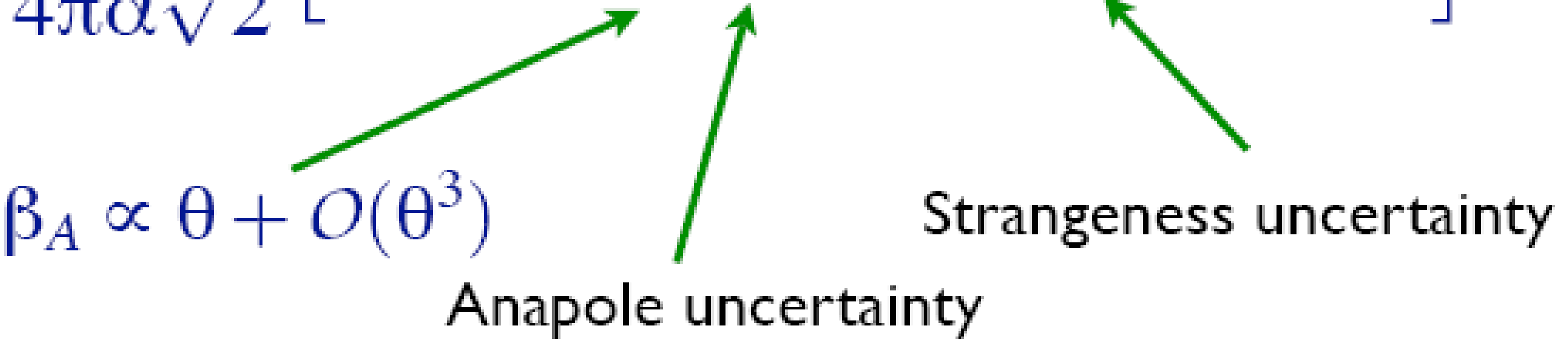
Extraction of Low Energy Coupling Constants $C_{1u,1d}$

- Precise measurement of the proton's weak charge in PVES

$$Q^p_{\text{weak}} = -2(2C_{1u} + C_{1d}) \qquad Q^2 = 0.03\,\text{GeV}^2,\ \theta = 8^\circ$$

- At low energy and small scattering angle:

$$A_{LR} = -\frac{G_\mu Q^2}{4\pi\alpha\sqrt{2}}\left[Q_{\text{weak}} + \beta_A \tilde{G}^p_A \sqrt{Q^2} + \beta_V Q^2 + \ldots\right]$$



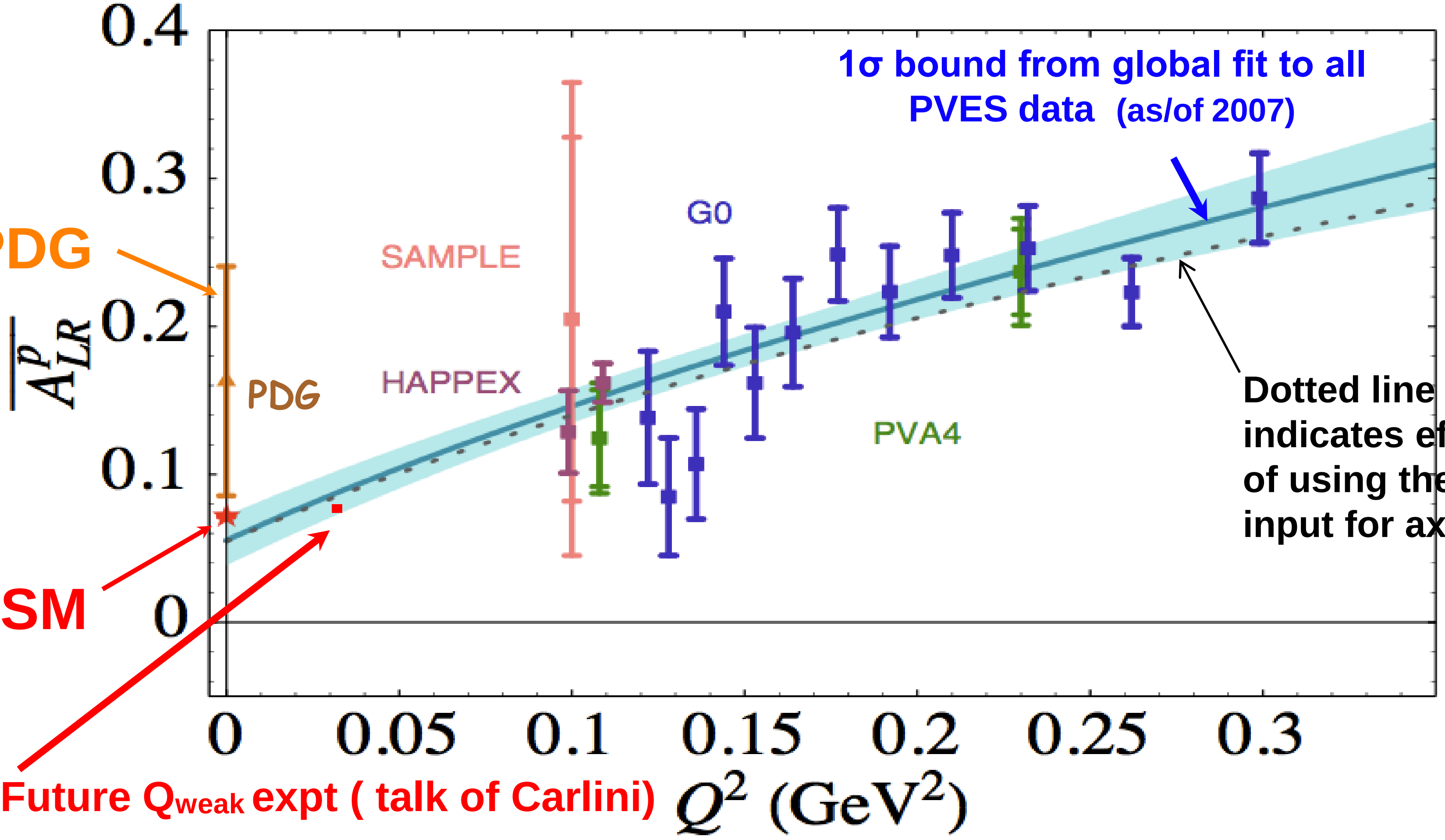
$$\beta_A \propto \theta + O(\theta^3)$$

Anapole uncertainty

Strangeness uncertainty

Use Global Fit to Extract Slope at 0° and $Q^2 = 0$

$$\overline{A^p_{LR}} = A_z/(-G_F Q^2/4\pi\alpha\sqrt{2}) = Q^p_{weak} + Q^2 B(Q^2)$$



1σ bound from global fit to all PVES data (as/of 2007)

Dotted line indicates effect of using theoretical input for axial terms

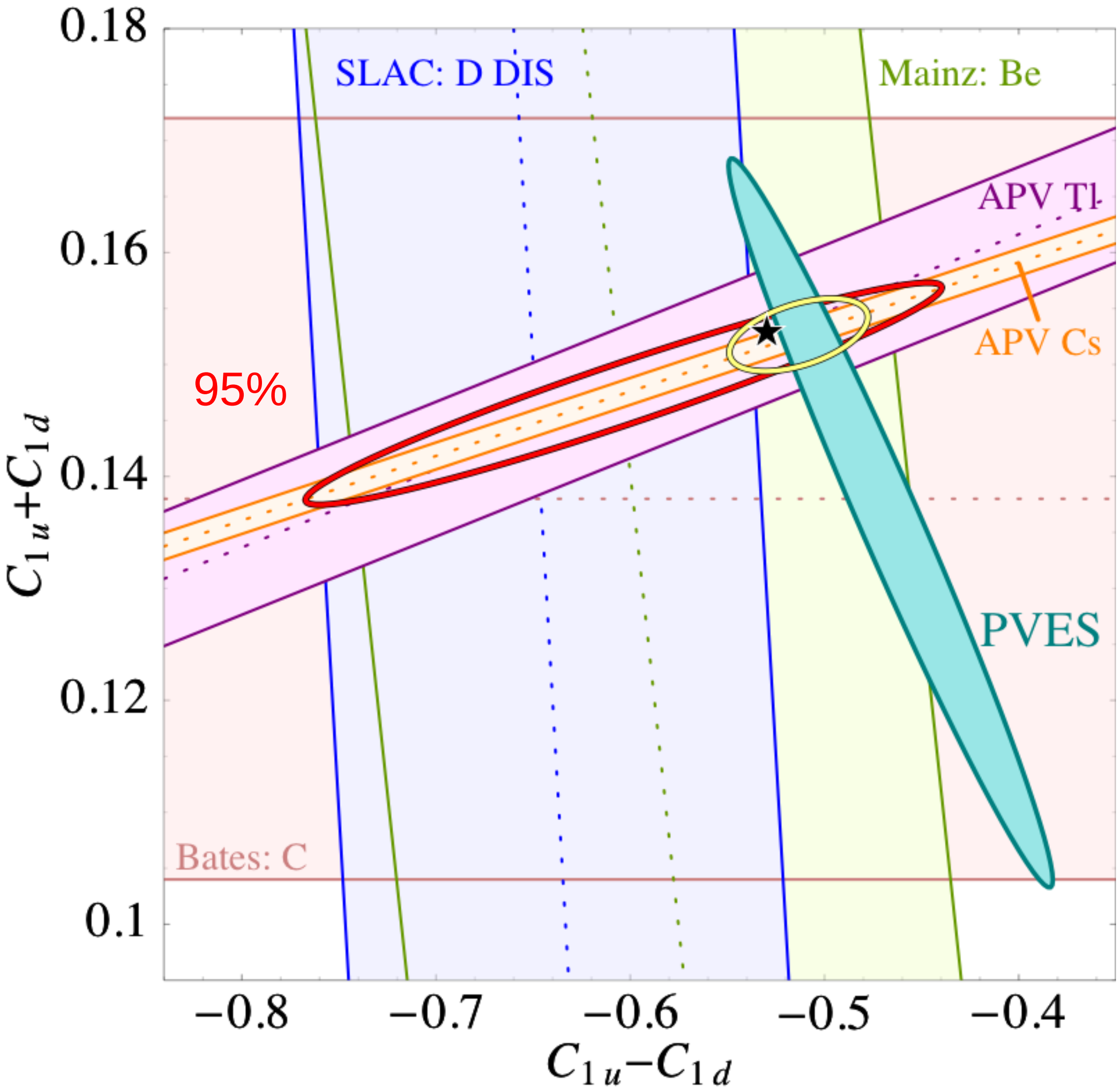
PDG

SM

Future Q_{weak} expt (talk of Carlini)

(R.D. Young, R.D. Carlini, A.W. Thomas, and J. Roche, PRL 99, 122003 (2007))

New update on C_{1q} couplings – Dec 2006



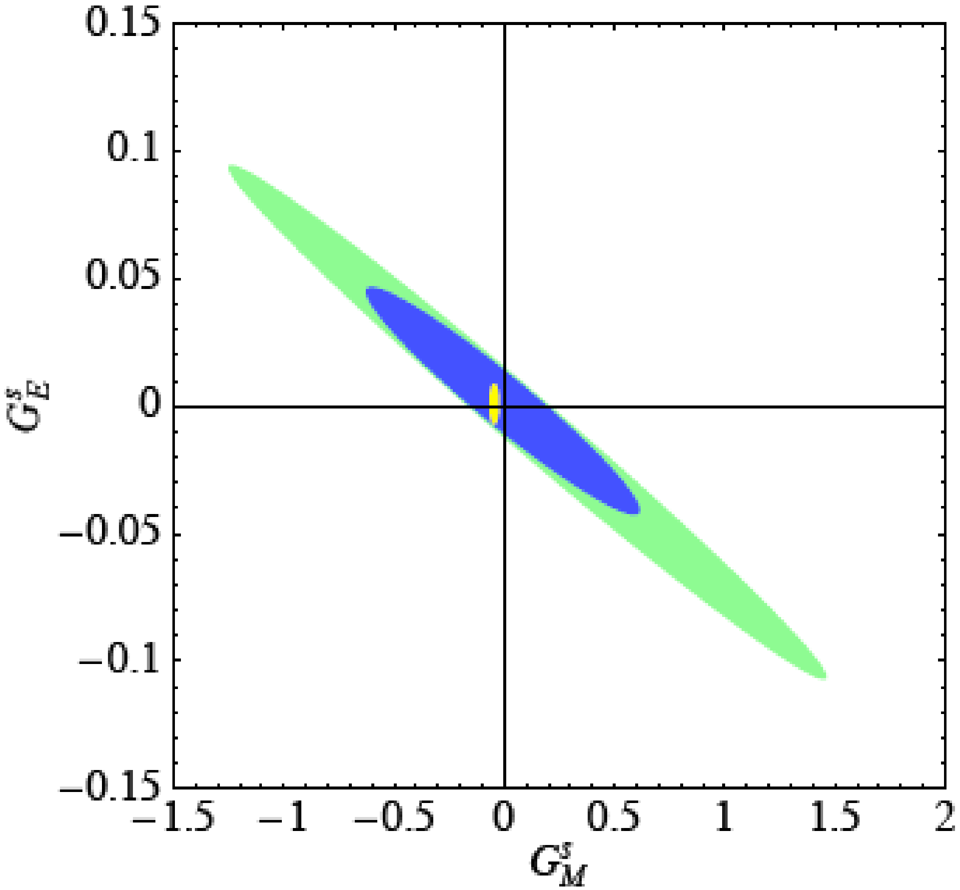
(Young et al.)

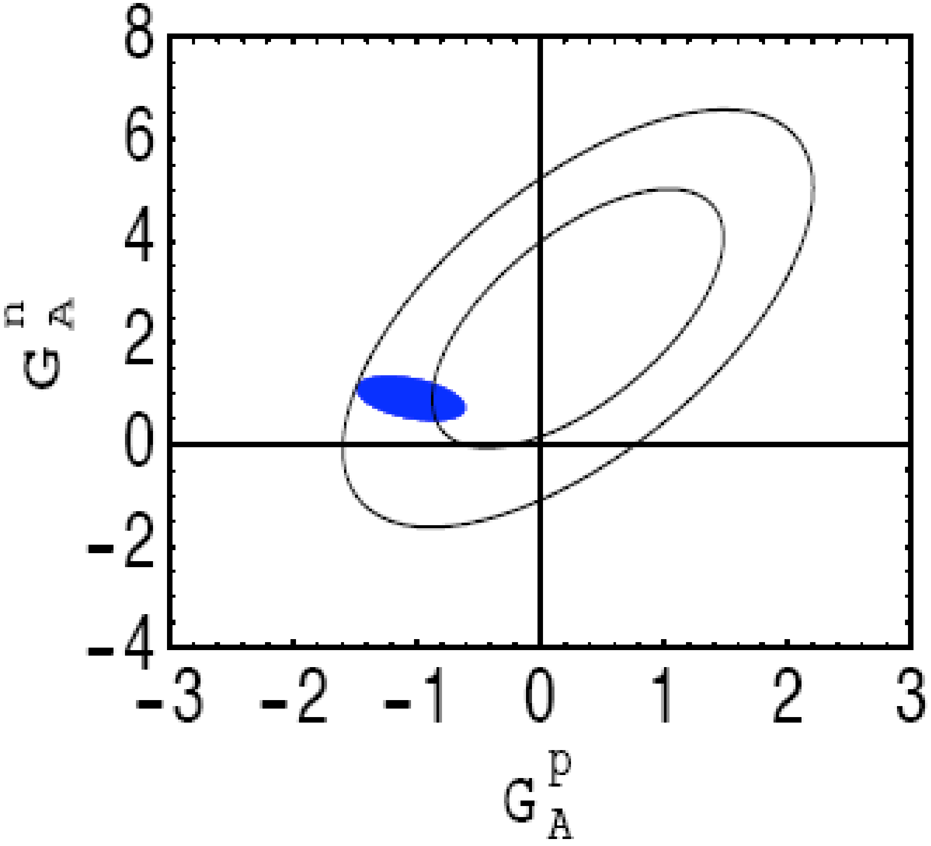
Dramatic improvement in knowledge of weak couplings!

Factor of 5 increase in precision of Standard Model test

Effect of Including Theoretical Constraints?

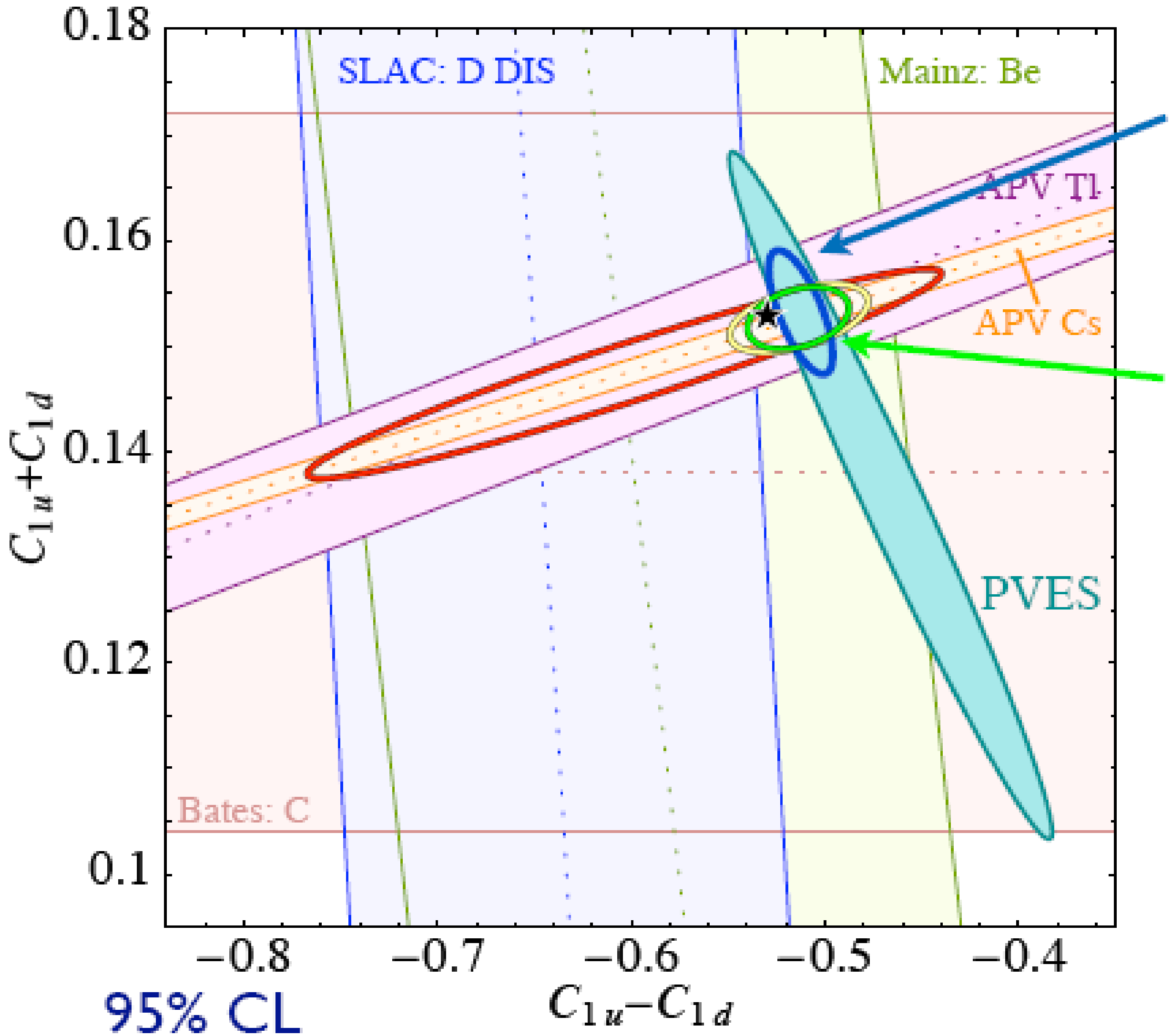
- Seems natural given independent verification by χQCD noted above





This gives an interesting hint that anapole term may differ from expectations in an interesting manner

With Best Constraints from Lattice QCD

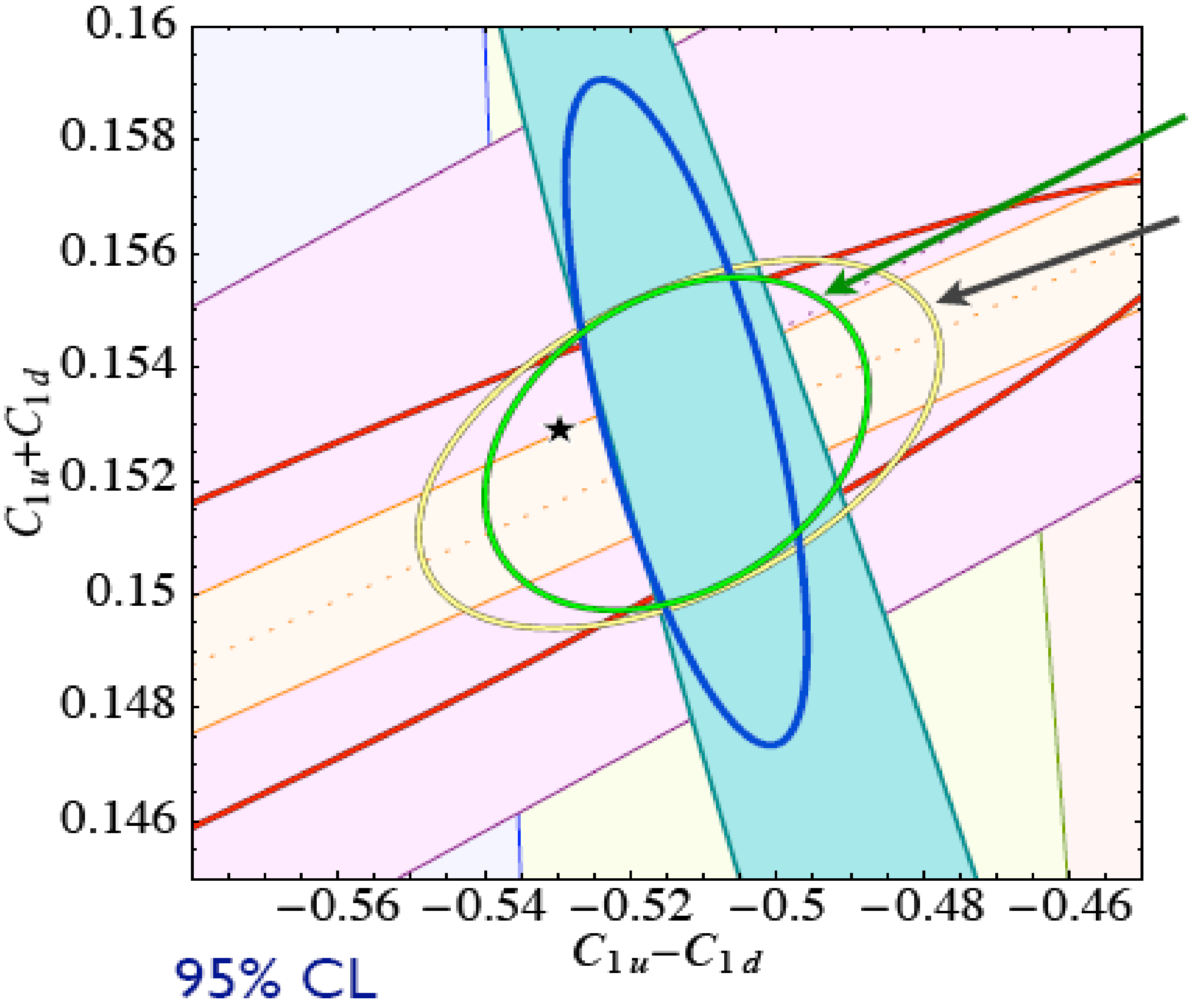


PVES with theory

Net constraint

95% CL

No Significant Change in Conclusion



With lattice QCD input

With NO theoretical input

For Standard Model tests the difference is clearly not so important and is not used below

General Limits on Physics Beyond SM

$$\mathcal{L}^{\rm PV}_{\rm SM} = -\frac{G_F}{\sqrt{2}}\bar{e}\gamma_\mu\gamma_5 e \sum_q C^{\rm SM}_{1q}\bar{q}\gamma^\mu q$$

Erler et al., PRD68(2003)

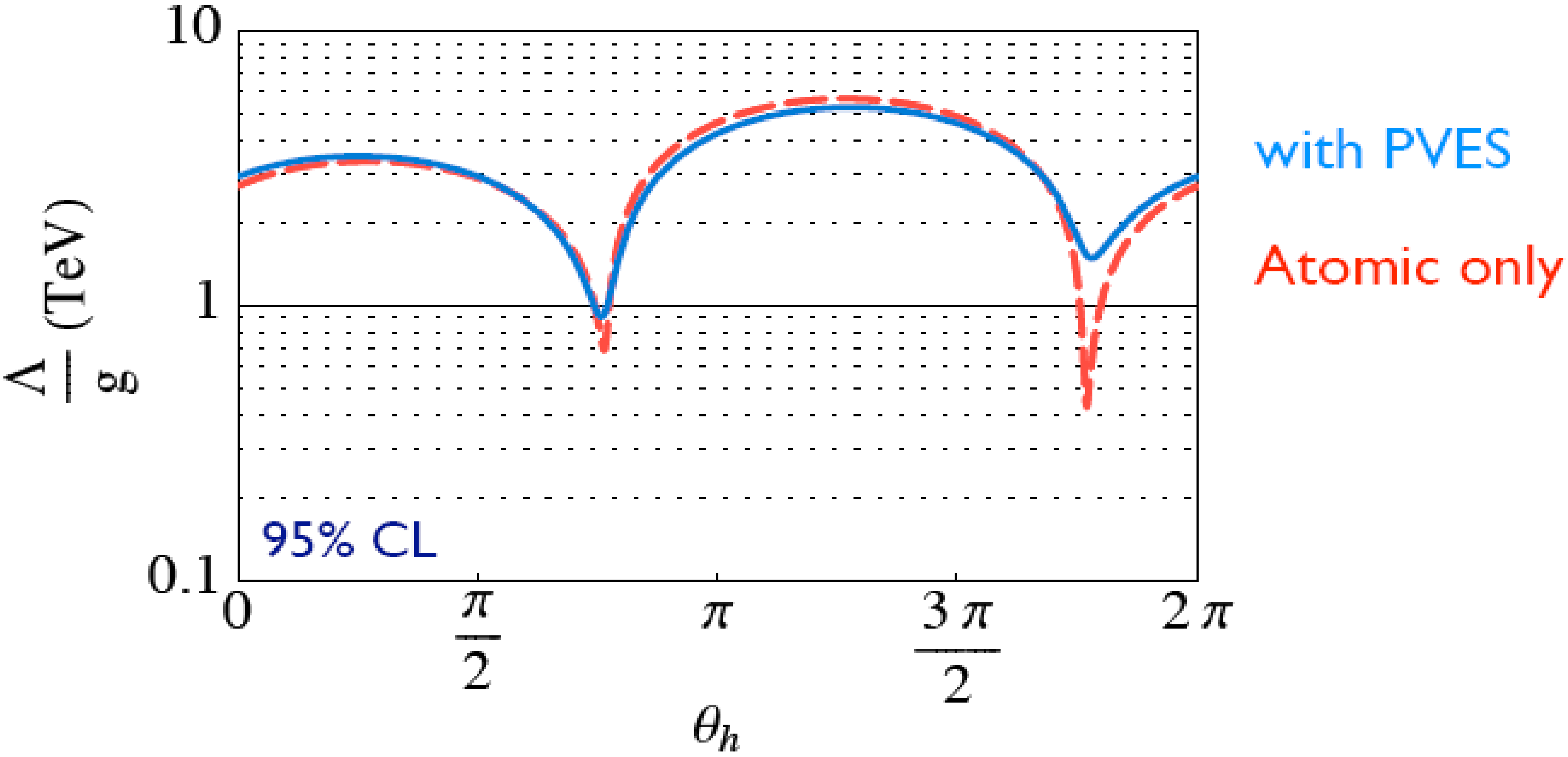
$$\mathcal{L}^{\rm PV}_{\rm NP} = \frac{g^2}{4\Lambda^2}\bar{e}\gamma_\mu\gamma_5 e \sum_q h^q_V\bar{q}\gamma^\mu q$$

Full isospin coverage for limits on new physics!

$$h^u_V = \cos\theta_h \qquad h^d_V = \sin\theta_h$$

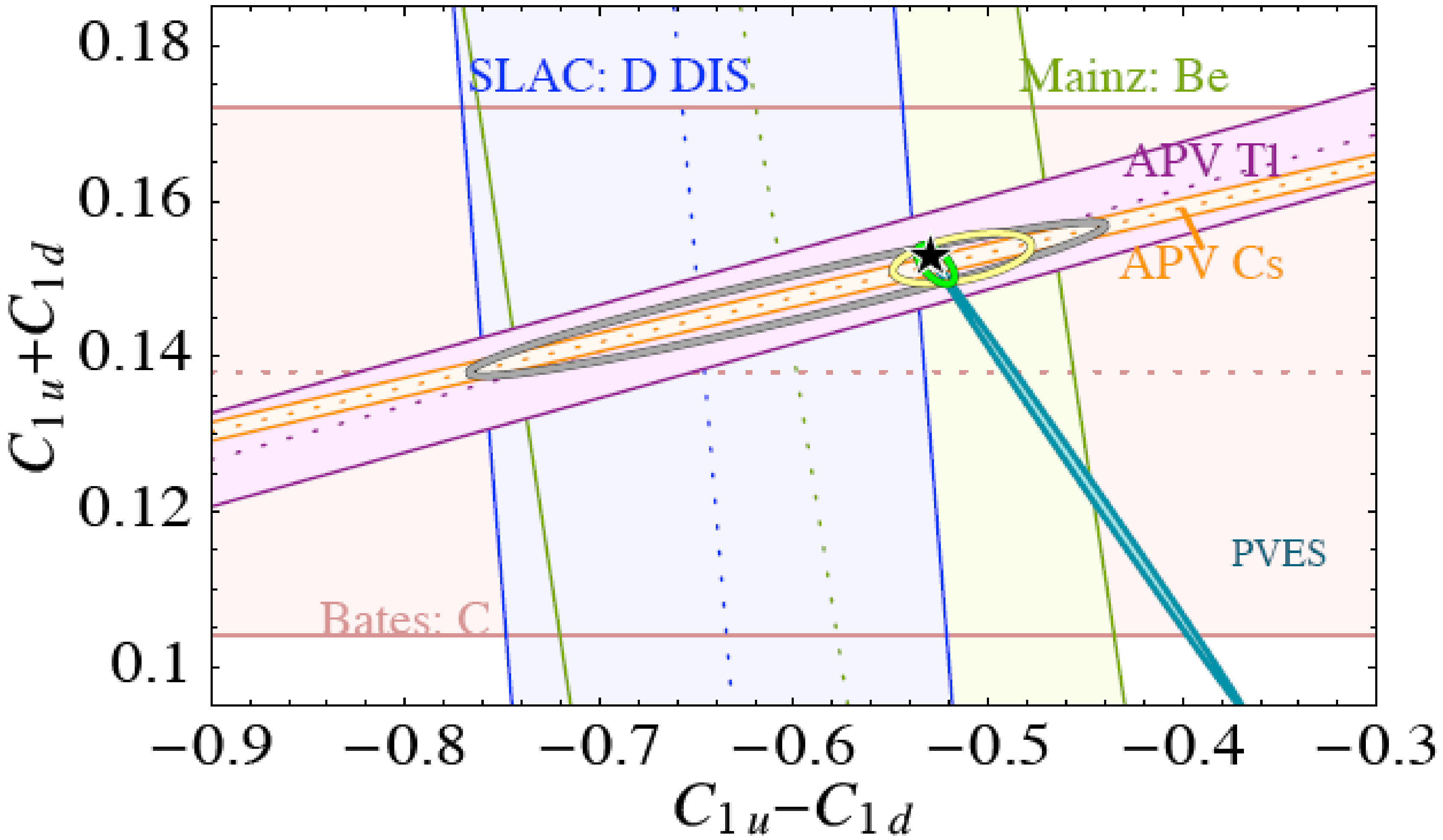
Data sets limits on $\frac{g^2}{\Lambda^2}$

Raises Mass of New Z’ to 0.9 TeV – from 0.4 TeV

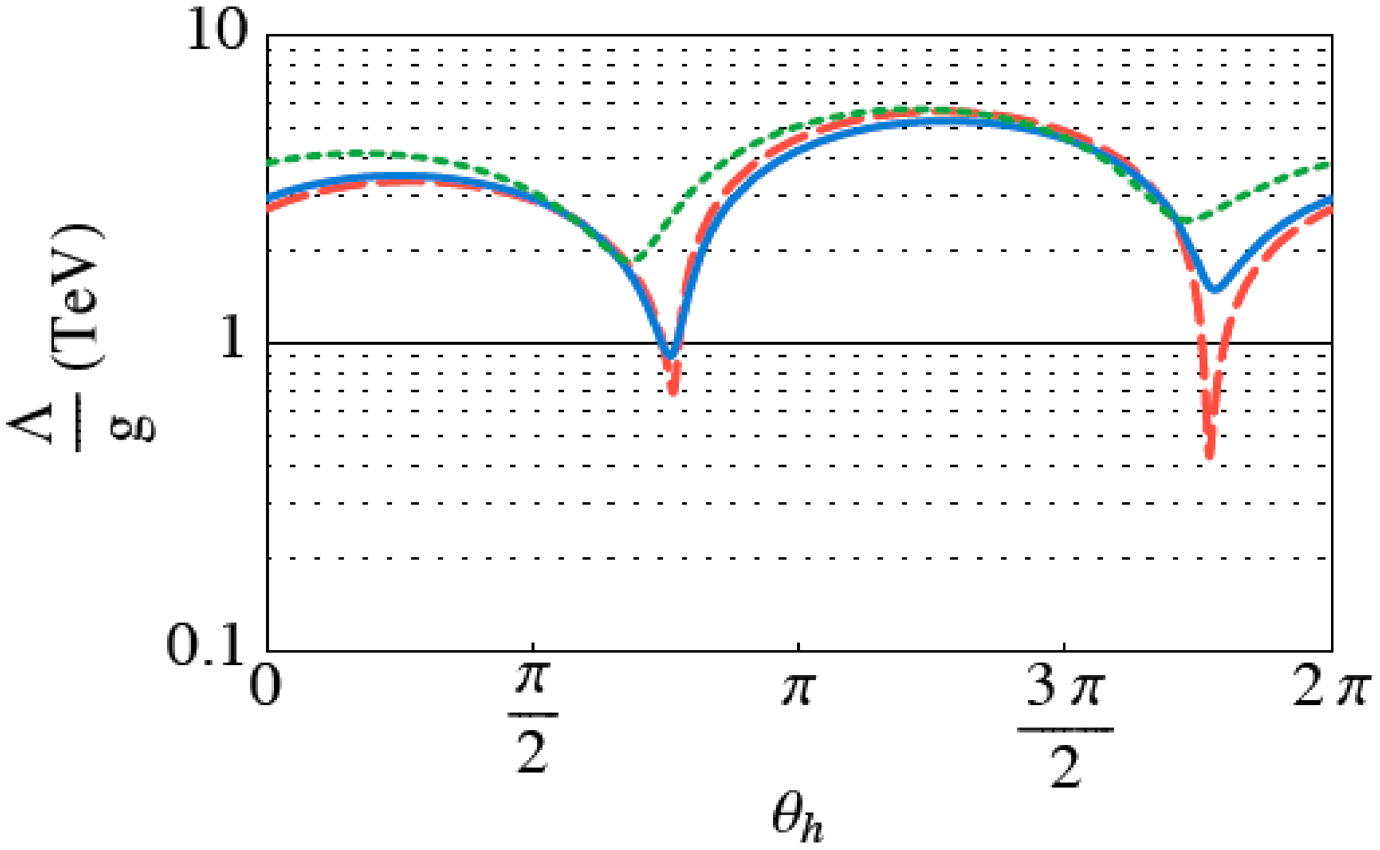


New physics scale >0.9 TeV! (from 0.4 TeV)

Future Q_{weak} – IF in Agreement with SM



IF in accord with Standard Model…



future Qweak

with PVES

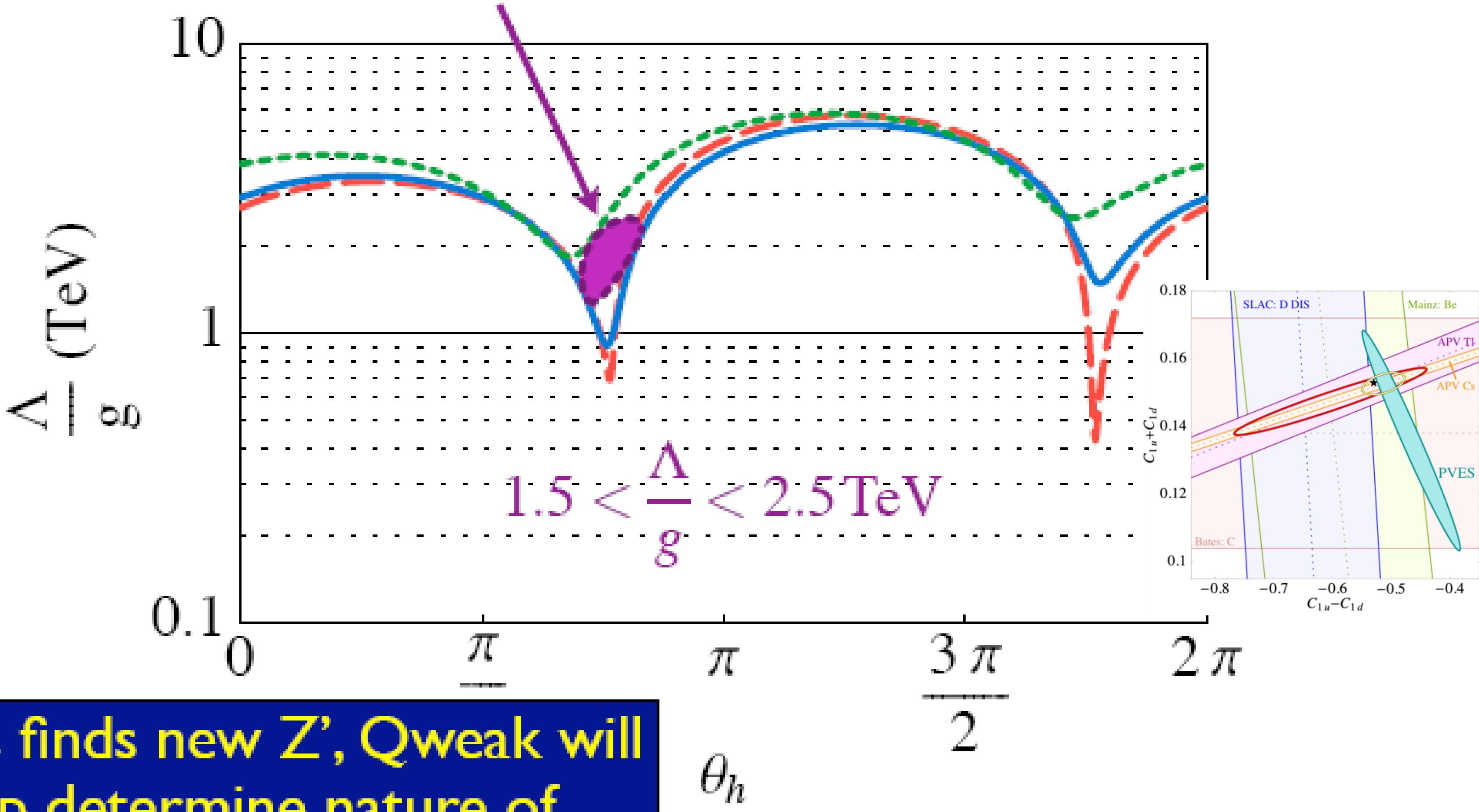
Atomic only

95% CL

Qweak constrains new physics to beyond 2 TeV

Or… Discovery

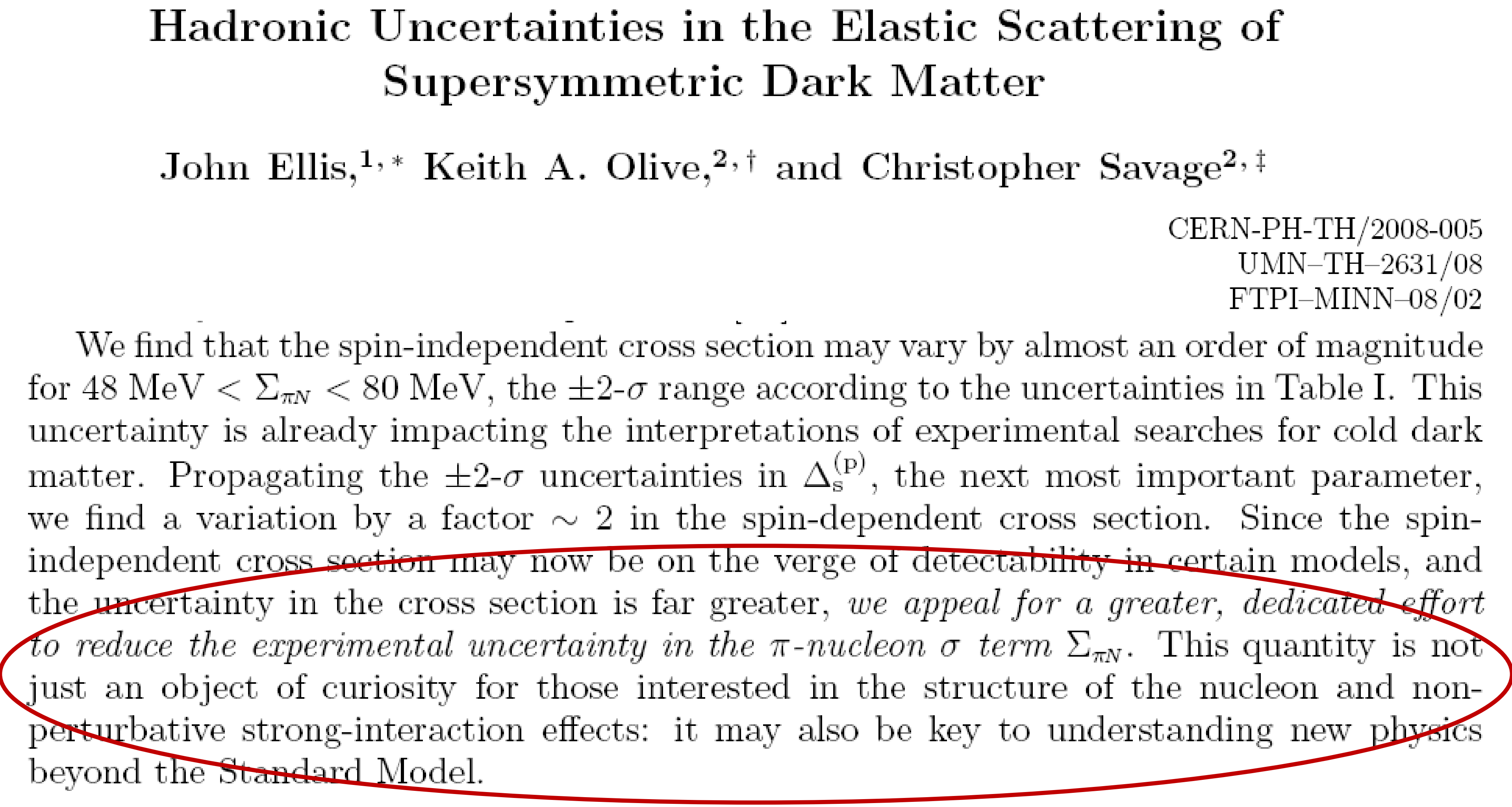
Assume Qweak takes central value of current measurements



$$1.5 < \frac{\Lambda}{g} < 2.5\,\text{TeV}$$

If LHC finds new Z’, Qweak will help determine nature of interaction

Final Remark on 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)

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

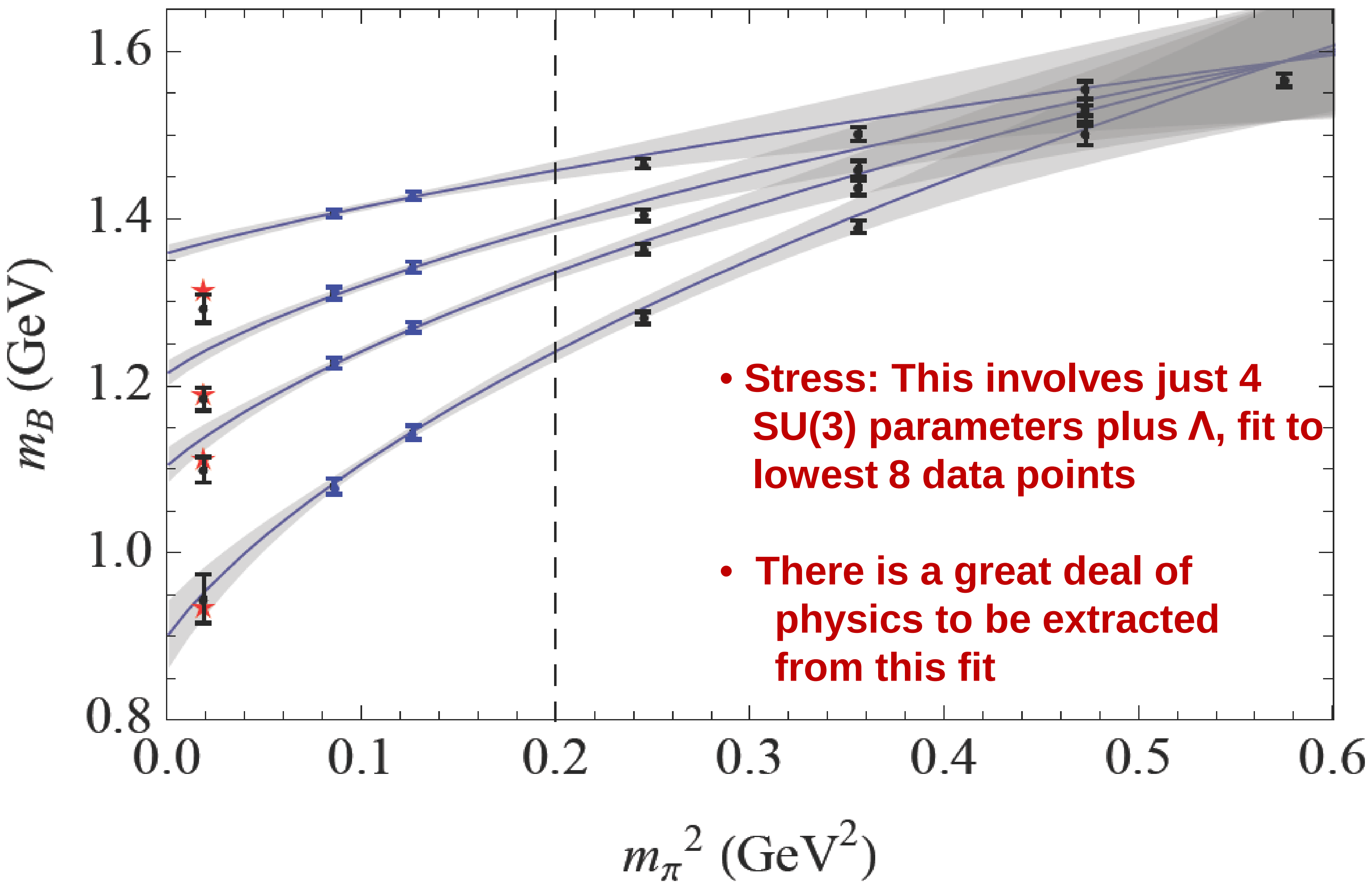
- Data does not lie in “power counting region”
  - hence use finite range regularization (FRR)

- FRR suppresses Goldstone boson loops when Compton wavelength is too small ($m_{GB} > 0.4$ GeV)

- see talk of R. Young

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]

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)

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

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 !

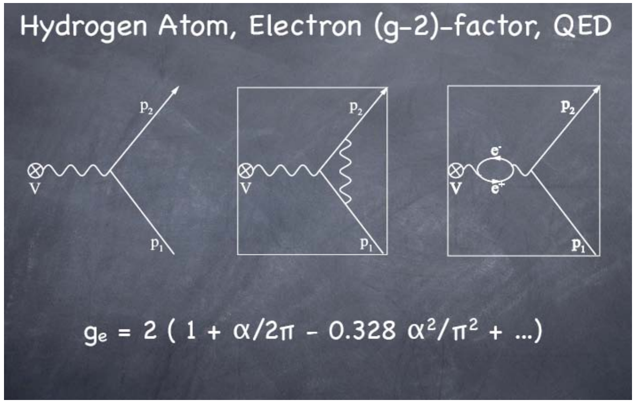
Profound Consequences for Dark Matter Searches and for dense matter – possible kaon condensation

Summary

- **Strange content of N small**
  - **— Less than 5% of μ^p and 2% of proton charge radius**

- **Theory agrees well but order of magnitude more accurate than state-of-the-art experiments**

- ***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

- **Precise parity violating electron scattering data, dominated by Jefferson Lab, also enables very accurate tests of Standard Model couplings $C_{1u,1d}$**

- ***Data so far has raised the mass scale above which new physics is allowed from 0.4 to 0.9 GeV***

- **Future measurements in Q_{weak} experiment (Carlini, this meeting) will more than double this limit OR discover New Physics**

Thanks especially to Ross Young and Roger Carlini