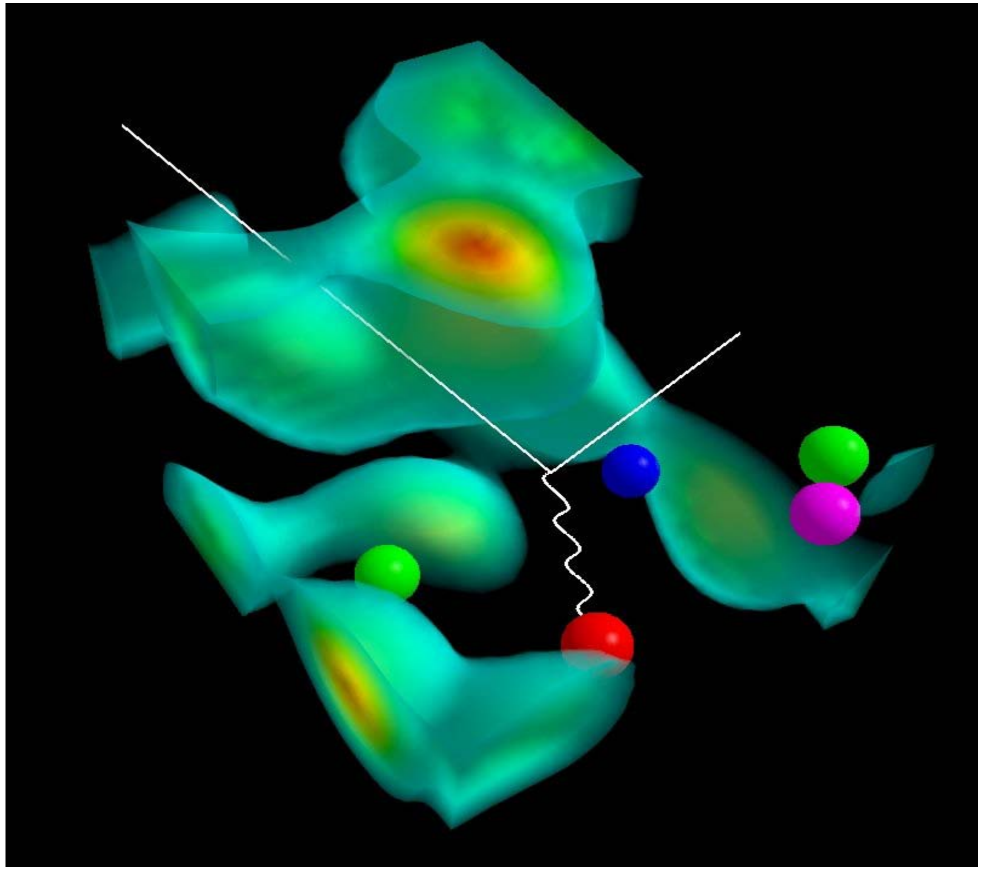
Strangeness in the Nucleon : What have we learned?



Anthony W. Thomas

CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

Australian Government
Australian Research Council

PAVI11
Rome: September 5-9 2011

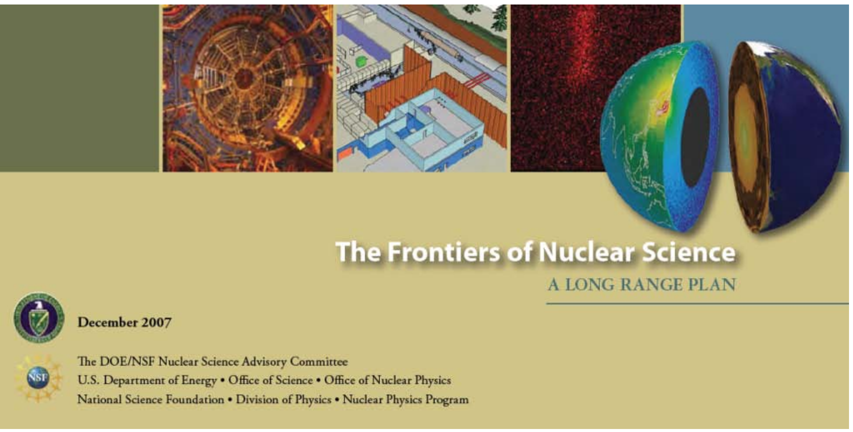
ADELAIDE UNIVERSITY AUSTRALIA

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

Outline

- Strange Vector Current
  - “Lamb shift” for QCD
- Overview of lattice data
- Strange sigma commutator
  - Implications for Dark Matter Searches
- The H-dibaryon – re-incarnated?
- The s-quark as a heavy d-quark – CSV
- Strange quark sea

Quark and Gluon Propagators



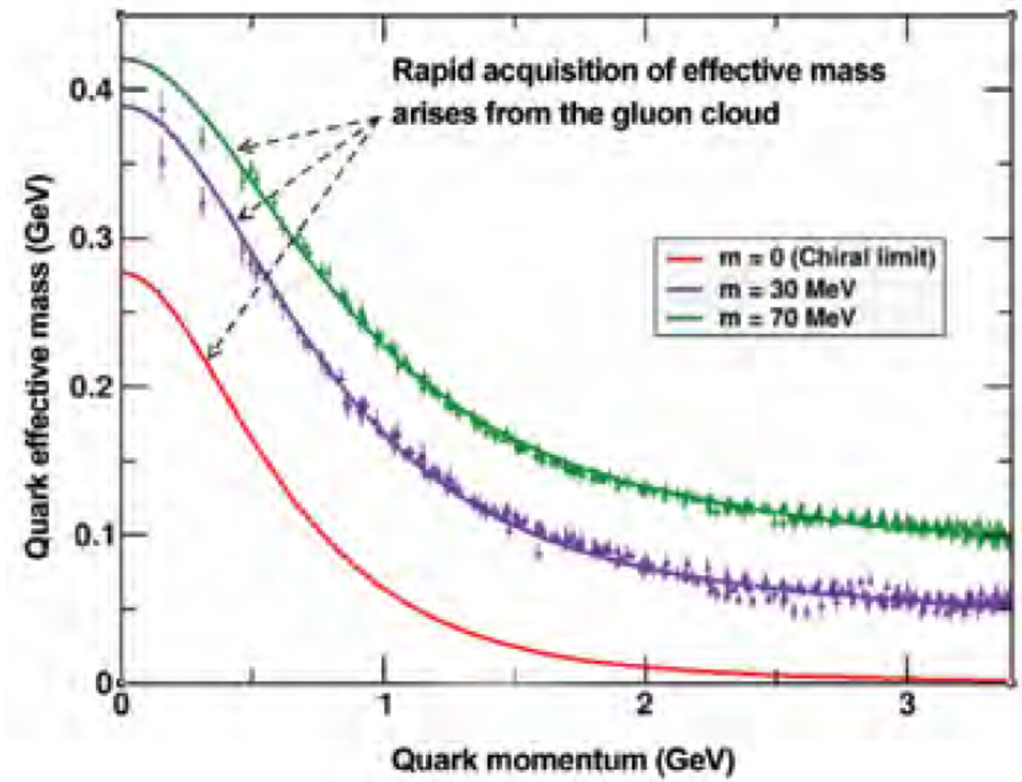


Figure 2.1: Mass from nothing. In QCD a quark's effective mass depends on its momentum. The function describing this can be calculated and is depicted here. Numerical simulations of lattice QCD (data, at two different bare masses) have confirmed model predictions (solid curves) that the vast bulk of the constituent-mass of a light quark comes from a cloud of gluons, that are dragged along by the quark as it propagates. In this way, a quark that appears to be absolutely massless at high energies (m = 0, red curve) acquires a large constituent mass at low energies.

CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

ADELAIDE UNIVERSITY AUSTRALIA

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

Strange Vector Current

Strange Vector Form Factors

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

- **Calculation of $G_{E,M}^{s}\,(Q^2)$:**
  - **- Indirect: Adelaide−JLab**
  - **- Direct: Kentucky**

- **Experimental determination of $G_{E,M}^{s}\,(Q^2)$**
  - **- G0 and Happex**
  - **- Mainz PVA4 (and earlier Bates)**

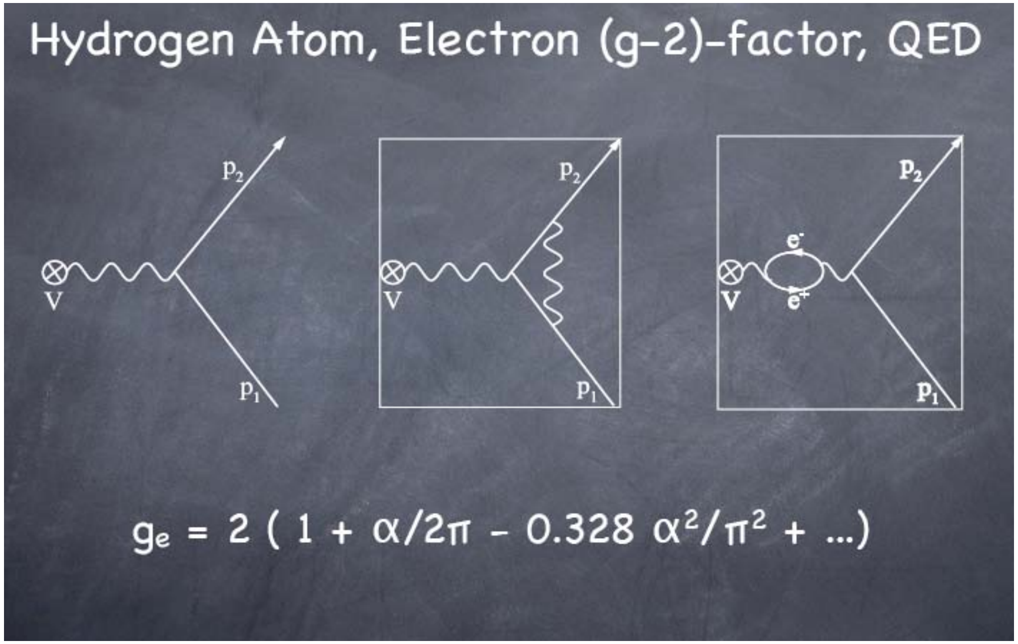
CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

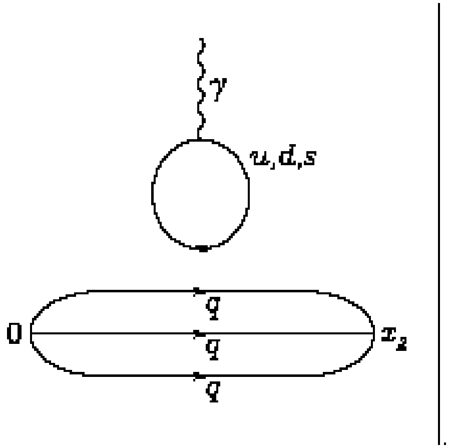
ADELAIDE UNIVERSITY AUSTRALIA

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

Testing Non-Perturbative QCD

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

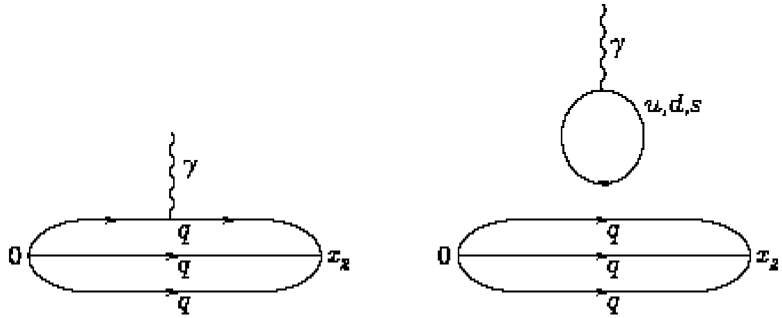




- Checking theoretical calculations versus data constitutes a fundamental test of non-perturbative QCD

Indirect Approach

Leinweber et al., Phys Rev D62 (2000)



CS

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

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

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

(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

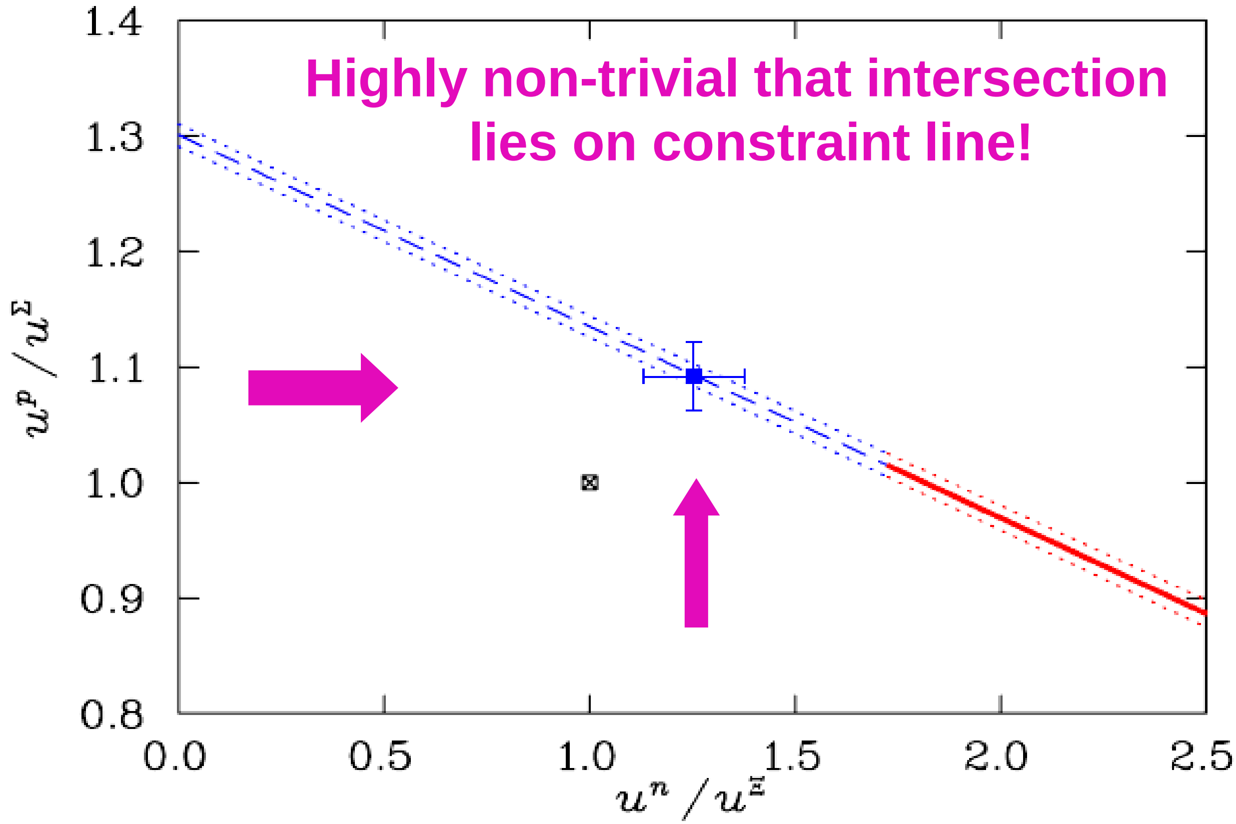
$O_N = 1/3\, [\, n + 2p - (\, u^n / u^\Xi\,)\, (\Xi^0 - \Xi^-)\,]$

CoEPP ARC Centre of Excellence for Particle Physics at the Terascale

ADELAIDE UNIVERSITY AUSTRALIA

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

First Accurate Determination of G_M^s from QCD



1.10±0.03

1.25±0.12

Yields : $G_M^{\,s} = -\,0.046 \pm 0.019\ \mu_N$

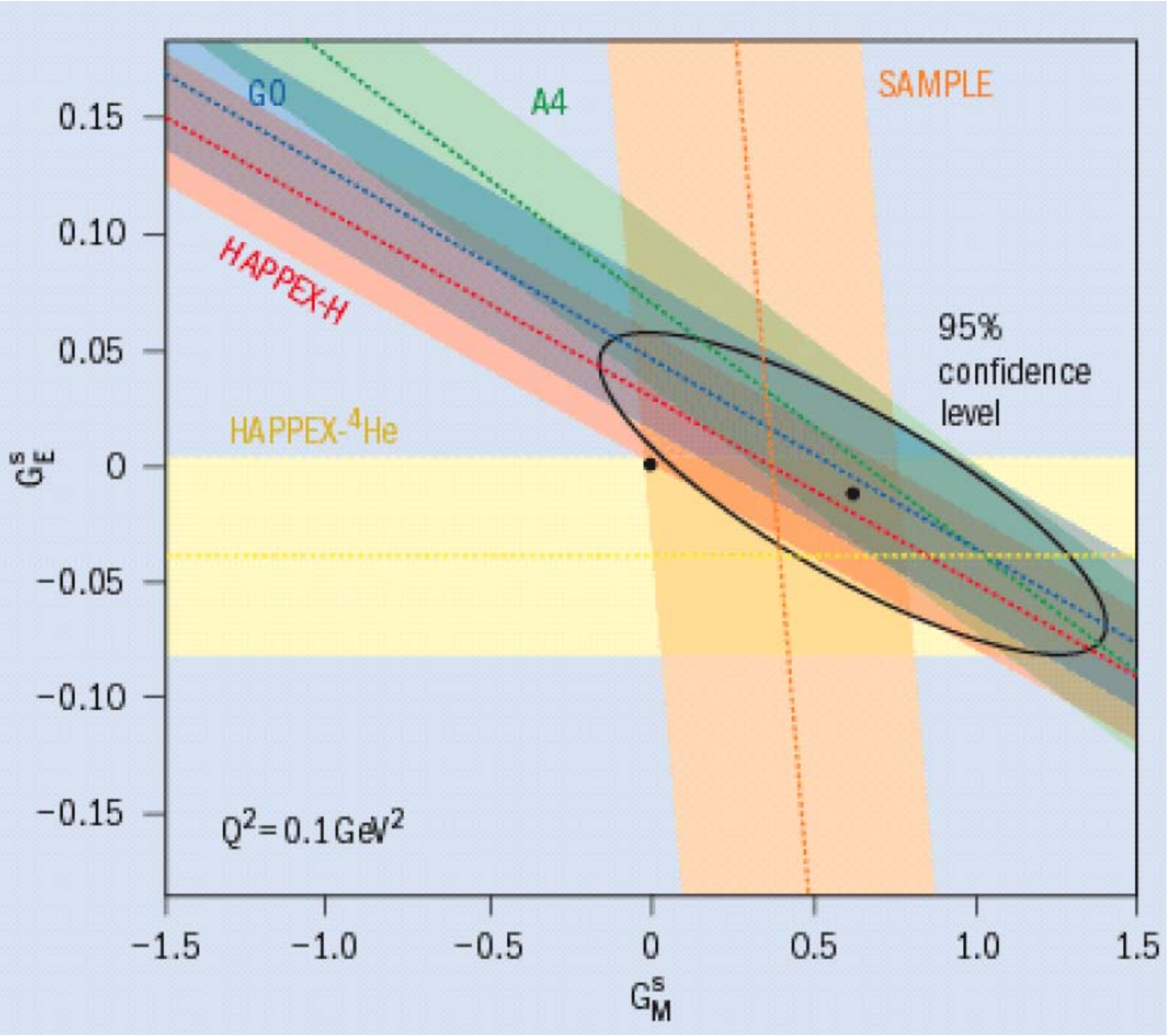
Leinweber et al., PRL 94 (2005) 212001

CoEPP ARC Centre of Excellence for Particle Physics at the Terascale

ADELAIDE UNIVERSITY AUSTRALIA

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

Caveat Emptor – CERN Courier 2005

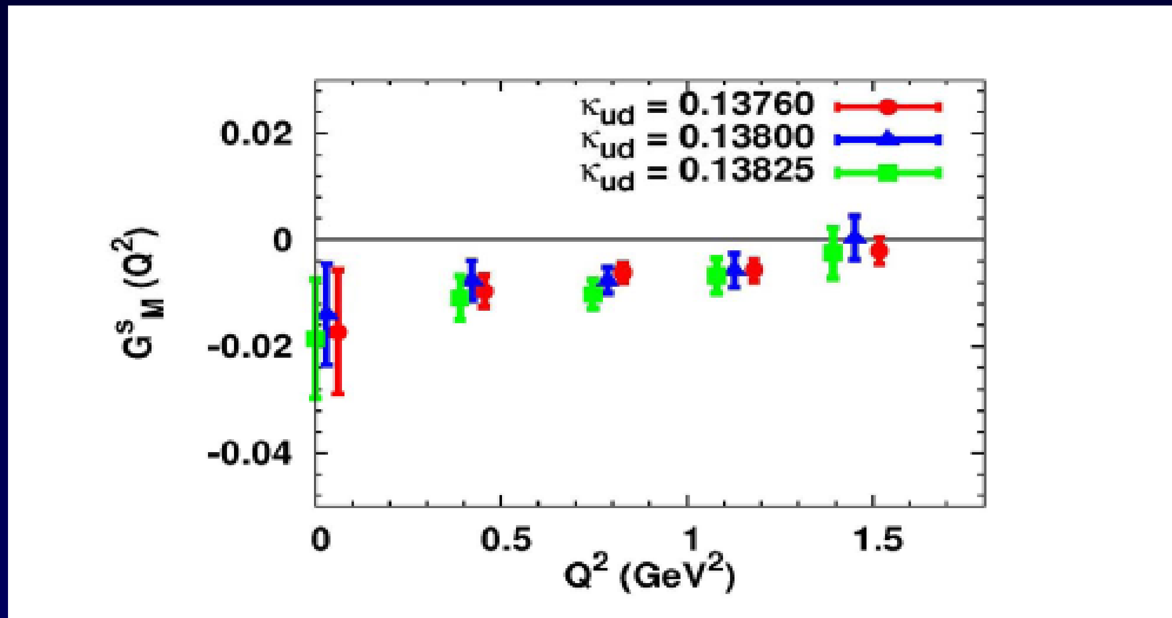


State of the Art Magnetic Moments

	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^Σ	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)

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. Result of Doi et al. increases by factor ~1.8 when light quark mass takes physical value with m_s fixed
(Wang et al., hep-ph/0701082 : Phys Rev D75 (2008))

Experiment: Parity Violating Electron Scattering

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

Neutral-weak form factors

Axial form factor

Assume charge symmetry:

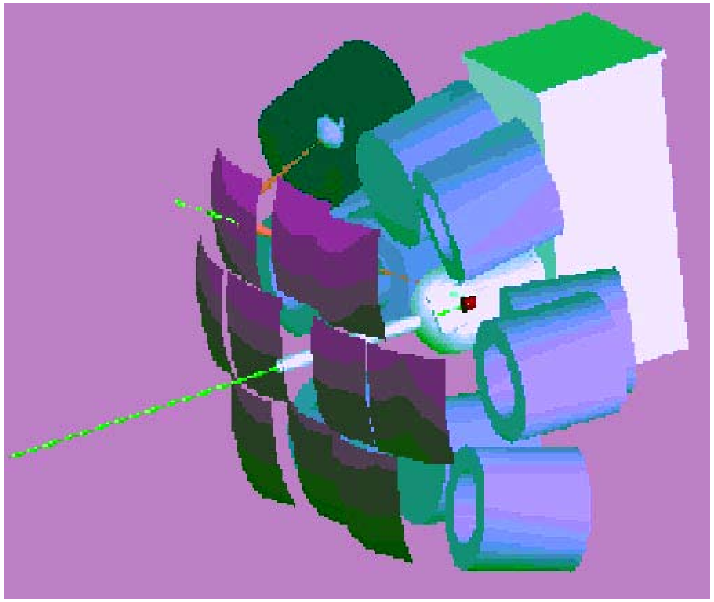
$$4G_{E,M}^{pZ} = \underbrace{(1 - 4\sin^2\theta_W)}_{\text{Proton weak charge (tree level)}} G_{E,M}^{p\gamma} - G_{E,M}^{n\gamma} - \underbrace{G_{E,M}^{s}}_{\text{Strangeness}}$$

Proton weak charge

(tree level)

Strangeness

MIT-Bates & A4 at Mainz

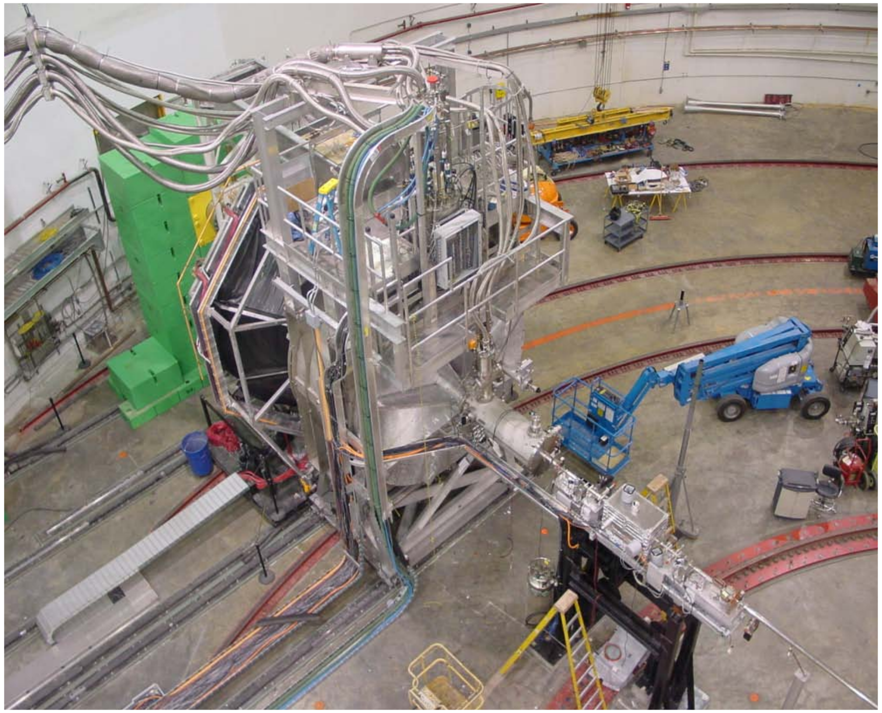


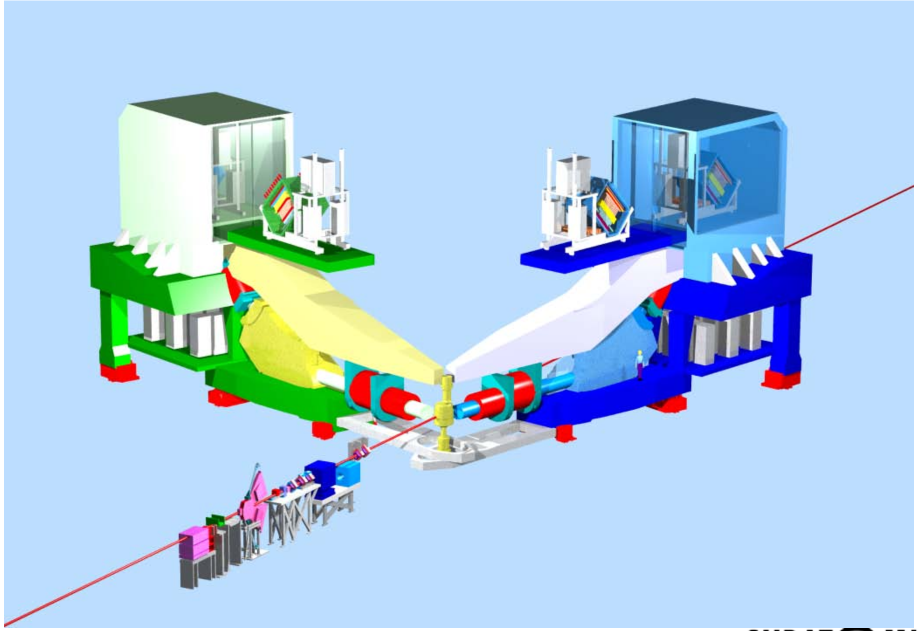
ADELAIDE UNIVERSITY AUSTRALIA

CoEPP ARC Centre of Excellence for Particle Physics at the Terascale

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

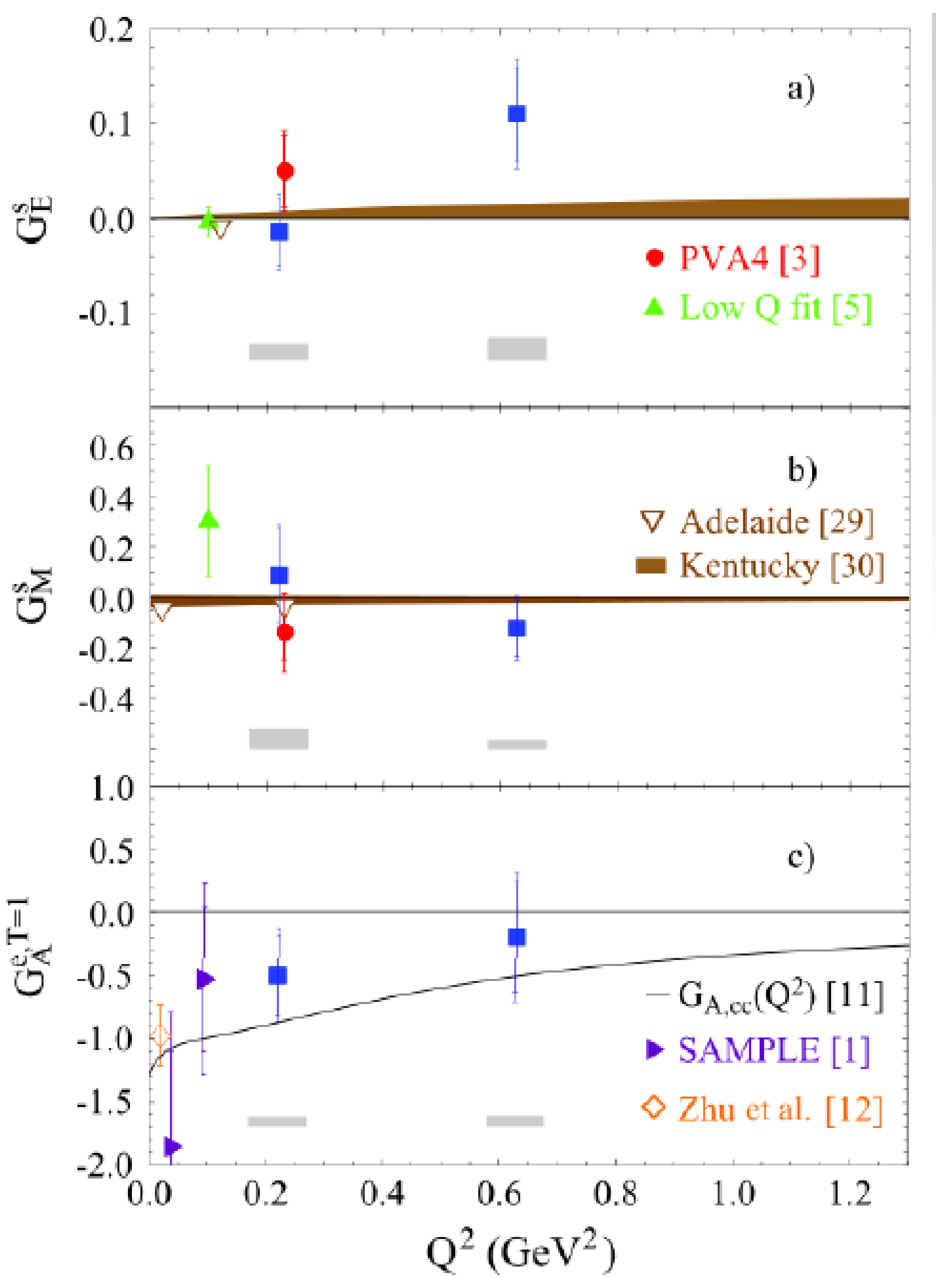
G0 and HAPPEx at Jlab





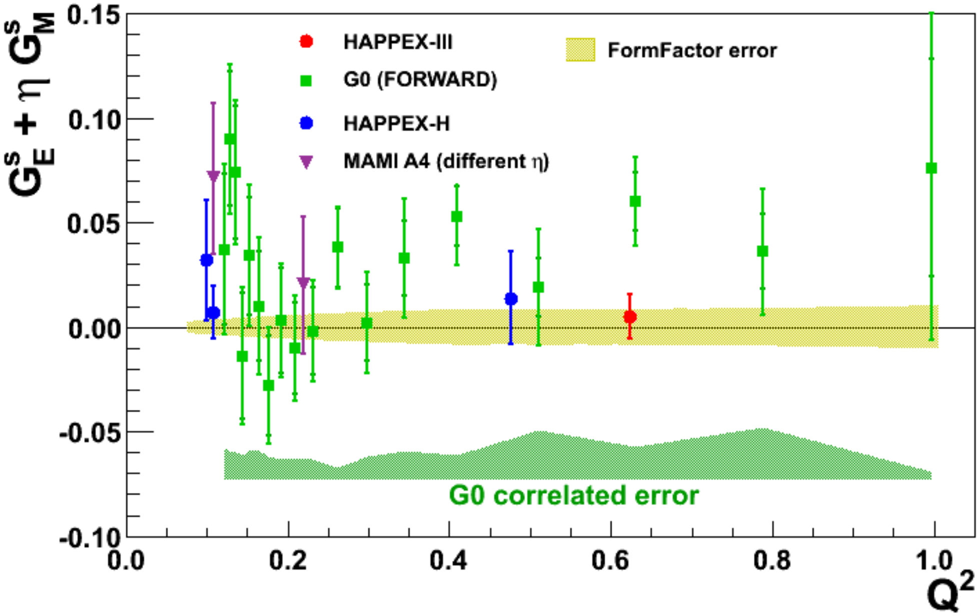
ADELAIDE UNIVERSITY AUSTRALIA

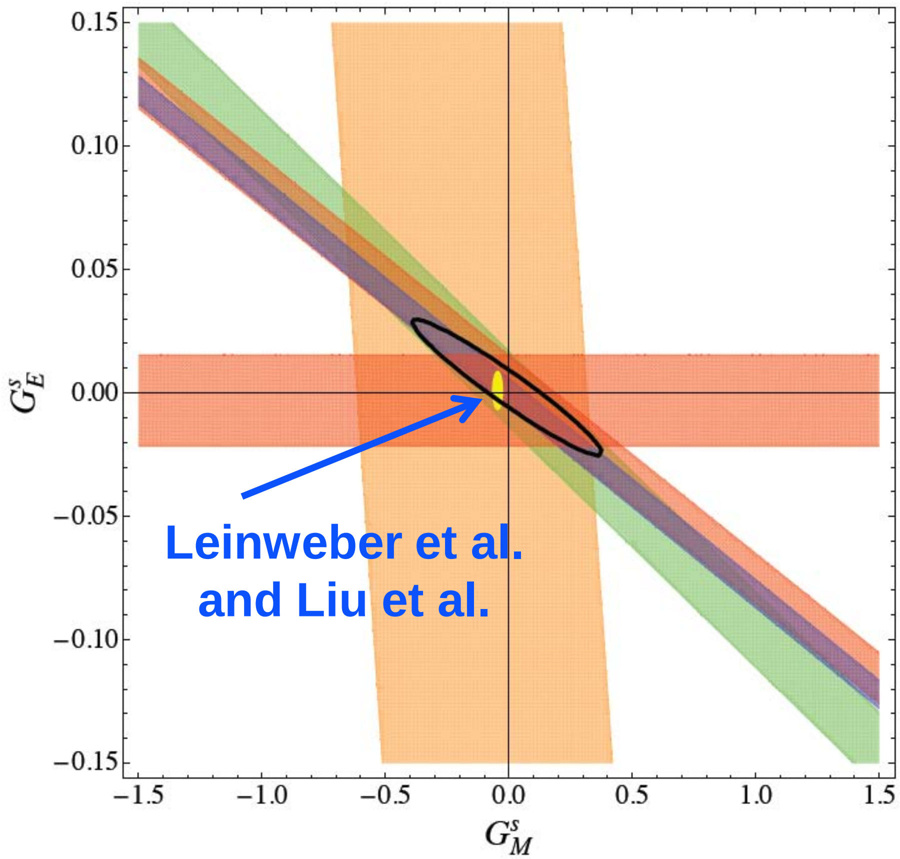
PVES Data by 2010



Data Analysis

Q^2 = 0.1 GeV^2



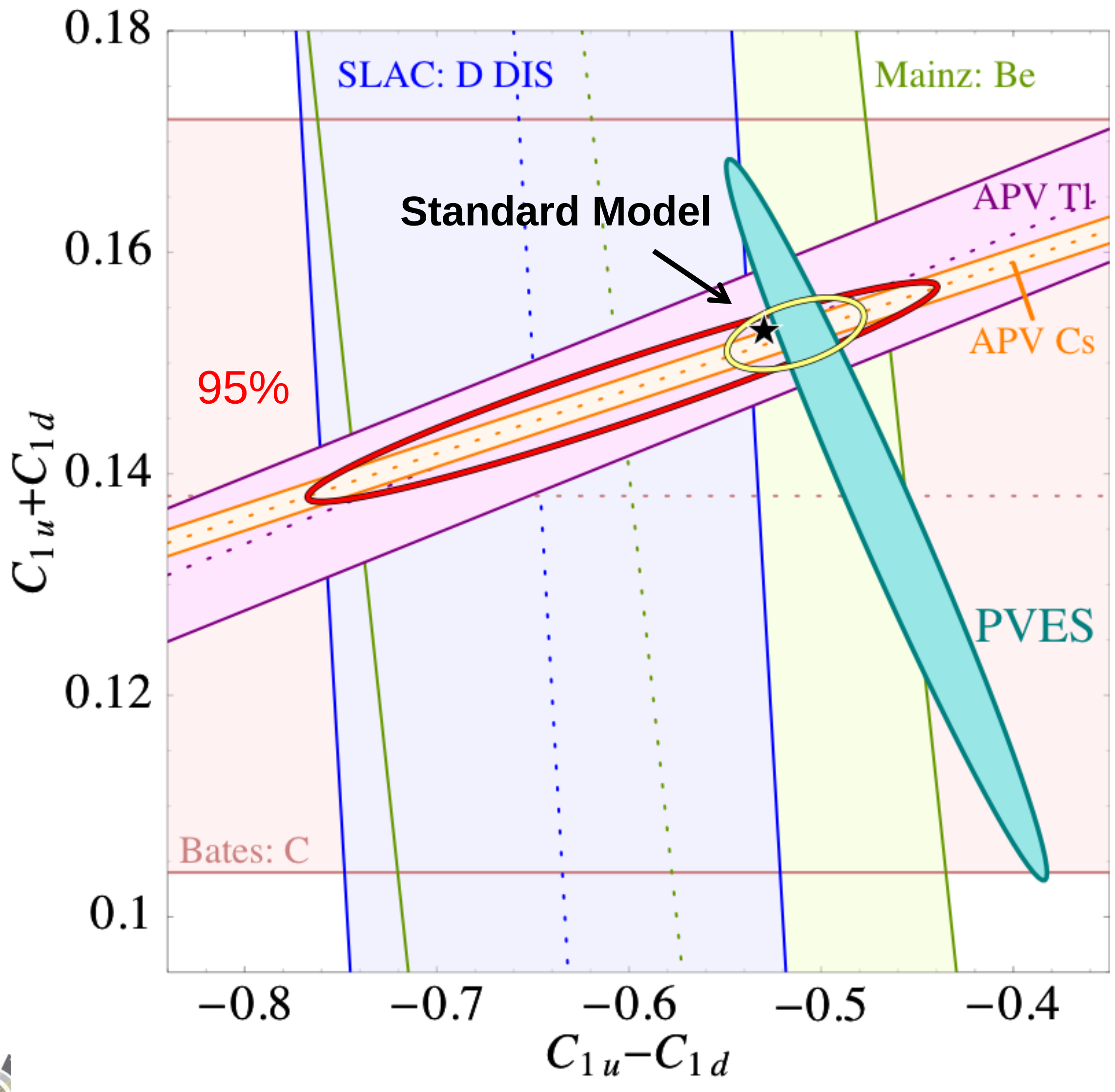


- **QCD analogue of Lamb shift works beautifully !**

Young et al., PRL 99 (2007)122003 & Young arXiv 1004.5163 [nucl-th]


Qweak Working/Collaboration Meeting
TRIUMF
30 July 2008

Major progress on C_{1q} couplings



$$Q_{weak} = 2C_{1u} + C_{1d}$$

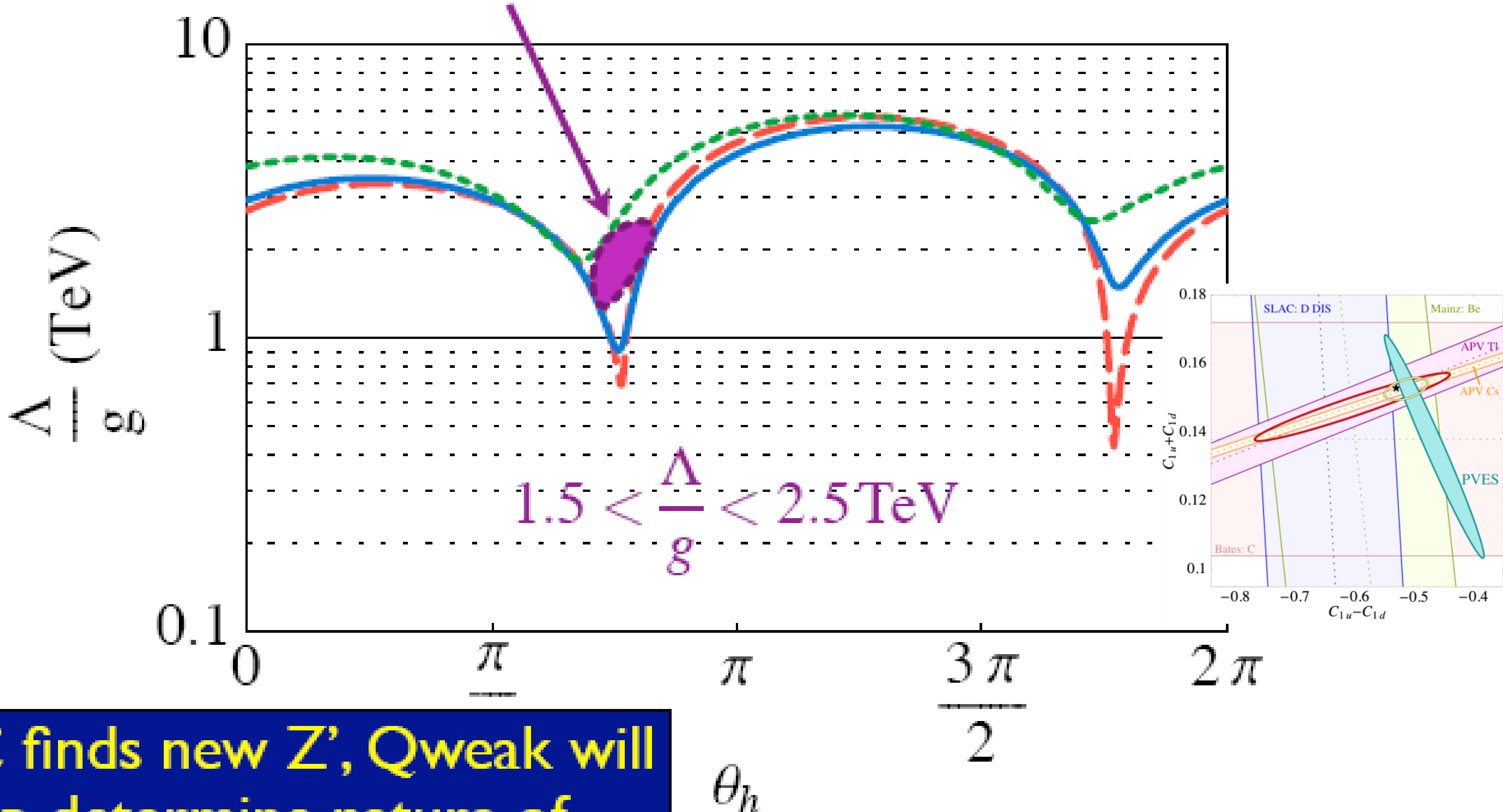
$$L_{eff} \sim C_{1q}\, \bar{e}\gamma^{\mu}\gamma_5 e\, \bar{q}\gamma_{\mu} q$$

Factor of 5 increase in precision of Standard Model test

Young et al., PRL 99, 102002 (2006)

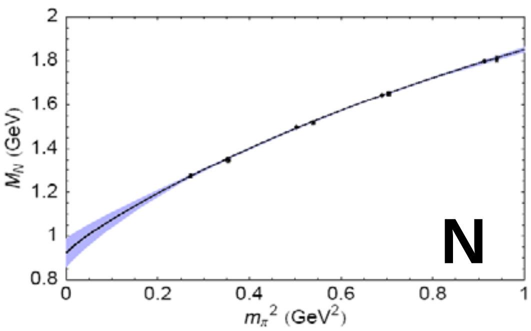
Potential for Q_{weak} Discovery

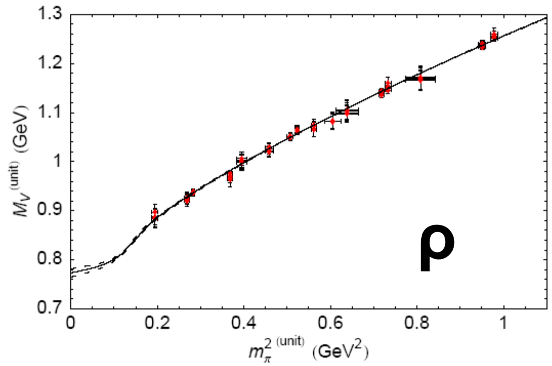
Assume Qweak takes central value of current measurements

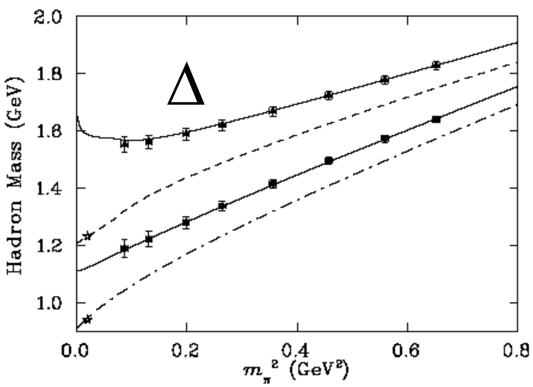


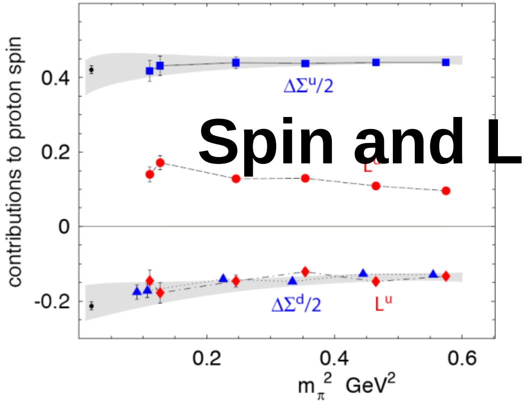
If LHC finds new Z', Qweak will help determine nature of interaction

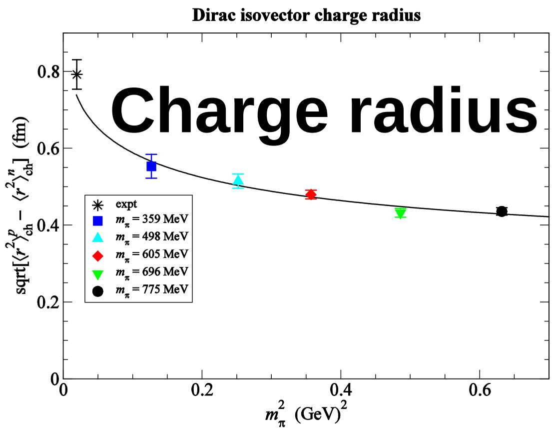
Why are the strange form factors so small?

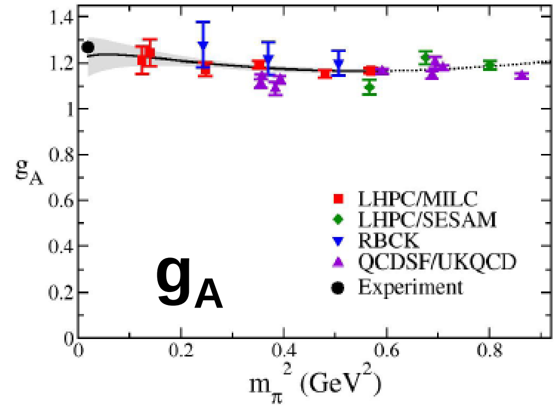


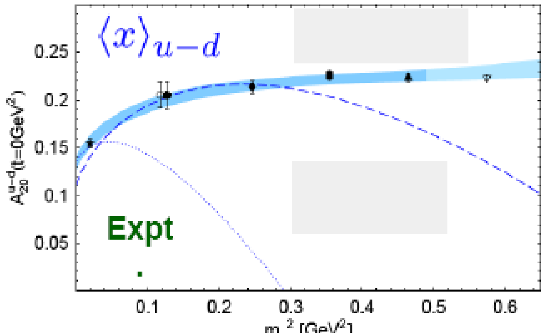












$$a + b\, m_\pi^2 + c\, m_\pi^3 + d\, m_\pi^4 \ln m_\pi + e\, m_\pi^5 + \ldots$$

The smooth behavior for m_π above 400 MeV cannot result from a <u>different</u> cancellation in every case??

Very simple lesson / universal feature of lattice data

- Meson loops are suppressed once the meson

  mass exceeds ~0.4 GeV

  − in this region observables either ~ c M or c/M , with $M = M_0 + m_q$

- This corresponds to a remarkably small current

  mass – m_q ~ 40 MeV

- Maybe scale intrinsic to instantons BUT certainly (as in FRR)

  the finite size of hadron suppresses loops

Strange scalar form factor

(strange σ commutator)

Sigma Commutators

These are a direct measure of the breaking of chiral symmetry in QCD

- $\sigma_{\pi N} = \langle N|\, m_l\, (\bar{u}u + \bar{d}d)\, |N\rangle \sim 45\text{-}65$ **MeV?**

  (Gasser, Leutwyler, Sainio...)

- $\sigma_s = \langle N|\, m_s\, \bar{s}s\, |N\rangle \sim 300$ **MeV?**

  (Kaplan, Manohar, early lattice...)

These are the measure of the contribution of the masses of the quarks to the nucleon mass

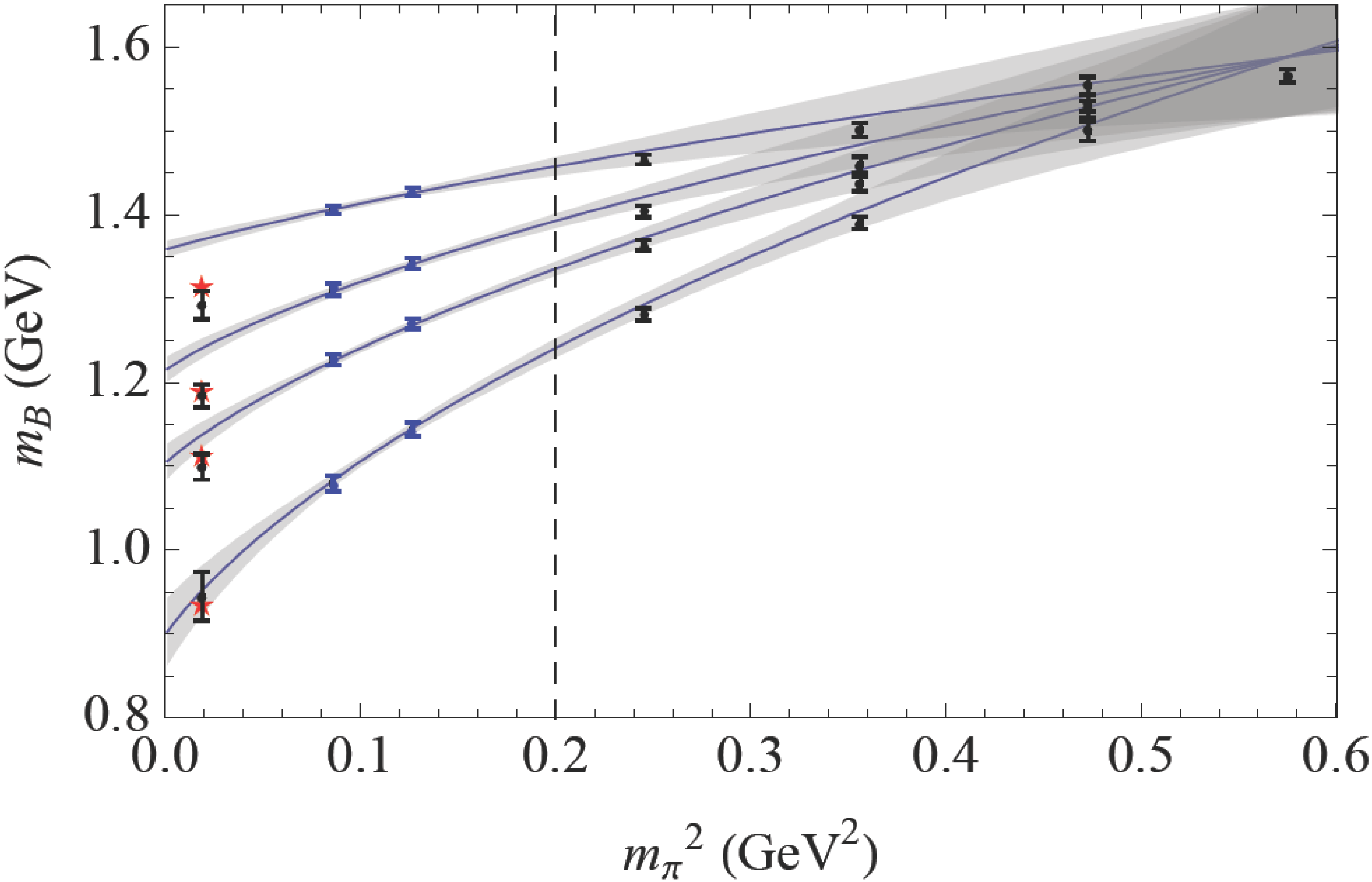
$m_l = (m_u + m_d)/2$

Can use lattice QCD to measure these

- **Feynman-Hellmann theorem:**
  - $\sigma_{\pi N} = m_l \ \partial M_N / \partial m_l$
  - $\sigma_s = m_s \ \partial M_N / \partial m_s$
- **Hence IF we have a reliable parametrization of the mass of the nucleon vs m_π and m_K we can evaluate the σ-terms by differentiation**

Octet Baryon Masses - LHPC Data

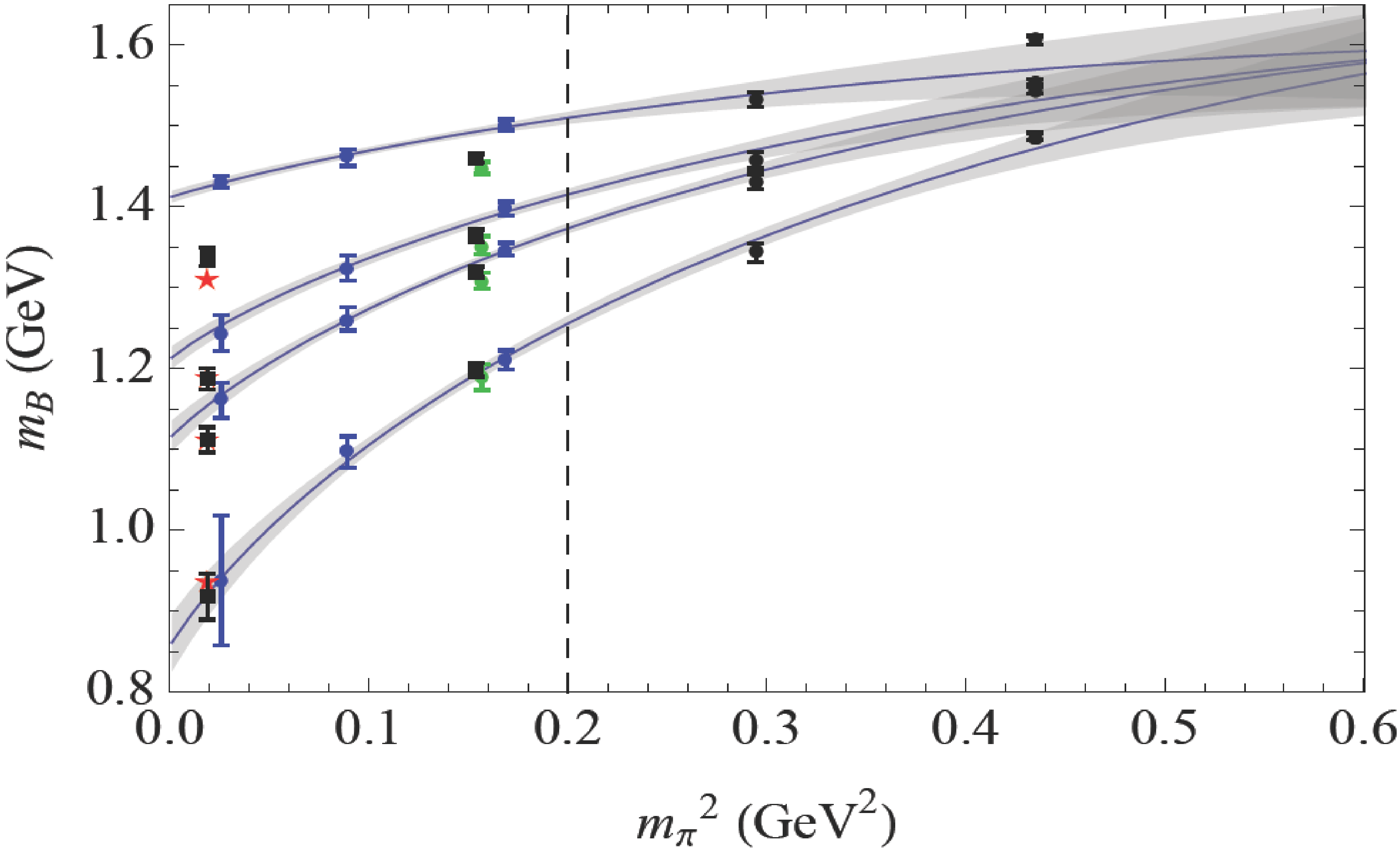
(lattice data: Walker-Loud et al.. arXiv:0806.4549)



Young et al., arXiv:0901.3559 [nucl-th]
Phys Rev D81, 014503 (2010)

PACS-CS Data

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



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 <u>small</u>

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

NOT several 100 MeV !

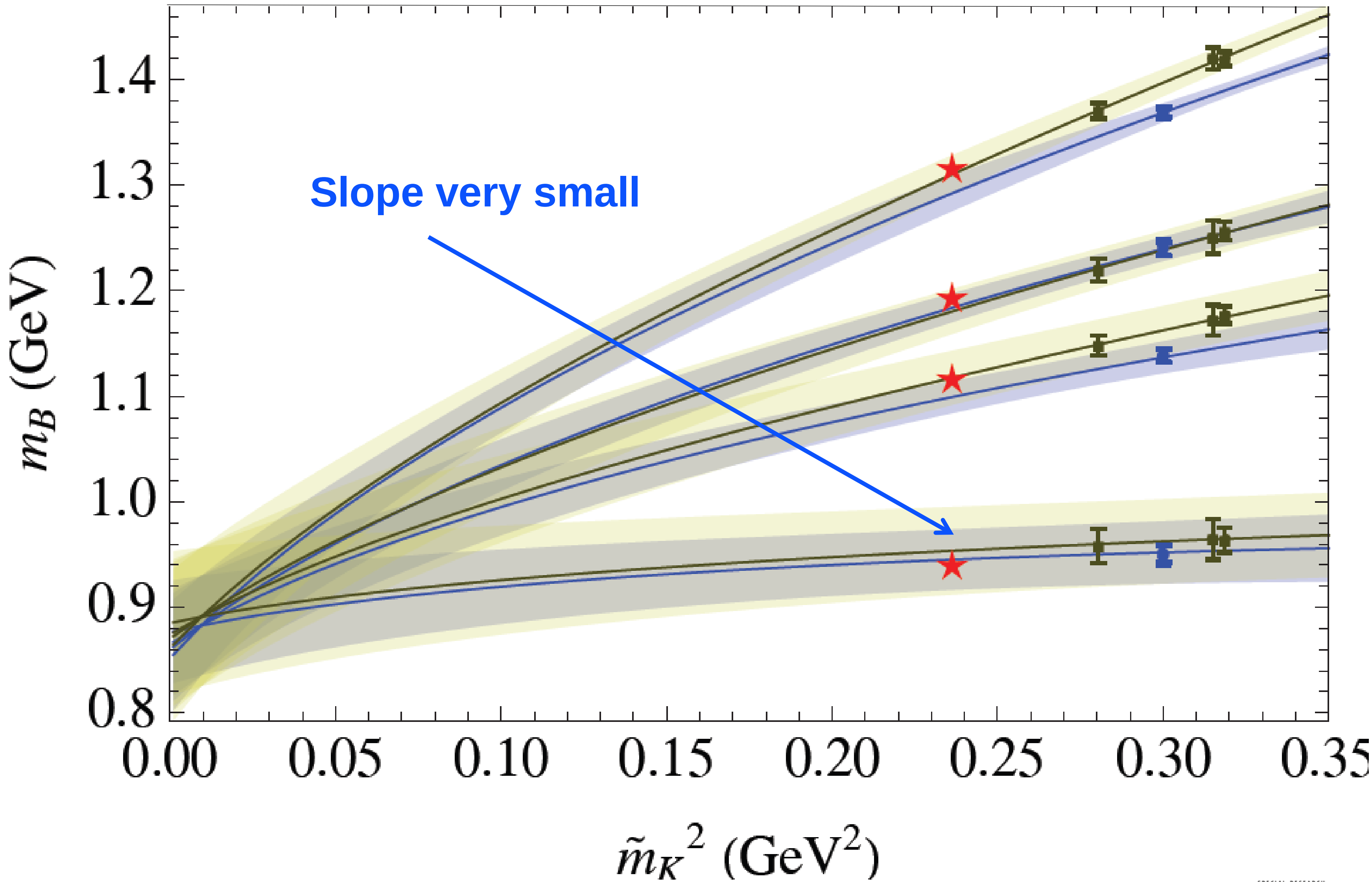
Profound Consequences for Dark Matter Searches

CoEPP

ADELAIDE UNIVERSITY AUSTRALIA

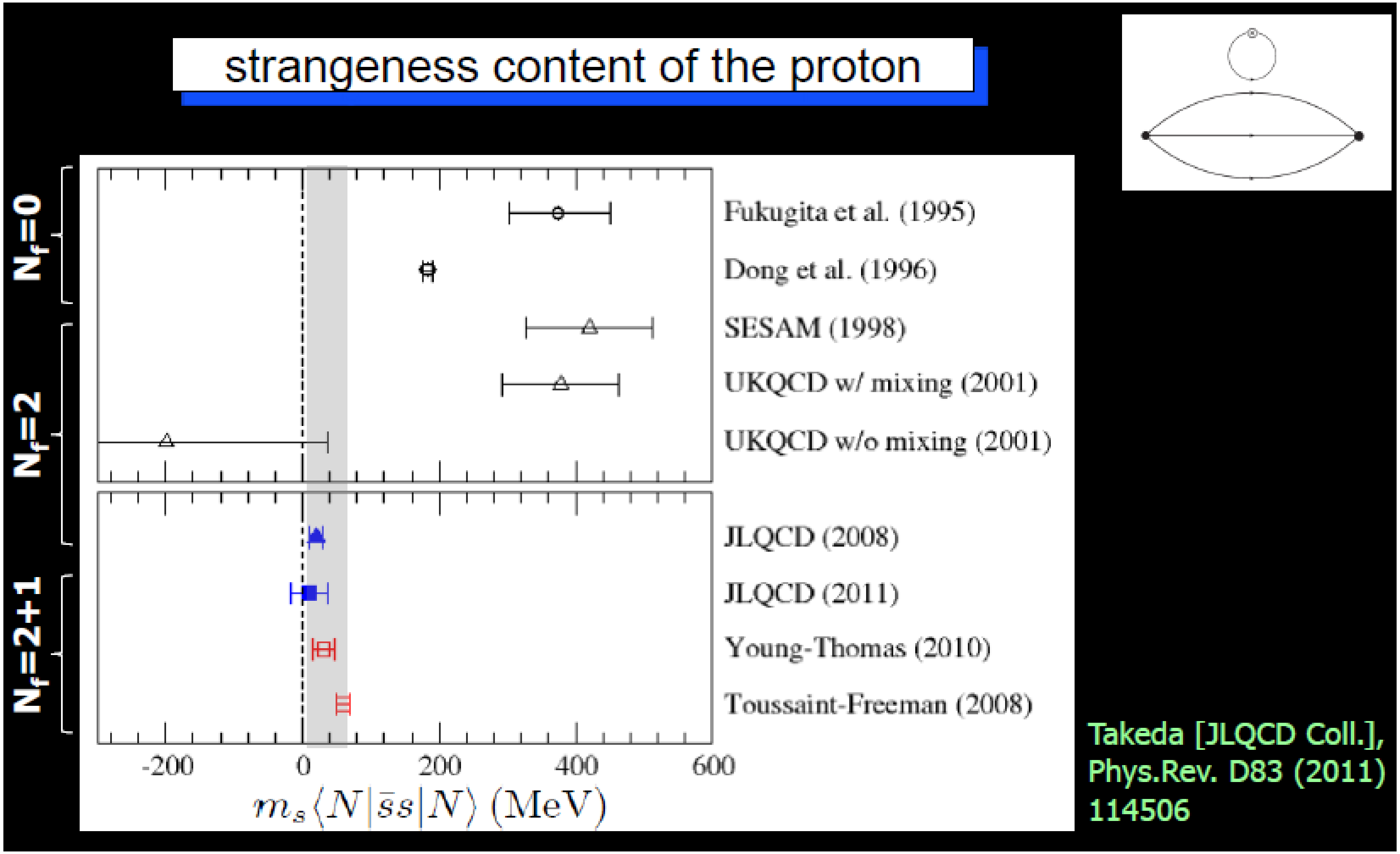
SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

Dependence of Octet Masses on m_s



from Young, AIPCP (2011)

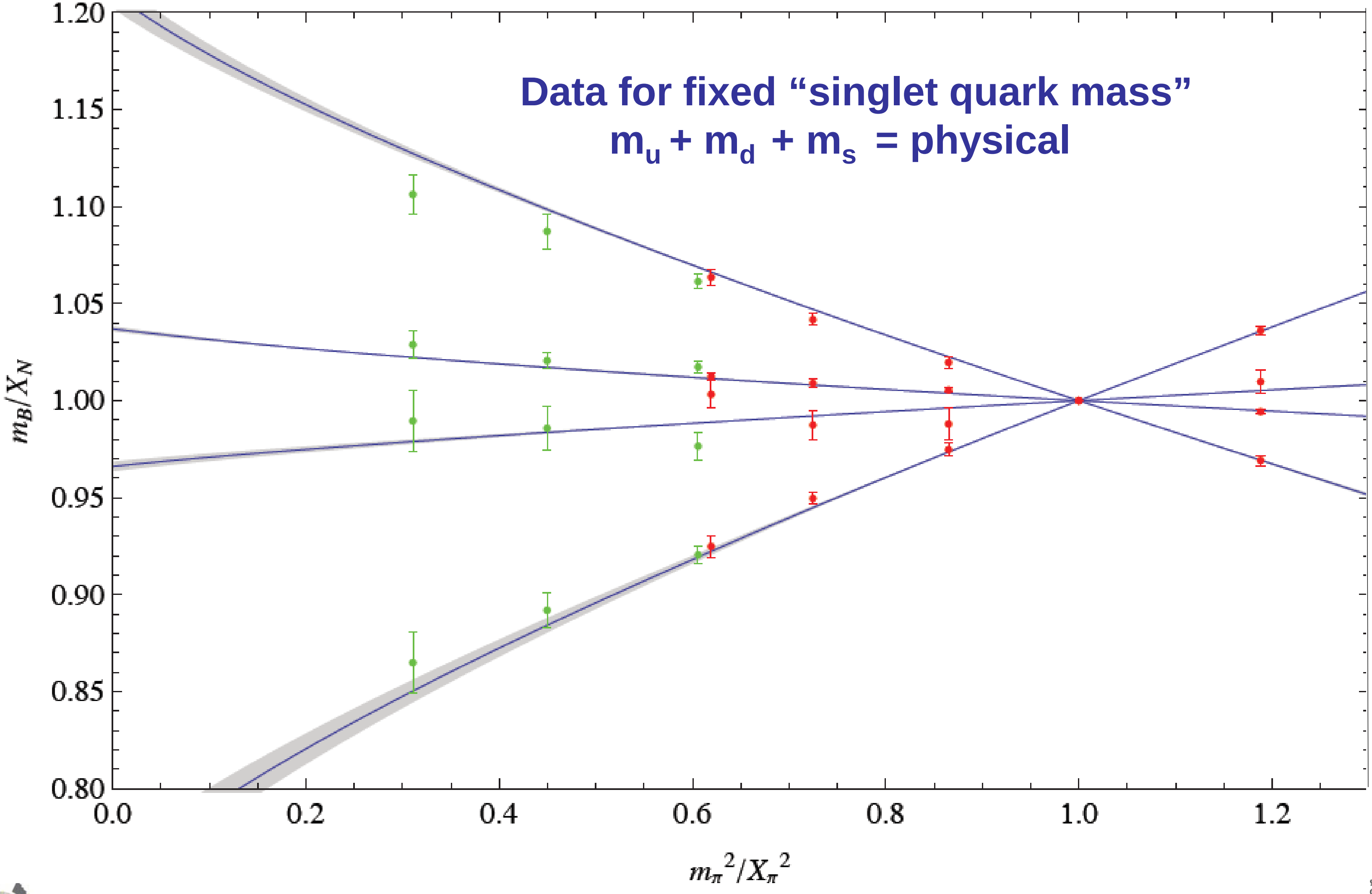
New techniques – new answers



from Hatsuda PANIC 2011

Further check: Comparison with UKQCD data

(Data: Bietenholz et al., Phys.Lett. B690 (2010) 436-441)



Uses same parameters fit to PACS-CS data earlier!

– analysis: Shanahan et al.

ADELAIDE UNIVERSITY AUSTRALIA

CoEPP ARC Centre of Excellence for Particle Physics at the Terascale

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

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.

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

σ terms

Neutralino (0.3 GeV / cc : WMAP)

What Ellis et al. really wanted...

Use naive SU(3) to extract σ_0 from octet masses:

$$\sigma_0 = m_\ell \langle N | \bar{u}u + \bar{d}d - 2\bar{s}s | N \rangle$$

Then use difference from $\sigma_{\pi N}$ to extract what is really needed, namely σ_s

$$\sigma_\ell - \sigma_0 = 2\frac{m_\ell}{m_s}\sigma_s$$

Problem : a small error in σ_0 leads to a huge error in σ_s <u>– its much better to determine σ_s directly</u>!

ADELAIDE UNIVERSITY AUSTRALIA

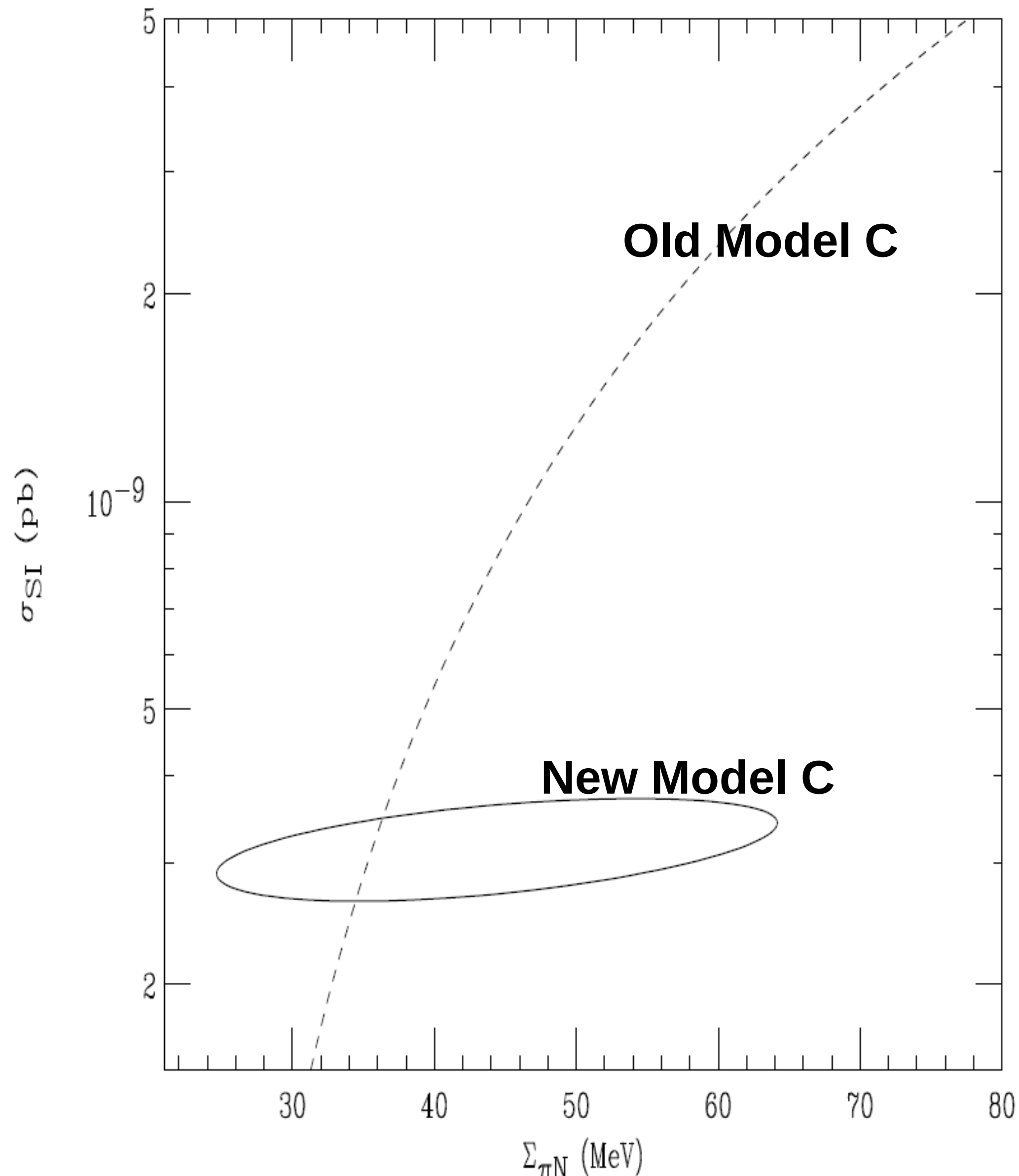
SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

CMSSM Predictions for Dark Matter σ

In response to request by Ellis, Olive & Savage....

Cross section accurately fixed (e.g. "New model C") c.f. using old relation to unknown πN sigma commutator ("Old Model C")

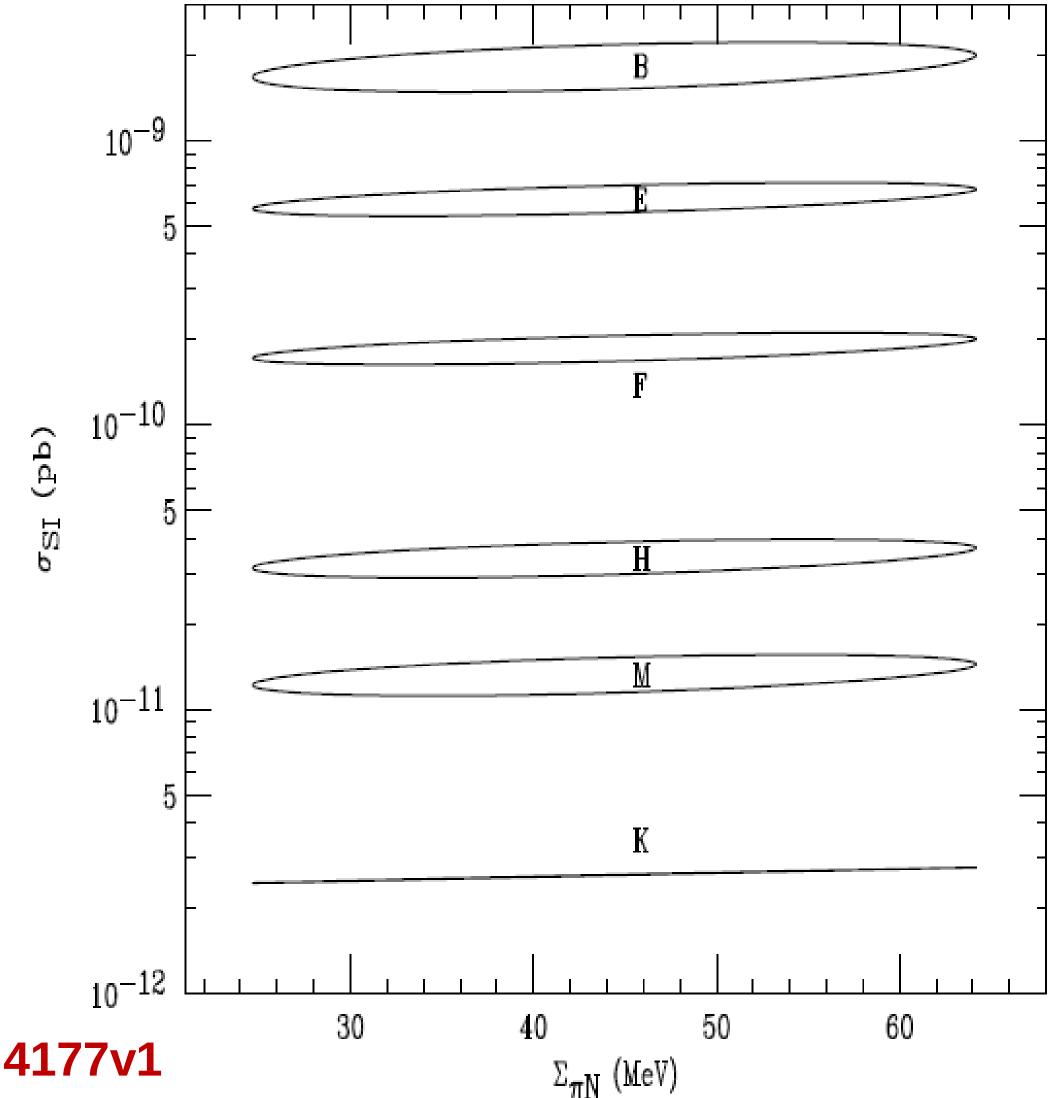
Giedt et al., arXiv: 0907.4177v1
PRL 103 (2009) 201802



CMSSM Predictions for Dark Matter σ

95% CL predictions for all Constrained Minimal Super-Symmetric Standard Model extensions consistent with astrophysical data

Cross sections 1-2 orders of magnitude smaller than before BUT very well determined and separated!



Giedt et al., arXiv: 0907.4177v1
PRL 103 (2009) 201802

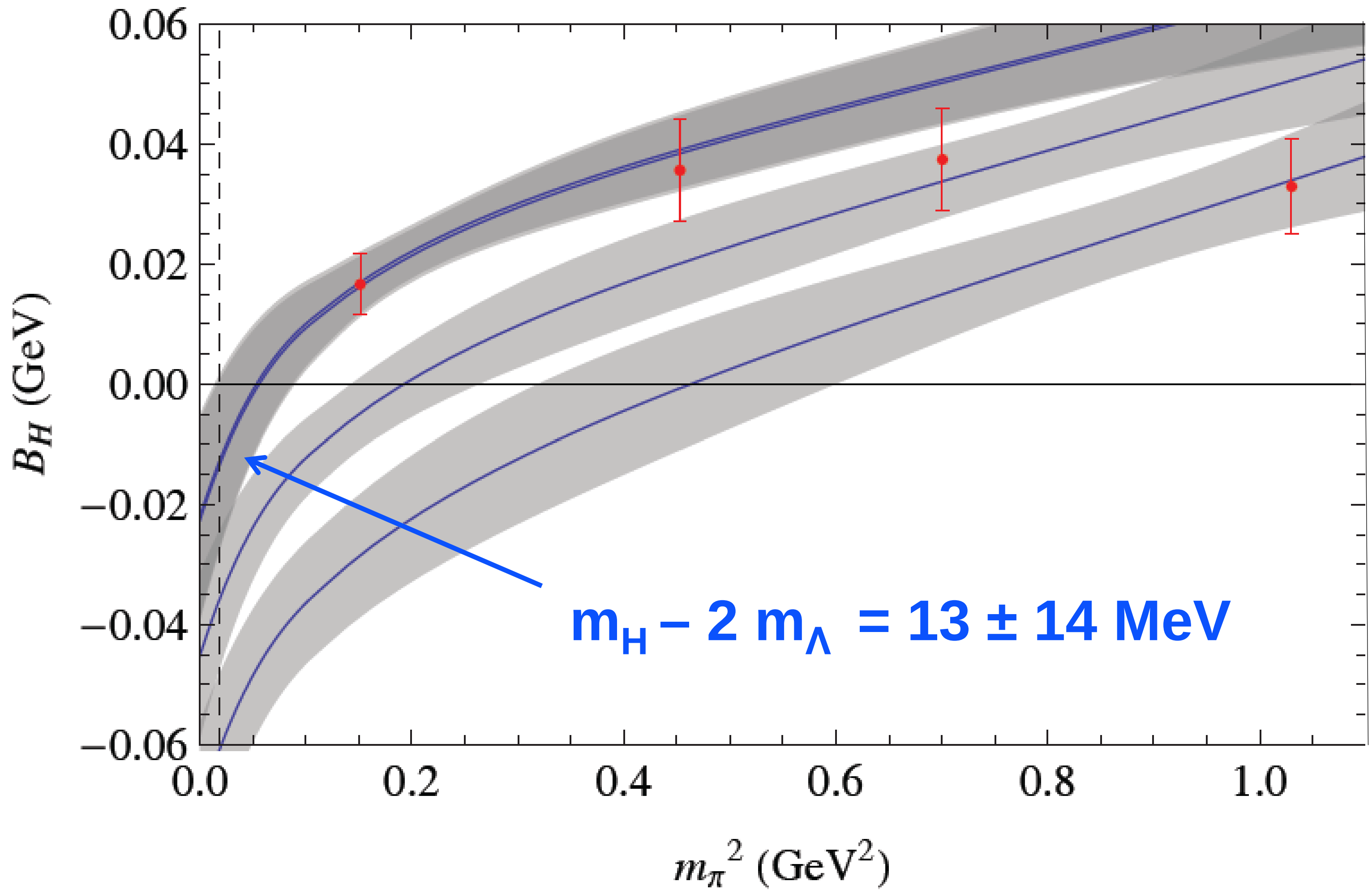
ADELAIDE UNIVERSITY AUSTRALIA

Latest Strange Twist

The H-di-baryon again

Using data from NPLQCD & HAL: H bound at larger m_l

$\rightarrow$ H-di-baryon almost bound at physical masses



Shanahan at al., PRL (arXiv:1106.2851)

ELSEVIER

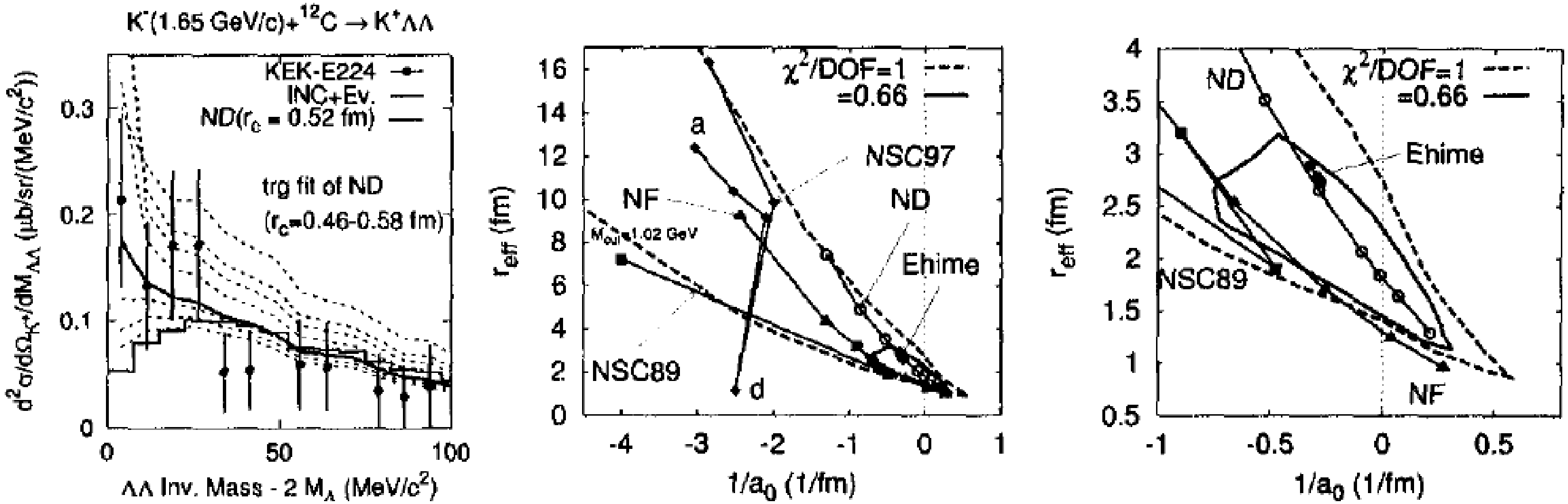
Nuclear Physics A691 (2001) 242c–245c

NUCLEAR PHYSICS A

www.elsevier.com/locate/npe

$\Lambda - \Lambda$ correlation in (K^-, K^+) reaction — Is there a virtual pole ?

A. Ohnishi[a], Y. Hirata[a,b], Y. Nara[b,c], S. Shinmura[d] and Y. Akaishi[e]

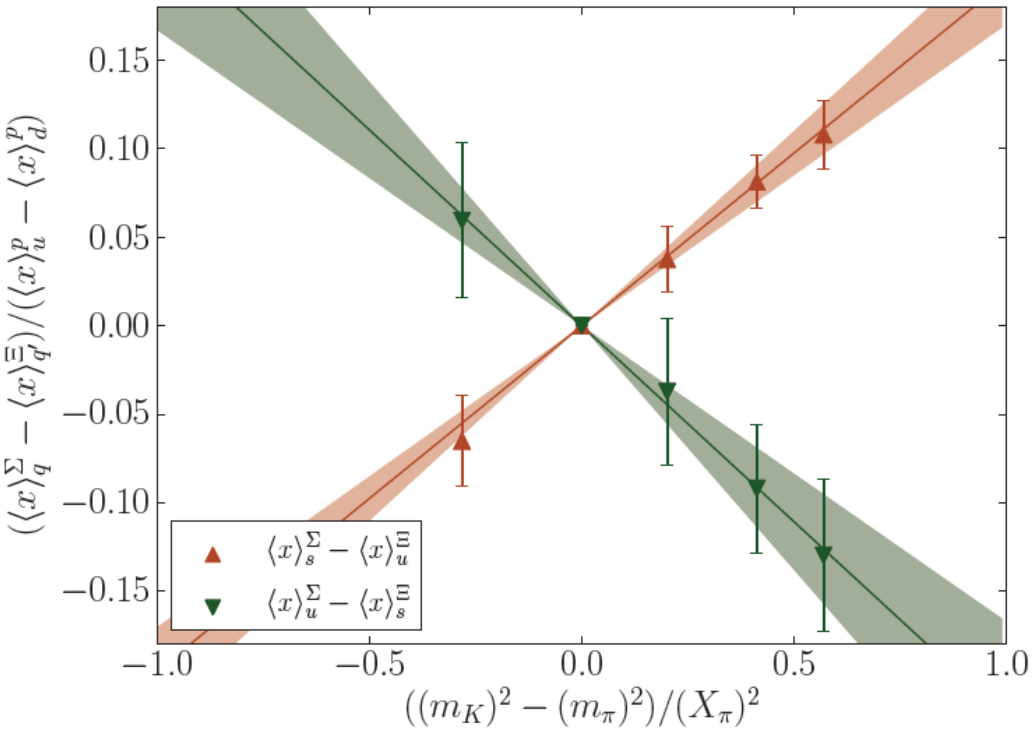


In this paper, we have studied the hyperon momentum distribution and correlation between $\Lambda\Lambda$ in (K^-, K^+) reactions. Global understanding of K^+ and Λ momentum distribution is achieved in a microscopic transport model. The correlation function analysis suggests that attractive $\Lambda\Lambda$ interaction is necessary, and the best fit interaction makes $\Lambda\Lambda$ system barely unbound. It may be possible that a virtual pole of $\Lambda\Lambda$ system would exist. Higher statistics data is desired to determine $\Lambda\Lambda$ interaction more precisely.

Charge Symmetry Violation

– s-quark as heavy d

Lattice QCD − Octet Moments Probe CSV



$$\frac{\delta u}{\langle x\rangle^p_{u-d}} = \frac{m_\delta}{\overline{m}_q} \frac{(\langle x\rangle_u^{\Sigma^+} - \langle x\rangle_s^{\Xi^0})/\langle x\rangle^p_{u-d}}{(m_K^2 - m_\pi^2)/X_\pi^2}$$

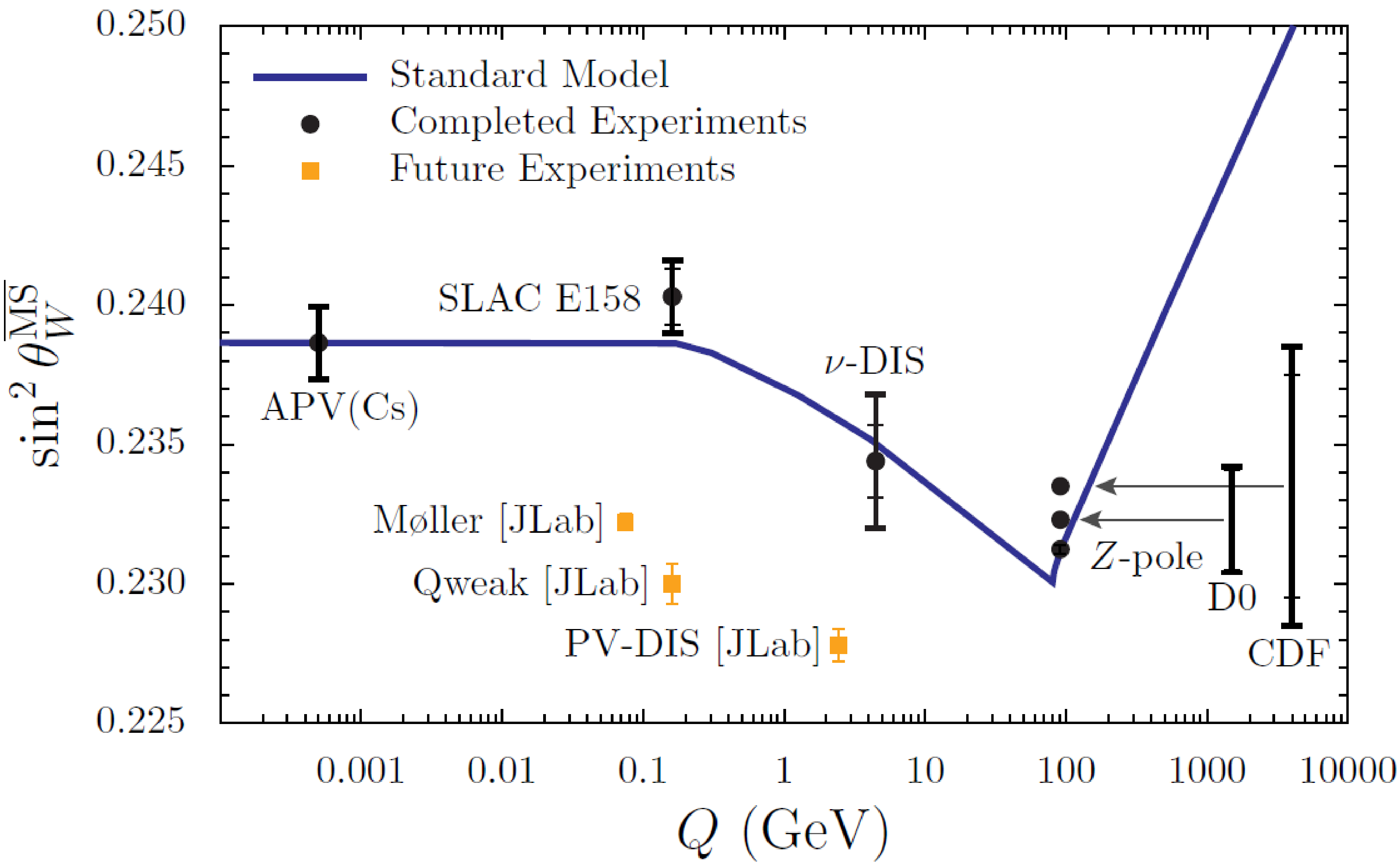
$$\frac{\delta d}{\langle x\rangle^p_{u-d}} = \frac{m_\delta}{\overline{m}_q} \frac{(\langle x\rangle_s^{\Sigma^+} - \langle x\rangle_u^{\Xi^0})/\langle x\rangle^p_{u-d}}{(m_K^2 - m_\pi^2)/X_\pi^2}$$

Deduce: $\delta u = -0.0023(6), \quad \delta d = 0.0020(3)$

- **in excellent agreement with phenomenological estimates of Rodionov *et al*.** $\delta u^- = -0.0014$ **and** $\delta d^- = 0.0015$

Horsley et al., arXiv: 1012.0215 [hep-lat]
Phys Rev D83 (2011) 051501(R)

The Standard Model works… again



Bentz et al., Phys Lett B693 (2010) 462
(arXiv: 0908.3198)

Summary of Corrections to NuTeV Analysis

- **Isovector EMC effect:** $\Delta R^{\rho^0} = -0.0019 \pm 0.0006$
  - **using NuTeV functional**
- **CSV:** $\Delta R^{\mathrm{CSV}} = -0.0026 \pm 0.0011$
  - **again using NuTeV functional**
- **Strangeness:** $\Delta R^{s} =$ - 0.0011 ± 0.0014
  - **this is largest uncertainty (systematic error) ; desperate need for an accurate determination of $s^-(x)$, e.g. semi-inclusive DIS?**
- **Final result:** $\sin^2\theta_W = 0.2221 \pm 0.0013(\mathrm{stat}) \pm 0.0020(\mathrm{syst})$
  - **c.f. Standard Model:** $\sin^2\theta_W = 0.2227 \pm 0.0004$

CoEPP ARC Centre of Excellence for Particle Physics at the Terascale

ADELAIDE UNIVERSITY AUSTRALIA

Bentz et al., Phys Lett B693 (2010) 462 (arXiv: 0908.3198)

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

Strange Quark Sea – still mysterious

PHYSICAL REVIEW D **79**, 094502 (2009)

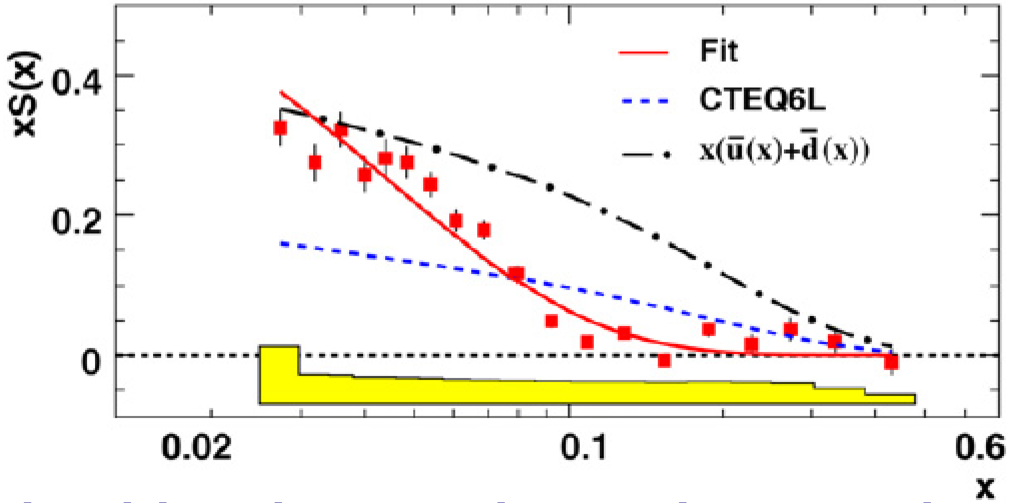
Moments of nucleon's parton distribution for the sea and valence quarks from lattice QCD

M. Deka,[1,*] T. Streuer,[2] T. Doi,[1] S. J. Dong,[1] T. Draper,[1] K. F. Liu,[1] N. Mathur,[3] and A. W. Thomas[4]

We provide results for both the connected and disconnected insertions. The perturbatively renormalized $\langle x \rangle$ for the strange quark at $\mu = 2$ GeV is $\langle x \rangle_{s+\bar{s}} = 0.027 \pm 0.006$ which is consistent with the experimental result.

Hermes:

Physics Letters B 666 (2008) 446–450



Odd shape: interpreted (e.g.) by Chang and Peng (PRL 2011) as 5-q component of nucleon wave function

? LO analysis & model dependence? − needs more work!

CoEPP ARC Centre of Excellence for Particle Physics at the Terascale

ADELAIDE UNIVERSITY AUSTRALIA

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

Summary

- QCD yields excellent agreement with experiment

  − success analogous to Lamb shift in QED

- σ_s evaluated using new techniques and order of

  magnitude smaller than previously thought

  − with dramatic consequences for Dark Matter searches

- Rumours of the death of the H-di-baryon may be

  "much exaggerated" − likely just unbound!

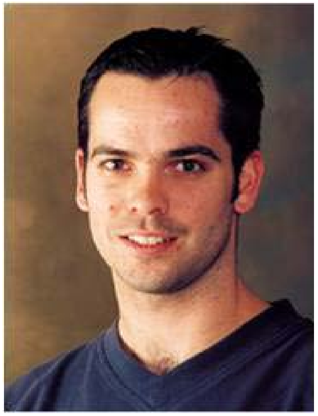
Summary (cont.)

- Can use lattice simulations with s acting as a heavy d-quark – to probe CSV

- Of critical importance to interpretation of NuTeV expt.

- Strange sea also needed there AND presents its own mysteries − e.g. apparentlyodd shape of $s + \bar{s}$

- $s - \bar{s}$ likely small (meson cloud picture – recall kaon loops suppressed as general result of lattice studies)



Dynamical Symmetry Breaking in the Sea of the Nucleon

$$(S - \bar{S})^{(n)} = \int_0^1 dx\, x^n [s(x) - \bar{s}(x)] = V_\Lambda^{(n)} \cdot f_{\Lambda K}^{(n)} - V_K^{(n)} \cdot f_{K\Lambda}^{(n)}$$

$$f_{K\Lambda}^{(n)}|_{\mathrm{LNA}} = \frac{27}{25} \frac{M^2 g_A^2}{(4\pi f_\pi)^2} (M_\Lambda - M)^2 (-1)^n \frac{m_K^{2n+2}}{\Delta M^{2n+4}} \log(m_K^2/\mu^2),$$

nth moment of $\bar{s}$ is of order $m_K^{2n+2} \log m_K^2$

LNA contribution to the nth moment of s is of order $m_K^2 \log m_K^2$

Compared with the first case: dbar-ubar asymmetry in the proton

$$f_{\pi N}^{(n)}|_{\mathrm{LNA}} = [3M^2 g_A^2/(4\pi f_\pi)^2] \times \begin{cases} (-1)^{n/2}[(n+4)/(2n+4)](m_\pi/M)^{n+2} \log(m_\pi^2/\mu^2) & (n = 0, 2, 4, \ldots) \\ (-1)^{(n+1)/2}[(n+5)/2](m_\pi/M)^{n+3} \log(m_\pi^2/\mu^2) & (n = 1, 3, 5, \ldots) \end{cases}$$

$$(\overline{D} - \overline{U})^{(n)} = -\frac{1}{3} V_\pi^{(n)} \cdot f_{\pi\Delta}^{(n)}$$

Strange Quark Asymmetry

- **Required in principle by chiral symmetry (s and $\bar{s}$ have different chiral behaviour*)**

- **Experimental constraint primarily through opposite sign di-muon production with neutrinos (CCFR & NuTeV)**

	$\langle x\, s^- \rangle$	ΔR^s	ΔR^{total}	$\sin^2\theta_W \pm$ syst.
Mason *et al.* [8]	0.00196 ± 0.00143	-0.0018 ± 0.0013	-0.0063 ± 0.0018	0.2214 ± 0.0020
NNPDF [9]	0.0005 ± 0.0086	-0.0005 ± 0.0078	-0.0050 ± 0.0079	$0.2227 \pm large$
Alekhin *et al.* [31]	$0.0013 \pm 0.0009 \pm 0.0002$	$-0.0012 \pm 0.0008 \pm 0.0002$	-0.0057 ± 0.0015	0.2220 ± 0.0017
MSTW [32]	$0.0016^{+0.0011}_{-0.0009}$	$-0.0014^{-0.0010}_{+0.0008}$	-0.0059 ± 0.0015	0.2218 ± 0.0018
CTEQ [33]	$0.0018^{+0.0016}_{-0.0004}$	$-0.0016^{+0.0014}_{-0.0004}$	$-0.0061^{+0.0019}_{-0.0013}$	$0.2216^{+0.0021}_{-0.0016}$
This work (Eq. (10))	0.0 ± 0.0020	0.0 ± 0.0018	-0.0045 ± 0.0022	0.2232 ± 0.0024

*** Signal & Thomas, Phys Lett B191 (1987) 205; Thomas et al., PRL 85 (2000) 2892**

CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale
ADELAIDE UNIVERSITY AUSTRALIA
SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

Separate Neutrino and Anti-Neutrino Ratios

- **Biggest criticism of this explanation was that NuTeV actually measured R^{ν} and $R^{\bar{\nu}}$, separately: Claim we should compare directly with these.**

- **Have done this:**

$$\delta R^{\nu} = \frac{2\left(3\, g_{Lu}^2 + g_{Ru}^2\right)\left\langle x_A\, u_A^- - x_A\, d_A^- \right\rangle}{\left\langle 3\, x_A\, u_A + 3\, x_A\, d_A + x_A\, \bar{u}_A + x_A\, \bar{d}_A + 6\, x_A\, s_A \right\rangle}$$

$$\delta R^{\bar{\nu}} = \frac{-2\left(3\, g_{Rd}^2 + g_{Ld}^2\right)\left\langle x_A\, u_A^- - x_A\, d_A^- \right\rangle}{\left\langle x_A\, u_A + x_A\, d_A + 3\, x_A\, \bar{u}_A + 3\, x_A\, \bar{d}_A + 6\, x_A\, \bar{s}_A \right\rangle}$$

- **Then R^{ν} moves from 0.3916 ± 0.0013 c.f. 0.3950 in the Standard Model to 0.3933 ± 0.0015;**

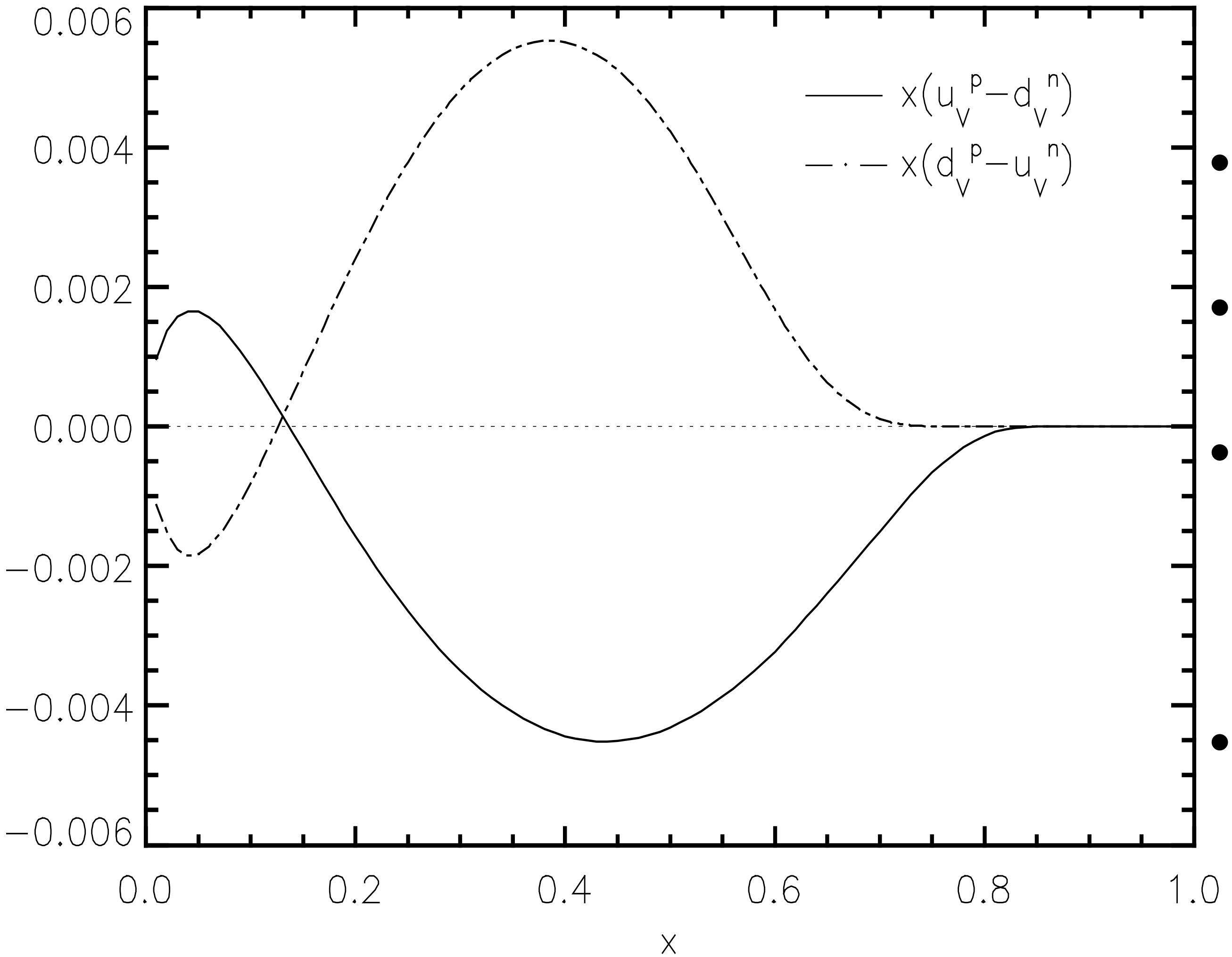
  $R^{\bar{\nu}}$ **moves from 0.4050 ± 0.0027 to 0.4034 ± 0.0028, c.f. 0.4066 in SM**

- **This is tremendous improvement : χ^2 changes from 7.2 to 2.6 for the two ratios!**

ADELAIDE UNIVERSITY AUSTRALIA

Bentz et al., Phys Lett B693 (2010) 462 (arXiv: 0908.3198)

Application to Charge Symmetry Violation



- **d in p : uu left**
- **u in n : dd left**
- **Hence m_2 lower by about 4 MeV for d in p than u in n**
- **Hence $d^p > u^p$ at large x.**

From: Rodionov et al., Mod Phys Lett A9 (1994) 1799

CoEPP ARC Centre of Excellence for Particle Physics at the Terascale

ADELAIDE UNIVERSITY AUSTRALIA

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

Remarkably Similar to MRST Fit 10 Years Later

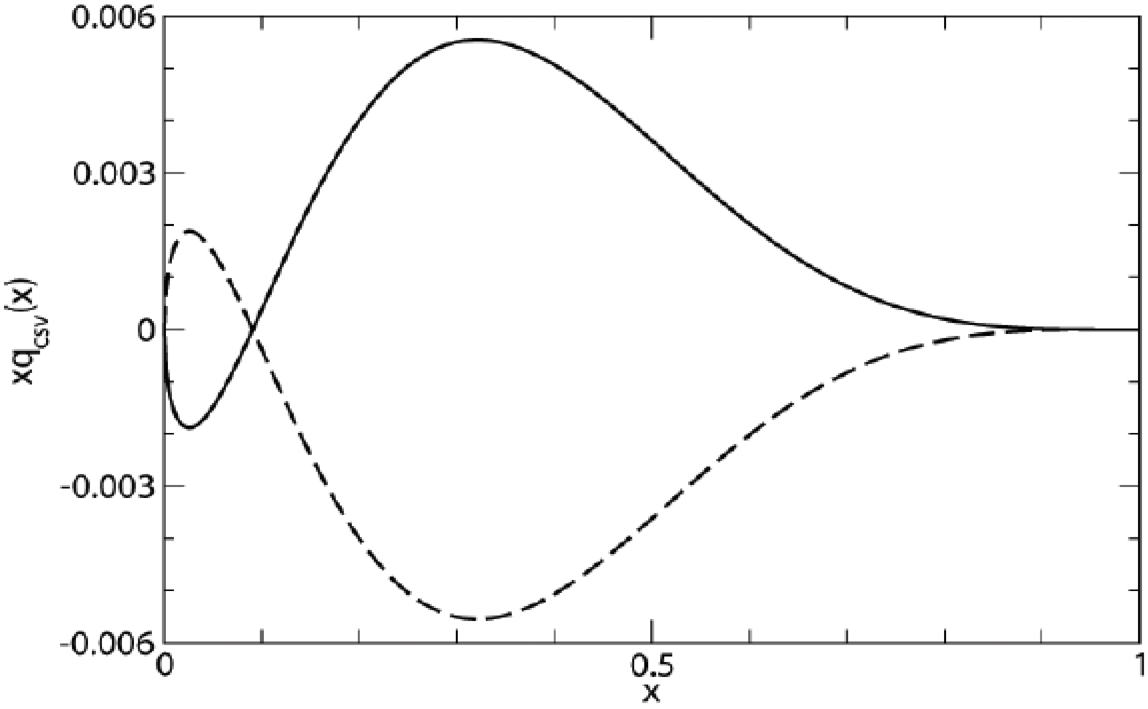


FIG. 5: The phenomenological valence quark CSV function from Ref. [23], corresponding to best fit value $\kappa = -0.2$ defined in Eq. (35). Solid curve: $x\delta d_{\rm v}$; dashed curve: $x\delta u_{\rm v}$.