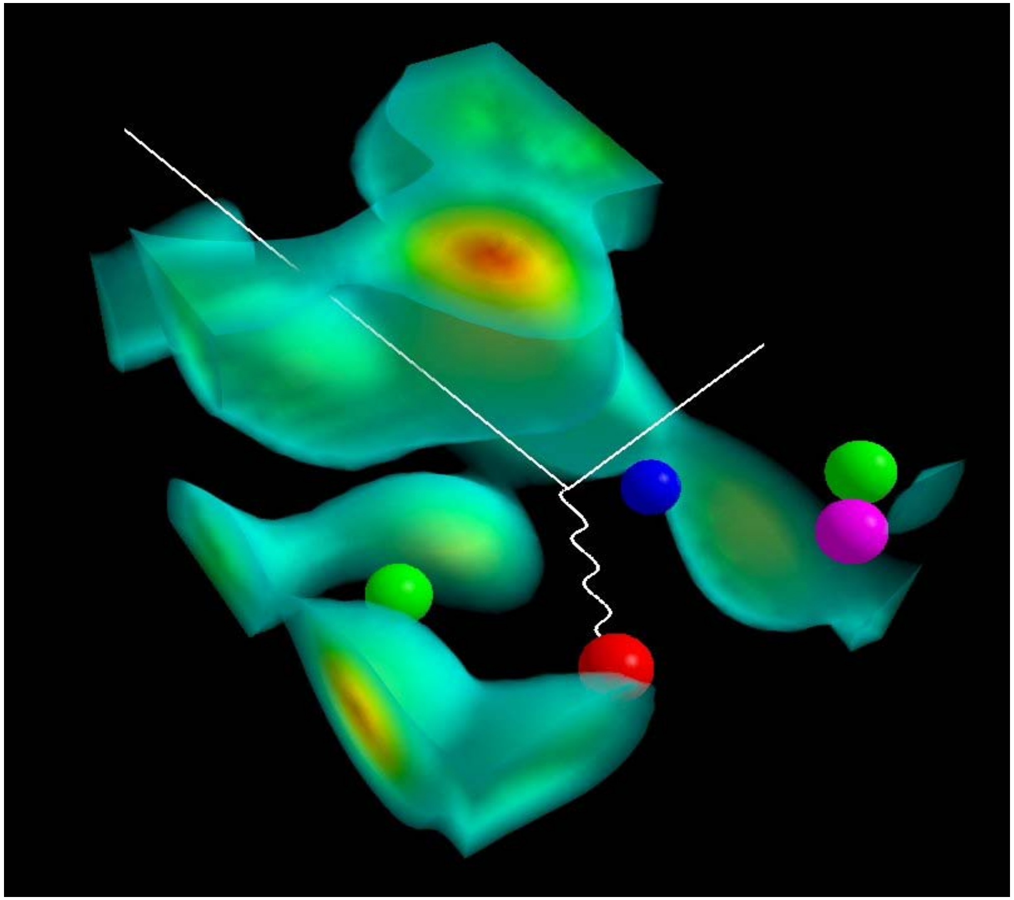
Quarks, Nuclei and the Standard Model



Australian Government

Australian Research Council

Anthony W. Thomas

Celebration of the 80th Birthdays of Magda and Torleif Ericson
CERN : September 27th 2010

ADELAIDE UNIVERSITY AUSTRALIA

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

Outline

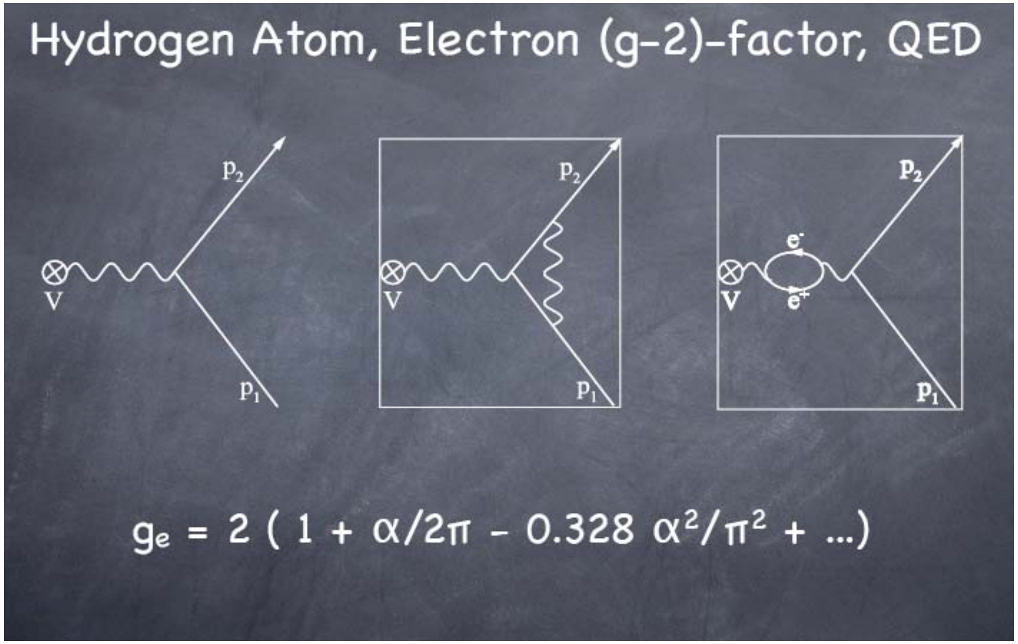
- Nucleon Structure
  - strangeness
- Nucleon & Hadron Structure in-Medium
  - Isovector EMC effect
- Symmetry Breaking and Standard Model Tests
  - NuTeV, PVES, Qweak…

ADELAIDE
UNIVERSITY
AUSTRALIA

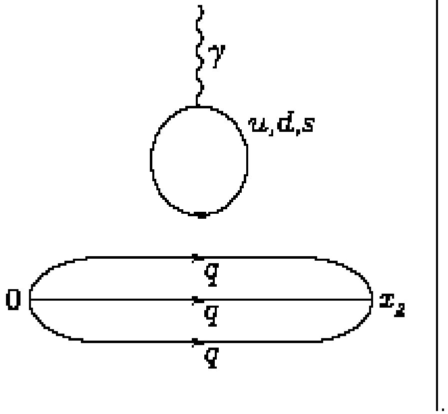
SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

Testing Non-Perturbative QCD

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


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

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



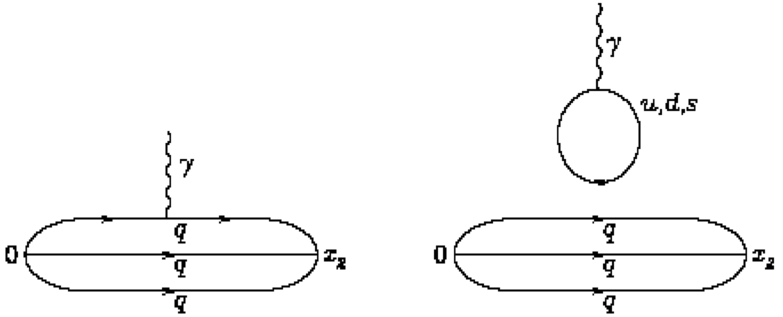
- It is a fundamental test of non-perturbative QCD

Strange Quarks in the Proton

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

- Calculation of $G_{E,M}^{s}$ (Q^2) :
  - Direct: Kentucky
  - Indirect: JLab-Adelaide
- Experimental determination of $G_{E,M}^{s}$ (Q^2)
  - G0 and Happex
  - Mainz PVA4 and Bates
- Strangeness sigma commutator

Magnetic Moments within QCD



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

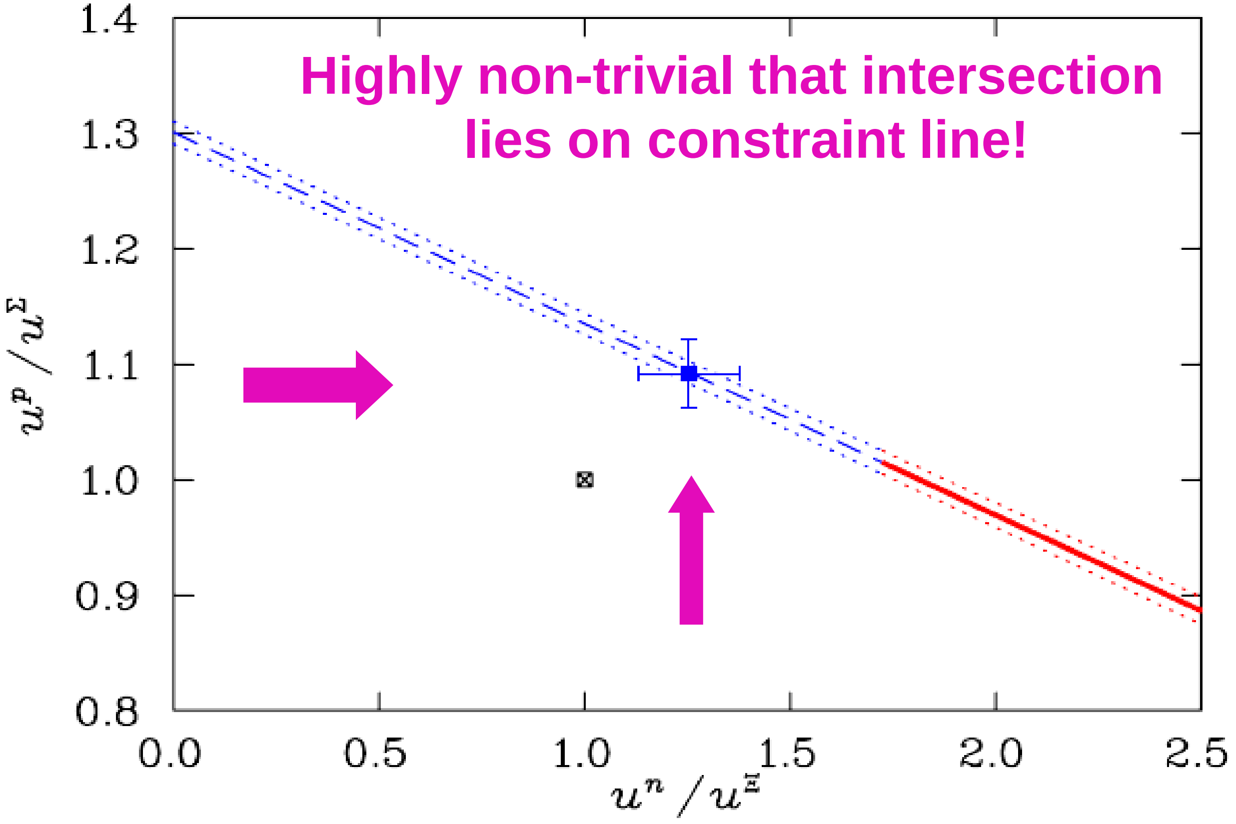
Just these ratios from Lattice QCD

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

ADELAIDE
UNIVERSITY
AUSTRALIA

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

First Accurate Determination of G_M^s from QCD



Highly non-trivial that intersection lies on constraint line!

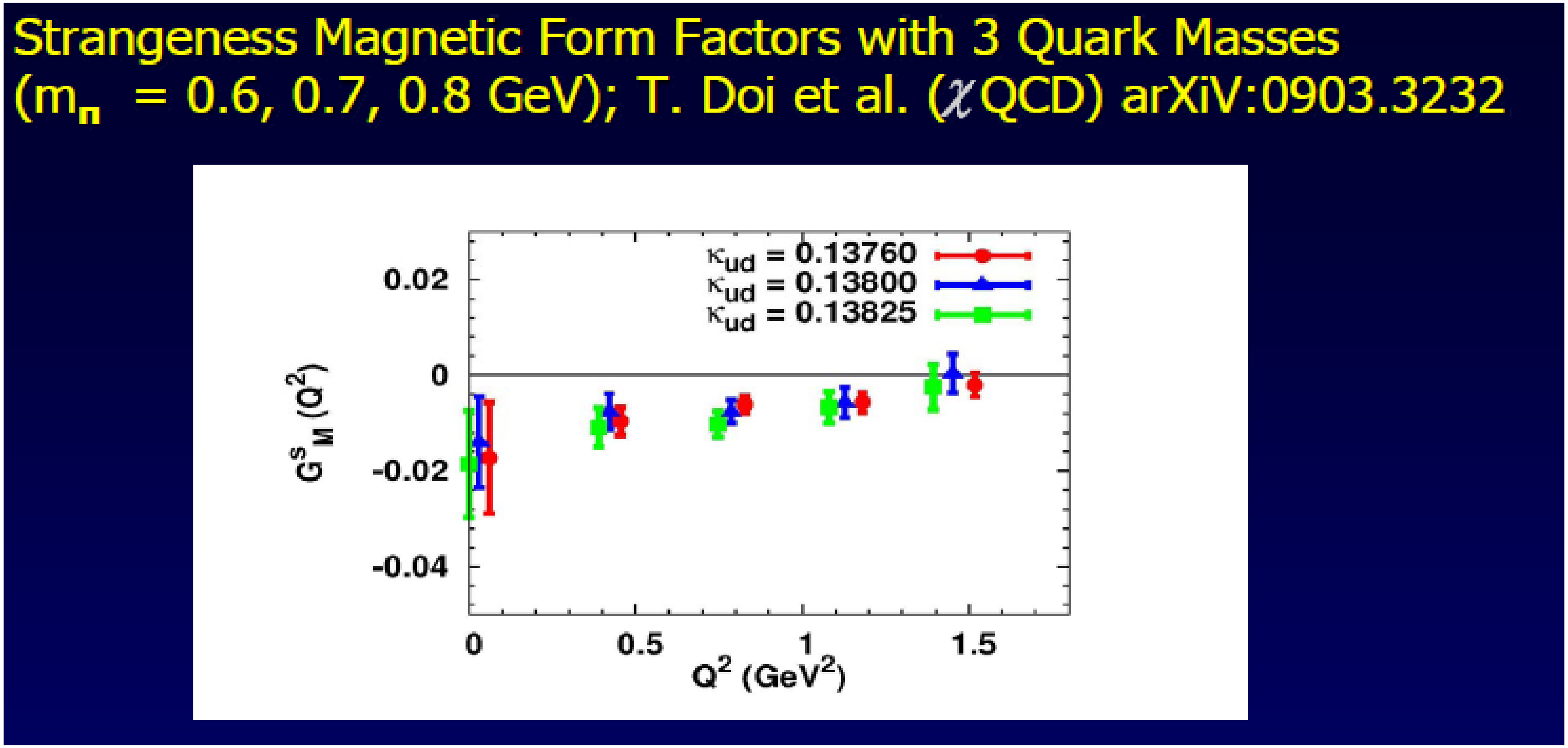
1.10±0.03

1.25±0.12

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

Leinweber et al., PRL 94 (2005) 212001

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.)

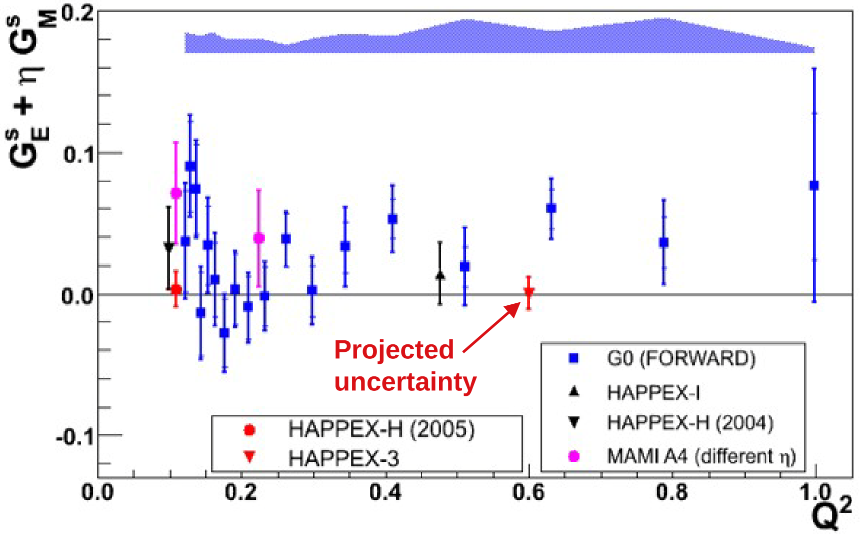
N.B. Result of Doi et al. would increase by factor ~1.8 when light quark mass takes physical value with m_s fixed
(Wang et al., hep-ph/0701082 : Phys Rev D75 (2008))

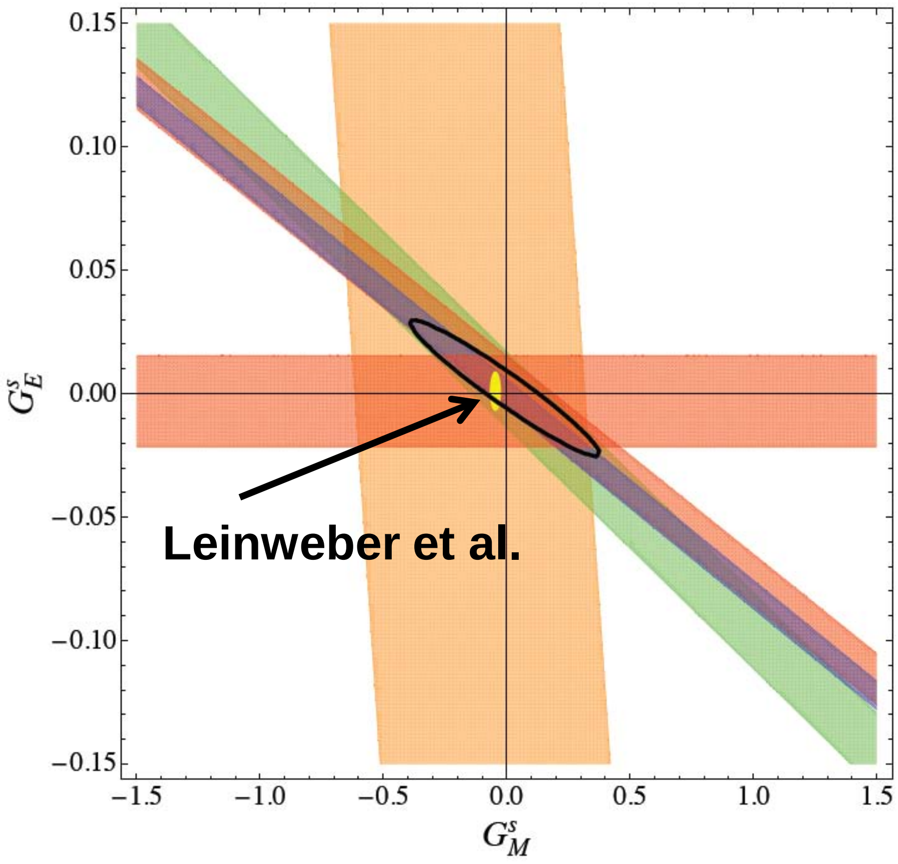
ADELAIDE UNIVERSITY AUSTRALIA

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

Global Analysis of PVES Data

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





Leinweber et al.

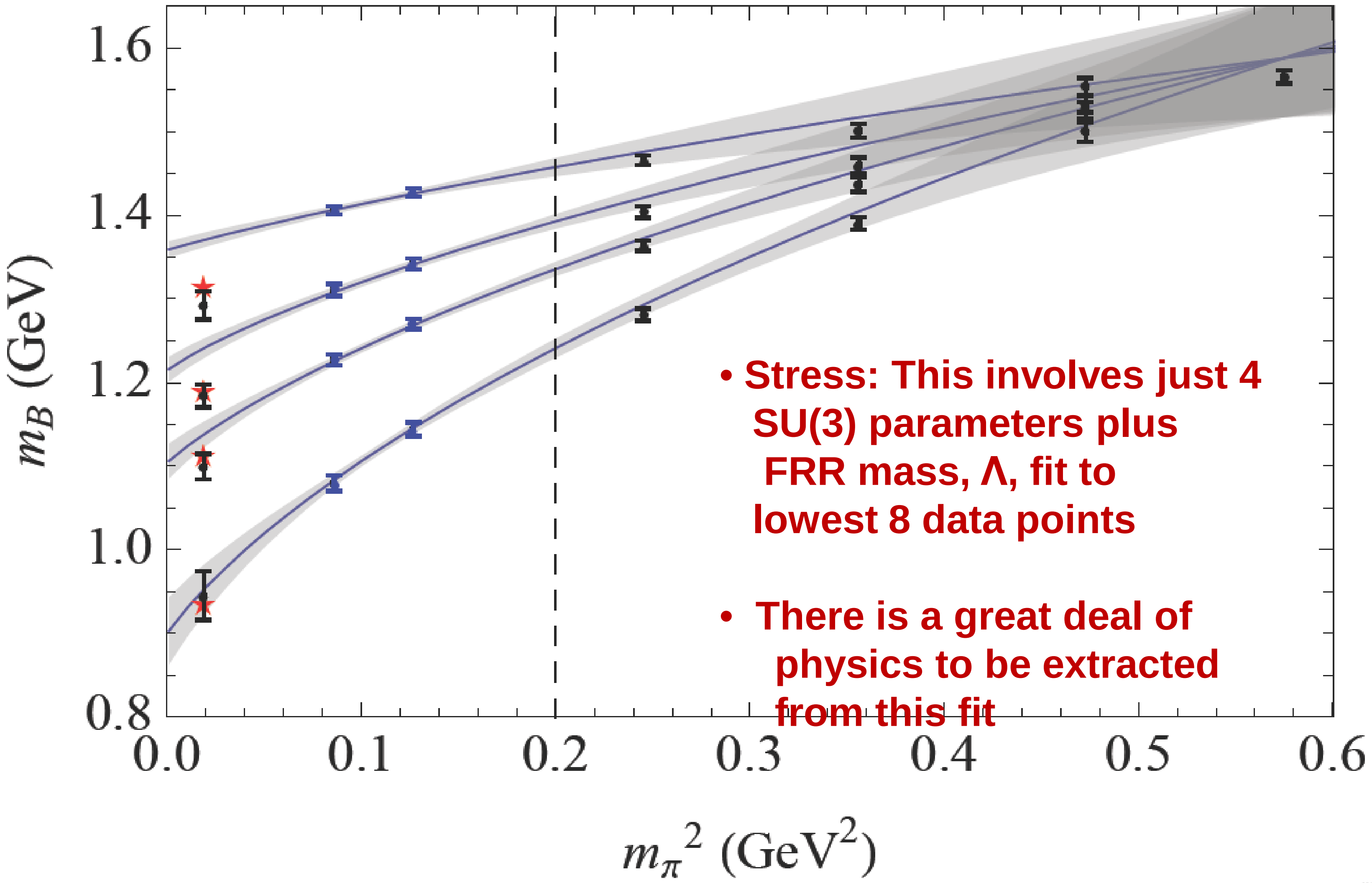
- ➢**Proton not all that strange**

- ➢**New data not yet included at 0.23 and 0.6 GeV^2 (PVA4 , G0, HAPPEx III – data taken this year)**

Global analysis: Young et al., PRL 99 (2007)122003 and Young arXiv 1004.5163 [nucl-th]

Octet Baryon Masses - LHPC Data

(Walker-Loud et al., arXiv:0806.4549)



- Stress: This involves just 4 SU(3) parameters plus FRR mass, 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]
Phys Rev D81, 014503 (2010)

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 !

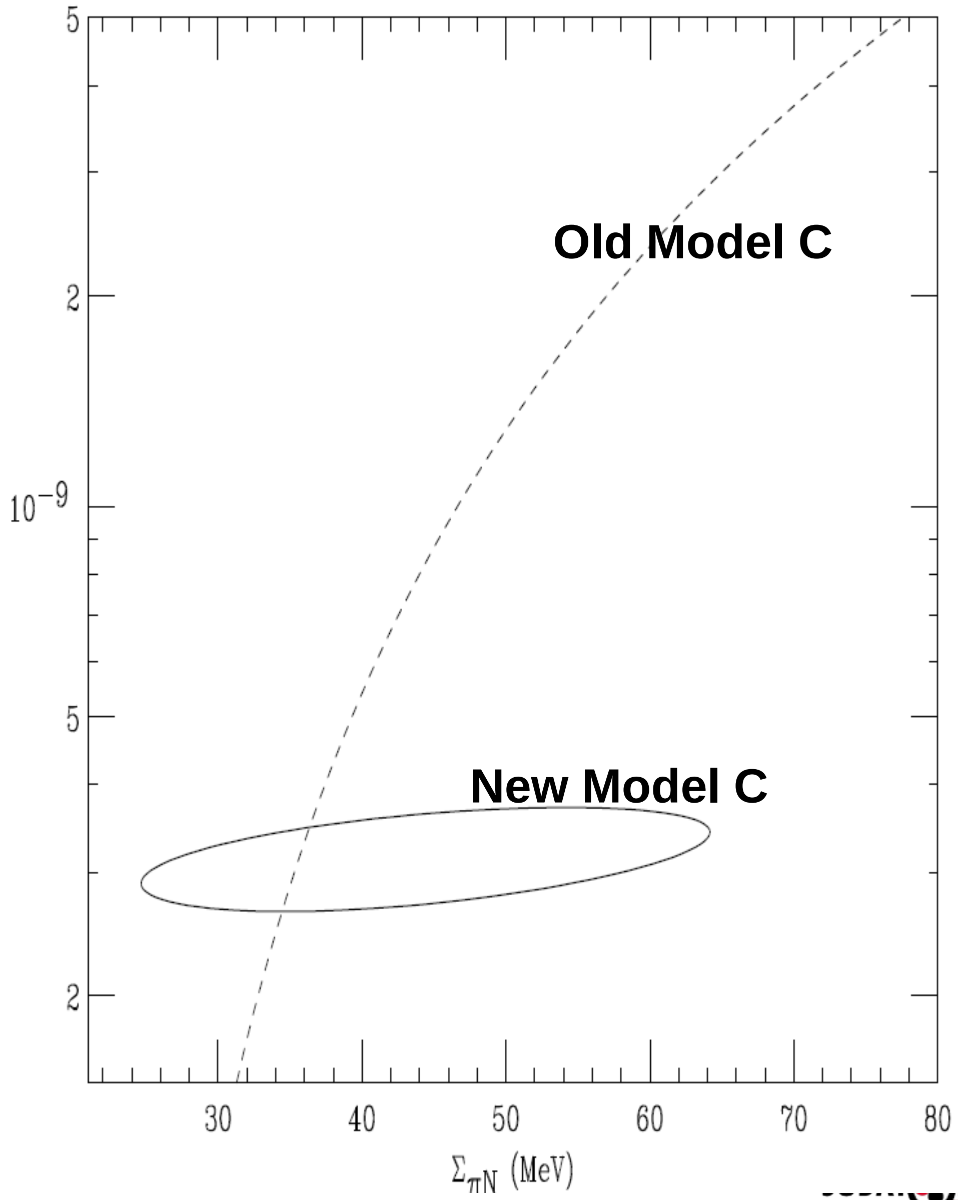
Profound Consequences for Dark Matter Searches

(and s-wave K condensation)

CMSSM Predictions for Dark Matter σ

In response to request by Ellis, Olive & Savage, who explored CMSSM

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

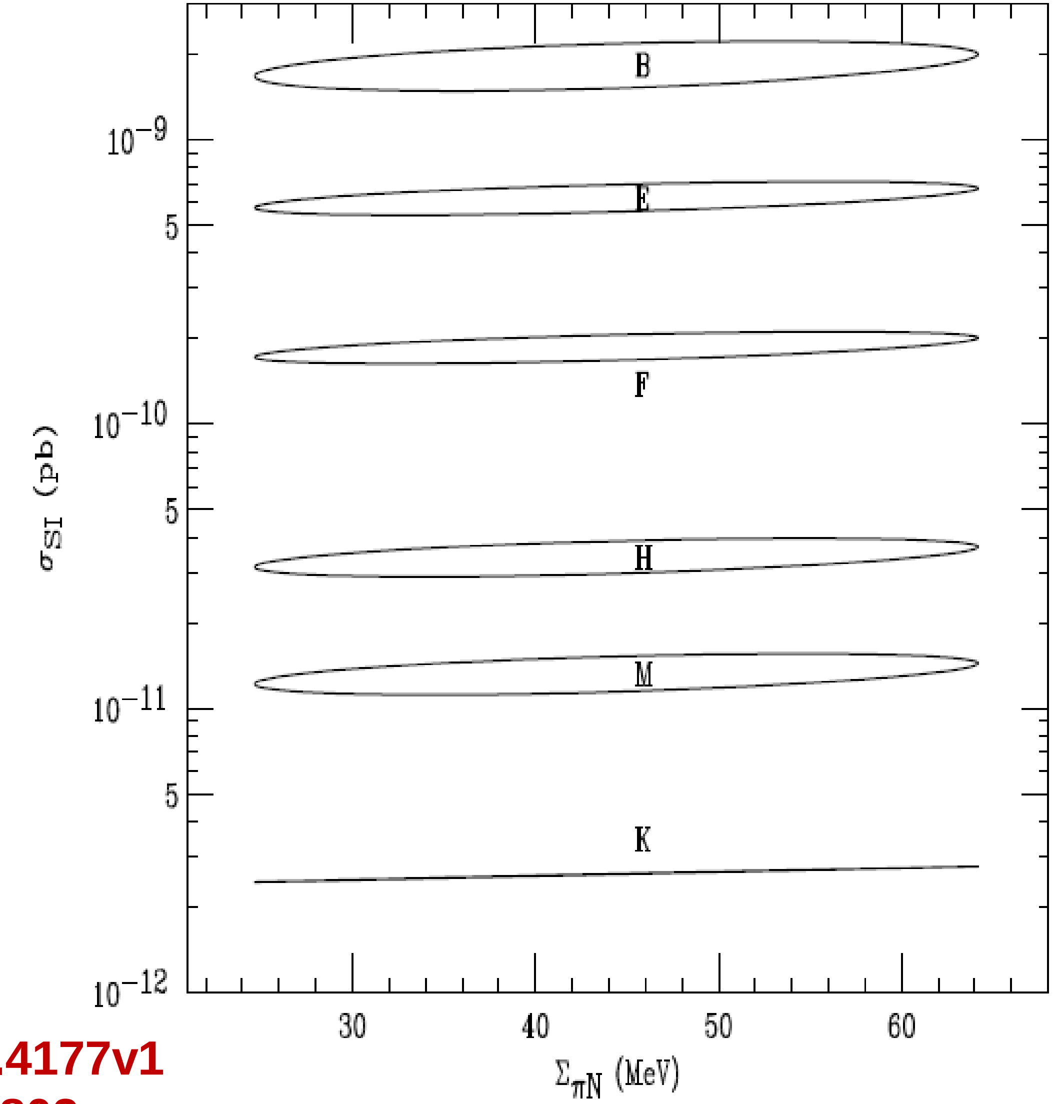


Giedt et al., arXiv: 0907.4177v1
PRL 103 (2009) 201802

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!

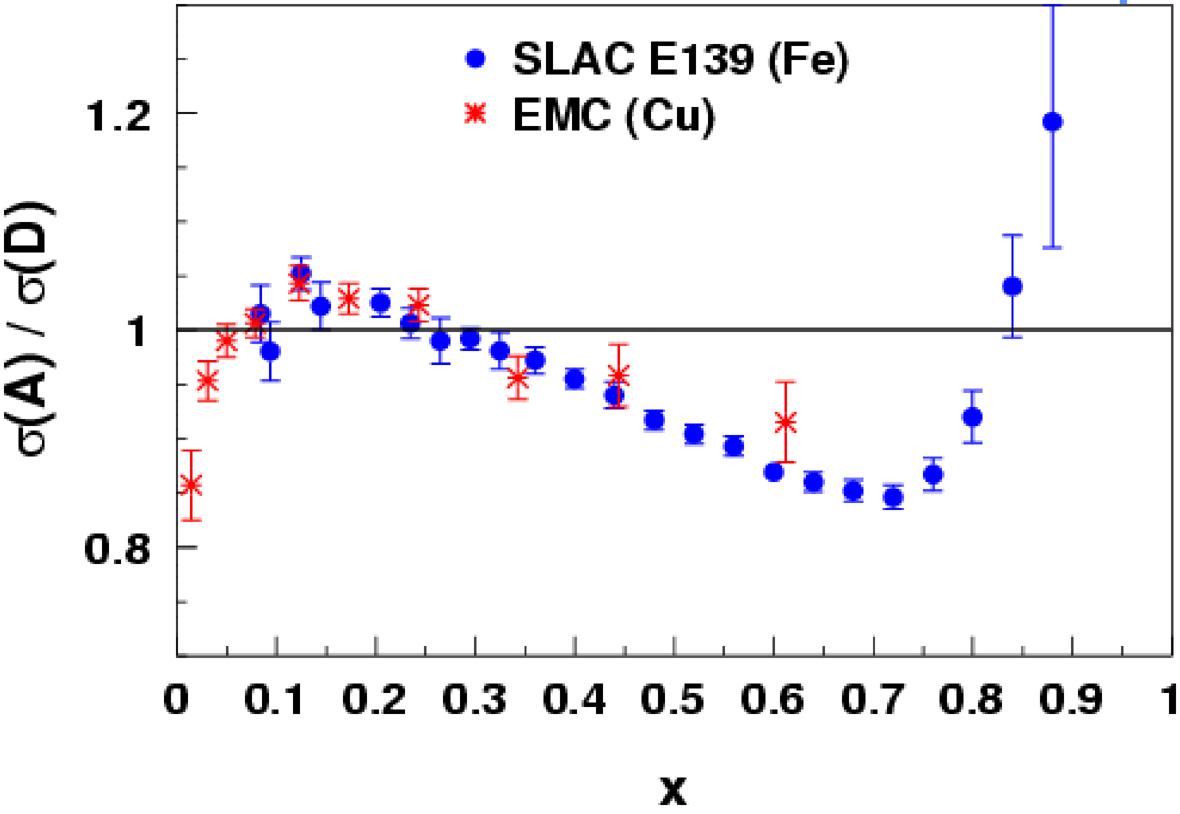


Giedt et al., arXiv: 0907.4177v1
PRL 103 (2009) 201802

Nucleon and Hadron Structure in-Medium

The EMC Effect: Nuclear PDFs

- Observation **stunned and electrified** the HEP and Nuclear communities 20 years ago
- Nearly 1,000 papers have been generated…..
- Medium modifies the momentum distribution of the quarks!



J. Ashman *et al*., Z. Phys. C57, 211 (1993)

J. Gomez *et al*., Phys. Rev. D49, 4348 (1994)

Ref.TH.3553-CERN

PIONIC CORRECTIONS AND THE EMC ENHANCEMENT OF THE SEA IN IRON

M. Ericson and A.W. Thomas
CERN - Geneva

Recent Calculations for Finite Nuclei

Spin dependent EMC effect TWICE as large as unpolarized

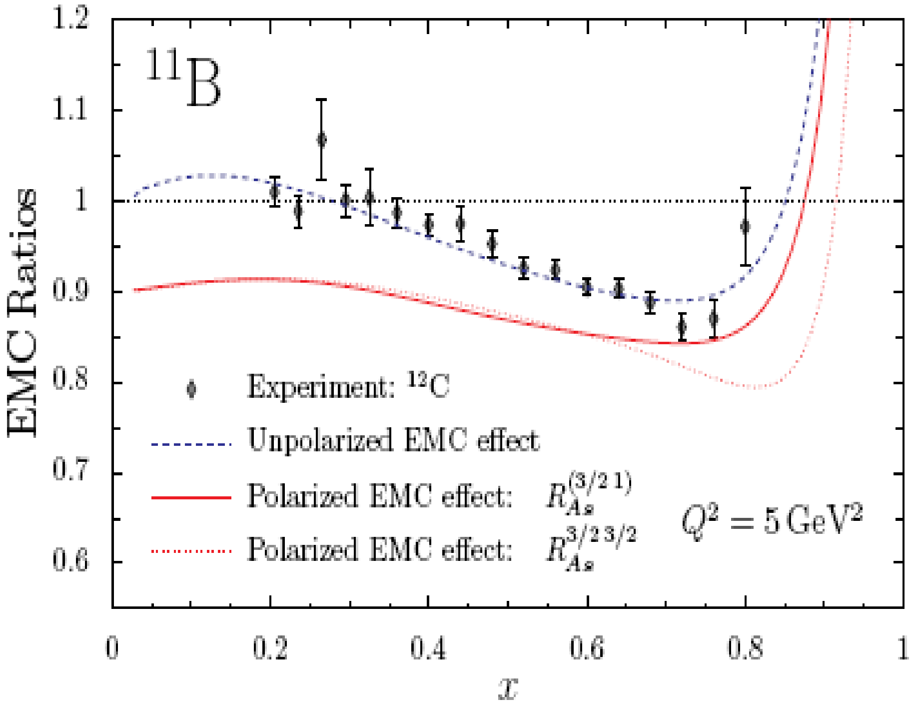


FIG. 7: The EMC and polarized EMC effect in ^{11}B. The empirical data is from Ref. [31].

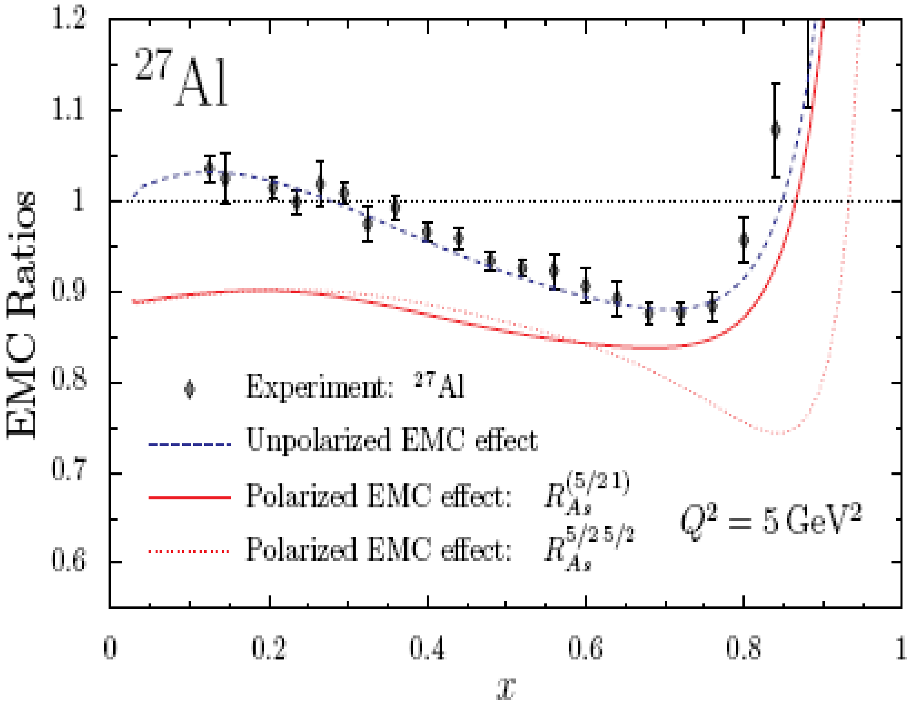


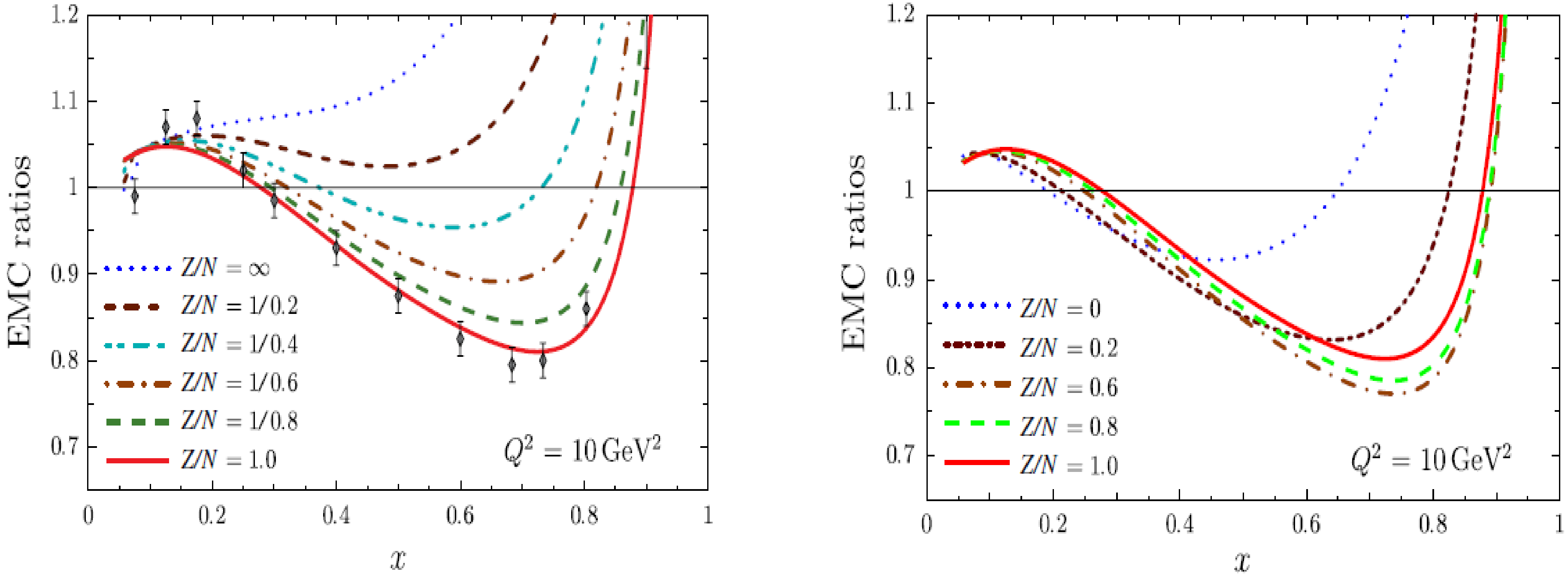
FIG. 9: The EMC and polarized EMC effect in ^{27}Al. The empirical data is from Ref. [31].

Cloët et al., Phys. Lett. B642 (2006) 210 (nucl-th/0605061)

Iso-vector EMC Effect

Cloet, Bentz,Thomas

PRL **102,** 252301 (2009) PHYSICAL REVIEW LETTERS week ending 26 JUNE 2009



Means that excess neutrons in Fe shift momentum from all u- to all d-quarks and subtracting their direct contribution does not remove this effect

This has implications for the NuTeV anomaly

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?

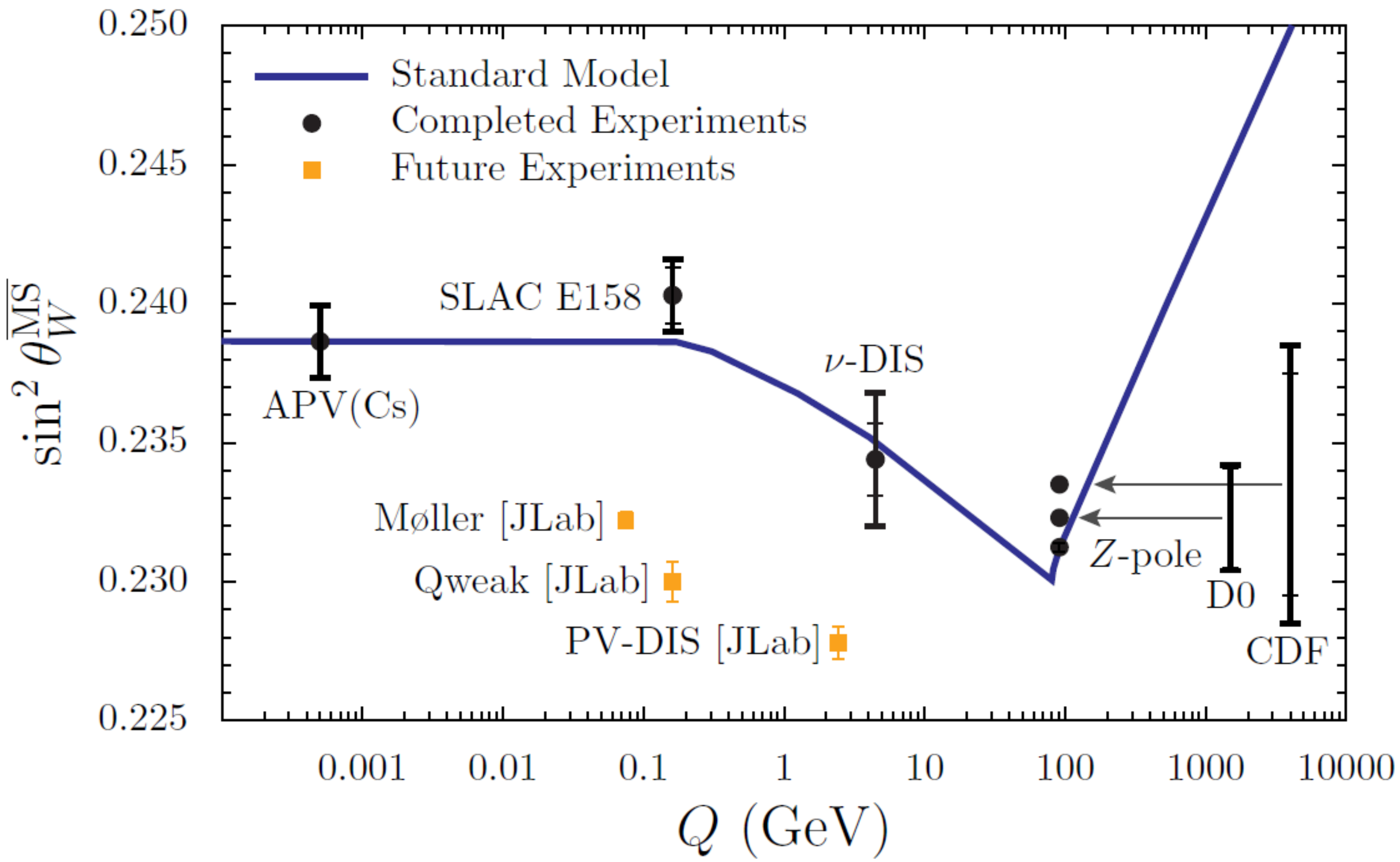
- **Final result:** $\sin^2\theta_W = 0.2221 \pm 0.0013(\mathrm{stat}) \pm 0.0020(\mathrm{syst})$

  − c.f. Standard Model: $\sin^2\theta_W = 0.2227 \pm 0.0004$

Bentz et al., arXiv: 0908.3198

The Standard Model works… again

Apply Charge Symmetry Violation and Iso-vector EMC corrections plus estimate systematic error arising from $s^-(x) \neq 0$:



Bentz et al., arXiv: 0908.3198

Standard Model Tests using PVES

Success of Strangeness Search Leads Naturally to Measurement of $\sin^2\theta_W$ Using 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:

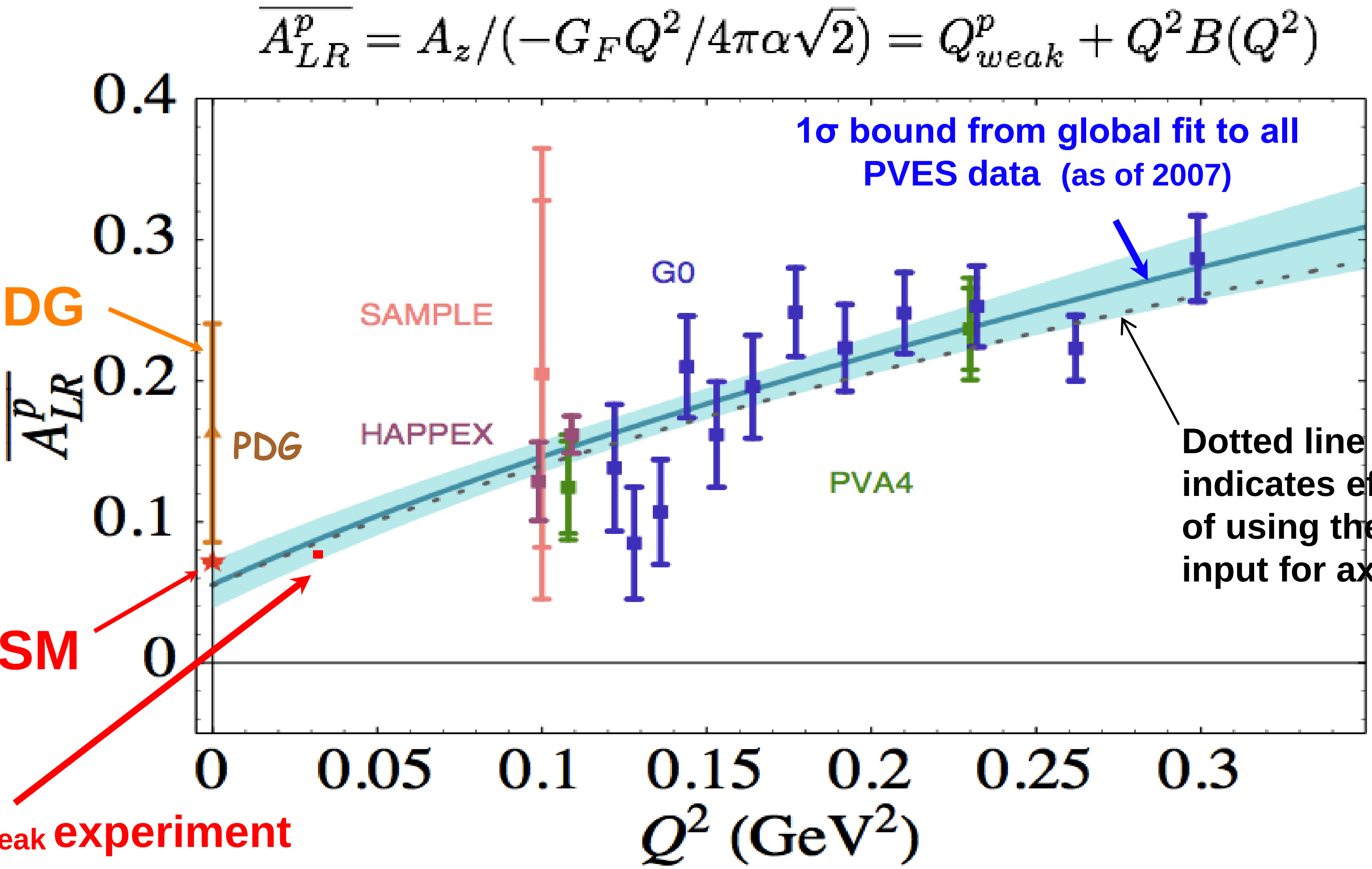
$$4G^{pZ}_{E,M} = \underline{(1-4\sin^2\theta_W)}\, G^{p\gamma}_{E,M} - G^{n\gamma}_{E,M} - \underline{G^{s}_{E,M}}$$

Proton weak charge
(tree level)

Strangeness

Use data to constrain the parameters of the electroweak theory

Global Fit to PVES: Extract Slope at 0º 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)

PDG

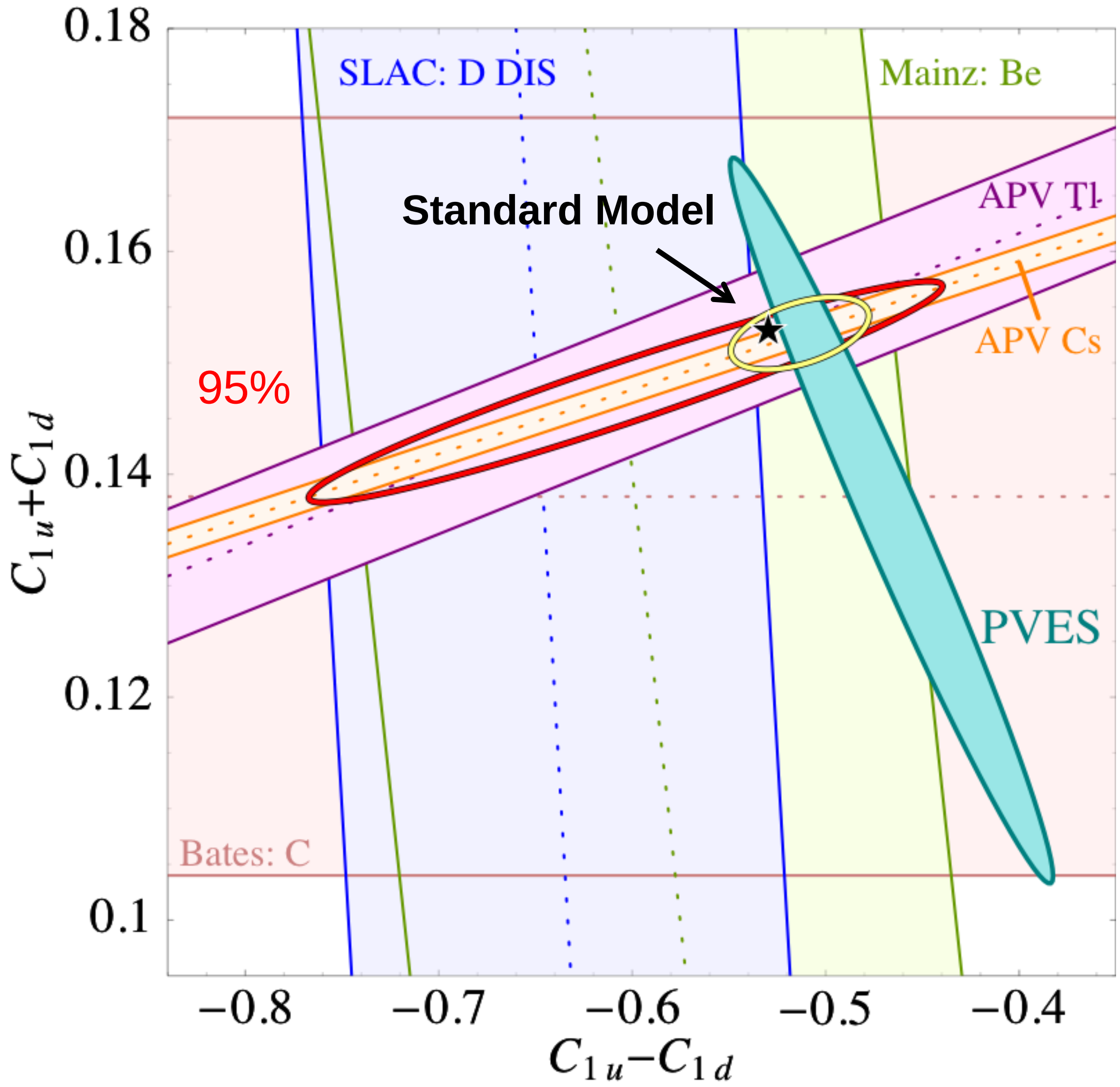
SM

Q_{weak} experiment

Dotted line indicates effect of using theoretical input for axial terms

(R.D. Young et al., PRL 99, 122003 (2007))

PVES : Orthogonal constraint to atomic PV



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

$$L_{eff} \sim C_{1q}\, \bar{e}\gamma^{\mu}\gamma_{5}e\; \bar{q}\gamma_{\mu}q$$

PVES on H yields dramatic improvement in knowledge of weak couplings!

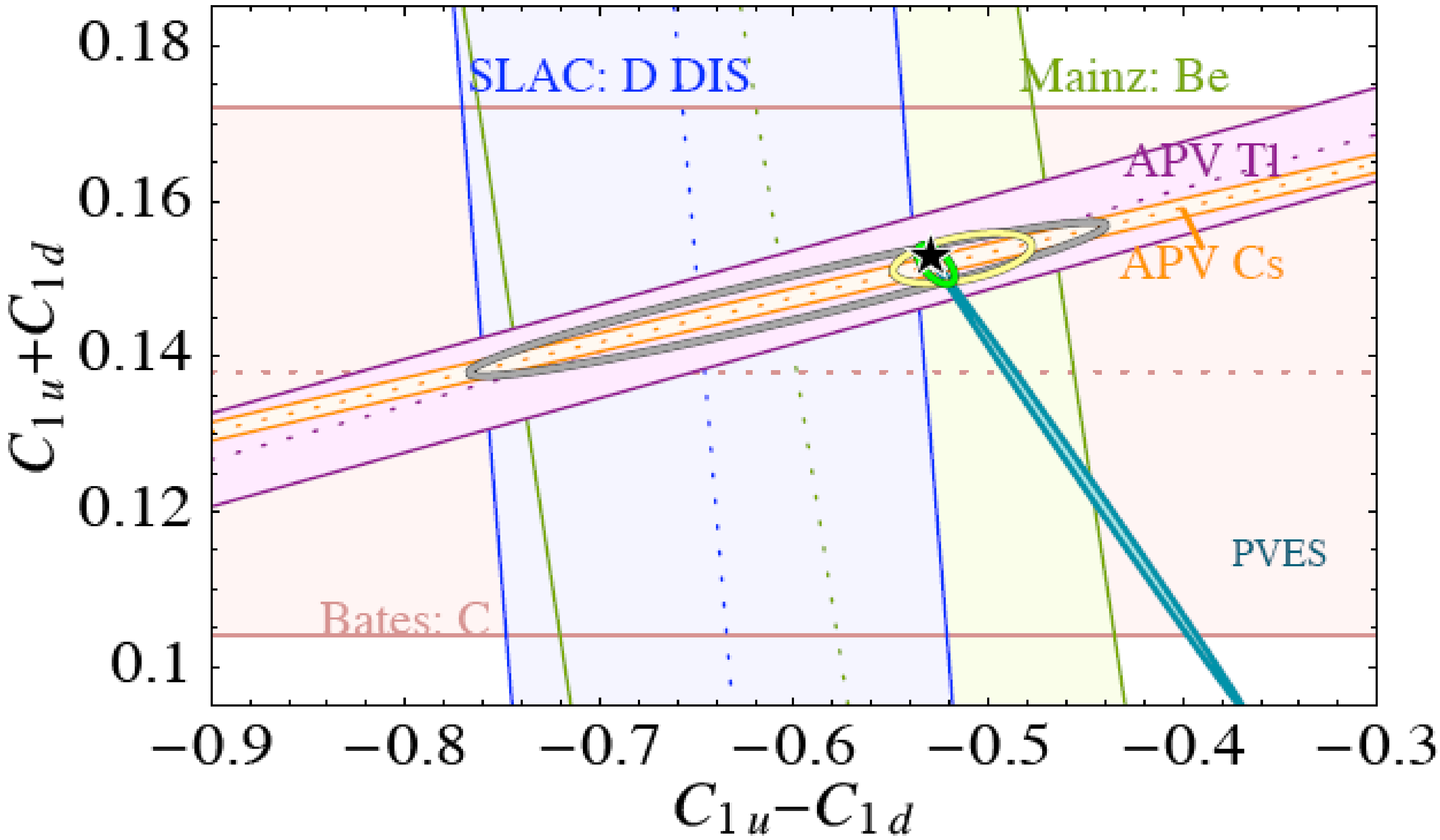
Factor of 5 increase in precision of Standard Model test

Young et al., Phys Rev Lett 99 (2007) 122003

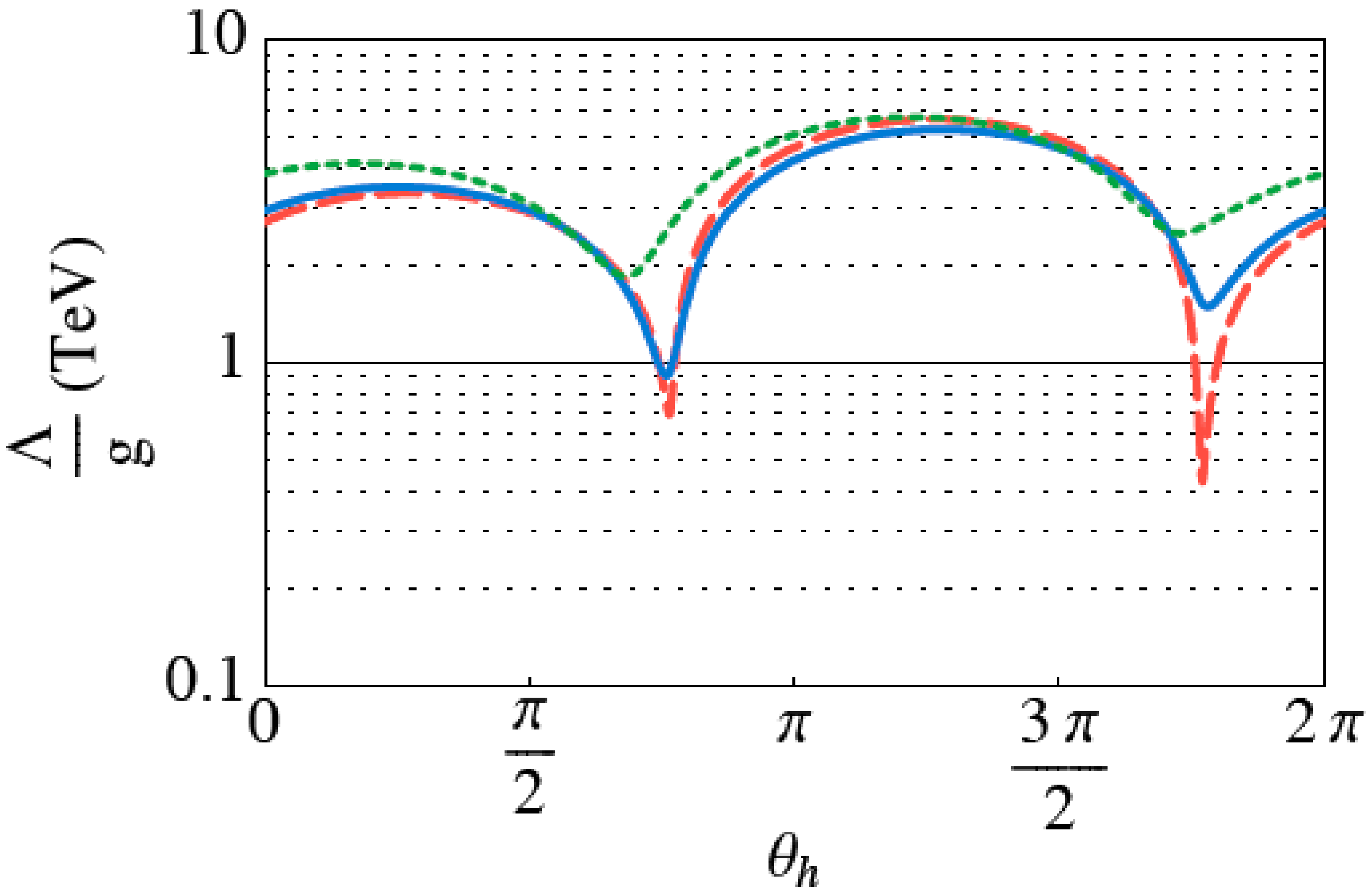
ADELAIDE
UNIVERSITY
AUSTRALIA

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

Q_{weak} at JLab – if in agreement with SM



Lower Limit on Mass Scale for New Physics



Q_{weak} limit *if* data agrees with Standard Model

with PVES

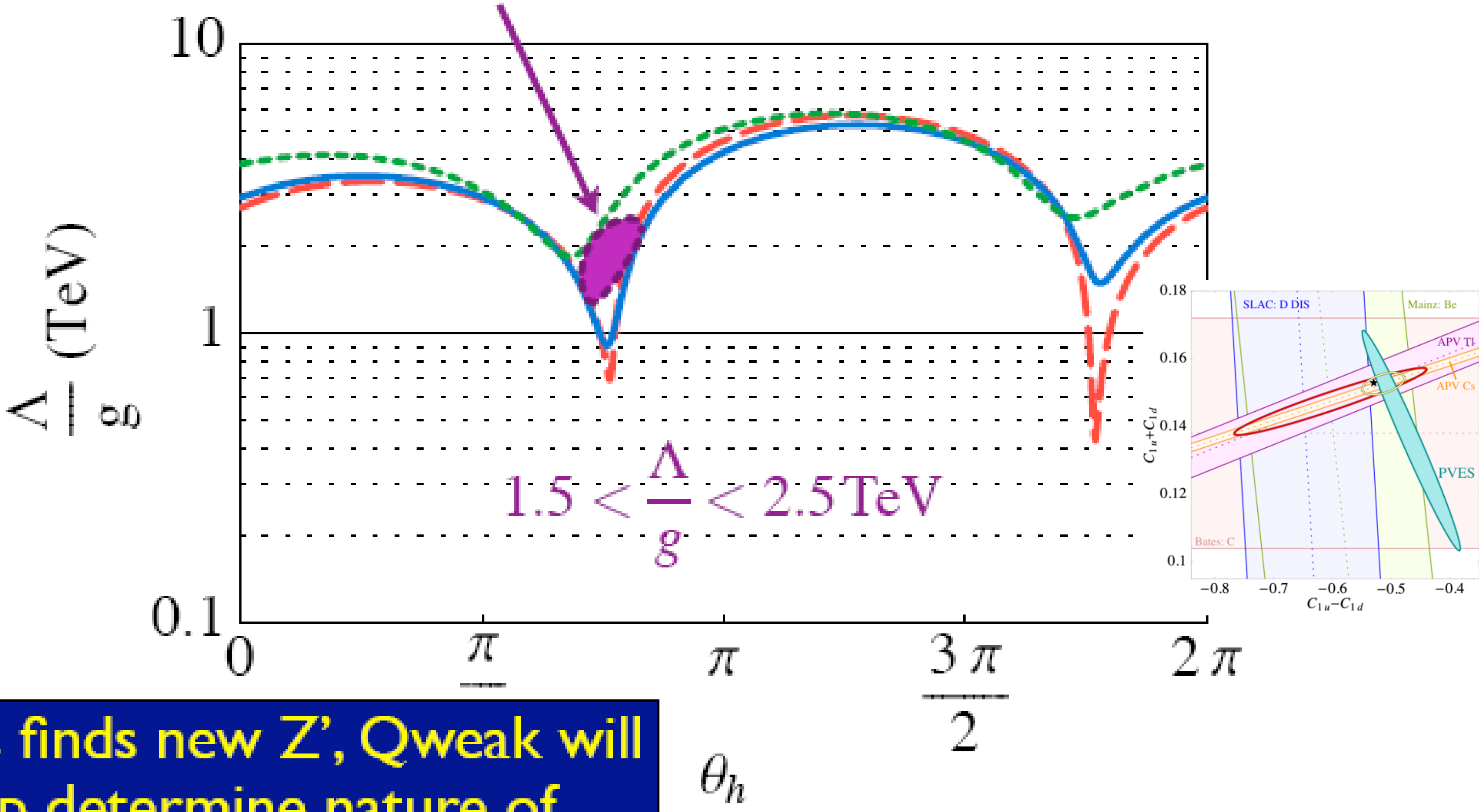
Atomic only

95% CL

Qweak constrains new physics to beyond 2 TeV

Or… Discovery

Assume Qweak takes central value of current measurements



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

Joyeux Anniversaires!

Separate Neutrino and Anti-neutrino Ratios

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

- **Have done this:**

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

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

- **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 :**
  chisq changes from 7.2 to 2.6 for the two ratios!

Bentz et al., arXiv: 0908.3198

Correction to Paschos-Wolfenstein from ρ_p - ρ_n

$$\Delta R_{\mathrm{PW}} \simeq \left(1 - \frac{7}{3} s_W^2\right) \frac{\langle x_A\, u_A^- - x_A\, d_A^- - x_A\, s_A^- \rangle}{\langle x_A\, u_A^- + x_A\, d_A^- \rangle}$$

- **Excess of neutrons means d-quarks feel more repulsion than u-quarks**

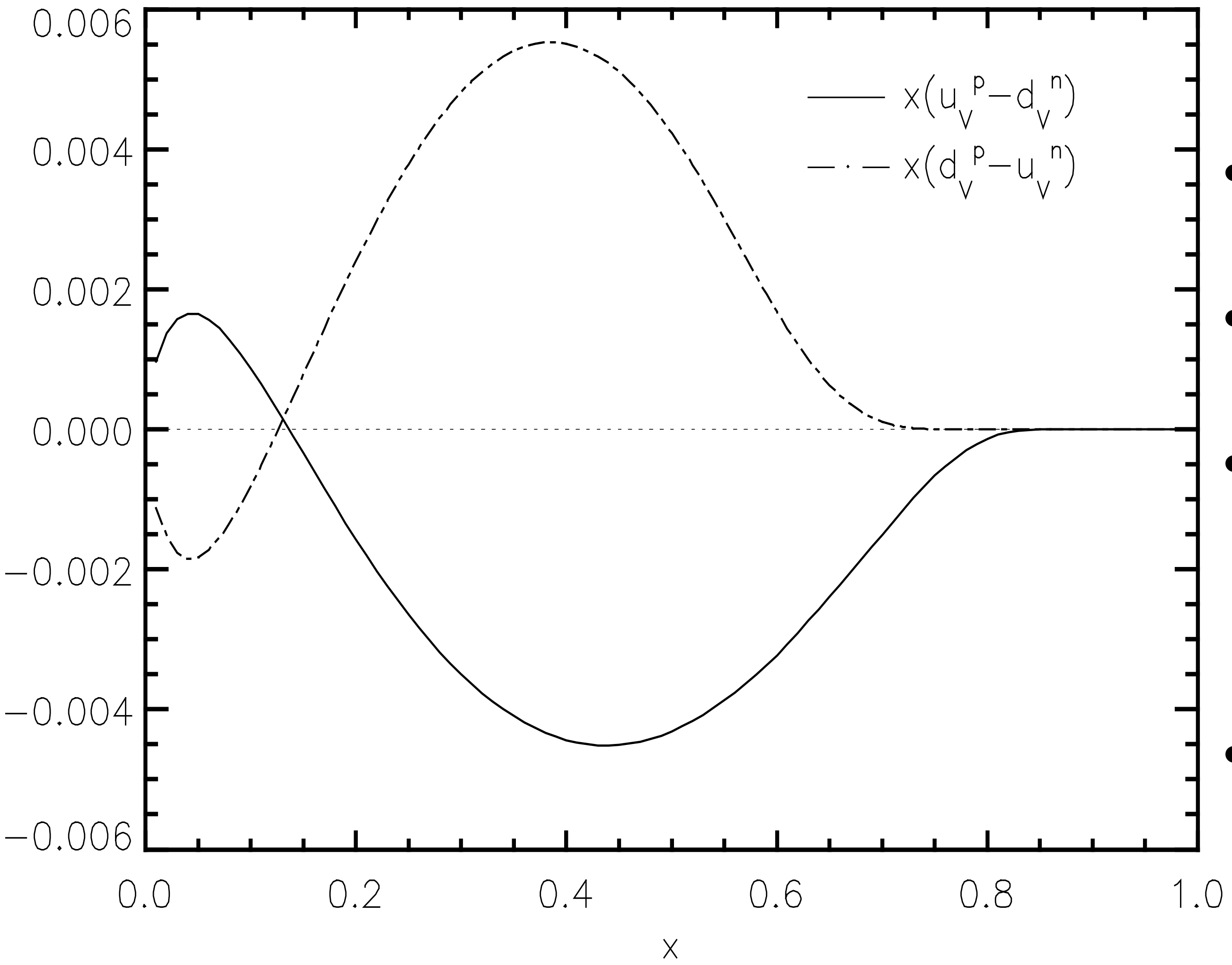
- **Hence shift of momentum from all u to all d in the nucleus!**

- **Negative change in ΔR_{PW} and hence $\sin^2\theta_W$ ↑**

- **Isovector force controlled by ρ_p – ρ_n and symmetry energy of nuclear matter − both well known!**

- **N.B. ρ^0 mean field included in QHD and QMC and earlier work with Bentz but no-one thought of this!!**

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

Remarkably Similar to Recent MRST Fit

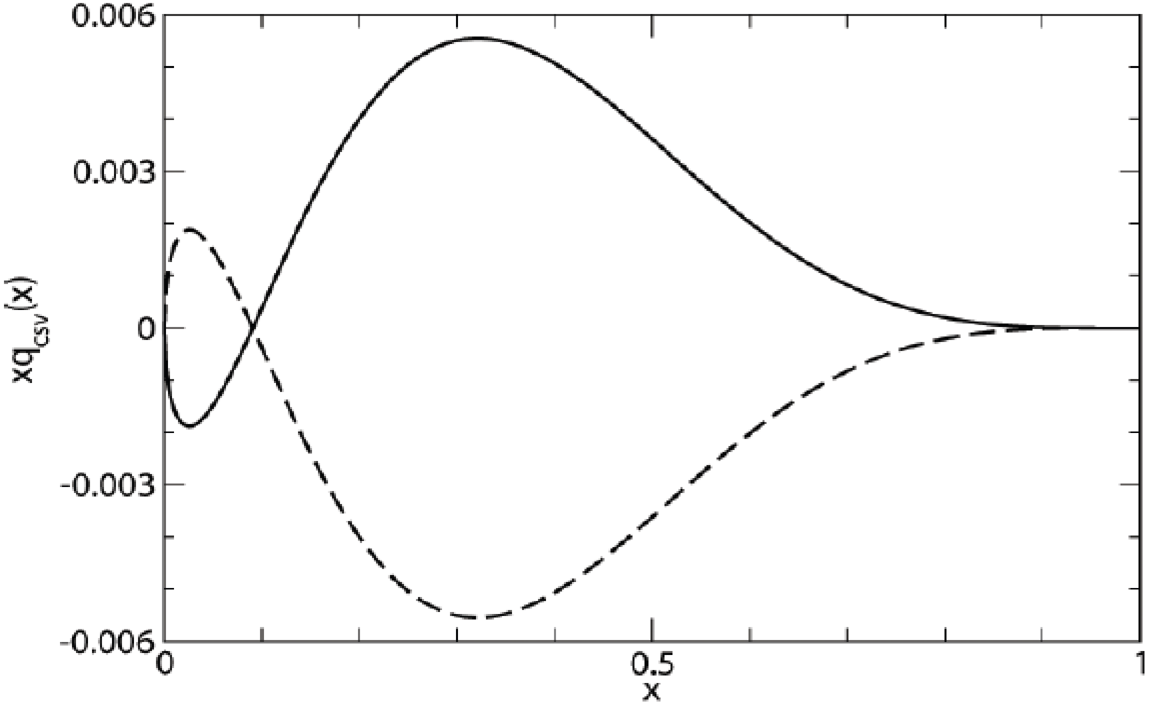
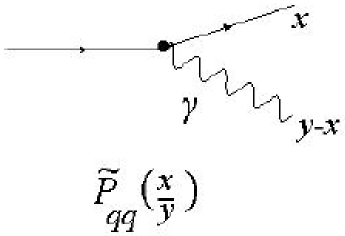


FIG. 5: The phenomenological valence quark CSV function from Ref. [23], corresponding to best fit value $\kappa = -0.2$ defined in Eq. (35). Solid curve: $x\delta d_{\rm v}$; dashed curve: $x\delta u_{\rm v}$.

An additional source of CSV

- In addition to the u-d mass difference, MRST (Eur Phys J C39 (2005) 155) and Glück et al (PRL 95 (2005) 022002) suggested that "QED splitting":



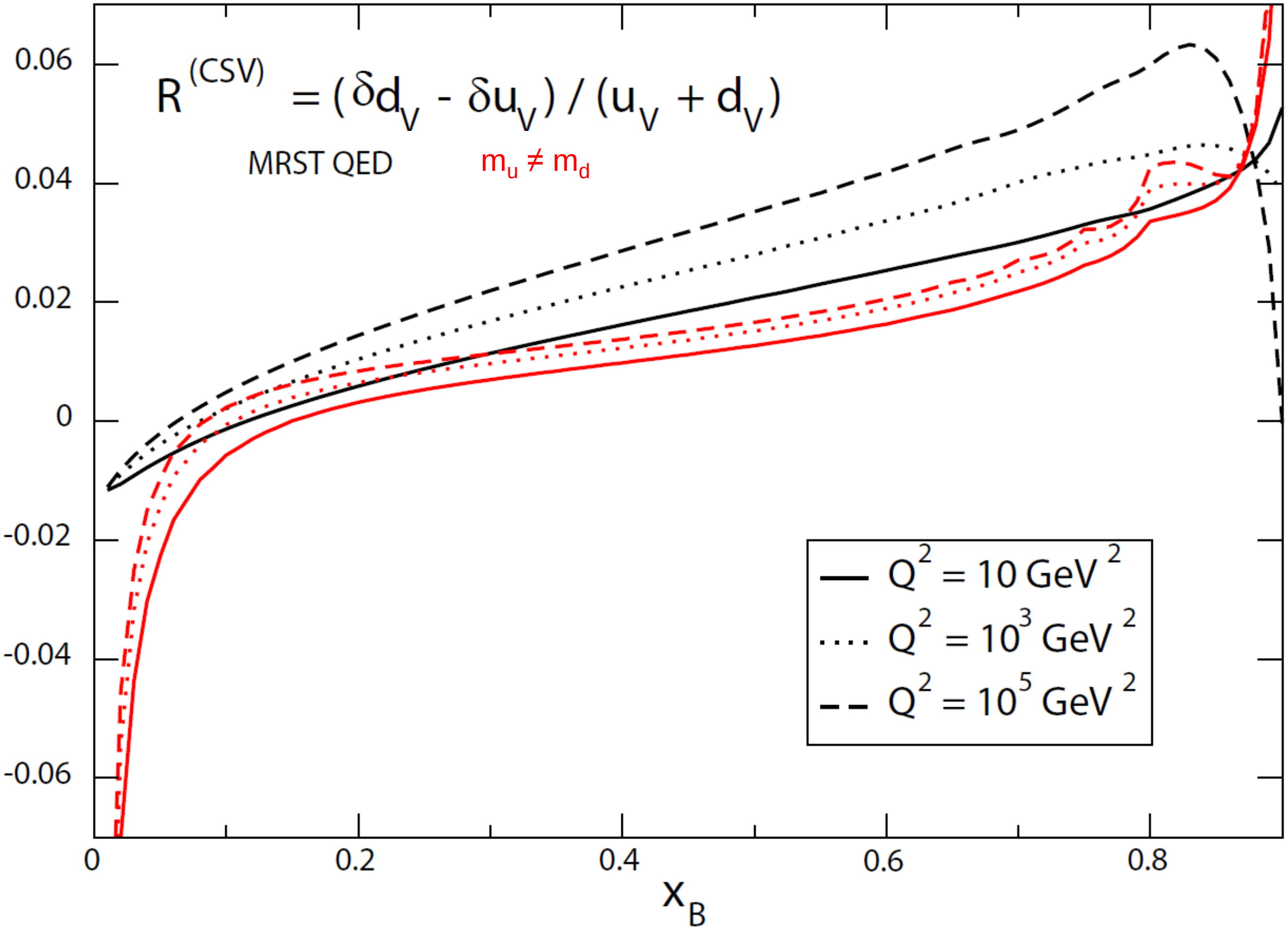
- which is obviously larger for u than d quarks, would be an additional source of CSV. Assume zero at some low scale and then evolve − so CSV from this source grows with Q^2

- Effect on NuTeV is exactly as for regular CSV and magnitude but grows logarithmically with Q^2

- For NuTeV it gives: $\Delta R^{\mathrm{QED}} = -0.0011$ to which we assign 100% error

LHeC: Ideal to test CSV and QED Splitting

- **Effect increases with Q^2. Use (e^-, ν) and (e^+, $\bar{\nu}$) on p and d**
- **This gives CSV <u>and</u> d/u unambiguously**



Hobbs, Londergan and Thomas, in preparation