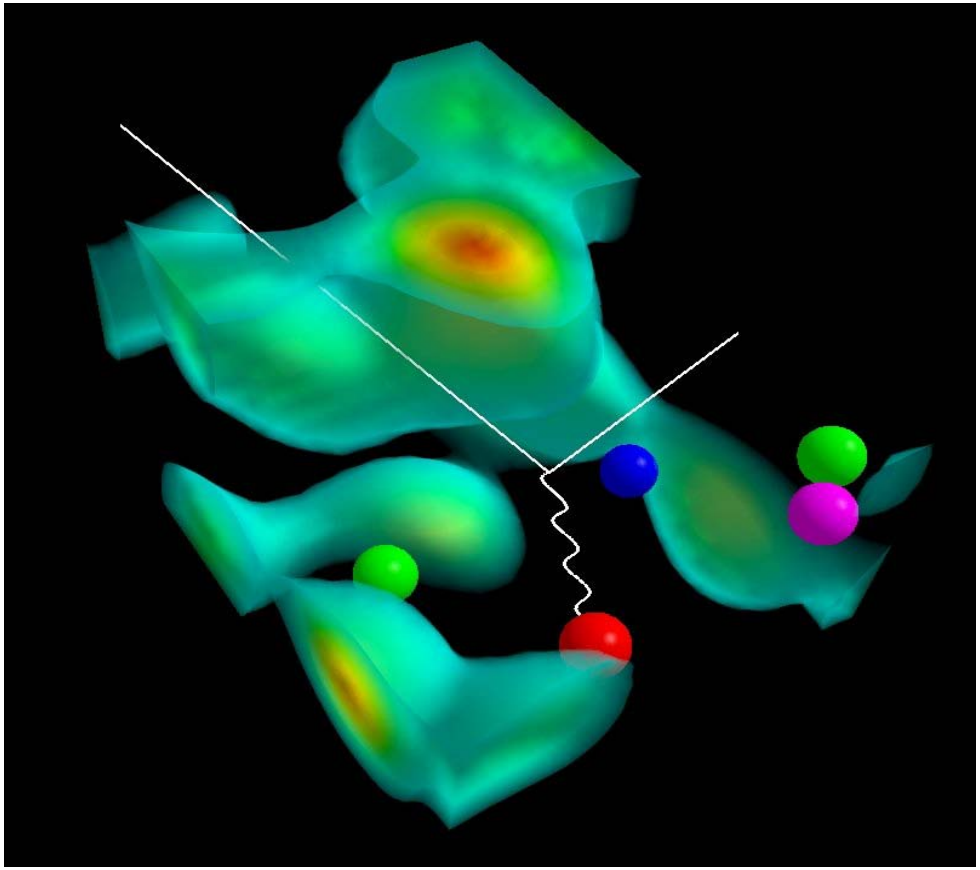
Physics Beyond the Standard Model



Australian Government

Australian Research Council

Anthony W. Thomas

T(r)opical Workshop

Cairns : October 1st 2010

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SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

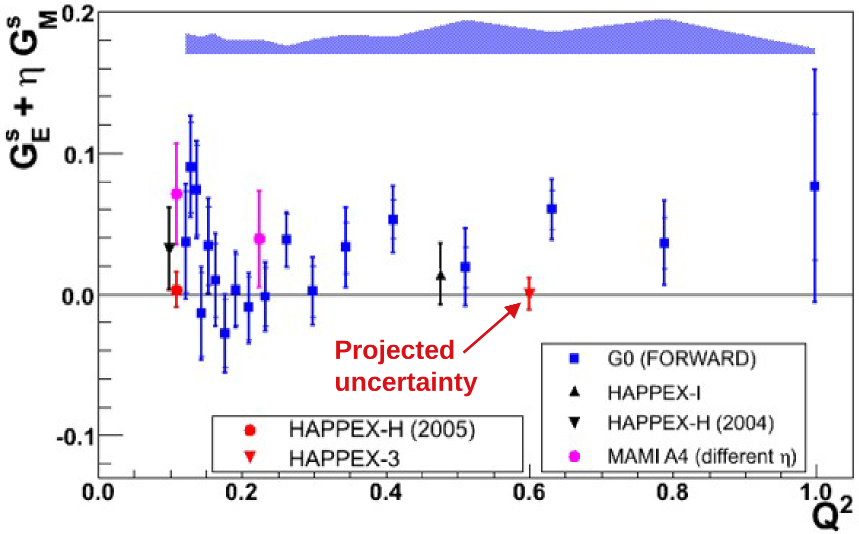
Outline

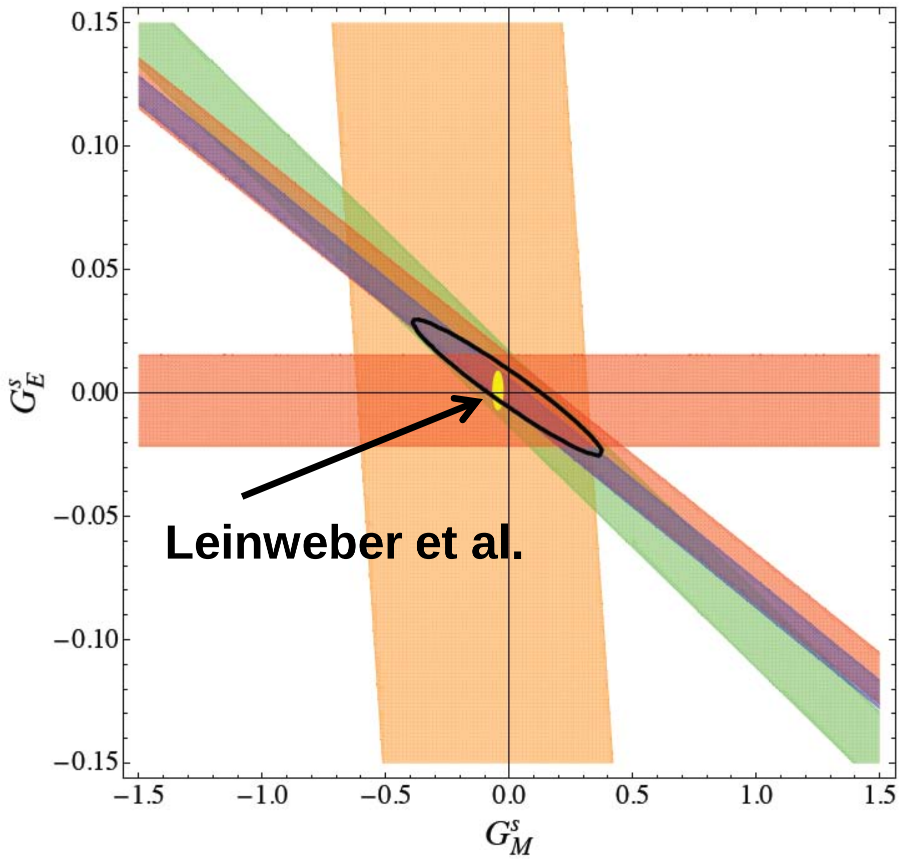
- Strangeness in the Nucleon
- Dark Matter
- The NuTeV anomaly
- Resolution of the NuTeV anomaly
  - CSV in parton distribution functions
  - a new EMC effect
  - strange quark asymmetry

Strangeness in the Nucleon and Dark Matter

Global Analysis of PVES Data

Q^2 = 0.1 GeV^2



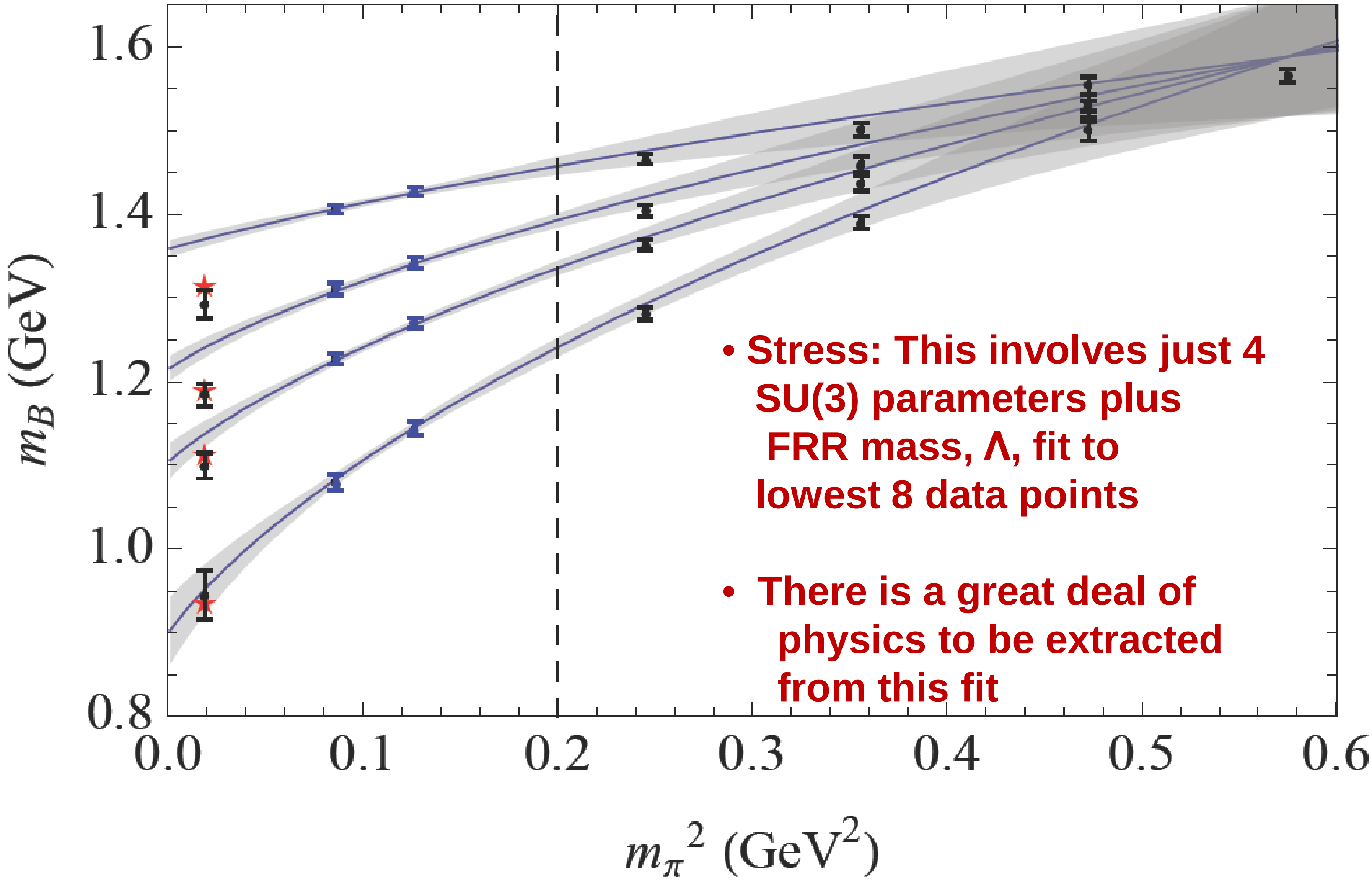


- ➢Proton not all that strange
- ➢New data not yet included at 0.23 and 0.6 GeV^2 (PVA4 , G0, HAPPEx III – data taken this year)

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)

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SUB CRUCE LUMEN

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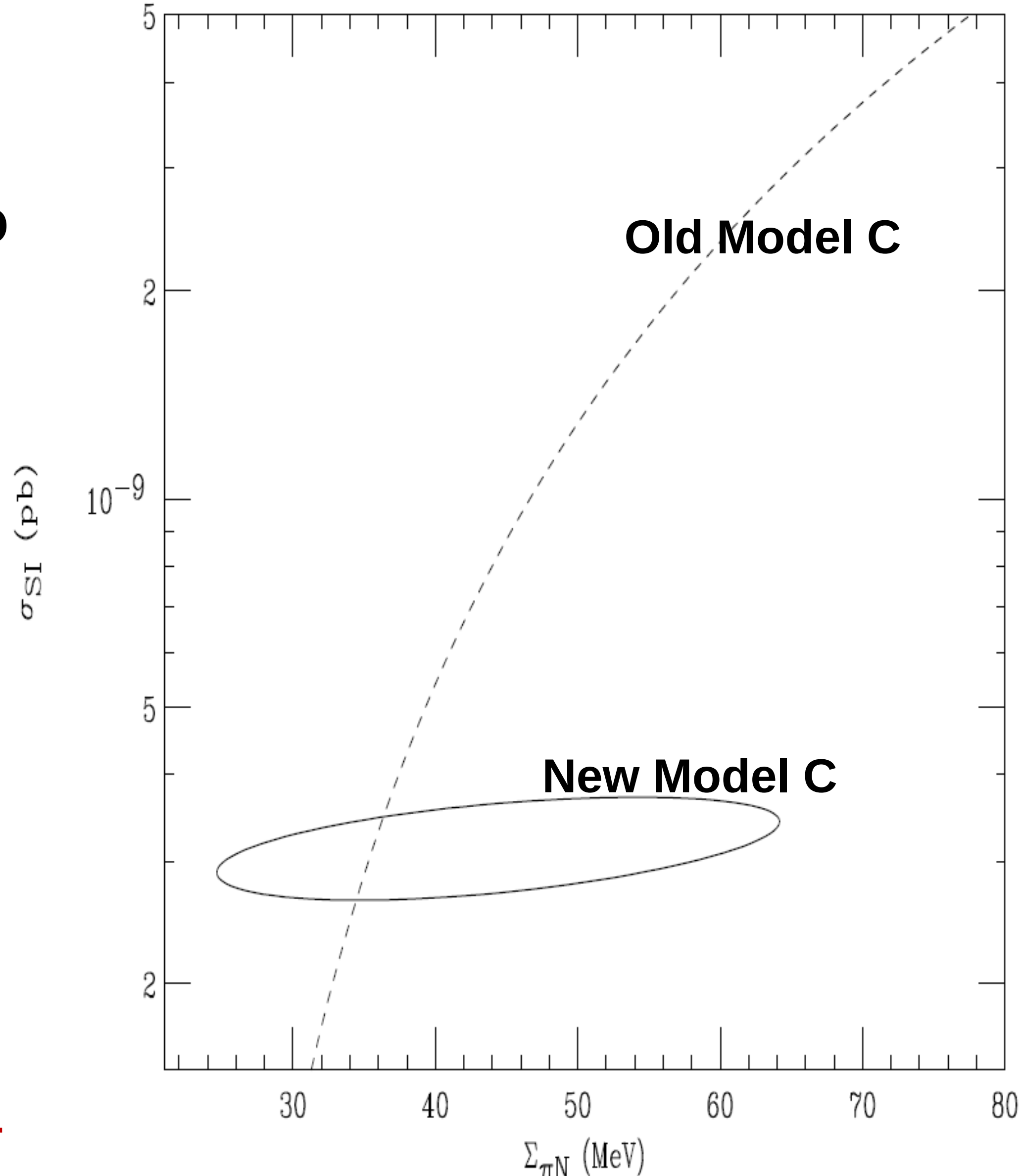
CMSSM Predictions for Dark Matter σ

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

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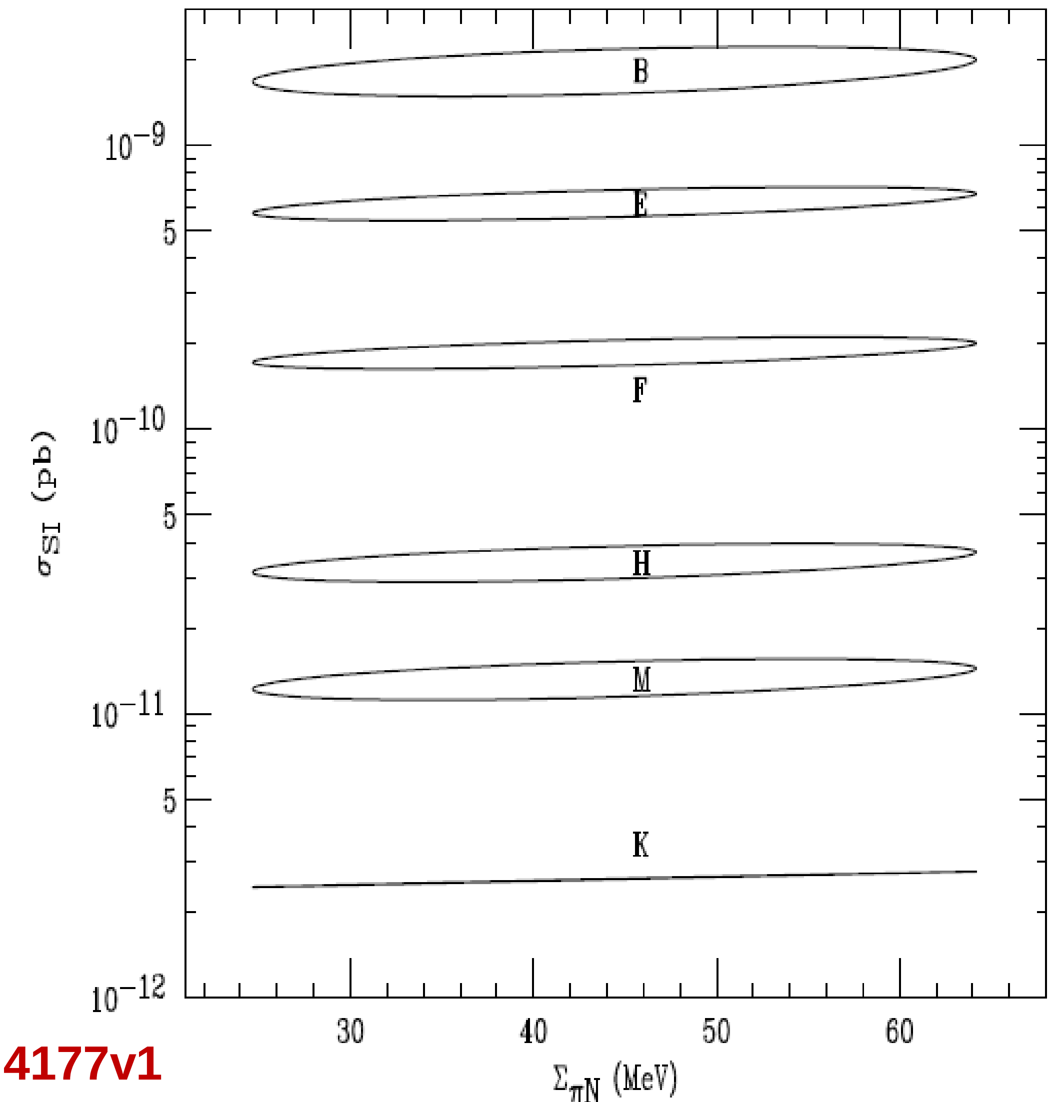
CMSSM Predictions for Dark Matter σ

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!

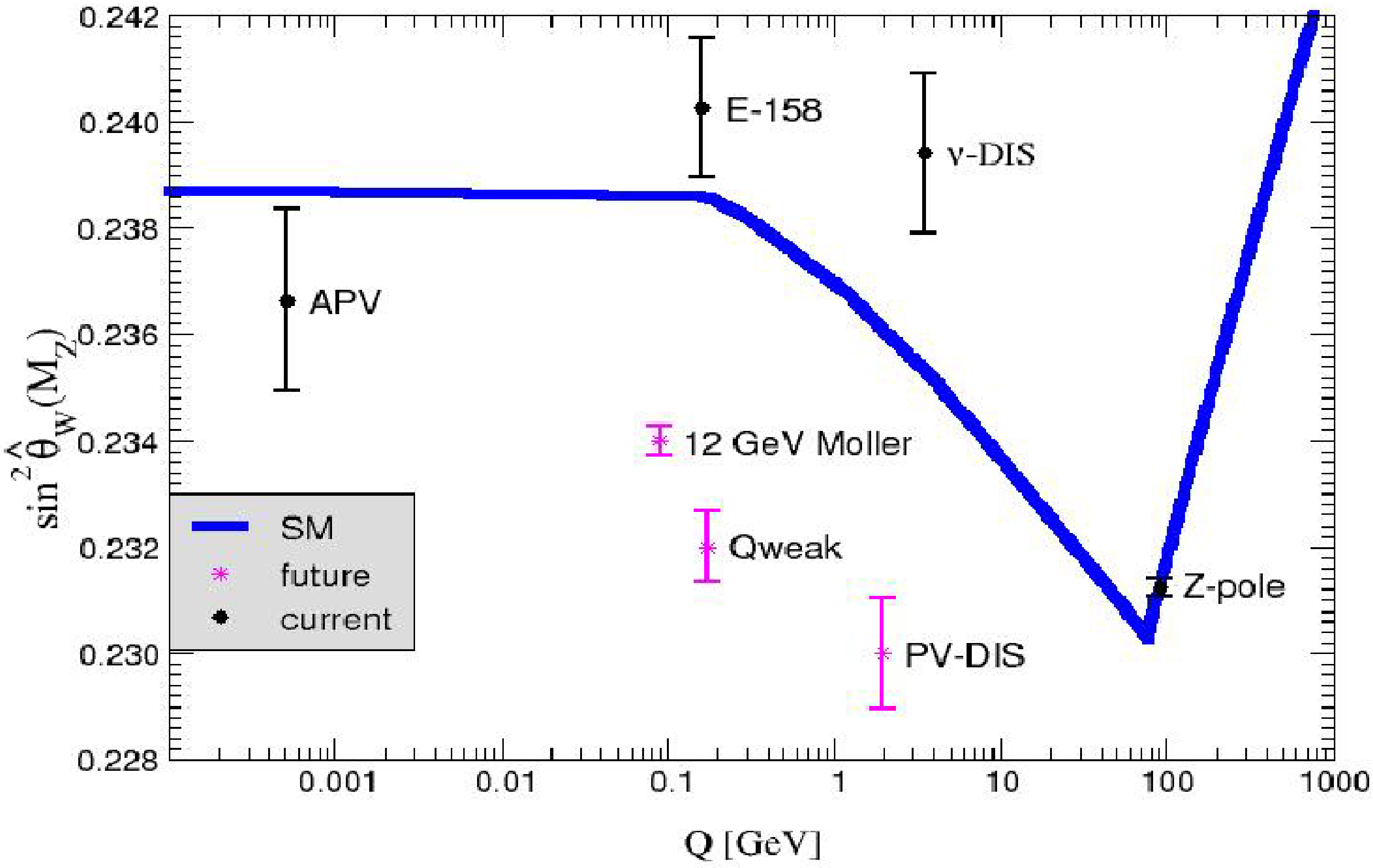


Giedt et al., arXiv: 0907.4177v1
PRL 103 (2009) 201802

The NuTeV anomaly

Radiative Corrections Test of Weak Neutral Current

Not so long ago….



SM line: Erler & Ramsey-Musolf, Phys.Rev.D72:073003,2005

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Paschos-Wolfenstein Ratio

NuTeV measured (approximately) P-W ratio:

$$R^{PW} = \frac{\sigma(\nu\, Fe \rightarrow \nu\, X) - \sigma(\bar{\nu}\, Fe \rightarrow \bar{\nu}\, X)}{\sigma(\nu\, Fe \rightarrow \mu^-\, X) - \sigma(\bar{\nu}\, Fe \rightarrow \mu^+\, X)} = \frac{NC}{CC} \text{ ratio}$$

$$= \tfrac{1}{2} - \sin^2\theta_W$$

$\sin^2\theta_W = 1 - M_W^2/M_Z^2$ = NuTeV: $0.2277 \pm 0.0013 \pm 0.0009$

other methods

c.f. Standard Model = 0.2227 ± 0.0004

(c.f. 1978: 0.230 ± 0.015)

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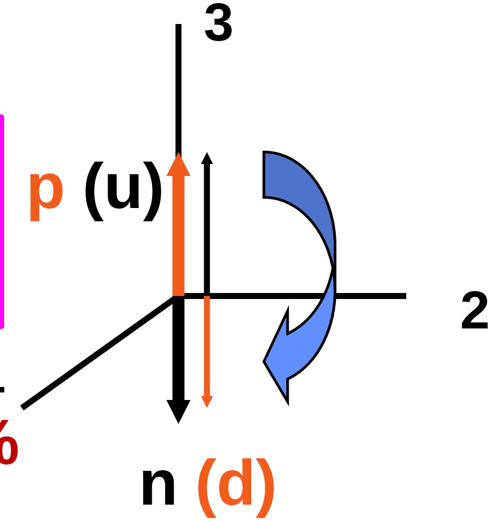
This Sum Rule Assumes Charge Symmetry

Traditionally there is NO label "p" on PDF's !

Its <u>assumed</u> that charge symmetry: $e^{i \pi I_2}$ is exact.



Good at < 1% : e.g. $(m_n - m_p) / m_p \sim 0.1\%$

That is: $u \equiv u^p = d^n$

$d \equiv d^p = u^n$ **etc.**

Hence:

$$F_2^n = 4/9 \times (d(x) + \bar{d}(x)) + 1/9 (u(x) + \bar{u}(x))$$

up-quark in n **down-quark in n**

Correction to Paschos-Wolfenstein from CSV

- **General form of the correction is:**

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

- **$u_A = u^p + u^n$; $d_A = d^p + d^n$ and hence**

  $u_A - d_A = (u^p - d^n) - (d^p - u^n) \equiv \delta u - \delta d$

- **N.B. In general the corrections are C-odd and so involve only valence distributions: $q^- = q - \bar{q}$**

Davidson *et al*., hep-ph/0112302

Charge Symmetry Violation

Estimates of Charge Symmetry Violation*

- Origin of effect is $m_d \neq m_u$
- Unambiguously predicted : $\delta d_V - \delta u_V > 0$
- Biggest % effect is for minority quarks, i.e. δd_V
- Same physics that gives : d_V / u_V small as $x \rightarrow 1$

  and : g^p_1 and $g^n_1 > 0$ at large x

Close & Thomas, Phys Lett B212 (1988) 227

i.e. mass difference of quark pair spectators to hard scattering

* Sather, Phys Lett B274 (1992) 433; Rodionov et al., Mod Phys Lett A9 (1994) 1799

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Non-Perturbative Structure of Nucleon

To calculate PDFs need to evaluate non-perturbative matrix elements

Using either : i) lattice QCD or ii) Model

i) Lattice QCD can only calculate low moments of $u^p - d^p$

quite a lot has been learnt....

BUT nothing yet about CSV

Modeling Valence Distribution

Formally, using OPE ($A_+ = 0$ gauge) *:

$$q(x, Q^2_0) = 1/4\pi \int_{-1}^{1} dz \exp[-i\, M\, x\, z\,] \langle p|\, \psi_+^+\, (z;00\text{-}z)\, \psi_+(0)\, |p\rangle$$

Insert complete set of states : $\sum_n \int d^3 p_n\, |n\rangle \langle n| = 1$

and do $\int$ dz using translational invariance)

$$q(x, Q^2_0) = \sum_n \int d^3 p_n\ \ |\langle n\, |\, \psi_+(0)\, |\, p \rangle|^2\, \delta(\, M\,(1-x) - p^+_n\,)$$

$$\text{with } p^+_n = (\, m_n^2 + \overline{p}_n^{\,2}\,)^{1/2} + p_z > 0$$

* **Q^2_0 is the scale at which nucleon momentum is carried by predominantly valence quarks: below 1 GeV^2**

Di-quark Spectator States Dominate Valence

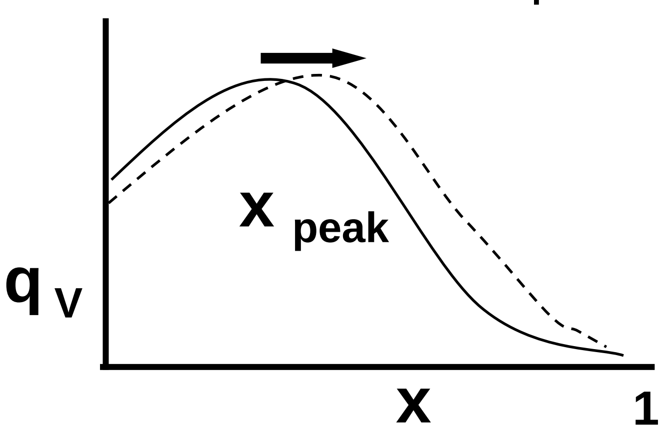
For s-wave valence quarks, most likely three-momentum is zero :

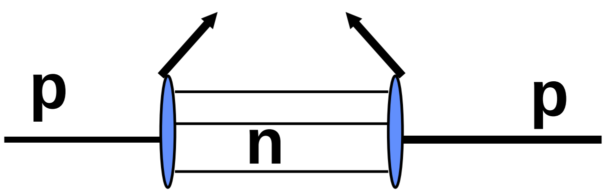
$\delta(M (1 - x) - m_n)$ **determines x where** $q (x, Q^2_0)$ **is maximum**

i.e. $x_{peak} = (M - m_n) / M$ **and hence lowest** $m_n \rightarrow$ **large – x behaviour**

Natural choice is two-quark state

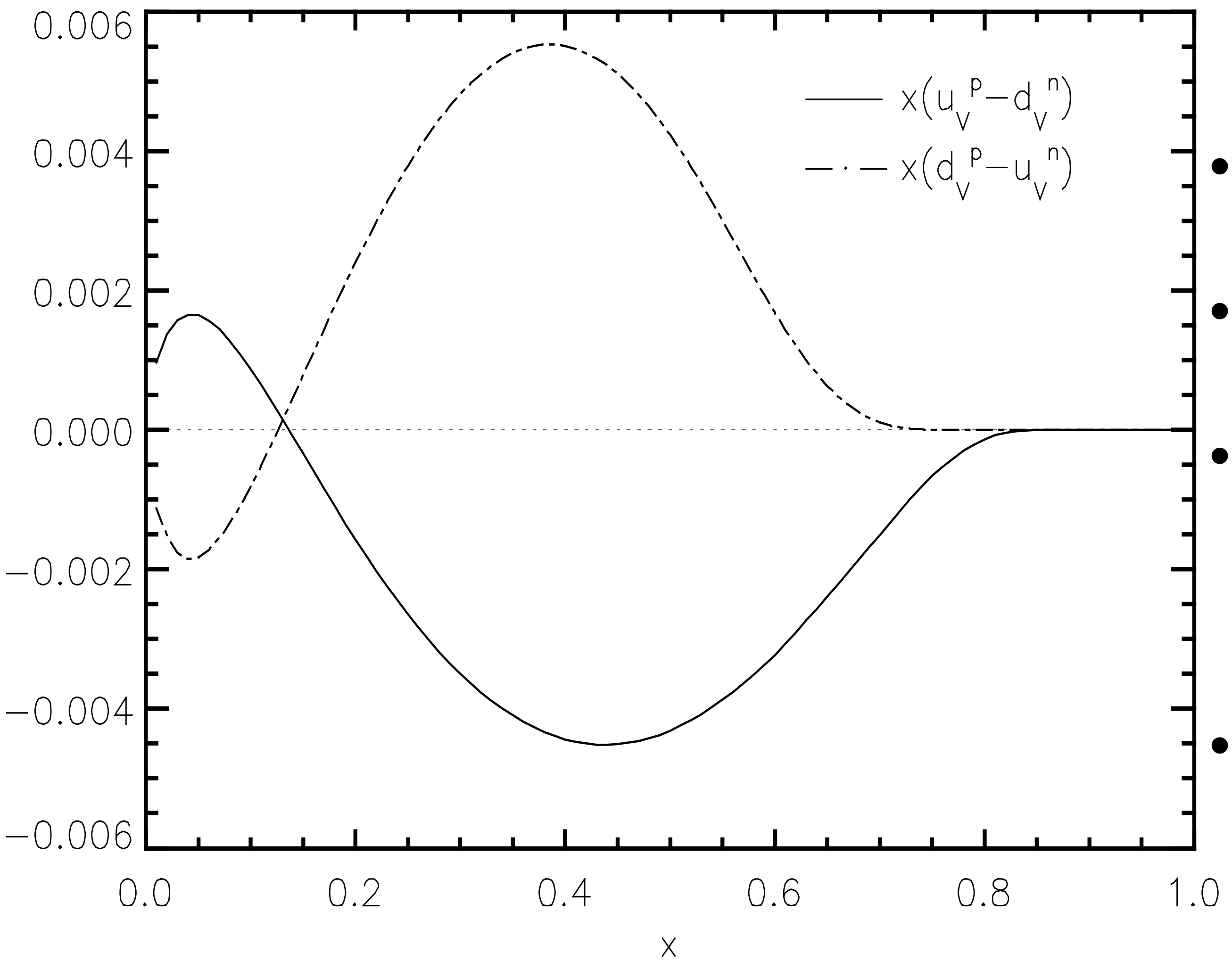
$m_2 / M = 2/3$ **(CQM);**
= 3/4 MIT bag → $x_{peak} \sim 1/4$ **to 1/3**





If $m_2 \downarrow$ **:** x_{peak} **moves to right**

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

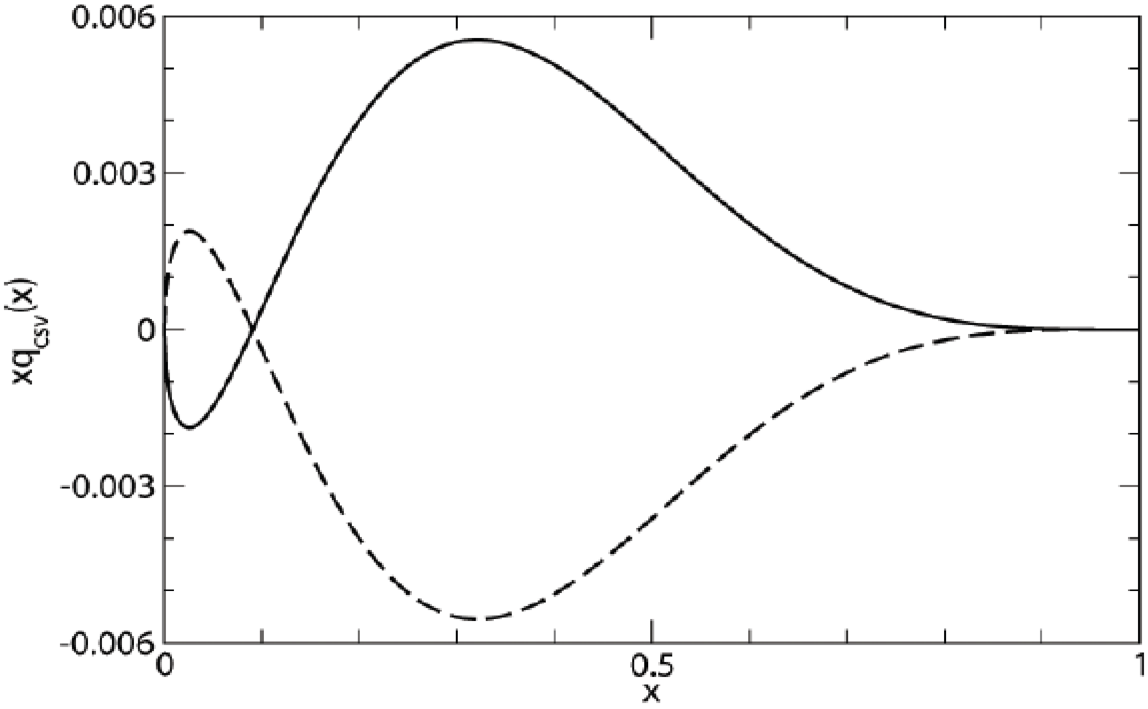


FIG. 5: The phenomenological valence quark CSV function from Ref. [23], corresponding to best fit value $\kappa = -0.2$ defined in Eq. (35). Solid curve: $x\delta d_v$; dashed curve: $x\delta u_v$.

MRST, Eur Phys J C35 (2004) 325

Model Calculations Reduce NuTeV by 1σ

Two original ('92 and '93) calculations agree very (too?) well with each other and with recent approximation based on phenomenological PDFs

Includes effect of NuTeV acceptance

(Zeller *et al*., hep-ex/0203004)

TABLE II: CSV corrections to determination of $\sin^2\theta_W$ in neutrino scattering. *PW* is the contribution to the Paschos-Wolfenstein ratio, *Nu* is the result weighted by the NuTeV functional. ΔU is the total contribution from $\delta u_{\rm v}$, ΔD is the contribution from $\delta d_{\rm v}$ and *Tot* is the total CSV correction.

	ΔU_{PW}	ΔD_{PW}	Tot_{PW}	ΔU_{Nu}	ΔD_{Nu}	Tot_{Nu}
Rodionov	-.0010	.0011	-.0020	-.00065	-.00081	-.0015
Sather	-.00078	.0013	-.0021	-.00060	-.0011	-.0017
analytic	-.0008	.0014	-.0022	-.0006	-.0012	-.0017

Londergan & Thomas, Phys Lett B558 (2003) 132

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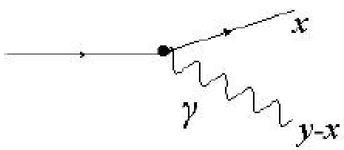
An additional source of CSV

- 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":



$$\tilde{P}_{qq}\left(\frac{x}{y}\right)$$

- 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

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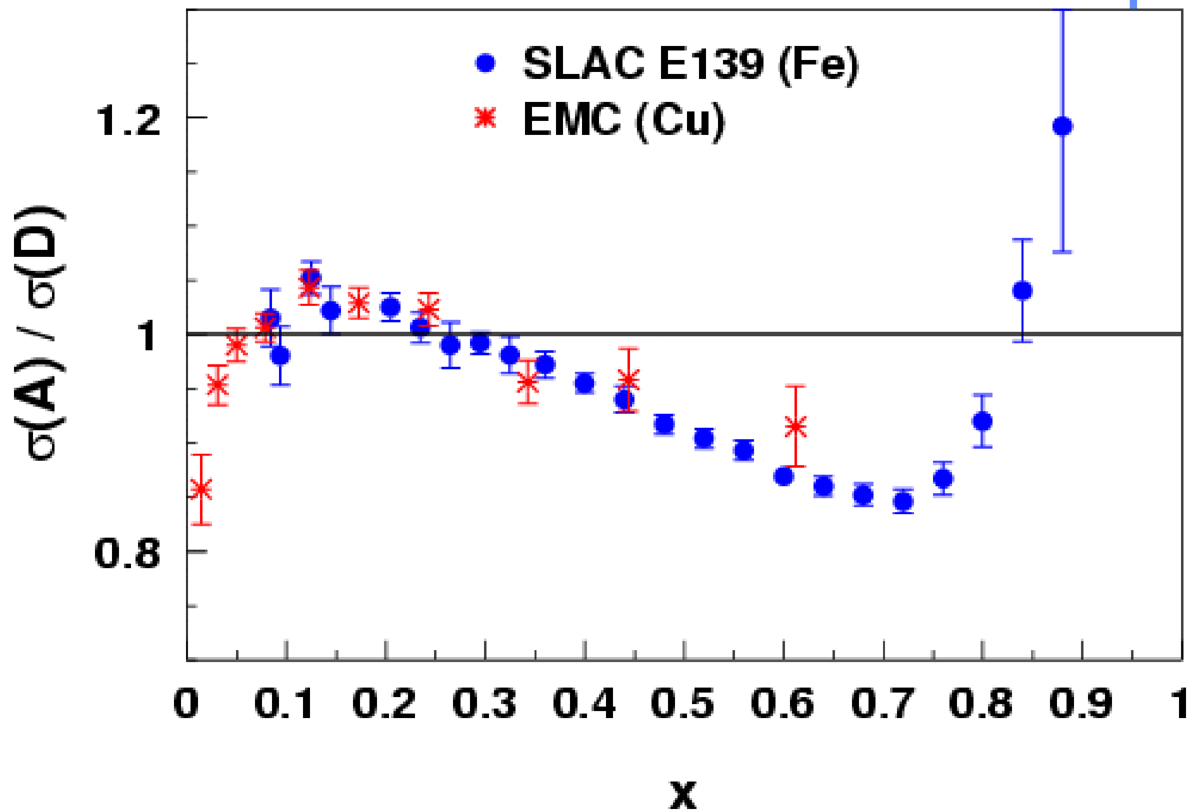
Isovector EMC Effect

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)

Attempt to Understand this based on QMC

- **Two major, recent papers:**
  1. Guichon, Matevosyan, Sandulescu, Thomas, Nucl. Phys. A772 (2006) 1.
  2. Guichon and Thomas, Phys. Rev. Lett. 93 (2004) 132502

- **Built on earlier work on QMC: e.g.**
  3. Guichon, Phys. Lett. B200 (1988) 235
  4. Guichon, Saito, Rodionov, Thomas, Nucl. Phys. A601 (1996) 349

- **Major review of applications of QMC to many nuclear systems:**
  5. Saito, Tsushima, Thomas, Prog. Part. Nucl. Phys. 58 (2007) 1-167 (hep-ph/0506314)

Recent Calculations for Finite Nuclei

Spin dependent EMC effect TWICE as large as unpolarized

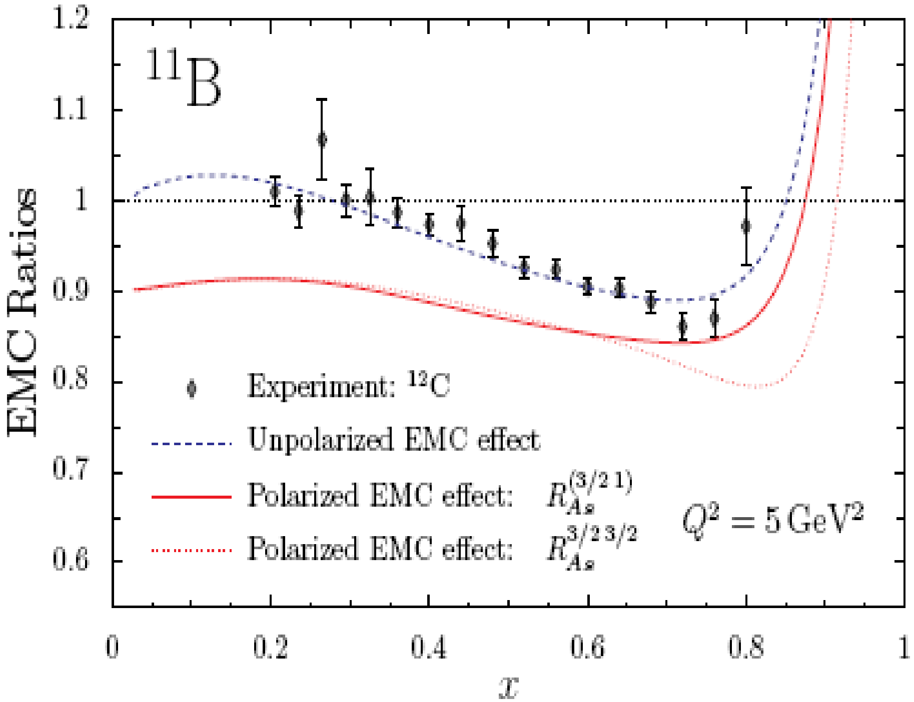


FIG. 7: The EMC and polarized EMC effect in ^{11}B. The empirical data is from Ref. [31].

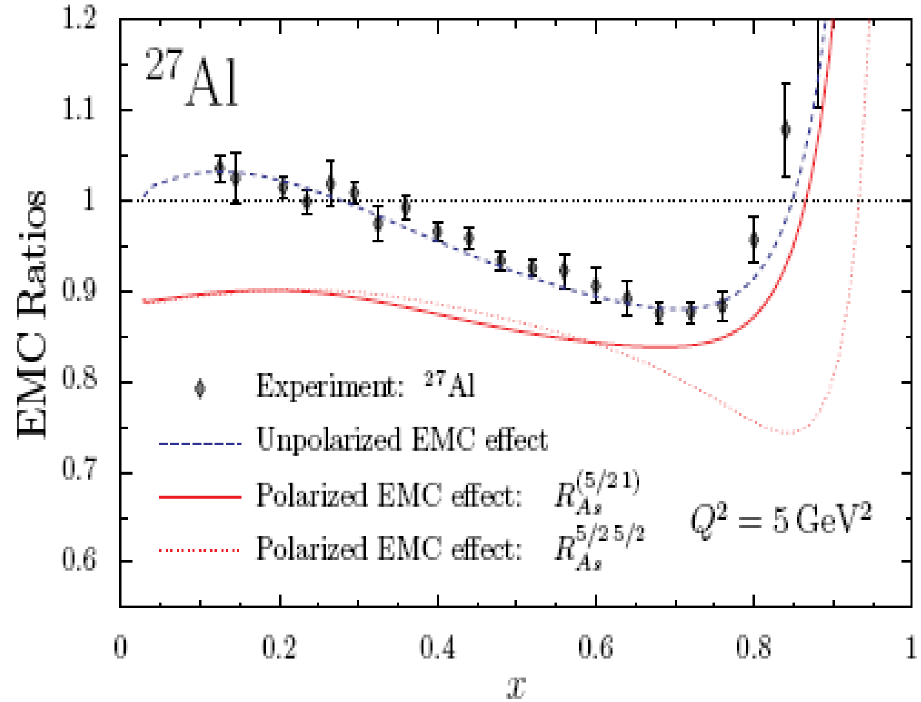


FIG. 9: The EMC and polarized EMC effect in ^{27}Al. The empirical data is from Ref. [31].

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

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NuTeV Reassessed

- New realization concerning EMC effect:
  - isovector force in nucleus (like Fe) with N≠Z effects ALL u and d quarks in the nucleus
  - subtracting structure functions of extra neutrons is not enough
  - *there is a shift of momentum from all u to all d quarks*

- This has same sign as charge symmetry violation associated with $m_u \neq m_d$

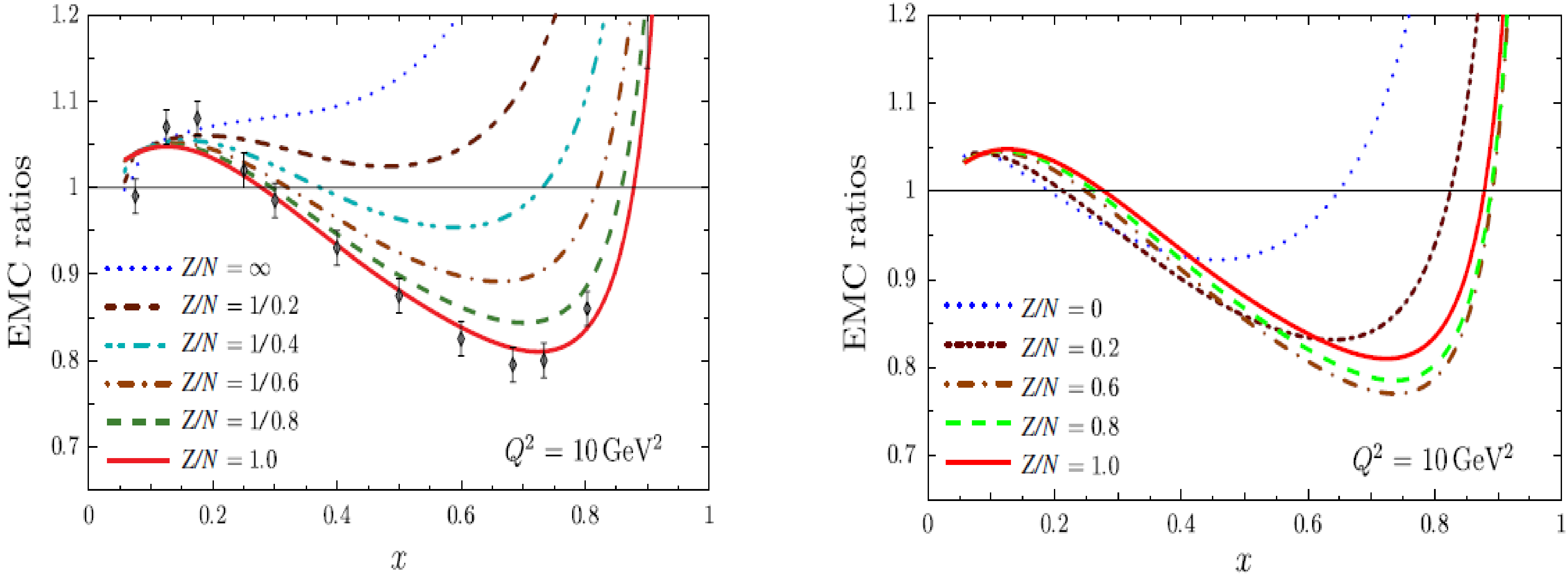
- Sign and magnitude of both effects exhibit little model dependence

Cloet et al., arXiv: 0901.3559v1 ; Londergan et al., Phys Rev D67 (2003) 111901

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 <u>all</u> u- to <u>all</u> d-quarks and subtracting their direct contribution does not remove this effect

This has implications for the NuTeV anomaly – more than 1σ reduction of "anomaly"

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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}	$\sin^2\theta_W \pm \text{syst.}$
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	$0.2227 \pm \mathit{large}$
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

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

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:**

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

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

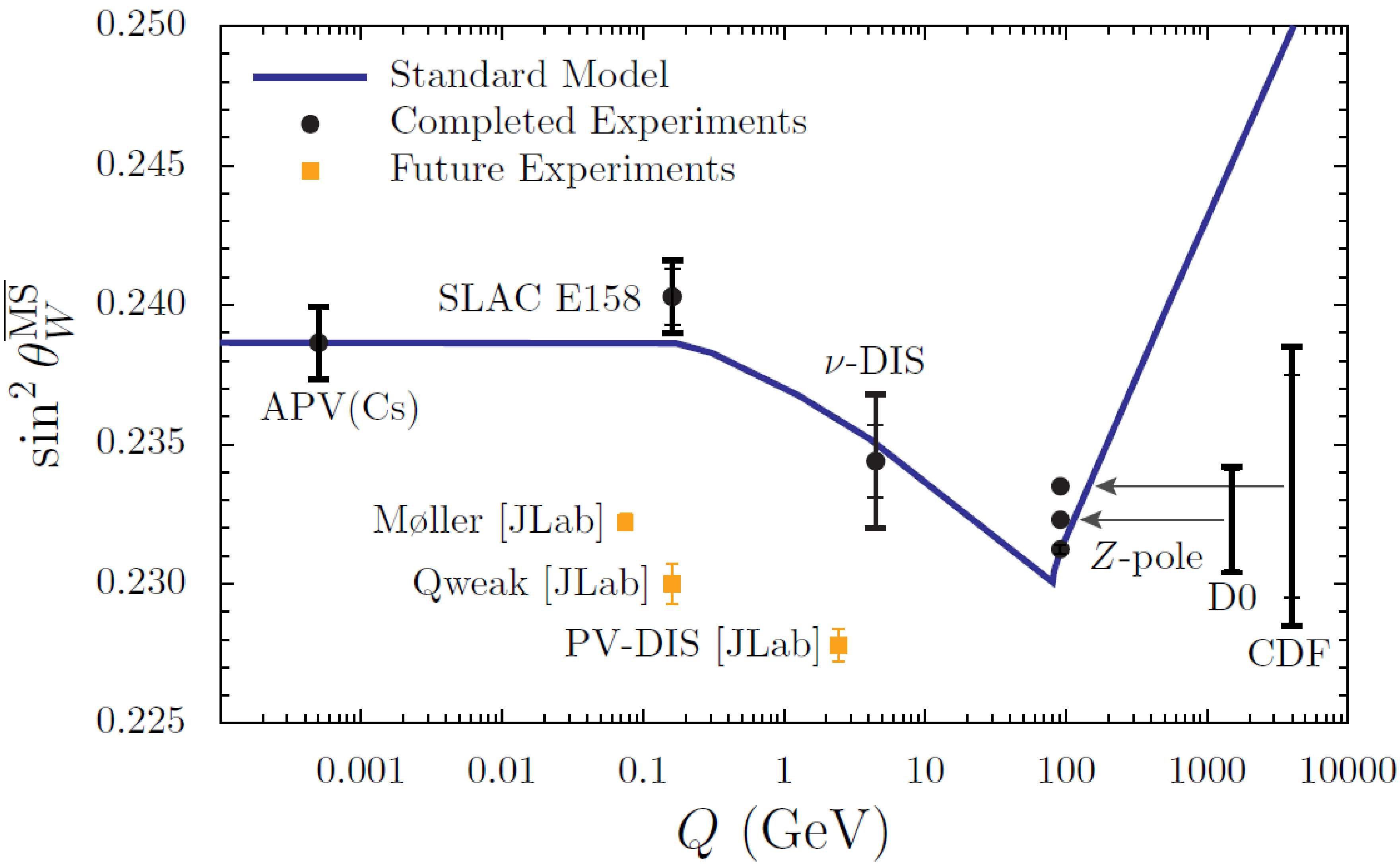
- **Then R^{ν} moves from 0.3916 ± 0.0013 c.f. 0.3950 in the Standard Model to 0.3933 ± 0.0015;**

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

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

Bentz et al., arXiv: 0908.3198

The Standard Model works… again



Bentz et al., arXiv: 0908.3198

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Summary

- Standard Model has again survived major tests:
    - strange quarks as analog of Lamb shift in QED

- Determination of $m_s < \bar{s}s >$ in proton has important implications for dark matter detection

- The outstanding discrepancy with Standard Model predictions for Z^0 was NuTeV anomaly

    - this is resolved by CSV and newly discovered isovector correction to nuclear structure functions

- Parity Violating DIS is an ideal way to test *both* effects

- Major remaining uncertainty is $s(x) - \bar{s}(x)$ …..

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