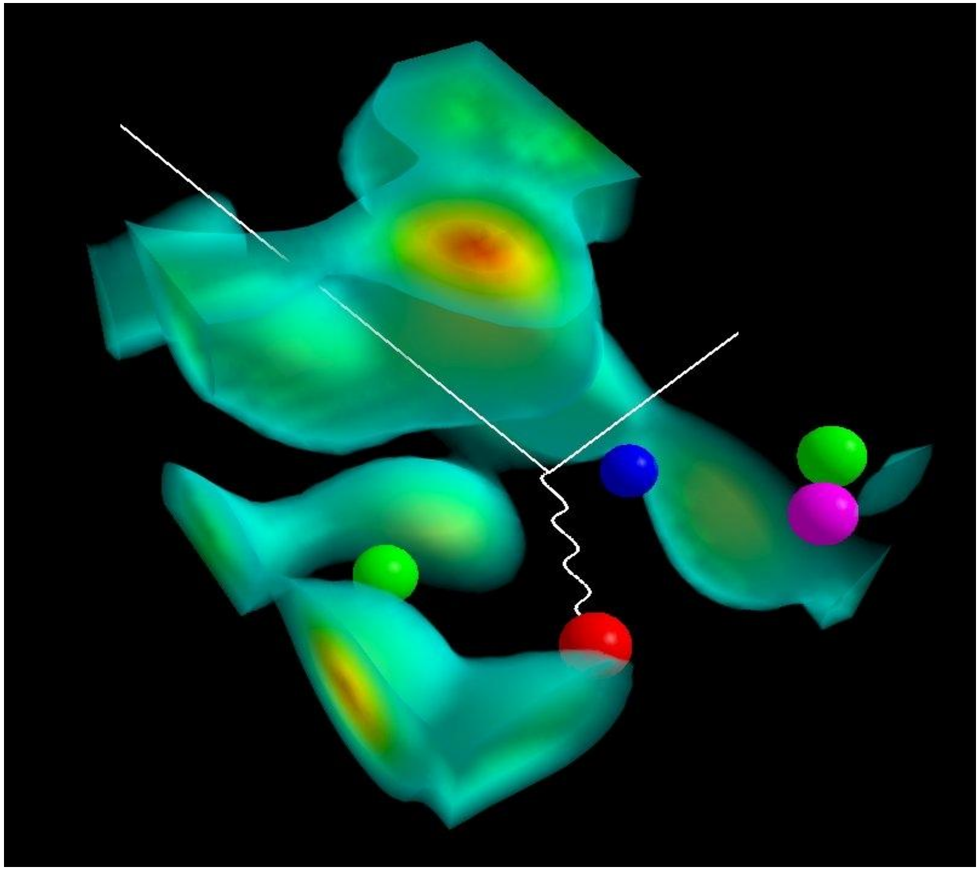
The Weinberg Angle and Possible New Physics Beyond the Standard Model



Anthony W. Thomas

CSSM Seminar: Nov 18th and 25th 2009

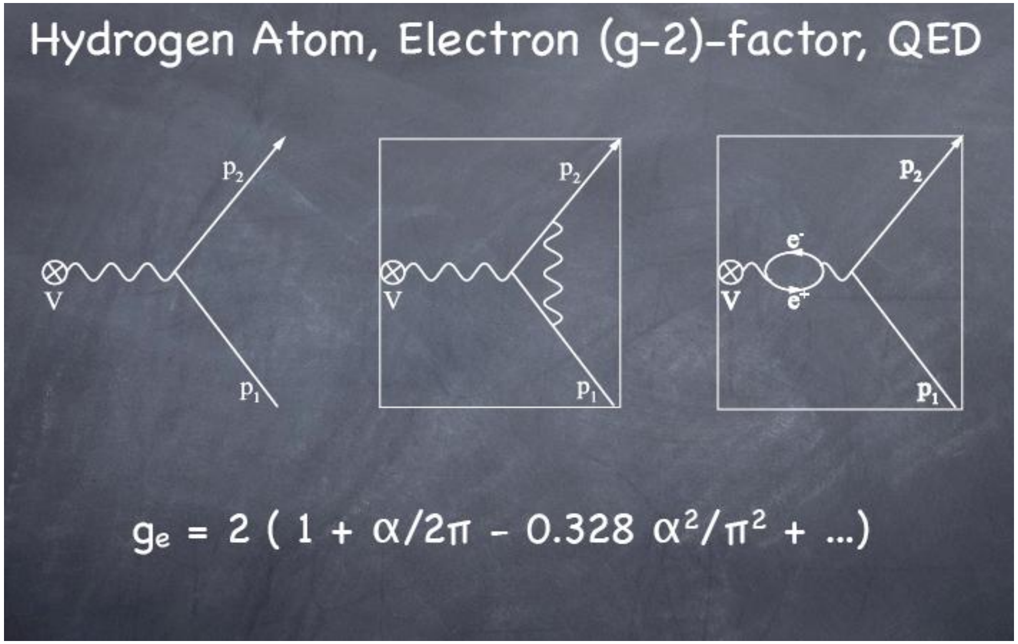
Outline

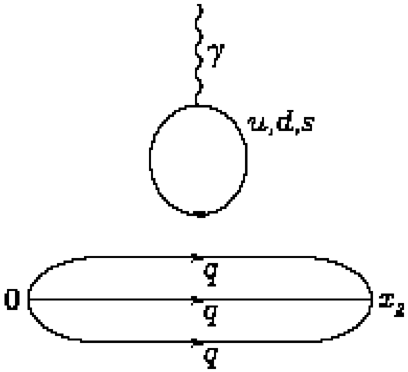
- Testing non-perturbative QCD at JLab
- Testing the Neutral Current Couplings at JLab
- The NuTeV anomaly
- Resolution of the NuTeV anomaly
  - CSV in parton distribution functions
  - a new EMC effect

Non-perturbative QCD

Testing Non-Perturbative QCD

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





- It is a fundamental test of non-perturbative QCD

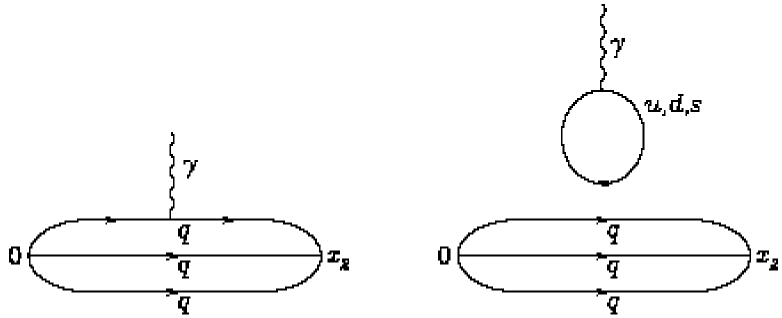
Strange Quarks in the Proton

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

- Calculation of $G_{E,M}^{s}$ (Q^2) :
  - Direct: Kentucky (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)



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

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

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

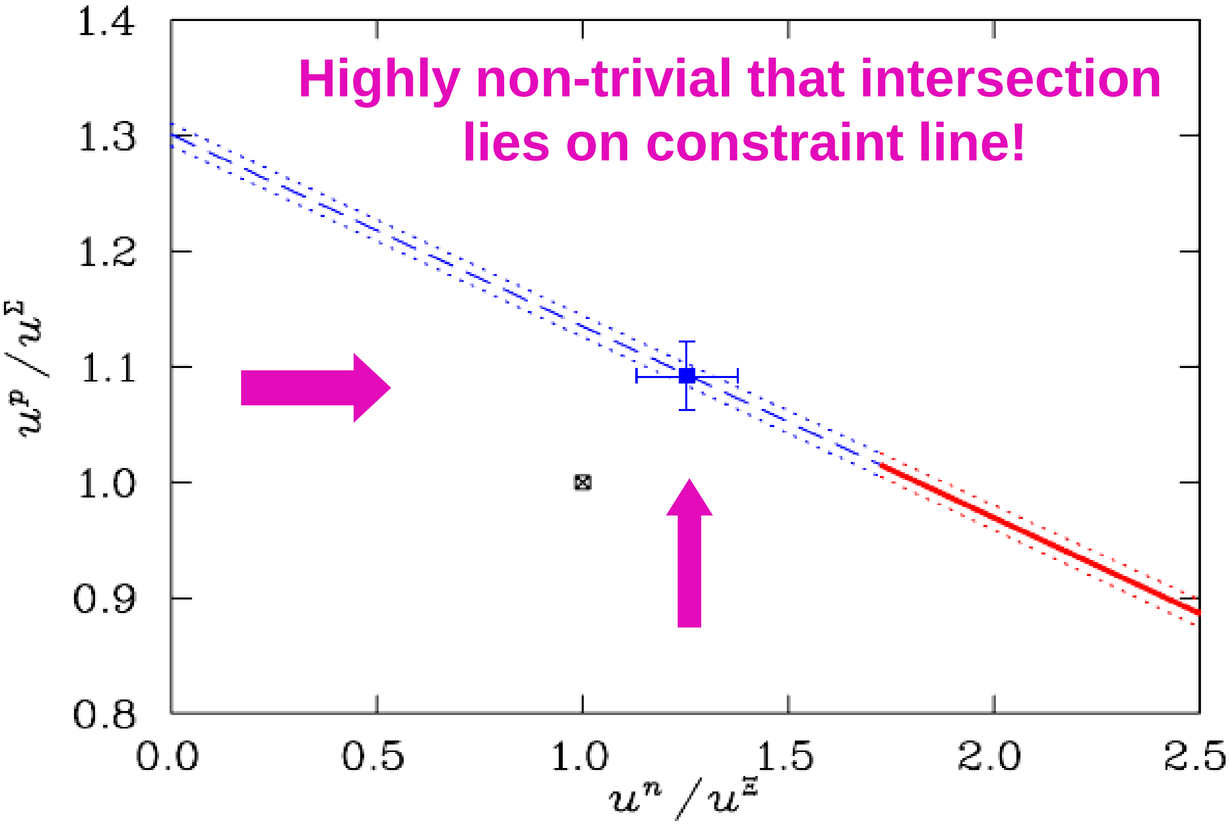
⇒ $\Sigma^+ - \Sigma^- = u^\Sigma$

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

Just these ratios from Lattice QCD

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

First Accurate Determination of G_M^s from QCD



1.10±0.03

1.25±0.12

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

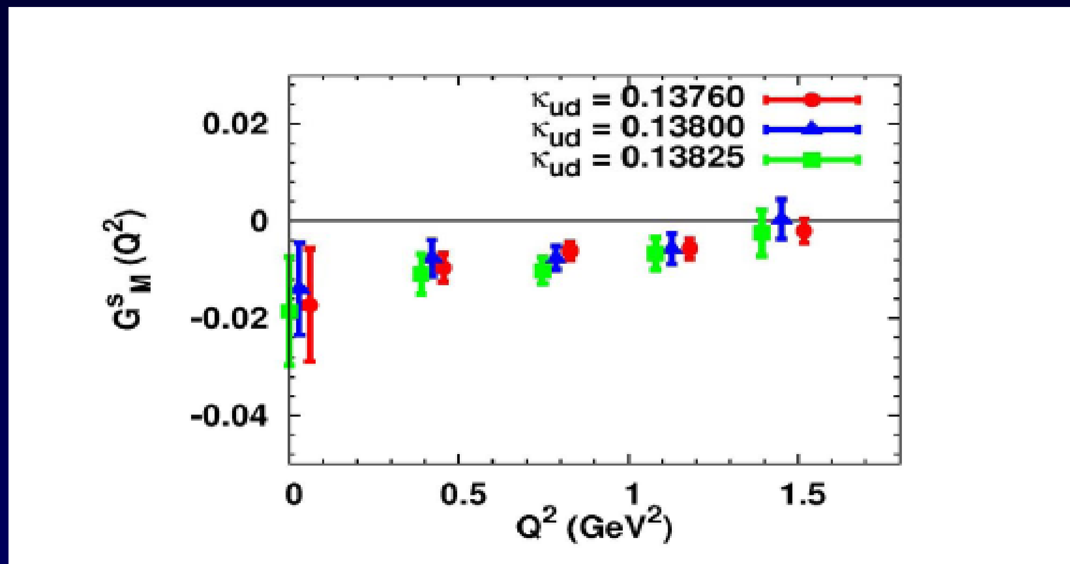
Leinweber et al., PRL 94 (2005) 212001

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)

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

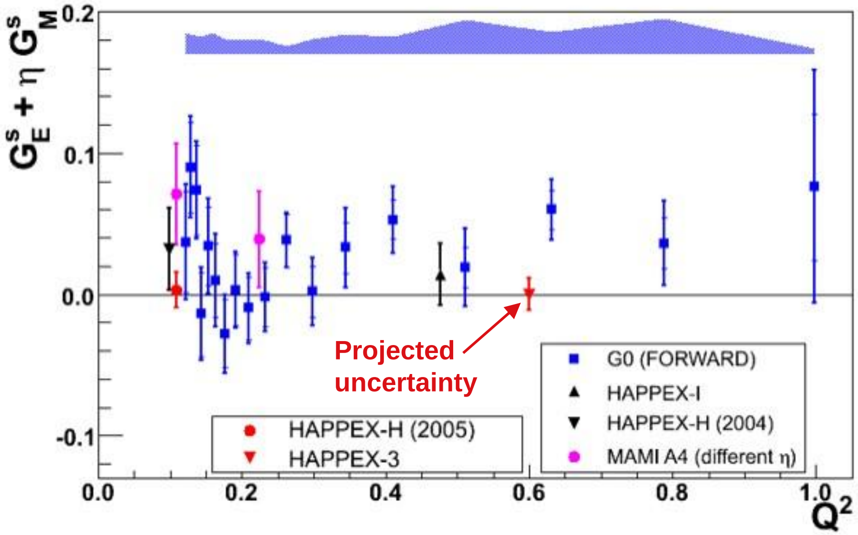


$$G_M^S(Q^2=0) = -\,0.017(25)(07)\ \mu_N$$

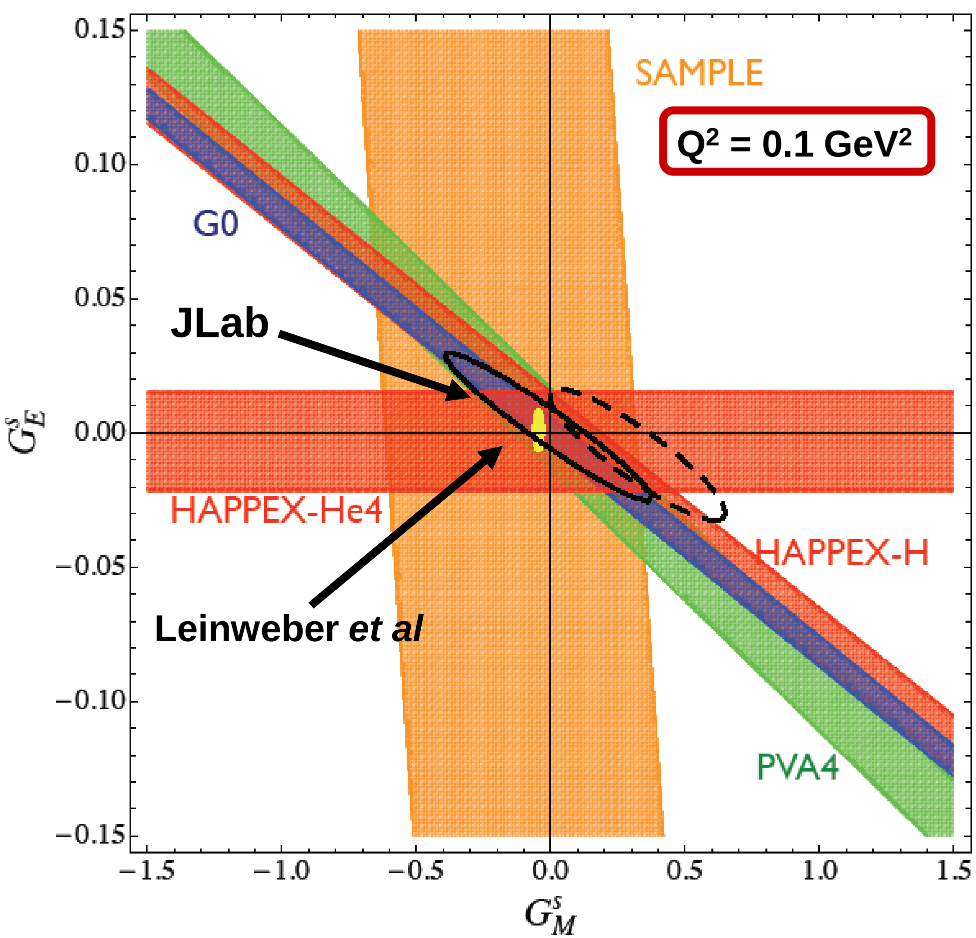
c.f. -0.046 ± 0.019 (Leinweber et al.)

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)

Global Analysis of PVES Data



From NSAC Long Range Plan

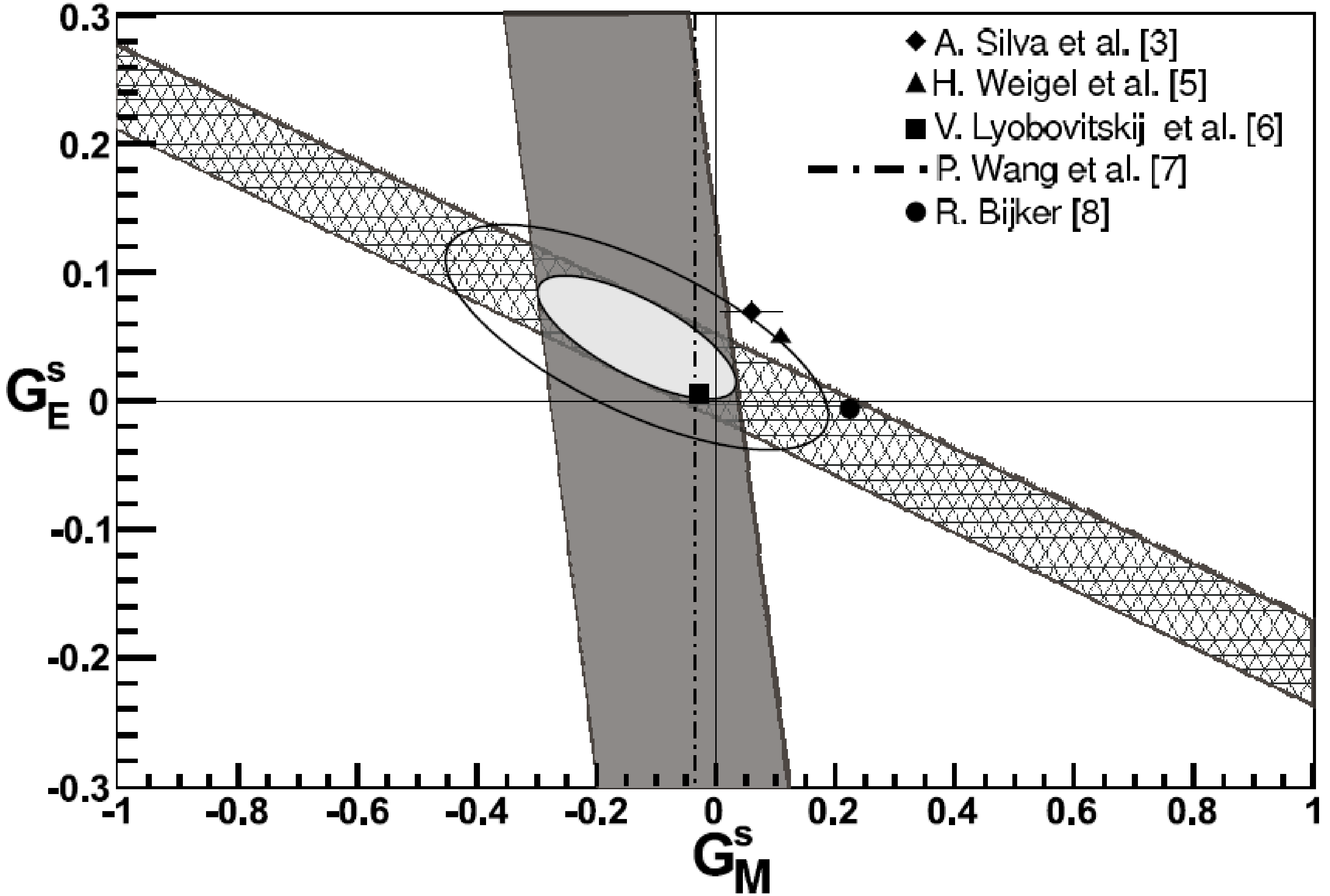


- **Proton not all that strange**
- **New data not yet included at 0.23 and 0.6 GeV^2 (PVA4 – just out, G0 – final analysis, HAPPEx III – will start this year)**

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

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

arXiv: 0903.2733v1



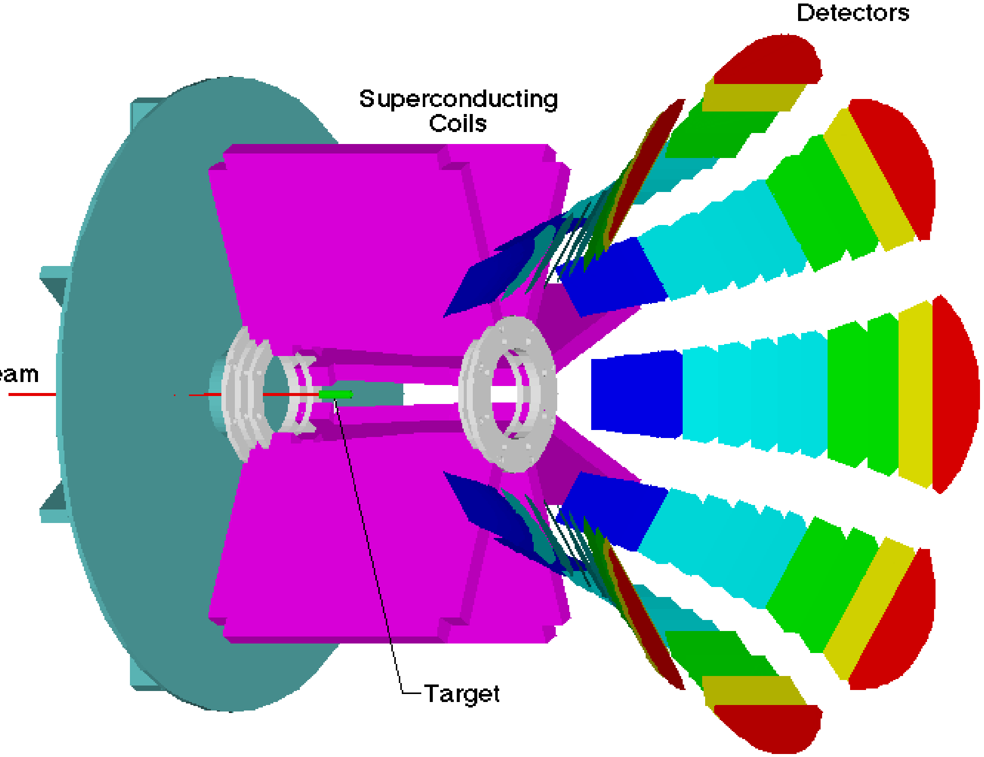
$G_M^s = -0.14 \pm 0.11 \pm 0.11\ \mu_N$; $G_E^s = 0.050 \pm 0.038 \pm 0.019$

The G0 experiment at JLAB

• Forward and backward angle PV e-p elastic and e-d (quasielastic) in JLab Hall C

G_E^s, G_M^s and G_A^e separated over range $Q^2 \sim 0.1-1.0\ (\mathrm{GeV/c})^2$

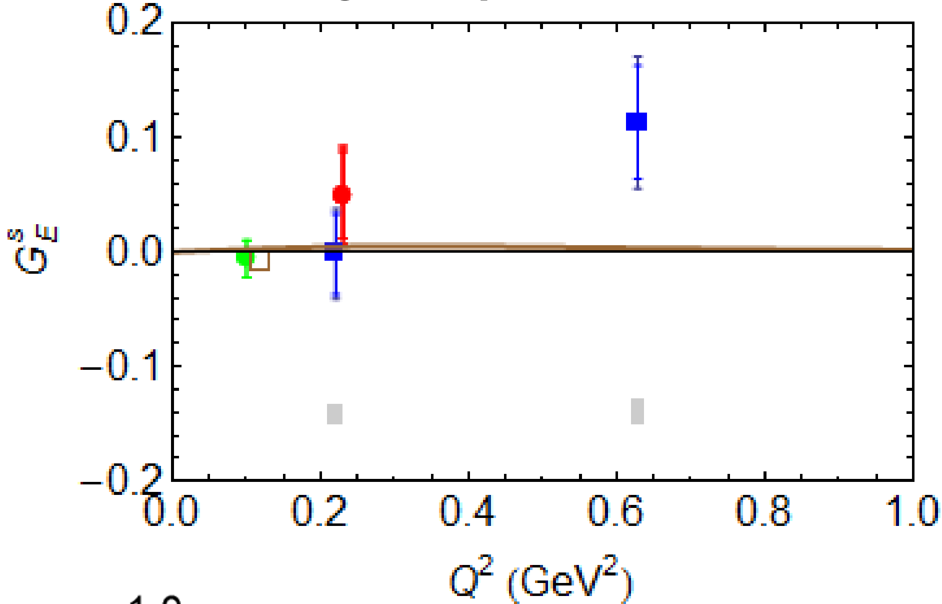
• superconducting toroidal magnet

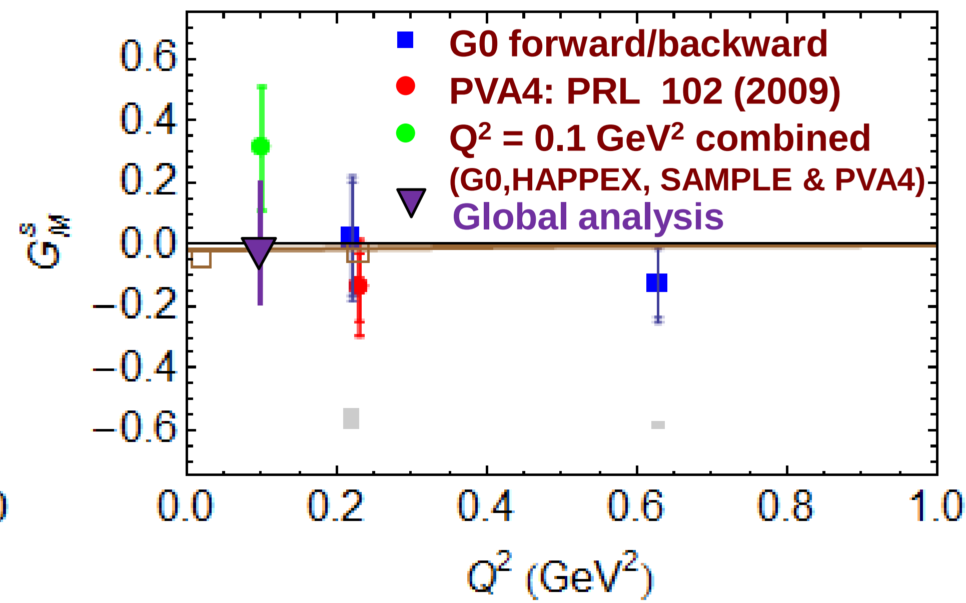


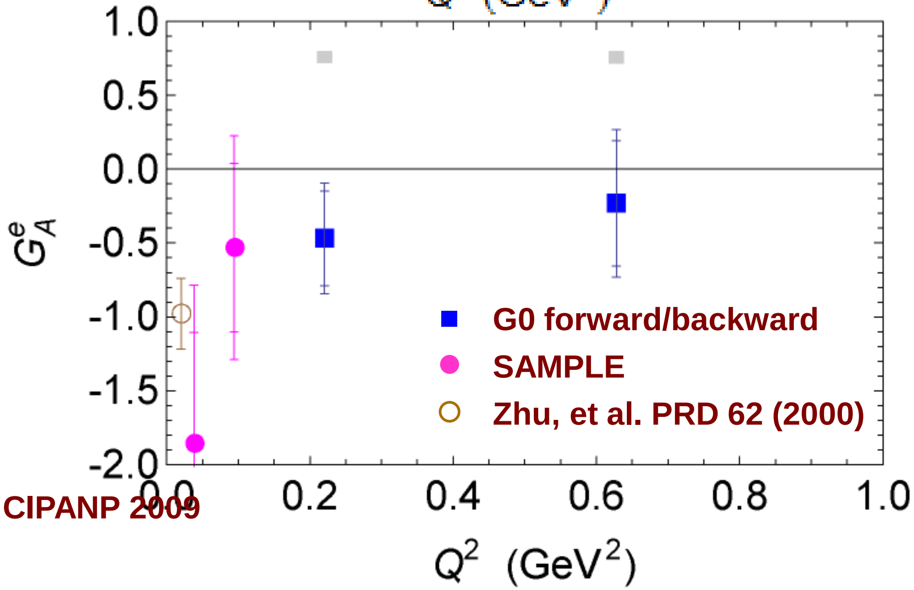
- scattered particles detected in segmented scintillator arrays in spectrometer focal plane
- custom electronics count and process scattered particles at > 1 MHz
- *forward angle data published 2005*
- *backward angle data: 2006-2007*

Form Factor Results

- **Using interpolation of G0 forward measurements**







Global uncertainties

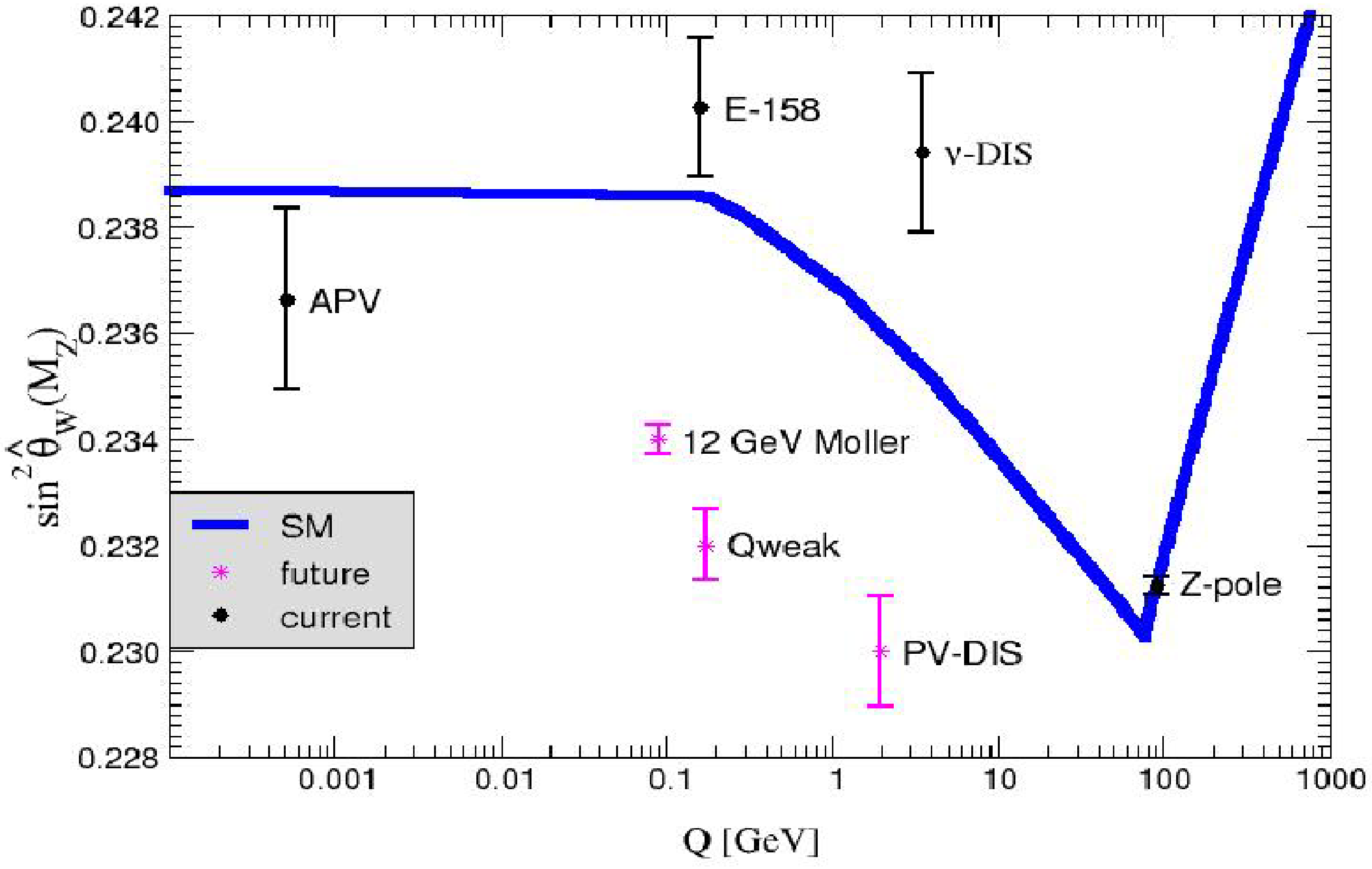
Some calculations:

- **Leinweber, et al. PRL 97 (2006) 022001**
- **Leinweber, et al. PRL 94 (2005) 152001**
- **Wang, et al arXiv:0807.0944 (Q^2 = 0.23 GeV^2)**
- **Doi, et al, arXiv:0903.3232**

The Weak Neutral Current

Radiative Corrections Test of Weak Neutral Current

One year ago….



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

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

- Proton target

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

Neutral-weak form factors

Axial form factor

Assume charge symmetry:

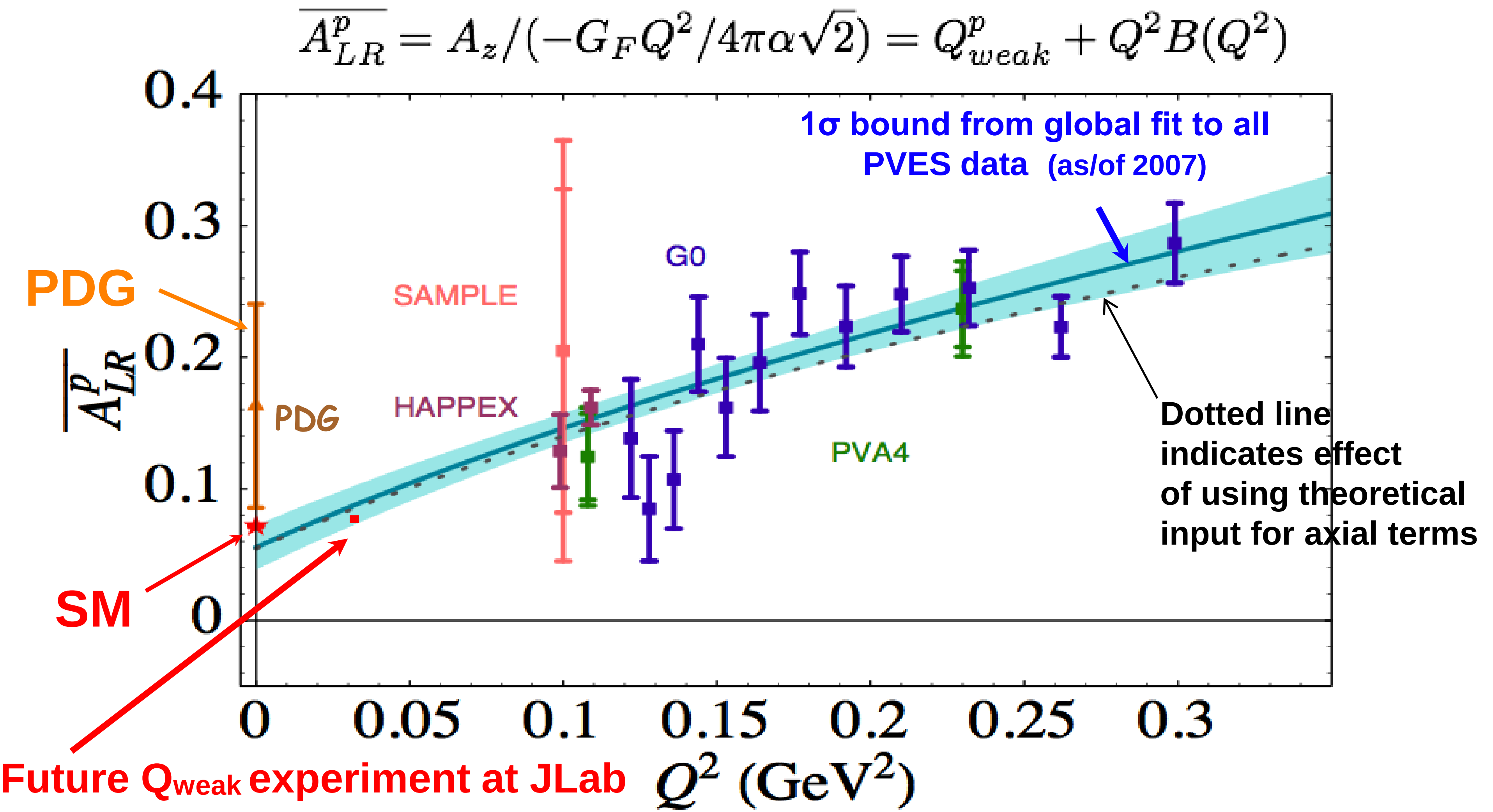
$$4G_{E,M}^{pZ} = (1 - 4\sin^2\theta_W) G_{E,M}^{p\gamma} - G_{E,M}^{n\gamma} - G_{E,M}^{s}$$

Proton weak charge (tree level)

Strangeness

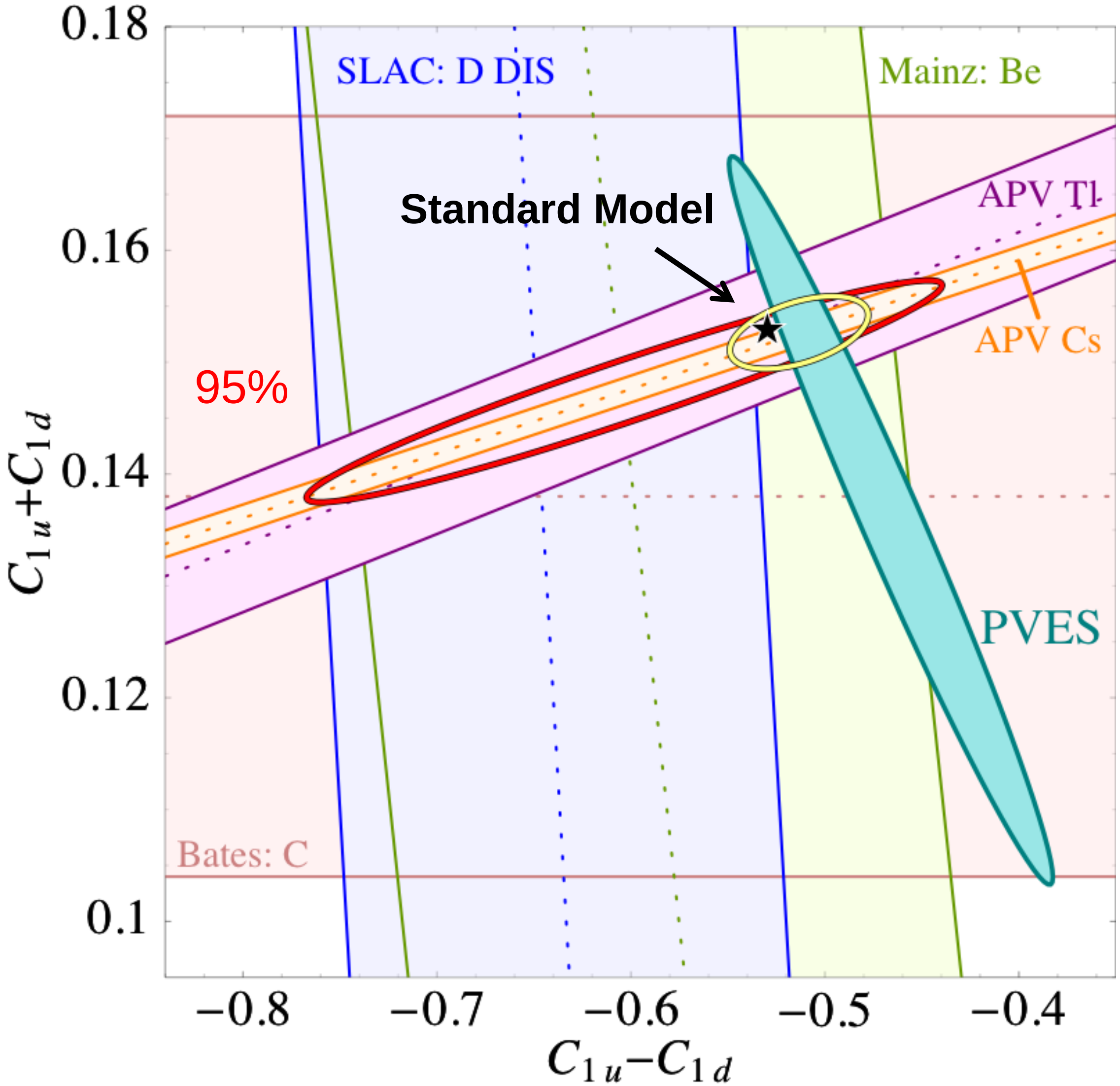
Use data to constrain the parameters of the electroweak theory

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



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

Major progress on C_{1q} couplings



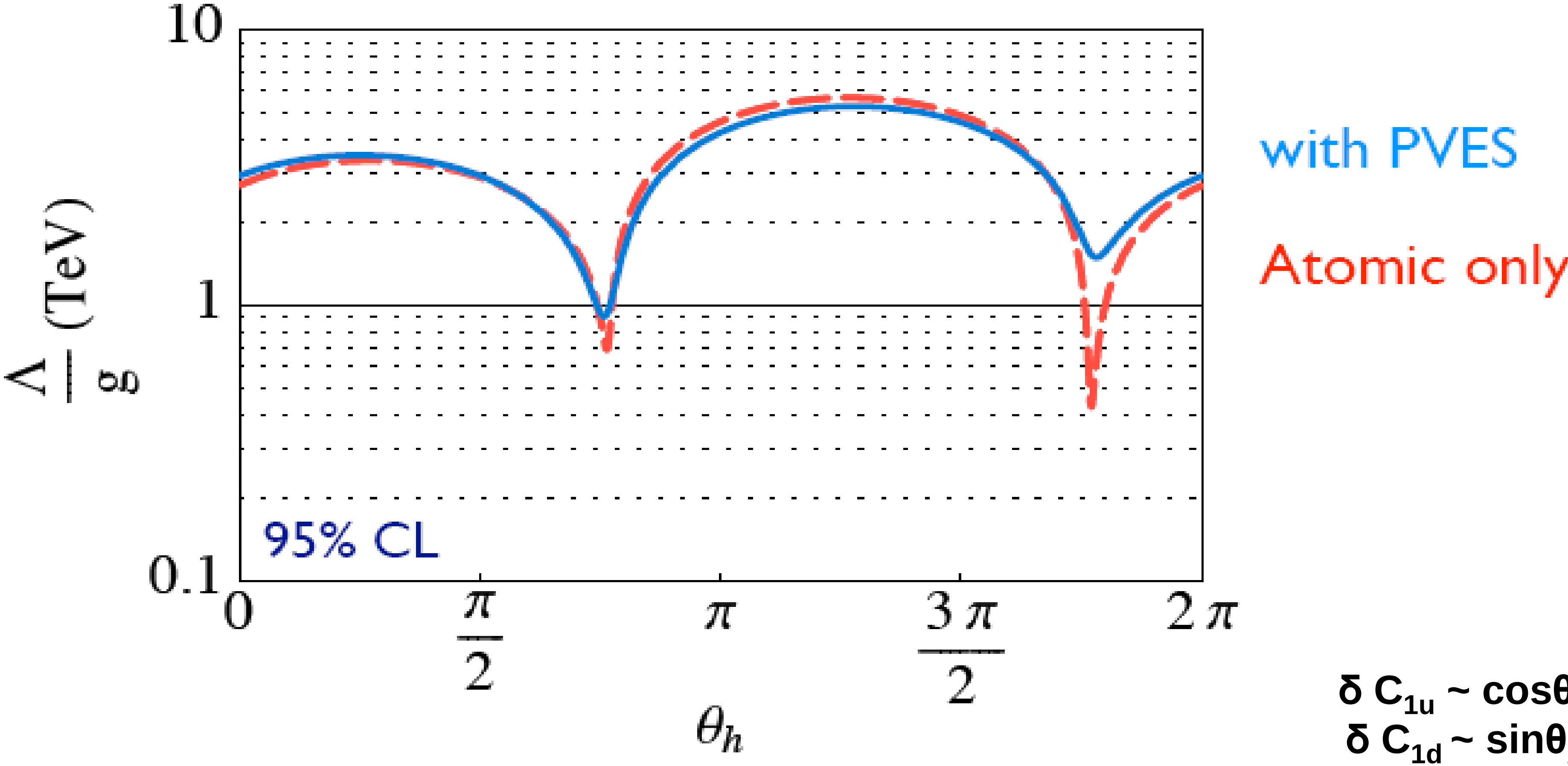
$$Q_{weak} = 2C_{1u} + C_{1d}$$

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

Dramatic improvement in knowledge of weak couplings!

Factor of 5 increase in precision of Standard Model test

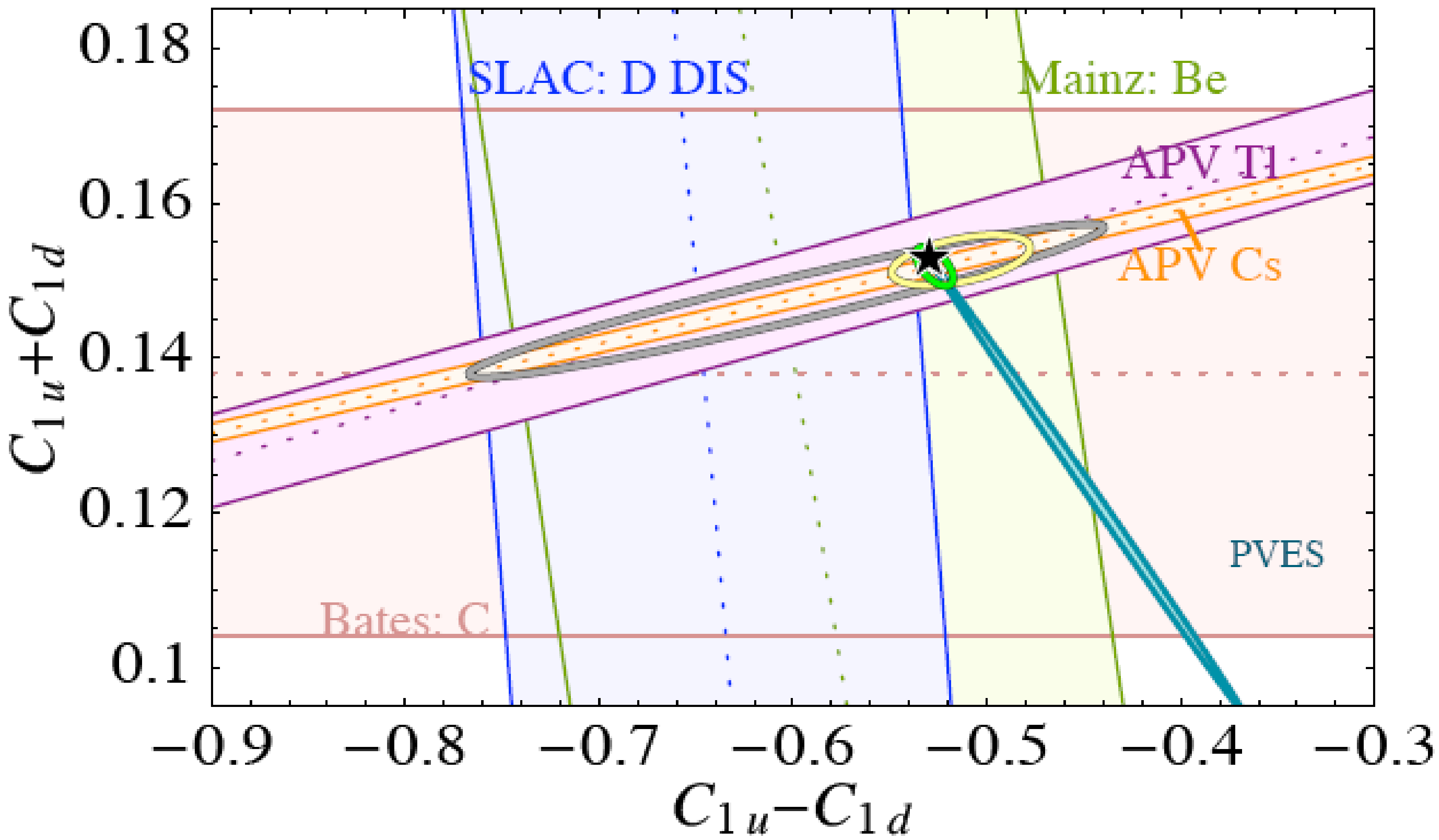
Raises Mass of New Z' to 0.9 TeV – from 0.4 TeV



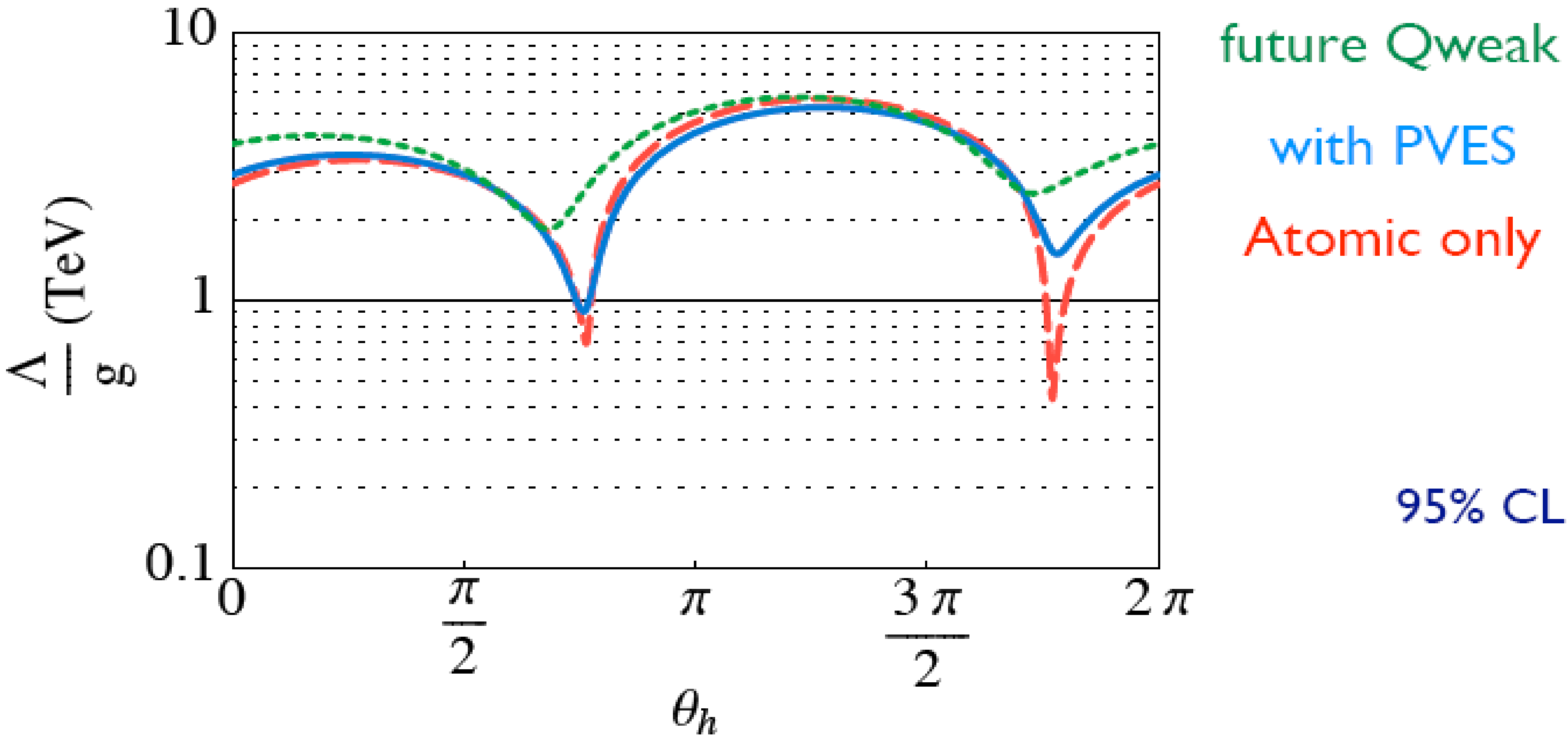
$\delta C_{1u} \sim \cos\theta_h$
$\delta C_{1d} \sim \sin\theta_h$

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

Future Q_{weak} at JLab – if in Agreement with SM



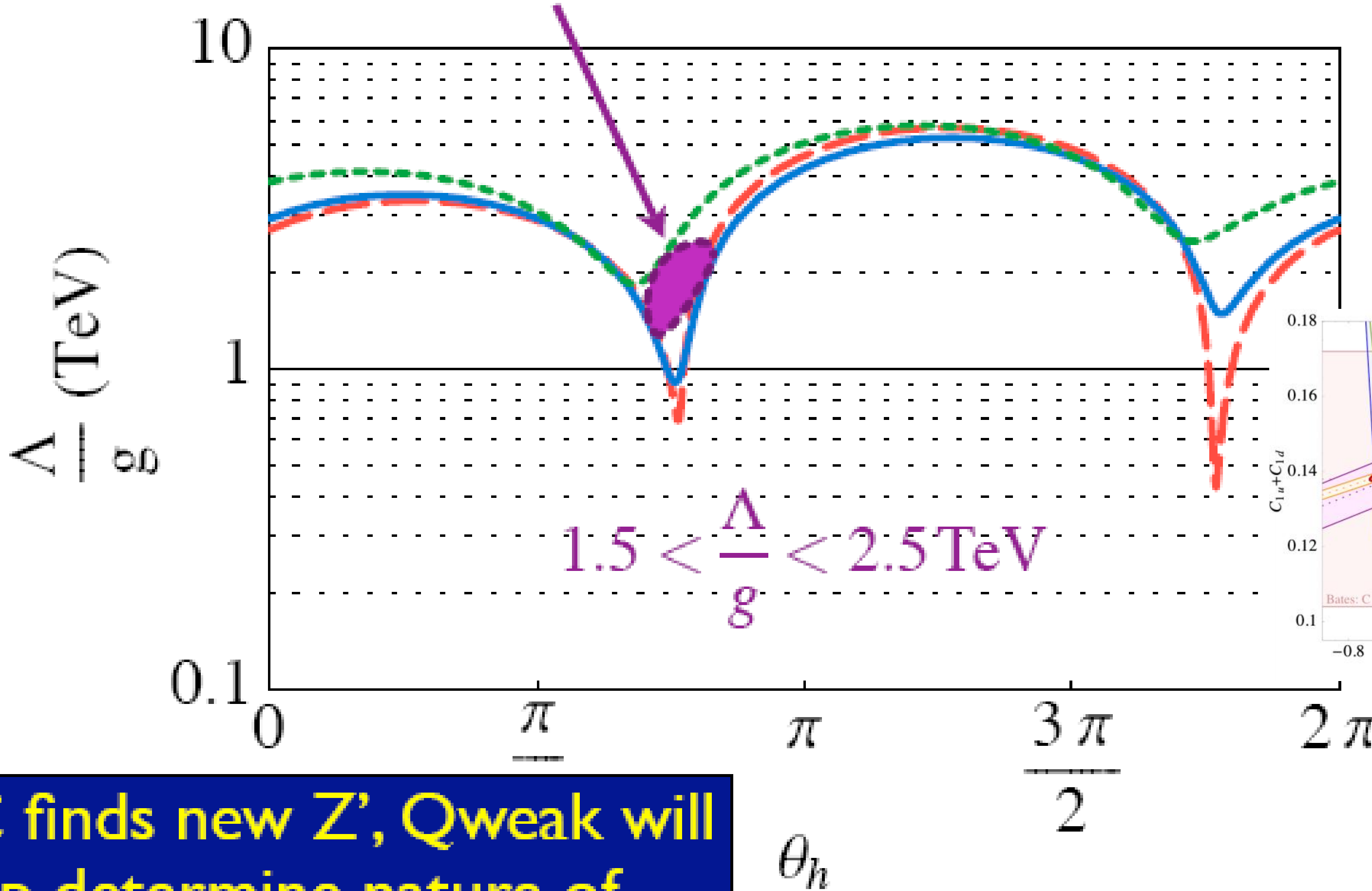
IF in accord with Standard Model…

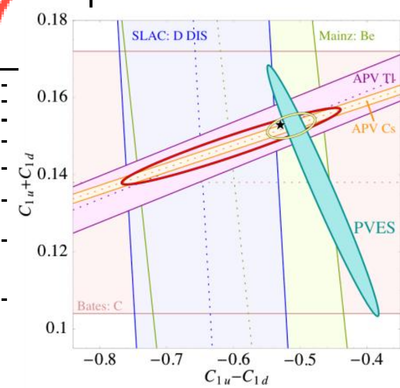


Qweak constrains new physics to beyond 2 TeV

Or… Discovery

Assume Qweak takes central value of current measurements





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

The NuTeV anomaly

NuTeV Anomaly

Phys. Rev. Lett. 88 (2002) 091802 : 409 citations since….

Fermilab press conference, Nov. 7, 2001:

"We looked at $\sin^2 \theta_W$," said Sam Zeller. The predicted value was 0.2227. The value we found was 0.2277…. might not sound like much, but the room full of physicists fell silent when we first revealed the result."

"3 σ discrepancy) 99.75% probability ν are not like other particles…. only 1 in 400 chance that our measurement is consistent with prediction ," MacFarland said.

Paschos-Wolfenstein Ratio

NuTeV measured (approximately) P-W ratio:

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

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

		NuTeV
$\sin^2\theta_W = 1 - M_W^2/M_Z^2$	=	$0.2277 \pm 0.0013 \pm 0.0009$
		other methods
c.f. Standard Model	=	0.2227 ± 0.0004

(c.f. 1978: 0.230 ± 0.015)

Parton Distribution Functions

Proton contains a number of non-interacting quarks and gluons (partons), which carry fraction x of the momentum of the target: p = (xP; 0 0 xP)

Define: PDF's (number densities) u(x), d(x), s(x) etc..

e.g. x u(x) dx is the fraction of the momentum of the proton carried by up quarks with momentum between (x, x + dx) in the infinite momentum frame

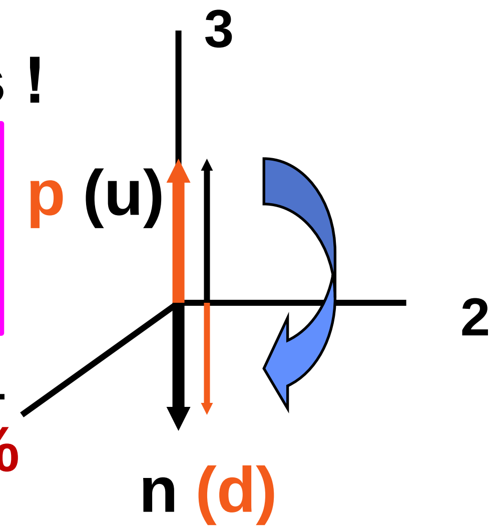
Then for e (or μ) DIS :

$$F_2^{ep}(x) = 2\,x\,F_1(x) = 4/9\; x\,(\,u(x) + \bar{u}(x)\,) + 1/9\; x\,(\,d(x) + \bar{d}(x)\,)$$

Charge Symmetry

N.B. NO label "p" on the 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: $u \equiv u^p = d^n$

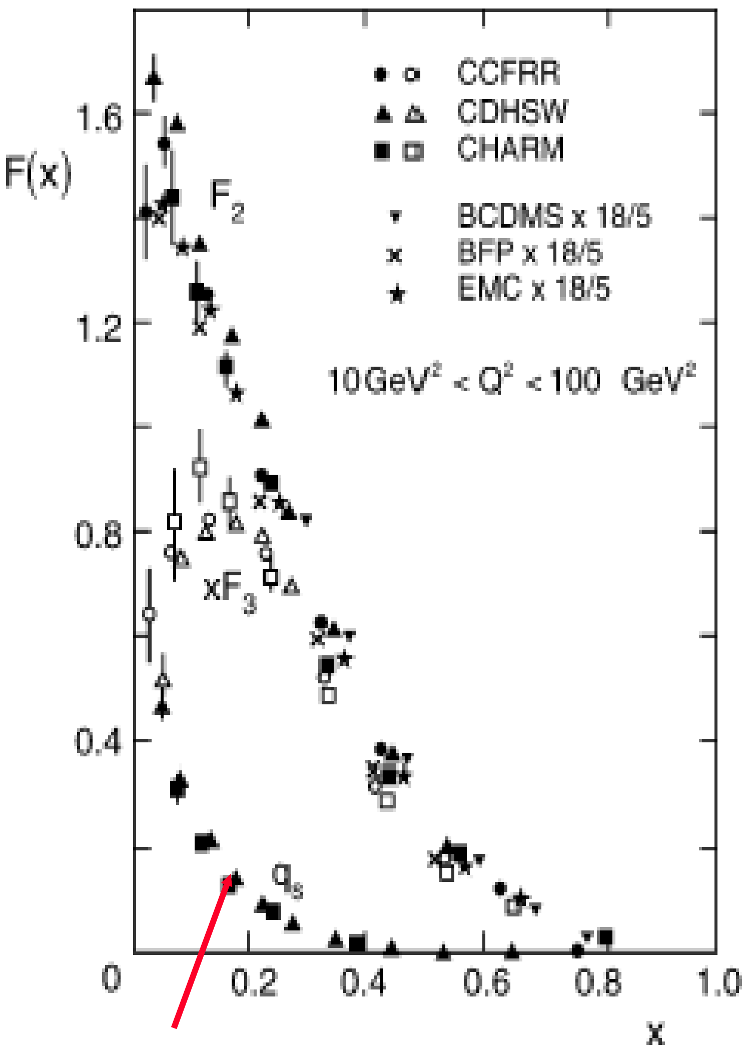
$d \equiv d^p = u^n$ **etc.**

Hence:

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

up-quark in n (arrow to $d(x)$) **down-quark in n** (arrow to $u(x)$)

Summary of PDF Data



"sea" confined to small x

$$F_2^{eD} \equiv \frac{F_2^{ep} + F_2^{en}}{2} = \frac{5x}{18}\left[u + \bar{u} + d + \bar{d} + \frac{2}{5}(s + \bar{s})\right]$$

F_2 same up to famous factor 5/18 !

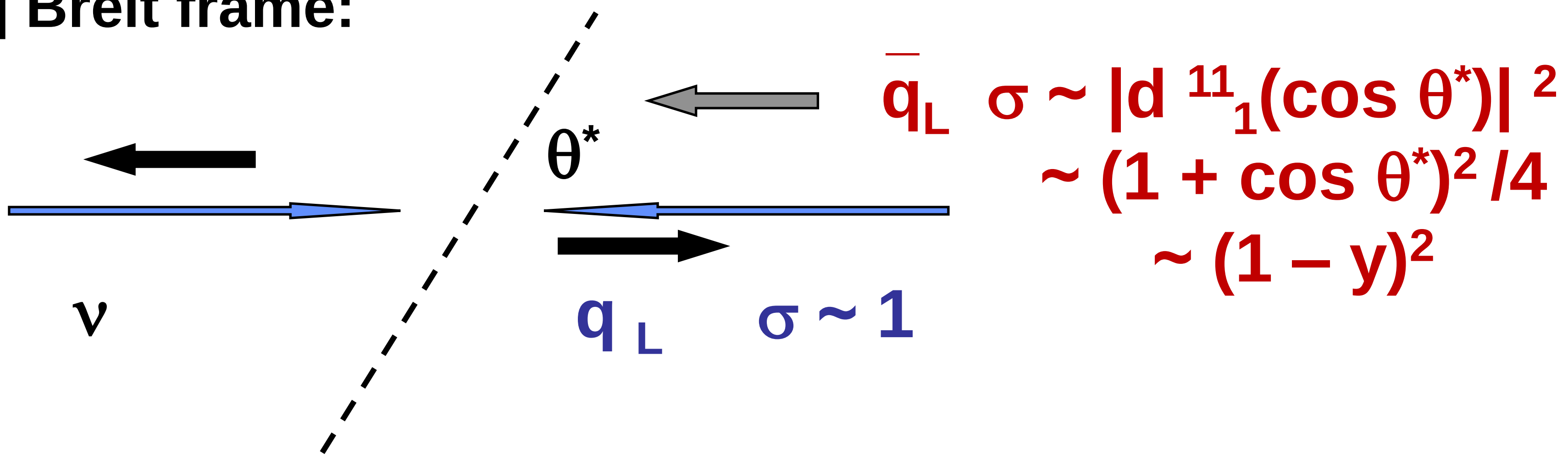
$$F_2^{\nu p} + F_2^{\nu n} = 2x\left[u + \bar{u} + d + \bar{d} + 2s\right]$$

$$\frac{F_3^{\nu p}(x) + F_3^{\bar{\nu} p}(x)}{2} = (u(x) - \bar{u}(x)) + (d(x) - \bar{d}(x)).$$

F_3 measures "valence" quarks

Neutrino Scattering

In ν – q Breit frame:



Use covariant variables, x, Q^2 and y = ν / ε = p . q / p . k ε (0,1)

$$\frac{d^2\sigma^{\nu p}}{dx\,dy} = \frac{G_F^2 s}{\pi}\left[x(d(x)+s(x)) + x\,(1-y)^2\,\bar{u}(x)\right],$$

$$\frac{d^2\sigma^{\bar{\nu} p}}{dx\,dy} = \frac{G_F^2 s}{\pi}\left[x(\bar{d}(x)+\bar{s}(x)) + x\,(1-y)^2\,u(x)\right].$$

Summary of Charged Current Cross Section

$$\int_0^1 dy\,(1-y)^2 = 1/3$$

$$\sigma_{CC}(\nu\, N{=}Z) \sim x\,\{\,(u + d + 2s) + 1/3\,(\bar{u} + \bar{d} + 2\bar{c})\,\}$$

$$\sigma_{CC}(\bar{\nu}\, N{=}Z) \sim x\,\{\,1/3\,(u + d + 2c) + (\bar{u} + \bar{d} + 2\bar{s})\,\}$$

and hence:

$$\sigma_{CC}\,(\nu\, N{=}Z) - \sigma_{CC}\,(\bar{\nu}\, N{=}Z) = 2/3\ x\,\{u - \bar{u} + d - \bar{d}\} + 2\ x\,\{s - \bar{s}\} + 2/3\ x\,\{c - \bar{c}\}$$

$$= 2/3\ x\,(\,u_V + d_V\,) + \ldots$$

(Valence distributions: $\int dx\, u_V = 2\ ;\ \int dx\, d_V = 1$ **)**

Neutral Current Cross Section

Z coupling	g_L	g_R
u, c, t	$+1/2 - 2/3 \sin^2\theta_w$	$-2/3 \sin^2\theta_W$
d, s, b	$-1/2 + 1/3 \sin^2\theta_w$	$+1/3 \sin^2\theta_W$

In Cross Section :

$\nu\, q_L \sim 1$; $\nu\, q_R \sim 1/3$

$\nu\, \bar{q}_L \sim 1/3$; $\nu\, \bar{q}_R \sim 1$

Hence, <u>for N=Z nucleus</u>: defining $g^2_L = g^2_{Lu} + g^2_{Ld} = ½ - \sin^2\theta_W + 5/9 \sin^2\theta_W$

and $g^2_R = g^2_{Ru} + g^2_{Rd} = 5/9 \sin^2\theta_W$

$$\sigma_{NC}(\nu A) \sim (g^2_L + g^2_R/3) \times (u + d) + (g^2_R + g^2_L/3) \times (\bar{u} + \bar{d})$$

$$\sigma_{NC}(\bar{\nu} A) \sim (g^2_L + g^2_R/3) \times (\bar{u} + \bar{d}) + (g^2_R + g^2_L/3) \times (u + d)$$

Finally : Paschos-Wolfenstein

$$\sigma_{NC}(\nu A) - \sigma_{NC}(\bar{\nu} A) \sim 2/3\,(g^2_L - g^2_R)\; x\,(u_V + d_V)$$

c.f. $\sigma_{CC}(\nu\, N{=}Z) - \sigma_{CC}(\bar{\nu}\, N{=}Z) \sim 2/3\; x\,(u_V + d_V)$ ….earlier

and therefore ratio of NC to CC cross section differences is

$$R^{PW} = g^2_L - g^2_R = \tfrac{1}{2} - \sin^2\theta_W$$

Provided: i) Charge Symmetry ii) $s(x) = \bar{s}(x)$

iii) $c(x) = \bar{c}(x)$ iv) No higher-twist effects (e.g. VMD shadowing)

Correction to Paschos-Wolfenstein from CSV

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

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

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

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

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)

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

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

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

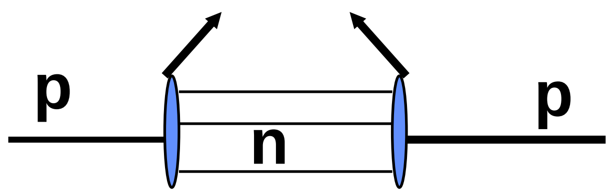
Di-quark Spectator States Dominate Valence

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

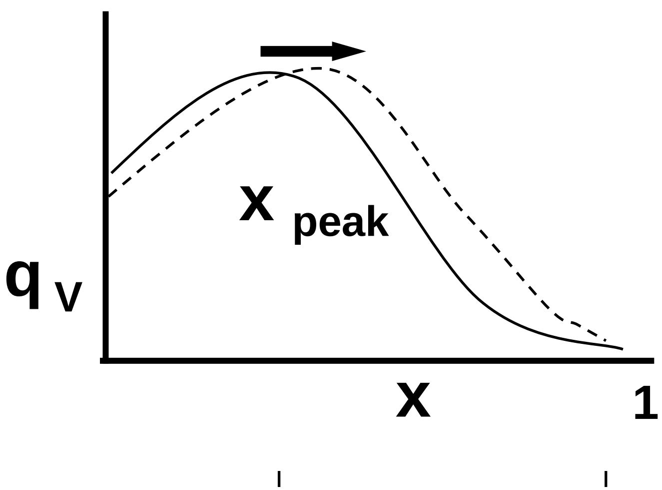
$\delta(M (1 – x) – m_n)$ determines x where $q (x, Q^2_0)$ is maximum

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

Effect of "Hyperfine" Interaction

Δ – N mass splitting) S=1 "di-quark" mass is 0.2 GeV greater S=0

SU(6) wavefunction for proton :

remove d-quark : ONLY S=1 left

c.f. remove u-quark : 50% S=0 and 50% S=1

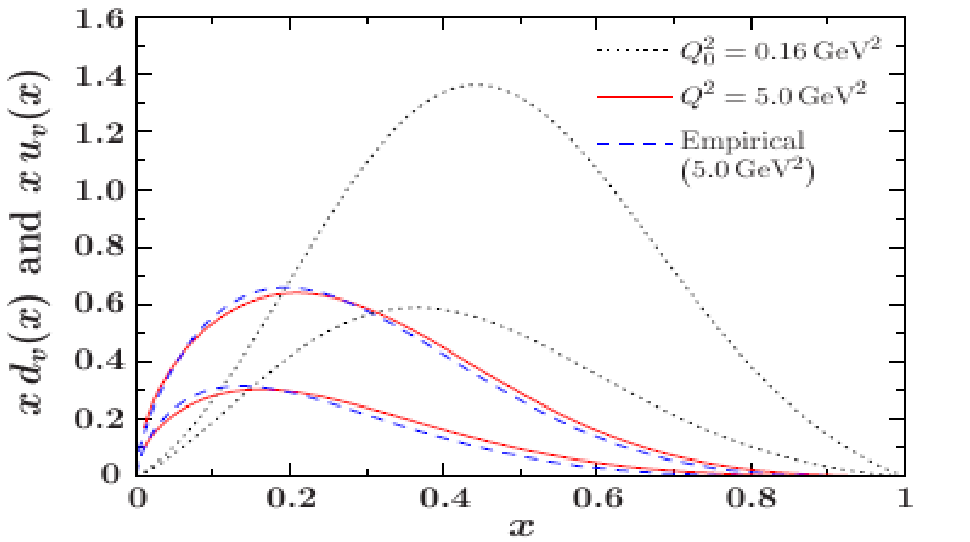
Hence*:

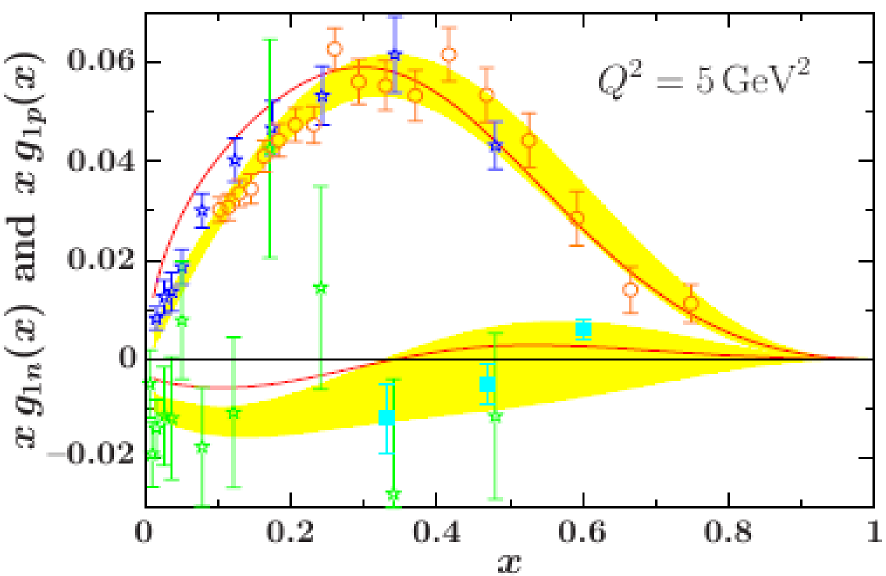
- u(x) dominates over d(x) for x > 0.3
- $u^{\uparrow}$ dominates over $u^{\downarrow}$ at large x
  and hence: $g^p_1(x) > 0$ at large x
- Similarly $g^n_1(x) > 0$ at large x

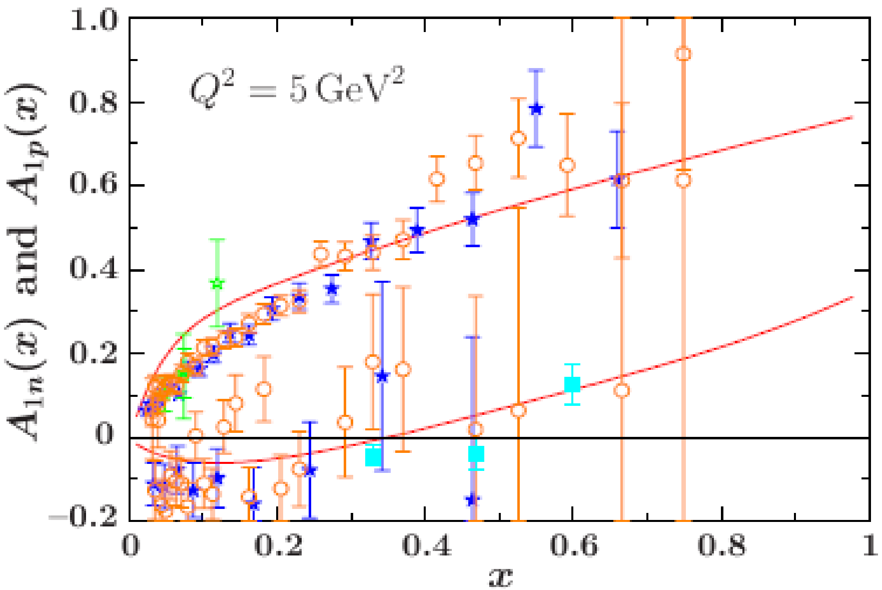
*Close & Thomas: 1988

More Modern (Confining) NJL Calculations

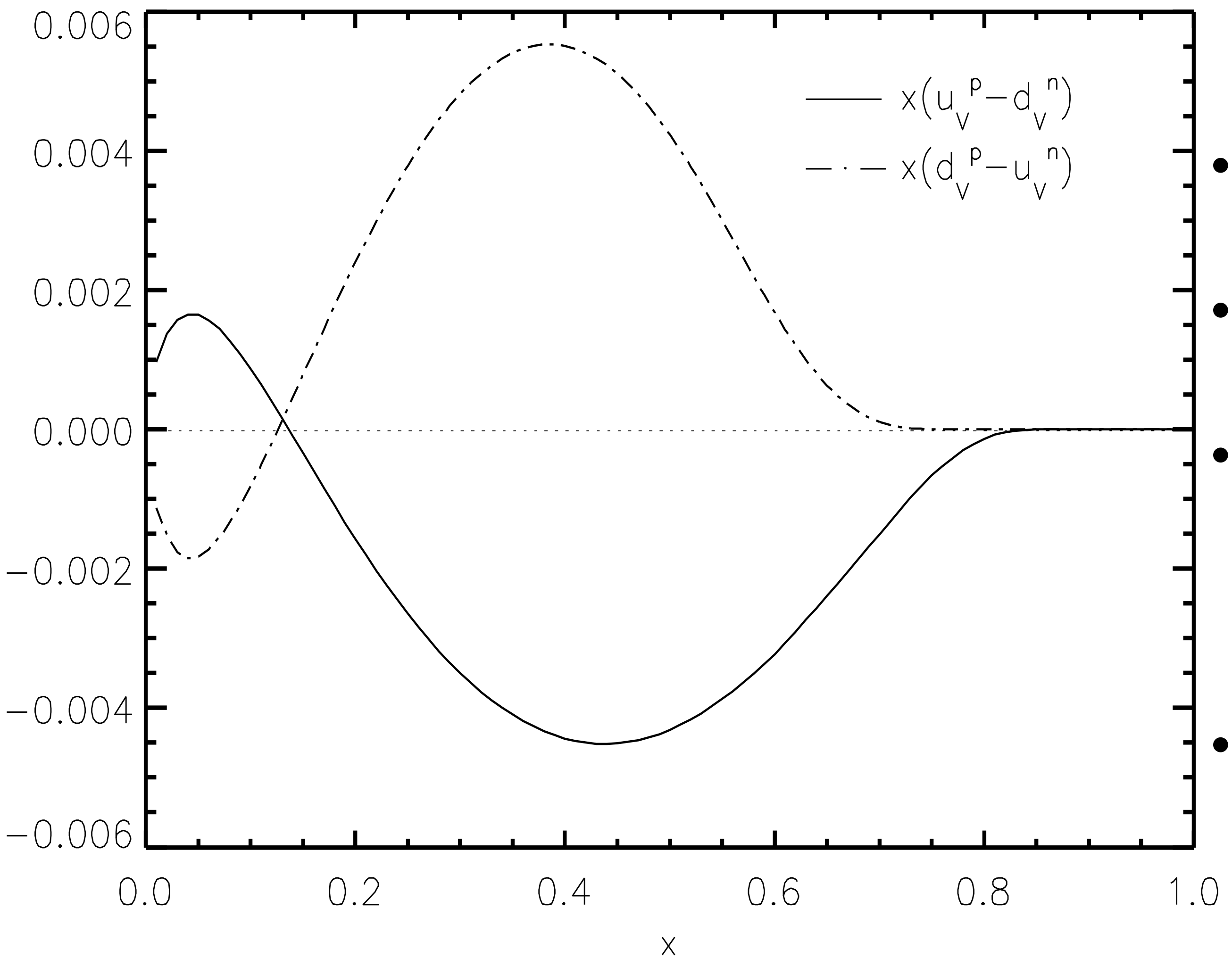
Cloet et al.,
Phys. Lett. B621, 246 (2005)
(μ = 0.4 GeV)







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

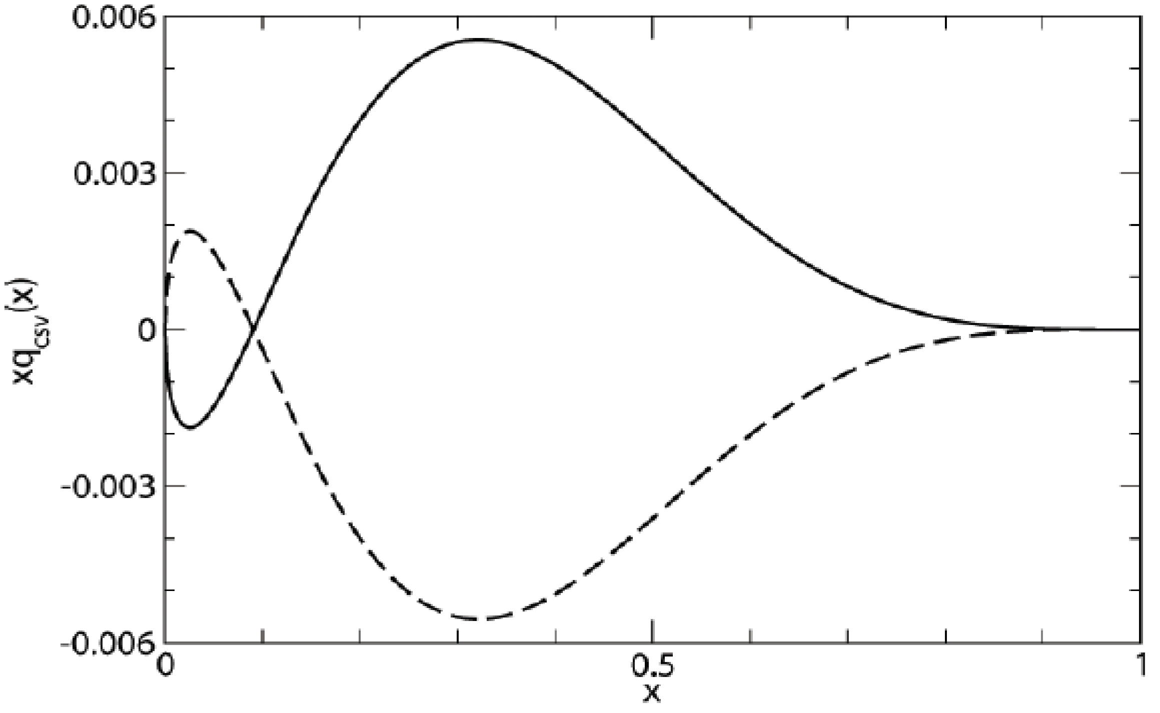


FIG. 5: The phenomenological valence quark CSV function from Ref. [23], corresponding to best fit value $\kappa = -0.2$ defined in Eq. (35). Solid curve: $x\delta d_{\rm v}$; dashed curve: $x\delta u_{\rm v}$.

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

BUT How Model Dependent ?

Sather ('92) : "Close and Thomas reproduced the strong deviation of the ratio d/u from 2 at large x, which signals the breaking of SU(6) symmetry. A related approach employed here predicts the breaking of isospin (actually charge symmetry) albeit on a much smaller scale"

Consider n=2 only (i.e. valence PDFs) & set $E_{n=2} \sim m_2$:

$$q_V(x,Q^2_0) = M \int d^3p\, P(p)\, \delta(p_z / M - m_2 / M - x)$$

And hence (e.g.): $m_2 \rightarrow m_2 + \delta m_2$

$$\delta q_V(x) = \delta m_2 / M \quad d q_V / dx$$

///'ly $M \rightarrow M + \delta M$

Now could use model OR phenomenological distributions…

OR….

For NuTeV it is (Essentially) Model Independent

Need : $\delta D_V \equiv \int dx\, x\, \delta d_V$

$$= -\frac{\delta m_2}{M} \int dx\, x\, \frac{dd_V}{dx} + O(\delta M / M)$$

Integrate by parts:

$$= -\frac{\delta m_2}{M} \int d_V(x)\, dx \; + \; x\, d_V \Big|_0^1$$

Unity – normalization

i.e. **model independent**

vanishes

Full Result

$$\delta D_V = \frac{\delta M}{M} D_V + \frac{\delta m_2}{M} \sim 0.0046$$

$$\delta U_V = \frac{\delta M}{M} (U_V - 2) \sim -0.0020$$

Small dependence on "bag / quark model" scale (Q^2_0) :

$D_V \sim 0.2$: $U_V \sim 0.6$ − i.e. 10% & 30% respectively

Correction to Paschos-Wolfenstein is therefore :

$$\Delta R^{PW} = 0.5\,(g^2_L - g^2_R) \frac{\delta U_V - \delta D_V}{U_V + D_V} \sim -0.0020$$

N.B. Ratio of non-singlet moments independent of Q^2 under NLO evolution

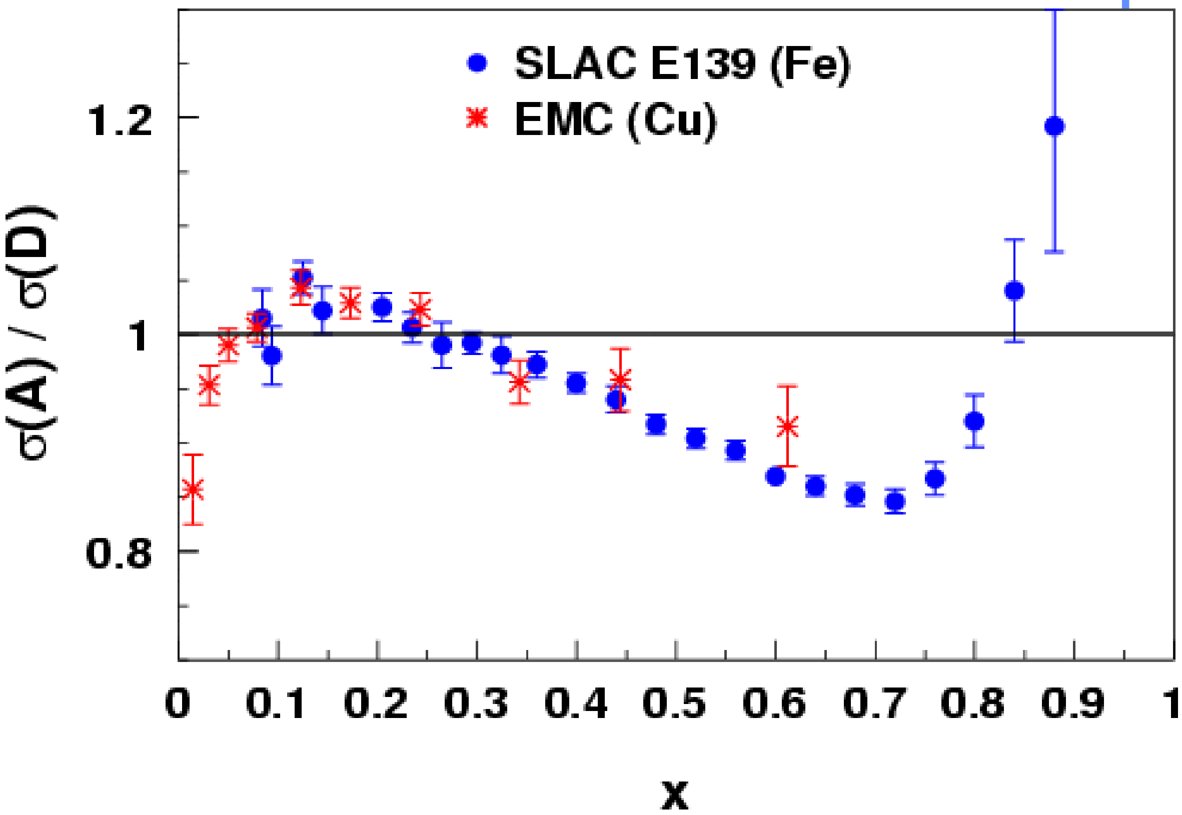
Isovector EMC Effect

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 led to QMC

- Two major, recent papers:

  I. Guichon, Matevosyan, Sandulescu, Thomas,
  Nucl. Phys. A772 (2006) 1.
  II. Guichon and Thomas, Phys. Rev. Lett. 93 (2004) 132502

- Built on earlier work on QMC: e.g.

  III. Guichon, Phys. Lett. B200 (1988) 235
  IV. Guichon, Saito, Rodionov, Thomas,
  Nucl. Phys. A601 (1996) 349

- Major review of applications of QMC to many nuclear systems:

  V. Saito, Tsushima, Thomas,
  Prog. Part. Nucl. Phys. 58 (2007) 1-167 (hep-ph/0506314)

Recently Developed Covariant Model Built on the Same Physical Ideas

- Use NJL model (χ'al symmetry)

- Ensure confinement through proper time regularization
  (following the Tübingen group)

- Self-consistently solve Faddeev Eqn. in mean scalar field

- This solves chiral collapse problem common for NJL
  (because of <u>scalar polarizability</u> again)

- Can test against experiment
  – e.g. spin-dependent EMC effect

- Also apply same model to NM, NQM and SQM – hence n-star

Covariant Quark Model for Nuclear Structure

- **Basic Model:**

- **Bentz & Thomas, Nucl. Phys. A696 (2001) 138**
- **Bentz, Horikawa, Ishii, Thomas, Nucl. Phys. A720 (2003) 95**

- **Applications to DIS:**

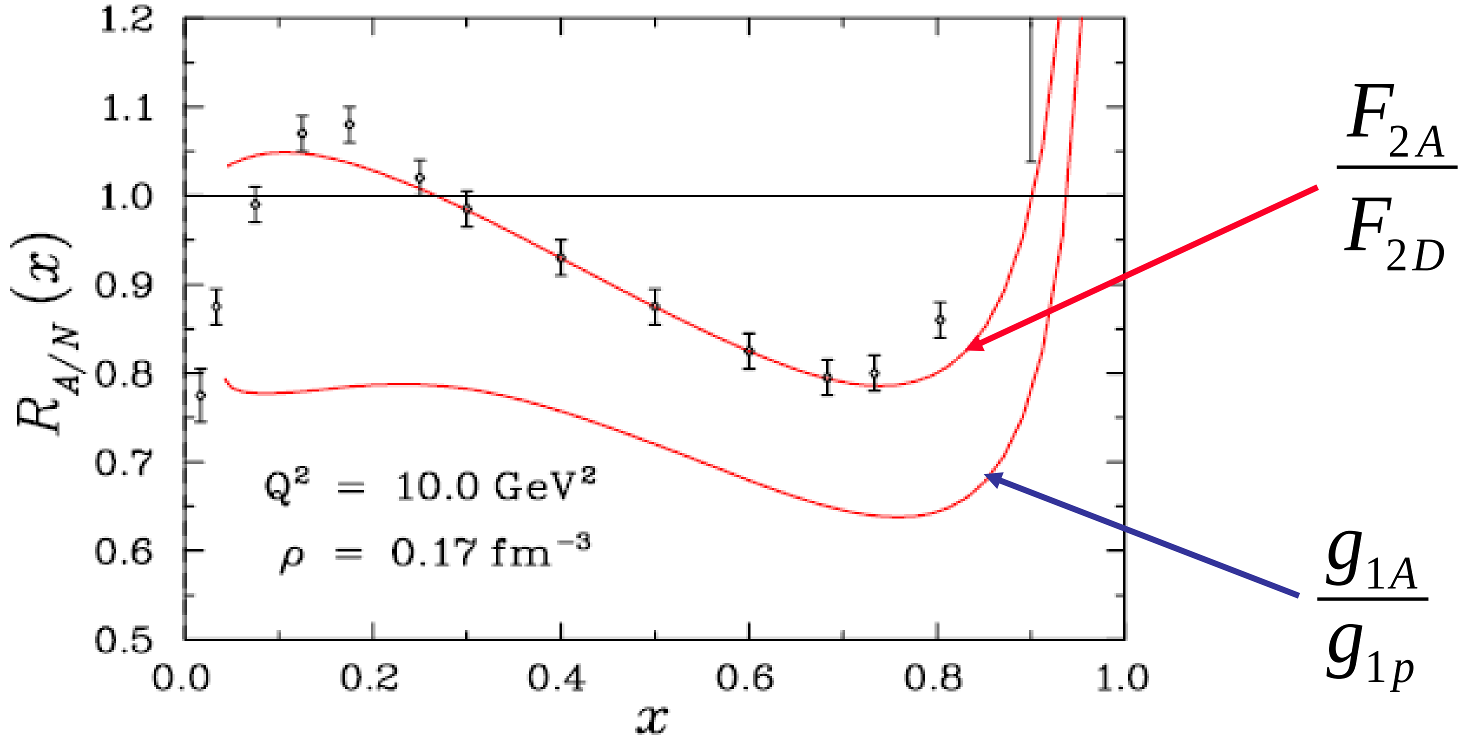
- **Cloet, Bentz, Thomas, Phys. Rev. Lett. 95 (2005) 052302**
- **Cloet, Bentz, Thomas, Phys. Lett. B642 (2006) 210**

- **Applications to neutron stars – including SQM:**

- **Lawley, Bentz, Thomas, Phys. Lett. B632 (2006) 495**
- **Lawley, Bentz, Thomas, J. Phys. G32 (2006) 667**

g_1(A) – "Polarized EMC Effect"

- Calculations described here) larger effect for polarized structure than unpolarized: <u>mean scalar field modifies lower components of the confined quark's Dirac wave function</u>
- Spin-dependent parton distribution functions for nuclei <u>unmeasured</u>



(Cloet, Bentz, AWT, PRL 95 (2005) 0502302)

Recent Calculations for Finite Nuclei

Spin dependent EMC effect TWICE as large as unpolarized

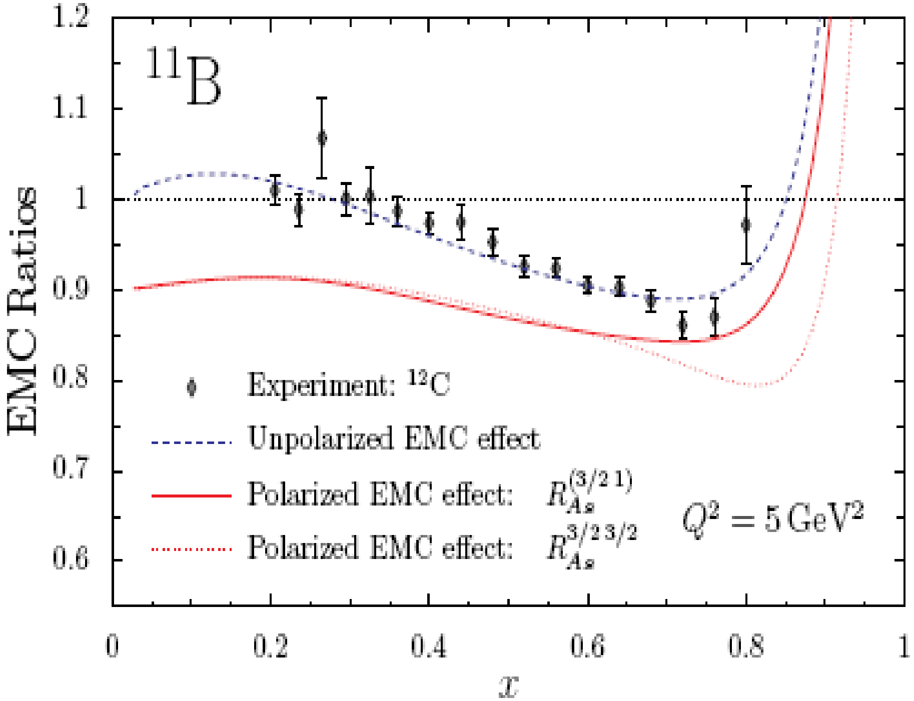


FIG. 7: The EMC and polarized EMC effect in ^{11}B. The empirical data is from Ref. [31].

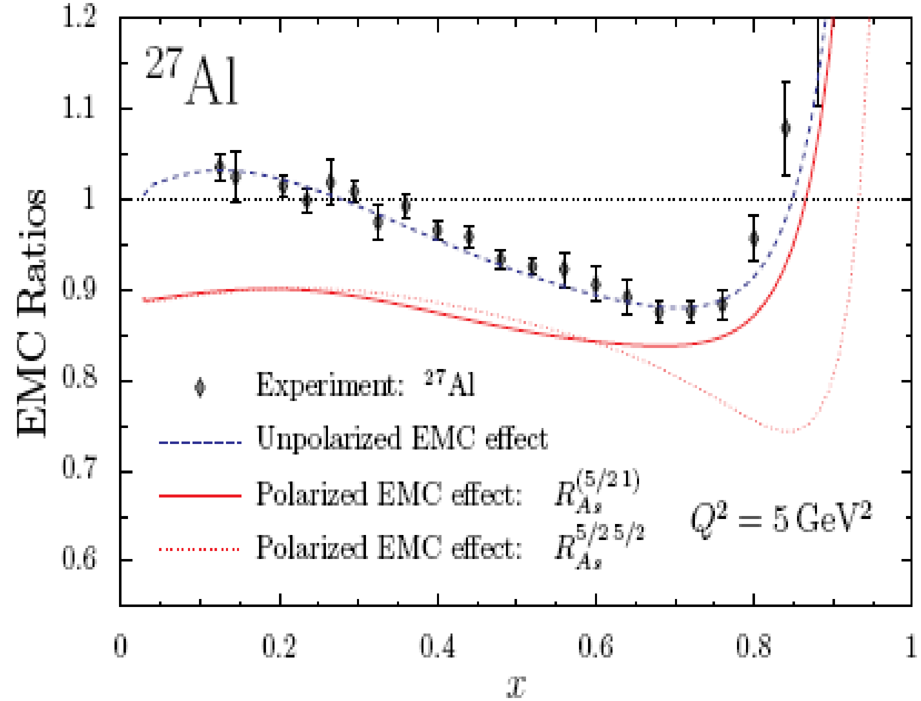


FIG. 9: The EMC and polarized EMC effect in ^{27}Al. The empirical data is from Ref. [31].

Cloet, Bentz, Thomas, Phys. Lett. B642 (2006) 210 (nucl-th/0605061)

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 $m_u \neq m_d$**

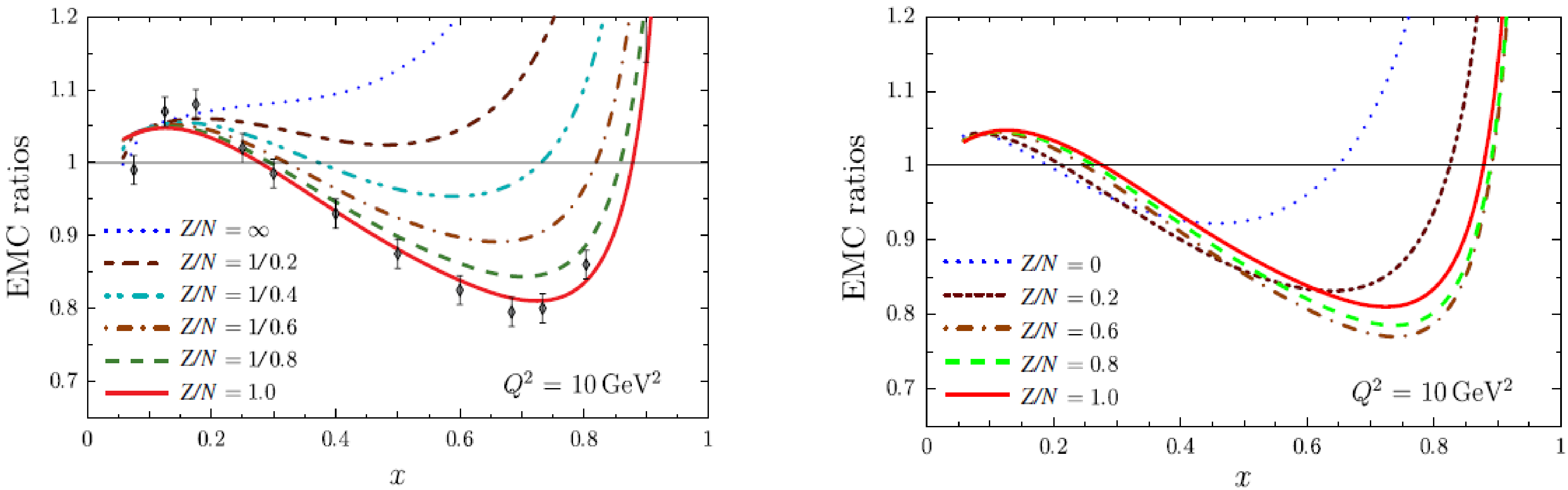
- **Sign and magnitude of both effects exhibit little model dependence**

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

Isovector EMC Effect

Cloet, Bentz, Thomas

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



$$q(x) = \frac{p^+}{p^+ - V^+}\, q_0\!\left(\frac{p^+}{p^+ - V^+}\, x - \frac{V_q^+}{p^+ - V^+}\right)$$

Correction to Paschos-Wolfenstein from ρ_p - ρ_n

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

- **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 $\sin^2\theta_W \uparrow$**

- **Isovector force controlled by $\rho_p - \rho_n$ and symmetry energy of nuclear matter − both well known!**

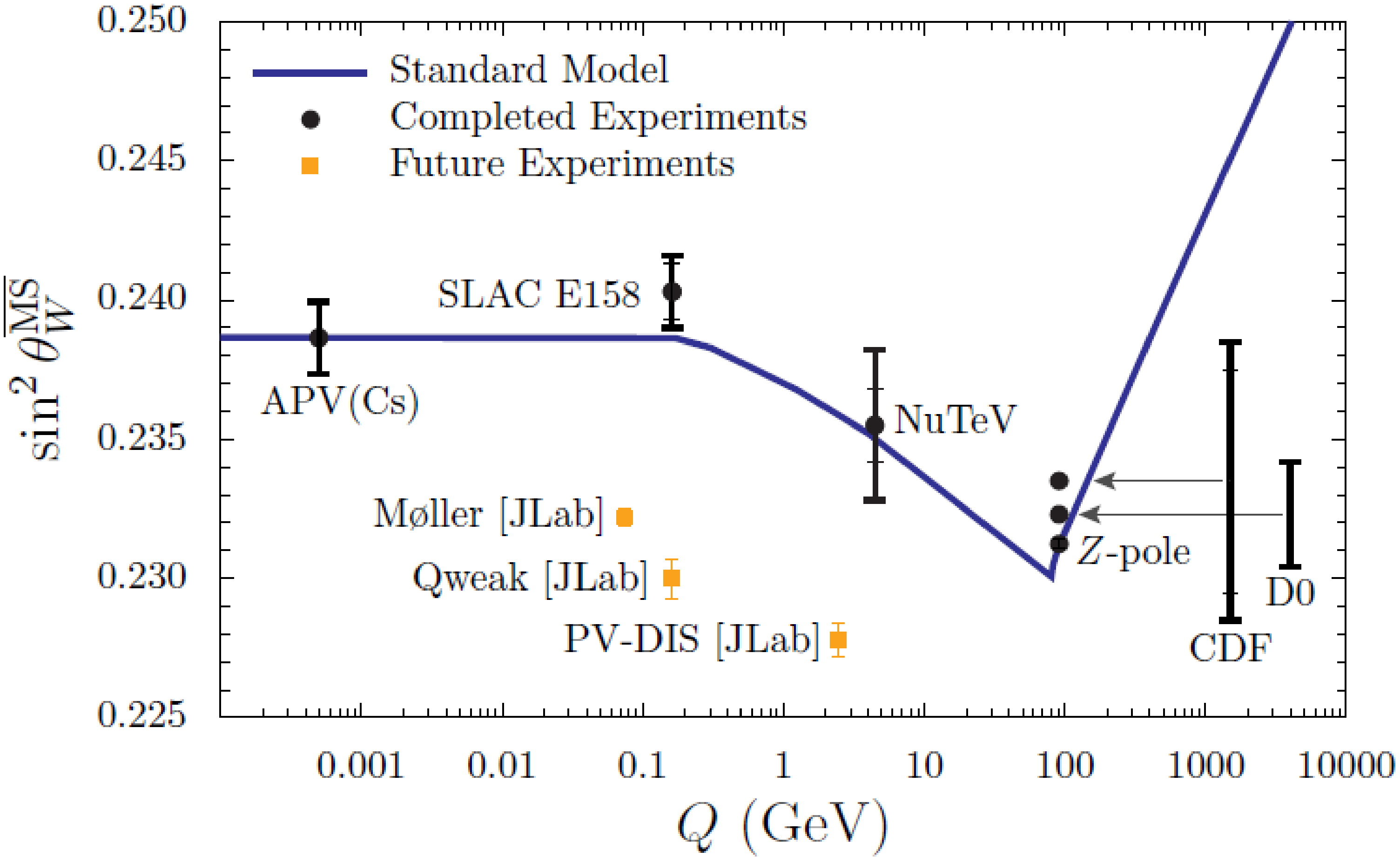
- **N.B. ρ^0 mean field included in QHD and QMC and earlier work with Bentz but no-one thought of this!!**

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:** $\Delta R^{s} = 0.0 \pm 0.0018$
  - **this is largest uncertainty (systematic error)**
- **Final result:** $\sin^2\theta_W = 0.2232 \pm 0.0013(\mathrm{stat}) \pm 0.0024(\mathrm{syst})$
  - **c.f. Standard Model:** $\sin^2\theta_W = 0.2227 \pm 0.0004$

The Standard Model Works Again

Apply CSV and isovector EMC corrections
plus estimate systematic error arising from $s^-(x) \neq 0$:



Bentz et al., arXiv: 0908.3198

Summary

- JLab has made extremely important tests of fundamental features of the Standard Model
  - strange quarks as analog of Lamb shift in QED
  - weak charge of the proton

- Future Q_{weak} and possible Møller scattering have potential for further major advance

- The major 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 $s(x) - \bar{s}(x)$ …..

Outlook

- **s-quark condensate is also much smaller than hitherto thought : major implications for dark matter searches (PRL Nov 09)!**

- **Role of heavy quarks in dark matter interactions??**

- **Radiative corrections for PV e-p scattering – traditional approximations likely dubious!**

Erler: Radiative corrections and Z'

Chisq for Standard Model =48/45; PVES gives reduction by 0.7

Z'	electroweak	CDF	LEP 2	$\theta_{ZZ'}^{\rm min}$	$\theta_{ZZ'}^{\rm max}$	$\chi^2_{\rm min}$
Z_χ	1,141	892	673	−0.0016	0.0006	47.3
Z_ψ	147	878	481	−0.0018	0.0009	46.5
Z_η	427	982	434	−0.0047	0.0021	47.7
Z_I	1,204	789		−0.0005	0.0012	47.4
Z_S	1,257	821		−0.0013	0.0005	47.3
Z_N	623	861		−0.0015	0.0007	47.4
Z_R	442			−0.0015	0.0009	46.1
Z_{LR}	998	630	804	−0.0013	0.0006	47.3
$Z_{\not L}$	(803)	(740)		−0.0094	0.0081	47.7
Z_{SM}	1,403	1,030	1,787	−0.0026	0.0006	47.2

arXiv:0909.5309 [hep-ph]

Strange quark condensate & dark matter detection

Octet-baryon masses

- Leading-order expansion $O(1)$

$$M_N = M_0 + 2(\alpha_M + \beta_M)m_q + 2\sigma_M(2m_q + m_s)$$

$$M_\Lambda = M_0 + (\alpha_M + 2\beta_M)m_q + \alpha_M m_s + 2\sigma_M(2m_q + m_s)$$

$$M_\Sigma = M_0 + \frac{1}{3}(5\alpha_M + 2\beta_M)m_q + \frac{1}{3}(\alpha_M + 4\beta_M)m_s + 2\sigma_M(2m_q + m_s)$$

$$M_\Xi = M_0 + \frac{1}{3}(\alpha_M + 4\beta_M)m_q + \frac{1}{3}(5\alpha_M + 2\beta_M)m_s + 2\sigma_M(2m_q + m_s)$$

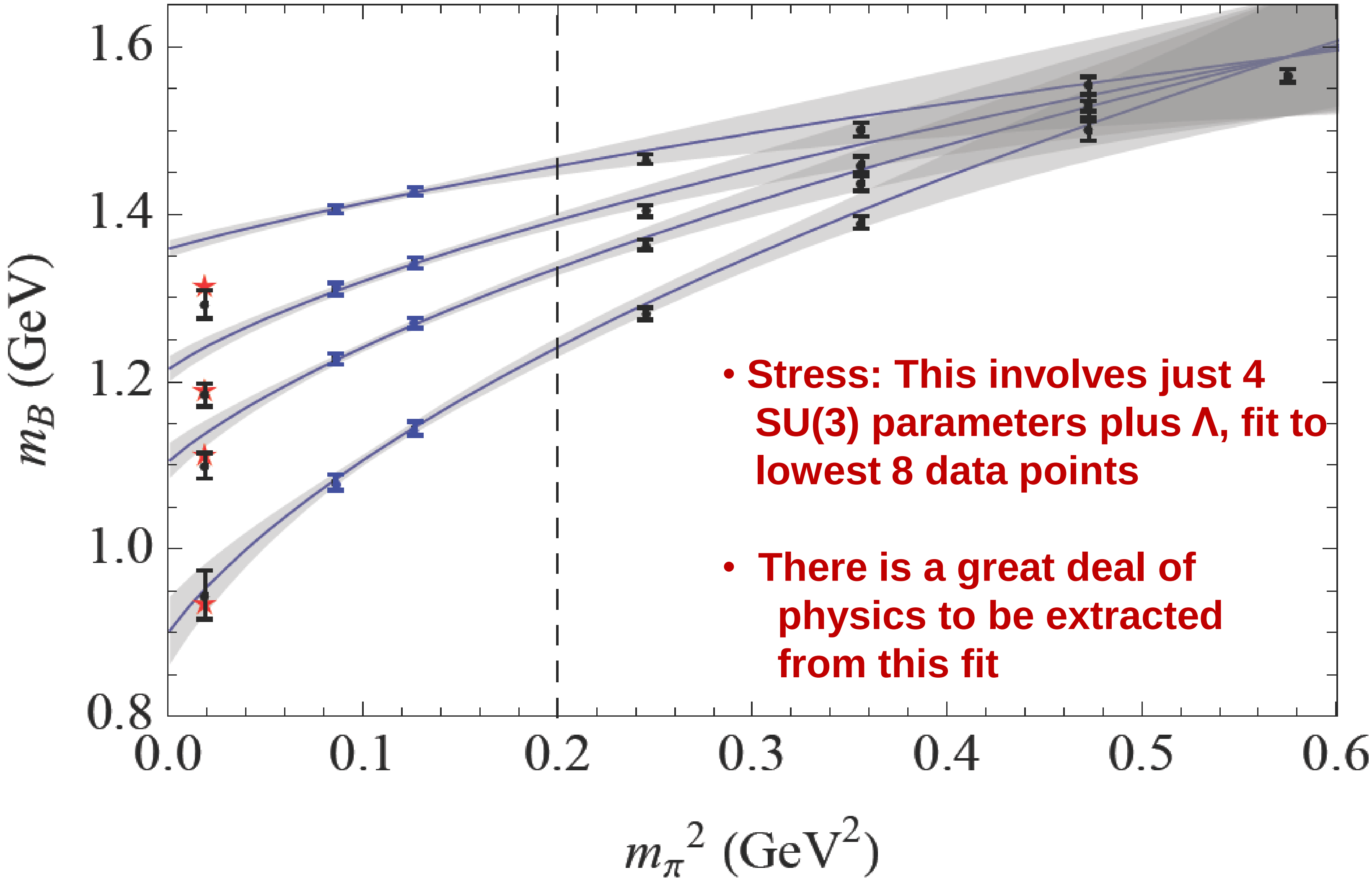
$$m_\pi^2 = 2Bm_q \quad m_K^2 = B(m_q + m_s)$$

$$m_q \to \frac{m_\pi^2}{2B}, \quad m_s \to \frac{2m_K^2 - m_\pi^2}{2B} \qquad \{\alpha, \beta, \sigma\} \to B\{\alpha', \beta', \sigma'\}$$

Fit using SU(3) expansions plus FRR loops (π, η and K)

LHPC Data

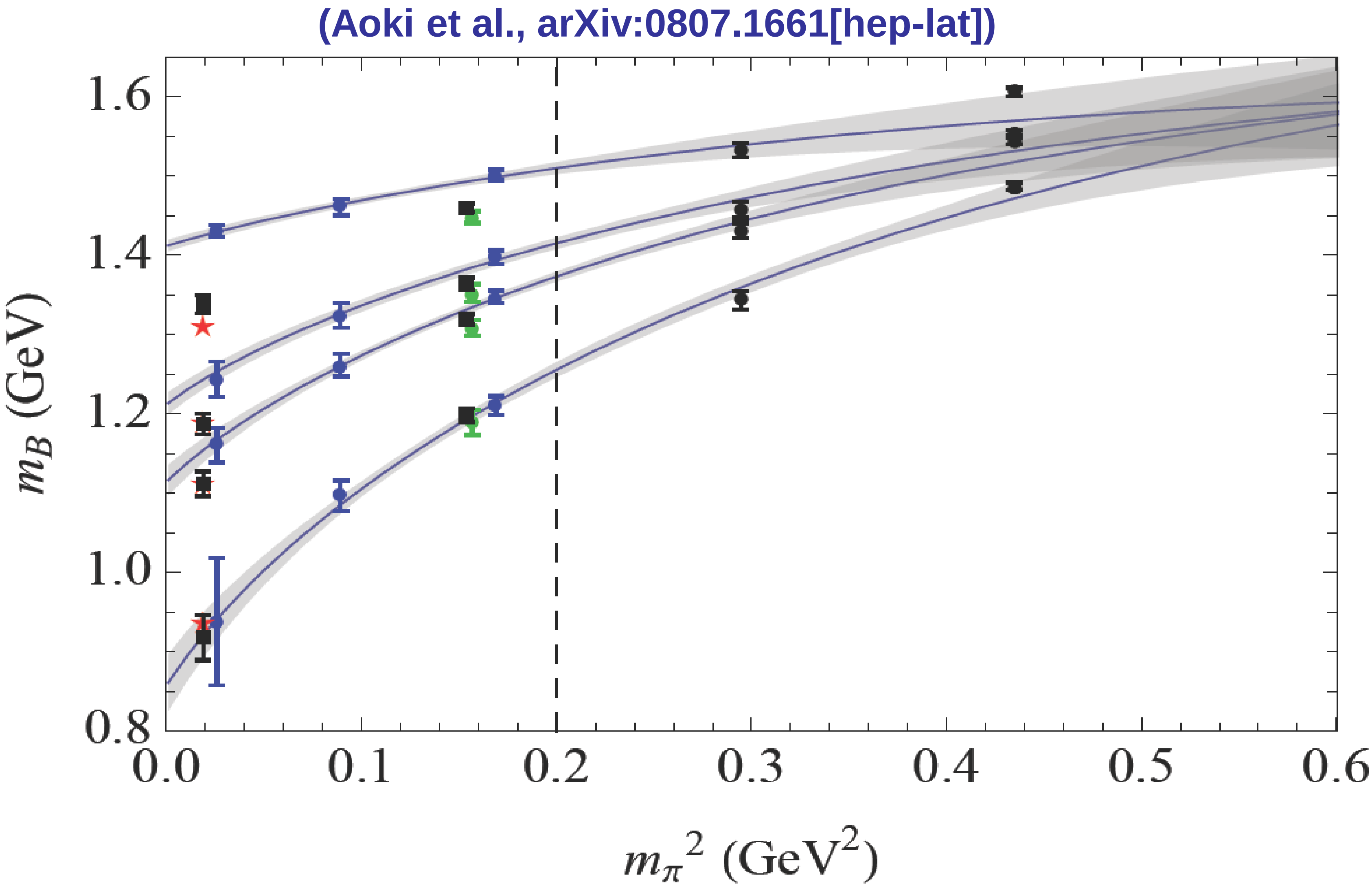
(Walker-Loud et al.. arXiv:0806.4549)



- **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]

PACS-CS Data



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)

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

N. B. Masses are absolute calculations based upon heavy quark potential, which involves no chiral physics

Young & Thomas, arXiv:0901.3559 [nucl-th]

Sigma Commutator

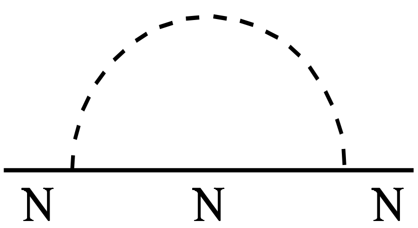
$$\sigma = \langle N \,|\, (m_u + m_d)\,(\bar{u}\,u + \bar{d}\,d)/2 \,|\, N \rangle \equiv m_q\, \partial M_N / \partial m_q$$

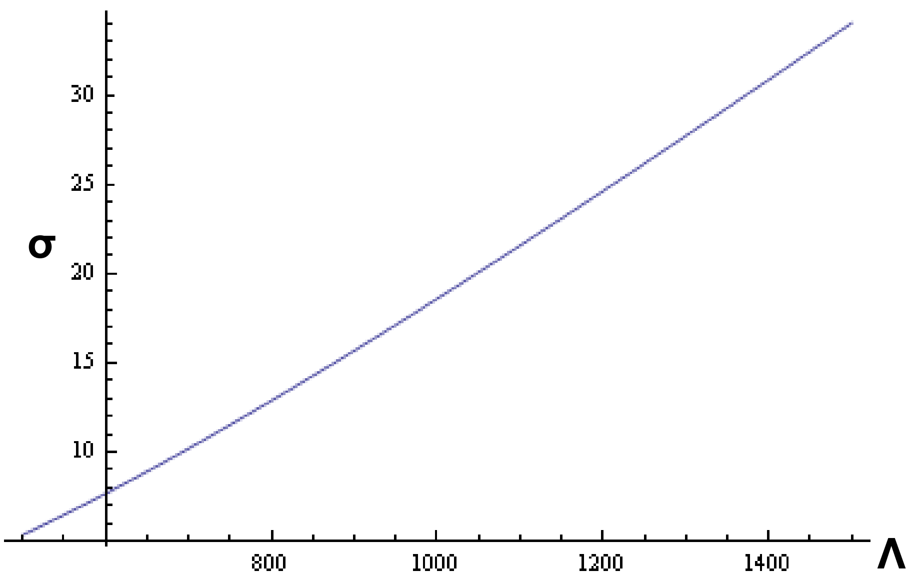
$$= \langle N|[Q_5,[Q_5,H_{QCD}]]|N\rangle$$

$$= \sigma_{val} + \sigma_{sea}$$

LNA

$$\delta\sigma = 35\,\Lambda - 23 + \frac{9.6}{\Lambda} - \frac{3}{\Lambda^2} + \frac{0.8}{\Lambda^3} + \ldots = 18 \text{ MeV } (\Lambda = 1\text{GeV})$$





Naïve Expansion Traditionally Used to Extract σ Terms is Hopeless!

- Leading-order expansion $O(1)$

$$
\begin{aligned}
M_N &= M_0 + 2(\alpha_M + \beta_M) m_q + 2\sigma_M (2m_q + m_s) \\
M_\Lambda &= M_0 + (\alpha_M + 2\beta_M) m_q + \alpha_M m_s + 2\sigma_M (2m_q + m_s) \\
M_\Sigma &= M_0 + \frac{1}{3}(5\alpha_M + 2\beta_M) m_q + \frac{1}{3}(\alpha_M + 4\beta_M) m_s + 2\sigma_M (2m_q + m_s) \\
M_\Xi &= M_0 + \frac{1}{3}(\alpha_M + 4\beta_M) m_q + \frac{1}{3}(5\alpha_M + 2\beta_M) m_s + 2\sigma_M (2m_q + m_s)
\end{aligned}
$$

Need $O(m_\pi^6)$ to get accurate light quark σ term

While for strange condensate expansion is useless !

BUT through FRR have closed expression and can evaluate ….

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)
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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

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.

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

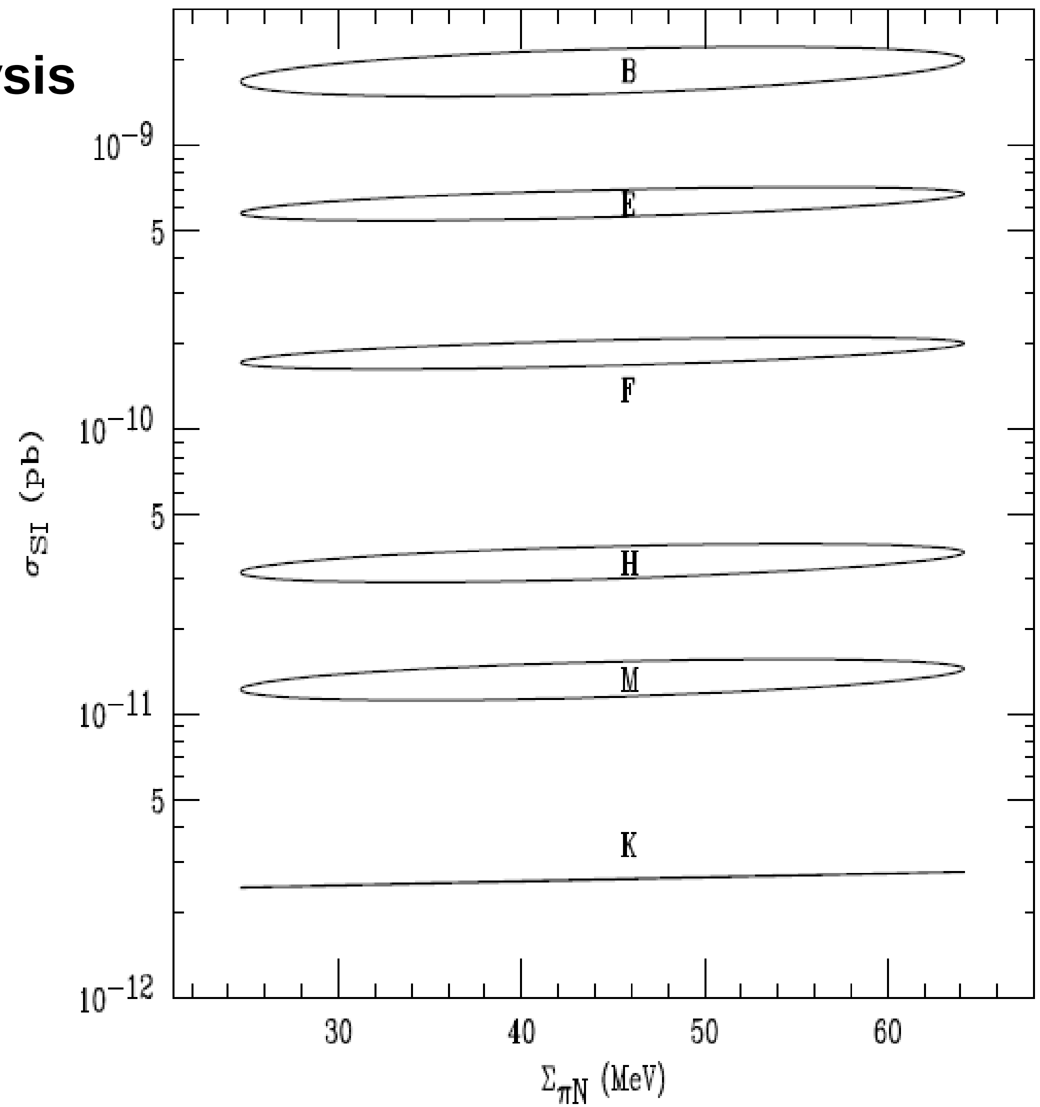
spin

σ terms

Neutralino (0.3 GeV / cc :WMAP)

CMSSM Predictions for Dark Matter σ

Combining σ_s from this analysis with result of Toussaint & Freeman (2009) – to yield σ_s = 50 ± 8 MeV – calculate 95% CL predictions for all Constrained Minimal Super-Symmetric Standard Model extensions consistent with astrophysical data

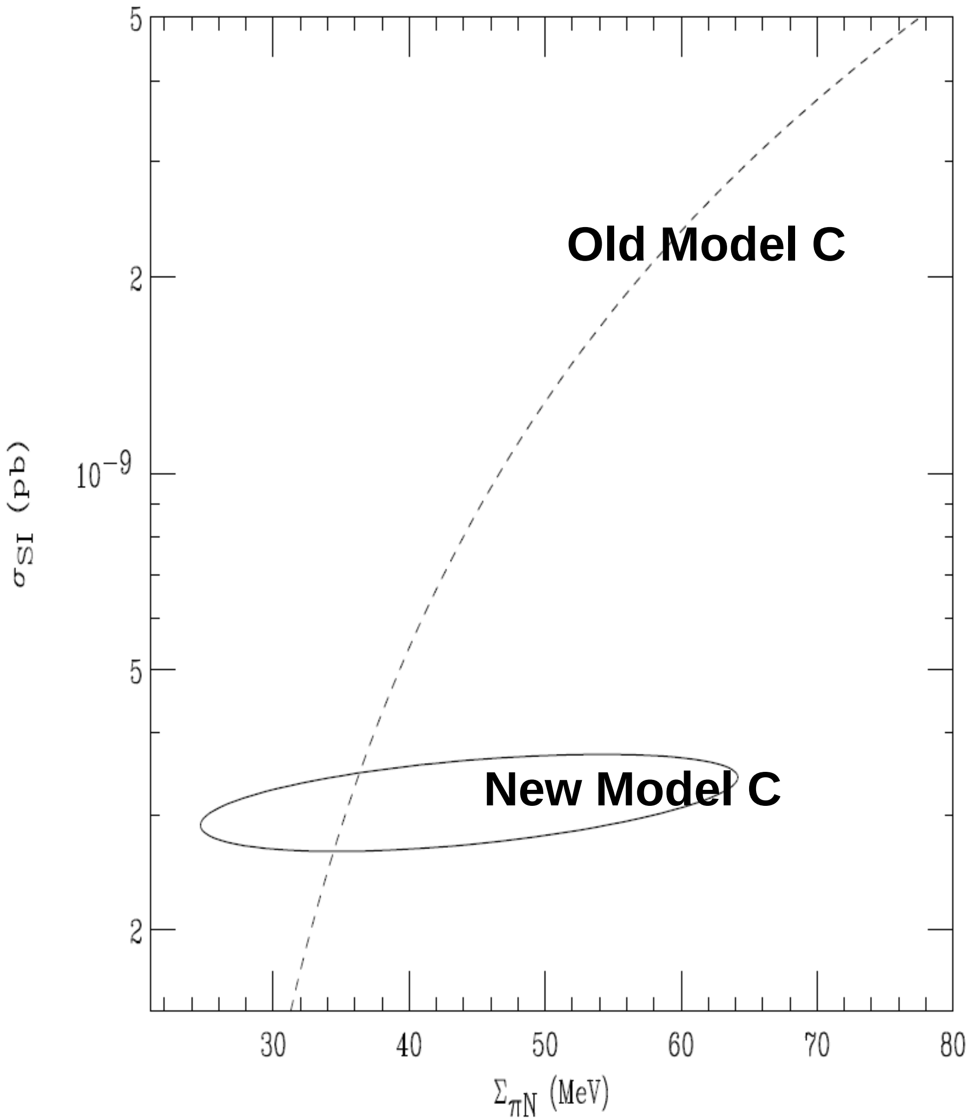


Giedt et al., arXiv: 0907.4177

CMSSM Predictions for Dark Matter σ

Using σ_s from this analysis as well as Toussaint & Freeman (2009) calculate 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

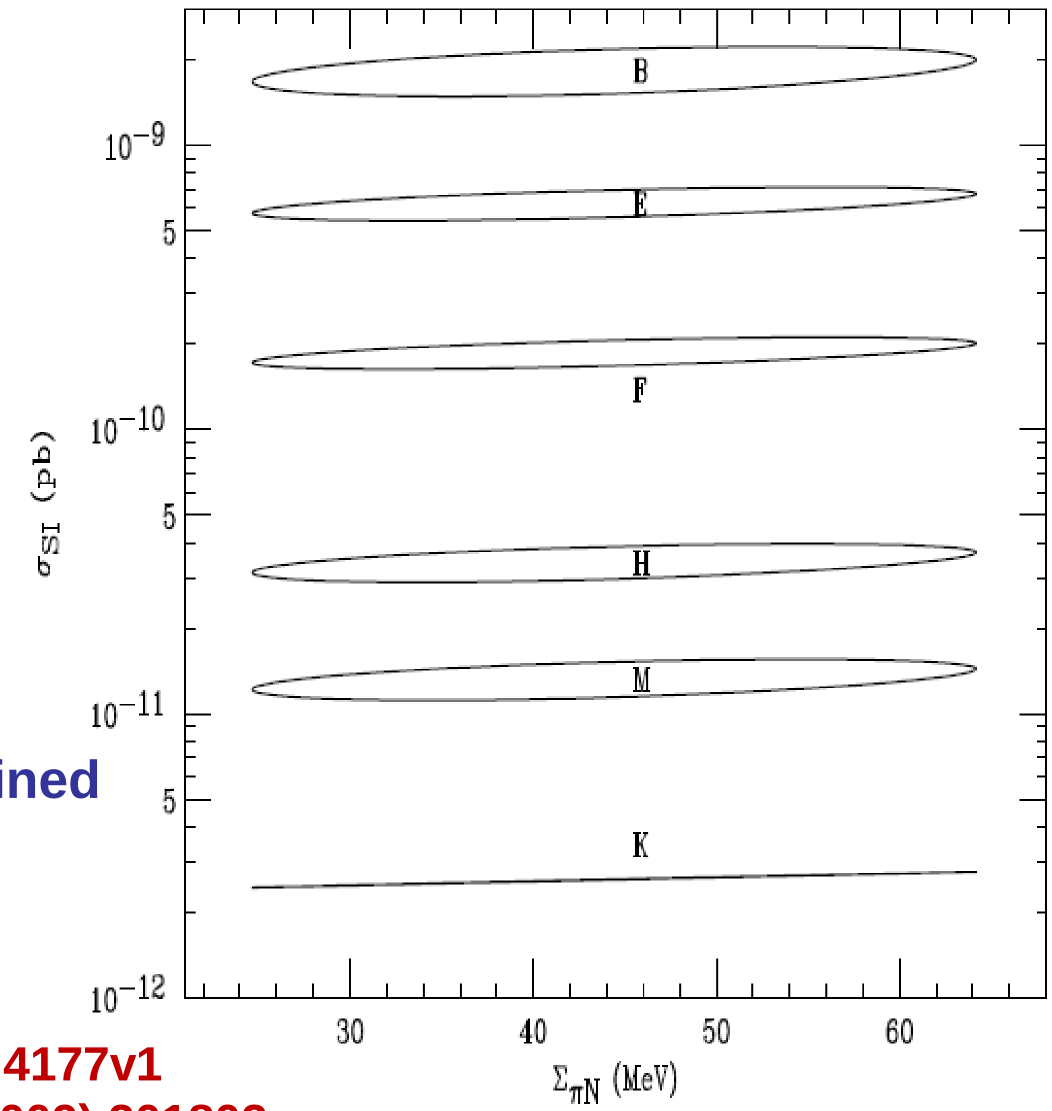


Giedt et al., arXiv: 0907.4177v1

CMSSM Predictions for Dark Matter σ

Using σ_s from this analysis as well as Toussaint & Freeman (2009) calculate 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
Just appeared in PRL 103 (2009) 201802