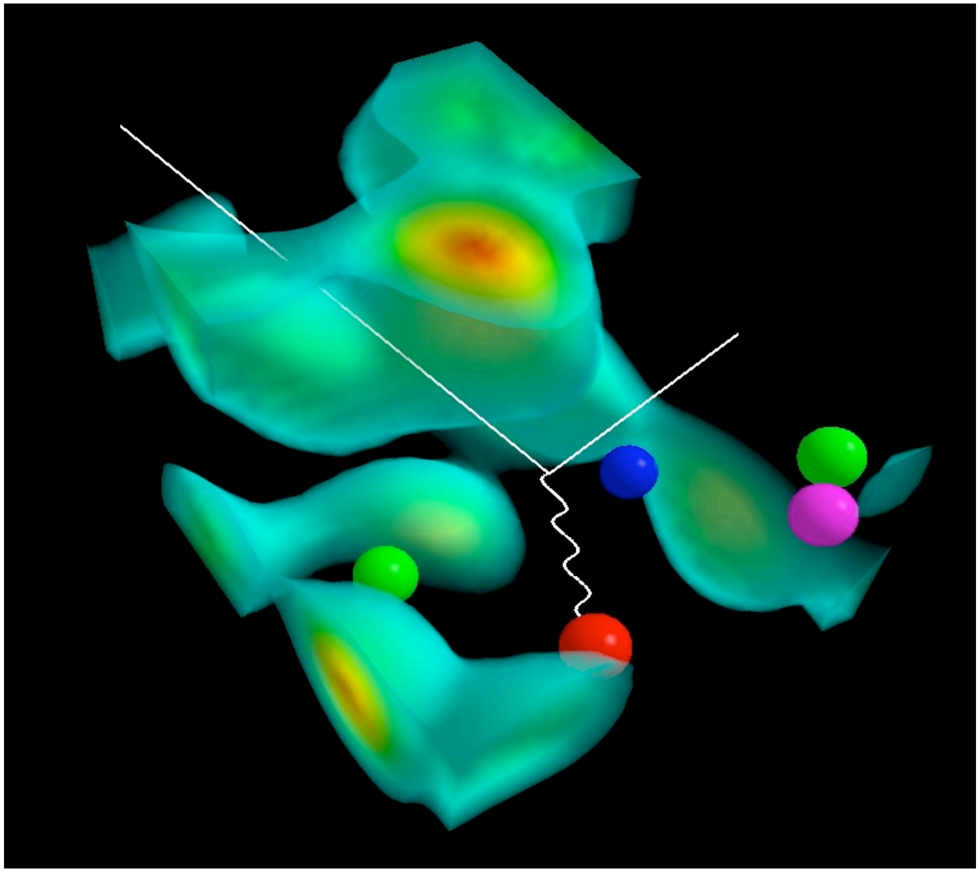
The Weinberg Angle and Possible New Physics Beyond the Standard Model



Anthony W. Thomas

Jefferson Lab : October 2nd 2009

Outline

- The Standard Model
- 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

Building Blocks of the Universe

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2		
Flavor	Mass GeV/c²	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c²	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

- Each quark comes in 3 “colours”: red, green and blue.
- Leptons do not carry color charge.

These are the building blocks of matter!

Force Carriers of the Universe

BOSONS force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

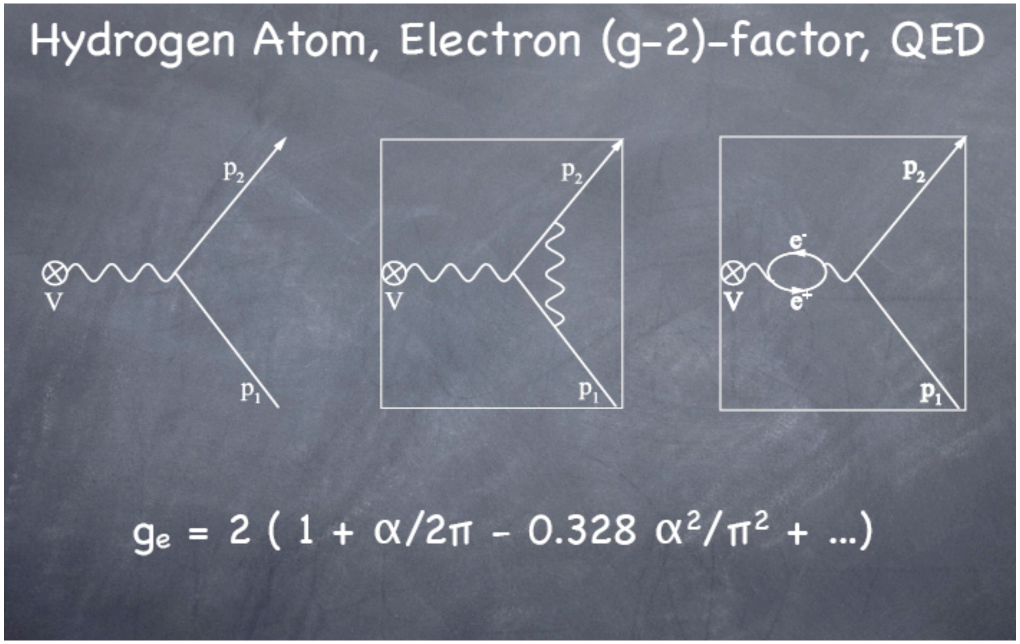
Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

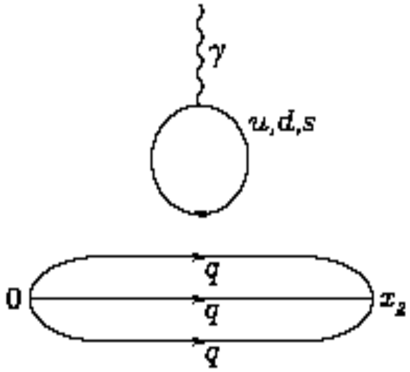
- **The massless photon mediates the long-range e.m. interactions.**
- **Gluons carry color and mediate the strong interaction.**
- **The very massive W^-, W^+, and Z^0 bosons mediate the weak interaction**

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

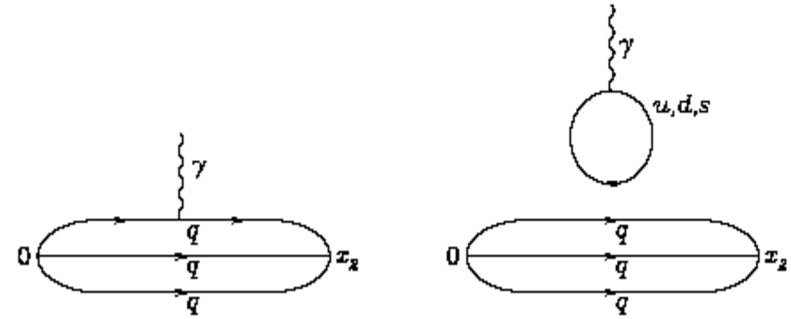
Strange Quarks in the Proton

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

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

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

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

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

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

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

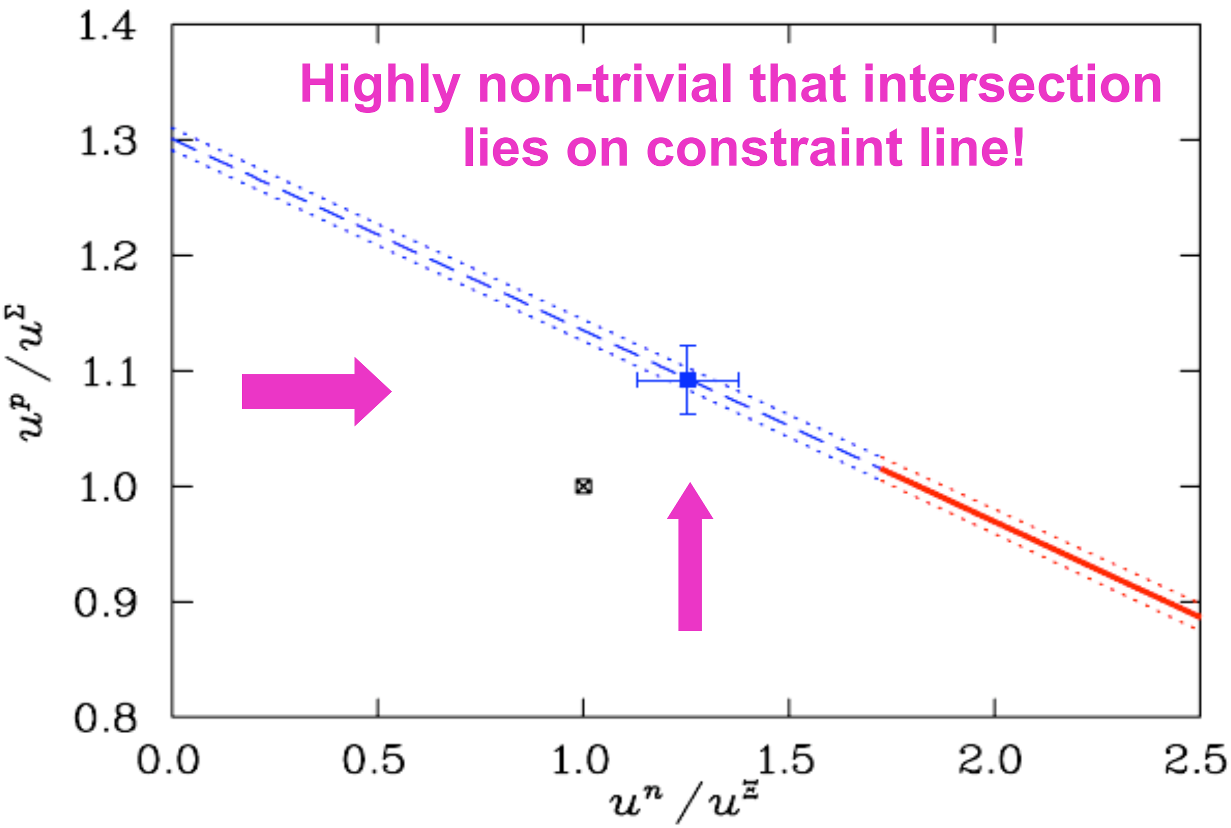
$$\Rightarrow \quad \Sigma^+ - \Sigma^- = u^\Sigma$$

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 ± 0.019 μ_N

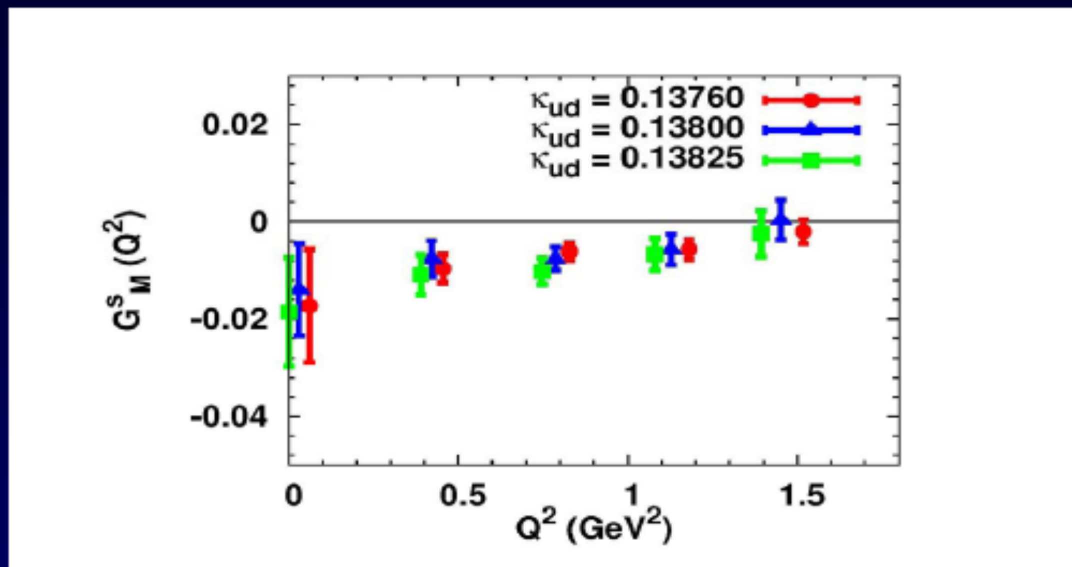
Leinweber et al., PRL 94 (2005) 212001

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

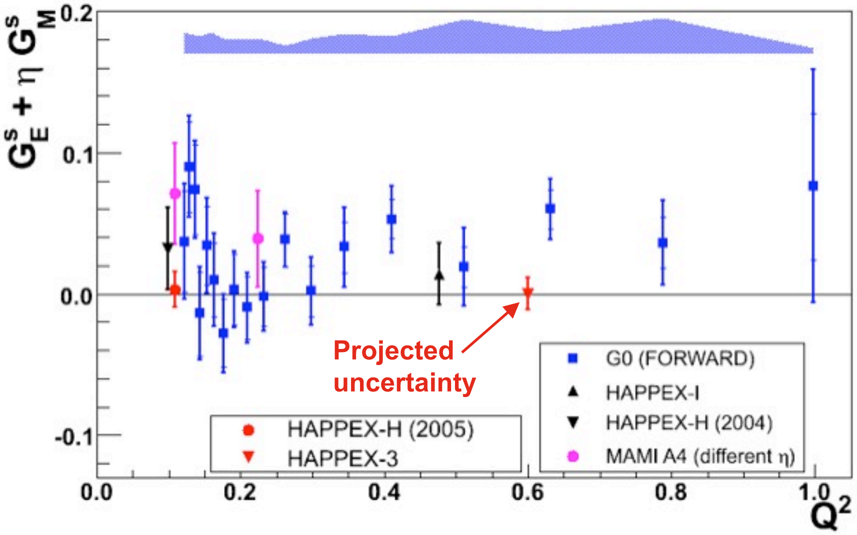


$$G_M^S(Q^2=0) = -\,0.017(25)(07)\ \mu_N$$

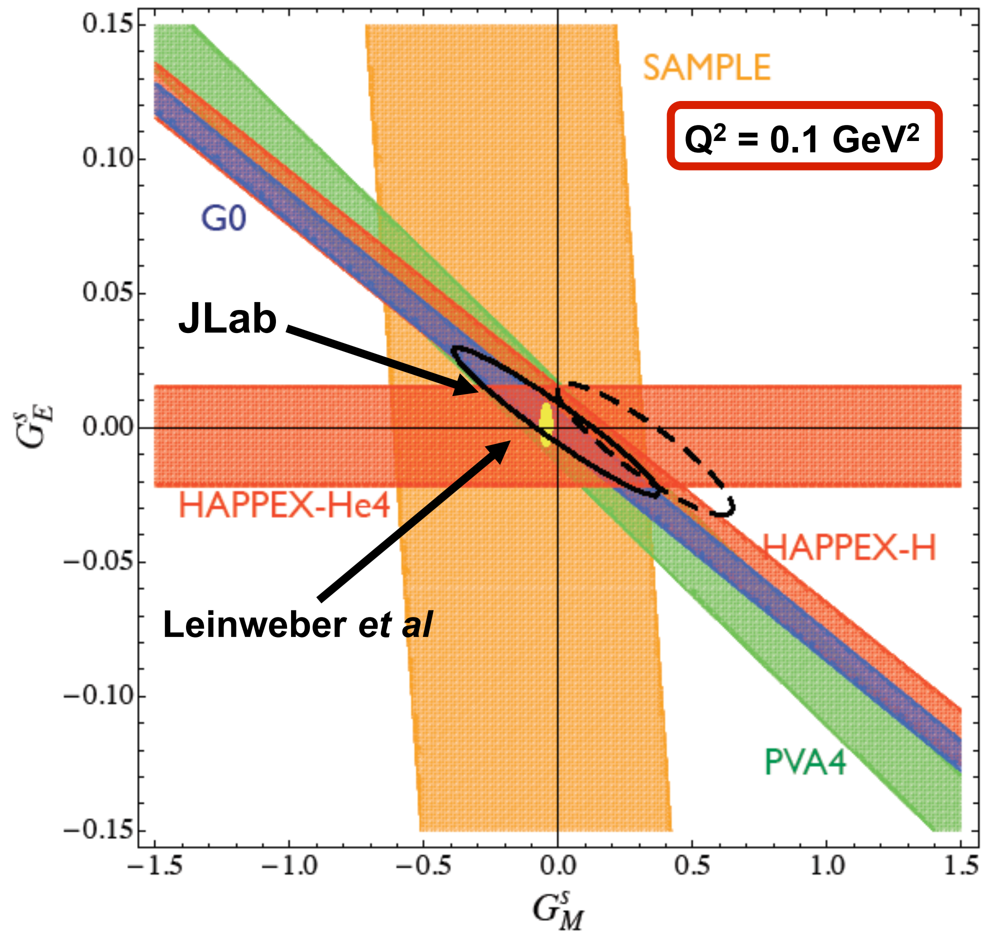
c.f. -0.046 ± 0.019 (Leinweber et al.)

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

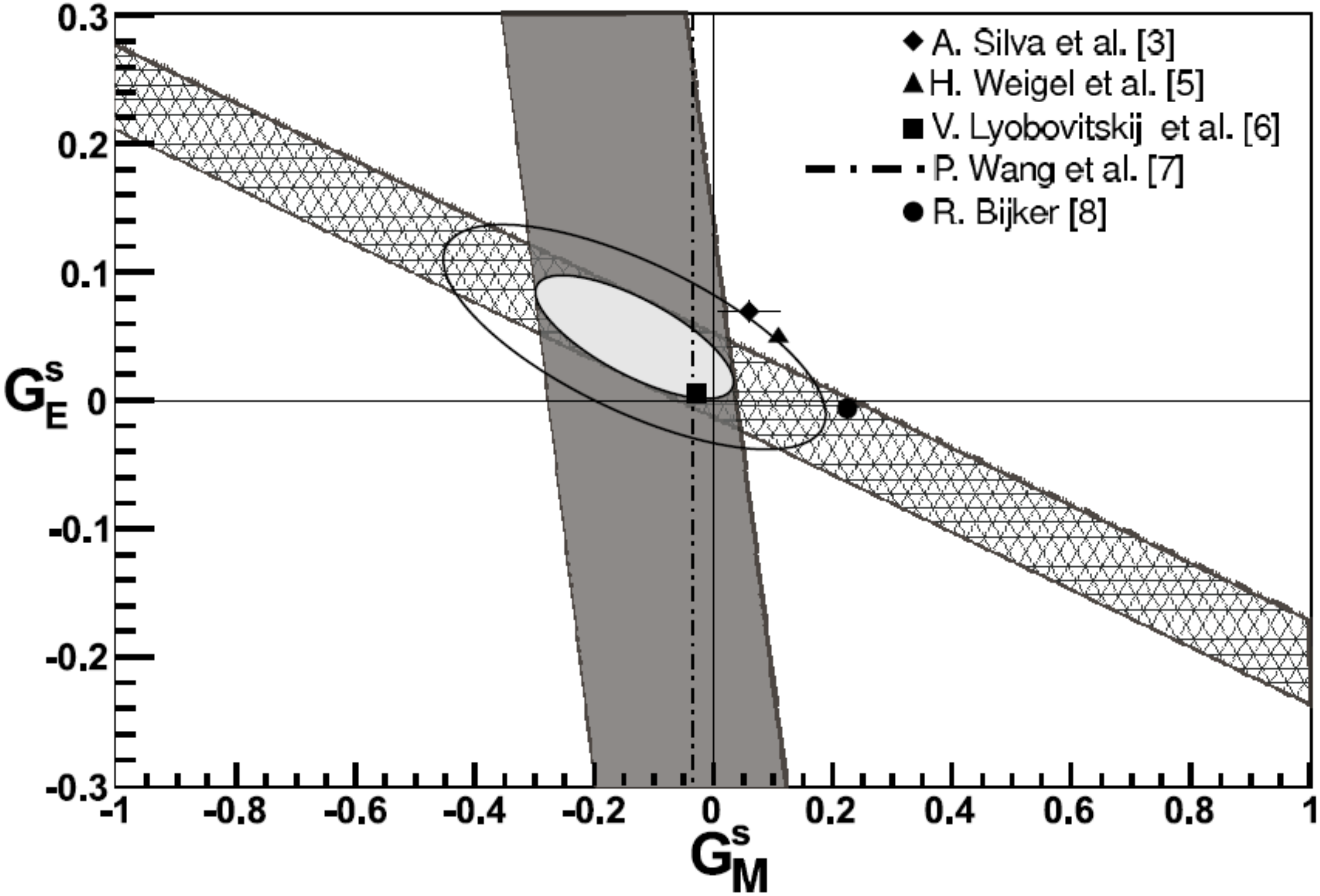


- ➢**Proton not all that strange**
- ➢**New data not yet included at 0.23 and 0.6 GeV² (PVA4 – just out, G0 – final analysis, HAPPEx III – will start this year)**

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

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

arXiv: 0903.2733v1



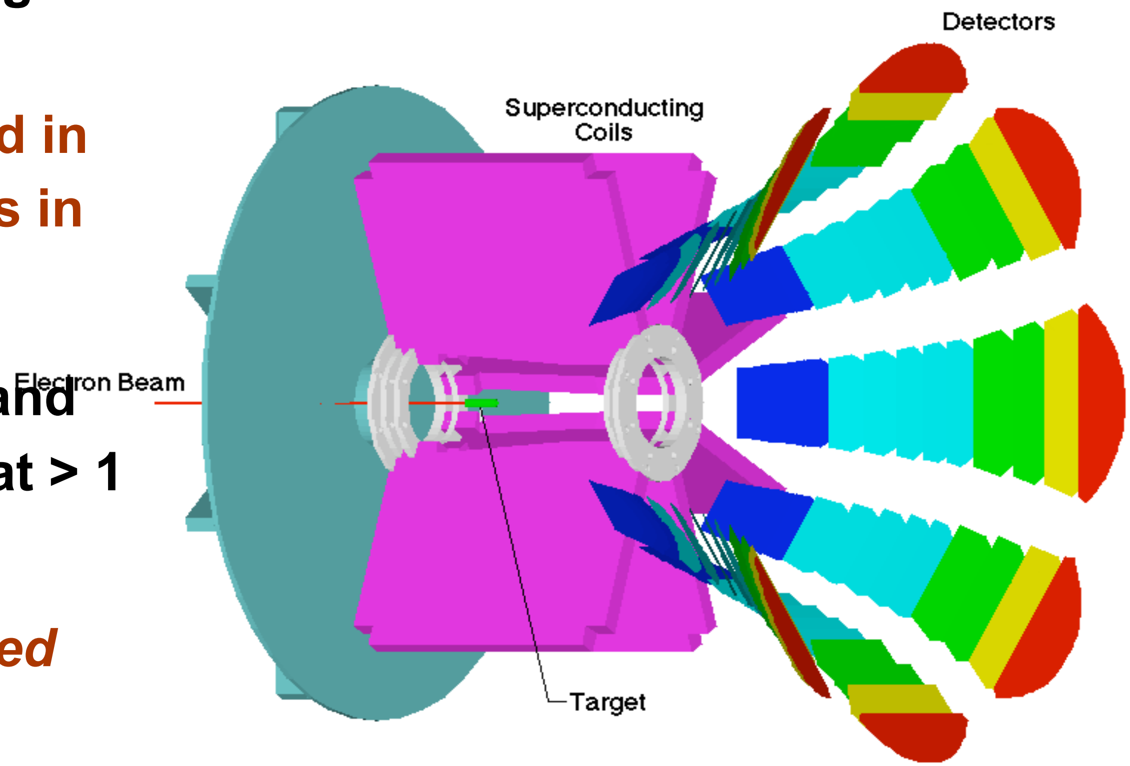
$G_M^s = -0.14 \pm 0.11 \pm 0.11\ \mu_N$; $G_E^s = 0.050 \pm 0.038 \pm 0.019$

The G0 experiment at JLAB

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

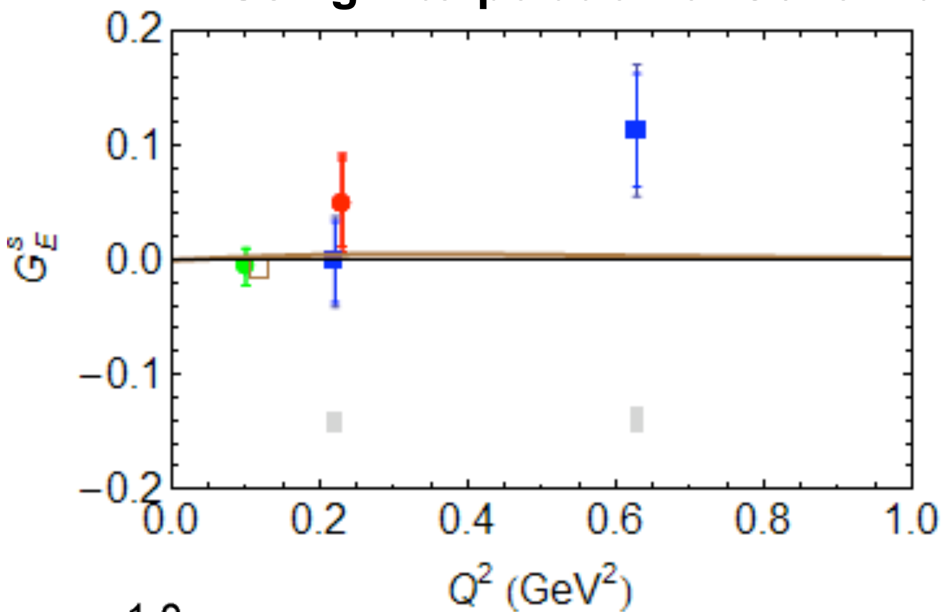
G_E^s , G_M^s and G_A^e separated
over range $Q^2 \sim 0.1 - 1.0\ (\mathrm{GeV/c})^2$

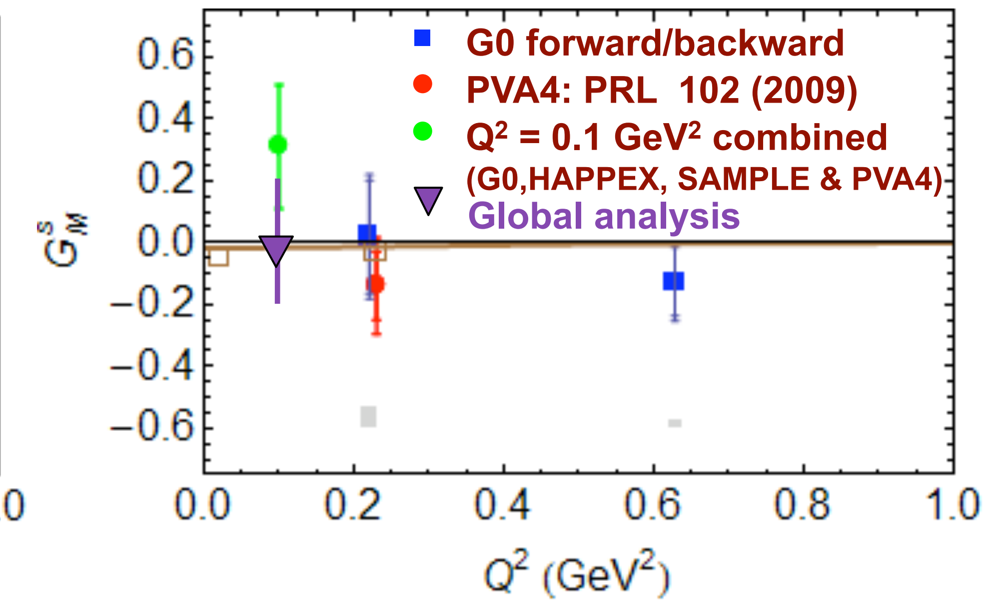
- **superconducting toroidal magnet**
  - **scattered particles detected in segmented scintillator arrays in spectrometer focal plane**
  - **custom electronics count and process scattered particles at > 1 MHz**
  - ***forward angle data published 2005***
  - ***backward angle data: 2006-2007***

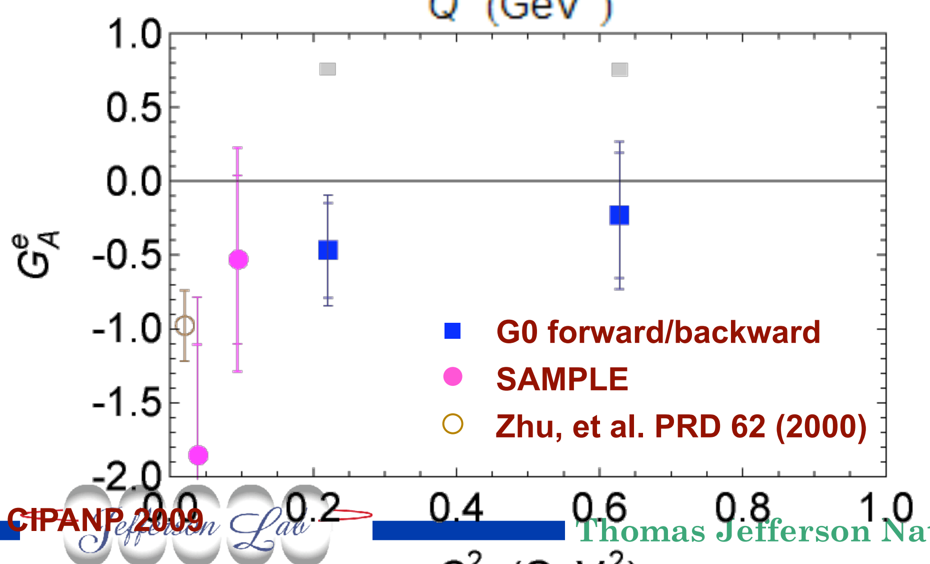


Form Factor Results

- **Using interpolation of G0 forward measurements**







Global uncertainties

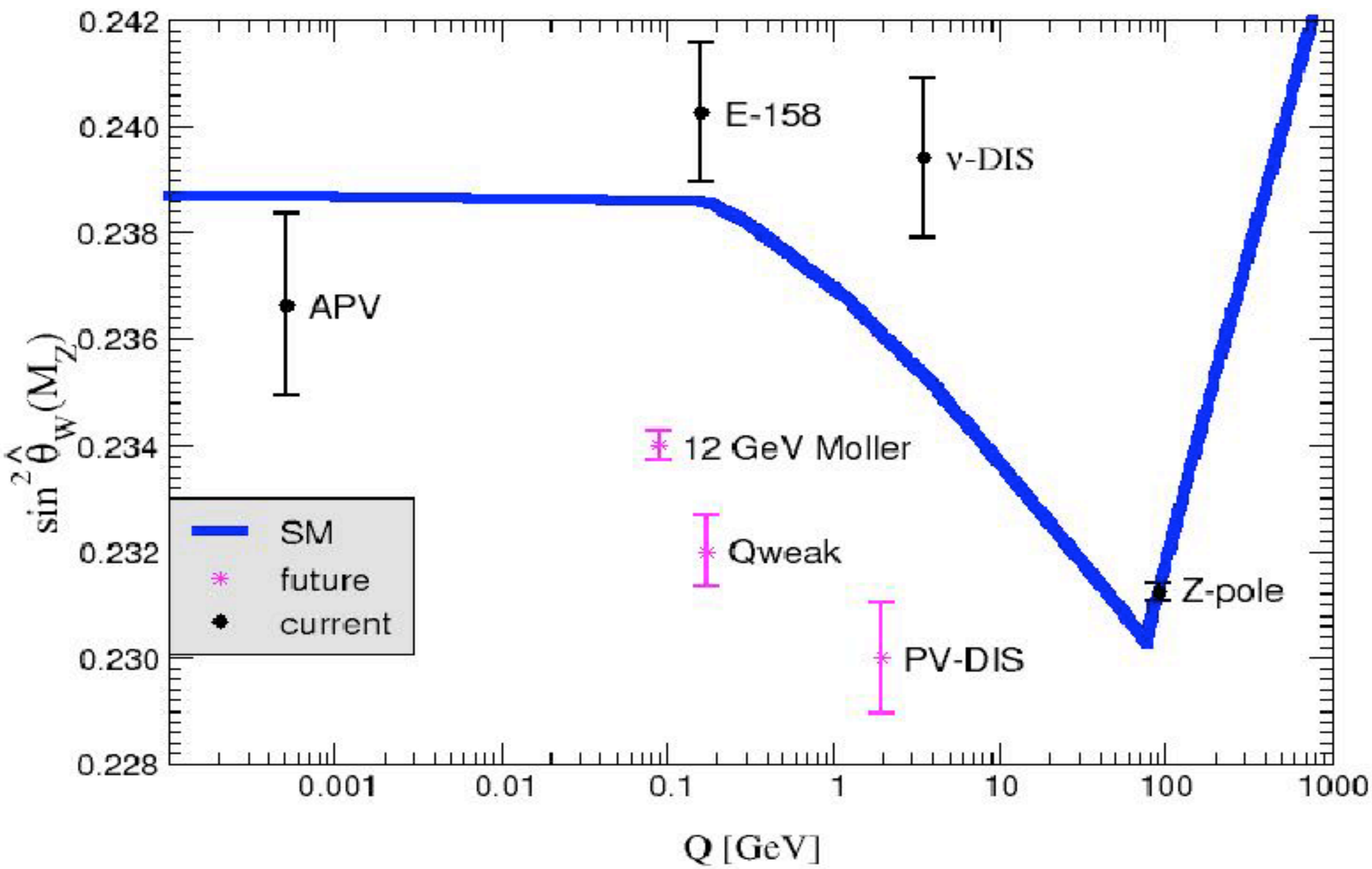
Some calculations:

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 (G_E^{pZ}, G_M^{pZ}) — Axial form factor ($\tilde{G}_A^p$)

Assume charge symmetry:

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

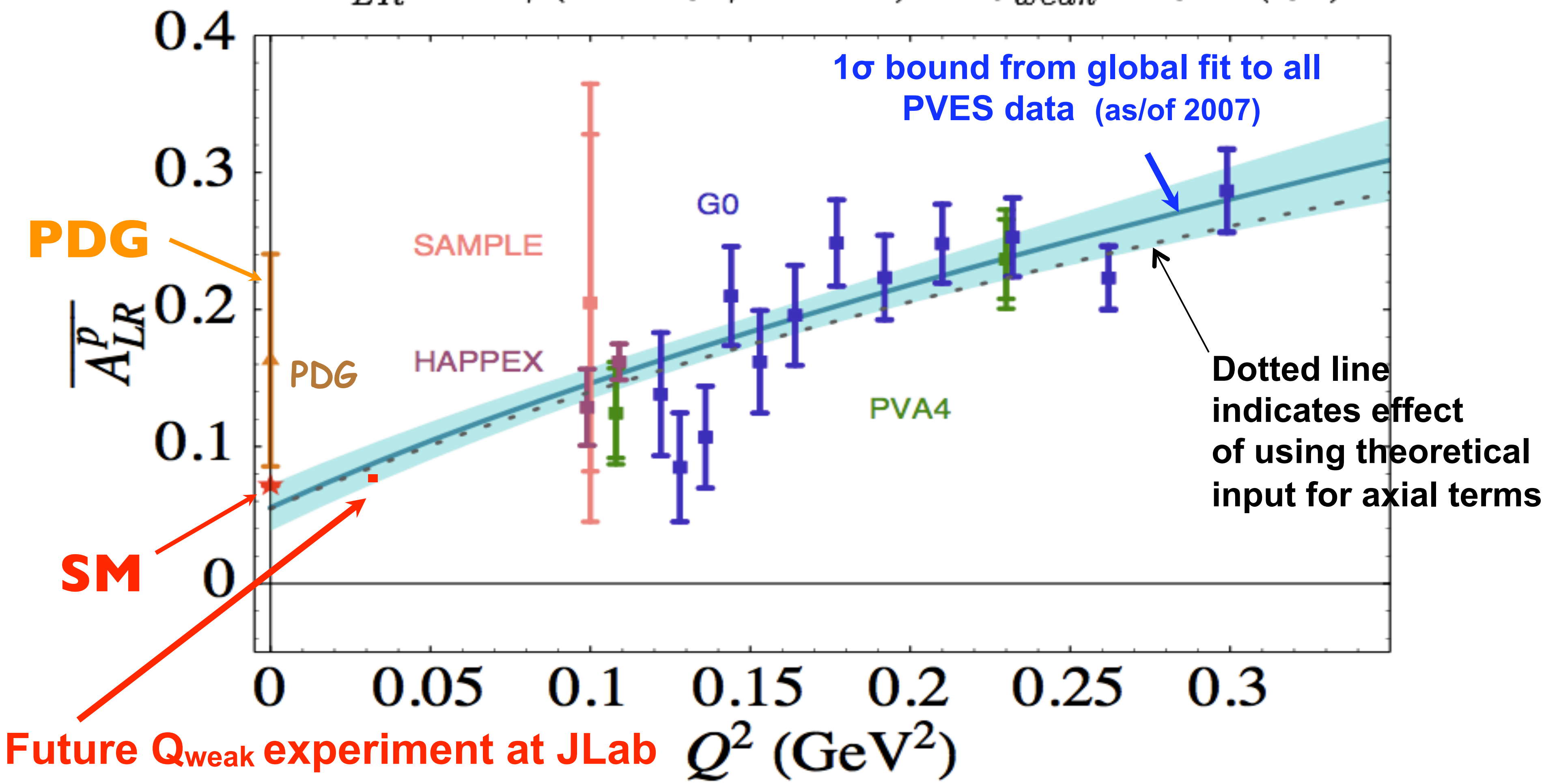
$(1 - 4\sin^2\theta_W)$: Proton weak charge (tree level)

$G_{E,M}^{s}$: Strangeness

Use data to constrain the parameters of the electroweak theory

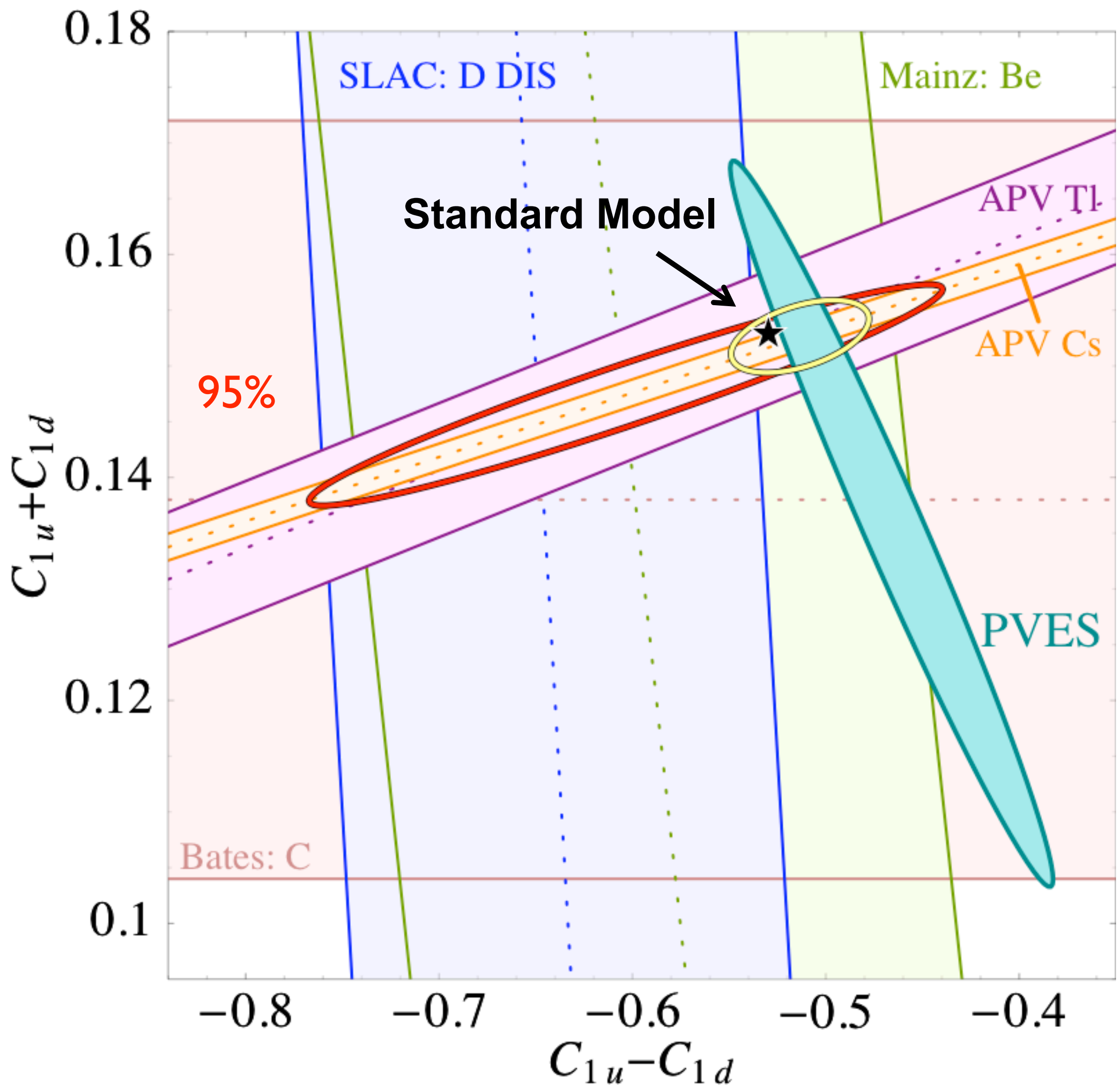
Use Global Fit to Extract Slope at 0° and $Q^2 = 0$

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



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

Major progress on C_{1q} couplings



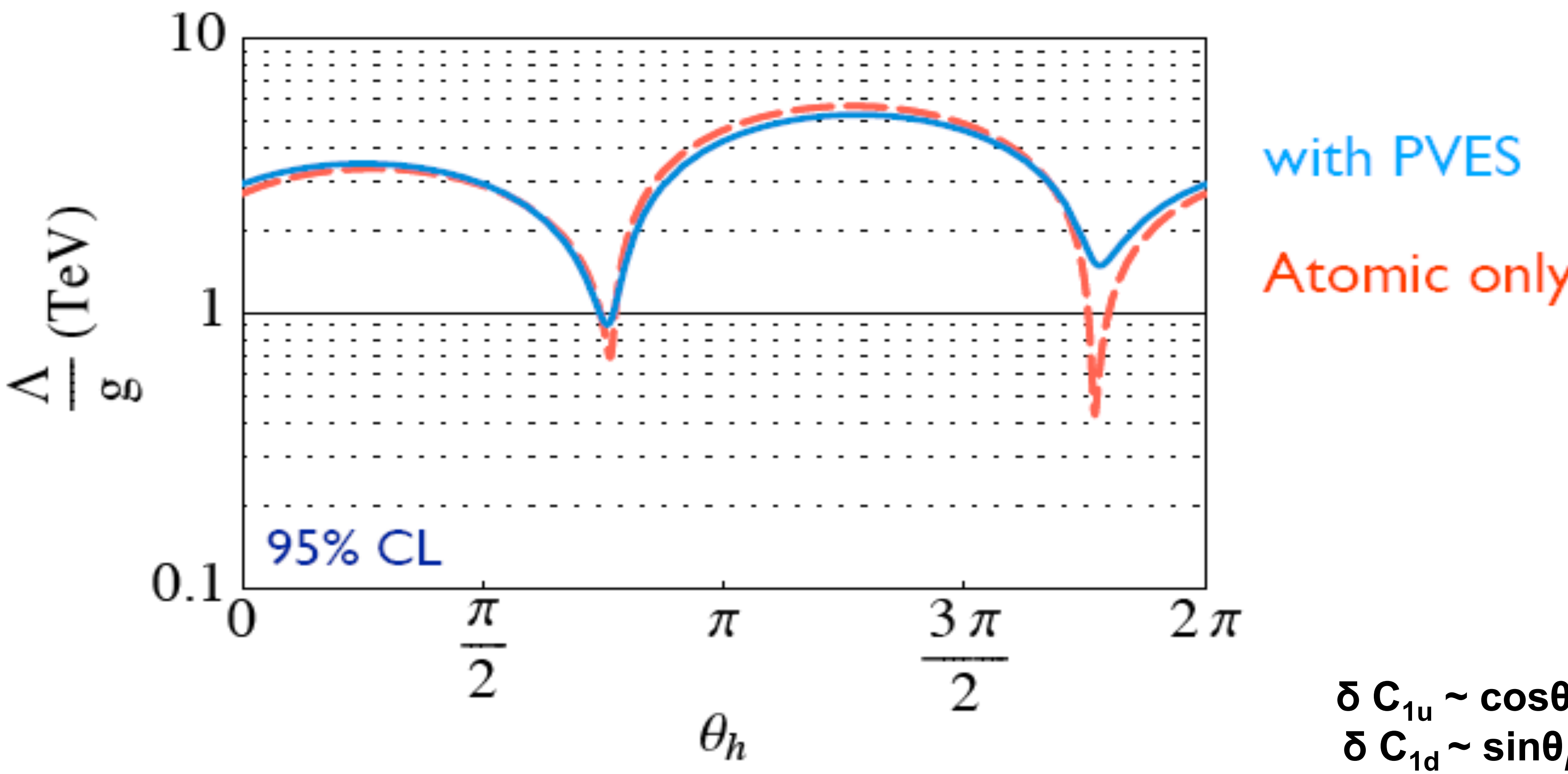
$$Q_{weak} = 2C_{1u} + C_{1d}$$

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

Dramatic improvement in knowledge of weak couplings!

Factor of 5 increase in precision of Standard Model test

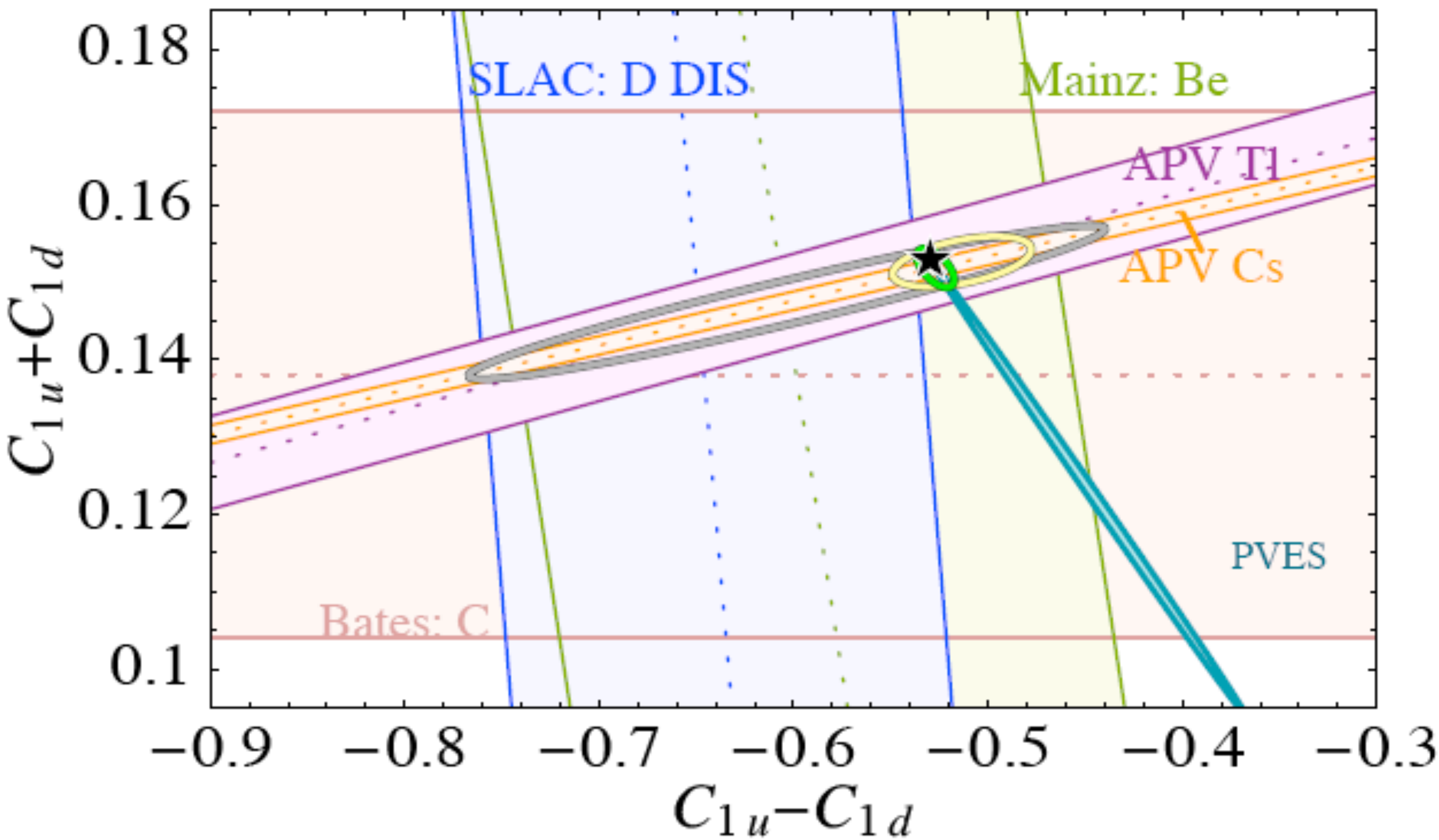
Raises Mass of New Z' to 0.9 TeV – from 0.4 TeV



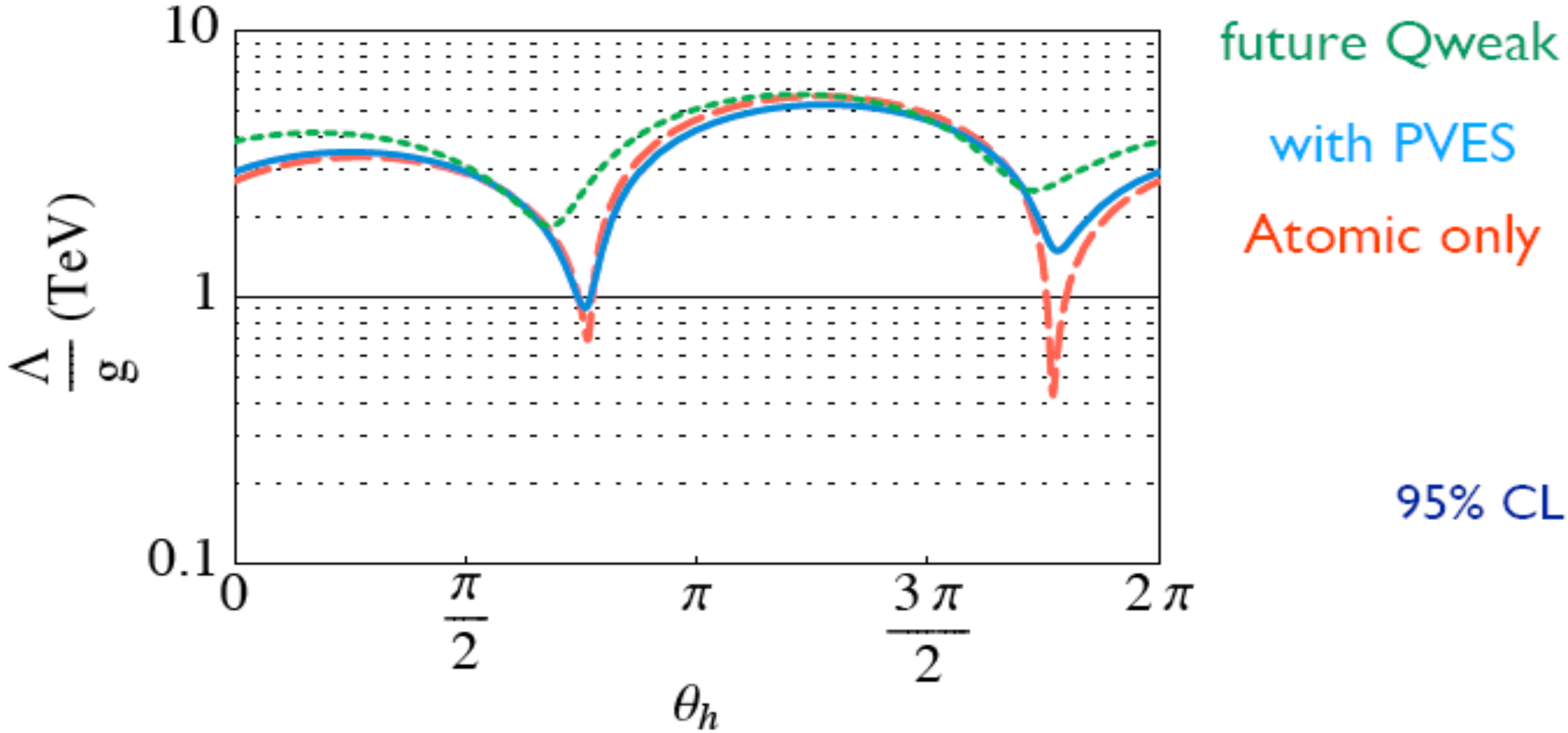
$\delta\ C_{1u} \sim \cos\theta_h$
$\delta\ C_{1d} \sim \sin\theta_h$

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

Future Q_{weak} at JLab – <u>if</u> in Agreement with SM



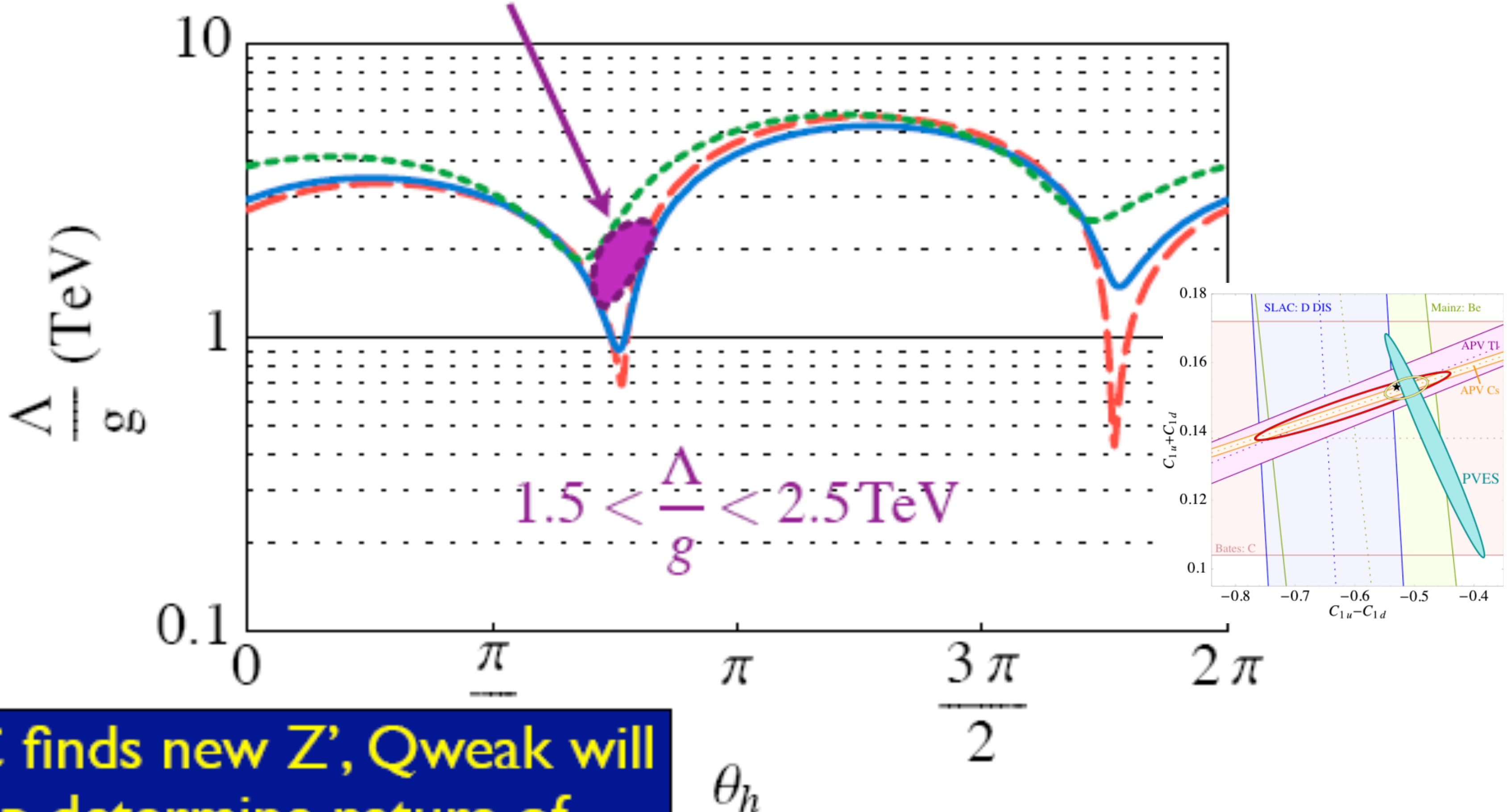
IF in accord with Standard Model…



Qweak constrains new physics to beyond 2 TeV

Or… Discovery

Assume Qweak takes central value of current measurements

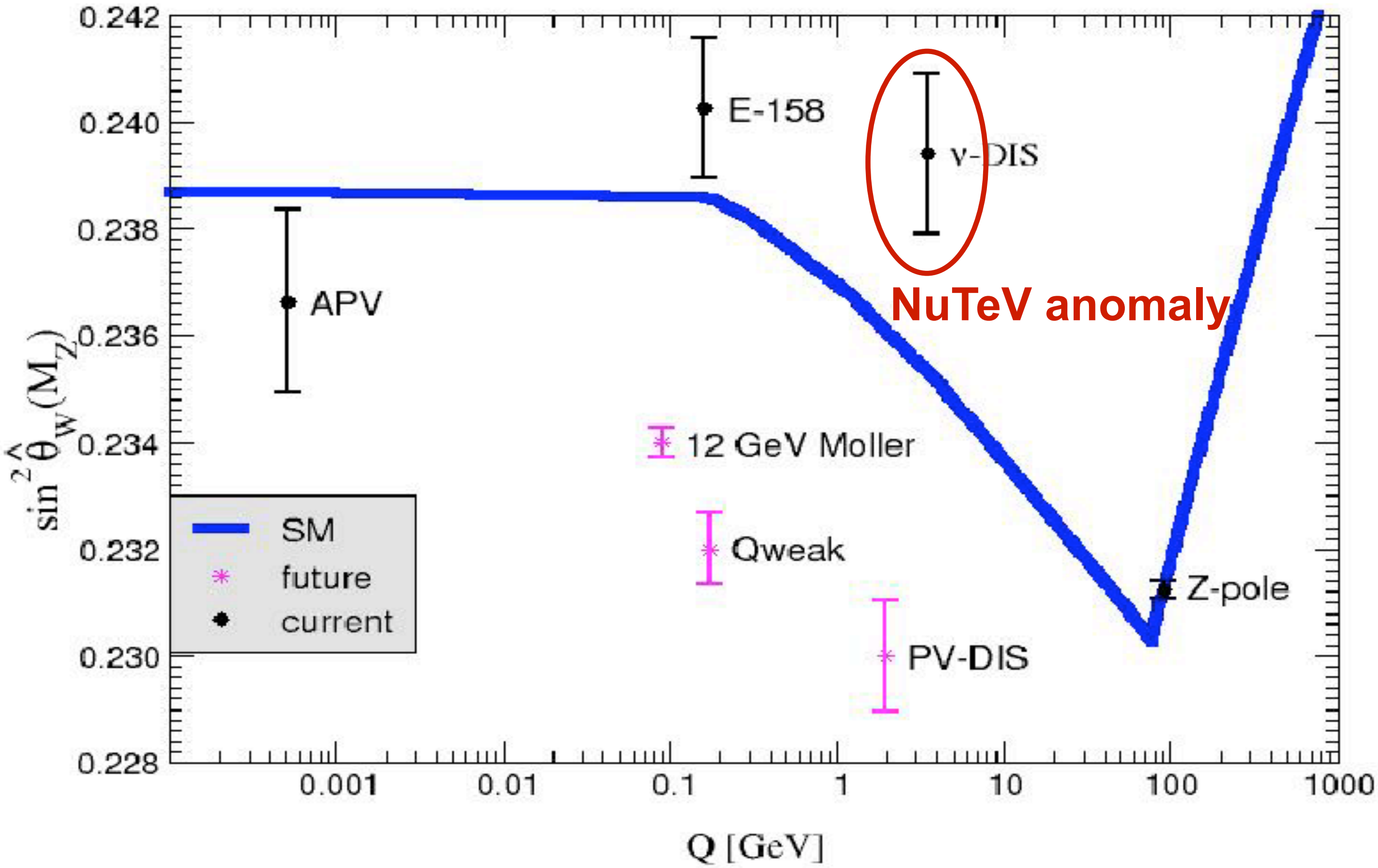


If LHC finds new Z', Qweak will help determine nature of interaction

The NuTeV anomaly

Radiative Corrections as Standard Model Test

One year ago….



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:

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

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

NuTeV

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

other methods

c.f. Standard Model $= 0.2227 \pm 0.0004$

(c.f. 1978: 0.230 ± 0.015)

From: Zeller, hep-ex/0207037, 37th Rencontres de Moriond

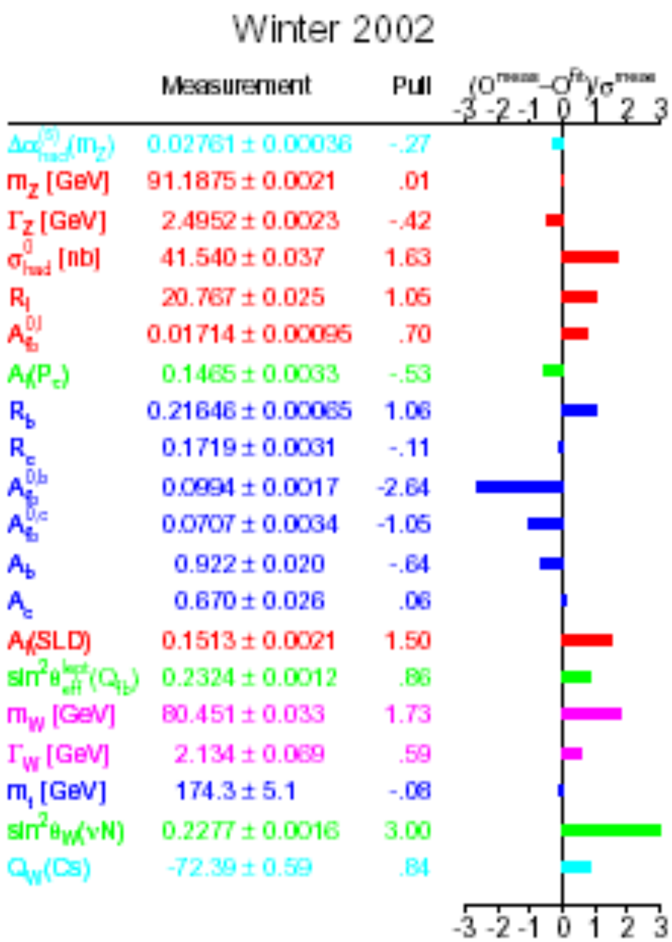


Figure 1: The current global electroweak fit including the NuTeV $\sin^2\theta_W$ result. The horizontal bars indicate the pull of each measurement, in standard deviations, from its standard model expectation. Plot is courtesy of the LEPEWWG.

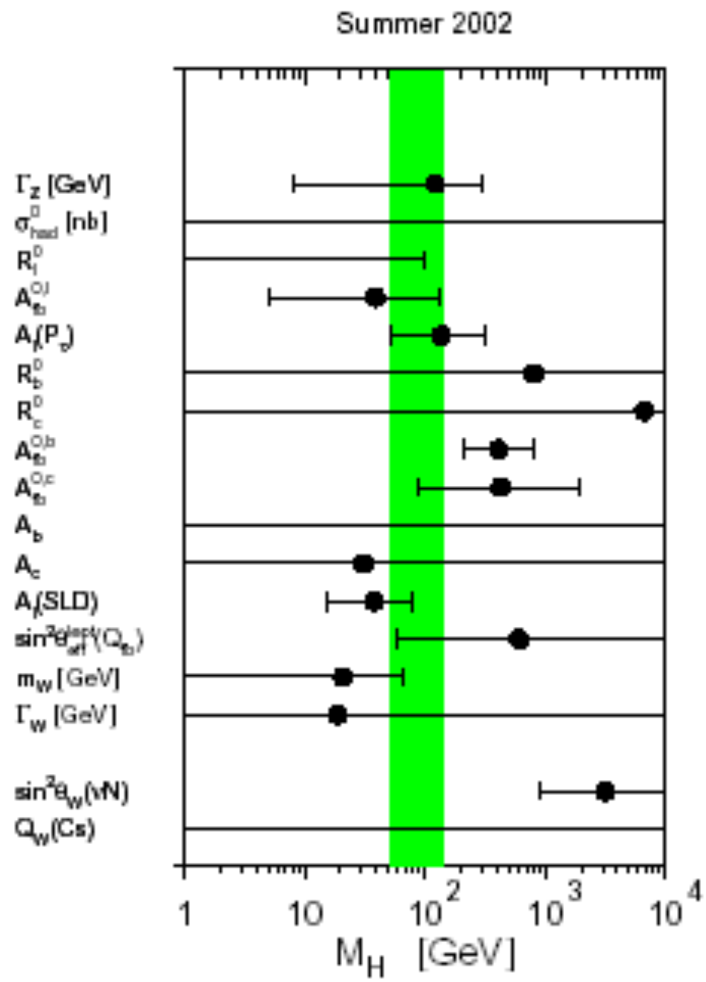


Figure 2: Sensitivity of the precision electroweak data to m_H. Most of the data is consistent with a low m_H, except for $A^{0,b}_{FB}$ and NuTeV $\sin^2\theta_W$. Plot is courtesy of the LEPEWWG.

Final comment on significance

- **LEP I lineshape also “shy” of 3 neutrinos**

- **Possibly suggests NC neutrino couplings differ from SM**

  e.g. Babu & Pati, Barshay & Kreyerhoff

Zeller: hep-ex/0207037:

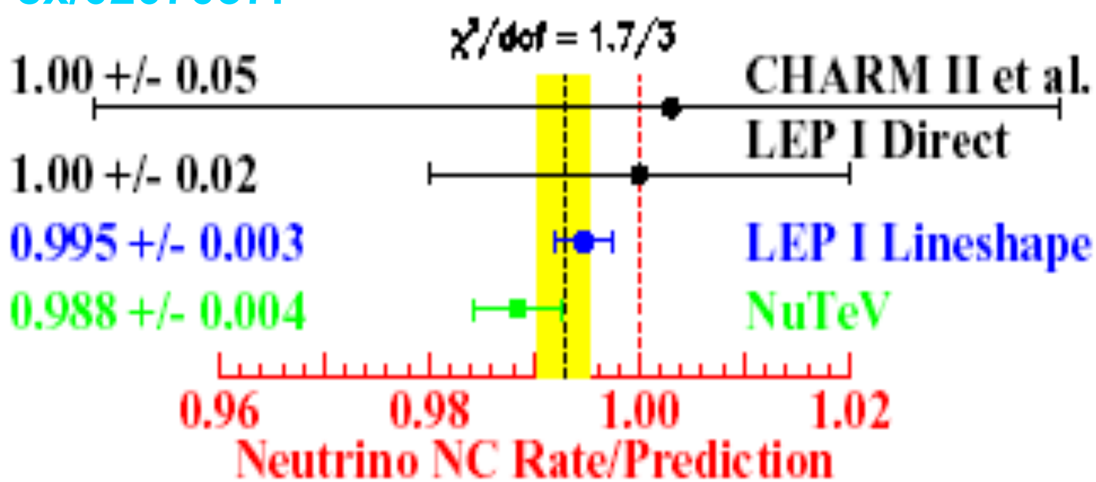


Figure 3: Experimental constraints on neutrino neutral current interaction rates relative to the standard model expectation. The two precise measurements, LEP I $\Gamma(Z \rightarrow \nu\overline{\nu})$ and NuTeV ρ_0^2, are both below expectation.

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

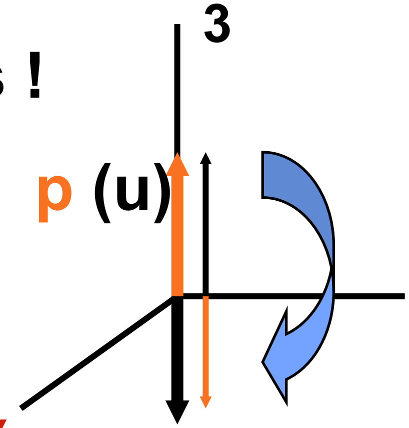
Then for e (or μ) DIS :

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

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.

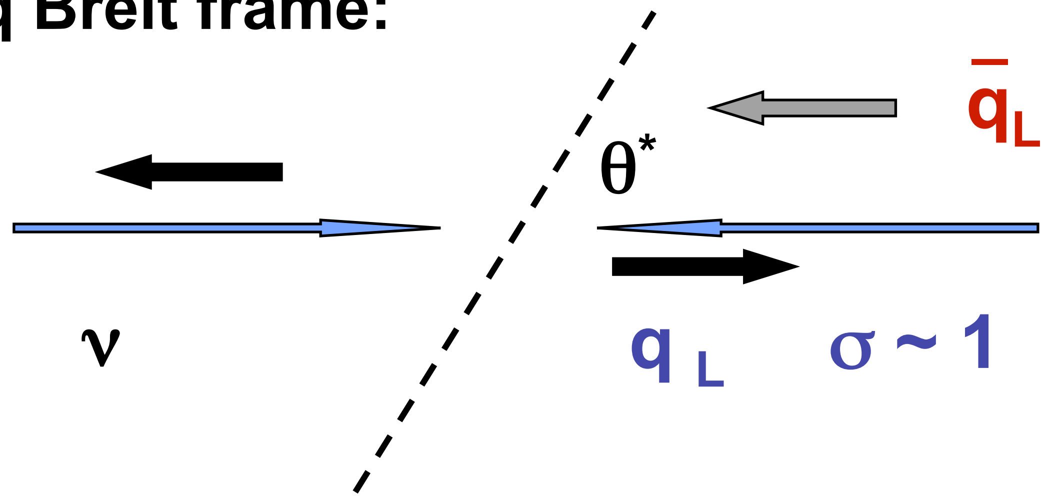
Hence:

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

up-quark in n down-quark in n

Neutrino Scattering

In ν – q Breit frame:



$\bar{q}_L \quad \sigma \sim |d^{11}{}_1(\cos\theta^*)|^2$

$\sim (1 + \cos\theta^*)^2/4$

$\sim (1 - y)^2$

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, for N=Z nucleus: 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

$$R^{PW} = g_L - g^2_R = \frac{1}{2} - \sin^2\theta_W$$

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:**

$$\Delta R_{\rm PW} \simeq \left(1 - \frac{7}{3} s^2_W\right) \frac{\langle x_A\, u^-_A - x_A\, d^-_A - x_A\, s^-_A \rangle}{\langle x_A\, u^-_A + x_A\, d^-_A \rangle}$$

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

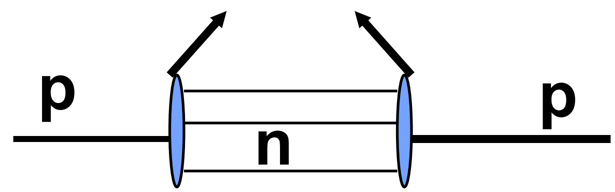
For s-wave valence quarks, most likely three-momentum is zero :

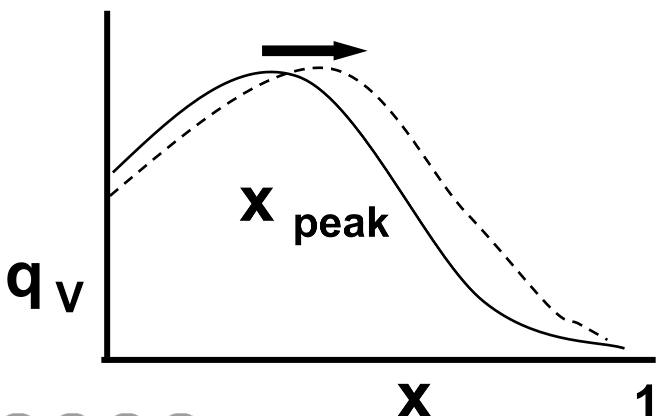
$\delta(M(1-x) - m_n)$ determines x where $q(x, Q^2_0)$ is maximum

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

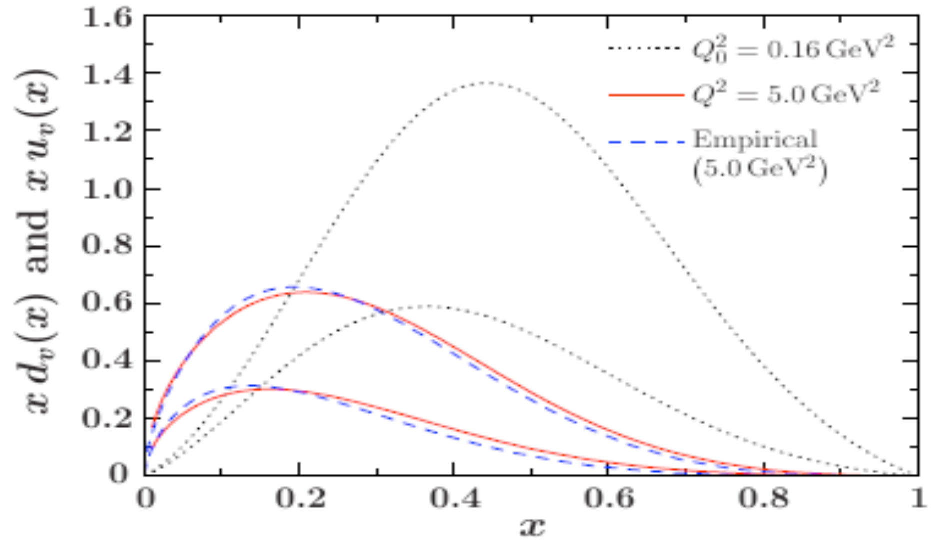
Hence[*]:

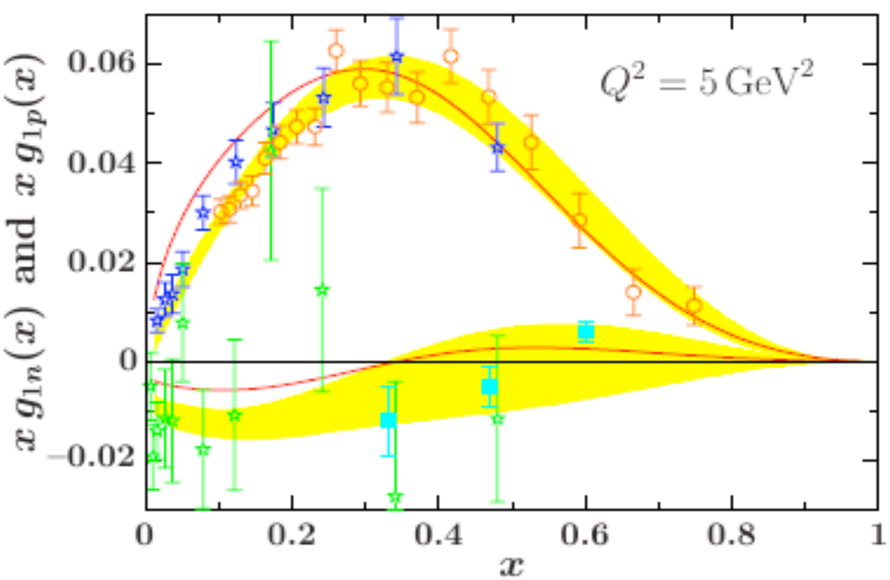
- u(x) dominates over d(x) for x > 0.3
- $u^{\uparrow}$ dominates over $u^{\downarrow}$ at large x
  and hence: $g^p_1(x) > 0$ at large x
- Similarly $g^n_1(x) > 0$ at large x

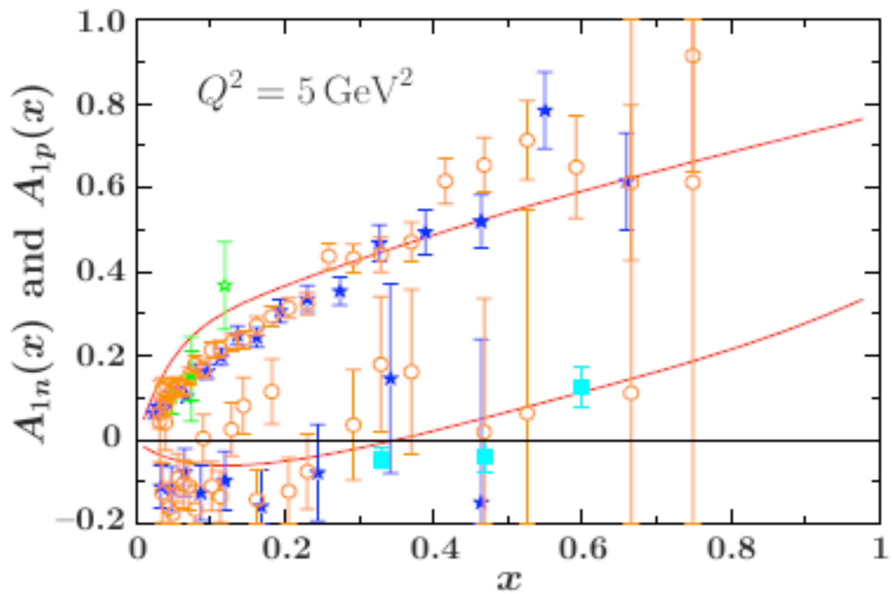
[*]Close & Thomas: 1988

More Modern (Confining) NJL Calculations

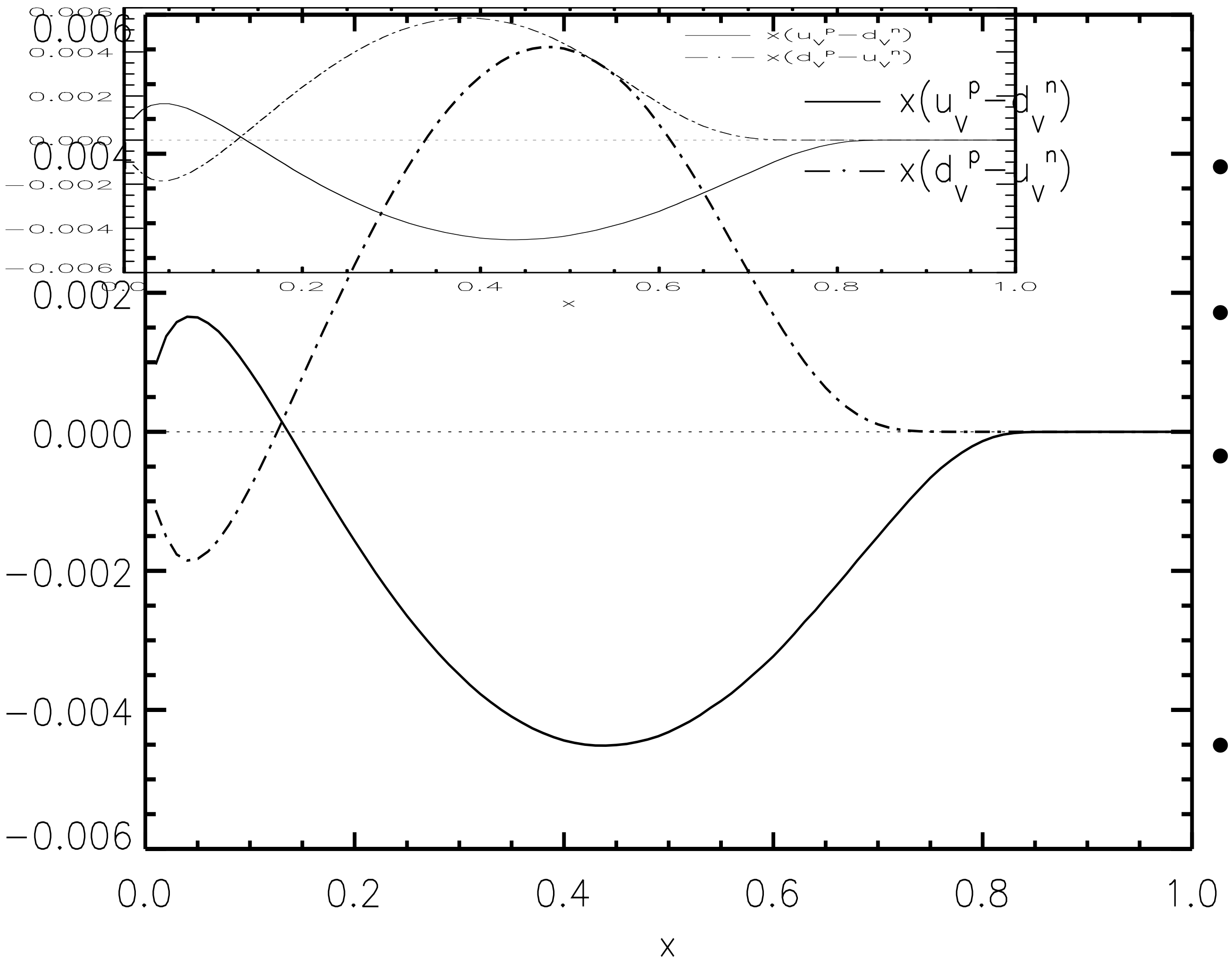
Cloet et al., Phys. Lett. B621, 246 (2005) (μ = 0.4 GeV)







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

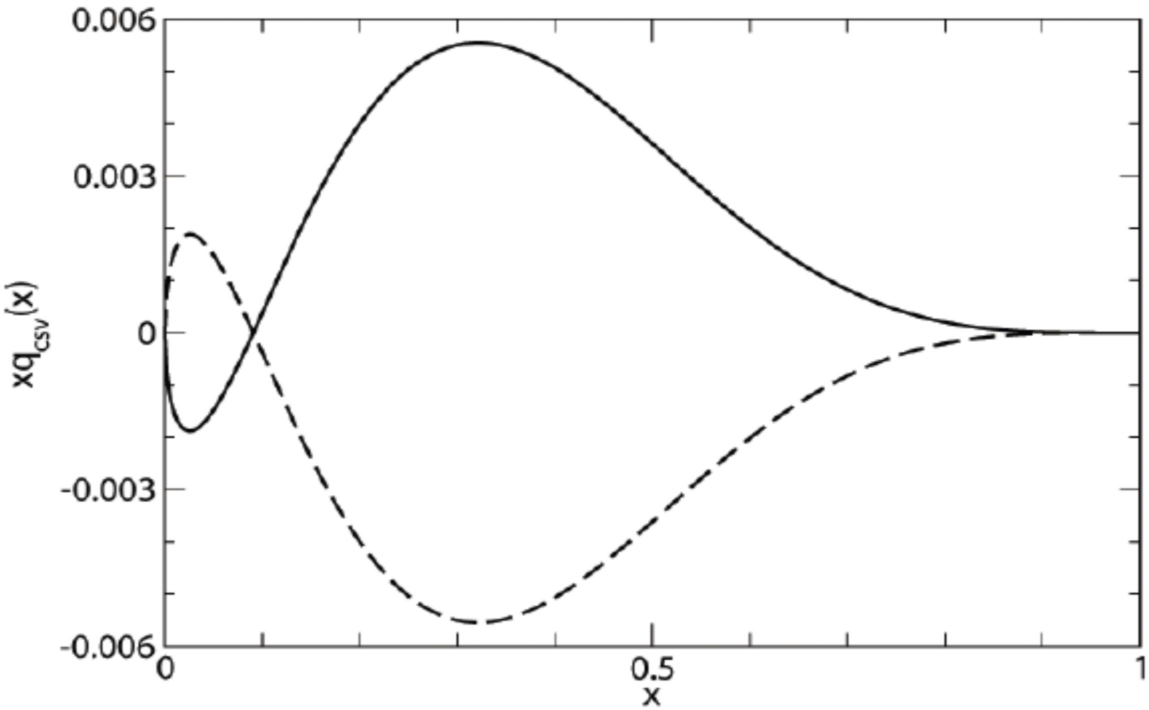


FIG. 5: The phenomenological valence quark CSV function from Ref. [23], corresponding to best fit value $\kappa = -0.2$ defined in Eq. (35). Solid curve: $x\delta d_v$; dashed curve: $x\delta u_v$.

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 :

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

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

Integrate by parts:

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

vanishes

Unity – normalization
i.e. <u>model independent</u>

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) :

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

Correction to Paschos-Wolfenstein is therefore :

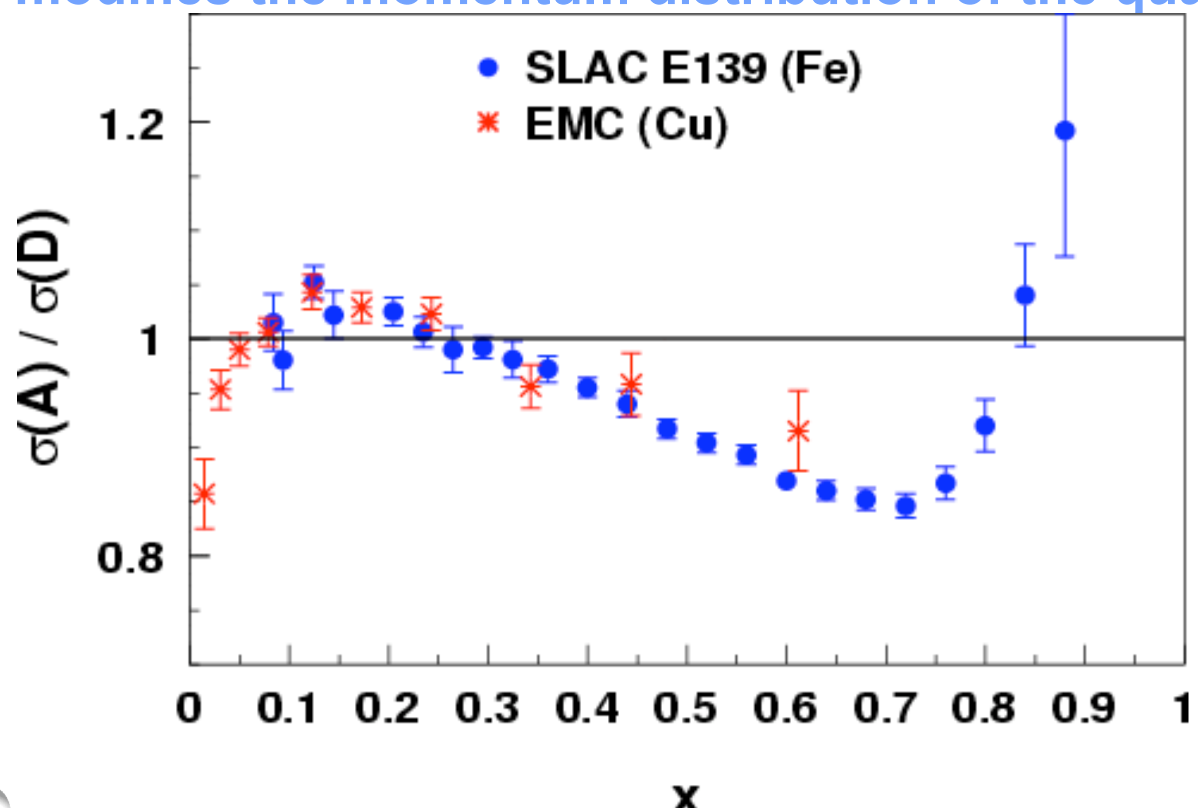
$$\Delta R^{PW} = 0.5\,(g^2_L - g^2_R)\, \frac{\delta U_V - \delta D_V}{U_V + D_V} \sim -0.0020$$

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 scalar polarizability 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**

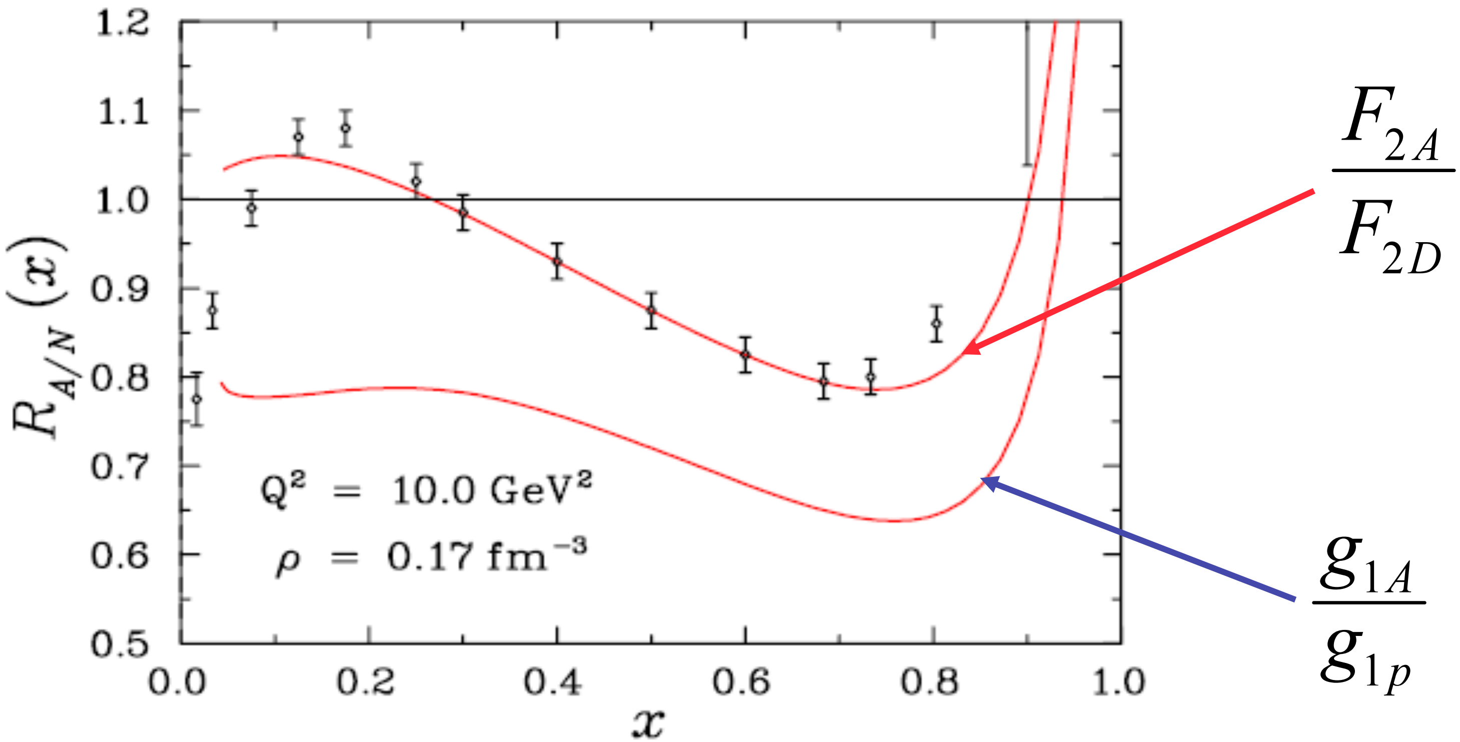
- **Applications to neutron stars – including SQM:**

- **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: mean scalar field modifies lower components of the confined quark's Dirac wave function
- Spin-dependent parton distribution functions for nuclei unmeasured



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

Recent Calculations for Finite Nuclei

Spin dependent EMC effect TWICE as large as unpolarized

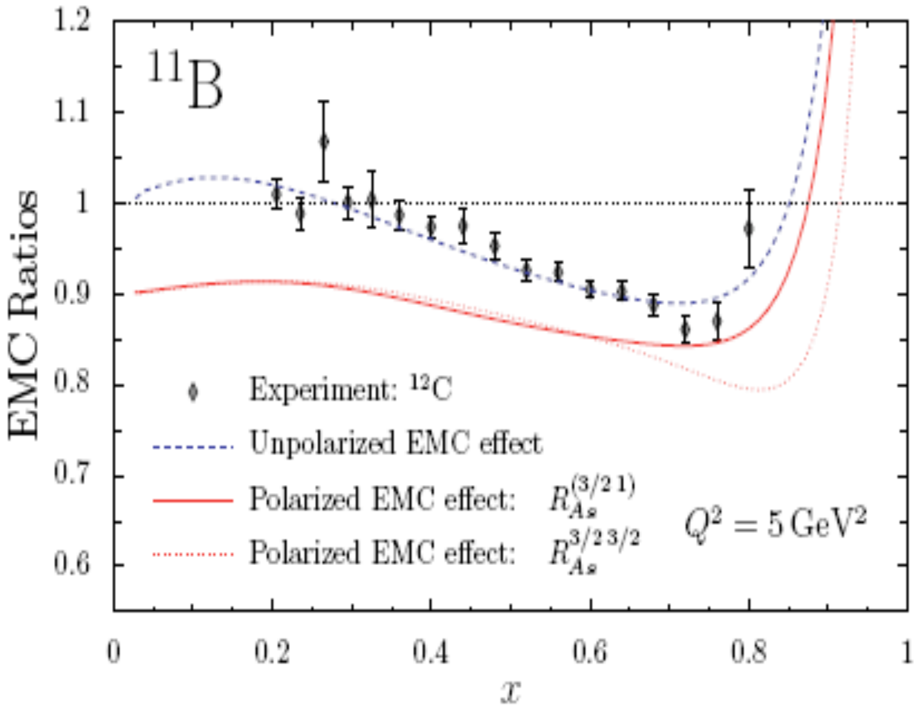


FIG. 7: The EMC and polarized EMC effect in ^{11}B. The empirical data is from Ref. [31].

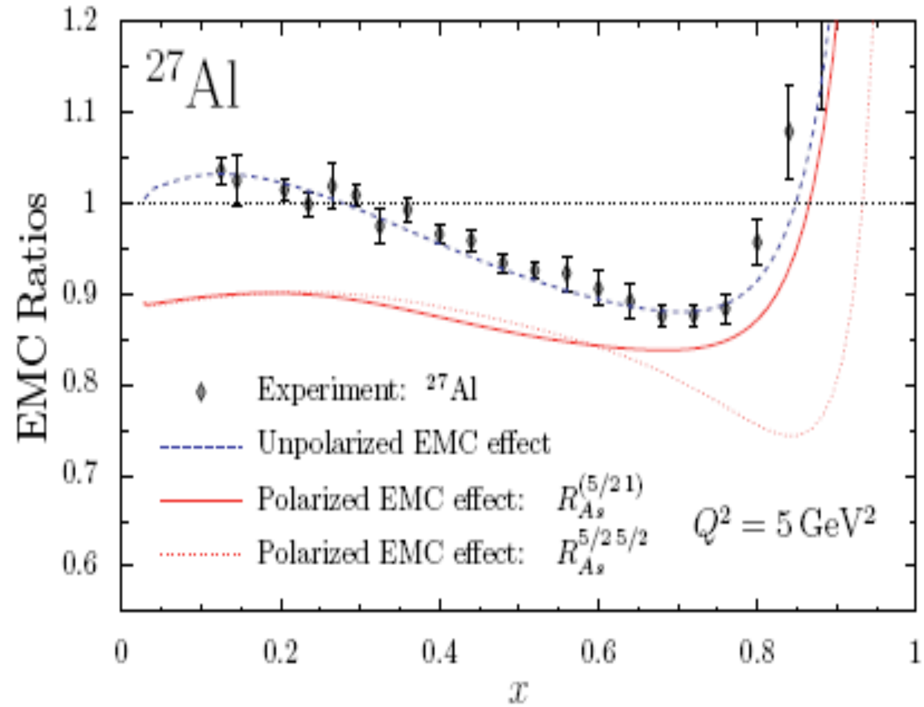


FIG. 9: The EMC and polarized EMC effect in ^{27}Al. The empirical data is from Ref. [31].

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 $m_u \neq m_d$

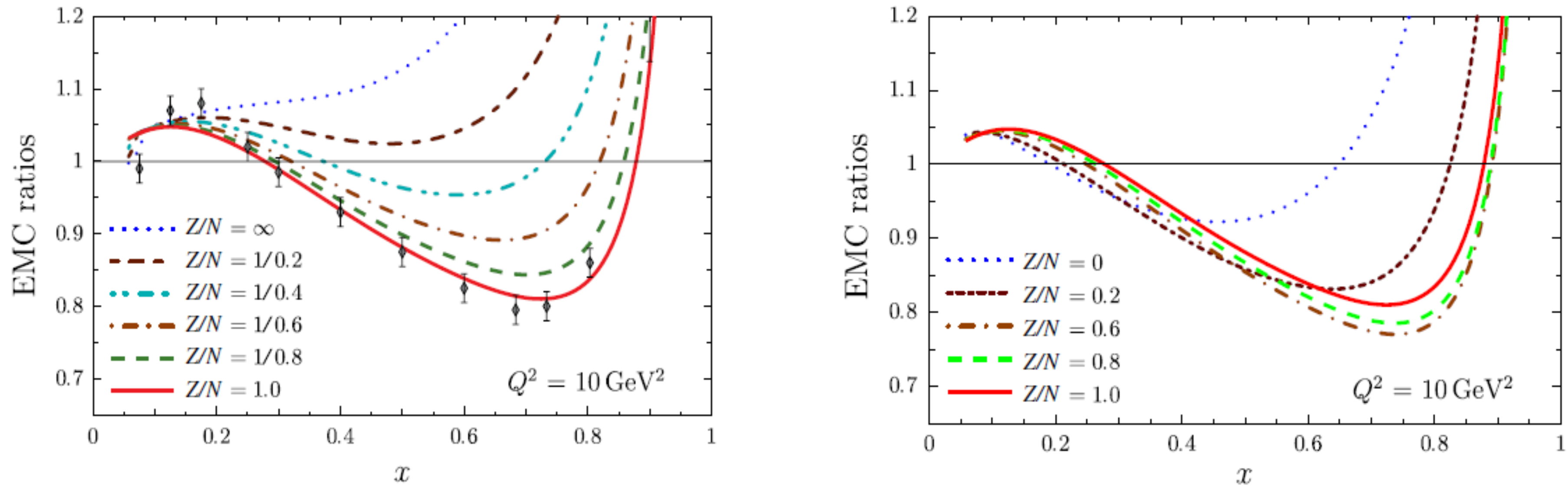
- Sign and magnitude of both effects exhibit little model dependence

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

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

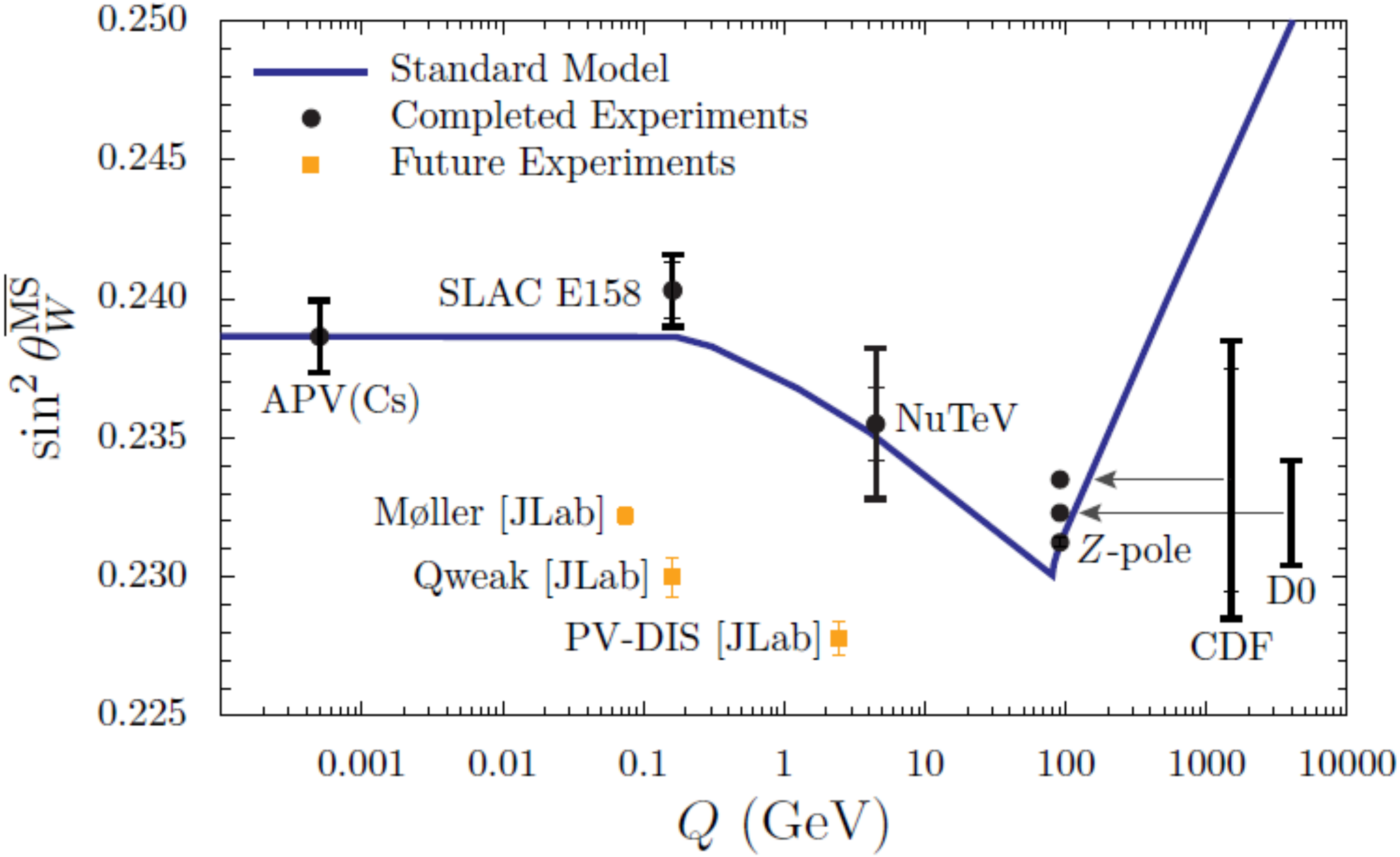
- **Excess of neutrons means d-quarks feel more repulsion than u-quarks**
- **Hence shift of momentum from all u to all d in the nucleus!**
- **Negative change in ΔR_{PW} and hence $\sin^2\theta_W$ ↑**
- **Isovector force controlled by $\rho_p - \rho_n$ and symmetry energy of nuclear matter both well 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 $s(x) - \bar{s}(x)$ …..