Parity Violation

and determination of $\sin^2\theta_W$

Shufang Su • U. of Arizona

Hall C 2006 summer workshop

Outline

- Determination of $\sin^2\theta_{eff}$
- Neutral current measurements
  - parity violating electron scattering (PVES)
    ee Moller scattering (SLAC E158, Jlab 12 GeV)
    ep elastic scattering (Jlab Qweak)
  - Parity violation deep inelastic scattering (DIS-parity)
  - atomic parity violation (APV)
  - neutrino-nucleus deep inelastic scattering (NuTeV)

  [probe new physics beyond SM
  some QCD issue

- Conclusion

Low energy precision measurements

- address questions difficult to study at high energy
  weak interactions (parity violation)
- high precision low energy experiment available

size of loop effects from new physics: $(\alpha/\pi)(M/M_{new})^2$

- muon g-2: $M=m_\mu$, $\delta^{new} \sim 2\times10^{-9}$, $\delta^{exp} < 10^{-9}$
- β-decay, π-decay: $M=m_W$, $\delta^{new} \sim 10^{-3}$, $\delta^{exp} \sim 10^{-3}$
- parity-violating electron scattering: $M=m_W$, $\delta^{new} \sim 10^{-3}$,

$$\mathcal{L}_{PV} = -\frac{G_\mu}{2\sqrt{2}} Q_W^f \bar{e}\gamma^\mu\gamma_5 e \bar{f}\gamma_\mu f$$

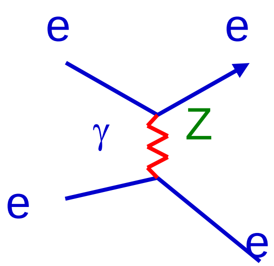
$Q_W^{e,p} \sim 1-4\sin^2\theta_W \sim 0.1$

✓ $1/Q_W^{e,p} \approx 10$ more sensitive to new physics

✓ need $\delta^{exp} \sim 10^{-2}$ "easier" experiment

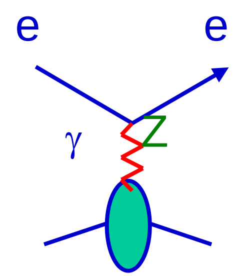
- probe new physics off the Z-resonance
  - sensitive to new physics not mix with Z

Møller Scattering



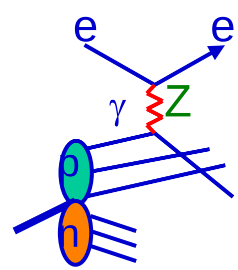
- Purely Leptonic

Q-Weak (JLab)



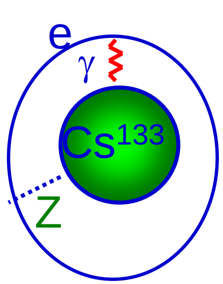
- Coherent quarks in P
- Results in ~2009
- $2(2C_{1u}+C_{1d})$

DIS-Parity



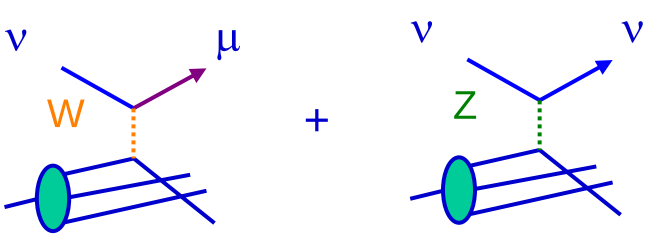
- Isoscaler quark scattering
- $(2C_{1u}-C_{1d})+Y(2C_{2u}-C_{2d})$

Atomic Parity Violation



- Coherent quarks in entire nucleus
- Nuclear structure uncertainties
- $-376\ C_{1u} - 422\ C_{1d}$

Neutrino Scattering



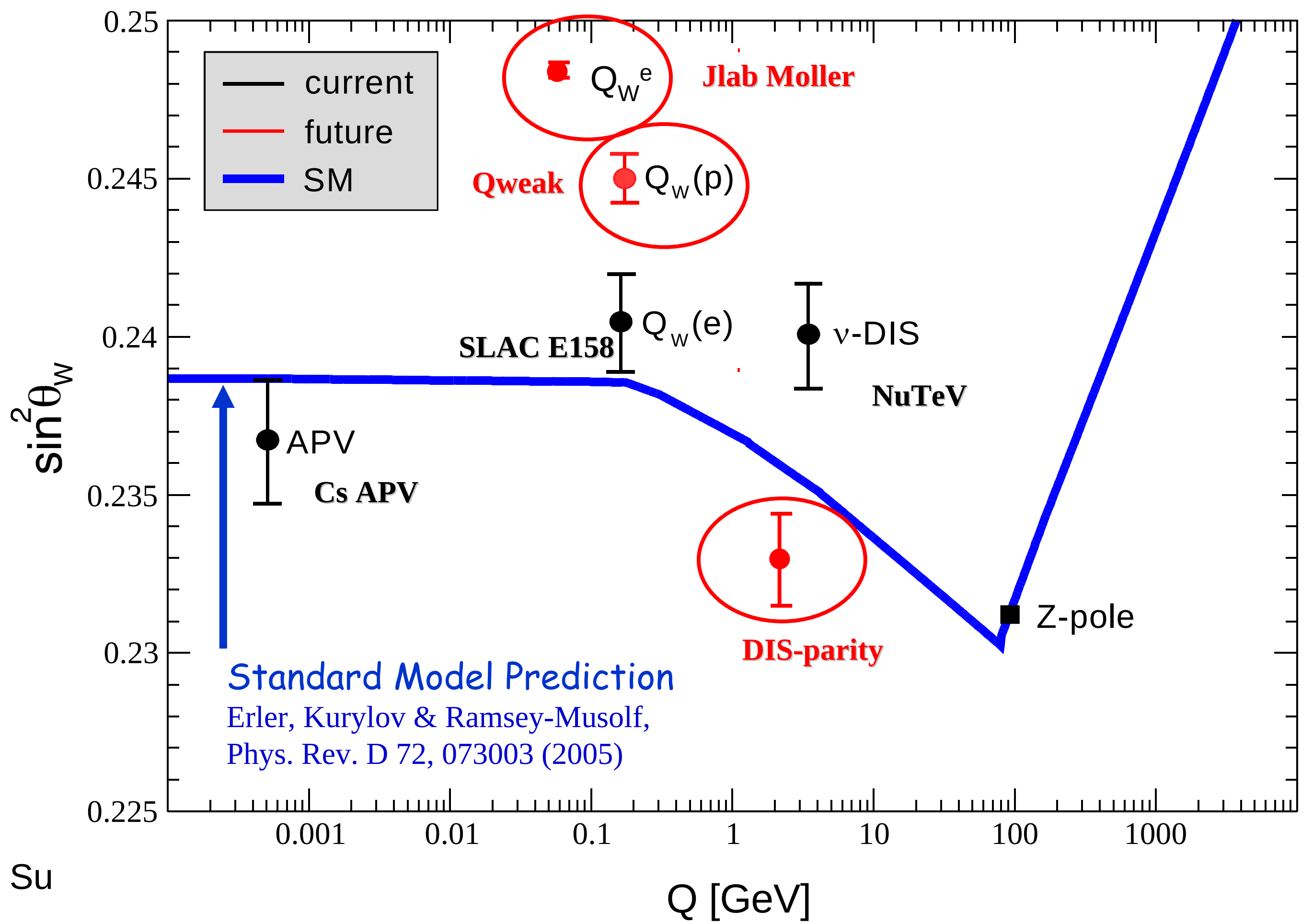
- Quark scattering (from nucleus)
- Weak charged and neutral current difference

Courtesy of P. Reimer and R. Arnold

Test of $\sin^2\theta_W$ running

Weak mixing angle $\sin\theta_W$

$g \sin\theta_W = g' \cos\theta_W = e$



Precision of $\sin^2\theta_W$ determination

Measurement	$\Delta\sin^2\theta_W/\sin^2\theta_W$	$\Delta\sin^2\theta_W$
Z-pole	0.07%	0.00016
0.5% $Q_w(Cs)$	0.7%	0.0016
NuTeV	0.7%	0.0016
13.1% $Q_w(e)^{SLAC}$	0.5%	0.0013
2.5% $Q_w(e)^{Jlab}$	0.1%	☆ 0.00025 (on par with Z pole)
4% $Q_W(p)$	0.3%	0.00072
0.8% DIS-parity	0.45%	0.0011

Talk by D. Mack

Talk by K. Paschke

Sensitivity to new physics scale

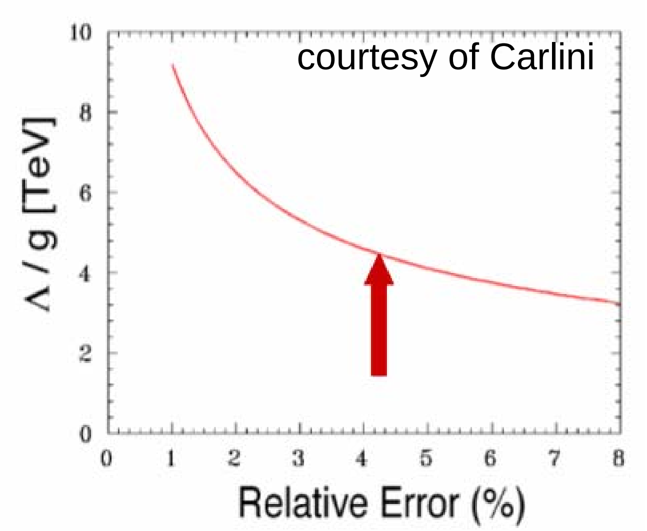
$$L_{eq}^{\mathrm{PV}} = L_{\mathrm{SM}}^{\mathrm{PV}} + L_{\mathrm{new}}^{\mathrm{PV}} = -\frac{G_\mu}{2\sqrt{2}}\bar{e}\gamma_\mu\gamma_5 e \sum_q Q_W^q \bar{q}\gamma^\mu q + \frac{g^2}{4\Lambda^2}\bar{e}\gamma_\mu\gamma_5 e \sum_q h_V^q \bar{q}\gamma^\mu q$$

Ramsey-Musolf(1999)

Λ: new physics scale **O(1)**

Take $\delta\ Q_W^p$=4%

$$\frac{\Lambda}{g} \sim \frac{1}{\sqrt{\sqrt{2}G_F|\delta Q_W^p|}} \sim 4.6\mathrm{TeV}$$



- **probe new physics scale comparable to LHC**
- **confirmation of LHC discovery (couplings, charges)**

NC exp as a indirect probe of new physics

SM is a low energy approximation of a more fundamental theory

- SUSY: minimal Supersymmetric extension of SM (MSSM)

  each SM particle ⟷ (spin differ by ½) superpartner

  - with R-parity : loop corrections
  - without R-parity: tree-level contribution
- extra Z'
  - exists in extension of SM
  - constraints from Z-pole observable (mix with Z)
- leptoquark
- extra-dimension …

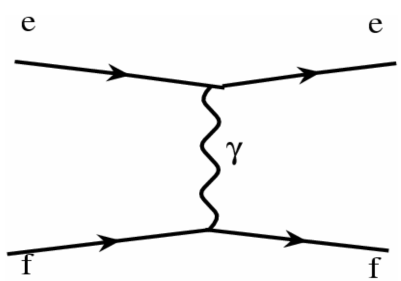
Misc. model sensitivities (non-SUSY)

Courtesy of D. Mack

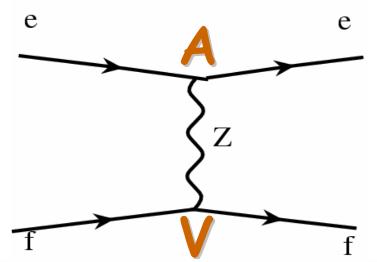
Experiment	Z' $M(Z_X)$ (TeV)	Z' $M(Z_{LR})$ (TeV)	Leptoquarks $M_{LQ}(up)$ (TeV)	Leptoquarks $M_{LQ}(down)$ (TeV)	Compositeness (LL) e-q (TeV)	Compositeness (LL) e-e (TeV)
Colliders (LEP2, CDF, Hera)	.67	.80	"1.5"	"1.5"		
0.5% $Q_w(Cs)$ exists!	1.2	★1.3	★4.0	3.8	★ 28	---
13.1% $Q_w(e)$ exists!	.66	.34	---	---	---	13
2.5% $Q_w(e)$	★1.5	.77	---	---	---	★29
4% $Q_w(p)$ under construction	.95	.45	3.1	★ 4.3	★ 28	----

scaled from R-Musolf, PRC 60 (1999), 015501 **Collider limits from Erler and Langacker, hep-ph/0407097**

Moller and Qweak



$$\mathcal{L}_{PC} = \frac{e^2}{q^2} Q_e Q_f \bar{e}\gamma^\mu e \bar{f}\gamma_\mu f$$



$$\mathcal{L}_{PV} = \frac{G_\mu}{\sqrt{2}} g_A^e Q_W^f \bar{e}\gamma^\mu\gamma_5 e \bar{f}\gamma_\mu f$$

weak charge $Q_W^f = 2g_V^f = 2\, I_3^f - 4Q_f s^2$

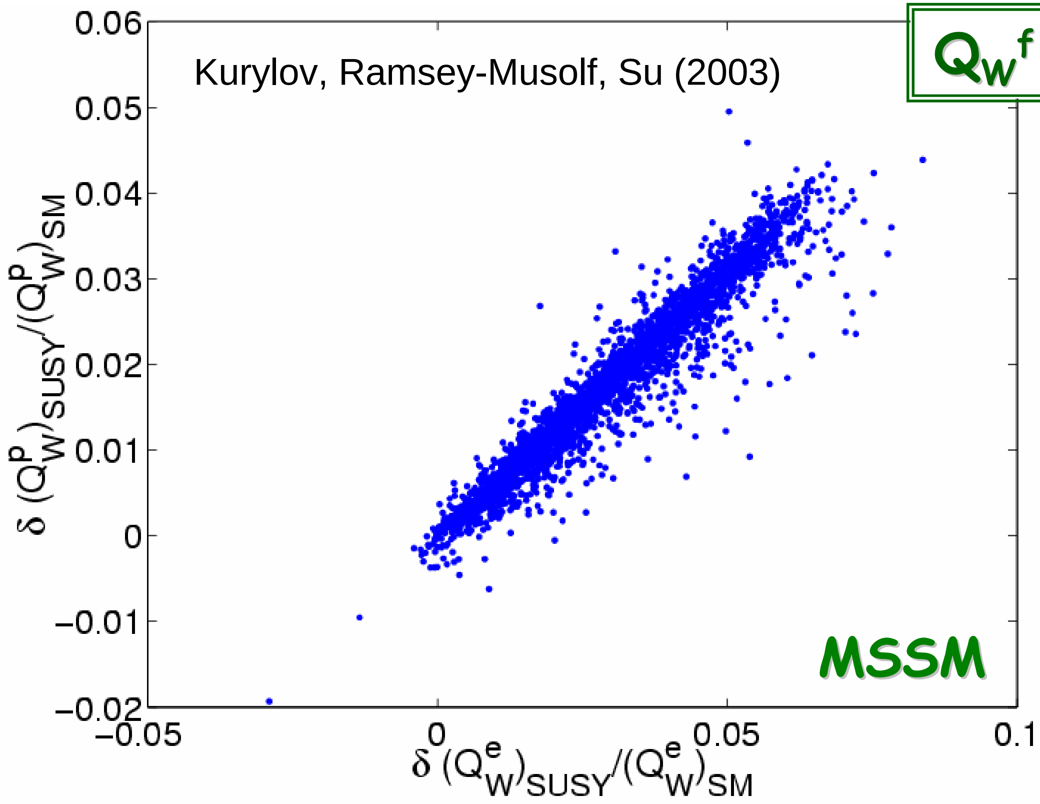
$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} \propto Q_W^f$$

Moller and Qweak

	Q_W^p (Qweak)	Q_W^e (SLAC)	Q_W^e (Jlab)
$Q_W^{e,p}$ tree	$1-4s^2$	$-(1-4s^2)$	
$Q_W^{e,p}$ loop	0.0721	-0.0449	
q^2	0.03 GeV^2	0.026 GeV^2	0.008 GeV^2
A_{LR}	-0.29 ppm	-0.131 ppm	-0.04 ppm
exp precision	4%	13%	2.5%
$\delta \sin^2\theta_W$	0.0007	0.0013	0.00025

- ✓ clean environment: Hydrogen target
- ✓ theoretically clean: small hadronic uncertainties
- ✓ tree level ~ 0.1 $\Rightarrow$ sensitive to new physics

MSSM correction to weak charge



$Q_W^f = \rho\,(2T^f_3 - 4Q_f\,\kappa\,s^2) + \lambda_f$

- Q_W^e and Q_W^p correlated

dominant : $\delta\kappa$ (<0)

$\Rightarrow$

negative shift in $\sin^2\theta_W$

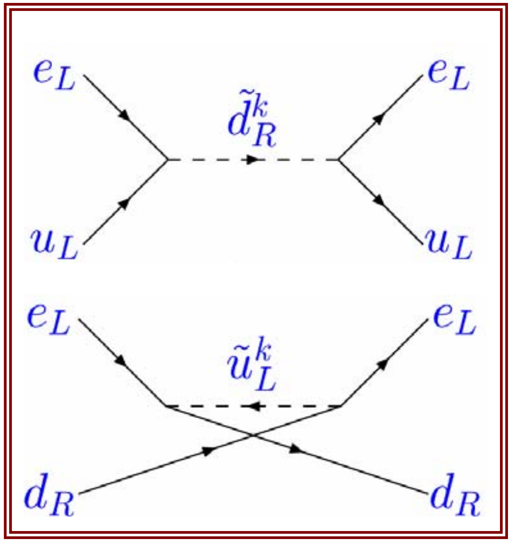
$\delta\,(Q_W^p)_{SUSY}\,/\,(Q_W^p)_{SM} < 4\%$, $\delta\,(Q_W^e)_{SUSY}\,/\,(Q_W^e)_{SM} < 8\%$

R-parity violating (RPV)

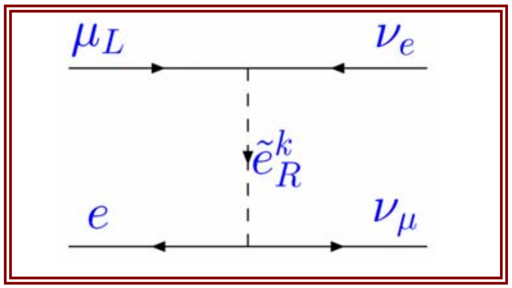
- RPV operators contribute to $Q_W^{e,p}$ at tree level

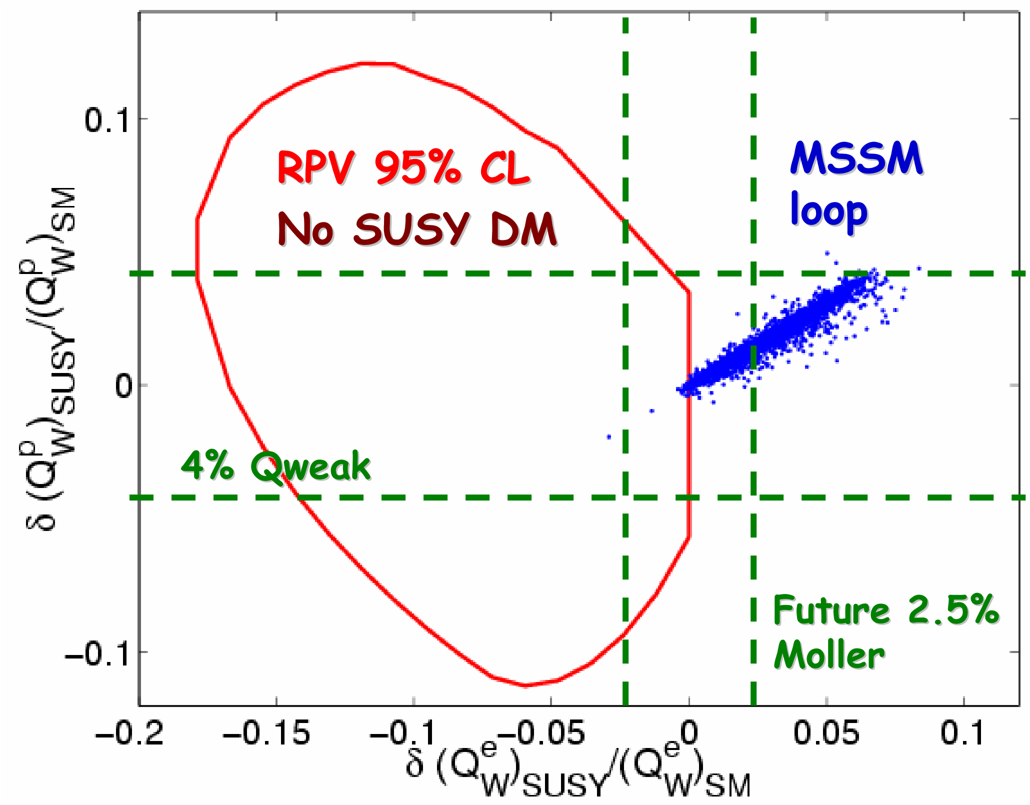
Kurylov, Ramsey-Musolf, Su (2003)

δQ^p_W



G_μ

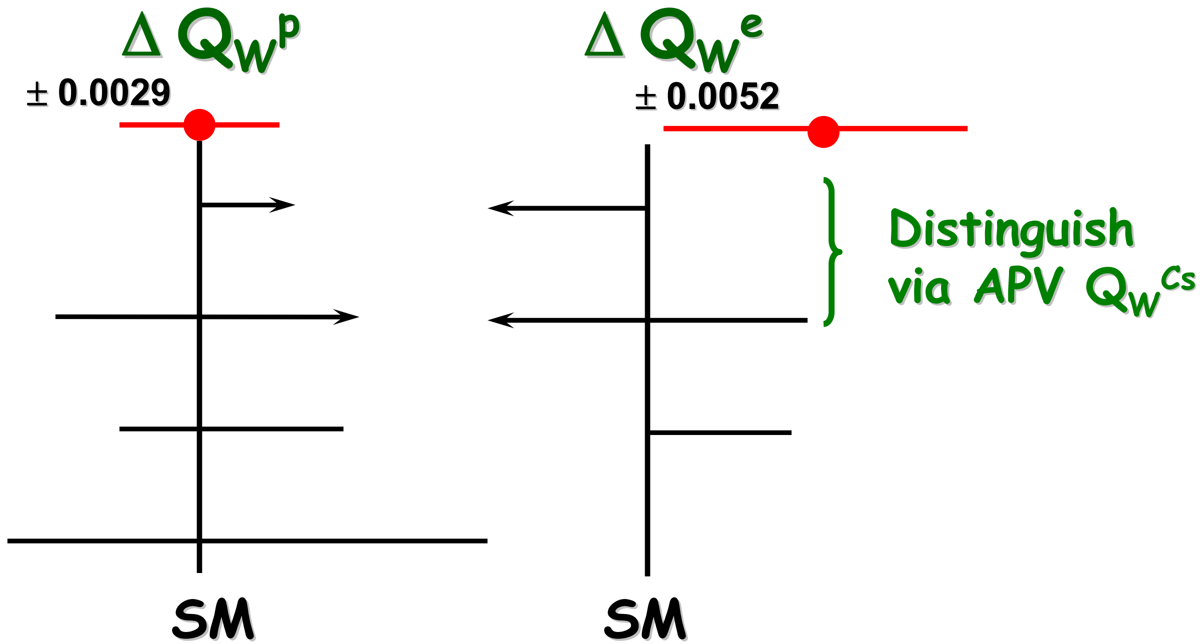




Correlation between Q_W^p , Q_W^e

- Distinguish new physics — Erler, Kurylov and Ramsey-Musolf (2003)

- exp
- MSSM:
- extra Z':
- RPV SUSY
- leptoquark



Combinations of NC exps could be used to distinguish various new physics

Extract Q_W^p

use kinematics to simplify: at forward angle θ

$$A_{LR} = \frac{G_\mu}{4\sqrt{2}\pi\alpha} q^2 \left[Q_W^p + F(\theta, q^2) \right]$$

Musolf et. al., (1994)

?

$$F \sim \frac{q^2}{4m_p^2}(1+\mu_p)\mu_n + \text{stange quarks } \mathcal{O}(q^2) + \mathcal{O}(q^4)$$

- measure $F(\theta,q^2)$ over finite range in q^2, extrapolate F to small q^2
  existing PVES: SAMPLE, HAPPEX, G0, A4
- minimize effect of F by making q^2 small
- $q^2 \sim 0.03$ GeV^2, still enough statistics
  $\Rightarrow \delta Q^p_W / Q^p_W \mid_{\text{hadronic effects}} \approx 2\ \%$

QCD correction to ep scattering

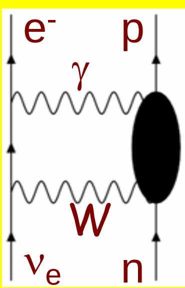
Box diagram contribution to Q_W^P

Erler, Kurylov and Ramsey-Musolf (2003)

$$\mathrm{box}_{\gamma Z} = \frac{5\alpha}{2\pi}(1-4s^2)\left[\ln\left(\frac{m_Z^2}{\Lambda^2}\right) + C_{\gamma Z}(\Lambda)\right]$$

suppression non-calculable

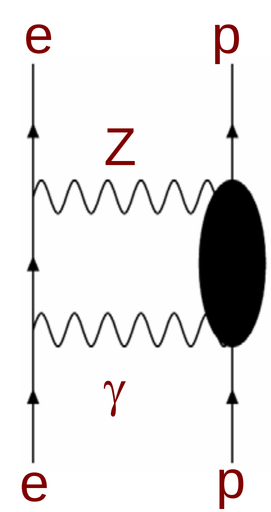
Similar to nuclear β-decay

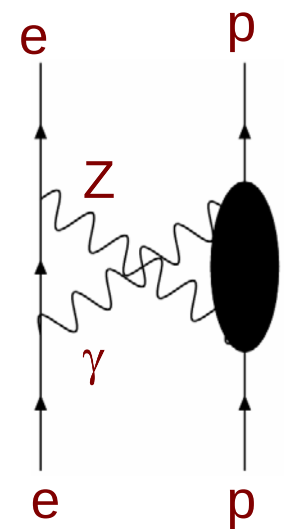


$$= \frac{G_F}{\sqrt{2}}\frac{\alpha}{2\pi}\left[\ln\left(\frac{m_W^2}{\Lambda^2}\right) + C_{\gamma W}(\Lambda)\right]$$

$|C_{\gamma W}| < 2$ (CKM unitarity)

$|C_{\gamma Z}| < 2$ → 0.65%





6%

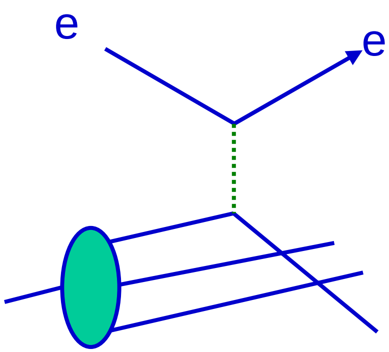
$\Lambda_{QCD} < k_{loop} < O(m_Z)$

non-perturbative

Total theoretical uncertainty ~ 0.8%

DIS-parity: eD scattering

Longitudinally polarized electrons on unpolarized deuterium target — Cahn and Gilman, PRD 17 1313 (1978).



$$A_d = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$

$$= -\left(\frac{3G_\mu Q^2}{\pi\alpha 2\sqrt{2}}\right)\frac{2C_{1u} - C_{1d}[1 + R_s(x)] + Y\,(2C_{2u} - C_{2d})\,R_v(x)}{5 + R_s(x)}$$

$$Y \approx -\left(\frac{3G_\mu Q^2}{\pi\alpha 2\sqrt{2}}\right)\frac{2C_{1u} - C_{1d} + Y\,(2C_{2u} - C_{2d})}{5}$$

$$\frac{2s(x)}{x) + d(x)} \xrightarrow{\text{large x}} 0$$

$$R(x, Q^2) = \sigma_L/\sigma_T \approx 0.2 \qquad R_v(x) = \frac{u_v(x) + d_v(x)}{} \xrightarrow{\text{large x}} 1$$

$$\mathcal{L}_{\rm PV}^{eq} = \frac{G_\mu}{\sqrt{2}}\sum_q [C_{1q}\bar{e}\gamma^\mu\gamma_5 e\bar{q}\gamma_\mu q + C_{2q}\bar{e}\gamma^\mu e\bar{q}\gamma_\mu\gamma_5 q]$$

Sensitivity to $\sin^2\theta_W$

$$C_{1u} = -\frac{1}{2} + \frac{4}{3}\sin^2(\theta_W) \approx -0.19, \quad C_{1d} = \frac{1}{2} - \frac{2}{3}\sin^2(\theta_W) \approx 0.35,$$

$$C_{2u} = -\frac{1}{2} + 2\sin^2(\theta_W) \approx -0.04, \quad C_{2d} = \frac{1}{2} - 2\sin^2(\theta_W) \approx 0.04.$$

$$\text{with } \sin^2(\theta_W) \approx 0.23$$

$$A_d \approx 10^{-4}Q^2\left[\frac{3}{2}(1+Y) - \left(\frac{10}{3} + 6Y\right)\sin^2(\theta_W)\right]$$

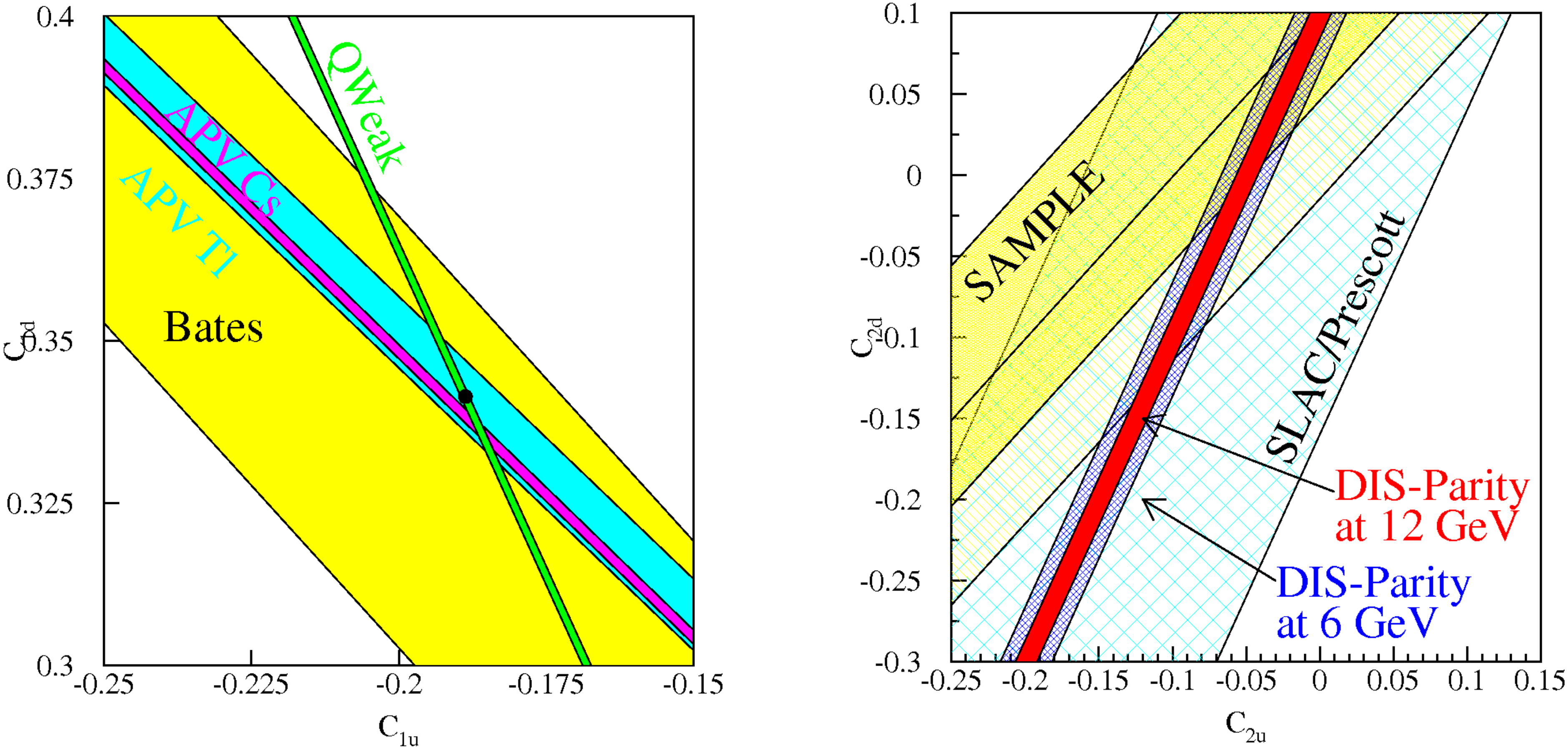
Large asymmetry

Q^2 = 3.7 GeV^2, A_d = 0.0003

"Easy experiment"

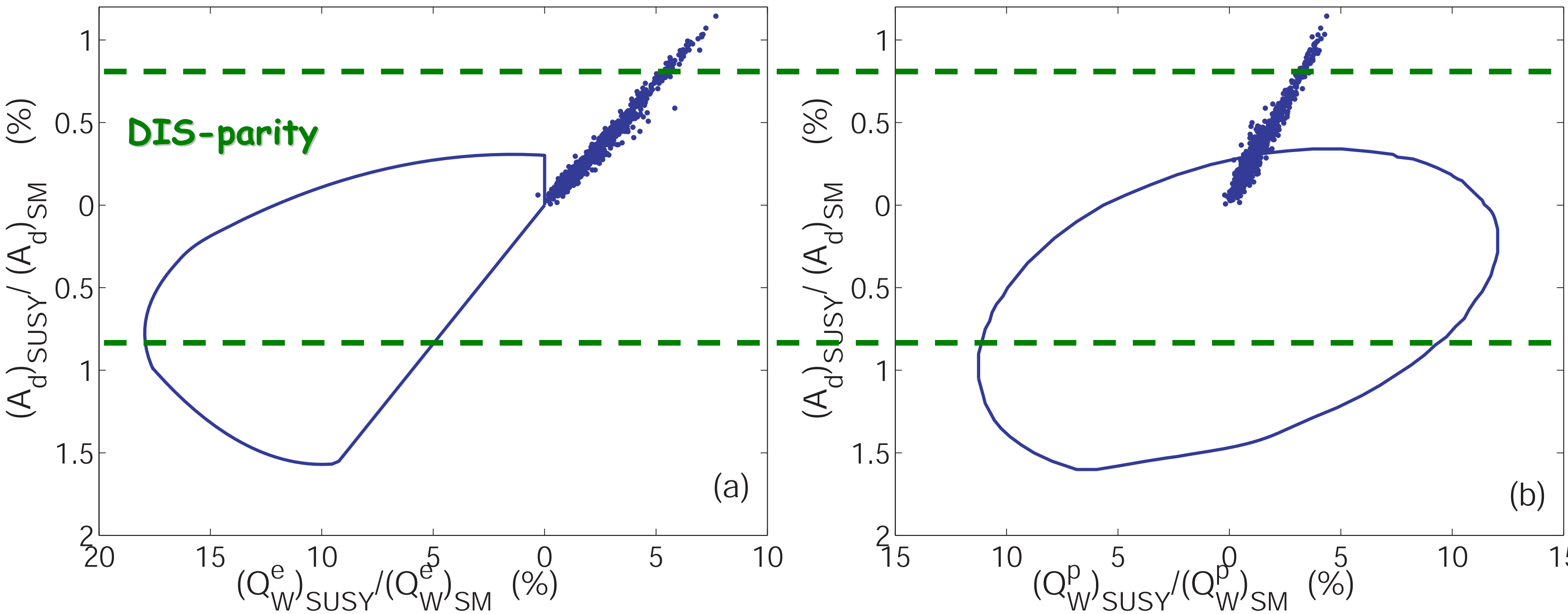
$\delta A_d/A_d = 0.8\% \rightarrow \delta \sin^2\theta_W/\sin^2\theta_W = 0.45\%$

Ranges of C_{1u}, C_{1d}, C_{2u}, C_{2d}



Courtesy of P. Reimer

SUSY contributions



Atomic parity violation

Two approaches

- rotation of polarization plane of linearly polarized light
- apply external E field $\Rightarrow$ parity forbidden atomic transition

Boulder group: cesium APV 0.35% exp uncertainty wood et. Al. (1997)

$$n'P_{1/2} \rightarrow nS_{1/2} \sim \frac{G_F}{2\sqrt{2}} C_{SP}(Z) Q_W(Z,N) + \ldots$$

atomic structure

1% Blundell et. al. (1990, 1992)

Dzuba et. Al. (1989)

$\Rightarrow$ reduced error 0.6% (exp + theory)

via transition dipole amplitude measurement

Bennett and Wieman (1999)

+ 2.5 σ deviation (2002)

- Breit interaction ⇩ Derevianko (2000), Dzuba et. al. (2001)
- Uehling potential ⇧ Johnson et. al. (2001), Milstein et. al. (2002)
- QED self-energy and vertex ⇩

Dzuba et. Al. (2002), Kuchiev and Flambaum (2002), Milstein et. al. (2002)

$Q_W(Z,N)=(2Z+N)Q_W^u+(Z+2N)Q_W^d$

finite nuclear size

nucleon substructure

nuclear spin-dependent term

$\delta \sim \pm 0.15\%$

Pollock and Wieman (2001)

Q_W^{Cs} (exp) = -72.65 ± 0.48 Q_W^{Cs}(SM)=-72.09 (3) agree

03)

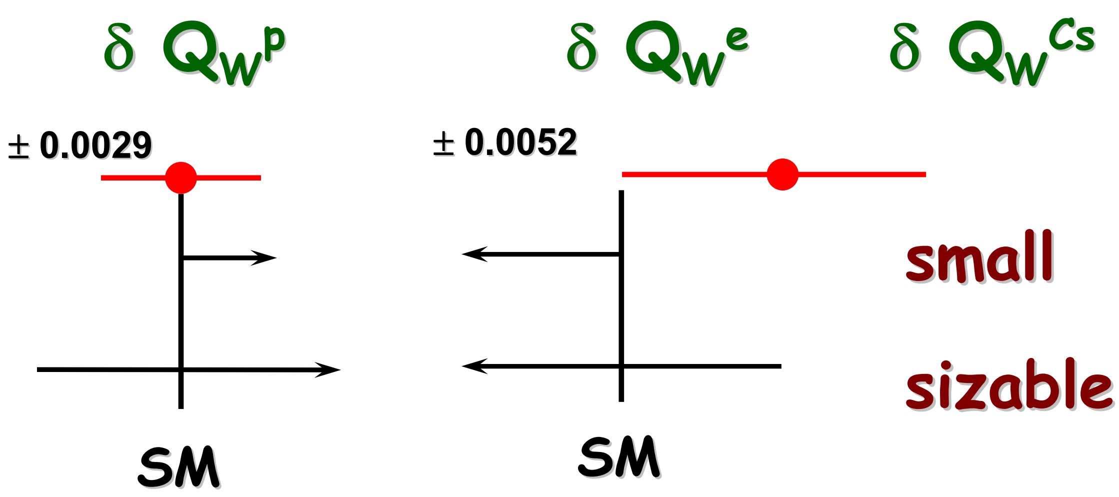
Sensitivity to new physics

➢ Distinguish new physics

- $\delta Q_W(Z,N)=(2Z+N)\,\delta Q_W^u+(2N+Z)\,\delta Q_W^d$

MSSM: $\delta Q_W^u>0$, $\delta Q_W^d<0$ $\Rightarrow$ $\delta Q_W(Z,N)/Q_W(Z,N)<0.2\,\%$ for Cs

- exp
- MSSM:
- extra Z':



Erler, Kurylov and Ramsey-Musolf (2003)

Outlook -- APV

- Paris group: more precise Cs APV
- Seattle group: Ba^+ APV $6S_{1/2} \rightarrow 5D_{3/2}$
- Berkeley group: isotope Yb APV

eliminate large atomic structure theory uncertainties

Ramsey-Musolf(1999)

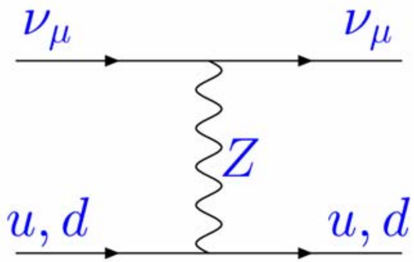
$$\mathcal{R}_1 = \frac{Q_W(N') - Q_W(N)}{Q_W(N') + Q_W(N)} \approx \frac{N' - N}{N' + N}$$

0.2% uncertainties

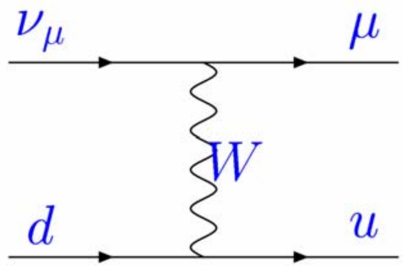
comparable to Q_W^p in sensitivity to new physics

NuTeV experiment

NC



CC



$$\mathcal{L} = -\frac{G_\mu}{\sqrt{2}}\bar{\nu}\gamma^\mu(1-\gamma^5)\nu \times (\epsilon_L^f \bar{f}\gamma_\mu(1-\gamma^5)f + \epsilon_R^f \bar{f}\gamma_\mu(1+\gamma^5)f)$$

$g_{L,R}^2 = (\varepsilon^u_{L,R})^2 + (\varepsilon^d_{L,R})^2$

$$R_\nu = \frac{\sigma_{\nu N}^{NC}}{\sigma_{\nu N}^{CC}} = \frac{\sigma(\nu_\mu N \to \nu_\mu X)}{\sigma(\nu_\mu N \to \mu^- X)} = g_L^2 + r g_R^2 \qquad R_{\bar{\nu}} = \frac{\sigma_{\bar{\nu} N}^{NC}}{\sigma_{\bar{\nu} N}^{CC}} = \frac{\sigma(\bar{\nu}_\mu N \to \bar{\nu}_\mu X)}{\sigma(\bar{\nu}_\mu N \to \mu^+ X)} = g_L^2 + \bar{r} g_R^2$$

$$r \sim \frac{1}{\bar{r}} \sim \frac{\sigma_{\bar{\nu} N}^{CC}}{\sigma_{\nu N}^{CC}} \sim \frac{1}{2}$$

$\delta R^\nu = -0.0033 \pm 0.0015 \quad \delta R^{\bar{\nu}} = -0.0019 \pm 0.0026$

- exp fit: $(g_L^{eff})^2 = 0.3005 \pm 0.0014$, $(g_R^{eff})^2 = 0.0310 \pm 0.0011$
- SM EW fit: $(g_L^{eff})^2 = 0.3042$, $(g_R^{eff})^2 = 0.0301$

NuTeV anomaly

$$g_L^2 = \epsilon_L(u)^2 + \epsilon_L(d)^2 = \frac{1}{2} - \sin^2\theta_W + \frac{5}{9}\sin^4\theta_W \qquad g_R^2 = \epsilon_R(u)^2 + \epsilon_R(d)^2 = \frac{5}{9}\sin^4\theta_W$$

- **exp fit (ρ=1): $\sin^2\theta_W^{\text{on-shell}} = 0.2277 \pm 0.0016$**
- **SM fit to Z-pole: $\sin^2\theta_W^{\text{on-shell}} = 0.2227 \pm 0.00037$ (3 σ away)**

To explain NuTeV anomaly

- **nuclear shadowing**
  Miller and Thomas (2002), Zeller et. Al. (2002), Kovalenkov, schmidt and Yang (2002)
- **asymmetry in strange sea distribution**
  Davidson, Forte, Gambino, Rius and Strumia (2002), Goncharov et. al. (2001)
- **isospin symmetry breaking**
  Bodek et. al. (1999), Zeller et. Al. (2002)
- **QCD corrections**
  Dobrescu and Ellis (2003), Kretzer et. al. (2003), Davidson et. al. (2002)

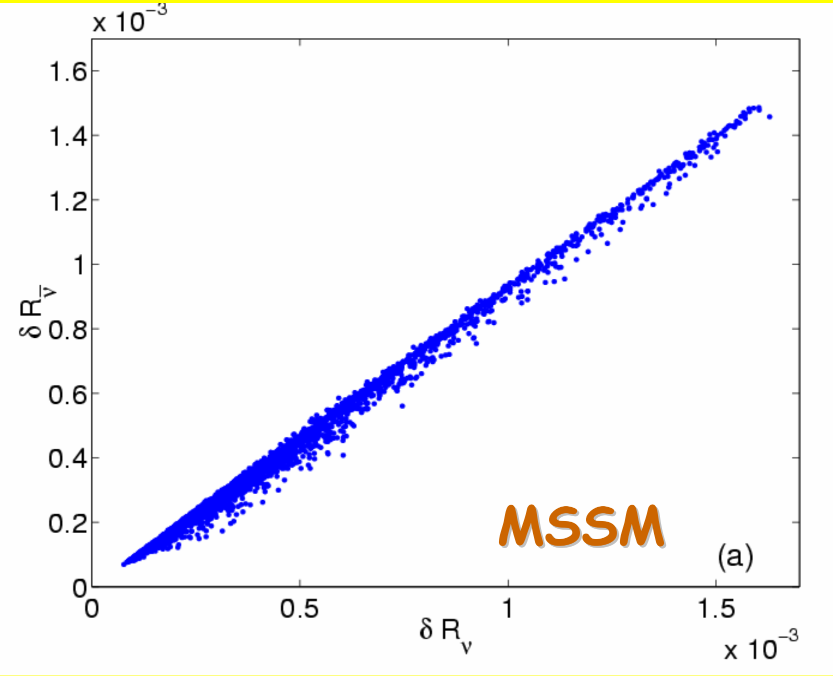
...

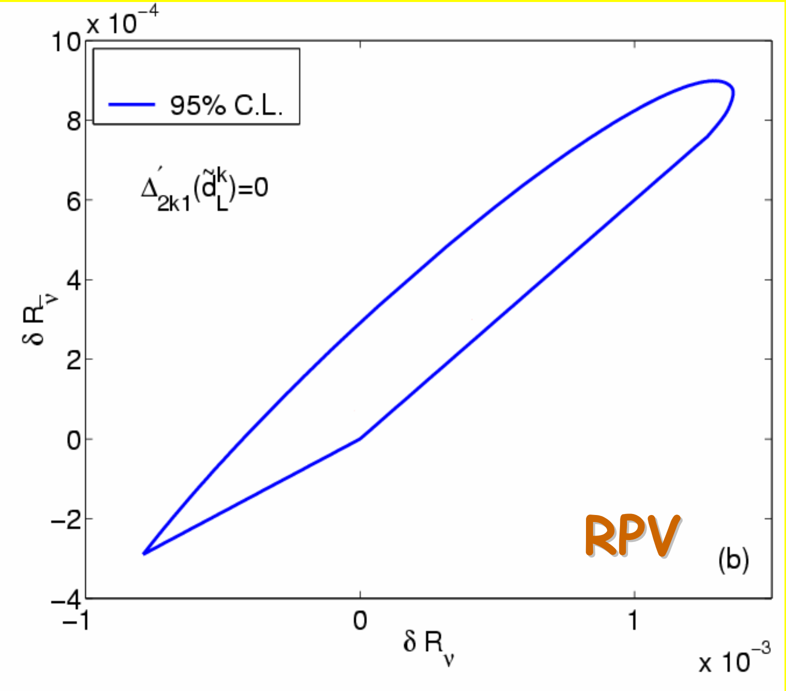
New physics explanation

Difficult !

- **Supersymmetry:** $\delta R_{\nu, \bar{\nu}} > 0$

Kurylov, Ramsey-Musolf, Su (2003), Davidson, Forte, Gambino, Rius and Strumia (2002)





Conclusion

- precision measurements of $\sin^2\theta_W$ at low energy
  - PV ee, ep scattering (E158, Jlab Moller, Qweak)
  - eD DIS-parity
  - APV measurements
  - NuTeV
- consistency check of SM
- sensitive to new physics
  complementary to direct searches
- combinations of several exp
  $\Rightarrow$ distinguish various new physics
- uncertainties caused by QCD
  - extract from experimental measurements
  - SM predictions

Talks in this workshop

Talk in parity violation

- **K. Paschke: DIS-parity**
- **D. Mack: Moller Parity**