Probing Supersymmetry with Parity-Violating Lepton Scattering

Shufang Su • U. of Arizona

based on work with A. Kurylov, M. Ramsey-Musolf

S. Su
Direct vs. indirect detection

- provide complementary information
- success of SM
- consistency check of any new physics scenario

**LEP EWWG July 2010**

S. Su
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:** \((\alpha/\pi)(M/M_{\text{new}})^2\)

- **muon g-2:** \(M=m_\mu\), \(\delta_{\text{new}} \sim 2 \times 10^{-9}\), \(\delta_{\text{exp}} < 10^{-9}\)
- **\(\beta\)-decay, \(\pi\)-decay:** \(M=m_W\), \(\delta_{\text{new}} \sim 10^{-3}\), \(\delta_{\text{exp}} \sim 10^{-3}\)
- **parity-violating electron scattering:** \(M=m_W\), \(\delta_{\text{new}} \sim 10^{-3}\)

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

- \(Q_{W}\)\(^{e,p} \sim 1 - 4 \sin^2 \theta_W \sim 0.1\)

- **1/\(Q_{W}\)\(^{e,p} \approx 10\) more sensitive to new physics**
- **need \(\delta_{\text{exp}} \sim 10^{-2}\) “easier” experiment**

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

S. Su
Neutral current experiments

• Determination of $\sin^2 \theta_{\text{eff}}$

• Neutral current measurements
  ➔ PVES
  ➔ PVDIS
  ➔ APV
  ➔ NuTeV
Neutral current experiments

- Determination of $\sin^2 \theta_{\text{eff}}$
- Neutral current measurements
  - PVES
  - APV
  - PVDIS
  - NuTeV

William J. Marciano, “Overview of the weak mixing angle”
Michael J. Ramsey-Musolf, “Physics beyond the SM and the Precision Frontier”
Wally Melnitchouk, “SM correction to parity-violating electron scattering”
Ian C. Cloet, “Theoretical Interpretation of neutrino/antineutrino scattering”
Weifu Chang, “Physics beyond the SM; Sensitivities of PVLS”

Krishna S. Kumar, “Low energy test of SM: experimental overview”
APV talks by Andrei Derevianko, Justin Torgerson, Lorenz Willmann, Eduardo Gomez-Garxia,
Maarten de Kieviet, Thomas Stoehlker
Møller Scattering

• Purely Leptonic

\[ \text{Q-Weak (JLab)} \]

\[ e + e \rightarrow e + e + \gamma + Z \]

\[ \text{Coherent quarks in } p \]

\[ \text{in operation now} \]

\[ 2(2C_{1u} + C_{1d}) \]

DIS-Parity

\[ e + \gamma + Z \rightarrow e + e + \gamma + Z \]

• Isoscaler quark scattering

\[ (2C_{1u} - C_{1d}) + Y(2C_{2u} - C_{2d}) \]

Atomic Parity Violation

• Coherent quarks in entire nucleus

\[ \text{Neutrino Scattering} \]

\[ \nu + Z \rightarrow \nu + \mu + W \]

• Quark scattering (from nucleus)

\[ \text{Weak charged and neutral current difference} \]

\[ -376 C_{1u} - 422 C_{1d} \]

S. Su

Courtesy of P. Reimer and R. Arnold
Test of $\sin^2\theta_W$ running

**Weak mixing angle** $\sin\theta_W$

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

Plot you have seen 10 times in this meeting
### Precision of $\sin^2\theta_W$ determination

<table>
<thead>
<tr>
<th>Measurement</th>
<th>$\Delta\sin^2\theta_W/\sin^2\theta_W$</th>
<th>$\Delta\sin^2\theta_W$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Z-pole</strong></td>
<td>0.07%</td>
<td>0.00017</td>
</tr>
<tr>
<td>0.5% $Q_w$ (Cs)</td>
<td>0.6%</td>
<td>0.0013</td>
</tr>
<tr>
<td><strong>NuTeV</strong></td>
<td>0.7%</td>
<td>0.0016</td>
</tr>
<tr>
<td>13.1% $Q_w$ (e)$^{\text{SLAC}}$</td>
<td>0.5%</td>
<td>0.0013</td>
</tr>
<tr>
<td>4% $Q_w$ (p)</td>
<td>0.3%</td>
<td>0.00072</td>
</tr>
<tr>
<td>2.1% $Q_w$ (e)$^{\text{Jlab}}$</td>
<td>0.1%</td>
<td>0.00026                          (on par with Z pole)</td>
</tr>
<tr>
<td>0.76% (0.5%) $\text{PVDIS}$</td>
<td>0.45% (0.28%)</td>
<td>0.0011 (0.0006)</td>
</tr>
<tr>
<td><strong>reactor based $\nu_e$ e scattering</strong></td>
<td>1%</td>
<td>0.0025</td>
</tr>
</tbody>
</table>

S. Su

Tuesday, November 9, 2010
Sensitivity to new physics scale

\[ L_{eq}^{PV} = L_{SM}^{PV} + L_{new}^{PV} = -\frac{G_{\mu}}{2\sqrt{2}} \bar{e} \gamma_{\mu} \gamma_5 e \sum_{q} Q_{W}^{q} \bar{q} \gamma_{\mu} q + \frac{g^2}{4\Lambda^2} \bar{e} \gamma_{\mu} \gamma_5 e \sum_{q} h_{\nu}^{q} \bar{q} \gamma_{\mu} q \]

\( \Lambda: \text{new physics scale} \quad O(1) \)

Ramsey-Musolf(1999)

Take \( \delta Q_{W}^{p} = 4\% \)

\[ \frac{\Lambda}{g} \sim \frac{1}{\sqrt{2} G_{F} |\delta Q_{W}^{p}|} \sim 4.6 \text{ TeV} \]

courtesy of Carlini

- probe new physics scale comparable to LHC
- confirmation of LHC discovery (couplings, charges)
## Misc. model sensitivities (non-SUSY)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$M(Z')$ $M(Z_{LR})$ (TeV)</th>
<th>Leptoquarks $M_{LQ}(up)$ $M_{LQ}(down)$ (TeV)</th>
<th>Compositeness (LL) $e$-$q$ $e$-$e$ (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>direct limits</td>
<td>0.69 0.63</td>
<td>0.3 0.3</td>
<td>---  ---</td>
</tr>
<tr>
<td>EW fit</td>
<td>0.78 0.86</td>
<td>1.5 1.5</td>
<td>11-26 8-10</td>
</tr>
<tr>
<td>0.5% $Q_w$(Cs)</td>
<td>1.2 ★1.3</td>
<td>★4.0 3.8</td>
<td>★28  ---</td>
</tr>
<tr>
<td>13.1% $Q_w$(e)</td>
<td>0.66 0.34</td>
<td>---  ---</td>
<td>---  13</td>
</tr>
<tr>
<td>4% $Q_w$(p)</td>
<td>0.95 0.45</td>
<td>3.1 ★4.3</td>
<td>★28  ---</td>
</tr>
<tr>
<td>2.5% $Q_w$(e)</td>
<td>★1.5 0.77</td>
<td>---  ---</td>
<td>---  ★29</td>
</tr>
</tbody>
</table>

Scaled from R-Musolf, PRC 60 (1999), 015501

Collider limits from Erler and Langacker, hep-ph/0407097

S. Su
SM is a low energy approximation of a more fundamental theory

- **SUSY**: minimal Supersymmetric extension of SM (MSSM)
  - each SM particle \( \leftrightarrow \) 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 ...**
Moller and Qweak

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

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

\( Q_W^f = 2 g_V^f = 2 I_3^f - 4 Q_f s^2 \)

\( A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} \propto Q_W^f \)
### Moller and Qweak

<table>
<thead>
<tr>
<th></th>
<th>$Q_{W}^{e,p}$ (Qweak)</th>
<th>$Q_{W}^{e}$ (SLAC)</th>
<th>$Q_{W}^{e}$ (Jlab)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_{W}^{e,p}$ tree</td>
<td>1-4$s^2$</td>
<td>-(1-4$s^2$)</td>
<td></td>
</tr>
<tr>
<td>$Q_{W}^{e,p}$ loop</td>
<td>0.0713</td>
<td>-0.0449</td>
<td></td>
</tr>
<tr>
<td>$q^2$</td>
<td>0.03 GeV$^2$</td>
<td>0.026 GeV$^2$</td>
<td>0.008 GeV$^2$</td>
</tr>
<tr>
<td>$A_{LR}$</td>
<td>-0.29 ppm</td>
<td>-0.131 ppm</td>
<td>-0.04 ppm</td>
</tr>
<tr>
<td>exp precision</td>
<td>4%</td>
<td>13%</td>
<td>2.1%</td>
</tr>
<tr>
<td>$\delta \sin^{2}\theta_{W}$</td>
<td>0.0007</td>
<td>0.0013</td>
<td>0.00026</td>
</tr>
</tbody>
</table>

- **clean environment**: Hydrogen target
- **theoretically clean**: small hadronic uncertainties
- **tree level ~ 0.1** ⇒ sensitive to new physics
\[ Q_W^f = \rho [2 I_3^f - 4 \kappa Q_f \sin^2 \theta_W] + \lambda_f \]
\[ Q_W^f = \rho [2 I_3^f - 4 \kappa Q_f \sin^2 \theta_W] + \lambda_f \]
\[ Q^f_W = \rho [2I_3^f - 4\kappa Q_f \sin^2 \theta_W] + \lambda_f \]
SUSY contributions

\[ Q_W^f = \rho [2 I_3^f - 4 \kappa Q_f \sin^2 \theta_W] + \lambda_f \]

**universal**

**universal**

**universal**

**flavor dependent**
$Q_W^f = \rho [2I_3^f - 4\kappa Q_f \sin^2 \theta_W] + \lambda_f$

universal

SUSY contributions

flavor dependent

S. Su
MSSM correction to weak charge

\[ Q_W^f = \rho \left( 2T_f^3 - 4Q_f \kappa s^2 \right) + \lambda_f \]

- \( Q_W^e \) and \( Q_W^p \) correlated
- dominant: \( \delta \kappa < 0 \)
- negative shift in \( \sin^2 \theta_W \)

\[ \delta (Q_W^p)_{\text{SUSY}} / (Q_W^p)_{\text{SM}} < 4\%, \quad \delta (Q_W^e)_{\text{SUSY}} / (Q_W^e)_{\text{SM}} < 8\% \]

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SUSY contributions

\[ Q_{W}^e \]

\[ M_{\text{SUSY}_{\text{other}}} = 1 \text{ TeV} \]

S. Su

Tuesday, November 9, 2010
SUSY contributions

$M_{\text{SUSY}_{\text{other}}} = 1 \text{ TeV}$

S. Su

Tuesday, November 9, 2010
R-parity violating (RPV)

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

### Table IV: 95% C.L. ranges for the $\delta Q_{W}$

<table>
<thead>
<tr>
<th>Quantity</th>
<th>$\Delta'<em>{11k}(d</em>{R}^{k})$</th>
<th>$\Delta'<em>{1k1}(q</em>{L}^{k})$</th>
<th>$\Delta_{12k}(\tilde{q}_{R}^{k})$</th>
<th>$\Delta'<em>{21k}(d</em>{R}^{k})$</th>
<th>$\Delta'<em>{2k1}(d</em>{L}^{k})$</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta</td>
<td>V_{ud}</td>
<td>^{2}/</td>
<td>V_{ud}</td>
<td>^{2}$</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>$\delta Q_{W}^{Cs}/Q_{W}^{Cs}$</td>
<td>-4.82</td>
<td>5.41</td>
<td>0.05</td>
<td>0</td>
<td>0</td>
<td>$-0.0040 \pm 0.0066$</td>
</tr>
<tr>
<td>$\delta R_{e/\mu}$</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>-2</td>
<td>0</td>
<td>$-0.0042 \pm 0.0033$</td>
</tr>
<tr>
<td>$\delta G_{\mu}/G_{\mu}$</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0.00025 $\pm 0.001875$</td>
</tr>
<tr>
<td>$\delta Q_{W}^{e}/Q_{W}^{e}$</td>
<td>0</td>
<td>0</td>
<td>-29.8</td>
<td>0</td>
<td>0</td>
<td>0.14 $\pm 0.11$</td>
</tr>
<tr>
<td>$\delta R_{\nu}$</td>
<td>0</td>
<td>0</td>
<td>-0.21</td>
<td>0.22</td>
<td>0.08</td>
<td>$-0.0033 \pm 0.0007$</td>
</tr>
<tr>
<td>$\delta R_{\bar{\nu}}$</td>
<td>0</td>
<td>0</td>
<td>-0.077</td>
<td>0.132</td>
<td>0.32</td>
<td>$-0.0019 \pm 0.0016$</td>
</tr>
</tbody>
</table>
I) Obtain 95% CL allowed region in RPV coefficients
II) Evaluate $\delta Q_{W}^{e}$ and $\delta Q_{W}^{p}$

FIG. 9: Relative shifts in electron and proton weak charges due to SUSY effects (updated plot from Ref. [142]). Dots indicate MSSM loop corrections for $\sim 3000$ randomly-generated SUSY-breaking parameters. Interior of truncated elliptical regions (a) and (b) give possible shifts due to R-parity non-conserving SUSY interactions (95% confidence), using value of $|V_{ud}|^2$ in Table. III, respectively. The arrows indicate correlated effects. For example, while both the superpartner loops and leptoquark exchange give a positive contribution to the proton weak charge, only MSSM give rise to a sizable effect on the electron weak charge [134, 136]. For the general class of $Z'$ theories based on $E_6$ gauge group, with neutral gauge bosons having mass $\lesssim 1000$ GeV, the effects on $Q_{p}^{W}$ and $Q_{e}^{W}$ also correlate, but $\delta Q_{e,p}^{W} / Q_{e,p}^{W}$ can have either sign in this case [134, 136]. In the case when $E_6 Z'$ models and MSSM have similar effects on the electron and proton weak charge, measurement of the cesium weak charge using atomic parity violation can further tell these two apart, as explained in Sec. V D below.

If we relax the assumption of R-parity conservation, tree level corrections to the weak charges are generated via RPV interactions. In this manner one obtains the following effective four-fermion Lagrangian, using the notation of $\Delta (')_{ijk}$ as defined in Eq. (48):

$$L_{\text{EFF}}^{{\text{RPV}}} = -\Delta'_{1k1} (\tilde{q}_{kL}) \bar{d}_{R} \gamma^{\mu} d_{R} \bar{e}_{L} \gamma^{\mu} e_{L} + \Delta'_{11k} (\tilde{d}_{kR}) \bar{u}_{L} \gamma^{\mu} u_{L} \bar{e}_{L} \gamma^{\mu} e_{L} - \Delta_{2k} (\tilde{e}_{kR}) \left[\bar{\nu}_{\mu L} \gamma^{\mu} \nu_{L} \bar{e}_{L} \gamma^{\mu} e_{L}\right] + \text{h.c.},$$

where we have taken $|q|^2 \ll m^2 \tilde{f}$ and have retained only the terms relevant for the PVES scattering. The last term contributes to the muon decay, which affects the extraction of the fermi constant from the muon decay lifetime. Note the absence from Eq. (166) of the parity-violating contact four-electron interaction. This is because the superpotential in Eq. (12) can only produce parity-conserving contact interactions between identical leptons.
I) Obtain 95% CL allowed region in RPV coefficients
II) Evaluate $\delta Q_{W}^{e}$ and $\delta Q_{W}^{p}$

\[ \frac{\delta (Q_{W})_{\text{SUSY}}}{(Q_{W})_{\text{SM}}} \]

I) Obtain 95% CL allowed region in RPV coefficients
II) Evaluate $\delta Q^e_W$ and $\delta Q^p_W$

**Figure 9**: Relative shifts in electron and proton weak charges due to SUSY effects (updated plot from Ref. [142]). Dots indicate MSSM loop corrections for $\sim 3000$ randomly-generated SUSY-breaking parameters. Interior of truncated elliptical regions (a) and (b) give possible shifts due to R-parity non-conserving SUSY interactions (95% confidence), using value of $|\delta V_{ud}|^2$ in Table. III, respectively.

The arrows indicate correlated effects. For example, while both the superpartner loops and leptoquark exchange give a positive contribution to the proton weak charge, only MSSM give rise to a sizable effect on the electron weak charge [134, 136].

If we relax the assumption of R-parity conservation, tree level corrections to the weak charges are generated RPV interactions. In this manner one obtains the following effective four-fermion Lagrangian, using the notation of $\Delta$ as defined in Eq. (48):

$$L_{EFP} = -\Delta'_{1k1}(\bar{q}_k L)\bar{d}_R \gamma^\mu d_R \bar{e}_L \gamma^\mu e_L + \Delta'_{11k}(\bar{d}_k R)\bar{u}_L \gamma^\mu u_L \bar{e}_L \gamma^\mu e_L + \Delta_{12k}(\bar{e}_k R)\left[\bar{\nu}_\mu L \gamma^\mu \nu_L \bar{e}_L \gamma^\mu e_L + h.c.\right].$$

Where we have taken $|q^2| \ll m^2$ and have retained only the terms relevant for the PVES scattering. The last term contributes to the muon decay, which affects the extraction of the Fermi constant from the muon decay lifetime. Note the absence from Eq. (166) of the parity-violating contact four-electron interaction. This is because the superpotential in Eq. (12) can only produce parity-conserving contact interactions between identical leptons.
Correlation between $Q_{Wp}$, $Q_{We}$

**Distinguish new physics**


$\Delta Q_{Wp} \pm 0.0029$

$\Delta Q_{We} \pm 0.001$

- $\text{exp}$
- $\text{MSSM}$
- extra $Z'$
- RPV SUSY
- leptonquark

Distinguish via APV $Q_{Wc}$
Correlation between $Q_{Wp}$, $Q_{We}$

**Distinguish new physics**

$$\Delta Q_{Wp} \pm 0.0029$$

$$\Delta Q_{We} \pm 0.001$$

- exp
- MSSM
- extra $Z'$
- RPV SUSY
- leptonquark


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

S. Su

Tuesday, November 9, 2010
Distinguish new physics

- \( \delta Q_w (Z,N) = (2Z+N) \delta Q^u_w + (2N+Z) \delta Q^d_w \)

MSSM

- \( \delta Q^u_w > 0 \)
- \( \delta Q^d_w < 0 \) \( \Rightarrow \) \( \delta Q_w(Z,N) / Q_w(Z,N) < 0.2 \% \) for Cs

- \( \delta Q^p_w \) \( \pm 0.0029 \)
- \( \delta Q^e_w \) \( \pm 0.001 \)
- \( \delta Q^c^Cs_w \) small
- \( \delta Q^s_w \) sizable


S. Su
Longitudinally polarized electrons on unpolarized deuterium target

Cahn and Gilman (1978)

\[ A_d = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} \]

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

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

\[ \delta A_d/A_d = 0.76\% \rightarrow \delta \sin^2 \theta_W/\sin^2 \theta_W = 0.45\% \]

\[ \delta A_d/A_d = 0.5\% \rightarrow \delta \sin^2 \theta_W/\sin^2 \theta_W = 0.28\% \]
Ranges of $C_{1u}$, $C_{1d}$, $C_{2u}$, $C_{2d}$

Courtesy of P. Reimer
SUSY contributions

SUSY contributions


PVDIS 0.76%
SUSY contributions

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

\[ g_{L,R}^2 = (\epsilon_{L,R}^u)^2 + (\epsilon_{L,R}^d)^2 \]

\[ R_\nu = \frac{\sigma_{NC}^{\nu N}}{\sigma_{CC}^{\nu N}} = \frac{\sigma(\nu_\mu N \rightarrow \nu_\mu X)}{\sigma(\nu_\mu N \rightarrow \mu^- X)} = g_L^2 + r g_R^2 \]

\[ R_{\bar{\nu}} = \frac{\sigma_{NC}^{\bar{\nu} N}}{\sigma_{CC}^{\bar{\nu} N}} = \frac{\sigma(\bar{\nu}_\mu N \rightarrow \bar{\nu}_\mu X)}{\sigma(\bar{\nu}_\mu N \rightarrow \mu^+ X)} = g_L^2 + \bar{r} g_R^2 \]

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

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

- **exp fit**: \((g_L^{\text{eff}})^2 = 0.3005 \pm 0.0014, (g_R^{\text{eff}})^2 = 0.0310 \pm 0.0011\)

- **SM EW fit**: \((g_L^{\text{eff}})^2 = 0.3042, (g_R^{\text{eff}})^2 = 0.0301\)
**SM QCD effects:**

- **nuclear shadowing**

- **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)
  
  *As we have heard this morning ...*

- **QCD corrections**
  Dobrescu and Ellis (2003), Kretzer et. al. (2003), Davidson et. al. (2002)

...
Difficult!

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

- **Extra Z’**: family non-universal, finetuning
  
  Langacker and Plumacher (2000)

- **Leptoquark**: tune mass splitting
  
  Davidson, Forte, Gambino, Rius and Strumia (2002)

- $\nu_\mu$ mixing with extra heavy neutrino: constraints from other observables
  
  Babu and Pati (2002), Loinaz et. al. (2003)
Difficult!

New physics explanation

- Supersymmetry: \( \delta R^\nu, \nu > 0 \)

- Extra Z': family non-universal, finetuning
  - Langacker and Plumacher (2000)

- Leptoquark: tune mass splitting
  - Davidson, Forte, Gambino, Rius and Strumia (2002)

- \( \nu_\mu \) mixing with extra heavy neutrino:
  - constraints from other observables

MSSM

RPV

Kurylov, Ramsey-Musolf, SS (2002)
Difficult!

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

- **Extra Z'**: family non-universal, finetuning
  Langacker and Plumacher (2000)

- **Leptoquark**: tune mass splitting
  Davidson, Forte, Gambino, Rius and Strumia (2002)

- **$\nu_\mu$ mixing with extra heavy neutrino**: constraints from other observables
  Babu and Pati (2002), Loinaz et. al. (2003)
Conclusion

Precision measurements played an important role in developing and testing SM.

They will be a crucial tool in probing new physics beyond the SM.

Low energy precision measurement can probe new physics not mix with Z (comparing with Z-pole precision observables) precision frontier.

Complementary to what we may learn from LHC.

Opportunities and challenges for both experimentalists and theorists.