Lepton Flavor Violation, Leptogenesis and Neutrino Mixing in QLC scenarios

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- Neutrino Mixing vs. Quark Mixing
- Quark-Lepton Complementarity: $\theta_\odot + \theta_C = \pi/4$
- Scenario 1 for QLC
- Scenario 2 for QLC

K.A. Hochmuth, W.R., hep-ph/0607103

Neutrino Mixing

PMNS matrix parameterized as

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \mathrm{diag}(1, e^{i\alpha}, e^{i(\beta+\delta)})$$

with current limits

$$|U| = \begin{pmatrix} 0.79 \div 0.86 & 0.50 \div 0.60 & 0 \div 0.16 \\ 0.20 \div 0.55 & 0.40 \div 0.73 & 0.61 \div 0.80 \\ 0.21 \div 0.56 & 0.42 \div 0.74 & 0.59 \div 0.79 \end{pmatrix} \quad \text{and } |J_{CP}^{\mathrm{lep}}| \leq 0.037 \quad (\text{at } 2\sigma)$$

$$\begin{pmatrix} 0.76 \div 0.87 & 0.48 \div 0.63 & 0 \div 0.20 \\ 0.13 \div 0.60 & 0.33 \div 0.77 & 0.57 \div 0.82 \\ 0.14 \div 0.61 & 0.35 \div 0.77 & 0.55 \div 0.81 \end{pmatrix} \quad \text{and } |J_{CP}^{\mathrm{lep}}| \leq 0.048 \quad (\text{at } 3\sigma)$$

where $J_{CP}^{\mathrm{lep}} = \mathrm{Im}\left\{U_{e1}\, U_{\mu 2}\, U_{e2}^{*}\, U_{\mu 1}^{*}\right\} = \frac{1}{8}\, \sin 2\theta_{12}\, \sin 2\theta_{23}\, \sin 2\theta_{13}\, \cos\theta_{13}\, \sin\delta$

Neutrino Mixing vs. Quark Mixing

"Best-fit matrix":

$$|U| = |U_\ell^\dagger \, U_\nu| = \begin{pmatrix} 0.83 & 0.56 & 0 \\ 0.39 & 0.59 & 0.71 \\ 0.39 & 0.59 & 0.71 \end{pmatrix}$$

M. Maltoni *et al.*, New J. Phys. **6**, 122 (2004), hep-ph/0405172v5

to be compared to CKM matrix

$$V_{\rm CKM} = V_{\rm up}^\dagger \, V_{\rm down} = \begin{pmatrix} 1 - \frac{1}{2}\lambda^2 & \lambda & A\,\lambda^3\,(\rho - i\eta) \\ -\lambda & 1 - \frac{1}{2}\lambda^2 & A\,\lambda^2 \\ A\,\lambda^3\,(1 - \rho + i\eta) & -A\,\lambda^2 & 1 \end{pmatrix}$$

$$\longrightarrow |V_{\rm CKM}| = \begin{pmatrix} 0.9742 & 0.2272 & 0.0039 \\ 0.2272 & 0.9742 & 0.0418 \\ 0.0083 & 0.0418 & 1 \end{pmatrix} \text{ and } J_{CP}^{\rm qua} = A^2\,\lambda^6\,\bar\eta = 3.1 \cdot 10^{-5}$$

CKMfitter Group, Eur. Phys. J. C **41**, 1 (2005); A. Hocker and Z. Ligeti, hep-ph/0605217

Parameterization of PMNS Matrix

Wolfenstein parameterization says: at zeroth order no quark mixing:

$$V_{\rm CKM} = \mathbb{1} + \mathcal{O}(\lambda)$$

Doesn't work for PMNS matrix, need different zeroth order mixing:

$$U = U_{\rm bimax} + \mathcal{O}(\lambda_\nu) \text{ with } U_{\rm bimax} = \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\ -\frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \\ \frac{1}{2} & -\frac{1}{2} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

Small parameter λ_ν defined via

$$U_{e2} = \sqrt{\frac{1}{2}}\,(1-\lambda_\nu) \stackrel{!}{=} 0.56 \Rightarrow \lambda_\nu \simeq 0.21 \text{ or } \lambda_\nu = 0.22^{+0,07,\,0.10}_{-0.07,\,0.11} \text{ at } 2(3)\sigma$$

W.R., Phys. Rev. D **69**, 033005 (2004)

Parameterize further the mass matrix with

$$|U_{e3}| = A_\nu\,\lambda_\nu^n \;,\; |U_{\mu 3}| = \sqrt{\frac{1}{2}}\,(1 - B_\nu\,\lambda_\nu^m)\;,\; \frac{\Delta m^2_\odot}{\Delta m^2_{\rm A}} = C_\nu\,\lambda_\nu^2$$

Quark-Lepton Complementarity

M. Raidal, Phys. Rev. Lett. **93**, 161801 (2004); H. Minakata and A. Y. Smirnov, Phys. Rev. D **70**, 073009 (2004)

$$\theta_{12} + \theta_C = \frac{\pi}{4} \Rightarrow \sin^2\theta_{12} \simeq \frac{1}{2} - \lambda = 0.2805$$

Sometimes second relation

$$\theta_{23} + A\,\lambda^2 = \frac{\pi}{4} \Rightarrow \sin^2\theta_{23} \simeq \frac{1}{2} - A\,\lambda^2 = 0.4583$$

Important point: *CKM and bimaximal*: $\Rightarrow$ (i) $U_\nu = U_{\rm bimax}$ and $U_\ell = V_{\rm CKM}$ or (ii) $U_\ell = U_{\rm bimax}$ and $U_\nu = V_{\rm CKM}$

P. H. Frampton and R. N. Mohapatra, JHEP **0501**, 025 (2005); S. K. Kang, C. S. Kim and J. Lee, Phys. Lett. B **619**, 129 (2005); J. Ferrandis and S. Pakvasa, Phys. Lett. B **603**, 184 (2004); Phys. Rev. D **71**, 033004 (2005); N. Li and B. Q. Ma, Phys. Rev. D **71**, 097301 (2005); K. Cheung *et al.*, Phys. Rev. D **72**, 036003 (2005); Z. Z. Xing, Phys. Lett. B **618**, 141 (2005); C. A. de S. Pires, J. Phys. G **30**, B29 (2004); A. Datta, L. Everett and P. Ramond, Phys. Lett. B **620**, 42 (2005); S. Antusch, S. F. King and R. N. Mohapatra, Phys. Lett. B **618**, 150 (2005); N. Li and B. Q. Ma, Eur. Phys. J. C **42**, 17 (2005); T. Ohlsson, Phys. Lett. B **622**, 159 (2005); D. Falcone, Mod. Phys. Lett. A **21**, 1815 (2006); L. L. Everett, Phys. Rev. D **73**, 013011 (2006); A. Dighe, S. Goswami and P. Roy, Phys. Rev. D **73**, 071301 (2006); B. C. Chauhan *et al.*, hep-ph/0605032; F. Gonzalez-Canales and A. Mondragon, hep-ph/0606175...

Number of Phases

$$U = U_\ell^\dagger\, U_\nu \text{ where } U_X = e^{i\Phi}\, P_X\, \tilde{U}_X\, Q_X$$

- $\tilde{U}_X$ contains 3 angles and 1 "Dirac phase"
- $P_X \equiv \mathrm{diag}(1, e^{i\phi_X}, e^{i\omega_X})$ and $Q_X \equiv \mathrm{diag}(1, e^{i\rho_X}, e^{i\sigma_X})$

Leads to

$$U = \tilde{U}_\ell^\dagger\; P_\nu\, \tilde{U}_\nu\, Q_\nu \;\longleftrightarrow\; \text{6 angles and 6 phases}$$

- only one phase from $\tilde{U}_\ell$
- (U_ν is bimaximal $\Rightarrow \tilde{U}_\nu$ real)
- 2 phases in Q_ν "Majorana-like"

$\Rightarrow$ Mixing angles and Dirac phase depend on 4 (3) phases

$\Rightarrow$ Majorana phases depend on 6 (5) phases

P.H. Frampton, S.T. Petcov, W.R., Nucl. Phys. B **687**, 31 (2004)

First Realization of QLC

M. Raidal, Phys. Rev. Lett. **93**, 161801 (2004); H. Minakata and A. Y. Smirnov, Phys. Rev. D **70**, 073009 (2004)

Straightforward *minimal* implementation:

$$U = U_\ell^\dagger \, U_\nu \text{ with } U_\ell = V_{\rm CKM} \text{ and } U_\nu = U_{\rm bimax}$$

Can happen if

- m_ν is bimaximal
- $m_\ell = m_{\rm down}^T \Rightarrow m_{\rm up} = {\rm diag}$
- $m_D = m_{\rm up}$ to get see-saw $m_\nu = -m_D^T \, M_R^{-1} \, m_D = m_{\rm up} \, M_R^{-1} \, m_{\rm up}$

$\Rightarrow$ Structure of M_R gives bimaximal m_ν

leads to (approximate) realization of QLC

Neutrino Mixing in QLC1

$$U_\nu = U_{\rm bimax} = P_\nu\, \tilde{U}_{\rm bimax}\, Q_\nu = {\rm diag}(1, e^{i\phi}, e^{i\omega}) \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\ -\frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \\ \frac{1}{2} & -\frac{1}{2} & \frac{1}{\sqrt{2}} \end{pmatrix} {\rm diag}(1, e^{i\sigma}, e^{i\tau})$$

gives

$$\sin^2\theta_{12} = \frac{1}{2} - \frac{\lambda}{\sqrt{2}}\, \cos\phi + \mathcal{O}(\lambda^3)$$

$$|U_{e3}| = \frac{\lambda}{\sqrt{2}} + \mathcal{O}(\lambda^3)$$

$$\sin^2\theta_{23} = \frac{1}{2} - \left(A\,\cos(\omega-\phi) + \tfrac{1}{4}\right)\, \lambda^2 + \mathcal{O}(\lambda^4)$$

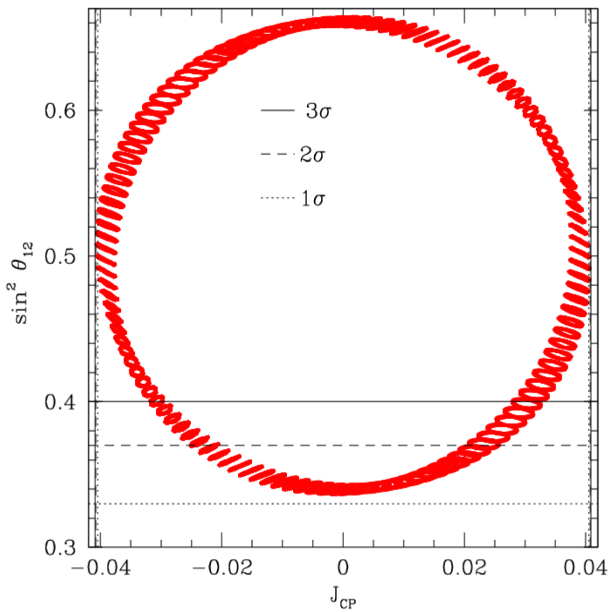
$$J_{CP}^{\rm lep} = \frac{\lambda}{4\sqrt{2}}\, \sin\phi + \mathcal{O}(\lambda^3) \propto J_{CP}^{\rm qua}\, \lambda^{-5}$$

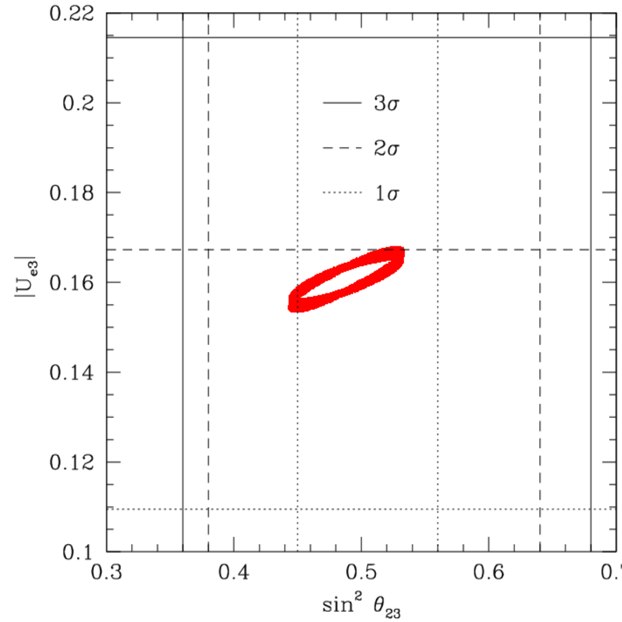
$$\sin\beta = -\sin(\phi+\tau) \text{ and } \sin(\alpha-\beta) = \sin(\phi+\tau-\sigma) \Rightarrow \sigma \triangleq \alpha$$

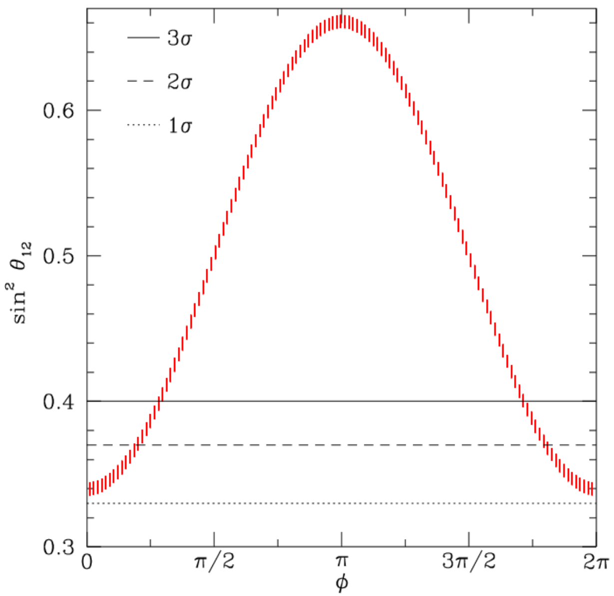
if m_ν is real:

$$J_{CP}^{\rm lep} = \frac{1}{8}\, A\, \eta\, \lambda^4 \propto J_{CP}^{\rm qua}\, \lambda^{-2}$$

THE ONE RING (and a small ellipse)







$$\sin^2\theta_{12} = \frac{1}{2} - \frac{\lambda}{\sqrt{2}}\cos\phi \qquad |U_{e3}| = \frac{\lambda}{\sqrt{2}} \qquad \sin^2\theta_{12} = \frac{1}{2} - \frac{\lambda}{\sqrt{2}}\cos\phi$$

$$J_{CP}^{\rm lep} = \frac{\lambda}{4\sqrt{2}}\sin\phi \qquad \sin^2\theta_{23} = \frac{1}{2} - c\,\lambda^2$$

- prediction of $\sin^2\theta_{12}$ close to 1σ value, requires ϕ close to zero
  $\Rightarrow$ little CP violation even though $|U_{e3}|$ sizable
- prediction for $|U_{e3}|$ close to 2σ limit

Beyond Neutrino Mixing in QLC1

$$m_\nu^{\rm bimax} = P_\nu \begin{pmatrix} A & B & -B \\ \cdot & (D+\frac{A}{2}) & (D-\frac{A}{2}) \\ \cdot & \cdot & (D+\frac{A}{2}) \end{pmatrix} P_\nu = -m_{\rm up}^{\rm diag}\, M_R^{-1}\, m_{\rm up}^{\rm diag}$$

with $P_\nu = {\rm diag}(1, e^{i\phi}, e^{i\omega})$ and

$$A = \frac{1}{2}\left(m_1 + m_2\, e^{-2i\sigma}\right)\ ,\ B = \frac{1}{2\sqrt{2}}\left(m_2\, e^{-2i\sigma} - m_1\right)\ ,\ D = \frac{m_3\, e^{-2i\tau}}{2}$$

with heavy neutrinos

$$M_R = -P_\nu \begin{pmatrix} \tilde{A}\, m_u^2 & \tilde{B}\, m_u\, m_c & -\tilde{B}\, m_u\, m_t \\ \cdot & \left(\tilde{D} + \frac{\tilde{A}}{2}\right) m_c^2 & \left(\tilde{D} - \frac{\tilde{A}}{2}\right) m_c\, m_t \\ \cdot & \cdot & \left(\tilde{D} + \frac{\tilde{A}}{2}\right) m_t^2 \end{pmatrix} P_\nu \sim m_t^2 \begin{pmatrix} \lambda^{16} & \lambda^{12} & \lambda^{8} \\ \cdot & \lambda^{8} & \lambda^{4} \\ \cdot & \cdot & 1 \end{pmatrix}$$

with e.g., $\tilde{A} = \frac{1}{2\, m_1} + \frac{e^{2i\sigma}}{2\, m_2} = A/(A^2 - 2B^2)$

Heavy Neutrino Masses in QLC1

$$M_1\, e^{i\phi_1} \simeq \frac{2\, m_u^2}{m_1 + m_2\, e^{-2i\sigma}} \xrightarrow{\text{NH}} \frac{2\, m_u^2}{\sqrt{\Delta m_\odot^2}}$$

$$M_2\, e^{i\phi_2} \simeq 2\, e^{2i(\sigma+\tau)}\, m_c^2\, \frac{m_1 + m_2\, e^{-2i\sigma}}{m_2\, m_3 + m_1\, m_3\, e^{2i\sigma} + 2\, m_1\, m_2\, e^{2i\tau}} \xrightarrow{\text{NH}} \frac{2\, m_c^2}{\sqrt{\Delta m_{\text{A}}^2}}$$

$$M_3\, e^{i\phi_3} \simeq \frac{m_t^2}{4\, m_1\, m_2\, m_3} \left(2e^{2i\tau} m_1\, m_2 + e^{2i\sigma}\, m_1\, m_3 + m_2\, m_3\right) \xrightarrow{\text{NH}} \frac{m_t^2}{4\, m_1}$$

should not be larger than Planck Mass:

$$m_1 \geq \frac{m_t^2}{4\, M_{\text{Pl}}} \simeq 2 \cdot 10^{-7}\ \text{eV and } m_3 \geq \frac{m_t^2}{2\, M_{\text{Pl}}} \simeq 10^{-7}\ \text{eV}$$

Diagonalization matrix:

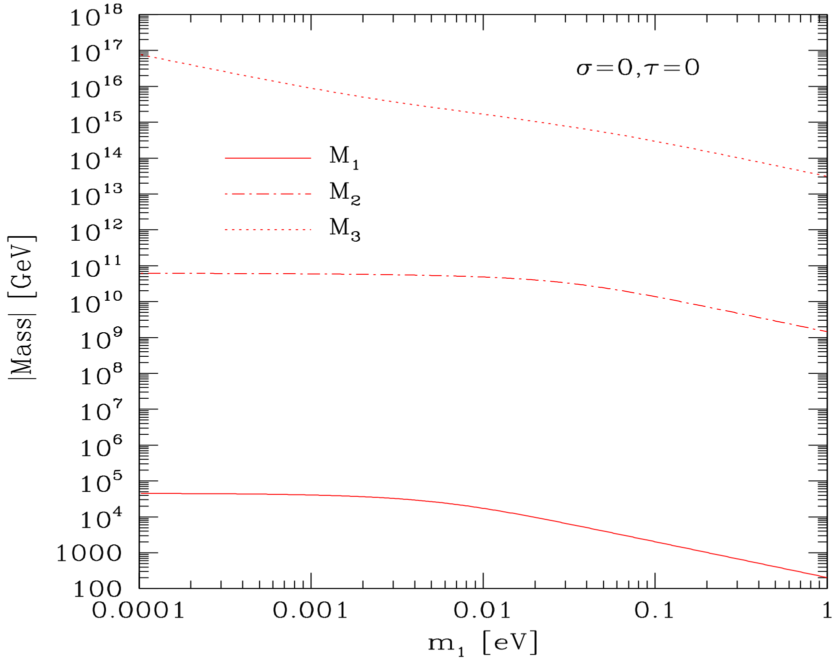
$$V_R \simeq \mathbb{1}$$

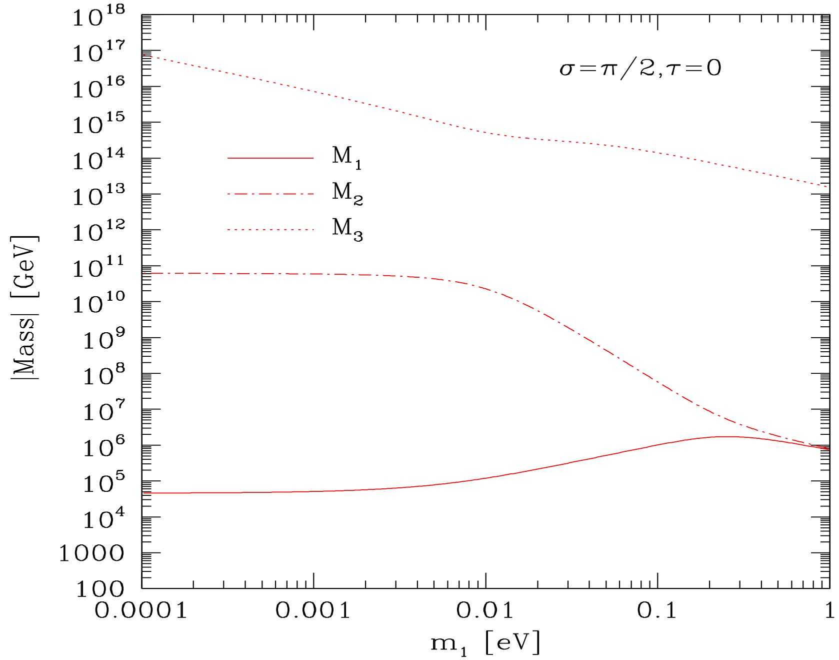
due to extremely hierarchical M_R (unless $\tilde{A}\, m_u^2 \ll \tilde{B}\, m_u\, m_c$). In this case:

$$M_1 \simeq M_2 \simeq \tilde{B}\, m_u\, m_c \simeq \frac{m_u\, m_c}{2\sqrt{2}\, m_1} \sim 10^6\ \text{GeV}$$

Beyond Neutrino Mixing in QLC1

$M_{1,2,3}$ depend on light neutrino masses and low energy Majorana phases!!





$\Rightarrow$ quasi-degenerate $M_1 \simeq M_2$ for $\sigma \simeq \alpha \simeq \pi/2$

$\Rightarrow$ requires $m_1 \simeq 0.5$ eV and $|m_{ee}| \simeq m_1 \cos 2\theta_{12} \simeq m_1 \sqrt{2}\,\lambda \simeq 0.16$ eV

Large cancellation in $|m_{ee}|$!

Beyond Neutrino Mixing in QLC1

Generic case:

$$V_R = i\, P_\nu^*\, \tilde{V}_R\, P_\nu\, R_\nu \;,\; \text{where } R_\nu = \mathrm{diag}(e^{-i\phi_1/2}, e^{-i\phi_2/2}, e^{-i\phi_3/2})$$

$$\tilde{V}_R \simeq \begin{pmatrix} 1 & \frac{m_u}{m_c}\,\frac{\tilde{B}}{\tilde{A}} & -\frac{m_u}{m_t}\,\frac{2\tilde{B}(\tilde{A}^2-2\tilde{B}^2)}{\tilde{A}(\tilde{A}^2-2\tilde{B}^2+2\tilde{A}\,\tilde{D})-4\tilde{B}^2\,\tilde{D}} \\ -\frac{m_u}{m_c}\,\frac{\tilde{B}}{\tilde{A}} & 1 & -\frac{m_c}{m_t}\,\frac{\tilde{A}(\tilde{A}^2-2\tilde{B}^2-2\tilde{A}\,\tilde{D})+4\tilde{B}^2\,\tilde{D}}{\tilde{A}(\tilde{A}^2-2\tilde{B}^2+2\tilde{A}\,\tilde{D})-4\tilde{B}^2\,\tilde{D}} \\ \frac{m_u}{m_t}\,\frac{\tilde{B}}{\tilde{A}} & \frac{m_c}{m_t}\,\frac{\tilde{A}(\tilde{A}^2-2\tilde{B}^2-2\tilde{A}\,\tilde{D})+4\tilde{B}^2\,\tilde{D}}{\tilde{A}(\tilde{A}^2-2\tilde{B}^2+2\tilde{A}\,\tilde{D})-4\tilde{B}^2\,\tilde{D}} & 1 \end{pmatrix}$$

for $m_1 = 0$ case:

$$\tilde{V}_R \simeq \begin{pmatrix} 1 & -\frac{m_u}{\sqrt{2}\,m_c} & \sqrt{2}\,\frac{m_u}{m_t} \\ \frac{m_u}{\sqrt{2}\,m_c} & 1 & -\frac{m_c}{m_t} \\ -\frac{m_u}{\sqrt{2}\,m_t} & \frac{m_c}{m_t} & 1 \end{pmatrix} \sim \begin{pmatrix} 1 & \lambda^4 & \lambda^8 \\ \lambda^4 & 1 & \lambda^4 \\ \lambda^8 & \lambda^4 & 1 \end{pmatrix}$$

Lepton Flavor Violation in QLC1

in basis in which charged leptons and heavy neutrinos are diagonal

$$\tilde{m}_D = V_R^T \, m_D \, U_\ell, \text{ here:}$$

$$\tilde{m}_D = V_R^T \, m_D \, V_{\rm CKM} \Rightarrow \begin{cases} \tilde{m}_D^\dagger \, \tilde{m}_D = V_{\rm CKM}^\dagger \, {\rm diag}(m_u^2, m_c^2, m_t^2) \, V_{\rm CKM} & \text{for LFV} \\ \tilde{m}_D \, \tilde{m}_D^\dagger = V_R^T \, {\rm diag}(m_u^2, m_c^2, m_t^2) \, V_R^* & \text{for } \eta_B \end{cases}$$

leads to prediction

$${\rm BR}(\mu \to e\gamma) \propto \left| (\tilde{m}_D^\dagger \, \tilde{m}_D)_{21} \right|^2 \simeq A^4 \, m_t^4 \left(\eta^2 - (1-\rho)^2\right) \lambda^{10} + \mathcal{O}(\lambda^{14})$$

and relative magnitude (note: no dependence on $M_{1,2,3}$!!)

$${\rm BR}(\mu \to e\gamma) : {\rm BR}(\tau \to e\gamma) : {\rm BR}(\tau \to \mu\gamma)$$
$$\simeq A^2 \left(\eta^2 - (1-\rho)^2\right) \lambda^6 : \left(\eta^2 - (1-\rho)^2\right) \lambda^2 : 1$$

see also Cheung, Kang, Kim and Lee, Phys. Rev. D **72**, 036003 (2005)

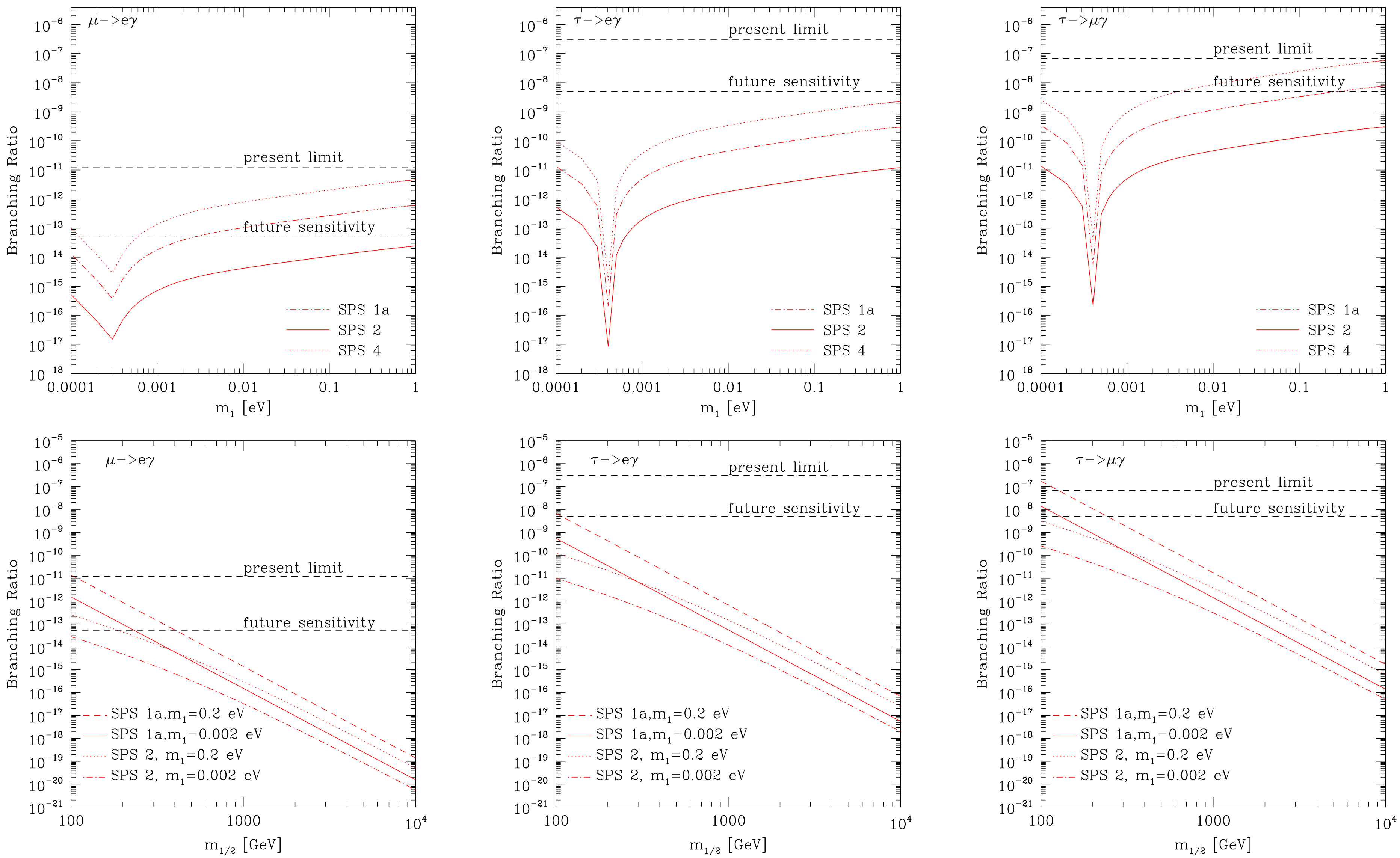
Lepton Flavor Violation in QLC1

Point	m_0	$m_{1/2}$	A_0	$\tan\beta$
1a $\simeq$ 1b	100	250	-100	10
$2 \simeq 3$	1450	300	0	10
4	400	300	0	50

slope $m_0(m_{1/2})$ for Point 1a (2): $m_0 = -A_0 = 0.4\, m_{1/2}$ ($m_0 = 2\, m_{1/2} + 850$ GeV)

- $\mu \to e\gamma$ can be observable for neutrino masses above 10^{-3} eV, unless SUSY masses approach TeV scale
- $\tau \to e\gamma$ is predicted to be very small
- $\tau \to \mu\gamma$ requires rather large neutrino masses
- $\mathrm{BR}(\mu \to e\gamma) : \mathrm{BR}(\tau \to e\gamma) : \mathrm{BR}(\tau \to \mu\gamma) \simeq \lambda^6 : \lambda^2 : 1$

Lepton Flavor Violation in QLC1



Leptogenesis in QLC1

$M_1 \lesssim 10^6$ GeV $\Rightarrow$ two possibilities:

- resonant leptogenesis: $\alpha \simeq \pi/2 \Rightarrow$ Maximal cancellation in $0\nu\beta\beta$
- decay of N_2 with $M_2 \simeq 10^{9 \ldots 11}$ GeV $\leftrightarrow$ flavor effects are important

Barbieri *et al.*, Nucl. Phys. B **575**, 61 (2000); Pilaftsis, Underwood, Phys. Rev. D **72**, 113001 (2005); Endoh, Morozumi, Xiong, Prog. Theor. Phys. **111**, 123 (2004); Fujihara *et al.*, Phys. Rev. D **72**, 016006 (2005); Abada *et al.*, JCAP **0604**, 004 (2006); Nardi, Nir, Roulet, Racker, JHEP **0601**, 164 (2006); Abada *et al.*, hep-ph/0605281; Blanchet, Di Bari, hep-ph/0607330; Antusch, King, Riotto, hep-ph/0609038; Branco *et al.*, hep-ph/0609067; Pascoli, Petcov, Riotto, hep-ph/0609125; Branco, Felipe, Joaquim, hep-ph/0609297

- without: ε_1 washed out by $\tilde{m}_1 = (\tilde{m}_D \, \tilde{m}_D^\dagger)_{11}$; summed over all flavors
- with: $\varepsilon_1^{e,\mu,\tau}$ washed out by $\tilde{m}_1^{e,\mu,\tau} = (\tilde{m}_D)_{1\alpha} \, (\tilde{m}_D^\dagger)_{\alpha 1}$; individual for each flavor
- N_2 (ε_2^τ) can generate Baryon Asymmetry: wash-out by N_1 via τ flavor $(\tilde{m}_1^\tau)$ much smaller than wash-out summed over all flavors $(\tilde{m}_1)$
  Vives, Phys. Rev. D **73**, 073006 (2006)

Leptogenesis in QLC1

Decay of second heaviest neutrino:

$$\varepsilon_2^\alpha \simeq -\frac{1}{8\pi\, v_u^2}\,\frac{1}{\left(\tilde{m}_D\,\tilde{m}_D^\dagger\right)_{22}}\left[\frac{3}{2}\,\frac{M_2}{M_3}\,\mathrm{Im}\left\{(\tilde{m}_D)_{2\alpha}\,(\tilde{m}_D^\dagger)_{\alpha 3}\,\left(\tilde{m}_D\,\tilde{m}_D^\dagger\right)_{23}\right\}\right.$$
$$\left. + \frac{M_1}{M_2}\,\left(\frac{M_2}{M_1}-2\right)\,\mathrm{Im}\left\{(\tilde{m}_D)_{2\alpha}\,(\tilde{m}_D^\dagger)_{\alpha 1}\,\left(\tilde{m}_D\,\tilde{m}_D^\dagger\right)_{21}\right\}\right]$$

in our case:

$$\varepsilon_2^\tau \simeq \frac{3}{2\,\pi}\,\frac{m_1}{\sqrt{\Delta m_{\mathrm{A}}^2}}\,\lambda^8\,\sin 2(\omega-\phi+\tau) \simeq 10^{-8}\,\left(\frac{m_1}{10^{-4}\,\mathrm{eV}}\right)\,\sin 2(\omega-\phi+\tau) \gg \varepsilon_2^{e,\mu}$$

and for Baryon Asymmetry:

$$\eta_B \simeq 10^{-2}\,\epsilon_2^\tau \simeq 10^{-10}\,\left(\frac{m_1}{10^{-4}\,\mathrm{eV}}\right)\,\sin 2(\omega-\phi+\tau) \stackrel{!}{=} 6\cdot 10^{-10}$$

leptogenesis phase *in principle* reconstructible via $\sin^2\theta_{23}-\frac{1}{2} \propto \lambda^2\,\cos(\omega-\phi)$,
$J_{CP} \propto \sin\phi$ and $\sin\beta \simeq -\sin(\phi+\tau)$

Second Realization of QLC

M. Raidal, Phys. Rev. Lett. **93**, 161801 (2004); H. Minakata and A. Y. Smirnov, Phys. Rev. D **70**, 073009 (2004)

Straightforward *minimal* implementation:

$$U = U_\ell^\dagger \, U_\nu \text{ with } U_\nu = V_{\rm CKM}^\dagger \text{ and } U_\ell = U_{\rm bimax}^T$$

Can happen if

- $m_\nu = V_{\rm CKM}^T \, m_\nu^{\rm diag} \, V_{\rm CKM}$ and $U_\ell = U_{\rm bimax}^T$
- $m_D = m_{\rm up}$ and M_R does not introduce additional rotations in $m_\nu = -m_D^T \, M_R^{-1} \, m_D$
- $\Rightarrow V_{\rm up} = V_{\rm CKM}^\dagger \Rightarrow V_{\rm down} = \mathbb{1}$; consistent with $m_{\rm down} = m_\ell^T$

leads to (approximate) realization of QLC

Neutrino Mixing in QLC2

$$U_\nu^\dagger = P_\nu \, V_{\rm CKM} \, Q_\nu = {\rm diag}(1, e^{i\phi}, e^{i\omega}) \, V_{\rm CKM} \, {\rm diag}(1, e^{i\sigma}, e^{i\tau})$$

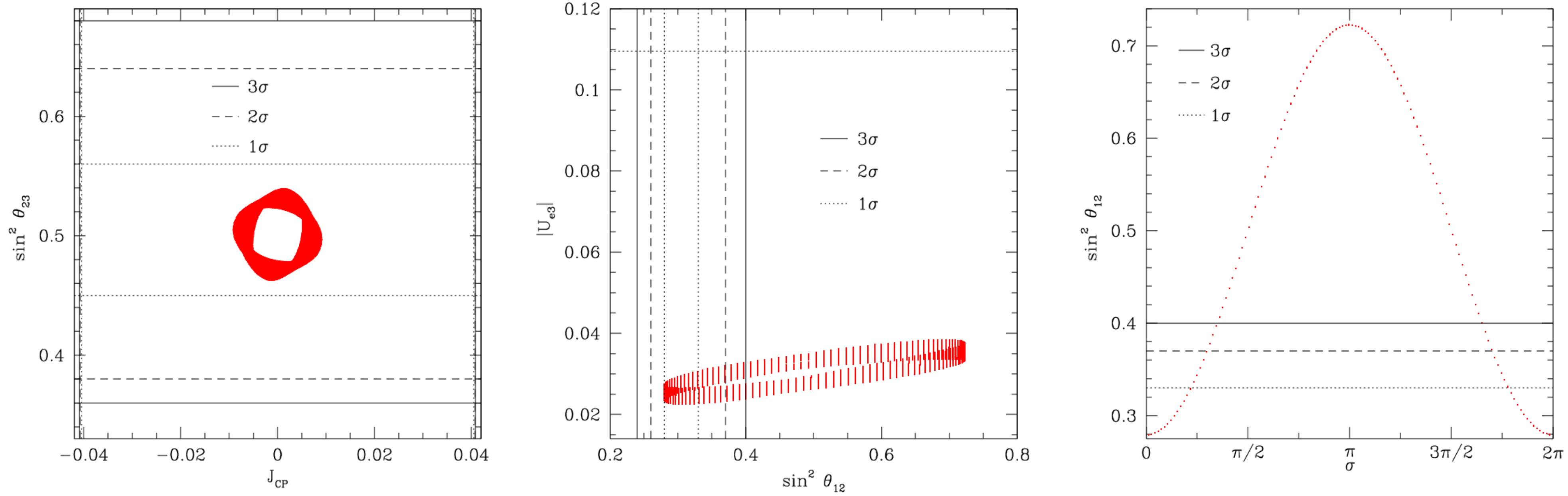
gives

$$\sin^2\theta_{12} = \frac{1}{2} - \lambda \, \cos\sigma + \mathcal{O}(\lambda^3)$$
$$|U_{e3}| = \frac{A}{\sqrt{2}} \, \lambda^2 + \mathcal{O}(\lambda^3)$$
$$\sin^2\theta_{23} = \frac{1}{2} - \sqrt{\tfrac{1}{2}} \, A \, \lambda^2 \, \cos(\tau - \sigma) + \mathcal{O}(\lambda^3) \, ,$$
$$J_{CP}^{\rm lep} = \frac{\lambda^2}{4\sqrt{2}} \, \sin(\tau - \sigma) + \mathcal{O}(\lambda^3) \propto J_{CP}^{\rm qua} \, \lambda^{-4}$$
$$\sin\beta = \sin(\sigma + \omega) \text{ and } \sin(\beta - \alpha) = \sin(\omega - \phi) \rightarrow \phi + \sigma \triangleq \alpha$$

if m_ν is real:

$$J_{CP}^{\rm lep} = 0$$

Neutrino Mixing in QLC2



$$\sin^2\theta_{23} = \frac{1}{2} - c\,\lambda^2\,\cos(\tau - \sigma) \qquad |U_{e3}| = \frac{A}{\sqrt{2}}\,\lambda^2 \qquad \sin^2\theta_{12} = \frac{1}{2} - \lambda\cos\sigma$$

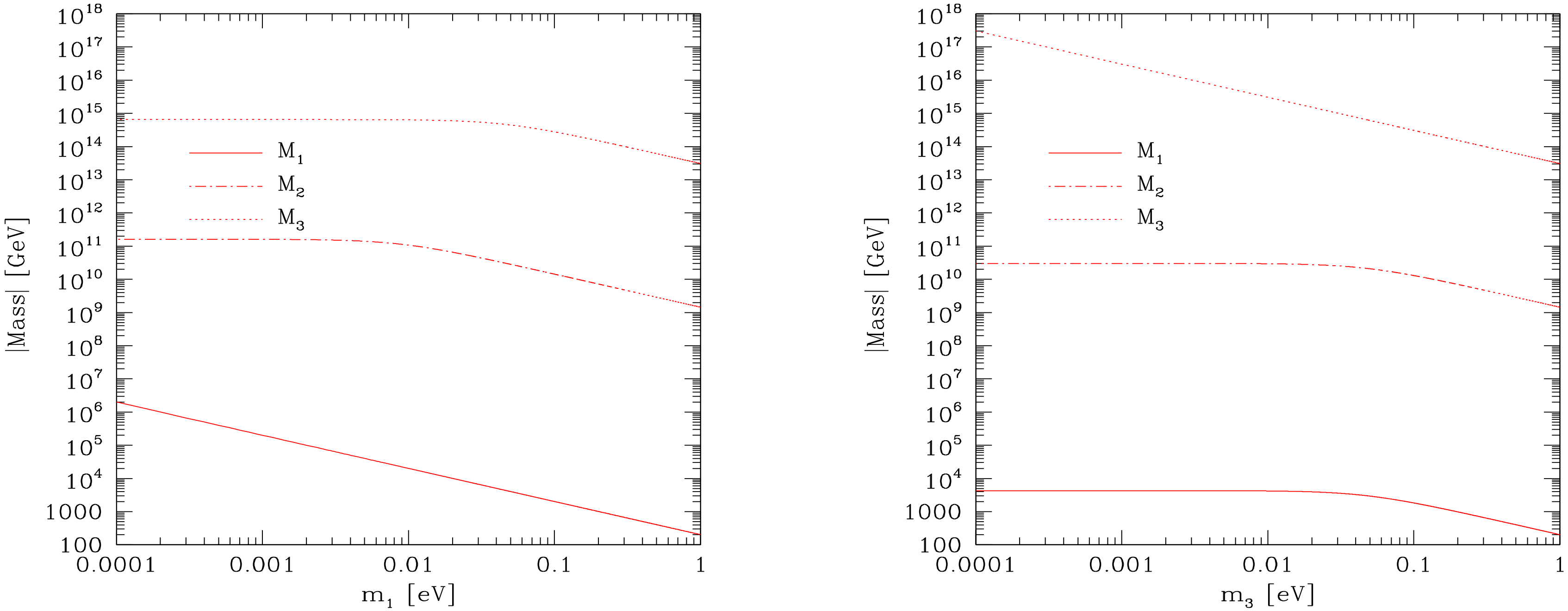
$$J_{CP}^{\rm lep} = \frac{\lambda^2}{4\sqrt{2}}\,\sin(\tau - \sigma) \qquad \sin^2\theta_{12} = \frac{1}{2} - \lambda\cos\sigma$$

- perfectly compatible with everything
- $|U_{e3}| \simeq 0.03$, compare with $|U_{e3}|^2 \simeq 0.03$ in QLC1

BEYOND NEUTRINO MIXING IN QLC2

$M_{1,2,3}$ depend only on light neutrino masses:

$$M_1 = \frac{m_u^2}{m_1} \;,\quad M_2 = \frac{m_c^2}{m_2} \;,\quad M_3 = \frac{m_t^2}{m_3} \quad \Rightarrow \text{no enhancement possible}$$



$$m_1 \geq \frac{m_u^2}{M_{\rm Pl}} \simeq 8 \cdot 10^{-17}\ \text{eV and } m_3 \geq \frac{m_t^2}{M_{\rm Pl}} \simeq 2 \cdot 10^{-7}\ \text{eV}$$

Lepton Flavor Violation in QLC2

in basis in which charged leptons and heavy neutrinos are diagonal:

$$\tilde{m}_D = V_R^T \, m_D \, U_\ell = m_{\rm up}^{\rm diag} \, P_\nu \, V_{\rm CKM} \, Q_\nu \, U_{\rm bimax}^T$$

$$\Rightarrow \tilde{m}_D^\dagger \, \tilde{m}_D = U_{\rm bimax} \, Q_\nu^\dagger \, V_{\rm CKM}^\dagger \, {\rm diag}(m_u^2, m_c^2, m_t^2) \, V_{\rm CKM} \, Q_\nu \, U_{\rm bimax}^T$$

leads to prediction

$${\rm BR}(\mu \to e\gamma) \propto \left| (\tilde{m}_D^\dagger \, \tilde{m}_D)_{21} \right|^2 \simeq \frac{1}{4} \, A^2 \, m_t^4 \, \lambda^4 + \mathcal{O}(\lambda^5)$$

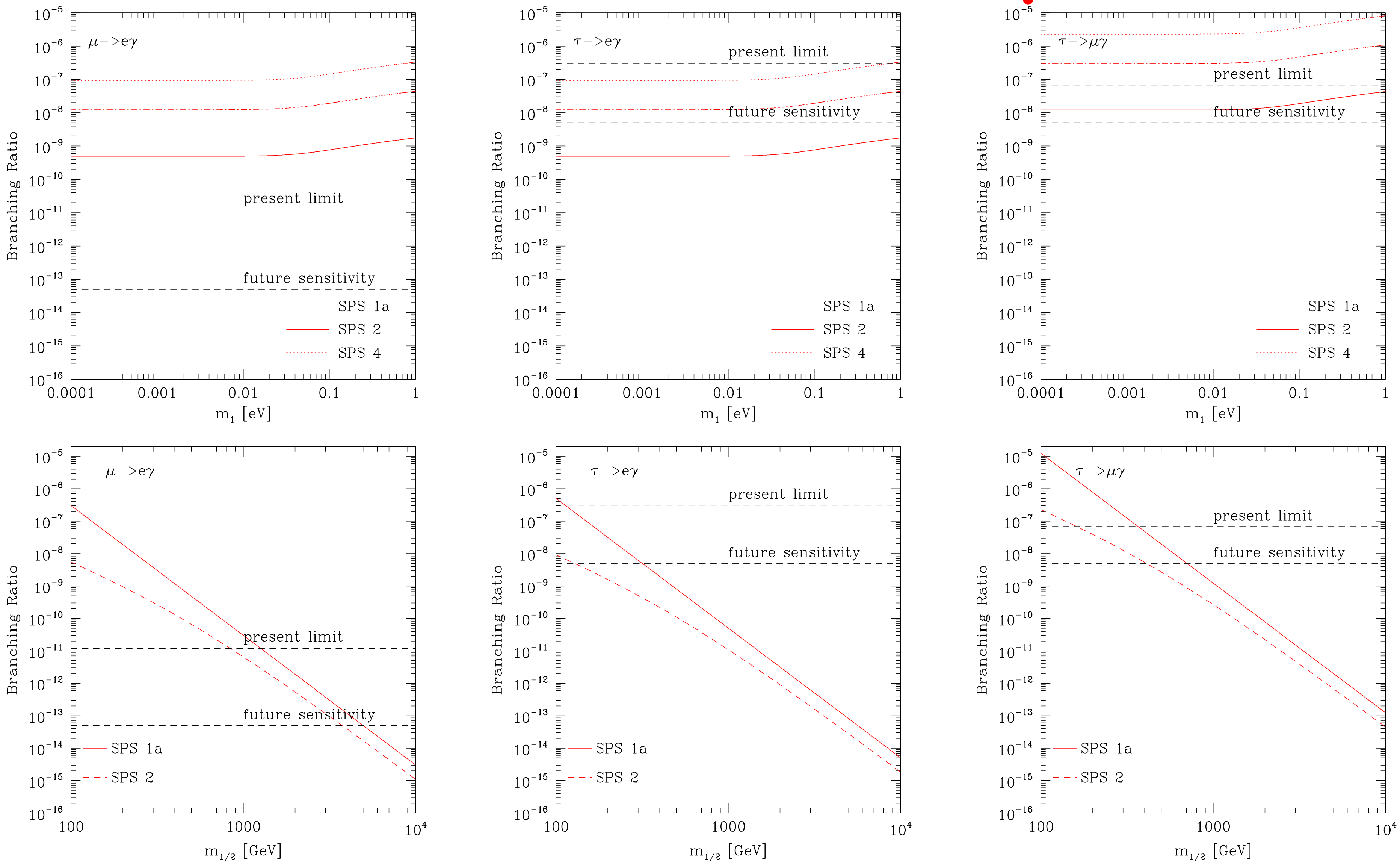
larger than in QLC1 by $\lambda^{-6} \simeq 9000$

relative magnitude (note: no dependence on $M_{1,2,3}$!!)

$${\rm BR}(\mu \to e\gamma) : {\rm BR}(\tau \to e\gamma) : {\rm BR}(\tau \to \mu\gamma)$$
$$\simeq A^2 \, \lambda^4 : A^2 \, \lambda^4 : 1$$

- $\mu \to e\gamma$ is too large
- if made small by increasing SUSY masses: $\tau \to e\gamma$ and $\tau \to \mu\gamma$ too small

Lepton Flavor Violation in QLC2



Leptogenesis in QLC2

$$\tilde{m}_D \, \tilde{m}_D^\dagger = \mathrm{diag}(m_u^2, m_c^2, m_t^2)$$

This means NO LEPTOGENESIS!!

Summary

QLC: simple, interesting and predictive scenario for Quark and Lepton Mixing

$$U = V_{\rm CKM}^\dagger \, U_{\rm bimax} \text{ or } U = U_{\rm bimax}^T \, V_{\rm CKM}^\dagger$$

plus up-quark masses and no additional parameters except for phases

Summary for QLC1:

- solar neutrino mixing close to 1σ bound, $|U_{e3}|^2 \simeq 0.03$ close to 2σ bound

$$\sin^2\theta_{12} \simeq \frac{1}{2} - |U_{e3}| \, \cos\phi \simeq \frac{1}{2} \pm \sqrt{|U_{e3}|^2 - 16 \, (J_{CP}^{\rm lep})^2}$$

- $\mu \to e\gamma$ observable for $m_1 \gtrsim 10^{-3}$ eV, unless SUSY masses $\gtrsim$ TeV; $\tau \to e\gamma$ very small, $\tau \to \mu\gamma$ requires large neutrino masses

$${\rm BR}(\mu \to e\gamma) : {\rm BR}(\tau \to e\gamma) : {\rm BR}(\tau \to \mu\gamma) \simeq \lambda^6 : \lambda^2 : 1$$

- leptogenesis possible via decay of second heaviest neutrino $\leftrightarrow$ flavor effects
- successful resonant leptogenesis depends on Majorana phase α, leading to two QD heavy and QD light neutrinos with maximal cancellation in $0\nu\beta\beta$

Summary for QLC2:

- Neutrino mixing perfectly compatible with everything; $|U_{e3}| \simeq 0.03$

$$\sin^2\theta_{23} \simeq \frac{1}{2} - |U_{e3}|\,\cos(\tau - \sigma) \simeq \frac{1}{2} \pm \sqrt{|U_{e3}| - 16\,(J_{CP}^{\rm lep})^2}$$

- $\mu \to e\gamma$ larger than in QLC1 by six inverse powers of $\lambda \simeq 10^4$; typically too large unless SUSY masses several TeV

- if $\mu \to e\gamma$ suppressed, $\tau \to e\gamma$ and $\tau \to \mu\gamma$ become too small; Relative magnitude

$$\mathrm{BR}(\mu \to e\gamma) : \mathrm{BR}(\tau \to e\gamma) : \mathrm{BR}(\tau \to \mu\gamma) \simeq A^2\,\lambda^4 : A^2\,\lambda^4 : 1$$

- there can be no leptogenesis

Final remark

K.A. Hochmuth and W.R, hep-ph/06**07**103

If the referee is in the audience: **please write a report!!**