Extension of the Standard Model by a gauged lepton flavor symmetry and leptogenesis

In collaboration with K. Hamaguchi and N. Nagata

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& ``work in progress'' [hep-ph/18xx.xxxxx]

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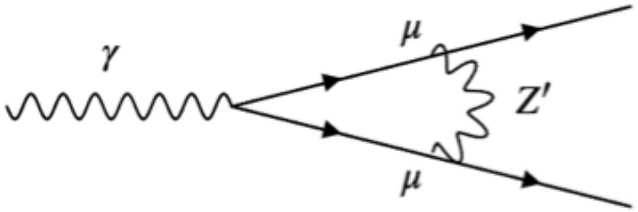
1, Introduction

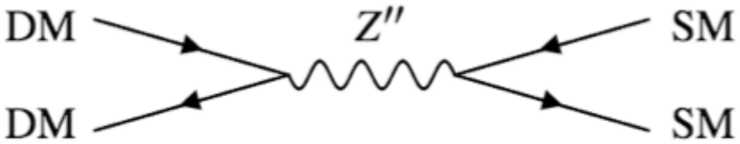
Extension of SM gauge sector by lepton flavor symmetry

$$\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times \mathrm{U}(1)_X$$

- Muon g-2

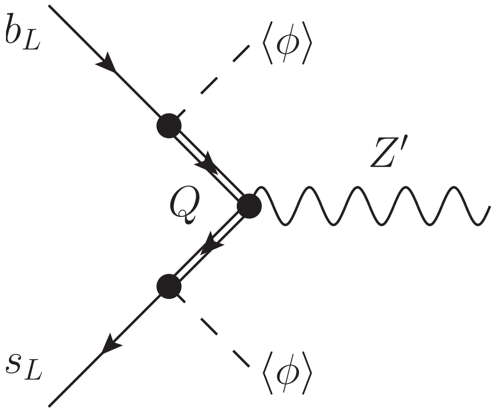


- Dark matter



- Anomaly in flavor physics

Ex) $B \to K^* \mu^+ \mu^-$ anomaly



1, Introduction

T. Araki, J. Heeck, and J. Kubo (2012)

U(1) gauge symmetry and neutrino mass matrix

$\mathrm{U}(1)_{L_\mu - L_\tau}$ gauge symmetry

→ Majorana mass

$$\begin{pmatrix} & 0 & 0 \\ 0 & 0 & \\ 0 & & 0 \end{pmatrix}$$

strong constraints

→ Light neutrino mass

$$\mathcal{M}_{\nu_L} \simeq -\mathcal{M}_D \mathcal{M}_R^{-1} \mathcal{M}_D^T$$

$$\Rightarrow \begin{pmatrix} * & & \\ & & * \\ & * & \end{pmatrix} \simeq - \begin{pmatrix} * & & \\ & * & \\ & & * \end{pmatrix} \begin{pmatrix} * & & \\ & & * \\ & * & \end{pmatrix} \begin{pmatrix} * & & \\ & * & \\ & & * \end{pmatrix}$$

$\mathrm{U}(1)_{L_\mu - L_\tau}$ gauge symmetry → Spontaneously breaking

1, Introduction

T. Araki, J. Heeck, and J. Kubo (2012)

U(1) gauge symmetry and neutrino mass matrix

SM singlet scalar σ breaks

~~$\mathrm{U}(1)_{L_\mu - L_\tau}$ gauge symmetry~~

→ Majorana mass

$$\begin{pmatrix} & & \\ & 0 & \\ & & 0 \end{pmatrix}$$

strong constraints

SM singlet scalar σ breaks the $\mathrm{U}(1)_{Y'}$ symmetry → Mass matrix has strong constraint even if the $\mathrm{U}(1)_{Y'}$ symmetry was broken

Two zero minor structure is especially interesting !

Abstract of this talk

Extra U(1) gauge symmetry

$$\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times \mathrm{U}(1)_X$$

1 zero minor   3 zero minor   4 zero minor   • • •

2 zero minor structure

neutrino mass

$$m_1, m_2, m_3$$

CP phase

$$\delta, \alpha_2, \alpha_3$$

Effective Majorana neutrino mass

$$\langle m_{\beta\beta} \rangle$$

as functions of $\theta_{12}, \theta_{23}, \theta_{13}, \delta m^2, \Delta m^2$

Leptogenesis

Dirac Yukawa couplings

$$\mathcal{L} \supset \lambda_\alpha N^c_\alpha (L_\alpha \cdot H)$$

sign of baryon asymmetry

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2, Analysis of mass matrix

Minimal gauged $\mathrm{U}(1)_{L_\mu - L_\tau}$ model

Gauge sector

$$\mathcal{G} = \mathcal{G}_{SM} \times U(1)_{L_\mu - L_\tau}$$

Fields

SM

$+\,3$ right-handed neutrinos

$: N_e, N_\mu, N_\tau$

$+\,1$ singlet scalar : σ

Charge assignment

field	$U(1)_{L_\mu - L_\tau}$
$e_{L,R}, \nu_e, N_e$	0
$\mu_{L,R}, \nu_\mu, N_\mu$	$+1$
$\tau_{L,R}, \nu_\tau, N_\tau$	-1
σ	$+1$
others	0

Lagrangian

$$\Delta\mathcal{L} = -\lambda_e N_e^c (L_e \cdot H) - \lambda_\mu N_\mu^c (L_\mu \cdot H) - \lambda_\tau N_\tau^c (L_\tau \cdot H)$$
$$-\frac{1}{2} M_{ee} N_e^c N_e^c - M_{\mu\tau} N_\mu^c N_\tau^c - \lambda_{e\mu} \sigma N_e^c N_\mu^c - \lambda_{e\tau} \sigma^* N_e^c N_\tau^c + \mathrm{h.c.}$$

2, Analysis of mass matrix

$U(1)_{L_\mu - L_\tau}$ gauge symmetry and neutrino mass matrix

Mass matrices

・Dirac mass

$$\mathcal{M}_D = \frac{v}{\sqrt{2}} \begin{pmatrix} \lambda_e & 0 & 0 \\ 0 & \lambda_\mu & 0 \\ 0 & 0 & \lambda_\tau \end{pmatrix}$$

・ charged lepton mass

$$\mathcal{M}_l = \frac{v}{\sqrt{2}} \begin{pmatrix} y_e & 0 & 0 \\ 0 & y_\mu & 0 \\ 0 & 0 & y_\tau \end{pmatrix}$$

→ Both are diagonal

・Majorana mass

$$\mathcal{M}_R = \begin{pmatrix} M_{ee} & \lambda_{e\mu} \langle \sigma \rangle & \lambda_{e\tau} \langle \sigma \rangle \\ \lambda_{e\mu} \langle \sigma \rangle & 0 & M_{\mu\tau} \\ \lambda_{e\tau} \langle \sigma \rangle & M_{\mu\tau} & 0 \end{pmatrix}$$

→ (μ, μ) and (τ, τ) components vanish

2, Analysis of mass matrix

Two zero minor conditions

Seesaw mechanism

$$\mathcal{M}_{\nu_L} = -\mathcal{M}_D \mathcal{M}_R^{-1} \mathcal{M}_D^T$$

$$\Rightarrow \boxed{\mathcal{M}_{\nu_L}^{-1} = -(\mathcal{M}_D^{-1})^T \mathcal{M}_R \mathcal{M}_D^{-1}}$$

The mass matrix can be diagonalized by PMNS matrix

$$U_{PMNS}^T \mathcal{M}_{\nu_L} U_{PMNS} = \mathrm{diag}(m_1, m_2, m_3)$$

$$\Rightarrow \boxed{\mathcal{M}_{\nu_L}^{-1} = U_{PMNS}\,\mathrm{diag}(m_1^{-1}, m_2^{-1}, m_3^{-1}) U_{PMNS}^T}$$

$$U_{PMNS} = \underbrace{\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}}_{=V} \begin{pmatrix} 1 & & \\ & e^{i\frac{\alpha_2}{2}} & \\ & & e^{i\frac{\alpha_3}{2}} \end{pmatrix}$$

2, Analysis of mass matrix

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$$U_{PMNS} \mathrm{diag}(m_1^{-1}, m_2^{-1}, m_3^{-1}) U_{PMNS}^T = -(\mathcal{M}_D^{-1})^T \mathcal{M}_R \mathcal{M}_D^{-1}$$

2, Analysis of mass matrix

Two zero minor conditions

(μ, μ) and (τ, τ) components on the both sides vanish

$$(\mathrm{LHS}) = (\mathrm{RHS}) = \begin{pmatrix} * & * & * \\ * & 0 & * \\ * & * & 0 \end{pmatrix}$$

➡ Two zero minor conditions

$$U_{PMNS}\mathrm{diag}(m_1^{-1}, m_2^{-1}, m_3^{-1})U^T_{PMNS} = -\begin{pmatrix} * & & \\ & * & \\ & & * \end{pmatrix}\begin{pmatrix} * & * & * \\ * & 0 & * \\ * & * & 0 \end{pmatrix}\begin{pmatrix} * & & \\ & * & \\ & & * \end{pmatrix}$$

2, Analysis of mass matrix

Two zero minor conditions

$$U_{\mathrm{PMNS}} = \underbrace{\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}}_{=V} \begin{pmatrix} 1 & & \\ & e^{i\frac{\alpha_2}{2}} & \\ & & e^{i\frac{\alpha_3}{2}} \end{pmatrix}$$

$$\begin{cases} \frac{1}{m_1}V_{\mu 1}^2 + \frac{1}{m_2}V_{\mu 2}^2 e^{i\alpha 2} + \frac{1}{m_3}V_{\mu 3}^2 e^{i\alpha_3} = 0 \\ \frac{1}{m_1}V_{\tau 1}^2 + \frac{1}{m_2}V_{\tau 2}^2 e^{i\alpha 2} + \frac{1}{m_3}V_{\tau 3}^2 e^{i\alpha_3} = 0 \end{cases}$$

Point

Neither the $\mathrm{U}(1)_{L_\mu - L_\tau}$ breaking singlet VEV $\langle\sigma\rangle$ nor Majorana masses appear in these conditions explicitly

→ This analysis has little dependence on the $\mathrm{U}(1)_{L_\mu - L_\tau}$ −symmetry breaking scale

2, Analysis of mass matrix

Analysis of two zero minor conditions

Two zero minor conditions include the CP phases $(\delta, \alpha_2, \alpha_3)$ and the neutrino mass (m_1)

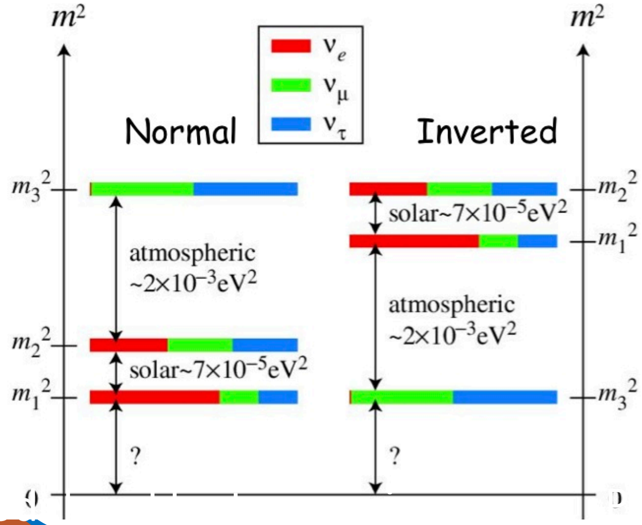
$$\Rightarrow \quad m_1, \delta, \alpha_2, \alpha_3 = f(\theta_{12}, \theta_{13}, \theta_{23}, \delta m^2, \Delta m^2)$$

Mixing angle

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\nu_{L\alpha} = \sum_{j=1}^{3} (U_{PMNS})_{\alpha j} \nu_{Lj} \quad (\alpha = e, \mu, \tau)$$

Squared mass difference



$$\delta m^2 = \Delta m^2_{\rm sol},$$

$$\Delta m^2 = \Delta m^2_{\rm atm} - \frac{1}{2} \Delta m^2_{\rm sol}$$

2, Analysis of mass matrix

Analysis of two zero minor conditions

Two zero minor conditions include the CP phases $(\delta, \alpha_2, \alpha_3)$ and the neutrino mass (m_1)

$$\Rightarrow \quad m_1, \delta, \alpha_2, \alpha_3 = f(\theta_{12}, \theta_{13}, \theta_{23}, \delta m^2, \Delta m^2)$$

complex eqs : more than three
$\Rightarrow$ generally no solution

complex eqs : zero or one
$\Rightarrow$ fewer predictions

$\Rightarrow$ Two zero minor structure is interesting !

2, Analysis of mass matrix

Summary so far

Two zero minor conditions

$$U_{PMNS}\mathrm{diag}(m_1^{-1}, m_2^{-1}, m_3^{-1})U_{PMNS}^T = \begin{pmatrix} * & * & * \\ * & 0 & * \\ * & * & 0 \end{pmatrix} = -(\mathcal{M}_D^{-1})^T \mathcal{M}_R \mathcal{M}_D^{-1}$$

neutrino mass: m_1, m_2, m_3

CP phase: $\delta, \alpha_2, \alpha_3$

Effective Majorana neutrino mass: $\langle m_{\beta\beta} \rangle$

as functions of $\theta_{12}, \theta_{23}, \theta_{13}, \delta m^2, \Delta m^2$

$$m_1, \delta, \alpha_2, \alpha_3 = f(\theta_{12}, \theta_{13}, \theta_{23}, \delta m^2, \Delta m^2)$$

Abstract of this talk

Extra U(1) gauge symmetry

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_X$$

1 zero minor   3 zero minor   4 zero minor   • • •

2 zero minor structure

neutrino mass

$$m_1, m_2, m_3$$

CP phase

$$\delta, \alpha_2, \alpha_3$$

Effective Majorana neutrino mass

$$\langle m_{\beta\beta} \rangle$$

as functions of $\theta_{12}, \theta_{23}, \theta_{13}, \delta m^2, \Delta m^2$

Leptogenesis

Dirac Yukawa couplings

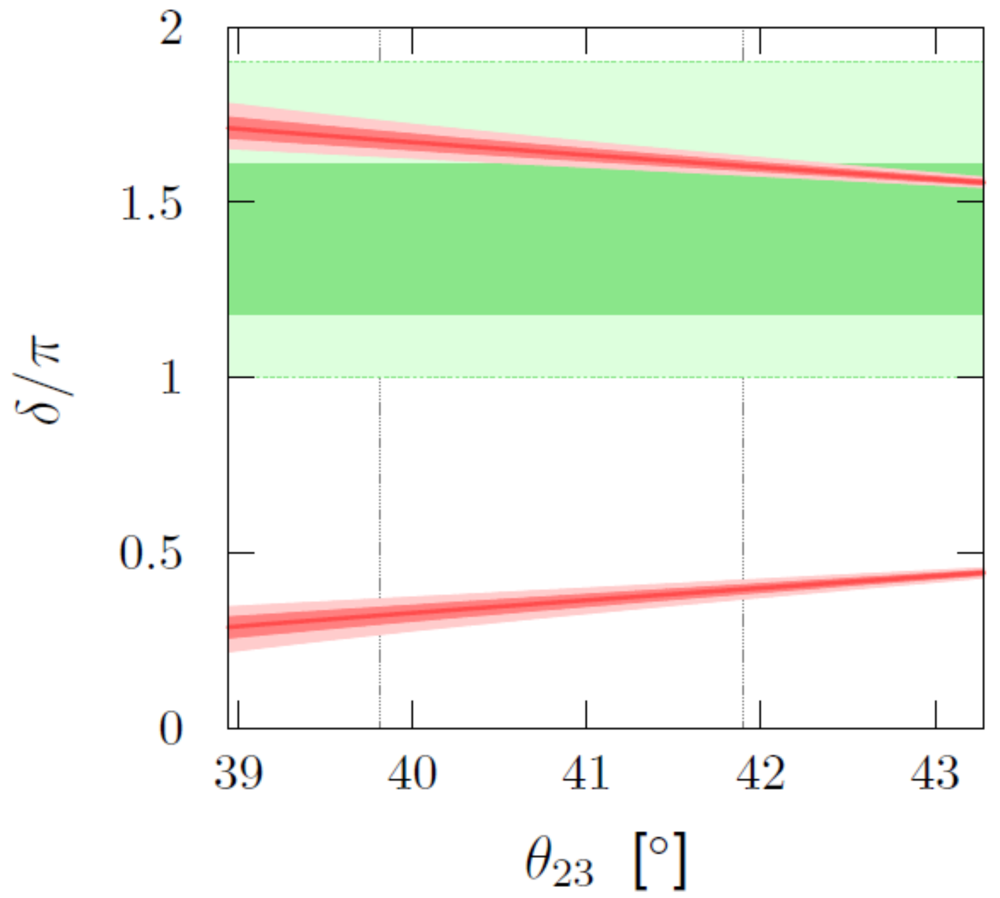
$$\mathcal{L} \supset \lambda_\alpha N_\alpha^c (L_\alpha \cdot H)$$

↕

sign of baryon asymmetry

3, Predictions for neutrino parameters

$\mathrm{U}(1)_{L_\mu - L_\tau}$ a) Dirac CP phases



dark (light) red band

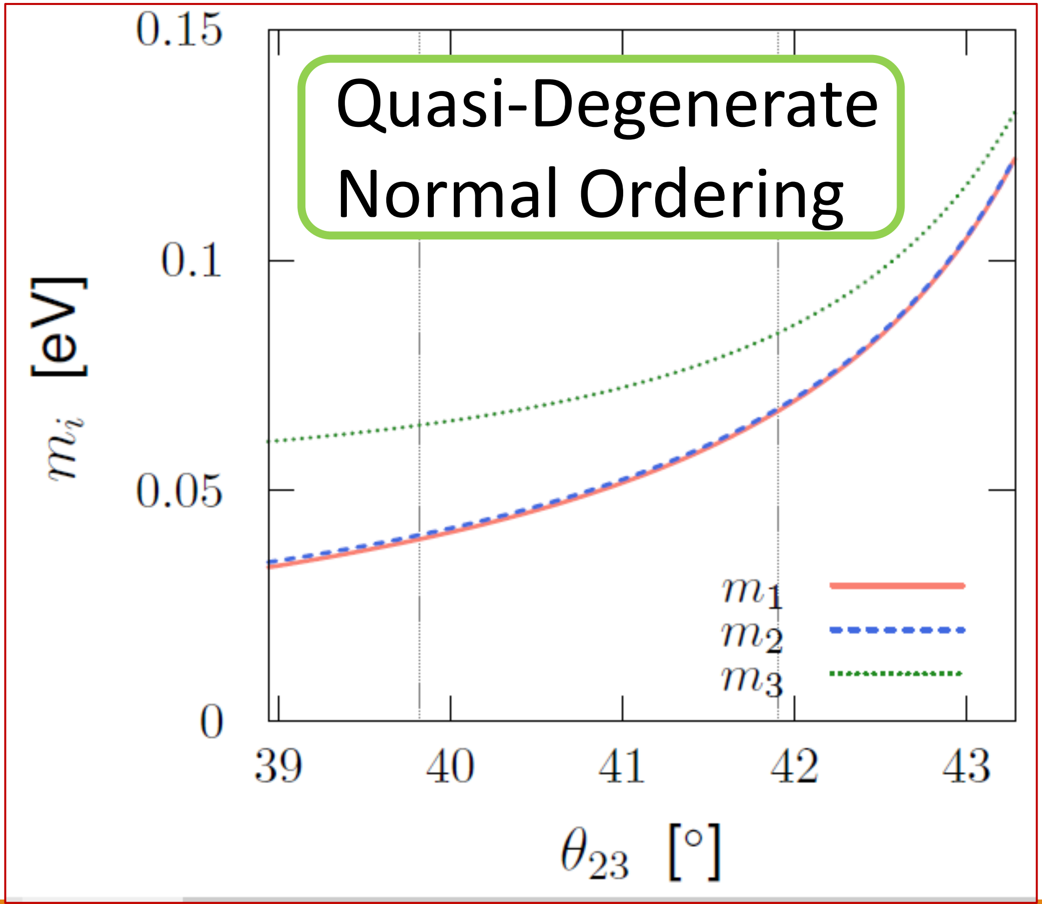
: uncertainty coming from the 1σ (2σ) errors in the parameters $\theta_{12}, \theta_{13}, \delta m^2$, and Δm^2

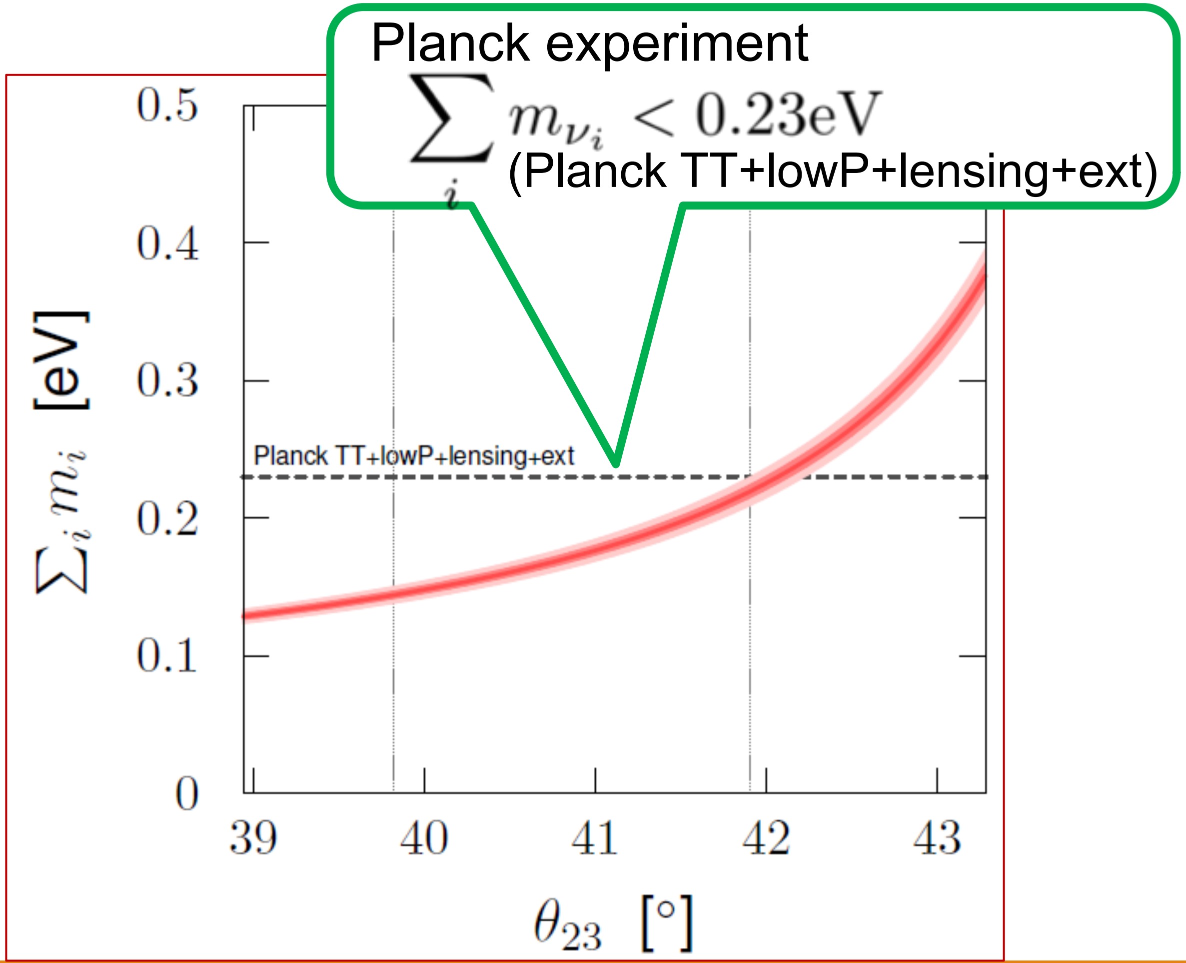
dark (light) green band

: 1σ (2σ) favored region of δ

3, Predictions for neutrino parameters

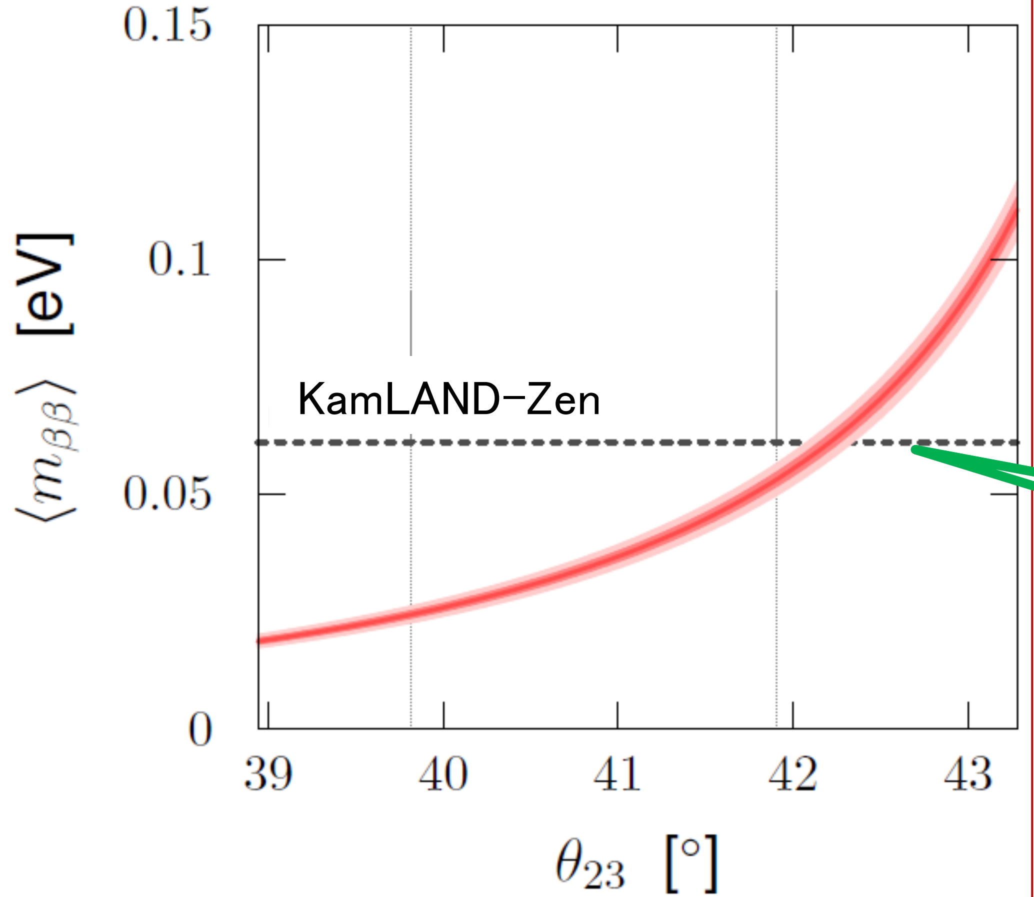
$U(1)_{L_\mu - L_\tau}$ b) Neutrino masses and sum of them

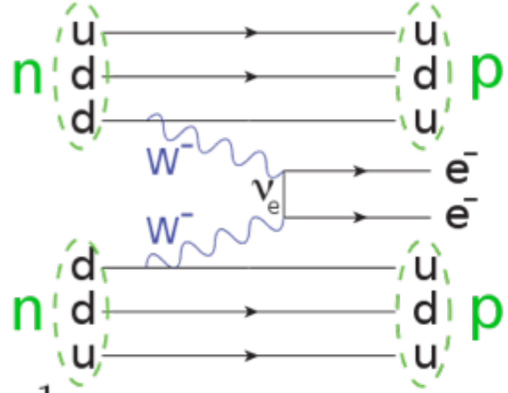




3, Predictions for neutrino parameters

$U(1)_{L_\mu - L_\tau}$ c) Effective Majorana neutrino mass





$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu} \left|M^{0\nu}\right|^2 \langle m_{\beta\beta} \rangle^2$$

The strongest bound on $\langle m_{\beta\beta} \rangle$

uncertainty of the nuclear matrix element for $^{136}\mathrm{Xe}$

$$\langle m_{\beta\beta} \rangle < 0.061\text{-}0.165\ \mathrm{eV}$$

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4, Implications for leptogenesis

Sign of baryon asymmetry

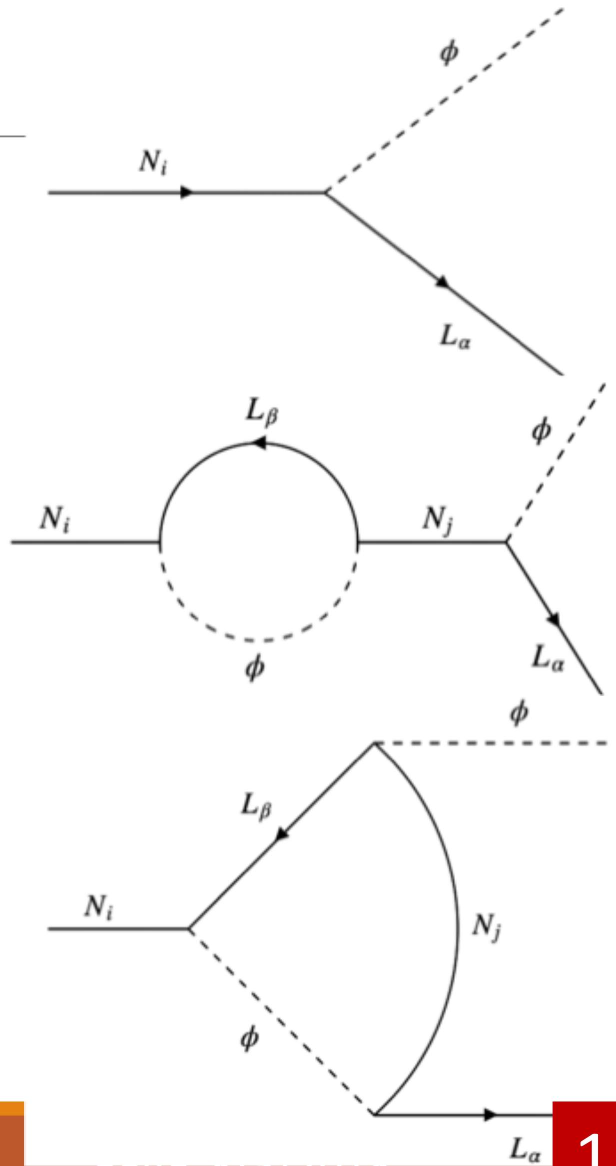
thermal

Decay of right-handed neutrino N_1

Asymmetry parameter

$$\epsilon_1 \simeq \frac{1}{8\pi}\frac{1}{(\hat{\lambda}\hat{\lambda}^\dagger)_{11}}\sum_{i=2,3}\mathrm{Im}\left[\left\{\left(\hat{\lambda}\hat{\lambda}^\dagger\right)_{1j}\right\}^2\right] f\left(\frac{M_j^2}{M_1^2}\right)$$

$$f(x) = \sqrt{x}\left[1 - (x+1)\ln\left(1+\frac{1}{x}\right) - \frac{1}{x-1}\right]$$



4, Implications for leptogenesis

Sign of baryon asymmetry

Seesaw mechanism

$$\mathcal{M}_{\nu_L} = -\mathcal{M}_D \mathcal{M}_R^{-1} \mathcal{M}_D^T$$

$$\Rightarrow \mathcal{M}_{\nu_L}^{-1} = -(\mathcal{M}_D^{-1})^T \mathcal{M}_R \mathcal{M}_D^{-1}$$

The mass matrix can be diagonalized by PMNS matrix

$$U_{PMNS}^T \mathcal{M}_{\nu_L} U_{PMNS} = \mathrm{diag}(m_1, m_2, m_3)$$

$$\Rightarrow \mathcal{M}_{\nu_L}^{-1} = U_{PMNS} \mathrm{diag}(m_1^{-1}, m_2^{-1}, m_3^{-1}) U_{PMNS}^T$$

$$\mathcal{M}_R = -\mathcal{M}_D U_{\mathrm{PMNS}} \mathrm{diag}(m_1, m_2, m_3) U_{\mathrm{PMNS}}^T \mathcal{M}_D$$

→ function of neutrino oscillation parameters $\theta_{12}, \theta_{23}, \theta_{13}, \delta m^2, \Delta m^2$

4, Implications for leptogenesis

Sign of baryon asymmetry

Seesaw mechanism

The mass matrix can be diagonalized

Majorana mass $\mathcal{M}_R$ is a function of the neutrino Yukawa couplings

$$\mathcal{M}_D = \mathrm{diag}(\lambda_e, \lambda_\mu, \lambda_\tau)$$

$$\mathcal{M}_R = -\mathcal{M}_D U_{\mathrm{PMNS}} \mathrm{diag}(m_1, m_2, m_3) U_{\mathrm{PMNS}}^T \mathcal{M}_D$$

→ function of neutrino oscillation parameters $\theta_{12}, \theta_{23}, \theta_{13}, \delta m^2, \Delta m^2$

4, Implications for leptogenesis

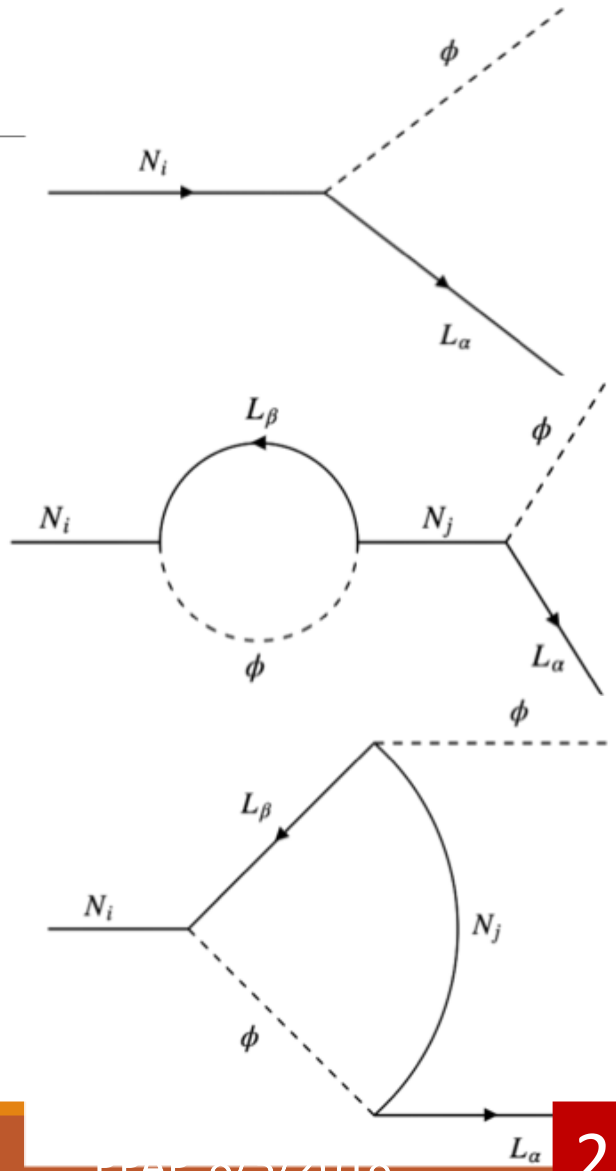
Sign of baryon asymmetry

Yukawa couplings

$$\mathrm{diag}(\lambda_e, \lambda_\mu, \lambda_\tau) = \lambda \mathrm{diag}(\cos\theta, \sin\theta\cos\phi, \sin\theta\sin\phi) \equiv \lambda n$$

Asymmetry parameter

$$\epsilon_1 \simeq \frac{1}{8\pi}\frac{\lambda^2}{(\hat{n}\hat{n}^\dagger)_{11}} \sum_{i=2,3} \mathrm{Im}\left[\left\{(\hat{n}\hat{n}^\dagger)_{1j}\right\}^2\right] f\left(\frac{M_j^2}{M_1^2}\right)$$



→ Sign of the asymmetry parameter depends on (θ, ϕ)

4, Implications for leptogenesis

Baryon asymmetry and asymmetry parameter

Relation between baryon and lepton generated

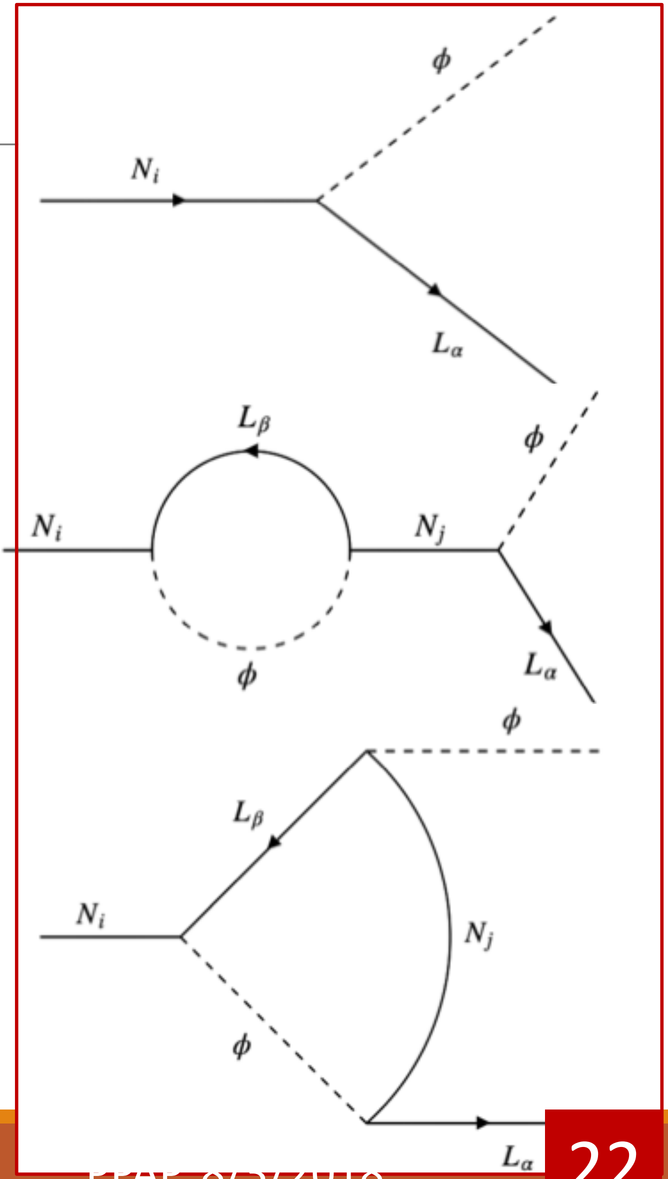
$$\frac{n_B/s}{n_L/s} = -\frac{28}{79} < 0$$

Observed baryon asymmetry of the universe

$$Y_{\Delta B} \equiv \frac{n_B}{s} \simeq 8.7 \times 10^{-11} > 0$$

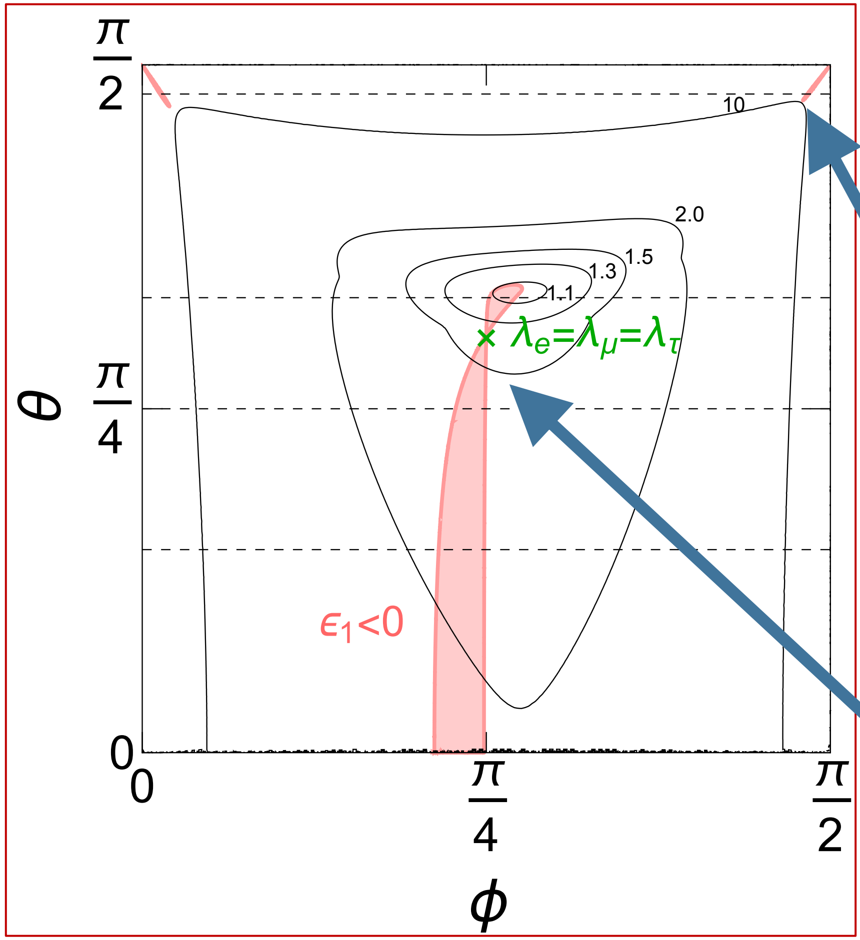
Sign of asymmetry parameter is negative

$$\epsilon_1 < 0$$



4, Implications for leptogenesis

$\mathrm{U}(1)_{L_\mu - L_\tau}$ a) Sign of asymmetry parameter



- Contours show the right handed neutrino mass ratio M_2/M_1

- Asymmetry parameter ϵ_1 can be negative ($\epsilon_1 < 0$) when some of the right handed neutrinos are degenerate in mass

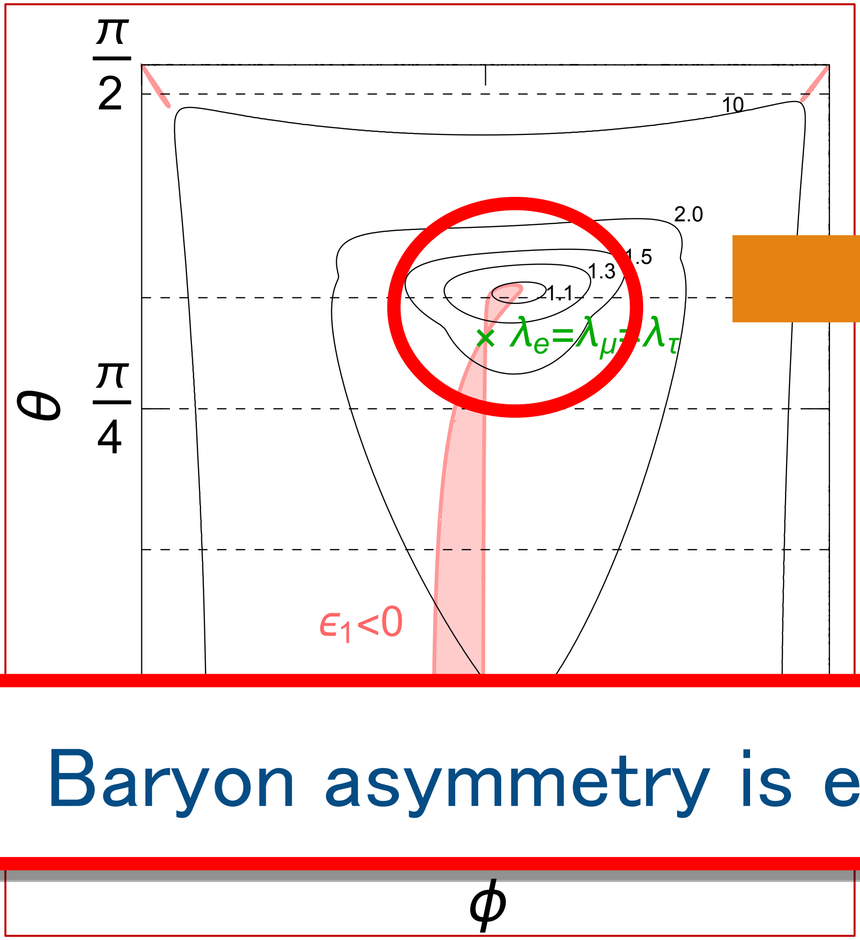
$M_2 \simeq M_3$

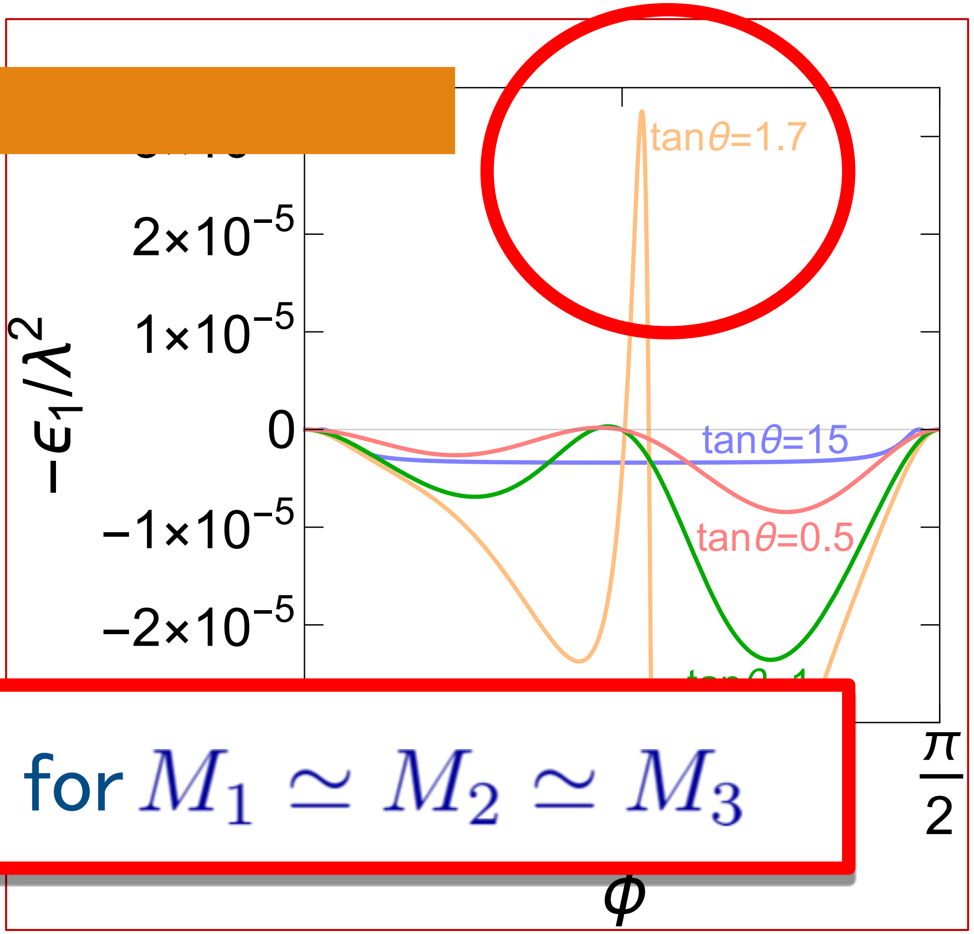
$M_1 \simeq M_2$

4, Implications for leptogenesis

$\mathrm{U}(1)_{L_\mu - L_\tau}$

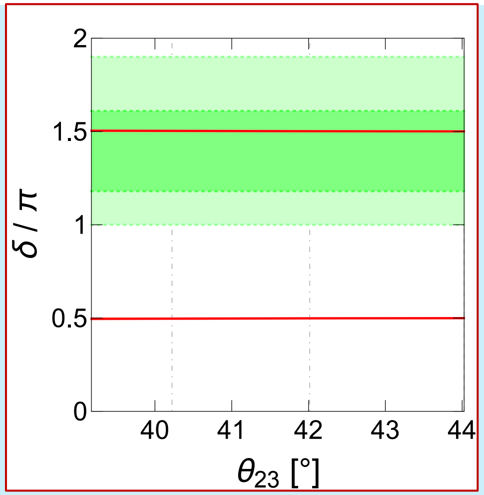
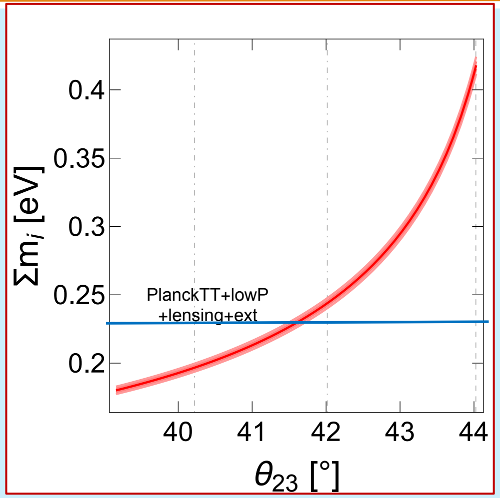
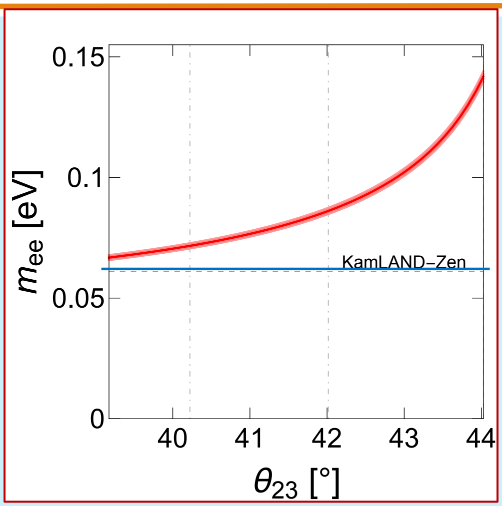
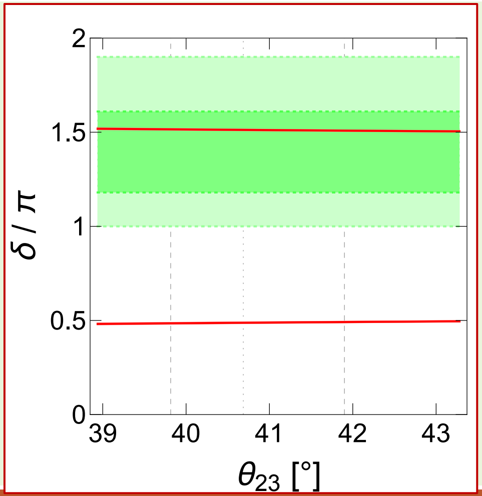
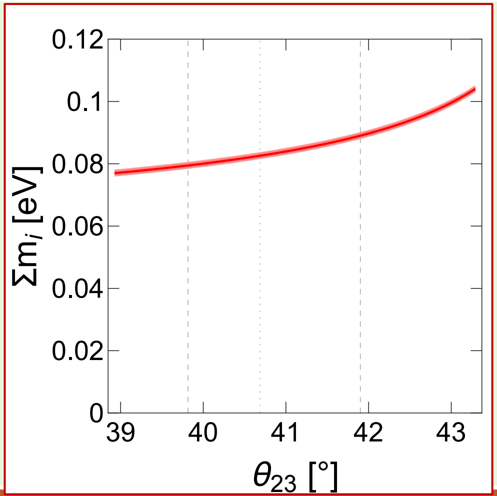
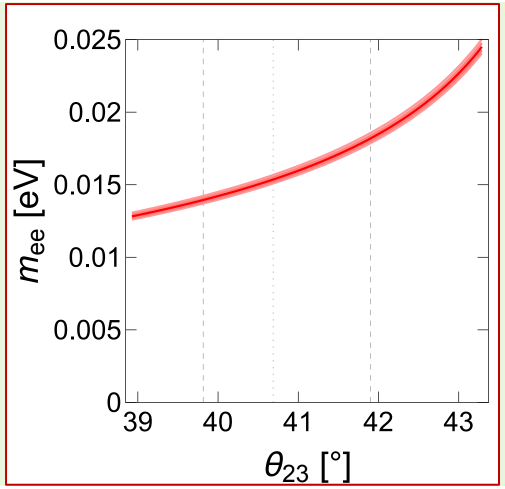
b) Scale of asymmetry parameter





Baryon asymmetry is enough large for $M_1 \simeq M_2 \simeq M_3$

5, Other U(1) gauge symmetries

X	δ/π	$\Sigma_i m_i$ [eV]	$\langle m_{\beta\beta}\rangle$ [eV]
$B-L_e-3L_\mu+L_\tau$			
$B-L_e+L_\mu-3L_\tau$			

5, Other U(1) gauge symmetries

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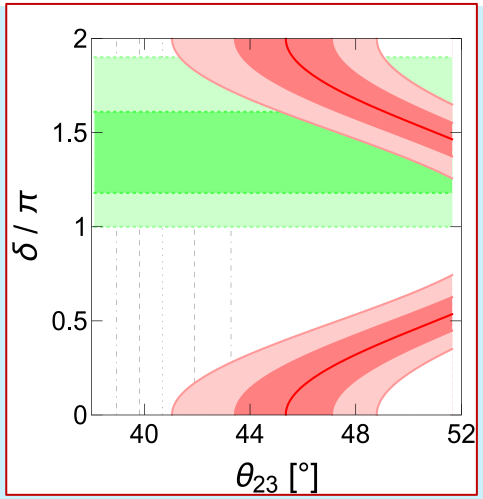
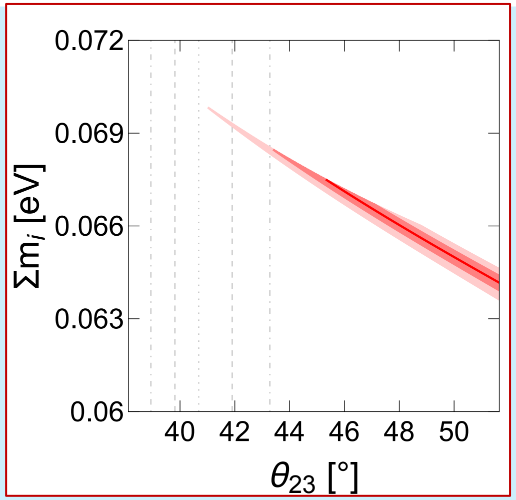
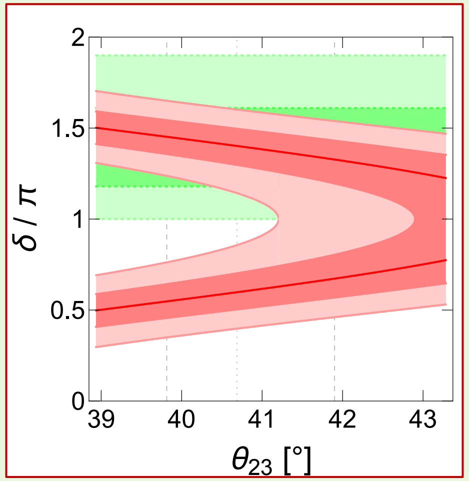
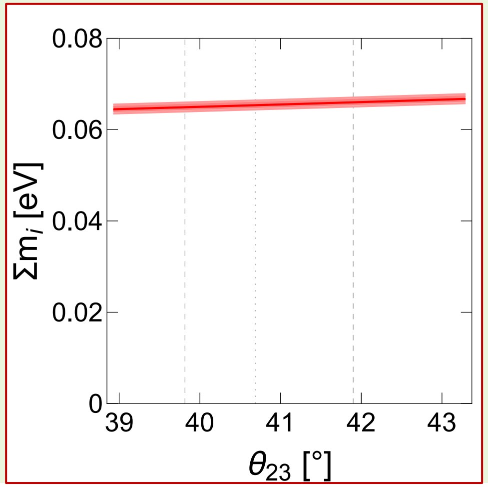
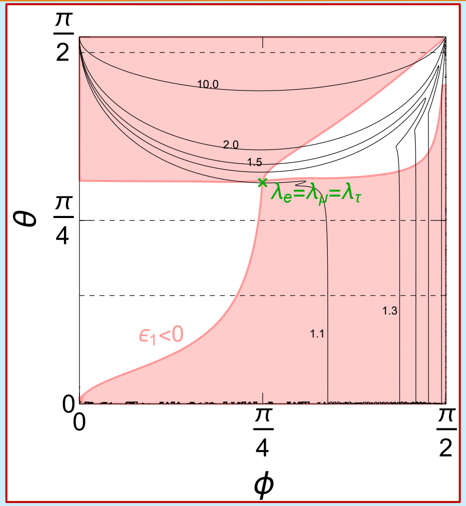
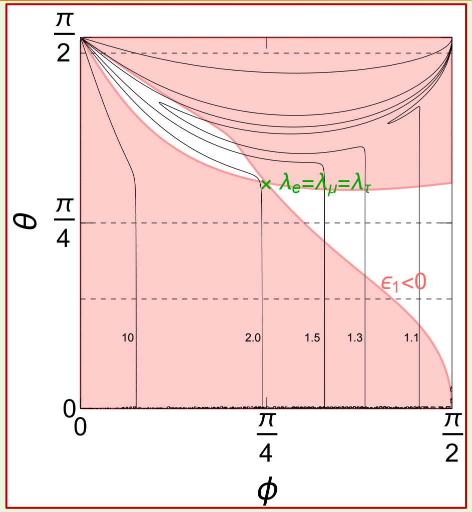
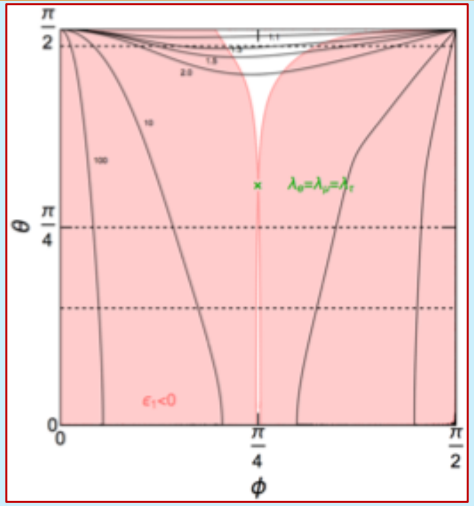
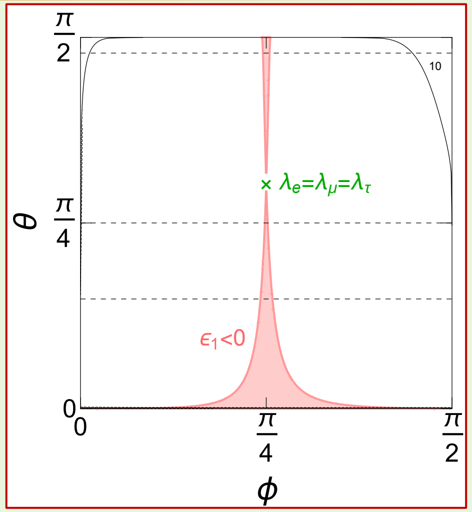
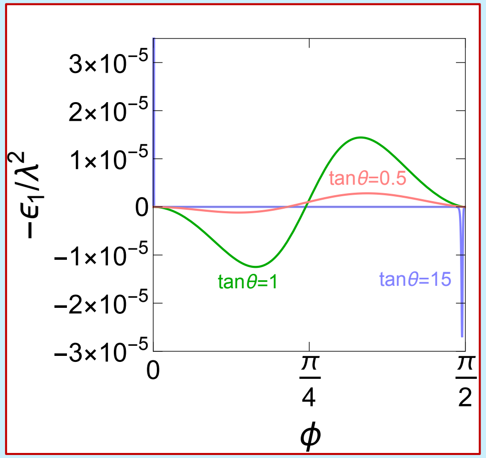
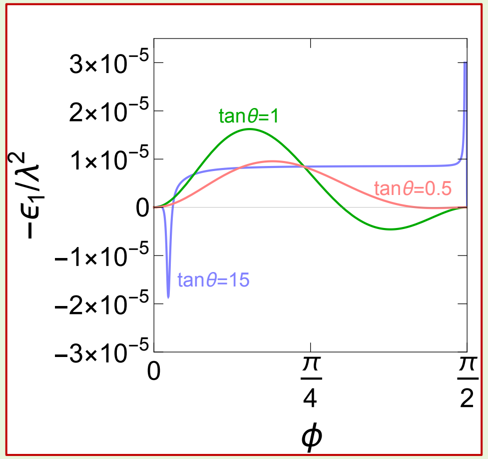
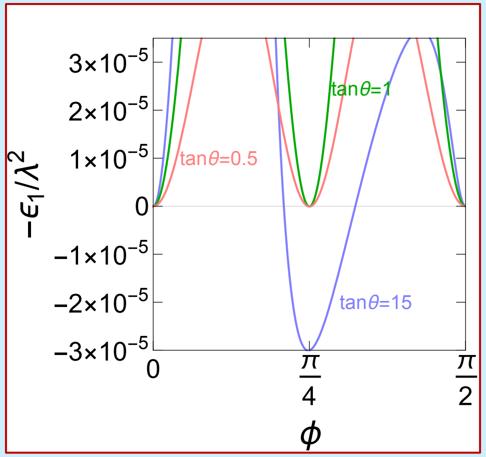
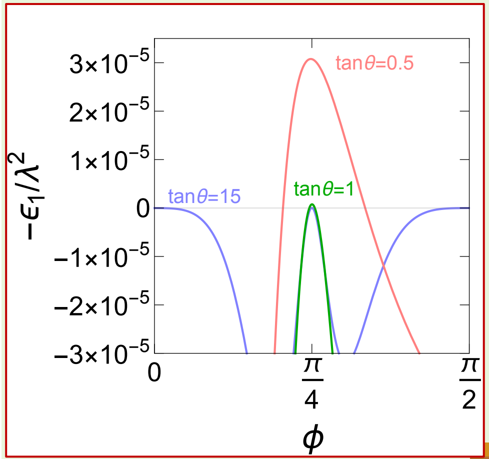
$B+L_e-3L_\mu-L_\tau$			0
$B+L_e-L_\mu-3L_\tau$			0

5, Other U(1) gauge symmetries

X	$B-L_e-3L_\mu+L_\tau$	$B-L_e+L_\mu-3L_\tau$	$B+L_e-3L_\mu-L_\tau$	$B+L_e-L_\mu-3L_\tau$
Sign				
Scale				

6, Conclusions

- 5 U(1) gauge symmetries satisfy two zero minor condition and consistent with the neutrino oscillation data.

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Back Up

1, Introduction

U(1) gauge symmetry and neutrino mass matrix

$$\mathrm{U}(1)_{y_e L_e + y_\mu L_\mu - (y_e + y_\mu) L_\tau}$$

$$L_e - L_\mu \quad \left(\begin{array}{c|c|c} 0 & & 0 \\ \hline & 0 & 0 \\ \hline 0 & 0 & \end{array}\right)$$

$$L_\mu - L_\tau \quad \left(\begin{array}{c|c|c} & 0 & 0 \\ \hline 0 & 0 & \\ \hline 0 & & 0 \end{array}\right)$$

$$L_e - L_\tau \quad \left(\begin{array}{c|c|c} 0 & 0 & \\ \hline 0 & & 0 \\ \hline & 0 & 0 \end{array}\right)$$

$$\mathrm{U}(1)_{B - x_e L_e - x_\mu L_\mu - (3 - x_e - x_\mu) L_\tau}$$

$$B - L_e - 3L_\mu - L_\tau \quad \left(\begin{array}{c|c|c} 0 & 0 & \\ \hline 0 & 0 & 0 \\ \hline & 0 & 0 \end{array}\right)$$

$$B - L_e + L_\mu - 3L_\tau \quad \left(\begin{array}{c|c|c} 0 & & 0 \\ \hline & 0 & 0 \\ \hline 0 & 0 & 0 \end{array}\right)$$

$$B + L_e - 3L_\mu - L_\tau \quad \left(\begin{array}{c|c|c} 0 & 0 & \\ \hline 0 & 0 & 0 \\ \hline & 0 & 0 \end{array}\right)$$

$$B + L_e - L_\mu - 3L_\tau \quad \left(\begin{array}{c|c|c} 0 & & 0 \\ \hline & 0 & 0 \\ \hline 0 & 0 & 0 \end{array}\right)$$

and eight others

1, Introduction

U(1) gauge symmetry and neutrino mass matrix

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$$\mathrm{U}(1)_{B - x_e L_e - x_\mu L_\mu - (3 - x_e - x_\mu) L_\tau}$$

$$B - L_e - 3L_\mu + L_\tau \quad \begin{pmatrix} & 0 & \\ 0 & 0 & \\ & & \end{pmatrix}$$

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$$B + L_e - L_\mu - 3L_\tau \quad \begin{pmatrix} & & \\ & & 0 \\ & 0 & 0 \end{pmatrix}$$

and eight others

2, Analysis of mass matrix

Minimal gauged $\mathrm{U}(1)_{L_\mu - L_\tau}$ model

Charge assignment

field	N_e	N_μ	N_τ
$\mathrm{U}(1)_{L_\mu - L_\tau}$	0	$+a$	$-a$

$|a| \neq 1$

$\mathrm{U}(1)_{L_\mu - L_\tau}$ charge of $N_\alpha^c L_\beta$

$$\begin{pmatrix} 0 & +1 & -1 \\ -a & -a+1 & -a-1 \\ +a & +a+1 & +a-1 \end{pmatrix}$$

Only (e, e) component in $\mathcal{M}_{\nu_L}$ can be non-zero

2, Analysis of mass matrix

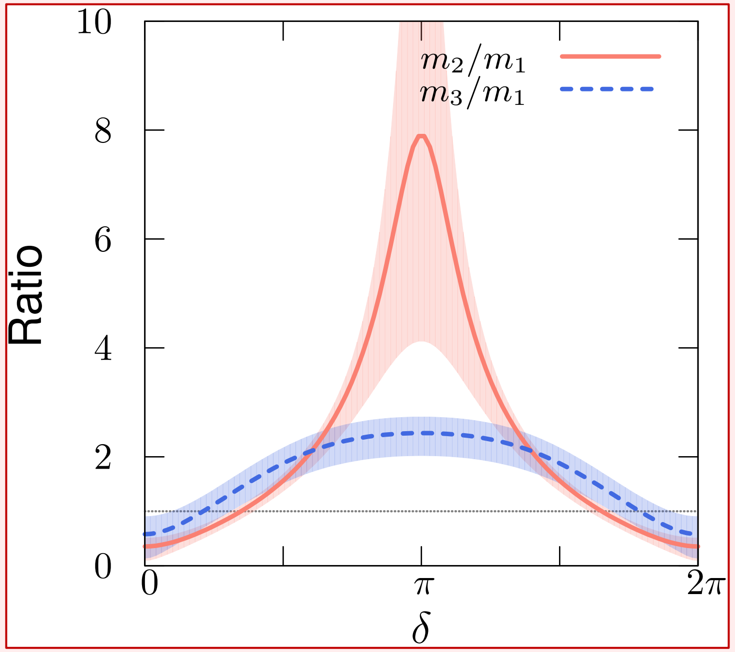
Analysis of two zero minor conditions

Two zero minor conditions

$$\begin{cases} \frac{1}{m_1}V_{\mu 1}^2 + \frac{1}{m_2}V_{\mu 2}^2 e^{i\alpha 2} + \frac{1}{m_3}V_{\mu 3}^2 e^{i\alpha_3} = 0 \\ \frac{1}{m_1}V_{\tau 1}^2 + \frac{1}{m_2}V_{\tau 2}^2 e^{i\alpha 2} + \frac{1}{m_3}V_{\tau 3}^2 e^{i\alpha_3} = 0 \end{cases}$$

$$\Longrightarrow \quad e^{i\alpha_2} = \frac{m_2}{m_1}R_2(\delta), \quad e^{i\alpha_3} = \frac{m_3}{m_1}R_3(\delta)$$

$$\Longrightarrow \quad \frac{m_2}{m_1} = \frac{1}{|R_2(\delta)|}, \quad \frac{m_3}{m_1} = \frac{1}{|R_3(\delta)|}$$



Neutrino mass ratios can be obtain as functions of the Dirac CP phase

2, Analysis of mass matrix

Analysis of two zero minor conditions

$$\frac{m_2}{m_1} = \frac{1}{|R_2(\delta)|}, \qquad \frac{m_3}{m_1} = \frac{1}{|R_3(\delta)|}$$

$$\Longrightarrow \begin{cases} \delta m^2 = m_1^2 \left(\dfrac{1}{|R_2(\delta)|} - 1 \right) \\ \Delta m^2 + \dfrac{\delta m^2}{2} = m_1^2 \left(\dfrac{1}{|R_3(\delta)|} - 1 \right) \end{cases}$$

$$m_1 = f(\theta_{12}, \theta_{23}, \theta_{13}, \delta m^2, \Delta m^2)$$

$$\Longrightarrow |R_3(\delta)| \left(1 - |R_2(\delta)|\right) - \epsilon \, |R_2(\delta)| \left(1 - |R_3(\delta)|\right) = 0 \,, \qquad \epsilon \equiv \frac{\delta m^2}{\Delta m^2 + \delta m^2/2} \ll 1$$

$$\Longrightarrow \delta = f(\theta_{12}, \theta_{23}, \theta_{13}, \epsilon)$$

Dirac CP phase and neutrino masses can be obtain as functuions of the neutrino oscillation parameters

2, Analysis of mass matrix

Quantum corrections to neutrino mass matrix

$U(1)_{L_\mu - L_\tau}$ symmetry breaking scale $\gg$ electroweak scale

→ Large quantum corrections break two zero minor structure of $\mathcal{M}_{\nu_L}$?

↓

Result

The two-zero minor neutrino-mass structure in our model is robust against quantum corrections

2, Analysis of mass matrix

Quantum corrections to neutrino mass matrix

The right-handed neutrinos are integrated out to give the following dimension-five effective operator:

$$\mathcal{L}_{eff} = \frac{1}{2} C_{\alpha\beta} (L_\alpha \cdot H)(L_\beta \cdot H) + \text{h.c.}$$

$$C_{\alpha\beta} = \begin{pmatrix} * & * & * \\ * & 0 & * \\ * & * & 0 \end{pmatrix}$$

@ right-handed neutrino mass scale

2, Analysis of mass matrix

Quantum corrections to neutrino mass matrix

The right-handed neutrinos are integrated out to give the following dimension-five effective operator:

$$\mathcal{L}_{eff} = \frac{1}{2} C_{\alpha\beta} (L_\alpha \cdot H)(L_\beta \cdot H) + \text{h.c.}$$

The renormalization group equation of the Wilson coefficient $C_{\alpha\beta}$ at one-loop level is

$$\mu \frac{dC}{d\mu} = -\frac{3}{32\pi^2} \left[(Y_e^\dagger Y_e)^T C + C (Y_e^\dagger Y_e) \right] + \frac{K}{16\pi^2} C$$

with

$$K = -3g_2^2 + 2\text{Tr}\left(3Y_u^\dagger Y_u + 3Y_d^\dagger Y_d + Y_e^\dagger Y_e \right) + 2\lambda$$

2, Analysis of mass matrix

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The right-handed neutrinos are integ…

the following dimension-five effectiv…

$$\mathcal{L}_{eff} = \frac{1}{2} C_{\alpha\beta} (L_\alpha \cdot H)(L_\beta \cdot H) + \ldots$$

The renormalization group equation of the Wilson coefficient…

Higgs quartic coupling

$$\mathcal{L}_{\rm quart} = -\frac{1}{2}\lambda (H^\dagger H)^2$$

$\mathrm{SU}(2)_L$ gauge coupling

up-type, down-type, and charged-lepton Yukawa matrices

with

$$K = -3g_2^2 + 2\mathrm{Tr}\left(3Y_u^\dagger Y_u + 3Y_d^\dagger Y_d + Y_e^\dagger Y_e\right) + 2\lambda$$

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$$C(t) = I_K(t)\mathcal{I}(t)C(0)\mathcal{I}(t)$$

Y_e : diagonal

$\Longrightarrow \mathcal{I}(t)$: diagonal

where

$$t \equiv \ln(\mu/\mu_0)$$ μ_0 : initial scale

$$I_K(t) = \exp\left[\frac{1}{16\pi^2}\int_0^t K(t')dt'\right],\ \mathcal{I}(t) = \exp\left[-\frac{3}{32\pi^2}\int_0^t Y_e^\dagger Y_e(t')dt'\right]$$

2, Analysis of mass matrix

Quantum corrections to neutrino mass matrix

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⇓

$$C(t) = I_K(t)\mathcal{I}(t)C(0)\mathcal{I}(t)$$

⇓

$$C^{-1}_{\mu\mu}(0) = C^{-1}_{\tau\tau}(0) = 0 \Longrightarrow C^{-1}_{\mu\mu}(t) = C^{-1}_{\tau\tau}(t) = 0$$

3, Predictions for neutrino parameters

Neutrino oscillation parameters

a) Normal Ordering (NO)

F. Capozzi, et al. [2017]

Parameter	Best fit	1σ range	2σ range
$\delta m^2/10^{-5}\mathrm{eV}^2$	7.37	$7.21 - 7.54$	$7.07 - 7.73$
$\Delta m^2/10^{-3}\mathrm{eV}^2$	2.525	$2.495 - 2.567$	$2.454 - 2.606$
$\sin^2\theta_{12}/10^{-1}$	2.97	$2.81 - 3.14$	$2.65 - 3.34$
$\sin^2\theta_{23}/10^{-1}$	4.25	$4.10 - 4.46$	$3.95 - 4.70$
$\sin^2\theta_{13}/10^{-1}$	2.15	$2.08 - 2.22$	$1.99 - 2.31$

3, Predictions for neutrino parameters

Neutrino oscillation parameters

b) Inverted Ordering (IO)

F. Capozzi, et al. [2017]

Parameter	Best fit	1σ range	2σ range
$\delta m^2/10^{-5}\mathrm{eV}^2$	7.37	7.21 – 7.54	7.07 – 7.73
$\Delta m^2/10^{-3}\mathrm{eV}^2$	2.505	2.473 – 2.539	2.430 – 2.582
$\sin^2\theta_{12}/10^{-1}$	2.97	2.81 – 3.14	2.65 – 3.34
$\sin^2\theta_{23}/10^{-1}$	5.89	$4.17 - 4.48 \oplus 5.67 - 6.05$	$3.99 - 4.83 \oplus 5.33 - 6.21$
$\sin^2\theta_{13}/10^{-2}$	2.16	2.07 – 2.24	1.98 – 2.33

3, Predictions for neutrino parameters

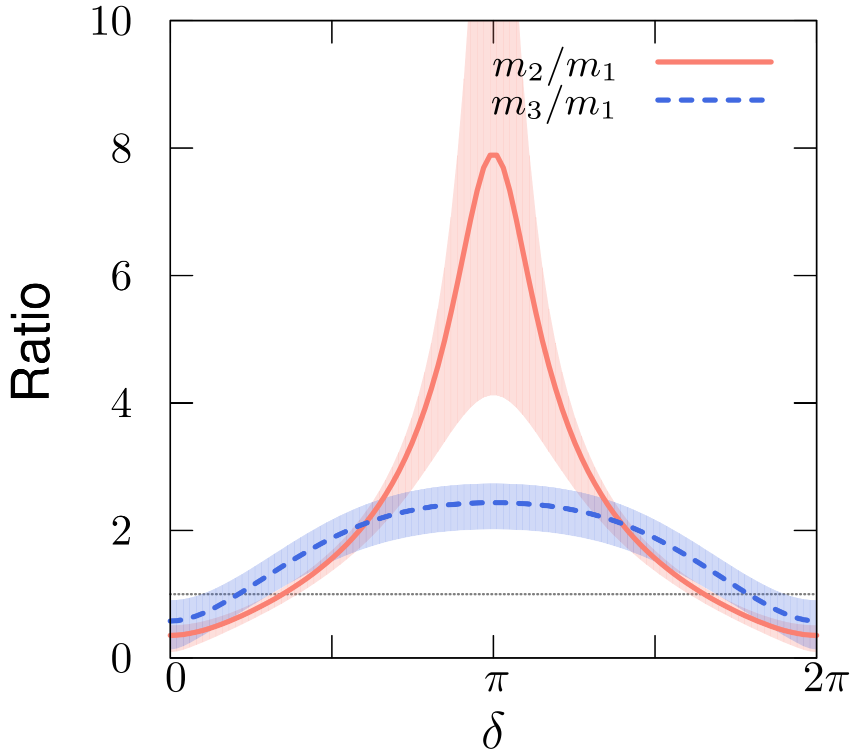
$\mathrm{U}(1)_X$ symmetry and two zero minor structure

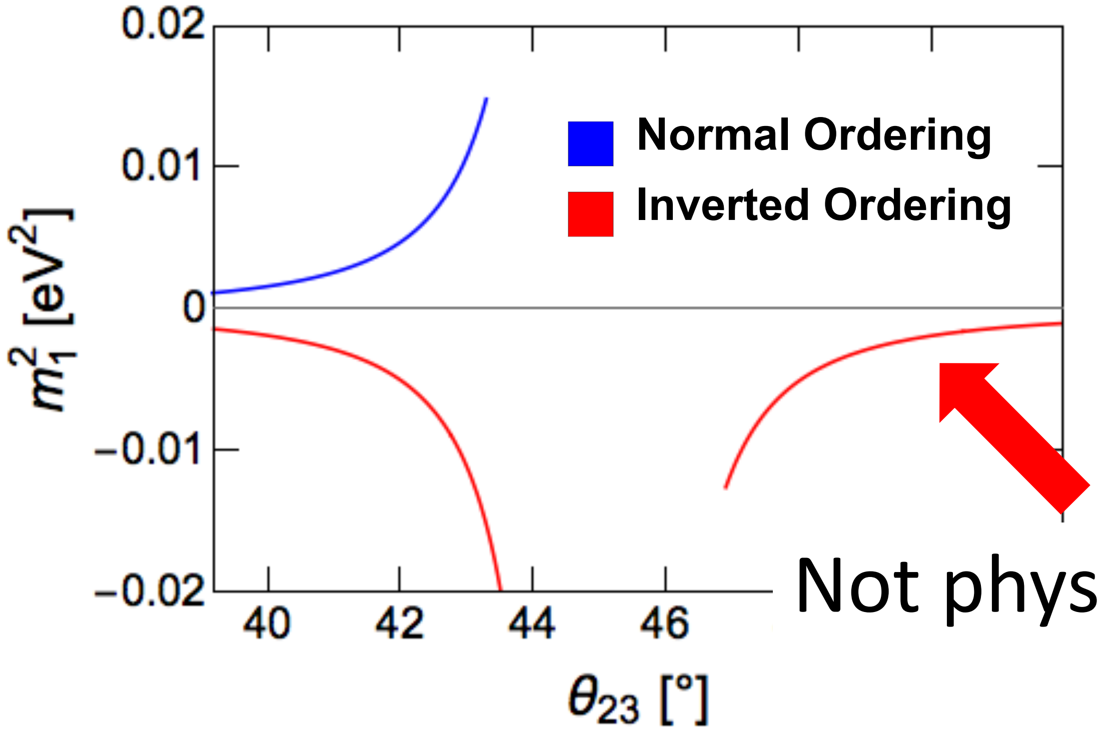
Five U(1) symmetries have two zero minor structure and consistent with neutrino oscillation data

X	$\mathcal{M}_R$	Mass Ordering
$L_\mu - L_\tau$:	$\begin{pmatrix} & & \\ & 0 & \\ & & 0 \end{pmatrix}$,	NO
$B - L_e - 3L_\mu + L_\tau$:	$\begin{pmatrix} & 0 & \\ 0 & 0 & \\ & & \end{pmatrix}$,	IO
$B - L_e + L_\mu - 3L_\tau$:	$\begin{pmatrix} & & 0 \\ & & \\ 0 & & 0 \end{pmatrix}$,	NO
$B + L_e - 3L_\mu - L_\tau$:	$\begin{pmatrix} & & \\ & 0 & 0 \\ & 0 & \end{pmatrix}$,	NO
$B + L_e - L_\mu - 3L_\tau$:	$\begin{pmatrix} & & \\ & & 0 \\ & 0 & 0 \end{pmatrix}$,	NO

3, Predictions for neutrino parameters

$\mathrm{U}(1)_{L_\mu - L_\tau}$ z) Mass ordering

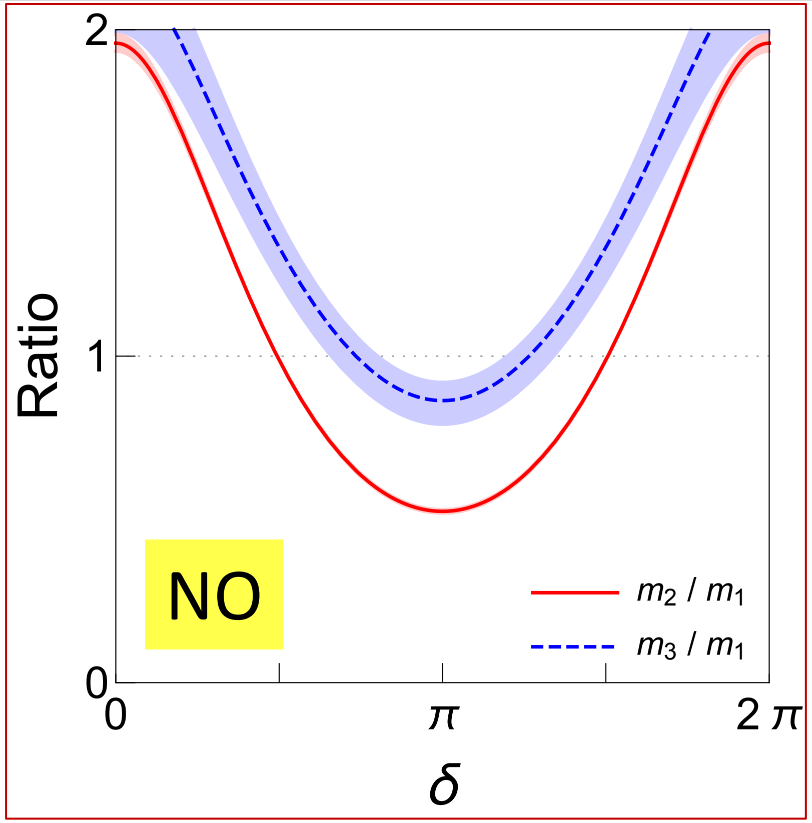


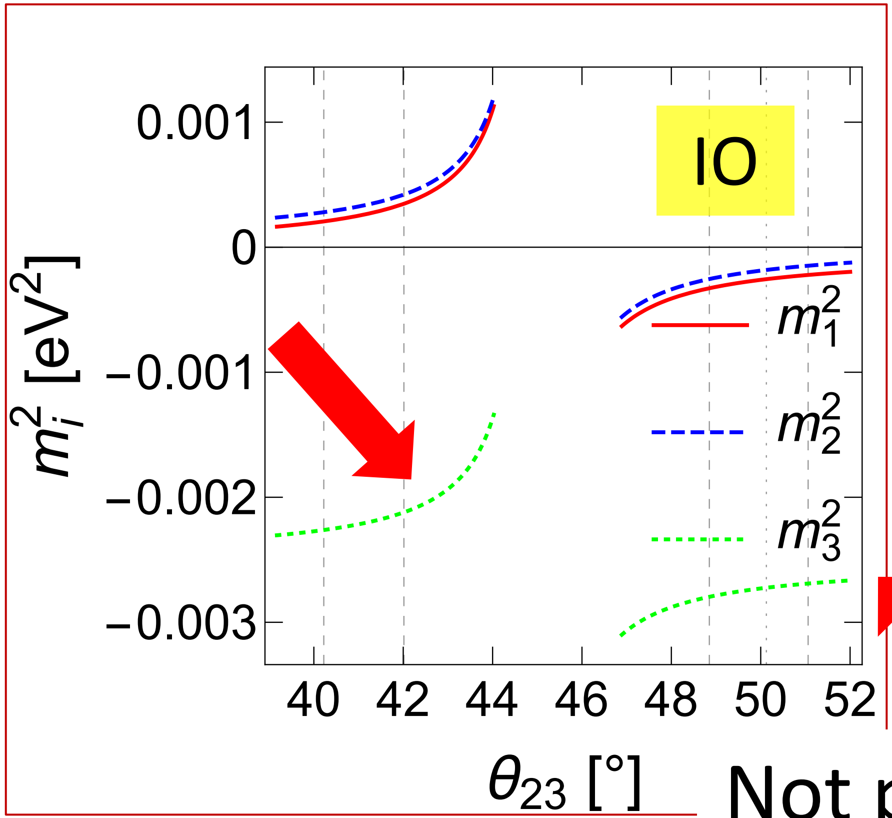


Mass : not physical → IO : excluded, NO : OK

3, Predictions for neutrino parameters

$U(1)_{B-L_e+L_\mu-3L_\tau}$ a) Mass Ordering



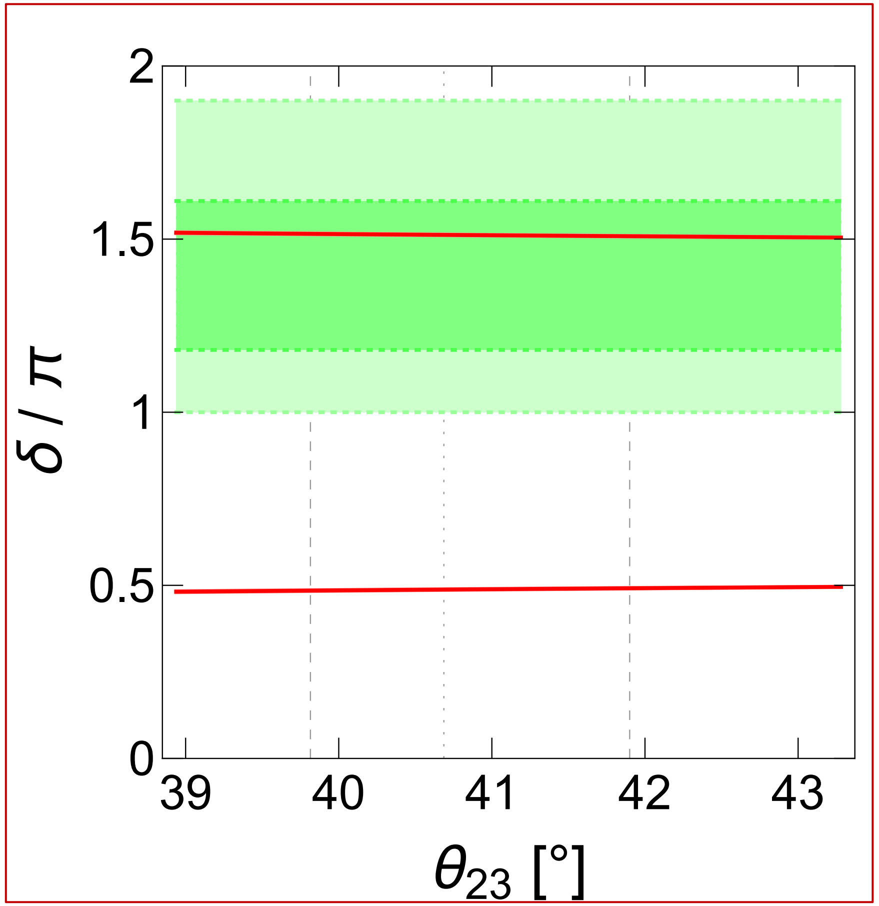


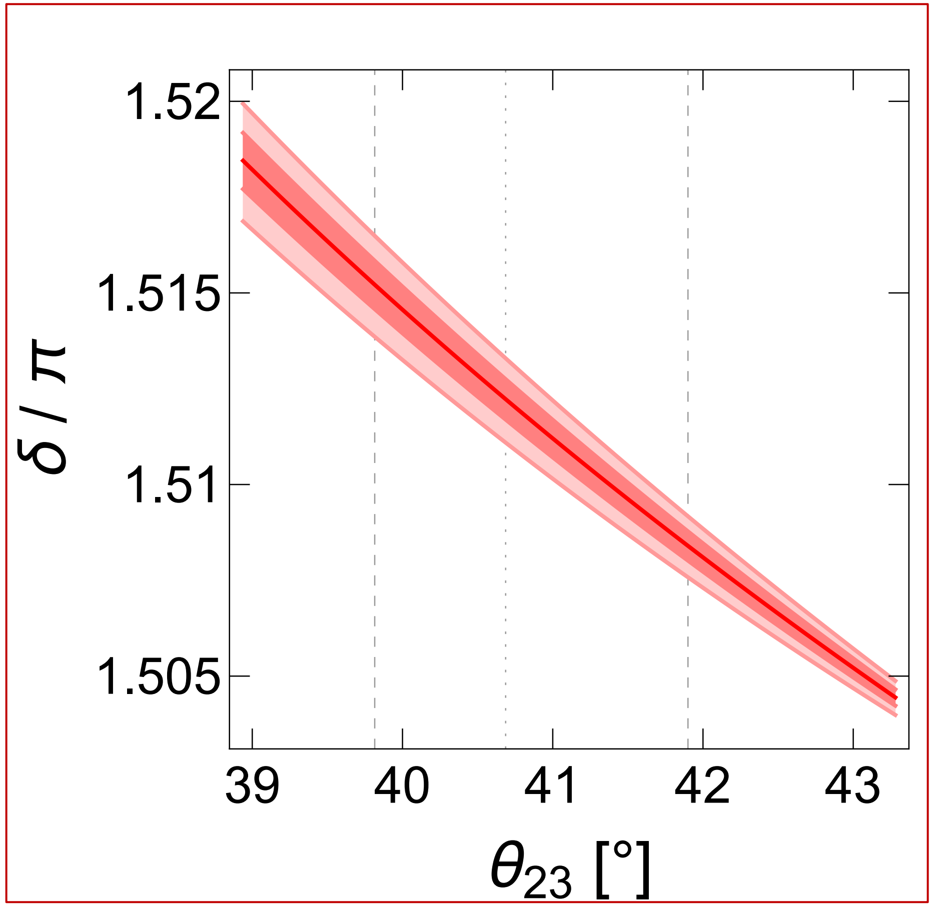
Not physical

IO : excluded, NO : OK

3, Predictions for neutrino parameters

$\mathrm{U}(1)_{B-L_e+L_\mu-3L_\tau}$ b) Dirac CP phase





3, Predictions for neutrino parameters

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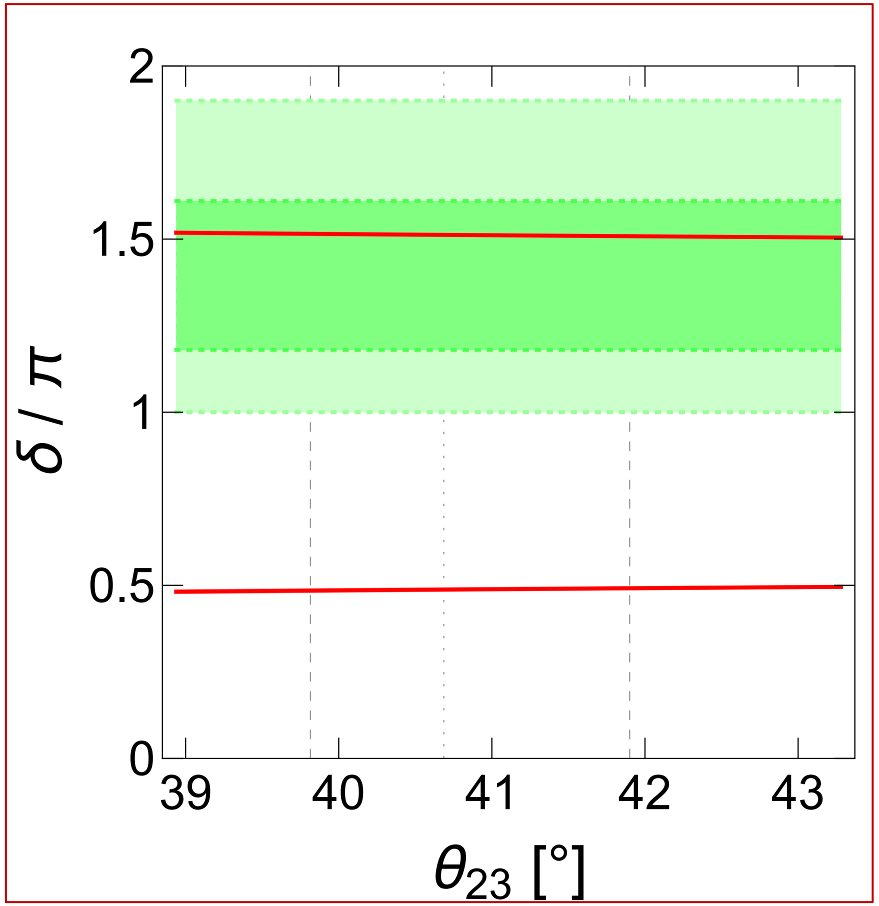


In the limit of $\dfrac{\delta m^2}{\Delta m^2 + \delta m^2/2} \to 0$

$$\cos\delta = \frac{4\cot 2\theta_{12}\cot 2\theta_{23}\sin\theta_{13}}{3-\cot 2\theta_{13}}$$

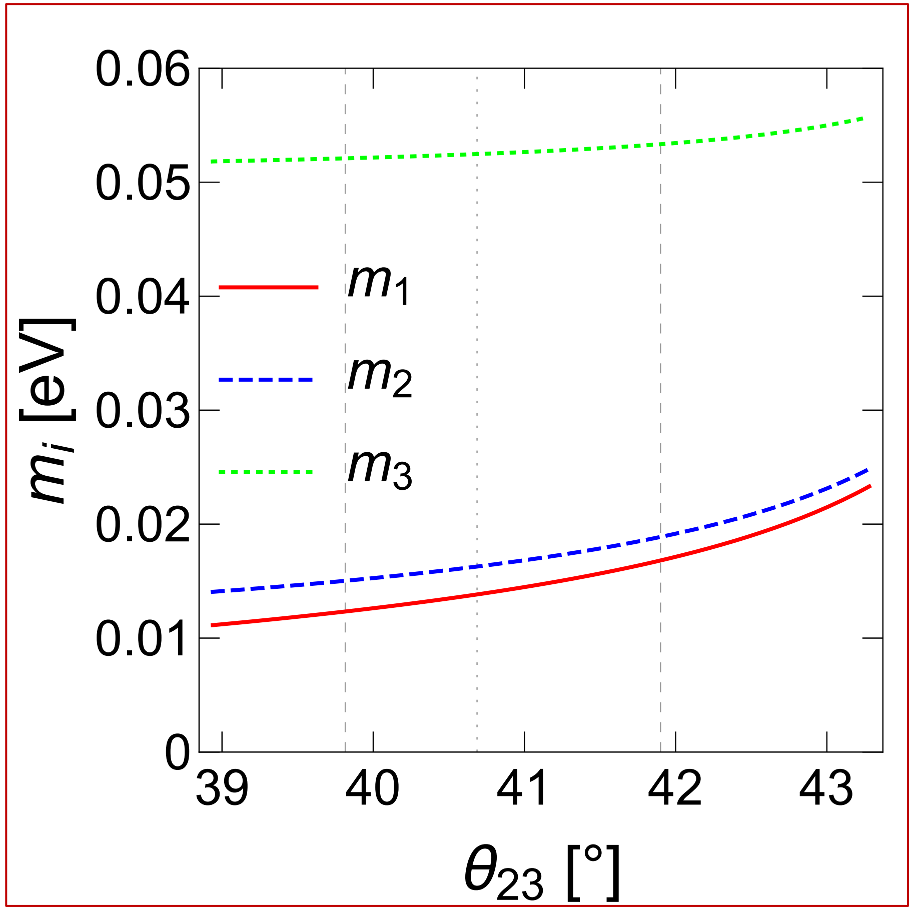
$$\simeq 0$$

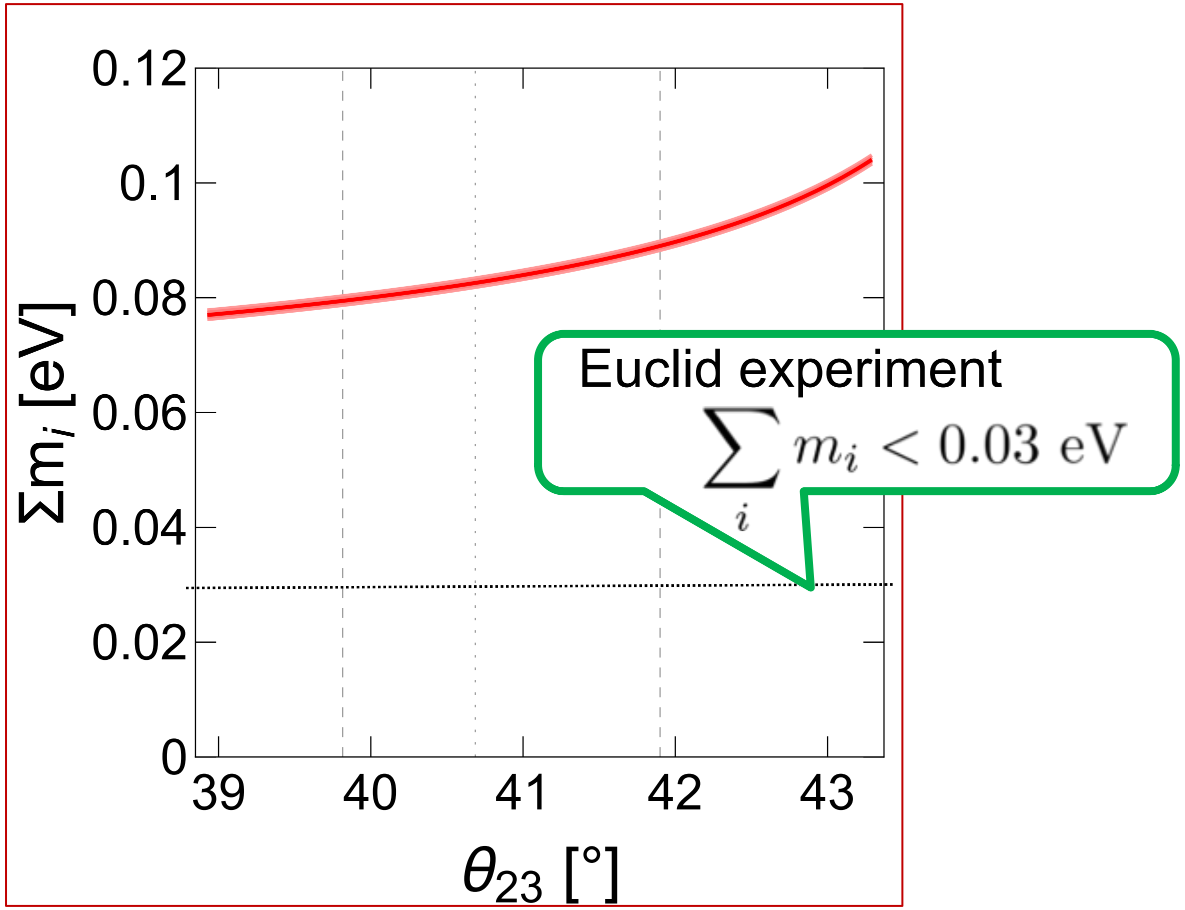
$\theta_{13} \ll 1$

$$\delta \simeq \frac{\pi}{2}, \frac{3}{2}\pi$$

3, Predictions for neutrino parameters

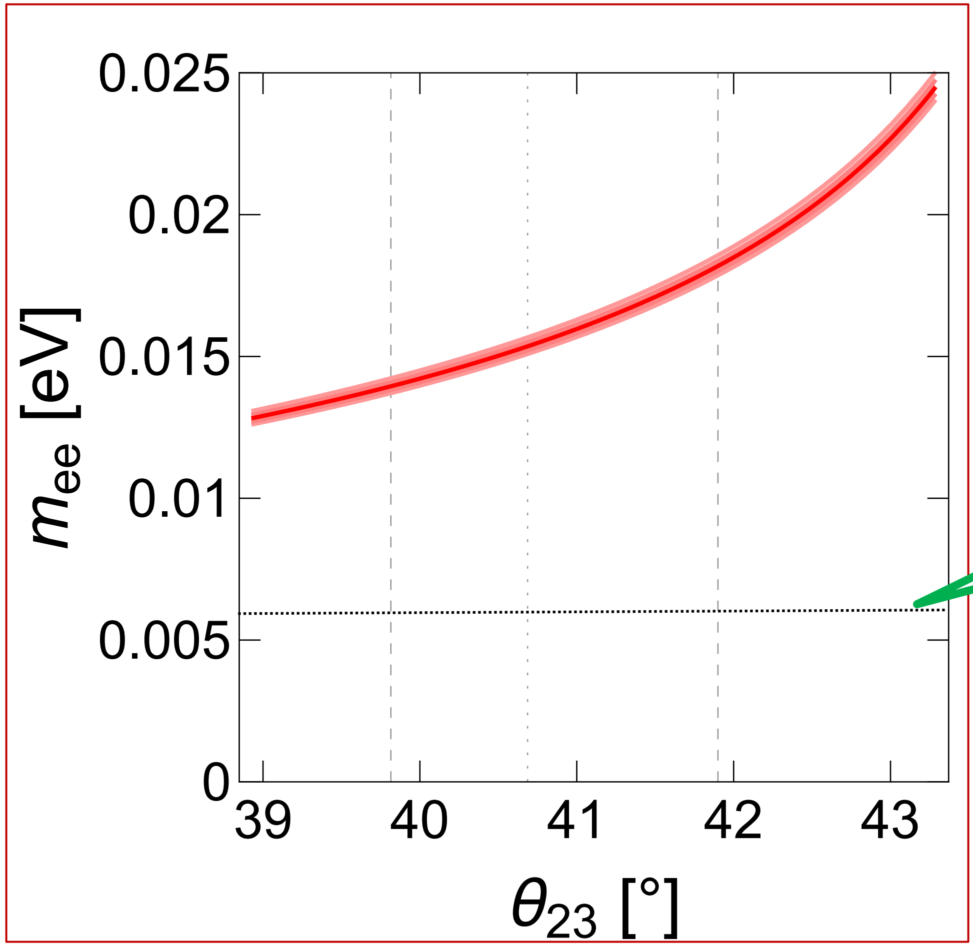
$\mathrm{U}(1)_{B-L_e+L_\mu-3L_\tau}$ c) Neutrino masses and sum of them





3, Predictions for neutrino parameters

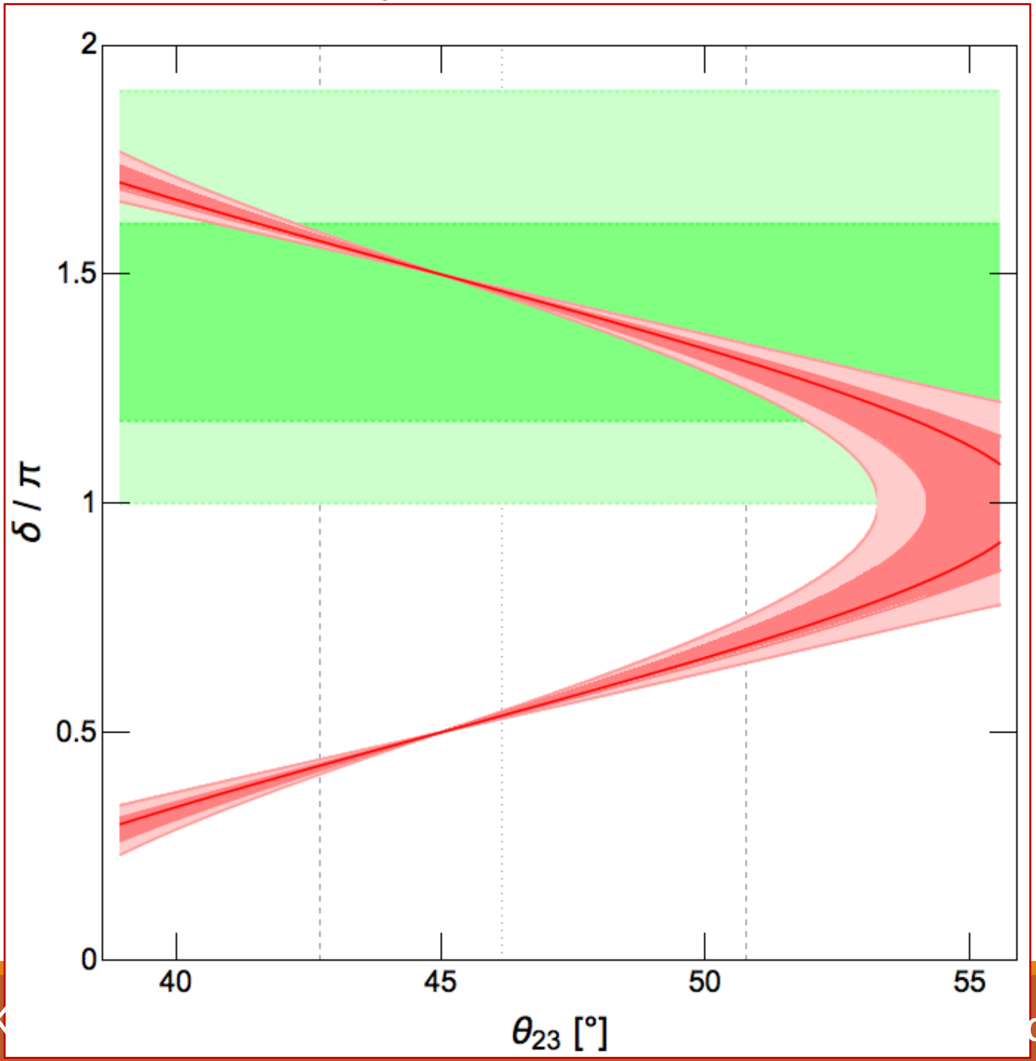
$\mathrm{U}(1)_{B-L_e+L_\mu-3L_\tau}$ d) Effective Majorana neutrino mass



CUPID experiment
$\langle m_{\beta\beta} \rangle <$ 6-15 [meV]

3, Predictions for neutrino parameters

$U(1)_{L_\mu - L_\tau}$ b) Dirac CP phases



T2K

$$\sin^2\theta_{23} = 0.55^{+0.05}_{-0.09}$$

dark (light) red band

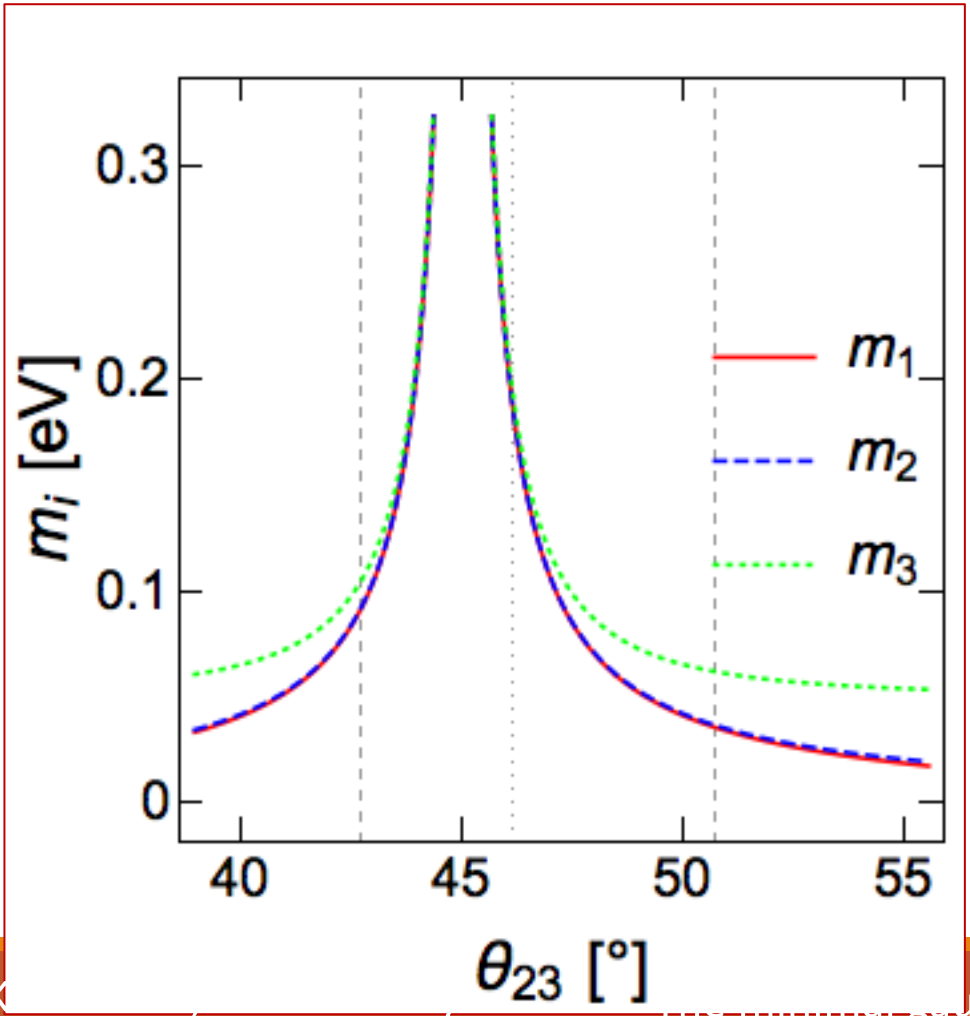
: uncertainty coming from the 1σ (2σ) errors in the parameters $\theta_{12}, \theta_{13}, \delta m^2,$ and Δm^2

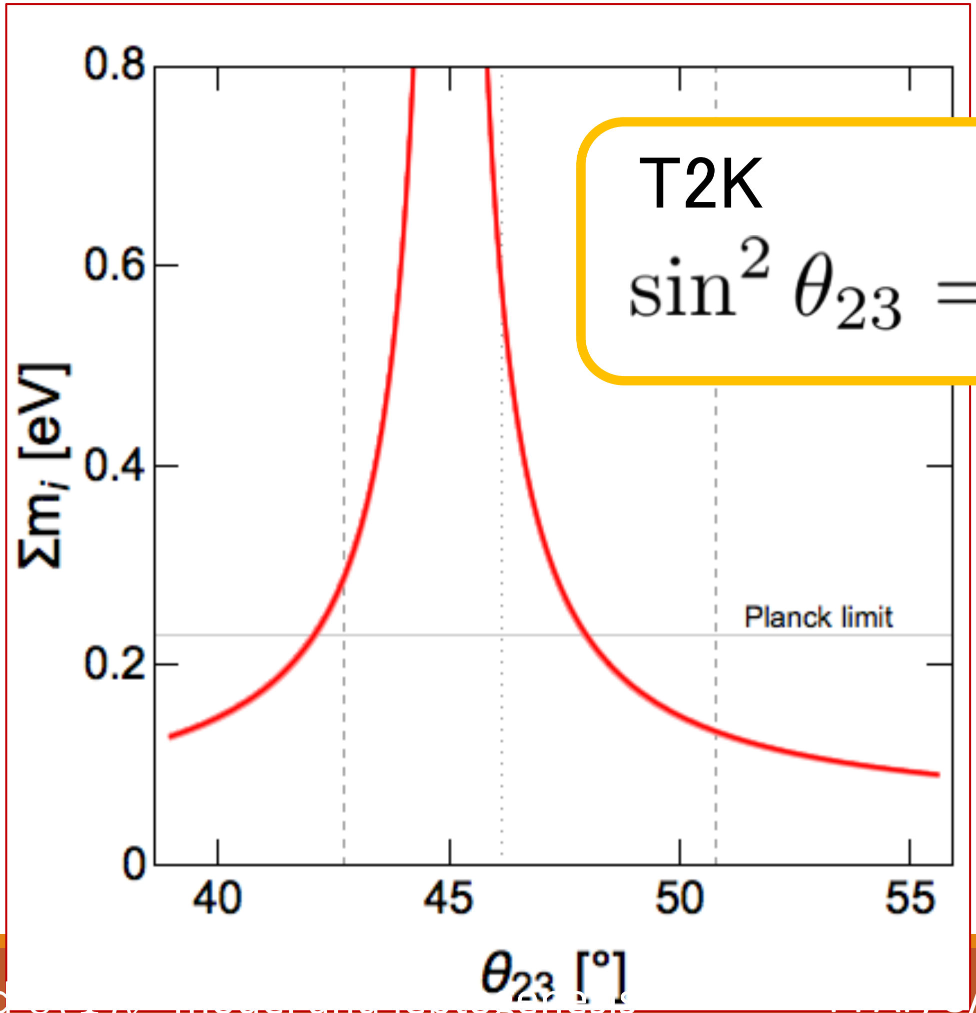
dark (light) green band

: 1σ (2σ) favored region of δ

3, Predictions for neutrino parameters

$U(1)_{L_\mu - L_\tau}$ c) Neutrino masses and sum of them



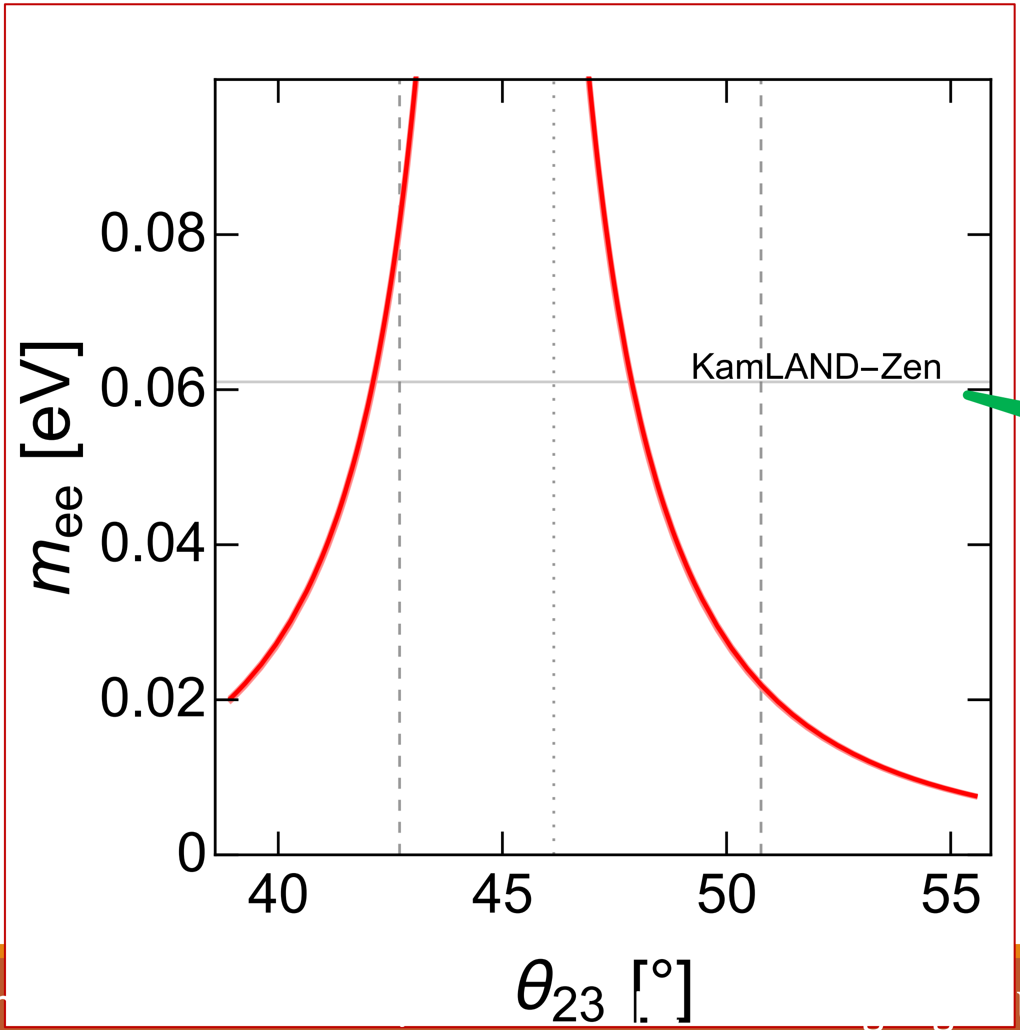


T2K

$$\sin^2\theta_{23} = 0.55^{+0.05}_{-0.09}$$

3, Predictions for neutrino parameters

$U(1)_{L_\mu - L_\tau}$ d) Effective Majorana neutrino mass



T2K

$$\sin^2\theta_{23} = 0.55^{+0.05}_{-0.09}$$

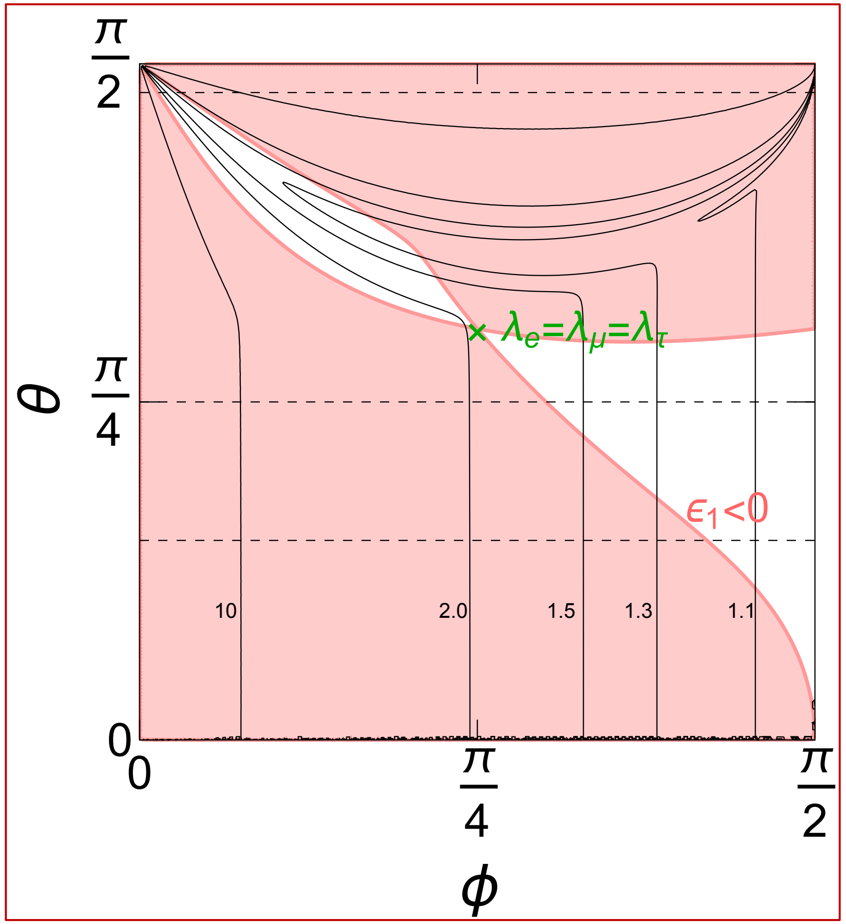
The strongest bound on $\langle m_{\beta\beta}\rangle$

uncertainty of the nuclear matrix element for ^{136}Xe

$$\langle m_{\beta\beta}\rangle < 0.061\text{-}0.165 \text{ eV}$$

4, Implications for leptogenesis

$\mathrm{U}(1)_{B-L_e+L_\mu-3L_\tau}$ a) Sign of asymmetry parameter

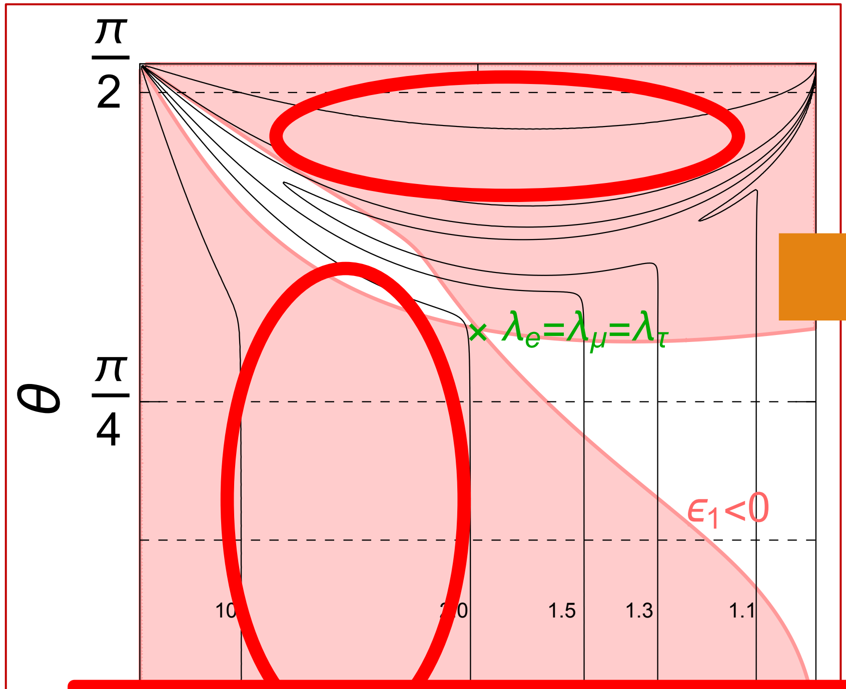


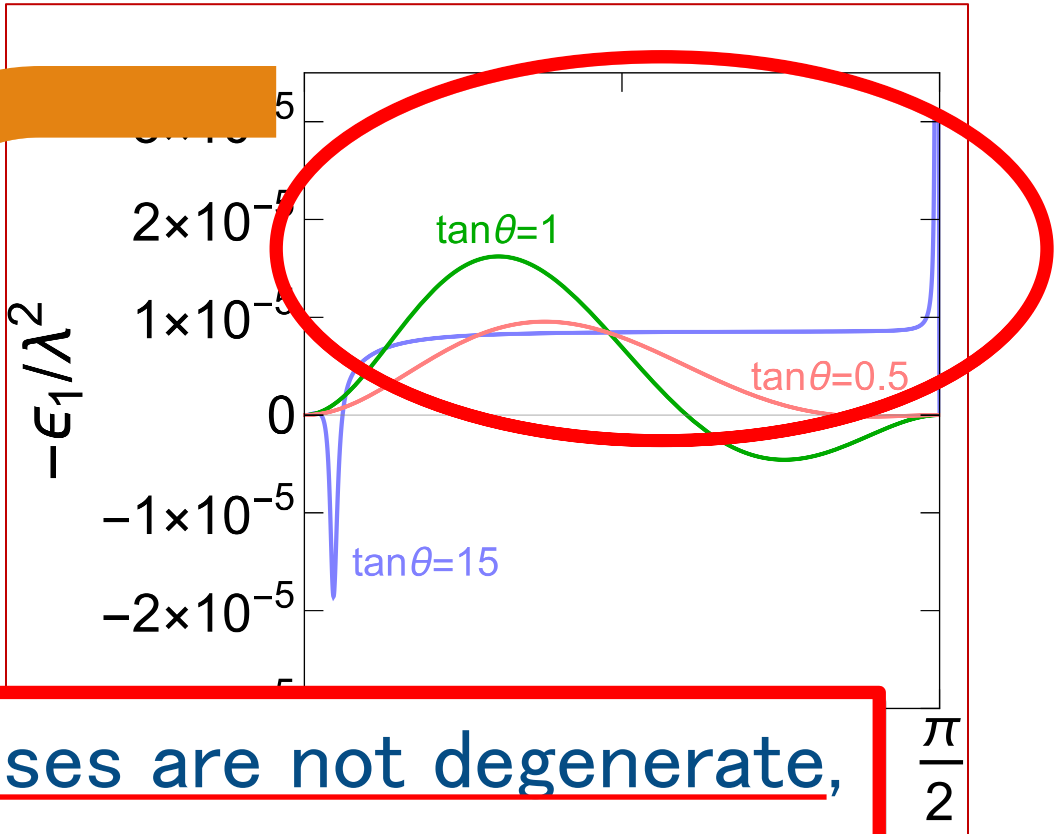
- $\epsilon_1 < 0$ can be obtain in large region
- ϵ_1 can be negative even if the right handed neutrinos are not degenerate in mass

4, Implications for leptogenesis

$\mathrm{U}(1)_{B-L_e+L_\mu-3L_\tau}$

b) Scale of asymmetry parameter





Even in regions where $\mathrm{N_R}$ masses are not degenerate, enough large ϵ_1 can be obtain