Predictions for the neutrino parameters in the minimal model extended by general lepton flavor dependent U(1) gauge symmetries

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Based on KA (arXiv : 1907.04042 [hep-ph])

Extension of Standard Model

Matter contents

SM fields + 3 right-handed neutrinos
N_α

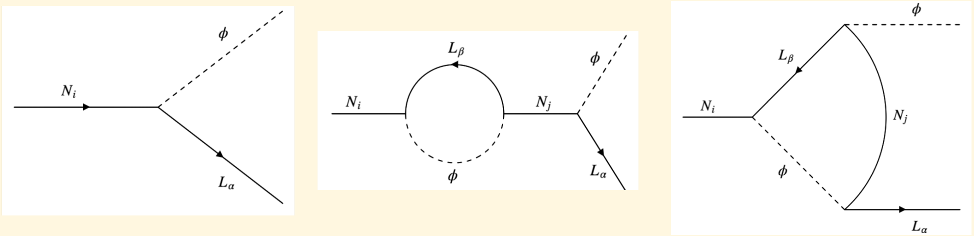
- Neutrino mass

$$\mathcal{L} \supset \lambda_\alpha N^c_\alpha (L_\alpha \cdot H) - \frac{1}{2} M_{\alpha\beta} N^c_\alpha N^c_\beta$$

Seesaw mechanism $(\mathcal{M}_D \ll \mathcal{M}_R)$

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

- Leptogenesis



Some motivations

Extension of Standard Model

Gauge sector

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times \underline{U(1)_{Y'}}$$

Y' : combination of $L_e - L_\mu$, $L_\mu - L_\tau$ and $B - L$

Extension of Standard Model

Gauge sector

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

Y' : combination of $L_e - L_\mu$, $L_\mu - L_\tau$ and $B - L$

field	quarks	leptons			Higgs
		e, ν_e, N_e	μ, ν_μ, N_μ	τ, ν_τ, N_τ	
charge	x_q	x_e	x_μ	x_τ	0

Anomaly cancellation condition

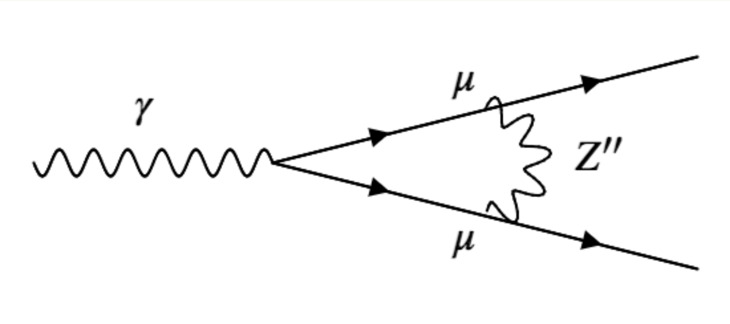
$$Y' = \begin{cases} x_e L_e + x_\mu L_\mu - (x_e + x_\mu) L_\tau & (x_q = 0) \\ B + x_e L_e + x_\mu L_\mu - (3 + x_e + x_\mu) L_\tau & (x_q = \frac{1}{3}) \end{cases}$$

Extension of Standard Model

Gauge sector

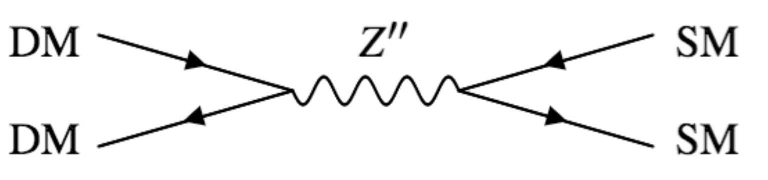
$$SU(3)_C \times SU(2)_L \times U(1)_Y \times \underline{U(1)_{L_\mu - L_\tau}}$$

● Muon g-2



S. Baek, N. G. Deshpande, X. G. He, and P. Ko (2001);
E. Ma, D. P. Roy, and S. Roy (2002); etc⋯

● Dark Matter



J.-C. Park, J. Kim, and S. C. Park (2016);
S. Baek (2016); etc⋯

Some motivations

Neutrino Mass Matrix Structure

Matter contents

SM fields + 3 right-handed neutrinos N_α

Seesaw mechanism

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

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

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

$\mathcal{M}_\nu$ Block diagonal

→ ~~Neutrino mixing~~

Neutrino Mixing Angles

Matter contents

SM fields + 3 right-handed neutrinos N_α

Neutrino experiments
(ex: Super-Kamiokande)

→ $\theta_{ij} \neq 0$

Seesaw mechanism

$$\mathcal{M}_\nu \simeq -$$

For $U(1)_{B+L}$

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

$\theta_{12}, \theta_{13} \neq 0$
$\theta_{23} = 0$

PMNS matrix

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

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

Neutrino Mixing Angles

Matter contents

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(ex: Super-Kamiokande)

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$= e, \mu, \tau)$

Minimal models can not explain the neutrino mixing as long as $U(1)_{B+L_e-3L_\mu-L_\tau}$ gauge symm. is conserved

Neutrino Mass Matrix Structure

Matter contents

SM fields + 3 right-handed neutrinos N_α + U(1) breaking scalar σ (singlet) or Φ (doublet)

Seesaw mechanism

$$\mathcal{M}_\nu^{-1} \simeq -(\mathcal{M}_D^T)^{-1} \mathcal{M}_R \mathcal{M}_D^{-1}$$

Neutrino Mass Matrix Structure

Matter contents

SM fields + 3 right-handed neutrinos (N_α) + U(1) breaking scalar: σ (singlet) or Φ (doublet)

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$$\mathcal{M}_\nu^{-1} \simeq -(\mathcal{M}_D^T)^{-1}\mathcal{M}_R\mathcal{M}_D^{-1}$$

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

$$\begin{pmatrix} * & * & * \\ * & \boxed{0} & \boxed{0} \\ * & 0 & * \end{pmatrix} \simeq -\begin{pmatrix} * & & \\ & * & \\ & & * \end{pmatrix}\begin{pmatrix} * & * & * \\ * & 0 & 0 \\ * & 0 & * \end{pmatrix}\begin{pmatrix} * & & \\ & * & \\ & & * \end{pmatrix}$$

Neutrino mixing

&

two-zero minor structure

Elements where zeros appear depend on $\mathrm{U}(1)_{Y'}$

Introduction

Neutrino Mass Matrix Structure

KA, K. Hamaguchi and N. Nagata, Eur. Phys. J. **C77** (2017) 763;
KA, K. Hamaguchi, N. Nagata, S.-Y. Tseng and K. Tsumura, Phys. Rev. D99 (2019) 055029.

Matter contents

SM fields + 3 right-handed neutrinos + U(1) breaking scalar

N_α σ (singlet) or Φ (doublet)

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

$$\begin{pmatrix} * & * & * \\ * & \boxed{0} & \boxed{0} \\ * & 0 & * \end{pmatrix} \simeq -\begin{pmatrix} * & & \\ & * & \\ & & * \end{pmatrix}\begin{pmatrix} * & * & * \\ * & 0 & 0 \\ * & 0 & * \end{pmatrix}\begin{pmatrix} * & & \\ & * & \\ & & * \end{pmatrix} = U_{\text{PMNS}}\,\text{diag}\left(m_1^{-1}, m_2^{-1}, m_3^{-1}\right) U_{\text{PMNS}}^T$$

Point

two-zero minor structure

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

Dirac CP (δ), Majorana CP (α_2, α_3), Mixing angle ($\theta_{12}, \theta_{13}, \theta_{23}$), Squared mass difference ($\delta m^2, \Delta m^2$)

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Matter contents

SM fields + 3 right-handed neutrinos + U(1) breaking scalar

N_α — σ (singlet) or Φ (doublet)

Seesaw mechanism

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

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

$$\begin{pmatrix} * & 0 & * \\ 0 & 0 & * \\ * & * & * \end{pmatrix} \simeq \begin{pmatrix} * & * & 0 \\ 0 & * & 0 \\ * & 0 & * \end{pmatrix} \begin{pmatrix} * & 0 & 0 \\ 0 & 0 & * \\ 0 & * & 0 \end{pmatrix} \begin{pmatrix} * & 0 & * \\ * & * & 0 \\ 0 & 0 & * \end{pmatrix} = U^*_{\text{PMNS}}\, \text{diag}\,(m_1, m_2, m_3)\, U^\dagger_{\text{PMNS}}$$

Point

two-zero texture structure

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

Dirac CP (δ), Majorana CP (α_2, α_3), Mixing angle ($\theta_{12}, \theta_{13}, \theta_{23}$), Squared mass difference ($\delta m^2, \Delta m^2$)

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

<u>neutrino mass</u>

m_1, m_2, m_3

<u>CP phase</u>

$\delta, \alpha_2, \alpha_3$

<u>Effective Majorana neutrino mass</u>

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

<u>Leptogenesis</u>

Dirac Yukawa couplings

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

sign of baryon asymmetry

1, Introduction	
2, Model	Two models (+singlet or +doublet scalar)
3, Mass Matrix	Analysis : two-zero minor (texture) condition Result : Dirac CP phase δ and sum of neutrino masses $\Sigma_i m_i$
4, Leptogenesis	Analysis : seesaw formula Result : sign of the asymmetry parameter
5, Conclusion	

Minimal Gauged $\mathrm{U}(1)_{Y'}$ Models

Singlet σ

Charge assignment

field	$U(1)_{B+L_e-3L_\mu-L_\tau}$
quark	$+1/3$
$e_{L,R}, \nu_e, N_e$	$+1$
$\mu_{L,R}, \nu_\mu, N_\mu$	-3
$\tau_{L,R}, \nu_\tau, N_\tau$	-1
σ	$+2$
others	0

Lagrangian

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

Doublet Φ_1

Charge assignment

field	$U(1)_{L_\mu - L_\tau}$
$e_{L,R}, \nu_e, N_e$	0
$\mu_{L,R}, \nu_\mu, N$	$+1$
$\tau_{L,R}, \nu_\tau, N_\tau$	-1
Φ_1	$+1$ (-1)
others	0

Lagrangian

$$\Delta\mathcal{L} = -y_e e_R^c L_e \Phi_2^\dagger - y_\mu \mu_R^c L_\mu \Phi_2^\dagger - y_\tau \tau_R^c L_\tau \Phi_2^\dagger - y_{\mu e} e_R^c L_\mu \Phi_1^\dagger - y_{e\tau}\tau_R^c L_e \Phi_1^\dagger - \lambda_e N_e^c (L_e \cdot \Phi_2) - \lambda_\mu N_\mu^c (L_\mu \cdot \Phi_2) - \lambda_\tau N_\tau^c (L_\tau \cdot \Phi_2) - \lambda_{\tau e} N_e^c (L_\tau \cdot \Phi_1) - \lambda_{e\mu} N_\mu^c (L_e \cdot \Phi_1) - \frac{1}{2} M_{ee} N_e^c N_e^c - M_{\mu\tau} N_\mu^c N_\tau^c + h.c.$$

Minimal Gauged $U(1)_{Y'}$ Models

Singlet σ

Mass matrix

- Dirac mass

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

- Majorana mass

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

Doublet Φ_1

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
Φ_1	$+1(-1)$
others	0

Lagrangian

$$\begin{aligned}\Delta\mathcal{L} = &- y_e e_R^c L_e \Phi_2^\dagger - y_\mu \mu_R^c L_\mu \Phi_2^\dagger - y_\tau \tau_R^c L_\tau \Phi_2^\dagger \\ &- y_{\mu e} e_R^c L_\mu \Phi_1^\dagger - y_{e\tau} \tau_R^c L_e \Phi_1^\dagger \\ &- \lambda_e N_e^c (L_e \cdot \Phi_2) - \lambda_\mu N_\mu^c (L_\mu \cdot \Phi_2) - \lambda_\tau N_\tau^c (L_\tau \cdot \Phi_2) \\ &- \lambda_{\tau e} N_e^c (L_\tau \cdot \Phi_1) - \lambda_{e\mu} N_\mu^c (L_e \cdot \Phi_1) \\ &- \frac{1}{2} M_{ee} N_e^c N_e^c - M_{\mu\tau} N_\mu^c N_\tau^c + h.c.\end{aligned}$$

- Charged lepton mass

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

Minimal Gauged $\mathrm{U(1)}_{Y'}$ Models

Singlet σ

Charge assignment

field	$U(1)_{B+L_e-3L_\mu-L_\tau}$
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σ	$+2$
others	0

Lagrangian

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

Doublet Φ_1

Charge assignment

field	$U(1)_{L_\mu-L_\tau}$
$e_{L,R}, \nu_e, N_e$	0
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Φ_1	$+1$ (-1)
others	0

Lagrangian

$$\Delta\mathcal{L} = -y_e e_R^c L_e \Phi_2^\dagger - y_\mu \mu_R^c L_\mu \Phi_2^\dagger - y_\tau \tau_R^c L_\tau \Phi_2^\dagger - y_{\mu e} e_R^c L_\mu \Phi_1^\dagger - y_{e\tau} \tau_R^c L_e \Phi_1^\dagger - \lambda_e N_e^c (L_e \cdot \Phi_2) - \lambda_\mu N_\mu^c (L_\mu \cdot \Phi_2) - \lambda_\tau N_\tau^c (L_\tau \cdot \Phi_2) - \lambda_{\tau e} N_e^c (L_\tau \cdot \Phi_1) - \lambda_{e\mu} N_\mu^c (L_e \cdot \Phi_1) - \frac{1}{2} M_{ee} N_e^c N_e^c - M_{\mu\tau} N_\mu^c N_\tau^c + h.c.$$

Minimal Gauged $\mathrm{U}(1)_{Y'}$ Models

Singlet σ

Charge assignment

field	$U(1)_{B+L_e-3L_\mu-L_\tau}$
quark	$+1/3$
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others	0

Lagrangian

$$\begin{aligned}\mathcal{L} = &-\lambda_e N_e^c(L_e\cdot H) - \lambda_\mu N_\mu^c(L_\mu\cdot H)\\ &-\lambda_\tau N_\tau^c(L_\tau\cdot H)\\ &-M_{e\tau}N_e^cN_\tau^c - \frac{1}{2}\lambda_{ee}\sigma N_e^cN_e^c\\ &-\lambda_{e\mu}\sigma N_e^cN_\mu^c - \frac{1}{2}\lambda_{\tau\tau}\sigma N_\tau^cN_\tau^c\end{aligned}$$

- Charged lepton mass

$$\mathcal{M}_l = \frac{1}{\sqrt{2}}\begin{pmatrix} y_e v_2 & 0 & y_{e\tau}v_1 \\ y_{\mu e}v_1 & y_\mu v_2 & 0 \\ 0 & 0 & y_\tau v_2 \end{pmatrix}$$

Assumption

Lepton flavor violation → Enough small

Doublet Φ_1

Mass matrix

- Dirac mass

$$\mathcal{M}_D = \frac{1}{\sqrt{2}}\begin{pmatrix} \lambda_e v_2 & \lambda_{e\mu}v_1 & 0 \\ 0 & \lambda_\mu v_2 & 0 \\ \lambda_{\tau e}v_1 & 0 & \lambda_\tau v_2 \end{pmatrix}$$

- Majorana mass

$$\mathcal{M}_l = \begin{pmatrix} M_{ee} & 0 & 0 \\ 0 & 0 & M_{\mu\tau} \\ 0 & M_{\mu\tau} & 0 \end{pmatrix}$$

Two-zero minor condition

Singlet σ

Seesaw mechanism

$$\mathcal{M}_\nu^{-1} \simeq -(\mathcal{M}_D^T)^{-1}\mathcal{M}_R\mathcal{M}_D^{-1}$$

PMNS matirx

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

$$\begin{pmatrix} * & * & * \\ * & 0 & 0 \\ * & 0 & * \end{pmatrix} = \mathcal{M}_\nu^{-1}$$

$$= U_{\text{PMNS}}\text{diag}(m_1^{-1}, m_2^{-1}, m_3^{-1})U_{\text{PMNS}}^T$$

Two complex equations in terms of $m_1, \delta, \alpha_2, \alpha_3$

Mass matrix

Two-zero texture condition

Doublet Φ_1

Seesaw mechanism

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

PMNS matirx

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

$$\Rightarrow \begin{pmatrix} * & 0 & * \\ 0 & 0 & * \\ * & * & * \end{pmatrix} = \mathcal{M}_\nu$$

$$= U_{\mathrm{PMNS}}^* \mathrm{diag}(m_1, m_2, m_3) U_{\mathrm{PMNS}}^\dagger$$

$\Rightarrow$ Two complex equations in terms of $m_1, \delta, \alpha_2, \alpha_3$

Mass matrix

Flow of analysis

Point

<u>neutrino mass</u>

m_1, m_2, m_3

<u>CP phase</u>

$\delta, \alpha_2, \alpha_3$

<u>Effective Majorana neutrino mass</u>

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

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

⇒

<u>Leptogenesis</u>

Asymmetry parameter

$\varepsilon(\theta_{ij}, \Delta m^2_{k1}, \lambda_\alpha)$

Neutrino oscillation parameter ($\theta_{ij}, \Delta m^2_{k1}$)

Neutrino Dirac Yukawa coupling (λ_α)

⇑

Two complex equations in terms of $m_1, \delta, \alpha_2, \alpha_3$

Two zero minor condition

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

Two complex equations

$$\begin{cases} \frac{1}{m_1}V_{\mu 1}^2 + \frac{1}{m_2}V_{\mu 2}^2 e^{i\alpha_2} + \frac{1}{m_3}V_{\mu 3}^2 e^{i\alpha_3} = 0 \\ \frac{1}{m_1}V_{\mu 1}V_{\tau 1} + \frac{1}{m_2}V_{\mu 2}V_{\tau 2}e^{i\alpha_2} + \frac{1}{m_3}V_{\mu 3}V_{\tau 3}e^{i\alpha_3} = 0 \end{cases}$$

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

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

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

Mass matrix

Two zero minor condition

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

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

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

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

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

→ CP phase and neutrino masses can be obtained as functuions of the neutrino oscillation parameters

Mass matrix

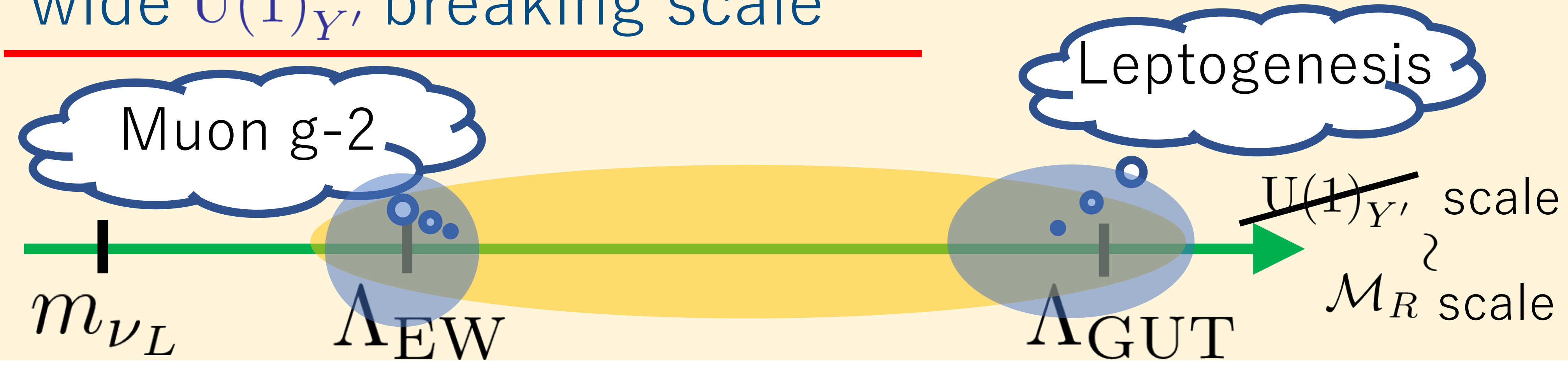
Notice !

The following discussion is applicable to

1, the other U(1) lepton flavor symmetries

→ The methods of analysis are same but the structures of the neutrino mass matrices are different

2, wide $\mathrm{U}(1)_{Y'}$ breaking scale



Mass matrix

5 Models

Y'	structural pattern: singlet	structural pattern: doublet	
$L_e - L_\mu$	$\mathbf{E_1^R}(+1)$	$\mathbf{A_2^\nu}(+1)$	$\mathbf{D_1^\nu}(-1)$
$L_\mu - L_\tau$	$\mathbf{C^R}(+1)$	$\mathbf{B_3^\nu}(+1)$	$\mathbf{B_4^\nu}(-1)$
$L_e - L_\tau$	$\mathbf{E_2^R}(+1)$	$\mathbf{A_1^\nu}(+1)$	$\mathbf{D_2^\nu}(-1)$
$B - 3L_e - L_\mu + L_\tau$	$\mathbf{A_1^R}(+2)$	—	
$B - 3L_e + L_\mu - L_\tau$	$\mathbf{A_2^R}(+2)$	—	
$B - L_e - 3L_\mu + L_\tau$	$\mathbf{B_3^R}(+2)$	—	
$B - L_e + L_\mu - 3L_\tau$	$\mathbf{B_4^R}(+2)$	—	
$B + L_e - 3L_\mu - L_\tau$	$\mathbf{D_1^R}(+2)$	—	
$B + L_e - L_\mu - 3L_\tau$	$\mathbf{D_2^R}(+2)$	—	
$B - 3L_e$	$\mathbf{F_1^R}(+6)$	—	
$B - \frac{3}{2}L_\mu - \frac{3}{2}L_\tau$	$\mathbf{F_1^R}(+3)$		
$B - 3L_\mu$	$\mathbf{F_2^R}(+6)$	—	
$B - \frac{3}{2}L_e - \frac{3}{2}L_\tau$	$\mathbf{F_2^R}(+3)$		
$B - 3L_\tau$	$\mathbf{F_3^R}(+6)$	—	
$B - \frac{3}{2}L_e - \frac{3}{2}L_\mu$	$\mathbf{F_3^R}(+3)$		

Mass matrix

5 Models

Y'	structural pattern: singlet	structural pattern: doublet	
$L_e - L_\mu$	$\mathbf{E}_1^{\mathbf{R}}(+1)$	$\mathbf{A}_2^{\nu}(+1)$	$\mathbf{D}_1^{\nu}(-1)$
$L_\mu - L_\tau$	$\mathbf{C}^{\mathbf{R}}(+1)$	$\mathbf{B}_3^{\nu}(+1)$	$\mathbf{B}_4^{\nu}(-1)$
$L_e - L_\tau$	$\mathbf{E}_2^{\mathbf{R}}(+1)$	$\mathbf{A}_1^{\nu}(+1)$	$\mathbf{D}_2^{\nu}(-1)$
$B - 3L_e - L_\mu + L_\tau$	$\mathbf{A}_1^{\mathbf{R}}(+2)$	–	
$B - 3L_e + L_\mu - L_\tau$	$\mathbf{A}_2^{\mathbf{R}}(+2)$	–	
$B - L_e - 3L_\mu + L_\tau$	$\mathbf{B}_3^{\mathbf{R}}(+2)$	–	
$B - L_e + L_\mu - 3L_\tau$	$\mathbf{B}_4^{\mathbf{R}}(+2)$	–	
$B + L_e - 3L_\mu - L_\tau$	$\mathbf{D}_1^{\mathbf{R}}(+2)$	–	
$B + L_e - L_\mu - 3L_\tau$	$\mathbf{D}_2^{\mathbf{R}}(+2)$	–	
$B - 3L_e$	$\mathbf{F}_1^{\mathbf{R}}$ $(+6)$	–	
$B - \frac{3}{2}L_\mu - \frac{3}{2}L_\tau$	$\mathbf{F}_1^{\mathbf{R}}$ $(+3)$		
$B - 3L_\mu$	$\mathbf{F}_2^{\mathbf{R}}$ $(+6)$	–	
$B - \frac{3}{2}L_e - \frac{3}{2}L_\tau$	$\mathbf{F}_2^{\mathbf{R}}$ $(+3)$		
$B - 3L_\tau$	$\mathbf{F}_3^{\mathbf{R}}$ $(+6)$	–	
$B - \frac{3}{2}L_e - \frac{3}{2}L_\mu$	$\mathbf{F}_3^{\mathbf{R}}$ $(+3)$		

Two-zero minor $\mathbf{R}$

$$\begin{pmatrix} * & * & * \\ * & 0 & 0 \\ * & 0 & * \end{pmatrix} = \mathcal{M}_\nu^{-1}$$

Two-zero texture ν

$$\begin{pmatrix} * & 0 & * \\ 0 & 0 & * \\ * & * & * \end{pmatrix} = \mathcal{M}_\nu$$

Mass matrix

5 Models

Y'	structural pattern		
	singlet	doublet	
$L_e - L_\mu$	$\mathbf{E_1^R}(+1)$	$\mathbf{A_2^\nu}(+1)$	$\mathbf{D_1^\nu}(-1)$
$L_\mu - L_\tau$	$\mathbf{C^R}(+1)$	$\mathbf{B_3^\nu}(+1)$	$\mathbf{B_4^\nu}(-1)$
$L_e - L_\tau$	$\mathbf{E_2^R}(+1)$	$\mathbf{A_1^\nu}(+1)$	$\mathbf{D_2^\nu}(-1)$
$B - 3L_e - L_\mu + L_\tau$	$\mathbf{A_1^R}(+2)$	–	
$B - 3L_e + L_\mu - L_\tau$	$\mathbf{A_2^R}(+2)$	–	
$B - L_e - 3L_\mu + L_\tau$	$\mathbf{B_3^R}(+2)$	–	
$B - L_e + L_\mu - 3L_\tau$	$\mathbf{B_4^R}(+2)$	–	
$B + L_e - 3L_\mu - L_\tau$	$\mathbf{D_1^R}(+2)$	–	
$B + L_e - L_\mu - 3L_\tau$	$\mathbf{D_2^R}(+2)$	–	
$B - 3L_e$ $B - \frac{3}{2}L_\mu - \frac{3}{2}L_\tau$	$\mathbf{F_1^R}$ $(+6)$ $(+3)$	–	
$B - 3L_\mu$ $B - \frac{3}{2}L_e - \frac{3}{2}L_\tau$	$\mathbf{F_2^R}$ $(+6)$ $(+3)$	–	
$B - 3L_\tau$ $B - \frac{3}{2}L_e - \frac{3}{2}L_\mu$	$\mathbf{F_3^R}$ $(+6)$ $(+3)$	–	

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

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

5 Models

Normal / Inverted

Y'	structural pattern		
	singlet	doublet	
$L_e - L_\mu$	$\mathbf{E}^{\mathbf{R}}_{\mathbf{1}}(+1)$	$\mathbf{A}^{\nu}_{\mathbf{2}}(+1)$	$\mathbf{D}^{\nu}_{\mathbf{1}}(-1)$
$L_\mu - L_\tau$	$\mathbf{C}^{\mathbf{R}}(+1)$	$\mathbf{B}^{\nu}_{\mathbf{3}}(+1)$	$\mathbf{B}^{\nu}_{\mathbf{4}}(-1)$
$L_e - L_\tau$	$\mathbf{E}^{\mathbf{R}}_{\mathbf{2}}(+1)$	$\mathbf{A}^{\nu}_{\mathbf{1}}(+1)$	$\mathbf{D}^{\nu}_{\mathbf{2}}(-1)$
$B - 3L_e - L_\mu + L_\tau$	$\mathbf{A}^{\mathbf{R}}_{\mathbf{1}}(+2)$	–	
$B - 3L_e + L_\mu - L_\tau$	$\mathbf{A}^{\mathbf{R}}_{\mathbf{2}}(+2)$	–	
$B - L_e - 3L_\mu + L_\tau$	$\mathbf{B}^{\mathbf{R}}_{\mathbf{3}}(+2)$	–	
$B - L_e + L_\mu - 3L_\tau$	$\mathbf{B}^{\mathbf{R}}_{\mathbf{4}}(+2)$	–	
$B + L_e - 3L_\mu - L_\tau$	$\mathbf{D}^{\mathbf{R}}_{\mathbf{1}}(+2)$	–	
$B + L_e - L_\mu - 3L_\tau$	$\mathbf{D}^{\mathbf{R}}_{\mathbf{2}}(+2)$	–	
$B - 3L_e$	$\mathbf{F}^{\mathbf{R}}_{\mathbf{1}}$ $(+6)$	–	
$B - \frac{3}{2}L_\mu - \frac{3}{2}L_\tau$	$\mathbf{F}^{\mathbf{R}}_{\mathbf{1}}$ $(+3)$		
$B - 3L_\mu$	$\mathbf{F}^{\mathbf{R}}_{\mathbf{2}}$ $(+6)$	–	
$B - \frac{3}{2}L_e - \frac{3}{2}L_\tau$	$\mathbf{F}^{\mathbf{R}}_{\mathbf{2}}$ $(+3)$		
$B - 3L_\tau$	$\mathbf{F}^{\mathbf{R}}_{\mathbf{3}}$ $(+6)$	–	
$B - \frac{3}{2}L_e - \frac{3}{2}L_\mu$	$\mathbf{F}^{\mathbf{R}}_{\mathbf{3}}$ $(+3)$		

Two complex equations have no solution

5 Models

Normal / Inverted

Y'	structural pattern: singlet	doublet	
$L_e - L_\mu$	$\mathbf{E_1^R}(+1)$	$\mathbf{A_2^\nu}(+1)$	$\mathbf{D_1^\nu}(-1)$
$L_\mu - L_\tau$	$\mathbf{C^R}(+1)$	$\mathbf{B_3^\nu}(+1)$	$\mathbf{B_4^\nu}(-1)$
$L_e - L_\tau$	$\mathbf{E_2^R}(+1)$	$\mathbf{A_1^\nu}(+1)$	$\mathbf{D_2^\nu}(-1)$
$B - 3L_e - L_\mu + L_\tau$	$\mathbf{A_1^R}(+2)$	–	
$B - 3L_e + L_\mu - L_\tau$	$\mathbf{A_2^R}(+2)$	–	
$B - L_e - 3L_\mu + L_\tau$	$\mathbf{B_3^R}(+2)$	–	
$B - L_e + L_\mu - 3L_\tau$	$\mathbf{B_4^R}(+2)$	–	
$B + L_e - 3L_\mu - L_\tau$	$\mathbf{D_1^R}(+2)$	–	
$B + L_e - L_\mu - 3L_\tau$	$\mathbf{D_2^R}(+2)$	–	
$B - 3L_e$	$\mathbf{F_1^R}$ $(+6)$	–	
$B - \frac{3}{2}L_\mu - \frac{3}{2}L_\tau$	$\mathbf{F_1^R}$ $(+3)$		
$B - 3L_\mu$	$\mathbf{F_2^R}$ $(+6)$	–	
$B - \frac{3}{2}L_e - \frac{3}{2}L_\tau$	$\mathbf{F_2^R}$ $(+3)$		
$B - 3L_\tau$	$\mathbf{F_3^R}$ $(+6)$	–	
$B - \frac{3}{2}L_e - \frac{3}{2}L_\mu$	$\mathbf{F_3^R}$ $(+3)$		

Two complex equations have <u>no solution</u>

$m_{Z'}$ below EW scale ruled out by experiments

Mass matrix

5 Models

Normal / Inverted

Y'	structural pattern: singlet	structural pattern: doublet
$L_e - L_\mu$	$\mathbf{E_1^R}(+1)$	$\mathbf{A_2^\nu}(+1)$ $\mathbf{D_1^\nu}(-1)$
$L_\mu - L_\tau$	$\mathbf{C^R}(+1)$	$\mathbf{B_3^\nu}(+1)$ $\mathbf{B_4^\nu}(-1)$
$L_e - L_\tau$	$\mathbf{E_2^R}(+1)$	$\mathbf{A_1^\nu}(+1)$ $\mathbf{D_2^\nu}(-1)$
$B - 3L_e - L_\mu + L_\tau$	$\mathbf{A_1^R}(+2)$	–
$B - 3L_e + L_\mu - L_\tau$	$\mathbf{A_2^R}(+2)$	–
$B - L_e - 3L_\mu + L_\tau$	$\mathbf{B_3^R}(+2)$	–
$B - L_e + L_\mu - 3L_\tau$	$\mathbf{B_4^R}(+2)$	–
$B + L_e - 3L_\mu - L_\tau$	$\mathbf{D_1^R}(+2)$	–
$B + L_e - L_\mu - 3L_\tau$	$\mathbf{D_2^R}(+2)$	–
$B - 3L_e$	$\mathbf{F_1^R}$ $(+6)$	–
$B - \frac{3}{2}L_\mu - \frac{3}{2}L_\tau$	$(+3)$	
$B - 3L_\mu$	$\mathbf{F_2^R}$ $(+6)$	–
$B - \frac{3}{2}L_e - \frac{3}{2}L_\tau$	$(+3)$	
$B - 3L_\tau$	$\mathbf{F_3^R}$ $(+6)$	–
$B - \frac{3}{2}L_e - \frac{3}{2}L_\mu$	$(+3)$	

Prediction values for neutrino mass conflict with Planck limit

KA, K. Hamaguchi, N. Nagata, S.-Y. Tseng and K. Tsumura, Phys. Rev. D99 (2019) 055029.

Two complex equations have no solution

$m_{Z'}$ below EW scale ruled out by experiments

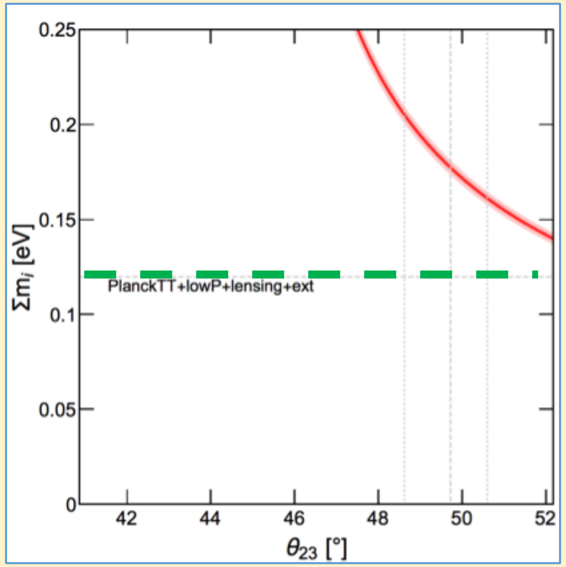
Mass matrix

Sum of neutrino masses

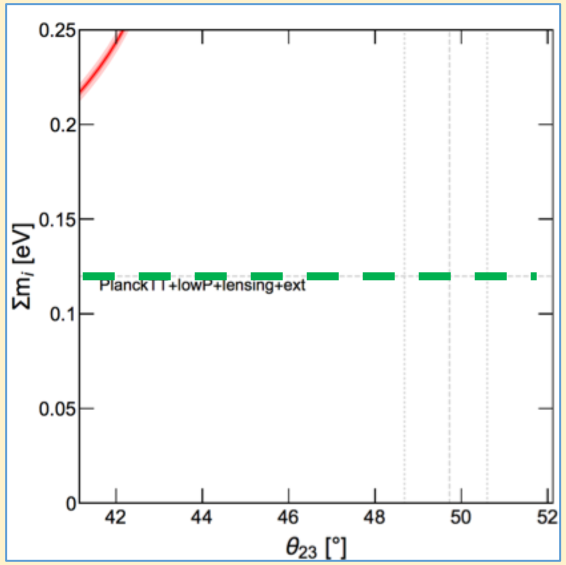
Planck limit (green dashed line)
$$\sum m_i < 0.12 \text{ eV}$$

$$B - L_e - 3L_\mu + L_\tau [\mathbf{B_3^R}]$$

Normal

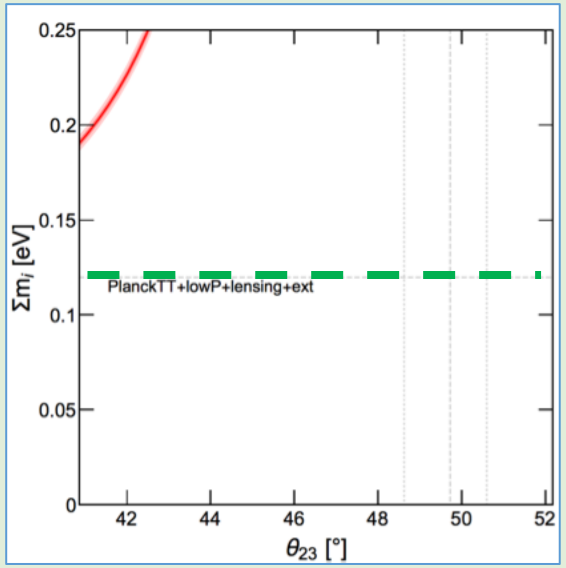


Inverted

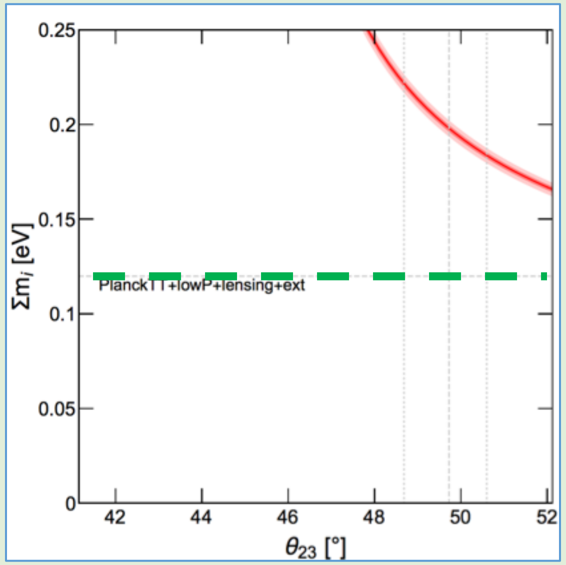


$$B - L_e + L_\mu - 3L_\tau [\mathbf{B_4^R}]$$

Normal



Inverted



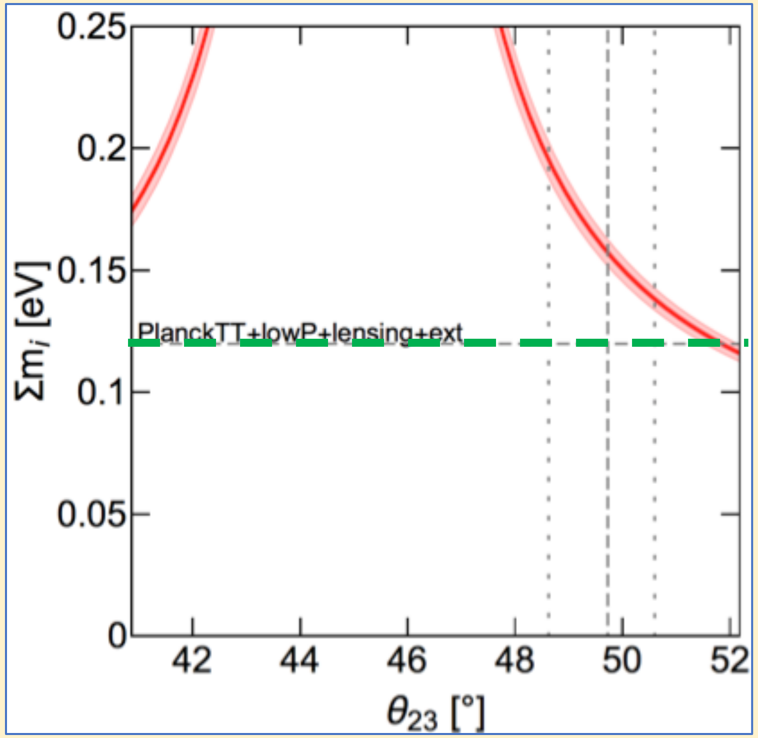
→ These cases are excluded by Planck limit

Mass matrix

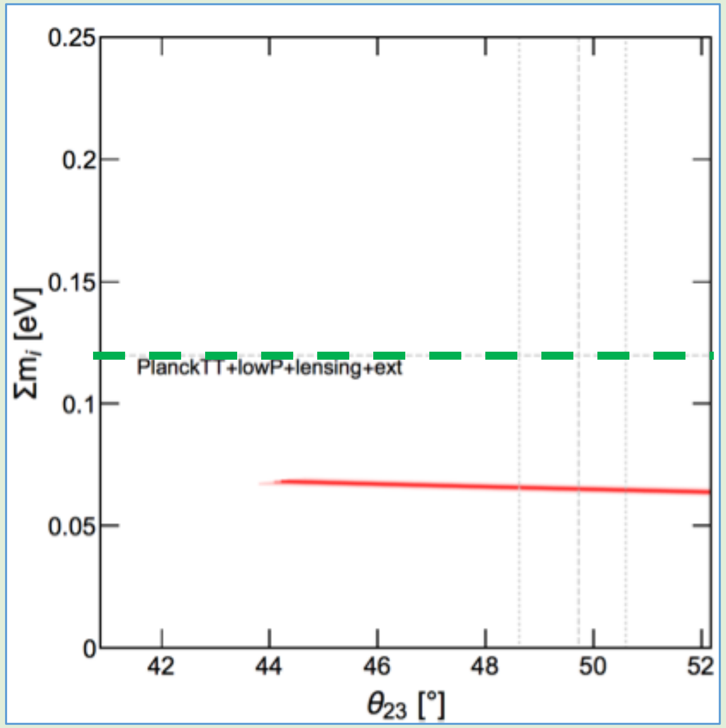
Sum of neutrino masses

Planck limit - - - - - -
$\sum m_i < 0.12$ eV

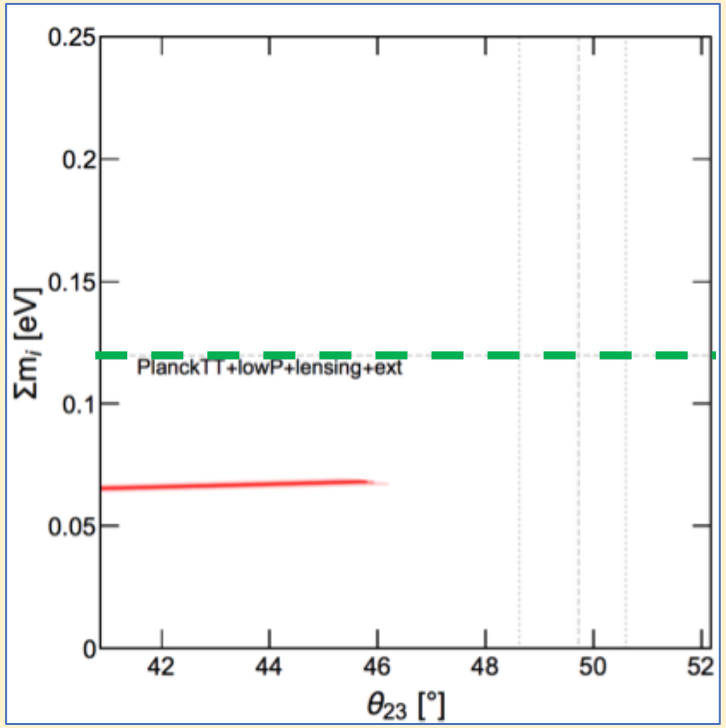
$L_\mu - L_\tau[\mathbf{C^R}]$



$B + L_e - 3L_\mu - L_\tau[\mathbf{D_1^R}]$



$B + L_e - L_\mu - 3L_\tau[\mathbf{D_2^R}]$

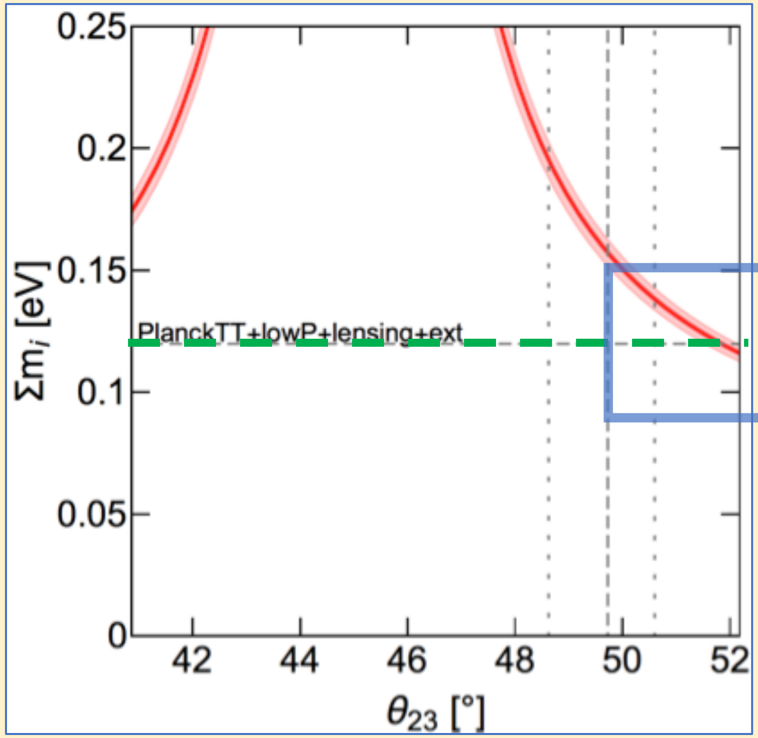


Mass matrix

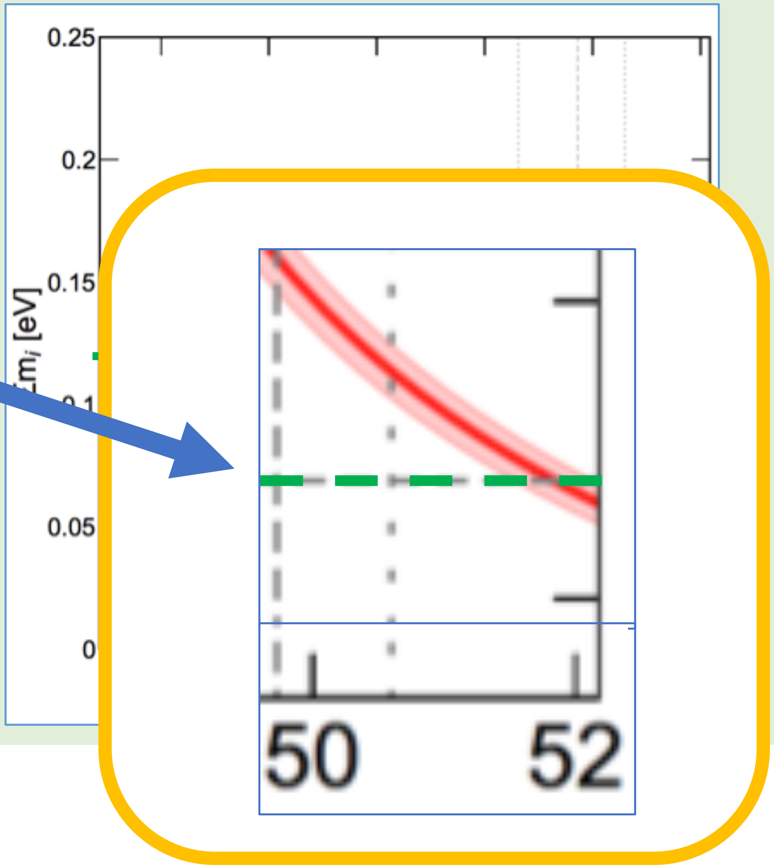
Sum of neutrino masses

dark (light) red band
: uncertainty coming from the 1 σ (2 σ) errors in the parameters

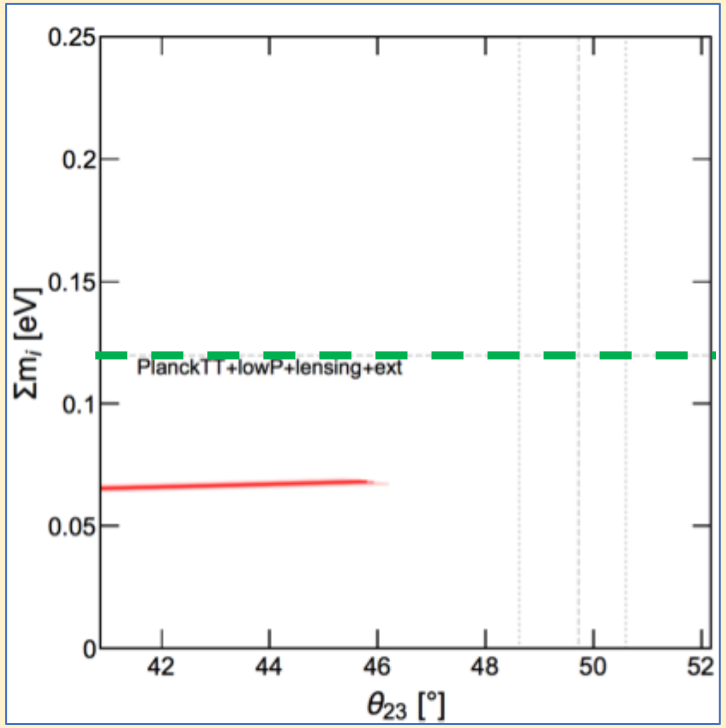
$L_\mu - L_\tau[\mathbf{C^R}]$



$B + L_e - 3L_\mu - L_\tau[\mathbf{D_1^R}]$



$B + L_e - L_\mu - 3L_\tau[\mathbf{D_2^R}]$

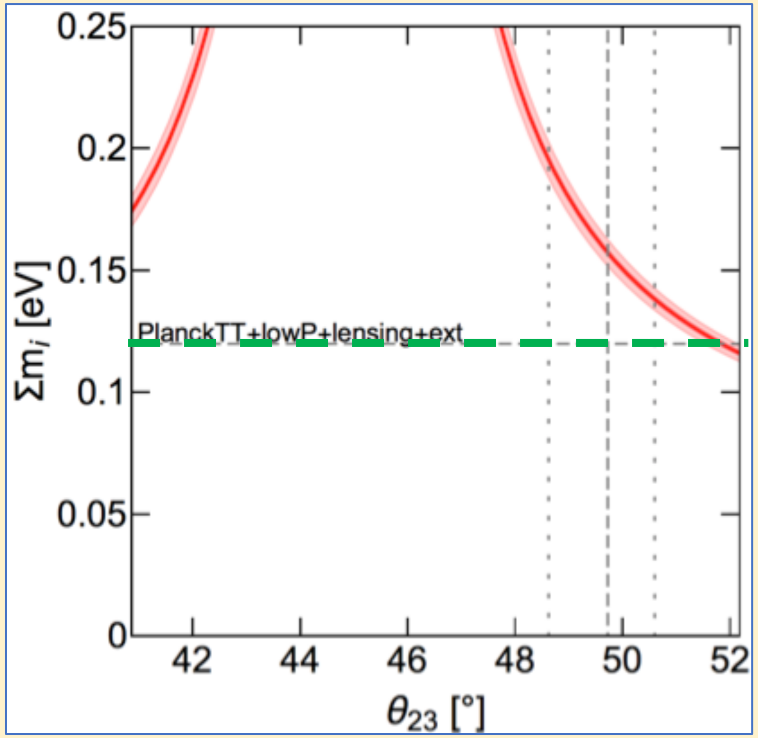


Mass matrix

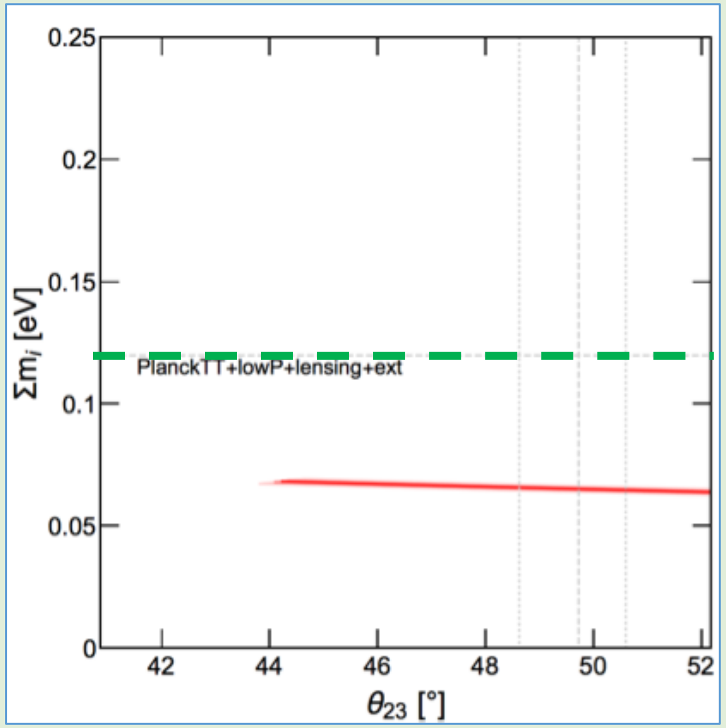
Sum of neutrino masses

Planck limit
$$\sum m_i < 0.12\ \text{eV}$$

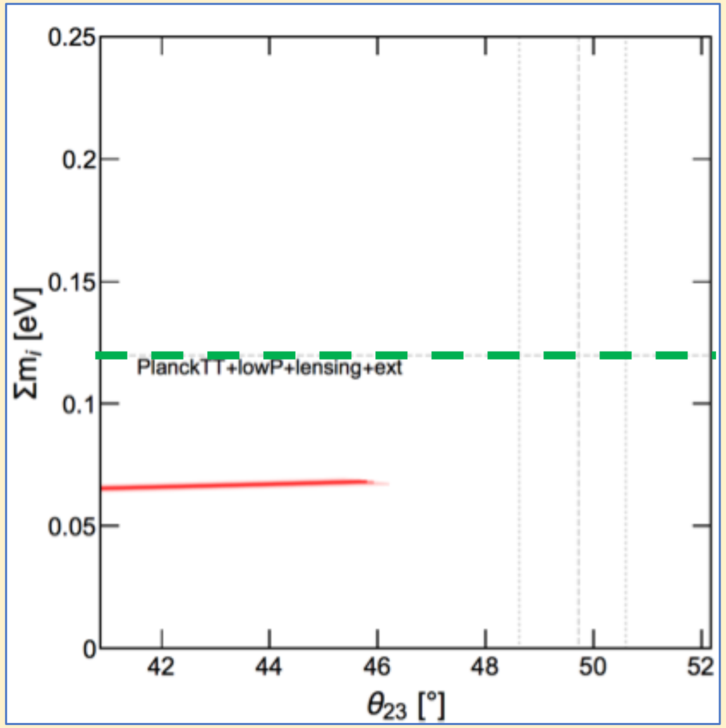
$L_\mu - L_\tau[\mathbf{C^R}]$



$B + L_e - 3L_\mu - L_\tau[\mathbf{D_1^R}]$



$B + L_e - L_\mu - 3L_\tau[\mathbf{D_2^R}]$

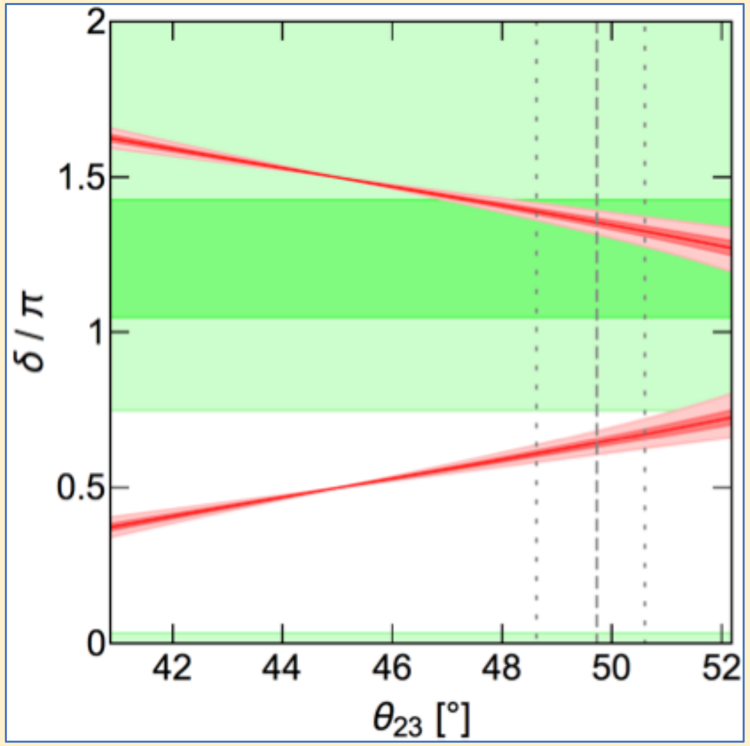


$\mathbf{C^R}$ case has a strong tension with Planck linit

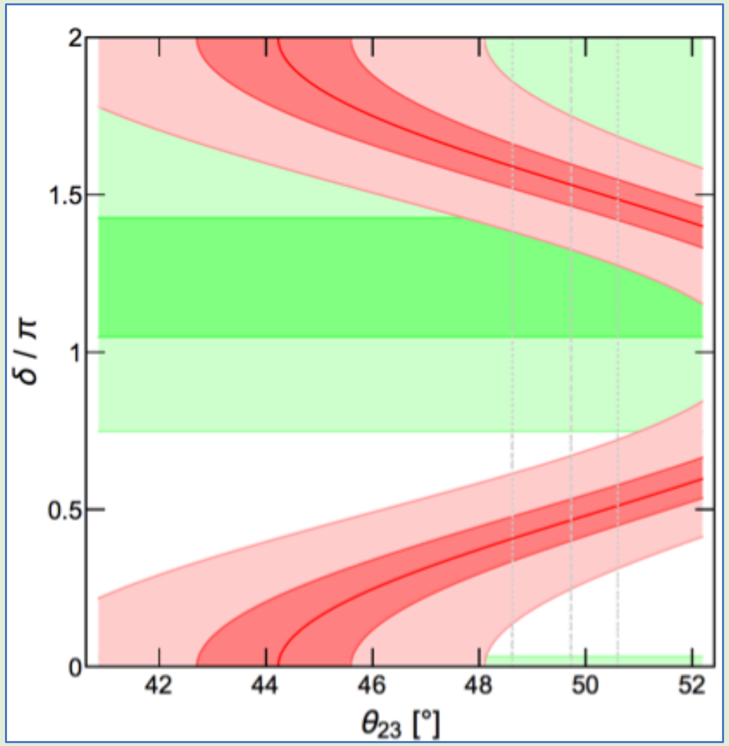
Dirac CP phase

dark (light) green band
: 1σ (3σ) favored region of δ

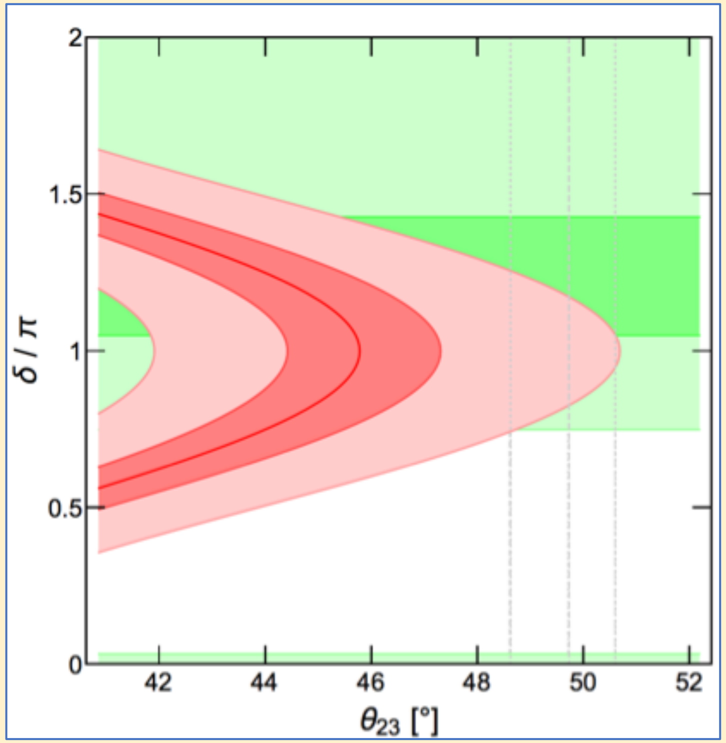
$L_\mu - L_\tau[\mathbf{C^R}]$



$B + L_e - 3L_\mu - L_\tau[\mathbf{D_1^R}]$

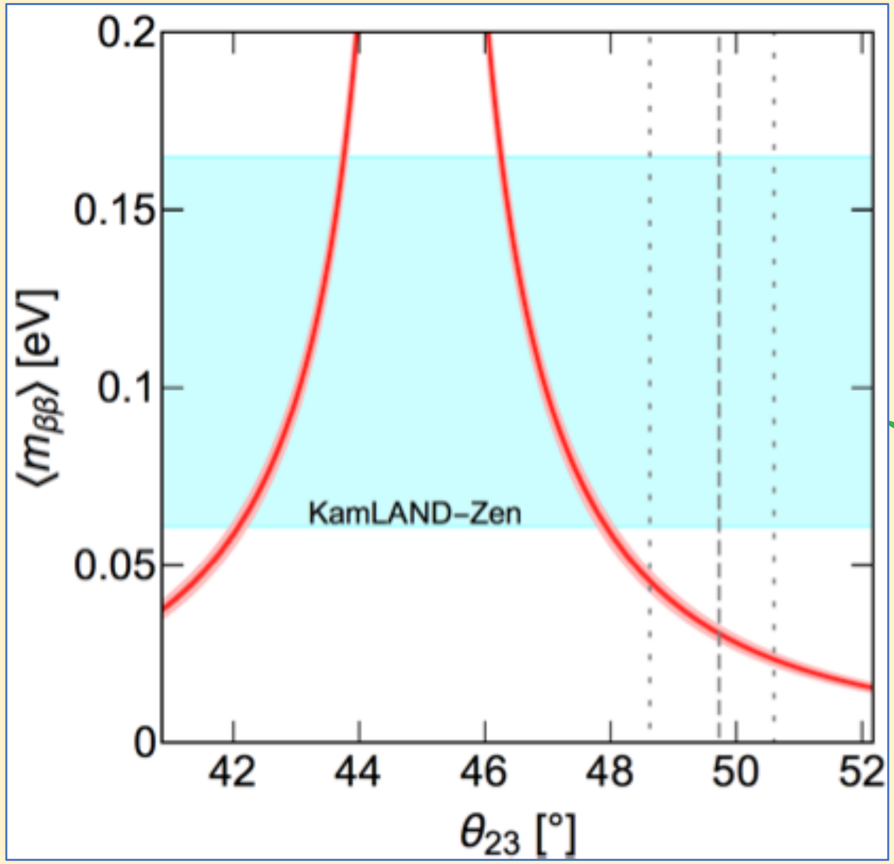


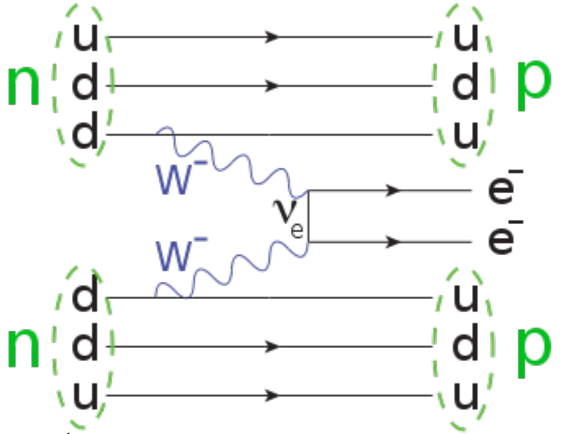
$B + L_e - L_\mu - 3L_\tau[\mathbf{D_2^R}]$



Effective Majorana neutrino mass

$L_\mu - L_\tau[\mathbf{C^R}]$





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

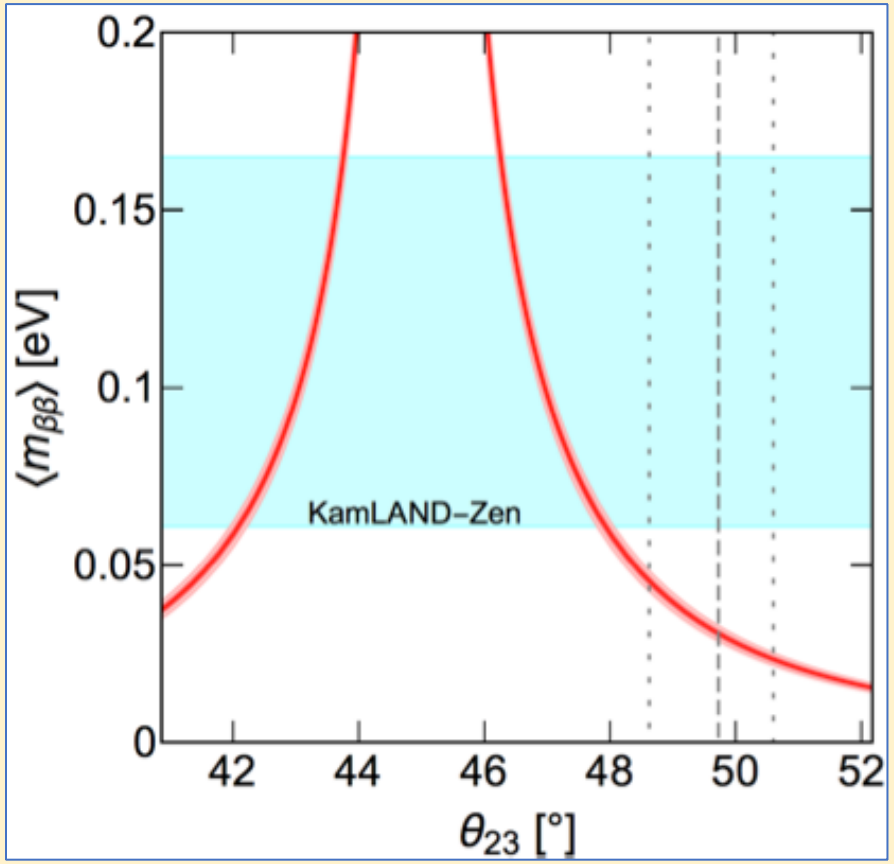
The strongest bound on $\langle m_{\beta\beta} \rangle$

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

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

Effective Majorana neutrino mass

$L_\mu - L_\tau[\mathbf{C^R}]$



$$B + L_e - 3L_\mu - L_\tau[\mathbf{D_1^R}]$$
$$B + L_e - L_\mu - 3L_\tau[\mathbf{D_2^R}]$$
$$\Rightarrow \langle m_{\beta\beta}\rangle = 0$$

$$\because \langle m_{\beta\beta}\rangle = |(U_{\mathrm{PMNS}}\mathrm{diag}(m_1, m_2, m_3)U_{\mathrm{PMNS}}^T)_{ee}|$$
$$= |(U_{\mathrm{PMNS}}^*\mathrm{diag}(m_1, m_2, m_3)U_{\mathrm{PMNS}}^\dagger)_{ee}|$$
$$= |(\mathcal{M}_{\nu_L})_{ee}| = 0$$

Neutrinoless double beta decay processes are observed

⇒ $\mathbf{D_1^R}$, $\mathbf{D_2^R}$ cases are rejected

Summary

- In this work, minimal $\mathrm{U}(1)_{Y'}$ models are analyzed and only the 3 cases with a scalar singlet survive experimental constraints.

- By analyzing two-zero minor condition, we found the prediction, which is independent of the U(1) breaking scale, for the CP phases, the neutrino masses, and the effective Majorana neutrino mass.

Parameters

Parameters in this model

in Lagranginan

Dirac Yukawa coupling

$$\lambda_e,\ \lambda_\mu,\ \lambda_\tau$$

Majorana mass

$$\lambda_{e\mu},\ \lambda_{e\tau},\ M_{ee},\ M_{\mu\tau}$$

φ : phase

from experiments

Mixing angle

$$\theta_{12},\ \theta_{23},\ \theta_{13}$$

Squared mass difference

$$\Delta m^2_{21},\ \Delta m^2_{31}$$

Lightest neutrino mass

$$m_1$$

CP phase

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

Parameters

Parameters in this model

in Lagranginan

Dirac Yukawa coupling

$$\lambda_e,\ \lambda_\mu,\ \lambda_\tau$$

Majorana mass

$$\lambda_{e\mu},\ \lambda_{e\tau},\ M_{ee},\ M_{\mu\tau}$$

φ : phase

from experiments

Mixing angle

$$\theta_{12},\ \theta_{23},\ \theta_{13}$$

Squared mass difference

$$\Delta m_{21}^2,\ \Delta m_{31}^2$$

Lightest neutrino mass

$$m_1$$

CP phase

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

Two zero minor condition

Leptogenesis

Parameters

Parameters in this model

in Lagranginan

from experiments

Dirac Yukawa coupling

$$\lambda_e,\ \lambda_\mu,\ \lambda_\tau$$

Majorana mass

$$\lambda_{e\mu},\ \lambda_{e\tau},\ M_{ee},\ M_{\mu\tau}$$

φ : phase

Mixing angle

$$\theta_{12},\ \theta_{23},\ \theta_{13}$$

Squared mass difference

$$\Delta m^2_{21},\ \Delta m^2_{31}$$

$$\mathcal{M}_R = -\mathcal{M}_D U_{\text{PMNS}} \begin{pmatrix} m_1 & & \\ & m_2 & \\ & & m_3 \end{pmatrix} U^T_{\text{PMNS}} \mathcal{M}_D$$

Parameters

Parameters in this model

in Lagranginan

Dirac Yukawa coupling

$\lambda_e, \ \lambda_\mu, \ \lambda_\tau$

→ Free parameters

Majorana mass

$\lambda_{e\mu}, \ \lambda_{e\tau}, \ M_{ee}, \ M_{\mu\tau}$

φ : phase

from experiments

Mixing angle

$\theta_{12}, \ \theta_{23}, \ \theta_{13}$

Squared mass difference

$\Delta m^2_{21}, \ \Delta m^2_{31}$

Lightest neutrino mass

m_1

CP phase

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

Baryon asymmetry

Sign of baryon asymmetry

Yukawa couplings

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

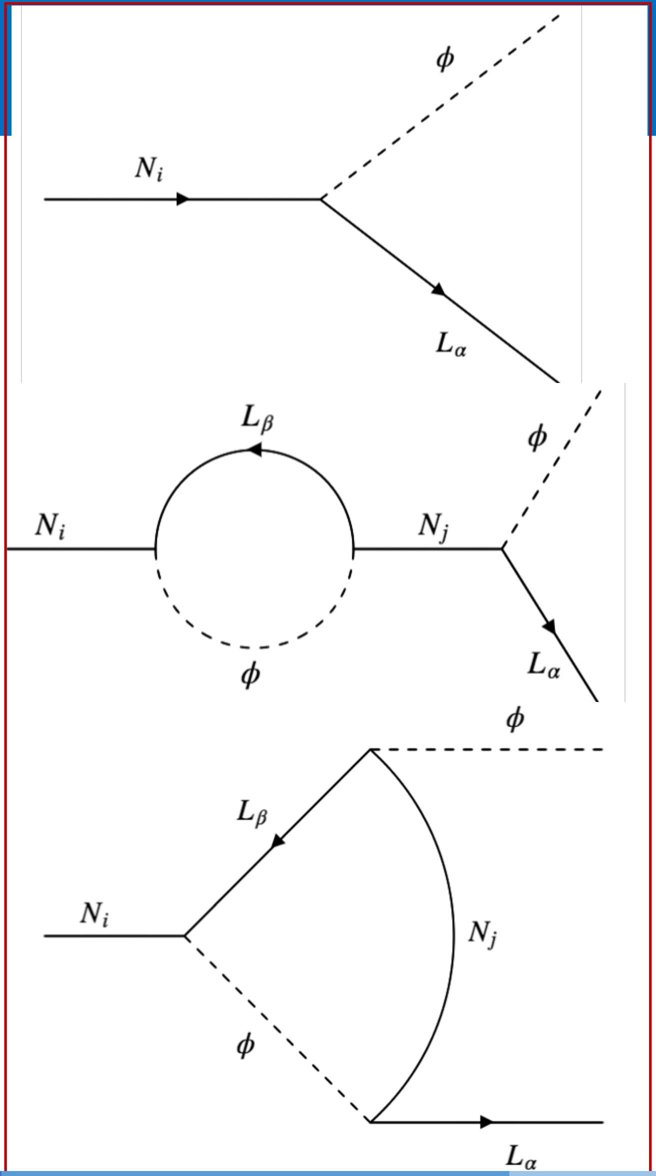
$$\equiv \lambda n$$

n_α	$\rightarrow$	$\hat{n}_\alpha$
$\lambda_\alpha N_\alpha (L_\alpha \cdot H)$	$\rightarrow$	$\hat{\lambda} N_i (L_\alpha \cdot H)$

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)



Baryon asymmetry

Sign of baryon asymmetry

Relation between baryon and lepton generated

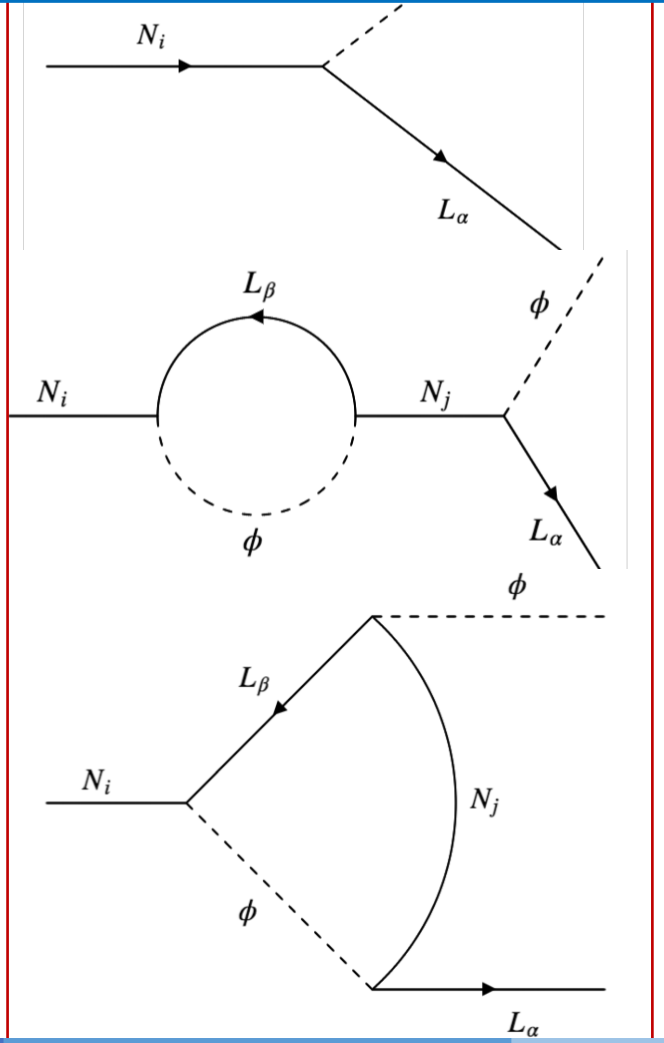
$$\frac{n_B/s}{n_L/s} = -\frac{28}{79} < 0$$

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

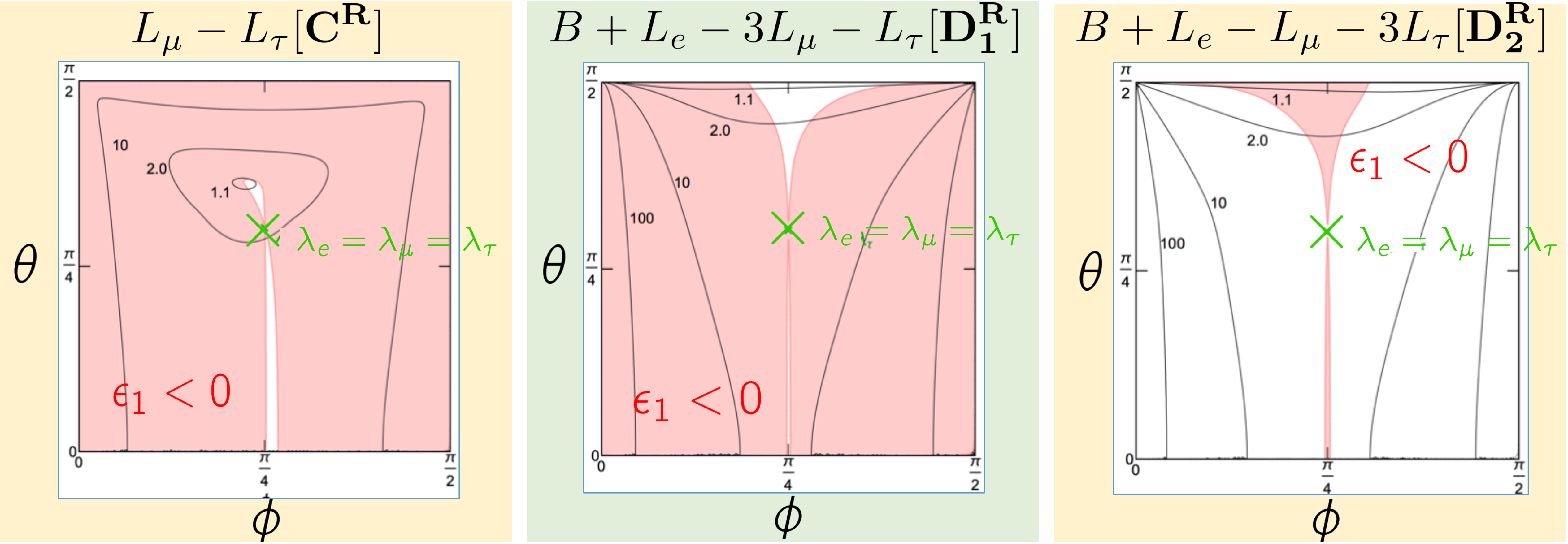
$$\epsilon_1 < 0$$



Results

$$(\lambda_e, \lambda_\mu, \lambda_\tau) = \lambda(\cos\theta, \sin\theta\cos\phi, \sin\theta\sin\phi)$$

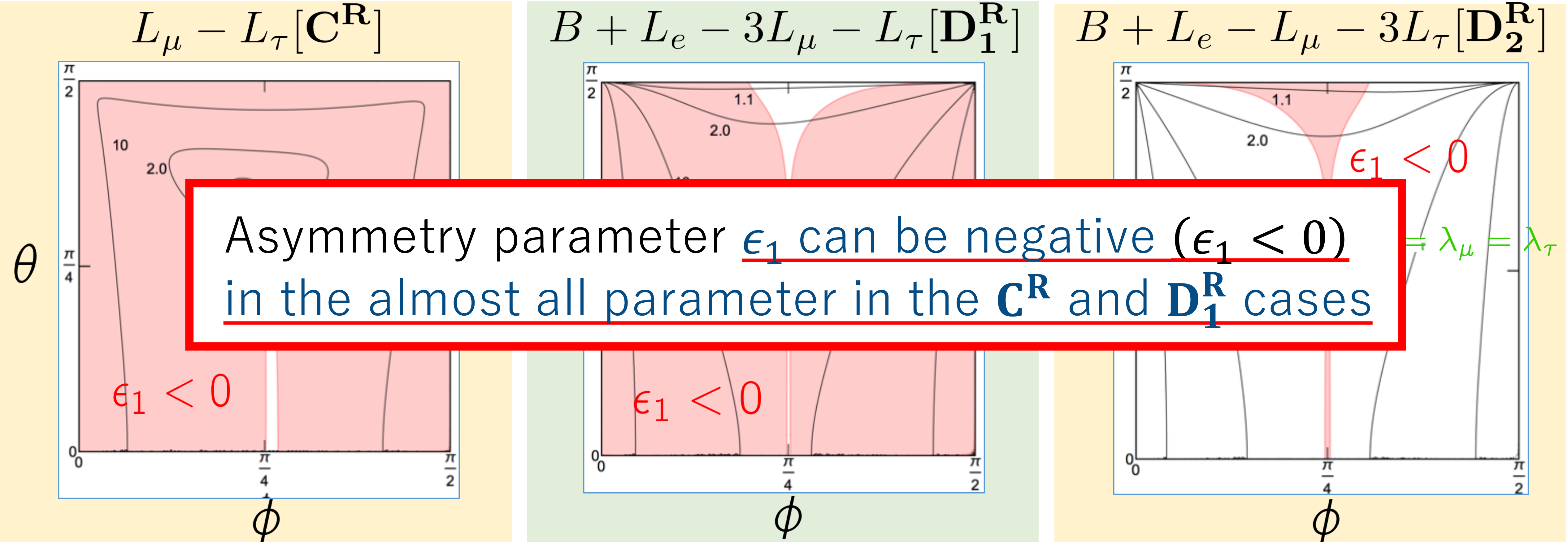
Sign of baryon asymmetry



Results

$(\lambda_e, \lambda_\mu, \lambda_\tau) = \lambda(\cos\theta, \sin\theta\cos\phi, \sin\theta\sin\phi)$

Sign of baryon asymmetry



Asymmetry parameter ϵ_1 can be negative ($\epsilon_1 < 0$) in the almost all parameter in the $\mathbf{C^R}$ and $\mathbf{D_1^R}$ cases

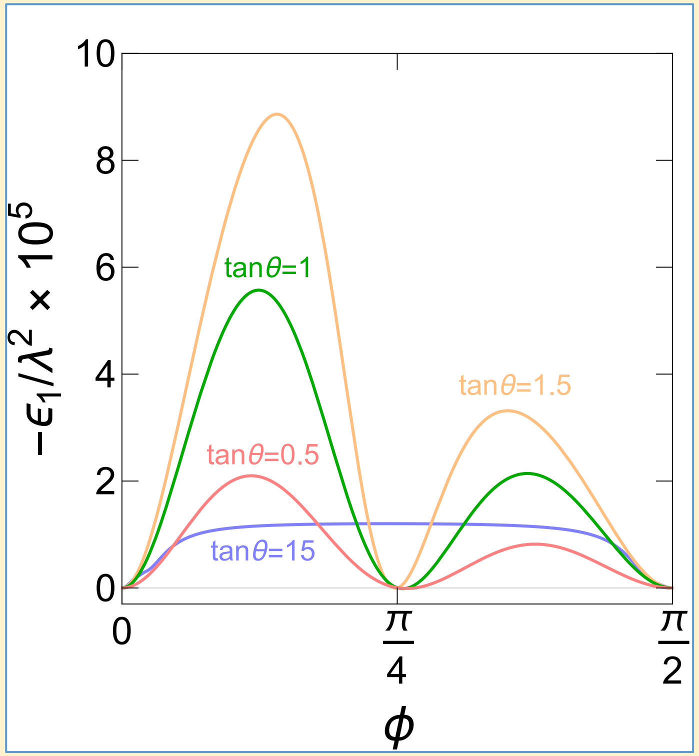
Leptogenesis

Results

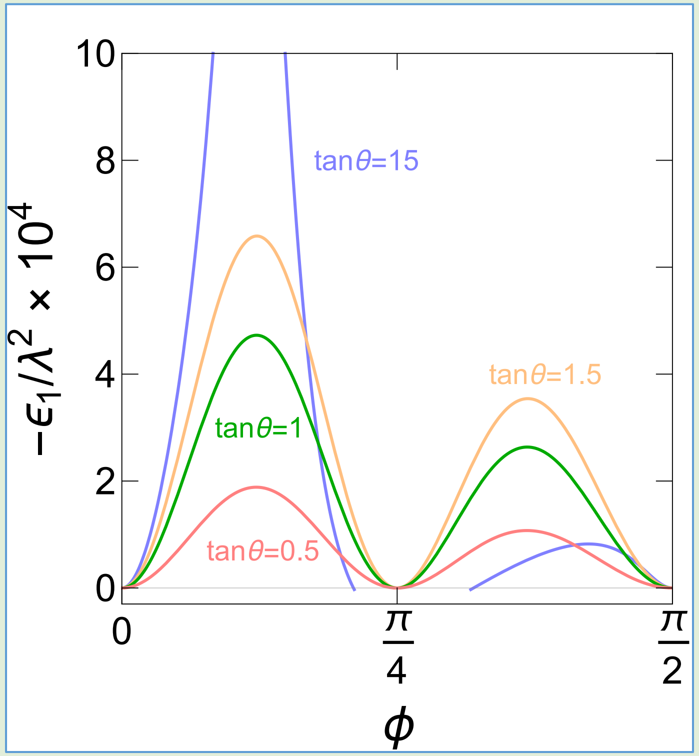
$(\lambda_e, \lambda_\mu, \lambda_\tau)$
$= \lambda(\cos\theta, \sin\theta\cos\phi, \sin\theta\sin\phi)$

Size of baryon asymmetry

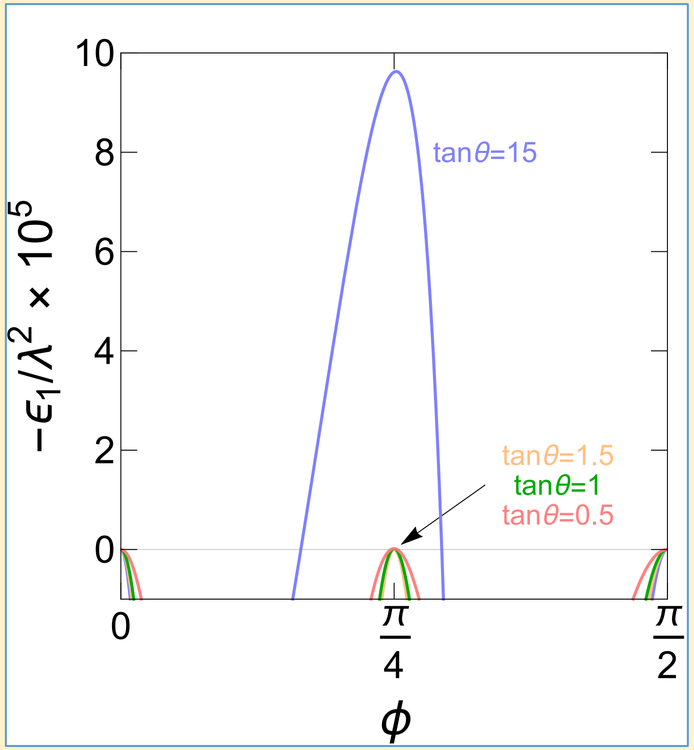
$L_\mu - L_\tau[\mathbf{C^R}]$



$B + L_e - 3L_\mu - L_\tau[\mathbf{D_1^R}]$



$B + L_e - L_\mu - 3L_\tau[\mathbf{D_2^R}]$



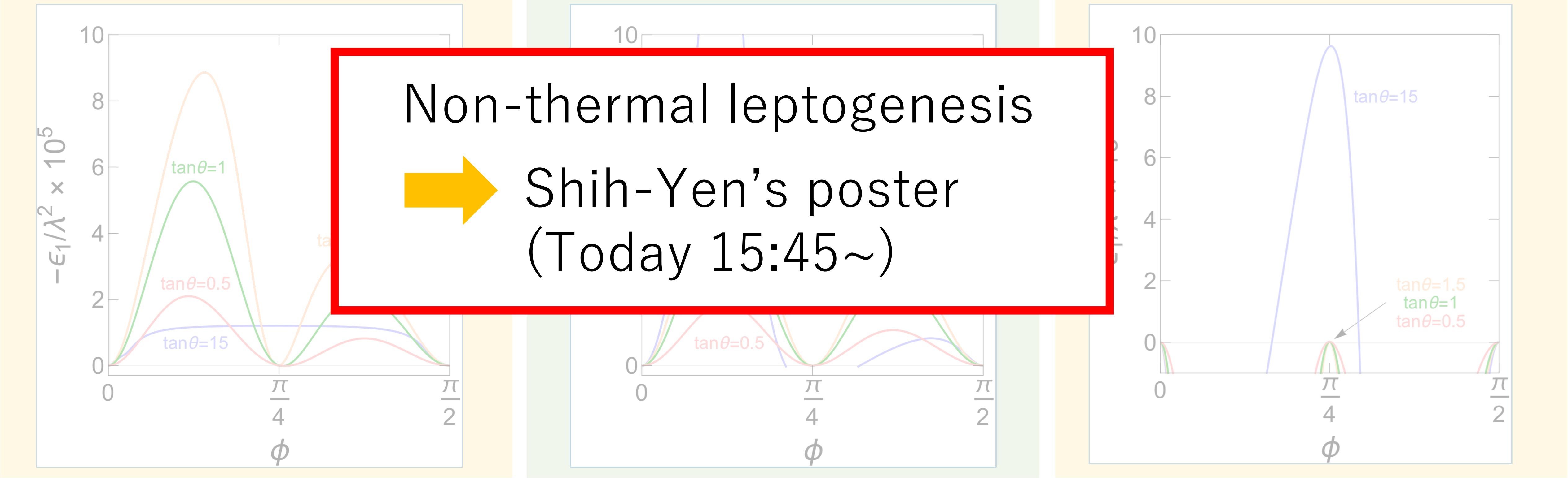
Leptogenesis

Results

$(\lambda_e, \lambda_\mu, \lambda_\tau)$
$= \lambda(\cos\theta, \sin\theta\cos\phi, \sin\theta\sin\phi)$

Size of baryon asymmetry

$L_\mu - L_\tau[\mathbf{C^R}]$ | $B + L_e - 3L_\mu - L_\tau[\mathbf{D_1^R}]$ | $B + L_e - L_\mu - 3L_\tau[\mathbf{D_2^R}]$



Non-thermal leptogenesis

→ Shih-Yen's poster (Today 15:45~)

Conclusion

- Only $\mathbf{C^R}$, $\mathbf{D_1^R}$ and $\mathbf{D_2^R}$ cases with a singlet scalar satisfy two-zero minor condition and are consistent with the neutrino oscillation data.

- By analyzing two-zero minor condition, we found the prediction, which is independent of the $\mathrm{U(1)_{Y'}}$ breaking scale, for the CP phases, the neutrino masses, and the effective Majorana neutrino mass.

- We found that, in the $\mathbf{C^R}$ and $\mathbf{D_1^R}$ cases, the correct sign of the baryon asymmetry can be obtained, and it is possible that enough large baryon asymmetry can be realized.

Muon g-2

$$\delta a_\mu = a_\mu(\text{exp}) - a_\mu(\text{SM})$$
$$= (26.1 \pm 8.0) \times 10^{-10}$$

K. Hagiwara, R. Liao, A. D. Martin, D. Nomura, and T. Teubner (2011)

Anomalous magnetic moment

Interaction between magnetic moment and magnetic field

$$H_{\text{int}} = -\vec{\mu}_\mu \cdot \vec{B}$$
$$\vec{\mu}_\mu = g_s \mu_B \vec{s}$$

g_s : Landé g factor

$\vec{s}$: muon spin

$\mu_B = \dfrac{e\hbar}{2mc}$: Bohr magneton

Muon g-2

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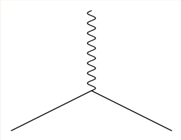
$$H_{\text{int}} = -\vec{\mu}_\mu \cdot \vec{B}$$
$$\vec{\mu}_\mu = g_s \mu_B \vec{s}$$

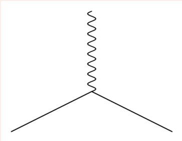
Classical level

$$g_s = 2$$

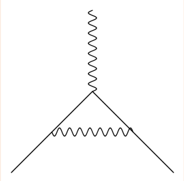


\+ Quantum corrections

$$g_s =$$



$$+$$



$$+ \cdots$$

$$= 2 + \frac{\alpha}{2\pi} + \cdots$$

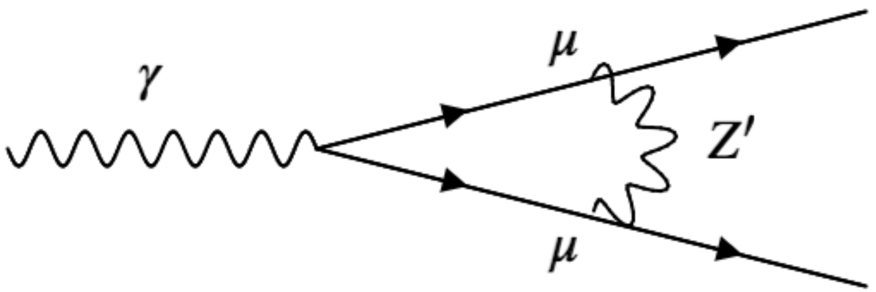
$$a_\mu = g_s - 2$$

: Quantum corrections

Muon g-2

$$\delta a_\mu = a_\mu(\mathrm{exp}) - a_\mu(\mathrm{SM}) = (26.1 \pm 8.0) \times 10^{-10}$$

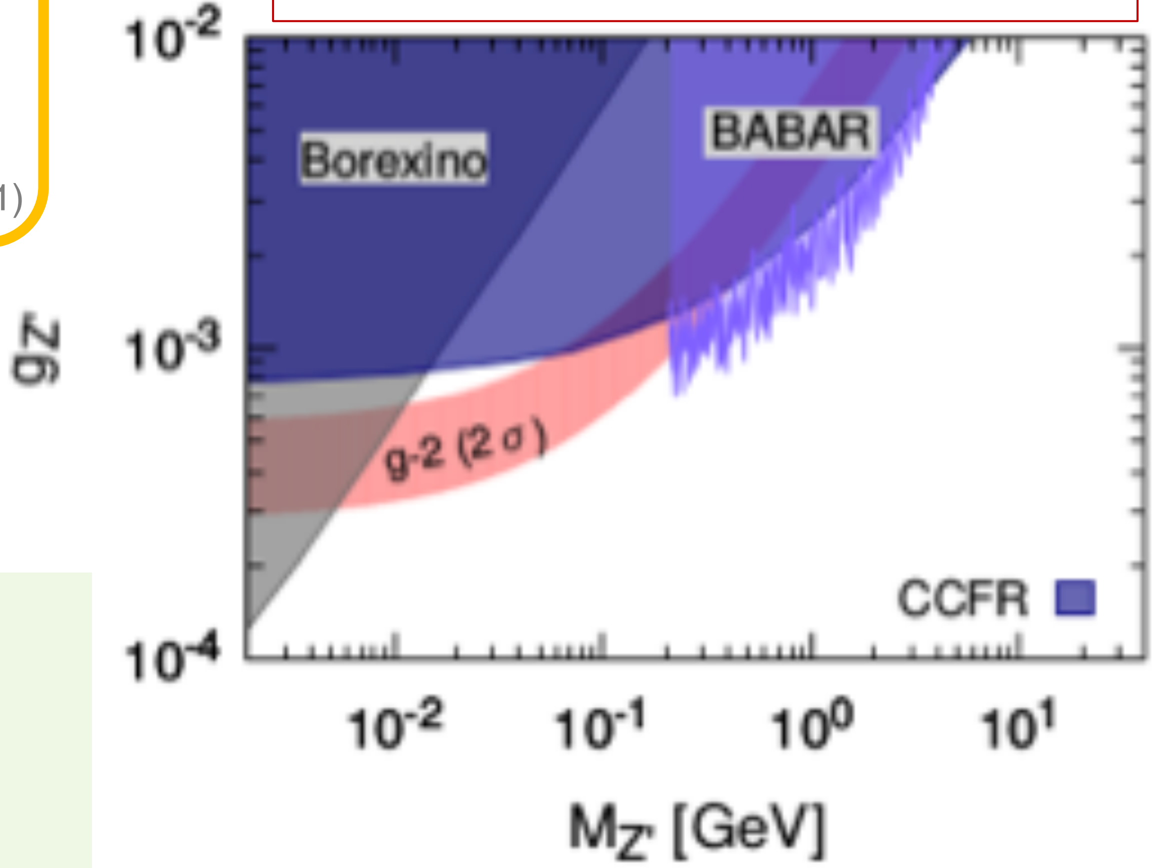
K. Hagiwara, R. Liao, A. D. Martin, D. Nomura, and T. Teubner (2011)



Z'boson contributes to muon g-2

$$\delta a_\mu = \frac{g_{Z'}^2}{8\pi^2}\int_0^1 dx \frac{2m_\mu^2 x^2(1-x)}{x^2 m_\mu^2 + (1-x)m_{Z'}^2}$$

T. Araki, S. Hosino, T. Ota, J. Sato, and T.Shimomura (2017)



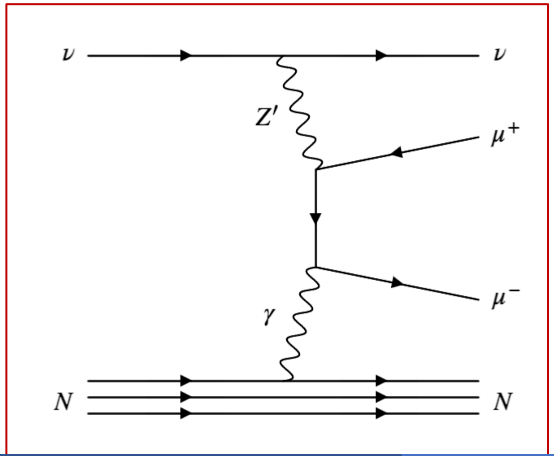
Neutrinoless Trident Production

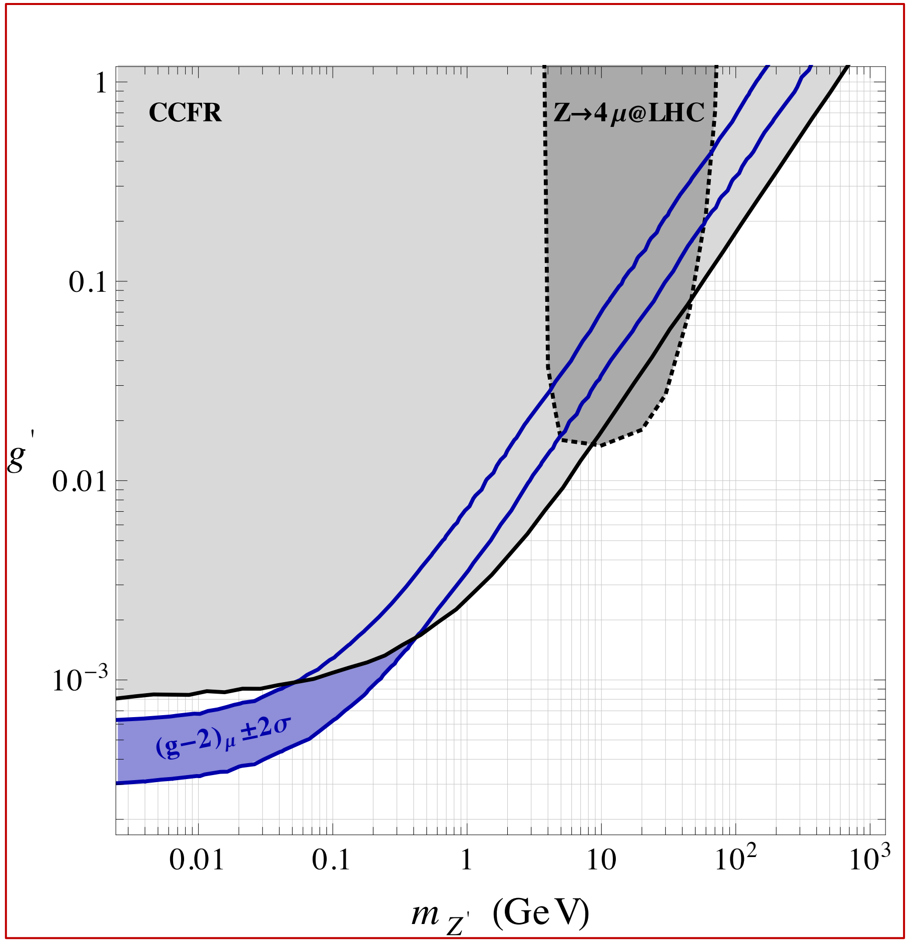
W. Altmannshofer, S. Gori, M. Pospelov, and I. Yavin (2014)

$m_{Z'} \gg \sqrt{s}$

$$\frac{\sigma^{(\mathrm{SM+Z'})}}{\sigma^{(\mathrm{SM})}} \simeq \frac{1+\left(1+4\sin^2\theta_W+2v_{\mathrm{SM}}^2/v_{Z'}^2\right)^2}{1+(1+4\sin^2\theta_W)^2}$$

$$\sigma_{\mathrm{CCFR}}/\sigma_{\mathrm{SM}} = 0.82 \pm 0.28$$





Neutrinoless Trident Production

W. Altmannshofer, S. Gori, M. Pospelov, and I. Yavin (2014)

$$m_\mu \ll m_{Z'} \ll \sqrt{s}$$

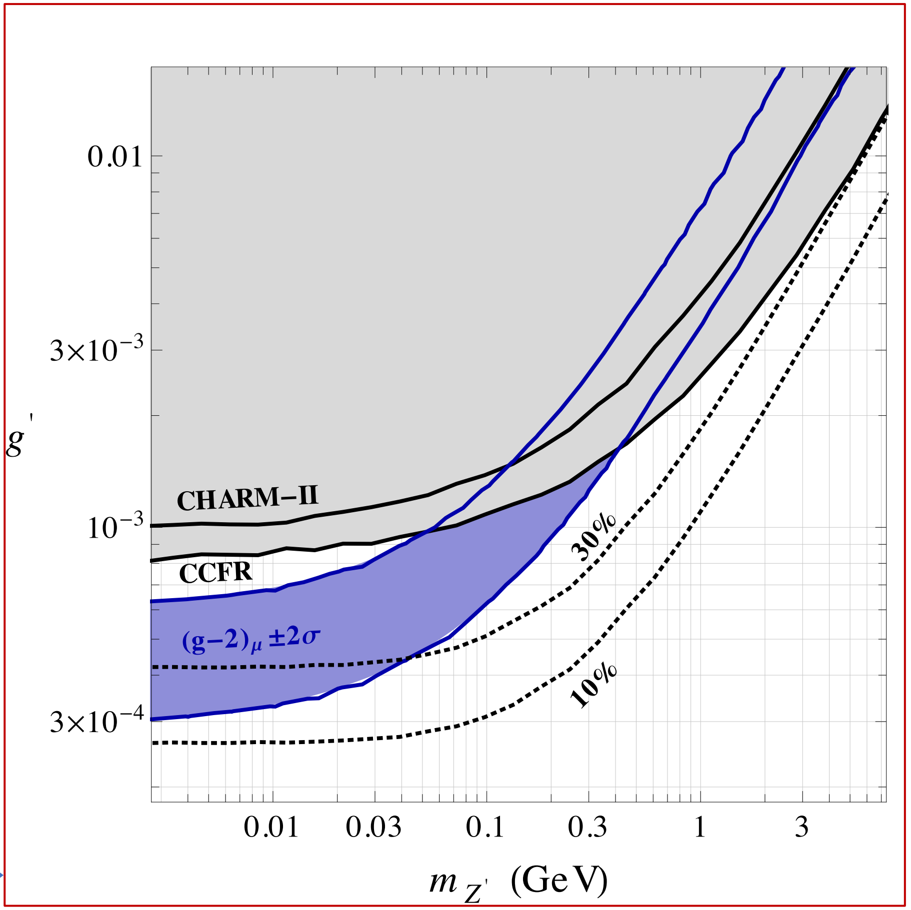
$$\sigma^{(\mathrm{SM+Z'})} = \sigma^{(\mathrm{SM})} + \sigma^{(\mathrm{inter})} + \sigma^{(\mathrm{Z'})}$$

$$\sigma^{(\mathrm{SM})} \simeq \frac{1}{2}(C_V^2 + C_A^2)\frac{2G_F^2 \alpha s}{9\pi^2}\left(\log\left(\frac{s}{m_\mu^2}\right) - \frac{19}{6}\right)$$

$$\sigma^{(\mathrm{inter})} \simeq \frac{G_F}{\sqrt{2}}\frac{g'^2 C_V \alpha}{3\pi^2}\log^2\left(\frac{s}{m_\mu^2}\right)$$

$$\sigma^{(\mathrm{Z'})} \simeq \frac{1}{m_{Z'}^2}\frac{g'^4 \alpha}{6\pi^2}\log\left(\frac{m_{Z'}^2}{m_\mu^2}\right)$$

$$\Rightarrow \sigma_{\mathrm{CHARM-II}}/\sigma_{\mathrm{SM}} = 1.58 \pm 0.57$$



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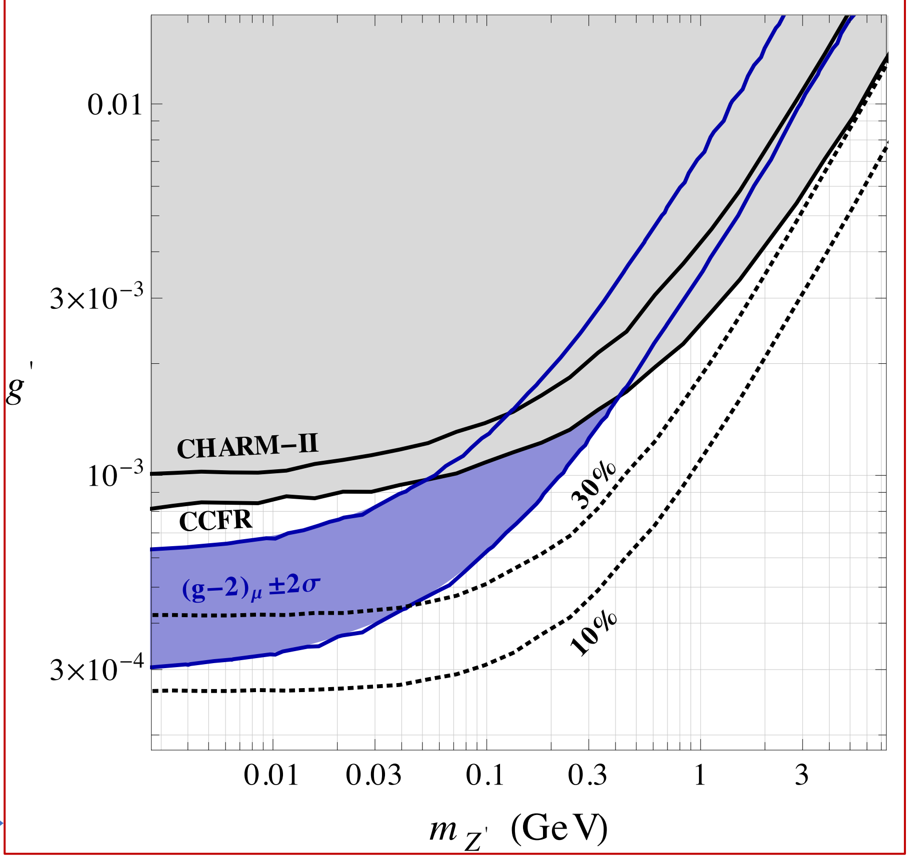
$$\sigma^{(\mathrm{inter})} \simeq \frac{G_F}{\sqrt{2}}\frac{g'^2 C_V \alpha}{3\pi^2}\log^2\left(\frac{s}{m_\mu^2}\right)$$

$$\sigma^{(\mathrm{Z'})} \simeq \frac{1}{m_\mu^2}\frac{7g'^4\alpha}{72\pi^2}\log\left(\frac{m_\mu^2}{m_{Z'}^2}\right)$$

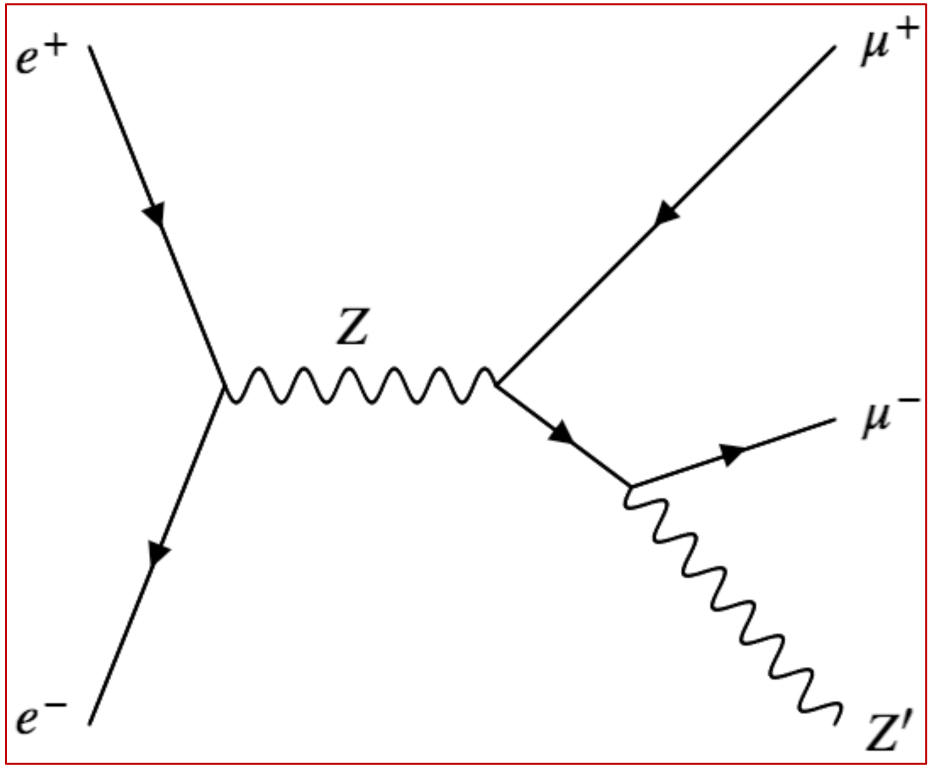
$$\Rightarrow \quad \sigma_{\mathrm{CHARM-II}}/\sigma_{\mathrm{SM}} = 1.58 \pm 0.57$$

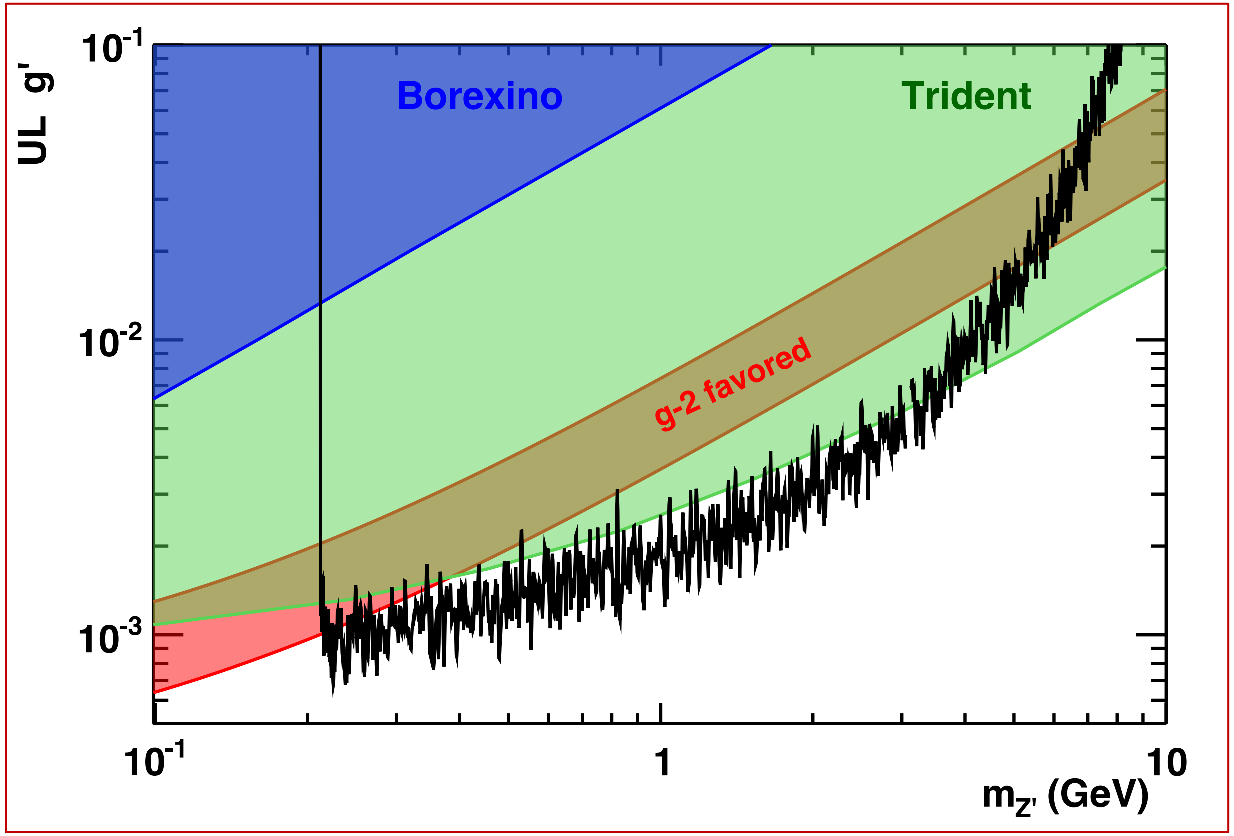


BABAR experiment

BABAR, Phys. Rev. **D94**, 011102 (2016)

$$e^+e^- \to \mu^+\mu^- Z',\ Z' \to \mu^+\mu^-$$



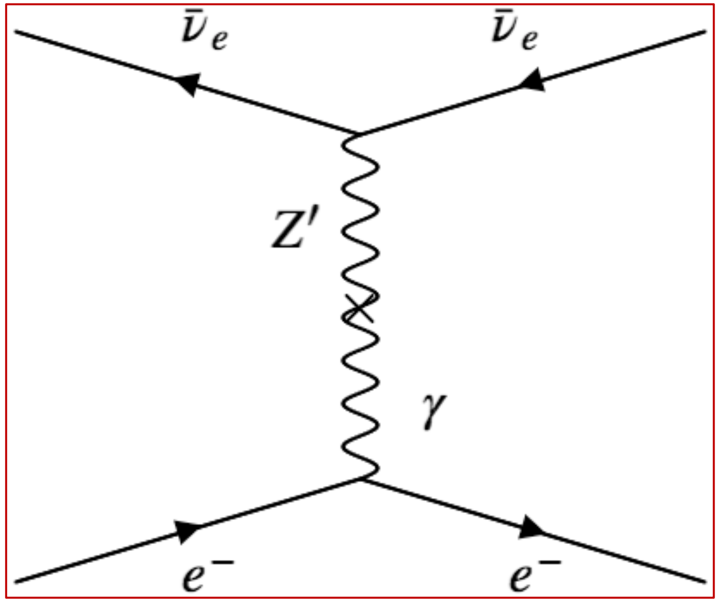


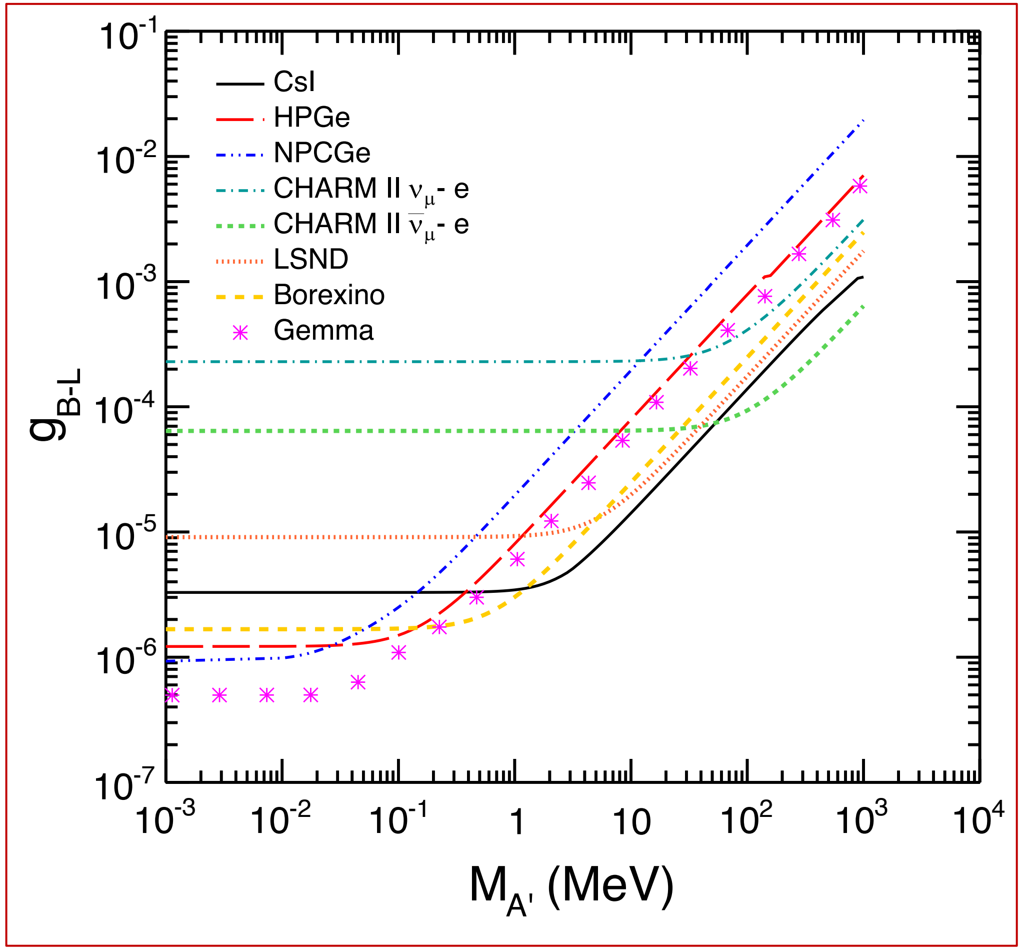
Neutrino-electron scattering

S. Bilmis, I. Turan, T. M. Aliev, M. Daniz, L. Singh, and H. T. Wong (2015)

Kinetic mixing $\mathcal{L} \supset \frac{1}{2}\epsilon B_{\mu\nu}F'^{\mu\nu}$

contributes to ν_μ-e^- process





Scalar doublet VEVs in the doublet cases

Doublet Φ_1

Scalar doubelt VEVs

$$\langle\Phi_1\rangle = \begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \langle\Phi_2\rangle = \begin{pmatrix} 0 \\ v_2 \end{pmatrix}$$

$\mathrm{U}(1)_{L_\mu - L_\tau}$-symm. breaking scale

$$\Rightarrow v \equiv \sqrt{v_1^2 + v_2^2} \simeq 246\ \mathrm{GeV}$$

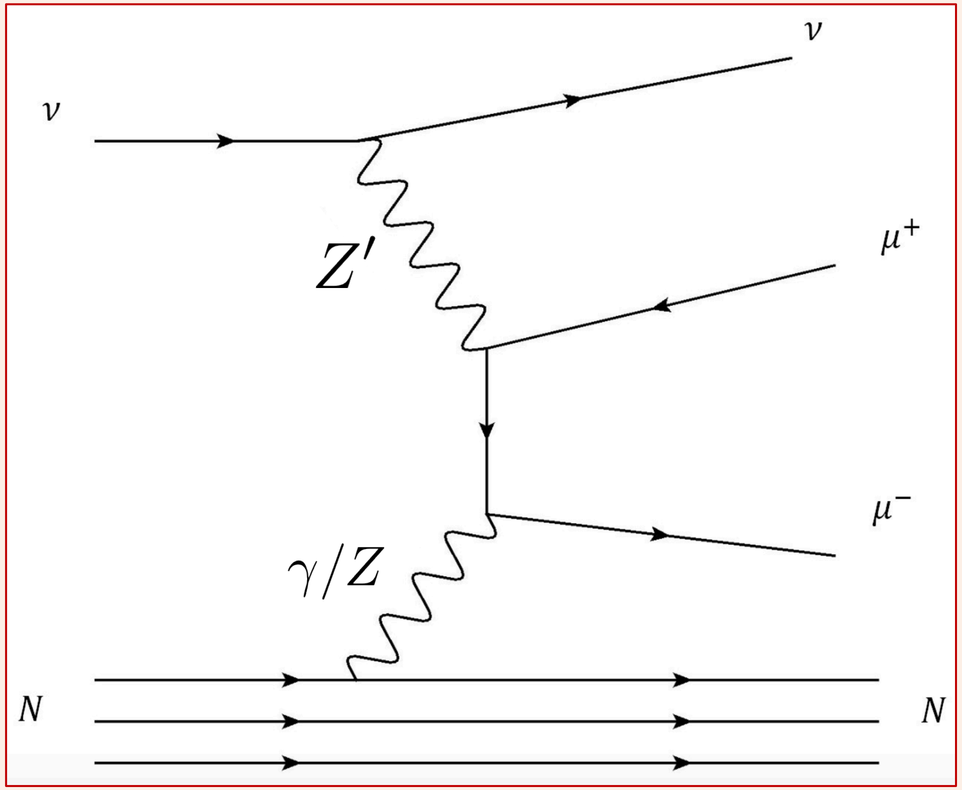
$\mathrm{U}(1)_{L_\mu - L_\tau}$ -symm. breaking scale in the doublet cases should be below the EW scale

Neutrino Trident Production

Neutrino Trident Production

the production of a $\mu^+\mu^-$ pair from the scattering of a muon- neutrino with heavy nuclei

Sensitive to light Z' coupled with muon



Neutrino Trident Production

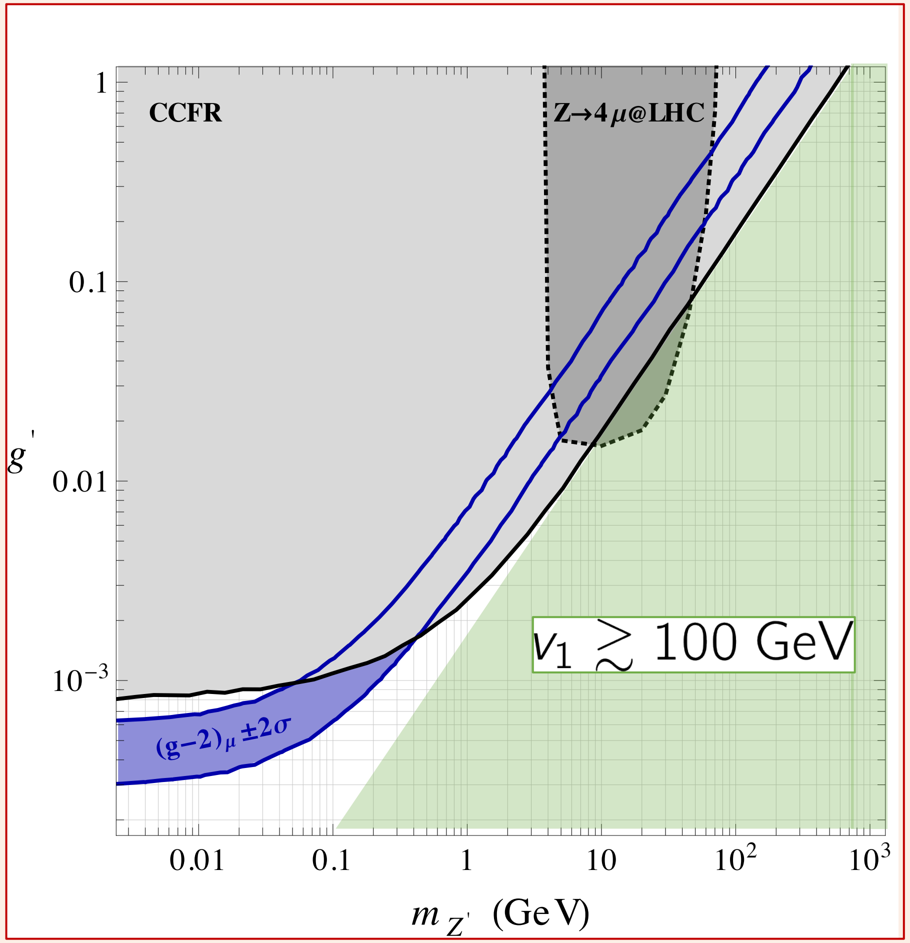
Neutrino Trident Production

the production of a $\mu^+\mu^-$ pair from the scattering of a muon- neutrino with heavy nuclei

Sensitive to light Z' coupled with muon

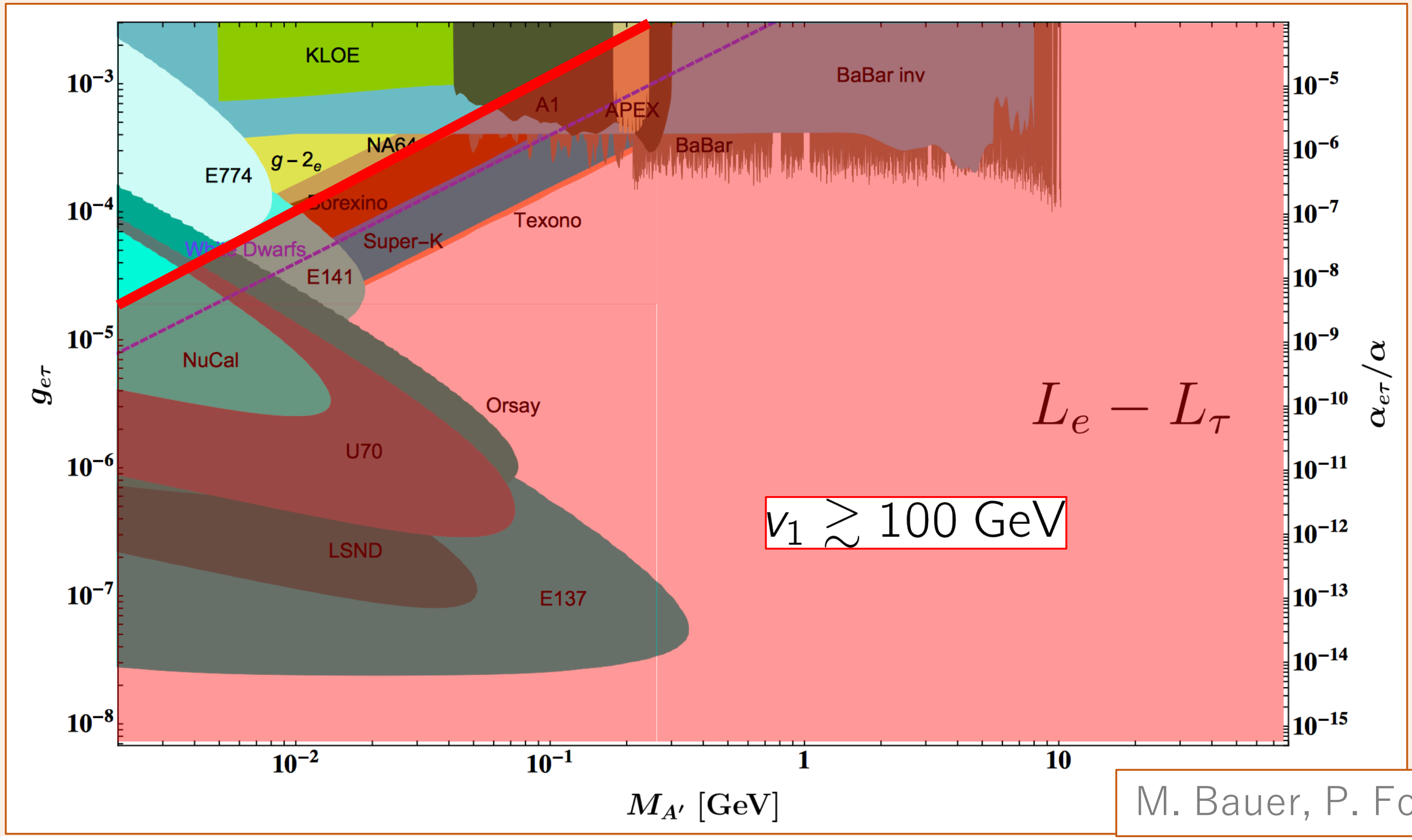
$$v_1 \lesssim 100\ \text{GeV} \Longrightarrow g_{Z'} \lesssim 10^{-2}$$

Z' is lighter than tauon : $m_{Z'} \lesssim m_\tau$



The minimal gauged $\mathrm{U}(1)_{L_e-L_\tau}$ model

○ Constraints on $(m_{Z'}, g_{Y'})$



The VEV of Φ_1 (v_1) breaks not only $\mathrm{U}(1)_{Y'}$ but also $\mathrm{SU}(2)_L$

v_1 should be lower than the electroweak scale$(v_1 \lesssim 100$ GeV$)$

M. Bauer, P. Foldenauer and J. Jaeckel, JHEP **1807** (2018) 094

Lepton Flavor Violation

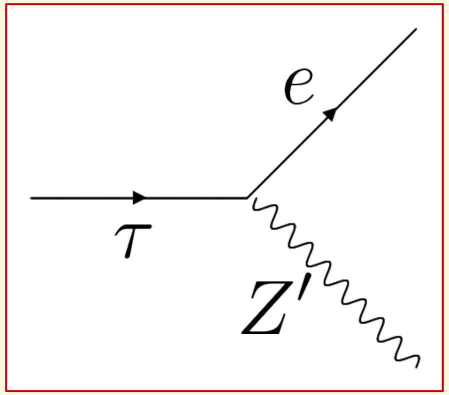
Doublet Φ_1

Z' current

$$J^{\mu}_{Z'} \supset \bar{e}_L \gamma^{\mu} \tau_L$$

$$m_{Z'} \lesssim m_{\tau}$$

Lepton Flavor Violation



For simplisity

$$\mathcal{M}_l = \frac{1}{\sqrt{2}} \begin{pmatrix} y_e v_2 & 0 & y_{e\tau} v_1 \\ 0 & y_{\mu} v_2 & 0 \\ 0 & 0 & y_{\tau} v_2 \end{pmatrix}$$

Appendix

Lepton Flavor Violation

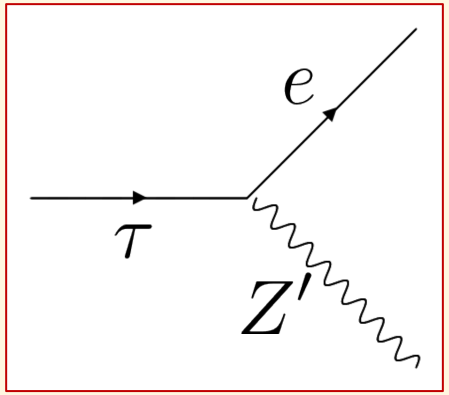
Doublet Φ_1

Z' current

$$J^{\mu}_{Z'} \supset \bar{e}_L \gamma^{\mu} \tau_L$$

$m_{Z'} \lesssim m_\tau$

Lepton Flavor Violation



For simplisity

$$\mathcal{M}_l = \frac{1}{\sqrt{2}} \begin{pmatrix} y_e v_2 & 0 & y_{e\tau} v_1 \\ 0 & y_\mu v_2 & 0 \\ 0 & 0 & y_\tau v_2 \end{pmatrix}$$

diagonalizing

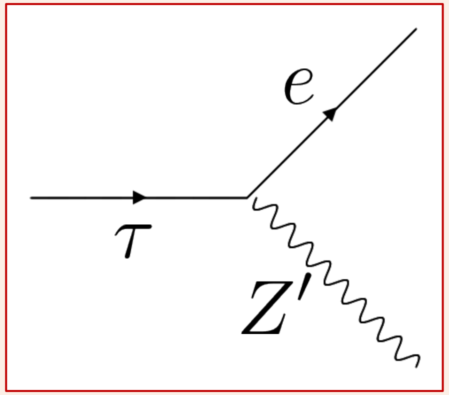
$$\mathcal{M}_l = U_L^* \begin{pmatrix} m_e & & \\ & m_\mu & \\ & & m_\tau \end{pmatrix} U_R^T$$

$$U_{L,R} \equiv \begin{pmatrix} \cos\theta_{L,R} & 0 & e^{-i\phi}\sin\theta_{L,R} \\ 0 & 1 & 0 \\ -e^{-i\phi}\sin\theta_{L,R} & 0 & \cos\theta_{L,R} \end{pmatrix} \qquad \frac{\tan\theta_R}{\tan\theta_L} = \frac{m_e}{m_\tau}$$

Lepton Flavor Violation

Decay width

$$\Gamma(\tau \to eZ') = \frac{g_{Z'}^2 m_\tau}{128\pi} \sin^2 2\theta_L \left(2 + \frac{m_\tau^2}{m_{Z'}^2}\right)\left(1 - \frac{m_{Z'}^2}{m_\tau^2}\right)^2$$



ARGUS limit

ARGUS collaboration (1995)

$$B(\tau \to eX) \lesssim 2.7 \times 10^{-3}$$

$\mathcal{M}_l \simeq$ diagonal

Limit on the mixing angle θ_L

$$|\sin 2\theta_L| \lesssim \begin{cases} 7 \times 10^{-5} & (m_{Z'}, g_{Z'}) = (100\ \mathrm{MeV}, 10^{-3}) \\ 1 \times 10^{-5} & (m_{Z'}, g_{Z'}) = (10\ \mathrm{MeV}, 5 \times 10^{-4}) \end{cases}$$

$$\theta_L \simeq 0, \frac{\pi}{2}$$

$$U_{L,R} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \text{ or } \begin{pmatrix} 0 & 0 & e^{-i\phi} \\ 0 & 1 & 0 \\ -e^{-i\phi} & 0 & 0 \end{pmatrix}$$

Lepton Flavor Violation

a) K. Hayasaka et al (1995) b) BaBar Collaboration (2010)
c) A. Jodidio et al (1986) d) TWIST Collaboration (2015)
e) MEG Collaboration (2016)

Other experimental limits

○ Limits on $y_{e\tau}$

a) $BR(\tau^- \to e^- \mu^+ \mu^-) < 2.7 \times 10^{-8}$

b) $BR(\tau \to e\gamma) < 3.3 \times 10^{-8}$

○ Limits on $y_{\mu e}$

c) $\dfrac{BR(\mu \to eX)}{BR(\mu \to e\nu\bar{\nu})} < 2.6 \times 10^{-6}$

d) $BR(\mu \to eX) \lesssim 10^{-5}$ for $m_{Z'} = 13\text{-}80\ \mathrm{MeV}$

e) $BR(\mu \to e\gamma) < 4.2 \times 10^{-13}$

⇨ Charged lepton-flavor mixing is extremely small

⇨ $\theta_L = 0$ or $\pi/2$ (No charged lepton-flavor mixing)

Minimal Gauged $\mathrm{U}(1)_{L_\alpha - L_\beta}$ Models

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

$a = -1$

$$\sigma \to \sigma^*$$

Appendix

Neutrino oscillation parameters

NuFIT v4.0 result with the Super-Kamiokande atmospheric data

www.nu-fit.org

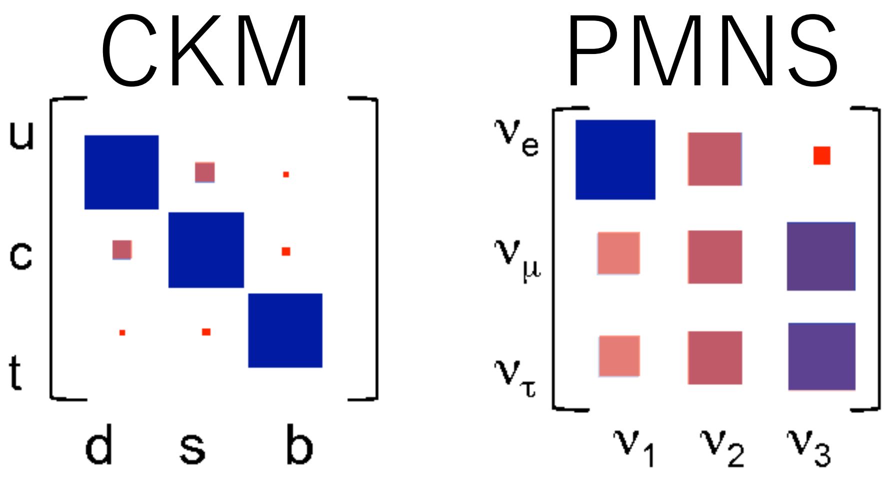
	Normal Ordering		Inverted Ordering	
Parameter	Best fit $\pm 1\sigma$	3σ range	Best fit $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	0.275–0.350	$0.310^{+0.013}_{-0.012}$	0.275–0.350
$\sin^2\theta_{23}$	$0.582^{+0.015}_{-0.019}$	0.428–0.624	$0.582^{+0.015}_{-0.018}$	0.433–0.623
$\sin^2\theta_{13}$	$0.02240^{+0.00065}_{-0.00066}$	0.02044–0.02437	$0.02263^{+0.00065}_{-0.00066}$	0.02067–0.02461
$\Delta m^2_{21}/10^{-5}\ \mathrm{eV}^2$	$7.39^{+0.21}_{-0.20}$	6.79–8.01	$7.39^{+0.21}_{-0.20}$	6.79–8.01
$\Delta m^2_{3\ell}/10^{-3}\ \mathrm{eV}^2$	$2.525^{+0.033}_{-0.031}$	2.431–2.622	$-2.512^{+0.034}_{-0.031}$	$-$(2.606–2.413)
$\delta\ [^\circ]$	217^{+40}_{-28}	135–366	280^{+25}_{-28}	196–351

PMNS matrix

PMNS matrix

: lepton version of the CKM matrix

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



$$j^{\mu}_{W,l} = 2\bar{e}_L\gamma^{\mu}P_L\nu_L$$
$$= 2\bar{e}'_L U_{\mathrm{PMNS}}\gamma^{\mu}P_L\nu'_L$$

Quantum correction 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

Appendix

Quantum correction 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

Quantum correction to neutrino mass matrix

The right-handed neutrinos are integrated out to give the following dimension-five effe

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

The renormalization group equation of the Wilson coe

Higgs quartic coupling

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

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

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

with

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

Quantum correction to neutrino mass matrix

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

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

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

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

where

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

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

Quantum correction to neutrino mass matrix

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

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

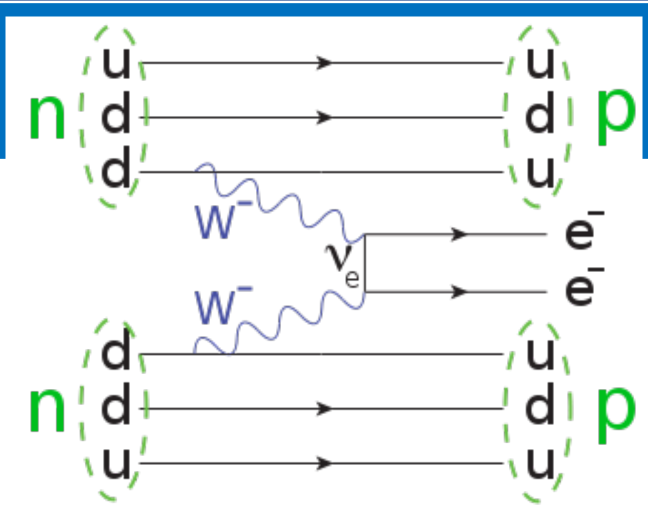
⇓

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

⇓

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

Neutrinoless double beta decay



Decay half time

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

Nuclear matrix element

Phase space factor

Effective Majorana mass

$$\langle m_{\beta\beta}\rangle \equiv \left|\sum_i (U_{\rm PMNS})^2_{ei}\right|$$

$$= \left|c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 e^{i\alpha_2} m_2 + s_{13}^2 e^{i(\alpha_3 - 2\delta)} m_3\right|$$