Lepton Number Violating New Physics and Neutrinoless Double Beta Decay

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Based on

JHEP **06** (2011) 091 (`arXiv:1105.0901 [hep-ph]`) and

JHEP **05** (2012) 017 (`arXiv:1201.3031 [hep-ph]`)

together with: S. Choubey, M. Lindner, A. Merle, M. Mitra, W. Rodejohann.

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Contents

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Contents

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Basics of neutrinoless double beta decay

Modes of $\beta\beta$ decay:

$$(Z,A) \to (Z+2,A) + 2e^- + 2\bar{\nu}_e \quad (2\nu\beta\beta)$$

$$(Z,A) \to (Z+2,A) + 2e^- \quad (0\nu\beta\beta)$$

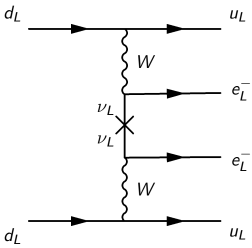
Total decay rate of $0\nu\beta\beta$:

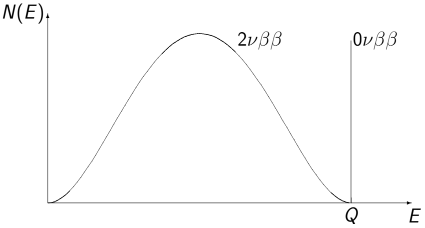
$$\Gamma^{0\nu}/\ln 2 = (T^{0\nu}_{1/2})^{-1} = |M_{ee}|^2 \left|\mathcal{M}^{0\nu}\right|^2 G^{0\nu}(Q,Z)$$

$M_{ee} = \sum_i U_{ei}^2 m_i$

$\mathcal{M}^{0\nu}$: nuclear matrix element

$G^{0\nu}(Q,Z)$: phase space factor





▸ $0\nu\beta\beta$ in colored seesaw model

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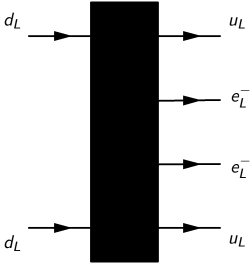
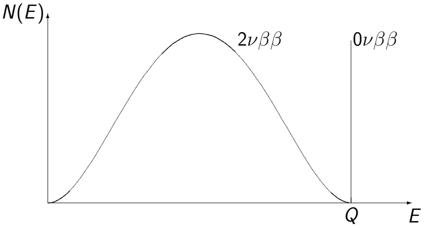
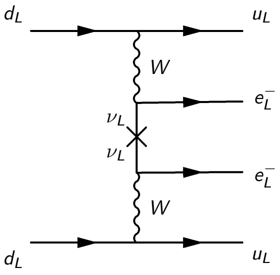




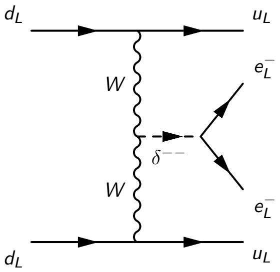
$0\nu\beta\beta$ in colored seesaw model

New Physics mechanisms for the black box

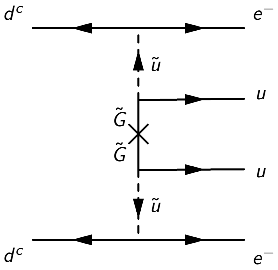
- Mass mechanism



- Higgs triplet model



- SUSY



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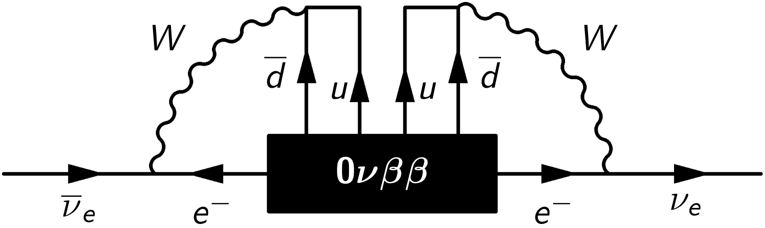
Contents

Schechter–Valle theorem

- Connects $0\nu\beta\beta$ and a non-zero Majorana neutrino mass.

Schechter and Valle, Phys. Rev. **D25** (1982) 2951

- Assumptions:
  - u quark, d quark and e are massive
  - standard left-handed interaction exists: $(\overline{\nu_{eL}}\gamma_\mu e_L + \overline{u_L}\gamma_\mu d_L)\, W^\mu$



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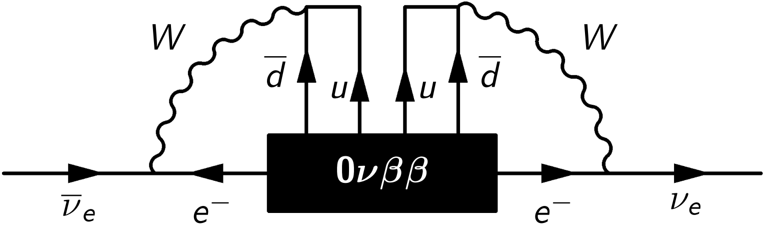
Schechter–Valle theorem

How big is this mass?

Estimation: $m_\nu \sim \frac{1}{(16\pi^2)^4} \frac{\text{MeV}^5}{M_W^4} \approx 10^{-23}\,\text{eV}$



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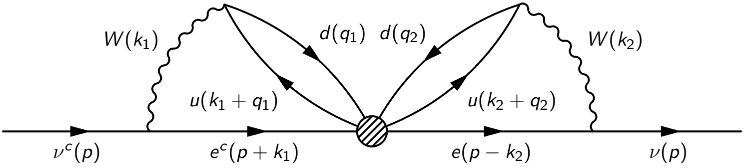
Parameterization of the black box

Most general Lorentz-invariant Lagrangian for $0\nu\beta\beta$ (point-like operators):

$$\mathcal{L} = \frac{G_F^2}{2} m_p^{-1} \left(\epsilon_1 J J j + \epsilon_2 J^{\mu\nu} J_{\mu\nu} j + \epsilon_3 J^\mu J_\mu j + \epsilon_4 J^\mu J_{\mu\nu} j^\nu + \epsilon_5 J^\mu J j_\mu \right)$$

with $J = \overline{u} \left(1 \pm \gamma_5\right) d,\ J^\mu = \overline{u} \gamma^\mu \left(1 \pm \gamma_5\right) d$ etc. Pas et al., Phys. Lett. **B498** (2001) 35

	$\lvert\epsilon_1\rvert$	$\lvert\epsilon_2\rvert$	$\lvert\epsilon_3^{LLz}\rvert$, $\lvert\epsilon_3^{RRz}\rvert$	$\lvert\epsilon_3^{LRz}\rvert$, $\lvert\epsilon_3^{RLz}\rvert$	$\lvert\epsilon_4\rvert$	$\lvert\epsilon_5\rvert$
from [Pas et. al, 2001]	3×10^{-7}	2×10^{-9}	4×10^{-8}	1×10^{-8}	2×10^{-8}	2×10^{-7}
our calc.	2.0×10^{-7}		1.5×10^{-8}			



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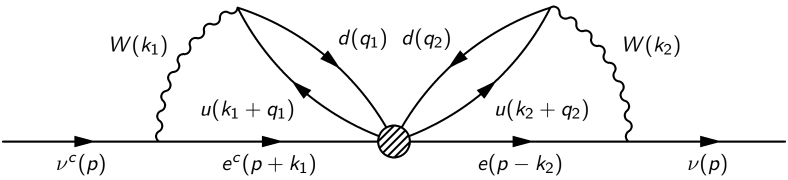
Decay mediated by the operator $J_R^\sigma J_{\sigma R} j_L$

- Choose $J_R^\sigma J_{R\sigma} j_L \propto \overline{u}\gamma^\sigma P_R d \overline{u}\gamma_\sigma P_R d \overline{e} P_L e^c$
- Mass correction

$$\delta m_\nu = \frac{128 g^4 G_F^2 \epsilon_3 m_u^2 m_e^2 m_d^2}{(16\pi^2)^4 m_p} F\left(M_W^2/\mu^2\right)$$

For $\mu = 100\,\mathrm{MeV}$:

$$\delta m_\nu = 9.4 \times 10^{-25}\,\mathrm{eV}$$



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Discussion

- The radiatively generated masses are many orders of magnitude smaller than the observed neutrino masses.
- Lepton number violating New Physics (at tree-level not necessarily related to neutrino masses) may induce black box operators which explain an observed rate of $0\nu\beta\beta$.
- The smallness of the black box contributions implies that other neutrino mass terms (Dirac/Majorana) must exist.
- ν's mainly Majorana: Mass mechanism is the dominant part of the black box operator.
- ν's mainly Dirac: Other lepton number violating New Physics dominates $0\nu\beta\beta$. Translating an observed rate of $0\nu\beta\beta$ into neutrino masses would be completely misleading.

Contents

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Motivation

TeV-scale particles can lead to the same contribution to $0\nu\beta\beta$ as sub-eV-scale neutrinos:

$$\mathcal{A}_l \simeq G_F^2 \left| \sum_i \frac{U_{ei}^2\, m_i}{\langle p^2 \rangle - m_i^2} \right| \simeq (2.7\,\mathrm{TeV})^{-5}$$

$$\left(M_{ee} = \left| \sum U_{ei}^2\, m_i \right| \simeq 0.5\,\mathrm{eV} \text{ and } \langle p^2 \rangle \simeq 0.01\ \mathrm{GeV}^{-2} \gg m_i^2 \right)$$

Contribution of two heavy scalars or vectors with mass M_1 and a heavy fermion with mass M_2:

$$\mathcal{A} \propto \frac{1}{M_1^4\, M_2}$$

Colored seesaw scenario – the model

- Extend SM by color octet scalar and fermions

$$\Phi \sim (8, 2, +1) \text{ and } \Psi_i \sim (8, 1, 0)$$

- Lagrangian of the new sector:

$$-\mathcal{L}_\nu = Y_\nu^{\alpha i} \bar{L}_\alpha \, i\sigma_2 \, \mathrm{Tr}(\Phi^* \Psi_i) + \frac{1}{2} M_{\Psi_i} \mathrm{Tr}(\bar{\Psi}_i^c \Psi_i) + \lambda_{\Phi H} \mathrm{Tr}(\Phi^\dagger H)^2 + \mathrm{H.c.}$$

$\Rightarrow$ no neutrino mass at tree-level.

- Coupling of Φ to quarks:

$$\mathcal{L}_Q = \bar{d}_R \kappa_D \Phi^\dagger Q_L + \bar{u}_R \kappa_U Q_L \Phi + \mathrm{H.c.}$$

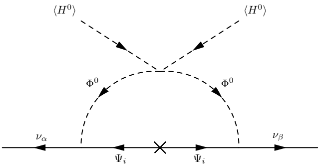
Perez, Wise, Phys. Rev. D **80** (2009) 053006, Perez et al., JHEP **01** (2011) 046.

Current mass limits: $M_\Phi \geq 1.92$ TeV, $M_\Psi \gtrsim 1$ TeV.

ATLAS Collaboration, arXiv:1108.6311 [hep-ex] and arXiv:1109.6572 [hep-ex]

Colored seesaw scenario – neutrino mass

- One-loop neutrino mass matrix



$$M_\nu^{\alpha\beta} = \sum_i v^2 \frac{\lambda_{\Phi H}}{16\pi^2} Y_\nu^{\alpha i} Y_\nu^{\beta i} \mathcal{I}(M_\Phi, M_{\Psi_i})$$

$$\text{with loop function } \mathcal{I}_i \equiv \mathcal{I}(M_\Phi, M_{\Psi_i}) = M_{\Psi_i} \frac{M_\Phi^2 - M_{\Psi_i}^2 + M_{\Psi_i}^2 \ln\left(\frac{M_{\Psi_i}^2}{M_\Phi^2}\right)}{(M_\Phi^2 - M_{\Psi_i}^2)^2}$$

Express Yukawas as

$$Y_\nu = \sqrt{\frac{16\pi^2}{\lambda_{\Phi H}}} \frac{1}{v}\, U \sqrt{M_\nu^d}\, \mathcal{R} \sqrt{(\mathcal{I}^d)^{-1}}$$

$$\text{with Casas–Ibarra matrix } \mathcal{R} = \begin{pmatrix} \hat{c}_2 \hat{c}_3 & \hat{c}_2 \hat{s}_3 & \hat{s}_2 \\ -\hat{c}_1 \hat{s}_3 - \hat{s}_1 \hat{s}_2 \hat{c}_3 & \hat{c}_1 \hat{c}_3 - \hat{s}_1 \hat{s}_2 \hat{s}_3 & \hat{s}_1 \hat{c}_2 \\ \hat{s}_1 \hat{s}_3 - \hat{c}_1 \hat{s}_2 \hat{c}_3 & -\hat{s}_1 \hat{c}_3 - \hat{c}_1 \hat{s}_2 \hat{s}_3 & \hat{c}_1 \hat{c}_2 \end{pmatrix}$$

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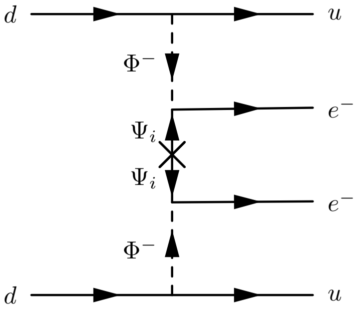
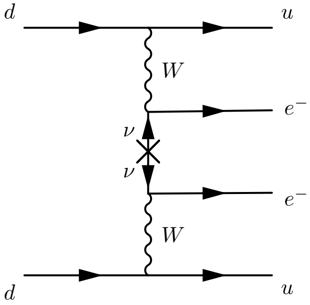
Neutrinoless double beta decay

- direct contribution



- indirect contribution



- $\mathcal{A} \simeq \frac{y_{11}^2}{M_\Phi^4} \sum_i \frac{(Y_\nu^{ei})^2}{M_{\Psi_i}}$
- $\mathcal{A}_l \simeq G_F^2 \frac{M_{ee}}{\langle p^2 \rangle}$

For $\mathcal{R}_{ij} = \delta_{ij}$: $\mathcal{A} \simeq \frac{16\pi^2}{\lambda_{\Phi H} v^2} \frac{y_{11}^2}{M_\Phi^4} \left(\sum_i \frac{m_i U_{ei}^2}{M_{\Psi_i} \mathcal{I}_i} \right)$

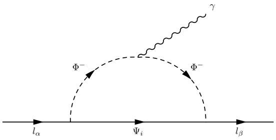
Current limit for ^{76}Ge: $T_{1/2} \geq 1.9 \times 10^{25}$ yrs

Half-life formula

Klapdor-Kleingrothaus et al., Eur. Phys. J. **A12** (2001) 147

Lepton flavor violation

$$\mathrm{Br}(l_\alpha \to l_\beta \gamma) = \frac{3\alpha_{\mathrm{em}}}{4\pi G_F^2 M_\Phi^4} \left| \sum_i Y_\nu^{\beta i} (Y_\nu^{\alpha i})^* \mathcal{F}(x_i) \right|^2$$



$$\text{with } \mathcal{F}(x_i) = \frac{1 - 6x_i + 3x_i^2 + 2x_i^3 - 6x_i^2 \ln(x_i)}{12(x_i - 1)^4} \text{ and } x_i = \frac{M_{\Psi_i}^2}{M_\Phi^2}.$$

For choice $\mathcal{R}_{ij} = \delta_{ij}$

$$\mathrm{Br}(\mu \to e\gamma) = \frac{3\alpha_{\mathrm{em}}}{4\pi G_F^2 M_\Phi^4} \frac{(16\pi^2)^2}{\lambda_{\Phi H}^2 v^4} \left| \sum_i \frac{\mathcal{F}(x_i)}{\mathcal{I}_i} U_{ei} U_{\mu i}^* m_i \right|^2$$

Current limit at 90% C.L.:

$$\mathrm{Br}(\mu \to e\gamma) \leq 2.4 \times 10^{-12}$$

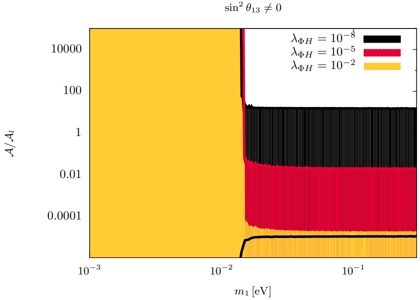
MEG Collaboration, Phys. Rev. Lett. **107** (2011) 171801

Three non-degenerate color octet fermions

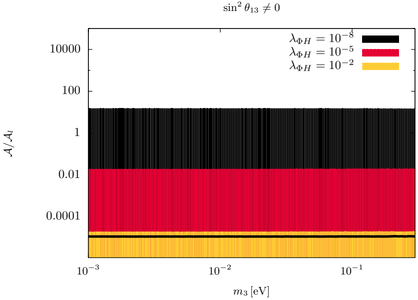
Ratio of particle physics amplitudes $\mathcal{A}/\mathcal{A}_l$

$$\mathcal{A} \simeq \frac{16\pi^2}{\lambda_{\Phi H} v^2} \frac{y_{11}^2}{M_\Phi^4} \left(\sum_i \frac{m_i U_{ei}^2}{M_{\Psi_i} \mathcal{I}_i} \right) \qquad \mathcal{A}_l = G_F^2 \frac{M_{ee}}{\langle p^2 \rangle}$$

normal hierarchy



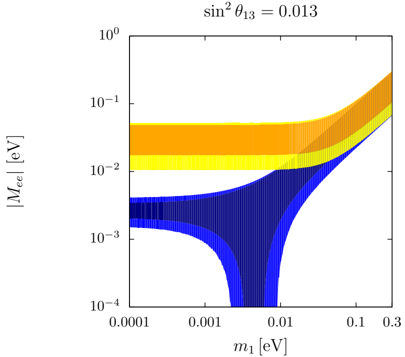
inverted hierarchy

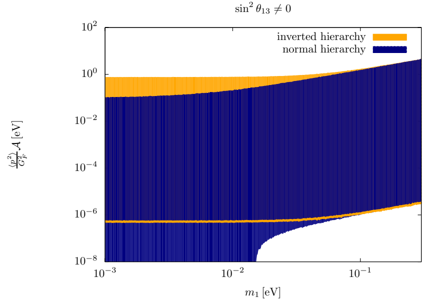


Three non-degenerate color octet fermions

effective mass
$M_{ee} = \sum_i U_{ei}^2 m_i$

"color effective mass" $\frac{\langle p^2 \rangle}{G_F^2} \mathcal{A}$





$\lambda_{\Phi H} = 10^{-8}$

Contents

Summary

- Neutrinoless double beta decay is a sensitive test for lepton number violating New Physics.
- The black box theorem is valid, but it is only of academic interest:
  - Radiatively generated masses are far too small to account for the neutrino masses observed in oscillation experiments.
  - Other operators must give the leading contribution to neutrino masses, which could be of Dirac or Majorana type.
- In the colored seesaw model, "direct" and "indirect" contributions to $0\nu\beta\beta$ exist: Depending on the model parameters, either of the contributions can be dominant.

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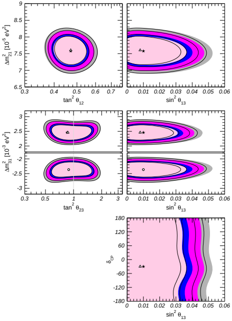
Thank You!

Thanks for your attention!

Backup slides

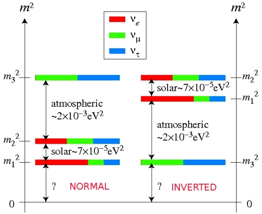
Neutrinos are massive



Gonzalez-Garcia et al., JHEP **04** (2010) 056

- Neutrino oscillation experiments show that neutrinos have a mass.

▸ Oscillation parameters



Mohapatra et al., `arXiv:hep-ph/0412099`

$\overset{?}{\Longleftrightarrow}$

- Is lepton number conserved in Nature?
  $\to 0\nu\beta\beta$

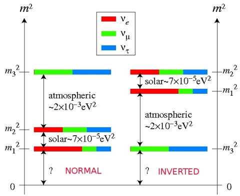
Oscillation parameters

parameter	best fit $\pm 1\sigma$	2σ	3σ
Δm^2_{21} $[10^{-5}\ \mathrm{eV}^2]$	$7.59^{+0.20}_{-0.18}$	7.24–7.99	7.09–8.19
Δm^2_{31} $[10^{-3}\ \mathrm{eV}^2]$	$2.50^{+0.09}_{-0.16}$ $-(2.40^{+0.08}_{-0.09})$	$2.25 - 2.68$ $-(2.23 - 2.58)$	$2.14 - 2.76$ $-(2.13 - 2.67)$
$\sin^2\theta_{12}$	$0.312^{+0.017}_{-0.015}$	0.28–0.35	0.27–0.36
$\sin^2\theta_{23}$	$0.52^{+0.06}_{-0.07}$ 0.52 ± 0.06	0.41–0.61 0.42–0.61	0.39–0.64
$\sin^2\theta_{13}$	$0.013^{+0.007}_{-0.005}$ $0.016^{+0.008}_{-0.006}$	0.004–0.028 0.005–0.031	0.001–0.035 0.001–0.039
δ	$\left(-0.61^{+0.75}_{-0.65}\right)\pi$ $\left(-0.41^{+0.65}_{-0.70}\right)\pi$	$0 - 2\pi$	$0 - 2\pi$

upper (lower) values refer to normal (inverted) hierarchy back

Schwetz et al., New J. Phys. **13** (2011) 109401

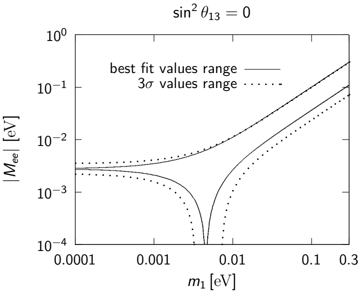
Effective mass $|M_{ee}|$

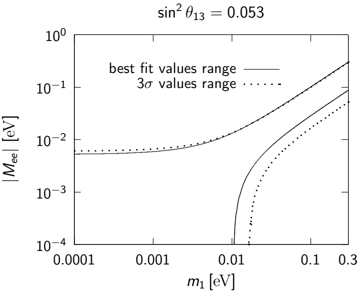


- Normal hierarchy:

$$m_2 = \sqrt{m_1^2 + \Delta m_{21}^2} \quad \text{and} \quad m_3 = \sqrt{m_1^2 + \Delta m_{31}^2}$$

$$M_{ee} = c_{13}^2 \left(m_1 c_{12}^2 + e^{i2\alpha} s_{12}^2 \sqrt{m_1^2 + \Delta m_{21}^2} \right) + e^{i2\beta} s_{13}^2 \sqrt{m_1^2 + \Delta m_{31}^2}$$





No symmetry can protect zero Majorana mass

Assume an unbroken discrete symmetry:

$$\nu_{eL} \to \eta_\nu \nu_{eL}, \quad e_L \to \eta_e e_L,$$
$$q_L \to \eta_q q_L (q = u, d), \quad W_L^{+\mu} \to \eta_W W_L^{+\mu}.$$

- Majorana mass term forbidden: $\eta_\nu^2 \neq 1$
- Invariance of the left-handed interaction: $\eta_\nu^* \eta_e \eta_W = \eta_u^* \eta_d \eta_W = 1$
- Existence of $0\nu\beta\beta$: $\eta_u^2 \eta_d^{*2} \eta_e^2 = 1$

These equations cannot be solved simultaneously!

Takasugi, Phys. Lett. **B149** (1984) 372, Nieves, Phys. Lett. **B147** (1984) 375

SV – decay mediated by the operator $J_L J_L j_L$

- Choose $J_L J_L j_L \propto \overline{u} P_L d \overline{u} P_L d \overline{e} P_L e^c$
- Mass correction

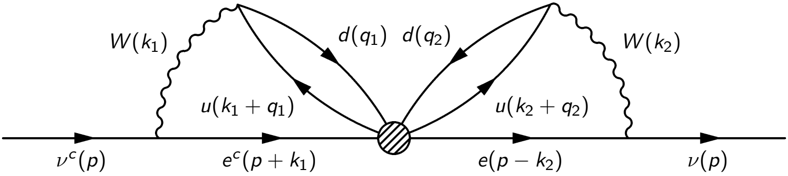
$$\delta m_\nu = \Sigma(\not{p} = m_\nu) \propto p^2\Big|_{\not{p}=m_\nu}$$

- Physical neutrino mass m_ν is solution of

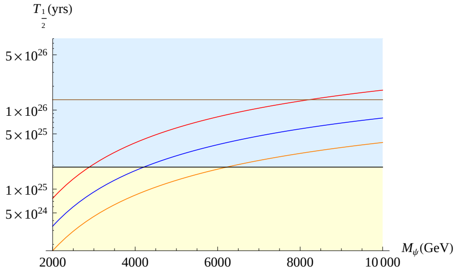
$$\not{p} - \Sigma(\not{p})\big|_{\not{p}=m_\nu} = 0$$

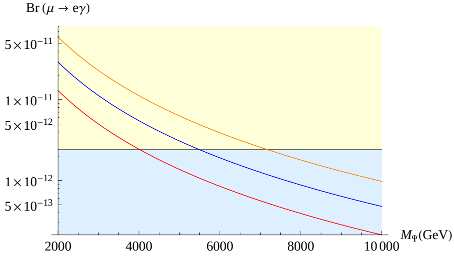
- Result:

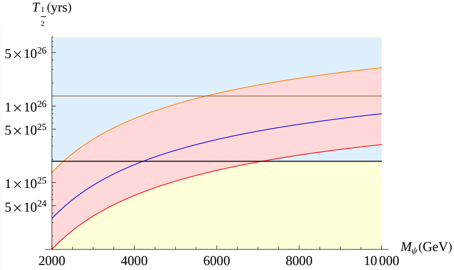
$$\delta m_\nu = 0$$



2 color octet fermions – normal hierarchy







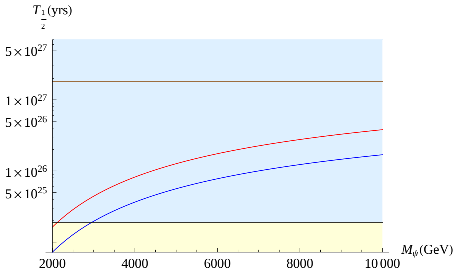
Top figures

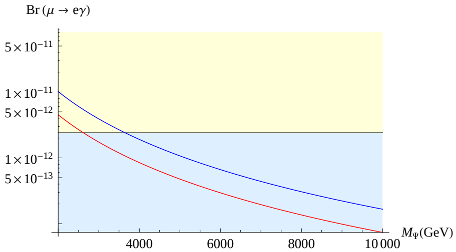
$\lambda_{\Phi H} = 0.15 \times 10^{-8}$; $\lambda_{\Phi H} = 0.1 \times 10^{-8}$; $\lambda_{\Phi H} = 0.7 \times 10^{-9}$.

Right figure

$\lambda_{\Phi H} = 10^{-9}$; $\mathcal{M}_{\Phi\Psi} = 600$; $\mathcal{M}_{\Phi\Psi} = 380$; $\mathcal{M}_{\Phi\Psi} = 190$.

2 color octet fermions – inverted hierarchy





Parameters

$\lambda_{\Phi H} = 0.15 \times 10^{-8}$, $\lambda_{\Phi H} = 0.1 \times 10^{-8}$

Case of three color octet fermions – setup

- Minimal deviation from tri-bimaximal mixing with non-zero θ_{13}:

$$U_{\mathrm{PMNS}} \simeq \begin{pmatrix} -\frac{2}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \lambda e^{-i\delta} \\ \frac{1}{\sqrt{6}} - \frac{\lambda}{\sqrt{3}} e^{i\delta} & \frac{1}{\sqrt{3}} + \frac{\lambda}{\sqrt{6}} e^{i\delta} & -\frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} + \frac{\lambda}{\sqrt{6}} e^{i\delta} & \frac{1}{\sqrt{3}} - \frac{\lambda}{\sqrt{6}} e^{i\delta} & \frac{1}{\sqrt{2}} \end{pmatrix} \mathrm{diag}(1, e^{i\alpha}, e^{i(\beta+\delta)})$$

$$\bullet \mathcal{A}_l \simeq \frac{G_F^2}{\langle p^2 \rangle} \left(\frac{2m_1}{3} + \frac{m_2}{3} e^{i2\alpha} + m_3 \lambda^2 e^{i2\beta} \right)$$

$$\bullet \mathcal{A} \simeq \frac{y_{11}^2}{M_\Phi^4} \frac{16\pi^2}{\lambda_{\Phi H} v^2} \left(\frac{2m_1}{3\mathcal{I}_1 M_{\Psi_1}} + \frac{m_2 e^{i2\alpha}}{3\mathcal{I}_2 M_{\Psi_2}} + \frac{m_3 \lambda^2 e^{i2\beta}}{\mathcal{I}_3 M_{\Psi_3}} \right)$$

$$\bullet\, \mathrm{Br}(\mu \to e\gamma) \propto \Bigg| (2e^{i\delta}\lambda - \sqrt{2}) \frac{m_1 \mathcal{F}(x_1)}{\mathcal{I}_1} + (\sqrt{2} e^{i2\alpha} + \lambda e^{i2\alpha + i\delta}) \frac{m_2 \mathcal{F}(x_2)}{\mathcal{I}_2} - 3 e^{i2\beta + i\delta} \lambda \frac{m_3 \mathcal{F}(x_3)}{\mathcal{I}_3} \Bigg|^2$$