Zee Model with a Flavor Dependent Global U(1) Symmetry

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Osaka U.

Collaboration with Takaaki Nomura (KIAS)

1905.XXXXX [hep-ph]

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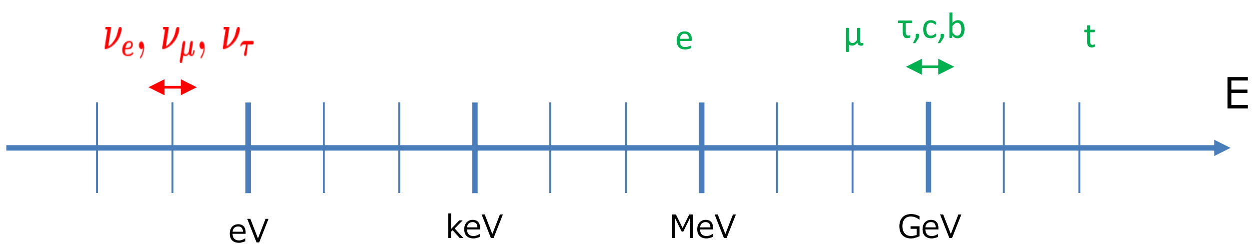
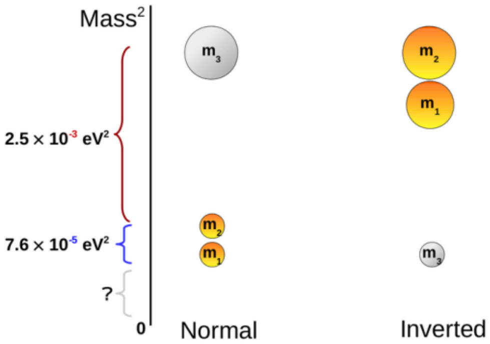
Neutrinos as the Evidence of BSM

- Neutrino physics shows the clear evidence of BSM, and it is still mysterious.
  - What is the origin of **tiny** neutrino masses?



  - Are neutrinos **Majorana** or **Dirac** particles?
  - Which are the correct mass hierarchy, **Normal** or **Inverted**?



http://www.hyper-k.org

  - Does the neutrino sector contain **CP-violation**?

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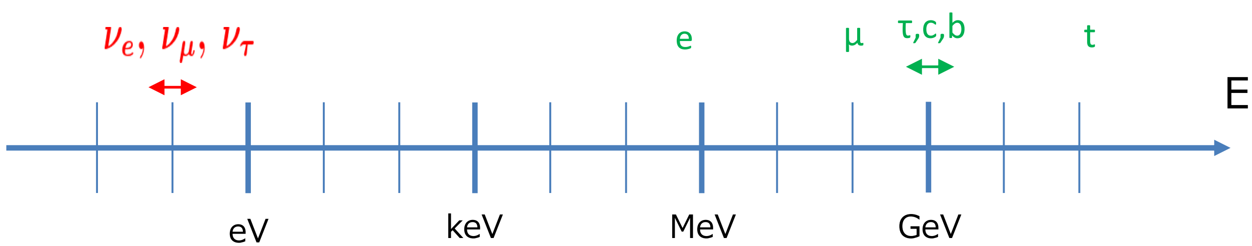

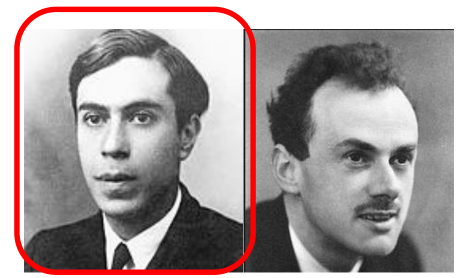

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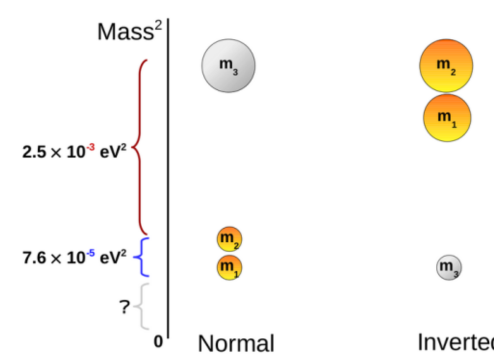


http://www.hyper-k.org

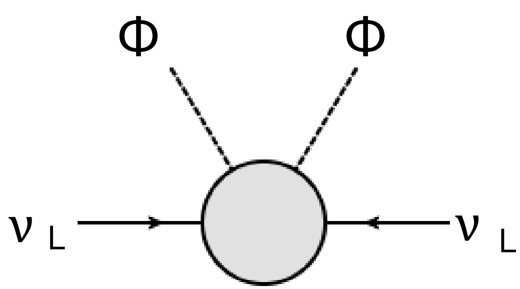
In my talk, ...

Neutrino Mass Generations

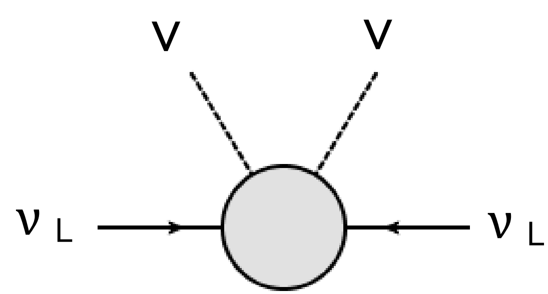
Weinberg (1979)

- Majorana neutrino masses are described by a dimension 5 operator

$$\mathcal{L}_{\rm eff} = \frac{C^{ij}}{M}(\overline{L_i^c}\Phi)(\Phi^{c\dagger}L_j) \quad \Rightarrow \quad (m_\nu)_{ij} = C^{ij}\frac{v^2}{M}$$



$$\langle\Phi\rangle = v$$



- From ν experiments, m_ν should be O(0.1) eV.

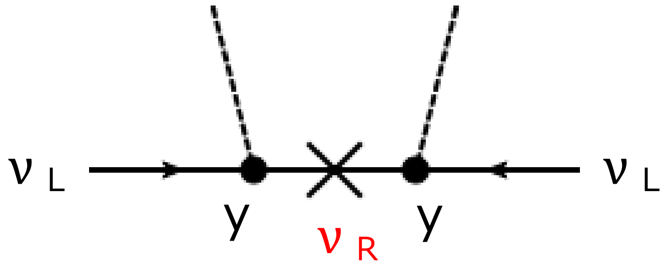
Eg.,
- **M ~ O(10^{15}) GeV** if C ~ 1.
- **C ~ O(10^{-8})** if M ~ v.

Renormalizable Models

Mikowski (1977), Yanagida, Gell-Mann (1979)

Mohapatra, Senjanovic (1980)

- The type-I seesaw mechanism

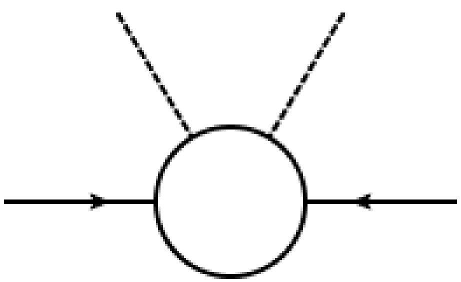


$$m_\nu = y^2 \frac{v^2}{M_R}$$

$$M \to M_R \qquad C \to y^2$$

- Radiative seesaw mechanism

$$m_\nu = c \left(\frac{1}{16\pi^2} \right)^N \frac{v^2}{M}$$



Loop structure

Usually, more suppressions like $(m_l/v)^p$ can appear depending on a model.

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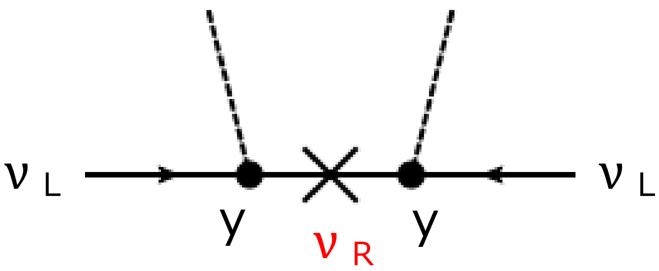

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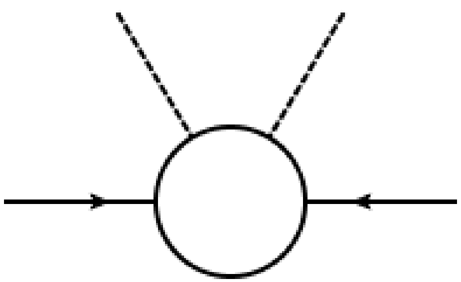

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Radiative Seesaw Models

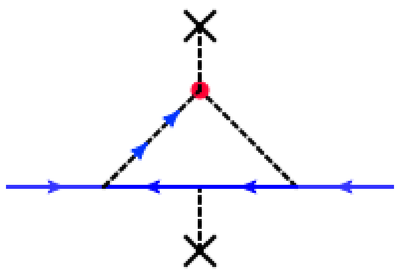
:Lepton # line

:Exact Z_2 line

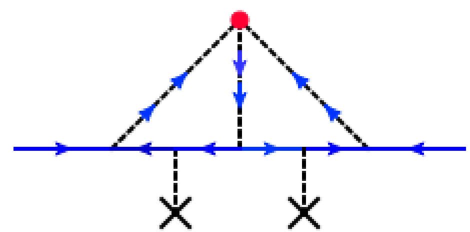
× : VEV

:Lepton # Violation (2 units)

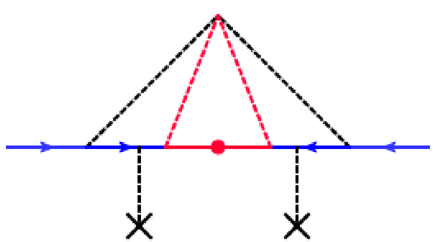
Zee (1980)



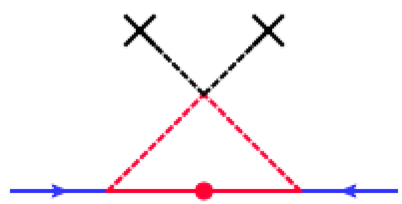
Zee-Babu (1986)



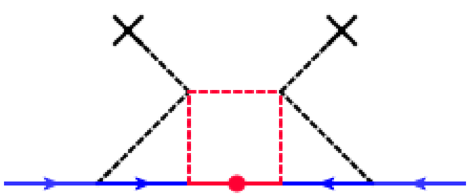
Krauss-Nasri-Trodden (2003)



Ma (2006)



Aoki-Kanemuera-Seto (2009)



The Zee Model

Zee, PLB93, 389 (1980)

- Only the Higgs sector is extended from the SM (No RH neutrino)
- Higgs sector: 2-Higgs doublets (Φ_1, Φ_2) + charged singlet ($S^{\pm}$)
- A softly-broken Z_2 symmetry is imposed (Zee-Wolfenstein model).

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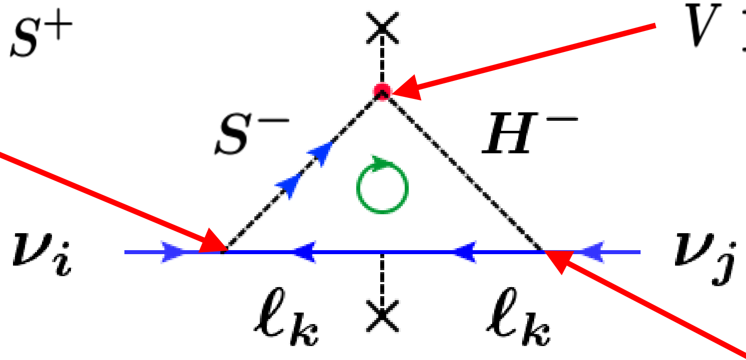
$$\mathcal{L}_Y \supset F_{ij}\,\overline{L_L^{ic}}\,L_L^j\,S^+$$

$$V \supset \mu\,\Phi_1 \cdot \Phi_2 S^-$$



$$\frac{\sqrt{2}m_\ell}{v}\cot\beta\,\delta_{kj}$$

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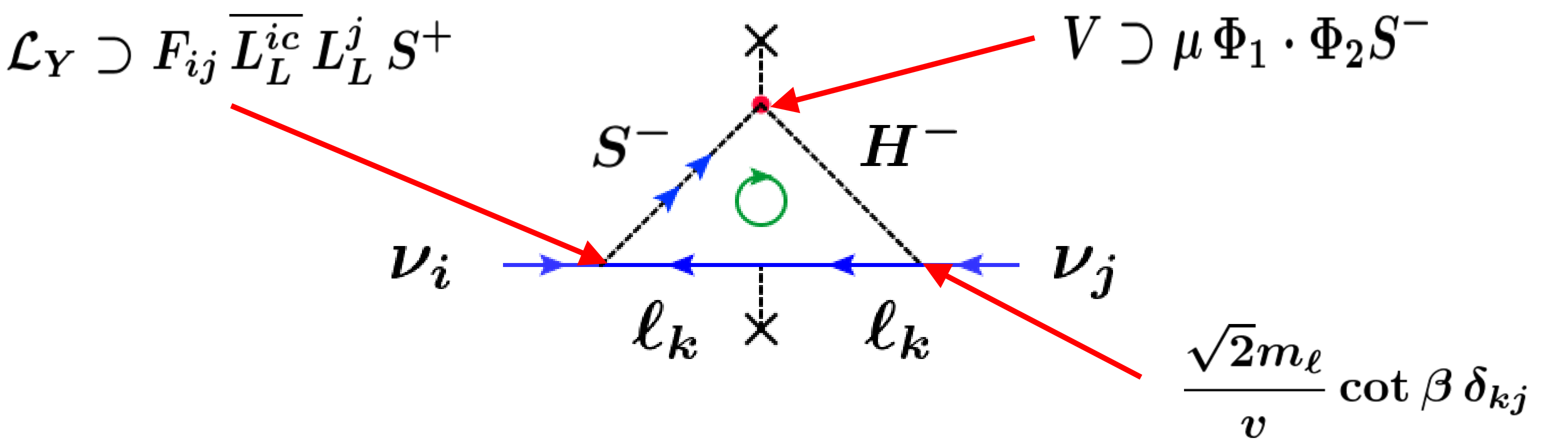


$$m_\nu = \frac{1}{8\pi^2} \frac{\mu \cot\beta}{m_{H_2^\pm}^2 - m_{H_1^\pm}^2} \log \frac{m_{H_2^\pm}^2}{m_{H_1^\pm}^2} (F m_\ell^2 + m_\ell^2 F^T) \sim (0.1\ \mathrm{eV}) \times \frac{\mu}{\mathrm{GeV}} \times \frac{F}{0.1}$$

For $\tan\beta = 1$, $m_{H2(1)} = 400$ (300) GeV, $m_l = m_\mu$.

Neutrino Mixing

c.f. F : anti-symmetric

$$m_\nu = \begin{pmatrix} 0 & a & b \\ a & 0 & c \\ b & c & 0 \end{pmatrix} \qquad V^T m_\nu V = \text{diag}(m_1, m_2, m_3)$$

$$\Rightarrow \quad m_1 + m_2 + m_3 = 0$$

$$V_{12}^2 = \frac{1}{1 - \frac{m_1}{m_2}} \left[\left(\frac{m_1}{m_2} - \frac{m_3}{m_2} \right) V_{13}^2 - \frac{m_1}{m_2} \right] \qquad \because \ (m_\nu)_{11} = 0 \ \& \ \text{Orthgonality}$$

$$|x| = |m_1/m_2| \lesssim 1$$

$$\Rightarrow \quad V_{12}^2 = \frac{1}{1-x} \left[(1+2x) V_{13}^2 - x \right]$$

- $x > 0$ [N.H.]
- $x < 0$ [I.H.]

For $V_{13} \ll 1$, only the IH is possible.

$$\Rightarrow \quad \boxed{V_{12}^2 \simeq \frac{1}{2}}$$

BUT

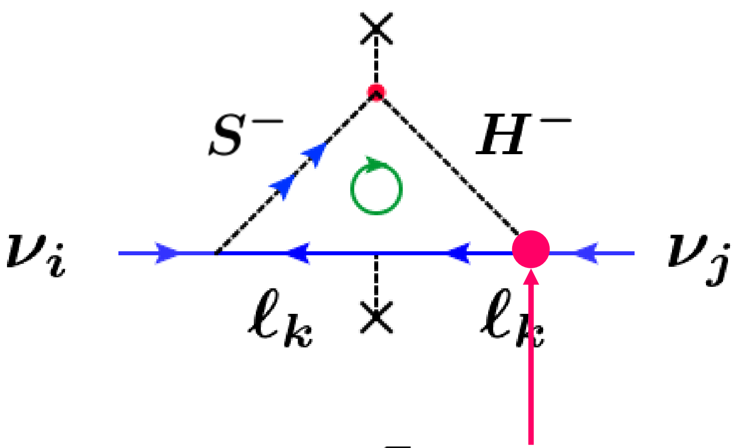
$$\boxed{(V_{12}^{\text{exp}})^2 \sim \frac{1}{3}}$$

Zee model with Type-III Yukawa

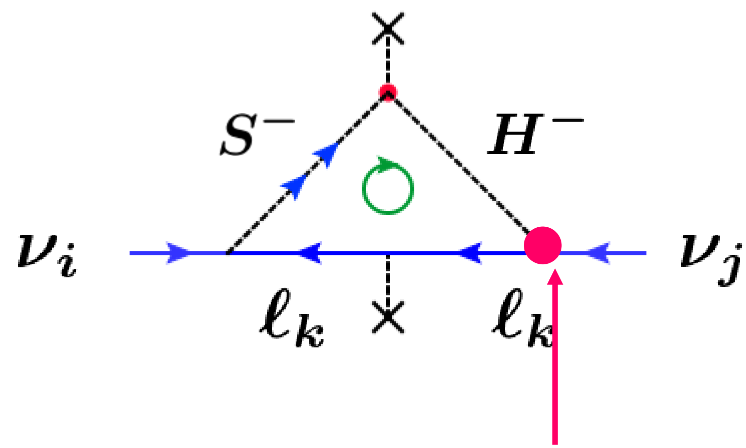
- In this way, the simple Zee model has been excluded.

Hasegawa, Lim, Ogure, 0303252 (PRD)
He, 0307172 (EPJC)
Sierra, Restrepo, 0604012 (JHEP)
Garcca, Ohlsson, Riad, Wirn,
1701.05345 (JHEP), Etc···

- A way out is to forget about the Z_2 symmetry.



$$\frac{\sqrt{2}m_\ell}{v}\cot\beta\;\delta^{kj}$$



$$\frac{\sqrt{2}m_\ell}{v}\cot\beta\;Y_\ell^{kj}$$

- We can explain neutrino mixings,

  but we have many parameters and the quark sector may also have FCNCs···.

We solved these two problems at the same time

by a simple extension!!

Our Extension

Same particle content

Global U(1) symmetry w/ flavor dependent charges

	Q_L^i	u_R^i	d_R^i	L_L^i	e_R^i	Φ_1	Φ_2	S^+
$SU(3)_c$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$SU(2)_L$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$
$U(1)_Y$	$1/6$	$2/3$	$-1/3$	$-1/2$	-1	$1/2$	$1/2$	1
$U(1)'$	0	0	0	q_L^i	q_R^i	q	0	q_S

This kind of model has been known as **Branco-Grimus-Lavoura (BGL)** models.

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Global U(1) symmetry w/ flavor dependent charges

	Q_L^i	u_R^i	d_R^i	L_L^i	e_R^i	Φ_1	Φ_2	S^+
$SU(3)_c$	**3**	**3**	**3**	**1**	**1**	**1**	**1**	**1**
$SU(2)_L$	**2**	**1**	**1**	**2**	**1**	**2**	**2**	**1**
$U(1)_Y$	$1/6$	$2/3$	$-1/3$	$-1/2$	-1	$1/2$	$1/2$	1
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- Yukawa interaction

Only Φ_2 couples to quarks

$\rightarrow$ No tree level FCNCs

$$\mathcal{L}_Y = -(\tilde{Y}_u)_{ij}\bar{Q}_L^i\Phi_2^c u_R^j - (\tilde{Y}_d)_{ij}\bar{Q}_L^i\Phi_2 d_R^j + \text{h.c.}$$

$$-(\tilde{Y}_e^1)_{ij}\bar{L}_L^i\Phi_1 e_R^j - (\tilde{Y}_e^2)_{ij}\bar{L}_L^i\Phi_2 e_R^j - \tilde{F}_{ij}\overline{L_L^{ci}}(i\tau_2)L_L^j S^+ + \text{h.c.}$$

The structure of these couplings depend on the charge assignment.

Structure of the Yukawa Matrices

- **Class I : $q_R = (0,0,-q)$, $q_L = q_S = 0$**

$$\tilde{Y}_e^1 = \begin{pmatrix} 0 & 0 & \times \\ 0 & 0 & \times \\ 0 & 0 & \times \end{pmatrix}, \quad \tilde{Y}_e^2 = \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ \times & \times & 0 \end{pmatrix}, \quad \tilde{F} = \begin{pmatrix} 0 & \times & \times \\ & 0 & \times \\ & & 0 \end{pmatrix}$$

- **Class II : $q_R = 0$, $q_L = (0,0,q)$, $q_S = -q$**

$$\tilde{Y}_e^1 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \times & \times & \times \end{pmatrix}, \quad \tilde{Y}_e^2 = \begin{pmatrix} \times & \times & \times \\ \times & \times & \times \\ 0 & 0 & 0 \end{pmatrix}, \quad \tilde{F} = \begin{pmatrix} 0 & 0 & \times \\ & 0 & \times \\ & & 0 \end{pmatrix}$$

- **Class III : $q_R = (0,0,-q)$, $q_L = (0,0,-2q)$, $q_S = q$**

$$\tilde{Y}_e^1 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \times \end{pmatrix}, \quad \tilde{Y}_e^2 = \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \tilde{F} = \begin{pmatrix} 0 & 0 & \times \\ & 0 & \times \\ & & 0 \end{pmatrix}$$

Analysis

$$Y_\ell^1,\ \ Y_\ell^2,\ \ F$$

Charged lepton masses

$$m_\ell = \frac{v}{\sqrt{2}}(Y_\ell^1 c_\beta + Y_\ell^2 s_\beta)$$

$$= V_L\, m_\ell^{\rm diag}\, V_R^\dagger$$

$$\Rightarrow\ Y_\ell^{1,2} = Y_\ell^{1,2}(\theta_L,\ \theta_R)$$

Neutrino masses

$$m_\nu \propto F\, m_\ell^{\rm diag} (-Y_\ell^1 s_\beta + Y_\ell^2 c_\beta)^\dagger V_R$$

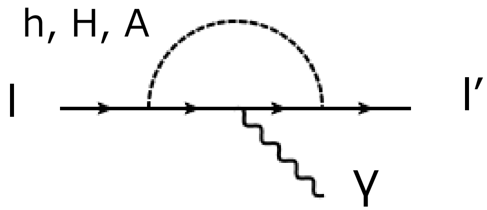
$$= V\, m_\nu^{\rm diag}\, V^T$$

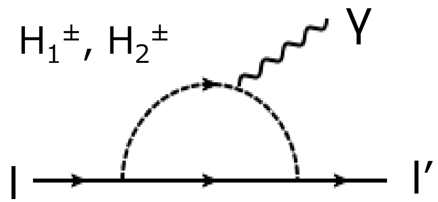
$$\Downarrow$$

$$\{\Delta m_{21}^2,\ \ \Delta m_{31}^2,\ \ \theta_{12},\ \ \theta_{13},\ \ \theta_{23}\}$$

LFVs of charged leptons

Preliminary



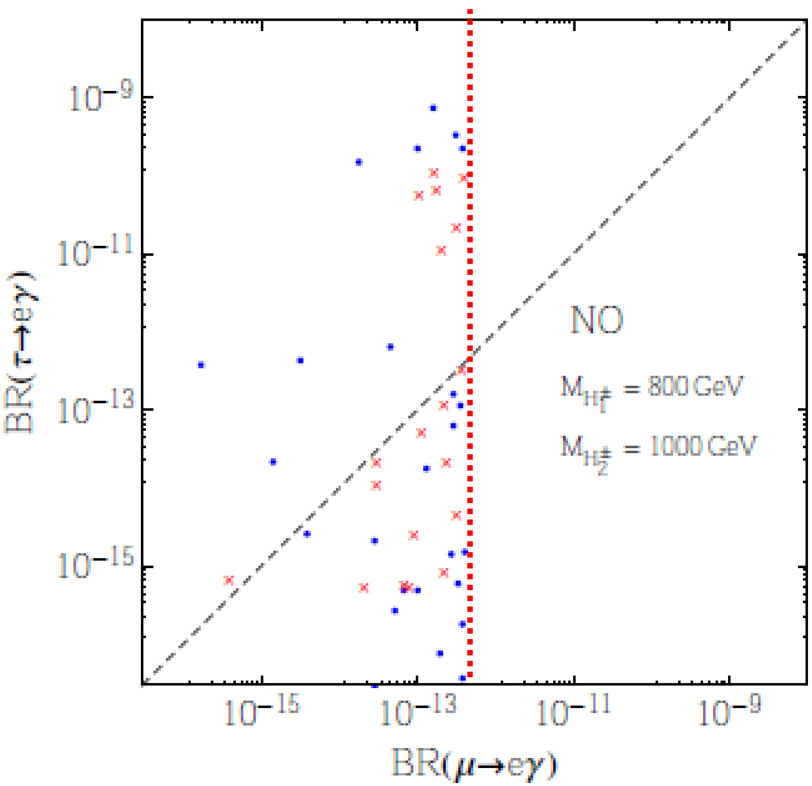


$\sin(\beta-\alpha) = 1$

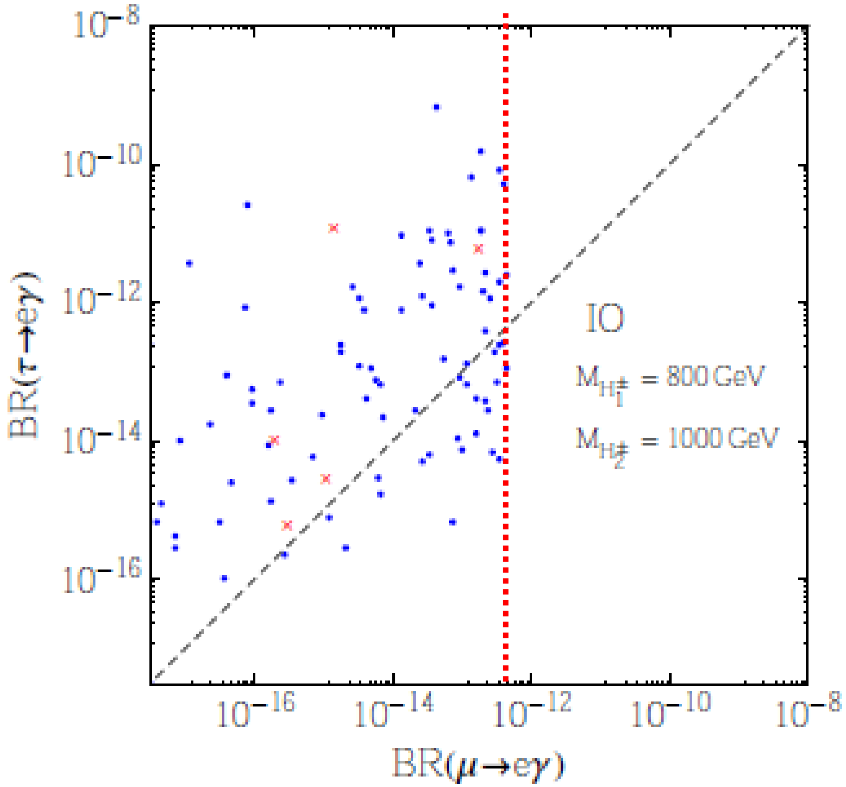
$m_H = m_A = m_{H1+} = 800$ GeV

$m_{H2+} = 1000$ GeV

Normal Hierarchy



Inverted Hierarchy



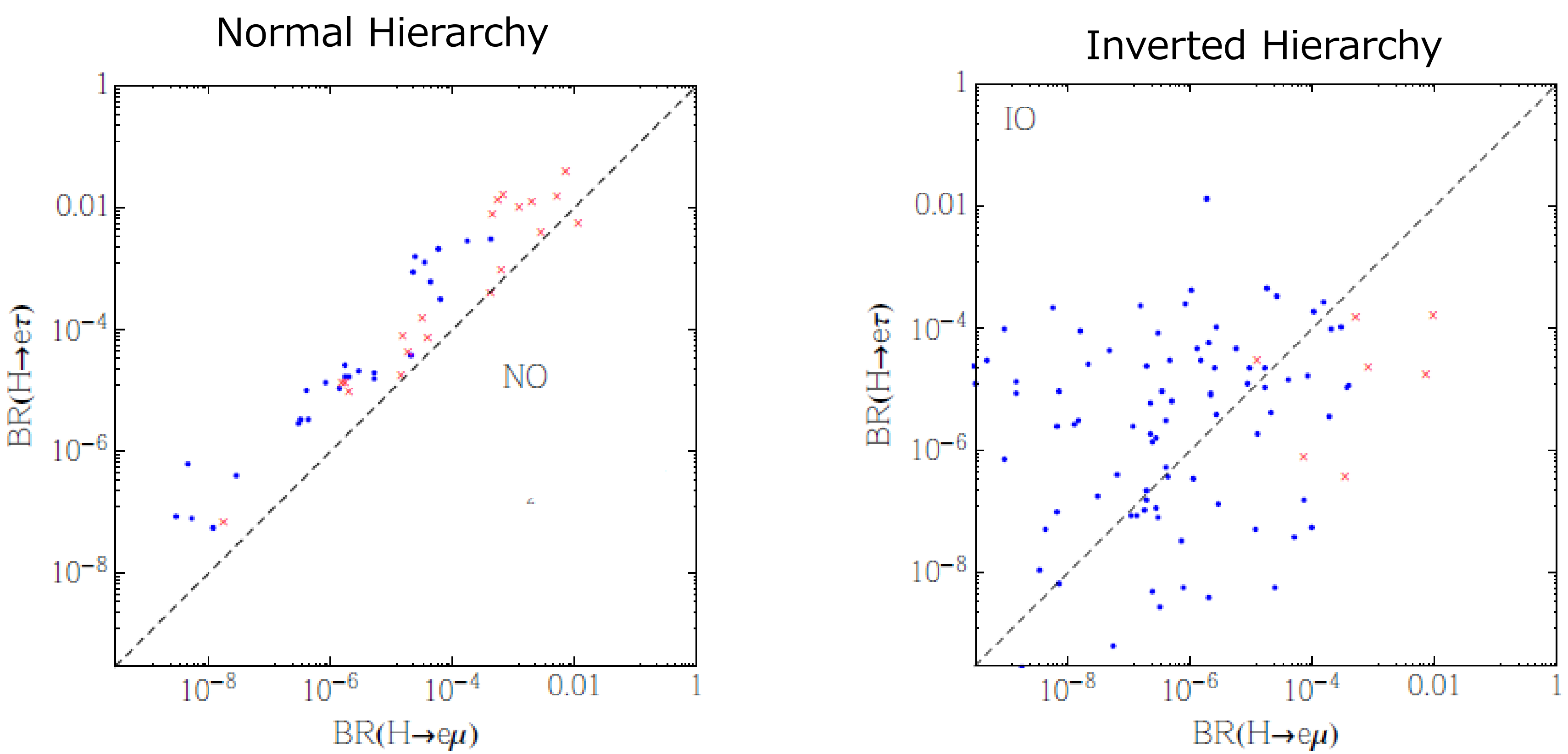
LFV Higgs Decays

Preliminary

H decay

$\sin(\beta-\alpha) = 1$

$m_H = m_A = m_{H1+} = 800$ GeV, $m_{H2+} = 1000$ GeV



In the NH case, **BR(H → eτ) ≳ BR(H → eμ)**

Summary

- We got “2 birds with 1 stone”.

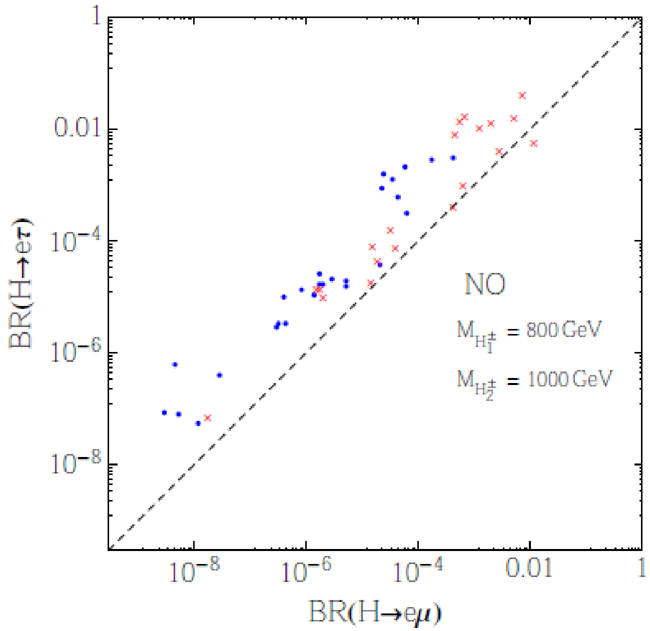
https://www.forbes.com/sites/brentbeshore/2013/04/17/
how-killing-two-birds-with-one-stone-kills-us-and-our-work/

Global U(1) symmetry

Another source of LFV

No FCNCs in the quark sector

Preliminary

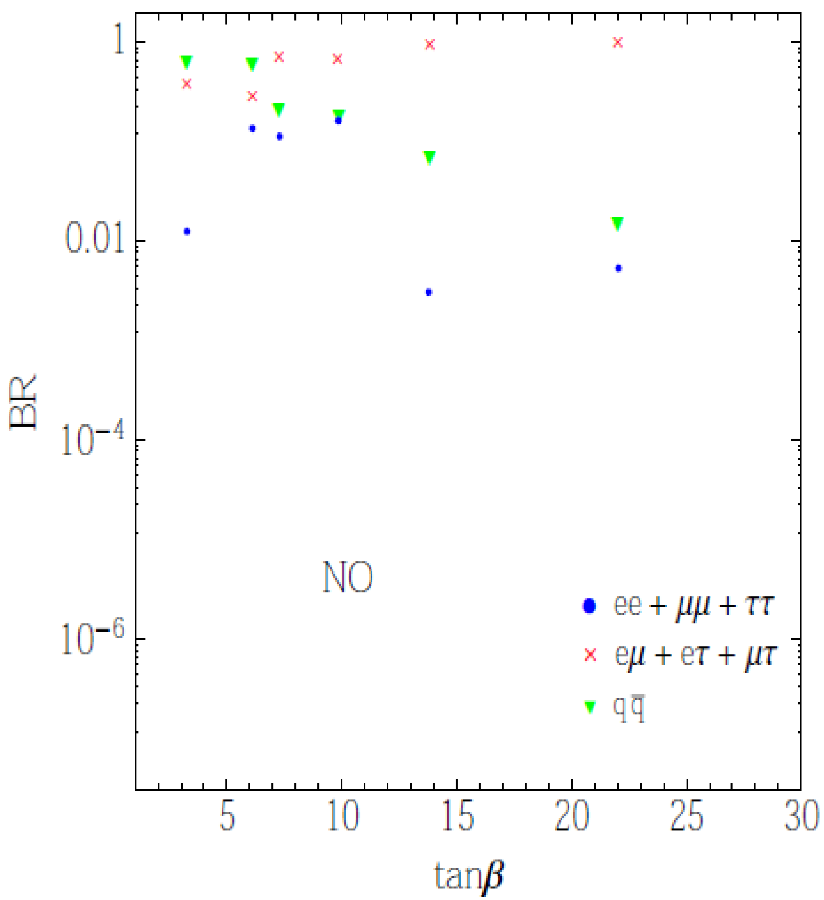


- Characteristic pattern in the LFV Higgs decays can appear. It can be a smoking gun sig. at LHC!

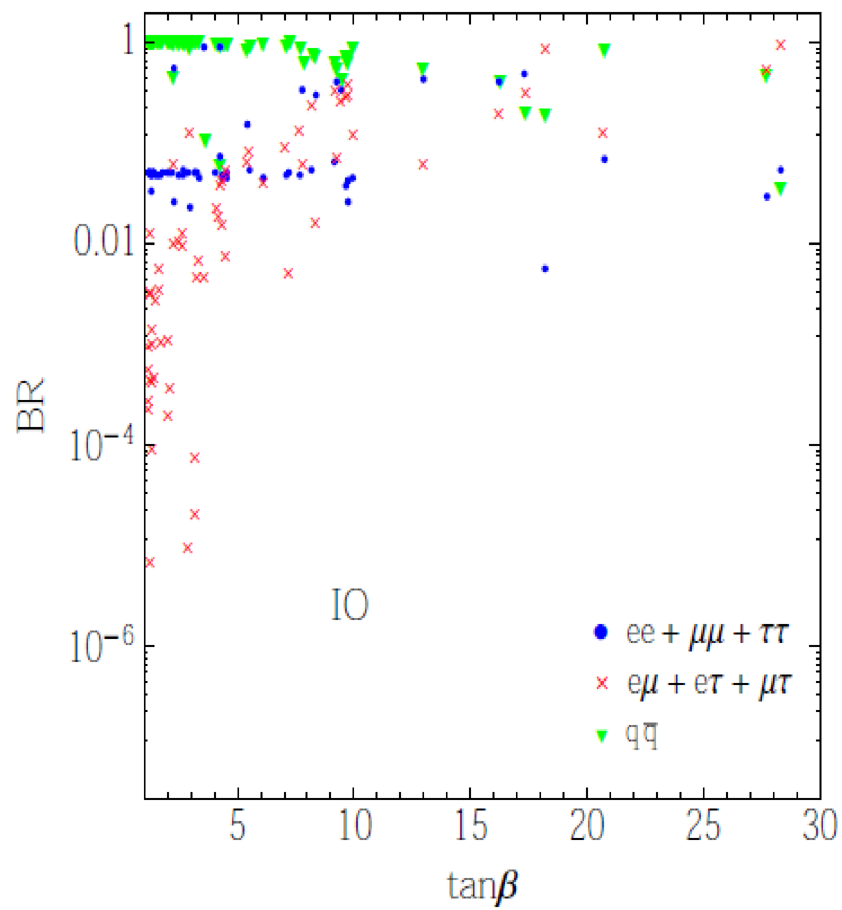
LFV Higgs Decays

$\sin(\beta-\alpha) = 1$, $m_H = 300$ GeV

Normal Hierarchy

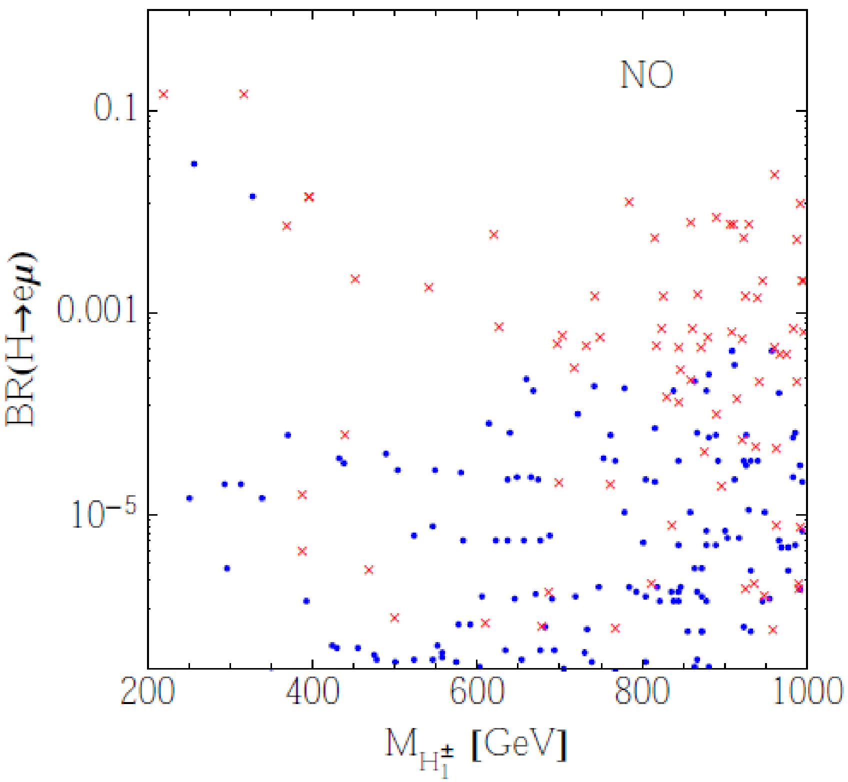


Inverted Hierarchy



LFV Higgs Decays

Normal Hierarchy



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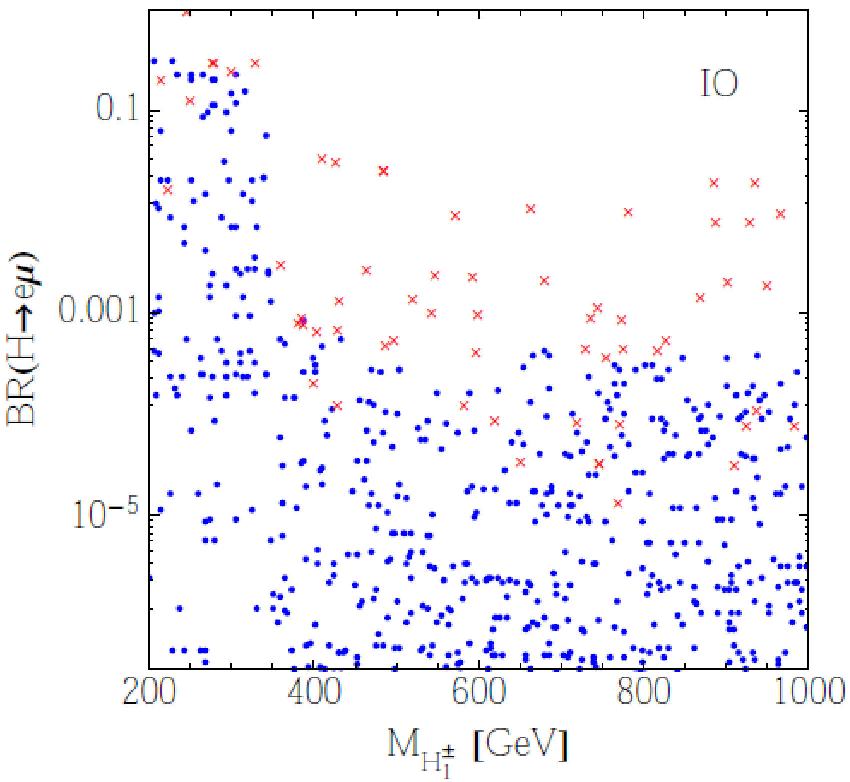

Neutrino masses

$$\mathcal{M}_\nu^{ij} =$$

Class I

$$C_\nu [F U_L (\cot\beta\, M_\ell P_1 M_\ell^\dagger + \cot\beta\, M_\ell P_2 M_\ell^\dagger \cot\beta - \tan\beta\, M_\ell P_3 M_\ell^\dagger)]^{ij} + (i \leftrightarrow j)$$

Class II

$$C_\nu [F U_L (\cot\beta\, M_\ell M_\ell^\dagger P_1 + \cot\beta\, M_\ell M_\ell^\dagger P_2 - \tan\beta\, M_\ell M_\ell^\dagger P_3)]^{ij} + (i \leftrightarrow j)$$

$$P_1 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \quad P_2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \quad P_3 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}.$$