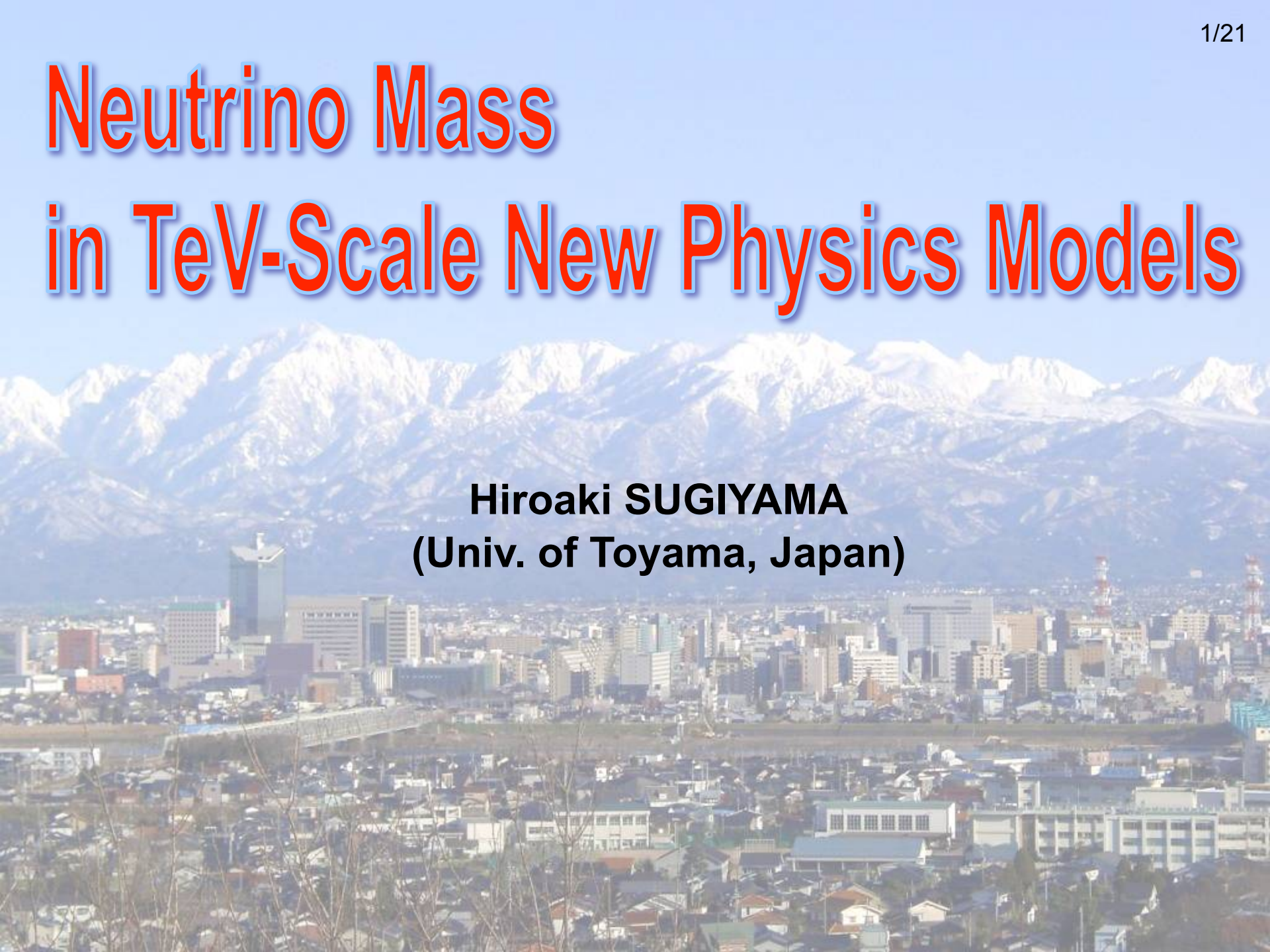
Neutrino Mass in TeV-Scale New Physics Models



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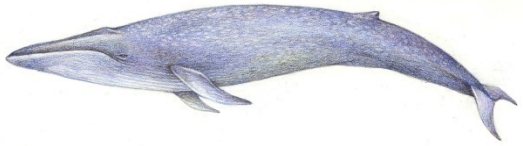
Introduction

Neutrino masses are extremely smaller than other fermion masses.

$\text{neutrino} \lesssim 1\,\text{eV}$ $\quad \text{muon} = 100\,\text{MeV}$ $\quad \text{tau} = 1.8\,\text{GeV}$ $\quad \text{top} = 172\,\text{GeV}$



$1\,\text{MeV}$ "$\simeq$" $1\,\text{kg}$

Naïve : Tree-level neutrino mass with SM Higgs VEV

Particles : $\text{SM} + \nu_R$ ⟵ **No extension of scalar sector**

Interactions : $(y_\nu)_{i\ell}\,\overline{\nu_{Ri}}\,\Phi^T_{\text{SM}}\,i\sigma_2\,L_\ell$

$\Rightarrow$  **Dirac neutrino mass :** $m_\nu = y_\nu \langle \phi^0_{\text{SM}} \rangle$

$y_\nu \sim 10^{-12}$ ⟵ **Unnatural ?**

Other mechanism ? (Seesaw etc.)

Generated at loop-level ?
Extended scalar sector

S. Nasri and S. Moussa, MPLA**17**, 771 (2002)
S. Kanemura, T. Nabeshima, HS, PLB**703**, 66 (2011)

Seesaw : Tree-level neutrino mass with SM Higgs VEV

Particles : $\mathrm{SM} + \nu_R$ ⟵ **No extension of scalar sector**

Interactions : $(y_\nu)_{i\ell}\,\overline{\nu_{Ri}}\,\Phi_{\mathrm{SM}}^T\,i\sigma_2\,L_\ell + \dfrac{1}{2}M_{Ri}\,\overline{\nu_{Ri}}\,(\nu_{Ri})^c$

$\Rightarrow$  **Majorana neutrino mass :** $m_\nu = \dfrac{(y_\nu v)^2}{M_R}$

P. Minkowski, PLB**67**, 421 (1977)
T. Yanagida, KEK-79-18, p.95 (1979)
M. Gell-Mann, et al., in *Supergravity* (1979)

$y_\nu \sim 1,\ M_R \sim 10^{14}\,\mathrm{GeV}$

Far from experimental reach

$y_\nu \sim 10^{-6},\ M_R \sim 10^{3}\,\mathrm{GeV}$

Why light ? Low-scale cut-off ?
(Extra Dim., Strong Dynamics, etc.)

Generated at loop-level ?
Extended scalar sector

S. Kanemura, T. Nabeshima, HS, PRD**85**, 033004 (2012)

New scalars which couple only with leptons (“leptophilic”)

- **Lepton – Lepton – New scalar : predictive**
- Lepton – New Fermion – New scalar : free

TeV scale ⇒ Production & decay @ collider experiments

⇒ **Flavor structure** of leptonic decay via the Yukawa

Predictions

Oscillation data

Measurements

Parameters unrelated to ν oscillation

- The lightest mass eigenvalue
- Majorana CP-violating phases

Origin of neutrino mass

Lepton flavor mixing structure

$$U_{\rm mix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_{21}} & 0 \\ 0 & 0 & e^{i\alpha_{31}} \end{pmatrix}$$

Yukawa Interactions with Leptophilic Scalars

$\mathrm{SU}(2)_L$ singlet

$\overline{L_\ell^c}\, i\sigma_2\, L_{\ell'}\, s^+$: **Singly charged (e.g., in Zee model)**

$\overline{(\ell_R)^c}\, \ell'_R\, s^{++}$: **Doubly charged (e.g., in Zee-Babu model)**

Loop-level Majorana mass with SM Higgs VEV

$\mathrm{SU}(2)_L$ doublet

$\overline{\nu_{Ri}}\, \Phi_\nu^T\, i\sigma_2\, L_\ell$: **Neutrinophilic doublet**

Dirac neutrinos

$\mathrm{SU}(2)_L$ triplet

$\overline{L_\ell^c}\, i\sigma_2\, \Delta\, L_{\ell'}$ **(e,g., in Higgs Triplet Model)**

Majorana neutrinos

Tree-level mass with new VEV



	Doubly charged	Singly charged	Neutral
$\mathrm{SU}(2)_L$ **singlet**	**ii)** $s^{++} \to \overline{\ell_R}\,\overline{\ell'_R}$	**iv)** $s^{+} \to \overline{\ell_L}\,\overline{\nu_L}$	
$\mathrm{SU}(2)_L$ **doublet**		**iii)** $\phi_\nu^{+} \to \overline{\ell_L}\,\nu_R$	$\phi_\nu^{0} \to \overline{\nu_L}\,\nu_R$
$\mathrm{SU}(2)_L$ **triplet**	**i)** $\Delta^{++} \to \overline{\ell_L}\,\overline{\ell'_L}$	**iii)** $\Delta^{+} \to \overline{\ell_L}\,\overline{\nu_L}$	$\Delta^{0} \to \overline{\nu_L}\,\overline{\nu_L}$

Doubly Charged Scalar

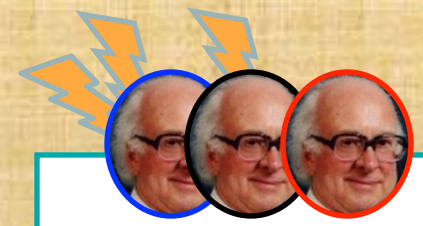


	Doubly charged	Singly charged	Neutral
$\mathrm{SU}(2)_L$ **singlet**	ii) $s^{++} \to \overline{\ell_R}\,\overline{\ell'_R}$	iv) $s^{+} \to \overline{\ell_L}\,\overline{\nu_L}$	
$\mathrm{SU}(2)_L$ **doublet**		iii) $\phi_\nu^{+} \to \overline{\ell_L}\,\nu_R$	$\phi_\nu^{0} \to \overline{\nu_L}\,\nu_R$
$\mathrm{SU}(2)_L$ **triplet**	i) $\Delta^{++} \to \overline{\ell_L}\,\overline{\ell'_L}$	iii) $\Delta^{+} \to \overline{\ell_L}\,\overline{\nu_L}$	$\Delta^{0} \to \overline{\nu_L}\,\overline{\nu_L}$

Doubly Charged Higgs - Triplet -

Higgs Triplet Model (or HTM-like ones)

W. Konetschny and W. Kumer, PLB**70**, 433 (1977)
M. Magg and C. Wetterich, PLB**94**, 61 (1980)
T.P. Cheng and L.F. Li, PRD**22**, 2860 (1980)
J. Schechter and J.W.F. Valle, PRD**22**, 2227 (1980)



$$\Delta \equiv \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix} \quad Y = 1,\ L\# = -2$$

Symmetric

Yukawa : $h_{\ell\ell'}\left[\overline{L^c_\ell}\, i\sigma_2\, \Delta\, L_{\ell'}\right]$

Majorana neutrino mass : $(m_\nu)_{\ell\ell'} = 2\, h_{\ell\ell'} \langle \Delta^0 \rangle \quad \langle \Delta^0 \rangle \ll \langle \phi^0_{\rm SM} \rangle$

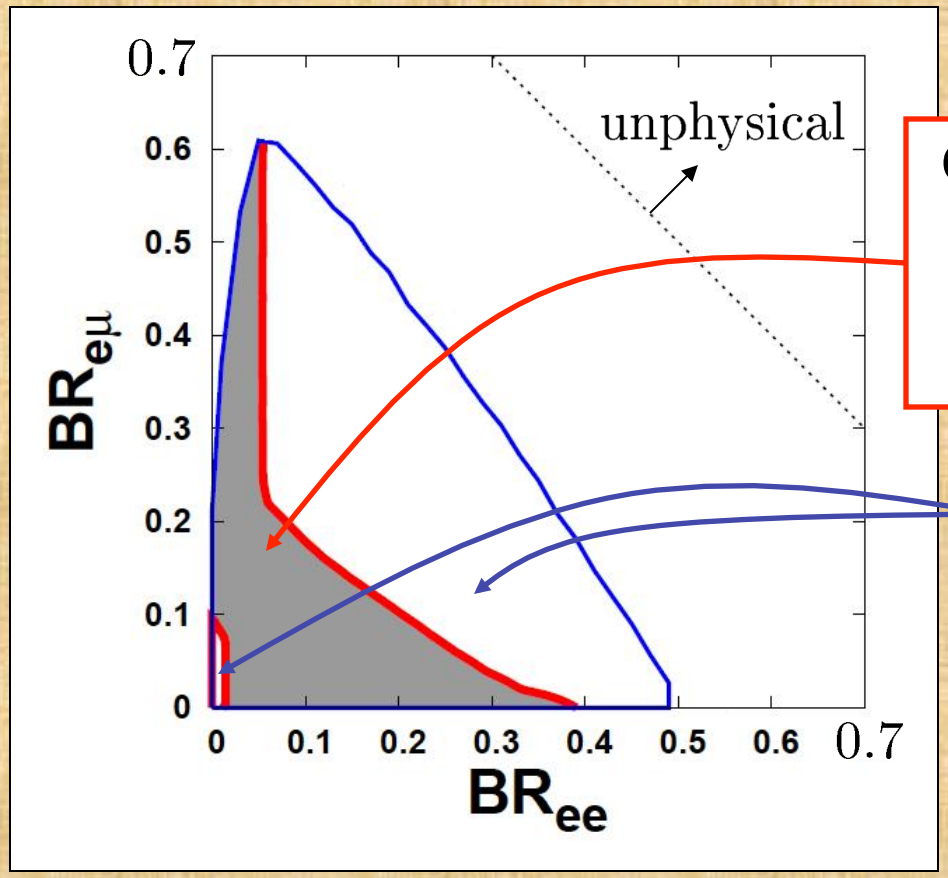
$$m_{\Delta^{\pm\pm}} = 500\,\text{GeV} \;\Rightarrow\; \sigma(pp \to \Delta^{++}\Delta^{--}) = 3.2 \times 10^{-1}\,[\text{fb}]\ @8\text{TeV LHC}$$
$$1.7\,[\text{fb}]\ @14\text{TeV LHC}$$

Loop suppression ?

S. Kanemura, HS, PRD**86**, 073006 (2012)

Information on Non-Zero m_0 (the lightest neutrino mass)

$$\sum_{\ell,\ell'} \mathrm{BR}(\Delta^{\pm\pm} \to \ell_L^{\pm}\ell_L'^{\pm}) \simeq 100\,\% \Rightarrow \mathrm{BR}(\Delta^{\pm\pm} \to \ell_L^{\pm}\ell_L'^{\pm}) = \frac{2}{1+\delta_{\ell\ell'}} \frac{|(m_\nu)_{\ell\ell'}|^2}{\sum_j m_j^2}$$



Observation in shaded region

$\Rightarrow$ **Impossible with** $m_0 = 0$

$\Rightarrow m_0 \neq 0$

Possible with $m_0 = 0$

A.G. Akeroyd, M. Aoki, HS, PRD**77**,075010

See also J. Garayoa, T. Schwetz, JHEP**0803**,009
M. Kadastki, M. Raidal, L. Rebane, PRD**77**, 115023

Doubly Charged Scalar - Singlet -

Zee-Babu Model

A. Zee, NP**B264**, 99 (1986)
K.S. Babu, PLB**203**, 132 (1988)

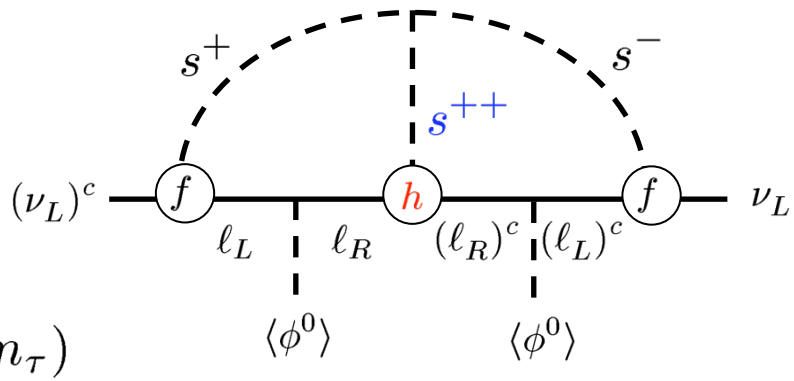
Yukawa : $h_{\ell\ell'}\left[\overline{(\ell_R)^c}\,\ell'_R\,s^{++}\right]$, $f_{\ell\ell'}\left[\overline{L^c_\ell}\,i\sigma_2\,L_{\ell'}\,s^{+}\right]$

Symmetric **Antisymmetric**

Majorana neutrino mass :

$$(m_\nu)_{\ell\ell'} \propto \left(f\, m_\ell^{\rm diag}\, h\, m_\ell^{\rm diag}\, f\right)_{\ell\ell'}$$

$$m_\ell^{\rm diag} \equiv {\rm diag}(m_e, m_\mu, m_\tau)$$



$m_{s^{\pm\pm}} = 500\,{\rm GeV} \;\Rightarrow\; \sigma(pp \to s^{++}s^{--}) = 1.4\times10^{-1}[{\rm fb}]$ @8TeV LHC

$7.2\times10^{-1}[{\rm fb}]$ @14TeV LHC

Prediction for neutrino mass matrix

$$\mathrm{Det}(m_\nu) \propto \mathrm{Det}(f) = 0 \longrightarrow m_1 = 0 \text{ or } m_3 = 0$$

$$(m_\nu)_{\ell\ell'} \propto \left(f\, m_\ell^{\mathrm{diag}}\, h\, m_\ell^{\mathrm{diag}}\, f \right)_{\ell\ell'}$$

"Prediction" for leptonic decay

Negligible contribution of m_e to m_ν (assumption)

$$\Rightarrow \mathrm{BR}_{\mu\mu} : \mathrm{BR}_{\mu\tau} : \mathrm{BR}_{\tau\tau} \sim 1 : 0 : 0$$

$$\mathrm{BR}_{\ell\ell'} \equiv \mathrm{BR}(s^{\pm\pm} \to \ell_R^{\pm} \ell_R'^{\pm}) \propto |h_{\ell\ell'}|^2$$

$$h_{\mu\mu} : h_{\mu\tau} : h_{\tau\tau} \sim 1 : \frac{m_\mu}{m_\tau} : \frac{m_\mu^2}{m_\tau^2} \simeq 1 : 0.06 : 0.003$$

K.S. Babu and C. Macesanu, PRD**67**, 073010 (2003)
D. Aristizabal Sierra and M. Hirsch, JHEP**0612**, 052 (2006)
M. Nebot *et al.*, PRD**77**, 093013 (2008)

Measurement :

$$\mathrm{BR}_{\mu\mu} : \mathrm{BR}_{\mu\tau} : \mathrm{BR}_{\tau\tau} \sim 1 : 0 : 0 \Rightarrow m_1 = 0 \text{ or } m_3 = 0 \text{ ?}$$

Singly Charged Scalar

	Doubly charged	Singly charged	Neutral
 $\mathrm{SU}(2)_L$ **singlet**	**ii)** $s^{++} \to \overline{\ell_R}\,\overline{\ell'_R}$	**iv)** $s^{+} \to \overline{\ell_L}\,\overline{\nu_L}$	
 $\mathrm{SU}(2)_L$ **doublet**		**iii)** $\phi_\nu^{+} \to \overline{\ell_L}\,\nu_R$	$\phi_\nu^{0} \to \overline{\nu_L}\,\nu_R$
 $\mathrm{SU}(2)_L$ **triplet**	**i)** $\Delta^{++} \to \overline{\ell_L}\,\overline{\ell'_L}$	**iii)** $\Delta^{+} \to \overline{\ell_L}\,\overline{\nu_L}$	$\Delta^{0} \to \overline{\nu_L}\,\overline{\nu_L}$

Singly Charged Higgs - Doublet or Triplet -

Neutrinophillic Doublet

F. Wang. W. Wang, J.M. Jang, Europhys. Lett. **76**, 388 (2006)
S. Gabriel and S. Nandi, PLB**655**, 141 (2007)
S.M. Davidson and H.E. Logan, PRD**80**, 905008 (2009)

Yukawa : $(y_\nu)_{i\ell}\left[\overline{\nu_{Ri}}\,\Phi_\nu\, i\sigma_2\, L_\ell\right]$

Only for neutrinos

$\nu_{Ri},\ \Phi_\nu$: Z_2 **odd**

Dirac neutrino mass : $(m_\nu)_{i\ell} = (y_\nu)_{i\ell}\langle\phi_\nu^0\rangle \qquad \langle\phi_\nu^0\rangle \ll \langle\phi_{\rm SM}^0\rangle$

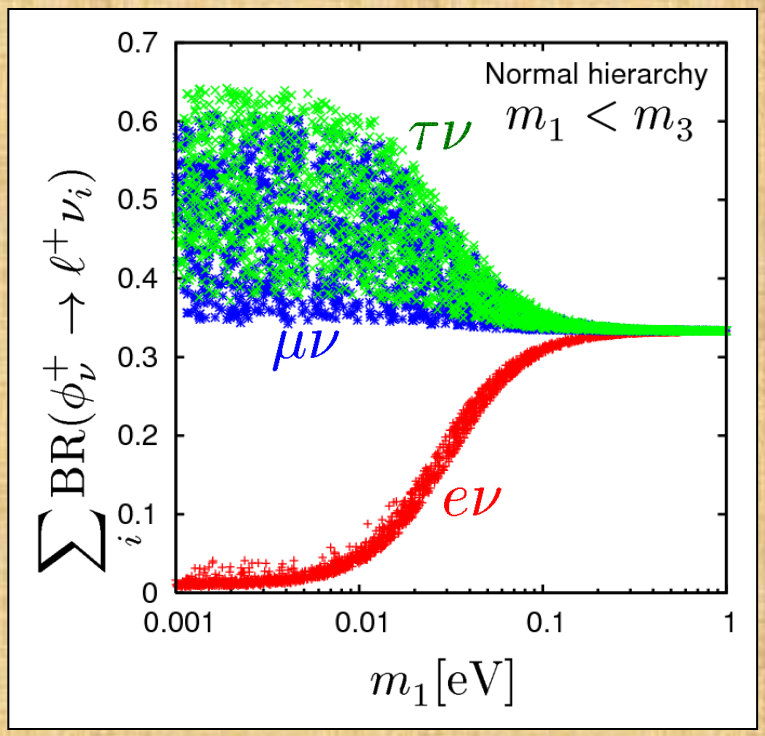
$$m_{\phi_\nu^\pm} = 500\,\text{GeV} \;\Rightarrow\; \sigma(pp\to\phi_\nu^+\phi_\nu^-) = 8.0\times10^{-2}[\text{fb}]\ \text{@8TeV LHC}$$
$$4.2\times10^{-1}[\text{fb}]\ \text{@14TeV LHC}$$

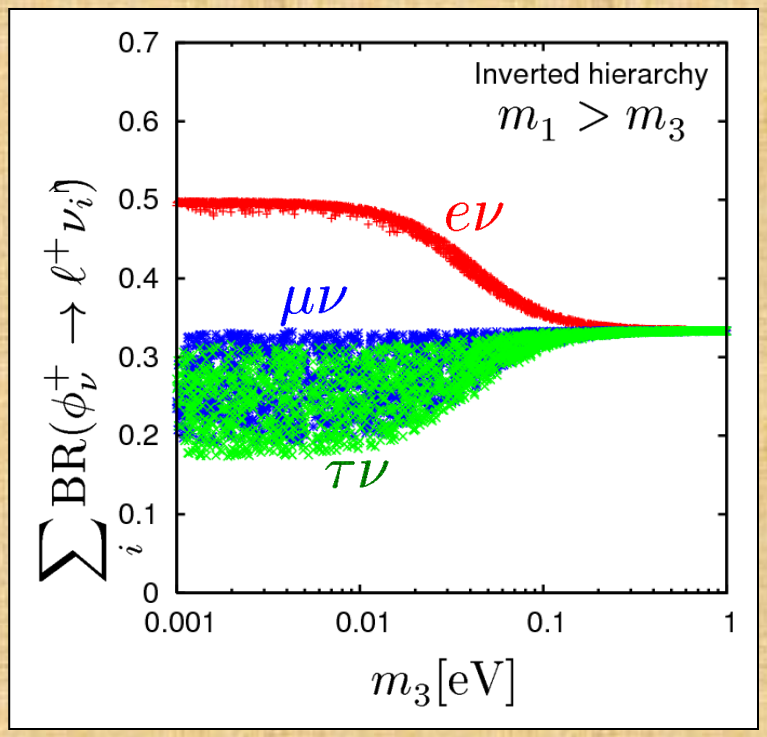
cf. $m_{\Delta^\pm} = 500\,\text{GeV} \;\Rightarrow\; \sigma(pp\to\Delta^+\Delta^-) = 3.4\times10^{-2}[\text{fb}]\ \text{@8TeV LHC}$
$$1.8\times10^{-1}[\text{fb}]\ \text{@14TeV LHC}$$

Loop suppression ?

S. Kanemura, T. Matsui, SH, work in progress

$$\sum_{i,\ell} \mathrm{BR}(\phi_\nu^+ \to \ell^+ \nu_i) \simeq 100\,\% \quad \Rightarrow \quad \sum_i \mathrm{BR}(\phi_\nu^+ \to \ell^+ \nu_i) = \frac{\sum_i m_i^2 |(U_{\mathrm{MNS}})_{\ell i}|^2}{\sum_j m_j^2}$$



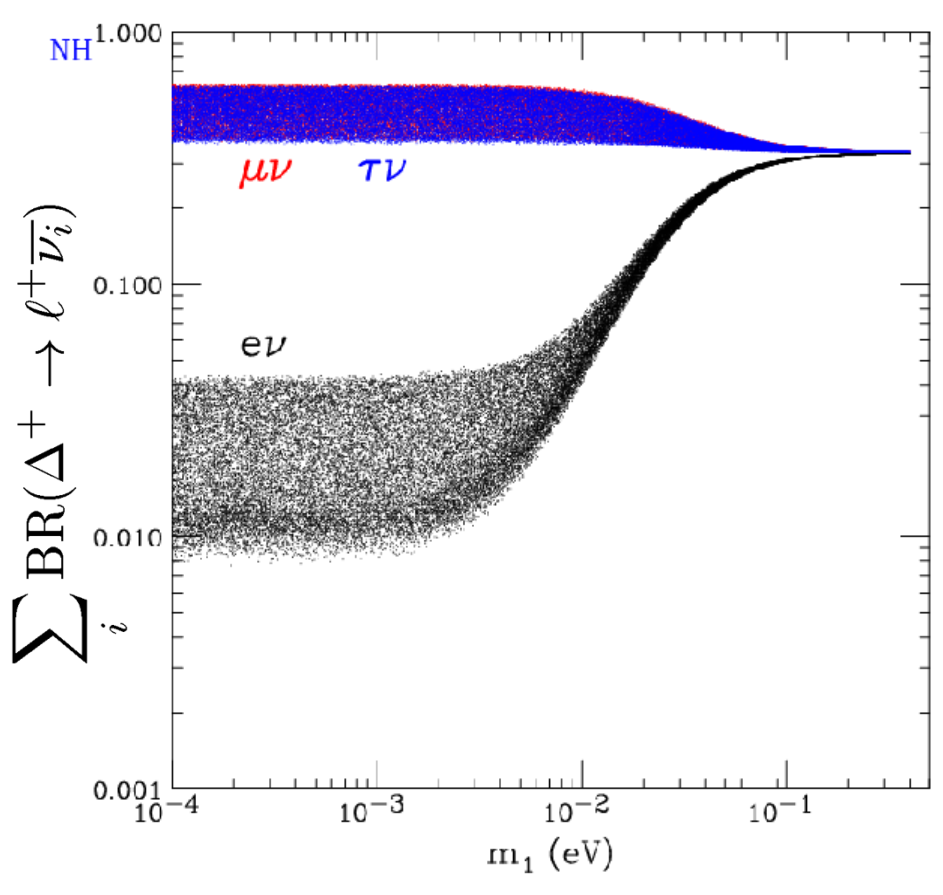


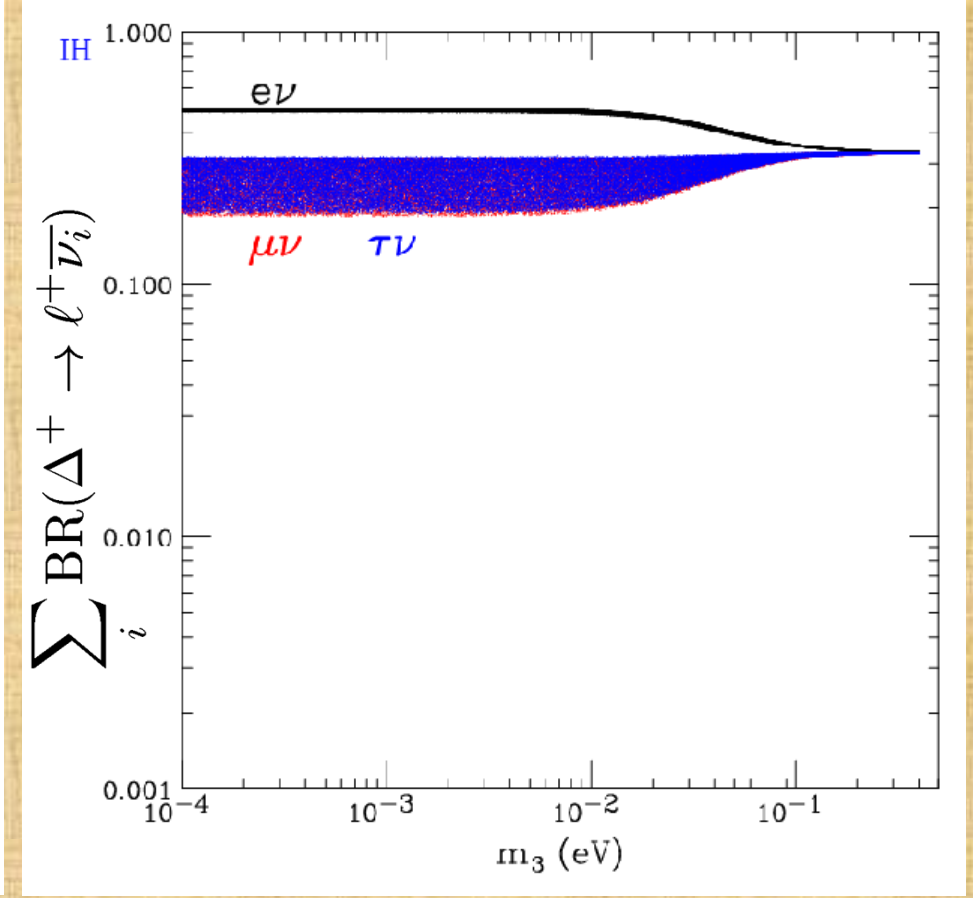
S.M. Davidson and H.E. Logan, PRD**80**, 905008 (2009)

Measurement :

$$\mathrm{BR}_\mu \simeq \mathrm{BR}_\tau \qquad \frac{\mathrm{BR}_e}{\mathrm{BR}_\mu} \longrightarrow \begin{cases} m_1 < m_3 \quad \text{or} \quad m_1 > m_3 \\ m_0 (= \min(m_1, m_3)) \end{cases}$$

The same for triplet





P. Fileviez Perez *et al.*, PRD**78**, 015018 (2008)

$$\mathrm{BR}_\ell \equiv \sum_i \mathrm{BR}(\phi_\nu^+ \to \ell^+ \nu_i) = \sum_i \mathrm{BR}(\Delta^+ \to \ell^+ \overline{\nu_i}) = \frac{\sum_i m_i^2 |(U_{\mathrm{MNS}})_{\ell i}|^2}{\sum_j m_j^2}$$

Singly Charged Scalar - Singlet 1 -

The simplest Zee Model

A. Zee, PLB**93**, 389 (1980)
L. Wolfenstein, NP**B175**, 93 (1980)

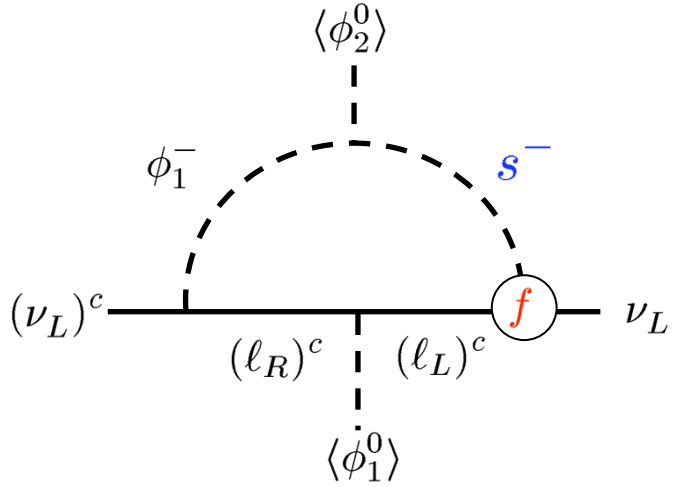
No Flavor-Changing-Neutral-Current

Yukawa : $f_{\ell\ell'}\left[\overline{L_\ell^c}\, i\sigma_2\, L_{\ell'}\, s^+\right],\ \frac{m_\ell}{\langle\phi_1^0\rangle}\left[\overline{L_\ell}\,\Phi_1\,\ell_R\right]$

Antisymmetric

Majorana neutrino mass :

$$(m_\nu)_{\ell\ell'} \propto (m_\ell^2 - m_{\ell'}^2)\, f_{\ell\ell'}$$



Excluded by Oscillation data

e.g., X.G. He, EPJC**34**, 371 (2004)

General (Original) Zee Model

A. Zee, PLB**93**, 389 (1980)

Yukawa : $f_{\ell\ell'}\left[\overline{L^c_\ell}\, i\sigma_2\, L_{\ell'}\, s^+\right]$, **Antisymmetric**

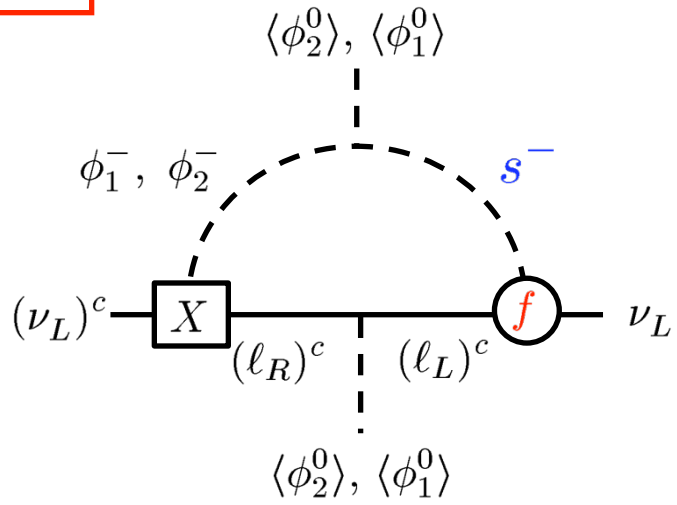
$$\frac{m_\ell}{\langle\phi_1^0\rangle}\left[\overline{L_\ell}\,\Phi_1\,\ell_R\right] + (y_2)_{\ell\ell'}\left[\overline{L_\ell}\left(\Phi_2 - \frac{\langle\phi_2^0\rangle}{\langle\phi_1^0\rangle}\Phi_1\right)\ell'_R\right]$$

Incl. FCNC

Majorana neutrino mass :

$$(m_\nu)_{\ell\ell'} \propto \left(X m_\ell^{\rm diag} f + (X m_\ell^{\rm diag} f)^T\right)_{\ell\ell'}$$

$$m_\ell^{\rm diag} \equiv {\rm diag}(m_e, m_\mu, m_\tau)$$



$$m_{s^\pm} = 500\,{\rm GeV} \;\Rightarrow\; \sigma(pp \to s^+ s^-) = 3.4\times10^{-2}[{\rm fb}]\ @8{\rm TeV\ LHC}$$
$$1.8\times10^{-1}[{\rm fb}]\ @14{\rm TeV\ LHC}$$

"Prediction" for neutrino mass matrix

Negligible contributions of m_e and m_μ to m_ν (assumption)

$$\Rightarrow \quad (m_\nu)_{\ell\ell'} \sim m_\tau \left(X_{\ell\tau} f_{\tau\ell'} + (f^T)_{\ell\tau} (X^T)_{\tau\ell'} \right)$$

$$\Rightarrow \quad \mathrm{Det}(m_\nu) \simeq 0 \quad \longrightarrow \quad m_1 \simeq 0 \text{ or } m_3 \simeq 0$$

$$\Downarrow$$

"Prediction"

$$\frac{\mathrm{BR}_\tau}{\mathrm{BR}_e - \mathrm{BR}_\mu} \simeq \frac{1 + 2s_{13}^2}{1 - 2s_{13}^2}$$

$$\begin{cases} m_3 \simeq 0 \\ \sin^2 2\theta_{13} \simeq 0.114 \\ \delta \simeq \pi \\ \alpha_{21} \simeq \pi \quad \textbf{(Majorana phase)} \end{cases}$$

Daya Bay : $\sin^2 2\theta_{13} = 0.092 \pm 0.017$

Measurement :

$$\frac{\mathrm{BR}_\tau}{\mathrm{BR}_e - \mathrm{BR}_\mu} \simeq 1 \quad \Rightarrow \quad m_3 \simeq 0,\ \delta \simeq \pi,\ \alpha_{21} \simeq \pi \quad ?$$

See also X.G. He, S.K. Majee, JHEP**1203**, 023 (2012)

Singly Charged Scalar - Singlet 2 -

Yukawa : $f_{\ell\ell'}\left[\overline{L^c_\ell}\, i\sigma_2\, L_{\ell'}\, s^+\right]$

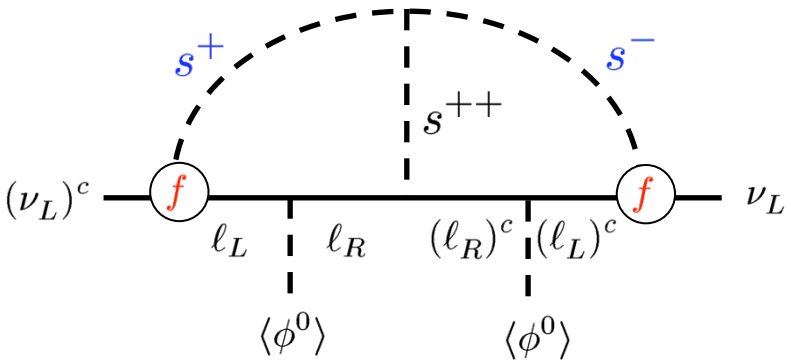
Antisymmetric

Majorana neutrino mass :

$$\frac{1}{2}(m_\nu)_{\ell\ell'}\left[\overline{(\nu_{L\ell})^c}\,\nu_{L\ell'}\right]$$

$$=\frac{1}{2}(fXf)_{\ell\ell'}\left[\overline{(\nu_{L\ell})^c}\,\nu_{L\ell'}\right]$$

Example : Zee-Babu model

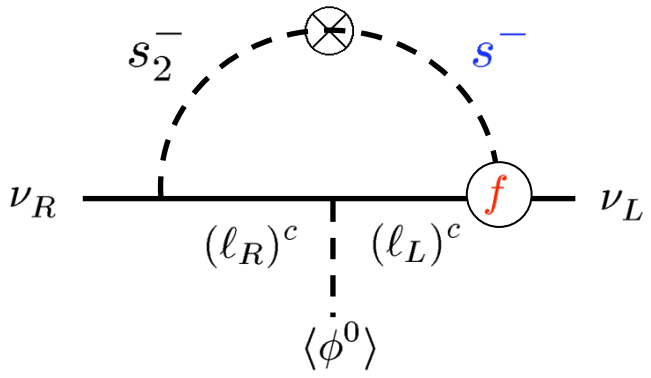


Dirac neutrino mass :

$$(m_\nu)_{i\ell}\left[\overline{\nu_{Ri}}\,\nu_{L\ell}\right]$$

$$=(Xf)_{i\ell}\left[\overline{\nu_{Ri}}\,\nu_{L\ell}\right]$$

Example : 1-loop model



A. Zee, NP**B264**, 99 (1986)
K.S. Babu, PLB**203**, 132 (1988)

S. Nasri and S. Moussa, MPLA**17**, 771 (2002)
S. Kanemura, T. Nabeshima, HS, PLB**703**, 66 (2011)

Prediction for neutrino mass matrix

$$\mathrm{Det}(m_\nu) \propto \mathrm{Det}(f) = 0 \longrightarrow m_1 = 0 \text{ or } m_3 = 0$$

Prediction for leptonic decay

$m_1 = 0$

$$\Rightarrow \mathrm{BR}_e : \mathrm{BR}_\mu : \mathrm{BR}_\tau \simeq 2 : [5 + 2\sqrt{2}\, s_{13} \cos\delta] : [5 - 2\sqrt{2}\, s_{13} \cos\delta]$$

$m_3 = 0$

$$\Rightarrow \mathrm{BR}_e : \mathrm{BR}_\mu : \mathrm{BR}_\tau = 2 : [1 + 0.5 \sin^2 2\theta_{13}] : [1 + 0.5 \sin^2 2\theta_{13}]$$

Measurement :

$$\mathrm{BR}_e : \mathrm{BR}_\mu : \mathrm{BR}_\tau \simeq 2 : 5 : 5 \Rightarrow m_1 = 0$$

$$\mathrm{BR}_e : \mathrm{BR}_\mu : \mathrm{BR}_\tau \simeq 2 : 1 : 1 \Rightarrow m_3 = 0$$

K.S. Babu and C. Macesanu, PRD**67**, 073010 (2003)
D. Aristizabal Sierra and M. Hirsch, JHEP**0612**, 052 (2006)
M. Nebot *et al*., PRD**77**, 093013 (2008)
S. Kanemura, T. Nabeshima, HS, PLB**703**, 66 (2011)

Summary

TeV-scale new scalars which couple only with leptons

$$\begin{cases} \overline{L_\ell^c}\, i\sigma_2\, L_{\ell'}\, s^+ & \overline{(\ell_R)^c}\, \ell'_R\, s^{++} \\ \overline{\nu_{Ri}}\, \Phi_\nu^T\, i\sigma_2\, L_\ell & \overline{L_\ell^c}\, i\sigma_2\, \Delta\, L_{\ell'} \end{cases}$$ (others ?)

Flavor structure of leptonic decay via the Yukawa

Predictions

Oscillation data

Measurements

Parameters unrelated to ν oscillation

- **The lightest mass eigenvalue**
- **Majorana CP-violating phases**

Origin of neutrino mass

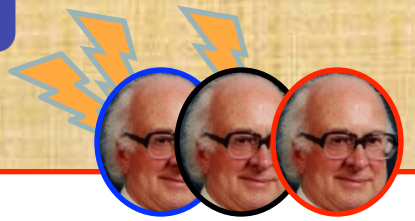
- $\langle \phi^0_{\rm SM} \rangle$ **? Different VEV ?**
- **Tree ? Loop ?**
- **Dirac ? Majorana ?**

Flavor structure of mass matrix

Flavored Higgs ?
(Flavor Symmetry)

backup

Summary of My Hope - 1



$\mathrm{SU}(2)_L$ **triplet :** $h_{\ell\ell'}\left[\overline{L^c_\ell}\, i\sigma_2\, \Delta\, L_{\ell'}\right]$

Doubly charged : $\mathrm{BR}_{\ell\ell'} \longrightarrow$

$$\begin{cases} (m_\nu)_{\ell\ell'} = h_{\ell\ell'}\langle\Delta^0\rangle \\ m_1 < m_3 \quad \textbf{or not} \qquad m_0 = 0 \ \textbf{or not} \\ \sin\alpha_{21} = 0,\ \sin\alpha_{31} = 0 \ \textbf{or not} \end{cases}$$

Singly charged : $\mathrm{BR}_\mu \simeq \mathrm{BR}_\tau,\ \dfrac{\mathrm{BR}_e}{\mathrm{BR}_\mu} \longrightarrow$

$$\begin{cases} (m_\nu)_{\ell\ell'} = h_{\ell\ell'}\langle\Delta^0\rangle \\ \qquad \textbf{or}\ \ (m_\nu)_{i\ell} = (y_\nu)_{i\ell}\langle\phi^0_\nu\rangle \\ m_1 < m_3 \ \textbf{or not} \\ m_0 \end{cases}$$

$\mathrm{SU}(2)_L$ **doublet :** $(y_\nu)_{i\ell}\left[\overline{\nu_{Ri}}\, \Phi_\nu\, i\sigma_2\, L_\ell\right]$

Summary of My Hope - 2

singly charged $\mathrm{SU}(2)_L$ singlet : $f_{\ell\ell'}\left[\overline{L^c_\ell}\, i\sigma_2\, L_{\ell'}\, s^+\right]$

$$\mathrm{BR}_e : \mathrm{BR}_\mu : \mathrm{BR}_\tau \simeq 2:5:5 \Rightarrow \begin{cases} m_1 = 0 \\ (m_\nu)_{\ell\ell'} \propto (fXf)_{\ell\ell'} \quad \text{or} \quad (m_\nu)_{i\ell'} \propto (Xf)_{i\ell'} \end{cases}$$

(Majorana) **(Dirac)**

$$\mathrm{BR}_e : \mathrm{BR}_\mu : \mathrm{BR}_\tau \simeq 2:1:1 \Rightarrow \begin{cases} \\ m_3 = 0 \end{cases}$$

$$\frac{\mathrm{BR}_\tau}{\mathrm{BR}_\mu - \mathrm{BR}_e} \simeq 1 \Rightarrow \begin{cases} (m_\nu)_{\ell\ell'} \sim m_\tau \left(X_{\ell\tau} f_{\tau\ell'} + (f^T)_{\ell\tau} (X^T)_{\tau\ell'} \right) \\ m_3 = 0,\ \sin^2 2\theta_{13} \simeq 0.118,\ \delta \simeq \pi,\ \alpha_{21} \simeq \pi \end{cases}$$

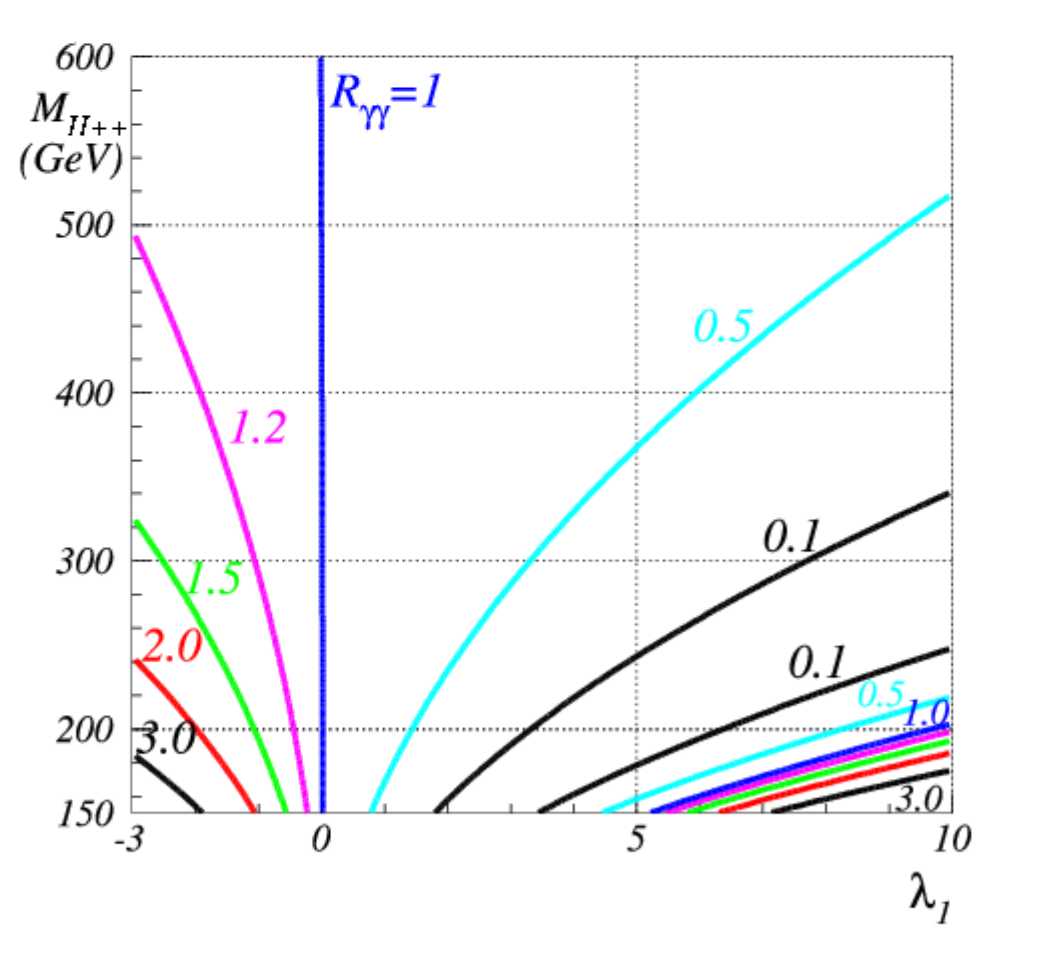
doubly charged $\mathrm{SU}(2)_L$ singlet : $h_{\ell\ell'}\left[\overline{(\ell_R)^c}\, \ell'_R\, s^{++}\right]$

$$\mathrm{BR}_{\mu\mu} : \mathrm{BR}_{\mu\tau} : \mathrm{BR}_{\tau\tau} \sim 1:0:0 \Rightarrow$$

Zee-Babu model ??

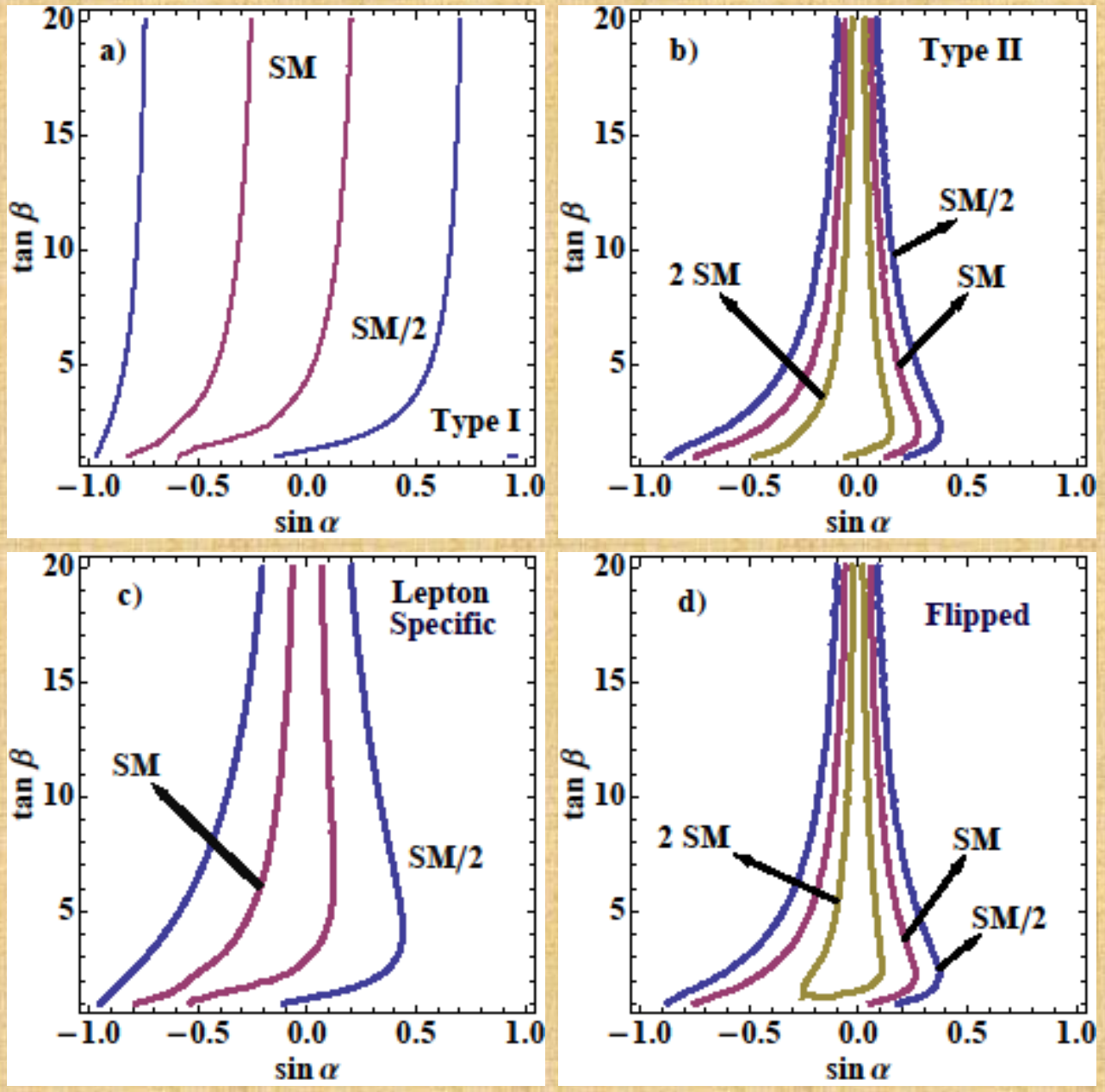
$$(m_\nu)_{\ell\ell'} \propto (f m_\ell^{\mathrm{diag}}\, h\, m_\ell^{\mathrm{diag}} f)_{\ell\ell'}$$

$h \to \gamma\gamma$ in the HTM



A.G. Akeroyd, S. Moretti, PRD**86**, 035015 (2012)

$h \to \gamma\gamma$ in the THDMs



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