What can we hope on nutrino physics at the LHC

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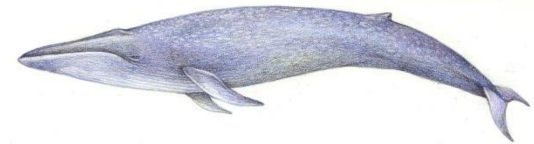
Introduction

Neutrino masses are extremely smaller than other fermion masses.

neutrino $\lesssim 1\,\mathrm{eV}$ electron $= 0.5\,\mathrm{MeV}$ tau $= 1.8\,\mathrm{GeV}$ top $= 172\,\mathrm{GeV}$



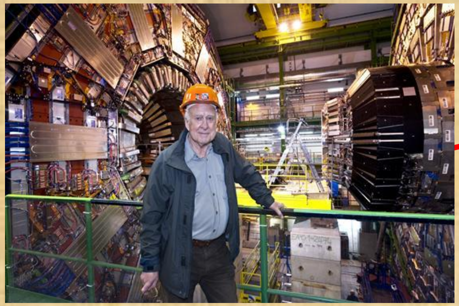
$1\,\mathrm{MeV}$ "$\simeq$" $1\,\mathrm{kg}$

$\longrightarrow$ **Neutrino-specific mechanism to generate their masses ?**

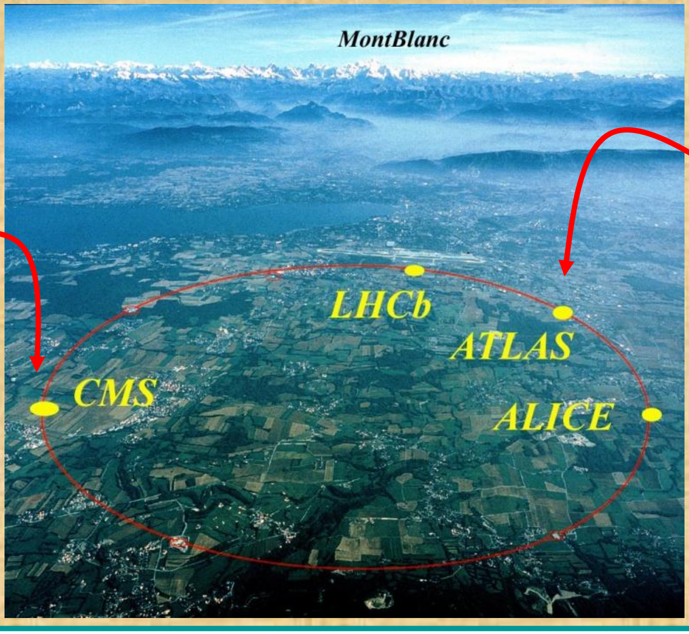
Yukawa with SM Higgs? ⇒ **Seesaw with very heavy particle ?** ⇒ **Far from experimental reach**

Yukawa with new scalar ? ⇒ **Light new scalar ?** ⇒ **LHC ?**

Large Hadron Collider



first event of Higgs at CMS (4 Apr. 2008)



first event of Higgs at ATLAS (4 Apr. 2008)

pp **collider at** $\sqrt{s} = 7,\, 8,\, 14\,\mathrm{TeV}$ **(cf. Tevatron:** $p\bar{p}$ **at** $\sqrt{s} = 1.96\,\mathrm{TeV}$**)**

26.7km ring (cf. 26.4km loop subway in Nagoya, Japan)

ATLAS: Higgs, new phys.

CMS: Higgs, new phys.

ALICE: quark-gluon plasma

LHCb: B phys.

TOTEM (near CMS): elastic and diffractive cross sections

LHCf (near ATLAS): cosmic ray

New scalars at the LHC

Leptophilic Scalars !

Origin of neutrino masses

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)

Radiative neutrino mass

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

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

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

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

Tree neutrino mass (doublet and triplet)

Model

Yukawa interactions

LHC

Scalar decay into leptons

Goal (Hope)

Origin of neutrino mass

Neutrino mass matrix

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

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

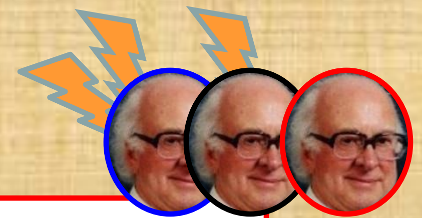
$m_0,\ \alpha_{21},\ \alpha_{31}$

T2K, DCHOOZ, Daya Bay, RENO, …

Neutrino oscillation data

Doubly Charged Scalar

Doubly Charged Higgs - Triplet -



Target : $h_{\ell\ell'}\left[\overline{L^c_\ell}\, i\sigma_2\, \Delta\, L_{\ell'}\right]$ $\quad \Delta \equiv \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$

Symmetric

Higgs Triplet Model

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)

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

Neutrino masses : $(m_\nu)_{\ell\ell'} = h_{\ell\ell'}\langle\Delta^0\rangle$

Scalar potential :

Soft breaking of $L\#$

$$V = -m_\Phi^2[\Phi^\dagger\Phi] + m_\Delta^2[\mathrm{Tr}(\Delta^\dagger\Delta)] - \left(\mu\,[\Phi^T i\sigma_2\Delta^\dagger\Phi] + \mathrm{h.c.}\right) + \mathrm{quartic}$$

$$\langle\Delta^0\rangle \sim \frac{\mu\,\langle\phi^0\rangle^2}{m_\Delta^2}$$

Set up

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

$$\begin{cases} (m_\nu)_{\ell\ell'} = h_{\ell\ell'} \langle \Delta^0 \rangle \\ \qquad = \left(U^*_{\rm MNS}\, {\rm diag}(m_1, m_2 e^{i\alpha_{21}}, m_3 e^{i\alpha_{31}})\, U^\dagger_{\rm MNS} \right)_{\ell\ell'} \\ 10\,{\rm eV} \lesssim \langle \Delta^0 \rangle \lesssim 10\,{\rm KeV} \end{cases}$$

$$m_{\Delta^{\pm\pm}} \leq m_{\Delta^\pm}$$

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

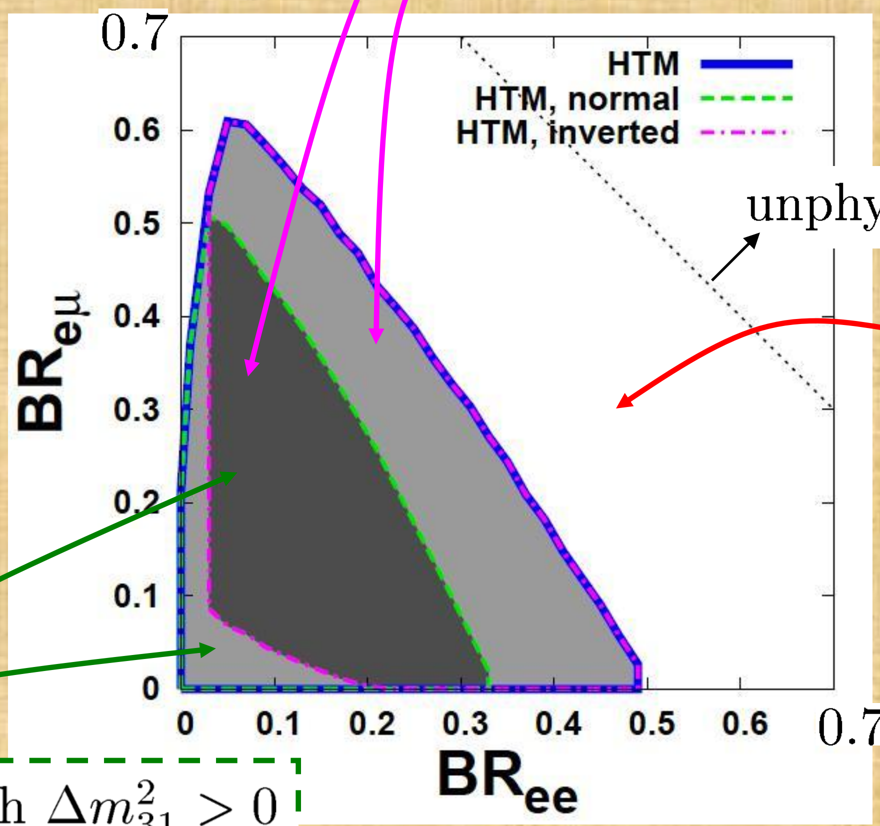
$$1.7\,[{\rm fb}] \text{ @14TeV LHC}$$

w/o QCD K-factor

$$\mathrm{BR}_{\ell\ell'} \equiv \mathrm{BR}(\Delta^{\pm\pm} \to \ell^\pm \ell'^\pm) = \frac{2}{1+\delta_{\ell\ell'}} \frac{|(m_\nu)_{\ell\ell'}|^2}{\sum_j m_j^2}$$

Information on $\mathrm{sign}(\Delta m^2_{31})$

possible with $\Delta m^2_{31} < 0$



unphysical $(\mathrm{BR}_{ee} + \mathrm{BR}_{e\mu} \geq 1)$

unreachable in HTM

$H^{\pm\pm} \neq SU(2)_{\mathrm{L}}$ triplet ?
(ex. $Y = 4$ singlet,
$SU(2)_{\mathrm{R}}$ triplet)
other mechanism for m_ν ?
(ex. see-saw with ν_R)

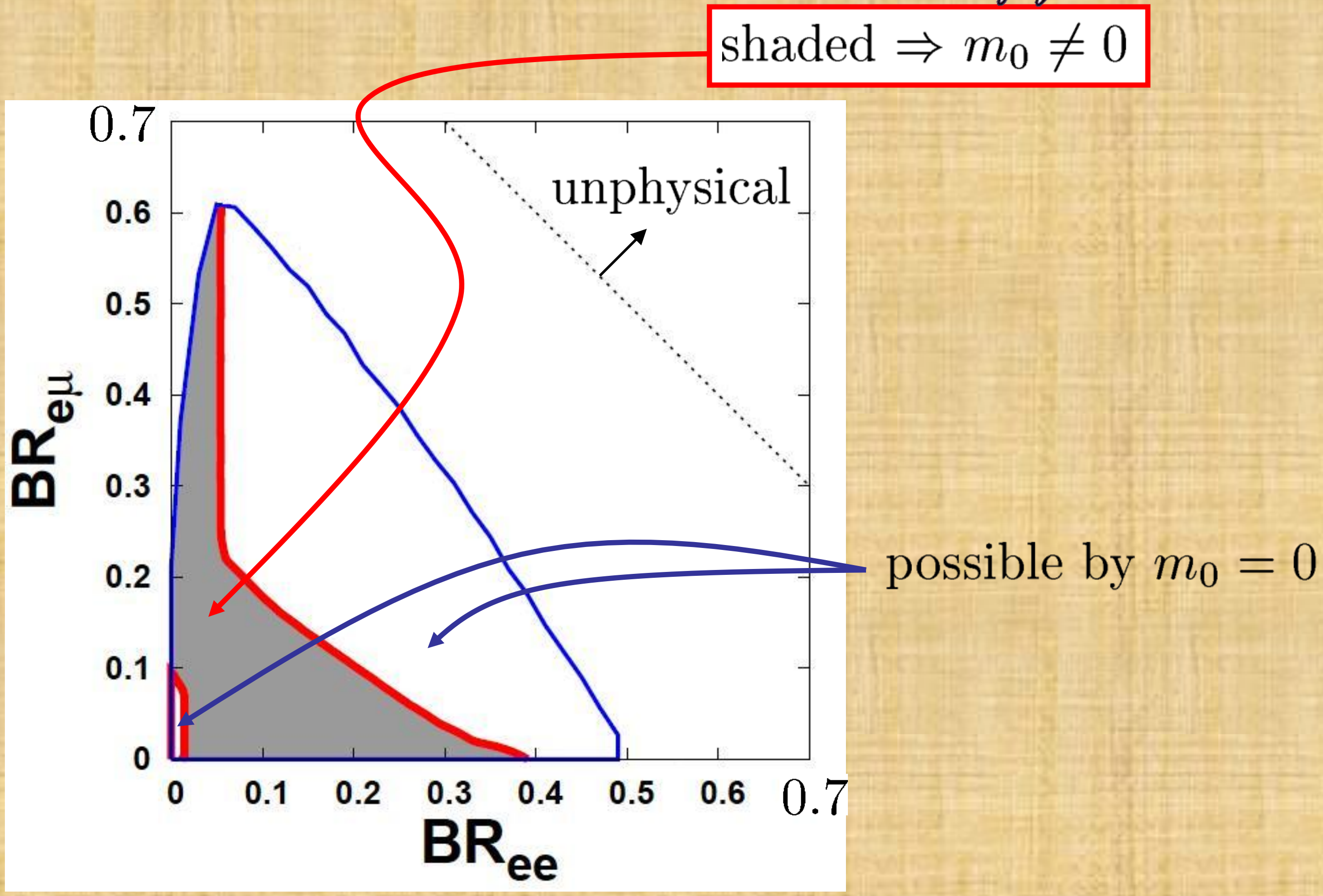
possible with $\Delta m^2_{31} > 0$

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

Information on Non-Zero m_0

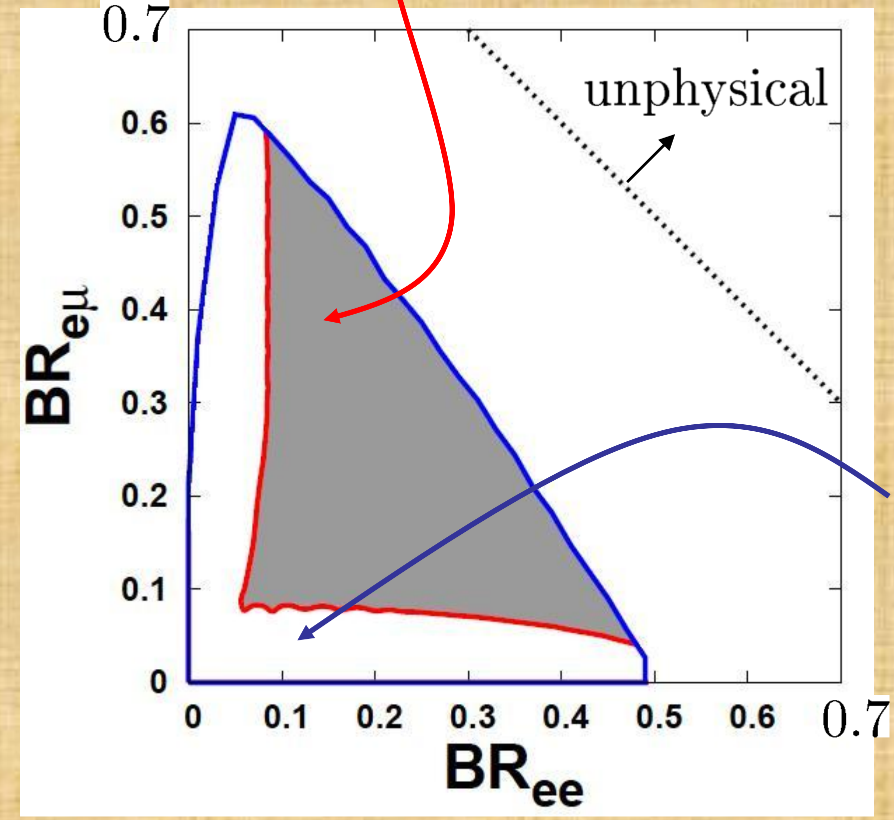
the lightest mass



Note: Knowledge on sign(Δm^2_{31}) is not assumed

Information on CP-Violation with Majorana Phases

shaded $\Rightarrow$ CP violation by Majorana phases



possible by $\alpha_{21}, \alpha_{31} = 0, \pi$

Note: Knowledge on $\mathrm{sign}(\Delta m_{31}^2)$ is not assumed

Doubly Charged Scalar - Singlet -

Target : $h_{\ell\ell'}\left[\overline{(\ell_R)^c}\,\ell'_R\,s^{++}\right]$

Symmetric

Zee-Babu Model

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

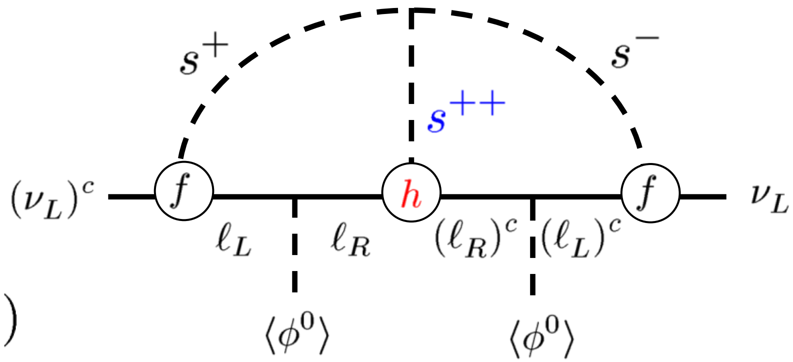
Yukawa : $h_{\ell\ell'}\left[\overline{(\ell_R)^c}\,\ell'_R\,s^{++}\right],\; f_{\ell\ell'}\left[\overline{L^c_\ell}\,i\sigma_2\,L_{\ell'}\,s^{+}\right]$

Mass eigenstate

Neutrino masses :

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

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



$$m_{s^{\pm\pm}} = 500\,{\rm GeV} \;\Rightarrow\; \sigma(pp \to s^{++}s^{--}) = 1.4\times 10^{-1}[{\rm fb}]\ \text{@8TeV LHC}$$

$$7.2\times 10^{-1}[{\rm fb}]\ \text{@14TeV LHC}$$

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

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

No e contribution (assumption)

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

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

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

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)

Singly Charged Scalar

Singly Charged Higgs - Doublet or Triplet -

Neutrinophillic Doublet

S. Gabriel and S. Nandi, PLB**655**, 141 (2007)
S.M. Davidson and H.E. Logan, PRD**80**, 905008 (2009)

Only for neutrinos

Neutrino Yukawa : $(y_\nu)_{i\ell}\left[\overline{\nu_{Ri}}\,\Phi_\nu\, i\sigma_2\, L_\ell\right]$ $\quad \nu_{Ri},\ \Phi_\nu$ **:** Z_2 **odd**

Dirac neutrinos : $(m_\nu)_{i\ell} = (y_\nu)_{i\ell}\langle\phi_\nu^0\rangle$

$$\langle\phi_\nu^0\rangle \ll \langle\phi_{\rm SM}^0\rangle$$

(Spontaneous Symmetry Breaking $\Longrightarrow m_{H_\nu^0} \propto \langle\phi_\nu^0\rangle$ **)**

Scalar potential : **Soft breaking of** Z_2

$$V = -m_{11}^2[\Phi_{\rm SM}^\dagger\Phi_{\rm SM}] + m_{22}^2[\Phi_\nu^\dagger\Phi_\nu] - \left(m_{12}^2[\Phi_{\rm SM}^\dagger\Phi_\nu] + {\rm h.c.}\right) + {\rm quartic}$$

$$\langle\phi_\nu^0\rangle \simeq \frac{m_{12}^2\langle\phi_{\rm SM}^0\rangle}{m_{22}^2}$$

Set up for Dirac neutrinos

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

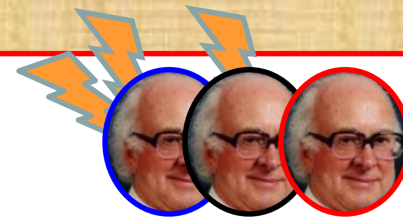
$$\left\{\begin{array}{l} (m_\nu)_{i\ell} = (y_\nu)_{i\ell}\langle\phi_\nu^0\rangle \\ \qquad = \left(\mathrm{diag}(m_1, m_2, m_3)\, U_{\mathrm{MNS}}^\dagger\right)_{i\ell} \\ 10\,\mathrm{eV} \lesssim \langle\phi_\nu^0\rangle \lesssim 10\,\mathrm{KeV} \end{array}\right.$$

$$m_{\phi_\nu^\pm} \leq m_{H_\nu^0}$$

$$m_{\phi_\nu^\pm} = 500\,\mathrm{GeV} \;\Rightarrow\; \sigma(pp \to \phi_\nu^+\phi_\nu^-) = 8.0\times 10^{-2}[\mathrm{fb}]\ \text{@8TeV LHC}$$

$$4.2\times 10^{-1}[\mathrm{fb}]\ \text{@14TeV LHC}$$

Set up for Majorana neutrinos (“HTM-like” case)



Target : $h_{\ell\ell'}\left[\overline{L_\ell^c}\, i\sigma_2\, \Delta\, L_{\ell'}\right]$

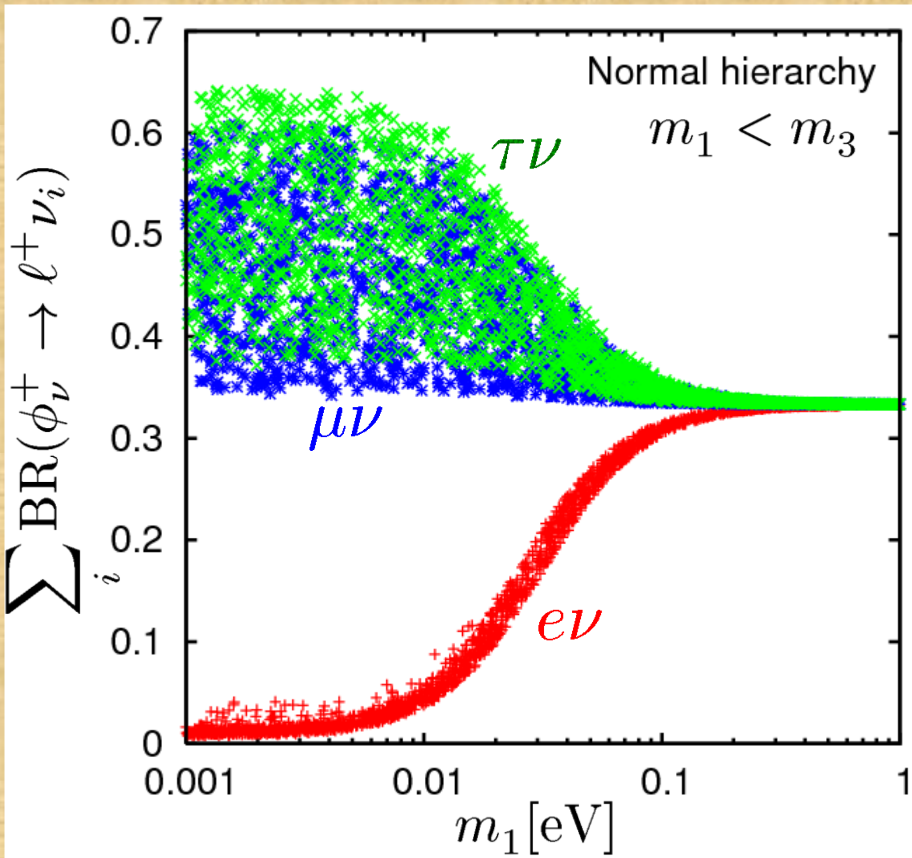
$$\left\{\begin{array}{l} (m_\nu)_{\ell\ell'} = h_{\ell\ell'}\langle\Delta^0\rangle \\ \qquad = \left(U_{\mathrm{MNS}}^*\,\mathrm{diag}(m_1, m_2 e^{i\alpha_{21}}, m_3 e^{i\alpha_{31}})\, U_{\mathrm{MNS}}^\dagger\right)_{\ell\ell'} \\ 10\,\mathrm{eV} \lesssim \langle\Delta^0\rangle \lesssim 10\,\mathrm{KeV} \end{array}\right.$$

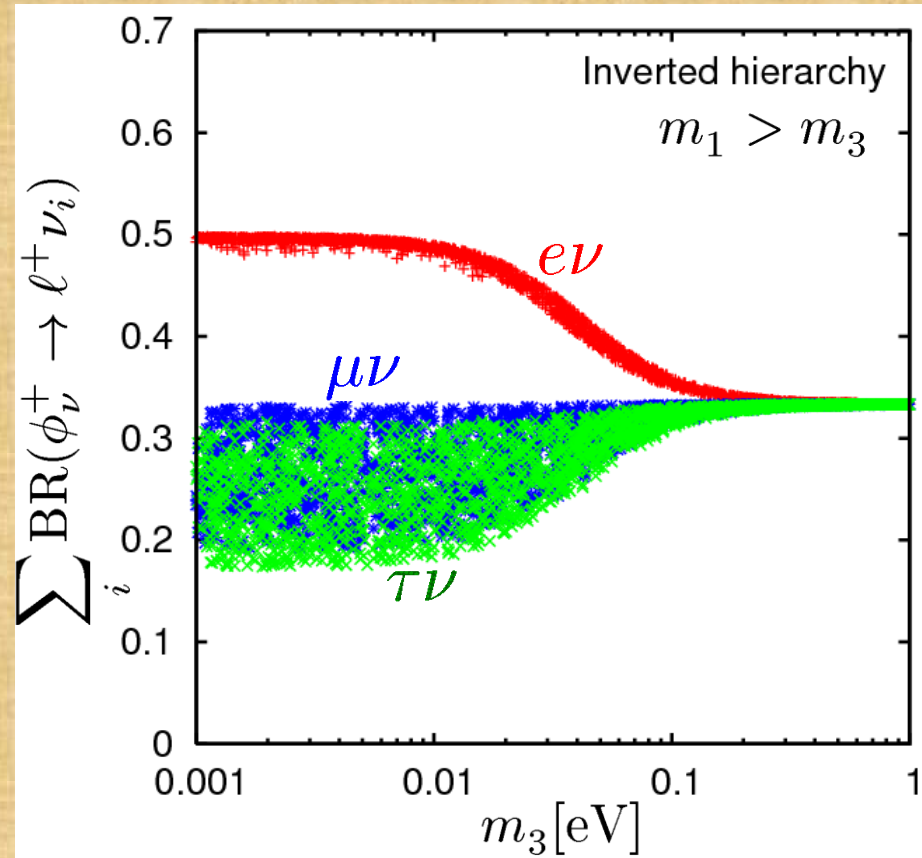
$m_{\Delta^{\pm\pm}} \simeq m_{\Delta^\pm} \simeq m_{\Delta^0}$ (See also, S. Kanemura and K. Yagyu, arXiv:1201.6287)

$$m_{\Delta^\pm} = 500\,\mathrm{GeV} \;\Rightarrow\; \sigma(pp \to \Delta^+\Delta^-) = 3.4\times 10^{-2}[\mathrm{fb}]\ \text{@8TeV LHC}$$

$$1.8\times 10^{-1}[\mathrm{fb}]\ \text{@14TeV LHC}$$

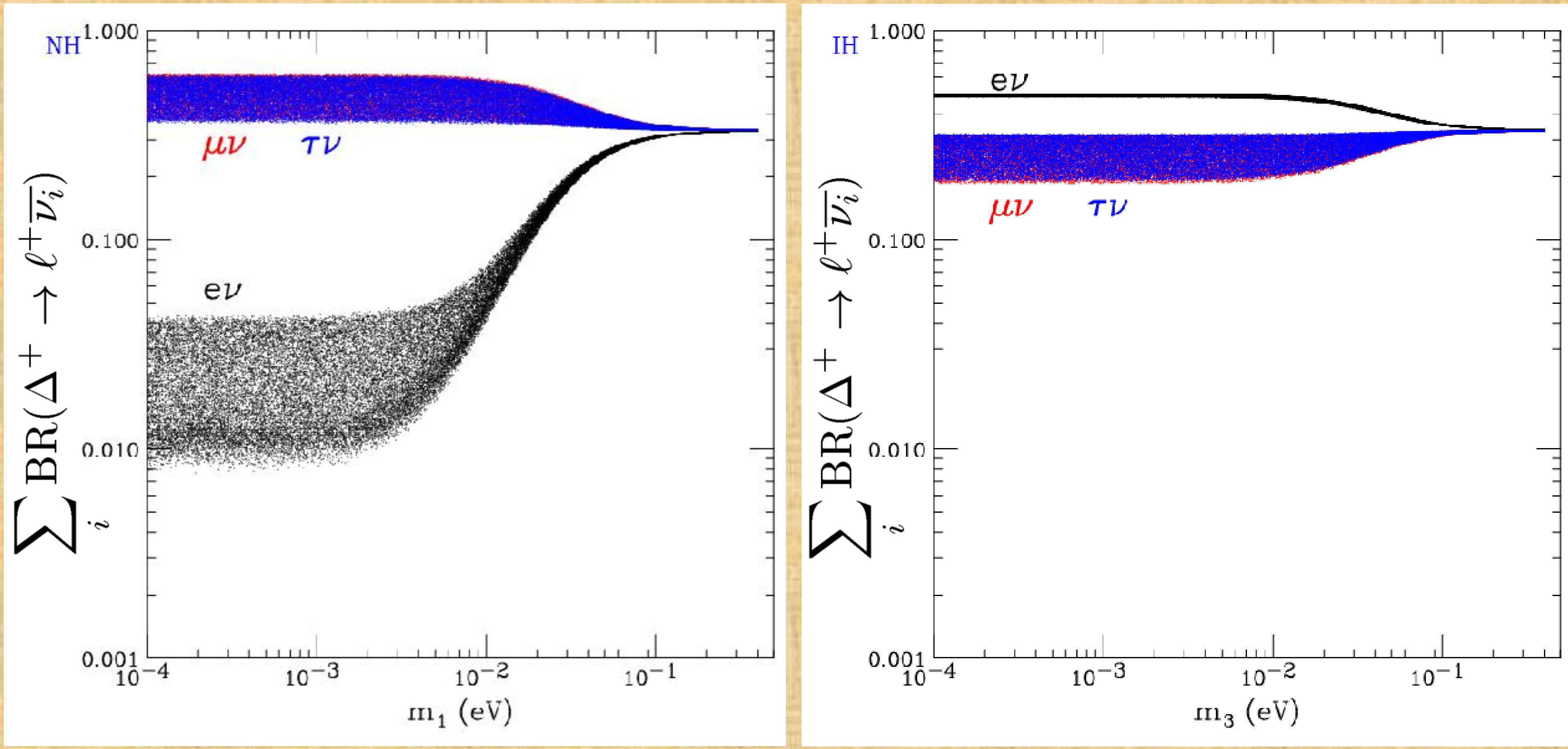
$$\mathrm{BR}_\ell \equiv \sum_i \mathrm{BR}(\phi_\nu^+ \to \ell^+ \nu_i) = \sum_i \mathrm{BR}(\Delta^+ \to \ell^+ \overline{\nu_i}) = \frac{\sum_i m_i^2 |(U_{\mathrm{MNS}})_{\ell i}|^2}{\sum_j m_j^2}$$





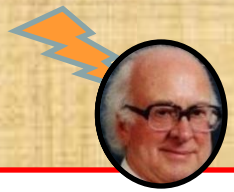
S.M. Davidson and H.E. Logan, PRD**80**, 905008 (2009)

$\mathrm{BR}_\mu \simeq \mathrm{BR}_\tau$ $\qquad \dfrac{\mathrm{BR}_e}{\mathrm{BR}_\mu} \longrightarrow \begin{cases} \mathrm{sign}(m_3 - m_1) \\ m_0 (= \min(m_1, m_3)) \end{cases}$



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

Singly Charged Scalar - Singlet 1 -



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

Antisymmetric

$\simeq$ **Mass eigenstate (assumption)**

Simplest Zee Model

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

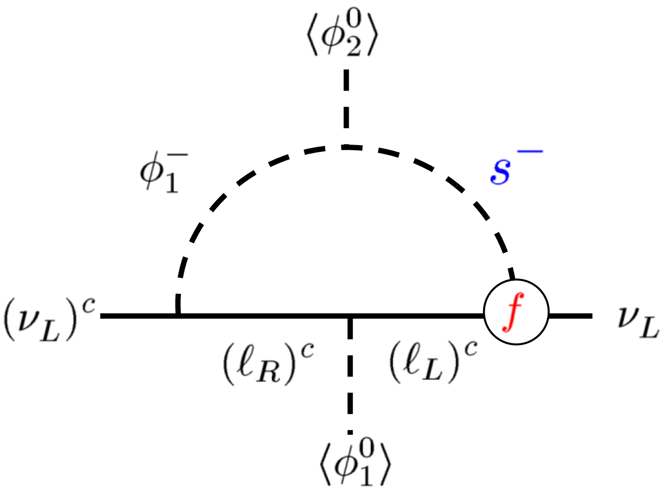
Doublet Yukawa : $\frac{m_\ell}{\langle \phi_1^0 \rangle}\left[\overline{L_\ell}\, \Phi_1\, \ell_R\right]$

No Flavor-Changing-Neutral-Current

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

Excluded by Oscillation data

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



General (Original) Zee Model

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

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

Incl. FCNC

Set up

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

$\simeq$ **Mass eigenstate (assumption)**

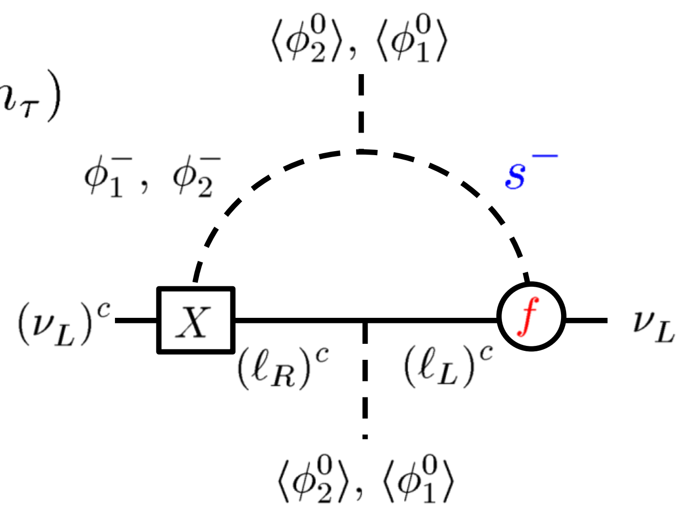
Antisymmetric

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

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

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

τ **dominance (assumption)**



$$m_{s^\pm} = 500\,{\rm GeV} \;\Rightarrow\; \sigma(pp \to s^+ s^-) = 3.4 \times 10^{-2}[{\rm fb}]\ @8{\rm TeV\ LHC}$$
$$1.8 \times 10^{-1}[{\rm fb}]\ @14{\rm TeV\ LHC}$$

$$\mathrm{Det}(m_\nu) = m_\tau \, \mathrm{Det}\Big(X_{\ell\tau} f_{\tau\ell'} + (f^T)_{\ell\tau}(X^T)_{\tau\ell'}\Big) = 0 \longrightarrow m_1 = 0 \text{ or } m_3 = 0$$

$m_1 = 0$

$$\left|\frac{m_2}{m_3}\right| = \frac{c_{23}^2 c_{13}^2}{|c_{23}s_{12}s_{13} + c_{12}s_{23}e^{i\delta}|^2} \gtrsim 1$$

Not acceptable

$m_3 = 0$

$$\frac{\mathrm{BR}_\tau}{\mathrm{BR}_\mu - \mathrm{BR}_e} \simeq \frac{17}{15}$$

$$\begin{cases} \sin^2 2\theta_{13} \simeq 0.118 \\ \delta \simeq \pi \\ \alpha_{21} \simeq \pi \end{cases}$$

$$\mathrm{BR}_\ell \equiv \sum_i \mathrm{BR}(s^- \to \ell \nu_i)$$

$$\begin{cases} \dfrac{f_{\mu\tau}}{f_{e\tau}} = -\dfrac{\tan\theta_{13}}{s_{23}} e^{-i\delta} \\ f_{e\mu} \text{ : Arbitlary} \end{cases}$$

$$s_{23} = \frac{1}{\sqrt{2}}, \; s_{12} = \frac{1}{\sqrt{3}}, \; \left|\frac{m_1}{m_2}\right| \simeq 1 \Rightarrow \begin{cases} s_{13} \simeq 3 - \sqrt{2} \simeq 0.17 \\ \delta \simeq \pi \\ \alpha_{21} \simeq \pi \end{cases}$$

Singly Charged Scalar - Singlet 2 -

Set up

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

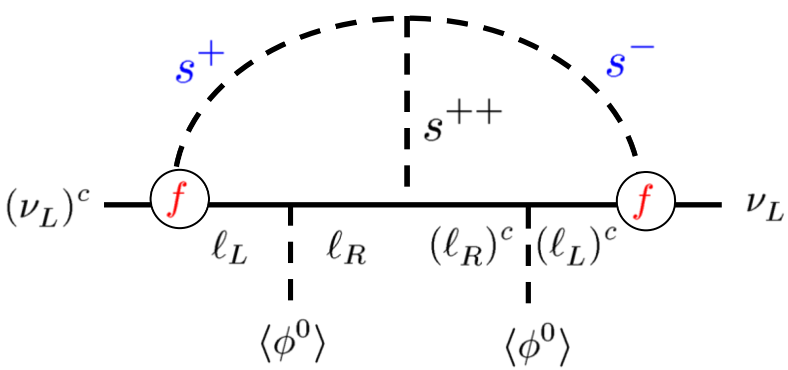
Antisymmetric

$\simeq$ Mass eigenstate (assumption)

Majorana neutrinos :

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

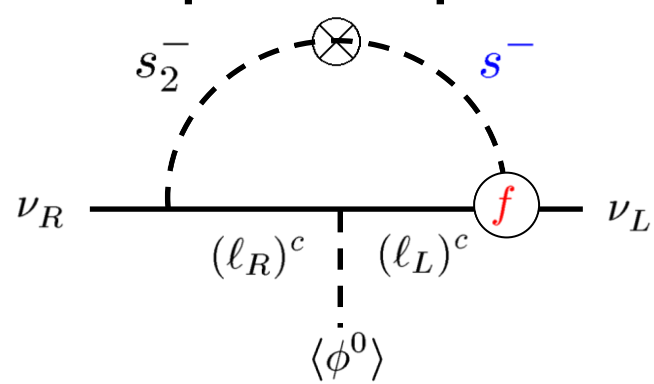
Example : Zee-Babu model



Dirac neutrinos :

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

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)

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

$m_1 = 0$

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

$$\mathrm{BR}_\ell \equiv \sum_i \mathrm{BR}(s^- \to \ell \nu_i) = \frac{1}{3} \sum_{\ell'} |f_{\ell\ell'}|^2$$

$$\frac{f_{e\tau}}{f_{\mu\tau}} = \frac{\tan\theta_{12}}{\cos\theta_{13}} \cos\theta_{23} + \sin\theta_{23} \tan\theta_{13} e^{i\delta} \simeq \frac{1}{2} + \frac{1}{\sqrt{2}} s_{13} e^{i\delta}$$

$$\frac{f_{e\mu}}{f_{\mu\tau}} = \frac{\tan\theta_{12}}{\cos\theta_{13}} \sin\theta_{23} - \cos\theta_{23} \tan\theta_{13} e^{i\delta} \simeq \frac{1}{2} - \frac{1}{\sqrt{2}} s_{13} e^{i\delta}$$

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)

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

$$m_3 = 0$$

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

$$\mathrm{BR}_\ell \equiv \sum_i \mathrm{BR}(s^- \to \ell \nu_i) = \frac{1}{3} \sum_{\ell'} |f_{\ell\ell'}|^2$$

$$\frac{f_{e\tau}}{f_{e\mu}} = -\tan\theta_{23} \simeq -1$$

$$\frac{f_{\mu\tau}}{f_{e\mu}} = \frac{\tan\theta_{13}}{\cos\theta_{23}} e^{-i\delta} \simeq \sqrt{2}\, s_{13} e^{-i\delta} \lesssim 0.3\, e^{-i\delta}$$

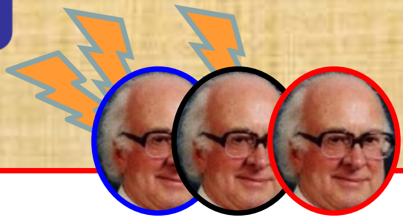
K.S. Babu and C. Macesanu, PRD**67**, 073010 (2003)

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 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 : $\mathrm{BR}_{\ell\ell'} \longrightarrow \begin{cases} (m_\nu)_{\ell\ell'} = h_{\ell\ell'}\langle\Delta^0\rangle \\ \Delta m^2_{31} > 0 \text{ or not ?} \quad m_0 = 0 \text{ or not ?} \\ \sin\alpha_{21} = 0,\ \sin\alpha_{31} = 0 \text{ or not ?} \end{cases}$

Singly charged : $\mathrm{BR}_\mu \simeq \mathrm{BR}_\tau,\ \dfrac{\mathrm{BR}_e}{\mathrm{BR}_\mu} \longrightarrow \begin{cases} (m_\nu)_{\ell\ell'} = h_{\ell\ell'}\langle\Delta^0\rangle \\ \quad \text{or } (m_\nu)_{i\ell} = (y_\nu)_{i\ell}\langle\phi^0_\nu\rangle \\ \Delta m^2_{31} > 0 \text{ or not ?} \\ m_0 \end{cases}$

$\mathrm{SU}(2)_L$ **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 :** $f_{\ell\ell'}\left[\overline{L_\ell^c}\, i\sigma_2\, L_{\ell'}\, s^+\right]$

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

$$(m_\nu)_{\ell\ell'} \propto (f\,X\,f)_{\ell\ell'} \quad \textbf{or} \quad (m_\nu)_{i\ell'} \propto (X\,f)_{i\ell'}$$

(Majorana)  **(Dirac)** 

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

$$\frac{\mathrm{BR}_\tau}{\mathrm{BR}_\mu - \mathrm{BR}_e} \simeq \frac{17}{15} \;\Longrightarrow\; \begin{cases} (m_\nu)_{\ell\ell'} \sim m_\tau \Big(X_{\ell\tau} f_{\tau\ell'} + (f^T)_{\ell\tau} (X^T)_{\tau\ell'} \Big) \\ m_3 = 0,\; \sin^2 2\theta_{13} \simeq 0.118,\; \delta \simeq \pi,\; \alpha_{21} \simeq \pi \end{cases}$$

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

$$\mathrm{BR}_{\mu\mu} : \mathrm{BR}_{\mu\tau} : \mathrm{BR}_{\tau\tau} \sim 1:0:0 \;\Longrightarrow\;$$ **Zee-Babu model ??**

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