Prospects of two–loop neutrino mass models after θ_{13} measurements and LHC data

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Outline

- Motivation
- Two–loop neutrino mass models
- Predictions, experimental testings
- Conclusions

What we know about neutrinos

- The best fit of neutrino mass and mixing parameters:

Quantity	Value
Δm^2_{21}(eV^2)	$(7.59 \pm 0.21) \times 10^{-5}$
Δm^2_{31}(eV^2)	$(2.53^{+0.13}_{-0.08}) \times 10^{-3}$ (NH) $-(2.4^{+0.1}_{-0.07}) \times 10^{-3}$ (IH)
$\sin^2\theta_{12}$	$0.320^{+0.015}_{-0.017}$
$\sin^2\theta_{23}$	$0.49^{+0.08}_{-0.05}$ $0.53^{+0.08}_{-0.07}$
$\sin^2\theta_{13}$	$0.026^{+0.003}_{-0.004}$ $0.027^{+0.003}_{-0.004}$

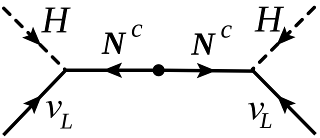
Forero, Tórtola, Valle (2012)

- The origin of neutrino mass, type of hierarchy, the *CP*-violating parameter, and whether neutrinos are Dirac or Majorana are still unknown.

The origin of neutrino mass (seesaw mechanism)

- Adding right-handed neutrino N^c which transforms as singlet under $SU(2)_L$,

$$\mathcal{L} = f_\nu \, (L \cdot H) \, N^c + \tfrac{1}{2} M_R N^c N^c$$



- Integrating out the N^c, $\Delta L = 2$ operator is induced:

$$\mathcal{L}_{\text{eff}} = -\frac{f_\nu^2}{2} \frac{(L \cdot H)\,(L \cdot H)}{M_R}$$

- Once H acquires VEV, neutrino mass is induced:

$$m_\nu \simeq f_\nu^2 \frac{v^2}{M_R}$$

- For $f_\nu v \simeq 100$ GeV, $M_R \simeq 10^{14}$ GeV.

Minkowski (1977)
Yanagida (1979)
Gell-Mann, Ramond, Slansky (1980)
Mohapatra & Senjanovic (1980)

Radiative neutrino mass generation

- An alternative to seesaw is radiative neutrino mass generation, where neutrino mass is absent at tree level but arises at loop level.
- The smallness of neutrino mass is explained by loop and chiral suppressions.
- New physics scale typically near TeV and thus accessible to LHC.
- Further tests in observable LFV processes.

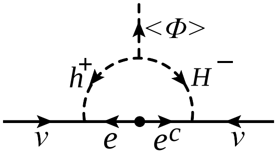
Zee model

- Introducing a singly charged scalar and extra scalar doublet,

$$\mathcal{L} = f_{ij} L_i^a L_j^b h^+ \epsilon_{ab} + \mu H^a \Phi^b h^- \epsilon_{ab} + \text{h.c.}$$

Zee (1980)

- Neutrino mass arises at one-loop.



- The minimal version of this model in which only one Higgs doublet couples to fermions yields

$$m_\nu = \begin{pmatrix} 0 & m_{e\mu} & m_{e\tau} \\ m_{e\mu} & 0 & m_{\mu\tau} \\ m_{e\tau} & m_{\mu\tau} & 0 \end{pmatrix}, \quad m_{ij} \simeq \frac{f_{ij}}{16\pi^2} \frac{(m_i^2 - m_j^2)}{\Lambda}$$

It requires $\theta_{12} \simeq \pi/4 \rightarrow$ ruled out by neutrino data.

Koide (2001)
Frampton *et al.* (2002)
He (2004)

$\Delta L = 2$ operators

$$
\begin{aligned}
\mathcal{O}_1 &= L^i L^j H^k H^l \epsilon_{ik}\epsilon_{jl} \\
\mathcal{O}_2 &= L^i L^j L^k e^c H^l \epsilon_{ij}\epsilon_{kl} \\
\mathcal{O}_3 &= L^i L^j Q^k d^c H^l \epsilon_{ij}\epsilon_{kl}, \quad L^i L^j Q^k d^c H^l \epsilon_{ik}\epsilon_{jl}\} \\
\mathcal{O}_4 &= \{L^i L^j \bar{Q}_i \bar{u^c} H^k \epsilon_{jk}, \quad L^i L^j \bar{Q}_k \bar{u^c} H^k \epsilon_{ij}\} \\
\mathcal{O}_5 &= L^i L^j Q^k d^c H^l H^m \bar{H}_i \epsilon_{jl}\epsilon_{km} \\
\mathcal{O}_6 &= L^i L^j \bar{Q}_k \bar{u^c} H^l H^k \bar{H}_i \epsilon_{jl} \\
\mathcal{O}_7 &= L^i Q^j \bar{e^c} \bar{Q}_k H^k H^l H^m \epsilon_{il}\epsilon_{jm} \\
\mathcal{O}_8 &= L^i \bar{e^c} \bar{u^c} d^c H^j \epsilon_{ij} \\
\mathcal{O}_9 &= L^i L^j L^k e^c L^l e^c \epsilon_{ij}\epsilon_{kl}
\end{aligned}
$$

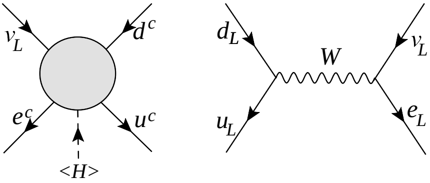
Babu & Leung (2001)

de Gouvea & Jenkins (2008)

Angel, Rodd, & Volkas (2012)

Operator $\mathcal{O}_8$

- Operator $\mathcal{O}_8 = L_i H_j d^c \bar{u^c} \bar{e^c} \epsilon_{ij}$ induces neutrino mass at two–loop:



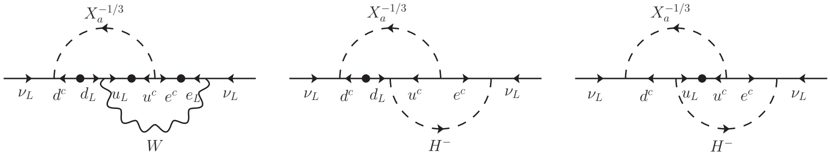
$$m_\nu \sim \frac{m_\tau m_b m_t v}{(16\pi^2)^2 \Lambda^3}$$

- Scale of new physics near TeV.
- This operator can be realized in model with scalar leptoquarks.

  Babu & JJ (2010)

Two–loop neutrino mass model with leptoquarks

$$\mathcal{L} \supset Y_{ij} L_i \cdot \Omega d_j^c + F_{ij} u_i^c e_j^c \chi^{-1/3} + \mu \Omega^\dagger H \chi^{-1/3} + \text{h.c.}$$



$$(M_\nu)_{ij} = \hat{m}_0 Y_{ik} (D_d)_k (V^T)_{kl} (D_u)_l (F^\dagger)_{lj} (D_\ell)_j I_{jkl} + \text{transpose},$$

$$\hat{m}_0 = \left(\frac{3g^2 \sin 2\theta}{(16\pi^2)^2}\right) \left(\frac{m_t m_b m_\tau}{M_1^2}\right)$$

$$D_u = \text{diag.}\left[\frac{m_u}{m_t}, \frac{m_c}{m_t}, 1\right],\ D_d = \text{diag.}\left[\frac{m_d}{m_b}, \frac{m_s}{m_b}, 1\right],\ D_\ell = \text{diag.}\left[\frac{m_e}{m_\tau}, \frac{m_\mu}{m_\tau}, 1\right]$$

Neutrino mass matrix

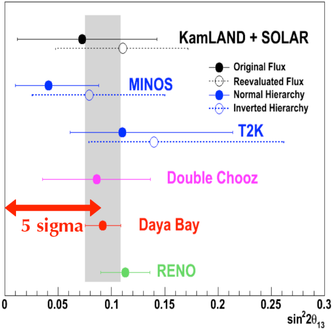
$$M_\nu \simeq m_0 \begin{pmatrix} 0 & \frac{1}{2}\frac{m_\mu}{m_\tau}xy & \frac{1}{2}y \\ \frac{1}{2}\frac{m_\mu}{m_\tau}xy & \frac{m_\mu}{m_\tau}xz & \frac{1}{2}z + \frac{1}{2}\frac{m_\mu}{m_\tau}x \\ \frac{1}{2}y & \frac{1}{2}z + \frac{1}{2}\frac{m_\mu}{m_\tau}x & 1 + w \end{pmatrix}$$

$$x \equiv \frac{F_{23}^*}{F_{33}^*}, \quad y \equiv \frac{Y_{13}}{Y_{33}}, \quad z \equiv \frac{Y_{23}}{Y_{33}}; \qquad w \equiv \frac{F_{32}^*}{F_{33}^*}\frac{Y_{32}}{Y_{33}}\left(\frac{m_c}{m_t}\right)\left(\frac{m_s}{m_b}\right)\frac{I_{jk2}}{I_{jk3}}$$

$$m_0 = 2\,\hat{m}_0 F_{33}^* Y_{33} I_{jk3}; \qquad (M_\nu)_{11} \simeq y\frac{F_{13}^*}{F_{33}^*}\frac{m_e}{m_\tau}m_0$$

- This mass matrix has normal hierarchy structure.
- The (1,1) entry is highly suppressed, i.e. $\ll 0.01$ eV.
- w may be significant for $M_{LQ} < 1$ TeV.

Predictions for $w \ll 1$



$$(\sin^2 2\theta_{13})_{\text{exp}} = 0.092 \pm 0.016 \pm 0.005 \text{ (Daya Bay)}$$

$$(\sin^2 2\theta_{13})_{\text{exp}} = 0.113 \pm 0.013 \pm 0.019 \text{ (RENO)}$$

- For $w \ll 1$,

$$M_\nu \simeq m_0 \begin{pmatrix} 0 & \frac{1}{2}\frac{m_\mu}{m_\tau}xy & \frac{1}{2}y \\ \frac{1}{2}\frac{m_\mu}{m_\tau}xy & \frac{m_\mu}{m_\tau}xz & \frac{1}{2}z + \frac{1}{2}\frac{m_\mu}{m_\tau}x \\ \frac{1}{2}y & \frac{1}{2}z + \frac{1}{2}\frac{m_\mu}{m_\tau}x & 1 \end{pmatrix}$$

- This implies $\det M_\nu = 0$. Together with $(M_\nu)_{11} \simeq 0$,

$$m_1 \simeq 0, \ \alpha \simeq 0, \ \beta \simeq 2\delta + \pi$$

$$\tan^2\theta_{13} \simeq \sqrt{\frac{\Delta m_{21}^2}{\Delta m_{31}^2}} \sin^2\theta_{12}$$

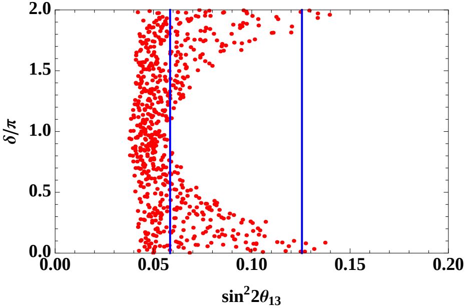
$$\sin^2 2\theta_{13} \simeq 0.16$$

Predictions for $w \gg 1$

- For $w \gg 1$,

$$w \equiv \frac{F_{32}^*}{F_{33}^*}\frac{Y_{32}}{Y_{33}}\left(\frac{m_c}{m_t}\right)\left(\frac{m_s}{m_b}\right)\frac{I_{jk2}}{I_{jk3}} \gg 1 \quad \rightarrow \quad |F_{33}Y_{33}| \ll |F_{32}Y_{32}|$$

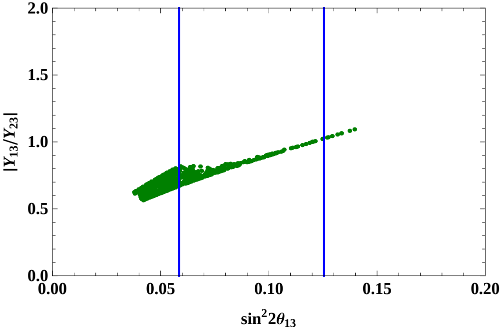
- This could generate $(M_\nu)_{13} \simeq (M_\nu)_{11} \simeq 0$.
  Glashow, Frampton, & Marfatia (2002)
  Xing (2002)



- The value of θ_{13} is consistent with current measurements (the blue lines correspond to 2σ allowed value from Daya Bay).

Predictions for $w \gg 1$

- Requiring $|F_{32}Y_{32}| \leq 1$ implies that LQ cannot be heavier than 1 TeV.



The neutrino mass fit gives $|Y_{13}| \sim |Y_{23}|$ or $|y| \sim |z|$.

Leptoquark branching ratios

The ratios of LQ decay widths:

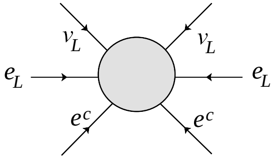
$$\Gamma(\omega^{2/3} \to e^+ b) : \Gamma(\omega^{2/3} \to \mu^+ b) = |y|^2 : |z|^2$$

$$\Gamma(X_a^{-1/3} \to \mu^- t) : \Gamma(X_a^{-1/3} \to \tau^- t) = |x|^2 : 1$$

- Since $|y| \sim |z|$, $\omega^{-2/3}$ will decay equally to both electron and muon.
- Since $|F_{33}| \ll |F_{23}|$, $|x| \gg 1$, $X_a^{-1/3}$ will dominantly decay to muon.

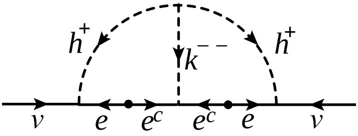
Operator $\mathcal{O}_9$

- Operator $\mathcal{O}_9 = L^\alpha L^\beta L^\delta L^\gamma e^c e^c \epsilon_{\alpha\beta}\epsilon_{\delta\gamma}$ induces neutrino mass at two–loop:



- A realization of this operator is model with singly- and doubly-charged scalars.

Two–loop neutrino mass model with singly- and doubly-charged scalars



$$\mathcal{L} \supset f_{ij} L_i^\alpha L_j^\beta h^+ \epsilon_{\alpha\beta} + h_{ij} e_i^c e_j^c k^{--} + \mu h^+ h^+ k^{--}$$

$$(M_\nu)_{ij} \simeq \frac{16\mu}{(16\pi^2)^2 m_h^2} f_{ik} m_{\ell_k} h_{kl}^* m_{\ell_l} f_{lj} I\left(\frac{m_k^2}{m_h^2}\right)$$

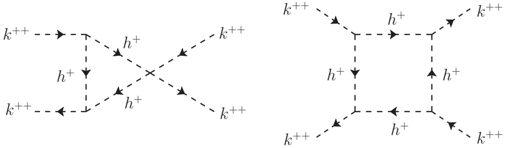
$$I(r) = -\int_0^1 dx \int_0^{1-x} dy \frac{1}{x + (r-1)y + y^2} \ln \frac{y(1-y)}{x + ry}$$

- Due to Fermi statistics, $f_{ij} = -f_{ji}$, whereas $h_{ij} = h_{ji}$.
- Since det $f = 0$, the lightest neutrino is massless.

Zee (1985)
Babu (1988)

μ value

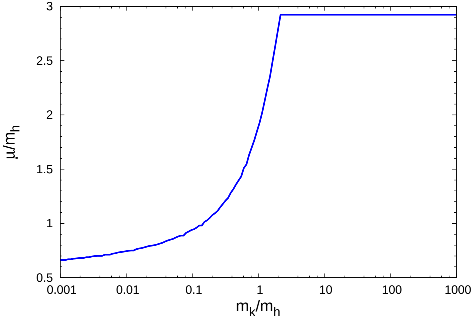
$$V_S \supset \frac{1}{2}\lambda_1\left(H^\dagger H\right)^2 + \frac{1}{2}\lambda_2\left(h^+h^-\right)^2 + \frac{1}{2}\lambda_3\left(k^{++}k^{--}\right)^2$$



$$\begin{aligned}
\lambda_2^{1-\text{loop}} &= -\frac{\mu^4}{\pi^2(m_k^2-m_h^2)^2}\left[-2+\frac{m_k^2+m_h^2}{m_k^2-m_h^2}\ln\frac{m_k^2}{m_h^2}\right] \\
&\quad +\frac{\lambda_2\mu^2}{4\pi^2(m_k^2-m_h^2)}\left[-1+\frac{m_k^2}{m_k^2-m_h^2}\ln\frac{m_k^2}{m_h^2}\right] \\
&\quad +\frac{\lambda_6\mu^2}{8\pi^2(m_k^2-m_h^2)}\left[1-\frac{m_h^2}{m_k^2-m_h^2}\ln\frac{m_k^2}{m_h^2}\right] \\
\lambda_3^{1-\text{loop}} &= \frac{\lambda_6\mu^2}{16\pi^2 m_h^2}-\frac{\mu^4}{6\pi^2 m_h^4}
\end{aligned}$$

The coupling μ is restricted by perturbativity and vacuum stability.

μ value



Neutrino mass matrix

$$M_\nu = \zeta \begin{pmatrix} \epsilon^2\omega_{\tau\tau} + 2\epsilon\epsilon'\omega_{\mu\tau} & \epsilon\omega_{\tau\tau} + \epsilon'\omega_{\mu\tau} & -\epsilon\omega_{\mu\tau} - \epsilon'\omega_{\mu\mu} \\ +\epsilon'^2\omega_{\mu\mu} & -\epsilon\epsilon'\omega_{e\tau} - \epsilon'^2\omega_{e\mu} & -\epsilon^2\omega_{e\tau} - \epsilon\epsilon'\omega_{e\mu} \\ & & \\ \epsilon\omega_{\tau\tau} + \epsilon'\omega_{\mu\tau} & \omega_{\tau\tau} - 2\epsilon'\omega_{e\tau} & -\omega_{\mu\tau} - \epsilon\omega_{e\tau} \\ -\epsilon\epsilon'\omega_{e\tau} - \epsilon'^2\omega_{e\mu} & +\epsilon'^2\omega_{ee} & +\epsilon'\omega_{e\mu} + \epsilon\epsilon'\omega_{ee} \\ & & \\ -\epsilon\omega_{\mu\tau} - \epsilon'\omega_{\mu\mu} & -\omega_{\mu\tau} - \epsilon\omega_{e\tau} & \omega_{\mu\mu} + 2\epsilon\omega_{e\mu} \\ -\epsilon^2\omega_{e\tau} - \epsilon\epsilon'\omega_{e\mu} & +\epsilon'\omega_{e\mu} + \epsilon\epsilon'\omega_{ee} & +\epsilon^2\omega_{ee} \end{pmatrix},$$

$$\zeta \quad \equiv \quad \frac{16\mu}{(16\pi^2)^2}\frac{f_{\mu\tau}^2}{m_h^2} I\left(\frac{m_k^2}{m_h^2}\right); \quad \omega_{ij} \equiv m_{\ell_i} h_{ij}^* m_{\ell_j}; \quad \epsilon \equiv f_{e\tau}/f_{\mu\tau}; \quad \epsilon' \equiv f_{e\mu}/f_{\mu\tau}.$$

Since $f \cdot (1, -\epsilon, \epsilon')^T = 0$, then $M_\nu \cdot (1, -\epsilon, \epsilon')^T = 0$. This leads to

$$\epsilon = \frac{(M_\nu)_{12}(M_\nu)_{33} - (M_\nu)_{13}(M_\nu)_{23}}{(M_\nu)_{22}(M_\nu)_{33} - (M_\nu)_{23}^2}; \quad \epsilon' = \frac{(M_\nu)_{12}(M_\nu)_{23} - (M_\nu)_{13}(M_\nu)_{22}}{(M_\nu)_{22}(M_\nu)_{33} - (M_\nu)_{23}^2}$$

Babu & Macesanu (2002)

ϵ and ϵ'

- Normal hierarchy

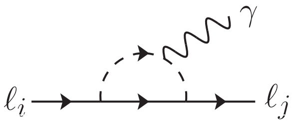
$$\frac{f_{e\tau}}{f_{\mu\tau}} = \tan\theta_{12}\frac{\cos\theta_{23}}{\cos\theta_{13}} + \tan\theta_{13}\sin\theta_{23}e^{-i\delta}$$
$$\frac{f_{e\mu}}{f_{\mu\tau}} = \tan\theta_{12}\frac{\sin\theta_{23}}{\cos\theta_{13}} - \tan\theta_{13}\cos\theta_{23}e^{-i\delta}$$

- Inverted hierarchy

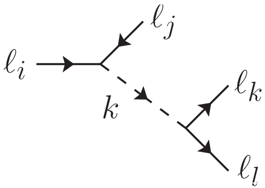
$$\frac{f_{e\tau}}{f_{\mu\tau}} = -\sin\theta_{23}\cot\theta_{13}e^{-i\delta}$$
$$\frac{f_{e\mu}}{f_{\mu\tau}} = \cos\theta_{23}\cot\theta_{13}e^{-i\delta}$$

Lepton flavor violation

- $\ell_i \to \ell_j \gamma$



- $\ell_i^- \to \ell_j^+ \ell_k^- \ell_l^-$



Neutrino mass matrix (simplified)

- Ignoring terms proportional to electron mass yields

$$M_\nu \simeq \zeta \begin{pmatrix} \epsilon^2\omega_{\tau\tau} + 2\epsilon\epsilon'\omega_{\mu\tau} + \epsilon'^2\omega_{\mu\mu} & \epsilon\omega_{\tau\tau} + \epsilon'\omega_{\mu\tau} & -\epsilon\omega_{\mu\tau} - \epsilon'\omega_{\mu\mu} \\ \epsilon\omega_{\tau\tau} + \epsilon'\omega_{\mu\tau} & \omega_{\tau\tau} & -\omega_{\mu\tau} \\ -\epsilon\omega_{\mu\tau} - \epsilon'\omega_{\mu\mu} & -\omega_{\mu\tau} & \omega_{\mu\mu} \end{pmatrix}$$

$$h_{\tau\tau} = h_{\mu\mu}\frac{m_\mu^2}{m_\tau^2}\frac{(M_\nu)_{22}}{(M_\nu)_{33}}; \quad h_{\mu\tau} = -h_{\mu\mu}\frac{m_\mu}{m_\tau}\frac{(M_\nu)_{23}}{(M_\nu)_{33}}$$

- From $\zeta\omega_{\mu\mu} = (M_\nu)_{33}$,

$$f_{\mu\tau}^2 = 16\pi^4\left[\frac{\mu}{m_h}\frac{m_k}{m_h}I\left(\frac{m_k^2}{m_h^2}\right)\right]^{-1}\frac{(M_\nu)_{33}}{m_\mu^2}\left(\frac{h_{\mu\mu}^*}{m_k}\right)^{-1}$$

- The smallest $f_{\mu\tau}$ will be obtained when $[(\mu/m_h)(m_k/m_h)I]^{-1}$ and $(h_{\mu\mu}/m_k)^{-1}$ are minimum.
- The smallest m_h can be determined with the help of BR$(\mu \to e\gamma)$:

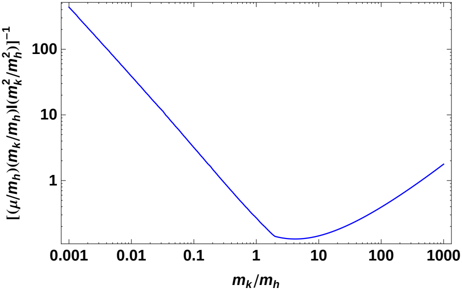
$$\frac{f_{\mu\tau}}{m_h} < \frac{3.5}{\sqrt{|\epsilon|}} \times 10^{-5}\ \text{GeV}^{-1}$$

- $h_{\mu\mu}/m_k$ is bounded by $\tau^- \to \mu^+\mu^-\mu^-$ and $\tau^- \to e^+\mu^-\mu^-$ processes:

$$\frac{|h_{\mu\mu}h_{\mu\tau}|}{m_k^2} < 8.1 \times 10^{-9}\ \text{GeV}^{-2}; \quad \frac{|h_{\mu\mu}h_{e\tau}|}{m_k^2} < 7.3 \times 10^{-9}\ \text{GeV}^{-2}$$

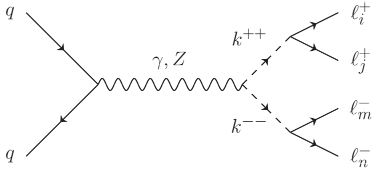
- $h_{e\tau}$ does not appear in neutrino mass matrix, while $h_{\mu\tau}$ is fixed by neutrino mass.
- In the most relaxed situation, the upper bound of $|h_{\mu\mu}|/m_k$ is obtained from $\tau^- \to \mu^+\mu^-\mu^-$.

$$m_h > (3760\ \text{GeV}) \left[\frac{\mu}{m_h}\frac{m_k}{m_h} I\left(\frac{m_k^2}{m_h^2}\right)\right]^{-1/2} \left[|\epsilon|^2 \left|\frac{(M_\nu)_{23}}{\text{eV}}\right| \left|\frac{(M_\nu)_{33}}{\text{eV}}\right| \left(\frac{\text{GeV}}{m_\mu}\right)^3 \left(\frac{\text{GeV}}{m_\tau}\right)\right]^{1/4}$$



- By imposing the perturbativity bound on μ, $[(\mu/m_h)(m_k/m_h)I(m_k^2/m_h^2)]^{-1/2}$ will be minimum when $m_k \simeq 4.1 m_h$.
- $m_h > 583$ GeV in NH.
  $m_h > 875$ GeV in IH.
- LEP limit: ~ 100 GeV.

$k^{\pm\pm}$ mass



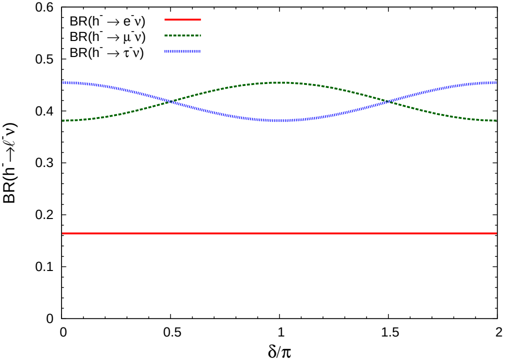
ATLAS and CMS limits: $m_k > 400$ GeV, assuming 100% decay into muons.

Decay rates

- The branching ratios of $h \to \ell\nu$ depend on ϵ and ϵ':

$$\mathrm{BR}(h \to e\nu) : \mathrm{BR}(h \to \mu\nu) : \mathrm{BR}(h \to \tau\nu) = |\epsilon|^2 + |\epsilon'|^2 : 1 + |\epsilon'|^2 : 1 + |\epsilon|^2$$

- In normal hierarchy, $|\epsilon|$ and $|\epsilon'|$ are δ-dependent:



- In IH hierarchy, $|\epsilon|$ and $|\epsilon'|$ are δ-independent:

$$\mathrm{BR}(h^- \to e^-\nu) \simeq 0.49; \quad \mathrm{BR}(h^- \to \mu^-\nu) \simeq 0.26; \quad \mathrm{BR}(h^- \to \tau^-\nu) \simeq 0.26.$$

- Measuring these ratios can probe the neutrino mass hierarchy.

Aristizabal-Sierra & Hirsch (2006)

Boundedness of scalar potential

- With 125 GeV Higgs mass, the Higgs self-quartic coupling will turn negative around 10^{10} GeV.
- In this model,

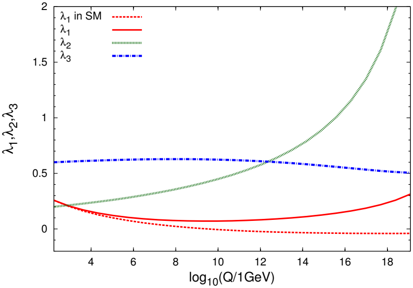
$$V_S = \frac{1}{2}\boldsymbol{x}^T \cdot \boldsymbol{\lambda} \cdot \boldsymbol{x}; \qquad \boldsymbol{\lambda} = \begin{pmatrix} \lambda_1 & \lambda_4 & \lambda_5 \\ \lambda_4 & \lambda_2 & \lambda_6 \\ \lambda_5 & \lambda_6 & \lambda_3 \end{pmatrix}; \qquad \boldsymbol{x}^T \equiv \left(|H|^2, |h|^2, |k|^2\right)$$

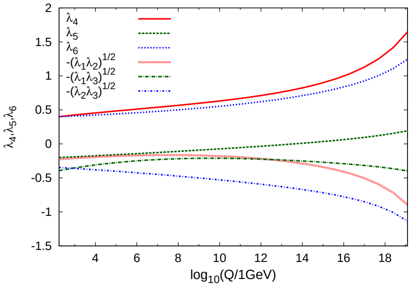
- The boundedness will be obeyed if matrix $\boldsymbol{\lambda}$ is co-positive, i.e.:

$$\begin{aligned} &(1) \quad \boldsymbol{\lambda}_{ii} \geq 0, \\ &(2) \quad \lambda_4 \geq -\sqrt{\lambda_1\lambda_2}; \quad \lambda_5 \geq -\sqrt{\lambda_1\lambda_3}; \quad \lambda_6 \geq -\sqrt{\lambda_2\lambda_3}, \\ &(3) \quad \lambda_4\sqrt{\lambda_3} + \lambda_6\sqrt{\lambda_1} + \lambda_5\sqrt{\lambda_2} + \sqrt{\lambda_1\lambda_2\lambda_3} \geq 0 \quad \text{or} \quad \det \boldsymbol{\lambda} \geq 0. \end{aligned}$$

Hadeler (1983)
Klimenko (1985)

Boundedness of scalar potential





Conclusions

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- The phenomenology of new particles can be correlated to the neutrino mass hierarchy.
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Thank you