Neutrino Mass Models

Hundreds of models

A handful of ideas

SO(10) Grand Unification

Unifies all members of a family into a single 16-plet

$u_r : \{-++\ +-\}$	$d_r : \{-++\ -+\}$	$u^c_r : \{+--\ ++\}$	$d^c_r : \{+--\ --\}$
$u_b : \{+-+\ +-\}$	$d_b : \{+-+\ -+\}$	$u^c_b : \{-+-\ ++\}$	$d^c_b : \{-+-\ --\}$
$u_g : \{++-\ +-\}$	$d_g : \{++-\ -+\}$	$u^c_g : \{--+\ ++\}$	$d^c_g : \{--+\ --\}$
$\nu : \{---\ +-\}$	$e : \{---\ -+\}$	$\nu^c : \{+++\ ++\}$	$e^c : \{+++\ --\}$

Predicts right-handed neutrino and thus neutrino masses

Frist 3 spins refer to color, last 2 are weak spins

$$Y = \frac{1}{3}\Sigma(C) - \frac{1}{2}\Sigma(W)$$

Eg: $Y(e^c) = \frac{1}{3}(3) - \frac{1}{2}(-2) = 2$

Minimal SO(10) Model

$$\mathcal{L}_{\mathsf{Yukawa}} = Y_{10}\, \mathbf{16}\, \mathbf{16}\, \mathbf{10}_H + Y_{126}\, \mathbf{16}\, \mathbf{16}\, \overline{\mathbf{126}}_H$$

Two Yukawa matrices determine all fermion masses and mixings, including the neutrinos

$$\begin{aligned} M_u &= \kappa_u Y_{10} + \kappa'_u Y_{126} \\ M_d &= \kappa_d Y_{10} + \kappa'_d Y_{126} \\ M_\nu^D &= \kappa_u Y_{10} - 3\kappa'_u Y_{126} \\ M_l &= \kappa_d Y_{10} - 3\kappa'_d Y_{126} \end{aligned}$$

$$\begin{aligned} M_{\nu R} &= \langle \Delta_R \rangle Y_{126} \\ M_{\nu L} &= \langle \Delta_L \rangle Y_{126} \end{aligned}$$

Model has only 12 real parameters plus 7 phases

Babu, Mohapatra (1993)
Fukuyama, Okada (2002)
Bajc, Melfo, Senjanovic, Vissani (2004)
Fukuyama, Ilakovac, Kikuchi, Meljanac, Okada (2004)
Aulakh et al (2004)
Bertolini, Frigerio, Malinsky (2004)
Babu, Macesanu (2005)
Bertolini, Malinsky, Schwetz (2006)
Dutta, Mimura, Mohapatra (2007)
Bajc, Dorsner, Nemevsek (2009)
Joshipura, Patel (2012)
Dueck, Rodejohann (2013)
Altarelli, Meloni (2013)
Meloni, Ohlsson, Riad (2014)

Specific Example: Type I Seesaw

Input at the GUT scale:

$$\begin{aligned} m_u &= 0.0006745 & m_c &= 0.3308 & m_t &= 97.335 \\ m_d &= 0.0009726 & m_s &= 0.02167 & m_b &= 1.1475 \\ m_e &= 0.000344 & m_\mu &= 0.0726 & m_\tau &= 1.350 \text{ GeV} \\ s_{12} &= 0.2248 & s_{23} &= 0.03278 & s_{13} &= 0.00216 \\ & & \delta_{CKM} &= 1.193\ . \end{aligned}$$

Output for neutrinos:

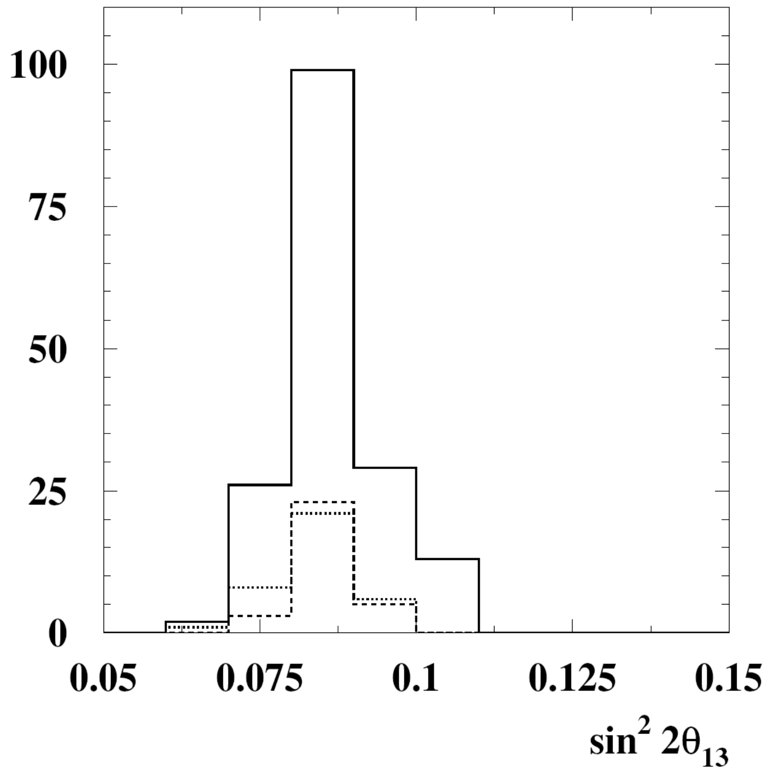
$$\sin^2\theta_{12} \simeq 0.27, \quad \sin^2 2\theta_{23} \simeq 0.90, \quad \sin^2 2\theta_{13} \simeq 0.08$$

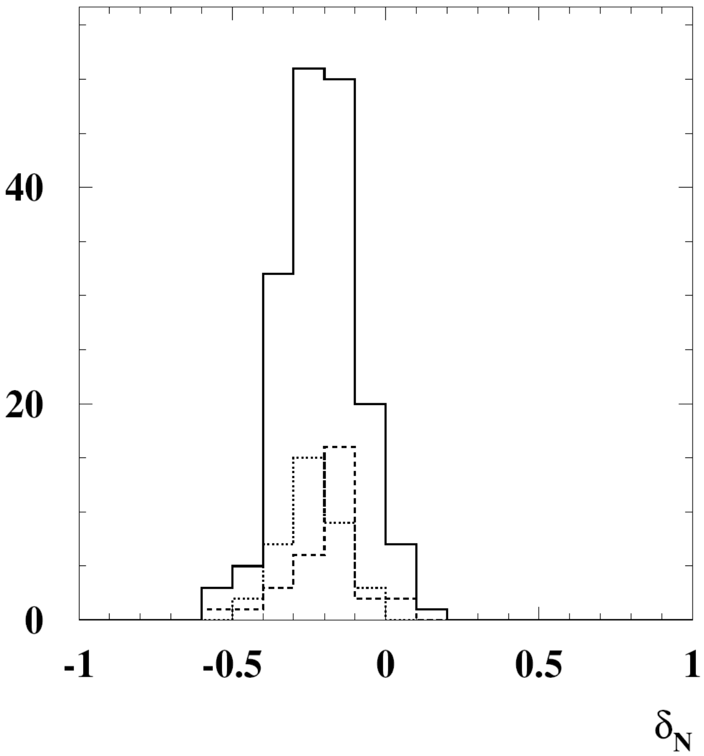
$$m_i = \{0.0021e^{0.11i},\ 0.0098e^{-3.08i},\ 0.048\} \text{ eV}$$

$$\Delta m^2_{23}/\Delta m^2_{12} \simeq 24$$

C. Macesanu, KSB (2005)

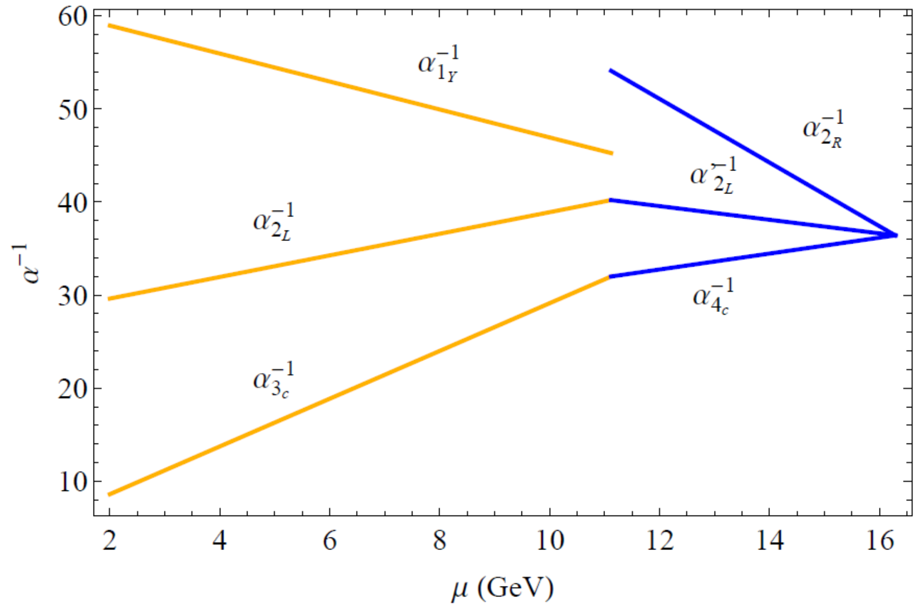
Theta(13) in Minimal SO(10)





$\sin^2 2\theta_{13}$ and CP violating phase δ_N

$\sin^2 2\theta_{13} = 0.089 \pm 0.010 \pm 0.005$ Daya Bay (2012)



obs.	*fit*	*pull*	*obs.*	*fit*	*pull*
m_u(MeV)	0.49	0.03	$\|V_{us}\|$	0.225	0.038
m_d(MeV)	0.78	0.75	$\|V_{cb}\|$	0.042	−0.208
m_s(MeV)	32.5	−1.50	$\|V_{ub}\|$	0.0038	−0.659
m_c(GeV)	0.287	−1.49	J	3.1×10^{-5}	0.589
m_b(GeV)	1.11	−2.77	$\sin^2\theta^l_{12}$	0.318	0.611
m_t(GeV)	71.4	0.70	$\sin^2\theta^l_{23}$	0.353	−1.548
r	0.031	0.10	$\sin^2\theta^l_{13}$	0.0222	−0.758
η_B	5.699×10^{-10}	−0.001			

Altarelli, Meloni (2013)

Effective $\Delta L = 2$ Operators for Neutrino Mass

Standard seesaw operator ($d = 5$):

$$\mathcal{O}_1 = L^i L^j H^k H^l \epsilon_{ik} \epsilon_{jl}$$

Weinberg (1979)

Dimension–7 operators:

$$\mathcal{O}_2 = L^i L^j L^k e^c H^l \epsilon_{ij} \epsilon_{kl}$$

Leung, KSB (2003)

$$\mathcal{O}_3^{(a)} = L^i L^j Q^k d^c H^l \epsilon_{ij} \epsilon_{kl}$$

$$\mathcal{O}_3^{(b)} = L^i L^j Q^k d^c H^l \epsilon_{ik} \epsilon_{jl}$$

$$\mathcal{O}_4^{(a)} = L^i L^j \bar{Q}_i \bar{u^c} H^k \epsilon_{jk}$$

$$\mathcal{O}_4^{(b)} = L^i L^j \bar{Q}_k \bar{u^c} H^k \epsilon_{ij}$$

$$\mathcal{O}_8 = L^i \bar{e^c} \bar{u^c} d^c H^j \epsilon_{ij}$$

De Gouvea, Jenkins (2008)
Bonnet, Herrnandez, Ota, Winter (2009)
Angel, Rodd, Volkas (2012)
Bonnet, Hirsch, Ota, Winter (2013)
Cai, Clarke, Schmidt, Volkas (2014)

Dimension–9 operators:

$$\mathcal{O}_9 = L^i L^j L^k e^c L^l e^c \epsilon_{ij} \epsilon_{kl}$$

$$\mathcal{O}_{10} = L^i L^j L^k e^c Q^l d^c \epsilon_{ij} \epsilon_{kl}$$

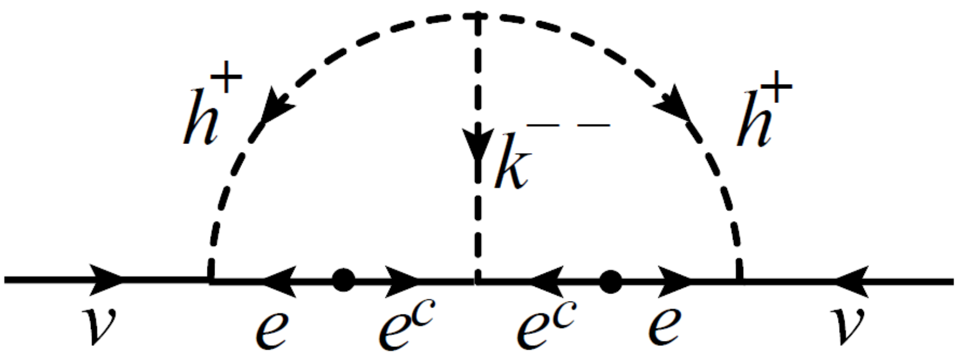
....

Two–loop neutrino mass model

$$\mathcal{L} = f_{ij} L_i^a L_j^b h^+ \epsilon_{ab} + g_{ij} e_i^c e_j^c k^{--} + \mu h^+ h^+ k^{--} + \text{h.c.}$$

$$\Downarrow$$

$$\mathcal{O}_9 = L^i L^j L^k e^c L^l e^c \epsilon_{ij} \epsilon_{kl}$$



Zee (1985)
KSB (1988)

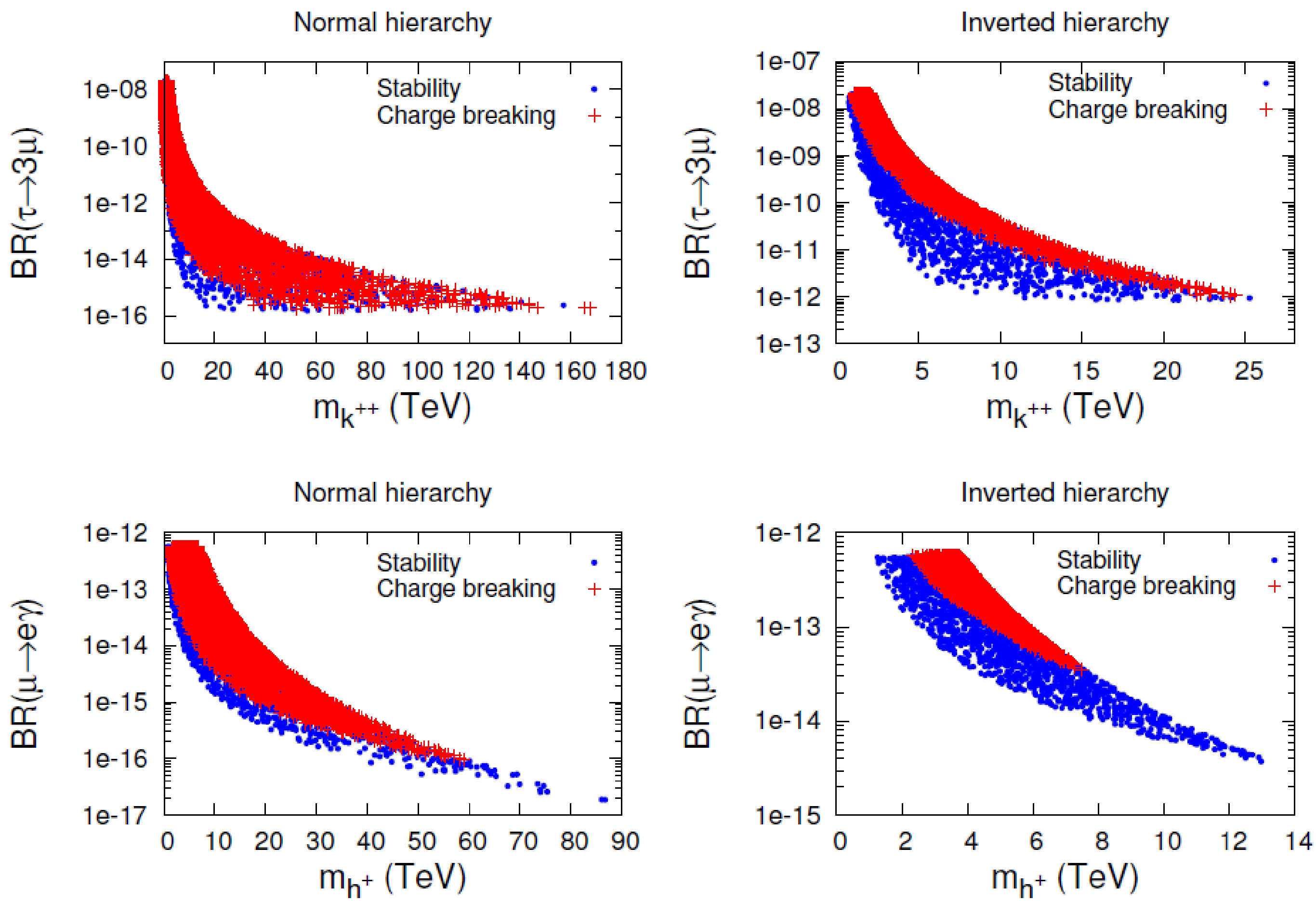
Fits to neutrino masses and mixing angles $\Rightarrow$

Lower limits on branching ratios for $\mu \to 3e$, $\mu - e$ conversion in nuclei, as well as $\mu \to e\gamma$ and $\tau \to 3\mu$ follow

K.S. Babu, J. Julio (2013)
D. Schmitz, T.Schwetz, H. Zhang (2014)
J. Herrero-Garcia, M. Nebot, N. Rius, A. Santamaria (2014)

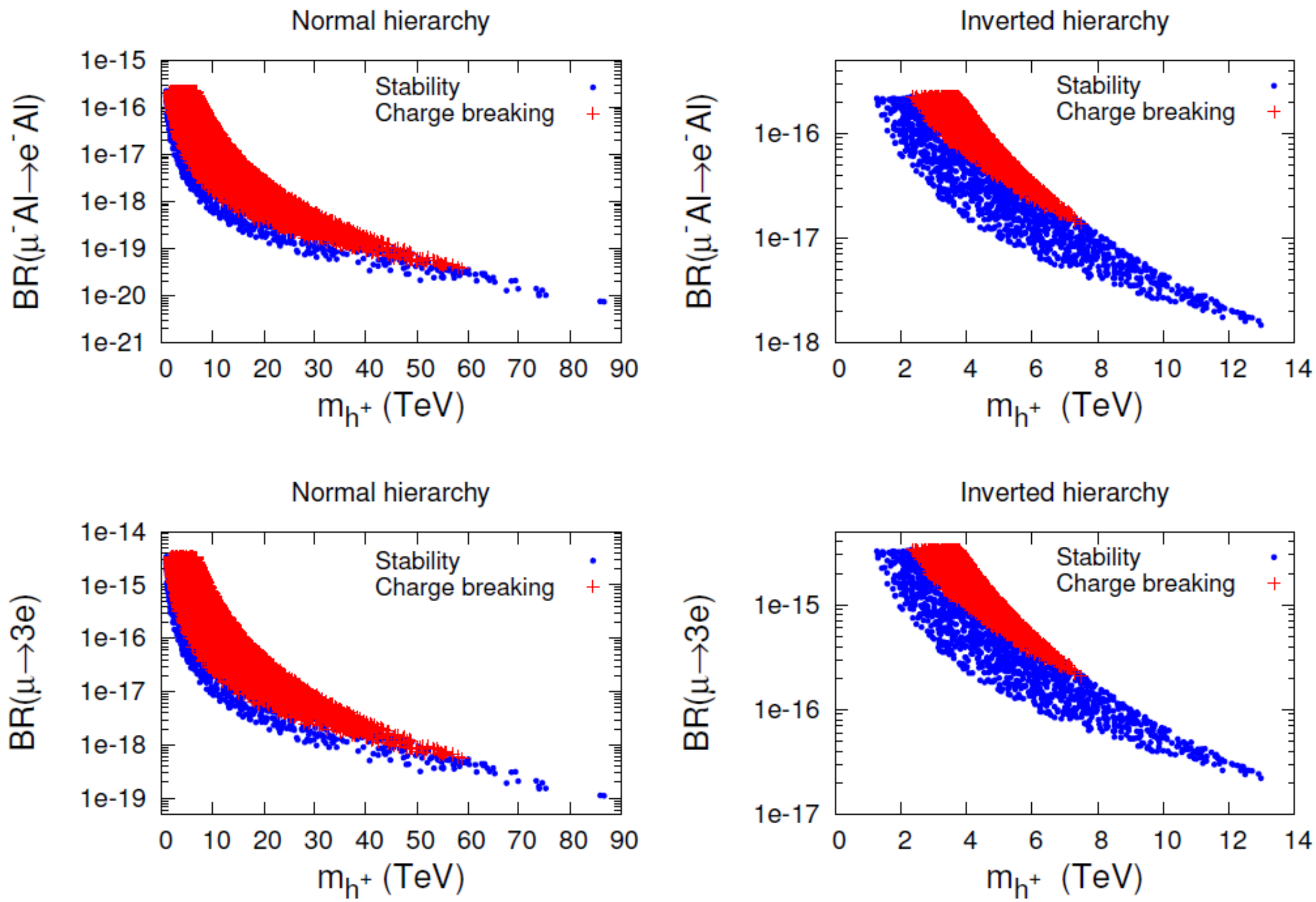
M. Nebot, J. Oliver, D. Paolo, A. Santamaria (2008)
D. Sierra, M. Hirsch (2006)
K.S. Babu, C. Macesanu (2005)

LFV in Radiative Neutrino Mass Model



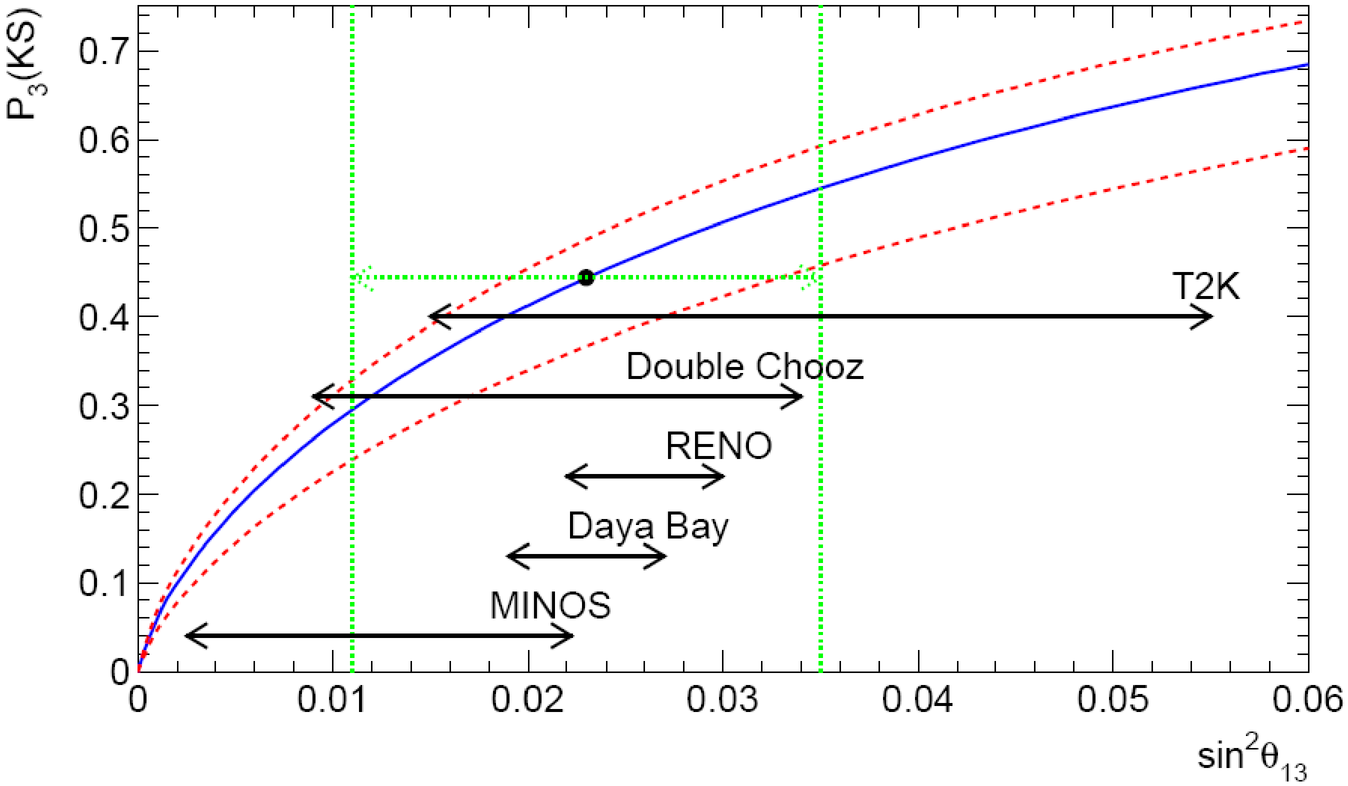
K.S. Babu, J. Julio (2013)

LFV in Radiative Neutrino Mass Model (cont.)



Backup Slides

Neutrino Mass Anarchy



De Gouvea, Murayama (2012)

Lepton mixing matrix described by random draw of numbers in a unitary matrix

Texture zeros for neutrinos

$$A_1 : \begin{pmatrix} 0 & 0 & X \\ 0 & X & X \\ X & X & X \end{pmatrix} \qquad A_2 : \begin{pmatrix} 0 & X & 0 \\ X & X & X \\ 0 & X & X \end{pmatrix}$$

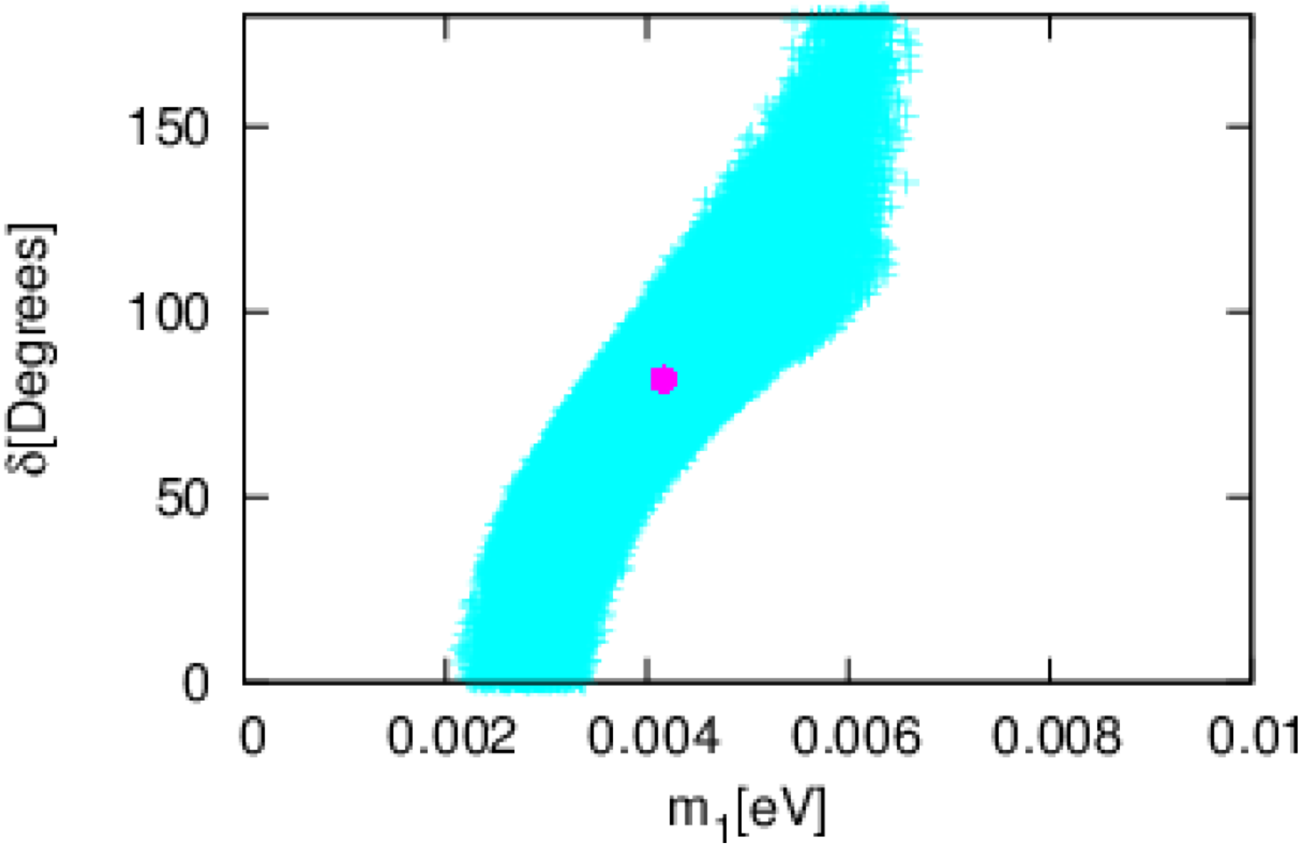
$$B_1 : \begin{pmatrix} X & X & 0 \\ X & 0 & X \\ 0 & X & X \end{pmatrix} \qquad B_2 : \begin{pmatrix} X & 0 & X \\ 0 & X & X \\ X & X & 0 \end{pmatrix}$$

$$B_3 : \begin{pmatrix} X & 0 & X \\ 0 & 0 & X \\ X & X & X \end{pmatrix} \qquad B_4 : \begin{pmatrix} X & X & 0 \\ X & X & X \\ 0 & X & 0 \end{pmatrix}$$

$$C : \begin{pmatrix} X & X & X \\ X & 0 & X \\ X & X & 0 \end{pmatrix}$$

Frampton, Glashow, Marfatia (2002)
Xing (2002)
Merle, Rodejohann (2006)
Goswami et. al (2006)

Predictions for Model A1



K. Babu, Z. Devi, S. Goswami (2014)
J. Liao, D. Marfatia, K. Whisnant (2014)

Tri-bimaximal Neutrino Mixing

$$U = \begin{pmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix} \cdot P$$

Harrison, Perkins, Scott (2002)

Neutrino mixing angles are geometrical!

Exact symmetry excluded by Daya Bay and RENO data at 5 σ

A variety of models based on A_4 and other symmetries

Ma, Rajasekaran (2001)
Xing (2002)
Babu, Ma, Valle (2003)
Altarelli, Feruglio (2005)
He, Keum, Volkas (2006)
Mohapatra, Nasri, Yu (2006)
King, Malinsky (2007)
Verzielas, King, Ross (2007)
Chen, Mahanthappa (2007)
Honda, Tanimoto (2008)
Everett, Stuart (2009)
Grimus, Lavoura, Ludl (2009)

There is generically a vacuum alignment problem:

A_4 needs two triplet Higgs: $\langle\chi\rangle = (1,1,1)$ $\langle\phi\rangle = (0,1,0)$