Massive neutrinos in a grounds-up approach

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(Atwood, Bar-Shalom + A. S.)

OUTLINE

- **Introduction**
- **ν-oscillations – a brief reminder**
- **The 2 Higgs doublet model "for the top" (t2HDM)**
- **The 3g2HDM: our leptonic extension to the t2HDM**
- **ν-oscillations in the 3g2HDM**
- **Leptogenesis in the 3g2HDM**
- **Summary & outlook**

Introduction

- 2 monumental discoveries of the 90's:

$$\mathbf{m_t \sim m_{Gold} >> m_{u,d,c,s,b}}$$
$$\mathbf{m_\nu \neq 0 \ << eV}$$

Perhaps an important hint from the seesaw connection:

$$\mathbf{m_\nu \sim \frac{m_t^2}{\Lambda_{GUT}}}$$

Based on the seesaw mechanism:

$$\mathbf{m_\nu = m_{\nu_D} M_{\nu_R}^{-1} m_{\nu_D}^T}$$ **, a strong hint for**

✓ **Large Dirac ν-mass :** $\mathbf{m_{\nu_D} \sim m_t}$

✓ **Super-heavy Majorana neutrinos :** $\mathbf{M_{\nu_R} \sim m_{GUT}}$

Introduction

The goal of this work

to suggest a natural relation between the large m_t , the observed ν-oscilations and the heavy Majorana mass scale in a two Higgs doublet model, based on a gorunds-up approach

⇓

the 2HDM "for the 3rd generation" (3g2HDM)

(same status for the top-quark and the 3rd generation rh-ν)

ν-oscillations (evidence)

- Solar effect: $\nu_e \rightarrow \nu_\mu$ or $\nu_e \rightarrow \nu_\tau$
- Atmospheric effect: ν_μ - disappearance
- Reactor/accelerator effects:
  - KamLAND: reactor $\bar{\nu}_e$ – disappearance (L~180 km)
  - K2K: accelerator ν_μ - disappearance (L~250 km)

- **LSND effect: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ (not compatible with above in the 3ν-oscillation picture - to be confirmed by MiniBooNE)**

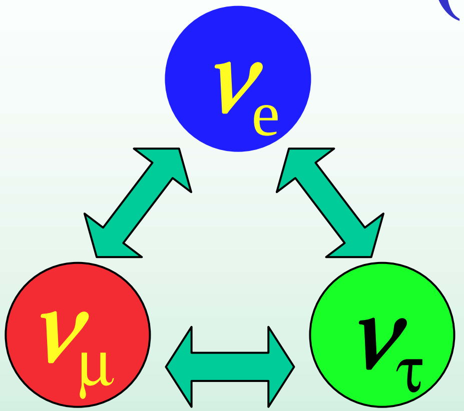
2 oscillation "periods" emerging:

– $\Delta m^2_{sol} \sim 8.2 \cdot 10^{-5}$ [eV]^2, $\theta_{sol} \sim 32^o$ (solar + KamLAND)

– $\Delta m^2_{atm} \sim 2.2 \cdot 10^{-3}$ [eV]^2, $\theta_{atm} \sim 45^o$ (atmospheric + K2K)

$\Delta m^2_{LSND} > 0.1$ [eV]^2

ν-oscillations
(the standard parametrization)



3 mixing angles; $\theta_{12} \sim \theta_{sol}$, $\theta_{23} \sim \theta_{atm}$, θ_{13}

3 mass diff.: $\Delta m^2_{13} \sim \Delta m^2_{23} \approx \Delta m^2_{atm} >> \Delta m^2_{12} \approx \Delta m^2_{sol}$

CP-violating phase δ

PMNS-matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Atmospheric ν
K2K

Reactor ν
Solar ν

$c_{ij} = \cos\theta_{ij}$
$s_{ij} = \sin\theta_{ij}$

upcoming challenge

Present limit: $\sin^2\theta_{13} < 0.041$ *(CHOOZ)*

The Two Higgs doublet Model

"for the top-quark" (t2HDM) Das&Kao PLB1996

- Basic idea: large top mass effectively "explained" by an inherent large **$\tan\beta \equiv v_t/v_q$:**

ϕ_t couples only to the top-quark
ϕ_q couples to all other quarks

Working assumption: $\tan\beta >> 1$

$$\mathcal{L}_Y^{\text{quark}} = -Y^d \overline{Q}_L \phi_q d_R - Y_1^u \overline{Q}_L \tilde{\phi}_q \begin{matrix} u_R \\ c_R \end{matrix} - Y_2^u \overline{Q}_L \tilde{\phi}_t t_R$$

A minimal low energy effective theory which captures the dominant features of phenomenology, and models some underlying dynamics of EW symmetry breaking at distances much shorter than the EW- scale

New&rich phenomenology of the t2HDM

- **Enhanced H^+cb Yukawa: Γ_{H^+cb} α V_{tb} (not V_{cb}!)**
- **Enhanced H^0cc Yukawa: Γ_{H^0cc} α $m_c \times \tan\beta$ (not $m_c/\tan\beta$!)**
- **New tree-level FC H^0tc & H^0tu couplings (no FCNC in d-quark sector!)**

implications for:

CPV in B-physics (Kiers,Soni,Wu: PRD1999, PRD2000)

FC Z-decays (Atwood,SBS,Eilam,Soni: PRD2002)

b-jet & c-jet physics in hadron colliders

(Atwood,SBS,Eilam,Soni: PRD2004)

The Two Higgs doublet Model "for the 3rd generation" (3g2HDM)

- **Extension of the t2HDM Yukawa texture to the leptonic sector:**

$$\mathcal{L}_Y = -Y^d \overline{Q}_L \phi_q d_R - Y_1^u \overline{Q}_L \tilde{\phi}_q \begin{matrix} u_R \\ c_R \end{matrix} - Y_2^u \overline{Q}_L \tilde{\phi}_t t_R$$

$$- Y^e \overline{L}_L \phi_q e_R - Y_1^\nu \overline{L}_L \tilde{\phi}_q \begin{matrix} N_1 \\ N_2 \end{matrix} - Y_2^\nu \overline{L}_L \tilde{\phi}_t N_3$$

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_Y + \mathrm{M}_N^{ij} \mathrm{N}_i \mathrm{N}_j / 2$$

N = right-handed Majorana neutrinos

3g2HDM (cont.)

Our Anzats : **Quark-lepton similarity:** $Y_1^{\nu} \approx Y_1^{u} \equiv Y_1$ & $Y_2^{\nu} \approx Y_2^{u} \equiv Y_2$

$$m_{\nu_D} \approx \underset{\Downarrow}{\overset{L_Y}{}} m_u = \frac{v_q}{\sqrt{2}} \begin{pmatrix} a & b & 0 \\ a & b & ct_\beta \\ 0 & \delta b & ct_\beta \end{pmatrix}$$

$$\left\{ \begin{matrix} m_u \sim a \cdot v_q & m_c \sim b \cdot v_q & m_t \sim c \cdot v_q \cdot t_\beta \\ a \sim O(10^{-3}) & b \sim O(10^{-1}) & c \sim O(1) \end{matrix} \right\}$$

$t_\beta = \tan\beta \sim O(10)$ **key parameter**

1. **Simplifications (no loss of generality):**
   - Similar Yukawa couplings within each generation **($\delta \sim O(1)$)**
   - **$(Y_1)_{31}=0$**
2. **$(Y_2)_{13}=0$: avoid fine-tuning for ν-oscillation, e.g.,**
   - ✓ **$(Y_1)_{31}$, $(Y_2)_{13} << (Y_{1,2})_{ij \neq 13,31}$** from vanishingly small overlap of corresponding N & L wave-functions in ED-models **(Raidal&Strumia PLB2003)**
   - ✓ **$(Y_2)_{13}=0$** from some flavor symmetry of the underlying short-distance theory: any texture-zero can be enforced by means of an Abelian symmetry with an appropriate scalar sector **(Grimus et al. EPJC2004)**
   - ✓ **$(Y_1)_{31}$, $(Y_2)_{13} \rightarrow 0$** dictated from an underlying SO(10) GUT relation ($m_{\nu_D} \approx m_u$) along with the empirically known up-quark mass matrix **(Buchmuller&Wyler PLB2001)**

ν-oscillations in the 3g2HDM

Seesaw in the basis of a diagonal M_N :

$$\mathsf{L} = \mathbf{m}_{\nu_D} \bar{\nu}_L N + M_N^{ij} N_i N_j / 2$$

$$\mathbf{m}_{\nu_D} = \frac{\mathbf{v}_q}{\sqrt{2}} \begin{pmatrix} \mathbf{a} & \mathbf{b} & \mathbf{0} \\ \mathbf{a} & \mathbf{b} & \mathbf{c}t_\beta \\ \mathbf{0} & \delta\mathbf{b} & \mathbf{c}t_\beta \end{pmatrix}$$

$$\mathbf{M}_N = M \cdot \begin{pmatrix} \varepsilon_{M1} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \varepsilon_{M2} & 0 \\ \mathbf{0} & \mathbf{0} & \varepsilon_{M3} \end{pmatrix}$$

$$\mathbf{m}_\nu = -\mathbf{m}_{\nu_D} \mathbf{M}_N^{-1} \mathbf{m}_{\nu_D}^T = \mathbf{m}_\nu^0 \begin{pmatrix} \varepsilon & \varepsilon & \delta\bar{\varepsilon} \\ \cdot & \varepsilon + \omega & \delta\bar{\varepsilon} + \omega \\ \cdot & \cdot & \delta^2 \bar{\varepsilon} + \omega \end{pmatrix}, \quad \text{With:}$$

$$\mathbf{m}_\nu^0 \equiv \frac{\mathbf{v}_q^2}{2\mathbf{M}}$$

$$\varepsilon \equiv \frac{\mathbf{a}^2}{\varepsilon_{M1}} + \frac{\mathbf{b}^2}{\varepsilon_{M2}} \quad , \quad \bar{\varepsilon} \equiv \varepsilon - \frac{\mathbf{a}^2}{\varepsilon_{M1}}$$

$$\omega \equiv \frac{\mathbf{c}^2 \mathbf{t}_\beta^2}{\varepsilon_{M3}}$$

ν-oscillations in the 3g2HDM (cont.)

Masses and mix. Angles:

$$\tan 2\theta_{23} \sim \frac{2r\omega}{\varepsilon(\delta^2 - r)} , \; \tan 2\theta_{12} \sim 2\frac{g}{f} , \; \theta_{13} \sim \frac{\varepsilon(\delta + r)}{2^{3/2} r\omega}$$

$$\mathbf{m}_\nu^0 \equiv \frac{\mathbf{v}_q^2}{2\mathbf{M}}$$

$$\varepsilon \equiv \frac{\mathbf{a}^2}{\varepsilon_{\mathbf{M1}}} + \frac{\mathbf{b}^2}{\varepsilon_{\mathbf{M2}}} \; , \; \bar{\varepsilon} \equiv \varepsilon - \frac{\mathbf{a}^2}{\varepsilon_{\mathbf{M1}}}$$

$$\omega \equiv \frac{\mathbf{c}^2 \mathbf{t}_\beta^2}{\varepsilon_{\mathbf{M3}}}$$

$$m_1 \sim \varepsilon m_\nu^0 \left(1 - g \sin 2\theta_{12} + f \sin^2 \theta_{12}\right)$$

$$m_2 \sim \varepsilon m_\nu^0 \left(1 + g \sin 2\theta_{12} + f \cos^2 \theta_{12}\right)$$

$$m_3 \sim 2\omega m_\nu^0$$

$$\left[define: \;\; r \equiv \frac{\varepsilon}{\bar{\varepsilon}} \; , \; g \equiv \frac{|r - \delta|}{\sqrt{2r}} \; , \; f \equiv \frac{\delta^2 - 2\delta - r}{2r} \right]$$

ν-oscillations in the 3g2HDM (cont.)

Key relations/predictions of the 3g2HDM with the quark-lepton similarity anzats

1) The triple ν_{light}- $\nu_h(\Lambda_{GUT})$-top seesaw relation:

$$\omega = \frac{c^2 t_\beta^2}{\varepsilon_{M3}}$$

$$m_\nu^0 = \frac{v_q^2}{2M}$$

$$m_t \approx c\frac{v_t}{\sqrt{2}} \approx c t_\beta \frac{v_q}{\sqrt{2}}$$

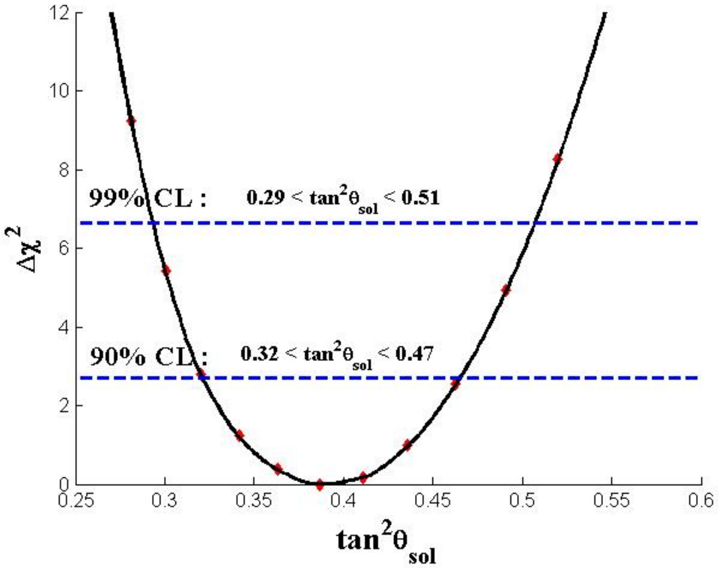
$$\Rightarrow \quad m_3 \sim 2\omega m_\nu^0 \sim 2\frac{m_t^2}{M_{N_3}}$$

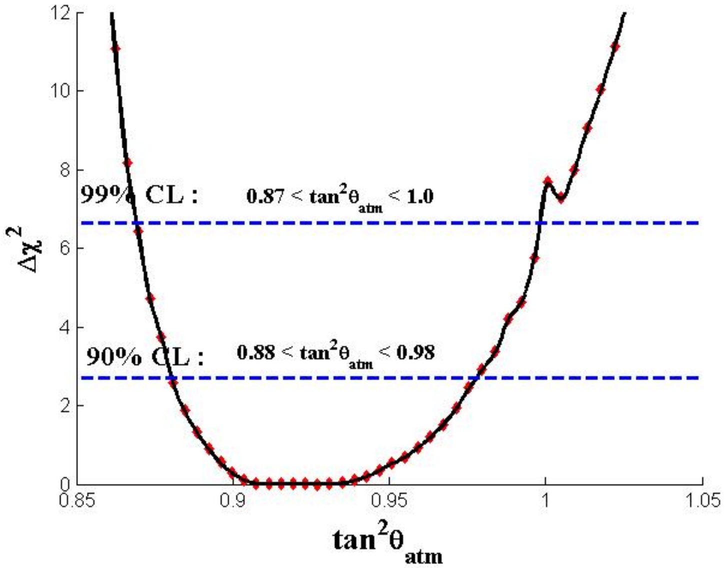
2) ν_h mass-scale with normal hierarchy ($m_3 >> m_2 >> m_1$):

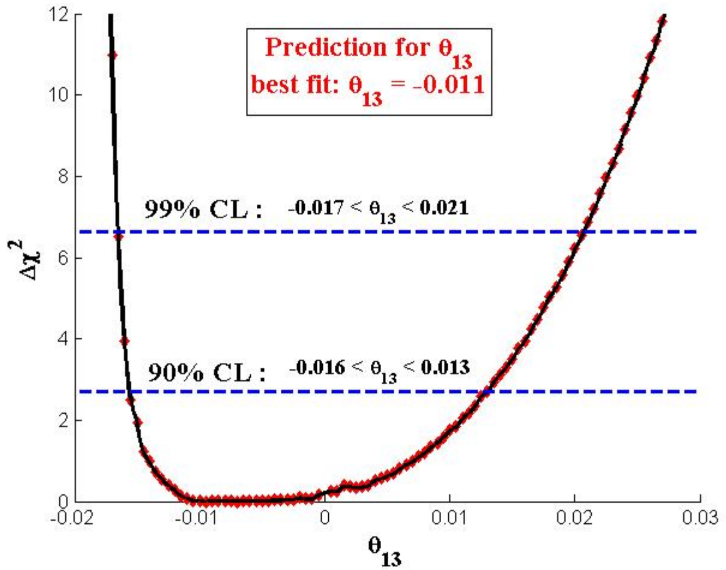
$$m_3 \sim \sqrt{\Delta m_{atm}^2} \quad \xrightarrow{\text{heaviest } \nu_h} \quad M_{N_3} \sim 2\frac{m_t^2}{\sqrt{\Delta m_{atm}^2}} \sim 10^{15}\ GeV$$

$$m_2 \sim \sqrt{\Delta m_{sol}^2} \quad \xrightarrow{\nu_h \text{ mass-scale}} \quad M \sim \frac{v_q^2}{2m_\nu^0} \xrightarrow{m_\nu^0 \sim \sqrt{\Delta m_{sol}^2}/2} \frac{v_q^2}{\sqrt{\Delta m_{sol}^2}} \xrightarrow{v_q \sim 10\,GeV} 10^{13}\ GeV$$

Numbers for ν-oscillations: mixing angles



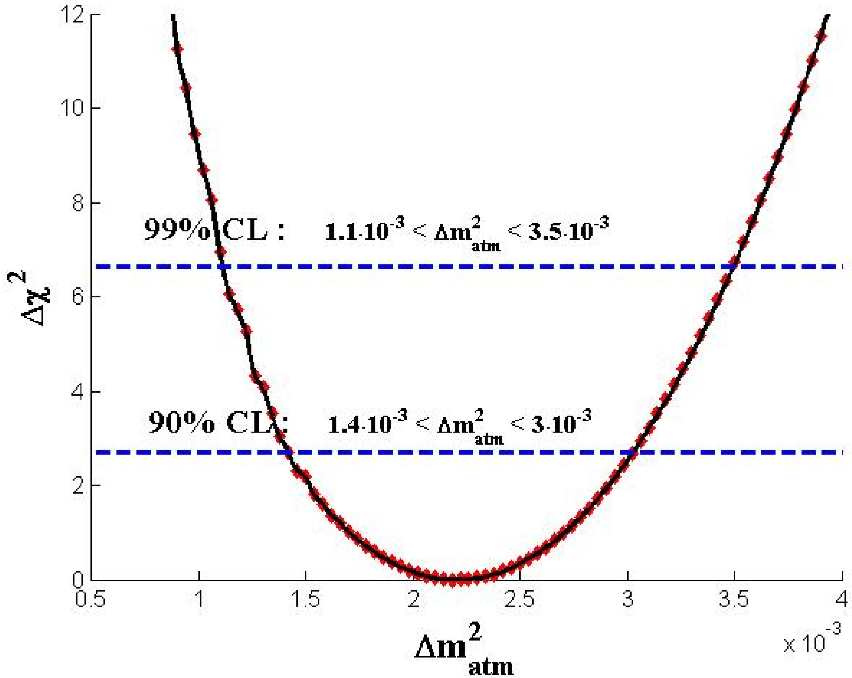


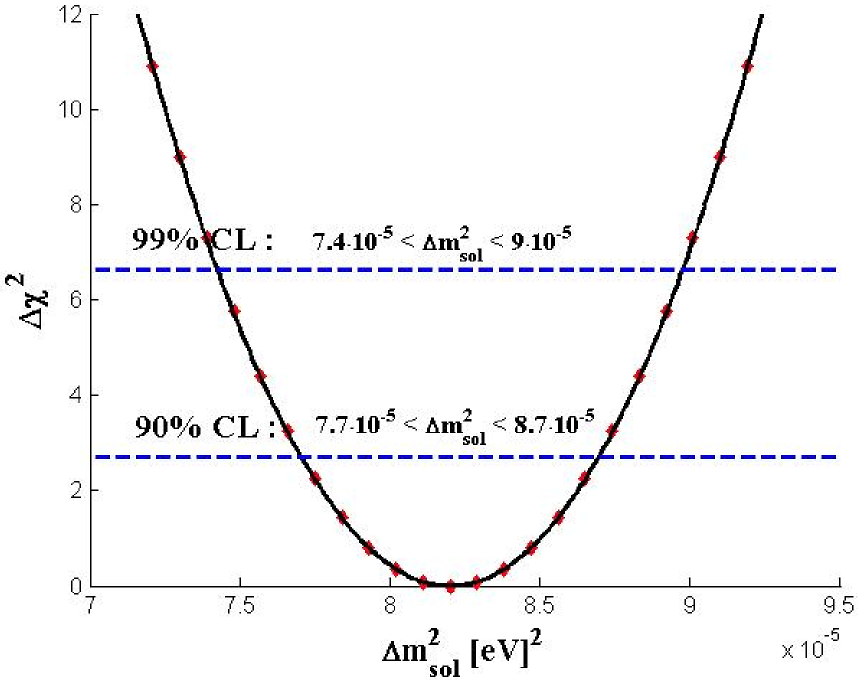


At 3σ

3g2HDM	Measured e.g. Gonzalez-Garcia, hep-ph/0410030
$28.0^0 < \theta_{sol} < 36.0^0$	$27.9^0 < \theta_{sol} < 37.8^0$
$42.9^0 < \theta_{atm} < 45.2^0$	$35.3^0 < \theta_{atm} < 55.4^0$
$-0.96^0 < \theta_{13} < 1.36^0$	$\lvert\theta_{13}\rvert < 11.7^0$

Numbers for ν-oscillations: masses





At 3σ

3g2HDM	Measured e.g. Gonzalez-Garcia, hep-ph/0410030
$7.3\cdot10^{-5} < \Delta m^2_{sol} < 9.1\cdot10^{-5}$	$7.3\cdot10^{-5} < \Delta m^2_{sol} < 9.3\cdot10^{-5}$
$1\cdot10^{-3} < \Delta m^2_{atm} < 3.7\cdot10^{-3}$	$1.6\cdot10^{-3} < \Delta m^2_{atm} < 3.6\cdot10^{-3}$

Heavy Majorana Spectrum in the 3g2HDM

best fit from ν-oscillation and quark-lepton similarity

$$r \sim 1 \Rightarrow \frac{a^2}{\varepsilon_{M1}} << \frac{b^2}{\varepsilon_{M2}}$$

$$\varepsilon \sim 0.6\ ,\ \omega = 5.3 \approx \frac{c^2 t_\beta^2}{\varepsilon_{M3}}$$

$a \sim O(10^{-3})$ ⟸ $m_u \sim O(a \cdot v_q)$

$b \sim O(10^{-1})$ ⟸ $m_c \sim O(b \cdot v_q)$

$c \sim O(1)$ ⟸ $m_t \sim O(c \cdot v_q \cdot t_\beta)\ ;\ t_\beta \sim O(10)$

$$\varepsilon_{M3} \approx 10^2\ ,\ \varepsilon_{M2} \approx 10^{-2}\ ,\ \varepsilon_{M1} >> 10^{-6}$$

$$M_{N_3} \approx 10^{15}\ \text{GeV}\ ,\ M_{N_2} \approx 10^{11}\ \text{GeV}\ ,\ M_{N_1} >> 10^{7}\ \text{GeV}$$

$$M \sim \frac{v_q^2}{2m_\nu^0} \xrightarrow{m_\nu^0 \sim \sqrt{\Delta m_{sol}^2}/2} \frac{v_q^2}{\sqrt{\Delta m_{sol}^2}} \xrightarrow{v_q \sim 10\, GeV} 10^{13}\ GeV$$

$$M_{N_3} \sim M \cdot \frac{c^2 t_\beta^2}{\omega} \sim 10^{15}\ GeV$$ ⬅ **$\omega \sim 5$, $c \sim O(1)$, $t_\beta \sim O(10)$**

$$M_{N_2} \sim M \cdot \frac{b^2}{\varepsilon} \sim 10^{11}\ GeV$$ ⬅ **$b \sim O(0.1)$, $\varepsilon \sim O(1)$**

$$M_{N_1} >> M_{N_2} \cdot \frac{a^2}{b^2} \sim 10^7\ GeV$$ ⬅ **$r \sim 1$**

Leptogenesis from CP-asymmetry ε_{Ni} in the decays $N_i \rightarrow L\phi$

density of N_i — asymmetry washout

$$\frac{n_L}{s} = \varepsilon_{N_i} Y_{N_i}(T >> M_{N_i})\eta \xrightarrow{L\rightarrow B} \frac{n_B}{s} = a_{sph}\frac{n_L}{s}$$

CPV/L#V asymmetry — spheleron processes

ε_{Ni} in the 3g2HDM (for $M_{N1} << M_{N2}, M_{N3}$):

$$\varepsilon_{N_i} \rightarrow \varepsilon_{N_1}(N_1 \rightarrow L\phi_1) = -\frac{3}{16\pi}\frac{\mathrm{Im}\left[(Y_1^+ Y_1)_{21}^2\right]}{(Y_1^+ Y_1)_{11}}\frac{M_{N_1}}{M_{N_2}}$$

$$\varepsilon_{N_1}^{3g2HDM} \approx -\frac{3}{8\pi}\varepsilon\sqrt{\Delta m_{sol}^2}\tan^2\beta\frac{M_{N_1}}{m_t^2}\cdot \sin 2(\varphi_b - \varphi_a)$$

$\varphi_{a,b} = \arg(a,b)$

Leptogenesis in the 3g2HDM (cont.)

washout: determind by the "decay parameter" K which measures the amount of asymmetry-damping caused by the inverse N_1 decay:

$$K = \frac{\Gamma_{N_1}}{H(T \sim M_{N_1})} \sim 4.8 \cdot 10^{-3} a^2 \cdot \frac{M_{Plank}}{M_{N_1}} \xrightarrow{a \sim O(10^{-3})} \frac{6 \cdot 10^{10}}{M_{N_1}/GeV}$$

for e.g., $10^9 < M_{N1}/GeV < 10^{10} \Rightarrow 6 < K < 60$

(the mildly strong washout regime: strong enough to be almost independent of the initial conditions but not too strong to result in a significant efficiency loss)

$$\eta \approx \frac{0.5}{K^{1.2}} \sim 6 \cdot 10^{-14} \left[\frac{M_{N_1}}{GeV} \right]^{1.2}$$

(a good fit to the numerical solution of the B-eqs. – see e.g., Di Bari, hep-ph/0406115)

Overall Baryon asym. in the 3g2HDM

$$\frac{n_B}{s} \approx -1.4\cdot 10^{-3}\varepsilon_{N_1}\eta \approx 10^{-17}\varepsilon\sqrt{\Delta m^2_{sol}}\,tan^2\beta\,\frac{M_{N_1}^{2.2}}{m_t^2\cdot(GeV)^{1.2}}\cdot sin2(\varphi_b-\varphi_a)$$

For best fitted parameters (ε, Δm^2_{sol}) & $\tan\beta \sim O(10)$:

$$\frac{n_B}{s} \approx 2\cdot 10^{-31}\cdot\left[M_{N_1}/GeV\right]^{2.2}\cdot sin2(\varphi_b-\varphi_a)$$

Compatible with observed value $n_B/s \sim 8.5\cdot 10^{-11}$ if e.g.,

$M_{N1} \sim 10^{10}$ GeV & $\sin 2(\varphi_b - \varphi_a) \sim 0.05$

Or (max. CP): $M_{N1} \sim 2.7\cdot 10^9$ GeV & $\sin 2(\varphi_b - \varphi_a) \sim 1$

SUMMARY & OUTLOOK

- **3g2HDM: an effective grounds-up approach based on quark-lepton similarity:**
  - **top-quark and 3rd generation Majorana ν_R are "treated" similarly**
  - **Both are naturally rendered very massive, compard**
  - **to others, as only they couple to 2nd doublet with huge**
  - **VEV…that huge VEV gives rise to a**
  - **key parameter: a naturally large $\tan\beta \approx O(10)$ which is effectively responsible for the large m_t**
  - **Based on an $m_\nu \sim m_u$ relation at the EW scale**

SUMMARY & OUTLOOK

- **Predictions (with normal hierarchy $m_3 >> m_2 >> m_1$):**
  - **a triple t - ν - N seesaw connection:**

$$m_{\nu_3} \approx \frac{m_t^2}{M_{N_3}}$$

  - $-0.02 < \theta_{13} < 0.02$ (3σ)
  - $43^0 < \theta_{atm} < 45^0$ (3σ)
  - $28^0 < \theta_{sol} < 36^0$ (3σ)
  - $M_{N1} << M_{N2} << M_{N3}$
- **Easily fits:**
  ν-oscillation data & Baryogenesis through Leptogenesis
- **Outlook: ν-CPV, EW-Leptogenesis with TeV N_i, LFV**

$$\varepsilon_{N_1} = \frac{\Gamma(N_1 \to L\phi_1) - \Gamma(N_1 \to \bar{L}\bar{\phi}_1)}{\Gamma(N_1 \to L\phi_1) + \Gamma(N_1 \to \bar{L}\bar{\phi}_1)}$$

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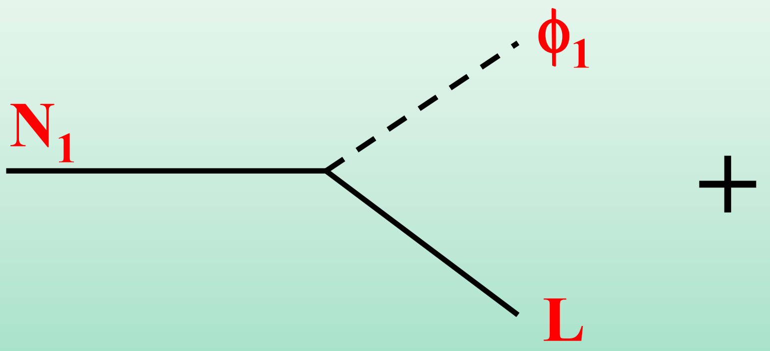

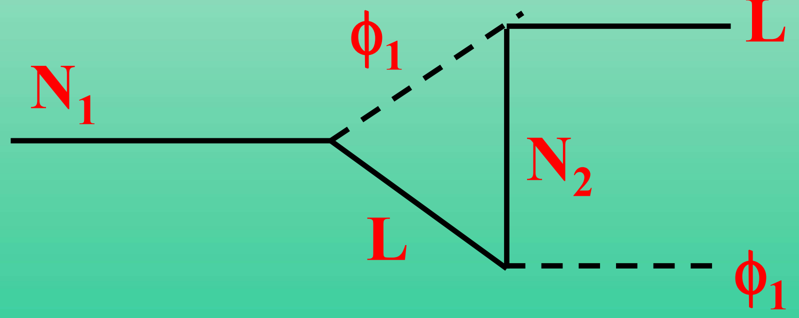

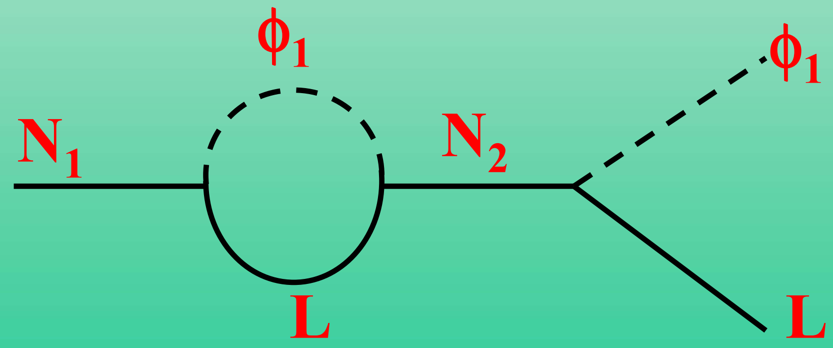

Leptogenesis from CP-asymmetry ε_{N_i} in the decays $N_i \to L\phi$

density of N_i

asymmetry washout

$$\frac{n_L}{s} = \varepsilon_{N_i} Y_{N_i} (T >> M_{N_i}) \eta \xrightarrow{L \to B} \frac{n_B}{s} = a_{sph} \frac{n_L}{s}$$

CPV/L#V asymmetry

spheleron processes

ε_{Ni} in the 3g2HDM (for $M_{N1} << M_{N2}, M_{N3}$):

$$\varepsilon_{N_i} \to \varepsilon_{N_1} = \varepsilon_{N_1}^{\phi_1} + \varepsilon_{N_1}^{\phi_2} \quad \textbf{with :} \quad \begin{pmatrix} h_1 = c_\beta \cdot Y_1^\nu + s_\beta \cdot Y_2^\nu \\ h_2 = -s_\beta \cdot Y_1^\nu + c_\beta \cdot Y_2^\nu \end{pmatrix}$$

$$\varepsilon_{N_1}^{\phi_a} = -\frac{1}{16\pi (h_a^+ h_a)_{11}} \sum_{b=1,2} \sum_{j=2,3} \text{Im}\left[(h_a^+ h_b)_{1j} (h_b^+ h_a)_{1j} + 2 (h_a^+ h_a)_{1j} (h_b^+ h_b)_{1j}\right] \frac{M_{N_1}}{M_{N_j}}$$

$$\varepsilon_{N_1}^{3g2HDM} \approx -\frac{3}{8\pi} \varepsilon \sqrt{\Delta m_{sol}^2}\, tan^2 \beta \frac{M_{N_1}}{m_t^2} \cdot sin2(\varphi_b - \varphi_a)$$

$\varphi_{a,b} = \arg(a,b)$