Neutrino mass hierarchies in the double seesaw model

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Outline

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Fermion mass hierarchies

Large hierarchies for charged fermion masses

$m_t = 171.2 \pm 2.1\ \mathrm{GeV}$	$m_b = 4.20^{+0.17}_{-0.07}\ \mathrm{GeV}$	$m_\tau = 1.78\ \mathrm{GeV}$
$m_c = 1.27^{+0.07}_{-0.11}\ \mathrm{GeV}$	$m_s = 104^{+26}_{-34}\ \mathrm{MeV}$	$m_\mu = 105\ \mathrm{MeV}$
$m_u = 1.5 - 3.3\ \mathrm{MeV}$	$m_d = 3.5 - 6.0\ \mathrm{MeV}$	$m_e = 0.51\ \mathrm{MeV}$
$m_t/m_c \sim 125 - 150$	$m_b/m_s \sim 30 - 60$	$m_\tau/m_\mu \sim 17$
$m_c/m_u \sim 350 - 900$	$m_s/m_d \sim 11 - 37$	$m_\mu/m_e \sim 205$

What about neutrinos?

$$\Delta m^2_{12} = 7.67 \times 10^{-5}\mathrm{eV}^2$$

$$\left|\Delta m^2_{23}\right| = 2.46 \times 10^{-3}\mathrm{eV}^2$$

$$1 < h = \frac{m_3}{m_2} < 6$$

$$h' = \frac{m_2}{m_1} > 1$$

($h = 1$ for degenerate or inverted)

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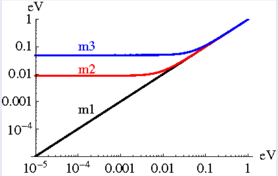

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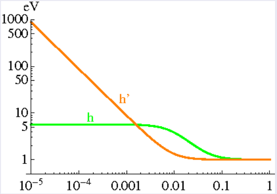

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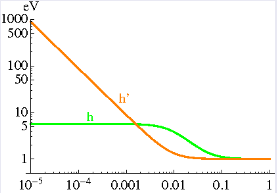

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The type I seesaw

Dirac vs Majorana masses?

$$\mathcal{L}^{lepton} = -\overline{\ell_L} H Y_e e_R - \overline{\ell_L} \widetilde{H} Y_\nu^\dagger N_R + \text{h.c.}$$

- We do not know the mechanism which generates Yukawa couplings, but it seems it produces them hierarchical (see Y_u, Y_d, Y_e)
- Hierarchical $Y_\nu \quad \Rightarrow \quad h >> 6$

$\Rightarrow$ Dirac masses disfavoured from the point of view of hierarchies

The seesaw mechanism

$$\mathcal{L}^{lepton} = -\overline{\ell_L} H Y_e e_R - \overline{\ell_L} \widetilde{H} Y_\nu^\dagger N_R + \frac{1}{2} \overline{N_R} M_N N_R{}^c + \text{h.c.}$$

- If $M >> M_{EW} \quad \Rightarrow \quad m_\nu = \frac{v^2}{2} Y^T M^{-1} Y$

$\Rightarrow$ naturally small neutrino masses. What about hierarchies?

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Hierarches from the seesaw mechanism

The "naive" seesaw

$$m_1 \sim \frac{v^2}{2}\frac{y_1^2}{M_1} \quad m_2 \sim \frac{v^2}{2}\frac{y_2^2}{M_2} \quad m_3 \sim \frac{v^2}{2}\frac{y_3^2}{M_3} \quad \Rightarrow \quad h = \frac{m_3}{m_2} \sim \frac{y_3^2}{y_2^2}\frac{M_2}{M_3}$$

The seesaw mechanism tends to generate large hierarchies

- All known Yukawa couplings are hierarchical $\Rightarrow$ also $Y_{\nu i}$
- Majorana masses: we do not know
  - M_i degenerate $\rightarrow h \sim (y_3/y_2)^2$ hierarchy is reinforced
  - M_i hierarchical (as y_i) $\rightarrow h \sim (y_3/y_2)$ h still hierarchical
  - M_i very hierarchical (as y_i^2) $\rightarrow h \sim 1$

Including mixing effects in the right-handed sector

- Starting in a basis where $M_N = D_M$

$$m_\nu \propto Y^T D_M^{-1} Y = V_L^* D_Y V_R^T D_M^{-1} V_R D_Y V_L^\dagger$$

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Seesaw: 2 generations

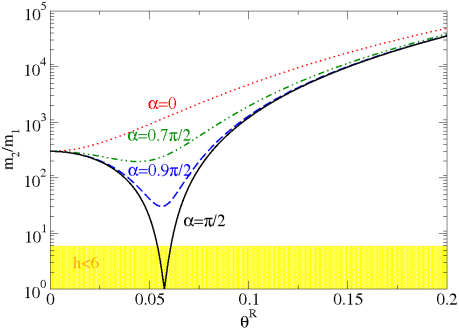
- Varying the V_R parameters θ_R and α, the hierarchy can vary

$$V_R = \begin{pmatrix} e^{i\alpha} & 0 \\ 0 & 1 \end{pmatrix} \times \begin{pmatrix} \cos\theta_R & \sin\theta_R \\ -\sin\theta_R & \cos\theta_R \end{pmatrix}$$

$$y_1 : y_2 = 1 : 300$$

$$M_1 : M_2 = 1 : 300$$

$$\cos\theta_R = \frac{M_2 y_2^2 - M_1 y_1^2}{(M_1+M_2)(y_2^2 - y_1^2)} \qquad \alpha = \frac{\pi}{2}$$



Casas, Ibarra, Jiménez 07

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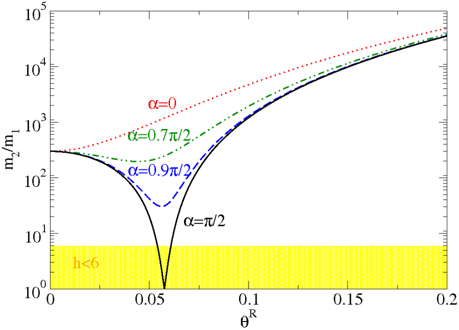

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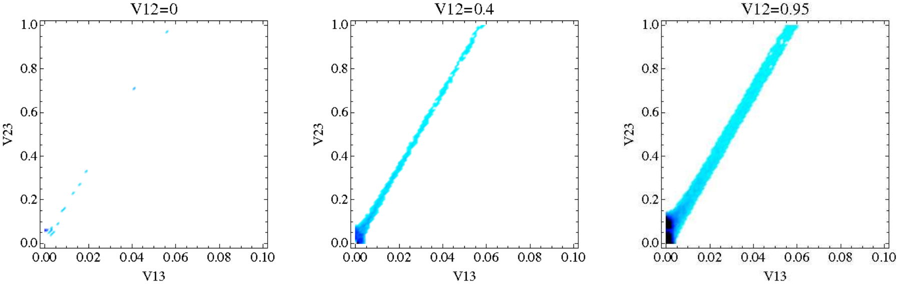

Casas, Ibarra, Jiménez 07

- Hierarchical Majorana masses: mild hierarchy can be accomodated
  $\rightarrow$ no need of cancellations in the 3 generation case
  $\rightarrow$ V_R is constrained by the requirement of $h < 6$ ("CKM-like")
- Degenerate Majorana masses: soft hierarchy only with cancellations among V_R elements

Is there any mechanism where mild hierarchies arise more naturally?

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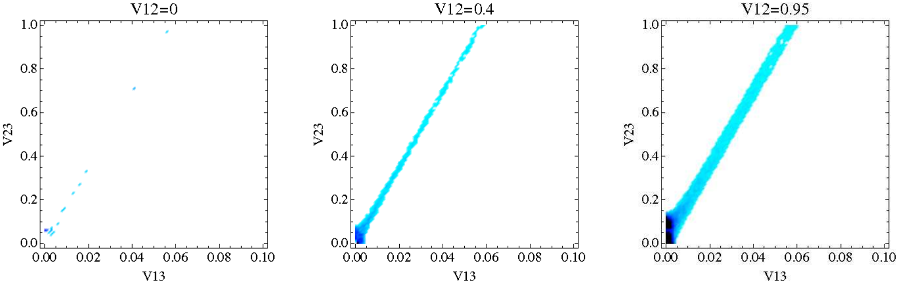

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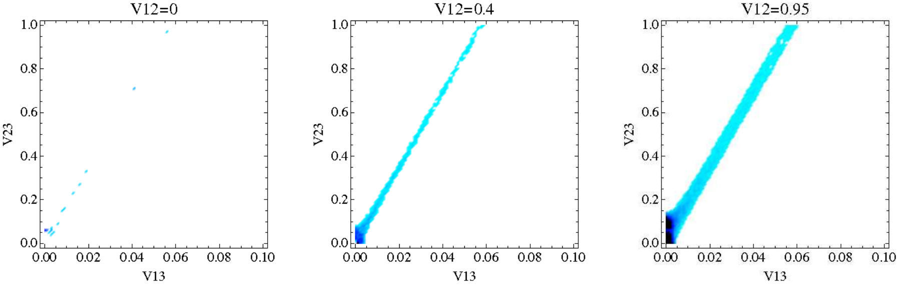

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The double seesaw

- Add to the SM 3 singlets N_R and 3 singlets S:

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Hierarchies in the "naive" double seesaw

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- y_i and M_i are both Dirac parameters $\Rightarrow$ it's natural they are hierarchical
- μ_i are Majorana parameters $\Rightarrow$ can be hierarchical or degenerate
- Ex.: $\frac{\mu_i}{\mu_j} \sim 1 \quad \frac{y_i}{y_j} \sim \frac{M_i}{M_j} \quad \Rightarrow \quad h \sim 1$

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Double seesaw: 2 generations

CB, Ibarra, in progress

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$h < 6$ for any Ω and $\theta_R \ll \frac{y_1}{y_2}$

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Hierarchical M and μ

- "constraints" on hierarchies
  if $\frac{\mu_i}{\mu_j} \sim \frac{y_i}{y_j}$ then M either more or less hierarchical
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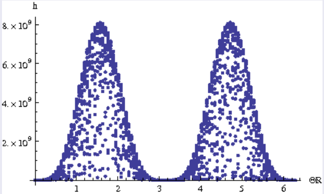

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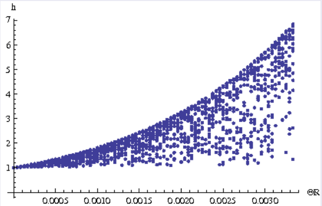

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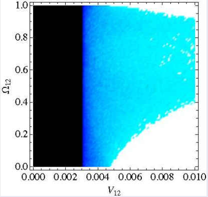
$\mu_1 = \mu_2$

$h < 6$ for any Ω and $\theta_R \ll \frac{y_1}{y_2}$

no need of fine-tuning



Hierarchical M and μ

- "constraints" on hierarchies
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- constraints on both angles

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Double seesaw: 2 generations

CB, Ibarra, in progress

$$m_\nu \propto Y^T D_M^{-1} \mu D_M^{-1} Y = V_L^* D_Y V_R{}^T D_M^{-1} \Omega^\dagger D_\mu \Omega^* V_R D_Y V_L^\dagger$$

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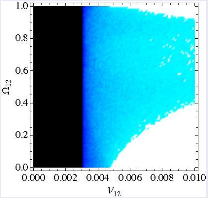

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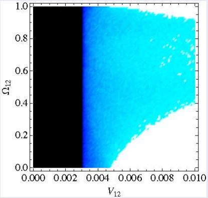

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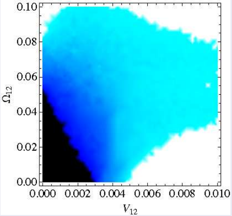

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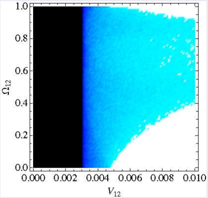

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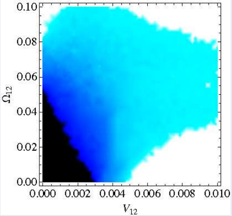

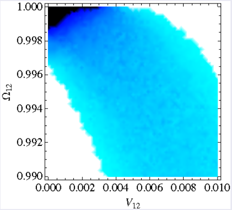

Double seesaw: 3 generations

CB, Ibarra, in progress

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$$y_1 : y_2 : y_3 = M_1 : M_2 : M_3 = 1 : 300 : (300)^2$$
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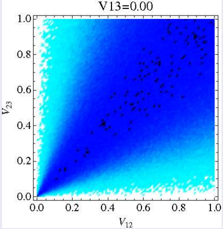
$h < 6$ for any Ω and V_R as $\longrightarrow$



Hierarchical M and μ

- "constraints" on hierarchies
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EXAMPLE $\longrightarrow$

hier(μ_i) $\sim$ hier(y_i)
hier(M_i) $\sim$ hier($\sqrt{y_i}$)
$V_{13} \simeq 0$

$$\Omega \sim \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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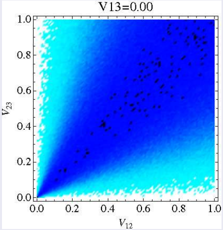

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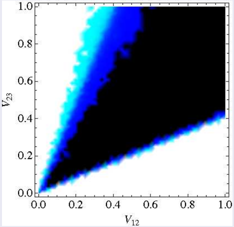

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Outline

Summary and conclusions

- Experimentally we know that the hierarchy of neutrino masses (at least the two heaviest) is much softer than for charged fermions: $m_3/m_2 < 6$
- If neutrino's Yukawa couplings are as hierarchical as other Yukawa couplings, Dirac masses are disfavoured because $h \gg 6$
- The seesaw mechanism offers a way to generate light neutrino masses and soft hierarchies, but the high energy parameters must respect certain constraints:
  - for random V_R large hierarchies are usually generated
  - hierarchical Majorana masses M_i, V_R "CKM-like" $\rightarrow h < 6$
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- In the double seesaw soft hierarchies are generated more naturally:
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