

Problemas del modelo estándar y posibles soluciones

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Modelo estándar

Es un modelo de concordancia

19 parámetros libres:

6 masas de quarks

3 masas de leptones cargados

3 ángulos de mezcla CKM

1 fase CP

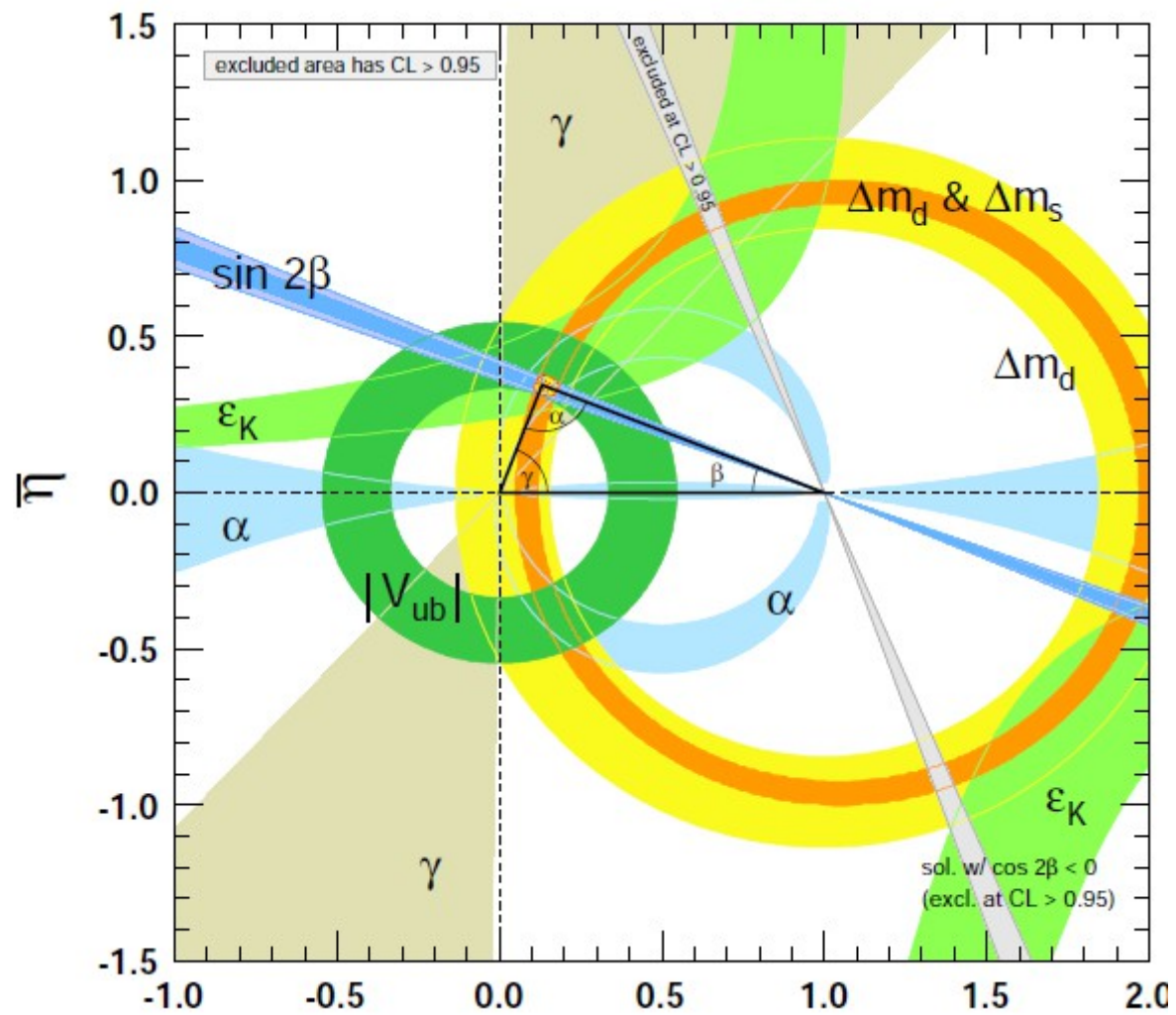
3 constantes de acoplamiento

Valor de expectación del vacío

Masa del Higgs

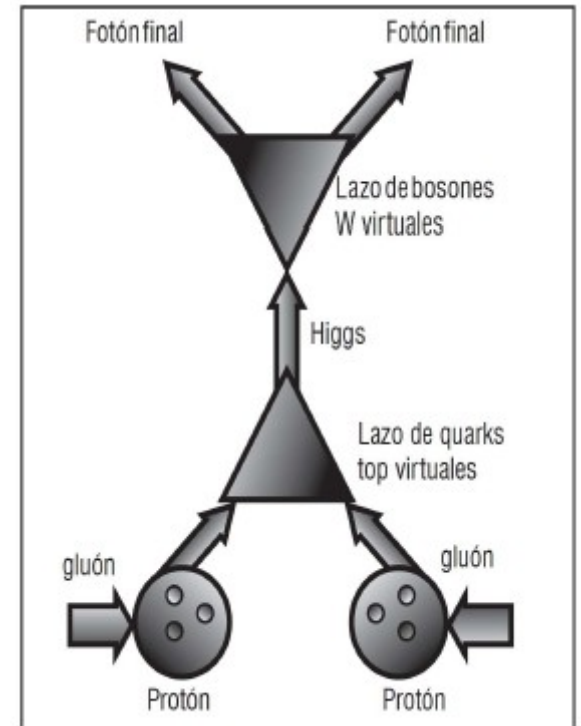
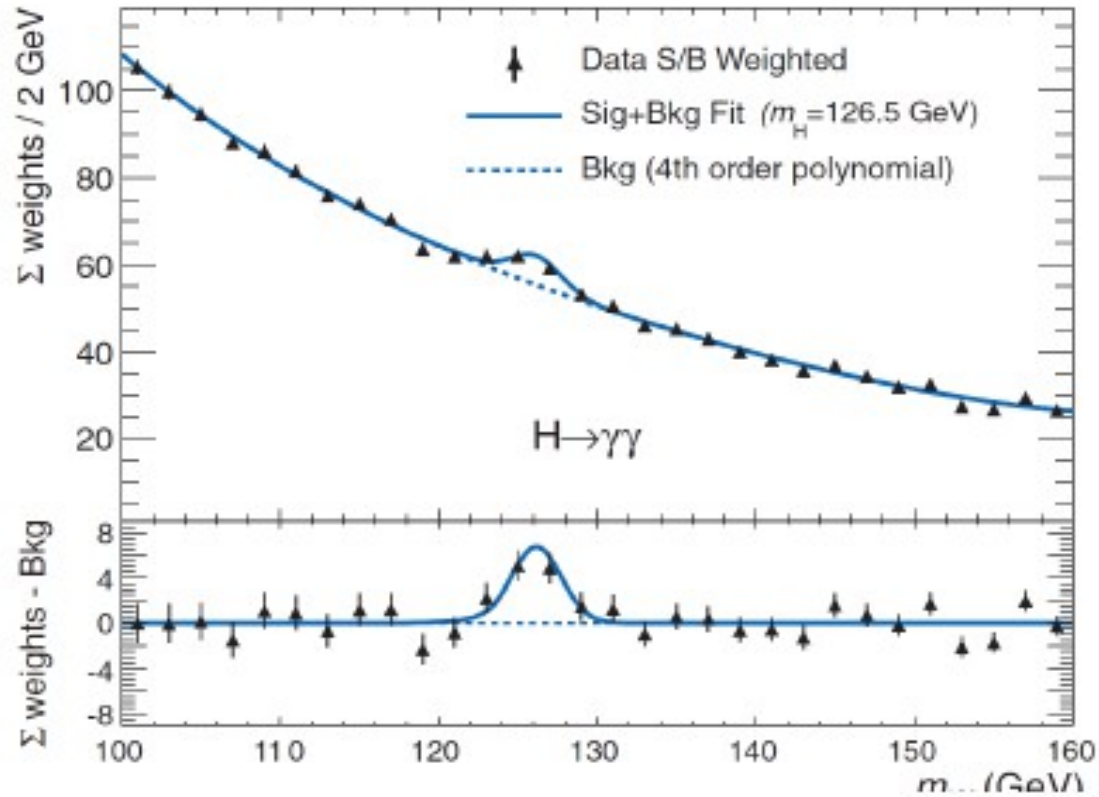
Θ QCD



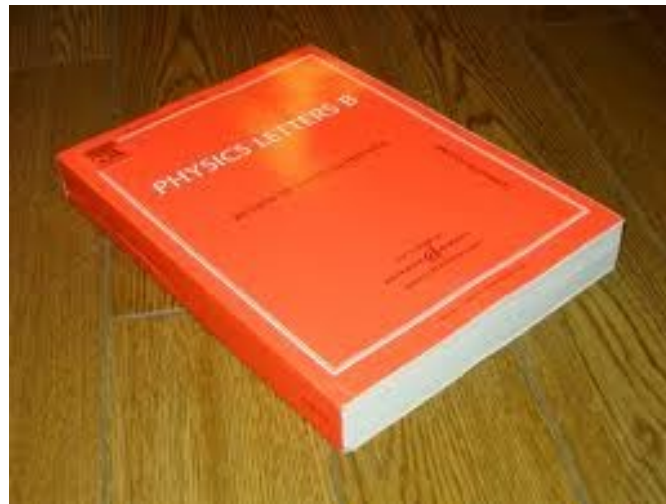


$$V_{\text{CKM}} = \begin{pmatrix} 0,97428 \pm 0,00015 & 0,2253 \pm 0,0007 & 0,00347^{+0,00016}_{-0,00012} \\ 0,2252 \pm 0,0007 & 0,97345^{+0,00015}_{-0,00016} & 0,0410^{+0,0011}_{-0,0007} \\ 0,00862^{+0,00026}_{-0,00020} & 0,0403^{+0,0011}_{-0,0007} & 0,999152^{+0,000030}_{-0,000045} \end{pmatrix}$$

Y finalmente, el Higgs



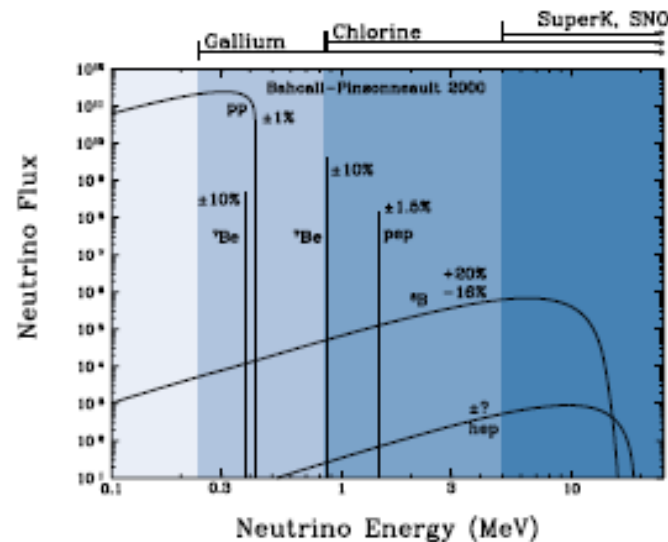
Concordancia: Cientos de experimentos son verificados y concuerdan con las expectativas del modelo estándar, fijando sólo 19 parámetros



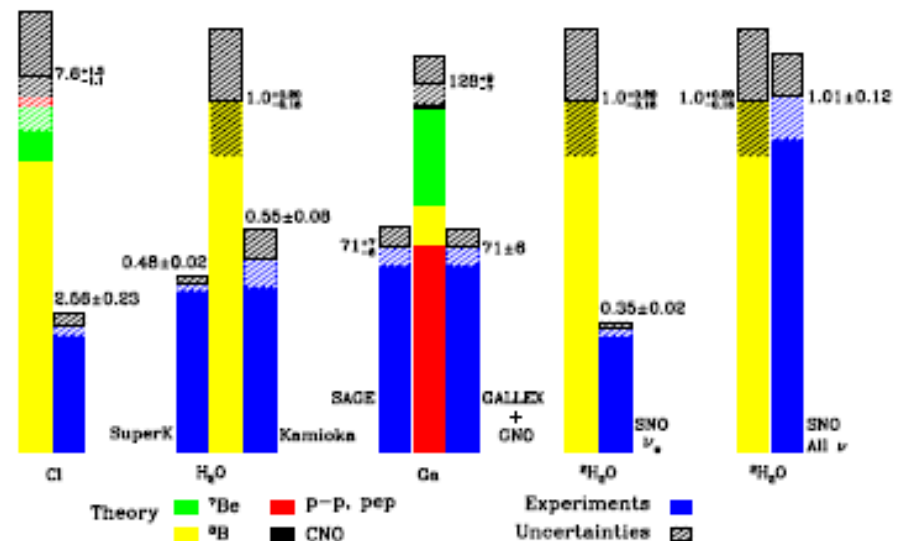
Algo nuevo al SM: Masas y mezclas de los neutrinos

$$N_{Obs}^{th} = \sum_i \int dE_\nu \int dT \phi_i \lambda_i(E_\nu) \times \frac{d\sigma(E_\nu, T)}{dT} \times t \times N_e \times R(T, T')$$

1. Modelo estándar solar (MES): $\phi_i, \lambda_i(E_\nu)$
2. Experimento: $R(T, T'), N_e$
3. Modelo estándar electro-débil: $\frac{d\sigma(E_\nu, T)}{dT}$

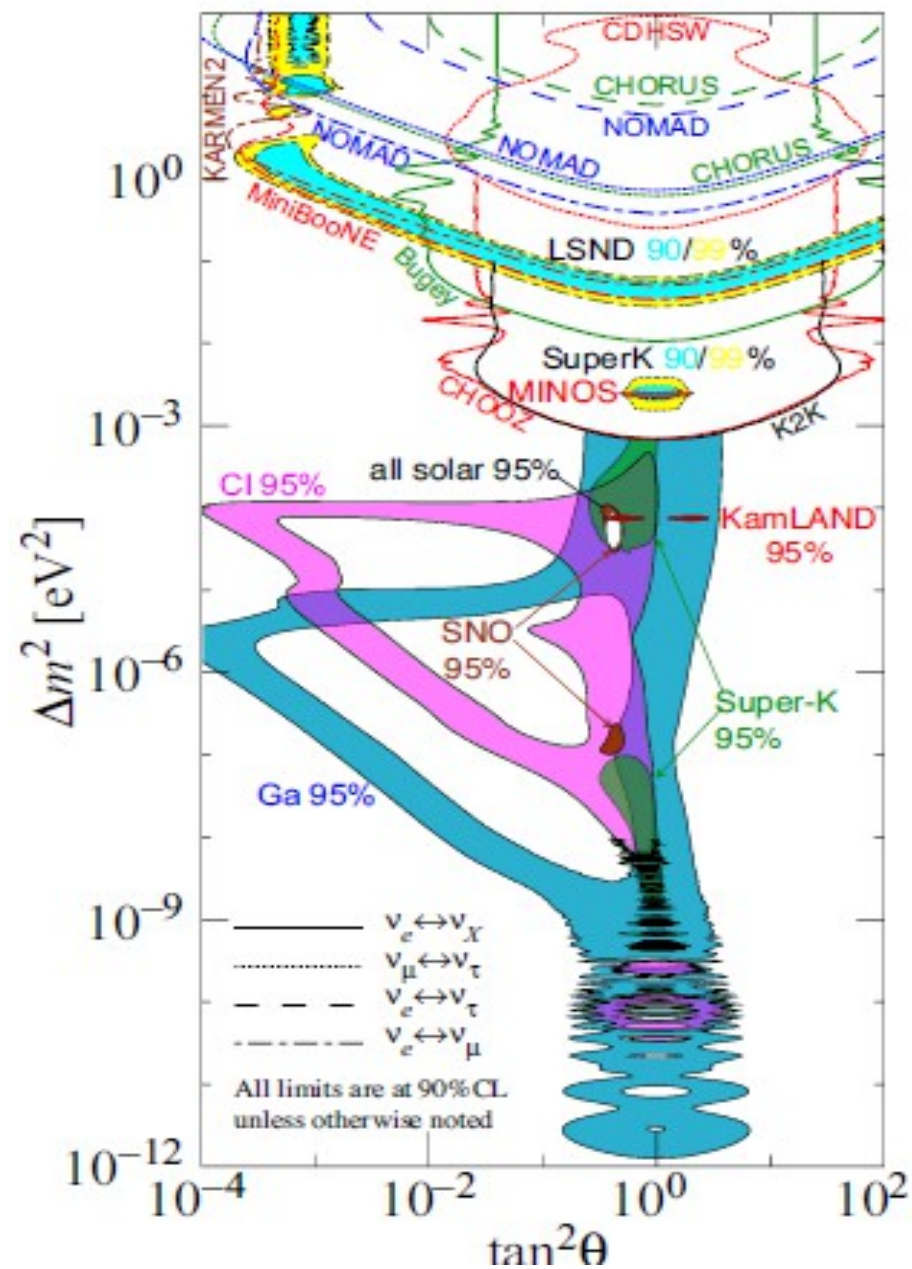
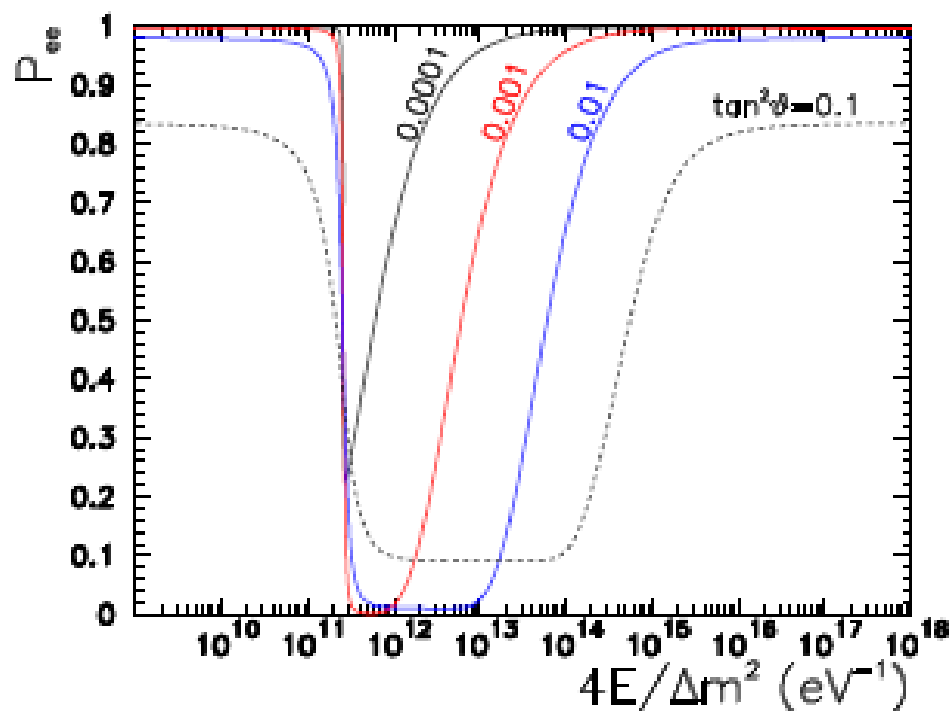


Total Rates: Standard Model vs. Experiment
Bahcall-Pinsonneault 2000



Los neutrinos oscilan:

$$|\nu_\alpha\rangle = \sum_a U_{\alpha a}^* |\nu_a\rangle$$



Problemas en el paraíso

$$M^{ij} = \frac{v}{\sqrt{2}} \lambda^{ij}$$

Si el neutrino es de Dirac e introducimos su masa de igual forma que a los demás fermiones entonces el acoplamiento del quark top es del orden de la unidad, mientras que el del neutrino es 12 órdenes de magnitud menor.

Problemas en el paraíso

- No hay suficiente violación en el ME para generar la asimetría materia antimateria.
- Hay una evidencia abrumadora de que existe un componente de materia oscura cuya composición no está en el ME.
- Problema de Θ QCD
- ¿Qué protege la masa del Higgs para que sea pequeña?

Preguntas abiertas en el sector leptónico

1. ¿Cuál es la escala de masas del neutrino?
2. ¿Cuál es la jerarquía de masas?
3. ¿Existe violación de CP en el sector leptónico?
4. ¿Cuál es la naturaleza del neutrino: Dirac ó Majorana?



¿Qué importancia tiene que sea el neutrino una partícula de Majorana?

1. La ecuación que describe su comportamiento es diferente que la ecuación de Dirac
2. Sería su propia anti-partícula
3. Generaría muchos otros procesos que de otra forma no son posibles en el SM (o con una probabilidad muy baja de que ocurra):

Decaimiento doble beta sin neutrinos

Is the neutrino a Dirac or a Majorana particle?

There is another crucial difference between Dirac and Majorana neutrinos [3, 4, 5]. If we consider the neutrino-electron scattering, either Dirac or Majorana, the effective Lagrangian at low energies can be written as:

$$\mathcal{L}_{\nu e} = \frac{G_F}{\sqrt{2}} [\bar{u}_{\nu\ell} \gamma^\mu (1 - \gamma^5) u_{\nu\ell}] [\bar{u}_e \gamma_\mu (g_V^\ell - g_A^\ell \gamma^5) u_e], \quad (1)$$

If the neutrino is a Majorana particle, then the following identity is valid:

$$\bar{v}_{\nu\ell}^f \gamma_\mu (1 - \gamma^5) v_{\nu\ell}^i = \bar{u}_{\nu\ell}^f \gamma_\mu (1 - \gamma^5) u_{\nu\ell}^i,$$

$$\mathcal{M}^D(\nu\ell e \rightarrow \nu\ell e) = -i \frac{G_F}{\sqrt{2}} [\bar{u}_e^f \gamma^\mu (g_V^\ell - g_A^\ell \gamma^5) u_e^i] [\bar{u}_{\nu\ell}^f \gamma_\mu (1 - \gamma^5) u_{\nu\ell}^i],$$

$$\mathcal{M}^M(\nu\ell e \rightarrow \nu\ell e) = i \frac{2G_F}{\sqrt{2}} [\bar{u}_e^f \gamma^\mu (g_V^\ell - g_A^\ell \gamma^5) u_e^i] [\bar{u}_{\nu\ell}^f \gamma_\mu \gamma^5 u_{\nu\ell}^i].$$

If amplitudes are so different: why are not the cross sections for Majorana and Dirac cases different?

Neutrinos have negative helicity. An extra factor

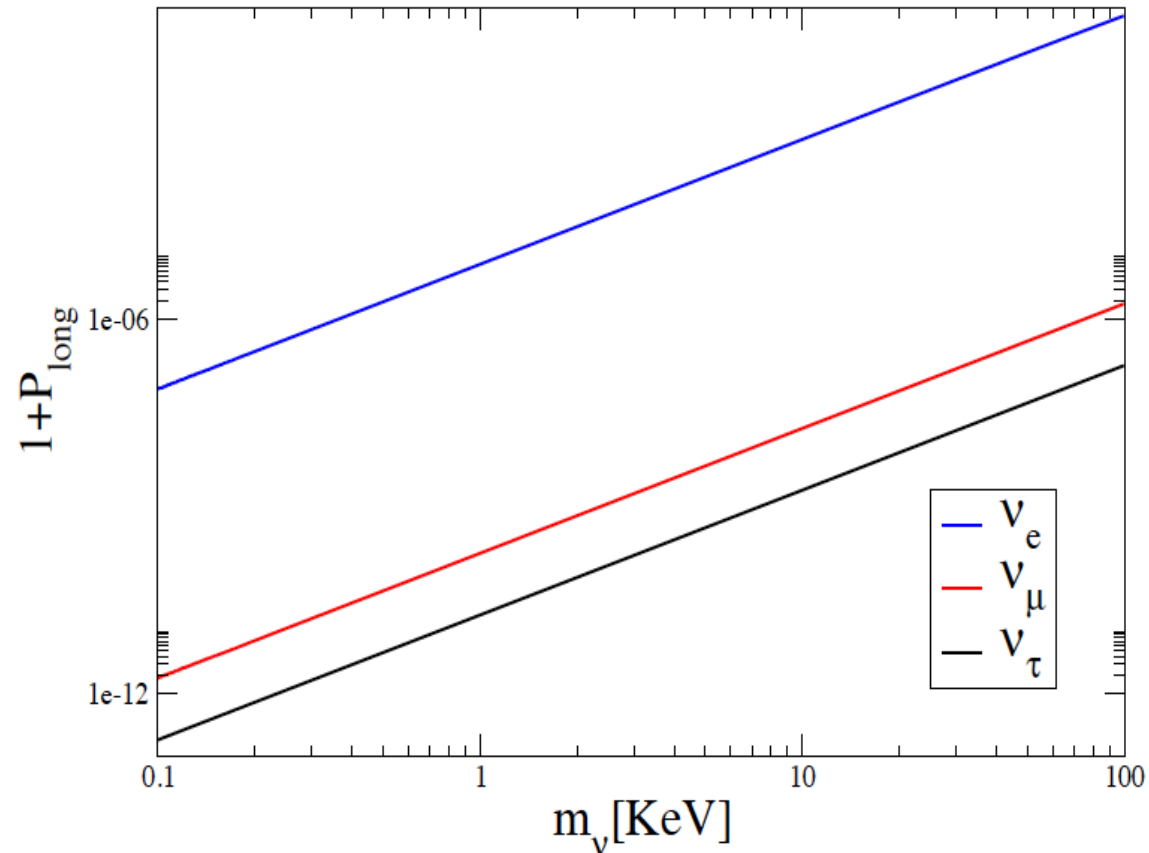
$$(1 - \gamma_5)/2$$

is usually added and both amplitudes become identical

Almost completely left handed!

for the pure leptonic decay of a pseudoscalar meson $P^+ \rightarrow \ell^+ + \nu_\ell$.

$$P_{\text{long}} = \frac{(E - W)|\vec{k}|}{WE - |\vec{k}|^2},$$



In any case...forget for a moment the value of the neutrino polarization and compute:

neutrino-electron scattering $\nu_\ell(p_\nu, s_\nu) + e(p_e) \rightarrow \nu_\ell(p'_\nu) + e(p'_e)$

$$s_\nu = (0, s_\perp, 0, s_{||})$$

For the Dirac case (in CM) [B. Kayser, R. Schrock PLB 112 (1982) 137]

$$\begin{aligned} \frac{d\sigma^D}{d\Omega} = & \frac{G_F^2}{8\pi^2 s} \left((m_e^2 (E_\nu - p^2 \cos \theta) (g_A^\ell{}^2 - g_V^\ell{}^2) \right. \\ & + (E_\nu E_e + p^2) (g_V^\ell + g_A^\ell)^2 + (E_\nu E_e + p^2 \cos \theta)^2 (g_V^\ell - g_A^\ell)^2 \\ & - p [s^{1/2} (E_\nu E_e + p^2) s_{||} (g_V^\ell + g_A^\ell)^2 + (E_\nu E_e + p^2 \cos \theta) \\ & \times ((E_e + E_\nu \cos \theta) s_{||} + m_\nu s_\perp \sin \theta \cos \phi)] (g_V^\ell - g_A^\ell)^2 \\ & \left. + m_e (E_\nu (1 - \cos \theta) s_{||} - m_\nu |s_\perp| \sin \theta \cos \phi) (g_A^\ell{}^2 - g_V^\ell{}^2) \right), \end{aligned}$$

For the Majorana:

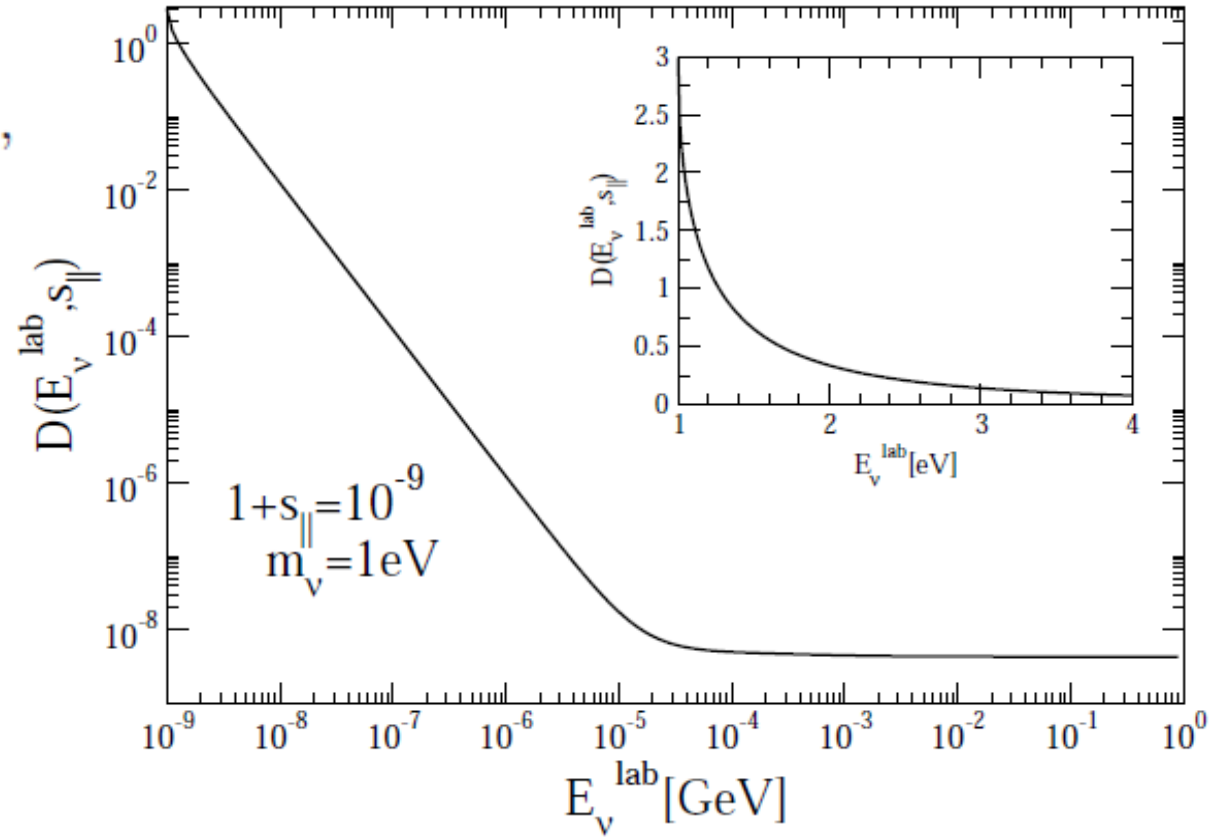
$$\begin{aligned}
 \frac{d\sigma^M}{d\Omega} &= \frac{G_F^2}{4\pi^2 s} \left(((E_\nu E_e + p^2)^2 + (E_\nu E_e + p^2 \cos \theta)^2 \right. \\
 + \quad & m_\nu (E_\nu^2 - p^2 \cos \theta) (g_V^{\ell 2} + g_A^{\ell 2}) + m_e^2 (E_\nu^2 - p^2 \cos \theta + 2m_\nu^2) \\
 \times \quad & (g_A^{\ell 2} - g_V^{\ell 2}) - 2g_V^\ell g_A^\ell p (2E_\nu E_e + p^2 (1 + \cos \theta)) \\
 \times \quad & \left. (E_\nu s_{||} (1 - \cos \theta) - m_\nu |s_\perp| \sin \theta \cos \phi) \right).
 \end{aligned}$$

They are different!!!!

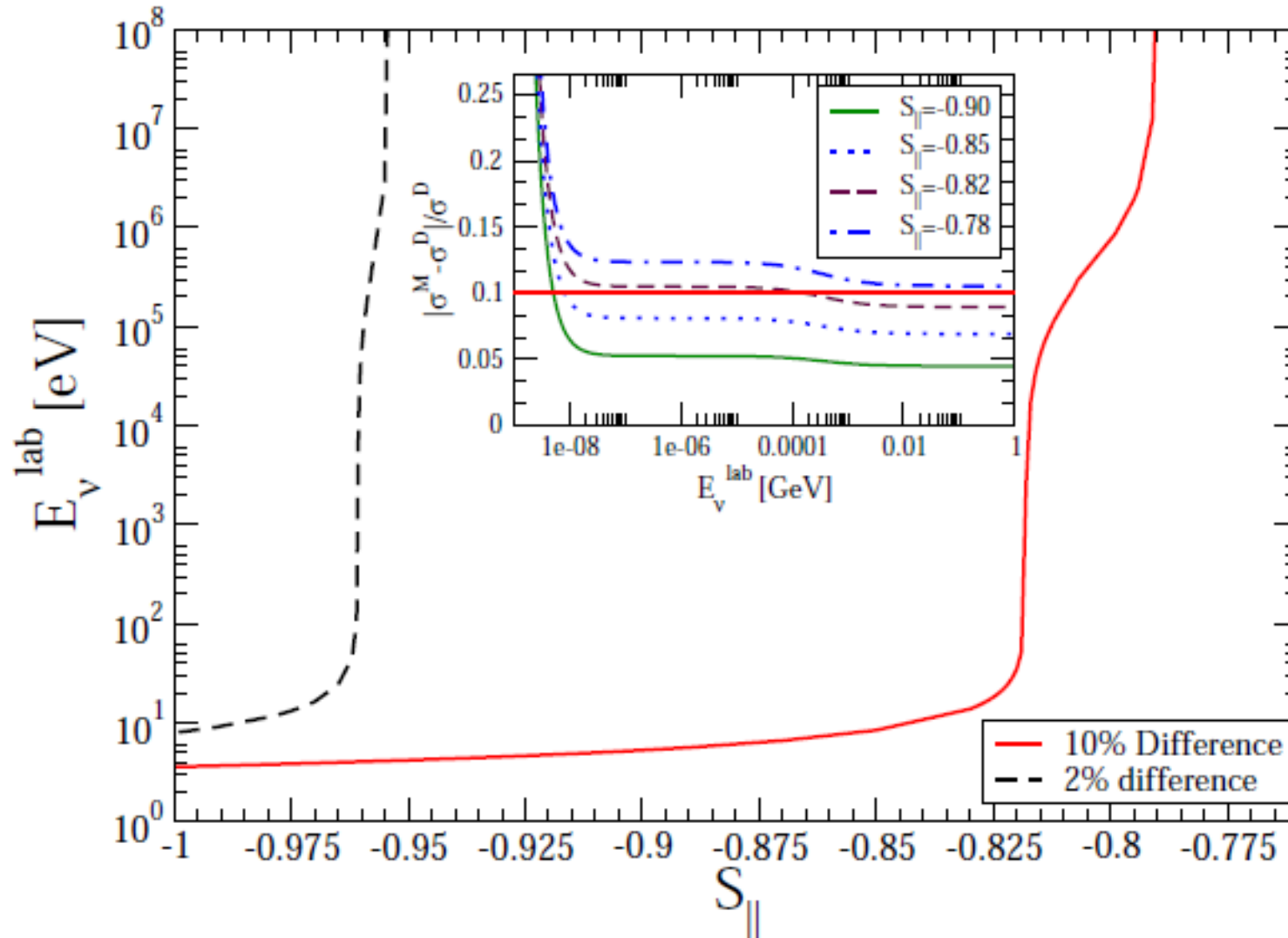
Seriously?

$$D(E_\nu^{\text{lab}}, s_{\parallel}) = \frac{|\sigma(\nu_{pol}^D e) - \sigma(\nu_{pol}^M e)|}{\sigma(\nu_{pol}^D e)},$$

For man made neutrinos, which are produced via charged currents, it is extremely difficult to have significant differences between Dirac and Majorana neutrinos.



Don't lose your faith...



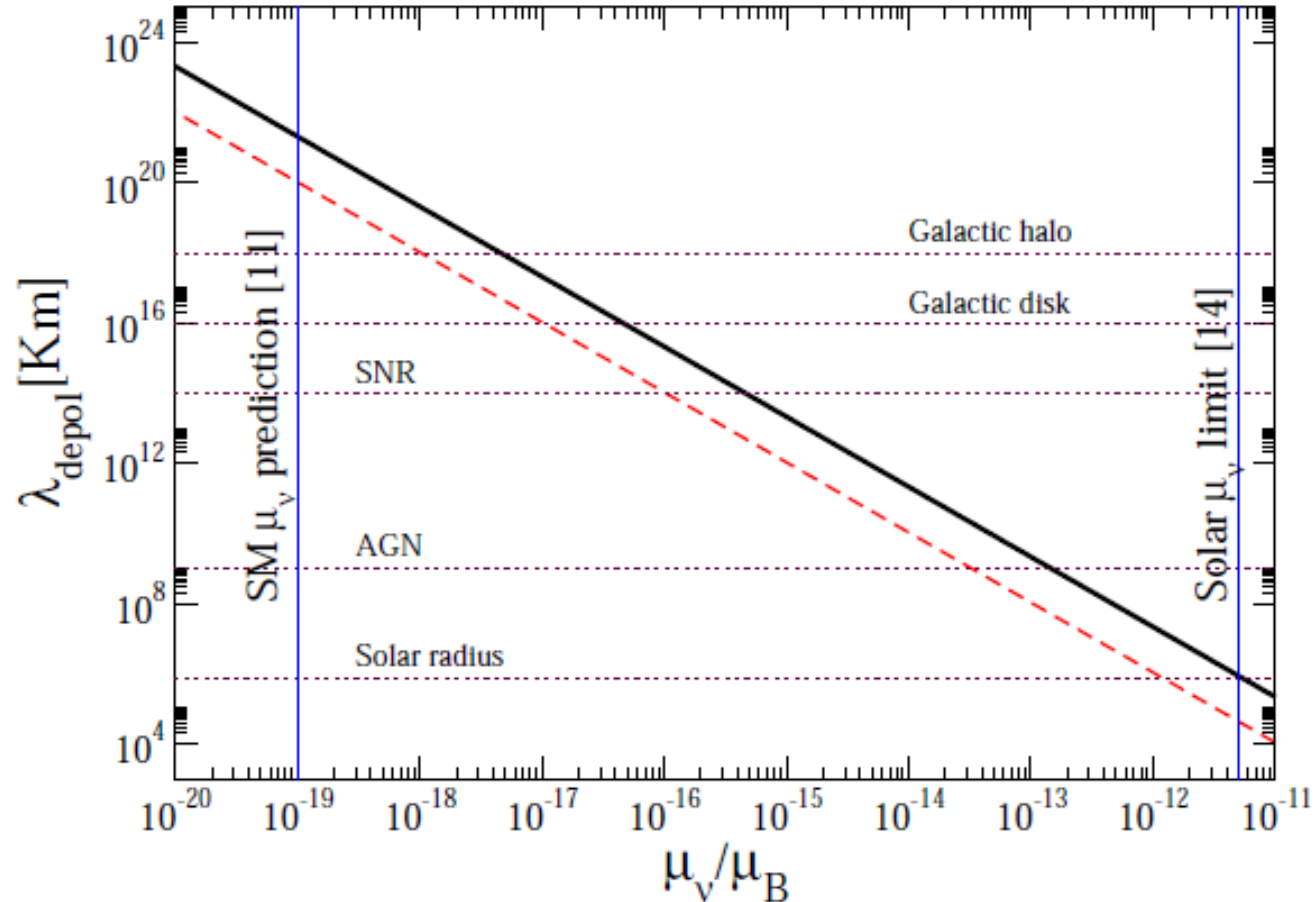
Can we (or nature) change the neutrino initial polarization?

Yes, we (nature) can...
Bargmann-Michel-Telegdi:

$$\frac{dS^\mu}{d\tau} = 2\mu(G^{\mu\nu} S_\nu - u^\mu G_{\alpha\beta} u_\alpha S_\beta) + 2\varepsilon(\tilde{G}^{\mu\nu} S_\nu - u^\mu \tilde{G}_{\alpha\beta} u_\alpha S_\beta)$$

What is the magnetic field needed in order to have such changes in the neutrino's helicity? In order to estimate this, we recall previous studies where the depolarization rate of neutrinos was calculated [15, 16, 17]. In the case of a random distribution of electromagnetic fields, the average neutrino's helicity $\langle h \rangle$ changes as dictated by the equation $\langle h(t) \rangle = \exp(-\Gamma_{depol})\langle h(0) \rangle$, where

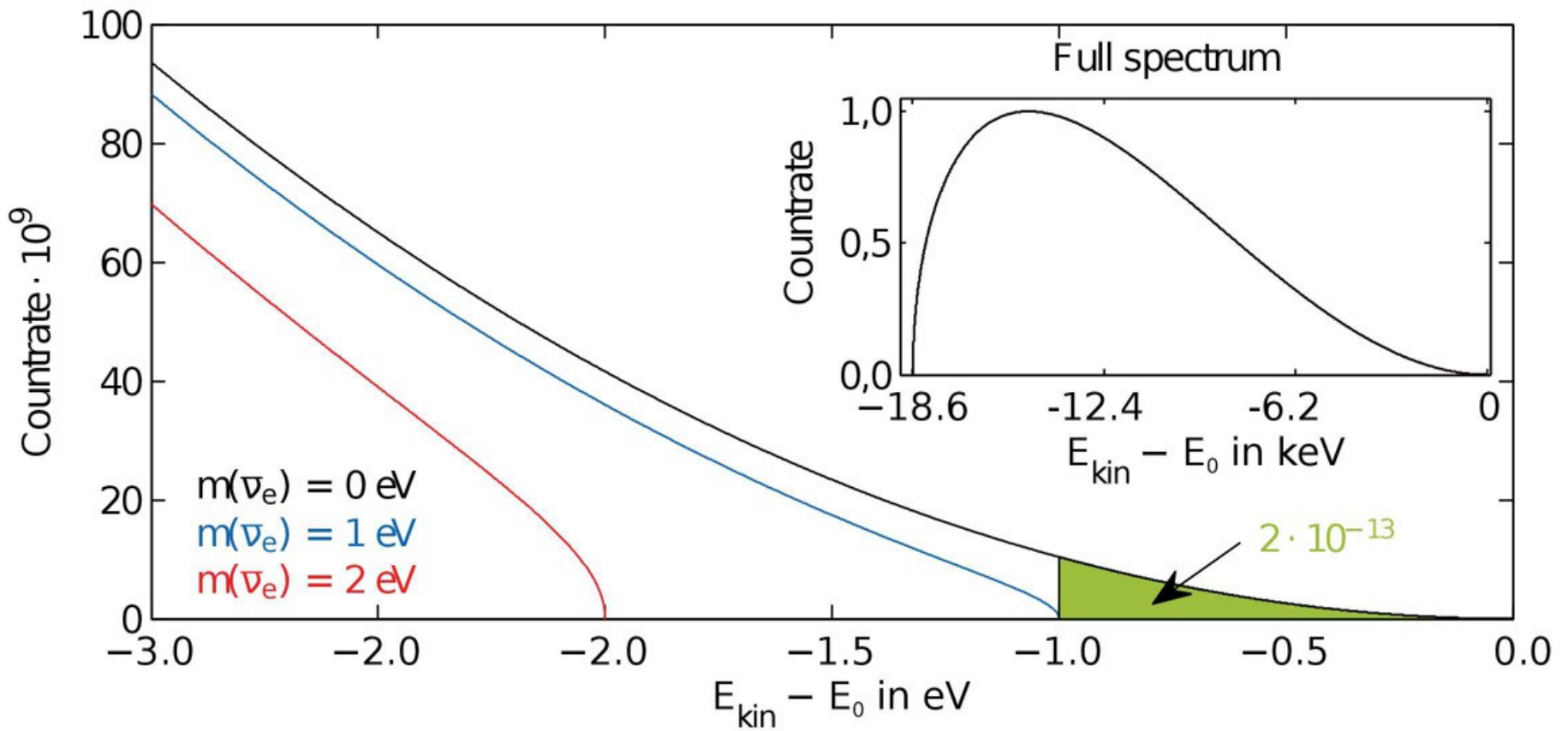
$$\Gamma_{depol} = 0.0132\mu_\nu^2 T^3, \quad (11)$$



For the next days...

To study the change of the neutrino helicity in the Sun and look for changes in the neutrino rate at future neutrino telescopes.

Escala absoluta de las masas del neutrino



¿Es posible obtener una estimación de la masa absoluta del neutrino de forma teórica?

Un intento: Escala de masas del neutrino

Utilicemos texturas:

$$M^f = \begin{pmatrix} 0 & C_f & 0 \\ C'_f & D_f & B_f \\ 0 & B'_f & A_f \end{pmatrix}.$$

$$H \equiv MM^\dagger \quad H = \begin{pmatrix} |C|^2 & CD^* & CB'^* \\ DC^* & |B|^2 + |C'|^2 + |D|^2 & B'^*D + A^*B \\ B'C^* & B'D^* + AB^* & |A|^2 + |B'|^2 \end{pmatrix}.$$

$$\text{Tr}(\tilde{H}) = m_1^2 + m_2^2 + m_3^2,$$

$$\text{Tr}^2(\tilde{H}) - \text{Tr}(\tilde{H}^2) = 2m_1^2m_2^2 + 2m_1^2m_3^2 + 2m_2^2m_3^2,$$

$$\text{Det}(\tilde{H}) = m_1^2m_2^2m_3^2,$$

Solución:

$$\tilde{m}_1 \leq a' \leq \tilde{m}_3 \quad \begin{cases} b' &= \sqrt{\frac{(a' - \tilde{m}_1)(a' + \tilde{m}_2)(\tilde{m}_3 - a')}{a'}} \\ d' &= -a' + \tilde{m}_1 - \tilde{m}_2 + \tilde{m}_3 \end{cases}$$

$$c' = \sqrt{\frac{\tilde{m}_1 \tilde{m}_2 \tilde{m}_3}{a'}}$$

$$a' = \frac{a}{m_3}, \quad b' = \frac{b}{m_3}, \quad c' = \frac{c}{m_3}$$

$$\begin{aligned}
& \left| V_{\text{CKM}}^{th} \right|_{1\sigma} \\
& = \begin{pmatrix} 0.97427 \pm 0.00023 & 0.22533_{-0.00096}^{+0.0010} & 0.00351_{-0.00023}^{+0.0072} \\ 0.22520 \pm 0.00100 & 0.97324_{-0.00023}^{+0.00058} & 0.0458_{-0.010}^{+0.0033} \\ 0.00894_{-0.00069}^{+0.0016} & 0.0451_{-0.010}^{+0.048} & 0.998944_{-0.00016}^{+0.00042} \end{pmatrix}
\end{aligned}$$

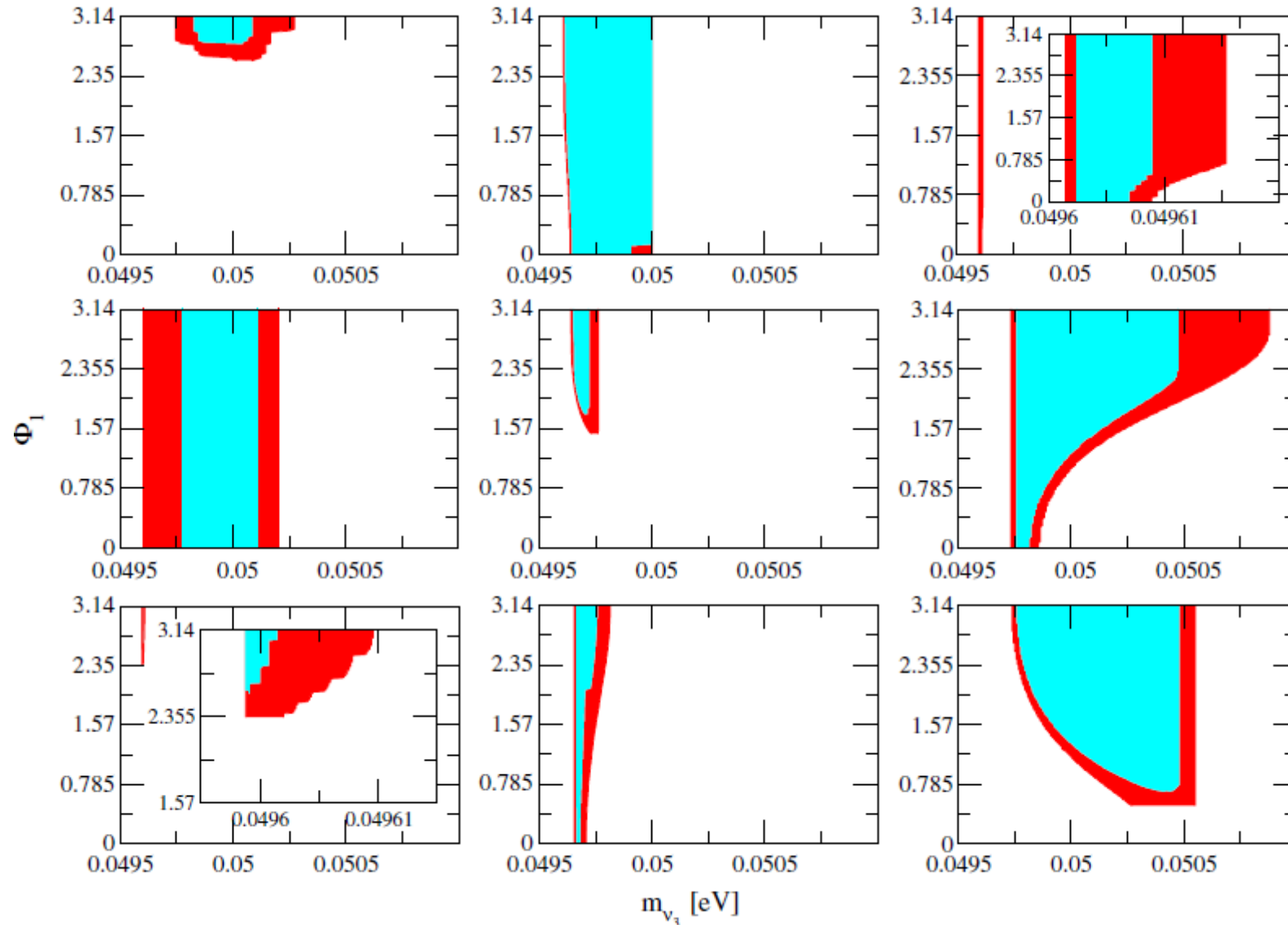
Parametrization	a'_u 1 σ C.L.	a'_d 1 σ C.L.	ϕ_{bfp}	χ_{min}^2
(2, 2)	$0.993 < a'_u < 0.997$	$0.9982 < a'_d < 1.0$	$\phi_{\text{bfp}} = 1.5723$	1.27
(2, 3)	$0.9950 < a'_u < 0.9977$	$0.99915 < a'_d < 1.0$	$\phi_{\text{bfp}} = 1.568$	1.48
(3, 2)	$0.9945 < a'_u < 0.9978$	$0.9989 < a'_d < 1.0$	$\phi_{\text{bfp}} = 1.568$	2.13
(3, 3)	$0.9958 < a'_u < 0.9978$	$0.99949 < a'_d < 1.0$	$\phi_{\text{bfp}} = 1.5723$	2.163

Table 1. Allowed values of the parameters a'_u and a'_d at 68% C.L.

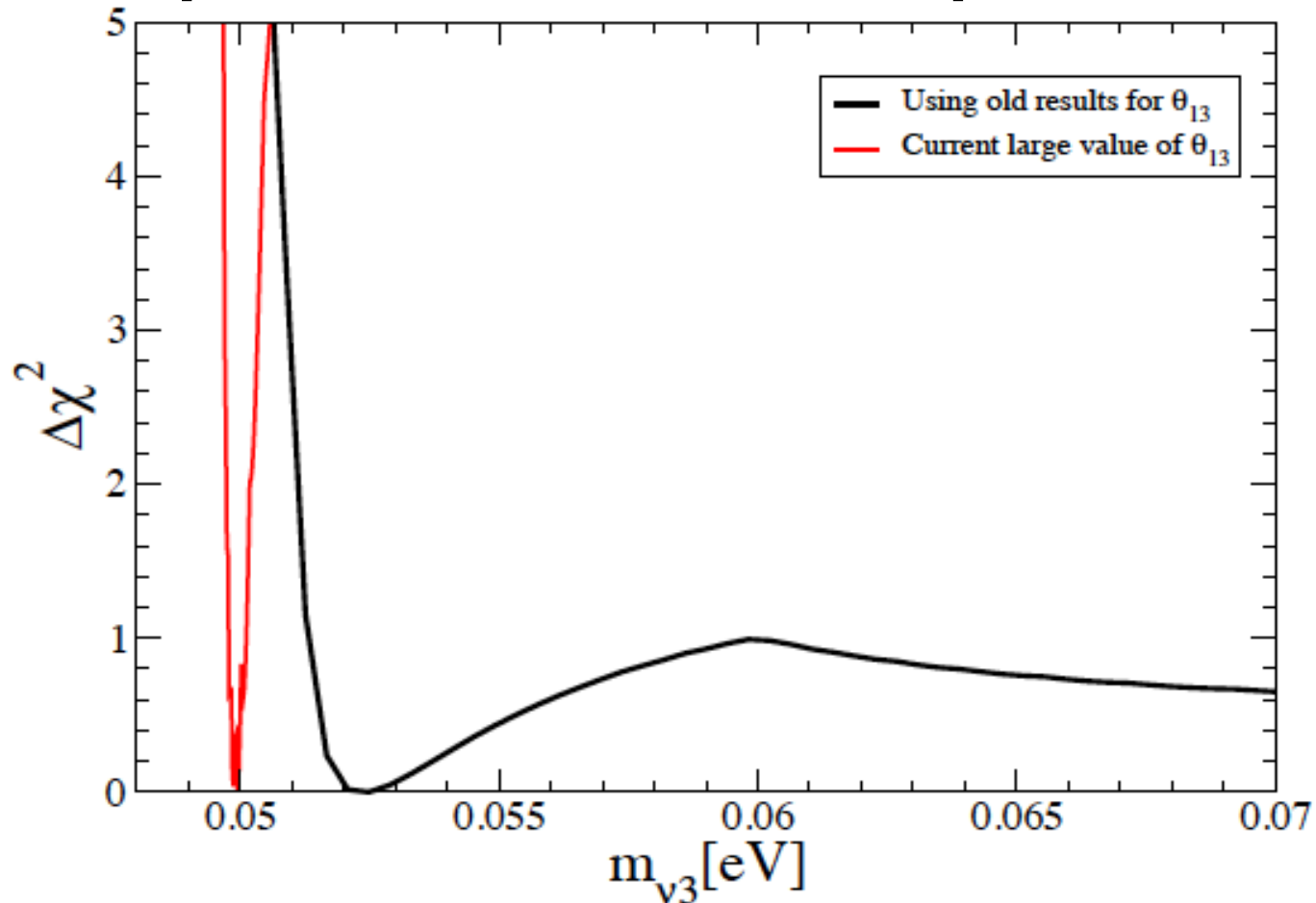
$$\chi_{\text{leptons}}^2(a_b, a_\nu, \Phi_1, m_{\nu 3})$$

$$= \sum_{i=1}^9 \left(\frac{U_{\text{PMNS}}^{\text{th}}(a_b, a_\nu, \Phi_1, m_{\nu 3}) - |U_{\text{PMNS}}|}{\delta U_{\text{PMNS}}} \right)^2.$$

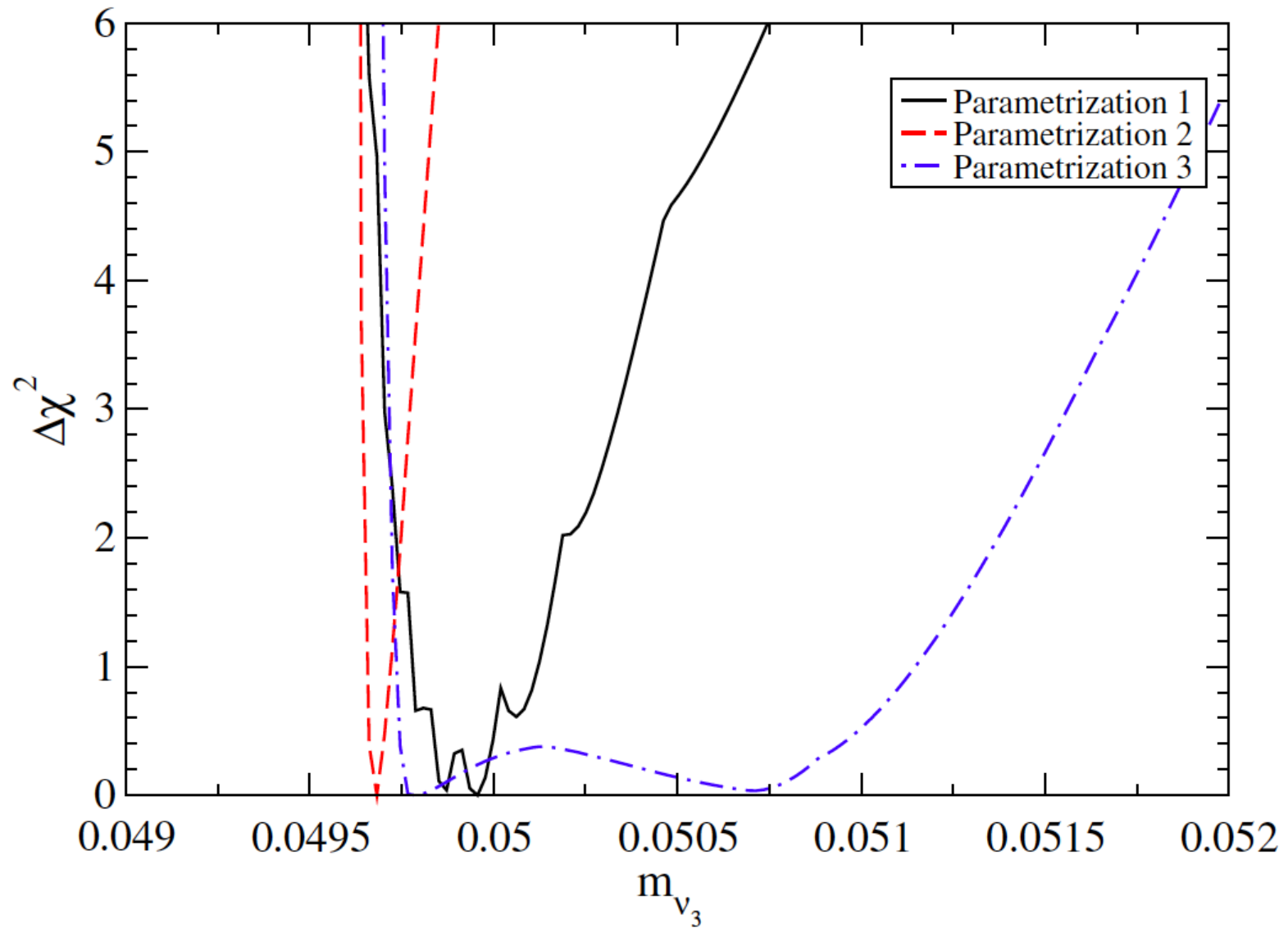
$$U_{\text{PMNS}}^{\text{th}} = O_l^T P^{l-\nu} O_\nu,$$



La importancia de la precisión



La masa del neutrino debe de ser del orden de 0.05 eV para dar valores consistentes de La matriz U_{PMNS}



La masa del neutrino debe de ser del orden de 0.05 eV para dar valores consistentes de La matriz U_{PMNS}

El sector leptónico

Parametrization	$m_{\nu_3}^{\text{bfp}}$	Φ_1^{bfp}	a_ν^{bfp}	a_l^{bfp}	χ_{\min}^2
(1, 1)	4.99×10^{-2}	$\Phi_1 = 3.14159$	$a_\nu = 0.2125$	$a_l = 0.0000$	$\chi_{\min}^2 = 4.6932$
(2, 2)	4.96×10^{-2}	$\Phi_1 = 2.80233$	$a_\nu = 0.6750$	$a_l = 0.0375$	$\chi_{\min}^2 = 0.0033$
(3, 3)	4.99×10^{-2}	$\Phi_1 = 1.679911$	$a_\nu = 0.4250$	$a_l = 0.9875$	$\chi_{\min}^2 = 0.7727$
(1, 2)	4.96×10^{-2}	$\Phi_1 = 2.366666$	$a_\nu = 0.2250$	$a_l = 0.8375$	$\chi_{\min}^2 = 0.0008$
(2, 1)	4.99×10^{-2}	$\Phi_1 = 0.000000$	$a_\nu = 0.2125$	$a_l = 0.0000$	$\chi_{\min}^2 = 4.6931$
(3, 2)	4.96×10^{-2}	$\Phi_1 = 3.141592$	$a_\nu = 0.3250$	$a_l = 0.0000$	$\chi_{\min}^2 = 0.0063$
(1, 3)	4.96×10^{-2}	$\Phi_1 = 0.000000$	$a_\nu = 0.2125$	$a_l = .02500$	$\chi_{\min}^2 = 2.0005$
(2, 3)	4.99×10^{-2}	$\Phi_1 = 1.466076$	$a_\nu = 0.4250$	$a_l = 0.9875$	$\chi_{\min}^2 = 0.6872$
(3, 1)	4.95×10^{-2}	$\Phi_1 = 3.141592$	$a_\nu = 0.0375$	$a_l = 0.1625$	$\chi_{\min}^2 = 2.8631$

Table 2. Best fit points for the leptonic sector.

El problema de jerarquía

1. La masa del neutrino es muy pequeña comparada con la masa del quark top
2. La masa del Higgs es muy pequeña comparada con la masa de Planck

¿Dos dobletes es una posible solución?

Cancelación de Divergencias cuadráticas

Z. Phys. C 62, 253–263 (1994)

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Mass relations in the two Higgs doublet model from the absence of quadratic divergences [★]

Conrad Newton, Tai Tsun Wu

Abstract. By setting the quadratic divergences to zero, four mass relations are obtained for the Standard Model generalized to two Higgs doublets. These four mass relations are obtained most simply in terms of the original fields in the Lagrangian, before spontaneous $SU(2) \times U(1)$ symmetry breaking is applied. Unlike the case of the Standard Model, the Higgs tadpoles of the two Higgs doublet theory do not furnish a complete set of mass relations, giving only three of the four.

En el modelo estándar, para que haya cancelación:

$$\frac{3}{2}M_W^2 + \frac{3}{4}M_Z^2 + \frac{3}{4}m_H^2 = \sum_f N_f m_f^2$$

Se necesitaría:

$$m_H = 316 \text{ GeV}.$$

En dos dobletes

$$\begin{aligned} V = & \mu_1^2 \Phi_1^\dagger \Phi_1 + \mu_2^2 \Phi_2^\dagger \Phi_2 + \mu_{12}^2 (\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1) \\ & + \frac{1}{2} \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2} \lambda_2 (\Phi_2^\dagger \Phi_2)^2 \\ & + \lambda_3 (\Phi_1^\dagger \Phi_1) (\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2) (\Phi_2^\dagger \Phi_1) \\ & + \frac{1}{2} \lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \frac{1}{2} \lambda_5^* (\Phi_2^\dagger \Phi_1)^2 . \end{aligned}$$

La condición para la cancelación de divergencias cuadráticas:

$$\frac{3}{2} M_W^2 + \frac{3}{4} M_Z^2 + \frac{v^2}{2} (3\lambda_1 + 2\lambda_3 + \lambda_4) = \frac{1}{\cos^2 \beta} \sum_{f_1} N_{f_1} m_{f_1}^2$$

$$\frac{3}{2} M_W^2 + \frac{3}{4} M_Z^2 + \frac{v^2}{2} (3\lambda_2 + 2\lambda_3 + \lambda_4) = \frac{1}{\sin^2 \beta} \sum_{f_2} N_{f_2} m_{f_2}^2$$

Reescribiendo dichas condiciones:

$$m_{H^\pm}^2 = -\mu_{12}^2(\tan \beta + \cot \beta) - (\lambda_4 + \lambda_5)v^2,$$

$$m_A^2 = -\mu_{12}^2(\tan \beta + \cot \beta) - 2\lambda_5v^2,$$

$$\mathcal{M}^2 = \begin{bmatrix} -\mu_{12}^2 \tan \beta + 2\lambda_1 v_1^2 & \mu_{12}^2 + 2(\lambda_3 + \lambda_4 + \lambda_5)v_1 v_2 \\ \mu_{12}^2 + 2(\lambda_3 + \lambda_4 + \lambda_5)v_1 v_2 & -\mu_{12}^2 \cot \beta + 2\lambda_2 v_2^2 \end{bmatrix}.$$

$$\mathcal{M}^2 = \begin{bmatrix} m_1^2 \cos^2 \alpha + m_2^2 \sin^2 \alpha & (m_1^2 - m_2^2) \sin \alpha \cos \alpha \\ (m_1^2 - m_2^2) \sin \alpha \cos \alpha & m_2^2 \cos^2 \alpha + m_1^2 \sin^2 \alpha \end{bmatrix}.$$

Que implica:

$$\begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} m_1^2 \\ m_2^2 \end{bmatrix} = \begin{bmatrix} C_1 \\ C_2 \end{bmatrix} \quad \begin{aligned} A_{11} &= \frac{3 \cos^2 \alpha}{\cos^2 \beta} + \frac{2 \sin \alpha \cos \alpha}{\sin \beta \cos \beta}, & A_{12} &= \frac{3 \sin^2 \alpha}{\cos^2 \beta} - \frac{2 \sin \alpha \cos \alpha}{\sin \beta \cos \beta}, \\ A_{21} &= \frac{3 \sin^2 \alpha}{\sin^2 \beta} + \frac{2 \sin \alpha \cos \alpha}{\sin \beta \cos \beta}, & A_{22} &= \frac{3 \cos^2 \alpha}{\sin^2 \beta} - \frac{2 \sin \alpha \cos \alpha}{\sin \beta \cos \beta}, \end{aligned}$$

$$C_1 = \frac{4}{\cos^2 \beta} \sum_{f_1} N_{f_1} m_{f_1}^2 - 6M_W^2 - 3M_Z^2 - 2m_{H^\pm}^2$$

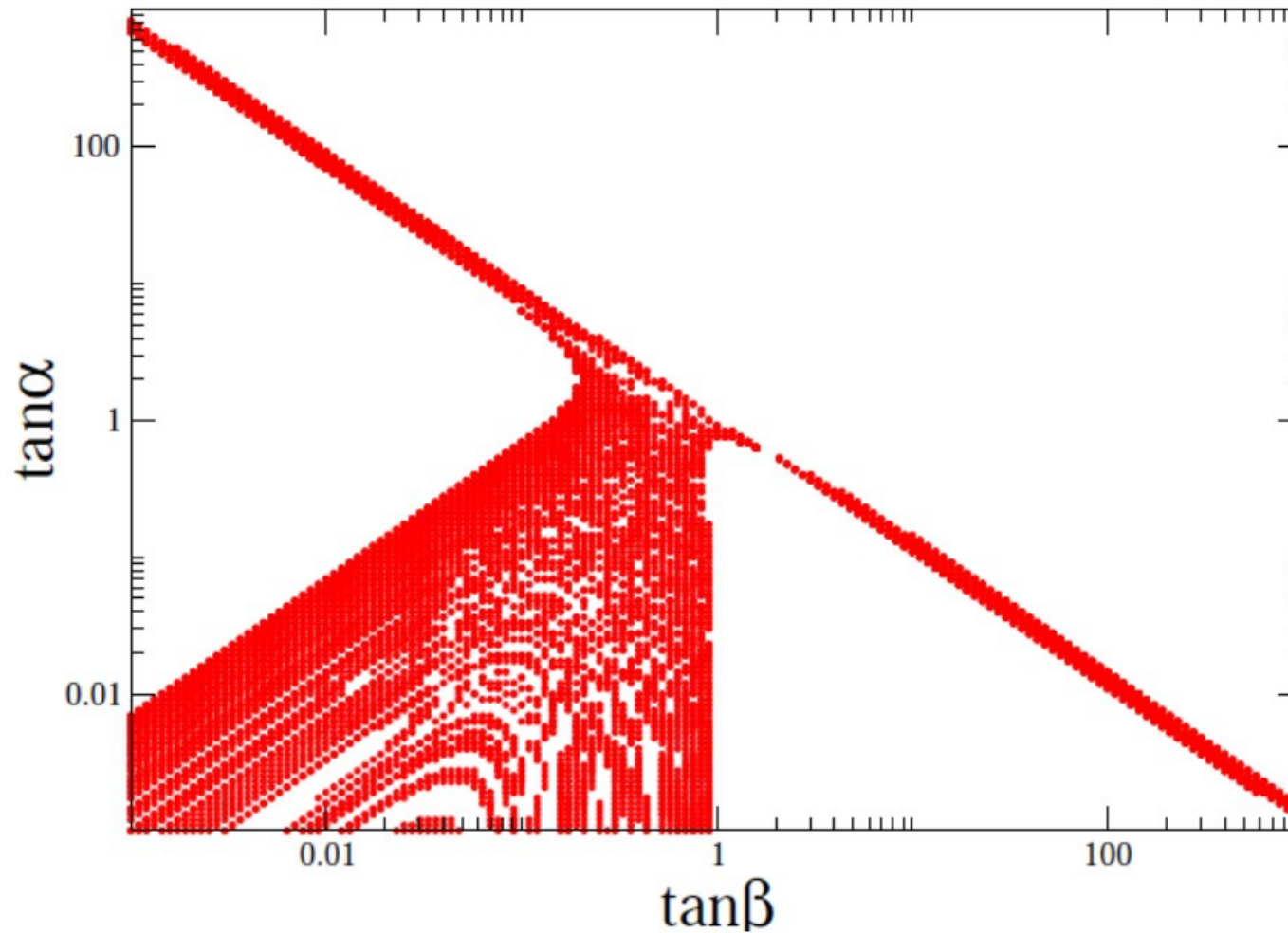
$$- m_A^2 - \frac{\mu_{12}^2}{\sin \beta \cos \beta} [1 + 3 \tan^2 \beta],$$

$$C_2 = \frac{4}{\sin^2 \beta} \sum_{f_2} N_{f_2} m_{f_2}^2 - 6M_W^2 - 3M_Z^2 - 2m_{H^\pm}^2$$

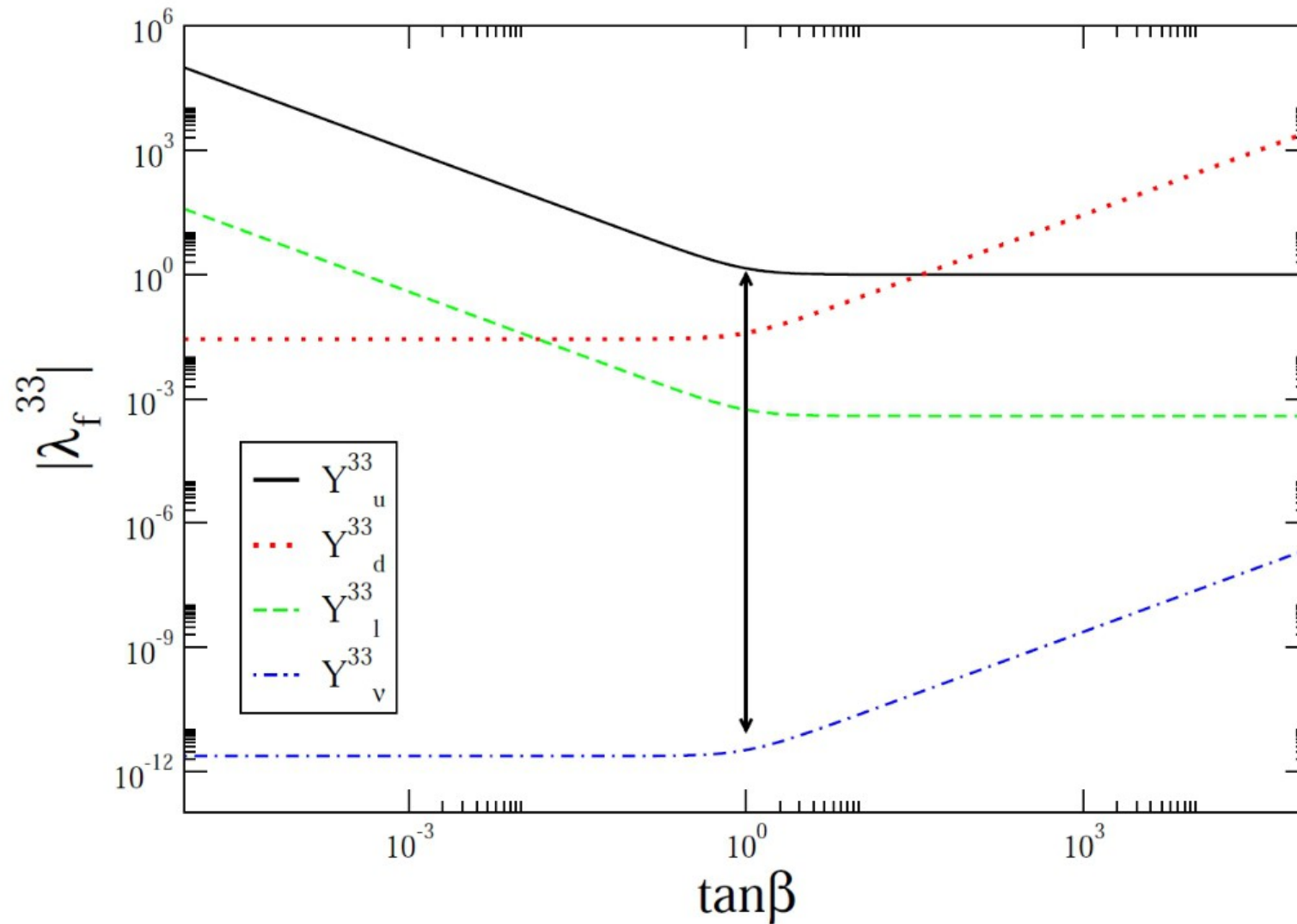
$$- m_A^2 - \frac{\mu_{12}^2}{\sin \beta \cos \beta} [1 + 3 \cot^2 \beta].$$

Ernest Ma, IJMP 2001

En un THDM tipo II



Masa del neutrino



O nos inventamos nuestro propio THDM

$$M_{ij} = y_{ij}^1 \frac{v_1}{\sqrt{2}} + y_{ij}^2 \frac{v_2}{\sqrt{2}}.$$

Proponemos el siguiente ansatz:

$$M_u = \frac{v \cos \beta}{\sqrt{2}} \lambda_u + \frac{v \sin \beta}{\sqrt{2}} \lambda_d$$

$$M_d = -\frac{v \sin \beta}{\sqrt{2}} \lambda_u + \frac{v \cos \beta}{\sqrt{2}} \lambda_d$$

$$M_f = \begin{pmatrix} 0 & C_f & 0 \\ C_f^* & D_f & B_f \\ 0 & B_f^* & A_u \end{pmatrix}$$

$$\lambda_f = \begin{pmatrix} 0 & \lambda_f^{12} & 0 \\ \lambda_f^{12*} & \lambda_f^{22} & \lambda_f^{23} \\ 0 & \lambda_f^{23*} & \lambda_f^{33} \end{pmatrix}$$

¡Reducción de parámetros!

$$2 \text{ parámetros} \longrightarrow A_u = \frac{v \cos \beta}{\sqrt{2}} \lambda_u^{33} + \frac{v \sin \beta}{\sqrt{2}} \lambda_d^{33}$$

$$2 \text{ parámetros} \longrightarrow A_d = \frac{v \sin \beta}{\sqrt{2}} \lambda_u^{33} + \frac{v \cos \beta}{\sqrt{2}} \lambda_d^{33}$$

$$\lambda_u^{33} = \frac{\sqrt{2}}{v} \frac{\sqrt{1 + \tan^2 \beta}}{1 - \tan^2 \beta} (m_t a_u - \tan \beta m_b a_d)$$

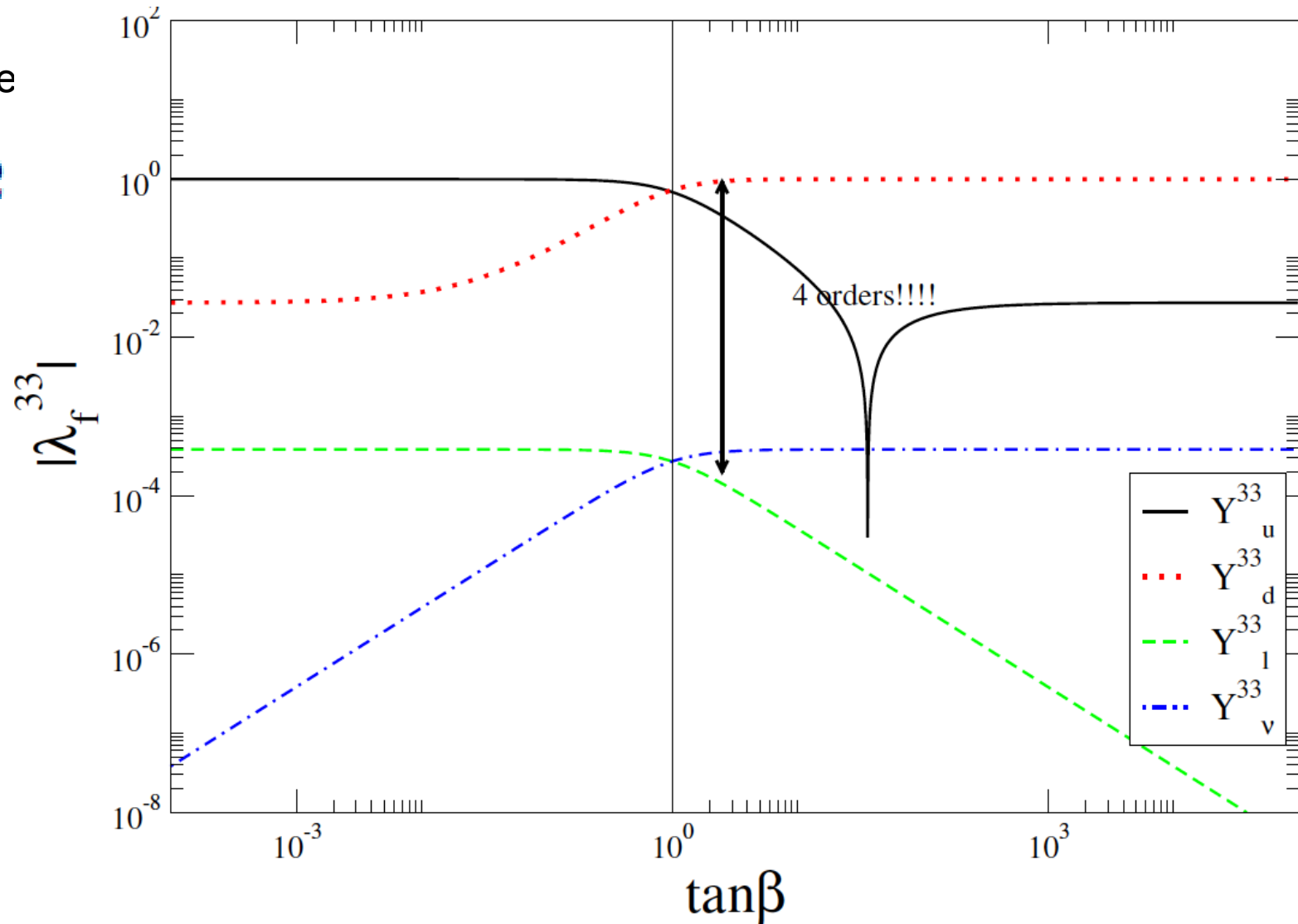
$$\lambda_d^{33} = \frac{\sqrt{2}}{v} \frac{\sqrt{1 + \tan^2 \beta}}{1 - \tan^2 \beta} (m_b a_b - \tan \beta m_t a_u)$$

¡No hay un problema tan grave en la jerarquía!

Con un sólo doblete

$$\lambda_\nu \sim 10^{-12}$$

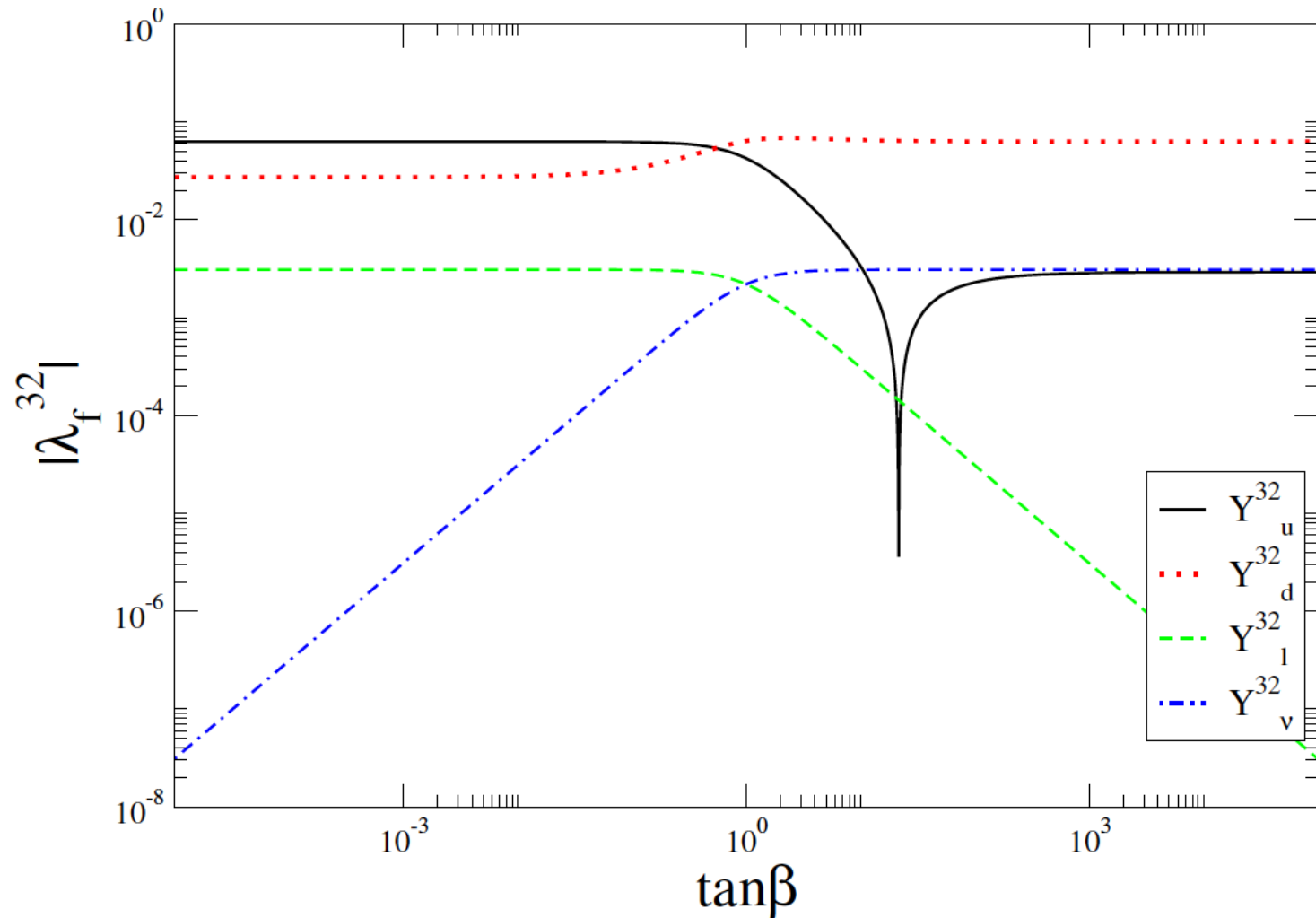
$$\lambda_{top} \sim 1$$



Con dos dobletes y nuestro ansatz.

Pero recuerden!!!

$$\tilde{m}_1 \leq a' \leq \tilde{m}_3 \quad \begin{cases} b' = \sqrt{\frac{(a' - \tilde{m}_1)(a' + \tilde{m}_2)(\tilde{m}_3 - a')}{a'}} \\ d' = -a' + \tilde{m}_1 - \tilde{m}_2 + \tilde{m}_3 \end{cases} \quad c' = \sqrt{\frac{\tilde{m}_1 \tilde{m}_2 \tilde{m}_3}{a'}}$$



Nuevas interacciones

$$\begin{aligned}
 \mathcal{L}_Y^l = & \frac{g}{2} \left(\frac{m_i}{m_W} \right) \bar{l}_i \left[\frac{\cos \alpha}{\cos \beta} \delta_{ij} + \frac{\sqrt{2} \sin(\alpha - \beta)}{g \cos \beta} \left(\frac{m_W}{m_i} \right) \tilde{Y}_{2ij}^l \right] l_j H^0 \\
 & + \frac{g}{2} \left(\frac{m_i}{m_W} \right) \bar{l}_i \left[-\frac{\sin \alpha}{\cos \beta} \delta_{ij} + \frac{\sqrt{2} \cos(\alpha - \beta)}{g \cos \beta} \left(\frac{m_W}{m_i} \right) \tilde{Y}_{2ij}^l \right] \\
 & \times l_j h^0 \\
 & + \frac{ig}{2} \left(\frac{m_i}{m_W} \right) \bar{l}_i \left[-\tan \beta \delta_{ij} + \frac{\sqrt{2}}{g \cos \beta} \left(\frac{m_W}{m_i} \right) \tilde{Y}_{2ij}^l \right] \gamma^5 l_j A^0.
 \end{aligned}$$

$$\begin{aligned}
 Br(\tau^- \rightarrow \mu^- \mu^+ \mu^-) = & \frac{5}{3} \frac{\tau_\tau}{2^{12} \pi^3} \frac{m_2^3 m_3^6}{v^4} \left\{ \frac{\cos^2(\alpha - \beta) \sin^2 \alpha}{m_{h^0}^4} + \frac{\sin^2(\alpha - \beta) \cos^2 \alpha}{m_{H^0}^4} \right. \\
 & \left. - 2 \frac{\cos(\alpha - \beta) \sin(\alpha - \beta) \cos \alpha \sin \alpha}{m_{h^0}^2 m_{H^0}^2} + \frac{\sin^2 \beta}{m_{A^0}^4} \right\} \frac{\chi_{23}^2}{\cos^4 \beta} \quad (
 \end{aligned}$$

Accesible experimentalmente en el orden de $10^{(-9)}$ en LHCb

Todavía falta...

- Fijar los acoplamientos de Yukawa y calcular los decaimientos que violan sabor
- Hallar una región que sea compatible con la cancelación de divergencias cuadráticas
- Estén pendientes!!

Conclusiones

- No hay suficiente violación en el ME para generar la asimetría materia antimateria.
- Hay una evidencia abrumadora de que existe un componente de materia oscura cuya composición no está en el ME.
- Problema de Θ QCD
- ¿Qué protege la masa del Higgs para que sea pequeña?

Conclusiones

- ¿Cuál es la escala de masas del neutrino?
- ¿Cuál es la jerarquía de masas?
- ¿Existe violación de CP en el sector leptónico?
- ¿Cuál es la naturaleza del neutrino: Dirac ó Majorana?