Majorana and Pseudo-Dirac Neutrinos at the ILC

XII SILAFAE - PUCP

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In collaboration with
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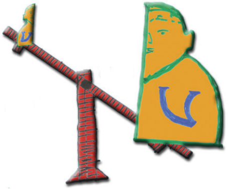
PONTIFICIA UNIVERSIDAD CATÓLICA DEL PERÚ

Type I Seesaw Mechanism

$\nu_e, \nu_\mu, \nu_\tau + \nu_{R1}, \nu_{R2}$
Where the ν_R have large masses.



The nature for the neutrinos can be:

- Dirac Type (LNC Process).
- Majorana Type (LNV Process).

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{\alpha=e,\mu,\tau} \bar{L}^{\alpha} Y_{\alpha 1} \Phi N_{1R} - \frac{1}{2} \bar{N}_{1R}^{c} M N_{2R} + h.c \tag{1}$$

$$M_{\nu} = \left(\begin{array}{c|cc} 0 & m_D & 0 \\ \hline m_D^T & 0 & M \\ 0 & M & 0 \end{array}\right) \tag{2}$$

Adding LNV parameters ϵ,μ,μ'.

$$M_{\nu} = \left(\begin{array}{c|cc} 0 & m_D & \varepsilon\, m_D' \\ \hline m_D^T & \mu' & M \\ \varepsilon\, {m_D'}^T & M & \mu \end{array}\right) \tag{3}$$

Parametrization

Mixing Matrix

$$U = \begin{pmatrix} (U_{a\ell})_{3x3} & (U_{ah})_{3x2} \\ (U_{s\ell})_{2x3} & (U_{sh})_{2x2} \end{pmatrix} \quad (4)$$

one can write

$$U_{a4} \simeq \pm Z_a \sqrt{\frac{m_3}{M_4}} \cosh\gamma \exp^{\mp i\theta} \qquad U_{a5} \simeq iZ_a \sqrt{\frac{m_3}{M_5}} \cosh\gamma \exp^{\mp i\theta} \quad (5)$$

Where γ, θ are parameters Casas-Ibarra R matrix

A. Donini , P. Hernandez , J. Lopez-Pavon , M. Maltoni , T. Schwetz
DOI: 10.1007/JHEP07(2012)161
A. Gago , P. Hernández, J. Jones-Pérez , M. Losada, A. Moreno Briceño
DOI: 10.1140/epjc/s10052-015-3693-1

With this parametrization, we can rebuild the mass matrix

$$M'_\nu = \begin{pmatrix} 0 & (m_D^{\rm new})_{a4} & (m_D^{\rm new})_{a5} \\ (m_D^{\rm new})^T_{a4} & M_4 & 0 \\ (m_D^{\rm new})^T_{a5} & 0 & M_5 \end{pmatrix} \quad (6)$$

$$(m_D^{\rm new})_{a4} \simeq \pm(Z_a)^* \sqrt{m_3 M_4} \cosh\gamma \, e^{\mp i\theta} \, , \quad (7)$$

$$(m_D^{\rm new})_{a5} \simeq -i(Z_a)^* \sqrt{m_3 M_5} \cosh\gamma \, e^{\mp i\theta} \, . \quad (8)$$

M_ν and M'_ν are related by are redefinition of ν_{R1}, ν_{R2} and $\mu, \epsilon \sim \mathcal{O}(m_\nu)$

we found : $\boxed{\mu' = \delta M \equiv M_5 - M_4}$,

$$\begin{cases} \mu' \to 0 \\ N_i \to \rm Pseudo-Dirac \;\; Neutrinos \end{cases} \quad (9)$$

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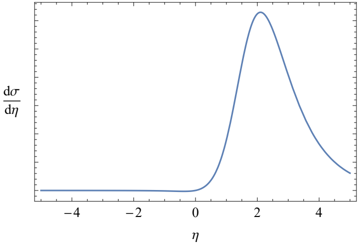
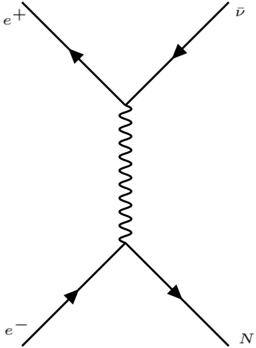
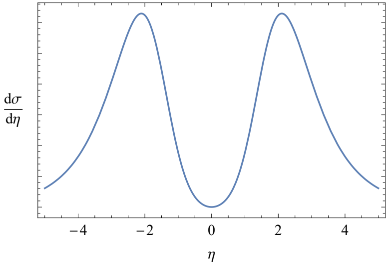
Pseudo-Dirac Neutrinos at the ILC

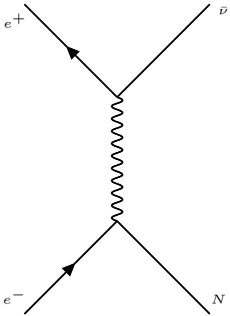
Dirac Neutrinos : $e^+e^- \longrightarrow \bar{\nu}N$

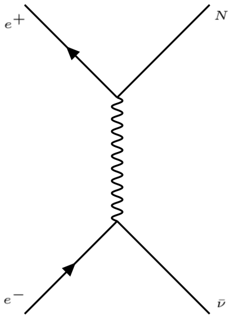




Majorana Neutrinos : $e^+e^- \longrightarrow \nu N$







$$e^- e^+ \longrightarrow \nu N^* \longrightarrow \nu \ell W^* \longrightarrow \nu \ell jj$$

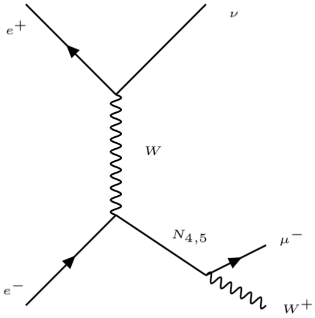


Diagram A (LNC)

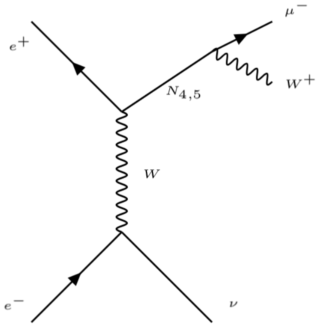


Diagram B (LNV)

the square element matrix.

$$|\mathcal{M}_A|^2 = \frac{1}{4}\left(\frac{g}{\sqrt{2}}\right)^6 \underbrace{\left[\sum_{j,k=4}^{5} \Omega_{Aj}\Omega_{Ak}^*\right]}_{\Phi_A} G_A^{\lambda\delta}\, \epsilon_\lambda^*(p_4)\, \epsilon_\delta(p_4) \tag{10}$$

where:

$$\Omega_{Aj} = \frac{U_{\mu j}^* U_{ej} U_{e\nu}^*}{f(M_j)}\,, \qquad f(M_j) \equiv q^2 - M_j^2 + iM_j\,\Gamma_j \tag{11}$$

in the LNC limit: $M_5 \to M_4$ y $\Gamma_5 \to \Gamma_4$

$$\Phi_A^{\rm LNC} = 4|Z_e|^2|Z_\mu|^2|U_{e\nu}|^2 \cosh^4\gamma_{45}\,\frac{m_3^2}{M_4^2}\frac{1}{|f(M_4)|^2}. \tag{12}$$

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$$|\mathcal{M}_B|^2 = \frac{1}{4}\left(\frac{g}{\sqrt{2}}\right)^6 \underbrace{\left[\sum_{j,k=4}^{5} \frac{M_j M_k}{q^2}\Omega_{Bj}\Omega^*_{Bk}\right]}_{\Phi_B} G_B^{\lambda\delta}\, \epsilon^*_\lambda(p_4)\, \epsilon_\delta(p_4) \qquad (13)$$

where:

$$\Omega_{Bj} = \frac{U^*_{\mu j} U^*_{ej} U_{e\nu}}{f(M_j)}\ , \qquad f(M_j) \equiv q^2 - M_j^2 + iM_j\,\Gamma_j \qquad (14)$$

in the LNC limit: $M_5 \to M_4$ y $\Gamma_5 \to \Gamma_4$

$$\Phi_B^{LNC} = 0 \qquad (15)$$

$$|\mathcal{M}_B|^2 = \frac{1}{4}\left(\frac{g}{\sqrt{2}}\right)^6 \underbrace{\left[\sum_{j,k=4}^{5} \frac{M_j M_k}{q^2}\Omega_{Bj}\Omega^*_{Bk}\right]}_{\Phi_B} G_B^{\lambda\delta}\,\epsilon^*_\lambda(p_4)\,\epsilon_\delta(p_4) \tag{13}$$

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in the LNC limit: $M_5 \to M_4$ y $\Gamma_5 \to \Gamma_4$

$$\Phi_B^{LNC} = 0 \tag{15}$$

We do an expansion:

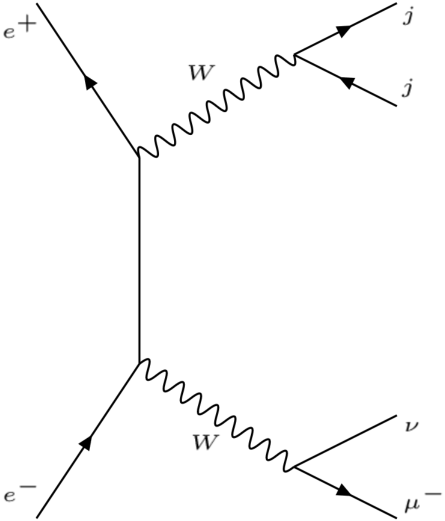
$$\Phi_B \xrightarrow{LNC} 4|Z_\mu|^2|Z_e|^2|U_{e\nu}|^2 \cosh^4\gamma_{45} \frac{m_3^2}{M_4^2}\frac{M_4^4}{q^2|f(M_4)|^4} \quad \times$$
$$\left[\left(1+\frac{\Gamma_4^2}{4M_4^2}\right)(\delta M)^2 + \frac{1}{4}(\delta\Gamma)^2 + \frac{\Gamma_4}{2M_4}\delta\Gamma\,\delta M\right] \tag{16}$$

we have : $\delta M \gg \delta\Gamma$
if we consider the heavy neutrino on-shell:

$$\left(\frac{\Phi_B}{\Phi_A}\right)_{\mathrm{on-shell}} \xrightarrow{LNC} \left(1+\frac{\Gamma_4^2}{4M_4^2}\right)\left(\frac{\delta M}{\Gamma_4}\right)^2 \tag{17}$$

Forward-Backward Asymmetry and Results

The condition for Displaced Vertices:



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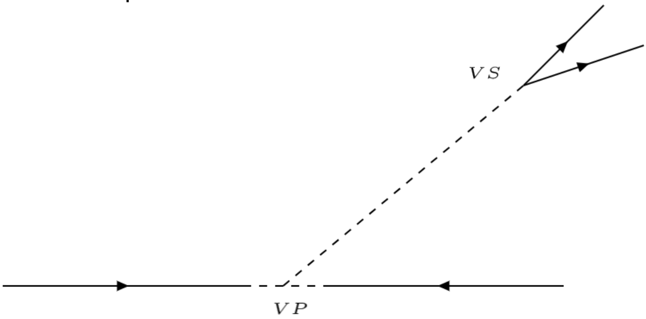


$$10\ \mu\mathrm{m} < L_T < 2.49\ \mathrm{m} \qquad L_z < 3.018\ \mathrm{m}. \tag{18}$$

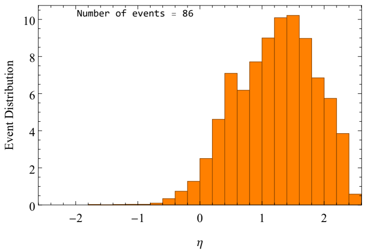
$$d_\ell \equiv \frac{|L_x\, p_y^\ell - L_y\, p_x^\ell|}{p_T^\ell} > 6\ \mu\mathrm{m} \tag{19}$$

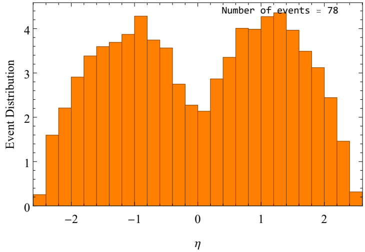
S. Antusch, E. Cazzato, O. Fischer
DOI: 10.1007/JHEP12(2016)007

In this work , we have two scenarios:

Name	Mass (GeV)	$\vert U_{\mu 4}\vert^2$	Γ_4 (meV)	$c\,\tau_4$ (μm)
Light	5	$1.0x10^{-5}$	0.02	10
Heavy	20	$5.0x10^{-6}$	20	0.01

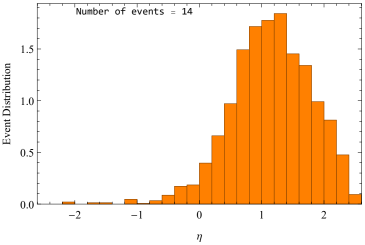
M=5 GeV

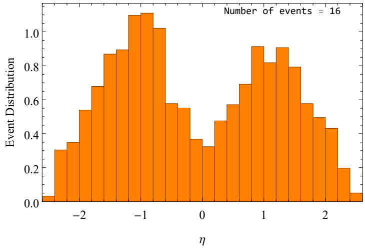




$\delta M < \Gamma$

$\delta M > \Gamma$





M=20 GeV

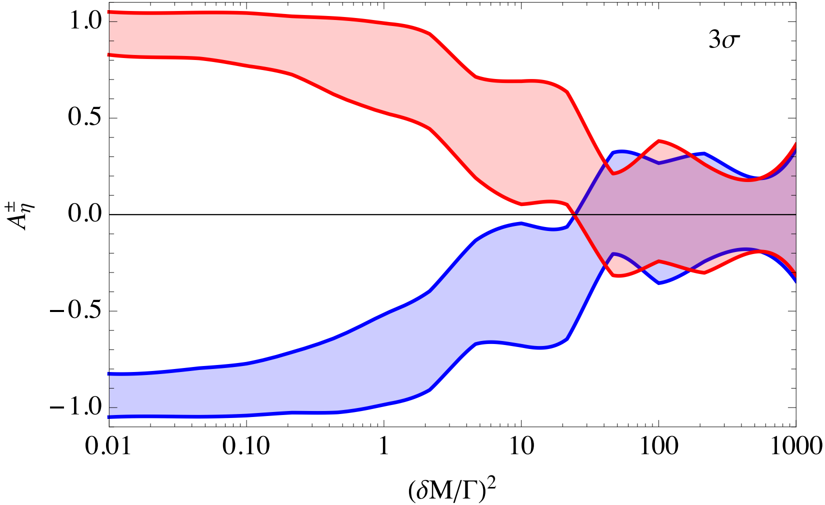
the asimetry was calculate with the next expresion:

$$A_\eta^\pm = \frac{N^\pm(\eta > 0) - N^\pm(\eta < 0)}{N^\pm_{\mathrm{tot}}} \quad (20)$$

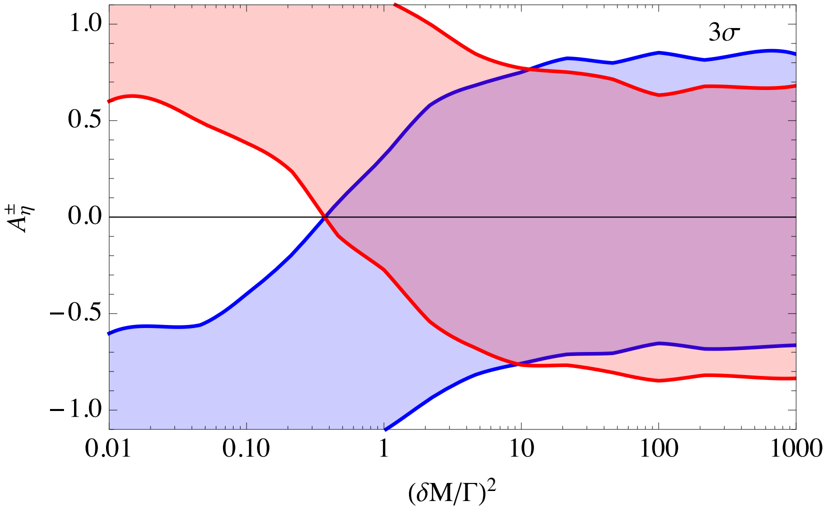
the total asimetry:

$$A_\eta^{tot} = \frac{A_\eta^- - A_\eta^+}{2} \quad (21)$$

M=5 GeV



M=20 GeV



Conclusions

- For M = 5 GeV, we found upper or lower limits on $\delta M \sim 50\mu eV$, and for M = 20 GeV, $\delta M \sim 20 meV$
- we can probe the nature of the neutrinos by the observing or not in the η distribution of the lepton.

Acknowledgments

Thanks

Acknowledgments

- **HEP-PUCP**
- **Becas Jóvenes Investigadores 2017 de países en vías de desarrollo del Programa de Cooperación 0'7 de la Universitat de València.**

Apendice A

Diagram A:

$$\Gamma^{\mu} = U_{eN}\gamma^{\mu}(1-\gamma^{5}) \tag{1}$$

$$\Gamma^{\lambda} = U^{*}_{\mu N}\gamma^{\lambda}(1-\gamma^{5}) \tag{2}$$

$$\Gamma^{\nu} = U^{*}_{e\nu}\gamma^{\nu}(1-\gamma^{5}) \tag{3}$$

Diagram B:

$$\Gamma^{\mu} = U_{e\nu}\gamma^{\mu}(1-\gamma^{5}) \tag{4}$$

$$\Gamma^{\lambda} = U^{*}_{\mu N}\gamma^{\lambda}(1-\gamma^{5}) \tag{5}$$

$$\Gamma^{\nu} = U^{*}_{eN}\gamma^{\nu}(1-\gamma^{5}) \tag{6}$$

$$\Gamma^{\mu\dagger} = U_{eN}(1-\gamma^5)\gamma^{\mu\dagger} \tag{7}$$

$$\gamma^{\mu\dagger} = \gamma^0\gamma^\mu\gamma^0 \tag{8}$$

we have:

$$\Gamma'^{\mu} = C\Gamma^{\mu T}C^\dagger \tag{9}$$

$$C(\gamma^\mu\gamma^5)^T C^{-1} = \gamma^\mu\gamma^\nu \tag{10}$$

$$C(\gamma^\mu)^T C^{-1} = -\gamma^\mu \tag{11}$$

Diagram A:

$$\Gamma'^{\mu} = -U_{eN}\gamma^\mu(1+\gamma^5) \tag{12}$$

Diagram B:

$$\Gamma'^{\mu} = -U_{e\nu}\gamma^\mu(1+\gamma^5) \tag{13}$$

Heavy neutrino propagator:

$$-iS_j = \frac{\not{q} + M_j}{q^2 - M_j^2 + iM_j\Gamma_j} \equiv \frac{\not{q} + M_j}{f(M_j)}, \tag{14}$$

Apendice B

$$C^T(1+\gamma^5)^T\gamma^{\lambda T}C^\dagger = \gamma^\lambda(1-\gamma^5) \quad (15)$$

$$C^T(1-\gamma^5)^T\gamma^{\mu T}C^\dagger = \gamma^\mu(1+\gamma^5) \quad (16)$$

$$C^T\gamma^{\mu T}(1+\gamma^5)^T C^\dagger = \gamma^\mu(1+\gamma^5) \quad (17)$$

$$v(p) = C\bar{u}^T(p) \quad (18)$$

$$u(p) = C\bar{v}^T(p) \quad (19)$$

$$u^T(p) = \bar{v}(p)C^T \quad (20)$$

$$v^T(p) = \bar{u}(p)C^T \quad (21)$$

$$\bar{u}^T(p) = C^\dagger v(p) \quad (22)$$

$$\bar{v}^T(p) = C^\dagger u(p) \quad (23)$$

Apendice C

$$Z_a \equiv (U_{\rm PMNS})_{a3} \pm i\sqrt{\frac{m_2}{m_3}}(U_{\rm PMNS})_{a2} \tag{24}$$

$$\begin{aligned} H &= \left(I + m_\ell^{1/2}\, R^\dagger\, M_h^{-1}\, R\, m_\ell^{1/2}\right)^{-1/2} \\ \bar{H} &= \left(I + M_h^{-1/2}\, R\, m_\ell\, R^\dagger\, M_h^{-1/2}\right)^{-1/2} \end{aligned} \tag{25}$$

$$(m_D^{\rm new})_{a4} \simeq \pm(Z_a)^* \sqrt{m_3 M_4} \cosh\gamma\, e^{\mp i\theta}\ , \tag{26}$$

$$(m_D^{\rm new})_{a5} \simeq -i(Z_a)^* \sqrt{m_3 M_5} \cosh\gamma\, e^{\mp i\theta}\ . \tag{27}$$

Dirac and Majorana Neutrinos

Dirac Neutrinos

$$\Psi = \Psi_L + \Psi_R \tag{28}$$

Majorana Neutrinos

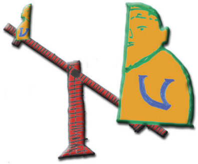
$$\Psi_R = C\overline{\Psi_L}^T \tag{29}$$

$$\Psi = \Psi_L + \Psi_R = \Psi_L + C\overline{\Psi_L}^T = \Psi^C \tag{30}$$

Majorana condition

mass terms: $m_R\overline{\nu}_R\nu_R^C$,$m_L\overline{\nu}_L\nu_L^C$

Type I Seesaw Mechanism



Fuente:*www.physics.umd.edu/news/photon/iss040/spot_research.html*

mass matrix

$$M_\nu = \left(\begin{array}{c|cc} 0 & m_D & 0 \\ \hline m_D^T & 0 & M \\ 0 & M & 0 \end{array}\right) \tag{31}$$

$$M_{light} \simeq -m_D(m)^{-1}{m_D}^T \tag{32}$$

$$M_{heavy} \simeq m \tag{33}$$

- The model was implement in SARAH 4.12.3, and the parameters are obtained from SPheno 3.3.8.
- The output of the previous programs is introduced in WHIZARD 2.6.0, in which e^+e^- interactions are generated.
- The simulation includes initial state polarization, ISR and Beamstrahlung.
- We used $\sqrt{s} = 250$ GeV and an integrated luminosity of $2ab^{-1}$.
- The Parton Shower and the Hadronization with Pythia 6, and for the events reconstrucction with Delphes 3.4.1, we use the DsiD card for the ILC.