Lepton Flavour Violation in Z decays

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1. Introduction
2. Neutrino generalities
3. General expressions for LFV/LNV $Z \to \ell_1 \ell_2$ with massive neutrinos
4. Contributions from the light neutrino sector
5. Contributions from a heavy neutrino sector
6. Conclusions

Aim

• Observed neutrinos are light but massive ⇒ flavour mixing

▷ What is the size of LFV in $Z \to \ell_1 \ell_2$ taking neutrino masses and mixings from oscillation experiments, assuming

1. three light neutrino flavours (νSM)

• Heavy neutrinos can explain the lightness of the observed ones (seesaw) and are predicted by GUT and string-inspired models.

▷ What is the effect on LFV/LNV in $Z \to \ell_1 \ell_2$, assuming

2. one heavy SU(2)$_L$⊗U(1)$_Y$ sequential Dirac neutrino

3. one heavy isosinglet Majorana neutrino

4. two heavy isosinglet Majorana neutrinos (includes the case of one heavy isosinglet neutrino)

Assumptions

• Experimental constraints from flavour diagonal and other flavour non-diagonal processes

• Results independent of neutrino mass models

Motivation

Best direct limits at 95% c.l.:

Process	LEP 1 *[PDG '98]*	TESLA Giga–Z *[G. Wilson '98]*
$\mathrm{BR}(Z \to e^{\mp}\mu^{\pm}) <$	1.7×10^{-6}	2×10^{-9}
$\mathrm{BR}(Z \to e^{\mp}\tau^{\pm}) <$	9.8×10^{-6}	$f \times 6.5 \times 10^{-8}$
$\mathrm{BR}(Z \to \mu^{\mp}\tau^{\pm}) <$	1.2×10^{-5}	$f \times 2.2 \times 10^{-8}$

$f = 0.2 - 1.0$

Neutrinos in the SM

Convention	LH		RH	Definition	
		$\mathcal{P}$			
Particles	ψ_L	$\longleftrightarrow$	ψ_R	neutrinos	$(L=1)$
	$\mathcal{C}\ \updownarrow$		$\updownarrow\ \mathcal{C}$		
Antiparticles	ψ_R^c	$\longleftrightarrow$	ψ_L^c	antineutrinos	$(L=-1)$
		$\mathcal{P}$			

Facts: Neutral, weakly interacting spin-$\frac{1}{2}$ fermions
There are three light flavours [Z lineshape]
Lepton Number is Conserved [$\not\exists\ (2\beta)_{0\nu}$]

$\Rightarrow$SM: Neutrinos taken massless: economical solution
[end-point of Kurie-plot of β decay, $\not\exists\ \nu_\alpha \to \nu_\beta\gamma$]
although no symmetry implies zero mass (unlike γ).
Consequences:
– RH neutrinos are sterile and therefore not needed, since they serve only to build Dirac mass terms
– Majorana mass terms $\overline{\psi_L^c}\psi_L$ $(|\Delta L=2|)$ not possible with one Higgs doublet, even at the loop-level or including non-perturbative effects (instantons), since $B-L$ is a good symmetry.

Neutrinos beyond the SM

New facts:

Neutrinos oscillate!

They must be massive. Two possibilities, since they are neutral:

- Neutrinos are Dirac fermions ν
  $\psi \equiv \nu = \nu_L + \nu_R$
  like quarks or charged leptons

- Neutrinos are Majorana fermions $\chi = \eta\, \chi^c$
  $\psi \equiv \chi = \chi_L + \eta\, \chi_L^c$
  with $\mathcal{CP}$ parity η^*

$\Rightarrow$ SM must be extended

$\circ$ Extend the Higgs sector: introduce Higgs triplets and allow LNV

– Impact on ρ parameter
– Spontaneous LNV $\Rightarrow$ "triplet Majoron" ruled out by LEP

$\surd$ • Extend the lepton sector with new neutrinos: 3 $\nu_L + \ldots$
($\#$ of $SU(2) \otimes U(1)$ isosinglet ν's not limited by gauge symmetry)

i. νSM: natural extension of the SM
introduce 3 RH isosinglet ν_R to form 3 light Dirac ν's
$\Rightarrow$ LNC, but possible LFV (like in quark sector)

ii. String-inspired models $\Rightarrow$ heavy Dirac isosinglets: LNC

iii. GUT's $\Rightarrow$ heavy RH Majorana isosinglets: LNV

Dirac and Majorana mass terms

$$-\mathcal{L}_m^\nu = \overbrace{\overline{\nu_R^0}\ \mathbf{m}_D\ \nu_L^0}^{\text{Dirac}} + \overbrace{\frac{1}{2}\ \overline{\nu_L^{0c}}\ \mathbf{m}_L\ \nu_L^0 + \frac{1}{2}\ \overline{\nu_R^{0c}}\ \mathbf{m}_R\ \nu_R^0}^{\text{Majorana}} + h.c.$$

$$= \frac{1}{2}\ \overline{\chi_L^{0c}}\ \mathbf{M}\ \chi_L^0 + h.c.$$

with $\nu_{L\,i}^0$ $(i = 1, \ldots, n_G)$, $\nu_{R\,j}^0$ $(j = 1, \ldots, n_R)$, introducing the Majorana fields $\chi^0 = \chi^{0c}$:

$$\chi_k^0 = \chi_{L\,k}^0 + \chi_{L\ k}^{0c} \equiv \begin{pmatrix} \nu_L^0 + \nu_L^{0c} \\ \nu_R^{0c} + \nu_R^0 \end{pmatrix}_{k=1,\ldots,n_G+n_R}$$

and **M** complex, symmetrix, $(n_G + n_R)$-dimensional:

$$\mathbf{M} \equiv \begin{pmatrix} \mathbf{m}_L & \mathbf{m}_D^T \\ \mathbf{m}_D & \mathbf{m}_R \end{pmatrix}$$

Diagonalization: $\mathbf{U}^T\ \mathbf{M}\ \mathbf{U} = \hat{\mathbf{M}}$

– Eigenvectors: $\chi_L^0 = \mathbf{U}\ \chi_L$
$\chi_L^{0c} = \mathbf{U}^*\ \chi_L^c$

– Eigenvalues: m_i complex in general

$\Rightarrow$ irrelevant phases to be absorbed by field rephasing (fully if $\mathcal{CP}$ is conserved)

$\Rightarrow$ physical states: $\xi_i \equiv \chi_{L\,i} + \eta_i\ \chi_{L\,i}^c$ with $\mathcal{CP}$ parity η_i^* namely $\mathbf{U} \to \mathbf{U}\ \sqrt{\boldsymbol{\eta}}$ with $\sqrt{\boldsymbol{\eta}}$=**diag**$(\sqrt{\eta_i})$

$\Rightarrow$ physical masses: $|m_i| = \eta_i m_i$ real and positive

Two Majorana neutrinos

$$n_G = n_R = 1$$

$$\mathbf{M} = \begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix} \qquad \mathbf{U} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

$$m_{1,2} = \frac{1}{2}\left\{ m_R + m_L \mp \sqrt{(m_R - m_L)^2 + 4m_D^2} \right\}$$

$$\tan 2\theta = \frac{2m_D}{m_R - m_L}, \quad \cos 2\theta = \frac{m_R - m_L}{\sqrt{(m_R - m_L)^2 + 4m_D^2}}$$

A. Two Majorana neutrinos: Dirac limit

$$m_L = m_R = 0$$

$$\theta = \frac{\pi}{4} \Rightarrow \left\{ \begin{array}{rcrcl} m_1 & = & -m_D < 0 & \rightsquigarrow & \eta_1 = -1 \\ m_2 & = & m_D > 0 & \rightsquigarrow & \eta_2 = +1 \end{array} \right.$$

$$\mathbf{U} \to \mathbf{U}\sqrt{\boldsymbol{\eta}} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ -1 & 1 \end{pmatrix} \begin{pmatrix} i & 0 \\ 0 & 1 \end{pmatrix}$$

or

$$\xi_1 = \chi_{1L} + \eta_1\, \chi^c_{1L} = \frac{1}{\sqrt{2}}[(\nu^{0c}_R - \nu^0_L) + \eta_1(\nu^0_R - \nu^{0c}_L)]$$

$$\xi_2 = \chi_{2L} + \eta_2\, \chi^c_{2L} = \frac{1}{\sqrt{2}}[(\nu^0_L + \nu^{0c}_R) + \eta_2(\nu^{0c}_L + \nu^0_R)]$$

so that

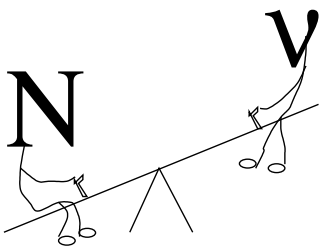
$$\begin{aligned} -\mathcal{L}^\nu_m &= \frac{m_D}{2}\,(-\overline{\chi_1}\chi_1 + \overline{\chi_2}\chi_2) = \frac{m_D}{2}\,(\overline{\xi_1}\xi_1 + \overline{\xi_2}\xi_2) \\ &= m_D\,(\overline{\nu^0_R}\nu^0_L + \overline{\nu^0_L}\nu^0_R) \end{aligned}$$

$\Rightarrow$ Two Majorana neutrinos of equal mass and opposite $\mathcal{CP}$ parities form a Dirac neutrino

B. Two Majorana neutrinos: seesaw

$m_L = 0,\ m_D \ll m_R$

(e.g. Higgs sector consists of Higgs doublets)



Light neutrino ν: Heavy neutrino N:

$$m_\nu \simeq \frac{m_D^2}{m_R} \ll m_N \qquad m_N \simeq m_R$$

$$(\eta_1 = -1) \qquad (\eta_2 = +1)$$

Light-heavy mixing:

$$\theta \simeq \frac{m_D}{m_R} \simeq \sqrt{\frac{m_\nu}{m_N}} \ll 1$$

Provides an explanation of the lightness of the known neutrinos:
There is a heavy scale m_R where Lepton Number is violated

$n_G + n_R$ Majorana neutrinos

($n_G \neq n_R$ in general)

Minimal seesaw

[T. Yanagida '79; M. Gell-Mann, P. Ramond, R. Slansky '79; R.N. Mohapatra, G. Senjanovic '80]

$$\left.\begin{array}{l} m_D \sim m_\ell \\ m_R \lesssim m_{\rm GUT} \end{array}\right\} \rightsquigarrow m_{\nu_\ell} \simeq \frac{m_\ell^2}{m_N} \sim \text{eV}$$

at the price of a tiny light-heavy mixing $\theta_\ell \simeq \sqrt{\dfrac{m_{\nu_\ell}}{m_N}}$

Interfamily seesaw

[W. Buchmüller, C. Greub '92; A. Pilaftsis '92]

Several heavy RH neutrinos with general Majorana mass terms $\mathbf{m}_R$ may produce not so small light-heavy mixings

CC and NC Lagrangians: B and C mixings

Interaction Lagrangians in $SU(2)_L \otimes U(1)_Y$, with ordinary charged leptons and n_G LH isodoublets and n_R RH isosinglet neutrinos

$$\begin{aligned} \ell^0_{Li} &= \sum_{j=1}^{n_G} \mathbf{U}^{\ell}_{ij}\, \ell_{Lj} &&= (e, \mu, \tau, \ldots) \\ \nu^0_{Li} &= \sum_{j=1}^{n_G+n_R} \mathbf{U}_{ij}\, \chi_{Lj} &&= (\nu_e, \nu_\mu, \nu_\tau, \ldots) \end{aligned}$$

[J. Schechter, J.W.F. Valle '80; J.G. Körner et al. '93]

▷ Charge Currents:

$$\begin{aligned} -\mathcal{L}_{CC} &= \frac{g}{\sqrt{2}} W_\mu\, \overline{\ell^0_{Li}} \gamma^\mu P_L \nu^0_{Li} + h.c. \\ &= \frac{g}{\sqrt{2}} W_\mu\, \mathbf{B}_{ij}\, \overline{\ell_{Li}} \gamma^\mu P_L \chi_{Lj} + h.c. \end{aligned}$$

with $\mathbf{B}_{ij} \equiv \sum_{k=1}^{n_G} \mathbf{U}^{\ell *}_{ki} \mathbf{U}_{kj}$ a rectangular $n_G \times (n_G + n_R)$ matrix

$\Rightarrow$ Lepton Flavour Change due to mixing

Generalization of the $n_G \times n_G$ LCKM matrix $\mathbf{V}_{ij} \equiv \sum_{k=1}^{n_G} \mathbf{U}^{\ell *}_{ki} \mathbf{U}^{\nu}_{kj}$

▷ Neutral Currents:

$$\begin{aligned} -\mathcal{L}^Z_{NC} &= \frac{g}{2c_W} Z_\mu\, [\overline{\nu^0_{Li}} \gamma^\mu P_L \nu^0_{Li} - \overline{\nu^{0c}_{L\ i}} \gamma^\mu P_R \nu^{0c}_{Li}] \\ &= \frac{g}{2c_W} Z_\mu\, \overline{\chi_i}\, [\mathbf{C}_{ij} P_L - \mathbf{C}^*_{ij} P_R]\, \chi_j \end{aligned}$$

with $\mathbf{C}_{ij} \equiv \sum_{k=1}^{n_G} \mathbf{U}^*_{ki} \mathbf{U}_{kj}$ a quadratic $(n_G + n_R)^2$ matrix

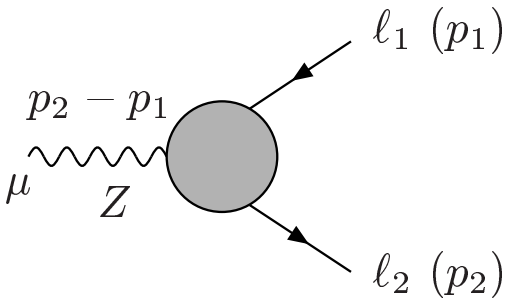
$\Rightarrow$ Flavour Changing Neutral Currents at tree level

$\Rightarrow$ Both L and R chiralities interact with the Z boson

$\Rightarrow$ Lepton Number Violation through $\nu - \nu^c$ mixing

Branching Ratio $Z \to \ell_1 \ell_2$

Born amplitude is zero



To one loop:

vertex + fermion self–energy graphs

$$\mathcal{M} = -\frac{ig\alpha_W}{16\pi c_W}\mathcal{V}(Q^2)\ \varepsilon_Z^\mu\ \bar{u}_{l_2}(p_2)\ \gamma_\mu(1-\gamma_5)\ u_{l_1}(-p_1)$$

$$\alpha_W = \frac{g^2}{4\pi}, \quad Q^2 = (p_2 - p_1)^2$$

$$\mathrm{BR}(Z \to l_1^\mp l_2^\pm) = \underbrace{\frac{\alpha_W^3 M_Z}{192\pi^2 c_W^2 \Gamma_Z}}_{\approx 10^{-6}} |\mathcal{V}(M_Z^2)|^2$$

Dirac

($i = 1, \ldots n_G$ ν's with isodoublet L and isosinglet R components):

$$\begin{aligned}\mathcal{V}_D(Q^2) &= \sum_{i=1}^{n_G} \mathbf{V}_{l_1 i}\mathbf{V}^*_{l_2 i}\ V(i)\\ V(i) &= v_W(i) + v_\phi(i) + v_{WW}(i) + v_{\phi\phi}(i) + v_{W\phi}(i) + v_\Sigma(i)\end{aligned}$$

Majorana

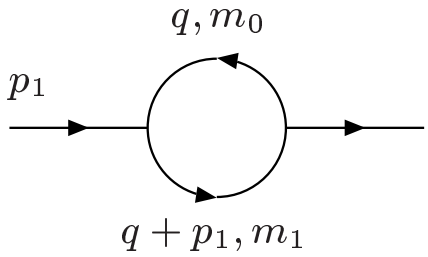
($i = 1, \ldots n_G$ isodoublet ν_L's + n_R isosinglet ν_R's):

$$\mathcal{V}_M(Q^2) = \sum_{i,j=1}^{n_G+n_R} \mathbf{B}_{l_1 i}\mathbf{B}^*_{l_2 j}\ V_M(i,j)$$

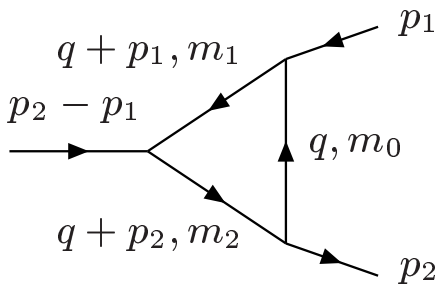
$$V_M(i,j) = v_W(i,j) + v_\phi(i,j) + v_{WW}(i) + v_{\phi\phi}(i) + v_{W\phi}(i) + v_\Sigma(i)$$

One–loop integrals

[G. Passarino, M. Veltman '79]



$$\frac{i}{16\pi^2}\{B_0, B^\mu\}(p_1^2; m_0^2, m_1^2) = \mu^{4-D}\int \frac{d^D q}{(2\pi)^D}\frac{\{1, q^\mu\}}{\mathcal{D}_0\mathcal{D}_1}$$



$$\frac{i}{16\pi^2}\{C_0, C^\mu, C^{\mu\nu}\}(p_1^2, Q^2, p_2^2; m_0^2, m_1^2, m_2^2) = \mu^{4-D}\int \frac{d^D q}{(2\pi)^D}\frac{\{1, q^\mu, q^\mu q^\nu\}}{\mathcal{D}_0\mathcal{D}_1\mathcal{D}_2}$$

in D dimensions, with $Q^2 = (p_2 - p_1)^2$ and

$$\begin{aligned}
\mathcal{D}_0 &= q^2 - m_0^2 + i\epsilon \\
\mathcal{D}_1 &= (q + p_1)^2 - m_1^2 + i\epsilon \\
\mathcal{D}_2 &= (q + p_2)^2 - m_2^2 + i\epsilon
\end{aligned}$$

Lorentz structure decomposition:

$$\begin{aligned}
B^\mu &= p_1^\mu B_1 \\
C^\mu &= p_1^\mu C_{11} + p_2^\mu C_{12} \\
C^{\mu\nu} &= p_1^\mu p_1^\nu C_{21} + p_2^\mu p_2^\nu C_{22} + (p_1^\mu p_2^\nu + p_2^\mu p_1^\nu) C_{23} + g^{\mu\nu} M_W^2 C_{24}
\end{aligned}$$

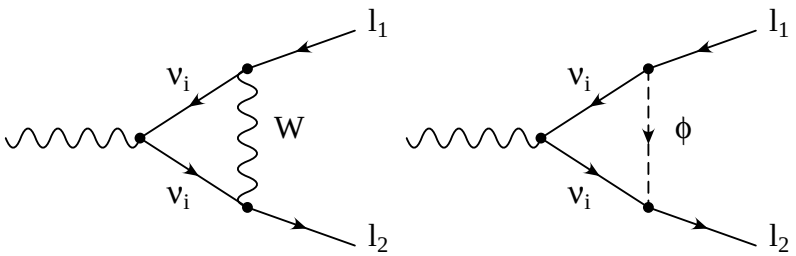
Abbreviations for dimensionless functions: UV–behaviour:

$$\begin{aligned}
\mathbb{B}_1 &\equiv B_1(0; m_i^2, M_W^2) && (D-4)\,\mathbb{B}_1 = 1 \\
\mathbb{C}_{..} &\equiv M_W^2\, C_{..}(0, Q^2, 0; M_W^2, m_i^2, m_j^2) && (D-4)\,\mathbb{C}_{24} = -\tfrac{1}{2} \\
\bar{\mathbb{C}}_{..} &\equiv M_W^2\, C_{..}(0, Q^2, 0; m_i^2, M_W^2, M_W^2) && (D-4)\,\bar{\mathbb{C}}_{24} = -\tfrac{1}{2}
\end{aligned}$$

1–loop contributions to $Z \to \ell_1 \ell_2$

('t Hooft-Feynman gauge)

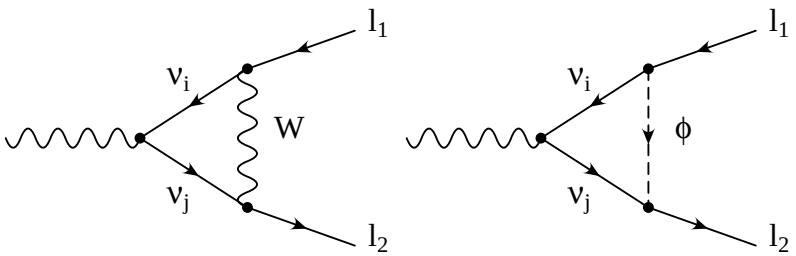
Dirac:



$$
\begin{aligned}
v_W(i) &= -(v_i + a_i)\ [\lambda_Q\ (\mathbb{C}_0 + \mathbb{C}_{11} + \mathbb{C}_{12} + \mathbb{C}_{23}) - 2\ \mathbb{C}_{24} + 1] \\
&\quad -(v_i - a_i)\ \lambda_i\ \mathbb{C}_0 \\
v_\phi(i) &= -(v_i + a_i)\ \frac{\lambda_i^2}{2}\ \mathbb{C}_0 \\
&\quad -(v_i - a_i)\ \frac{\lambda_i}{2}\ \left[\lambda_Q\ \mathbb{C}_{23} - 2\ \mathbb{C}_{24} + \frac{1}{2}\right]
\end{aligned}
$$

$$
v_i = I_3^{i_L} - 2 e_i s_W^2, \quad a_i = I_3^{i_L}, \quad \lambda_i = \frac{m_i^2}{M_W^2}, \quad \lambda_Q = \frac{Q^2}{M_W^2}
$$

Majorana (non-diagonal $Z\nu_i\nu_j$):

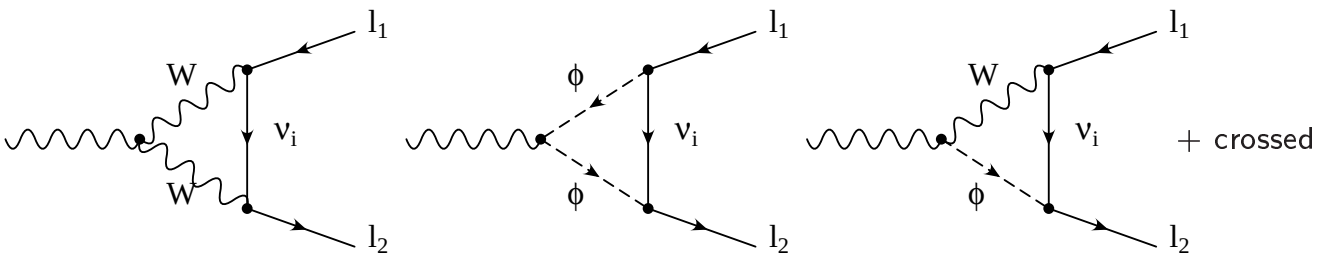


$$
\begin{aligned}
v_W(i,j) &= -\mathbf{C}_{ij}\ [\lambda_Q\ (\mathbb{C}_0 + \mathbb{C}_{11} + \mathbb{C}_{12} + \mathbb{C}_{23}) - 2\ \mathbb{C}_{24} + 1] \\
&\quad +\mathbf{C}_{ij}^*\ \sqrt{\lambda_i \lambda_j}\ \mathbb{C}_0 \\
v_\phi(i,j) &= -\mathbf{C}_{ij}\ \frac{\lambda_i \lambda_j}{2}\ \mathbb{C}_0 \\
&\quad +\mathbf{C}_{ij}^*\ \frac{\sqrt{\lambda_i \lambda_j}}{2}\ \left[\lambda_Q\ \mathbb{C}_{23} - 2\ \mathbb{C}_{24} + \frac{1}{2}\right]
\end{aligned}
$$

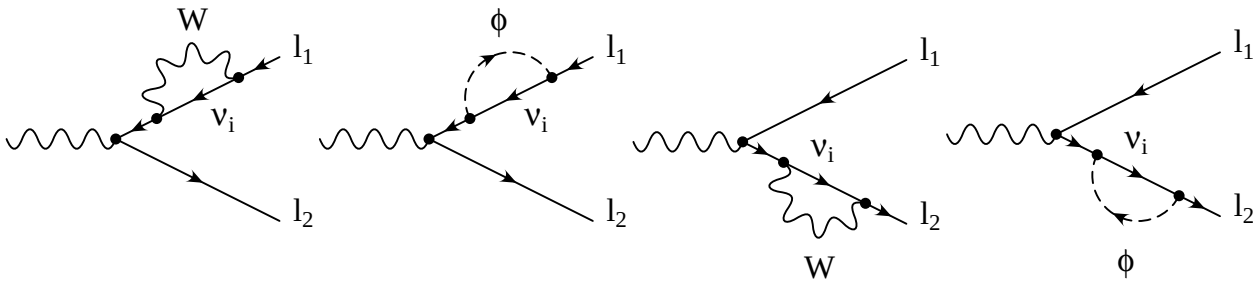
More 1–loop contributions to $Z \to \ell_1 \ell_2$

('t Hooft-Feynman gauge)

Dirac or Majorana:



$$
\begin{aligned}
v_{WW}(i) &= 2c_W^2\ (2I_3^{i_L})\left[\lambda_Q\ (\bar{\mathbb{C}}_{11}+\bar{\mathbb{C}}_{12}+\bar{\mathbb{C}}_{23})-6\ \bar{\mathbb{C}}_{24}+1\right] \\
v_{\phi\phi}(i) &= -(1-2s_W^2)\ (2I_3^{i_L})\ \lambda_i\ \bar{\mathbb{C}}_{24}\,, \\
v_{W\phi}(i) &= -2s_W^2\ (2I_3^{i_L})\ \lambda_i\ \bar{\mathbb{C}}_0
\end{aligned}
$$



$$
v_\Sigma(i) = \frac{1}{2}\underbrace{(v_i+a_i-4c_W^2 a_i)}_{v_l+a_l}\left[(2+\lambda_i)\mathbb{B}_1+1\right]
$$

The Majorana form factor can be cast into

$$
V_M(i,j) = \delta_{ij}\ F(\lambda_i) + \mathbf{C}_{ij}\ G(\lambda_i,\lambda_j) + \mathbf{C}_{ij}^*\sqrt{\lambda_i\lambda_j}\ H(\lambda_i,\lambda_j)
$$

The Dirac form factor reads

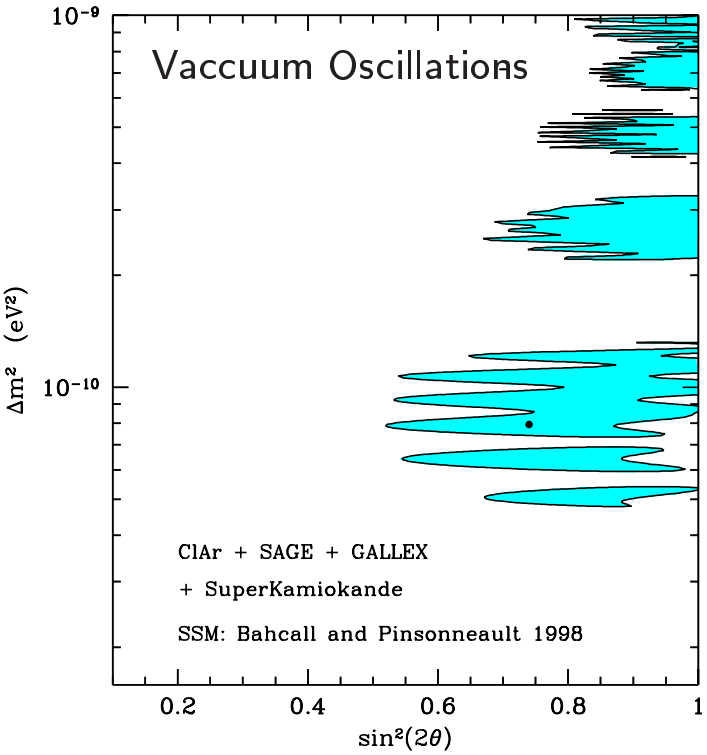
$$
V(i) = F(\lambda_i) + G(\lambda_i,\lambda_i)
$$

Loop integrals numerically evaluated with `LoopTools`

[T. Hahn '99]

Solutions of neutrino puzzles assuming oscillations

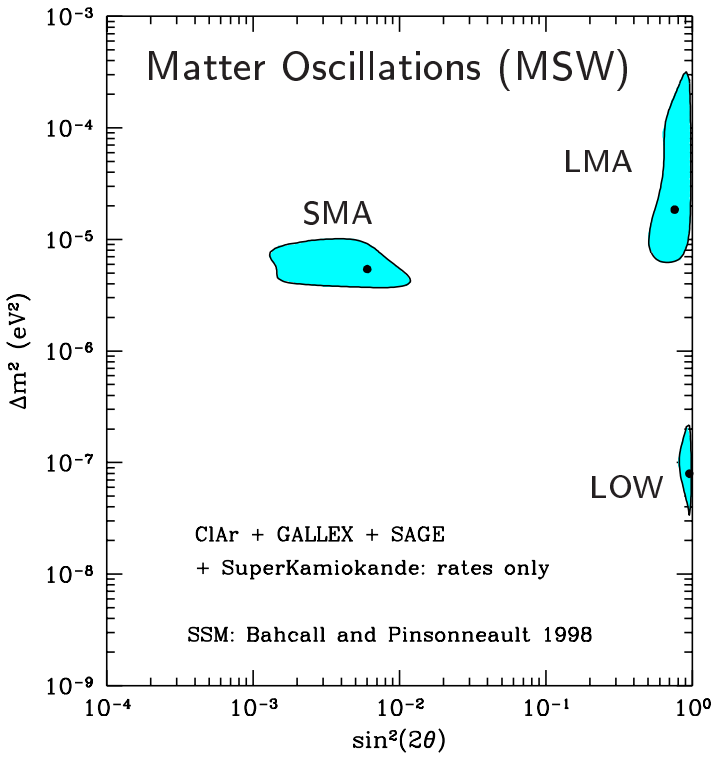
▷ Solar [Homestake (ClAr), SAGE, GALLEX, SuperK]:



VO:

$\Delta m^2_\odot \simeq (0.5 - 1.0) \times 10^{-10}$ eV^2

$\sin^2 2\theta_\odot \simeq 0.6 - 1.0$



SMA:

$\Delta m^2_\odot \simeq (4 - 10) \times 10^{-6}$ eV^2

$\sin^2 2\theta_\odot \simeq (0.1 - 1.0) \times 10^{-2}$

LMA:

$\Delta m^2_\odot \simeq (2 - 20) \times 10^{-5}$ eV^2

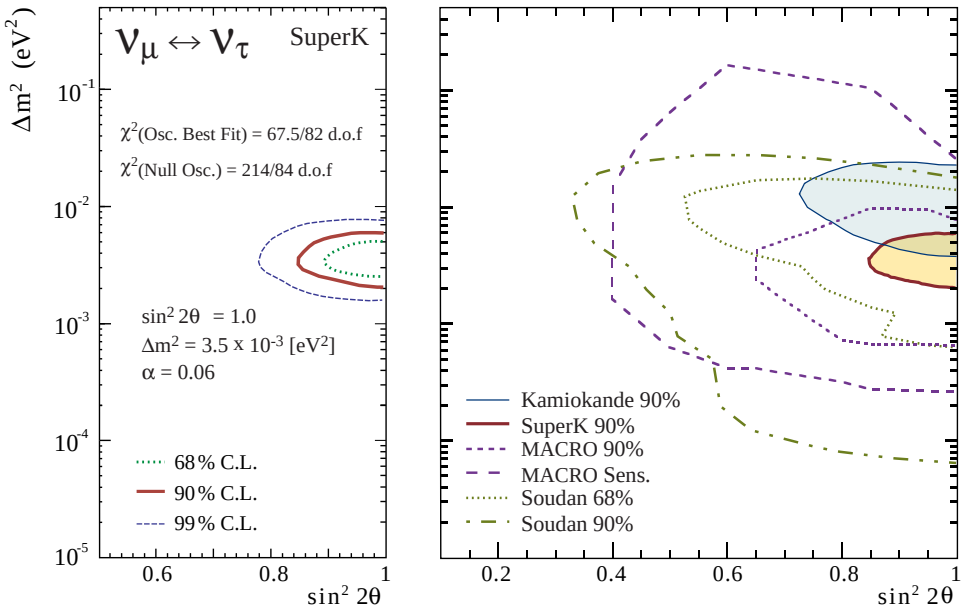
$\sin^2 2\theta_\odot \simeq 0.65 - 0.97$

LOW: very low probability

[J.N. Bahcall et al. '98]

Solutions of neutrino puzzles assuming oscillations

▷ Atmospheric [Kamiokande, SuperK, MACRO, Soudan]:



[W.A. Mann '99]

$$\Rightarrow \Delta m^2_{\rm atm} \simeq (2-6)\times 10^{-3}\ \text{eV}^2\ , \quad \sin^2 2\theta_{\rm atm} \simeq 0.82 - 1.0$$

▷ Reactor [CHOOZ]: No signs of $\bar{\nu}_e \to \nu_X$

$\Rightarrow$ exclude $\Delta m^2 > 7\times 10^{-4}$ eV^2 at $\sin^2 2\theta = 1$ (90% c.l.)

▷ Accelerator:

[LSND]: Signal of $\nu_\mu \to \nu_e$:

$$\Rightarrow 0.2 \lesssim \Delta m^2_{\rm LSND} \lesssim 2\ \text{eV}^2, \quad 2\times 10^{-3} \lesssim \sin^2 2\theta_{\rm LSND} \lesssim 4\times 10^{-2}$$

[KARMEN]: No signal of $\bar{\nu}_\mu \to \bar{\nu}_e$, partly incompatible with LSND

Conclusion

Ignoring LSND, all experiments compatible with 3 light neutrinos:

$$\Delta m^2_{\rm atm} \left\{ \begin{array}{c} m_3^2 \\ \\ m_2^2 \\ \\ m_1^2 \end{array} \right\} \Delta m^2_\odot$$

$$\Delta m^2_{31} = \Delta m^2_{32} \equiv \Delta m^2_{\rm atm}$$
$$\Delta m^2_{21} \equiv \Delta m^2_\odot \ll \Delta m^2_{\rm atm}$$

Note: Absolute neutrino mass scale bound only by ^3H β decay (< 3 eV)

Phenomenological mixing matrix for 3 light neutrinos

$$\mathbf{U} = \begin{pmatrix} \mathbf{U}_{e1} & \mathbf{U}_{e2} & \mathbf{U}_{e3} \\ \mathbf{U}_{\mu 1} & \mathbf{U}_{\mu 2} & \mathbf{U}_{\mu 3} \\ \mathbf{U}_{\tau 1} & \mathbf{U}_{\tau 2} & \mathbf{U}_{\tau 3} \end{pmatrix} = \begin{pmatrix} e^{i\alpha} & 0 & 0 \\ 0 & e^{i\beta} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times$$

$$\times \begin{pmatrix} c_{12}c_{13} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - c_{23}s_{12}s_{13}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

[S. Maki, M. Nakagawa, S. Sakata '62]

where

- $\theta_{12} \equiv \theta_\odot$ free [VO, LMA $\rightsquigarrow$ large; SMA $\rightsquigarrow$ small]
- $\theta_{23} \equiv \theta_{\rm atm} \simeq 45^\circ$
- $\theta_{13} \simeq 0$ [CHOOZ]

Oscillations are not sensitive to Majorana-type $\mathcal{CP}$-phases α, β and no information yet on Dirac-type $\mathcal{CP}$-phase δ: we take

- $\alpha = \beta = \delta = 0$

Conclusion:

$$\mathbf{U} \simeq \begin{pmatrix} c_{12} & s_{12} & 0 \\ -\frac{1}{\sqrt{2}}s_{12} & \frac{1}{\sqrt{2}}c_{12} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}}s_{12} & -\frac{1}{\sqrt{2}}c_{12} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

Results

The LCKM matrix is $\mathbf{V} = \mathbf{U}$. From its unitarity:

$$\begin{aligned} \mathrm{BR}(Z \to \ell_1^\mp \ell_2^\pm) &= \frac{\alpha_W^3 M_Z}{192\pi^2 c_W^2 \Gamma_Z} \Big| \sum_{i=1}^{3} \mathbf{V}_{\ell_1 i} \mathbf{V}^*_{\ell_2 i}\, V(i) \Big|^2 \\ &\simeq 10^{-6} \times \left| \sum_{i=1}^{3} \mathbf{V}_{\ell_1 i} \mathbf{V}^*_{\ell_2 i} [V(\lambda_i) - V(0)] \right|^2 \end{aligned}$$

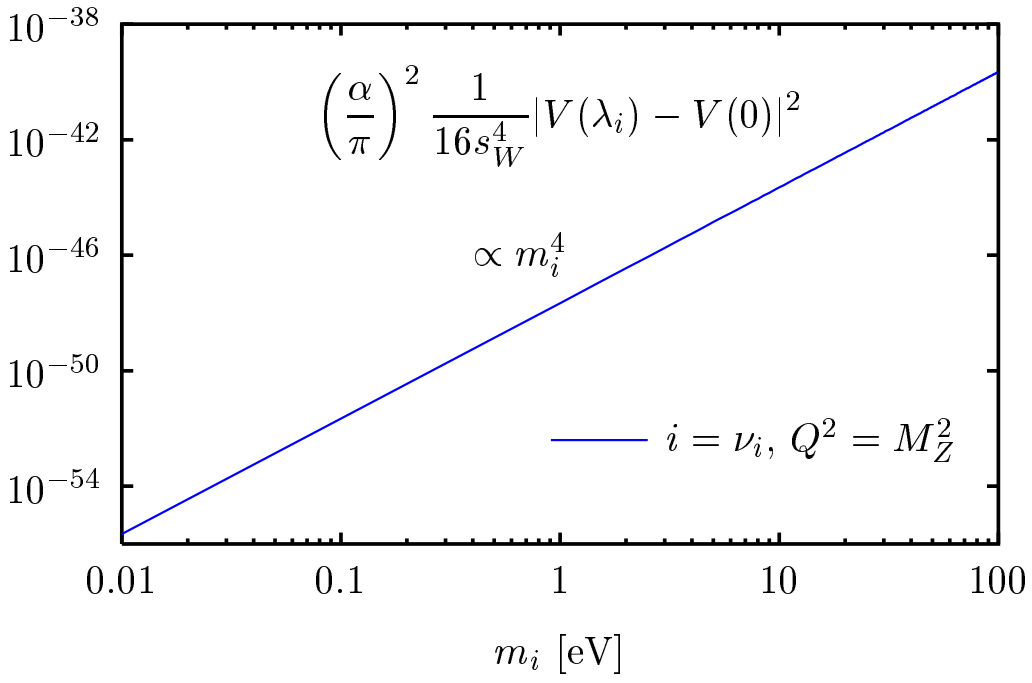
with $V(\lambda_i) - V(0) = a_1(\lambda_Z)\ \lambda_i$, $|a_1^2| = 11.832$ for $m_i \ll M_Z$

[G. Mann, T. Riemann '82]

Substituting phenomenological mixings θ_{ij} and $\lambda_{ij} = \dfrac{\Delta m^2_{ij}}{M_W^2}$,

$$\begin{aligned} \mathrm{BR}(Z \to e^\mp \mu^\pm) &\approx \mathrm{BR}(Z \to e^\mp \tau^\pm) \approx 0.6 \times 10^{-5} c_{12}^2 s_{12}^2 \lambda_{21}^2 \\ &\lesssim 4 \times 10^{-60} \\ \mathrm{BR}(Z \to \mu^\mp \tau^\pm) &\approx 0.3 \times 10^{-5} |s_{12}^2 \lambda_{21} - \lambda_{32}|^2 \\ &\sim (3 - 30) \times 10^{-55} \end{aligned}$$

[J.I., M. Jack, T. Riemann '00]



Expressions in terms of the heavy neutrino masses and the light-heavy mixings only

Contribution to LFV Z decays from n_G light neutrinos negligible, as if they were massless, allows to write the BR's in terms of the heavy masses and light-heavy mixings only:

▷ One heavy sequential Dirac neutrino

From unitarity of LCKM $\mathbf{V}$ for $n_G + 1$ generations

$$\mathrm{BR}(Z \to \ell_1^\mp \ell_2^\pm) = \frac{\alpha_W^3 M_Z}{192\pi^2 c_W^2 \Gamma_Z} \left|\mathbf{V}_{\ell_1 N} \mathbf{V}^*_{\ell_2 N}\right|^2 \left|V(\lambda_N) - V(0)\right|^2$$

▷ n_R heavy RH Majorana isosinglet neutrinos

From unitarity of $\mathbf{U}^\ell$ and $\mathbf{U}$ one gets useful relations for products of $\mathbf{B}$ and $\mathbf{C}$ matrix elements

[J.G. Körner et al. '93]

Reminding that

$$V_M(i,j) \equiv \delta_{ij}\ F(\lambda_i) + \mathbf{C}_{ij}\ G(\lambda_i, \lambda_j) + \mathbf{C}^*_{ij} \sqrt{\lambda_i \lambda_j}\ H(\lambda_i, \lambda_j)$$

one obtains

$$\mathrm{BR}(Z \to \ell_1^\mp \ell_2^\pm) = \frac{\alpha_W^3 M_Z}{192\pi^2 c_W^2 \Gamma_Z} \Bigg| \sum_{i,j=1}^{n_R} \mathbf{B}_{l_1 N_i} \mathbf{B}^*_{l_2 N_j}$$
$$\times \Big\{ \delta_{N_i N_j} [F(\lambda_{N_i}) - F(0) + G(\lambda_{N_i}, 0) + G(0, \lambda_{N_i}) - 2G(0,0)]$$
$$+ \mathbf{C}_{N_i N_j} [G(\lambda_{N_i}, \lambda_{N_j}) - G(\lambda_{N_i}, 0) - G(0, \lambda_{N_j}) + G(0,0)]$$
$$+ \mathbf{C}^*_{N_i N_j} \sqrt{\lambda_{N_i} \lambda_{N_j}}\ H(\lambda_{N_i}, \lambda_{N_j}) \Big\} \Bigg|^2$$

Present experimental constraints on light-heavy mixings

General formalism *[P. Langacker, D. London '88]* to describe

light-heavy mixings $\equiv s^2_{\nu_\ell}$

$\ell = e, \mu, \tau$. They are best constrained by

▷ Flavour diagonal processes (indirect)

√ Neglecting heavy neutrinos in the loops but taking into account the change induced in the light neutrino couplings:

- Non-universality of CC couplings
- Deviation of the quark CKM from unitarity
- Change of the invisible width of the Z boson

[E. Nardi et al. '92 & '94; S. Bergmann, A. Kagan '99]

$$s^2_{\nu_e} < 0.012, \qquad s^2_{\nu_\mu} < 0.0096, \qquad s^2_{\nu_\tau} < 0.016$$

• Including heavy neutrino effects in loops:

- μ decay and Δr *[P. Kalyniak et al. '95]*
- $Z \to \ell\bar{\ell}$ *[P. Kalyniak et al. '97]*

▷ Flavour non-diagonal processes, no neutrinos in the final state. They are direct and unambiguous signal for LFV

They proceed only through loops

√ $\mu \to e\gamma$, $\tau \to e\gamma/\mu\gamma$ *[P. Langacker, D. London '88]*

$$s^2_{\nu_e} s^2_{\nu_\mu} < 1.4 \times 10^{-8}$$ *[MEGA collab '99]*

√ $\mu \to e$ in nuclei and $\mu \to ee^+e^-$ *[J. Bernabéu et al. '95]*

- ...

√ $Z \to \ell_1\bar{\ell}_2$ *[A. Ilakovac, A. Pilaftsis '95; X.Y. Pham '98]* *[J.I., M. Jack, T. Riemann '00]*

Information from light-heavy mixing constraints

$\surd$ One heavy sequential Dirac

$$s^2_{\nu_\ell} \equiv |\mathbf{V}_{\ell N}|^2$$

$\circ$ One heavy isosinglet Majorana: $n_R = 1$ (minimal seesaw)

$$s^2_{\nu_\ell} \equiv |\mathbf{B}_{\ell N}|^2$$

$$\begin{aligned} \mathbf{B}_{\ell N} &= s_{\nu_\ell} \simeq \sqrt{\frac{m_{\nu_\ell}}{m_N}} \ll \text{present indirect bounds} \\ \mathbf{C}_{NN} &= \sum_\ell s^2_{\nu_\ell} \simeq \sum_\ell \frac{m_{\nu_\ell}}{m_N} \end{aligned}$$

$\surd$ Two heavy isosinglet Majorana: $n_R = 2$ (interfamily seesaw)

$$s^2_{\nu_\ell} \equiv \sum_{i=1}^{2} |\mathbf{B}_{\ell N_i}|^2$$

Exactly calculable in terms of $s^2_{\nu_\ell}$ and $r \equiv m^2_{N_2}/m^2_{N_1}$

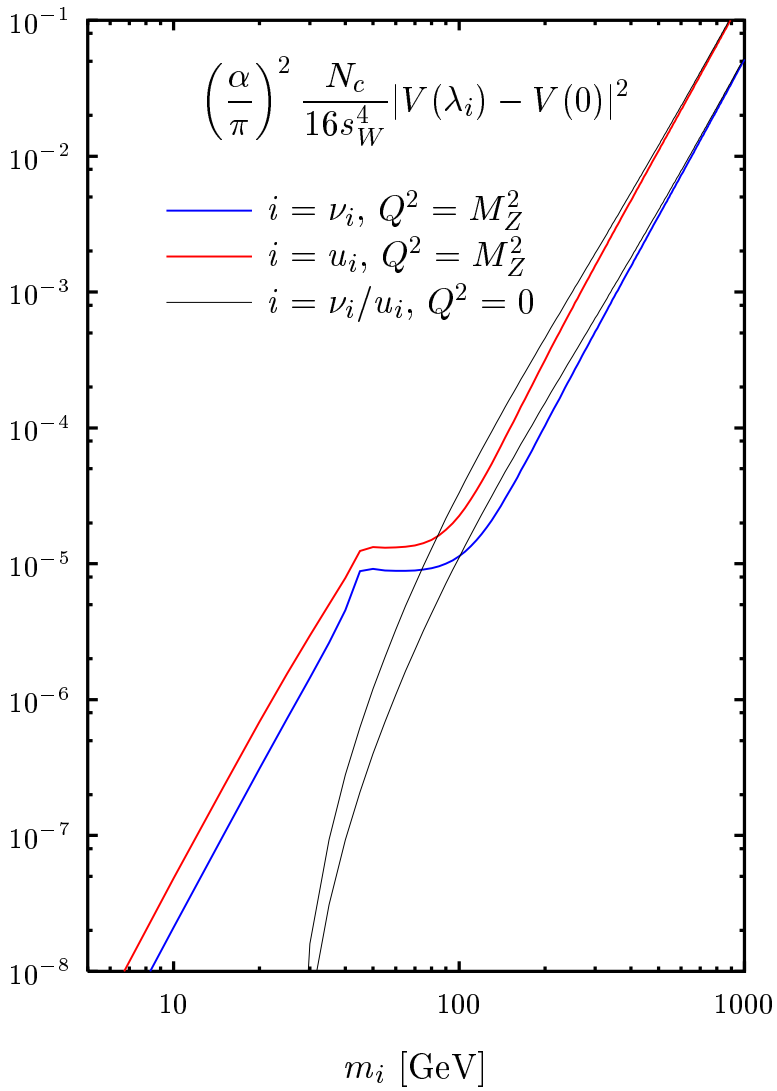
$$\begin{aligned} \mathbf{B}_{lN_1} &= \frac{r^{1/4}}{\sqrt{1+r^{1/2}}}\, s_{\nu_\ell} \\ \mathbf{B}_{lN_2} &= \frac{i}{\sqrt{1+r^{1/2}}}\, s_{\nu_\ell} \\ \mathbf{C}_{N_1N_1} &= \frac{r^{1/2}}{1+r^{1/2}} \sum_\ell s^2_{\nu_\ell} \\ \mathbf{C}_{N_2N_2} &= \frac{1}{1+r^{1/2}} \sum_\ell s^2_{\nu_\ell} \\ \mathbf{C}_{N_1N_2} &= -\mathbf{C}_{N_2N_1} = \frac{ir^{1/4}}{1+r^{1/2}} \sum_\ell s^2_{\nu_\ell} \end{aligned}$$

[J.G. Körner et al. '93]

Results

- One heavy sequential Dirac

[light-heavy mixing set to one and showing $\mathrm{B}_Z \equiv \frac{1}{2} \times \mathrm{BR}(Z \to \ell_1^{\mp} \ell_2^{\pm}) / \mathrm{BR}(Z \to \bar{\nu}\nu)$]



[J.I., M. Jack, T. Riemann '00]

For $\lambda_N = m_N^2 / M_W^2 \gg 1$

$$|V(\lambda_N) - V(0)|^2 = \frac{1}{4}\,\lambda_N^2 + 1.44\,\lambda_N \ln \lambda_N - 3.49\,\lambda_N + 2.07\,\ln^2 \lambda_N + \mathcal{O}(\ln \lambda_N).$$

Results

Taking present upper bounds for light-heavy mixings and showing perturbative unitarity mass limits for heavy masses:

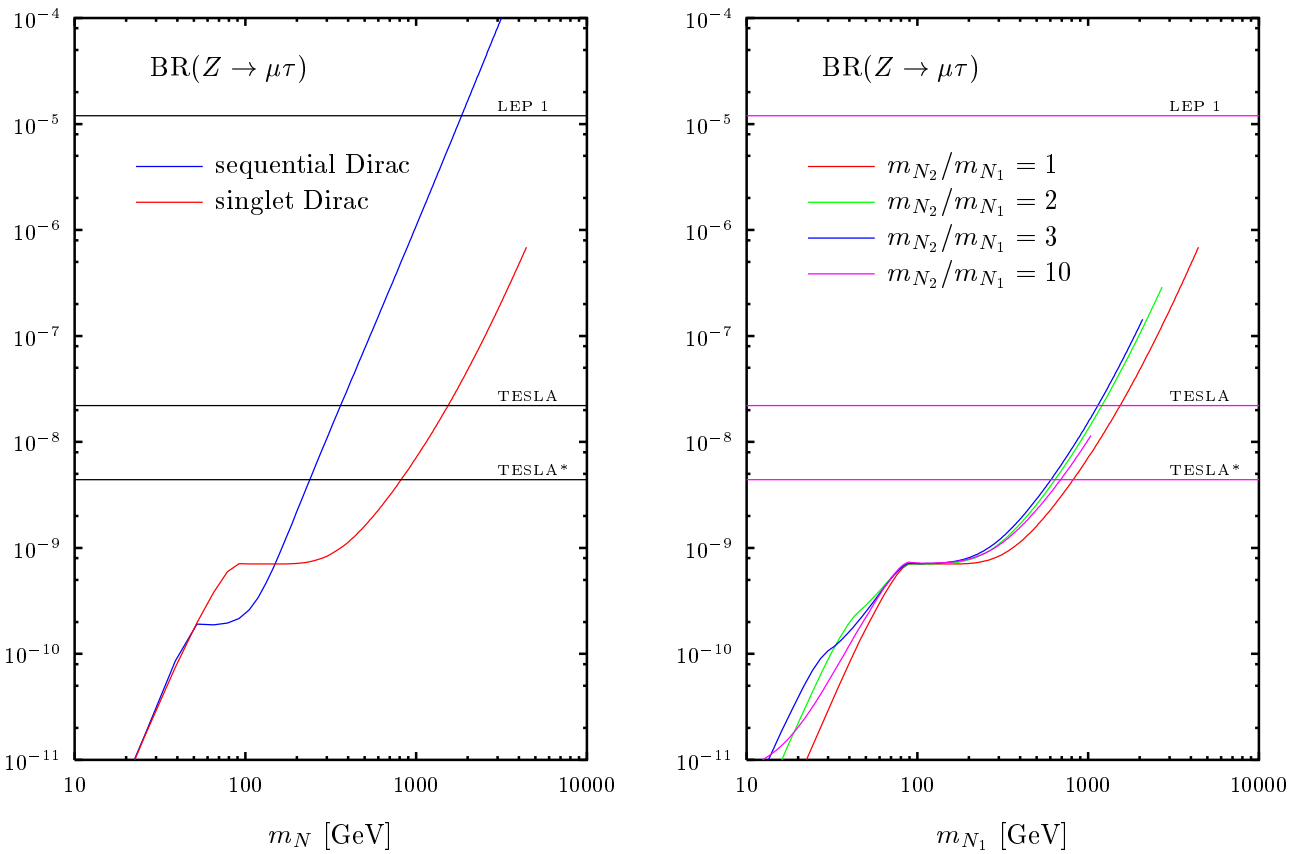
$$\Gamma_{N_i} \simeq (2\times)\frac{\alpha_W}{8M_W^2} m_{N_i}^3 \sum_{k=1}^{3} |\mathbf{B}_{l_k N_i}|^2 \leq \frac{1}{2} m_{N_i}$$

for Dirac (Majorana) neutrinos, due to different d.o.f.

One sequential Dirac

One singlet Dirac

Two True Majoranas



[J.I., M. Jack, T. Riemann '00]

Conclusions

- Not clear yet whether neutrinos are Dirac or Majorana particles (oscillations are insensitive and no signal from neutrinoless 2β)
- Concerning LFV/LNV $Z \to \ell_a \ell_b$ decays ($a \neq b$):
  - For the light neutrino sector:
    negligible effects: BR $\lesssim \mathcal{O}(10^{-54})$
  - For the heavy neutrino sector:
    - Flavour diagonal processes set indirect best bounds on the light-heavy mixings

$$s^2_{\nu_\ell} \equiv \begin{cases} \sum\limits_{\text{heavy } N} |\mathbf{V}_{\ell N}|^2 & \text{for Dirac} \\ \sum\limits_{\text{heavy } N} |\mathbf{B}_{\ell N}|^2 & \text{for Majorana} \end{cases} \sim \mathcal{O}(10^{-2})$$

      only improved by direct $\mu \to e\gamma \Rightarrow s_{\nu_e} s_{\nu_\mu} < 1.4 \times 10^{-8}$!!
      They are all (practically) mass independent
    - The relevant mixing factors for LFV/LNV Z decays are off-diagonal and are generally bound by the Schwartz inequalities $|\sum\limits_N \mathbf{B}_{l_a N} \mathbf{B}^*_{l_b N}|^2 < s^2_{\nu_a} s^2_{\nu_b}$
      They are exactly obtainable in particular cases considered here.
    - There is an interplay between heavy neutrino masses and light-heavy mixings effectively preventing non-decoupling
      One can obtain upper bounds to BR($Z \to \ell_1 \ell_2$) depending on neutrino type and number, assuming present constraints.
    - TESLA Giga$-Z$ might have a chance!

Fermion types

▷ Spinors:

$$\begin{array}{rclcrcl} \psi & = & \psi_L + \psi_R & ; & \psi_{L,R} & = & P_{L,R}\,\psi \\ \overline{\psi} & = & \psi^\dagger\gamma_0 & ; & \overline{\psi_{L,R}} & = & \overline{\psi}\,P_{R,L} \end{array}$$

with the chirality projector $P_{L,R} = \frac{1}{2}(1 \mp \gamma_5)$

▷ Conjugated spinors (particle–antiparticle conjugation $= \mathcal{CP}$):

$$\begin{array}{rcl} \psi^c & = & C\bar{\psi}^T \;; \quad C^\dagger = C^T = C^{-1} = -C,\; C\gamma_\mu C^{-1} = -\gamma_\mu^T \\ \overline{\psi^c} & = & \psi^T C \end{array}$$

describe particles with opposite charges and chiralities:

$$\begin{array}{rcll} \psi_L^c & \equiv & (\psi_L)^c = P_R\,\psi^c & \text{(Right–Handed!)} \\ \psi_R^c & \equiv & (\psi_R)^c = P_L\,\psi^c & \text{(Left–Handed!)} \end{array}$$

• Possible scalar bilinears $\rightsquigarrow$ mass terms (LH $\leftrightarrow$ RH):

$$\overline{\psi_L}\psi_R = \overline{\psi_R}\psi_L = \overline{\psi_L^c}\psi_R^c = \overline{\psi_R^c}\psi_L^c \quad \text{“Dirac” m.t. } (\Delta F = 0)$$

$$\left.\begin{array}{l} \overline{\psi_L}\psi_L^c = \overline{\psi_L^c}\psi_L \\ \overline{\psi_R}\psi_R^c = \overline{\psi_R^c}\psi_R \end{array}\right\} \quad \text{“Majorana” m.t. } (|\Delta F| = 2)$$

Weyl: only one chirality, ψ_L or ψ_R (massless fermion)

Dirac: two chiralities with ψ_L independent of ψ_R

$$\text{4 d.o.f.:} \quad \psi_L,\; \psi_R,\; \psi_L^c,\; \psi_R^c$$

Majorana: two chiralities with $\psi^c = \eta^*\,\psi$ ($\eta^* = \mathcal{CP}$ parity)
particle=antiparticle (genuinely neutral)

$$\text{2 d.o.f.:} \quad \psi_L = \eta\,\psi_R^c,\; \psi_R = \eta\,\chi_L^c$$