Z-boson decay and heavy neutrinos at FCC-ee

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6th FCC Physics Workshop, Cracow

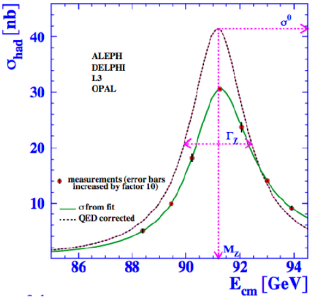
24/01/2023

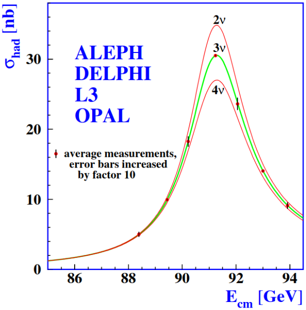
FCC

NATIONAL SCIENCE CENTRE POLAND

Altogether $17 \cdot 10^6$ Z-boson decays at LEP

- Cross section : Z mass and width





- ~30% QED corrections (ISR)

LEP EWWG, hep-ex/0509008

See Talks by : Alain Blondel, Guy Wilkinson, Roberto Franceschini etc.

N_{eff}: LEP and Now

ALEPH, OPAL, L3, DELPHI, MARKII (SLC): $N_\nu = 3.12 \pm 0.19$
CERN, 13.10.1989, Video (∼12,000 Z decays)
[LEP, 2006] (∼17 mln Z decays)

$$N_\nu = 2.9840 \pm 0.0082$$

Update: [P. Janot and S. Jadach, 2019](only 1σ off from N=3)

$$N_\nu = 2.9963 \pm 0.0074$$

Theorem: [C. Jarlskog, 1990]
In the Standard Model with n left-handed lepton doublets and $N - n$ right-handed neutrinos, the effective number of neutrinos, N_ν, defined by

$$\Gamma(Z \to \nu' s) \equiv N_\nu \Gamma_0,$$

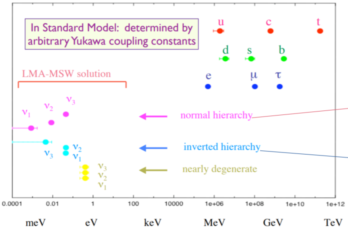
where Γ_0 is the standard width for one masseless neutrino, satisfies

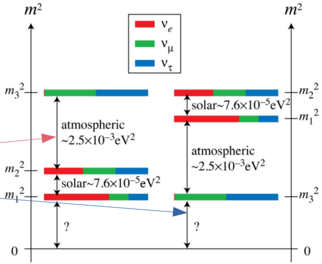
$$N_\nu \leq n.$$

$$\nu_\alpha^{(f)} = \underbrace{(V_{\mathrm{osc}})_{\alpha i}\, \nu_i^{(m)}}_{\text{SM part}} + \underbrace{(V_{lh})_{\alpha j}\, \widetilde{\nu}_j^{(m)}}_{\text{BSM part}}$$

Cosmology: $N_{eff} = 3.044$. J. Froustey, C. Pitrou, M. Volpe, JCAP 12 (2020) 015,
J. Bennett, G. Buldgen, M. Drewes, Y. Wong, JCAP 03 (2021) A01

Neutrino parameters, development





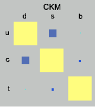
	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.6$)	
	bfp $\pm1\sigma$	3σ range	bfp $\pm1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$
$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \to 35.86$	$33.45^{+0.77}_{-0.74}$	$31.27 \to 35.87$
$\sin^2\theta_{23}$	$0.573^{+0.018}_{-0.023}$	$0.405 \to 0.620$	$0.578^{+0.017}_{-0.021}$	$0.410 \to 0.623$
$\theta_{23}/^\circ$	$49.2^{+1.0}_{-1.3}$	$39.5 \to 52.0$	$49.5^{+1.0}_{-1.2}$	$39.8 \to 52.1$
$\sin^2\theta_{13}$	$0.02220^{+0.00068}_{-0.00062}$	$0.02034 \to 0.02430$	$0.02238^{+0.00064}_{-0.00062}$	$0.02053 \to 0.02434$
$\theta_{13}/^\circ$	$8.57^{+0.13}_{-0.12}$	$8.20 \to 8.97$	$8.60^{+0.12}_{-0.12}$	$8.24 \to 8.98$
$\delta_{CP}/^\circ$	194^{+52}_{-25}	$105 \to 405$	287^{+27}_{-32}	$192 \to 361$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.515^{+0.028}_{-0.028}$	$+2.431 \to +2.599$	$-2.498^{+0.028}_{-0.029}$	$-2.584 \to -2.413$

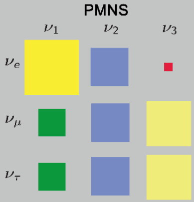
Neutrino Physics Enters Precisoin Era

Super-K, Hyper-K, T2K, NOvA, Antares, KM3NeT, Juno, Dune, SNO+, Daya Bay, Double Chooz, RENO, ...

$$U_{PMNS} = \begin{pmatrix} \{0.810, 0.829\} & \{0.539, 0.562\} & \{0.147, 0.169\} \\ \{-0.485, -0.479\} & \{0.467, 0.563\} & \{0.669, 0.743\} \\ \{0.278, 0.339\} & \{-0.683, -0.626\} & \{0.647, 0.728\} \end{pmatrix}$$

$$\theta_{12} = 33.9^o \pm 1.0^o$$
$$\theta_{23} = 36^o - 54^o$$
$$\theta_{13} = 9.12^o \pm 0.63^o$$
$$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}\ [eV^2]$$
$$\Delta m^2_{32} = (2.44 \pm 0.06) \times 10^{-3}\ [eV^2]$$



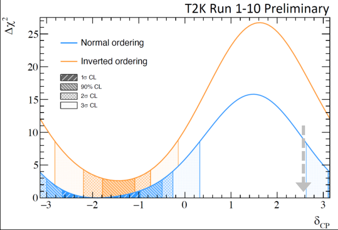


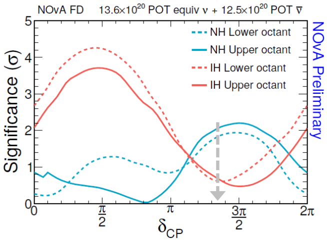
Conclusion: Neutrino Physics stepped in the precision era.

Till 2030: mass hierarchy, δ_{CP} (maybe), absolute masses, Majorana-Dirac, L. Wen, EPS2021.

Neutrinos

The CP Phase



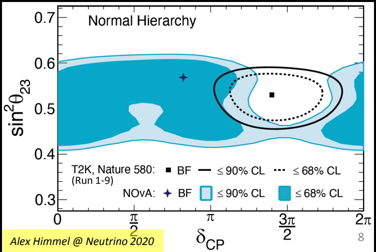


T2K

- δ = - π/2 favored
- Large range of values of δ_{CP} around $+\pi/2$ are excluded at 99.7%

NOvA

- Best-fit δ = 0.82 π
- Exclude **IH** δ = π/2 at >3σ
- Disfavor NH δ = 3π/2 at ~2σ



Clear tension exists

NOvA + T2K joint analysis is underway

Origin on neutrinos mass: Seesaw Roadmap

- Neutrino Mass in SM : No right-handed (RH) neutrinos, No Dirac Mass term for neutrinos
- Accidental lepton number conservation in SM ($\Delta L = 0$)
- Lepton number violation by SM dimension-5 operator : $\ell\ell HH/\Lambda$
- Simplest way: Type-I Seesaw Mechanism
- SM + RH neutrinos

Type-I Seesaw: Heavy Majorana neutrinos included

$$-\mathcal{L}_Y = y\overline{L}\widetilde{H}N + \frac{1}{2}M\overline{N^c}N + H.c.$$

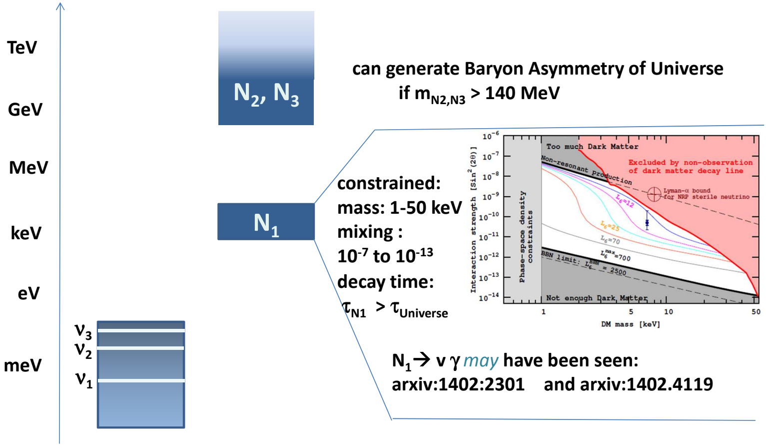
$$m_\nu = \begin{pmatrix} 0 & m_D^T \\ m_D & M \end{pmatrix}$$

$$m_\nu^{light} = -m_D^T M^{-1} m_D, m_\nu^{heavy} = M \text{ with } m_D << M$$

RHNs

RHNs are relevant in many places, e.g. collider physics and cosmology

A. Blondel et al. 1411.5230



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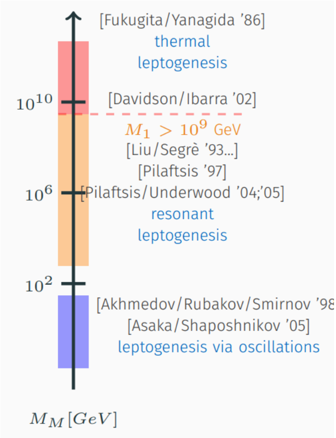
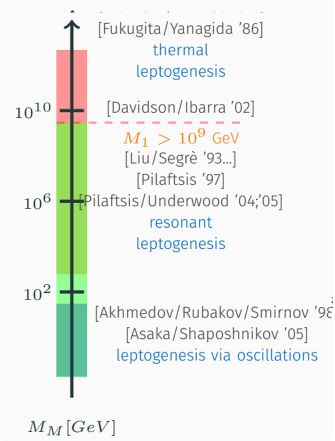
RHN: Leptogenesis

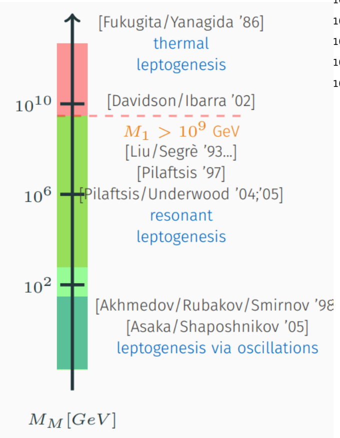


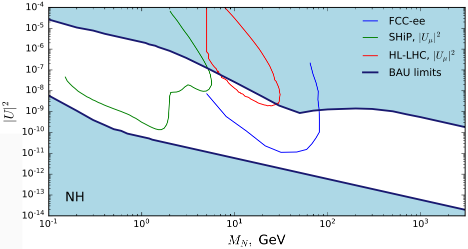
RHN: Leptogenesis



Juraj Klarić et. al., 2008.13771

RHN: Leptogenesis





Juraj Klarić et. al., 2008.13771

Heavy Neutrinos and Z-decay

- Heavy neutrinos can be searched for at high energy lepton colliders of very high luminosity.

- The Future Circular Collider, includes a high luminosity e^+e^- storage ring collider FCC-ee, able to address center-of-mass energies between 90 and 350 GeV.

- At the lower energies, a precision energy calibration is possible, down to 100 keV accuracy for m_Z.

- The very high luminosity of the FCC-ee at the Z pole, producing a total of 10^{12} Z bosons

A. Blondel, P. Janot, *FCC-ee overview: new opportunities create new challenges*, link

Eur. Phys. J. Plus (2022) 137:92 Page 9 of 19 92

Table 3 Measurement of selected precision measurements at FCC-ee, compared with present precision. Statistical errors are indicated in boed phase. The systematic uncertainties are initial estimates, aim is to improve down to statistical errors. This set of measurements, together with those of the Higgs properties, achieves indirect sensitivity to new physics up to a scale Λ of 70 TeV in a description with dim 6 operators, and possibly much higher in specific new physics (non-decoupling) models

Observable	Present value ± error	FCC-ee stat.	FCC-ee syst.	Comment and leading exp. error
m_Z (keV)	91186700 ± 2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200 ± 2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{\mathrm{eff}}$ ($\times 10^6$)	231480 ± 160	**2**	2.4	from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)(\times 10^3)$	128952 ± 14	**3**	Small	From $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
R_ℓ^Z ($\times 10^3$)	20767 ± 25	**0.06**	0.2–1	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_s(m_Z^2)$ ($\times 10^4$)	1196 ± 30	**0.1**	0.4–1.6	From R_ℓ^Z above
σ_{had}^0 ($\times 10^3$) (nb)	41541 ± 37	**0.1**	4	Peak hadronic cross section Luminosity measurement
$N_\nu(\times 10^3)$	2996 ± 7	**0.005**	1	Z peak cross sections Luminosity measurement

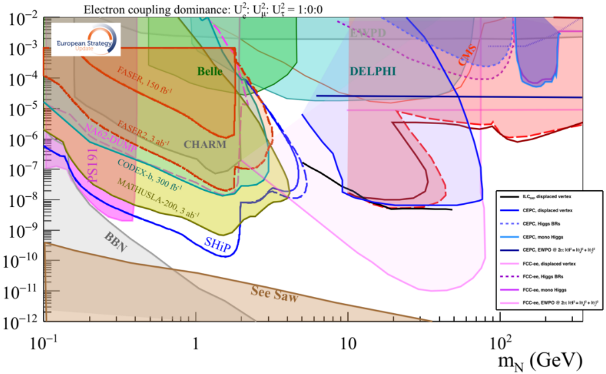
2 orders of magnitude better than LEP

RHNs

LFV Z-decays: $(10^{-6} \div 10^{-5})$. FCC-ee $\longrightarrow \sim 10^{-9}$ branching fractions.

FCC-ee is a heavy neutrino factory

ESPPU Briefieng Book 1910.11775



Resonant Leptogenesis, Collider Signals and Neutrinoless Double Beta Decay from Flavor and CP Symmetries, G. Chauhan, B. Dev, 2203.08538

Errors budget

GRIFFIN: Lisong Chen's talk on Friday;DIZET v.6.45, 2301.07168

	$\|\rho_Z^f\|$		$\sin^2\theta_{\rm eff}^f$		$\Gamma_{Z\to f\bar{f}}$	
	DIZET 6.45	GRIFFIN	DIZET 6.45	GRIFFIN	DIZET 6.45	GRIFFIN
$\nu\bar{\nu}$	1.00800	1.00814	0.231119	NAN	0.167206	0.167197
$\ell\bar{\ell}$	1.00510	1.00519	0.231500	0.231534	0.083986	0.083975
$u\bar{u}$	1.00578	1.00573	0.231393	0.231420	0.299938	0.299958
$d\bar{d}$	1.00675	1.00651	0.231266	0.231309	0.382877	0.382846
$b\bar{b}$	0.99692	0.99420	0.232737	0.23292	0.376853	0.377432

TH: ± 5 keV

FCC-ee EXP: 1.3 keV

Table 2: *The numerical comparison of the EWPOs and form factors ρ between* DIZET *and* GRIFFIN*. The partial width results are for a single fermion family.*

I. Dubovyk et al, https://doi.org/10.1016/j.physletb.2018.06.037

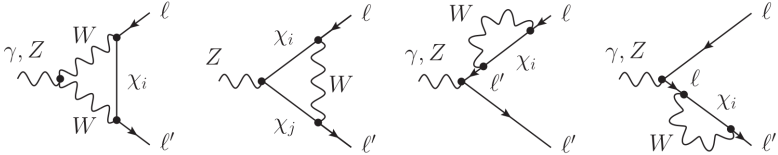
Γ_i [MeV]	Γ_e	Γ_ν
Born	81.142	160.096
$\mathcal{O}(\alpha)$	2.273	6.174
$\mathcal{O}(\alpha\alpha_s)$	0.288	0.458
$\mathcal{O}(\alpha_t\alpha_s^2,\, \alpha_t\alpha_s^3,\, \alpha_t^2\alpha_s,\, \alpha_t^3)$	0.038	0.059
$\mathcal{O}(N_f^2\alpha^2)$	0.244	0.416
$\mathcal{O}(N_f\alpha^2)$	0.120	0.185
$\mathcal{O}(\alpha_{\rm bos}^2)$	0.017	0.019

PDG

Z DECAY MODES

	Mode		Fraction (Γ_i/Γ)
Γ_1	e^+e^-	[a]	(3.3632 ± 0.0042) %
Γ_2	$\mu^+\mu^-$	[a]	(3.3662 ± 0.0066) %
Γ_3	$\tau^+\tau^-$	[a]	(3.3696 ± 0.0083) %

Z-decay and RHNs, $Z \to l_1^{\pm} l_2^{\mp}$: $Z \to ee, \mu\mu, \tau\tau, e\mu, \mu\tau, e\tau$



Sensitivity to all $l - \nu$ mixing elements and RHN masses

$$\mathcal{L}_{W^\pm} = -\frac{g}{\sqrt{2}} W_\mu^- \sum_{i=1}^{3} \sum_{j=1}^{5} B_{ij}\, \bar{\ell}_i \gamma^\mu P_L \chi_j + \text{h.c.},$$

$$\mathcal{L}_Z = -\frac{g}{4c_W} Z_\mu \sum_{i,j=1}^{5} \bar{\chi}_i \gamma^\mu \left(C_{ij} P_L - C_{ij}^* P_R \right) \chi_j,$$

$$B_{ij} = \sum_{k=1}^{3} \delta_{ik} U_{kj}^\nu;\;\; C_{ij} = \sum_{k=1}^{3} (U_{ki}^\nu)^* U_{kj}^\nu$$

$Z \to l_1^{\pm} l_2^{\mp} : Z \to ee, \mu\mu, \tau\tau, e\mu, \mu\tau, e\tau$

$$\Gamma(Z \to \bar{\ell}\ell') = \frac{\alpha}{3} M_Z |F_L^Z(M_Z^2)|^2$$

$$F_L^Z(q^2) = \frac{\alpha_W}{8\pi s_W c_W} \sum_{i,j}^{5} \mathbf{B}_{\ell \mathbf{i}}^{*} \mathbf{B}_{\ell' \mathbf{j}} \big[\delta_{ij} F(x_i; q^2) + \mathbf{C}_{\mathbf{ij}}^{*} G(x_i, x_j; q^2) + \mathbf{C}_{\mathbf{ij}} \sqrt{x_i x_j} H(x_i, x_j; q^2) \big],$$

F,G,H - a combination of the Passarino-Veltman 1-loop functions, and $x_i = m_{\chi_i}^2 / m_W^2$

G. Hernández-Tomé et al, Phys.Rev.D 101 (2020) 7, 075020 1912.13327

A Simple Model:

$$\mathcal{M} = \begin{pmatrix} 0 & 0 & 0 & 0 & m_1 \\ 0 & 0 & 0 & 0 & m_2 \\ 0 & 0 & 0 & 0 & m_3 \\ 0 & 0 & 0 & 0 & M \\ m_1 & m_2 & m_3 & M & \mu \end{pmatrix}, \quad \begin{matrix} m_{\chi_{1,2,3}} = 0, \\ m_{\chi_{4,5}} = \frac{1}{2}\left(\sqrt{4M'^2 + \mu^2} \mp \mu\right), \\ M'^2 = m_1^2 + m_2^2 + m_3^2 + M^2, \end{matrix}$$

- The complete mixing matrix can be written as :

B_{li}

$$U = \begin{pmatrix} -\frac{m_2}{\sqrt{m_1^2+m_2^2}} & -\frac{m_1 m_3}{m\sqrt{m_1^2+m_2^2}} & -\frac{m_1 M}{m M'} & -i\frac{m_1 m_{\chi_5}}{M'\sqrt{m_{\chi_5}^2+M'^2}} & \frac{m_1}{\sqrt{m_{\chi_5}^2+M'^2}} \\ \frac{m_1}{\sqrt{m_1^2+m_2^2}} & -\frac{m_2 m_3}{m\sqrt{m_1^2+m_2^2}} & -\frac{m_2 M}{m M'} & -i\frac{m_2 m_{\chi_5}}{M'\sqrt{m_{\chi_5}^2+M'^2}} & \frac{m_2}{\sqrt{m_{\chi_5}^2+M'^2}} \\ 0 & \frac{\sqrt{m_1^2+m_2^2}}{m} & -\frac{m_3 M}{m M'} & -i\frac{m_3 m_{\chi_5}}{M'\sqrt{m_{\chi_5}^2+M'^2}} & \frac{m_3}{\sqrt{m_{\chi_5}^2+M'^2}} \\ 0 & 0 & \frac{m}{M'} & -i\frac{M m_{\chi_5}}{M'\sqrt{m_{\chi_5}^2+M'^2}} & \frac{M'}{\sqrt{m_{\chi_5}^2+M'^2}} \\ 0 & 0 & 0 & i\frac{M'}{\sqrt{m_{\chi_5}^2+M'^2}} & \frac{m_{\chi_5}}{\sqrt{m_{\chi_5}^2+M'^2}} \end{pmatrix} \begin{matrix} \mathbf{e} \\ \mu \\ \tau \\ \\ \\ \end{matrix}$$

G. Hernández-Tomé et al, Phys.Rev.D 101 (2020) 7, 075020; 1912.13327

Nice features of the model

1. Two heavy Majorana neutrinos in general,
2. $\mu = 0 \longrightarrow m_{\chi_4} = m_{\chi_5}$, $m_\nu \sim \mathcal{O}(\text{eV}) \rightarrow$ Br $\mathcal{O}(10^{-55})$
3. The row elements in the last two columns have a general structure $\frac{X_i}{\sqrt{2}}(N_{i4} \pm i N_{i5}) \equiv X_i \Psi_D$

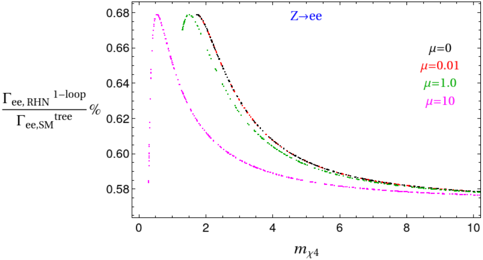
$\Longrightarrow$ Effectively (pseudo-)Dirac neutrino

$$U = \begin{pmatrix} -\frac{m_2}{\sqrt{m_1^2+m_2^2}} & -\frac{m_1 m_3}{m\sqrt{m_1^2+m_2^2}} & -\frac{m_1 M}{m M'} & -\frac{i}{\sqrt{2}}\frac{m_1}{M'} & \frac{1}{\sqrt{2}}\frac{m_1}{M'} \\ \frac{m_1}{\sqrt{m_1^2+m_2^2}} & -\frac{m_2 m_3}{m\sqrt{m_1^2+m_2^2}} & -\frac{m_2 M}{m M'} & -\frac{i}{\sqrt{2}}\frac{m_2}{M'} & \frac{1}{\sqrt{2}}\frac{m_2}{M'} \\ 0 & \frac{\sqrt{m_1^2+m_2^2}}{m} & -\frac{m_3 M}{m M'} & -\frac{i}{\sqrt{2}}\frac{m_3}{M'} & \frac{1}{\sqrt{2}}\frac{m_3}{M'} \\ 0 & 0 & \frac{m}{M'} & -\frac{i}{\sqrt{2}}\frac{M}{M'} & \frac{1}{\sqrt{2}}\frac{M}{M'} \\ 0 & 0 & 0 & \frac{i}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}.$$

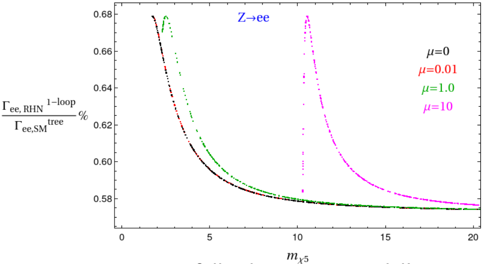
Majorana : LFV, LNV

Dirac : LFV

Seesaw type of models (no mixing decoupling)



$$\begin{pmatrix} 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & M \\ 1 & 1 & 1 & M & \mu \end{pmatrix}$$



Work in progress to cover fully the seesaw model's parameters.

Heavy neutrinos, CP-parity, neutrino mixings

- The nonzero eigenvalues of a real symmetric matrix can be either positive or negative.

$$m'_k = \rho_k m_k$$

where $m_k = |m'_k|$ and $\rho_k = \pm 1$

- Using the identity $\rho_k = e^{i(\pi/2)(\rho_k - 1)}$, we find

$$M = (U^\dagger)^T m U^\dagger, \quad U_{\ell k} = O_{\ell k} e^{i(\pi/4)(\rho_k - 1)}$$

- With $\chi_{kL} = \sum_{e,\mu,\tau \ldots} = U^*_{\ell K} \nu_{\ell K}, \quad U^*_{\ell K} = U_{\ell K} \rho_k$, the CP parity of the Majorana fields can be written as

$$\boxed{\eta_{CP}(\chi_k) = i\rho_k}$$

- Thus, the CP parity of the field of a Majorana neutrino with mass m_k is determined by the sign of the corresponding eigenvalue of the neutrino mass matrix and CP parities are reflected in $U_{\ell k}$.

E.g., Bilenky, Petcov, Rev. Mod. Phys. 1989

Constraints and the space of allowed light-heavy mixings

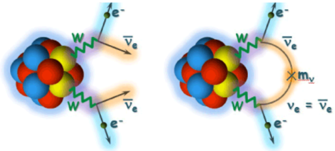
$$(i) \quad \sum_{N(heavy)} \mid B_{Ne} \mid^2 \leq \kappa^2, \quad [0.0054]$$

$$(ii) \quad \mid \sum_{\nu(light)} B_{\nu e}^2 m_\nu \mid < \kappa_{\mathbf{light}}^{\mathbf{2}}, \quad [0.68 \text{ eV}]$$

$$(iii) \quad \mid \sum_{N(heavy)} B_{Ne}^2 \frac{1}{m_N} \mid < \omega^{\mathbf{2}}, \quad [5 \times 10^{-5} \text{ TeV}^{-1}]$$

$$(iv) \quad \sum_{\nu(light)} \mid B_{\nu e} \mid^2 + \sum_{N(heavy)} \mid B_{Ne} \mid^2 = 1.$$

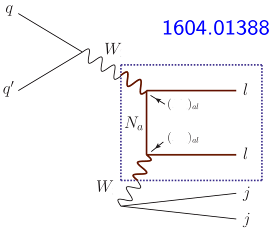
$$(v) \quad \sum_a B_{ae}^2 m_a = (M_L)_{\nu_e \nu_e} = 0 \Longrightarrow \sum_{\nu(\mathbf{light})} \mathbf{B_{\nu e}^2 m_\nu} = - \sum_{\mathbf{N(heavy)}} \mathbf{B_{Ne}^2 m_N}$$



Double beta decay which emits anti-neutrinos

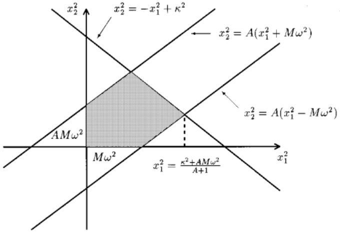
Neutrinoless double beta decay

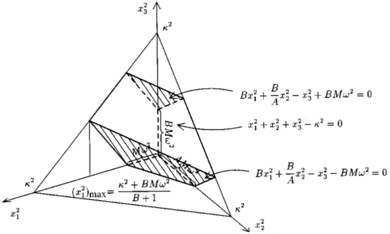
1604.01388



For CP-conserving cases, the theory constraints diminish the maxima of the LH mixings, e.g. for

$$
\begin{aligned}
&M_{N_1} = M,\ M_{N_2} = AM,\ M_{N_3} = BM, \\
&\eta_{CP}(N_1) = \eta_{CP}(N_2) = -\eta_{CP}(N_3) = +i, \\
&B_{eN_1} \equiv x_1,\ B_{eN_2} \equiv x_2,\ B_{eN_3} \equiv ix_3,
\end{aligned}
$$





$$
|B_{Ne}|^2_{max} \rightarrow \frac{\kappa^2 + M[TeV]\omega^2}{2} \xrightarrow{M \leq 1\ TeV} \frac{\kappa^2}{2}
$$

hep-ph/9612227

Largest mixing for almost degenerate heavy neutrinos with not the same CP-parities (to avoid $\beta\beta_{0\nu}$ Majorana constraint), $A \rightarrow 1$ for n=2, $A \gg B, B \rightarrow 1$ for n=3.

LNV, Majorana neutrinos, further constraints

Process	Present limits	Future	Experiment
$\mu^+ \to e^+\gamma$	$< 4.2 \times 10^{-13}$	5×10^{-14}	MEG II
$\mu^+ \to e^+e^-e^+$	$< 1.0 \times 10^{-12}$	10^{-16}	Mu3e
$\mu^- \mathrm{Al} \to e^- \mathrm{Al}$	$< 6.1 \times 10^{-13}$	10^{-17}	Mu2e, COMET
$\mu^- \mathrm{Si/C} \to e^- \mathrm{Si/C}$	$-$	5×10^{-14}	DeeMe
$\tau \to e\gamma$	$< 3.3 \times 10^{-8}$	5×10^{-9}	Belle II, FC
$\tau \to \mu\gamma$	$< 4.4 \times 10^{-8}$	10^{-9}	Belle II , FC
$\tau \to eee$	$< 2.7 \times 10^{-8}$	5×10^{-10}	Belle I I, FC
$\tau \to \mu\mu\mu$	$< 2.1 \times 10^{-8}$	5×10^{-10}	Belle II, FC
$\tau \to e$ had	$< 1.8 \times 10^{-8}$	3×10^{-10}	Belle II, FC

...

Application (1)

Alain Blondel, André de Gouvêa, Boris Kayser, 2105.06576

$$B(Z \to \nu_4 \nu_{\text{light}}) = 2|U_4|^2 \frac{B(Z \to \text{invisible})}{3} \left(1 + \frac{m_4^2}{2M_Z^2}\right) \left(1 - \frac{m_4^2}{M_Z^2}\right)^2 ; \quad \sum_{\alpha=e,\mu,\tau} |U_{\alpha 4}|^2 \equiv |U_4|^2,$$

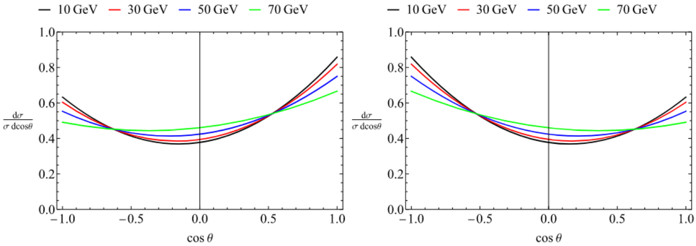


FIG. 1. Normalized differential cross-section for $e^+e^- \to Z \to \nu_4 \bar{\nu}_{\text{light}}$ (left) and $e^+e^- \to Z \to \bar{\nu}_4 \nu_{\text{light}}$ (right) as a function of the direction of the heavy (anti)neutrino $\cos\theta$, for different values of the heavy neutrino mass m_4. The neutrinos are assumed to be Dirac fermions.

”We estimate semiquantitatively that around 400 events are required to establish the Majorana or Dirac nature of the heavy neutrinos using the potential forward-backward asymmetry alone

Neutrinos, Corrections

Leptonic flavor changing Z0 decays in SU(2) x U(1) theories with right-handed neutrinos, *J. G. Korner, A. Pilaftsis and K. Schilcher, Phys. Lett. B* ***300*** *(1993), 381, hep-ph/9301290*

Mixing renormalization in Majorana neutrino theories, *B.A. Kniehl, A. Pilaftsis, Nucl.Phys.B 474 (1996) 286, hep-ph/9601390*

Effects of heavy Majorana neutrinos on lepton flavor violating processes, *G. Hernández-Tomé et al, Phys.Rev.D 101 (2020) 7, 075020 1912.13327*

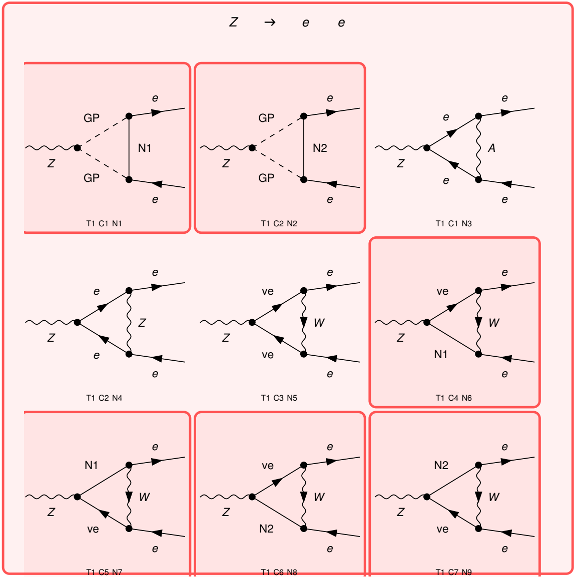
Improving Electro-Weak Fits with TeV-scale Sterile Neutrinos, *E. Akhmedov et al, JHEP 05 (2013) 081, 1302.1872*

Loop level constraints on Seesaw neutrino mixing, *E. Fernandez-Martinez et al, JHEP 10 (2015) 130, 1508.03051*

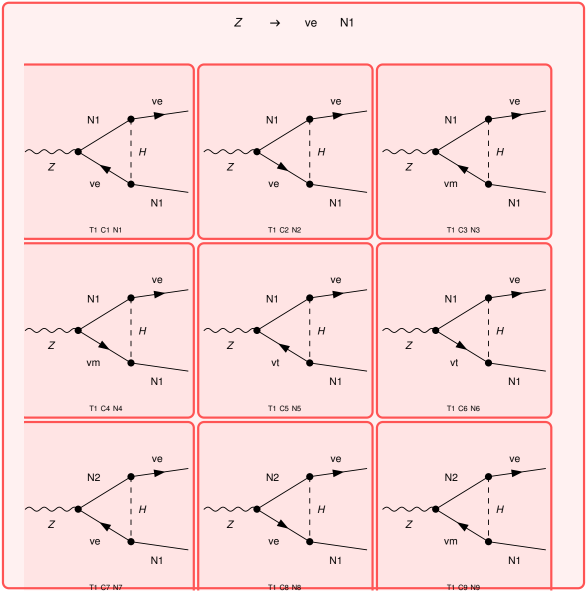
For RHNs we can compare SM HO terms with BSM effects:

$$HO = HO_{\rm SM} + HO_{BSM}\,.$$

Work in progress: Automation



Work in progress: Automation



- RHNs are promising candidates for BSM signals discovery at FCC-ee.
- Light-heavy mixings are sensitive to (heavy) neutrino CP-parities.

In this context:

- It is worth studying further seesaw and non-decoupling mixing models with $Z \to l_i l_j$ (LFV and LFC decays) and $Z \to \nu N_i$, NLO effects, Dirac/Majorana cases, consistency with low energy LFV/LFC/LNV effects, leptogenesis, ...