A (not so) short talk on CP and RHNs

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Polish Particle and Nuclear Theory Summit, Cracow

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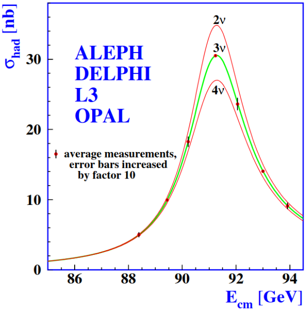
National Science Centre
Poland

First beautiful collider result with neutrinos

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



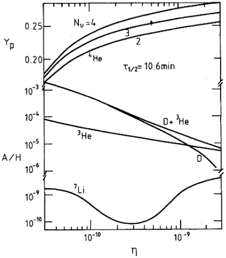
$$N_\nu \equiv \left(\frac{\Gamma_{inv}}{\Gamma_{lept}}\right)^{meas} \Bigg/ \left(\frac{\Gamma_{\nu\bar{\nu}}}{\Gamma_{lept}}\right)^{SM}$$

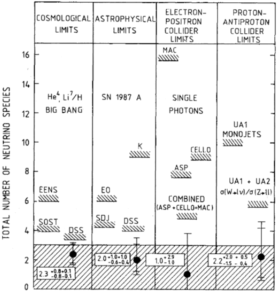
LEP EWWG, hep-ex/0509008

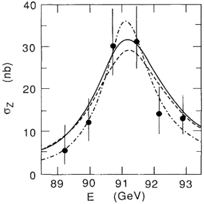
$N_{\rm eff}$: (Good) Things Come in 3s?

The Number of Neutrino Species,

D. Denegri, B. Sadoulet, M. Spiro, Rev.Mod.Phys. 62 (1990) 1







SLC,

$$N_\nu = 3.8 \pm 1.4$$

106 Z events

1989:

Initial measurements of Z-boson resonance parameters in e^+e annihilation, SLC Colaboration Phys. Rev. Lett. 63, 724

$N_{\rm eff}$: 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

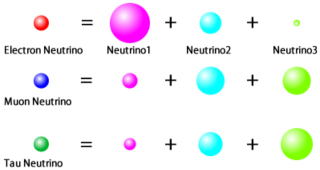
$$N_\nu \leq n.$$

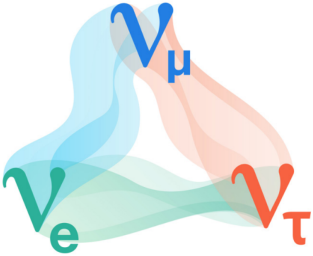
$$|\nu^{(f)}\rangle_\alpha = \underbrace{(V_{\rm osc})_{\alpha i}\,\nu_i^{(m)}}_{\text{SM part}} + \underbrace{(V_{lh})_{\alpha j}|\tilde{\nu}^{(m)}\rangle_j}_{\text{BSM part}}$$

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 oscillations

$$\nu_\alpha^{(f)} = (U_{\texttt{PMNS}})_{\alpha i} \nu_i^{(m)}$$



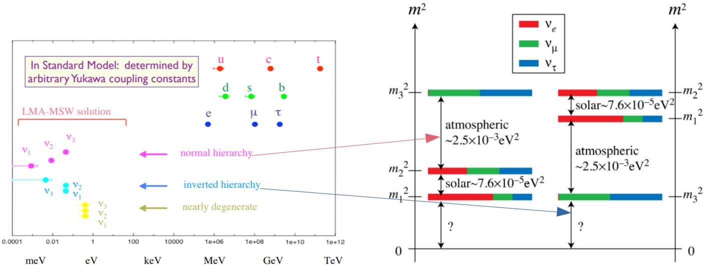


Mixing matrix

$$U_{\texttt{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

source: http://www.hyper-k.org/en/index.html; https://neutrinos.fnal.gov

Neutrino parameters ($\rightarrow$ S. Zieba, B. Karmakar



	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.6$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.269 \rightarrow 0.343$	$0.304^{+0.012}_{-0.012}$	$0.269 \rightarrow 0.343$
$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \rightarrow 35.86$	$33.45^{+0.77}_{-0.74}$	$31.27 \rightarrow 35.87$
$\sin^2\theta_{23}$	$0.573^{+0.018}_{-0.023}$	$0.405 \rightarrow 0.620$	$0.578^{+0.017}_{-0.021}$	$0.410 \rightarrow 0.623$
$\theta_{23}/^\circ$	$49.2^{+1.0}_{-1.3}$	$39.5 \rightarrow 52.0$	$49.5^{+1.0}_{-1.2}$	$39.8 \rightarrow 52.1$
$\sin^2\theta_{13}$	$0.02220^{+0.00068}_{-0.00062}$	$0.02034 \rightarrow 0.02430$	$0.02238^{+0.00064}_{-0.00062}$	$0.02053 \rightarrow 0.02434$
$\theta_{13}/^\circ$	$8.57^{+0.13}_{-0.12}$	$8.20 \rightarrow 8.97$	$8.60^{+0.12}_{-0.12}$	$8.24 \rightarrow 8.98$
$\delta_{\mathrm{CP}}/^\circ$	194^{+52}_{-25}	$105 \rightarrow 405$	287^{+27}_{-32}	$192 \rightarrow 361$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \rightarrow 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \rightarrow 8.04$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.515^{+0.028}_{-0.028}$	$+2.431 \rightarrow +2.599$	$-2.498^{+0.028}_{-0.029}$	$-2.584 \rightarrow -2.413$

CP phases, complex mixing elements

$$\begin{pmatrix} |\nu_\alpha^{(f)}\rangle \\ |\widetilde{\nu}_\beta^{(f)}\rangle \end{pmatrix} = \begin{pmatrix} U_{\rm PMNS} & V_{lh} \\ V_{hl} & V_{hh} \end{pmatrix} \begin{pmatrix} |\nu_i^{(m)}\rangle \\ |\widetilde{\nu}_j^{(m)}\rangle \end{pmatrix} \equiv \mathcal{U} \begin{pmatrix} |\nu_i^{(m)}\rangle \\ |\widetilde{\nu}_j^{(m)}\rangle \end{pmatrix} . \quad (1)$$

The SM flavor states $|\nu_\alpha^{(f)}\rangle$ are then given by

$$|\nu_\alpha^{(f)}\rangle = \sum_{i=1}^{3} \underbrace{(U_{\rm PMNS})_{\alpha i}\, |\nu_i^{(m)}\rangle}_{\text{SM part}} + \sum_{j=1}^{n_R} \underbrace{(V_{lh})_{\alpha j} |\widetilde{\nu}_j^{(m)}\rangle}_{\text{BSM part}} . \quad (2)$$

The mixing matrix $\mathcal{U}$ in (1) diagonalizes a general neutrino mass matrix

$$M_\nu = \begin{pmatrix} M_L & M_D \\ M_D^T & M_R \end{pmatrix}, \quad (3)$$

using a congruence transformation $\mathcal{U}^T M_\nu \mathcal{U} \simeq \mathrm{diag}(m_i, M_j)$

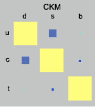
$$\begin{aligned} U_{\rm PMNS} &= U(\theta_{23})U(\theta_{13},\delta_{\rm CP})U(\theta_{12})U_M(\alpha_1,\alpha_2) \\ &= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\rm CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\rm CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \\ &\quad \times \begin{pmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{pmatrix} \end{aligned}$$

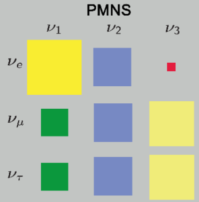
Neutrino Physics Enters Precisoin Era

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

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

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

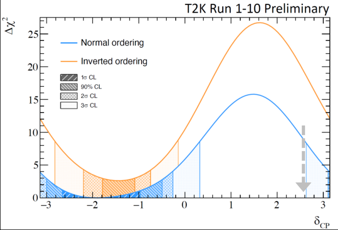


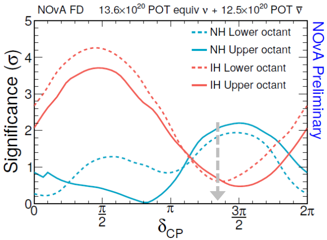


Conclusion: Neutrino Physics stepped in the precision era.

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

The CP Phase





T2K

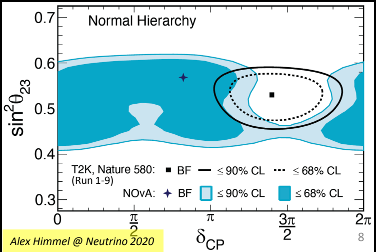
- δ = - π/2 favored
- Large range of values of δ_{CP} around $+\pi/2$ are excluded at 99.7%

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

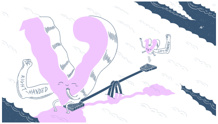
- Neutrino Mass in SM : No right-handed (RH) neutrinos, No Dirac Mass term for neutrinos
- Accidental lepton number conservation in SM ($\Delta L = 0$)
- Lepton number violation by SM dimension-5 operator : $\ell\ell HH/\Lambda$
- Simplest way: Type-I Seesaw Mechanism
- SM + RH neutrinos

Type-I Seesaw: Heavy Majorana neutrinos included

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

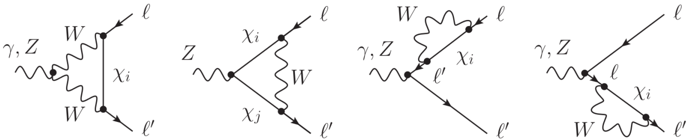
$$M_{SS} = \begin{pmatrix} 0 & M_D^T \\ M_D & M_R \end{pmatrix}$$

$$m_\nu^{light} = -M_D^T M_R^{-1} M_D, m_\nu^{heavy} = M_R \text{ with } |M_D| << |M_R|$$



How Light and Heavy Masses (Eigenvalues) Influence Active-Sterile Mixings (Eigenvectors)?

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

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

$$\mathcal{L}_Z = -\frac{g}{4c_W} Z_\mu \sum_{i,j=1}^{3+N} \bar{\chi}_i \gamma^\mu \left(C_{ij} P_L - C_{ij}^* P_R \right) \chi_j,$$

$$V_{ij} = \sum_{k=1}^{3} \delta_{ik} \mathcal{U}_{kj};\ C_{ij} = \sum_{k=1}^{3} (\mathcal{U}_{ki})^* \mathcal{U}_{kj}$$

Estimate Active-Sterile Mixing Using Singular Values* and $U_{\rm PMNS}^{\rm interval}$

Ω_1 : 3+1 scenario: $\Sigma = \{\sigma_1 = 1.0, \sigma_2 = 1.0, \sigma_3 < 1.0\}$

$$\begin{pmatrix} U_{\tt PMNS} & V_{lh} \\ V_{hl} & V_{hh} \end{pmatrix} = \begin{pmatrix} W_1 & 0 \\ 0 & W_2 \end{pmatrix} \left(\begin{array}{ccc|c} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & c & -s \\ \hline 0 & 0 & s & c \end{array}\right) \begin{pmatrix} Q_1^\dagger & 0 \\ 0 & Q_2^\dagger \end{pmatrix}.$$

We are interested in the estimation of the light-heavy mixing sector which is given by

$$V_{lh} = W_1 S_{12} Q_2^\dagger,$$

where $W_1 \in \mathbb{C}^{3\times 3}$ is unitary, $S_{12} = (0, 0, -s)^T$ and $Q_2 = e^{i\theta}, \theta \in (0, 2\pi]$. Taking into account exact values of the W_1 we can estimate the light-heavy mixing by the analytical formula

$$|V_{i4}| = |w_{i3}| \cdot |\sqrt{1 - \sigma_3^2}|, \quad i = e, \mu, \tau.$$

*Krzysztof Bielas, Wojciech Flieger, JG, Marek Gluza, PRD 98 (2018) 5, 053001

Estimation of the "light-heavy" mixing via CS decomposition

- (I): $m > EW$.

$$Ours^* : |V_{e4}| \in [0, 0.021]\,, \quad |V_{\mu 4}| \in [0.00013, 0.021]\,, \quad |V_{\tau 4}| \in [0.0115, 0.075]\,.$$
$$Others : |V_{e4}| \leq 0.041\ , \quad |V_{\mu 4}| \leq 0.030\ , \quad |V_{\tau 4}| \leq 0.087$$ [J. de Blas, 2013]

- (II): $\Delta m^2 \gtrsim 100 eV^2$.

$$Ours : |V_{e4}| \in [0, 0.082]\,, \quad |V_{\mu 4}| \in [0.00052, 0.099]\,, \quad |V_{\tau 4}| \in [0.0365, 0.44]\,.$$

- (III): $\Delta m^2 \sim 0.1 - 1 eV^2$.

$$Ours : |V_{e4}| \in [0, 0.130]\,, \quad |V_{\mu 4}| \in [0.00052, 0.167]\,, \quad |V_{\tau 4}| \in [0.0365, 0.436]\,.$$
$$Others : |U_{e4}| \in [0.114, 0.167]\ , \quad |V_{\mu 4}| \in [0.0911, 0.148]\ , \quad |V_{\tau 4}| \leq 0.361\ .$$
[C. Giunti et al., 2017] [M. Dantler et al., 2018]

$\longrightarrow$ In some cases, we improved (blue). In some not (red).

* W. Flieger, JG, Kamil Porwit, JHEP 03 (2020) 169

As an illustration let us take two U_{PMNS} matrices

$$U_1:\ \theta_{12} = 31.38^\circ, \theta_{23} = 38.4^\circ, \theta_{13} = 7.99^\circ,$$
$$U_2:\ \theta_{12} = 35.99^\circ, \theta_{23} = 52.8^\circ, \theta_{13} = 8.90^\circ,$$

and let us construct a contraction as

$$V = \frac{1}{2}U_1 + \frac{1}{2}U_2,$$

The set of singular values

$$\sigma_1(V) = 1,\ \boldsymbol{\sigma_2(V) = 0.991},\ \boldsymbol{\sigma_3(V) = 0.991}$$

for which we get the following unitary dilation

$$\mathcal{U} = \left(\begin{array}{ccc|cc} 0.822411 & 0.548133 & 0.146854 & 0.0169583 & -0.0368511 \\ -0.468394 & 0.520442 & 0.70103 & -0.133845 & 0.0197681 \\ 0.311417 & -0.643236 & 0.686702 & 0.0250273 & 0.130689 \\ \hline -0.0524981 & 0.122242 & -0.0336064 & 0.599485 & 0.788536 \\ -0.0671638 & 0.00403263 & 0.119588 & 0.788536 & -0.599485 \end{array}\right)$$

How Light and Heavy Masses (Eigenvalues) Influence Active-Sterile Mixings (Eigenvectors)?

$$M_{SS} = \begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix} = \begin{pmatrix} 0 & 0 \\ 0 & M_R \end{pmatrix} + \begin{pmatrix} 0 & M_D \\ M_D^T & 0 \end{pmatrix} \equiv \mathcal{M}_R + \mathcal{M}_D,$$

$\begin{pmatrix} 100 & -95 \\ -95 & 90 \end{pmatrix} \rightarrow \begin{matrix} \lambda_1 = 190.131 \\ \lambda_2 = -0.131 \end{matrix}$ When 3 light νs? SS-I, II, III, ESS, ISS, LSS - we can rearange to the same structure, W. Flieger, JG, Chin.Phys.C 45 (2021) 2, 023106

$$|m_D| \ll \lambda(M_R),\ \lambda(M_{SS}) \simeq \lambda(\mathcal{M}_R) \pm |m_D|$$

A relation between light and heavy masses and their mixings

$$\| \sin \Theta(V_{light}, V_{heavy}^{'})\| \leq \frac{1}{\delta} \|M_{SS} - \mathcal{M}_R\| = \frac{1}{\delta} \|\mathcal{M}_D\|,$$

$\delta = min(M_{N_i}) - max(m_{\nu_j})$

P. Denton et al, Bull.Am.Math.Soc. 59 (2022) 1

$$|v_{i,j}|^2 \prod_{k=1;k\neq i}^{n} (\lambda_i(A) - \lambda_k(A)) = \prod_{k=1}^{n-1} (\lambda_i(A) - \lambda_k(M_j)) \ .$$

What about CP effects in the heavy neutrino sector?

- Effects crucial for $(\beta\beta)_{0\nu}$ and colliders studies
- Needed for leptogenesis (standard way)
- Elegant theory for that.

RHNs at hadron collider, 1983

VOLUME 50, NUMBER 19 PHYSICAL REVIEW LETTERS 9 MAY 1983

Majorana Neutrinos and the Production of the Right-Handed Charged Gauge Boson

Wai-Yee Keung and Goran Senjanović

Physics Department, Brookhaven National Laboratory, Upton, New York 11973

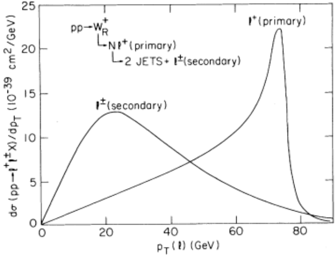
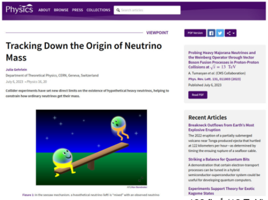
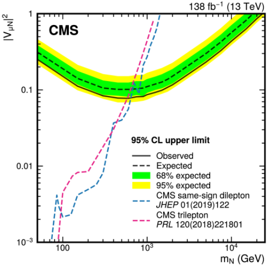


FIG. 2. Transverse momentum distributions of the primary and secondary leptons from W_R production for pp collision at $\sqrt{s} = 800$ GeV. The case $M_R = 200$ GeV, $m_N = 100$ GeV, and $\sin^2\theta_W = 0.25$ is illustrated.

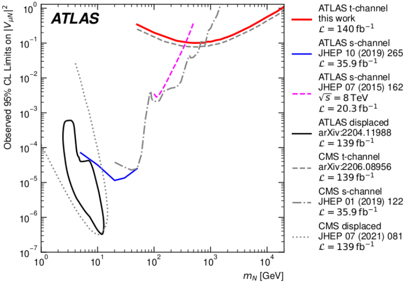
$$pp \to l^\pm l^\pm jj$$

LHC, present day





Search for $W^{\pm}W^{\pm} \to \ell^{\pm}\ell'^{\pm}$ quickly adopted by LHC groups!



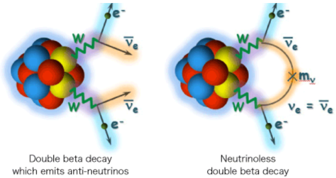
ATLAS ('23) [2305.14931]

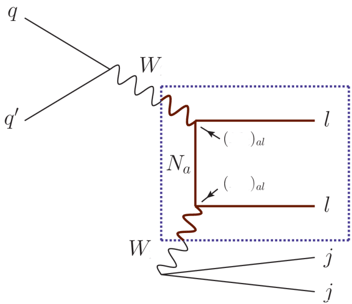
← CMS ('22) [2206.08956]

Talk by R. Ruiz, MTTD 2023, link

$e^-e^- \to W^-W^-$, $W^-W^- \to e^-e^-$, $pp \to lljj$, $(\beta\beta)_{0\nu}$

Lepton number violation and 'Diracness' of massive neutrinos composed of Majorana states, PRD'2016 1604.01388





e.g. $e^-e^- \to W^-W^-$, PLB'1995, hep-ph/9507269

$$\sigma(m_N(a) \gg \sqrt{s} \gg M_W) = \frac{G_F^2 s^2}{4\pi} \mid \sum_{\nu(a)} (V_{ae})^2 \frac{m_a}{s} + \sum_{N(a)} (V_{ae})^2 \frac{1}{m_a} \mid^2$$

$$\Psi_{Dirac} = e^{\pm i\alpha} \frac{1}{\sqrt{2}} (N_1 \pm i N_2) \longrightarrow \sigma(e^-e^- \to W^-W^-) = 0.$$

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

$$(i) \quad \sum_{N(heavy)} | V_{Ne} |^2 \leq \kappa^2, \quad [0.0030]$$

$$(ii) \quad | \sum_{\nu(light)} V_{\nu e}^2 m_\nu | < \kappa^{\mathbf{2}}_{\mathbf{light}}, \quad [0.68 \text{ eV}]$$

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

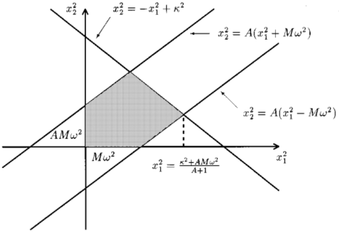
$$(iv) \quad \sum_{\nu(light)} | V_{\nu e} |^2 + \sum_{N(heavy)} | V_{Ne} |^2 = 1.$$

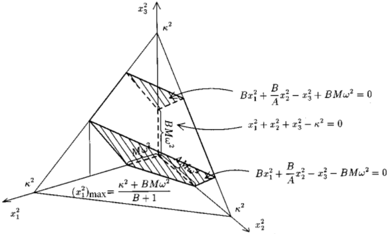
$$(v) \quad \sum_a V_{ae}^2 m_a = (M_L)_{\nu_e \nu_e} = 0 \Longrightarrow \sum_{\nu(\mathbf{light})} \mathbf{V^2_{\nu e} m_\nu} = - \sum_{\mathbf{N(heavy)}} \mathbf{V^2_{Ne} m_N}$$

$$\begin{pmatrix} U_{\text{PMNS}} & V_{lh} \\ V_{hl} & V_{hh} \end{pmatrix}, \begin{pmatrix} M_L = 0 & M_D \\ M_D^T & M_R \end{pmatrix}$$

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

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





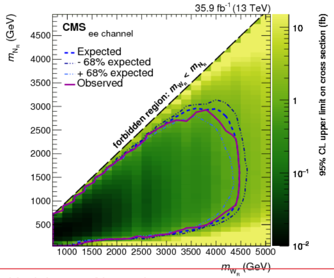
$$| V_{Ne} |^2_{max} \rightarrow \frac{\kappa^2 + M[TeV]\omega^2}{2} \overset{M \leq 1\ TeV}{\longrightarrow} \frac{\kappa^2}{2}$$ hep-ph/9612227

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.

CP mixing and destructive interference

LHC analysis = the same CPs of RHNs (real mixings)

$$| \sum_{\nu(a)} (V_{ae})^2 \frac{m_a}{s} + \sum_{N(a)} (V_{ae})^2 \frac{1}{m_a} |^2$$



GLUZA, JELIŃSKI, and SZAFRON

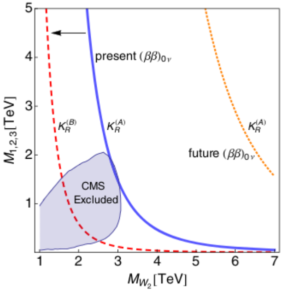


FIG. 3. The CMS vs m^N dominant $(\beta\beta)_{0\nu}$ exclusion limits on the masses of W_2 and N_a in the case when $(K_R)_{aj} = \delta_{aj}$ as in the (A) scenario. The shaded region is excluded by the CMS data related to $pp \to eejj$ at the LHC Run 1 [47]. Present $(\beta\beta)_{0\nu}$ experiments exclude the region under the blue solid curve. The dotted orange curve corresponds to a future bound on $T^{0\nu}_{1/2}$ [25]. For comparison, when the mixing matrix K_R is of the form (5) with $\theta_{13} = 0.9 \times \pi/4$ and $\phi_3 = \pi/2$, only the region under the dashed red curve is excluded. There are no available LHC data exclusion analyses for such "almost" Dirac neutrinos.

RHNs in Cosmology

A. Blondel et al. 1411.5230

TeV

GeV

MeV

keV

eV

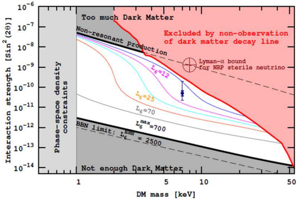
meV

N_2, N_3

can generate Baryon Asymmetry of Universe
if $m_{N2,N3}$ > 140 MeV

N_1

constrained:
mass: 1-50 keV
mixing :
10^{-7} to 10^{-13}
decay time:
$\tau_{N1} > \tau_{Universe}$

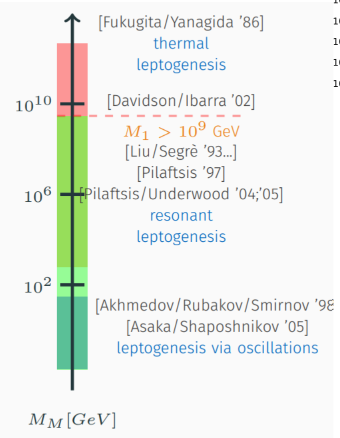


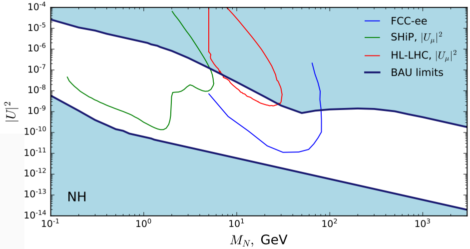
ν_3
ν_2
ν_1

$N_1 \rightarrow \nu\,\gamma$ *may* have been seen:
arxiv:1402:2301 and arxiv:1402.4119

;

RHN: Leptogenesis

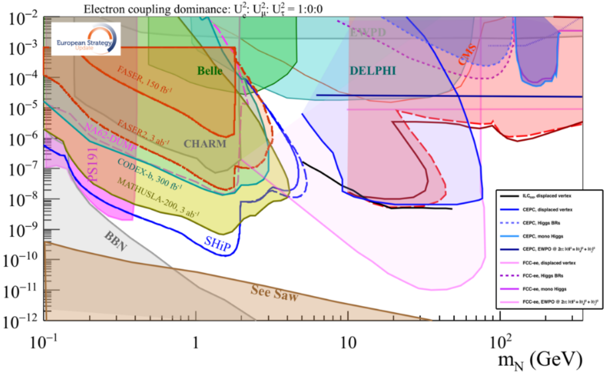




Juraj Klarić et. al., 2008.13771

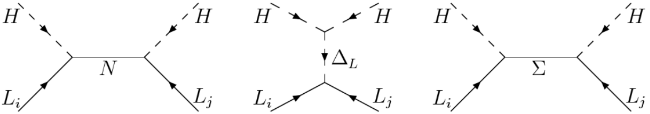
LFV Z-decays: $(10^{-6} \div 10^{-5})$. FCC-ee $\longrightarrow \sim 10^{-9}$ branching fractions.

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

Low scale CP and leptogenesis from RHNs sector

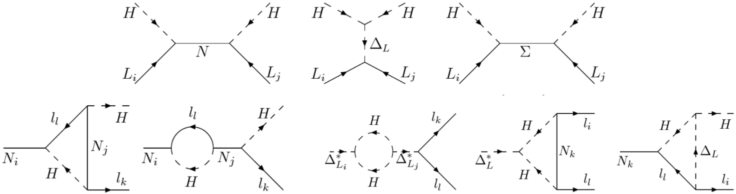


	Type of seesaw model		
	Type-I	Type-II	Type-III
Seesaw states	N	$\Delta_L = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \delta^0 & -\delta^+/\sqrt{2} \end{pmatrix}$	$\Sigma = \begin{pmatrix} \Sigma^0/\sqrt{2} & \Sigma^+ \\ \Sigma^- & -\Sigma^0/\sqrt{2} \end{pmatrix}$
Kin. term	$\mathrm{i}\overline{N}\partial\!\!\!/ N$	$\mathrm{Tr}[(D_\mu \Delta_L)^\dagger (D^\mu \Delta_L]$	$\mathrm{Tr}[\overline{\Sigma} i D\!\!\!\!/ \Sigma]$
Mass term	$-\frac{1}{2}\mathrm{Tr}[\overline{N} m_N N^c + \overline{N^c} m_N^* N]$	$-m_\Delta^2 \mathrm{Tr}[\Delta_L^\dagger \Delta_L]$	$-\frac{1}{2}\mathrm{Tr}[\overline{\Sigma} m_\Sigma \Sigma^c + \overline{\Sigma^c} m_\Sigma^* \Sigma]$
Interactions	$-\tilde{\phi}^\dagger \overline{N} Y_N L - \overline{L} Y_N{}^\dagger N \tilde{\phi}$	$-L^{\mathrm{T}} Y_\Delta C \mathrm{i}\tau_2 \Delta_L L + \mu \tilde{H}^{\mathrm{T}} \mathrm{i}\tau_2 \Delta_L \tilde{H}$	$-\tilde{\phi}^\dagger \overline{\Sigma} \sqrt{2} Y_\Sigma L - \overline{L} \sqrt{2} Y_\Sigma{}^\dagger \Sigma \tilde{\phi}$
ν masses	$\mathcal{M}_\nu^N = -\frac{v^2}{2} Y_N^{\mathrm{T}} \frac{1}{m_N} Y_N$	$\mathcal{M}_\nu^\Delta = 2 Y_\Delta v_{\Delta_L} = Y_\Delta \mu^* \frac{v^2}{m_\Delta^2}$	$\mathcal{M}_\nu^\Sigma = -\frac{v^2}{2} Y_\Sigma^{\mathrm{T}} \frac{1}{m_\Sigma} Y_\Sigma$
CP asym.	$\varepsilon_N \equiv \frac{\Gamma(N \to LH) - \Gamma(N \to \overline{L}\bar{H})}{\Gamma(N \to LH) + \Gamma(N \to \overline{L}\bar{H})}$	$\varepsilon_\Delta \equiv 2 \frac{\Gamma(\bar{\Delta}_L \to LL) - \Gamma(\Delta_L \to \overline{LL})}{\Gamma_\Delta + \Gamma_{\bar{\Delta}}}$	$\varepsilon_\Sigma \equiv \frac{\Gamma(\Sigma \to LH) - \Gamma(\overline{\Sigma} \to \overline{L}\bar{H})}{\Gamma(\Sigma \to LH) + \Gamma(\overline{\Sigma} \to \overline{L}\bar{H})}$

Leptogenesis: beyond the minimal type I seesaw scenario, Thomas Hambye, 1212.2888

Low scale CP and leptogenesis from RHNs sector

Minimal setup: > 1 RHNs needed (or Δ_L), complex couplings.



$$\varepsilon_N = -\frac{3}{32\pi^2}\frac{m_N^3}{\Gamma_N v^4} Im[(\mathcal{M}_\nu^N)_{\beta\alpha}(\mathcal{M}_\nu^H)^\dagger_{\alpha\beta}] \quad \longrightarrow \text{induced by decaying N and "H" in loop}$$

$$\varepsilon_\Delta = -\frac{1}{16\pi^2}\frac{m_\Delta^3}{\Gamma_\Delta v^4} Im[(\mathcal{M}_\nu^\Delta)_{\beta\alpha}(\mathcal{M}_\nu^H)^\dagger_{\alpha\beta}] \quad \longrightarrow \text{by decaying } \Delta_L \text{and heavy "H" in loop}$$

$$\varepsilon_\Sigma = -\frac{1}{32\pi^2}\frac{M_\Sigma^3}{\Gamma_\Sigma v^4} Im[(\mathcal{M}_\nu^\Sigma)_{\beta\alpha}(\mathcal{M}_\nu^H)^\dagger_{\alpha\beta}] \quad \longrightarrow \text{by decaying } \Sigma \text{ and heavy "H" in loop}$$

Not discussed: Footprints of CP from the heavy sector at low scale $\longrightarrow$ our review

arXiv:2310.20681

Summary and Outlook

- RHNs are promising candidates for BSM signals discovery at lepton and hadron colliders.
- 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, ...