Lepton number conservation and new probes of low-scale seesaw models JHEP04(2017)038 – arXiv:1712.07611 – arXiv:1712.07621

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Neutrino phenomena

- Neutrino oscillations (best fit from nu-fit.org): solar $\theta_{12} \simeq 34^{\circ} \qquad \Delta m_{21}^2 \simeq 7.4 \times 10^{-5} \text{eV}^2$ atmospheric $\theta_{23} \simeq 47^{\circ} \qquad |\Delta m_{23}^2| \simeq 2.5 \times 10^{-3} \text{eV}^2$ reactor $\theta_{13} \simeq 8.5^{\circ}$
- Absolute mass scale: cosmology $\Sigma m_{\nu_i} < 0.23 \text{ eV}$ [Planck, 2016] β decays $m_{\nu_e} < 2.05 \text{ eV}$ [Mainz, 2005; Troitsk, 2011]
 - Different mixing pattern from CKM, ν lightness \leftarrow Majorana ν
- Neutrino nature (Dirac or Majorana): Neutrinoless double β decays
 m_{2β} < 0.061 - 0.165 eV [KamLAND-ZEN, 2016]





Massive neutrinos and New Physics

- Standard Model $L = {\nu_L \choose \ell_L}, \tilde{\phi} = {H^{0*} \choose H^{-}}$
 - No right-handed neutrino $\nu_R \rightarrow$ No Dirac mass term

$$\mathcal{L}_{\text{mass}} = -Y_{\nu}\bar{L}\tilde{\phi}\nu_{R} + \text{h.c.}$$

 No Higgs triplet T → No Majorana mass term

$$\mathcal{L}_{\text{mass}} = -\frac{1}{2}f\overline{L}TL^{c} + \text{h.c.}$$



- - Radiative models
 - Extra-dimensions
 - R-parity violation in supersymmetry
 - Seesaw mechanisms $\rightarrow \nu$ mass at tree-level

+ BAU through leptogenesis



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Dirac neutrinos ?

• Add gauge singlet (sterile), right-handed neutrinos $\nu_R \Rightarrow \nu = \nu_L + \nu_R$ $\mathcal{L}_{mass}^{\text{leptons}} = -Y_\ell \bar{L} \phi \ell_R - Y_\nu \bar{L} \tilde{\phi} \nu_R + \text{h.c.}$

 $\Rightarrow \text{After electroweak symmetry breaking } \langle \phi \rangle = \begin{pmatrix} 0 \\ v \end{pmatrix} \\ \mathcal{L}_{\text{mass}}^{\text{leptons}} = -m_{\ell} \bar{\ell}_{L} \ell_{R} - m_{D} \bar{\nu}_{L} \nu_{R} + \text{h.c.}$

 \Rightarrow 3 light active neutrinos: $m_{\nu} \leq 1 \text{eV} \Rightarrow Y^{\nu} \leq 10^{-11}$



Majorana neutrinos ?

• Add gauge singlet (sterile), right-handed neutrinos ν_R $\mathcal{L}_{mass}^{\text{leptons}} = -Y_\ell \bar{L} \phi \ell_R - Y_\nu \bar{L} \tilde{\phi} \nu_R - \frac{1}{2} M_R \overline{\nu_R} \nu_R^c + \text{h.c.}$

 $\Rightarrow \text{After electroweak symmetry breaking } \langle \phi \rangle = \begin{pmatrix} 0 \\ v \end{pmatrix}$ $\mathcal{L}_{\text{mass}}^{\text{leptons}} = -m_{\ell} \ell_L \ell_R - m_D \bar{\nu}_L \nu_R - \frac{1}{2} M_R \overline{\nu_R} \nu_R^c + \text{h.c.}$

 $3\nu_R \Rightarrow 6$ mass eigenstates: $\nu = \nu^c$

- ν_R gauge singlets $\Rightarrow M_R$ not related to SM dynamics, not protected by symmetries $\Rightarrow M_R$ between 0 and M_P
- $M_R \overline{\nu_R} \nu_R^c$ violates lepton number conservation $\Delta L = 2$

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The seesaw mechanisms

- Seesaw mechanism: new fields + lepton number violation \Rightarrow Generate m_{ν} in a renormalizable way and at tree-level
- 3 minimal tree-level seesaw models \Rightarrow 3 types of heavy fields
 - type I: right-handed neutrinos, SM gauge singlets
 - type II: scalar triplets
 - type III: fermionic triplets



Towards testable Type I variants



• Taking $M_R \gg m_D$ gives the "vanilla" type 1 seesaw

$$\mathbf{m}_{\nu} = -m_D M_R^{-1} m_D^T$$

$$\mathbf{m}_{\nu} \sim 0.1 \,\mathrm{eV} \Rightarrow \begin{vmatrix} Y_{\nu} \sim 1 & \text{and} & M_R \sim 10^{14} \,\mathrm{GeV} \\ Y_{\nu} \sim 10^{-6} \,\mathrm{and} & M_R \sim 10^2 \,\mathrm{GeV} \end{vmatrix}$$

• m_{ν} suppressed by small active-sterile mixing m_D/M_R

• Cancellation in matrix product to get large m_D/M_R

• Lepton number, e.g. low-scale type I [Ilakovac and Pilaftsis, 1995] and others inverse seesaw [Mohapatra and Valle, 1986, Bernabéu et al., 1987]

linear seesaw [Akhmedov et al., 1996, Barr, 2004, Malinsky et al., 2005]

• Flavour symmetry, e.g. $A_4 \times \mathbb{Z}_2$ [Chao et al., 2010]

 A_4 or $\Sigma(81)$ [Chattopadhyay and Patel, 2017]

 $\mathbb{Z}(3)$ [Gu et al., 2009]

• Gauge symmetry, e.g. $U(1)_{B-L}$ [Pati and Salam, 1974] and others

 $m_{\nu} = 0$ equivalent to conserved L for models with 3 ν_R or less of equal mass [Kersten and Smirnov, 2007]

Extending the Kersten-Smirnov theorem

- Can the result of Kersten and Smirnov be generalized ?
- Are lepton number violating processes suppressed in all low-scale seesaw models ?

Theorem

- If: no cancellation between different orders of the seesaw expansion^a
 - no cancellations between different radiative orders^b

Then $m_{\nu} = 0$ equivalent to having the neutrino mass matrix, in the basis $(\nu_{L}^{C}, \{\nu_{R,1}^{(1)}...\nu_{R,n}^{(1)}\}, \{\nu_{R,1}^{(2)}...\nu_{R,n}^{(2)}\}, \{\nu_{R,1}^{(3)}...\nu_{R,m}^{(3)}\})$

$$\tilde{M} = \begin{pmatrix} 0 & \alpha & \pm i\alpha & 0\\ \alpha^T & M_1 & 0 & 0\\ \pm i\alpha^T & 0 & M_1 & 0\\ 0 & 0 & 0 & M_2 \end{pmatrix},$$
(1)

for an arbitrary number of ν_R and to all radiative orders, with M_1 and M_2 diagonal matrices with positive entries and α a generic complex matrix.

^aThis is a necessary requirement to satisfy phenomenological constraints ^bThese are highly fine-tuned solution that cannot be achieved solely by specific textures of the neutrino mass matrix

Corollary on lepton number violation

Using a unitary matrix D, let us construct

$$\mathcal{Q} = \left(egin{array}{ccccc} 1 & 0 & 0 & 0 \ 0 & \pm rac{i}{\sqrt{2}}D & rac{1}{\sqrt{2}}D & 0 \ 0 & rac{1}{\sqrt{2}}D & \pm rac{i}{\sqrt{2}}D & 0 \ 0 & 0 & 0 & 1 \end{array}
ight)$$

then through a change of basis

$$Q^{T}\tilde{M}Q = \begin{pmatrix} 0 & \pm i\sqrt{2}(D^{T}\alpha^{T})^{T} & 0 & 0\\ \pm i\sqrt{2}D^{T}\alpha^{T} & 0 & \pm iD^{T}M_{1}D & 0\\ 0 & \pm iD^{T}M_{1}D & 0 & 0\\ 0 & 0 & 0 & M_{2} \end{pmatrix} \sim \begin{pmatrix} 0 & M_{D}^{T} & 0 & 0\\ M_{D} & 0 & M_{R} & 0\\ 0 & M_{R}^{T} & 0 & 0\\ 0 & 0 & 0 & M_{2} \end{pmatrix}$$

- Similar to the L conserving limit of inverse and/or linear seesaw
- Explicitly L conserving taking the L assignment (+1, -1, +1, 0)

Corollary

The most general gauge-singlet neutrino extensions of the SM with no cancellation between different orders of the seesaw expansion, no fine-tuned cancellations between different radiative orders and which lead to three massless neutrinos are L conserving.

Eq. (1) as a sufficient condition

Directly obtained from the corollary¹

¹In the seesaw limit, light neutrinos are Majorana fermions whose mass violate L conservation. Eq. (1) being equivalent to L conservation implies that the light neutrinos are massless.



Necessary condition: tree level

• At tree-level and for the first order of the seesaw expansion

$$m_{\nu} \approx -m_D M_R^{-1} m_D^T$$

• If $m_D M_R^{-1} m_D^T = 0$ and using $Z = M_R^{-1} m_D^T$, then the exact blockdiagonalisation of the full neutrino mass matrix gives

[Korner et al., 1993, Grimus and Lavoura, 2000]

$$\begin{split} \mathbf{m}_{\nu} &= -\left(1 + Z^{*}Z^{T}\right)^{-\frac{1}{2}} Z^{T} m_{D}^{T} \left(1 + Z^{\dagger}Z\right)^{-\frac{1}{2}} \\ &- \left(1 + Z^{T}Z^{*}\right)^{-\frac{1}{2}} m_{D}Z \left(1 + ZZ^{\dagger}\right)^{-\frac{1}{2}} \\ &+ \left(1 + Z^{*}Z^{T}\right)^{-\frac{1}{2}} Z^{T} M_{R}Z \left(1 + ZZ^{\dagger}\right)^{-\frac{1}{2}} \end{split}$$

• All terms contain $m_D M_R^{-1} m_D^T$ thus

$$\mathbf{m}_{\nu} = \mathbf{0} \Rightarrow m_D M_R^{-1} m_D^T = \mathbf{0}$$

to all orders of the seesaw expansion

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An aside on the Kersten-Smirnov theorem

• Using tree-level contributions ($m_{\nu} = 0 \Leftrightarrow m_D M_R^{-1} m_D^T = 0$), they get the general result if $\#\nu_R \leq 3$

$$m_D = m \begin{pmatrix} y_1 & y_2 & y_3 \\ ay_1 & ay_2 & ay_3 \\ by_1 & by_2 & by_3 \end{pmatrix}, \text{ and } \frac{y_1^2}{M_{R,1}} = \frac{y_2^2}{M_{R,2}} = \frac{y_3^2}{M_{R,3}}$$

- For #ν_R > 3, the system of linear equations in their proof is under-constrained
- In general, no symmetry is present. Necessary to assume degenerate heavy neutrinos to make a statement.
- Justify this by requiring radiative stability but approach based on running of the Weinberg operator
 - \rightarrow Works only if Higgs boson lighter than all heavy neutrinos



Image: A matrix

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Necessary condition: one-loop level

• When $m_{\nu} = 0$ at tree-level, the one-loop induced masses are

$$\delta m_{ij} = \Re \left[\frac{\alpha_W}{16\pi^2 m_W^2} C_{ik} C_{jk} f\left(m_k\right) \right]$$

with C the mixing matrix in the neutral current and Higgs couplings and f the loop function

• In the basis where M_R is diagonal, the full neutrino mass matrix M is

$$M = \begin{pmatrix} 0 & m_{D1} & \dots & m_{Dn} \\ m_{D1}^T & \mu_1 & \dots & 0 \\ \vdots & \vdots & \ddots & 0 \\ m_{Dn}^T & 0 & \dots & \mu_n \end{pmatrix}$$

and at the first order in the seesaw expansion

$$\delta m = 0 \Rightarrow \sum_{i=1}^{n} \mu_i^{-2} m_{Di} m_{Di}^T f\left(\mu_i\right) = 0$$

Necessary condition: one-loop level

- Cancellation could still come from summation of non-zero terms ③
- But a rescaling $M \to \Lambda M$ does not affect the condition $m_{\nu} = \delta m = 0$
- f(x) being monotonically increasing and strictly convex,

$$\sum_{i=1}^{n} \mu_{i}^{-2} m_{Di} m_{Di}^{T} f(\mu_{i}) = 0 \to \Lambda^{-2} \sum_{i=1}^{n} \mu_{i}^{-2} m_{Di} m_{Di}^{T} f(\Lambda \mu_{i}) = 0$$

generate linearly independent equations from which

$$m_{\nu} = 0 \Rightarrow m_{Di}m_{Di}^T = 0$$

since $\mu_i > 0, f(\mu_i) > 0$

From the necessary one-loop condition to the theorem

• We write $m_{Di}^T = (u^i, v^i, w^i)$, then

$$m_{Di}m_{Di}^{T} = \begin{pmatrix} u^{iT}u^{i} & u^{iT}v^{i} & u^{iT}w^{i} \\ v^{iT}u^{i} & v^{iT}v^{i} & v^{iT}w^{i} \\ w^{iT}u^{i} & w^{iT}v^{i} & w^{iT}w^{i} \end{pmatrix} = 0$$

- We construct Yⁱ = u^{i*}u^{iT} + uⁱu^{i†}. Imposing u^{iT}uⁱ = 0 and excluding the trivial solution uⁱ = 0, rank(Yⁱ) = 2
- Yⁱ symmetric and real: we can build a basis of real orthogonal eigenvectors bⁱ_{1...ni}.
 For the zero n_i 2 eigenvalues,

$$Y^{i}b_{k}^{i} = 0 \Rightarrow ||u^{i}||^{2}(u^{iT}b_{k}^{i}) = 0 \Rightarrow u^{iT}b_{k}^{i} = 0$$

Then

$$u^{i'} = R_{u}^{i}u^{i} = \begin{pmatrix} b_{1}^{iT}u^{i} \\ b_{2}^{iT}u^{i} \\ b_{3}^{iT}u^{i} \\ \vdots \\ b_{n_{l}}^{iT}u^{i} \end{pmatrix} = \begin{pmatrix} u_{1}^{i'} \\ u_{2}^{i'} \\ 0 \\ \vdots \\ 0 \end{pmatrix}$$

From the necessary one-loop condition to the theorem

- Finally $u^{iT}u^i = 0 \Rightarrow u_2^{i'} = \pm iu_1^{i'}$
- Rinse and repeat for the other vectors, leaving M_R unaffected in the process, to get

$$m_{Di} = \begin{pmatrix} u_1^{i'} \pm i u_1^{i'} & 0 & 0 & 0 & 0 & \dots & 0 \\ v_1^{i'} \pm i v_1^{i'} & v_3^{i''} \pm i v_3^{i''} & 0 & 0 & \dots & 0 \\ w_1^{i'} \pm i w_1^{i'} & w_3^{i''} \pm i w_3^{i''} & w_5^{i'''} \pm i w_5^{i'''} & 0 & \dots & 0 \end{pmatrix}$$

By rearranging the columns and rows, flavour-basis mass matrix becomes

$$M = \begin{pmatrix} 0 & \alpha & \pm i\alpha & 0 \\ \alpha^T & M_1 & 0 & 0 \\ \pm i\alpha^T & 0 & M_1 & 0 \\ 0 & 0 & 0 & M_2 \end{pmatrix} = \tilde{M} \square$$

Consequences for phenomenology and model building

- Any symmetry that leads to massless light neutrinos contains L as a subgroup or an accidental symmetry
- Prove the requirement of a nearly conserved L in low-scale seesaw models, baring fine-tuned solutions involving different radiative orders
- Smallness of the light neutrino mass related to the smallness of the L breaking parameter, or equivalently to the degeneracy of the heavy neutrinos in pseudo-Dirac pairs
- Expect L violating signatures to be suppressed
 → Needs to be quantitatively assessed
- Seems to be applicable to type III seesaw variants as well
 → Currently investigating it



A new opportunity

• How to search for heavy neutrino with $m_{\nu} > O(1 \text{ TeV})$?

Use the Higgs sector to probe neutrino mass models

- $H\bar{\ell}_i\ell_j$:
 - Contribution negligible in the SM \rightarrow evidence of new physics if observed
 - Large branching ratios are possible: Br $(H \rightarrow \tau \mu) \sim 10^{-5}$ in ISS [Arganda, Herrero, Marcano, CW, 2015] Br $(H \rightarrow \tau \mu) \sim 1\%$ in SUSY-ISS [Arganda, Herrero, Marcano, CW, 2016]
 - Sensitive to off-diagonal Yukawa couplings Y_{ν}
- *HHH*:
 - Useful to validate the Higgs mechanism as the origin of EWSB
 - Sizeable SM 1-loop corrections (O(10%))
 - \rightarrow Quantum corrections cannot be neglected
 - One of the main motivations for future colliders
 - Sensitive to diagonal Yukawa couplings Y_v
- WWH production
 - Overlooked channel for BSM searches
 - t-channel process: different dependence on the heavy neutrino mass²
 - Sensitive to diagonal Yukawa couplings Y_{ν}

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The triple Higgs coupling

Scalar potential before EWSB:

$$V(\phi) = -\mu^2 |\phi|^2 + \lambda |\phi|^4$$



• After EWSB: $m_H^2 = 2\mu^2$, $v^2 = \mu^2/\lambda$

$$\phi = \begin{pmatrix} 0\\ \frac{v+H}{\sqrt{2}} \end{pmatrix} \rightarrow V(H) = \frac{1}{2}m_H^2 H^2 + \frac{1}{3!}\lambda_{HHH}H^3 + \frac{1}{4!}\lambda_{HHHH}H^2$$

and

$$\lambda_{HHH}^{0} = -\frac{3m_{H}^{2}}{v}, \quad \lambda_{HHHH}^{0} = -\frac{3m_{H}^{2}}{v^{2}}$$

Higgs physics

Experimental measurement of the HHH coupling







• Destructive interference between diagrams with and without λ_{HHH}



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Higgs physics

Future sensitivities to the SM HHH coupling





- At hadron colliders
 - Production: gg dominates, VBF cleanest
 - HL-LHC: $\sim 50\%$ for ATLAS or CMS [CMS-PAS-FTR-15-002] and [Baglio et al., 2013] $\sim 35\%$ combined
 - FCC-hh: 8% per experiment with 3 ${
 m ab}^{-1}$ using only $bar{b}\gamma\gamma$ [He et al., 2016]

 $\sim 5\%$ combining all channels

- At e⁺e⁻ collider
 - Main production channels: Higgs-strahlung and VBF
 - ILC: 27% at 500 GeV with 4 ab^{-1} [Fujii et al., 2015]

10% at 1 TeV with 5 ab⁻¹ [Fujii et al., 2015] \triangleleft

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LNV and Higgs



The inverse seesaw mechanism

- Lower seesaw scale from approximately conserved lepton number
- Add fermionic gauge singlets ν_R (L = +1) and X (L = -1)

[Mohapatra and Valle, 1986]

$$\mathcal{L}_{inverse} = -Y_{\nu}\overline{L}\widetilde{\phi}\nu_{R} - M_{R}\overline{\nu_{R}^{c}}X - \frac{1}{2}\mu_{X}\overline{X^{c}}X + \text{h.c.}$$
with $m_{D} = Y_{\nu}\nu$, $M^{\nu} = \begin{pmatrix} 0 & m_{D} & 0 \\ m_{D}^{T} & 0 & M_{R} \\ 0 & M_{R}^{T} & \mu_{X} \end{pmatrix}$
 $M_{\nu} \approx \frac{m_{D}^{2}}{M_{R}^{2}}\mu_{X}$
 $m_{\nu} \approx \frac{m_{D}^{2}}{M_{R}^{2}}\mu_{X}$
 $M_{N_{1},N_{2}} \approx \mp M_{R} + \frac{\mu_{X}}{2}$
 $2 \text{ scales: } \mu_{X} \text{ and } M_{R}$

- Decouple neutrino mass generation from active-sterile mixing
- Inverse seesaw: Y_ν ~ O(1) and M_R ~ 1 TeV
 ⇒ within reach of the LHC and low energy experiments

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Most relevant constraints for the ISS

Accommodate low-energy neutrino data using parametrization

$$vY_{\nu}^{T} = V^{\dagger} \operatorname{diag}(\sqrt{M_{1}}, \sqrt{M_{2}}, \sqrt{M_{3}}) R \operatorname{diag}(\sqrt{m_{1}}, \sqrt{m_{2}}, \sqrt{m_{3}}) U_{PMNS}^{\dagger}$$
$$M = M_{R} \mu_{X}^{-1} M_{R}^{T}$$
or

$$\mu_X = M_R^T Y_\nu^{-1} U_{\text{PMNS}}^* m_\nu U_{\text{PMNS}}^\dagger Y_\nu^{T^{-1}} M_R v^2 \qquad \text{and beyond}$$

- Charged lepton flavour violation \rightarrow For example: Br($\mu \rightarrow e\gamma$) < 4.2 × 10⁻¹³ [MEG, 2016]
- Global fit to EWPO and lepton universality tests [Fernandez-Martinez et al., 2016]
- Electric dipole moment: 0 with real PMNS and mass matrices
- Invisible Higgs decays: M_R > m_H, does not apply
- Yukawa perturbativity: $|\frac{Y_{\nu}^2}{4\pi}| < 1.5$

Calculation in the ISS



- Generically: impact of new fermions coupling through the neutrino portal
- New 1-loop diagrams and new counterterms

 \rightarrow Evaluated with <code>FeynArts</code>, <code>FormCalc</code> and <code>LoopTools</code>

• OS renormalization scheme

Formulas for both Dirac and Majorana fermions coupling through the neutrino portal are available (see PRD94(2016)013002 as well)



Momentum dependence



•
$$\Delta^{(1)}\lambda_{HHH} = \frac{1}{\lambda^0} \left(\lambda_{HHH}^{1r} - \lambda^0\right)$$

- Focus on 1 neutrino contribution, fixed mixing $B_{\tau 4} = 0.087, B_{e/\mu 4} = 0$
- Deviation from the SM correction in the insert

•
$$\max|(B^{\dagger}B)_{i4}|m_{n_4} = m_t$$

 $\rightarrow m_{n_4} = 2.7 \text{ TeV}$
tight perturbativity of λ_{HHH} bound
 $m_{n_4} = 7 \text{ TeV}$
width bound: $m_{n_4} = 9 \text{ TeV}$

- Largest positive correction at $q_H^* \simeq 500 \,\text{GeV}$, heavy ν decreases it
- Large negative correction at large q_H^* , heavy ν increases it

Higgs physics

Results using the Casas-Ibarra parametrization



- Random scan: 180000 points with degenerate M_R and μ_X

• $\Delta^{\text{BSM}} = \frac{1}{\lambda_{HHH}^{\text{1r,SM}}} \left(\lambda_{HHH}^{\text{1r,full}} - \lambda_{HHH}^{\text{1r,SM}} \right)$

- Strongest constraints:
 - Lepton flavour violation, mainly $\mu \rightarrow e\gamma$
 - Yukawa perturbativity (and neutrino width)
- Large effects necessarily excluded by LFV constraints ?

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Suppressing LFV constraints

- How to evade LFV constraints ?
- Approximate formulas for large Y_ν [Arganda, Herrero, Marcano, CW, 2015]:

$$\mathrm{Br}_{\mu \to e\gamma}^{\mathrm{approx}} = 8 \times 10^{-17} \mathrm{GeV}^{-4} \frac{m_{\mu}^{5}}{\Gamma_{\mu}} |\frac{\mathrm{v}^{2}}{2M_{R}^{2}} (Y_{\nu} Y_{\nu}^{\dagger})_{12}|^{2}$$

• Solution: Textures with $(Y_{\nu}Y_{\nu}^{\dagger})_{12} = 0$

$$Y_{\tau\mu}^{(1)} = |Y_{\nu}| \begin{pmatrix} 0 & 1 & -1 \\ 0.9 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$$

Or even take Y_ν diagonal





Results for $Y_{\tau\mu}^{(1)}$



• Right: Full calculation in black, approximate formula in green

Well described at M_R > 3 TeV by approximate formula

$$\Delta_{\text{approx}}^{\text{BSM}} = \frac{(1 \text{ TeV})^2}{M_R^2} \left(8.45 \operatorname{Tr}(Y_\nu Y_\nu^{\dagger} Y_\nu Y_\nu^{\dagger}) - 0.145 \operatorname{Tr}(Y_\nu Y_\nu^{\dagger} Y_\nu Y_\nu^{\dagger} Y_\nu Y_\nu^{\dagger}) \right)$$

• Can maximize $\Delta^{\rm BSM}$ by taking $Y_{\nu} \propto I_3$

Results in the ISS



- Diagonal Y_{ν} : full calculation in black, approximate formula in green
- Heavy ν effects at the limit of HL-LHC (35%) and ILC (10%) sensitivities
- Heavy ν effects clearly visible at the FCC-hh (5%)

An alternative probe of Y_{ν}

- Probe Y_{ν} at tree-level with off-shell N ? \rightarrow t-channel $e^+e^- \rightarrow W^+W^-H$
- Good detection prospects in SM [Baillargeon et al., 1994]
- SM contributions: e^+ $e^ W^ W^-$
 - SM+ISS contributions:





CoM energy dependence



- LO calculation, neglecting *m_e*
- Calculation done with FeynArts, FormCalc, BASES
- Deviation from the SM in the insert

• Polarized:
$$P_{e^-} = -80\%$$
, $P_{e^+} = 0$

•
$$Y_{\nu} = 1, M_{R_1} = 3.6 \text{ TeV},$$

 $M_{R_2} = 8.6 \text{ TeV}, M_{R_3} = 2.4 \text{ TeV}$

- $\sigma(e^+e^- \rightarrow W^+W^-H)_{\rm pol} \sim 2\sigma(e^+e^- \rightarrow W^+W^-H)_{\rm unpol}$
- Maximal deviation of -38% close to 3 TeV

Results in the ISS



• $\Delta^{\text{BSM}} = (\sigma^{\text{ISS}} - \sigma^{\text{SM}}) / \sigma^{\text{SM}}$ • Polarization $P_{e^-} = -80\%$

$$\begin{split} \mathcal{A}_{\text{approx}}^{\text{ISS}} &= \frac{(1 \text{ TeV})^2}{M_R^2} \text{Tr}(Y_\nu Y_\nu^\dagger) \\ &\times \left(17.07 - \frac{19.79 \text{ TeV}^2}{M_R^2} \right) \\ \Delta_{\text{approx}}^{\text{BSM}} &= (\mathcal{A}_{\text{approx}}^{\text{ISS}})^2 - 11.94 \mathcal{A}_{\text{approx}}^{\text{ISS}} \end{split}$$

• Fit agrees within 1% for $M_R > 3 \text{ TeV}$

- Maximal deviation of -38%
 - → ISS induces large destructive interference effects
- Sizeable deviations for a larger region than for HHH



Enhancing the deviations



- Stronger destructive interference from ISS for: central production – larger Higgs energy
- Cuts: $|\eta_H| < 1$, $|\eta_{W^{\pm}}| < 1$ and $E_H > 1$ TeV

	Before cuts	After cuts
$\sigma_{ m SM}$ (fb)	1.96	0.42
$\sigma_{\rm ISS}$ (fb)	1.23	0.14
Δ^{BSM}	-38%	-66%



Image: Image:

Conclusions

- ν oscillations \rightarrow New physics is needed to generate masses and mixing
- One of the simplest ideas: Add right-handed, sterile neutrinos
- Nearly conserved L is a cornerstone of low-scale type I seesaw variants
- Corrections to the HHH coupling from heavy ν as large as 30%
 → measurable at future colliders
- Corrections to W^+W^-H production as large as -66% after cuts
- Maximal for diagonal Y_{ν} and provide new probes of the $\mathcal{O}(10)$ TeV region
- Next Step: Assess impact on LNV processes Corrections to the di-Higgs production cross-section Sensitivity studies for W⁺W⁻H production



Backup slides



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Cancellation between different seesaw orders

• To second order in the expansion

$$m_{\nu}^{(2)} = -m_{\nu}^{(1)} + \frac{1}{2} \left(m_n^{(1)} u \theta + \theta^T m_{\nu}^{(1)} \right)$$

with $m_{\nu}^{(1)}$ the first order expression and θ is $Z^{\dagger}Z$ up to a unitary transformation

Then

$$(m_{\nu}^{(2)})_{ii} = 0 \Leftrightarrow -\hat{m}_{lii}^{(1)} + \hat{m}_{lii}^{(1)}\theta_{ii} = 0$$

and $\theta_{ii} = 1$

• This contradicts [Fernandez-Martinez et al., 2016] which gives $|| heta|| \leqslant 0.0075$



Direct constraints from JHEP05(2009)030



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Direct constraints from JHEP05(2009)030



Direct constraints from JHEP05(2009)030



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Details of one-loop proof I

• The loop function is

$$f(m_k) = m_k \left(3m_Z^2 g_{kZ} + m_H^2 g_{kH}\right)$$

where

$$g_{ab} = rac{m_a^2}{m_a^2 - m_b^2} \log rac{m_a^2}{m_b^2}$$

which gives

$$U_{l}^{T} (1 + Z^{T}Z^{*})^{-1} Z^{T} U_{h}^{*} f_{h} U_{h}^{\dagger} Z (1 + Z^{\dagger}Z)^{-1} U_{l} = 0$$
$$Z^{T} U_{h}^{*} f_{h} U_{h}^{\dagger} Z = 0$$

to the first order in the seesaw expansion

$$U_h \approx 1$$
$$Z^T F_h Z = 0$$

Details of one-loop proof II

Once we have

$$u^{i'}=\left(u_1^{i'},\pm iu_1^{i'},0,\ldots,0
ight)^T$$

Under this transformation, we have

$$u^{iT}v^i = 0 \to u'^{iT}v'^i = 0$$

leading us to conclude that

$$v^{i'} = \left(v_1^{i'}, \pm i v_1^{i'}, v_3^{i'}, v_4^{i'}, \dots, v_{n_i}^{i'}
ight)^T$$

• Similarly, we construct a second matrix R_v acting on $\left(v_3^{i'}, v_4^{i'}, \dots, v_{n_i}^{i'}\right)^T$ such that $v^{i'}$ is reduced to

$$v^{i''} = \left(v_1^{i'}, \pm iv_1^{i'}, v_3^{i''}, \pm iv_3^{i''}, 0, \dots, 0\right)^T$$

• Rinse and repeat for w



Fine-tuning

We adopt here the idea of [Lopez-Pavon et al., 2015], where the tree-level and one-loop contributions cancel.



Evolution of m_3 as a function of the rescaling parameter Λ . Input masses and couplings where chosen to give $m_{\nu} = m_{\text{tree}} + m_{1-\text{loop}} = 0.046 \text{ eV}$ at $\Lambda = 1$. A deviation of less then 10^{-7} here, is enough to spoil the cancellation and contradict experimental limits.

Renormalization procedure for the HHH coupling I

- No tadpole: $t_H^{(1)} + \delta t_H = 0 \Rightarrow \delta t_H = -t_H^{(1)}$
- Counterterms:

$$\begin{split} M_H^2 &\to M_H^2 + \delta M_H^2 \\ M_W^2 &\to M_W^2 + \delta M_W^2 \\ M_Z^2 &\to M_Z^2 + \delta M_Z^2 \\ e &\to (1 + \delta Z_e) e \\ H &\to \sqrt{Z_H} = (1 + \frac{1}{2} \delta Z_H) H \end{split}$$

• Full renormalized 1–loop triple Higgs coupling: $\lambda_{HHH}^{1r} = \lambda^0 + \lambda_{HHH}^{(1)} + \delta \lambda_{HHH}$

$$\frac{\delta\lambda_{HHH}}{\lambda^0} = \frac{3}{2}\delta Z_H + \delta t_H \frac{e}{2M_W \sin\theta_W M_H^2} + \delta Z_e + \frac{\delta M_H^2}{M_H^2} - \frac{\delta M_W^2}{2M_W^2} + \frac{1}{2}\frac{\cos^2\theta_W}{\sin^2\theta_W} \left(\frac{\delta M_W^2}{M_W^2} - \frac{\delta M_Z^2}{M_Z^2}\right)$$
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Renormalization procedure for the HHH coupling II

OS scheme

$$\begin{split} \delta M_W^2 &= Re \Sigma_{WW}^T(M_W^2) \\ \delta M_Z^2 &= Re \Sigma_{ZZ}^T(M_Z^2) \\ \delta M_H^2 &= Re \Sigma_{HH}(M_H^2) \end{split}$$

• Electric charge:

$$\delta Z_e = \frac{\sin \theta_W}{\cos \theta_W} \frac{\text{Re} \Sigma_{\gamma Z}^T(0)}{M_Z^2} - \frac{\text{Re} \Sigma_{\gamma \gamma}^T(M_Z^2)}{M_Z^2}$$

Higgs field renormalization

$$\delta Z_H = -\mathrm{Re} \frac{\partial \Sigma_{HH}(k^2)}{\partial k^2} \bigg|_{k^2 = M_H^2}$$



Next-order terms in the μ_X -parametrization

- Weaker constraints on diagonal couplings
 - \rightarrow Large active-sterile mixing $m_D M_R^{-1}$ for diagonal terms
- Previous parametrizations built on the 1st term in the $m_D M_R^{-1}$ expansion \rightarrow Parametrizations breaks down
- Solution: Build a parametrization including the next order terms
- The next-order μ_X -parametrization is then

$$\mu_X \simeq \left(\mathbf{1} - \frac{1}{2}M_R^{*-1}m_D^{\dagger}m_DM_R^{T-1}\right)^{-1}M_R^Tm_D^{-1}U_{\rm PMNS}^*m_\nu U_{\rm PMNS}^{\dagger}m_D^{T-1}M_R$$
$$\times \left(\mathbf{1} - \frac{1}{2}M_R^{-1}m_D^Tm_D^*M_R^{\dagger-1}\right)^{-1}$$



Results using the Casas-Ibarra parametrization



- Random scan: 180000 points with degenerate M_R and μ_X

• $\Delta^{\text{BSM}} = \frac{1}{\lambda_{HHH}^{\text{1r,SM}}} \left(\lambda_{HHH}^{\text{1r,full}} - \lambda_{HHH}^{\text{1r,SM}} \right)$

- Strongest constraints:
 - Lepton flavour violation, mainly $\mu \rightarrow e\gamma$
 - Yukawa perturbativity (and neutrino width)
- Large effects necessarily excluded by LFV constraints ?

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Constraints: focus on $\mu \rightarrow e\gamma$



- M_R and μ_X real and degenerate, Casas-Ibarra (C-I) parametrization
- Constrains μ_X
- Perturbativity $\rightarrow |\frac{Y_{\nu}^2}{4\pi}| < 1.5$ (Dotted line = non-perturbative couplings)

•
$$\frac{v^2 (Y_{\nu} Y_{\nu}^{\dagger})_{km}}{M_R^2} \approx \frac{1}{\mu_X} \frac{(U_{\text{PMNS}} \Delta m^2 U_{\text{PMNS}}^T)_{km}}{2m_{\nu_1}}$$



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Backup

IFT Madrid 13 / 13

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