Lepton number conservation in seesaw models and searches for heavy neutrinos

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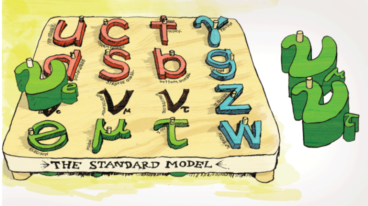
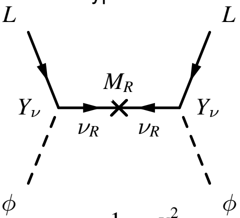
Massive neutrinos and New Physics

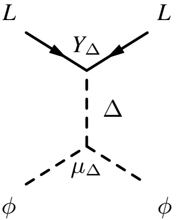
- Observation of ν oscillations
  $\Rightarrow$ at least 2 ν are massive
- BSM necessary for ν mass
  - Radiative models
  - Extra-dimensions
  - R-parity violation in supersymmetry
  - Seesaw mechanisms



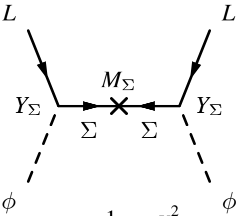
- 3 minimal tree-level seesaw models $\Rightarrow$ 3 types of heavy fields
  - type I: right-handed neutrinos, SM gauge singlets
  - type II: scalar triplets
  - type III: fermionic triplets



$$m_\nu = -\frac{1}{2} Y_\nu \frac{v^2}{M_R} Y_\nu^T$$

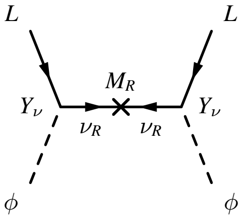


$$m_\nu = -2 Y_\Delta v^2 \frac{\mu_\Delta}{M_\Delta^2}$$



$$m_\nu = -\frac{1}{2} Y_\Sigma \frac{v^2}{M_\Sigma} Y_\Sigma^T$$

Towards testable Type I variants



- Taking $M_R \gg m_D$ gives the “vanilla” type 1 seesaw

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

$$\mathrm{m}_\nu \sim 0.1\,\mathrm{eV} \Rightarrow \left| \begin{array}{l} Y_\nu \sim 1 \quad \text{and} \quad M_R \sim 10^{14}\,\mathrm{GeV} \\ Y_\nu \sim 10^{-6}\, \text{and} \quad M_R \sim 10^{2}\,\,\mathrm{GeV} \end{array} \right.$$

- 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. $\mathrm{U}(1)_{B-L}$ [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 $(\nu_L^C, \{\nu_{R,1}^{(1)}...\nu_{R,n}^{(1)}\}, \{\nu_{R,1}^{(2)}...\nu_{R,n}^{(2)}\}, \{\nu_{R,1}^{(3)}...\nu_{R,m}^{(3)}\})$

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

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.

[a] This is a necessary requirement to satisfy phenomenological constraints

[b] These 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

$$Q = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \pm\frac{i}{\sqrt{2}}D & \frac{1}{\sqrt{2}}D & 0 \\ 0 & \frac{1}{\sqrt{2}}D & \pm\frac{i}{\sqrt{2}}D & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

then through a change of basis

$$Q^T\tilde{M}Q = \begin{pmatrix} 0 & \pm i\sqrt{2}(D^T\alpha^T)^T & 0 & 0 \\ \pm i\sqrt{2}D^T\alpha^T & 0 & \pm iD^TM_1D & 0 \\ 0 & \pm iD^TM_1D & 0 & 0 \\ 0 & 0 & 0 & M_2 \end{pmatrix} \sim \begin{pmatrix} 0 & M_D^T & 0 & 0 \\ M_D & 0 & M_R & 0 \\ 0 & M_R^T & 0 & 0 \\ 0 & 0 & 0 & M_2 \end{pmatrix}$$

- 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 corollary[1]

[1] In the seesaw limit, light neutrinos are Majorana fermions whose mass violates 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

$$\mathrm{m}_\nu \approx -m_D M_R^{-1} m_D^T$$

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

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

$$\begin{aligned}\mathrm{m}_\nu = &- \left(1 + Z^* Z^T\right)^{-\frac{1}{2}} Z^T m_D^T \left(1 + Z^\dagger Z\right)^{-\frac{1}{2}} \\ &- \left(1 + Z^T Z^*\right)^{-\frac{1}{2}} m_D Z \left(1 + Z Z^\dagger\right)^{-\frac{1}{2}} \\ &+ \left(1 + Z^* Z^T\right)^{-\frac{1}{2}} Z^T M_R Z \left(1 + Z Z^\dagger\right)^{-\frac{1}{2}}\end{aligned}$$

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

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

to all orders of the seesaw expansion

An aside on the Kersten-Smirnov theorem

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

$$m_D = m \begin{pmatrix} y_1 & y_2 & y_3 \\ a y_1 & a y_2 & a y_3 \\ b y_1 & b y_2 & b y_3 \end{pmatrix}, \quad \text{and} \quad \frac{y_1^2}{M_{R,1}} = \frac{y_2^2}{M_{R,2}} = \frac{y_3^2}{M_{R,3}}$$

- For $\#\nu_R > 3$, 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
  → Works only if Higgs boson lighter than all heavy neutrinos

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 ☹
- 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

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

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

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Form of the Dirac mass matrix

- 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 $Y^i = u^{i*} u^{iT} + u^i u^{i\dagger}$. Imposing $u^{iT} u^i = 0$ and excluding the trivial solution $u^i = 0$, $\mathrm{rank}(Y^i) = 2$
- Y^i symmetric and real: we can build a basis of real orthogonal eigenvectors $b^i_{1\ldots n_i}$. For the zero $n_i - 2$ eigenvalues,

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

- Then

$$u^{i'} = R^i_u u^i = \begin{pmatrix} b_1^{iT} u^i \\ b_2^{iT} u^i \\ b_3^{iT} u^i \\ \vdots \\ b_{n_i}^{iT} u^i \end{pmatrix} = \begin{pmatrix} u_1^{i'} \\ u_2^{i'} \\ 0 \\ \vdots \\ 0 \end{pmatrix}$$

Form of the Dirac mass matrix

- Once we have

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

from a bit of algebra and by excluding trivial solutions,

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

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

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

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

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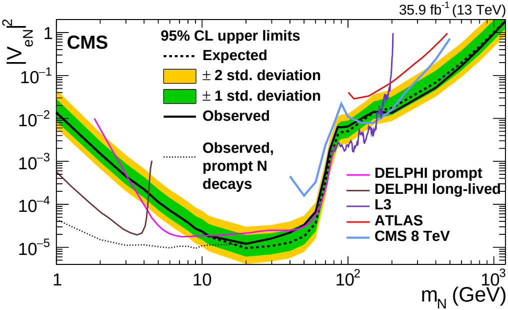
Consequences of the theorem

- Any symmetry that leads to massless light neutrinos contains L as a subgroup or an accidental symmetry
- Spectrum in the L conserving limit: 3 massless light neutrinos + heavy Dirac neutrinos + decoupled neutrinos
- 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 in low-scale type I seesaw variants
- Nearly conserved L is a cornerstone of low-scale type I seesaw variants
  $\Rightarrow$ Expect L violating signatures to be suppressed

L conserving searches for heavy neutrinos

- LNC searches required when seesaw scale above EW scale
  - tri-lepton + missing E_T [del Aguila and Aguilar-Saavedra, 2009] ...
  - LFV di-lepton + dijet [Arganda, Herrero, Marcano and **CW**, 2016]
- CMS results on tri-lepton searches [1802.02965]



- 33 search regions
- High mass regime: flavour, charge, lepton $p_T > 55, 15, 10\,\mathrm{GeV}$, OSSF $M_{\ell\ell} > 5\,\mathrm{GeV}$, $|M_{\ell\ell}$ or $M_{3\ell} - M_Z| < 15\,\mathrm{GeV}$, b jet veto, bins of $M_{2\ell\mathrm{OS}}^{\min}$, $M_{3\ell}$ and M_T
- Jets: anti-k_T, $R = 0.4$, $p_T > 25\,\mathrm{GeV}$, $|\eta| < 2.4$

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Simplified 3+1 Dirac neutrino model

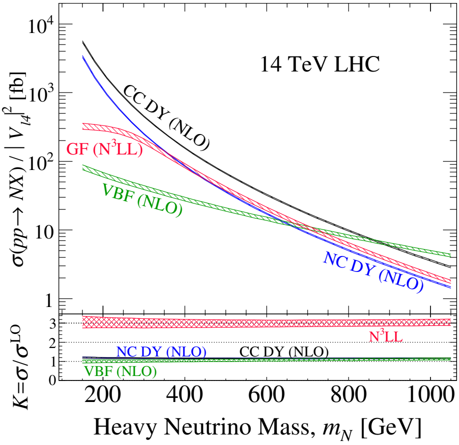
- Reproduce the behaviour of low-scale type I seesaw variants
- Interaction with heavy neutrino N, at leading order in mixing V

$$\begin{aligned}\mathcal{L}_{\text{Int.}} = \quad & - \quad \frac{g}{\sqrt{2}} W^+_\mu \sum_{\ell=e}^{\tau} \overline{N}\, V_{\ell 4}{}^* \, \gamma^\mu P_L \ell^- \\ & - \quad \frac{g}{2\cos\theta_W} Z_\mu \sum_{\ell=e}^{\tau} \overline{N}\, V_{\ell 4}{}^* \, \gamma^\mu P_L \nu_\ell \\ & - \quad \frac{g m_N}{2 M_W} h \sum_{\ell=e}^{\tau} \overline{N}\, V_{\ell 4}{}^* P_L \nu_\ell + \text{H.c.}\,,\end{aligned}$$

- Most relevant constraint: EWPO + low-energy, at 2σ [Blennow et al., 2016]

$$\begin{aligned}|V_{e4}| &< 0.050 \\ |V_{\mu 4}| &< 0.021 \\ |V_{\tau 4}| &< 0.075\end{aligned}$$

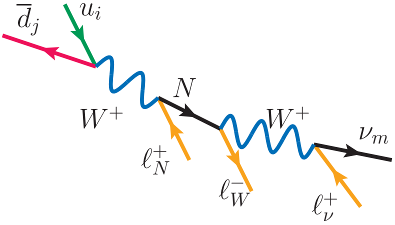
Heavy N production cross-section



- Dirac version of `HeavyNnlo` FeynRules model file
- LO/NLO+PS done with `MadGraph5_aMC@NLO+Pythia8`
- `MadAnalysis5`+ `FastJet`, anti-k_T with $R = 1$
- `NNPDF3.1 NLO+LUXqed` evolved with LHAPDF 6
- N^{3}LL(threshold) resummation within SCET formalism

  [Ruiz et al., 2017]
- $\mu_f, \mu_r = \frac{1}{2}\sum_k E_{T,k}$
- Band width = scale uncertainty

Signal: tri-lepton + MET

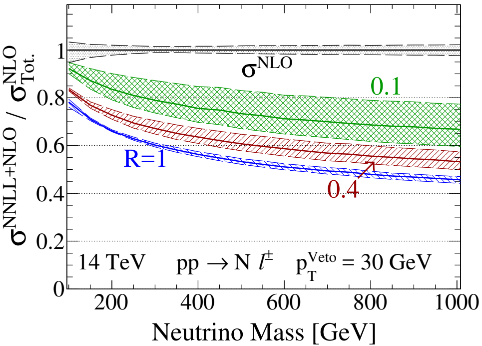


- Focus on lepton number conserving final state
- Produced from charged-current Drell-Yan and VBF
- Specific example $|V_{e4}| = |V_{\tau 4}| \neq 0$ and $|V_{\mu 4}| = 0$
  Signal: $pp \to \tau_h^\pm e^\mp \ell_X +$ MET
- Purely leptonic final state → include jet veto in analysis

Jet veto with fixed p_T

- Jets associated with color-singlet processes mostly forward and soft $\rightarrow$ veto central and hard jets associated with colored backgrounds

[Barger et al., 1990, Barger et al., 1991, Fletcher and Stelzer, 1993, Barger et al., 1995]

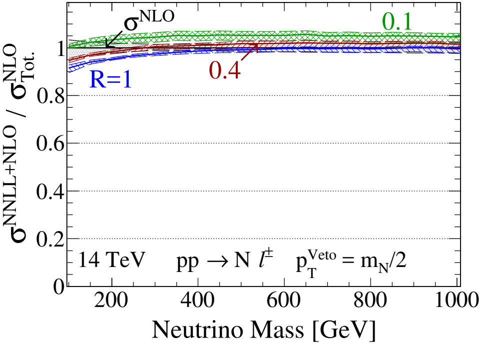


- Major issues:
  - Signal efficiency drops with m_N
  - $\alpha_s(p_T^{\mathrm{Veto}}) \log(Q^2/p_T^{\mathrm{Veto}\,2})$ corrections
- Jet veto: NLO + NNLL(veto) resummation within SCET formalism [Alwall et al., 2014, Becher et al., 2015]
- Residual scale uncertainties: $\pm 10/5/2\%$

Dynamical jet veto

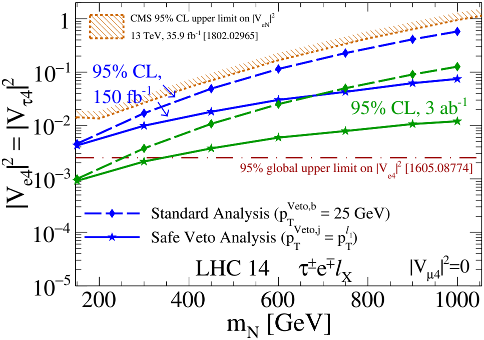
- Idea: Tie the veto scale to the hard scale
- Previously used for EW multiboson production

  [Denner et al., 2009, Nhung et al., 2013, Frye et al., 2016]



- $p_T^{\ell_W} \sim \frac{m_N}{2}(1 - M_W^2/m_N^2)$ and $p_T^{\rm Veto} = m_N/2 \Rightarrow Q^2/p_T^{\rm Veto\,2} \sim 4$
- Logs under control → No need for NNLL resummation anymore
- $p_T^{\rm Veto}$ increases with m_N → No drop in efficiency
- Mismatch here due to PDF sets used for jet veto vs no veto
- Can be used for τ at NLO since they are color-disconnected from the initial state

Results



- $p_T^{\ell\ [\tau_h]\ \{j\}} > 15\ [30]\ \{25\}$ GeV, $|\eta^{\mu,\tau_h,j}| < 2.4$, $|\eta^e| < 1.4$ or $1.6 < |\eta^e| < 2.4$
- Top background: killed by jet veto $p_T^{\mathrm{Veto}} = p_T^{\ell_1}$
- EW triboson: $S_T > 120\,\mathrm{GeV}$

$$S_T^{3W} \equiv \sum_\ell |\vec{p_T}^\ell| \sim 3\frac{M_W}{2} \sim 120\,\mathrm{GeV}$$
$$S_T^N \sim \frac{m_N}{3} + \frac{m_N}{2} + \frac{m_N}{4} = \frac{13}{12} m_N .$$

- EW diboson: $M_{\ell\ell} > 10\,\mathrm{GeV}$, $|M_{\ell\ell}\ \mathrm{or}\ M_{3\ell} - M_Z| < 15\,\mathrm{GeV}$
- Fake leptons: killed by jet veto

- Proxy for m_N: multi-body transverse mass [Barger et al., 1983, Barger et al., 1988]
- Up to $10 - 11$ improvement in $|V_{\ell 4}|$ reach

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Conclusions

- Nearly conserved L is a cornerstone of low-scale type I seesaw variants
- Expect L violating signatures to be suppressed
  → Under study
- Seems to be applicable to type III seesaw variants as well
  → Currently investigating it
- Dynamical jet veto:
  - reduces QCD uncertainties
  - improve signal efficiencies
  - improve background rejection
- $\mathcal{O}(10)$ improvement in $|V_{\ell 4}|$ sensitivity in tri-lepton searches for heavy N
- Broadly applicable to other color singlet processes

Backup slides

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 $||\theta|| \leqslant 0.0075$

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

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

which gives

$$U_l^T\left(1 + Z^T Z^*\right)^{-1} Z^T U_h^* f_h U_h^\dagger Z\left(1 + Z^\dagger Z\right)^{-1} U_l = 0$$

$$Z^T U_h^* f_h U_h^\dagger Z = 0$$

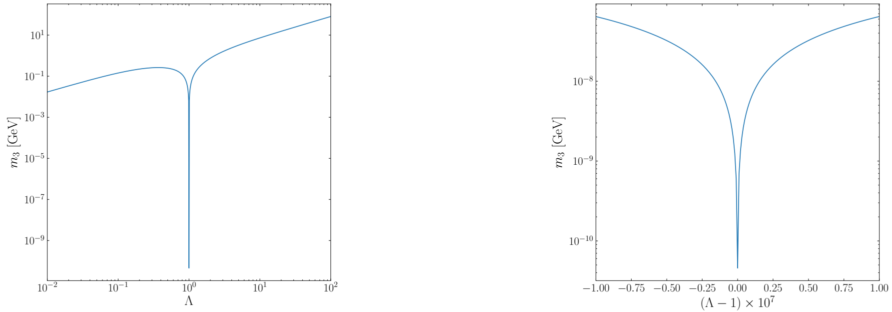
to the first order in the seesaw expansion

$$U_h \approx 1$$

$$Z^T F_h Z = 0$$

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 $m_\nu = m_{\text{tree}} + m_{\text{1-loop}} = 0.046\,\text{eV}$ at $\Lambda = 1$. A deviation of less then 10^{-7} here, is enough to spoil the cancellation and contradict experimental limits.

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