Direct and indirect searches of heavy neutrinos via the Higgs sector

Cédric Weiland

Institute for Particle Physics Phenomenology, Durham University[1]

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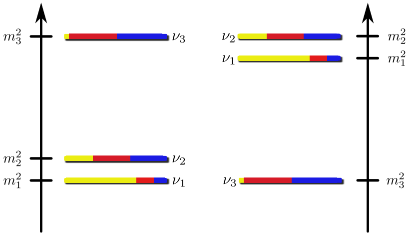
[1] Moving to the University of Pittsburgh, on September 1st

Neutrino phenomena

- Neutrino oscillations (best fit from nu-fit.org):

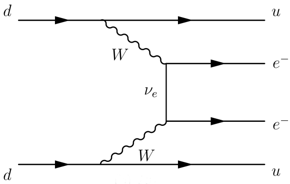
solar	$\theta_{12} \simeq 34^\circ$	$\Delta m^2_{21} \simeq 7.4 \times 10^{-5}\mathrm{eV}^2$
atmospheric	$\theta_{23} \simeq 47^\circ$	$\lvert\Delta m^2_{23}\rvert \simeq 2.5 \times 10^{-3}\mathrm{eV}^2$
reactor	$\theta_{13} \simeq 8.5^\circ$	



- Absolute mass scale:
  cosmology $\Sigma m_{\nu_i} < 0.12$ eV [Planck, 2018]
  β decays $m_{\nu_e} < 2.05$ eV [Mainz, 2005; Troitsk, 2011]

- Different mixing pattern from CKM, ν lightness $\overset{?}{\leftarrow}$ Majorana ν

- Neutrino nature (Dirac or Majorana):
  Neutrinoless double β decays
  $m_{2\beta} < 0.061 - 0.165$ eV [KamLAND-ZEN, 2016]



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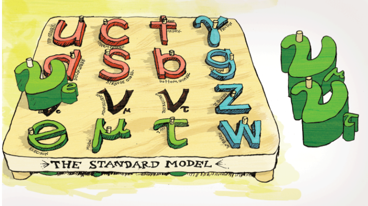
Massive neutrinos and New Physics

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

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

  - No Higgs triplet T
    $\to$ No Majorana mass term

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



- Necessary to go beyond the Standard Model for ν mass
  - Radiative models
  - Extra-dimensions
  - R-parity violation in supersymmetry
  - Seesaw mechanisms $\to$ ν mass at tree-level
    + BAU through leptogenesis

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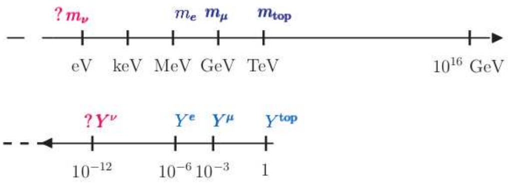
Dirac neutrinos ?

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

  $\Rightarrow$ After electroweak symmetry breaking $\langle \phi \rangle = \binom{0}{\text{v}}$
  $\mathcal{L}_{\text{mass}}^{\text{leptons}} = -m_\ell \bar{\ell}_L \ell_R - m_D \bar{\nu}_L \nu_R + \text{h.c.}$

  $\Rightarrow$ 3 light active neutrinos: $m_\nu \lesssim 0.1\text{eV} \Rightarrow Y^\nu \lesssim 10^{-12}$



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Majorana neutrinos ?

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

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

  $3\,\nu_R \Rightarrow$ 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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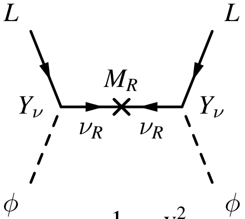
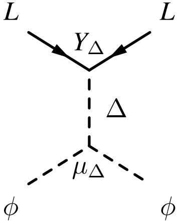
The seesaw mechanisms

- 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



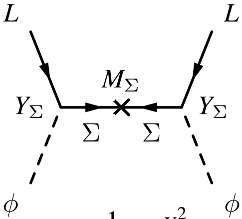
$$\mathrm{m}_\nu = -\frac{1}{2} Y_\nu \frac{\mathrm{v}^2}{M_R} Y_\nu^T$$

[Minkowski, 1977, Gell-Mann et al., 1979, Yanagida, 1979, Mohapatra and Senjanovic, 1980, Schechter and Valle, 1980]



$$\mathrm{m}_\nu = -2 Y_\Delta \mathrm{v}^2 \frac{\mu_\Delta}{M_\Delta^2}$$

[Magg and Wetterich, 1980, Schechter and Valle, 1980, Wetterich, 1981, Lazarides et al., 1981, Mohapatra and Senjanovic, 1981]



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

[Foot et al., 1989]

Higgs mass corrections and seesaw scale

- Seesaw scales and natural Yukawa couplings

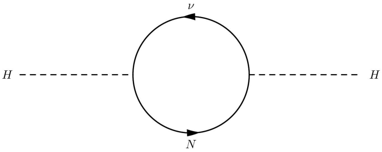
For $m_\nu \sim 0.1\,\mathrm{eV}$

Type I / Type III:
either $Y_\nu \sim \mathcal{O}(1)$ with $M \sim 10^{14}\mathrm{GeV}$
or $Y_\nu \sim \mathcal{O}(10^{-6})$ with $M \sim 1\,\mathrm{TeV}$

Type II:
$Y_\Delta \sim \mathcal{O}(1)$ and $M_\Delta \sim 1\,\mathrm{TeV}$
with $\mu_\Delta \sim 100\,\mathrm{eV}$

- But naturalness issues with the Higgs mass

[Vissani, 1998, Farina et al., 2013, de Gouvea et al., 2014, Clarke et al., 2015]...
Type I seesaw: fine-tuning of $\mathcal{O}(1) \Rightarrow M_{N_1}, M_{N_2} < \mathcal{O}(10^7)\,\mathrm{GeV}$
Type II seesaw: fine-tuning of $\mathcal{O}(1) \Rightarrow M < \mathcal{O}(200)\,\mathrm{GeV}$
Type III seesaw: fine-tuning of $\mathcal{O}(1) \Rightarrow M < \mathcal{O}(10^3)\,\mathrm{GeV}$



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A rich phenomenology

Sterile neutrino mass

- $10^9\,\mathrm{GeV} < M < 10^{15}\,\mathrm{GeV}$: GUT embedding
  Tension with naturalness

  E.g. Type I seesaw [Minkowski, 1977, Gell-Mann et al., 1979, Yanagida, 1979, Mohapatra and Senjanovic, 1980, Schechter and Valle, 1980]

- $M \sim \mathrm{TeV}$: Related to electroweak symmetry breaking ?
  Modified Higgs self-couplings
  New Higgs production modes
  Lepton flavour violating (LFV) Higgs decays

  E.g. Inverse seesaw [Mohapatra and Valle, 1986, Bernabéu et al., 1987]

- $M \sim$ GeV: New Higgs decay channels

  E.g. Minimal model: νMSM [Asaka et al., 2005]

- $M \sim \mathrm{keV}$: Warm dark matter candidate

- $M \sim \mathrm{eV}$: Anomalies in neutrino oscillations

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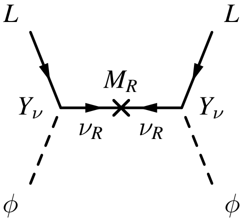
Towards testable Type I variants



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

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

- m_ν suppressed by small active-sterile mixing m_D/M_R

$$\mathrm{m}_\nu \sim 0.1\,\mathrm{eV} \Rightarrow \left| \begin{array}{lll} m_D/M_R \sim 10^{-12} & \text{for} & M_R \sim 10^{14}\,\mathrm{GeV} \\ m_D/M_R \sim 10^{-6} & \text{for} & M_R \sim 10^{2}\,\mathrm{GeV} \end{array} \right.$$

- 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 [Moffat, Pascoli, **CW**, 2017]

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 $(\nu_L^C, \{\nu_{R,1}^{(1)}...\nu_{R,n}^{(1)}\}, \{\nu_{R,1}^{(2)}...\nu_{R,n}^{(2)}\}, \{\nu_{R,1}^{(3)}...\nu_{R,m}^{(3)}\})$

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

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 [Moffat, Pascoli, **CW**, 2017]

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.

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
- In these models, 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
- Seems to be applicable to type III seesaw variants as well
  → Addendum in preparation

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The inverse seesaw: a typical low-scale seesaw model

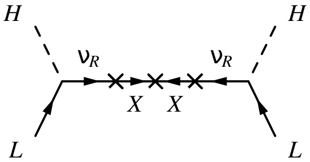
- Add fermionic gauge singlets ν_R ($L = +1$) and X ($L = -1$)
  [Mohapatra, 1986, Mohapatra and Valle, 1986, Bernabéu et al., 1987]...

$$\mathcal{L}_{inverse} = -Y_\nu \overline{L}\tilde{\phi}\nu_R - M_R \overline{\nu_R^c} X - \frac{1}{2}\mu_X \overline{X^c} X + \text{h.c.}$$

with $m_D = Y_\nu \text{v}\,, M^\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M_R \\ 0 & M_R^T & \mu_X \end{pmatrix}$

$$m_\nu \approx \frac{m_D^2}{M_R^2}\mu_X$$

$$m_{N_1,N_2} \approx \mp M_R + \frac{\mu_X}{2}$$



2 scales: μ_X and M_R

- Decouple neutrino mass generation from active-sterile mixing
- Inverse seesaw: $Y_\nu \sim \mathcal{O}(1)$ and $M_R \sim 1\,\text{TeV}$
  $\Rightarrow$ Potentially sizeable impact on the Higgs properties

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Modified couplings

- In ISS and other low-scale seesaw models: 3 light active and m heavy sterile neutrinos, with masses $m_1, ..., m_m$ and mixing V
- Modified couplings to $W^\pm$, Z^0, H

$$
\begin{aligned}
\mathcal{L} \ni & -\frac{g_2}{\sqrt{2}} \bar{\ell}_i \gamma^\mu W^-_\mu V_{ij} P_L n_j \\
& -\frac{g_2}{2\cos\theta_W} \bar{n}_i \gamma^\mu Z_\mu (V^\dagger V)_{ij} P_L n_j \\
& -\frac{g_2}{2M_W} \bar{n}_i (V^\dagger V)_{ij} H (m_i P_L + m_j P_R) n_j
\end{aligned}
$$

$$
V_{3\times m} = \begin{pmatrix} V_{e1} & V_{e2} & V_{e3} & V_{e4} & \cdots \\ V_{\mu 1} & V_{\mu 2} & V_{\mu 3} & V_{\mu 4} & \cdots \\ V_{\tau 1} & V_{\tau 2} & V_{\tau 3} & V_{\tau 4} & \cdots \end{pmatrix}
$$

- Naive scaling of the Higgs coupling:

$$
\frac{1}{M_W}(V^\dagger V)_{ij} m_N \sim \left(\frac{m_D}{M_R}\right)\frac{M_R}{M_W} \sim Y_\nu \qquad \text{for } H-\nu-N
$$

$$
\frac{1}{M_W}(V^\dagger V)_{ij} m_N \sim \left(\frac{m_D}{M_R}\right)^2\frac{M_R}{M_W} \sim Y_\nu \frac{m_D}{M_R} \qquad \text{for } H-N-N
$$

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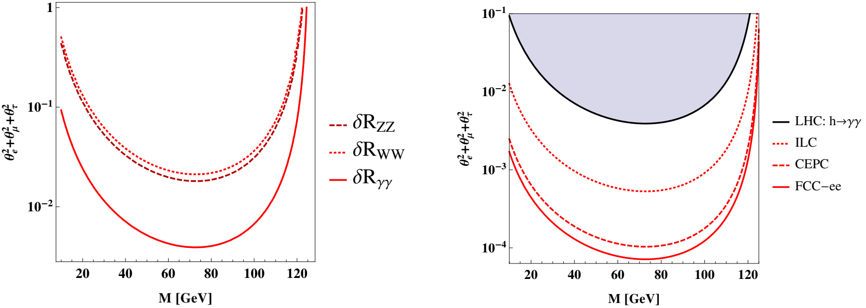
Modified Higgs decay width

- $m_N < m_H$: New kinematically accessible decay channels: $H \to \nu N / NN$
- Modify the total Higgs width $\Gamma_H = \Gamma_H^{\text{SM}} + \Gamma_H^{\text{new}}$
  [Cely et al., 2013, Antusch and Fischer, 2015]
- Derive constraints from precision measurements of $\text{Br}(H \to VV)$

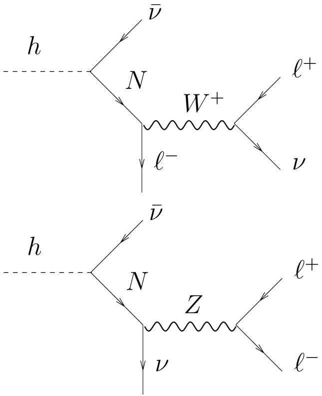


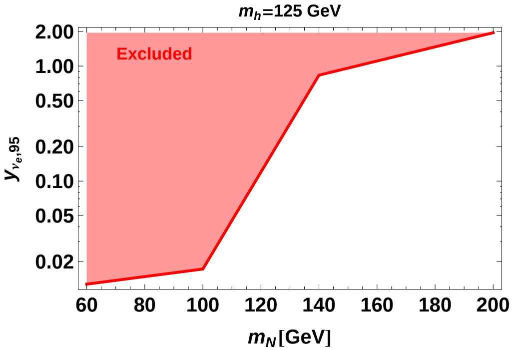
Figures taken from [Antusch and Fischer, 2015]

LHC limits derived using 7 and 8 TeV data

Focus on a specific final state

- Carefully chosen final state and dedicated analysis can do better, e.g. $H \to 2\ell 2\nu$ at a hadronic collider [Bhupal Dev et al., 2012]





Taken from [Bhupal Dev et al., 2012]

- Results based on recasting the 7 TeV CMS search for $H \to WW \to 2\ell 2\nu$ [Chatrchyan et al., 2012]

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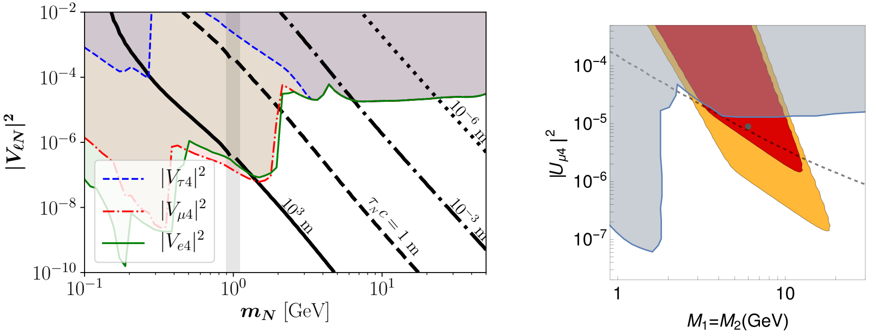
Displaced vertices from Higgs decays

- For $m_N \lesssim 10$ Gev, long-lived heavy neutrino
  $\Rightarrow$ Displaced vertex searches from H decays become very powerful
  [Gago et al., 2015]

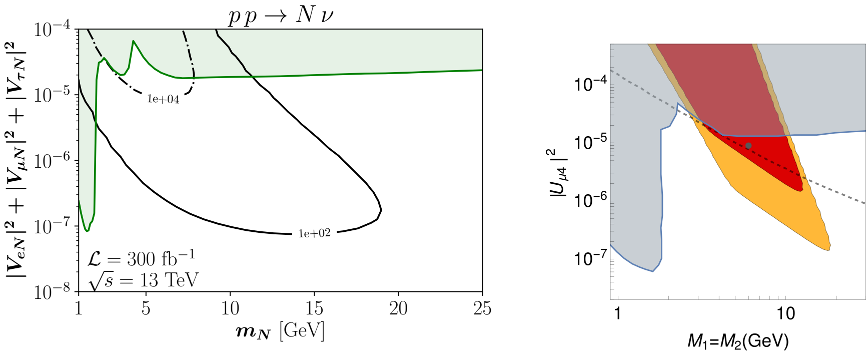


Figures taken from [Abada et al., 2018] and [Gago et al., 2015]

(Right) Red (orange): more than 250 (50) events with a displaced vertex, for $\mathcal{L} = 300\,\mathrm{fb}^{-1}$ at 13 TeV, blue: ruled out by direct searches, dashed line: reach of future $\mu - e$ conversion experiments (Mu2e, COMET)

Displaced vertices: Higgs relevance

- In the end, Higgs are subdominant: extra suppression factor of m_N/m_W [Abada et al., 2018]



Figures taken from [Abada et al., 2018] and [Gago et al., 2015]

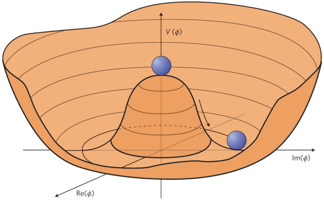
Number of displaced vertes events for $\mathcal{L} = 300\,\text{fb}^{-1}$ at 13 TeV. (Right) Red (orange): more than 250 (50) events, blue: ruled out by direct searches, dashed line: reach of future $\mu - e$ conversion experiments (Mu2e, COMET)

The Higgs sector in a nutshell

- Scalar potential before EWSB:

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

Both m and λ are free parameters



- After EWSB: $m_H^2 = 2m^2\,, \quad \mathrm{v}^2 = \mu^2/\lambda$

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

and

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

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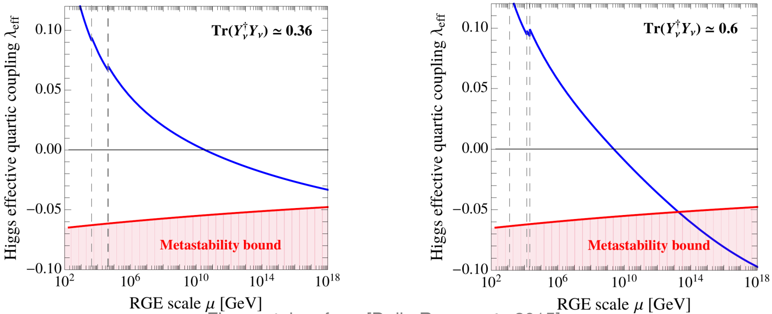
Vacuum stability constraints

- Similarly to the top quark, heavy N can destabilise the vacuum [Rodejohann and Zhang, 2012, Chakrabortty et al., 2013, Masina, 2013]...
- Evaluated by considering the running of the quartic Higgs coupling λ [Delle Rose et al., 2015]

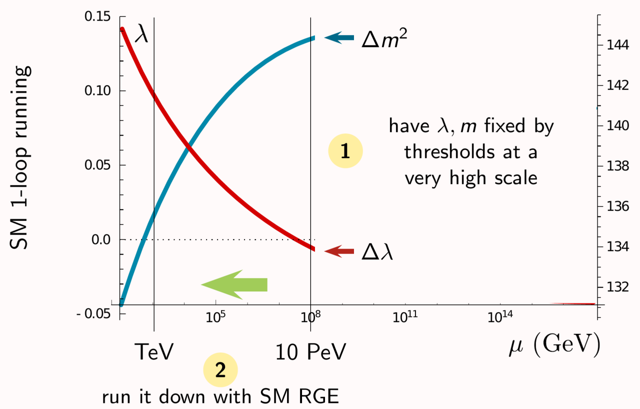
$$\beta_\lambda = \frac{1}{16\pi^2}\left[24\lambda^2 + \lambda\left(12y_t^2 + 4\mathrm{Tr}[Y_\nu^\dagger Y_\nu] - \frac{9}{5}g_1^2 - 9g_2^2\right) - 6y_t^4 - 2\mathrm{Tr}[Y_\nu^\dagger Y_\nu]^2 + \frac{27}{200}g_1^4 + \frac{9}{8}g_2^4 + \frac{9}{20}g_1^2 g_2^2\right]$$



Figures taken from [Delle Rose et al., 2015]

The neutrino option or: How I Learned to Stop Worrying and Love $m_N > m_H$

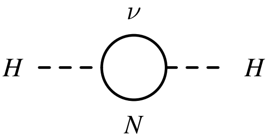
- Idea: Have the seesaw mechanism generate the scalar potential at a high scale where $\lambda \sim 0$ and $m = 0$ from scale invariance [Brivio and Trott, 2017]



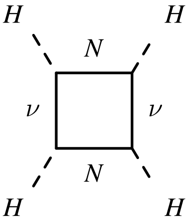
from Brivio, EPS-HEP 2017

Can the neutrino option work ?

- Threshold corrections in type I seesaw:



$$\Delta m^2 \simeq M_N^2 \frac{Y_\nu^2}{8\pi^2}$$



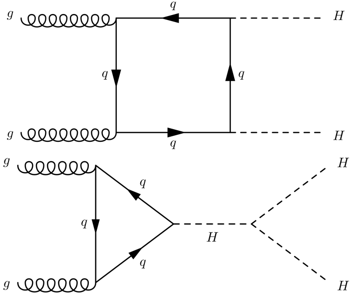
$$\Delta\lambda \simeq -5 \frac{Y_\nu^4}{64\pi^2}$$

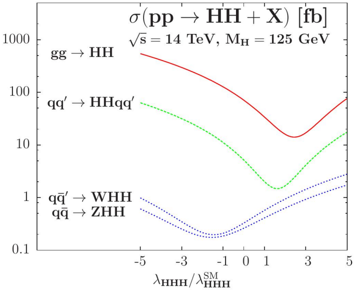
- Required assumptions:
  - These are the dominant contributions at $\mu \simeq M_N$
  - Threshold contributions from other BSM physics are negligible
  - SM loop corrections are negligible as well: true if $Y_\nu M_N \gg \langle\phi\rangle, \Lambda_{QCD}$
- All OK: minimal realisation is SM + 3 ν_R + 2 singlet scalars with scale invariance broken by the Coleman-Weinberg mechanism [Brdar et al., 2018]

The triple Higgs coupling: at the heart of SM probes

- Well-motivated study in the SM
  - Reconstruct the scalar potential
    → validate the Higgs mechanism as the origin of EWSB
  - Sizeable SM 1-loop corrections ($\mathcal{O}(10\%)$)
    → Quantum corrections cannot be neglected
  - One of the main motivations for future colliders

- Experimentally extracted from HH production





[Baglio et al., 2013]

Most relevant constraints for the ISS

- Accommodate low-energy neutrino data using parametrization
  [Casas and Ibarra, 2001; Arganda, Herrero, Marcano, **CW**, 2015; Baglio and **CW**, 2017]

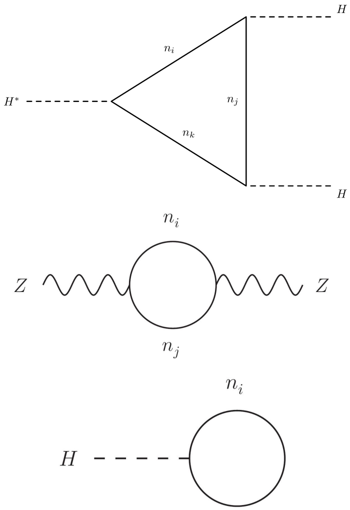
$$\mathrm{v}Y_\nu^T = U^\dagger \mathrm{diag}(\sqrt{M_1}, \sqrt{M_2}, \sqrt{M_3})\, R\, \mathrm{diag}(\sqrt{m_1}, \sqrt{m_2}, \sqrt{m_3}) U_{PMNS}^\dagger$$
$$M = M_R \mu_X^{-1} M_R^T$$

or

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

- Charged lepton flavour violation
  → For example: $\mathrm{Br}(\mu \to e\gamma) < 4.2 \times 10^{-13}$ [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: $|\frac{Y_\nu^2}{4\pi}| < 1.5$

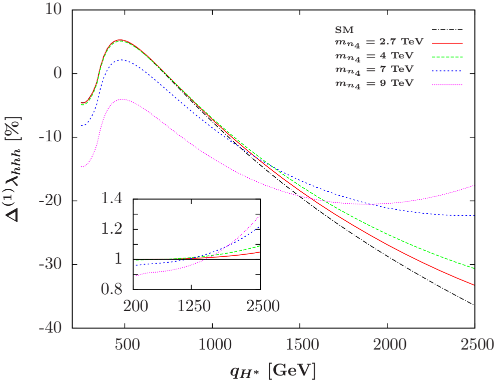
λ_{HHH}: Calculation in the ISS



- Generically: impact of new fermions coupling through the neutrino portal
- New 1-loop diagrams and new counterterms
  → Evaluated with `FeynArts`, `FormCalc` and `LoopTools`
- OS renormalization scheme

> Formulas for both Dirac and Majorana fermions coupling through the neutrino portal are available [Baglio and **CW**, 2016; Baglio and **CW**, 2017]

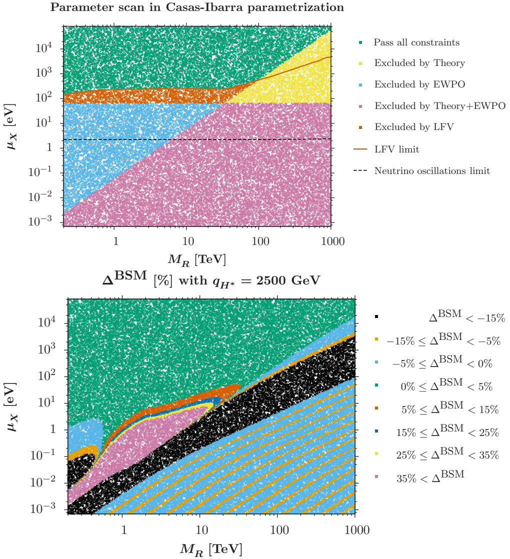
λ_{HHH}: Momentum dependence



- $\Delta^{(1)}\lambda_{HHH} = \frac{1}{\lambda^0}\left(\lambda^{1r}_{HHH} - \lambda^0\right)$
- Focus on 1 neutrino contribution, fixed mixing $V_{\tau 4} = 0.087$, $V_{e/\mu 4} = 0$
- Deviation from the SM correction in the insert
- $\max|(V^\dagger V)_{i4}|m_{n_4} = m_t$
  $\rightarrow m_{n_4} = 2.7\,\mathrm{TeV}$
  tight perturbativity of λ_{HHH} bound: $m_{n_4} = 7\,\mathrm{TeV}$
  width bound: $m_{n_4} = 9\,\mathrm{TeV}$

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

λ_{HHH}: Results using the Casas-Ibarra parametrization



- Random scan: 180000 points with degenerate M_R and μ_X

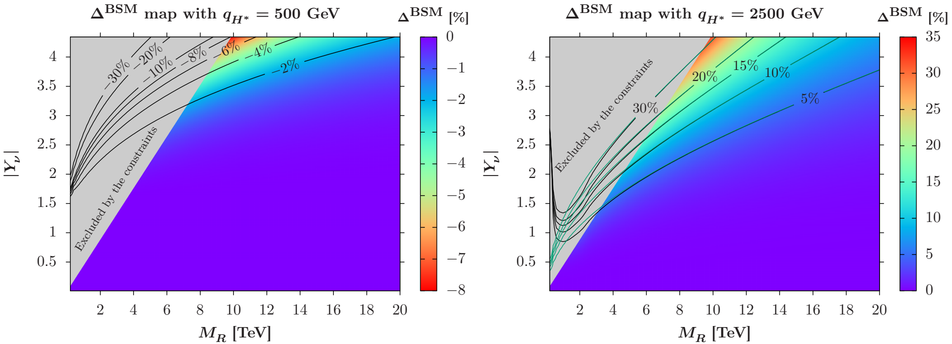
$$\begin{aligned} 0 &\leqslant \theta_i &\leqslant 2\pi, \ (i=1,2,3) \\ 0.2\ \text{TeV} &\leqslant M_R &\leqslant 1000\ \text{TeV} \\ 7\times 10^{-4}\ \text{eV} &\leqslant \mu_X &\leqslant 8.26\times 10^{4}\ \text{eV} \end{aligned}$$

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

- Strongest constraints:
  - Lepton flavour violation, mainly $\mu \to e\gamma$
  - Yukawa perturbativity (and neutrino width)

- Large effects necessarily excluded by LFV constraints ?
  $\rightarrow$ μ_X-parametrization with Y_ν diagonal

λ_{HHH}: Results using the μ_X-parametrization



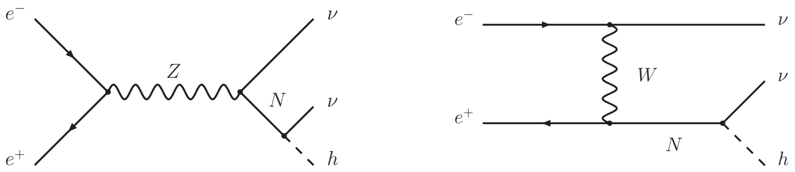
- $Y_\nu = \mathbb{1}$, $M_{R_1} = 3.6\,\text{TeV}$, $M_{R_2} = 8.6\,\text{TeV}$, $M_{R_3} = 2.4\,\text{TeV}$
  full calculation in black, approximate formula in green
- Well described at $M_R > 3$ TeV by approximate formula

$$\Delta^{\rm BSM}_{\rm approx} = 0.51\,\frac{(1\ \text{TeV})^2}{M_R^2}\left(8.45\,\mathrm{Tr}(Y_\nu Y_\nu^\dagger Y_\nu Y_\nu^\dagger) - 0.145\,\mathrm{Tr}(Y_\nu Y_\nu^\dagger Y_\nu Y_\nu^\dagger Y_\nu Y_\nu^\dagger)\right)$$

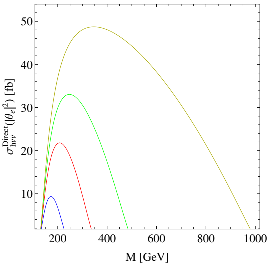
- Heavy ν effects at the limit of ILC (10%) sensitivity
- Heavy ν effects clearly visible at 100 TeV pp collider (5%)

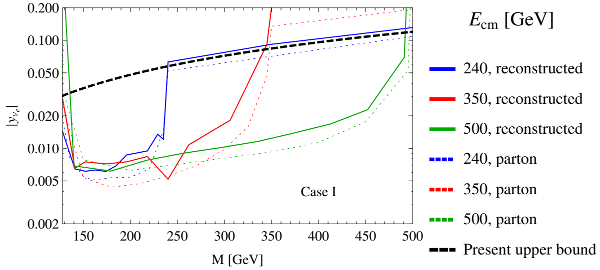
Higgs production at e^+e^- colliders: $H + \not{E}_T$

- Mono-Higgs production from sterile neutrino decays [Antusch et al., 2016]



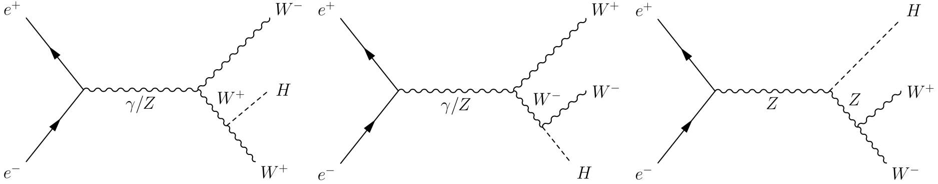
- Dominated by t-channel W exchange. Sensitivity to the di-jet plus $\not{E}_T$ final state at the ILC on the right.



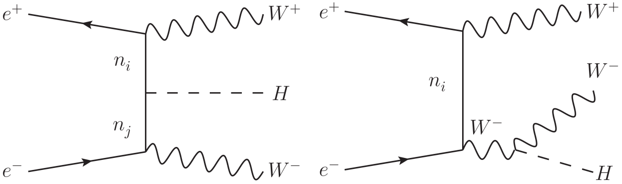


Higgs production at e^+e^- colliders: W^+W^-H

- Idea: Probe Y_ν at tree-level with off-shell N $\Rightarrow$ t-channel $e^+e^- \to W^+W^-H$
- Good detection prospects in SM [Baillargeon et al., 1994]
- SM contributions:

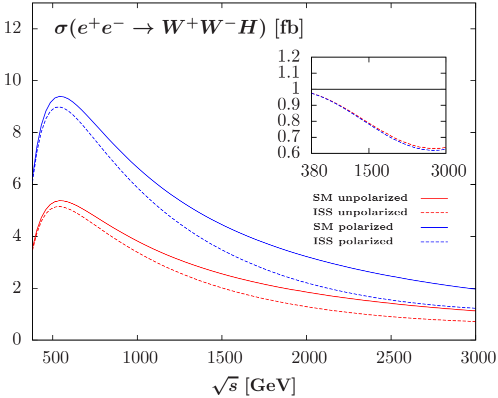


- SM+ISS contributions:



- SM electroweak corrections negligible for $\sqrt{s} > 600\,\mathrm{GeV}$ [Mao et al., 2009]
  $\Rightarrow$ neglected in our analysis

W^+W^-H production: CoM energy dependence



- LO calculation, neglecting m_e
- Calculation done with FeynArts, FormCalc, BASES
- Deviation from the SM in the insert
- Polarized: $P_{e^-} = -80\%$, $P_{e^+} = 0$
- $\sigma(e^+e^- \to W^+W^-H)_{\text{pol}} \sim 2\sigma(e^+e^- \to W^+W^-H)_{\text{unpol}}$
- $Y_\nu = \mathbb{1}$, $M_{R_1} = 3.6\,\text{TeV}$, $M_{R_2} = 8.6\,\text{TeV}$, $M_{R_3} = 2.4\,\text{TeV}$

- Destructive interference between SM and heavy neutrino contributions
- Maximal deviation of -38% close to $3\,\text{TeV}$

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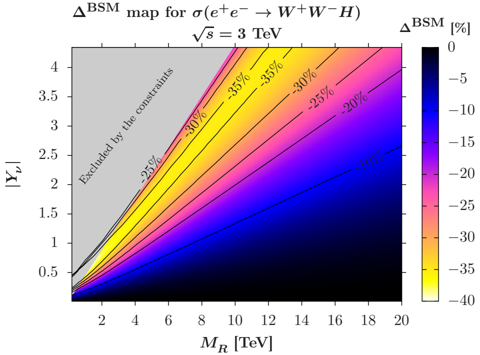
W^+W^-H production: Results in the ISS



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

$$\mathcal{A}^{\rm ISS}_{\rm approx} = \frac{(1\ \text{TeV})^2}{M_R^2}\mathrm{Tr}(Y_\nu Y_\nu^\dagger) \times \left(17.07 - \frac{19.79\ \text{TeV}^2}{M_R^2}\right)$$

$$\Delta^{\rm BSM}_{\rm approx} = (\mathcal{A}^{\rm ISS}_{\rm approx})^2 - 11.94\,\mathcal{A}^{\rm ISS}_{\rm approx}$$

- Fit agrees within 1% for $M_R > 3\,\mathrm{TeV}$

- Maximal deviation of -38%, $\sigma^{\rm ISS}_{\rm pol} = 1.23\,\mathrm{fb}$
  $\rightarrow$ ISS induces sizeable deviations in large part of the parameter space
- Provide a new probe of the $\mathcal{O}(10)\,\mathrm{TeV}$ region
  $\Rightarrow$ Complementary to existing observables

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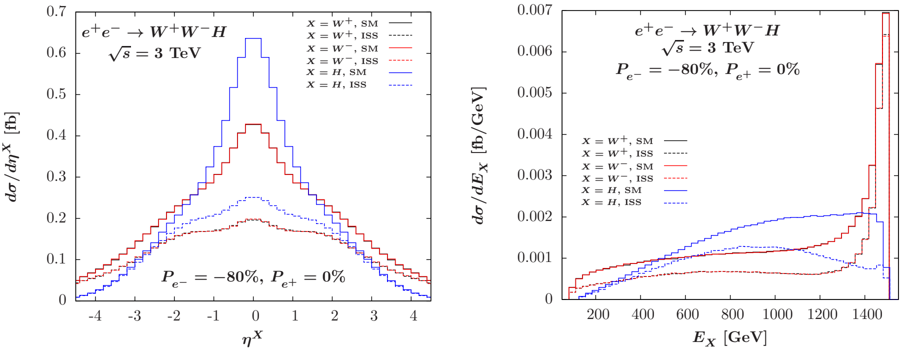
W^+W^-H production: Enhancing the deviations

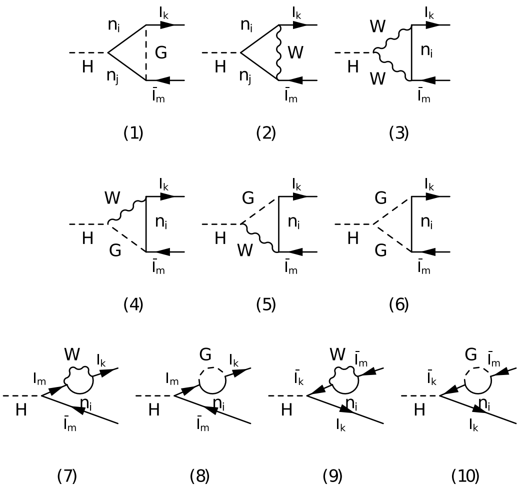


- Stronger destructive interference from ISS for: – central production
  – larger Higgs energy
- Cuts: $|\eta_H| < 1$, $|\eta_{W^\pm}| < 1$ and $E_H > 1$ TeV

	Before cuts	After cuts
σ_{SM} (fb)	1.96	0.42
σ_{ISS} (fb)	1.23	0.14
Δ^{BSM}	-38%	-66%

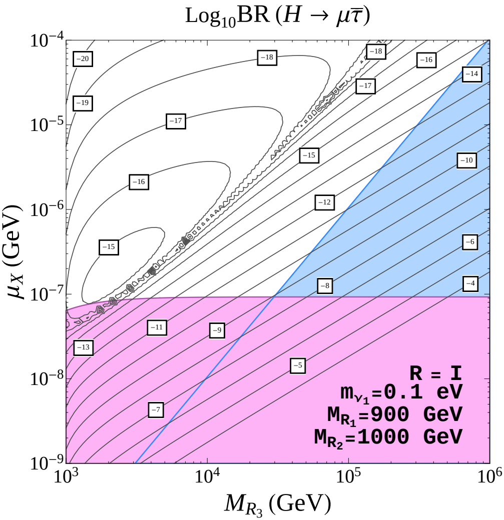
Modified Higgs decays: lepton flavour violation

- Arise at the one-loop level
  [Pilaftsis, 1992, Arganda et al., 2005]



- Absent in SM
  → Observation = BSM smoking gun
- Diagrams 1, 8, 10 dominate at large M_R
  [Arganda, Herrero, Marcano, **CW**, 2015]
- Enhancement from:
  -$\mathcal{O}(1)$ Y_ν couplings
  -TeV scale n_i
- Most relevant constraints: Low-energy neutrino data, other LFV decays (e.g. $\mu \to e\gamma$, $\tau \to 3\mu$)

Predictions using the modified C-I parametrization



- Grows with M_{R_3} and μ_X^{-1} due to Y_ν growth in C-I parametrization
- Similar behaviour with degenerate heavy neutrinos
- Excluded by $\mu \to e\gamma$
  Non-perturbative Y_ν
- $\mathrm{Br}(H \to \bar{\tau}\mu) \leqslant 10^{-9}$
- Conclusion left (mostly) unchanged from varying R

Large LFV Higgs decay rates from textures I

- Would the LHC observation of LFV Higgs decays exclude the ISS ?
  → Look for the largest possible $\mathrm{Br}(H \to \tau\mu)$
- Possibility to evade the $\mu \to e\gamma$ constraint ?
- Approximate formulas for large Y_ν:

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

$$\mathrm{Br}^{\text{approx}}_{H\to\mu\bar{\tau}} = 10^{-7}\frac{\mathrm{v}^4}{M_R^4}\left|(Y_\nu Y_\nu^\dagger)_{23} - 5.7(Y_\nu Y_\nu^\dagger Y_\nu Y_\nu^\dagger)_{23}\right|^2$$

$$\underset{(Y_\nu Y_\nu^\dagger)_{12}=0}{=} 10^{-7}\frac{\mathrm{v}^4}{M_R^4}\left|1 - 5.7[(Y_\nu Y_\nu^\dagger)_{22} + (Y_\nu Y_\nu^\dagger)_{33}]\right|^2 |(Y_\nu Y_\nu^\dagger)_{23}|^2$$

→ Different dependence on the seesaw parameters

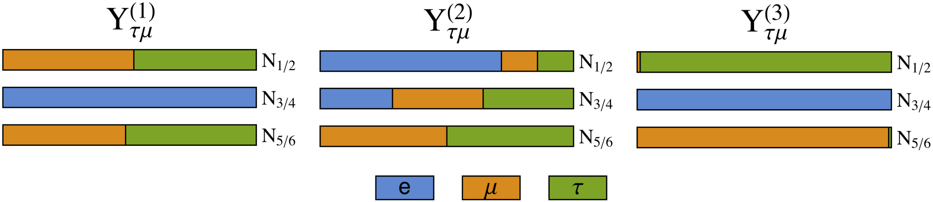
- Solution: Textures with $(Y_\nu Y_\nu^\dagger)_{12} = 0$ and $\frac{|Y_\nu^{ij}|^2}{4\pi} < 1.5$

Large LFV Higgs decay rates from textures II

- Textures with $(Y_\nu Y_\nu^\dagger)_{12} = 0$ and $\frac{|Y_\nu^{ij}|^2}{4\pi} < 1.5$

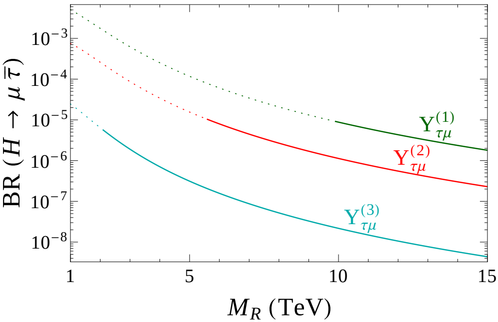
$$Y_{\tau\mu}^{(1)} = f \begin{pmatrix} 0 & 1 & -1 \\ 0.9 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}, \; Y_{\tau\mu}^{(2)} = f \begin{pmatrix} 0 & 1 & 1 \\ 1 & 1 & -1 \\ -1 & 1 & -1 \end{pmatrix}, \; Y_{\tau\mu}^{(3)} = f \begin{pmatrix} 0 & -1 & 1 \\ -1 & 1 & 1 \\ 0.8 & 0.5 & 0.5 \end{pmatrix}$$

- Flavour composition of the heavy neutrinos:



- 3 very different flavour patterns
- Heavy neutrino mixing of $\tau - \mu$ type is always present

LFV $H \to \tau\ell$ results



- $\text{Br}(H \to \tau\mu) < 0.25\%$ [CMS-PAS-HIG-17-001]
  $\text{Br}(H \to \tau\mu) < 1.43\%$ [ATLAS, EPJC77(2017)70]
- Numerics done with the full one-loop formulas
- Dotted: excluded by $\tau \to \mu\gamma$
  Solid: allowed by LFV, LUV,
- $\text{Br}^{\text{max}}(H \to \mu\bar{\tau}) \sim 10^{-5}$
- Same maximum branching ratio with hierarchical heavy N

- Similarly, $\text{Br}^{\text{max}}(H \to e\bar{\tau}) \sim 10^{-5}$ for $Y^{(i)}_{\tau e}$ (=$Y^{(i)}_{\tau\mu}$ with rows 1 and 2 exchanged)
- Out of LHC reach, within the reach of future colliders
- In a supersymmetric model, $\text{Br}^{\text{max}}(H \to \mu\bar{\tau}) \sim 10^{-2}$ [Arganda, Herrero, Marcano, **CW**, 2016] $\Rightarrow$ Within LHC reach

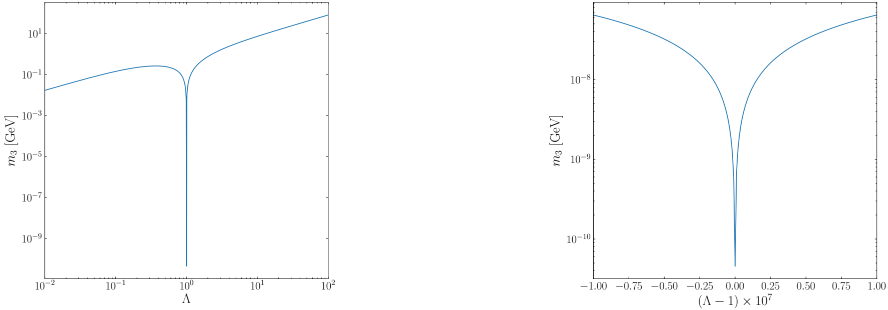
Conclusions

- ν oscillations $\rightarrow$ New physics is needed to generate masses and mixing
- One of the simplest ideas: Add right-handed, sterile neutrinos
- Naturalness requires seesaw scale $\leqslant 10^7$ GeV
- Models with nearly conserved lepton number $\rightarrow$ naturally large Yukawa Y_ν
- Modified H self-couplings
  – Vacuum stability provides constraints and new ideas for model building
  – λ_{HHH} can probe diagonal, real Y_ν and $\mathcal{O}(10\,\mathrm{TeV})$ regime at future colliders
- New Higgs production channel at e^+e^- colliders
  – Mono-Higgs from heavy neutrino decay
  – W^+W^-H from t-channel heavy neutrino exchange
- New Higgs decay channels
  – $H \rightarrow \nu N/NN$: Constraints on Y_ν from LHC data, displaced vertices
  – LFV Higgs decays: complementary to other LFV searches, different dependence on seesaw parameters

Backup slides

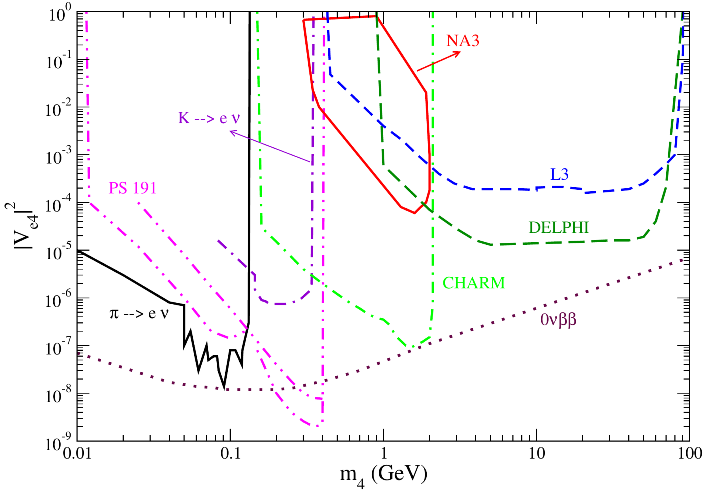
Fine-tuning

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

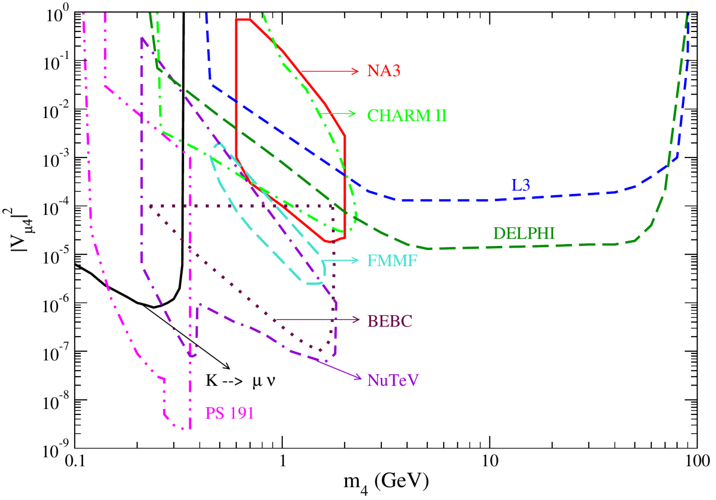


Evolution of m_3 as a function of the rescaling parameter Λ. Input masses and couplings where chosen to give $m_\nu = m_{\text{tree}} + m_{\text{1-loop}} = 0.046\,\text{eV}$ at $\Lambda = 1$.
A deviation of less then 10^{-7} here, is enough to spoil the cancellation and contradict experimental limits.

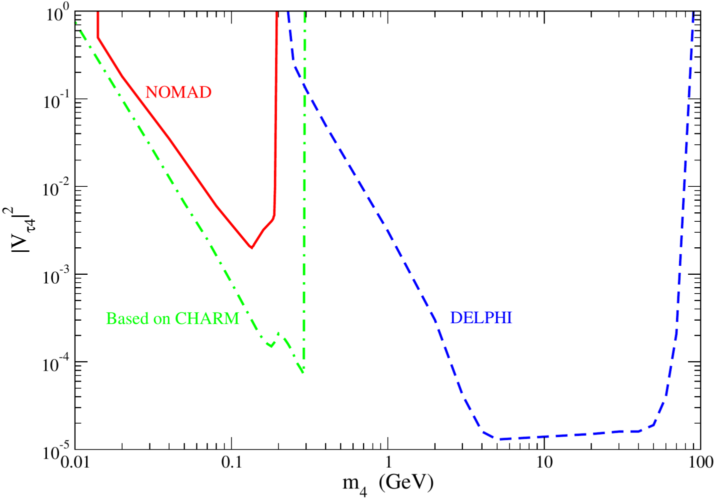
Direct constraints from JHEP05(2009)030



Direct constraints from JHEP05(2009)030



Direct constraints from JHEP05(2009)030



Experimental precision on $Br(H \to VV)$

Channel	$R_{\gamma\gamma}$	R_{WW}	R_{ZZ}
Atlas	$1.17^{+0.27}_{-0.27}$	$1.08^{+0.22}_{-0.20}$	$1.44^{+0.40}_{-0.33}$
CMS	$1.14^{+0.30}_{-0.23}$	$0.72^{+0.20}_{-0.18}$	$0.93^{+0.29}_{-0.25}$
combined	1.15(27)	0.88(20)	1.11(30)

Currently best measured decay ratios $R_{VV} = Br(HH \to VV)^{\text{exp}}/Br(H \to VV)^{\text{SM}}$ from CMS [Khachatryan et al., 2014, Chatrchyan et al., 2014a, Chatrchyan et al., 2014b] and ATLAS [Aad et al., 2013]. Taken from [Antusch and Fischer, 2015].

Future sensitivities to $Br(H \to VV)$

Branching ratio	ILC	CEPC	FCC-ee
$Br_{H\to WW}$	6.4	1.3	0.9
$Br_{H\to ZZ}$	19	5.1	3.1
$Br_{H\to\gamma\gamma}$	35	8	3.0
$Br_{e^+e^-\to h+\not{E}_T}$	11.0*	3.8	2.2

Estimated precision for the measurement of the Higgs boson branching ratios at future lepton colliders, for one year of running. The numbers are in percent, and taken from refs. [Baak et al., 2013, Bicer et al., 2014, Ruan, 2016].
$*)$ Estimated value obtained from the FCC-ee estimate rescaled with the ILC luminosity. Taken from [Antusch and Fischer, 2015].

Renormalization procedure for the HHH coupling I

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

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

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

$$\begin{aligned} \frac{\delta\lambda_{HHH}}{\lambda^0} = &\frac{3}{2}\delta Z_H + \delta t_H \frac{e}{2M_W \sin\theta_W M_H^2} + \delta Z_e + \frac{\delta M_H^2}{M_H^2} \\ &- \frac{\delta M_W^2}{2M_W^2} + \frac{1}{2}\frac{\cos^2\theta_W}{\sin^2\theta_W}\left(\frac{\delta M_W^2}{M_W^2} - \frac{\delta M_Z^2}{M_Z^2}\right) \end{aligned}$$

Renormalization procedure for the HHH coupling II

- OS scheme

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

- Electric charge:

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

- Higgs field renormalization

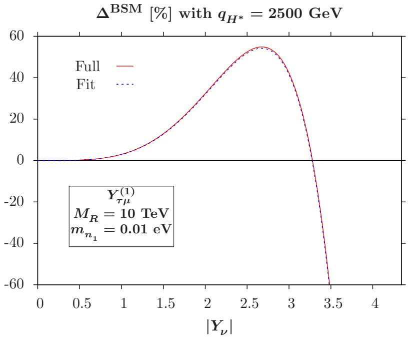
$$\delta Z_H = -\mathrm{Re}\frac{\partial\Sigma_{HH}(k^2)}{\partial k^2}\bigg|_{k^2=M_H^2}$$

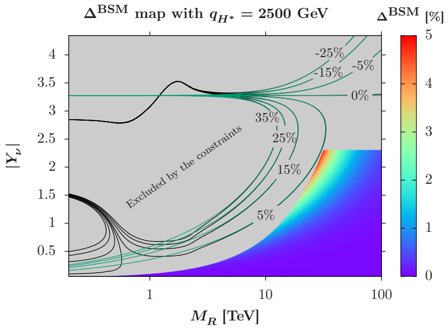
Next-order terms in the μ_X-parametrization

- 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

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

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





- $\Delta^{\rm BSM} = \frac{1}{\lambda_{HHH}^{1r,\rm SM}}\left(\lambda_{HHH}^{1r,\rm full} - \lambda_{HHH}^{1r,\rm SM}\right)$
- Right: Full calculation in black, approximate formula in green
- Well described at $M_R > 3$ TeV by approximate formula

$$\Delta^{\rm BSM}_{\rm approx} = \frac{(1\ \text{TeV})^2}{M_R^2}\left(8.45\,\mathrm{Tr}(Y_\nu Y_\nu^\dagger Y_\nu Y_\nu^\dagger) - 0.145\,\mathrm{Tr}(Y_\nu Y_\nu^\dagger Y_\nu Y_\nu^\dagger Y_\nu Y_\nu^\dagger)\right)$$

- Can maximize $\Delta^{\rm BSM}$ by taking $Y_\nu \propto \mathrm{I}_3$