Impact of heavy sterile neutrinos on the triple Higgs coupling

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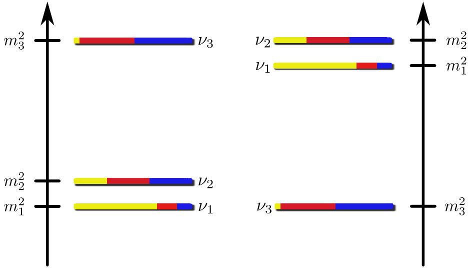
Neutrino phenomena

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

solar	$\theta_{12} \simeq 34^\circ$	$\Delta m^2_{21} \simeq 7.5 \times 10^{-5} \mathrm{eV}^2$
atmospheric	$\theta_{23} \simeq 42^\circ$	$\lvert\Delta m^2_{23}\rvert \simeq 2.5 \times 10^{-3} \mathrm{eV}^2$
reactor	$\theta_{13} \simeq 8.5^\circ$	

- Absolute mass scale:
  cosmology $\Sigma m_{\nu_i} < 0.23$ eV [Planck, 2016]
  β decays $m_{\nu_e} < 2.05$ eV [Mainz, 2005; Troitsk, 2011]



- Mixing pattern different from CKM, ν lightness $\overset{?}{\longleftarrow}$ Different mass generating mechanism ?
- SM: no ν mass term, lepton flavour is conserved
  $\Rightarrow$ need new Physics
  - Radiative models
  - Extra dimensions
  - R-parity violation in supersymmetry
  - Seesaw mechanisms

Massive neutrinos

- Simplest idea: Add Right-handed neutrinos ν_R (fermionic gauge singlet)
  $\mathcal{L}_{\text{mass}}^{\text{leptons}} = -Y_\ell \bar{L} H \ell_R - Y_\nu \bar{L} \tilde{H} \nu_R - \frac{1}{2} M_R \overline{\nu_R} \nu_R^c + \text{h.c.}$

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

  $3\ \nu_R$ without $M_R \Rightarrow$ 3 mass eigenstates: $\nu \neq \nu^c$
  $3\ \nu_R$ with $M_R \Rightarrow$ 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

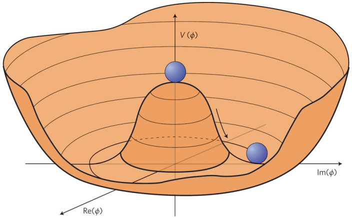
A new opportunity

- How to search for a heavy neutrino with $m_\nu > \mathcal{O}(1\,\mathrm{TeV})$?
  Can we put experimental limits on diagonal Yukawa couplings Y_ν ?

Use the Higgs sector to probe neutrino mass models

- Before EWSB:

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



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

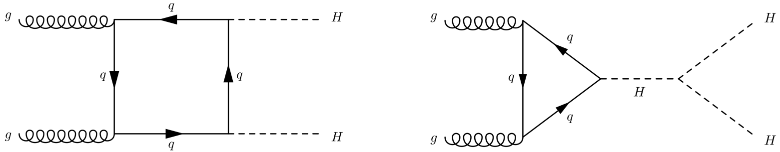
$$V(H) = \frac{1}{2}m_H^2 H^2 + \frac{1}{3!}\lambda_{HHH}H^3 + \frac{1}{4!}\lambda_{HHHH}H^4$$

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

- HHH: – Validate the Higgs mechanism as the origin of EWSB
  – Sizeable SM 1-loop corrections ($\mathcal{O}(10\%)$)
  – One of the main motivations for future colliders

Experimental prospects for the HHH coupling

- Extracted from HH production



- At hadron colliders
  - Main production channels: gg dominates, VBF more sensitive
  - 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 ab^{-1} using only $b\bar{b}\gamma\gamma$ [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]

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A generic approach

- To illustrate the impact of a new fermion coupling via the neutrino portal
- Simplified model with 3 light active and 1 heavy sterile neutrinos, with masses $m_1, \ldots, m_4$ and mixing B
- Modified couplings to $W^{\pm}$, Z^0, H

$$\begin{aligned}\mathcal{L} \ni & -\frac{g_2}{\sqrt{2}} \bar{\ell}_i \gamma^\mu W_\mu^- B_{ij} P_L n_j \\ & - \frac{g_2}{2\cos\theta_W} \bar{n}_i \gamma^\mu Z_\mu (B^\dagger B)_{ij} P_L n_j \\ & - \frac{g_2}{2M_W} \bar{n}_i (B^\dagger B)_{ij} H (m_{n_i} P_L + m_{n_j} P_R) n_j\end{aligned}$$

$$B_{3\times4} = \begin{pmatrix} B_{e1} & B_{e2} & B_{e3} & B_{e4} \\ B_{\mu1} & B_{\mu2} & B_{\mu3} & B_{\mu4} \\ B_{\tau1} & B_{\tau2} & B_{\tau3} & B_{\tau4} \end{pmatrix}$$

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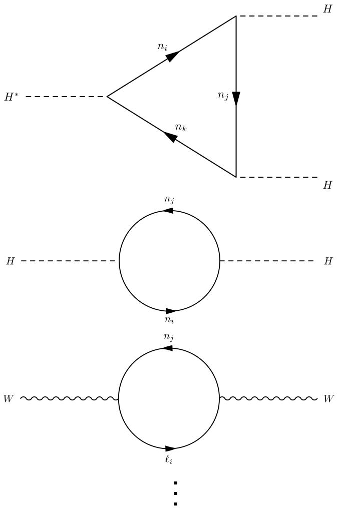
Beyond SM: simplified 3+1 Dirac model



- New 1-loop diagrams and new counterterms
  $\rightarrow$ Evaluated with `FeynArts`, `FormCalc` and `LoopTools`
- Strongest experimental constraints on active-sterile mixing: EWPO [de Blas, 2013]

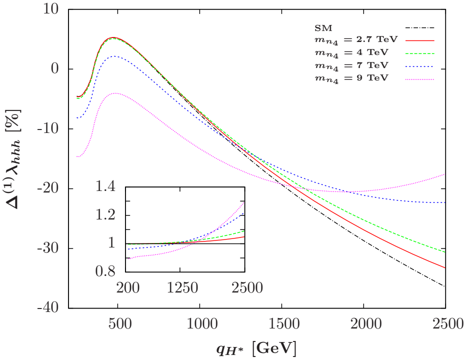
$$|B_{e4}| \leqslant 0.041$$
$$|B_{\mu 4}| \leqslant 0.030$$
$$|B_{\tau 4}| \leqslant 0.087$$

- Loose (tight) perturbativity of λ_{HHH}:

$$\left(\frac{\max|(B^\dagger B)_{i4}|\, g_2\, m_{n_4}}{2M_W}\right)^3 < 16\pi\ (2\pi)$$

- Width limit: $\Gamma_{n_4} \leqslant 0.6\, m_{n_4}$

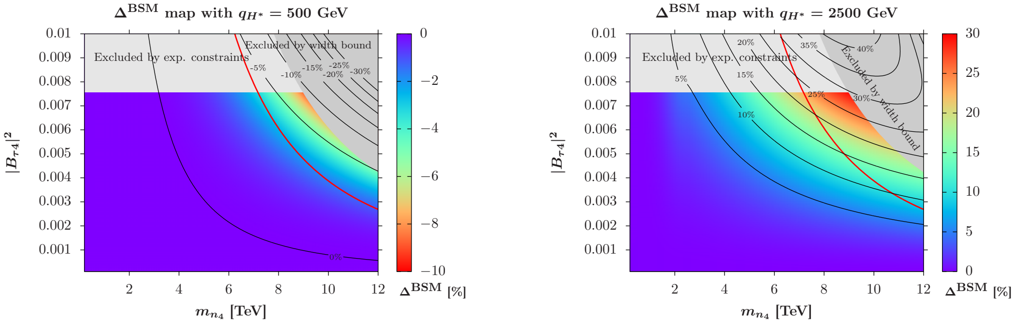
Momentum dependence



- $\Delta^{(1)}\lambda_{HHH} = \frac{1}{\lambda^0}\left(\lambda^{1r}_{HHH} - \lambda^0\right)$
- Assume $B_{\tau 4} = 0.087$, $B_{e4} = B_{\mu 4} = 0$
- Deviation of the BSM correction with respect to the SM correction in the insert
- $\max|(B^\dagger B)_{i4}|m_{n_4} = m_t \to m_{n_4} = 2.7\,\mathrm{TeV}$
  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

Results in 3+1 simplified model



- $\Delta^{\rm BSM} = \frac{1}{\lambda^{1r,{\rm SM}}_{HHH}} \left(\lambda^{1r,{\rm full}}_{HHH} - \lambda^{1r,{\rm SM}}_{HHH} \right)$
- Red line: tight perturbativity of λ_{HHH} bound
- Heavy ν effects below the HL-LHC sensitivity (35%)
- Heavy ν effects clearly visible at the ILC (10%) and FCC-hh (5%)
- Similar behaviour for active-sterile mixing B_{e4} and $B_{\mu 4}$

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The inverse seesaw mechanism

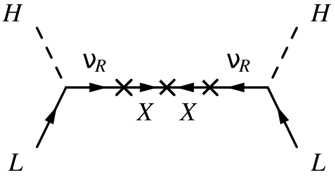
- Lower seesaw scale from approximately conserved lepton number
- Add fermionic gauge singlets ν_R $(L = +1)$ and X $(L = -1)$ [Mohapatra and Valle, 1986]

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

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 $M_R \sim 1\,\text{TeV}$
  $\Rightarrow$ within reach of the LHC and low energy experiments

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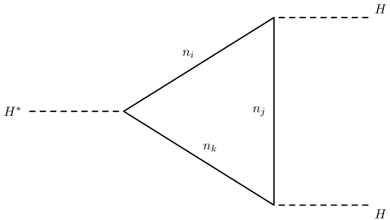
Calculation and constraints in the ISS



- Similar diagrams to the 3+1 Dirac scenario but with Majorana neutrinos

> Formulas for both Dirac and Majorana fermions coupling through the neutrino portal are available

- Accommodate low-energy neutrino data using parametrization

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

- Charged lepton flavour violation, e.g. $\mathrm{Br}(\mu \to e\gamma) < 4.2 \times 10^{-13}$ [MEG, 2016]
- Global fit to EWPO and lepton universality tests [Fernandez-Martinez et al., 2016]
- Width limit: $\Gamma_N \leqslant 0.6\, m_N$
- Yukawa perturbativity: $|\frac{Y_\nu^2}{4\pi}| < 1.5$

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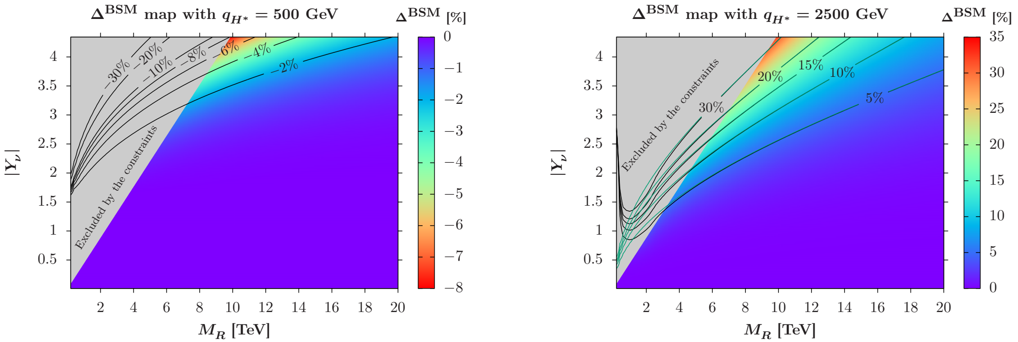
Results in the ISS



- $\Delta^{\mathrm{BSM}} = \dfrac{1}{\lambda_{HHH}^{1r,\mathrm{SM}}}\left(\lambda_{HHH}^{1r,\mathrm{full}} - \lambda_{HHH}^{1r,\mathrm{SM}}\right)$
- Full calculation in black
  approximate formula in green

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

- Largest deviations obtained for Y_ν diagonal
- Agree with 3+1 Dirac analysis despite stronger constraints

Conclusions

- ν oscillations $\rightarrow$ New physics is needed to generate masses and mixing
- One of the simplest ideas: Add right-handed, sterile neutrinos
- Corrections to the HHH coupling from heavy ν as large as 30%: measurable at future colliders
  - Maximal for diagonal Y_ν
  - Provide a new probe of the $\mathcal{O}(10)$ TeV region
  - Complementary to existing observables
- Generic effect, expected in all models with TeV fermions and large Higgs couplings
- Next step: Corrections to the di-Higgs production cross-section

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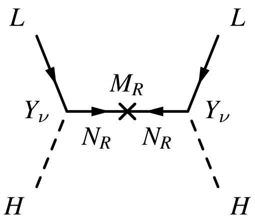
Backup slides

Type I and low-scale seesaw



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

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

- Cosmological limit: $\Sigma m_{\nu_i} < 0.23\ \mathrm{eV}$ [Planck, 2016]

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

- Type I seesaw: m_ν suppressed by small active-sterile mixing m_D/M_R
- Cancellation in matrix product (from L nearly conserved)
  $\rightarrow$ Low-scale seesaw with large active-sterile mixing m_D/M_R, e.g.
  inverse seesaw [Mohapatra and Valle, 1986, Bernabéu et al., 1987]
  linear seesaw [Akhmedov et al., 1996, Barr, 2004, Malinsky et al., 2005]
  low-scale type I [Ilakovac and Pilaftsis, 1995] and others

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: $\lambda_{HHH}^{1r} = \lambda^0 + \lambda_{HHH}^{(1)} + \delta\lambda_{HHH}$

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

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

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

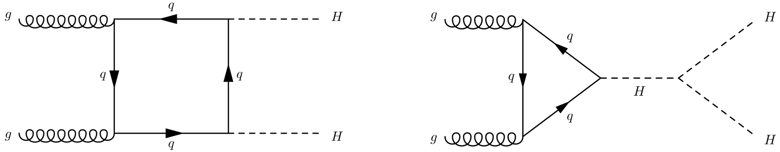
Next-order terms in the μ_X-parametrization

- 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

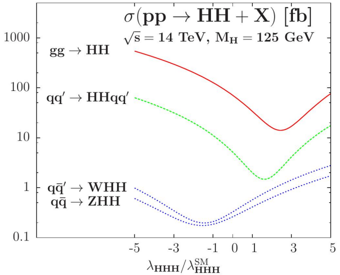
$$\mu_X \simeq \left(\mathbf{1} - \frac{1}{2} M_R^{*-1} m_D^\dagger m_D M_R^{T-1}\right)^{-1} M_R^T m_D^{-1} U_{\text{PMNS}}^* m_\nu U_{\text{PMNS}}^\dagger m_D^{T-1} M_R \left(\mathbf{1} - \frac{1}{2} M_R^{-1} m_D^T m_D^* M_R^{\dagger-1}\right)^{-1}$$

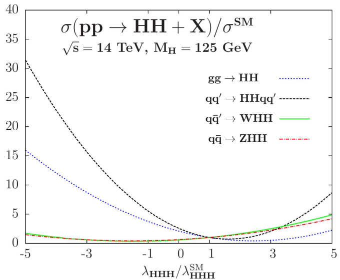
Experimental measurement of the HHH coupling

- Extracted from HH production



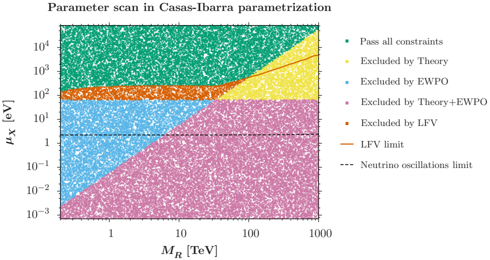
- Destructive interference between diagrams with and without λ_{HHH}

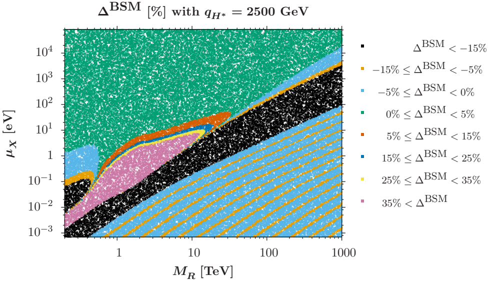




- Most sensitive channel in the SM: VBF [Baglio et al., 2013]

Results using the Casas-Ibarra parametrization





- Random scan: 180000 points with degenerate M_R and μ_X

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

- $\Delta^{\rm BSM} = \dfrac{1}{\lambda^{1r,\rm SM}_{HHH}}\left(\lambda^{1r,\rm full}_{HHH} - \lambda^{1r,\rm SM}_{HHH}\right)$
- Strongest constraints:
  - Lepton flavour violation, mainly $\mu \to e\gamma$
  - Yukawa perturbativity (and neutrino width)
- Large effects necessarily excluded by LFV constraints ?

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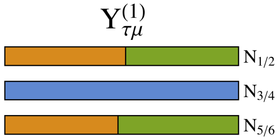
Suppressing LFV constraints

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

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

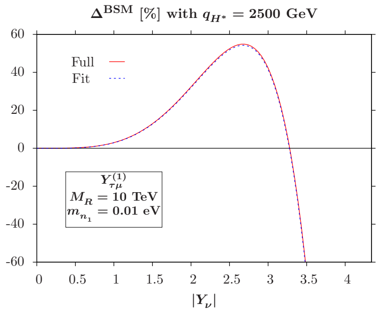
- Solution: Textures with $(Y_\nu Y_\nu^\dagger)_{12}=0$

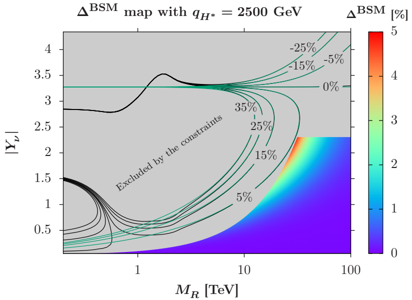
$$Y^{(1)}_{\tau\mu} = |Y_\nu|\begin{pmatrix} 0 & 1 & -1 \\ 0.9 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$$



- Or even take Y_ν diagonal

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





- $\Delta^{\rm BSM} = \frac{1}{\lambda^{1r,\rm SM}_{HHH}} \left(\lambda^{1r,\rm full}_{HHH} - \lambda^{1r,\rm SM}_{HHH}\right)$
- 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 $Y_\nu \propto \mathrm{I}_3$

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