Heavy sterile neutrinos and the triple Higgs coupling

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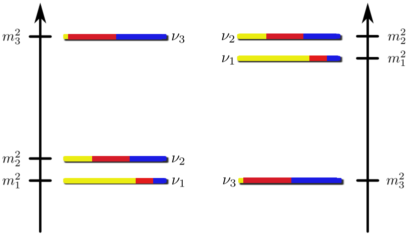
Neutrino phenomena



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

solar $\nu_e \longrightarrow \nu_{\rm others}$: $\theta_{12} \simeq 34^\circ$, $\Delta m^2_{21} \simeq 7.5 \times 10^{-5}{\rm eV}^2$

atmospheric $\overset{(-)}{\nu}_\mu \longrightarrow \overset{(-)}{\nu}_\tau$: $\theta_{23} \simeq 42^\circ$, $|\Delta m^2_{23}| \simeq 2.5 \times 10^{-3}{\rm eV}^2$

reactor $\bar\nu_e \longrightarrow \bar\nu_{\rm others}$: $\theta_{13} \simeq 8.5^\circ$

accelerator $\nu_\mu \longrightarrow \nu_{\rm others}$

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

- Oscillations give no information on:
  - 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]
  - Dirac/Majorana nature of neutrinos → $0\nu 2\beta$ decays
    $m_{2\beta} < 0.061 - 0.165$ eV [KamLAND-ZEN, 2016]

Massive neutrinos and New Physics

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

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

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

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

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

Dirac neutrinos ?

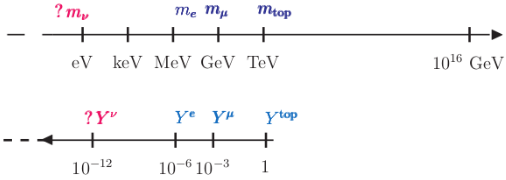
- Add gauge singlet (sterile), right-handed neutrinos ν_R $\quad \Rightarrow \nu = \nu_L + \nu_R$

  $$\mathcal{L}^{\text{leptons}}_{\text{mass}} = -Y_\ell \bar{L} H \ell_R - Y_\nu \bar{L} \tilde{H} \nu_R + \text{h.c.}$$

  $\Rightarrow$ After electroweak symmetry breaking $\langle H \rangle = \binom{0}{\mathrm{v}}$

  $$\mathcal{L}^{\text{leptons}}_{\text{mass}} = -m_\ell \bar{\ell}_L \ell_R - m_D \bar{\nu}_L \nu_R + \text{h.c.}$$

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



Majorana neutrinos ?

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

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

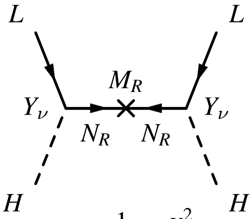
  $\Rightarrow$ 6 mass eigenstates: $\nu = \nu^c$

- ν_R gauge singlets
  $\Rightarrow$ M_R not related to SM dynamics, not protected by symmetries
  $\Rightarrow$ $M_R \overline{\nu_R} \nu_R^c$ is gauge and Lorentz invariant, renormalizable

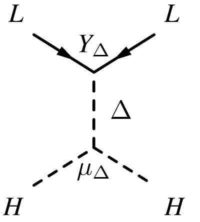
- $M_R \overline{\nu_R} \nu_R^c$ violates lepton number conservation $\Delta L = 2$

The seesaw mechanisms

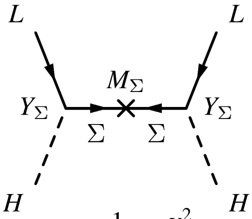
- Seesaw mechanism: New fields with a mass $M >$ EW scale (in general) and Majorana mass terms
- 3 minimal tree-level seesaw models $\Rightarrow$ 3 types of heavy fields
  - type I: right-handed neutrinos, SM gauge singlets
  - type II: scalar triplets
  - type III: fermionic triplets



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



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



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

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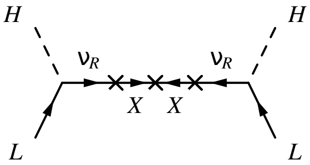
The inverse seesaw mechanism

- Inverse seesaw $\Rightarrow$ Consider fermionic gauge singlets ν_{Ri} $(L=+1)$ and X_i $(L=-1)$ [Mohapatra and Valle, 1986]

$$\mathcal{L}_{inverse} = -Y_\nu^{ij}\overline{L_i}\tilde{H}\nu_{Rj} - M_R^{ij}\overline{\nu_{Ri}^c}X_j - \frac{1}{2}\mu_X^{ij}\overline{X_i^c}X_j + \text{h.c.}$$

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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Probing the seesaw models

- Lepton number conservation is accidental in the SM (gauge group, field content and renormalizability)
- Unique dimension 5 operator for all seesaw mechanisms
  → Violates lepton number L ⇒ Majorana neutrinos

$$\delta\mathcal{L}^{d=5} = c_5 \frac{LLHH}{\Lambda_{\text{NP}}}$$

- To probe the several seesaw mechanisms, either
  - Directly produce the heavy states (LHC, LC, FCC)
  - Look for dimension $\geqslant 6$ operator effects → charged lepton flavour violation (cLFV), non-standard interactions, etc

How to probe the inverse seesaw ?

- Collider signatures
  - single lepton + dijet + missing energy [Das and Okada, 2013]
  - di-lepton + missing p_T [Bhupal Dev et al., 2012, Bandyopadhyay et al., 2013]
  - cLFV di-lepton + dijet [Arganda, Herrero, Marcano and **CW**, 2015]
  - tri-lepton + missing E_T [Mondal et al., 2012, Das et al., 2014]...
  - invisible Higgs decays [Banerjee et al., 2013]
- Low-energy / high-intensity:
  - deviations from lepton universality [Abada, Das, Teixeira, Vicente and **CW**, 2013]
  - (semi)leptonic decays of mesons [Abada, Teixeira, Vicente and **CW**, 2014]
  - charged lepton flavour violation [Bernabéu et al., 1987]...
  - neutrinoless double beta decay [Awasthi et al., 2013]...
  - charged lepton anomalous magnetic moment [Abada et al., 2014]
  - charged lepton electric dipole moment [Abada and Toma, 2016]

Something changed in 2012

- ν oscillations $\Rightarrow$ Extension of the SM that generates ν masses and mixing
- Numerous studies on TeV-scale neutrinos:
  - direct production at colliders
  - loop-induced effects
  - imprint on decays of hadrons, leptons and gauge bosons

Discovery of a scalar boson at the LHC in 2012, with properties compatible with the SM Higgs [ATLAS, 2012; CMS, 2012]

- New experimentally accessible observables and searches
- TeV-scale neutrinos + Large Yukawa couplings $\Rightarrow$ Possibly large deviations from SM properties in the Higgs sector

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TeV-scale neutrino impact on Higgs properties

- Effort to measure Higgs properties: mass, width, couplings
- LFV Higgs decays:
  - Negligible in SM → smoking gun for new Physics
  - ISS: $Br(H \to \tau\mu, \tau e) < \mathcal{O}(10^{-5})$ [Arganda, Herrero, Marcano and **CW**, 2015]
  - SUSY ISS: $Br(H \to \tau\mu) < \mathcal{O}(10^{-2})$, comparable with ATLAS and CMS sensitivity [Arganda, Herrero, Marcano and **CW**, 2016]
- HHH coupling, λ_{HHH}:
  - Measure needed to reconstruct the scalar potential and 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

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λ_{HHH}, a new observable for neutrino physics

- Corrections from any fermion that couples via the neutrino portal $\bar{L}H$
  - Sterile neutrinos N
  - Dark matter candidate
- Particularly sensitive to multi-TeV sterile neutrinos, different dependence on neutrino Yukawa couplings from LFV, etc

Probe a new part of the parameter space

- Effects illustrated with:
  - simplified model: 3+1 Dirac ν [Baglio and **CW**, PRD94(2016)013002]
  - TeV-scale seesaw model: inverse seesaw [in preparation]

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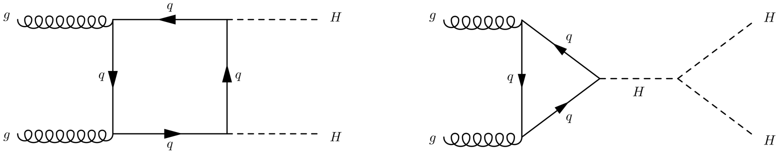
Experimental prospects for the HHH coupling

- Extracted from HH production



- Future sensitivities to the HHH coupling:
  - HL-LHC: $\sim 50\%$ for ATLAS or CMS [CMS-PAS-FTR-15-002]
    $\sim 35\%$ combined
  - 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]
  - FCC-hh: 8% per experiment with 3 ab^{-1} using only $b\bar{b}\gamma\gamma$ [Yao, 2016]
    $\sim 5\%$ combining all channels

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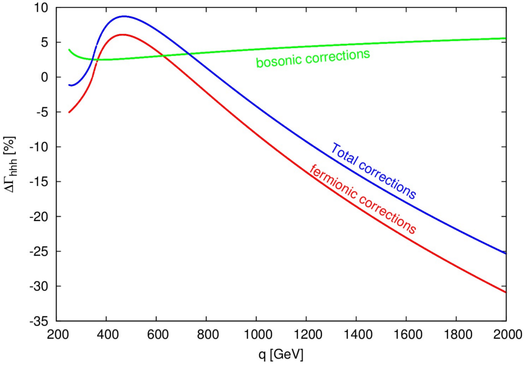
SM situation



taken from [Arhrib et al., 2015]

- tree-level: $\lambda^0_{HHH} = -\frac{3M_H^2}{\mathrm{v}}$
- Dominant contribution from top-quark loops
  [Kanemura et al., 2004]

$$\lambda_{HHH}(q^2, m_H^2, m_H^2) = -\frac{3m_H^2}{\mathrm{v}}\left[1 - \frac{1}{16\pi^2}\frac{16m_t^4}{v^2 m_H^2} \times \left\{1 + \mathcal{O}\left(\frac{m_H^2}{m_t^2}, \frac{q^2}{m_t^2}\right)\right\}\right]$$

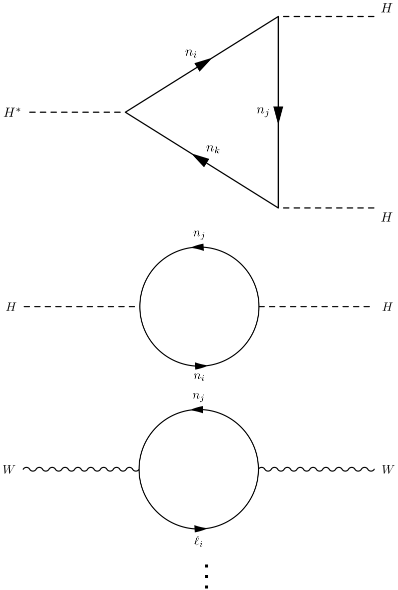
Beyond SM: simplified 3+1 Dirac model

- A first approach to clearly illustrate the impact of a new, TeV-scale fermion
- Simplified model with 3 light active and 1 heavy sterile neutrinos, parametrized by masses $m_1, ..., m_4$ and active-sterile mixing in B
- Modified couplings to $W^\pm$, Z^0, H

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

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

New contributions and constraints



- Sterile ν gives rise to new 1-loop diagrams and new counterterms
  $\rightarrow$ Evaluated with `FeynArts` and `LoopTools`
- Strongest experimental constraints on active-sterile mixing: EWPO

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

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

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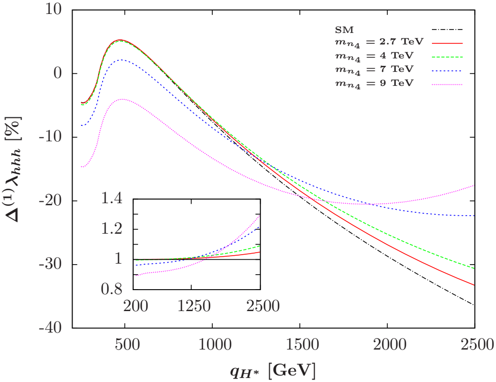
Numerical results I



- $\Delta^{(1)}\lambda_{HHH} = \frac{1}{\lambda^0}\left(\lambda^{1r}_{HHH} - \lambda^0\right)$
- 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
- $(B^\dagger B)_{44} m_{n_4} = m_t \to m_{n_4} = 2.7\,\text{TeV}$ 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

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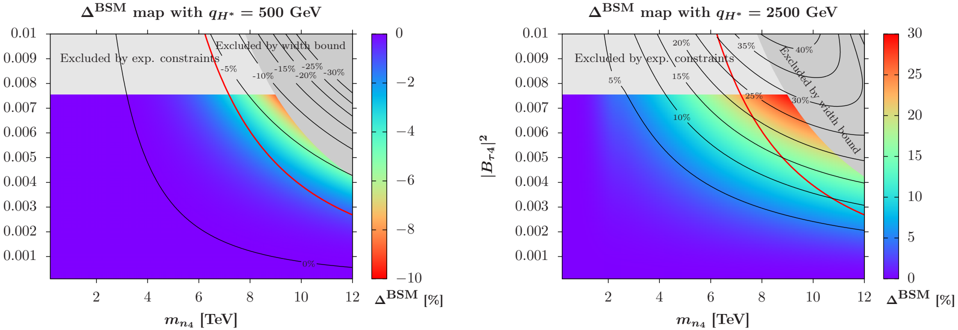
Numerical results II



- $\Delta^{\rm BSM} = \frac{1}{\lambda_{HHH}^{1r,\rm SM}}\left(\lambda_{HHH}^{1r,\rm full} - \lambda_{HHH}^{1r,\rm SM}\right)$
- Red line: tight perturbativity of λ_{HHH} bound
- Heavy ν effects at the limit of 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 $B_{\mu4}$

From the 3+1 Dirac model to the ISS

- TeV-scale neutrino induces sizeable corrections to λ_{HHH}
  - Decrease at $q_H^* \simeq 500\,\mathrm{GeV}$
  - Increase at large q_H^*
- Effects could be used to constrain the active-sterile mixing at the ILC and FCC-hh
- What are the effects in a realistic, appealing low-scale seesaw model ?
  - Additional constraints need to be included

Most relevant constraints for the ISS

- Accomodate low-energy neutrino data using μ_X-parametrization

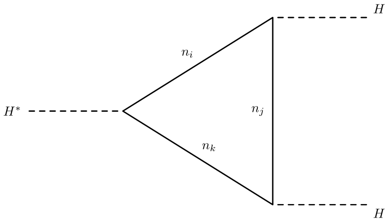
$$\mu_X = M_R^T \, m_D^{-1} \, U^*_{\text{PMNS}} m_\nu U^\dagger_{\text{PMNS}} \, m_D^{T\,-1} M_R \qquad \text{and beyond}$$

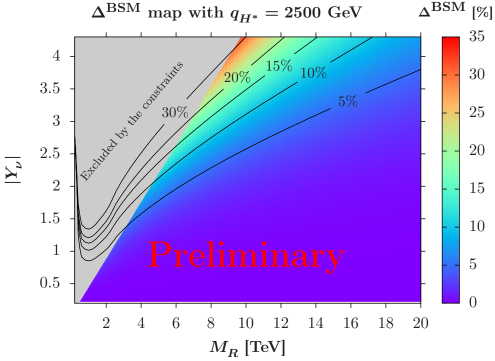
- Charged lepton flavour violation
  → For example: $\text{Br}(\mu \to e\gamma) < 4.2 \times 10^{-13}$ [MEG, 2016]
  $\text{Br}(\mu \to eee) < 1.0 \times 10^{-12}$ [SINDRUM, 1988]

- Global fit to EWPO and lepton universality tests [Fernandez-Martinez et al., 2016]

- Yukawa coupling perturbativity → $|\frac{Y_\nu^2}{4\pi}| < 1.5$

Numerical results





- Similar diagrams to the 3+1 Dirac scenario but with Majorana neutrinos
- μ_X-parametrization extended beyond the standard seesaw limit
- Assume Y_ν diagonal, hierarchical heavy neutrinos, $m_1 = 0.01\,\text{eV}$
- $\Delta^{\rm BSM}_{max} \simeq +30\%$, at the limit of the HL-LHC sensitivity (35%)
- Effects clearly visible at the ILC (10%) and FCC-hh (5%)
- Effects generically larger than 3+1 but stronger constraints

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Conclusions

- ν oscillations → New physics is needed to generate masses and mixing
- Inverse seesaw: appealing example of low-scale seesaw mechanisms
  - $Y_\nu \sim \mathcal{O}(1)$ and $M_R \sim 100\,\mathrm{GeV} - 10\,\mathrm{TeV}$

→ Corrections to the HHH coupling from heavy ν as large as 30%: measurable at future colliders
  – Larger effects when additional heavy neutrinos are present
  – Can probe a new part of the parameter space, unconstrained otherwise
  – Would deliver new constraints on active-sterile mixing: impact on astroparticle physics, cosmology, neutrino physics

→ Generic effect, expected to be present in all models including multi-TeV fermions with large Higgs couplings

→ Stay tuned for further studies of the impact of neutrinos on the Higgs properties ☺

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Backup slides

Renormalization procedure for the HHH coupling I

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

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

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

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

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Renormalization procedure for the HHH coupling II

- OS scheme

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

- 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

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

NLO terms in the μ_X-parametrization

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

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