WWH production and searches for heavy neutrinos

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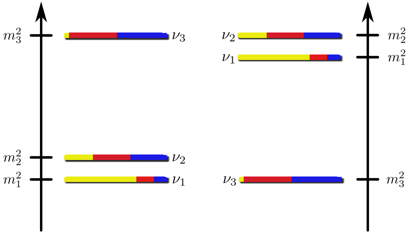
[1] Moving to the University of Pittsburgh, on September 1st

Neutrino phenomena

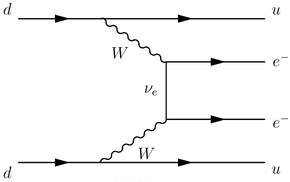


- Neutrino oscillations (best fit from nu-fit.org):

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]

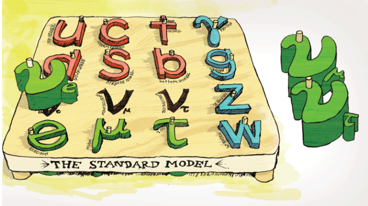
Massive neutrinos and New Physics

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

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

  - No Higgs triplet T $\rightarrow$ 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 → ν mass at tree-level + BAU through leptogenesis

Dirac neutrinos ?

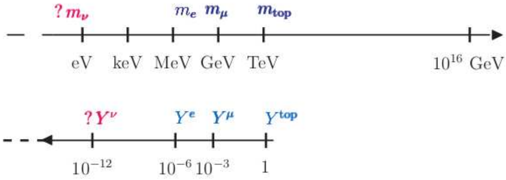
- Add gauge singlet (sterile), right-handed neutrinos ν_R $\Rightarrow \nu = \nu_L + \nu_R$

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

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



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

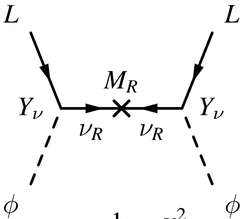
  $3\,\nu_R \Rightarrow$ 6 mass eigenstates: $\nu = \nu^c$

- ν_R gauge singlets
  $\Rightarrow M_R$ not related to SM dynamics, not protected by symmetries
  $\Rightarrow M_R$ between 0 and M_P

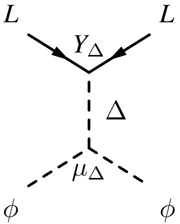
- $M_R\overline{\nu_R}\nu_R^c$ violates lepton number conservation $\Delta L = 2$

The seesaw mechanisms

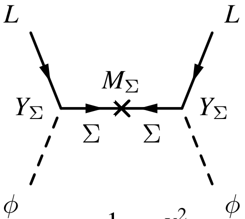
- Seesaw mechanism: new fields + lepton number violation
  ⇒ Generate m_ν in a renormalizable way and at tree-level
- 3 minimal tree-level seesaw models ⇒ 3 types of heavy fields
  - type I: right-handed neutrinos, SM gauge singlets
  - type II: scalar triplets
  - type III: fermionic triplets



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

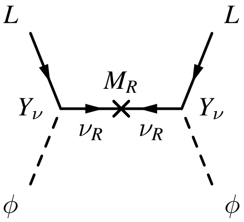


$$\mathrm{m}_\nu = -2 Y_\Delta \mathrm{v}^2 \frac{\mu_\Delta}{M_\Delta^2}$$



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

Towards testable Type I variants



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

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

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

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

$m_\nu = 0$ equivalent to conserved lepton number for models with arbitrary number of ν_R [Moffat, Pascoli, CW, 2017]

⇒ Nearly conserved L symmetry → Cancellation to get large m_D/M_R

- Explicitly realised in, 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]

The inverse seesaw mechanism

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

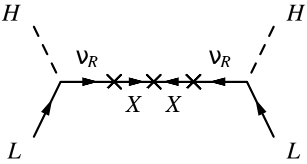
  [Mohapatra and Valle, 1986, Bernabéu et al., 1987]

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

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

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

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



2 scales: μ_X and M_R

- Decouple neutrino mass generation from active-sterile mixing
- Inverse seesaw: $Y_\nu \sim \mathcal{O}(1)$ and $M_R \sim 1\,\mathrm{TeV}$

  ⇒ within reach of the LHC and low energy experiments

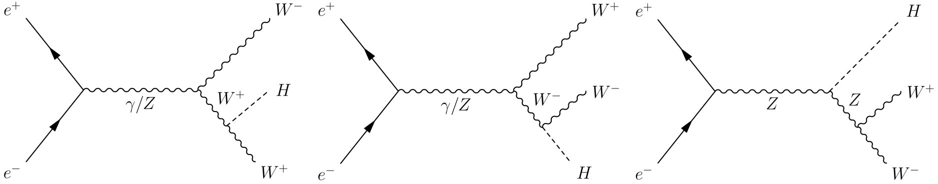
Using Higgs physics to probe neutrino mass models

Discovery of the Higgs boson give new ways to search for heavy neutrinos with $m_\nu > \mathcal{O}(1\,\mathrm{TeV})$

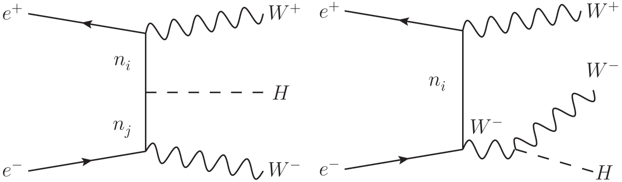
- $H\bar{\ell}_i\ell_j$:
  - Contribution negligible in the SM → evidence of new physics if observed
  - Large branching ratios are possible:
    $\mathrm{Br}(H \to \tau\mu) \sim 10^{-5}$ in ISS [Arganda, Herrero, Marcano, CW, 2015]
    $\mathrm{Br}(H \to \tau\mu) \sim 1\%$ in SUSY-ISS [Arganda, Herrero, Marcano, CW, 2016]
  - Sensitive to off-diagonal Yukawa couplings Y_ν
- HHH:
  - Useful to validate the Higgs mechanism as the origin of EWSB
  - One of the main motivations for future colliders
  - ISS: Deviations as large as 30% [Baglio, CW, 2017]
  - Sensitive to diagonal Yukawa couplings Y_ν
- WWH production
  - Overlooked channel for BSM searches
  - t-channel process: different dependence on the heavy neutrino mass
  - Sensitive to diagonal Yukawa couplings Y_ν

WWH production

- Idea: Probe Y_ν at tree-level with off-shell N ⇒ 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]
⇒ neglected in our analysis

Most relevant constraints for the ISS

- Accommodate low-energy neutrino data using μ_X-parametrization [Arganda, Herrero, Marcano, CW, 2015; Baglio, CW, 2017]

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

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

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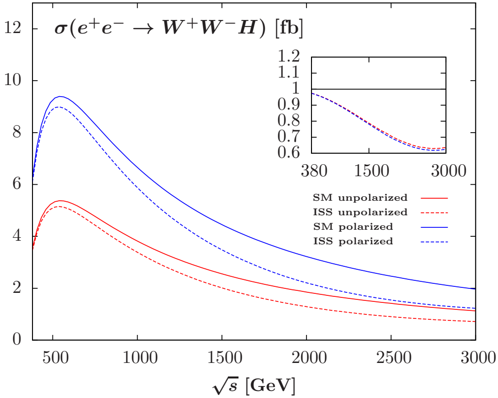
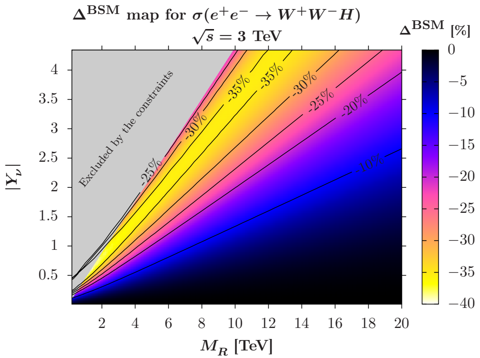
CoM energy dependence



- 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 $3\,\text{TeV}$

Results in the ISS



$\Delta^{\rm BSM}$ map for $\sigma(e^+e^- \to W^+W^-H)$
$\sqrt{s} = 3$ TeV

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

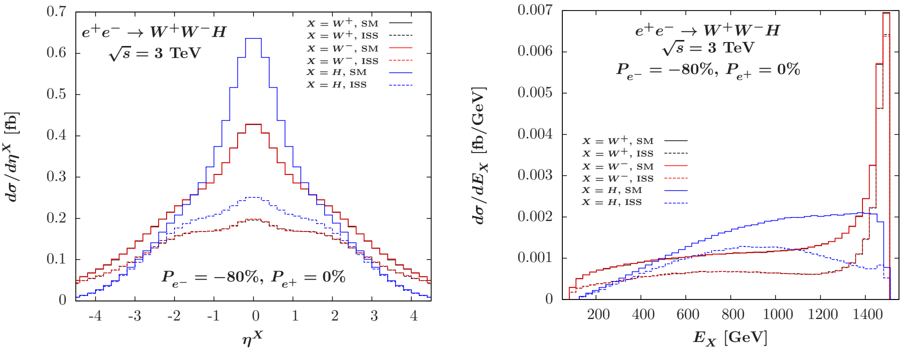
$$\mathcal{A}^{\rm ISS}_{\rm approx} = \frac{(1\ \text{TeV})^2}{M_R^2} \text{Tr}(Y_\nu Y_\nu^\dagger) \times \left(17.07 - \frac{19.79\ \text{TeV}^2}{M_R^2}\right)$$

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

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

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

Enhancing the deviations



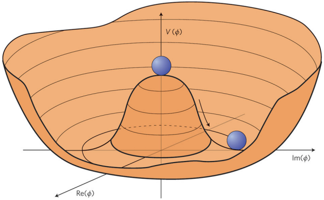
- Stronger destructive interference from ISS for: – central production
  – larger Higgs energy
- Cuts: $|\eta_H| < 1$, $|\eta_{W^\pm}| < 1$ and $E_H > 1$ TeV

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

Comparison: the triple Higgs coupling

- Scalar potential before EWSB:

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



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

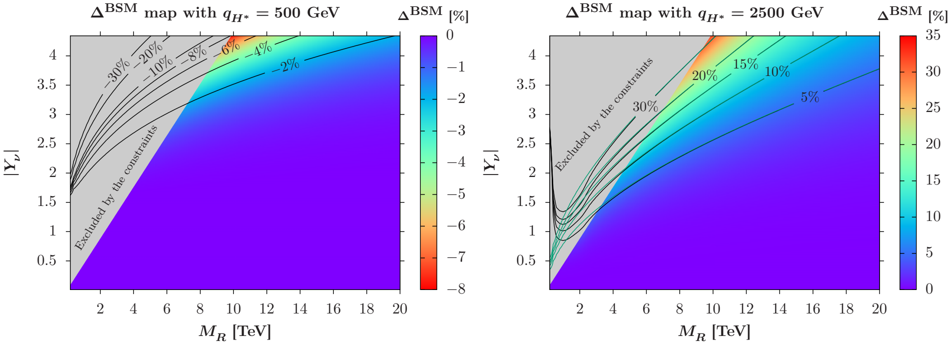
$$\phi = \begin{pmatrix} 0 \\ \frac{\mathrm{v}+H}{\sqrt{2}} \end{pmatrix} \to V(H) = \frac{1}{2}m_H^2 H^2 + \frac{1}{3!}\lambda_{HHH}H^3 + \frac{1}{4!}\lambda_{HHHH}H^4$$

and

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

Comparison: λ_{HHH} in the ISS

[JHEP04(2017)038]



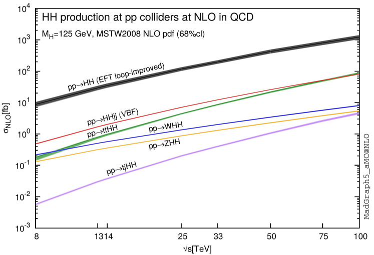
- $\Delta^{\rm BSM} = \frac{1}{\lambda_{HHH}^{1r,\rm SM}}\left(\lambda_{HHH}^{1r,\rm full} - \lambda_{HHH}^{1r,\rm SM}\right)$
- Diagonal Y_ν: full calculation in black, approximate formula in green
- Heavy ν effects at the limit of the ILC (10%) sensitivity
- Heavy ν effects clearly visible at the FCC-hh (5%)
- Sizeable deviation in a smaller part of the parameter space

Conclusions

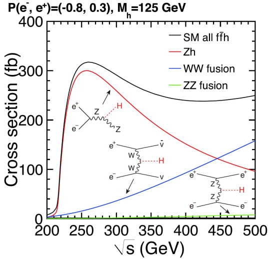
- ν oscillations → New physics is needed to generate masses and mixing
- Higgs sector allows new measurement to probe neutrino mass models
- Corrections to W^+W^-H production as large as -66% after cuts
- Maximal for diagonal Y_ν and provide new probes of the $\mathcal{O}(10)$ TeV region
- Larger deviations than for λ_{HHH}
- Complementarity with flavour observables

Backup slides

Future sensitivities to the SM HHH coupling



[Contino et al., 2017]



[Fujii et al., 2015]

- At hadron colliders
  - Production: gg dominates, VBF cleanest
  - 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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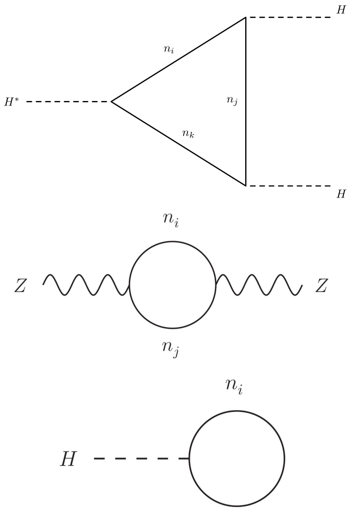
Calculation in the ISS



- 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
(see PRD94(2016)013002 as well)

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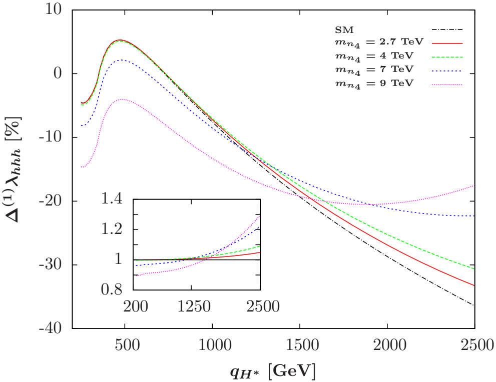
Momentum dependence



- $\Delta^{(1)}\lambda_{HHH} = \frac{1}{\lambda^0}\left(\lambda^{1r}_{HHH} - \lambda^0\right)$
- 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
- $\max|(B^\dagger B)_{i4}|m_{n_4} = m_t$
  $\rightarrow m_{n_4} = 2.7\,\mathrm{TeV}$
  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