Searching for heavy neutrinos with WWH production

EPJC78(2018)795

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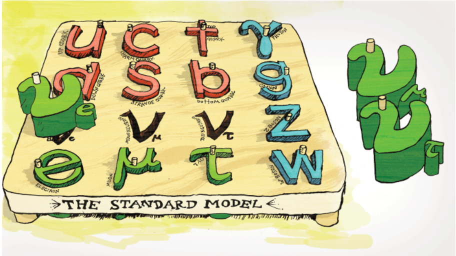
Massive neutrinos and New Physics

- Observation of ν oscillations
  $\Rightarrow$ at least 2 ν are massive
- Standard Model $L = \begin{pmatrix} \nu_L \\ \ell_L \end{pmatrix}, \tilde{\phi} = \begin{pmatrix} H^{0*} \\ H^- \end{pmatrix}$
  - 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 $\rightarrow$ ν mass at tree-level a renormalizable way
    + BAU through leptogenesis

Dirac neutrinos ?

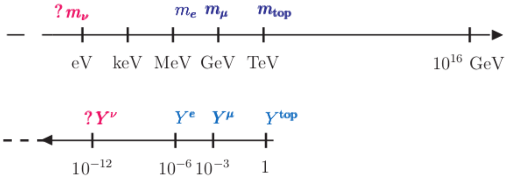
- Add gauge singlet (sterile), right-handed neutrinos ν_R $\Rightarrow \nu = \nu_L + \nu_R$

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

  $\Rightarrow$ After electroweak symmetry breaking $\langle \phi \rangle = \binom{0}{\text{v}}$

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

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



Majorana neutrinos ?

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

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

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

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

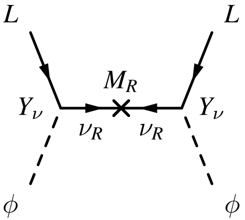
- ν_R gauge singlets
  $\Rightarrow M_R$ not related to SM dynamics, not protected by symmetries
  $\Rightarrow M_R$ between 0 and M_P

- $M_R \gg m_D \Rightarrow$ Type I seesaw mechanism

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

  $\Rightarrow$ Predicts the existence of heavy neutrinos

Towards testable Type I variants



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

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

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

- $m_D M_R^{-1}$ controls the phenomenology of the heavy neutrinos too
  → Cancellation in matrix product to get large $m_D M_R^{-1}$

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

⇒ Nearly conserved L symmetry ensures stability of the cancellation

- 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]

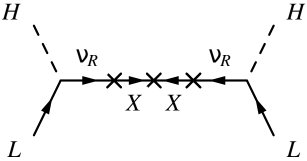
The inverse seesaw mechanism

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



$$\begin{aligned} m_\nu &\approx \frac{m_D^2}{M_R^2}\mu_X \\ m_{N_1,N_2} &\approx \mp M_R + \frac{\mu_X}{2} \end{aligned}$$

2 scales: μ_X and M_R

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

  $\Rightarrow$ within reach of colliders and low energy experiments

Using Higgs physics to search for heavy neutrinos

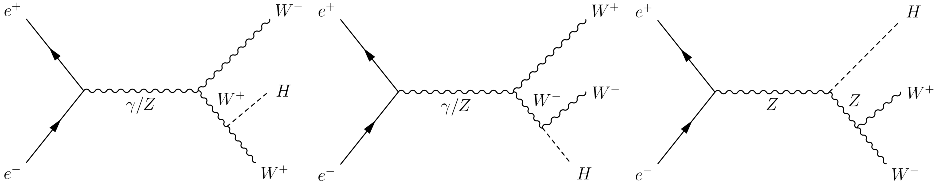
- How to search for heavy neutrinos with $m_N > \mathcal{O}(1\,\mathrm{TeV})$?

Use the Higgs sector to look for the effects of multi-TeV heavy neutrinos

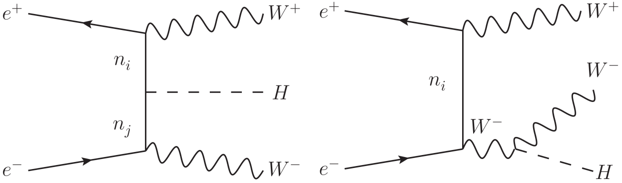
- $H\bar{\ell}_i\ell_j$:
  - Contribution negligible in the SM → evidence of new physics if observed
  - Large branching ratios are possible:
    $\mathrm{Br}(H\to\tau\mu)\sim(10^{-2})10^{-5}$ in (SUSY) ISS [Arganda, Herrero, Marcano, CW, 2015, 2016]
  - Within the reach of future e^+e^- colliders
  - 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%, within ILC, CLIC reach [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 $\Rightarrow$ 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

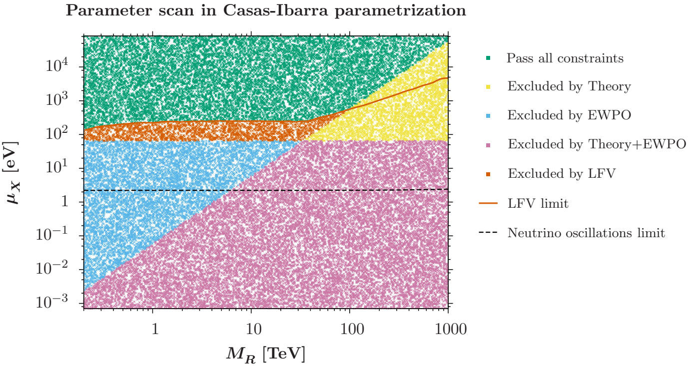
Most relevant constraints for the ISS

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

$$
\begin{aligned}
\mathrm{v} Y_\nu^T &= V^\dagger \mathrm{diag}(\sqrt{M_1}\,, \sqrt{M_2}\,, \sqrt{M_3})\; R\; \mathrm{diag}(\sqrt{m_1}\,, \sqrt{m_2}\,, \sqrt{m_3}) U_{PMNS}^\dagger \\
M &= M_R \mu_X^{-1} M_R^T \\
&\quad \text{or} \\
\mu_X &= M_R^T\; Y_\nu^{-1}\; U_{\mathrm{PMNS}}^* m_\nu U_{\mathrm{PMNS}}^\dagger\; {Y_\nu^T}^{-1} M_R \mathrm{v}^2 \qquad \text{and beyond}
\end{aligned}
$$

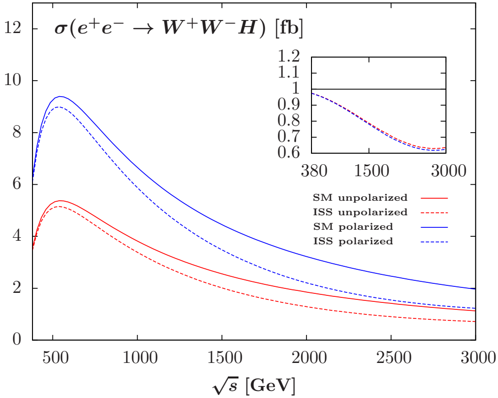
- Charged lepton flavour violation
  → For example: $\mathrm{Br}(\mu \to e\gamma) < 4.2 \times 10^{-13}$ [MEG, 2016]
- Global fit to EWPO and low-energy data [Fernandez-Martinez et al., 2016]
- Electric dipole moment: 0 with real PMNS and mass matrices
- Invisible Higgs decays: $M_R > m_H$, does not apply
- Yukawa perturbativity: $|\frac{Y_\nu^2}{4\pi}| < 1.5$

Impact of constraints



- Y_ν increases when M_R increases and/or μ_X decreases
- Strongest constraints:
  - Lepton flavour violation, mainly $\mu \to e\gamma$
  - Yukawa perturbativity (and neutrino width)
- Larger Y_ν (and effects) necessarily excluded by LFV constraints ?
  → Switch to μ_X-parametrization and use diagonal Y_ν

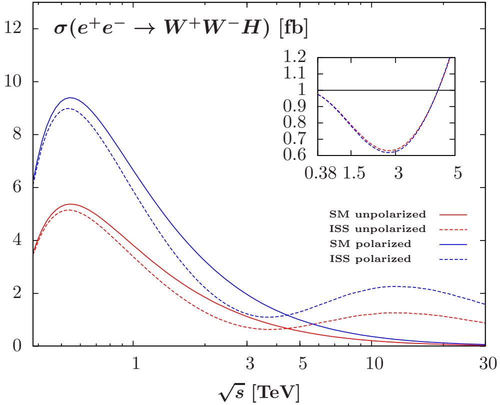
CoM energy dependence



- 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 $3\,\text{TeV}$

What about novel accelerators and muon colliders ?



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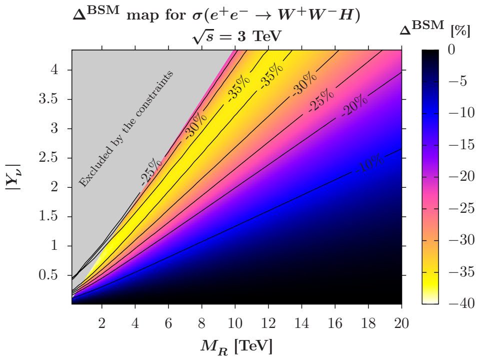
- $\sigma(e^+e^- \to W^+W^-H)_{\text{pol}}$ $\sim 2\sigma(e^+e^- \to W^+W^-H)_{\text{unpol}}$
- $Y_\nu = \mathbb{1}$, $M_{R_1} = 3.6\,\text{TeV}$, $M_{R_2} = 8.6\,\text{TeV}$, $M_{R_3} = 2.4\,\text{TeV}$
- Enhancement from the t-channel heavy neutrinos being on-shell $\Rightarrow$ t-channel diagrams with heavy neutrino dominate at high $\sqrt{s}$

- ALIC → Accelerating gradient 1 GeV/m, linear e^+e^- collider at 10-50 TeV LEMMA → muon collider in LHC tunnel could reach 28 TeV

Results in the ISS



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

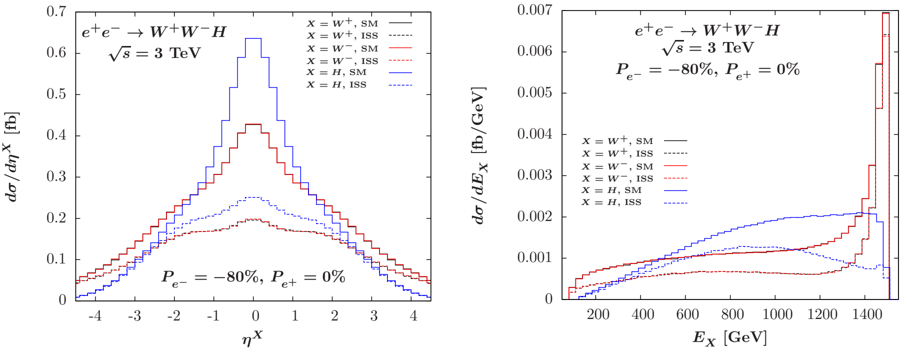
$$\mathcal{A}^{\rm ISS}_{\rm approx} = \frac{(1\ \text{TeV})^2}{M_R^2}\mathrm{Tr}(Y_\nu Y_\nu^\dagger) \times \left(17.07 - \frac{19.79\ \text{TeV}^2}{M_R^2}\right)$$

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

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

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

Enhancing the deviations

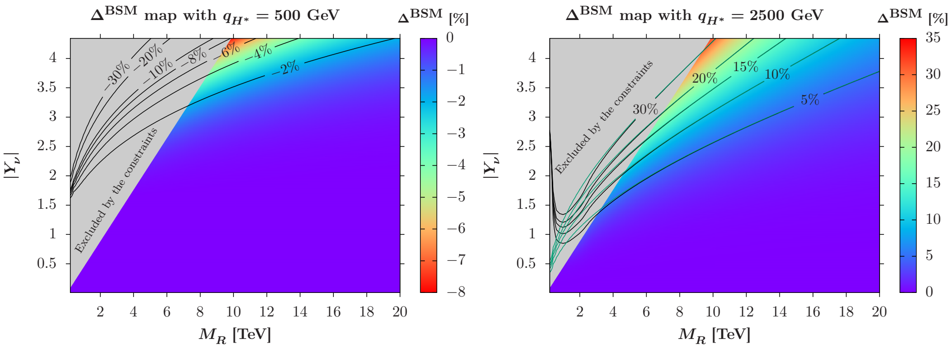


- Stronger destructive interference from ISS for: – central production
  – larger Higgs energy
- Cuts: $|\eta_H| < 1$, $|\eta_{W^\pm}| < 1$ and $E_H > 1$ TeV

	Before cuts	After cuts
$\sigma_{\rm SM}$ (fb)	1.96	0.42
$\sigma_{\rm ISS}$ (fb)	1.23	0.14
$\Delta^{\rm BSM}$	-38%	-66%

Comparison: λ_{HHH} in the ISS

[JHEP04(2017)038]



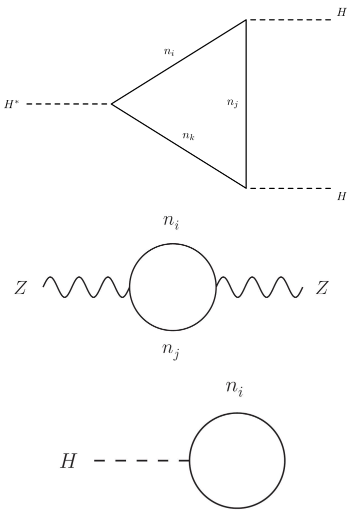
- $\Delta^{\rm BSM} = \frac{1}{\lambda^{1r,\rm SM}_{HHH}}\left(\lambda^{1r,\rm full}_{HHH} - \lambda^{1r,\rm SM}_{HHH}\right)$
- Diagonal Y_ν: full calculation in black, approximate formula in green
- Heavy ν effects at the limit of the ILC (10%) sensitivity [Fujii et al., 2015]
- Heavy ν effects clearly visible at CLIC (22%) [Abramowicz et al., 2017]
- 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 at CLIC
- 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

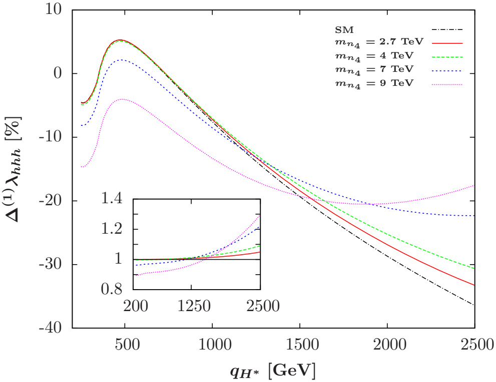
Calculation in the ISS



- 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)

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
- $\max|(B^\dagger B)_{i4}|m_{n_4} = m_t$
  $\to m_{n_4} = 2.7\,\mathrm{TeV}$
  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