Probing heavy neutrinos at lepton colliders

Muon Collider Meeting

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Outline

Introduction

WWH production

HHH Coupling

Outlook

Massive neutrinos and New Physics

- **Neutrino oscillations:** confirmed experimentally in 1998

  [Super-Kamiokande, PRL 81 (1998) 1562]

  $\Rightarrow$ neutrinos are massive! $\Rightarrow$ new physics required to account for their mass
- **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

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

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

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

- **Necessary to go beyond the Standard Model for ν mass**
  - Radiative models
  - R-parity violation in supersymmetry
  - Seesaw mechanisms $\rightarrow \nu$ mass at tree-level

The inverse seesaw (ISS) mechanism

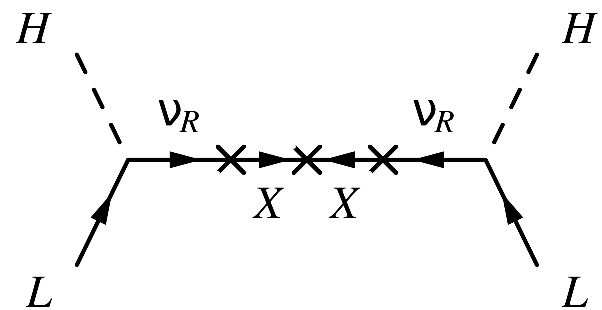
- Lower seesaw scale from (nearly) conserved lepton number
- Add fermionic gauge singlets ν_R ($L=+1$) and X ($L=-1$)

[Mohapatra, PRL 56 (1986) 561; Mohapatra, Valle, PRD 34 (1986) 1642; Bernabéu *et al.* , PLB 187 (1987) 303]

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

with $m_D = Y_\nu v/\sqrt{2}\,, M^\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M_R \\ 0 & M_R^T & \mu_X \end{pmatrix}$

$$m_\nu \approx \frac{m_D^2}{M_R^2}\mu_X, \quad m_{N_1,N_2} \approx \mp M_R + \frac{\mu_X}{2}$$



2 scales: μ_X and M_R

- Decouple neutrino mass generation from active-sterile mixing
- Inverse seesaw: $Y_\nu \sim \mathcal{O}(1)$ and $M_R \sim 1$ TeV
  $\Rightarrow$ within reach of the LHC and low energy experiments

Linking the Higgs sector and neutrinos

How to search for heavy neutrino with $m_\nu > \mathcal{O}(1\,\text{TeV})$?

Use the Higgs sector to probe neutrino mass models

- TeV-scale neutrinos + Large Yukawa couplings

$\Rightarrow$ Possibly large deviations from SM properties in the Higgs sector

- **Some Higgs observables:**
  - Lepton flavor violating Higgs decays [see e.g. Arganda *et al.* , PRD 91 (2015) 015001]
  - Triple Higgs coupling [**J.B.**, Weiland, PRD 94 (2016) 013002; JHEP 1704 (2017) 038]
  - Higgs production at lepton colliders [see Antusch, Cazzato, Fischer, Int.J.Mod.Phys. A32 (2017) 1750078; **J.B.**, Pascoli, Weiland, EPJC 78 (2018) 795]

Most relevant constraints for the ISS

- Accommodate low-energy neutrino data using μ_X-parametrization

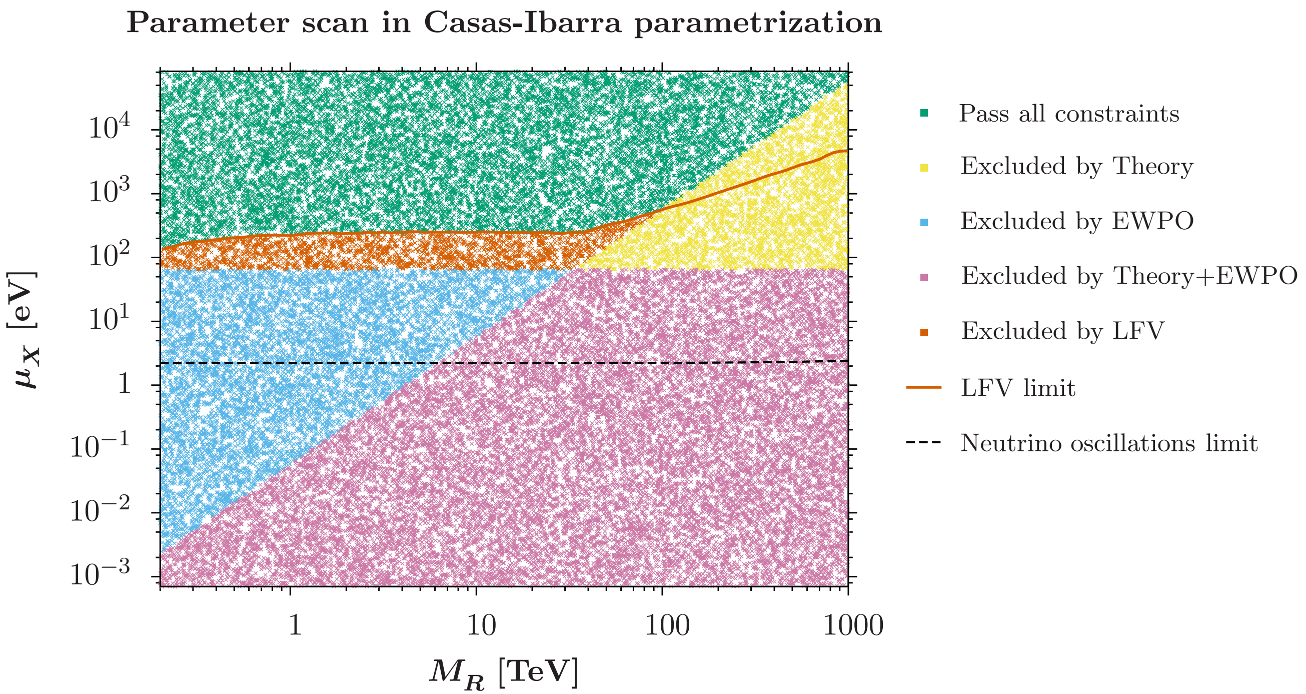
  $$\mu_X = M_R^T \, Y_\nu^{-1} \, U^*_{\rm PMNS} m_\nu U^\dagger_{\rm PMNS} \, Y_\nu^{T^{-1}} M_R v^2 \quad \text{and beyond}$$

  or Casas-Ibarra parametrization

  $$v Y_\nu^T = \mathrm{diag}(\sqrt{M_1}, \sqrt{M_2}, \sqrt{M_3}) \, R \, \mathrm{diag}(\sqrt{m_1}, \sqrt{m_2}, \sqrt{m_3}) U^\dagger_{\rm PMNS}$$

  with $M = M_R \mu_X^{-1} M_R^T$
- Charged lepton flavor violation (LFV)
  $\rightarrow$ For example: $\mathrm{Br}(\mu \rightarrow e\gamma) < 4.2 \times 10^{-13}$ [MEG, EPJC 76 (2016) 434]
- Global fit to EWPO and lepton universality tests [Fernandez-Martinez *et al.* , JHEP 1608 (2016) 033]
- Electric dipole moment: 0 with real PMNS and mass matrices
- Invisible Higgs decays: $M_R > m_H$, does not apply
- Yukawa perturbativity: $|Y_\nu^2/(4\pi)| < 1.5$

Parameter space (Casas-Ibarra parametrization)



Random scan:
180 000 points with degenerate (diagonal) M_R and μ_X

[**J.B.**, Weiland, JHEP 1704 (2017) 038]

Strongest constraints:

- LFV (mainly $\mu \to e\gamma$)
- Yukawa perturbativity

$\Rightarrow$ **Need to escape LFV**

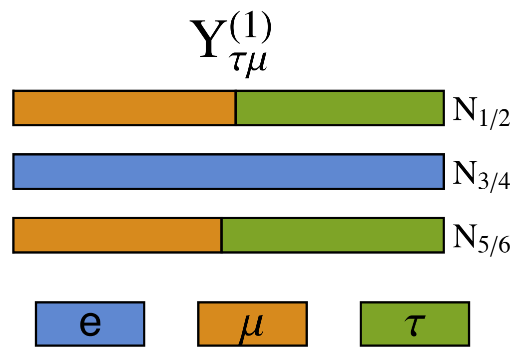
Suppressing LFV constraints

- How to evade the LFV constraints ?
- Approximate formulas for large Y_ν [Arganda *et al.* , PRD 91 (2015) 015001]

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

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

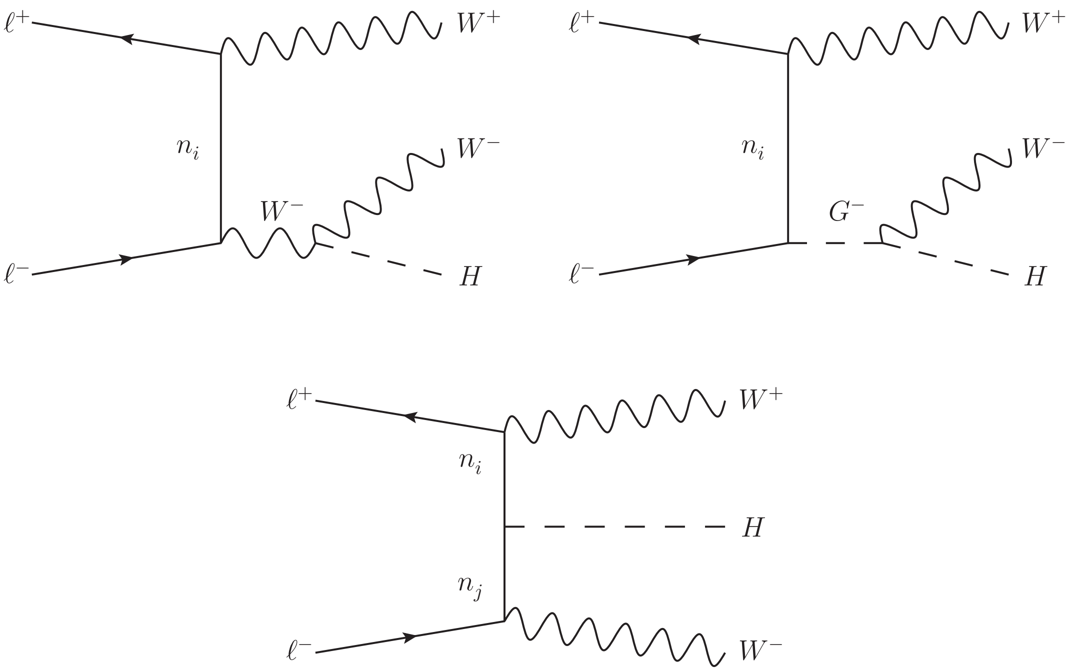
$$Y^{(1)}_{\tau\mu} = |Y_\nu|\begin{pmatrix} 0 & 1 & -1 \\ 0.9 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$$



[taken from Arganda *et al.* , PLB 752 (2016) 46]

- Or even take Y_ν diagonal

WWH calculation in the ISS



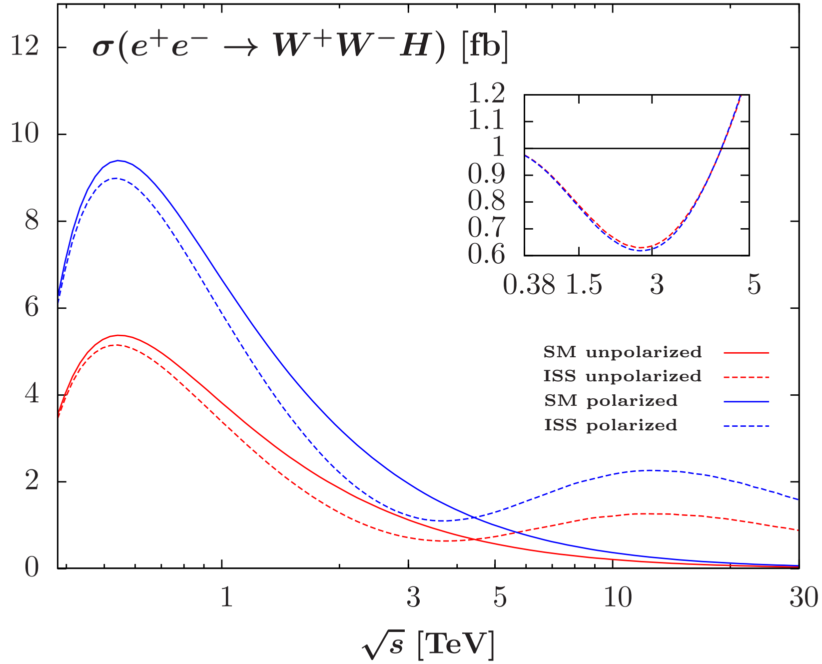
- Tree-level calculation with SM contributions + Majorana neutrinos contributions
- Destructive interference between SM and neutrinos
- SM electroweak corrections negligible for $\sqrt{s} > 600$ GeV

  [Mao *et al.* , EPJC 59 (2009) 761]

- Input values: G_μ scheme and PDG values for the masses

WWH results for diagonal Y_ν

[**J.B.**, Pascoli, Weiland, EPJC 78 (2018) 795; de Blas *et al.* , arXiv:1812.02093]



Polarized vs unpolarized beams:

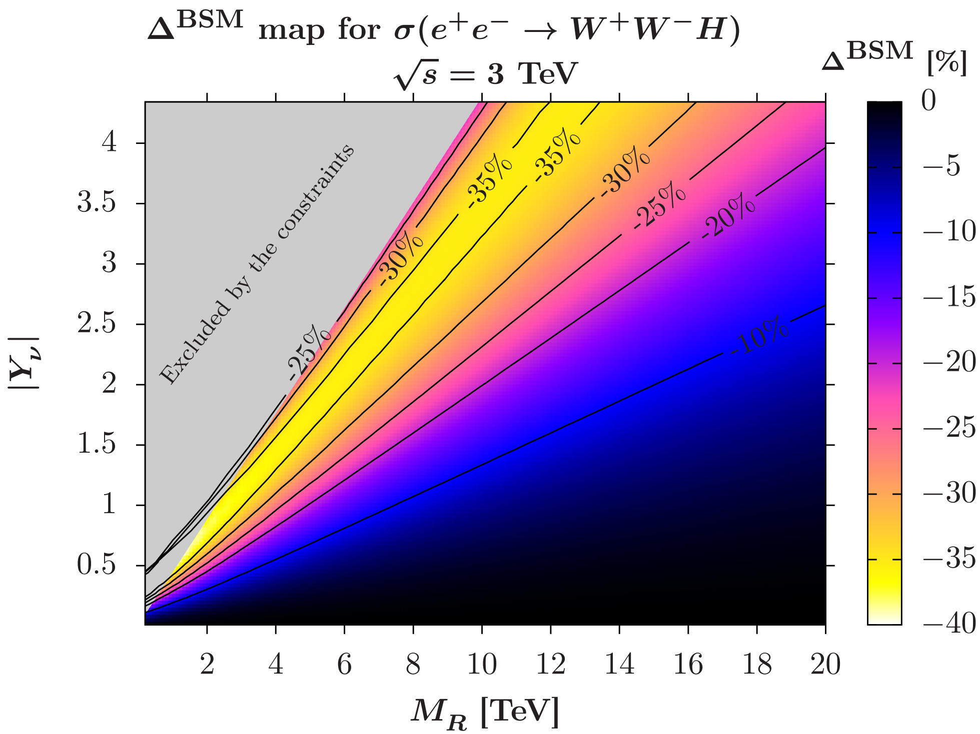
$$\sigma_{\rm pol} = \frac{1}{4}\Big[\left(1 - P_{e^+}\right)\left(1 + P_{e^-}\right)\sigma_{LR} + \left(1 + P_{e^+}\right)\left(1 - P_{e^-}\right)\sigma_{RL}\Big]$$

Heavy neutrino contribution

$$\Delta^{\rm BSM} = (\sigma^{\rm ISS} - \sigma^{SM})/\sigma^{SM}$$

- $Y_\nu = |Y_\nu| I_3$, M_R diagonal with $M_{R_1} = 1.51 M_R$, $M_{R_2} = 3.59 M_R$, $M_{R_1} = M_R$
- Benchmark scenario with $M_R = 2.4$ TeV, $|Y_\nu| = 1$
- **With $P_{e^+} = 0$, $P_{e^-} = -80\%$ (CLIC baseline), enhanced cross section AND keep same $\Delta^{\rm BSM}$, down to -38% at 3 TeV**
- **Beyond 5 TeV: sizable positive $\Delta^{\rm BSM}$**

WWH Contour map at 3 TeV



Heavy neutrino diagrams go like $|Y_\nu|^2/M_R^2\,(1+v^2/M_R^2)$:

$$\mathcal{A}^{\rm ISS}_{\rm approx} = \frac{(1~\text{TeV})^2}{M_R^2}\text{Tr}(Y_\nu Y_\nu^\dagger)\left(17.07 - \frac{19.70~\text{TeV}^2}{M_R^2}\right)$$

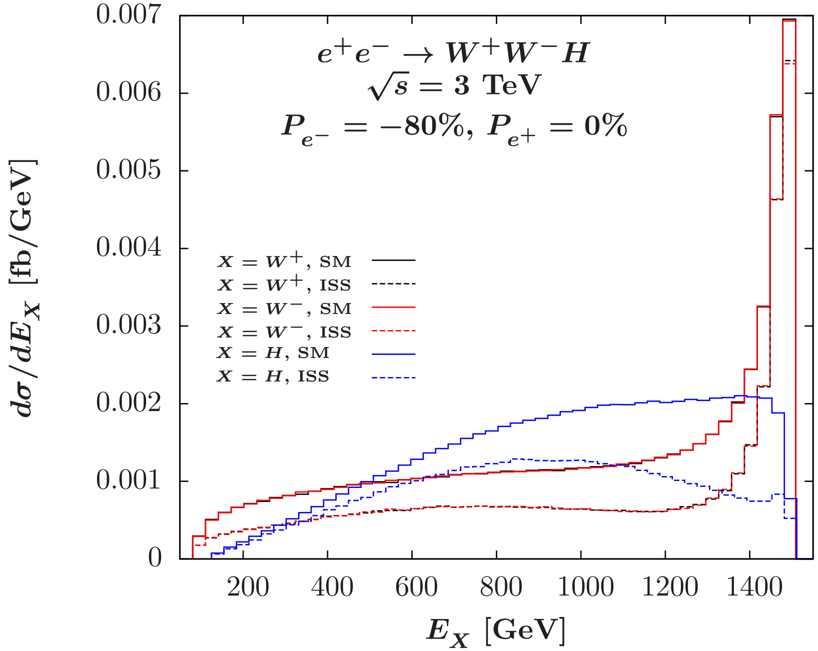
$$\Delta^{\rm BSM}_{\rm approx} = \left(\mathcal{A}^{\rm ISS}_{\rm approx}\right)^2 - 11.94\,\mathcal{A}^{\rm ISS}_{\rm approx}$$

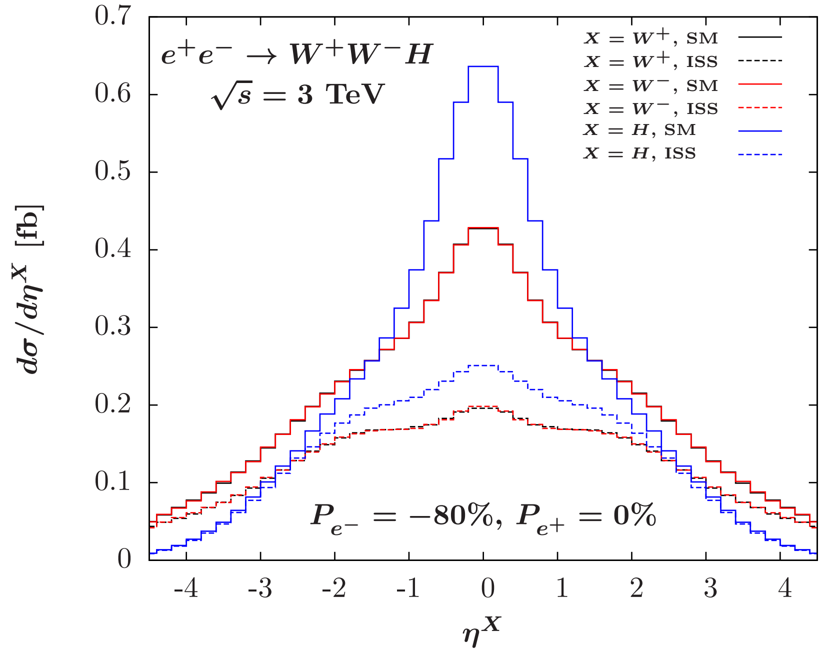
Maximal deviation: -38%, $\sigma^{\rm ISS}_{\rm pol} = 1.23$ fb

- $Y_\nu = |Y_\nu| I_3$, M_R diagonal with $M_{R_1} = 1.51 M_R$, $M_{R_2} = 3.59 M_R$, $M_{R_3} = M_R$
- **Sizable effects on a substantial part of the parameter space! Motivate a detailed sensitivity analysis** [**J.B.**, Han, Huang, Weiland, in preparation]
- Complementary to existing observables
  $\to$ **Provide a new probe of the $\mathcal{O}(10)$ TeV region of neutrino mass models**

Enhancing the deviation with cuts

Looking at distribution to enhance the deviation





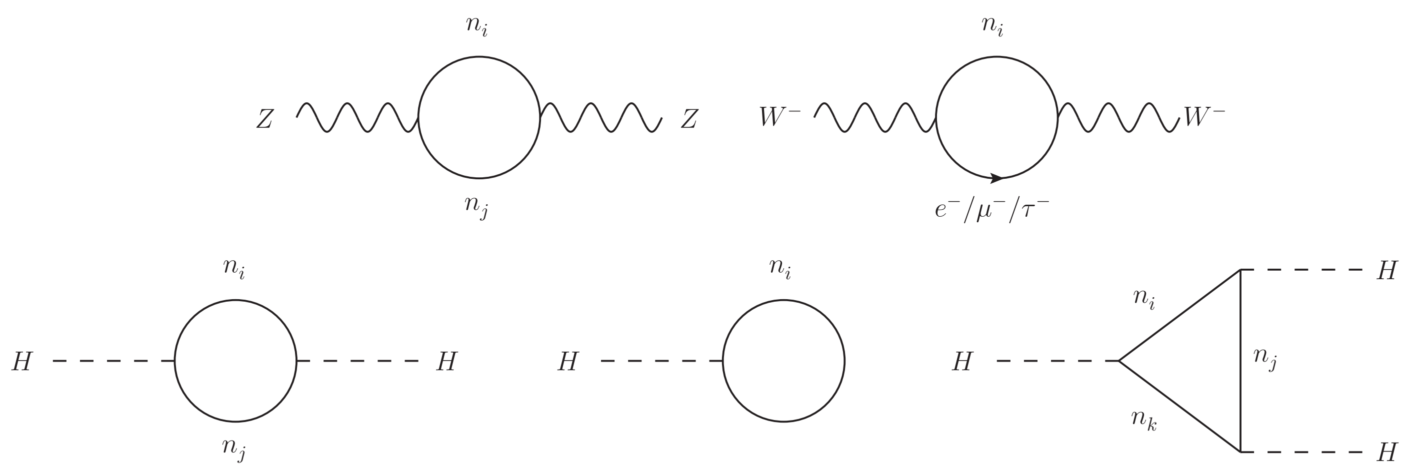
Choose $|\eta_{H/W^\pm}| < 1$ and $E_H > 1$ TeV

$\to$ Deviation enhanced to $\Delta^{\mathrm{BSM}} = -66\%$

$\sigma^{\mathrm{SM}}_{\mathrm{pol,cuts}} = 0.42$ fb and $\sigma^{\mathrm{ISS}}_{\mathrm{pol,cuts}} = 0.14$ fb

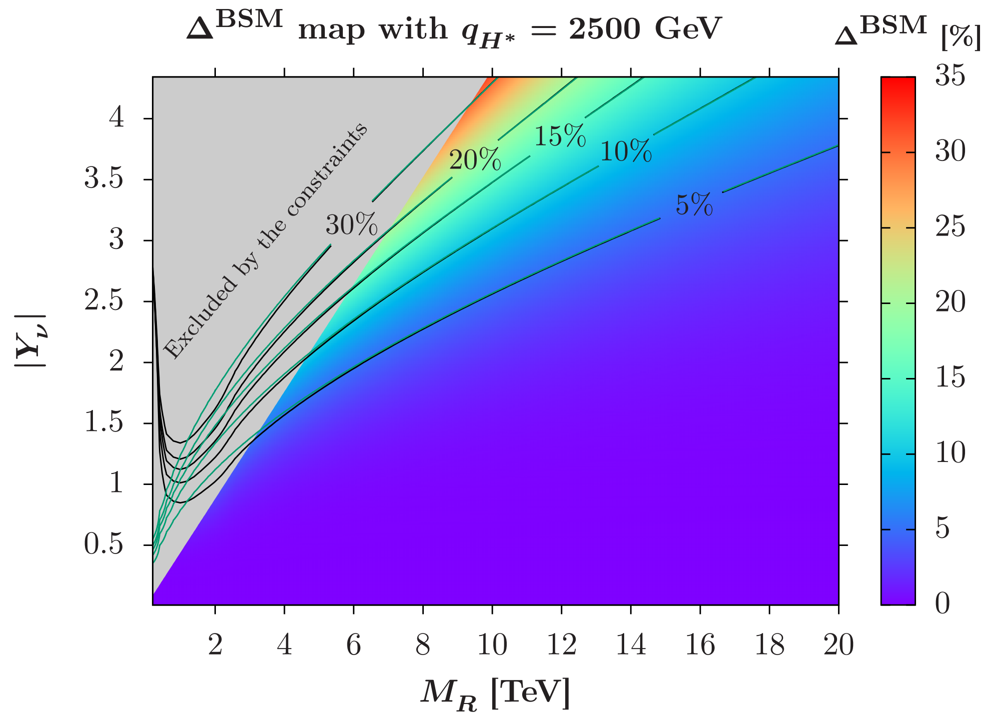
Comparison with λ_{HHH} probe

1-loop observable:
The triple Higgs coupling λ_{HHH} [**J.B.**, Weiland, JHEP 1704 (2017) 038]



- Measuring λ_{HHH}: A major target of future collider experiments
  $\rightarrow$ Look at the loop corrections modified by heavy neutrinos
- Define $\Delta^{\rm BSM} = \left(\lambda^{\rm full}_{HHH} - \lambda^{\rm SM}_{HHH}\right) / \lambda^{\rm SM}_{HHH}$

Comparison with λ_{HHH} probe



- Effects clearly visible at the CLIC 3 TeV! (13% sensitivity) [H. Abramowicz *et al.* , Eur.Phys.J C77 (2017) 475]; approximate formula in green
  Potentially stronger effect at energies beyond 3 TeV
- ***WWH* process probes a larger subset of the parameter space, *HHH* complementary probe**

Conclusions and outlook

- **Neutrino oscillations: New physics needed to generate m_ν**

  $\rightarrow$ low-scale seesaw generate tree-level m_ν, testable at current and future experiments

  Inverse seesaw allows for $Y_\nu \sim \mathcal{O}(1)$ AND $M_R \sim \mathcal{O}(0.1-10)$ TeV

- **How to probe the regime with real, diagonal Y_ν (hard to test)?**

  $\Rightarrow$ **Study of neutrino effects on Higgs properties**

- **Neutrino effects on W^+W^-H production cross section at lepton colliders: -38% effects can be reached at 3 TeV**

  $\rightarrow$ Measurable at future colliders such as CLIC

  $\rightarrow$ Probe a new part of the parameter space of the mass models

  $\rightarrow$ Generic effect applicable to a wide range of low-scale seesaw models

  $\rightarrow$ Can be enhanced to -66% effect with suitable cuts

- **Muon collider beyond 3 TeV with a fantastic potential:** recast of the results at electron-positron colliders with a different mixing (μN vs eN)

Backup slides

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 break down
- Solution: Build a parametrization including the next order terms
- The next-order μ_X-parametrization is then

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