



Constraining neutrino mass models at lepton colliders using WWH production

Terascale IRN Meeting, Strasbourg

[based on J.B., S. Pascoli, C. Weiland, arXiv:1712.07621 [hep-ph]]



Neutrino properties

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

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

⇒ neutrinos are massive! ⇒ new physics required to account for their mass

Different mixing pattern from CKM, ν lightness; **Majorana or Dirac ν ?**

- **No information through oscillations about:**

Absolute mass scale:

cosmology $\Sigma m_{\nu_i} < 0.23 \text{ eV}$ [Planck, A&A 594 (2016) A13]

β decays $m_{\nu_e} < 2.05 \text{ eV}$ [Mainz experiment, EPJC 40 (2005) 447; Troitsk, PRD 84 (2011)

112003]

Neutrino nature (Dirac or Majorana):

Neutrinoless double β decays $m_{2\beta} < 0.061 - 0.165 \text{ eV}$

[KamLAND-ZEN, PRL 117 (2016) 082503]



Massive neutrinos and New Physics

- **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

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

- **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

\rightarrow **heavy sterile fermions possible**

\Rightarrow **neutrino portal for Dark Matter?**

Dirac neutrinos?

Add **gauge singlet** (sterile), right-handed neutrinos

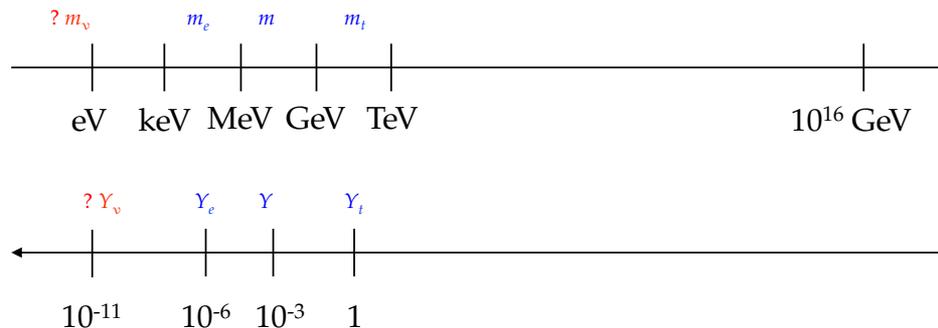
$$\nu_R \Rightarrow \nu = \nu_L + \nu_R$$

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

⇒ After electroweak symmetry breaking:

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

⇒ **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

$$\mathcal{L}_{\text{mass}}^{\text{leptons}} = -Y_\ell \bar{L} \phi l_R - Y_\nu \bar{L} \tilde{\phi} \nu_R - \frac{1}{2} M_R \bar{\nu}_R \nu_R^c + \text{h.c.}$$

⇒ After electroweak symmetry breaking:

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

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

- ν_R gauge singlets

⇒ M_R not related to SM dynamics, not protected by symmetries

⇒ M_R between 0 and M_P

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

The inverse seesaw (ISS) mechanism

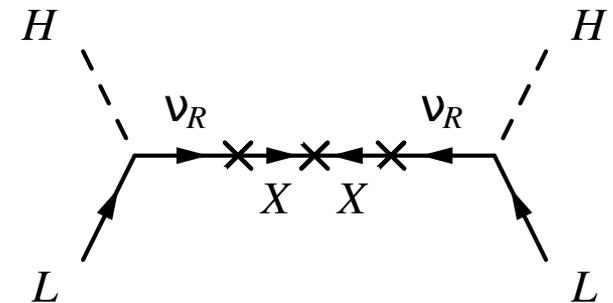
- Lower seesaw scale from (nearly) conserved lepton number
- Add **fermionic gauge singlets** ν_R ($L = +1$) and X ($L = -1$)

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

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

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
⇒ Possibly **large deviations from SM properties** in the Higgs sector
- **Some Higgs observables:**
 - Lepton flavor violating Higgs decays [see e.g. Argandaet *al.* , PRD 91 (2015) 015001]
 - Triple Higgs coupling [J.B., Weiland, PRD 94 (2016) 013002; JHEP 1704 (2017) 038]
 - **Higgs production at lepton colliders: This Work!**
→ Sensitive to **diagonal** Yukawa couplings Y_ν



Most relevant constraints for the ISS

- Accommodate low-energy neutrino data (NuFIT 3.0) with $\delta = 0$ and $m_1 = 0.01$ eV, using μ_X -parametrization

$$\mu_X = M_R^T Y_\nu^{-1} U_{\text{PMNS}}^* m_\nu U_{\text{PMNS}}^\dagger Y_\nu^{T-1} M_R \nu^2 \quad \text{and beyond}$$

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



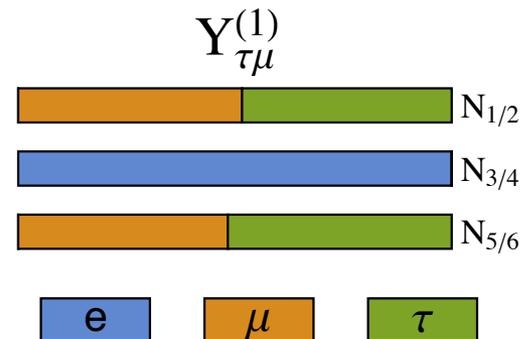
Suppressing LFV constraints

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

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

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

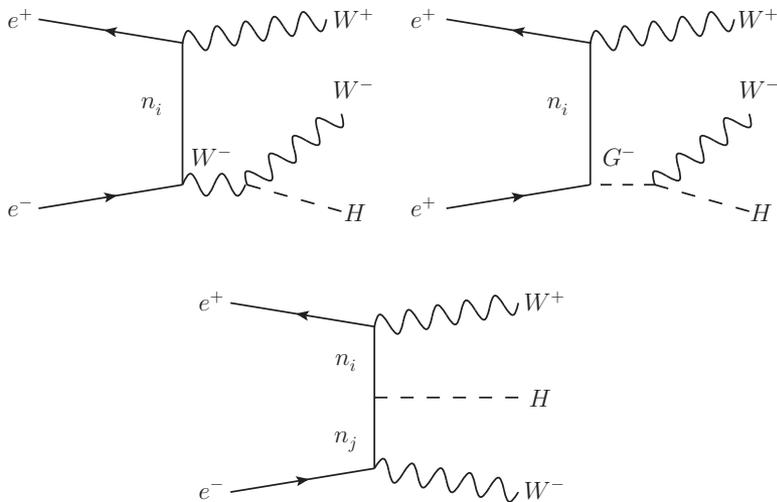
$$Y_{\tau\mu}^{(1)} = |Y_\nu| \begin{pmatrix} 0 & 1 & -1 \\ 0.9 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$$



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

- Or even take Y_ν diagonal

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]

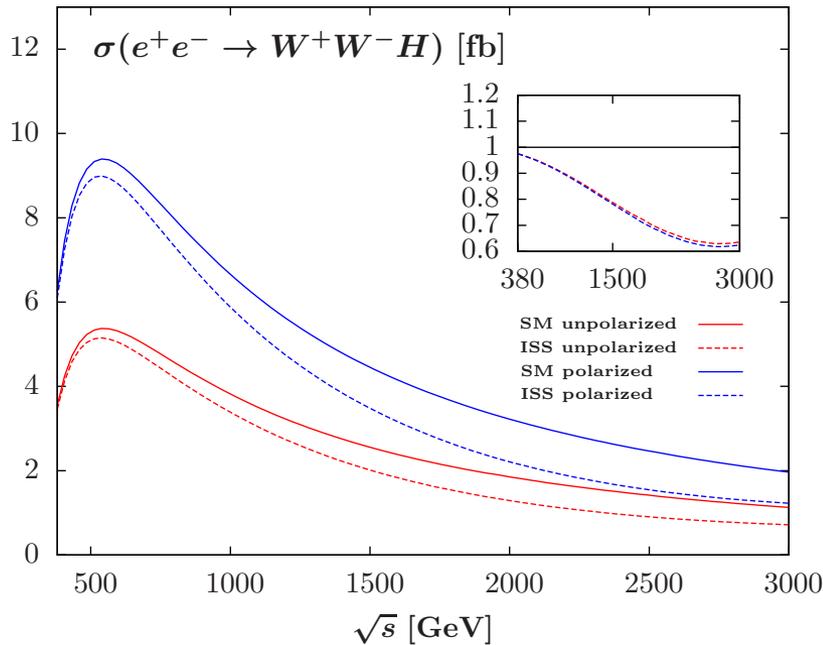
⇒ neglected in our analysis

- Tools for the calculation:

- FeynArts in Feynman-'t Hooft gauge (our own Model File)
- FormCalc to generate the matrix elements
- BASES to perform the Monte-Carlo integration

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

Results for Diagonal Y_ν



Polarized vs unpolarized beams:

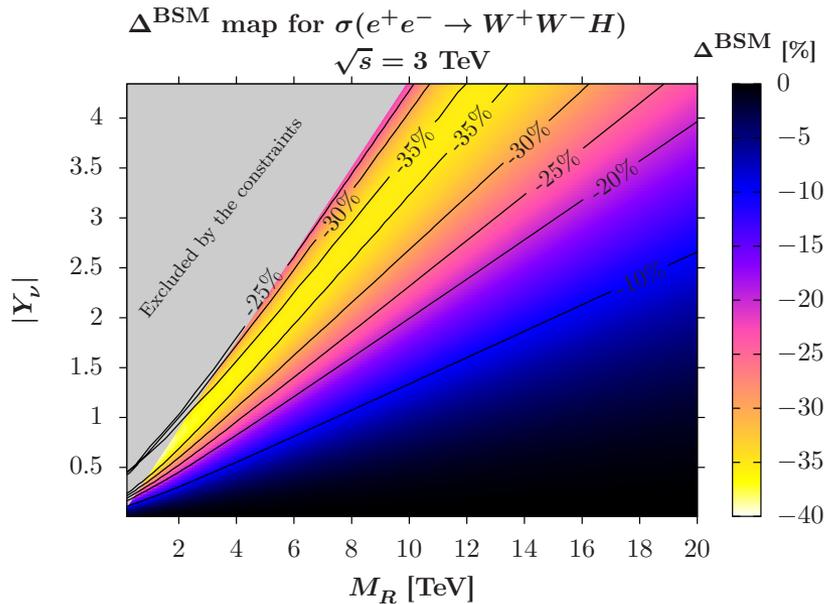
$$\sigma_{\text{pol}} = \frac{1}{4} \left[\left(1 - P_{e^+}\right) \left(1 + P_{e^-}\right) \sigma_{LR} + \left(1 + P_{e^+}\right) \left(1 - P_{e^-}\right) \sigma_{RL} \right]$$

Heavy neutrino contribution

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

- $Y_\nu = |Y_\nu| I_3$, M_R diagonal with $M_{R_1} = 1.51 M_R$, $M_{R_2} = 3.59 M_R$, $M_{R_3} = M_R$
- Benchmark scenario with $M_R = 2.4$ TeV, $|Y_\nu| = 1$
- **Negative Δ^{BSM} more important with increasing c.m. energy**
- **With $P_{e^+} = 0$, $P_{e^-} = -80\%$ (CLIC baseline), enhanced cross section AND keep same Δ^{BSM} , down to -38% at 3 TeV**

Contour map at 3 TeV



Heavy neutrino diagrams go like

$$|Y_\nu|^2 / M_R^2 (1 + v^2 / M_R^2):$$

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

$$\Delta_{\text{approx}}^{\text{BSM}} = (\mathcal{A}_{\text{approx}}^{\text{ISS}})^2 - 11.94 \mathcal{A}_{\text{approx}}^{\text{ISS}}$$

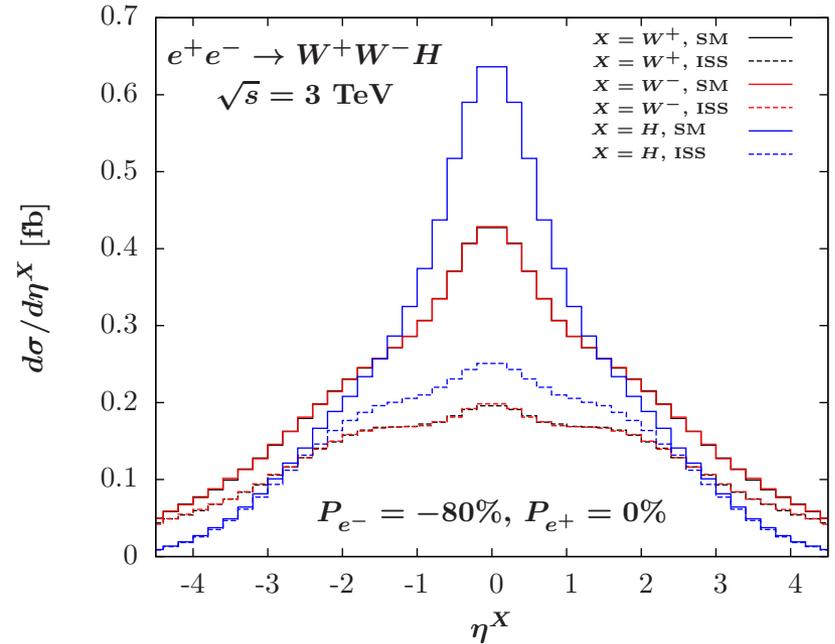
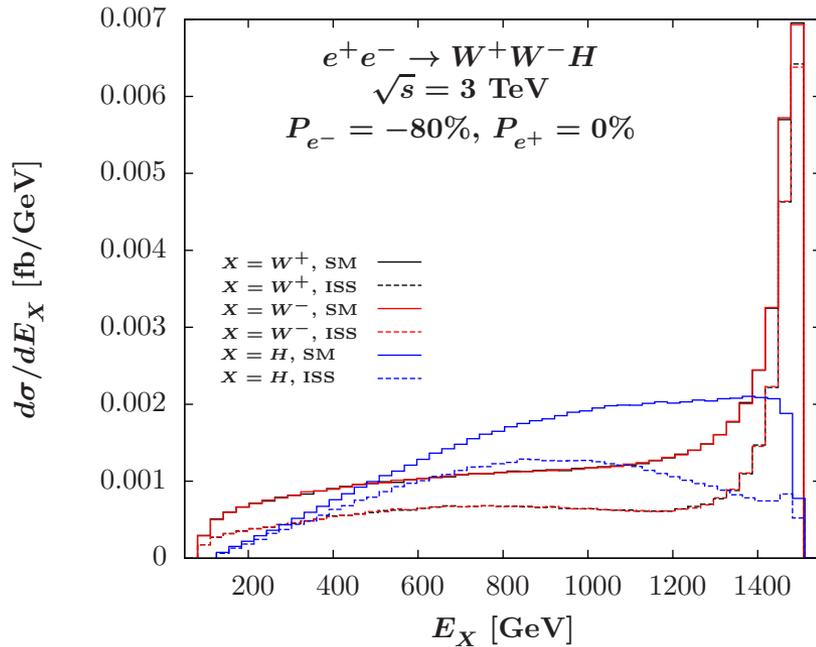
Maximal deviation: -38%, $\sigma_{\text{pol}}^{\text{ISS}} = 1.23 \text{ fb}$

- $Y_\nu = |Y_\nu| I_3$, 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 subset of the parameter space!**
Motivate a detailed sensitivity analysis [J.B., Pascoli, Weiland, in preparation]
- Complementary to existing observables
→ **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 $E_H > 1 \text{ TeV}$

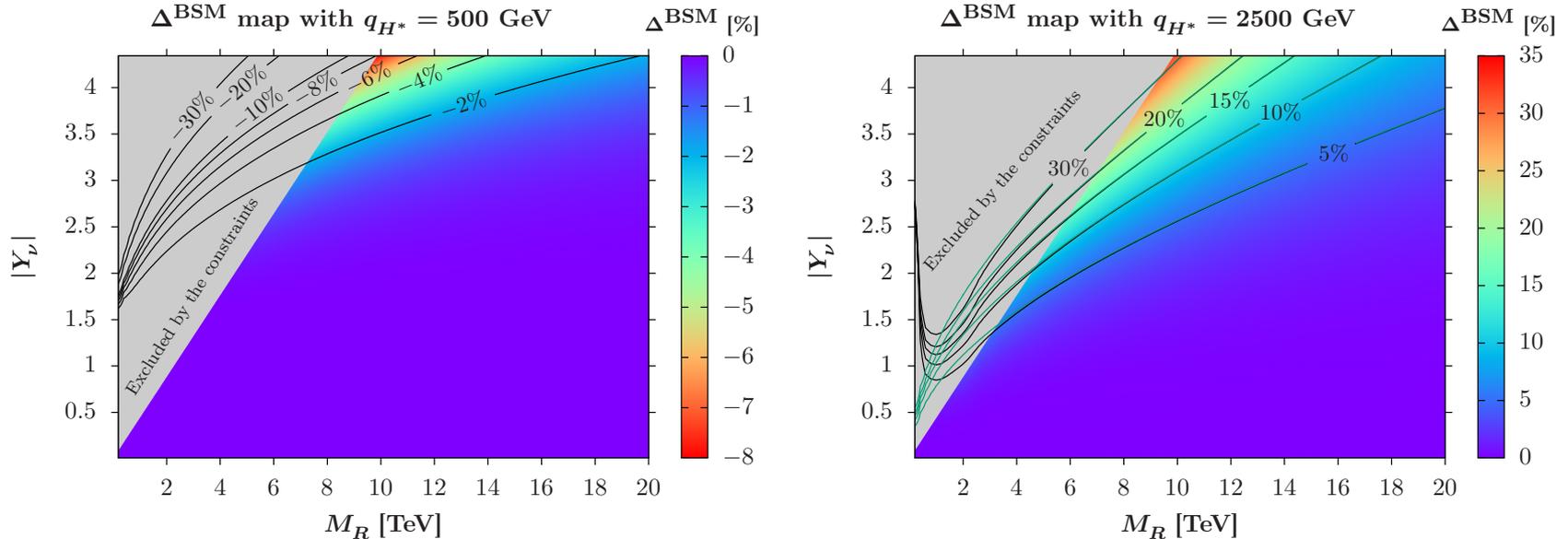
→ Deviation enhanced to $\Delta^{\text{BSM}} = -66\%$

$\sigma_{\text{pol,cuts}}^{\text{SM}} = 0.42 \text{ fb}$ and $\sigma_{\text{pol,cuts}}^{\text{ISS}} = 0.14 \text{ fb}$



Compare with other observables (I)

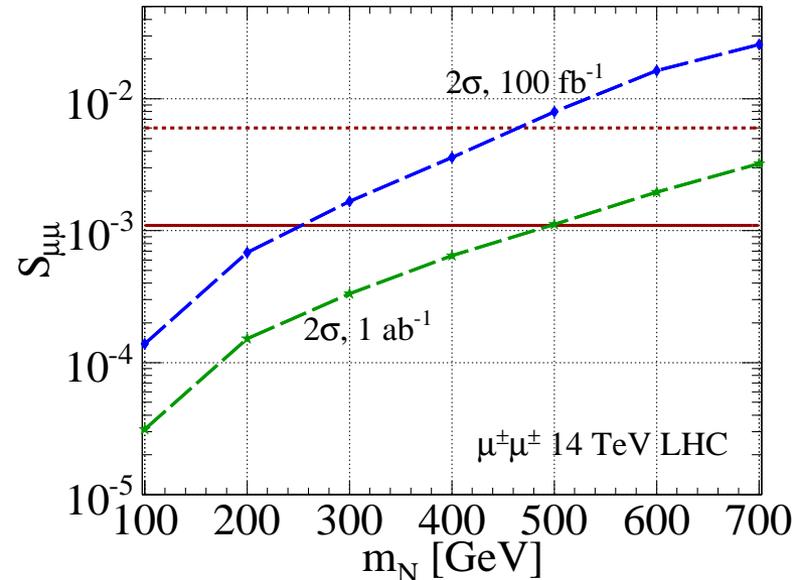
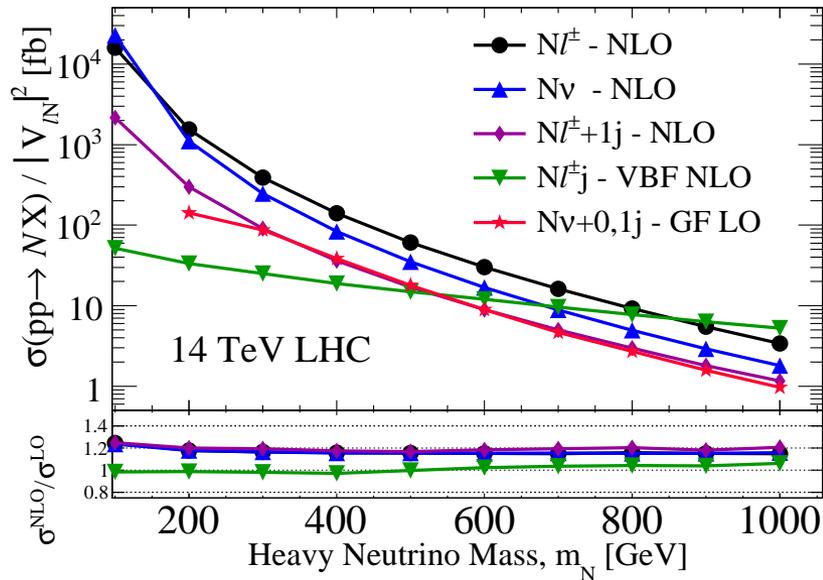
Indirect: The triple Higgs coupling λ_{HHH} [J.B., Weiland, JHEP 1704 (2017) 038]



- $\Delta^{BSM} = (\lambda_{HHH}^{\text{full}} - \lambda_{HHH}^{\text{SM}}) / \lambda_{HHH}^{\text{SM}}$, approximate formula in green
- Effects potentially visible at the 1 TeV ILC (10% sensitivity)
clearly visible at the FCC-hh (5% sensitivity)
- **WWH process probes a larger subset of the parameter space**

Compare with other observables (II)

Direct production of heavy neutrinos at the LHC



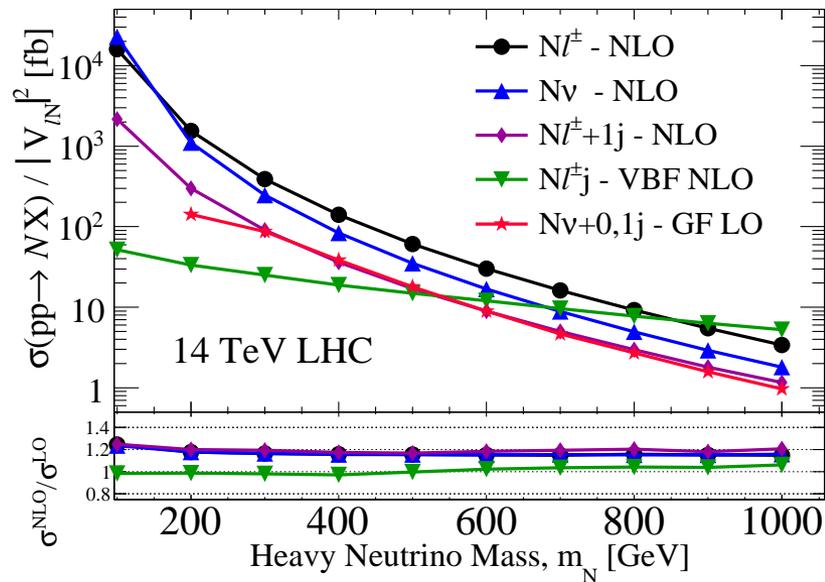
[Degrande, Mattelaer, Ruiz, Turner, PRD 94 (2016) 053002]

[Alva, Han, Ruiz, JHEP 1502 (2015) 072]

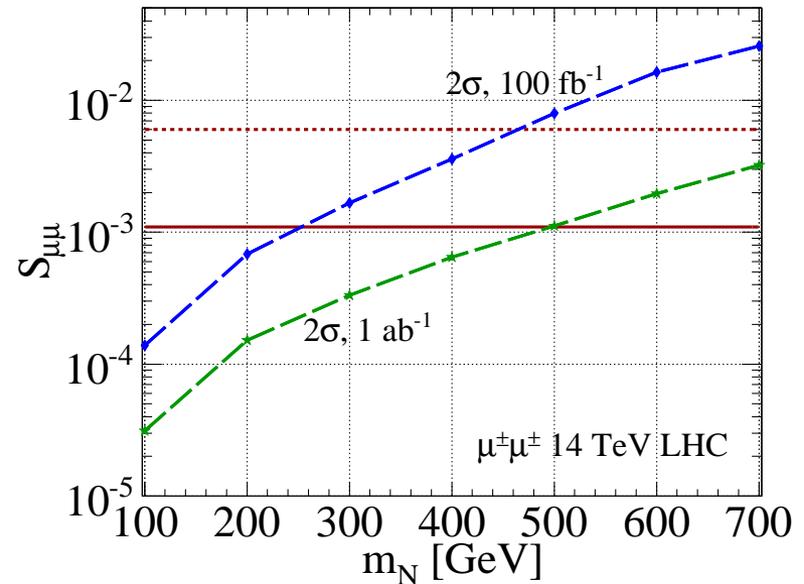
- 3 light neutrinos and 1 heavy (Majorana) neutrino N
- $|V_{\ell N}|^2$: Active-heavy neutrino mixing between N and ν_ℓ ,
 $S_{\mu\mu} \simeq |V_{\mu N}|^2$

Compare with other observables (II)

Direct production of heavy neutrinos at the LHC



[Degrande, Mattelaer, Ruiz, Turner, PRD 94 (2016) 053002]



[Alva, Han, Ruiz, JHEP 1502 (2015) 072]

- Solid line: EWPO limit on $S_{\mu\mu}$ [del Aguila, de Blas, Pérez-Victoria, PRD 78 (2008) 013010]
- Cross-sections very small for $m_N \sim 1 \text{ TeV} \Rightarrow$ hard to probe very heavy neutrinos



Conclusion and outlook

- **Neutrino oscillations: New physics needed to generate m_ν**
 - low-scale seesaw appealing to generate tree-level m_ν
 - 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 Y_ν diagonal?**
 - ⇒ **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**
 - Measurable at future colliders such as CLIC
 - Probe a **new part** of the **parameter space** of the mass models
 - **Generic effect applicable to a wide range of low-scale seesaw models**
 - Can be enhanced to –66% effect with suitable cuts
- **Future work:** Detailed sensitivity analysis at lepton colliders (1 TeV and 3 TeV baselines)



Backup slides



Next-order 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 in the $m_D M_R^{-1}$ expansion → **Parametrizations breaks down**
- Solution: Build a parametrization **including the next order terms**
- The next-order μ_X -parametrization is then

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

$$\times \left(\mathbf{1} - \frac{1}{2} M_R^{-1} m_D^T m_D^* M_R^{\dagger-1} \right)^{-1}$$