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Institut de Física d'Altes Energies

Light-scalar phenomenology in Flavour Aligned 2-Higgs Doublet Model

Luigi Delle Rose

LHC HWG3 (BSM) — Extended Higgs Sector
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Phys.Rev.D. 101 (2020) 025, *arXiv:1903.11146*

Introduction

Flavour anomalies have triggered the construction of several new physics scenarios with sources of flavour non-universality

A non-trivial flavour structure in the lepton sector is already required, within the SM, to explain the neutrino oscillations

It is plausible and very attractive if the mechanism behind flavour anomalies can be related to the same physics responsible for nonzero neutrino masses

The low-scale seesaw

The seesaw mechanism is the standard mechanism for neutrino masses

$$-\mathcal{L}_{\mathcal{M}_\nu} = \frac{1}{2} N_L^T C \mathcal{M} N_L + \text{h.c.} = \frac{1}{2} (\nu_L^T \, \nu_R^{c\,T}) C \begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix}$$

$$M_D = \frac{v}{\sqrt{2}} Y_\nu^*$$

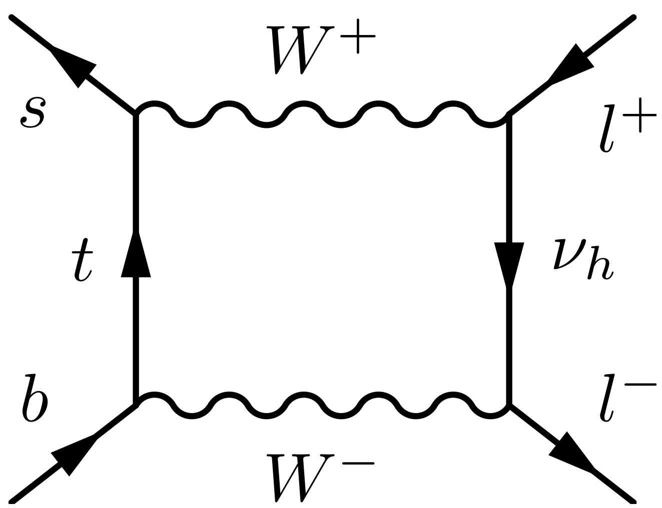
$$\begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix} = U \begin{pmatrix} \nu_l \\ \nu_h \end{pmatrix} \equiv \begin{pmatrix} U_{Ll} & \underline{U_{Lh}} \\ U_{R^c l} & U_{R^c h} \end{pmatrix} \begin{pmatrix} \nu_l \\ \nu_h \end{pmatrix}$$

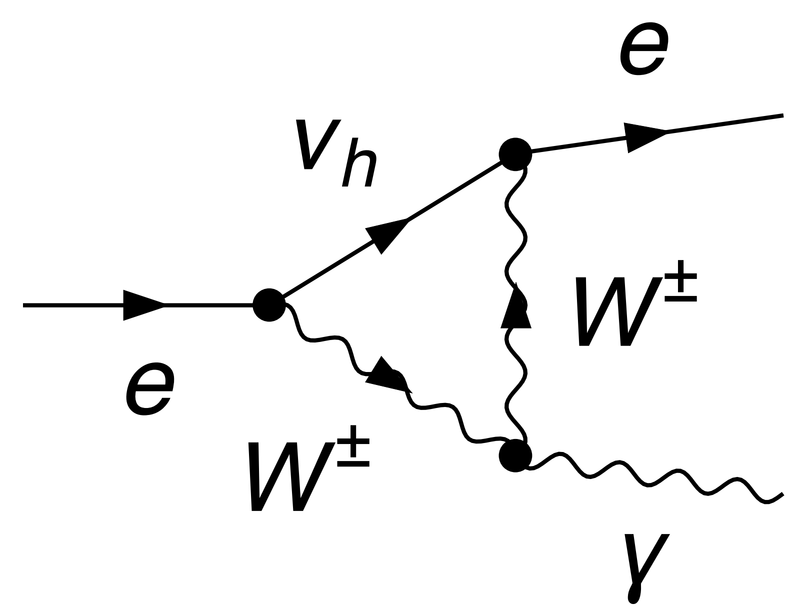
source of flavour non-universality

There are several realisations, a class among the most interesting ones is the **low-scale seesaw** (e.g. inverse, linear, etc.) characterised by *large Yukawas* and *EW/TeV scale masses*

ν_R in flavour observables

Example: one-loop contributions of heavy neutrinos to $b \to s\ell\ell$ and $(g-2)_\ell$





The coupling of the sterile neutrinos to leptons and the charged gauge boson is given by $\sim g\, U_{Lh}$, with $|U_{Lh}|^2 \lesssim 10^{-2} - 10^{-3}$

the strength of the interactions is fixed by the gauge coupling

To allow for more freedom one must rely on another mediator the charged Higgs boson is the most natural choice

The 2HDM + ν_R

The most general Yukawa Lagrangian of the 2HDM can be written as

$$-\mathcal{L}_Y = \bar{Q}'_L \left(Y'_{1d}\Phi_1 + Y'_{2d}\Phi_2\right) d'_R + \bar{Q}'_L \left(Y'_{1u}\tilde{\Phi}_1 + Y'_{2u}\tilde{\Phi}_2\right) u'_R + \bar{L}'_L \left(Y'_{1\ell}\Phi_1 + Y'_{2\ell}\Phi_2\right) \ell'_R + \bar{L}'_L \left(Y'_{1\nu}\tilde{\Phi}_1 + Y'_{2\nu}\tilde{\Phi}_2\right) \nu'_R + \text{h.c.},$$

potentially dangerous tree-level FCNC are avoided by a discrete Z_2 symmetry (type- I, II, III, IV), or by requiring an alignment in flavour space (A2HDM)

$$Y_{2,d} = \zeta_d\, Y_{1,d} \equiv \zeta_d\, Y_d\,, \qquad Y_{2,u} = \zeta_u^*\, Y_{1,u} \equiv \zeta_u^*\, Y_u\,, \qquad Y_{2,\ell} = \zeta_\ell\, Y_{1,\ell} \equiv \zeta_\ell\, Y_\ell\,,$$

$$Y_{2,\nu} = \zeta_\nu^*\, Y_{1,\nu} \equiv \zeta_\nu^*\, Y_\nu$$

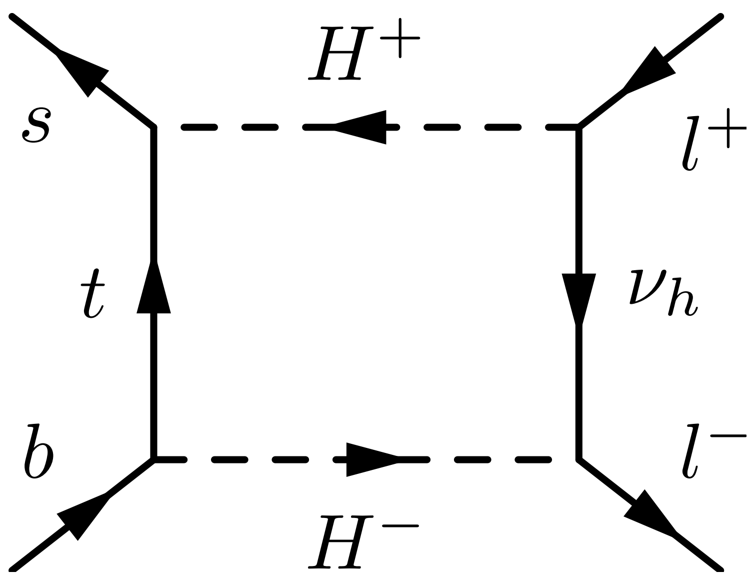
Aligned	Type I	Type II	Type III	Type IV
ζ_u	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
ζ_d	$\cot\beta$	$-\tan\beta$	$-\tan\beta$	$\cot\beta$
ζ_l	$\cot\beta$	$-\tan\beta$	$\cot\beta$	$-\tan\beta$

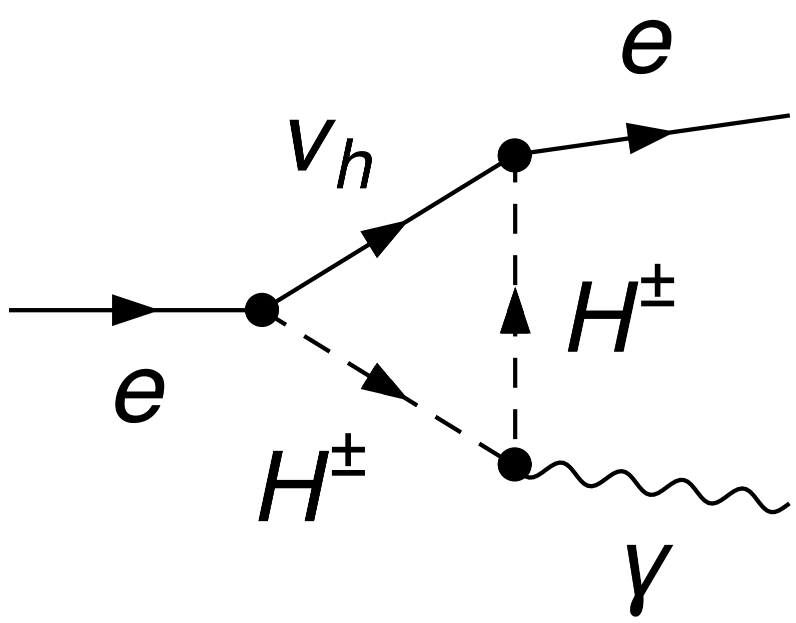
The charged Higgs boson currents in the lepton sector:

$$-\mathcal{L}_Y^{\rm CC} = \frac{\sqrt{2}}{v}\zeta_\ell \left[(\bar{\nu}_l\, U^\dagger_{Ll} + \bar{\nu}_h\, U^\dagger_{Lh}) m_\ell\, P_R\, \ell\right] H^+ - \frac{\sqrt{2}}{v}\zeta_\nu \left[(\bar{\nu}_l\, U^\dagger_{Ll}\, m_{\nu_l} + \bar{\nu}_h\, U^\dagger_{Lh}\, m_{\nu_h})\, P_L\, \ell\right] H^+ + \text{h.c.}$$

$\nu_R + H^\pm$ in flavour observables

Example: one-loop contributions of heavy neutrinos and charged Higgs to $b \to s\ell\ell$ and $(g-2)_\ell$





The coupling of the sterile neutrinos to leptons and the charged Higgs boson is given by $\sim \zeta_\nu (m_\nu / v)\, U_{Lh}$, with $|U_{Lh}|^2 \lesssim 10^{-2} - 10^{-3}$

In the A2HDM it is possibile to disentangle the quark and the lepton sectors

Comments

- *RG effects misalign the Yukawas, nevertheless the induced FCNCs are suppressed by mass hierarchies* $m_q m_{q'}^2/v^3$

Jung, Pich, Tuzon 2010
Li, Lu, Pich, 2014

- *Alignment in the neutrino sector is not strictly required*

- *new sources of CP violation in the* ζ_f *coefficients (not considered here)*

- *further extension:* $\zeta_f \to \zeta_{f_i}$

Botella, Cornet-Gomez, Nebot 2020

Flavour non-universality

Contributions to the R_{K^*} from the charged-currents:

$$R_{K^*} = \frac{BR(B^0 \to K^{*0} \mu^+ \mu^-)}{BR(B^0 \to K^{*0} e^+ e^-)} \qquad C_{9,10} = \sum_{i=1}^{n_R} |(U_{Lh})_{\ell i}|^2 \zeta_u^2 \zeta_\nu^2 \; f_{9,10}(m_{\nu_{h_i}}, m_{H^\pm})$$

Contributions to the g-2 from the charged-currents:

$$a_\ell^\pm = a_\ell^{W^\pm} + a_\ell^{H^\pm} = \frac{G_F\, m_\ell^2}{2\sqrt{2}\pi^2} \sum_{i=1}^{n_R} |(U_{Lh})_{\ell\, i}|^2 \left[\mathcal{G}_{W^\pm}\left(\frac{m^2_{\nu_{h_i}}}{M_W^2}\right) + \mathcal{G}_{H^\pm}\left(\frac{m^2_{\nu_{h_i}}}{M^2_{H^\pm}}\right)\right]$$

In the pure Z_2 symmetric or in the aligned 2HDM, the corrections to both electron and muon channels have fixed sign

Hierarchies in the U_{Lh} matrix lead to a decoupling of the three leptonic sectors

$$\boxed{\begin{aligned} \mathcal{G}_{W^\pm}(x) &= \frac{-x + 6x^2 - 3x^3 - 2x^4 + 6x^3 \log x}{4(x-1)^4}, \\ \mathcal{G}_{H^\pm}(x) &= \frac{\zeta_\nu^2}{3}\mathcal{G}_{W^\pm}(x) + \zeta_\nu \zeta_l \frac{x(-1 + x^2 - 2x \log x)}{2(x-1)^3} \end{aligned}}$$

Lepton flavour violation

The hierarchy among elements of $(U_{Lh})_{\alpha i}$ is experimentally required by lepton flavour violating (LFV) processes $\ell_\alpha \to \ell_\beta \gamma$

$$\mathrm{BR}(\ell_\alpha \to \ell_\beta \gamma) = \mathcal{C} \left| \overbrace{\sum_{i=1}^{n_R} (U^*_{Lh})_{\alpha i} (U_{Lh})_{\beta i}}^{\text{flavour non-universal coefficient}} \underbrace{\left[\mathcal{G}_{W^\pm}\left(\frac{m^2_{\nu_{h_i}}}{M_W^2} \right) + \mathcal{G}_{H^\pm}\left(\frac{m^2_{\nu_{h_i}}}{M^2_{H^\pm}} \right) \right]}_{\text{lepton flavour universal form factor}} \right|^2$$

Constraints at 90% CL:

$$BR(\mu \to e\gamma) \leq 4.2 \times 10^{-13},$$
$$BR(\tau \to e\gamma) \leq 3.3 \times 10^{-8},$$
$$BR(\tau \to \mu\gamma) \leq 4.4 \times 10^{-8}$$

$$\boxed{\begin{aligned} \mathcal{G}_{W^\pm}(x) &= \frac{-x + 6x^2 - 3x^3 - 2x^4 + 6x^3 \log x}{4(x-1)^4}, \\ \mathcal{G}_{H^\pm}(x) &= \frac{\zeta_\nu^2}{3} \mathcal{G}_{W^\pm}(x) + \zeta_\nu \zeta_l \frac{x(-1 + x^2 - 2x \log x)}{2(x-1)^3} \end{aligned}}$$

The parameter space

- constraints from neutrino data, in particular from the violation of unitarity of the PMNS matrix

- Higgs sector compliant with LHC/LEP direct and indirect searches (implemented through HiggsBounds/HiggsSignals)

- constraint from the tree-level $\tau \to \mu\nu\bar{\nu}$ on the combination $\zeta_\ell^2 m_\tau m_\mu / m_{H^\pm}^2$

- bounds from LFV processes ($\ell_\alpha \to \ell_\beta \gamma$)

- flavour constraints (mainly neutral meson mixings, neutral and charged meson decays to leptons, $b \to s\gamma$) mostly depend on $m_{H^\pm}, \zeta_u, \zeta_d$

  easily satisfied if ζ_u, ζ_d are taken to be small, similarly to the leptophilic type-IV

✤ we require $m_{\nu_h} > m_{H^\pm}$

✤ we require m_A to be much lighter than $m_{H^\pm}$, then $m_{H^\pm} \simeq m_H$ from EWPT

to facilitate the explanation of both $(g-2)_{e,\mu}$

Light-scalar phenomenology

Within the parameter space defined above (light scalars)

- the relevant decay modes for the BSM scalars are

$$g_\ell = \zeta_\ell m_\tau / m_{H^\pm}$$

  - $A \to \tau\tau$

$$BR(A \to \tau\tau) \simeq 100\,\%$$

  - $H^\pm \to \tau^\pm\nu, H^\pm \to W^\pm A$

$$BR(H^\pm \to \tau^\pm\nu) = BR(H \to \tau\tau) \simeq \frac{2g_\ell^2}{1+2g_\ell^2}$$

  - $H \to \tau\tau, H \to ZA$

$$BR(H^\pm \to W^\pm A) = BR(H \to ZA) \simeq \frac{1}{1+2g_\ell^2}$$

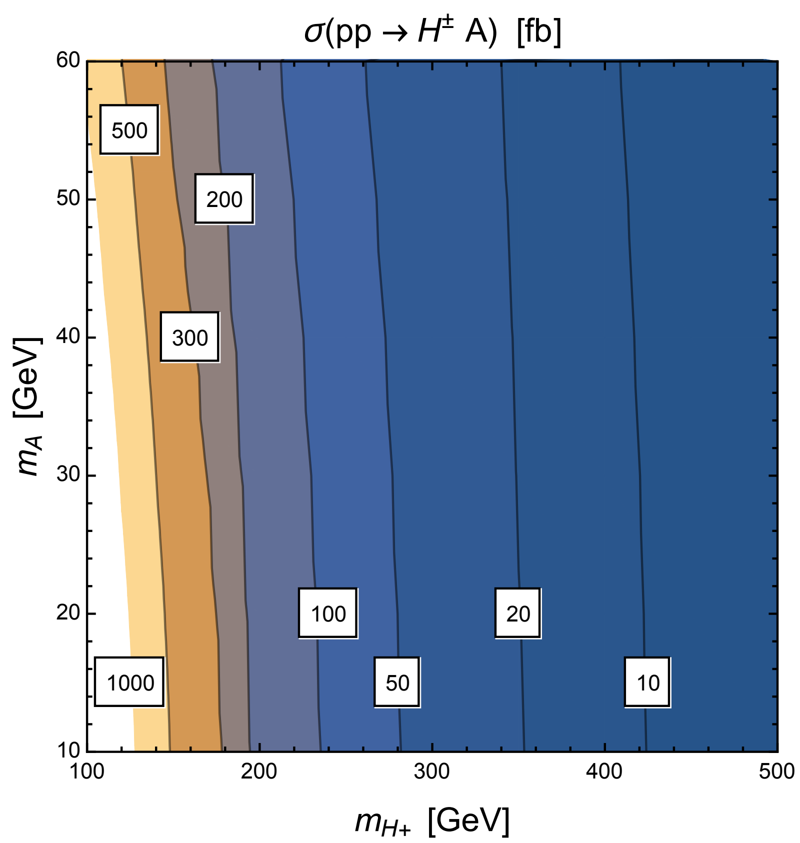
- the relevant production modes proceed through EW interactions (cross section depends only on the mass)

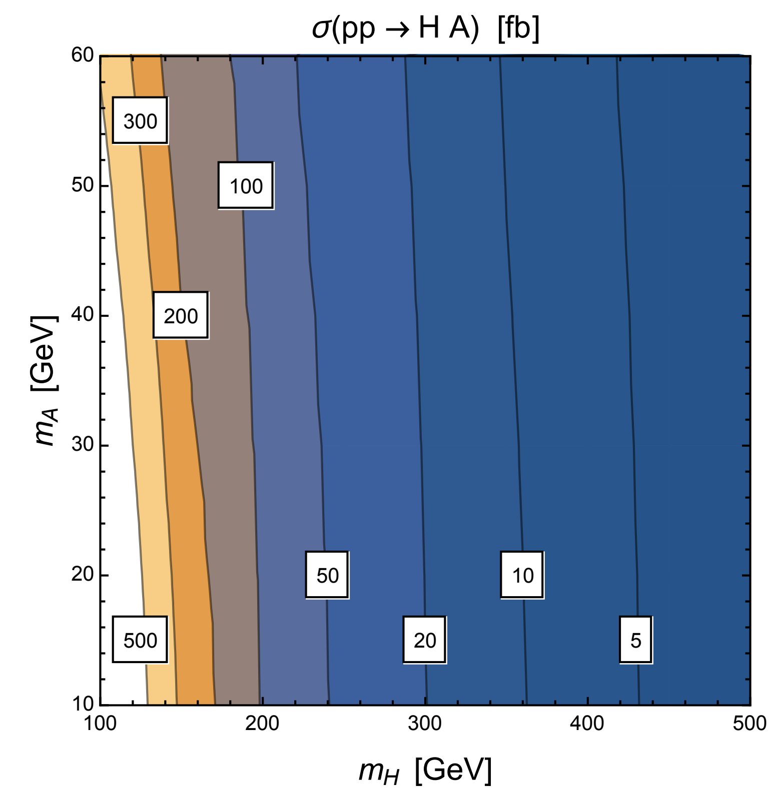
$$pp \to H^\pm A\,, \qquad pp \to H A\,, \qquad pp \to H^\pm H\,, \qquad pp \to H^+ H^-$$

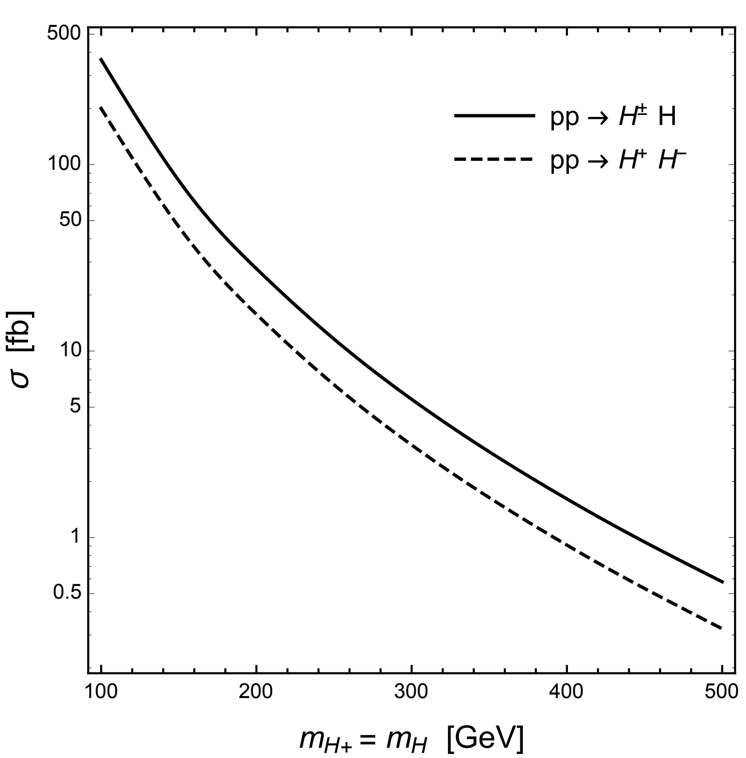
- the main signatures are

$$3\tau + \not{E}_T, \qquad 4\tau + W^\pm, \qquad 4\tau, \qquad 4\tau + Z,$$

Production cross section at LHC13TeV







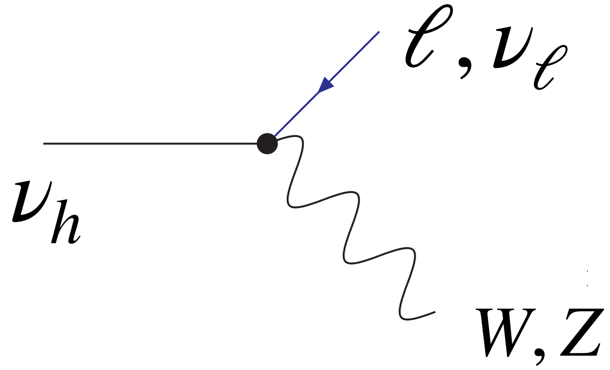
estimates of the inclusive cross sections for the relevant SM backgrounds

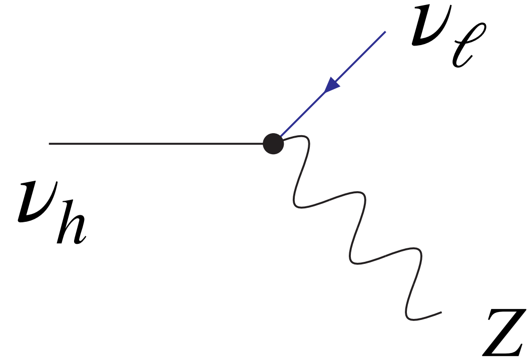
$$\sigma_{\rm SM}(ZW^{\pm} \to 3\tau + \not{E}_T) \simeq 94\,\text{fb},$$
$$\sigma_{\rm SM}(ZZ \to 4\tau) \simeq 11\,\text{fb},$$

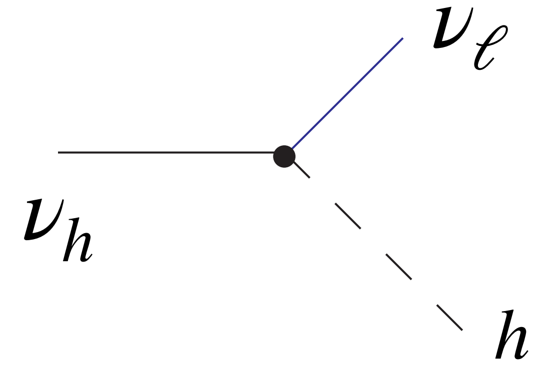
$$\sigma_{\rm SM}(ZZW^{\pm} \to 4\tau + W^{\pm}) \simeq 3.2\times 10^{-2}\,\text{fb},$$
$$\sigma_{\rm SM}(ZZZ \to 4\tau + Z) \simeq 1.1\times 10^{-2}\,\text{fb}\,.$$

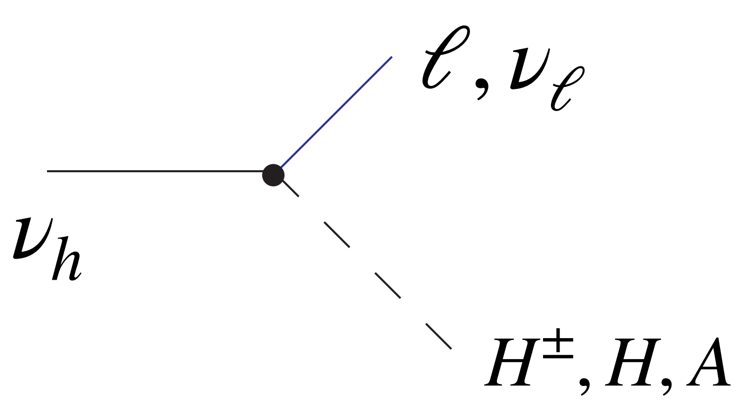
Future perspectives

- Global analysis of the model: relax constraints on $\zeta_{u,d}$
- Study of the $H^{\pm}, H, A$ / ν_R phenomenology









New production modes heavy neutrinos or charged Higgs at the LHC