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

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#### LHC HWG3 (BSM) — Extended Higgs Sector 07/07/2021

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### 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  $\frac{1}{2}$ *v* diag(*me, mµ, m*⌧ )*,* **R** *<sup>R</sup>* = *M<sup>R</sup>* ⌘ diag(*M*1*,...M<sup>n</sup><sup>R</sup>* )*,* (9)

p2

*Phe seesaw mechanism is the standard mechanism for neutrino masses* The seesaw mechanism is the standard mechanism for neutrino masses

$$
-\mathcal{L}_{\mathcal{M}_{\nu}} = \frac{1}{2} N_{L}^{T} C \mathcal{M} N_{L} + \text{h.c.} = \frac{1}{2} (\nu_{L}^{T} \nu_{R}^{c})^{T} C \begin{pmatrix} 0 & M_{D} \\ M_{D}^{T} & M_{R} \end{pmatrix} \begin{pmatrix} \nu_{L} \\ \nu_{R}^{c} \end{pmatrix}
$$

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

$$
\begin{pmatrix} \nu_{L} \\ \nu_{R} \end{pmatrix} = U \begin{pmatrix} \nu_{l} \\ \nu_{h} \end{pmatrix} \equiv \begin{pmatrix} U_{L1} & U_{Lh} \\ U_{R^{c}l} & U_{R^{c}h} \end{pmatrix} \begin{pmatrix} \nu_{l} \\ \nu_{h} \end{pmatrix}
$$

$$
M_{D} = \frac{v}{\sqrt{2}} Y_{\nu}^{*}
$$
  
source of flavour non-university

There are ceveral realications 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* There are several realisations, a class among the most interesting ones is the

## $\nu_R$  in flavour observables

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



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

box diagrams of the *<sup>b</sup>* ! *<sup>s</sup>*`+` transition. the strength of the interactions is fixed by the *gauge coupling* and charged Higgs (*H±*) currents are shown. *gauge coupling*

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

#### The  $2HDM + \nu_R$ III.  $\mathcal{L}$  II.  $\mathcal{L}$  $The 2HDM +  $\nu_{D}$$ level  $\mathbf{M}_{\mathrm{c}}$  , this problem is usually solved by enforcing that one of that one of the two Higgss  $\mathbf{M}_{\mathrm{c}}$ constrained and the resulting structures are functions of the mass matrices are functions of the mass matrices ◆ = *U* ✓ ⌫*<sup>l</sup>* ◆ ⌘ ✓ *ULl ULh*  ${\boldsymbol{\nu}}_{\mathbf{n}}$ ⌫*h*

form in the fermion mass eigenstate basis, namely, *<sup>Y</sup>*<sup>1</sup> <sup>=</sup> <sup>p</sup>2*/vM*, with *<sup>M</sup>* being the fermion

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

the aforementioned *H±A* signature in two separate subsections. We then conclude.

where the proportionality constants  $\overline{f}$  are arbitrary family universal complex parameters.  $\overline{f}$ 

*U*, via

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

ratentially dangerous tree-level FCNIC are avoided by a discrete Z<sub>2</sub> symmetry potentially dangerous tree ieven erve are avoided by a discrete z<sub>2</sub> symmetry<br>A new the 1,2 fields are the two Higgs are the two KAN 10 fields are the two Higgs (type- I, II, III, IV), or by requiring an alignment in flavour space (AZHDIYI) 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)  $\dot{\mathcal{C}}$ *H*<sup>+</sup> + h.c. 1 / / / / / 1 O

 $Y_{2,d} = \zeta_d Y_{1,d} \equiv \zeta_d Y_d$ ,  $Y_{2,u} = \zeta_u^* Y_{1,u} \equiv \zeta_u^* Y_u$ ,  $Y_{2,\ell} = \zeta_{\ell} Y_{1,\ell} \equiv \zeta_{\ell} Y_{\ell}$ , Besides implementing the standard *Z*<sup>2</sup> symmetry, potentially dangerous tree-level Flavour Changing Neutral Currents  $Y_{2,\nu} = \zeta_{\nu}^* Y_{1,\nu} \equiv \zeta_{\nu}^* Y_{\nu}$ same right-handed quark or lepton. This implies in the control of the control of the control of the control of  $\omega$ <sub>*f*</sub>  $\omega$  *f*,  $\omega$  *f*  $\omega$  *f*  $\omega$  $\frac{1}{\nu} Y_{\nu}$  $Y_{2,d} = \zeta_d Y_{1,d} \equiv \zeta_d Y_d$ , *v*  $Y_2 \ell = \zeta_\ell Y_1 \ell \equiv \zeta_\ell Y_\ell,$   $Y_2 \ell = \zeta_\ell Y_1 \ell \equiv \zeta_\ell Y_\ell,$  $v_1v_2 = v_1v_1v_2 + v_2v_3v_1v_2$ 



o currents in the lenton sector. e charged Higgs boson currents in the lepton sector: TABLE I: Relation between the ⇣*<sup>f</sup>* couplings of the A2HDM and the ones of the *Z*<sup>2</sup> symmetric  $\frac{1}{2}$ The charged Higgs boson currents in the lepton sector:

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

## $\nu_R$  +  $H^{\pm}$  in flavour observables

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

+

 $\overline{\phantom{a}}$ 



The coupling of the sterile neutrinos to leptons and the charged Higgs boson is given by  $\sim \zeta_{\nu}(m_{\nu}/\nu) U_{Lh}$ , with  $|U_{Lh}|^2 \lesssim 10^{-2} - 10^{-3}$  $\beta$ IVCITDY  $\sim \zeta_{\nu}(m_{\nu}/\nu) U_{Lh}$ , WILIT $|U_{Lh}| \ge 10$  -10 given by  $\sim \zeta_{\nu} (m_\nu/\nu) \, U_{Lh}$  , with  $\mid U_{Lh} \mid^2 \lesssim 10^{-5}$ 

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  $m_q m_{q^\prime}^2 /v^3$ Jung, Pich, Tuzon 2010 Li, Lu, Pich, 2014
- *• Alignment in the neutrino sector is not strictly required*
- new sources of CP violation in the  $\zeta_f$  coefficients (not considered here)
- *further extension:*  $\zeta_f \rightarrow \zeta_{f_i}$

Botella, Cornet-Gomez, Nebot 2020

#### Flavour non-universality 4(*<sup>x</sup>* 1)<sup>4</sup> *,* r non-l  $iniversalit$ Fiavour non-universally

*<sup>G</sup><sup>W</sup> <sup>±</sup>* (*x*) = *<sup>x</sup>* + 6*x*<sup>2</sup> <sup>3</sup>*x*<sup>3</sup> <sup>2</sup>*x*<sup>4</sup> + 6*x*<sup>3</sup> log *<sup>x</sup>*

Contributions to the R<sub>K</sub>\* from the charged-currents: if it were not for the rescaling induced by the neutrino mixing matrix. Nevertheless, the constant terms in *g*(*a*) and  $\frac{1}{2}$ Contributions to the R<sub>K</sub>\* from the charged-currents:

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

Contributions to the g-2 from the charged-currents: *<sup>g</sup>*(*b*) = 2<sup>X</sup> *n<sup>R</sup>*

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

 $\frac{1}{2}$  the contribution to  $\frac{1}{2}$  and  $\frac{1}{2}$  expressed (pseudo)scalars is the neutral (pseudo)scalars is in the neutral (pseudo)scalars is the neutral (pseudo)scalars is the neutral (pseudo)scalars is the neutral n channels have fixed:  $\sim$ electron and muon channels have fixed sign *g*(*d*) = 20 in the correction<br>*d*<br>alon *n<sup>R</sup>* <sup>2</sup> *<sup>G</sup><sup>H</sup><sup>±</sup>*  $\overline{2}$ ⌫*hi* In the pure Z<sub>2</sub> symmetric or in the aligned 2HDM, the corrections to both <sup>+</sup> *<sup>O</sup>*(*m*<sup>2</sup>

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

$$
\mathcal{G}_{W^{\pm}}(x) = \frac{-x + 6x^2 - 3x^3 - 2x^4 + 6x^3 \log x}{4(x - 1)^4},
$$

$$
\mathcal{G}_{H^{\pm}}(x) = \frac{\zeta_{\nu}^2}{3} \mathcal{G}_{W^{\pm}}(x) + \zeta_{\nu} \zeta_{l} \frac{x(-1 + x^2 - 2x \log x)}{2(x - 1)^3}
$$

*m*<sup>2</sup>

*f*

*m*<sup>2</sup>

## Lepton flavour violation

The hierarchy among elements of  $(U_{Lh})_{\alpha i}$  is experimentally required by lepton flavour violating (LFV) processes  $\ell_{\alpha} \rightarrow \ell_{\beta} \gamma$ been computed. New contributions have found to be important in some region of the parameter space. We have  $\frac{1}{2}$ 

flavour non-universal coefficient **g**(**b**) = 2x **c**) = 2

$$
BR(\ell_{\alpha} \to \ell_{\beta} \gamma) = C \left| \sum_{i=1}^{n_R} (U_{Lh}^*)_{\alpha i} (U_{Lh})_{\beta i} \left[ \mathcal{G}_{W^{\pm}} \left( \frac{m_{\nu_{h_i}}^2}{M_W^2} \right) + \mathcal{G}_{H^{\pm}} \left( \frac{m_{\nu_{h_i}}^2}{M_H^2} \right) \right] \right|^2
$$
lenton flavour universal

leptc form factor **that is a set of the s** lepton flavour universal versa  $\overline{)}$ ,  $\overline{$ 

Constraints at 90% CL:

 $BR(\mu \to e \gamma) \leq 4.2 \times 10^{-13}$ ,  $BR(\tau \to \mu \gamma) \leq 4.4 \times 10^{-8}$  9W<sup>±(*L*)</sup> –

$$
BR(\tau \to e \gamma) \le 3.3 \times 10^{-8},
$$
  
\n
$$
BR(\tau \to \mu \gamma) \le 4.4 \times 10^{-8},
$$
  
\n
$$
G_{W^{\pm}}(x) = \frac{-x + 6x^2 - 3x^3 - 2x^4 + 6x^3 \log x}{4(x - 1)^4},
$$
  
\n
$$
G_{H^{\pm}}(x) = \frac{\zeta_{\nu}^2}{3} G_{W^{\pm}}(x) + \zeta_{\nu} \zeta_{l} \frac{x(-1 + x^2 - 2x \log x)}{2(x - 1)^3}
$$

### 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  $\zeta_e^2 m_{\tau} m_{\mu}^2 / m_{H^{\pm}}^2$
- bounds from LFV processes  $(\ell_{\alpha} \to \ell_{\beta} \gamma)$
- flavour constraints (mainly neutral meson mixings, neutral and charged  $m$ eson decays to leptons,  $b \rightarrow s\gamma$ ) mostly depend on  $m_{H^{\pm}}, \zeta_u, \zeta_d$ *easily satisfied if*  $\zeta_u, \zeta_d$  *are taken to be small, similarly to the leptophilic type-IV*
- **→** we require  $m_{\nu_h} > m_{H^{\pm}}$
- $\bullet$  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*,*<sup>μ</sup>*

#### Light-scalar phenomenology FIG. 4. The LHC production cross sections of pairs of the extra Higgs bosons as functions of *m<sup>A</sup>* and *m<sup>H</sup><sup>±</sup>* = *mH*. FIG. 4. The LHC production cross sections of pairs of the extra Higgs bosons as functions of *m<sup>A</sup>* and *m<sup>H</sup><sup>±</sup>* = *mH*.

Within the parameter space defined above (light scalars) In the leptophilic scenario delineated above, the light pseudoscalar state *A* can decay at tree-level via *A* ! ⌧ ⌧ with

- the relevant decay modes for the BSM scalars are  $g_{\ell} = \zeta_{\ell} m_{\tau} / m_{H^{\pm}}$  $\mathcal{O}_{\ell}$   $\mathcal{O}_{\ell}$   $\mathcal{O}_{\ell}$   $\mathcal{O}_{\ell}$   $\mathcal{O}_{\ell}$   $\mathcal{O}_{\ell}$   $\mathcal{O}_{\ell}$   $\mathcal{O}_{\ell}$ interaction is completely fixed by the *SU*(2)*<sup>L</sup>* gauge coupling, and *H<sup>±</sup>* ! ⌧ *<sup>±</sup>*⌫, which is controlled by the ⇣` coupling.
	- $g_e = \zeta_e m_\tau / m_{H^\pm}$
- $A \rightarrow \tau\tau$ *BR(A*  $\rightarrow \tau \tau$ )  $\simeq 100\%$  $\bullet$   $A \to \tau \tau$   $BR(A \to \tau \tau) \simeq 100\%$  $H_{\text{A}}(A \times \nu) = 100 \text{ N}$  $A \rightarrow \tau \tau$  and  $A \rightarrow \tau \tau$  $\mathcal{B}R(A \to \tau\tau) \simeq 100\%$
- $H^{\pm} \rightarrow \tau^{\pm} \nu$ ,  $H^{\pm} \rightarrow W^{\pm} A$ 1  $BR(H^{\pm} \to \tau^{\pm} \nu) = BR(H \to \tau \tau) \simeq$  $2g^2_{\ell}$  $1 + 2g^2$ **n**  $H^{\pm} \rightarrow \tau^{\pm}$  is  $H^{\pm} \rightarrow W^{\pm}$   $A$  and  $\rho_{D}(H^{\pm} \rightarrow \tau^{\pm})$  and  $\rho_{\ell}^{2}$  and  $2g_{\ell}^{2}$ BR(*H<sup>±</sup>* ! *AW±*) = BR(*<sup>H</sup>* ! *AZ*) = <sup>1</sup>  $\mathcal{B}(\Pi \to \nu) - \mathcal{B}(\Pi \to \nu) = \frac{1}{1 + 2g_{\ell}^2}$ 
	- $\bullet$   $H \rightarrow \tau \tau$ ,  $H \rightarrow ZA$  $BR(H^{\pm} \rightarrow W^{\pm}A) = BR(H \rightarrow ZA) \simeq$  $BR(H^{\pm} \to W^{\pm}A) = BR(H \to ZA) \simeq \frac{1}{1 + 2g_{\ell}^2}$  $1 + 2g_{\ell}^2$
- the relevant production modes proceed through EW interactions (cross section depends only on the mass)  $\mathbf{r}$  relevant processes are the relevant processes are

$$
pp \to H^{\pm}A
$$
,  $pp \to HA$ ,  $pp \to H^{\pm}H$ ,  $pp \to H^+H^-$ 

with the corresponding cross sections being only functions of the masses of the corresponding particles. The cross • the main signatures are

The main signature resulting from the main signature  $\tilde{r}$  are characterised by final states with several states with several  $\tilde{r}$  $3\tau + \not{\!\! E}_T,$   $4\tau + W^{\pm},$   $4\tau,$   $4\tau + Z,$ 

#### Production cross section at LHC13TeV Analogously, for the heavy neutral scalar state *H* the two leading decay modes are *H* ! ⌧ ⌧ and *H* ! *AZ*. For large **Frouuction cross section at LHCTS TEV**

B. LHC phenomenology of the extra (pseudo)scalar bosons







interaction is completely fixed by the *SU*(2)*<sup>L</sup>* gauge coupling, and *H<sup>±</sup>* ! ⌧ *<sup>±</sup>*⌫, which is controlled by the ⇣` coupling.

estimates of the *inclusive cross sections* for the relevant SM backgrounds estimates of the inclusive cross sections for the

$$
\begin{array}{c}\n\overline{e} \stackrel{\cdot}{\underset{\sim}{\circ}} \\
\hline\n\end{array}\n\qquad \qquad \sigma_{\rm SM}(ZW^{\pm} \to 3\tau + \rlap{\,/}E_T) \simeq 94 \, \text{fb},
$$
\n
$$
\sigma_{\rm SM}(ZZ \to 4\tau) \simeq 11 \, \text{fb},
$$

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

# Future perspectives >>= >>< When  $\mathcal{M} = \mathcal{M} \cup \mathcal{M}$ **PECTIVES**

ee<sup>+</sup>

*,* ep : *Y* `*<sup>±</sup>*

*jj, Y* `*<sup>±</sup>*

 `⌥ u

- Global analysis of the model: relax constraints on *ζu*,*<sup>d</sup>*  $\sum$  :  $\overline{X}$   $\overline{$
- Study of the  $H^{\pm}$ ,  $H$ ,  $A$  /  $\nu_R$  phenomenology  $H A / \nu_{\rm e}$ , phe >>< pp : `↵⌫*jj,* `↵⌫`*<sup>±</sup>*

✓

>>=

