Scalars 2023

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Lepton flavor specific extended Higgs model

Based on 10.1103/PhysRevD.107.095001 [arXiv:2301.08641 [hep-ph]]

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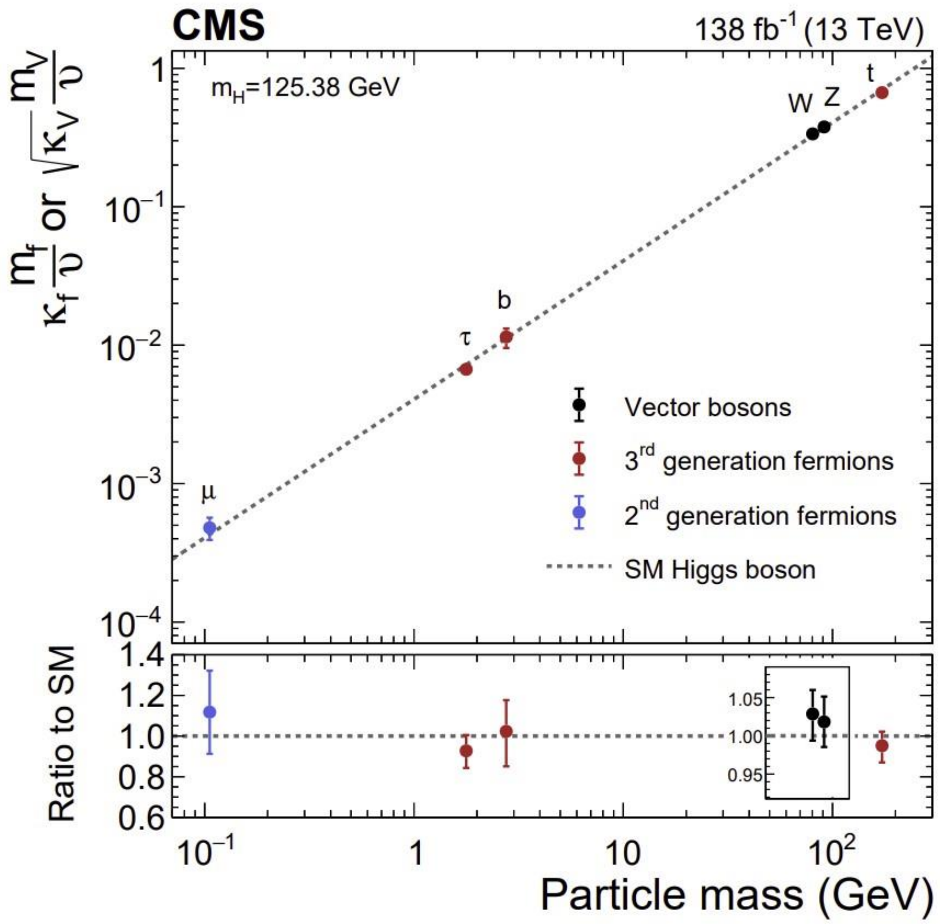
Outline

- Motivation
- The model (scalar sector, couplings, theoretical constraints)
- Benchmarks models
  - The model without $(q\tau)$-(μe) mixing
  - The aligned model (constraints and signatures)
- Final remarks

Motivation



Taken from *A portrait of the Higgs boson by the CMS experiment ten years after the discovery*, Nature 607 (2022) 60

Muon-specific 2HDM (Abe, Sato, and Yagyu):

- The muon and the remaning fields couple to different Higgs doublets
- A Z_4 symmetry makes the model free of tree-level FCNC and restricts the structure of Yukawa couplings
- Muon interactions of scalars can be substantially enhanced or supressed relative to those with tau leptons

Can the three leptonic generations couple to different *Higgses*?

Extending the muon-specific 2HDM

Our idea: each of the charged leptons couples to a different Higgs doublet

$$\Phi_e + \Phi_\mu + \Phi_\tau$$

Symmetry $(Z_4)_e \times (Z_4)_\mu \times (Z_4)_\tau$: no tree-level FCNC and diagonal Yukawa matrix

	L_ℓ	ℓ_R	Φ_ℓ	Other fields
$(Z_4)_\ell$	i	i	-1	1

Simplest implementation: 4HDM in which the fourth Higgs couples to quarks Φ_q

$\boxed{\text{Lepton Flavor Specific Extended Higgs Model}}$

The model: scalar sector

Fixing notation…

Scalar potential: $V = V_2 + V_4$

$$V_2 = m_{qq}^2 \Phi_q^\dagger \Phi_q + \ \dots$$
$$+ [m_{qe}^2 (\Phi_q^\dagger \Phi_e) + \ \dots$$
$$+ \mathrm{H.c.}]$$

$$V_4 = \lambda_1^q (\Phi_q^\dagger \Phi_q)^2 + \ \dots$$
$$+ \lambda_3^{qe} (\Phi_q^\dagger \Phi_q)(\Phi_e^\dagger \Phi_e) + \ \dots$$
$$+ \lambda_4^{qe} (\Phi_q^\dagger \Phi_e)(\Phi_e^\dagger \Phi_q) + \ \dots$$
$$+ \frac{1}{2} [\lambda_5^{qe} (\Phi_q^\dagger \Phi_e)^2 + \ \dots \ + \mathrm{H.c.}]$$

The model: scalar sector

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$$V_4 = \lambda_1^q (\Phi_q^\dagger \Phi_q)^2 + \ ...$$
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$$+ \frac{1}{2}[\lambda_5^{qe} (\Phi_q^\dagger \Phi_e)^2 + \ ... \ + \mathrm{H.c.}]$$

The model: scalar sector

Fixing notation…

Higgs doublets:

$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ (v_i + \phi_i + i\chi_i)/\sqrt{2} \end{pmatrix}, \quad (i = q, e, \mu, \tau)$$

$$\begin{aligned} v_q &= v \cos\beta_2 \cos\beta_3 \cos\beta_4 \\ v_e &= v \sin\beta_2 \cos\beta_3 \cos\beta_4 \\ v_\mu &= v \sin\beta_3 \cos\beta_4 \\ v_\tau &= v \sin\beta_4 \end{aligned}$$

Rotation to the Higgs basis

$$\begin{pmatrix} h_0 \\ H_1 \\ H_2 \\ H_3 \end{pmatrix} = \mathcal{O}_\beta \begin{pmatrix} \phi_q \\ \phi_e \\ \phi_\mu \\ \phi_\tau \end{pmatrix}$$

$$\mathcal{O}_\beta = \begin{pmatrix} c_{\beta_2} c_{\beta_3} c_{\beta_4} & s_{\beta_2} c_{\beta_3} c_{\beta_4} & s_{\beta_3} c_{\beta_4} & s_{\beta_4} \\ -s_{\beta_2} & c_{\beta_2} & 0 & 0 \\ -c_{\beta_2} c_{\beta_3} & -s_{\beta_2} s_{\beta_3} & c_{\beta_3} & 0 \\ -c_{\beta_2} c_{\beta_3} s_{\beta_4} & -s_{\beta_2} c_{\beta_3} s_{\beta_4} & -s_{\beta_3} s_{\beta_4} & c_{\beta_4} \end{pmatrix}$$

The model: scalar sector

Fixing notation…

Rotations to the mass basis:

SCALAR SECTOR

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \\ h_4 \end{pmatrix} = \mathcal{O}_\alpha \begin{pmatrix} \phi_q \\ \phi_e \\ \phi_\mu \\ \phi_\tau \end{pmatrix}$$

$$\mathcal{O}_\alpha = \mathbf{R}_{34}\mathbf{R}_{24}\mathbf{R}_{23}\mathbf{R}_{14}\mathbf{R}_{13}\mathbf{R}_{12}$$

$$\mathbf{R}_{24} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & c_{\alpha_{24}} & 0 & s_{\alpha_{24}} \\ 0 & 0 & 1 & 0 \\ 0 & -s_{\alpha_{24}} & 0 & c_{\alpha_{24}} \end{pmatrix}$$

The model: scalar sector

Fixing notation…

Rotations to the mass basis:

PSEUDOSCALAR SECTOR

$$\begin{pmatrix} G^0 \\ A_1 \\ A_2 \\ A_3 \end{pmatrix} = \mathcal{O}_\gamma \mathcal{O}_\beta \begin{pmatrix} \chi_q \\ \chi_e \\ \chi_\mu \\ \chi_\tau \end{pmatrix}$$

$$\mathcal{O}_\gamma = \mathbf{P}_{34}\mathbf{P}_{24}\mathbf{P}_{23}$$

$$\mathbf{P}_{24} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & c_{\gamma_{24}} & 0 & s_{\gamma_{24}} \\ 0 & 0 & 1 & 0 \\ 0 & -s_{\gamma_{24}} & 0 & c_{\gamma_{24}} \end{pmatrix}$$

The model: scalar sector

Fixing notation…

Rotations to the mass basis:

CHARGED SECTOR

$$\begin{pmatrix} G^+ \\ H_1^+ \\ H_2^+ \\ H_3^+ \end{pmatrix} = \mathcal{O}_\delta \mathcal{O}_\beta \begin{pmatrix} \phi_q^+ \\ \phi_e^+ \\ \phi_\mu^+ \\ \phi_\tau^+ \end{pmatrix}$$

$$\mathcal{O}_\delta = \mathbf{Q}_{34}\mathbf{Q}_{24}\mathbf{Q}_{23}$$

$$\mathbf{Q}_{24} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & c_{\delta_{24}} & 0 & s_{\delta_{24}} \\ 0 & 0 & 1 & 0 \\ 0 & -s_{\delta_{24}} & 0 & c_{\delta_{24}} \end{pmatrix}$$

The model: gauge couplings

$$\mathcal{L}_{\mathrm{k}} = \sum_{i=1}^{4} |D_\mu \Phi_i|^2 \longrightarrow \left(\sum_{i=1}^{4} C_i h_i\right)\left(\frac{g}{2c_W} m_Z Z_\mu Z^\mu + g m_W W_\mu^- W^{+\mu}\right)$$

$$\boxed{\alpha_{1j} = \beta_j} \longrightarrow \begin{array}{l} C_1 = 1 \\ C_k = 0 \ , \ k \neq 1 \end{array}$$

$j = 2, 3, 4$

Alignment limit

The model: Yukawa couplings

$$\mathcal{L}_Y^S = -\sum_{f\in\{q,e,\mu,\tau\}} \frac{m_f}{v}\left(\xi^f_{h_1}\bar{f}fh_1 + \xi^f_{h_2}\bar{f}fh_2 + \xi^f_{h_3}\bar{f}fh_3 + \xi^f_{h_4}\bar{f}fh_4\right)$$

$$\mathcal{L}_Y^P = -\sum_{f\in\{q,e,\mu,\tau\}} \left(-i\frac{m_f}{v}\right)\left(\xi^f_{A_1}\bar{f}\gamma_5 fA_1 + \xi^f_{A_2}\bar{f}\gamma_5 fA_2 + \xi^f_{A_3}\bar{f}\gamma_5 fA_3\right)$$

$$\xi^q_{h_j} = \frac{\mathcal{O}_{\alpha j,1}}{\hat{v}_1}, \qquad \ldots$$

$$\xi^q_{A_j} = \frac{(\mathcal{O}_\gamma \mathcal{O}_\beta)_{j,1}}{\hat{v}_1}, \qquad \ldots$$

$$\hat{v}_i \equiv v_i/v$$

The model: Yukawa couplings

$$\mathcal{L}_Y^S = -\sum_{f\in\{q,e,\mu,\tau\}} \frac{m_f}{v}\left(\xi_{h_1}^f \bar{f} f h_1 + \xi_{h_2}^f \bar{f} f h_2 + \xi_{h_3}^f \bar{f} f h_3 + \xi_{h_4}^f \bar{f} f h_4\right)$$

$$\mathcal{L}_Y^P = -\sum_{f\in\{q,e,\mu,\tau\}} \left(-i\frac{m_f}{v}\right)\left(\xi_{A_1}^f \bar{f}\gamma_5 f A_1 + \xi_{A_2}^f \bar{f}\gamma_5 f A_2 + \xi_{A_3}^f \bar{f}\gamma_5 f A_3\right)$$

$$\xi_{h_j}^{q} = \frac{\mathcal{O}_{\alpha j,1}}{\hat{v}_1}, \qquad \ldots$$

$$\xi_{A_j}^{q} = \frac{(\mathcal{O}_\gamma \mathcal{O}_\beta)_{j,1}}{\hat{v}_1}, \qquad \ldots$$

$$\hat{v}_i \equiv v_i / v$$

The model: Yukawa couplings

$$\mathcal{L}_Y^C = -\sum_j \left[\sum_{u,d} \frac{\sqrt{2}V_{ud}}{v} \bar{u}(m_u \xi^{qL}_{H_j^+} \mathrm{P}_L + m_d \xi^{qR}_{H_j^+} \mathrm{P}_R) d H_j^+ + \sum_l \frac{\sqrt{2}m_l}{v} \xi^{lL}_{H_j^+} \bar{\nu}_L l_R H_j^+ \right] + \mathrm{H.c.}$$

$$\xi^{qLR}_{H_j^+} = \frac{(\mathcal{O}_\delta \mathcal{O}_\beta)_{j,1}}{\hat{v}_1}, \qquad \ldots$$

$$\hat{v}_i \equiv v_i / v$$

The model: Yukawa couplings

$$\mathcal{L}_Y^C = -\sum_j \left[\sum_{u,d} \frac{\sqrt{2}V_{ud}}{v} \bar{u}(m_u \xi^{qL}_{H_j^+} \mathrm{P}_L + m_d \xi^{qR}_{H_j^+} \mathrm{P}_R) d H_j^+ + \sum_l \frac{\sqrt{2}m_l}{v} \xi^{lL}_{H_j^+} \bar{\nu}_L l_R H_j^+ \right] + \mathrm{H.c.}$$

$$\xi^{qLR}_{H_j^+} = \frac{(\mathcal{O}_\delta \mathcal{O}_\beta)_{j,1}}{\hat{v}_1}, \qquad \ldots$$

$$\hat{v}_i \equiv v_i / v$$

General Yukawa couplings too cumbersome to be shown here

The model: theoretical constraints

- Boundedness from below criteria

4. CRITERIA FOR COPOSITIVE MATRICES OF ORDER FOUR

For all neutral directions

Let A be a matrix of the form

$$A = \begin{pmatrix} a_1 & a_{12} & a_{13} & a_{14} \\ a_{12} & a_2 & a_{23} & a_{24} \\ a_{13} & a_{23} & a_3 & a_{34} \\ a_{14} & a_{24} & a_{34} & a_4 \end{pmatrix}. \qquad (4.1)$$

According to the signs of the off-diagonal elements of A, we consider eight different cases. Six of these cases are contained in the following theorem.

From Li Ping and Feng Yu Yu, *Criteria for copositive matrices of order four*, Linear Algebra and its Applications, Volume 194 (1993), doi.org/10.1016/0024-3795(93)90116-6.

The model: theoretical constraints

- Boundedness from below criteria
- Oblique parameters - arXiv:0802.4353 [hep-ph]
- Quartic couplings less than 4π

Benchmark models

- The model without $(q\tau)$-(μe) mixing
- The aligned model

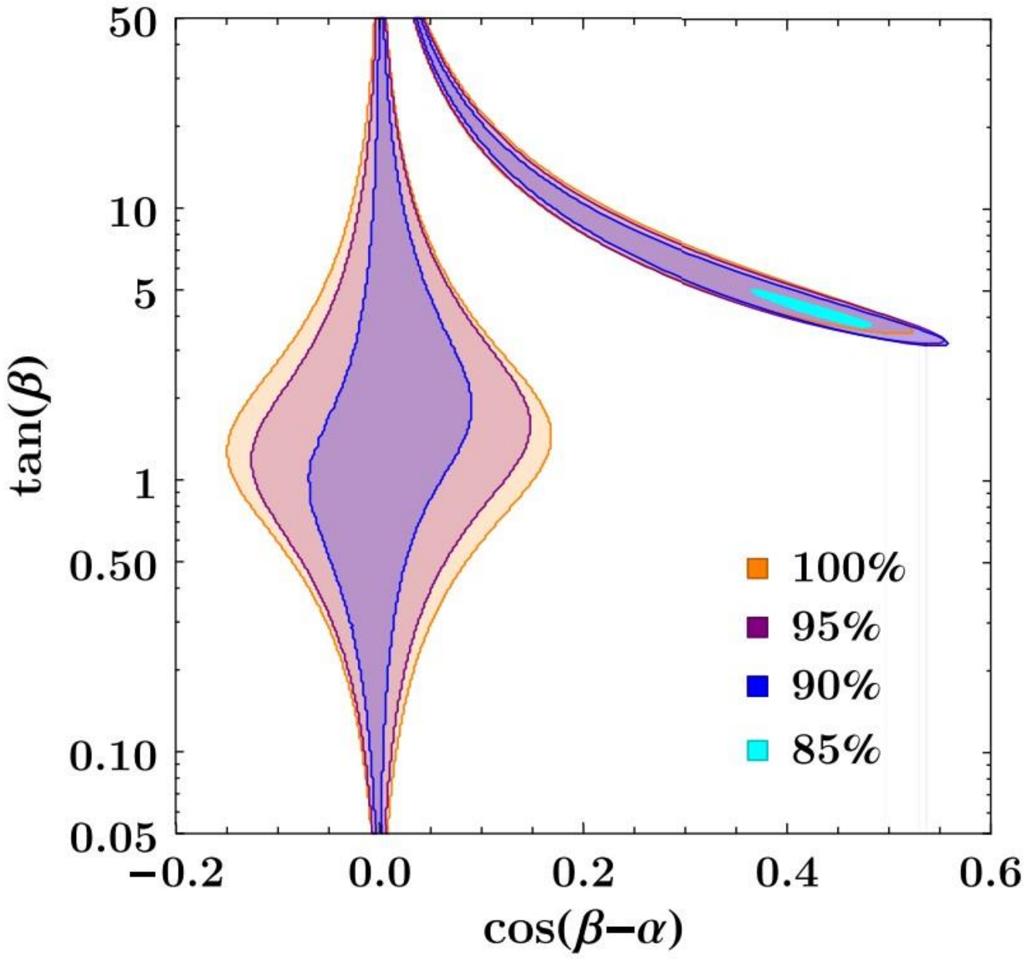
The model without ($q\tau$)-(μe) mixing

4 × 4 is broken into two **2 × 2**

Upper **2 × 2** very similar to lepton-specific 2HDM

$$\mu_X \equiv \frac{\sigma(pp \to H)\mathrm{BR}(H \to X)}{\sigma(pp \to H)_{\mathrm{SM}}\mathrm{BR}(H \to X)_{\mathrm{SM}}}$$

$$X = gg, \mu\mu, \tau\tau, \bar{c}c, \bar{b}b, \bar{t}t, \gamma\gamma, \gamma Z, WW, ZZ$$

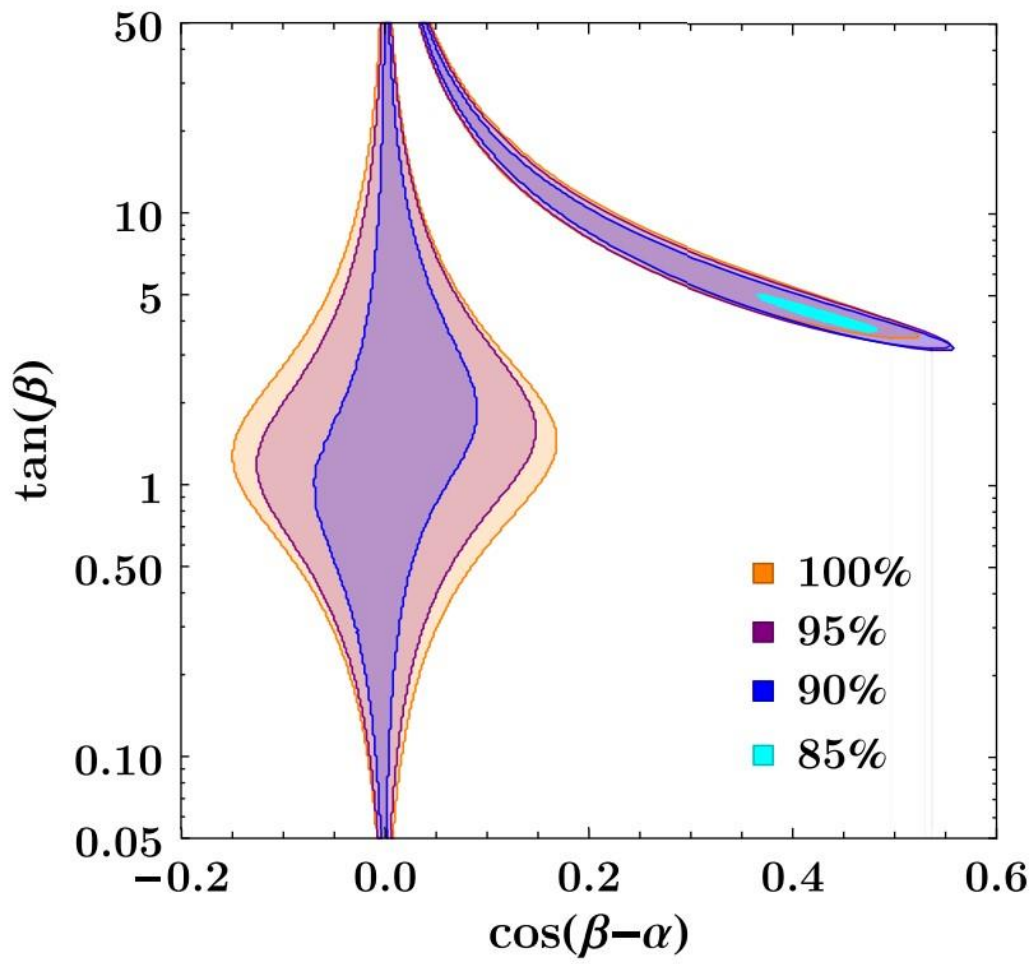


Allowed regions for different values of $(v_q^2 + v_\tau^2)^{1/2}/v$.

The model without $(q\tau)$-(μe) mixing

Much of the VEV is saturated by v_q and v_τ

Phenomenologically unacceptable (additional massless scalars, the coupling to the muon vanishes)



Allowed regions for different values of $(v_q^2 + v_\tau^2)^{1/2}/v$.

The aligned model

$$\boxed{\alpha_{1j} = \beta_j}$$

The aligned model

$$\lambda_1^i = \frac{1}{2v_i^3}\left(v_i M_{s,ii}^2 + \sum_{j\neq i} v_j m_{ij}^2\right)$$

$$\lambda_3^{ij} = \frac{1}{v_i v_j}(M_{s,ij}^2 - 2M_{c,ij}^2 + m_{ij}^2)$$

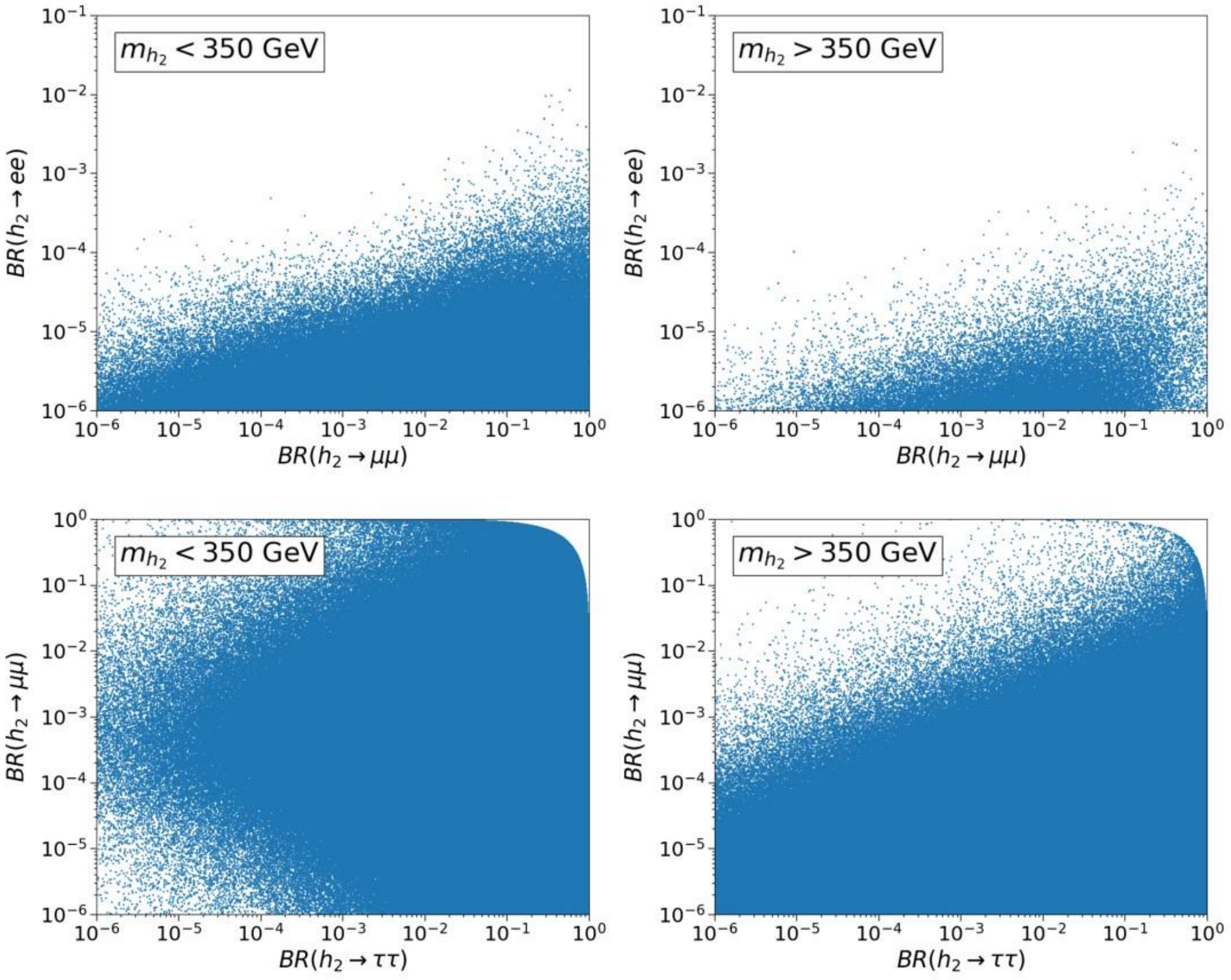
$$\lambda_4^{ij} = \frac{1}{v_i v_j}(2M_{c,ij}^2 - M_{p,ij}^2 - m_{ij}^2)$$

$$\lambda_5^{ij} = \frac{1}{v_i v_j}(M_{p,ij}^2 - m_{ij}^2)$$

The aligned model

- Bounded-from-below conditions
- Oblique parameters
- Quartic couplings and Yukawa couplings less than 4π
- Charged Higgs masses must exceed 80 GeV
- Higgs diphoton decay
- B and K meson oscillations
- $\boldsymbol{b \to s\gamma}$ constraints
- Searches for heavy neutral and charged Higgs bosons at the LHC

The aligned model

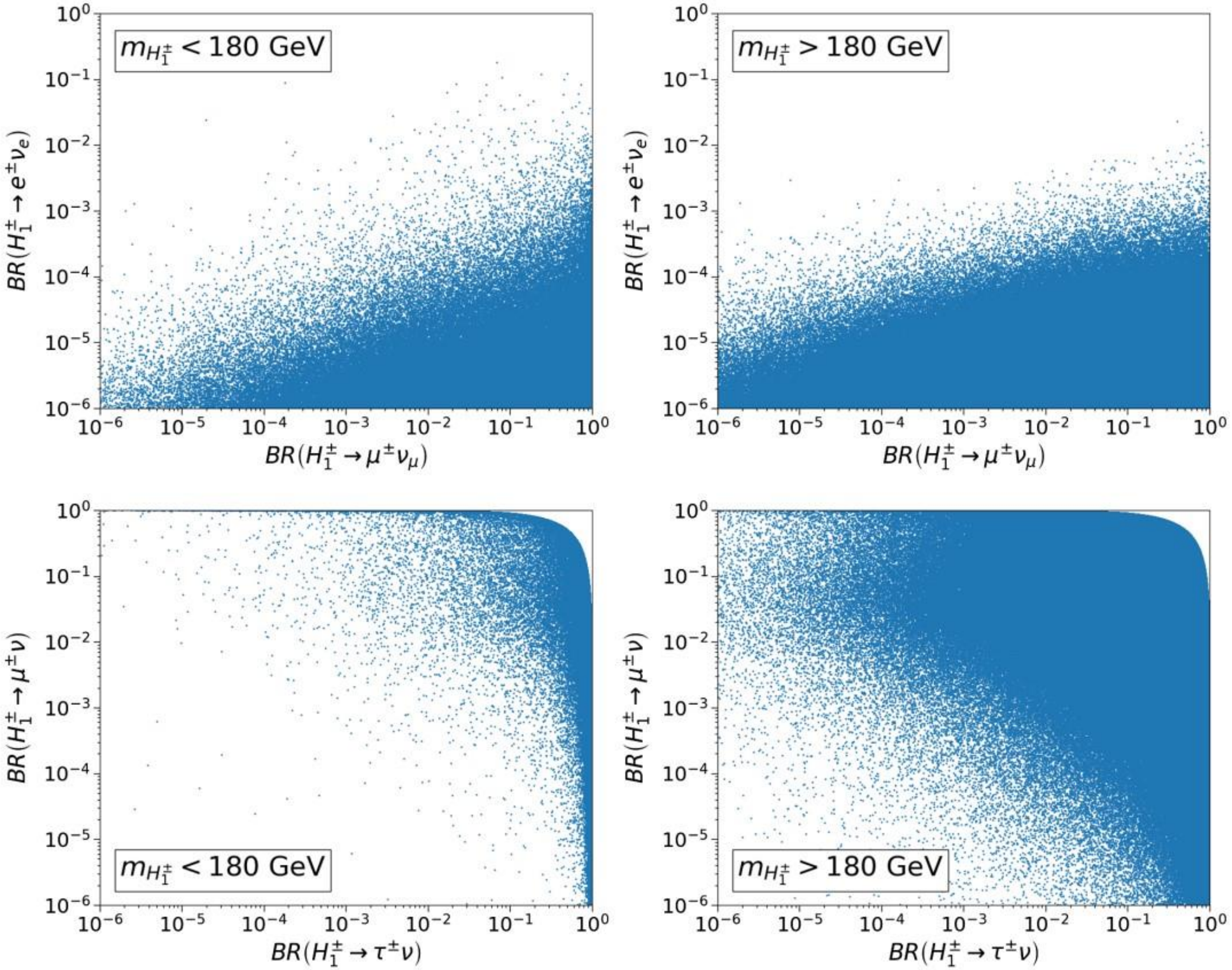


Masses > 350 GeV:

Opening of the top decay channel

Searches for heavy neutral Higgs bosons decaying into leptons, which generally focus on tauonic decays, should also study <u>muonic and electronic decays</u>

The aligned model



Masses > 180 GeV:

Opening of the top-bottom decay channel

There are more points in the region above 180 GeV since below that mass a much higher proportion of points are experimentally excluded

Concluding remarks

- We have studied a **4HDM** in which one scalar doublet couples to quarks and the other three couple to the electron, muon and tau families, respectively
- Dielectron and dimuon decays of the extra lightest neutral scalar can be much larger than expected
- An interesting signature arises from vector boson fusion into two Higgs bosons, each of which decays into an electron or muon pair

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- We have studied a **4HDM** in which one scalar doublet couples to quarks and the other three couple to the electron, muon and tau families, respectively
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POCH

Backup slides

Scalar benchmark points	S1	S2
$\beta_2/\pi, \beta_3/\pi, \beta_4/\pi$	0.05,0.16,0.18	0.04,0.14,0.21
$\alpha_{23}/\pi, \alpha_{24}/\pi, \alpha_{34}/\pi$	−0.09, −1.00, −0.70	−0.02, −0.05, 0.10
$\gamma_{23}/\pi, \gamma_{24}/\pi, \gamma_{34}/\pi$	0.50, 0.59, 0.80	0.16, 0.52, 0.39
$\delta_{23}/\pi, \delta_{24}/\pi, \delta_{34}/\pi$	0.08, −0.26, −0.96	0.62, −0.93, −0.95
$m_{h_2}, m_{h_3}, m_{h_4}$ (GeV)	269, 396, 483	175, 359, 360
$m_{A_1}, m_{A_2}, m_{A_3}$ (GeV)	439, 454, 484	265, 351, 369
$m_{H_1^\pm}, m_{H_2^\pm}, m_{H_3^\pm}$ (GeV)	438, 441, 443	289, 352, 370
$m^2_{qe}, m^2_{q\mu}, m^2_{q\tau}$ (GeV^2)	−17700, 71700, −340000	16000, −34600, −168000
$m^2_{e\mu}, m^2_{e\tau}, m^2_{\mu\tau}$ (GeV^2)	−18600, 20700, −53600	14000, −31200, −57400
BR$(h_2 \to ee)$	2.72×10^{-3}	1.63×10^{-4}
BR$(h_2 \to \mu\mu)$	4.68×10^{-1}	7.85×10^{-6}
BR$(h_2 \to \tau\tau)$	1.22×10^{-1}	7.42×10^{-1}

Backup slides

Charged benchmark points	C1	C2
$\beta_2/\pi, \beta_3/\pi, \beta_4/\pi$	0.05, 0.05, 0.09	0.10, 0.16, 0.11
$\alpha_{23}/\pi, \alpha_{24}/\pi, \alpha_{34}/\pi$	0.09, 0.54, 0.34	0.20, 0.88, 0.72
$\gamma_{23}/\pi, \gamma_{24}/\pi, \gamma_{34}/\pi$	−0.04, 0.66, 0.60	0.68, 0.50, −0.52
$\delta_{23}/\pi, \delta_{24}/\pi, \delta_{34}/\pi$	−0.98, 0.00, −0.36	1.00, 0.00, 0.77
$m_{h_2}, m_{h_3}, m_{h_4}$ (GeV)	127, 187, 208	180, 237, 240
$m_{A_1}, m_{A_2}, m_{A_3}$ (GeV)	131, 179, 244	161, 172, 173
$m_{H_1^\pm}, m_{H_2^\pm}, m_{H_3^\pm}$ (GeV)	164, 172, 229	158, 181, 234
$m^2_{qe}, m^2_{q\mu}, m^2_{q\tau}$ (GeV^2)	−14800, −17400, 6210	57000, −127000, −15100
$m^2_{e\mu}, m^2_{e\tau}, m^2_{\mu\tau}$ (GeV^2)	5880, 22100, 9060	−75600, −9570, 81300
$\mathrm{BR}(H_1^\pm \to e^\pm \nu_e)$	2.24×10^{-3}	1.68×10^{-2}
$\mathrm{BR}(H_1^\pm \to \mu^\pm \nu_\mu)$	5.36×10^{-1}	6.91×10^{-3}
$\mathrm{BR}(H_1^\pm \to \tau^\pm \nu_\tau)$	4.55×10^{-1}	5.23×10^{-1}