Phenomenology of flavoured 3HDMs

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Outline

The Standard Model is a tremendously successful theory that explains “boringly” well the existing collider measurements

However, it fails to explain:

- neutrino masses
- Dark Matter
- CPV and matter/antimatter asymmetry
- observed flavour structure

What simplest extensions of the SM can teach us about these problems?

Non-minimal Higgs sectors can provide natural explanation to CPV and fermion puzzles, and more..

Active model-building activity with non-minimal scalar sectors (see e.g. Ivanov, 1702.03776)

U(1) x U(1) Three Higgs doublet model

- **The most constraining realisable Abelian symmetry of 3HDM**
  Keus, King, Moretti 2014; Ivanov, Keus, Vdovin, 2012

- **Promote this symmetry to be a family symmetry of the fermion sector**
  Camargo-Molina, Mandal, Pasechnik, Wessén, JHEP 03 (2018) 024

softly broken

$\mathrm{U}(1)_{\mathrm{X}} \times \mathrm{U}(1)_{\mathrm{Z}}$

- No tree-level FCNCs
- Cabbibo-like mixing at tree-level
- Fermion mass hierarchies are partly explained by hierarchy of VEVs
- New scalar states couple dominantly to the second quark family (exotic collider signatures)

$$V_0 = -\sum_{i=1}^{3} \mu_i^2 |H_i|^2 + \sum_{i,j=1}^{3} \left(\frac{\lambda_{ij}}{2} |H_i|^2 |H_j|^2 + \frac{\lambda'_{ij}}{2} |H_i^\dagger H_j|^2 \right) , \quad V_{\mathrm{soft}} = \sum_{i=1}^{3} \frac{1}{2} (m_{ij}^2 H_i^\dagger H_j + \mathrm{c.c})$$

<u>All the parameters can be taken real</u>

$$\lambda_{ij} = \lambda_{ji} \,, \quad \lambda'_{ij} = \lambda'_{ji} \,, \quad m_{ij}^2 = m_{ji}^2 \,,$$

$$\lambda'_{11} = \lambda'_{22} = \lambda'_{33} = 0 \,, \quad m_{11}^2 = m_{22}^2 = m_{33}^2 = 0 \,.$$

The model is CP-conserving

Yukawa sector

$$\mathcal{L}^{\rm q}_{\rm Yukawa} = \sum_{i,j=1}^{2} \left\{ y^{\rm d}_{ij} \bar{d}^{i}_{\rm R} H_1^\dagger Q^j_{\rm L} - y^{\rm u}_{ij} \bar{u}^{i}_{\rm R} \tilde{H}_2^\dagger Q^j_{\rm L} \right\} + y_{\rm b} \bar{b}_{\rm R} H_3^\dagger Q^3_{\rm L} - y_{\rm t} \bar{t}_{\rm R} \tilde{H}_3^\dagger Q^3_{\rm L} + {\rm c.c.}$$

Fixed!

	$\mathrm{U}(1)_{\rm Y}$	$\mathrm{U}(1)_{\rm X}$	$\mathrm{U}(1)_{\rm Z}$
H_1	$\frac{1}{2}$	-1	$-\frac{2}{3}$
H_2	$\frac{1}{2}$	1	$\frac{1}{3}$
H_3	$\frac{1}{2}$	0	$\frac{1}{3}$
$Q^{1,2}_{\rm L}$	$\frac{1}{6}$	γ	δ
$Q^{3}_{\rm L}$	$\frac{1}{6}$	β	α
$u^{1,2}_{\rm R}$	$\frac{2}{3}$	$1+\gamma$	$\frac{1}{3}+\delta$
$t_{\rm R}$	$\frac{2}{3}$	β	$\frac{1}{3}+\alpha$
$d^{1,2}_{\rm R}$	$-\frac{1}{3}$	$1+\gamma$	$\frac{2}{3}+\delta$
$b_{\rm R}$	$-\frac{1}{3}$	β	$-\frac{1}{3}+\alpha$

$$(\beta-\gamma, \alpha-\delta) \notin \{(-1,-1), (-1,0), (0,0), (1,0), (1,1), (2,1)\}$$

Lepton sector is SM-like (couple to H_3 only)

$v_3 \gg v_{1,2}$ ⇒

heavy third generation
no tree level FCNCs
Cabibbo mixing enforced

The model is treatable fully analytically in this limit!

Dim-6 operators:

$$\bar{d}^{1,2}_{\rm R} \left(H_i^\dagger Q^3_{\rm L}\right)\left(H_j^\dagger H_k\right), \quad \bar{u}^{1,2}_{\rm R} \left(\tilde{H}_i^\dagger Q^3_{\rm L}\right)\left(H_j^\dagger H_k\right)$$

$$\bar{b}_{\rm R} \left(H_i^\dagger Q^{1,2}_{\rm L}\right)\left(H_j^\dagger H_k\right), \quad \bar{t}_{\rm R} \left(\tilde{H}_i^\dagger Q^{1,2}_{\rm L}\right)\left(H_j^\dagger H_k\right)$$

⇓

Full CKM?

Physical Higgs interactions

$$\xi \equiv \frac{\sqrt{v_1^2 + v_2^2}}{v_3}$$

$$\xi \ll 1$$

SM-like Higgs: $\mathcal{L} \supset \sum_q \frac{m_q}{v_3} \bar{q}q\, h_{125} + \mathcal{O}(\xi)$

Additional scalars' Yukawa couplings:

$$\mathcal{L} \supset \cos\theta_{\rm C} \frac{\sqrt{2}m_{\rm s}}{v_1} \bar{s}_{\rm R} c_{\rm L} H_{\rm a}^- - \cos\theta_{\rm C} \frac{\sqrt{2}m_{\rm c}}{v_2} \bar{c}_{\rm R} s_{\rm L} H_{\rm b}^+ + {\rm c.c.} + \mathcal{O}(\xi)$$
$$+ \frac{m_{\rm s}}{v_1} \bar{s}s h_{\rm a} - \frac{m_{\rm c}}{v_2} \bar{c}c h_{\rm b} + {\rm i}\frac{m_{\rm s}}{v_1} \bar{s}\gamma^5 s A_{\rm a} - {\rm i}\frac{m_{\rm c}}{v_2} \bar{c}\gamma^5 c A_{\rm b} + \mathcal{O}(\xi)\,,$$

Charged Higgses are mostly produced via $c\bar{s}$ fusion!

Main focus: $c\bar{s} \to H^+ \to W^+ h_{125}$ $\quad m_{H^\pm} > 200\ \text{GeV}$

Charged Higgs production and decays

Lagrangian can we represented model-independently as

$$\mathcal{L}_{kin} \supset D_\mu H^+ D^\mu H^- - m_{H^\pm}^2 \; H^+ H^- \, ,$$

$$\mathcal{L}_{int} \supset \kappa_{cs}^p \; \bar{c}_\mathrm{R} s_\mathrm{L} H^+ + \kappa_{cs}^m \; \bar{s}_\mathrm{R} c_\mathrm{L} H^- + i\kappa_{W h_{125}} \; \left(h_{125}\partial^\mu H^+ - H^+ \partial^\mu h_{125}\right) W_\mu^- + \mathrm{c.c.}\, .$$

giving rise to partial decay widths:

$$\Gamma\left(H^\pm \to W^\pm h_{125}\right) = \frac{\kappa_{W h_{125}}^2 m_{H^\pm}^3}{64\pi m_W^2}\left[1 - \frac{\left(m_{h_{125}} - m_W\right)^2}{m_{H^\pm}^2}\right]\left[1 - \frac{\left(m_{h_{125}} + m_W\right)^2}{m_{H^\pm}^2}\right]$$
$$\times \left[1 - \frac{2\left(m_{h_{125}}^2 + m_W^2\right)}{m_{H^\pm}^2} + \frac{\left(m_{h_{125}}^2 - m_W^2\right)^2}{m_{H^\pm}^4}\right]^{1/2} \, ,$$
$$\Gamma\left(H^+ \to c\bar{s}\right) = \frac{3\left[\left(\kappa_{cs}^p\right)^2 + \left(\kappa_{cs}^m\right)^2\right] m_{H^\pm}}{16\pi} = \frac{3\kappa_{cs}^2 m_{H^\pm}}{16\pi} \, .$$

Production cross section in NW approximation:

$$\sigma(pp \to H^\pm \to W^\pm h_{125}) = \sigma(pp \to H^\pm) \times \mathrm{BR}_{W h_{125}} = \kappa_{cs}^2 \times \sigma_0(m_{H^\pm}) \times \mathrm{BR}_{W h_{125}}$$

Analysis

$$pp \to H^{\pm} \to W^{\pm} h_{125} \to \ell^{\pm} + \not{E}_T + b\bar{b}$$

- implement the model-independent Lagrangian to FeynRules (leading order);
- generate UFO for MadGraph, use NNPDF for S/B event generation;
- use Pythia6 for showering/hadronisation of generated events;
- detector simulation via Delphes employing FastJet for jet clustering (anti-kT);
- for the multivariate analysis, we use Boosted Decision Tree Algorithm.

Selection criteria:
one charged lepton $\ell = \{e, \mu\}$ and at least two jets + missing transverse energy

b-tagging on the two leading-p_T jets reduces B, but also affects S

Two S categories:

- 1b-tag: In this category, we demand at least one b-tagged jet among the two leading p_T jets.
- 2b-tag: In this category, we demand that both the two leading p_T jets are b-tagged. This category is a subset of the 1b-tag category.

Parameter scan

Implementing Genetic Algorithm scan for points satisfying:

- There are no tachyonic scalar masses and the scalar potential is bounded from below
- The tree-level scalar four-point amplitudes satisfy $|\mathcal{M}| < 4\pi$.
- The SM Higgs-like scalar has a mass no more than 5 GeV away from the observed 125 GeV value, and has a Yukawa coupling to the top quark satisfying $|y_{t\bar{t}h_{125}}| \in [0.9, 1.1]$.
- The exotic decays $Z \to h_{\rm a,b} A_{\rm a,b}$ are kinematically forbidden, as to not be in conflict with the precision measurements of the Z width.
- The lightest charged Higgs has a mass in the range $[m_{H^\pm}^{(\rm min)}, 1000\,{\rm GeV}]$, with a different $m_{H^\pm}^{(\rm min)}$ for each run (taking values 250, 300, 400 or 450 GeV).
- The computed values of S', T' and U' fall within the error bars on S, T and U
- The value of $\kappa_{cs}^2 \times {\rm BR}_{Wh_{125}}$ is at least 0.5 above the 100 fb^{-1} discovery threshold for the 1b-tag category set by the MVA.

Charged Higgs search in cs fusion channel

$$pp \to H^\pm \to W^\pm h_{125} \to \ell^\pm + \not{E}_T + b\bar{b}$$

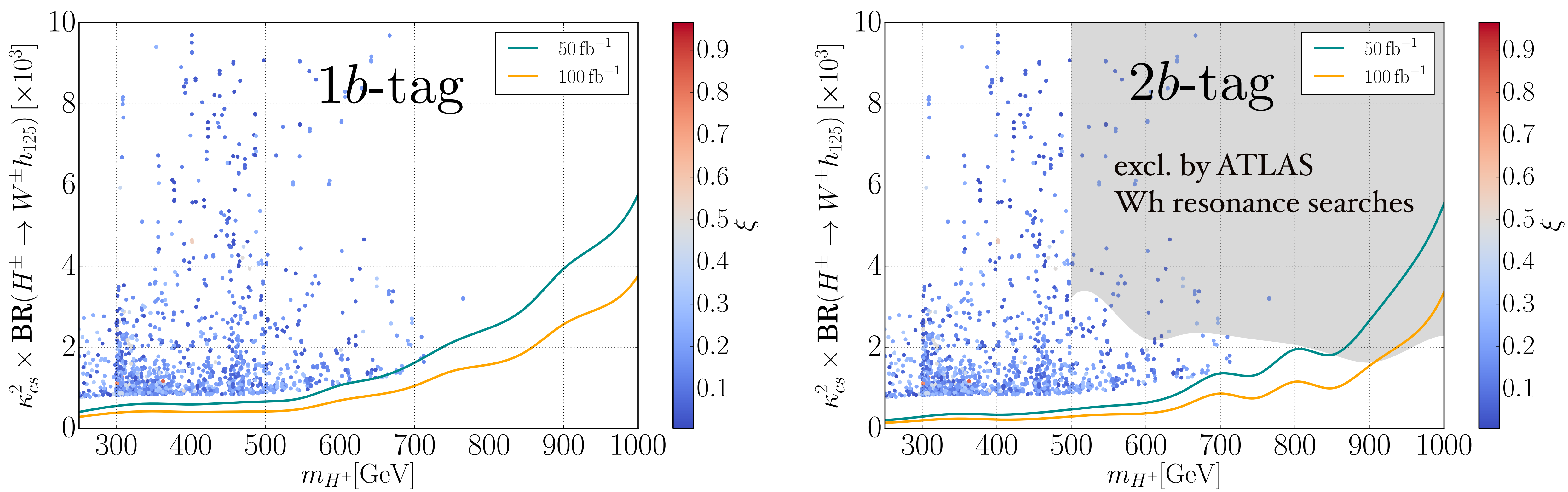
Parton-level CSs for typical backgrounds (no cuts!): LHC ($\sqrt{s} = 13$ TeV)

Process	$W + n\ j$	Wbj	$Wb\bar{b}$	$t\bar{t} + n\ j$	tj	tb	tW	WW	WZ	Wh_{125}
x-sec (pb)	1.53×10^5	308.9	41.7	431.3	174.6	2.6	54.0	67.8	25.4	1.1

Selection cuts:

- Lepton: $p_T(\ell) > 25$ GeV, $|\eta(\ell)| < 2.5$
- Jet: $p_T(J) > 25$ GeV, $|\eta(J)| < 4.5$
- Missing transverse energy: $\not{E}_T > 25$ GeV
- ΔR separation: $\Delta R(J_1, J_2) > 0.4$, $\Delta R(\ell, J) > 0.4$

5σ discovery contours



Flavour conservation

Yukawa sector of 2HDM:

$$-\mathcal{L}_Y = \sum_{a,b=1}^{3} \left\{ \bar{Q}_L^a \, [(\Gamma_1)_{ab}\, \phi_1 + (\Gamma_2)_{ab}\, \phi_2] \, n_R^b \; + \; \bar{Q}_L^a \, \left[(\Delta_1)_{ab}\, \tilde{\phi}_1 + (\Delta_2)_{ab}\, \tilde{\phi}_2\right] \, p_R^b \right\} + \text{h.c.},$$

Mass and FCNC matrices:

$$M_p = \frac{1}{\sqrt{2}} \left(\Delta_1 v_1 + \Delta_2 v_2\right) \, , \qquad M_n = \frac{1}{\sqrt{2}} \left(\Gamma_1 v_1 + \Gamma_2 v_2\right) ,$$

Diagonalisation:

$$D_u = V_L^\dagger M_p V_R = \text{diag}\{m_u, m_c, m_t\} \; , \qquad D_d = U_L^\dagger M_n U_R = \text{diag}\{m_d, m_s, m_b\}$$

FCNC matrices:

$$N_u = \frac{1}{\sqrt{2}} V_L^\dagger \left(\Delta_1 v_2 - \Delta_2 v_1\right) V_R \; , \qquad N_d = \frac{1}{\sqrt{2}} U_L^\dagger \left(\Gamma_1 v_2 - \Gamma_2 v_1\right) U_R$$

Simultaneous diagonalisation of mass and FCNC matrices is basis for models with flavour conservation

e.g. each family of the same charge couples to a single doublet, via Z2 or U(1)

CKM suppression of FCNCs in down-sector

Branco-Grimus-Lavoura (BGL): symmetry suppressed tree-level FCNCs first realised in the context of 2HDM

Impose a family symmetry: $$Q_{L1} \to e^{i\theta} Q_{L1}, \quad p_{R1} \to e^{2i\theta} p_{R1}, \quad \Phi_2 \to e^{i\theta} \Phi_2,$$

Allowed textures:

$$\Gamma_1 = \begin{pmatrix} 0 & 0 & 0 \\ \times & \times & \times \\ \times & \times & \times \end{pmatrix}, \qquad \Gamma_2 = \begin{pmatrix} \times & \times & \times \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix},$$

$$\Delta_1 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \times & \times \\ 0 & \times & \times \end{pmatrix}, \qquad \Delta_2 = \begin{pmatrix} \times & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix},$$

up-quark mass form:

$$M_p = \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & \times \\ 0 & \times & \times \end{pmatrix}$$

$$N_u = \mathrm{diag}\left(-\frac{m_{u_1}}{\tan\beta}, \, m_{u_2} \tan\beta \, , \, m_{u_3} \tan\beta \right)$$

No FCNCs in the up-sector!

CKM: $$V = V_L^\dagger U_L$$

$$U_L \equiv \begin{pmatrix} V(1,1) & V(1,2) & V(1,3) \\ \times & \times & \times \\ \times & \times & \times \end{pmatrix}$$

$$(N_d)_{aa} = m_a \left(\tan\beta - \frac{|V_{1a}|^2}{\sin\beta\cos\beta} \right),$$

$$(N_d)_{ab} = -\frac{V_{1a}^* V_{1b}}{\sin\beta\cos\beta} m_b \quad (a \neq b)$$

CKM-suppressed FCNCs in the down-sector!

BGL-like 3HDM: scalar sector

Das, Ferreira, Morais, Padilla-Gay, Pasechnik, Rodrigues, JHEP 11 (2021) 079

Impose a family symmetry:

$$\mathrm{U}(1): \ \phi_1 \to e^{i\alpha}\phi_1 \,, \qquad \phi_3 \to e^{i\alpha}\phi_3 \,.$$

$$\mathbb{Z}_2: \ \phi_1 \to -\phi_1 \,, \qquad \phi_2 \to \phi_2 \,, \qquad \phi_3 \to \phi_3 \,.$$

CP symmetry:

$$\phi_1 \to \phi_1^* \,, \qquad \phi_2 \to \phi_2^* \,, \qquad \phi_3 \to \phi_3^*$$

Invariant potential:

$$\begin{aligned} V_0(\phi_1,\phi_2,\phi_3) = {}& \mu_1^2\left(\phi_1^\dagger\phi_1\right) + \mu_2^2\left(\phi_2^\dagger\phi_2\right) + \mu_3^2\left(\phi_3^\dagger\phi_3\right) + \lambda_1\left(\phi_1^\dagger\phi_1\right)^2 \\ & + \lambda_2\left(\phi_2^\dagger\phi_2\right)^2 + \lambda_3\left(\phi_3^\dagger\phi_3\right)^2 + \lambda_4\left(\phi_1^\dagger\phi_1\right)\left(\phi_2^\dagger\phi_2\right) + \lambda_5\left(\phi_1^\dagger\phi_1\right)\left(\phi_3^\dagger\phi_3\right) \\ & + \lambda_6\left(\phi_2^\dagger\phi_2\right)\left(\phi_3^\dagger\phi_3\right) + \lambda_7\left(\phi_1^\dagger\phi_2\right)\left(\phi_2^\dagger\phi_1\right) + \lambda_8\left(\phi_1^\dagger\phi_3\right)\left(\phi_3^\dagger\phi_1\right) \end{aligned}$$

Soft-breaking potential:

$$V_{\text{soft}}(\phi_1,\phi_2,\phi_3) = \mu_{12}^2\phi_1^\dagger\phi_2 + \mu_{13}^2\phi_1^\dagger\phi_3 + \mu_{23}^2\phi_2^\dagger\phi_3 + \text{h.c.}\,, \qquad V = V_0 + V_{\text{soft}}$$

Higgs doublets:

$$\phi_k = \begin{pmatrix} w_k^+ \\ \frac{1}{\sqrt{2}}(v_k + h_k + i z_k) \end{pmatrix}, \qquad (k = 1,2,3)$$

$$v_1 = v\sin\beta_1\cos\beta_2 \,, \quad v_2 = v\sin\beta_2 \,, \quad v_3 = v\cos\beta_1\cos\beta_2 \,, \quad v = \sqrt{v_1^2 + v_2^2 + v_3^2}$$

BGL-like 3HDM: Yukawa sector

family symmetry:

$$\mathrm{U}(1):\ Q_{L3} \to e^{i\alpha} Q_{L3}\,, \quad p_{R3} \to e^{2i\alpha} p_{R3}\,,$$

$$\mathbb{Z}_2:\ Q_{L3} \to -Q_{L3}\,, \quad p_{R3} \to -p_{R3}\,, \quad n_{R3} \to -n_{R3}$$

Yukawa Lagrangian:

$$\mathscr{L}_Y = -\sum_{k=1}^{3} \left[\bar{Q}_{La} (\Gamma_k)_{ab}\, \phi_k\, n_{Rb} + \bar{Q}_{La} (\Delta_k)_{ab}\, \tilde{\phi}_k\, p_{Rb} + \text{h.c.} \right]$$

Allowed textures:

$$\Gamma_1 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \times & \times & 0 \end{pmatrix}, \quad \Delta_1 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \quad \Gamma_2, \Delta_2 = \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & 0 \end{pmatrix}, \quad \Gamma_3, \Delta_3 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \times \end{pmatrix}$$

Up/down mass matrices:

$$M_p = \frac{1}{\sqrt{2}} \sum_{k=1}^{3} \Delta_k v_k = \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & \times \end{pmatrix}, \quad M_n = \frac{1}{\sqrt{2}} \sum_{k=1}^{3} \Gamma_k v_k = \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ \times & \times & \times \end{pmatrix}$$

In the alignment limit, no FCNCs from SM Higgs state:

$$\begin{pmatrix} H_0 \\ H_1' \\ H_2' \end{pmatrix} = \mathcal{O}_\beta \cdot \begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix}$$

$$\mathscr{L}_Y^{H_0} = -\frac{H_0}{v} \left[\bar{n}_L \left(\frac{1}{\sqrt{2}} \sum_{k=1}^{3} \Gamma_k v_k \right) n_R + \bar{p}_L \left(\frac{1}{\sqrt{2}} \sum_{k=1}^{3} \Delta_k v_k \right) p_R + \text{h.c.} \right]$$

$$= -\frac{H_0}{v} \left[\bar{d}_L D_d d_R + \bar{u}_L D_u u_R + \text{h.c.} \right].$$

BGL-like 3HDM: tree-level FCNCs

CP-even BSM scalars interact with down-quarks as:

$$\mathscr{L}_Y^{H_1',H_2'} = -\frac{H_1'}{v}\bar{d}_L N_{d1} d_R - \frac{H_2'}{v}\bar{d}_L N_{d2} d_R + \text{h.c.}$$

FCNC matrices:

$$N_{d1} = \frac{v}{\sqrt{2}v_{13}} U_L^\dagger (\Gamma_1 v_3 - \Gamma_3 v_1) U_R \,,$$

$$N_{d2} = U_L^\dagger \left[\frac{v_2}{v_{13}}\frac{1}{\sqrt{2}}\left(\Gamma_1 v_1 + \Gamma_3 v_3\right) - \frac{v_{13}}{v_2}\frac{1}{\sqrt{2}}\Gamma_2 v_2\right] U_R$$

Bi-diagonalising matrices in the up-sector have block-diagonal form:

$$V_L = \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & 1 \end{pmatrix} \qquad (U_L)_{3A} = V_{3A}$$

Textures have the following structure:

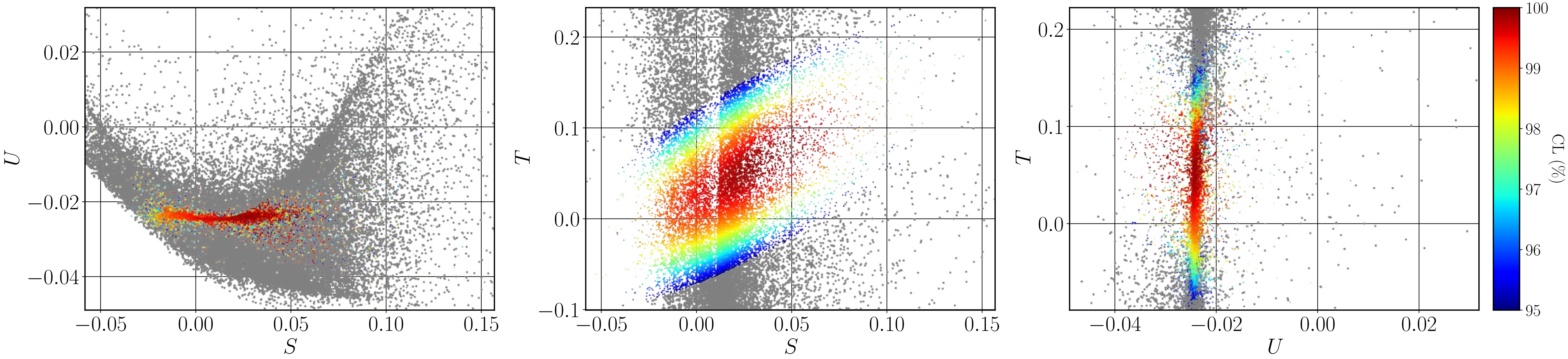
$$\Gamma_3 = (\Gamma_3)_{33} P \,, \qquad \frac{1}{\sqrt{2}}\left(\Gamma_1 v_1 + \Gamma_3 v_3\right) = P\, M_d \qquad P = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

physical
FCNC interactions:

$$(N_{d1})_{AB} = \frac{v\, v_3}{v_1 v_{13}} V_{3A}^* V_{3B} (D_d)_{BB} - \frac{1}{\sqrt{2}}\frac{v\, v_{13}}{v_1}(\Gamma_3)_{33} V_{3A}^* (U_R)_{3B} \,,$$

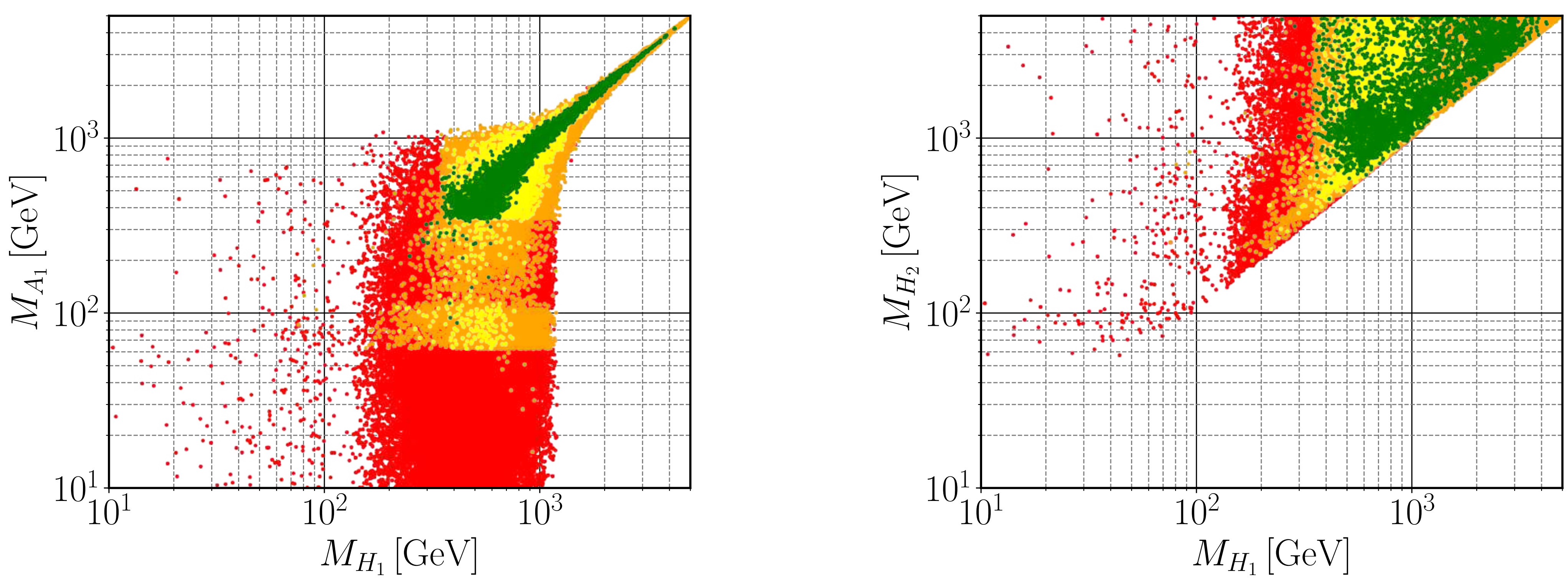
$$(N_{d2})_{AB} = \frac{v_{13}}{v_2}(D_d)_{BB}\delta_{AB} + \left(\frac{v_{13}}{v_2} + \frac{v_2}{v_{13}}\right) V_{3A}^* V_{3B} (D_d)_{BB} \,.$$

BGL-like 3HDM: numerical results



Points outside 95% CL for the oblique parameter STU analysis

Points within the 95% CL for the oblique parameter STU analysis



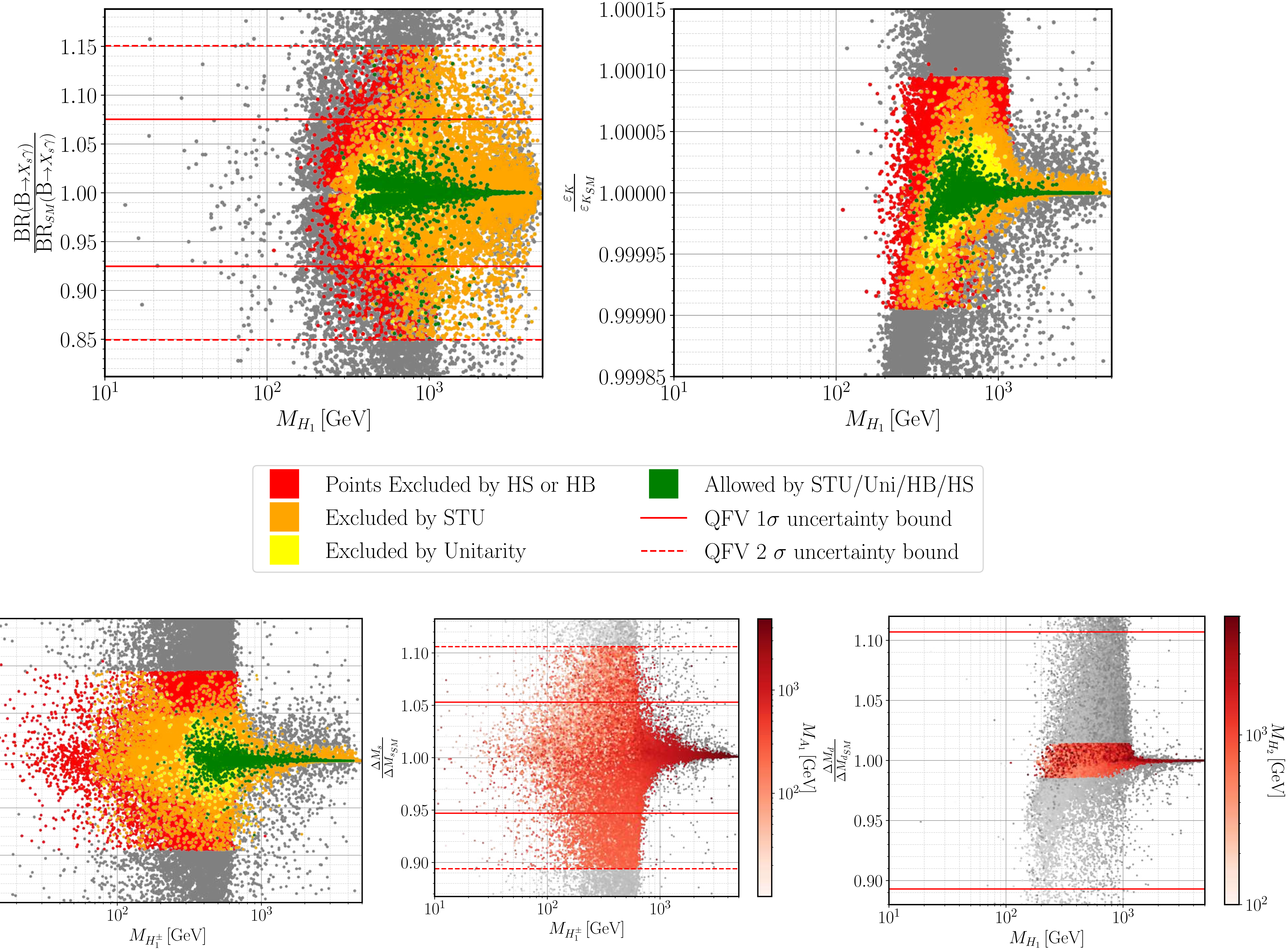
Points Excluded by HS or HB

Excluded by STU

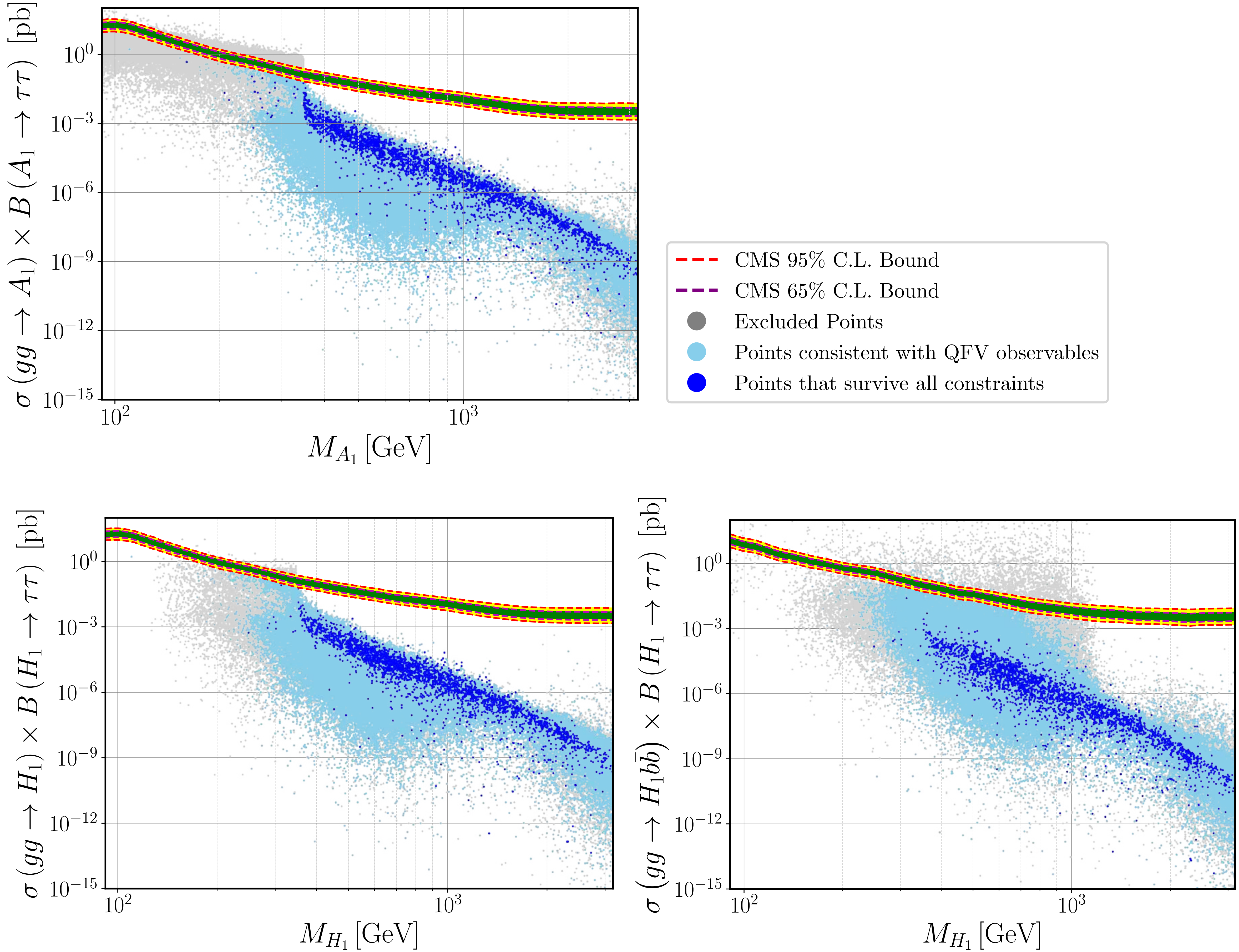
Excluded by Unitarity

Allowed by EW/Uni/HB/HS

FCNC observables



Predictions for the LHC searches



Summary

- additional scalars offers way to resolve some of the long-standing issues of the SM framework
- 3HDMs offer rich collider phenomenology at colliders
- flavour symmetries enable to generate very specific patterns in mass, mixing and FCNC hierarchies
- search for suitable UV complete theories giving rise to such models is under way