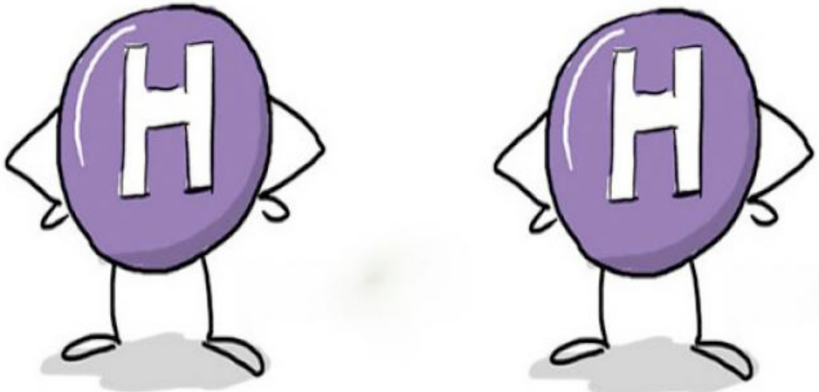
Alignment in Extended Higgs Models



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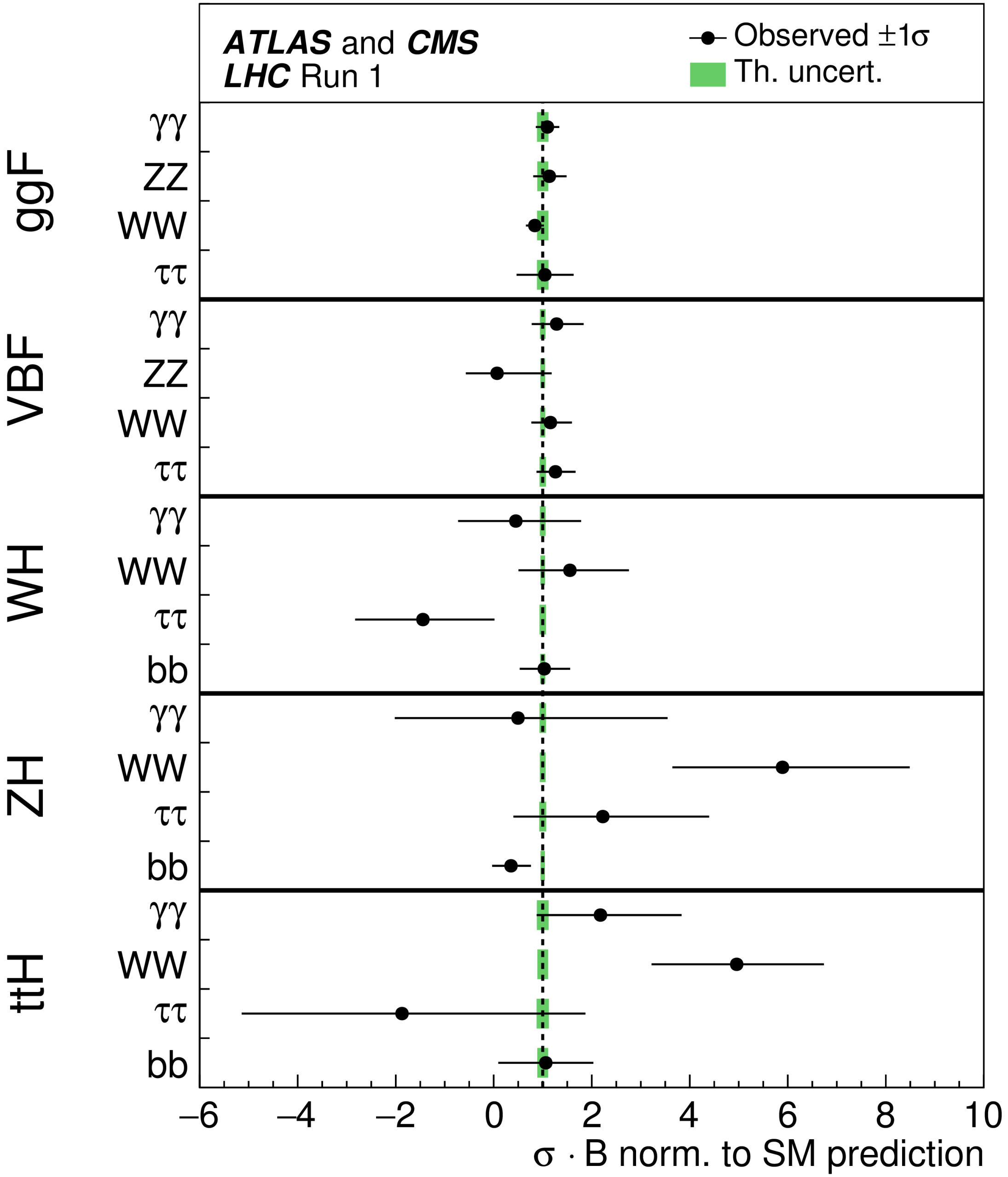
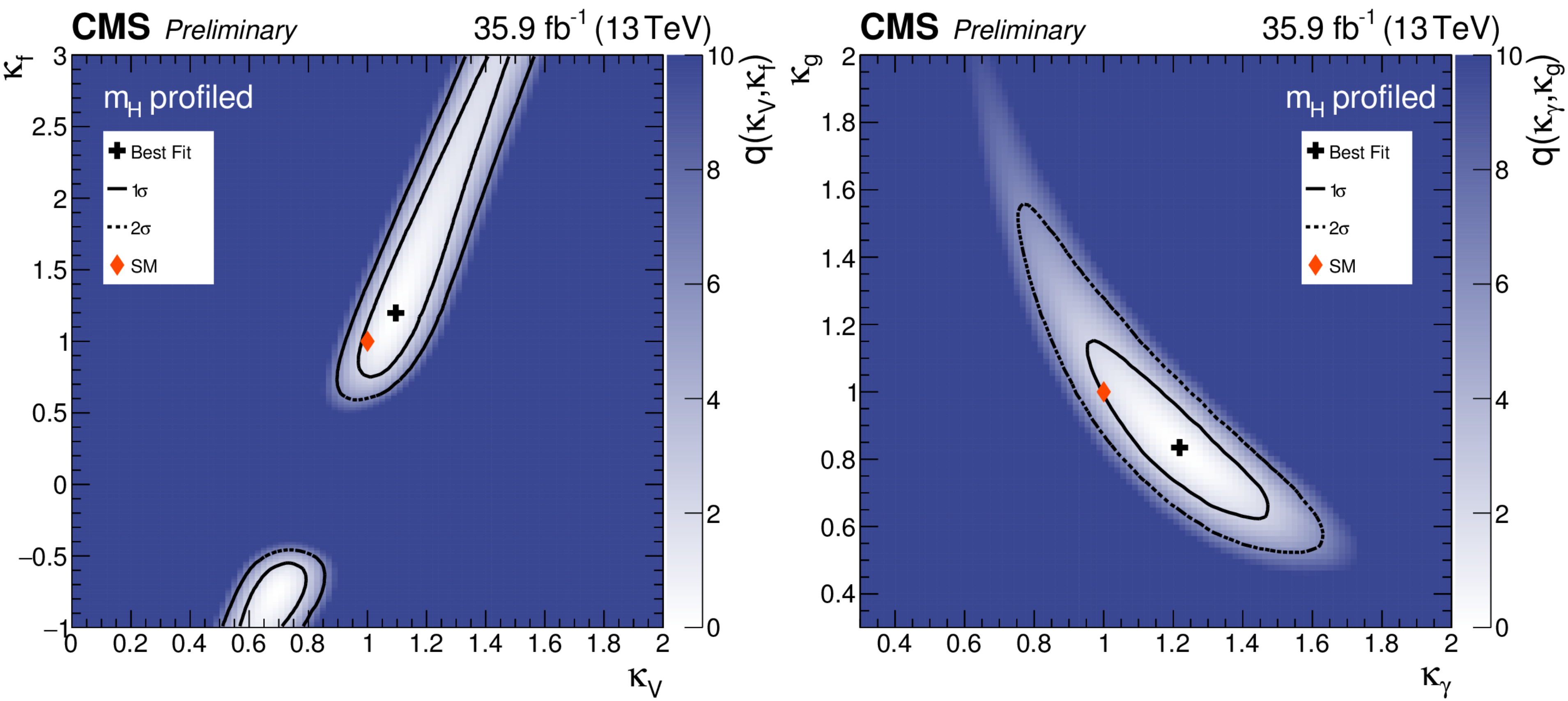
Nearly five years after the initial discovery of the Higgs boson at CERN, subsequent experimental studies of its properties reveal a particle that behaves very much like the Higgs boson of the Standard Model (SM).

After Run 1 of the LHC, the combined ATLAS/CMS Higgs data strongly support a SM-like Higgs boson interpretation.



ATLAS and CMS Collaborations, [*J. High Energy Phys. 08 (2016) 045*]

The Run-II Higgs data continues to be consistent with a SM-like Higgs boson interpretation.



Two-dimensional likelihood scans of κ_f versus κ_V (left) and κ_g versus κ_γ (right) based on the H->$\gamma\gamma$ decay channel . All four variables are expressed relative to the SM expectations. The mass of the Higgs boson is profiled in the fits. The crosses indicate the best-fit values, the diamonds indicate the Standard Model expectations. The color maps indicate the value of the test statistic q as described in CMS-PAS-HIG-16-040.

Why not an extended Higgs sector?

- The fermion and gauge boson sectors of the SM are not of minimal form ("who ordered that?"). So, why should the spin-0 (scalar) sector be minimal?

- Extended Higgs sectors can provide a dark matter candidate.

- Extended Higgs sectors can provide new sources of CP violation (which may be useful in baryogenesis).

- Models of new physics beyond the SM often require additional scalar Higgs states. E.g., two Higgs doublets are required in the minimal supersymmetric extension of the SM (MSSM).

Extended Higgs sectors are highly constrained

- The electroweak ρ parameter is very close to 1.
- One neutral Higgs boson of the extended Higgs sector must be SM-like.
- Higgs-mediated flavor-changing neutral currents (FCNCs) are suppressed.
- At present, only one Higgs scalar has been observed.

➢The electroweak ρ parameter is very close to 1.

For a Higgs sector consisting of scalars with weak isospin T and hypercharge $Y=2(Q-T_3)$,

$$\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = 1 \quad \Longleftrightarrow \quad \sum_{T,Y} \big[(2T+1)^2 - 3Y^2 - 1\big] |v_{T,Y}|^2 c_Y = 0$$

$v_{T,Y}$ is the scalar field vacuum expectation value (vev) and $c_Y=1$ for $Y\neq 0$ and $c_Y = \frac{1}{2}$ for $Y=0$.

To obtain $\rho=1$ naturally, independently of the vevs, we demand that $(2T+1)^2-3Y^2=1$. The simplest solutions are (T,Y)=(0,0) [Higgs singlets] and (T,Y)=(½,±1) [Higgs doublets].

Since the SM employs a Higgs doublet, the most common choice for an extended Higgs sector simply replicates the hypercharge-one Higgs doublet of the SM (with a possible addition of singlet scalars).

➢One neutral Higgs boson of the extended Higgs sector must be SM-like.

This motivates considering the so-called Higgs alignment limit. Consider an extended Higgs sector with *n* Higgs doublets Φ_i (and perhaps additional Higgs singlets ϕ_j). To conserve electric charge, assume only neutral scalar fields acquire vevs.

$$\langle\Phi_i^0\rangle = v_i/\sqrt{2}\,, \qquad\qquad \langle\phi_j^0\rangle = x_j\,.$$

Note that $v^2 \equiv \sum_i |v_i|^2 = 4m_W^2/g^2 = (246\text{ GeV})^2$.

Define a new linear combination of doublet Higgs fields (called the *Higgs basis*),

$$H_1 = \begin{pmatrix} H_1^+ \\ H_1^0 \end{pmatrix} = \frac{1}{v}\sum_i v_i^* \Phi_i\,, \qquad\qquad \langle H_1^0\rangle = v/\sqrt{2}\,,$$

and H_2, H_3, … , are the other linear combinations of doublet Higgs fields such that <H_k> = 0 (for k=2,3,…). That is, H_1^0 is aligned in field space with the direction of the Higgs vev. If $\sqrt{2}\,\mathrm{Re}\,H_1^0 - v$ is a mass eigenstate, then its tree-level couplings are precisely those of the SM Higgs boson! This is the exact alignment limit.

Achieving an approximate Higgs alignment

In general $\sqrt{2}\,\mathrm{Re}\,H_1^0 - v$ is not a mass-eigenstate due to mixing with other neutral scalars. Nevertheless, a SM-like Higgs boson is present in the Higgs spectrum if either

- the diagonal squared masses of the other neutral Higgs basis scalar fields are all large compared to the mass of the observed Higgs boson (the decoupling limit);

  and/or

- the elements of the neutral scalar squared-mass matrix that govern the mixing of $\sqrt{2}\,\mathrm{Re}\,H_1^0 - v$ with other neutral scalars are suppressed.

➢ In the decoupling limit, all Higgs bosons (excepting the SM-like Higgs boson) are significantly heavier than 125 GeV.

➢ Alignment without decoupling is possible, in which case additional Higgs states may be more accessible to LHC searches. In some cases, suppressed scalar mixing (which is necessary in this case) can be achieved by approximate symmetries.

If small deviations from SM Higgs behavior are confirmed…

Correlations among the deviations of Higgs observables from their SM values will contain critical clues to the structure of the extended Higgs sector (and more generally to new physics beyond the SM, if present).

Example: The 2HDM near the alignment limit

The 2HDM scalar potential in the Higgs basis contains the following terms,

$$\mathcal{V} \ni \cdots + \tfrac{1}{2} Z_1 (H_1^\dagger H_1)^2 + \cdots + \left[\tfrac{1}{2} Z_5 (H_1^\dagger H_2)^2 + Z_6 (H_1^\dagger H_1)(H_1^\dagger H_2) + \text{h.c.}\right] + \cdots$$

For simplicity, assume a CP-conserving potential (so that Z_5 and Z_6 can be taken real). The CP-odd scalar mass is m_A , and the two CP-even scalar masses are obtained from the diagonalization of the 2x2 squared mass matrix,

$$\mathcal{M}^2 = \begin{pmatrix} Z_1 v^2 & Z_6 v^2 \\ Z_6 v^2 & m_A^2 + Z_5 v^2 \end{pmatrix}.$$

The diagonalization angle is denoted conventionally by β-α.

The squared-mass matrix is given with respect to the Higgs basis states, $\{\sqrt{2}\,\mathrm{Re}\ H_1^0 - v\,,\sqrt{2}\,\mathrm{Re}\ H_2^0\}$,

$$\mathcal{M}^2 = \begin{pmatrix} Z_1 v^2 & Z_6 v^2 \\ Z_6 v^2 & m_A^2 + Z_5 v^2 \end{pmatrix}.$$

The CP-even Higgs mass eigenstates h and H (with $m_h < m_H$) are given by,

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} c_{\beta-\alpha} & -s_{\beta-\alpha} \\ s_{\beta-\alpha} & c_{\beta-\alpha} \end{pmatrix} \begin{pmatrix} \sqrt{2}\ \mathrm{Re}\ H_1^0 - v \\ \sqrt{2}\,\mathrm{Re}\ H_2^0 \end{pmatrix},$$

where α is the diagonalizing angle of the squared-mass matrix with respect to the Φ_1^0–Φ_2^0 basis of scalar fields and $\tan\beta \equiv \langle\Phi_2^0\rangle/\langle\Phi_1^0\rangle$. In the approximate alignment limit where $m_h^2 \simeq Z_1 v^2$, we have

$$|c_{\beta-\alpha}| \simeq \frac{|Z_6| v^2}{m_H^2 - m_h^2} \ll 1\,,$$

which can be achieved in two different ways:

1. $m_A \gg v$, corresponding to the decoupling limit.
2. $|Z_6| \ll 1$, allowing for approximate alignment without decoupling.

Higgs interaction	2HDM coupling	approach to alignment limit
hVW and hZZ	$s_{\beta-\alpha}$	$1-\frac{1}{2}c^2_{\beta-\alpha}$
hhh	*	$1+2(Z_6/Z_1)c_{\beta-\alpha}$
$hhhh$	*	$1+3(Z_6/Z_1)c_{\beta-\alpha}$
$h\overline{D}D$	$s_{\beta-\alpha}\mathbb{1}+c_{\beta-\alpha}\rho^D_R$	$\mathbb{1}+c_{\beta-\alpha}\rho^D_R$
$h\overline{U}U$	$s_{\beta-\alpha}\mathbb{1}+c_{\beta-\alpha}\rho^U_R$	$\mathbb{1}+c_{\beta-\alpha}\rho^U_R$

Type I and II 2HDM couplings of the SM-like Higgs boson h normalized to those of the SM Higgs boson, in the approach to the alignment limit. D is a column vector of three down-type fermion fields (either down-type quarks or charged leptons) and U is a column vector of three up-type quark fields. In the Type-I 2HDM, $\rho^D_R=\rho^U_R=\mathbb{1}\cot\beta$. In the Type-II 2HDM, $\rho^D_R=-\mathbb{1}\tan\beta$ and $\rho^U_R=\mathbb{1}\cot\beta$, where $\mathbb{1}$ is the 3×3 identity matrix. In the third column, the first non-trivial correction to alignment is exhibited. Expressions for the entries marked with a * can be found in H.E. Haber and D. O'Neil, Phys. Rev. D **74**, 015018 (2006).

Considerations beyond tree level

Loop effects can distinguish between the decoupling limit and the limit of alignment without decoupling.

Example: the $H^{\pm}$ loop contribution to the effective $h\gamma\gamma$ coupling is governed by the tree-level $hH^{+}H^{-}$ coupling.

- In the alignment limit without decoupling, the $H^{\pm}$ mass can be of $O(m_t)$, in which case the $H^{\pm}$ loop competes with the top loop.

- In the decoupling limit, the corresponding loop effects decouple.

ratio of couplings	approach to the alignment limit
hH^+H^-/hhh	$\frac{1}{3}\left[(Z_3/Z_1)+(Z_7/Z_1)c_{\beta-\alpha}\right]$

where Z_1, Z_3 and Z_7 are parameters in the Higgs basis scalar potential,

$$\mathcal{V} = Z_1(H_1^\dagger H_1)^2 + \cdots + Z_3(H_1^\dagger H_1)(H_2^\dagger H_2) + \cdots + Z_7(H_2^\dagger H_2)(H_1^\dagger H_2 + \text{h.c.})$$

Alignment without decoupling—accidental or due to a symmetry?

First attempt: Impose CP3 symmetry on the 2HDM scalar potential [P.M. Ferreira, H.E. Haber and J.P. Silva, Phys. Rev. D **79**, 116004 (2009)]

$$
\begin{aligned}
\mathcal{V} = {} & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - [m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.}] + \tfrac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 \\
& + \tfrac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\
& + \left\{ \tfrac{1}{2}\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \big[\lambda_6 (\Phi_1^\dagger \Phi_1) + \lambda_7 (\Phi_2^\dagger \Phi_2)\big] \Phi_1^\dagger \Phi_2 + \text{h.c.} \right\} .
\end{aligned}
$$

with $m_{11}^2 = m_{22}^2$, $m_{12}^2 = 0$, $\lambda_1 = \lambda_2 = \lambda_3 + \lambda_4 + \text{Re}\lambda_5$, and $\text{Im}\lambda_5 = \lambda_6 = \lambda_7 = 0$, which yields a CP-conserving Higgs sector with $Z_6 = 0$, i.e. exact alignment. This is natural alignment, as defined by P.S. Bhupal Dev and A. Pilaftsis, JHEP **1412**, 024 (2014).

What goes wrong?: The scalar spectrum includes a massless scalar.

Second attempt: $\mathbf{Add\ soft\ breaking\ by\ taking}\ m_{11}^2 \neq m_{22}^2\ \mathbf{and}\ m_{12}^2 \neq 0.$
There are no massless scalars. $Z_6 = 0$ still holds and exact alignment is maintained.

What goes wrong?: Extending the CP3 symmetry to the Yukawa couplings restricts the generational structure of the Yukawa interactions that is not compatible with data (P.M. Ferreria and J.P. Silva)

A possible fix: Impose the CP3 symmetry conditions of the scalar potential at the Planck scale and determine the low energy phenomenology after RG-running. Exact alignment is broken, but may be consistent with the Higgs data (P.S. Bhupal Dev and and A. Pilaftsis).

A successful symmetry: The inert doublet model (IDM)

By imposing an exact $\boldsymbol{Z}_2$ symmetry, $H_2 \rightarrow - H_2$, in the Higgs basis of the 2HDM, and extending this discrete symmetry to a Type-I Yukawa sector, one arrives at the IDM. This model exhibits exact Higgs alignment, with $Z_6 = Z_7 = 0$. The lightest $\boldsymbol{Z}_2$-odd particle (LOP) is stable and is a candidate for the dark matter.

Higgs sector of the minimal SUSY extension of the SM (MSSM)

The Higgs sector of the MSSM is a constrained Type-II 2HDM. The tree-level prediction of $m_h < m_Z$ was ruled out at the LEP collider. But the MSSM Higgs sector is rescued by radiative corrections.

$$m_h^2 \lesssim m_Z^2 + \frac{3g^2 m_t^4}{8\pi^2 m_W^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1-\frac{X_t^2}{12M_S^2}\right)\right]$$

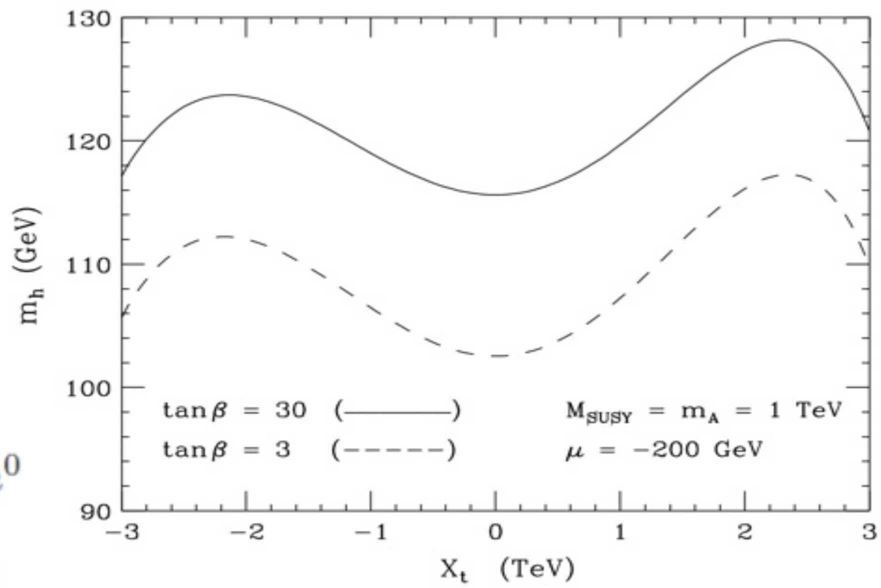
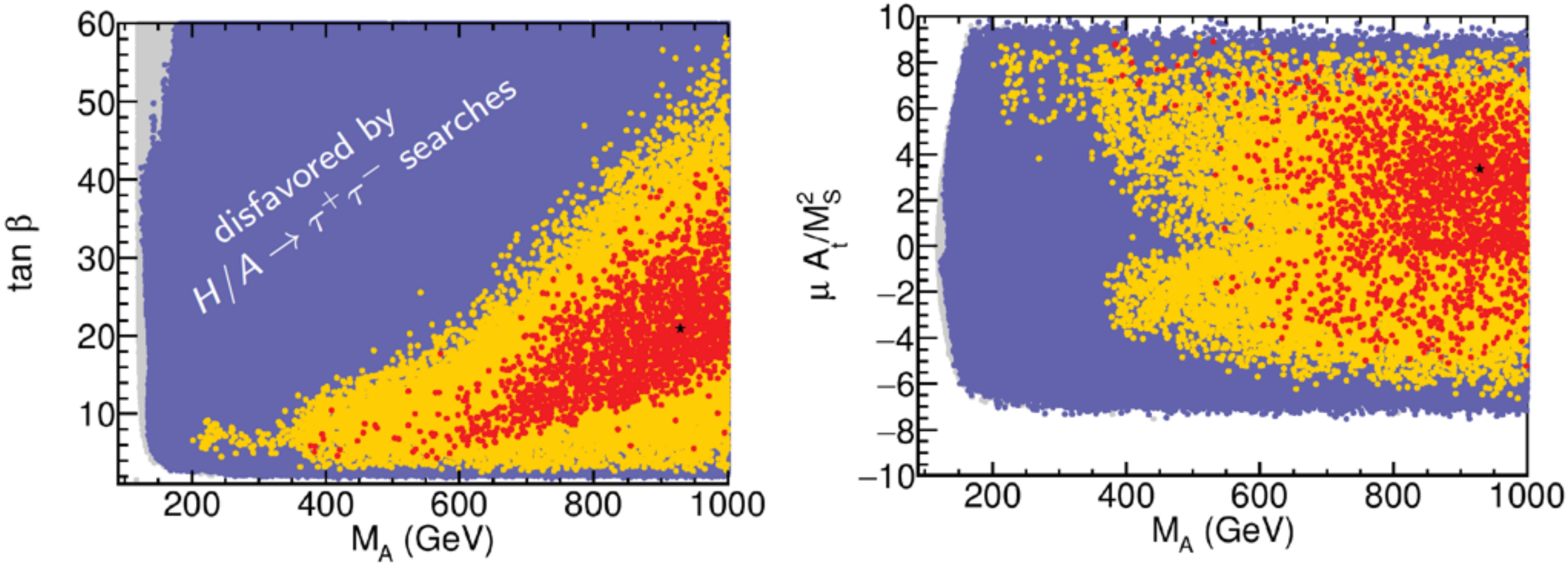


Figure taken from M. Carena and H.E. Haber (2003)

Large radiative corrections can easily accommodate the observed Higgs mass of 125 GeV (in some regions of the MSSM parameter space). Moreover, one can easily achieve a SM-like Higgs boson in the decoupling limit. Alignment without decoupling is still possible (just barely…), according to P. Bechtle et al., Eur. Phys. J. C **77**, 67 (2017), due to an accidental cancelation between tree-level and loop-level contributions to the effective Higgs squared-mass matrix.

Preferred parameter regions in a pMSSM-8 scan

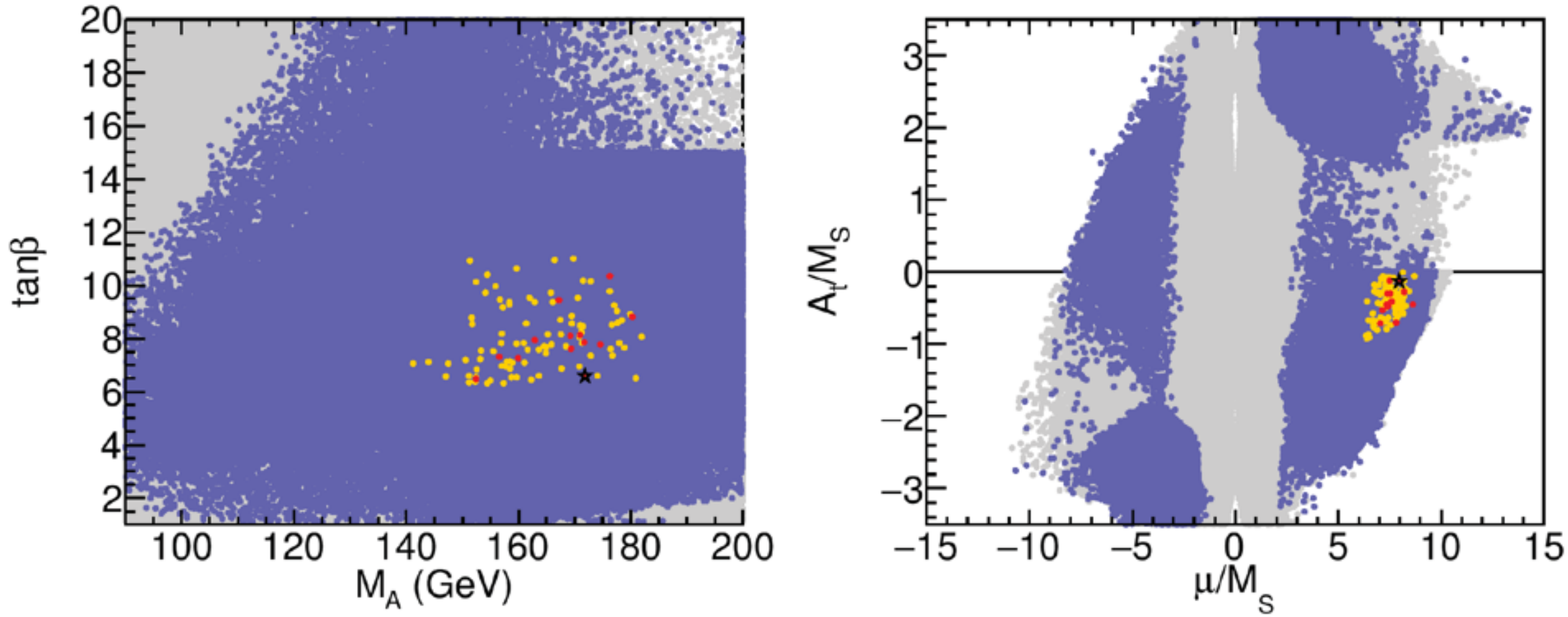
Case 1: h is SM-like



Points that do not pass the direct constraints from Higgs searches from `HiggsBounds` and from LHC SUSY particle searches from `CheckMATE` are shown in gray. Applying a global likelihood analysis to the points that pass the direct constraints, the color code employed is red for $\Delta\chi_h^2 < 2.3$, yellow for $\Delta\chi_h^2 < 5.99$ and blue otherwise. The best fit point is indicated by a black star.

Bottom line: m_A values as low as 200 GeV are still allowed in the MSSM.

Case 2: H is SM-like



Note: In the preferred region of the pMSSM-8 parameter space with a SM-like H, $X_t \sim -1.5 M_S$ with $150~\text{GeV} \lesssim m_{H^\pm} \lesssim 200~\text{GeV}$ and $m_h \lesssim 100~\text{GeV}$.

However, this parameter regime requires values of $\mu/M_S \gtrsim 6$ which can lead to the existence of color and charge breaking minima (and a destabilization of the electroweak vacuum).

Bottom line: The possibility that the heavier of two CP-even Higgs bosons of the MSSM is the observed 125 GeV Higgs boson is not yet excluded.

What about Higgs singlets?

➢ Extending the SM Higgs sector with a singlet scalar

H. Davoudiasl, R. Kitano, T. Li and H. Murayama (2005) argued for a new minimal SM to take into account a variety of phenomena not contained in the SM (e.g. dark matter, neutrino masses, etc.) Their model adds a Higgs singlet field to the Higgs sector with an exact $\boldsymbol{Z}_2$ symmetry, thereby providing a scalar dark matter candidate.

➢ Extending the MSSM Higgs sector with a singlet chiral superfield

The resulting model is called the NMSSM. It has a number of nice features.

- Provides an explanation of the origin of the supersymmetric Higgs mass parameter.
- Some parameter regimes are less fine-tuned than the MSSM.
- Does not rely on large radiative corrections to account for the observed Higgs mass.
- A "sweet spot" of the parameter space yields an approximate alignment limit.

See: M. Carena, H.E. Haber, I. Low, N.R. Shah and C.E.M. Wagner (2016)

➢Suppressing Higgs-mediated FCNCs

In the SM (with a single Higgs doublet), the diagonalization of the fermion mass matrices automatically yields diagonal neutral Higgs-fermion couplings. In models with multiple Higgs doublets, these couplings are generically non-diagonal in the fermion mass basis.

The Glashow-Weinberg and Paschos (GWP) condition for natural flavor conservation (1977) imposes a symmetry so that all right-handed fermions with a given electric charge q couple to exactly one Higgs doublet.

E.g., for the Higgs-quark interactions of the two-Higgs doublet model (2HDM):

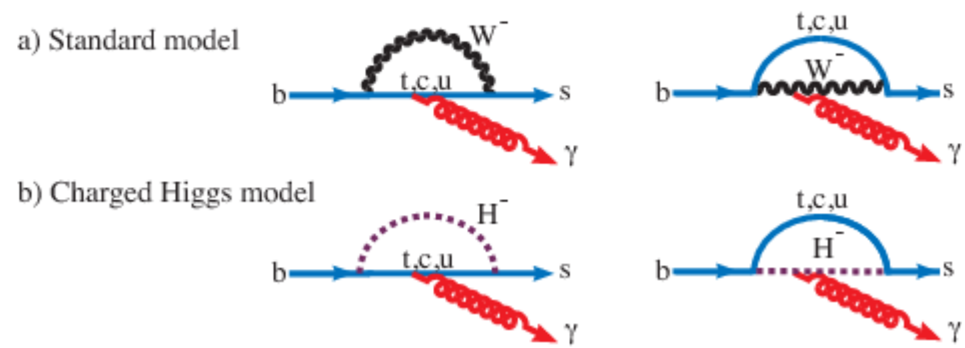
Type-I: All right-handed quarks couple to the same Higgs doublet.
Type-II: Right-handed quarks with q=2/3 and q=-1/3 couple to different Higgs doublets.

Even in models of extended Higgs sectors with no (or suppressed) tree-level FCNCs, one can generate neutral flavor changing processes at the loop level.

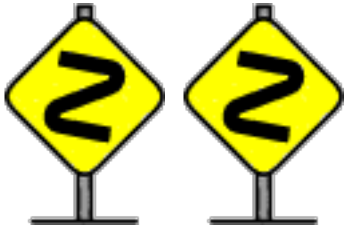
The most well known example is $b \to s\gamma$ which is mediated by a virtual charged Higgs boson.

In the Type-II 2HDM, the data for $B \to X_s + \gamma$ yields a 95% CL limit of:

$$m_{H^\pm} > 580 \text{ GeV}$$



M. Misiak and M. Steinhauser, Eur. Phys. J. C **77**, 201 (2017) [arXiv:1702.04571].



Additional flavor constraints arise due to tree-level exchange of a charged Higgs boson.

The largest discrepancy with SM expectations is currently observed in:

$$\mathscr{R}_D^{SM} = \frac{\mathscr{B}(\bar{B} \to D\tau^- \bar{\nu}_\tau)}{\mathscr{B}(\bar{B} \to De^- \bar{\nu}_e)} = 0.300 \pm 0.008$$

$$\mathscr{R}_{D^*}^{SM} = \frac{\mathscr{B}(\bar{B} \to D^*\tau^- \bar{\nu}_\tau)}{\mathscr{B}(\bar{B} \to D^*e^- \bar{\nu}_e)} = 0.252 \pm 0.003.$$

The significance of this deviation is roughly 4σ.

Note: this deviation cannot be accommodated in a Type-II 2HDM.

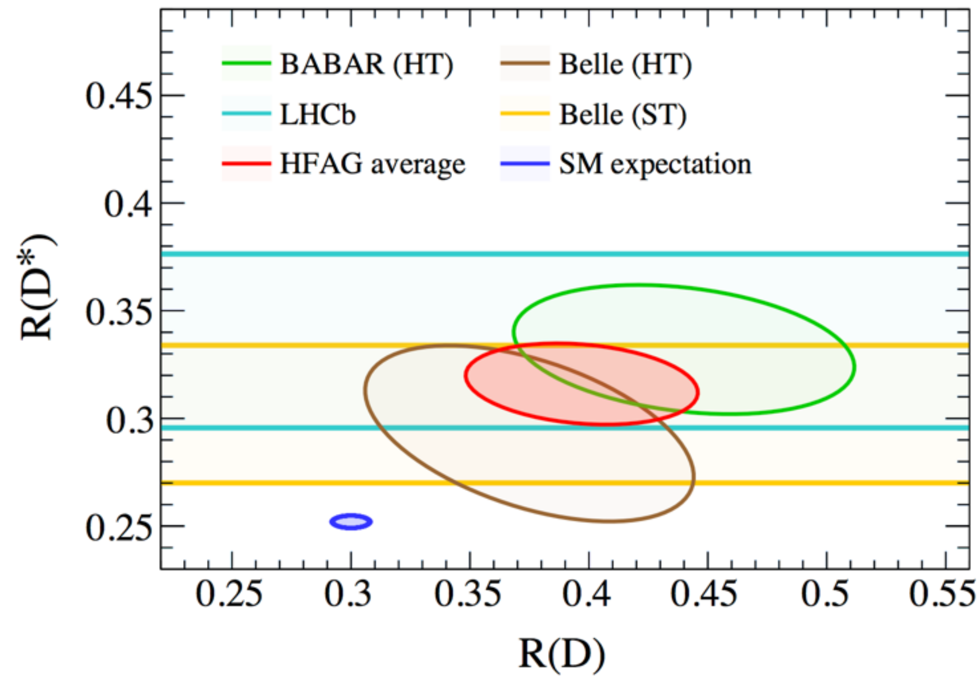
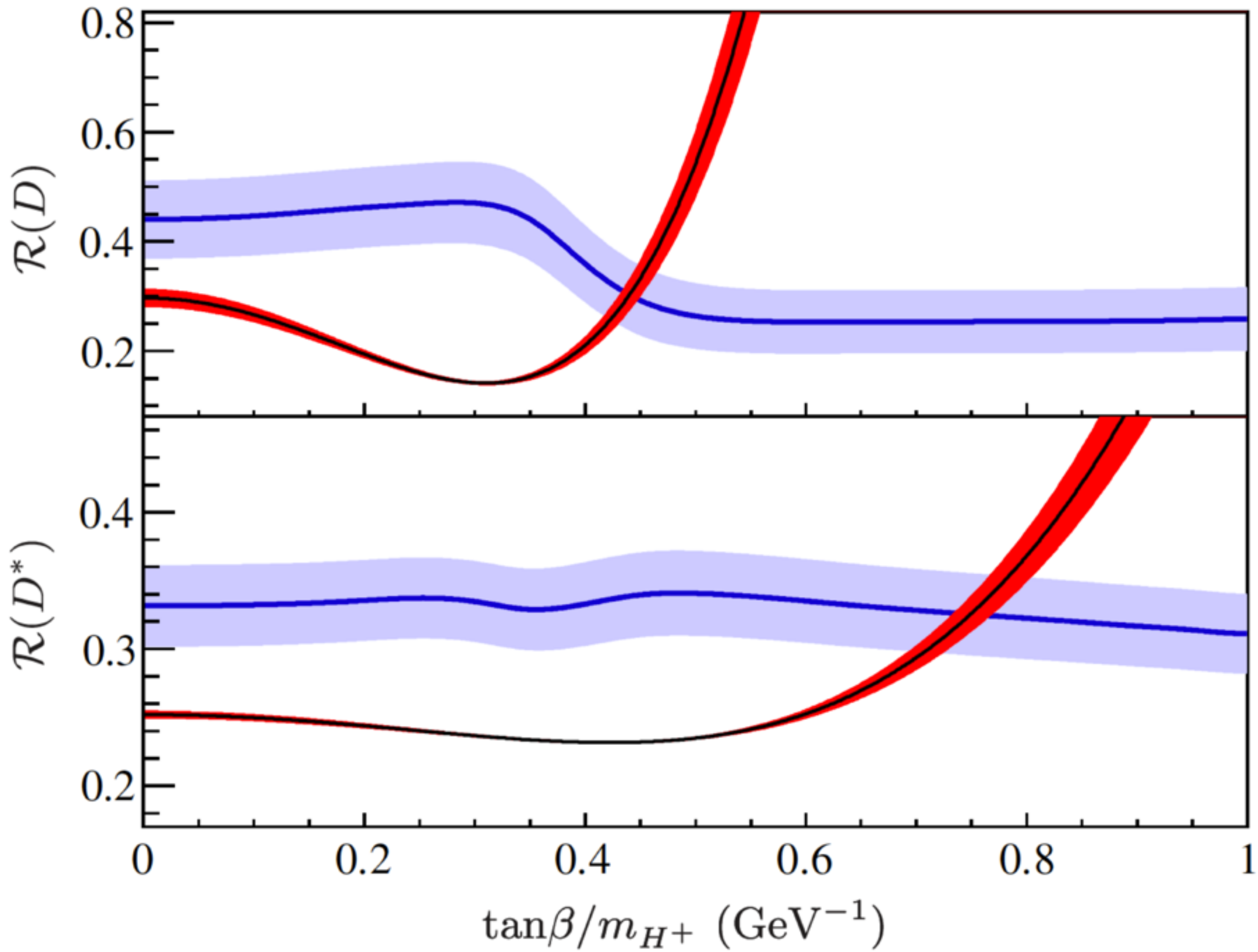


Figure 6. $\mathscr{R}_D$ **and** $\mathscr{R}_{D^*}$ **measurements:** Results from BABAR [28], Belle [34, 35], and LHCb [36], their values and 1-σ contours. The average calculated by the Heavy Flavor Averaging Group [37] is compared to SM predictions [19, 20, 21]. ST and HT refer to the measurements with semileptonic and hadronic tags, respectively.

Taken from G. Ciezarek et al., arXiv:1703.01766



Taken from J.P. Lees et al. [BaBar Collaboration], Phys. Rev. **D88**, 072012 (2013).

Higgs flavor alignment more generally

- One can impose by fiat that the diagonalization of the fermion mass matrix simultaneously diagonalizes the neutral Higgs-fermion Yukawa couplings. In absence of a symmetry, this is unstable with respect to RG-running.

- One can assert that flavor alignment is imposed at a very high energy scale (by new dynamics not specified).   In this case, RG-running yields small violations of Higgs flavor alignment at the electroweak scale that can be consistent with present data.

<u>Example:</u> the Yukawa couplings of the flavor aligned 2HDM are governed by three alignment parameters a_U, a_D and $a_E = \tan\beta$, which relate the two independent Yukawa coupling matrices of the up-type and down-type quarks and charged leptons, respectively.

High-scale flavor alignment in the 2HDM

The Yukawa Lagrangian in the Higgs basis of the 2HDM is

$$-\mathscr{L}_{\rm Y} = \overline{U}_L \left(\kappa^U H_1^{0\,\dagger} + \rho^U H_2^{0\,\dagger}\right) U_R - \overline{D}_L K^\dagger \left(\kappa^U H_1^- + \rho^U H_2^-\right) U_R$$
$$+\overline{U}_L K \left(\kappa^D H_1^+ + \rho^{D\,\dagger} H_2^+\right) D_R + \overline{D}_L \left(\kappa^D H_1^0 + \rho^{D\,\dagger} H_2^0\right) D_R\,,$$

where $\kappa^Q \equiv \sqrt{2} M_Q/v$ (for $Q = U,\ D$) and $M_U,\ M_D$ are the diagonal quark mass matrices. In the most general 2HDM, ρ^U and ρ^D are arbitrary complex 3×3 matrices, which yield neutral Higgs-mediated CP-violating and flavor-changing interactions. The Higgs couplings to leptons is similarly treated.

In the flavor-aligned 2HDM, $\rho^F = a^F \kappa^F$ for $F = U, D, E$, where a^F is called the alignment parameter.*

*A. Pich and P. Tuzon, Phys. Rev. D **80**, 091702 (2009) [arXiv:0908.1554 [hep-ph]].

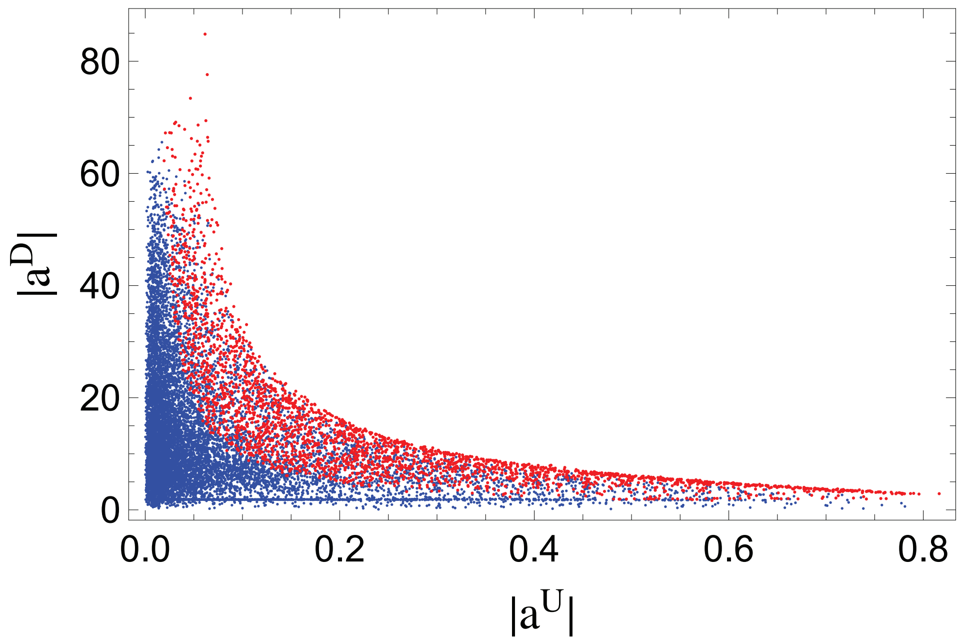
We impose $\rho^F = a^F \kappa^F$ at the Planck scale $M_{\rm P}$, and then generate flavor non-diagonal Higgs-fermion couplings via RG-running. We also work in the decoupling limit where the mass scale of the non-SM-like Higgs bosons is $\Lambda_H \gg m_h$. We then compare our numerical results to a one-loop leading log approximation,[†]

$$\begin{aligned}
\rho^U(\Lambda_H)_{ij} \simeq a^U\delta_{ij}\frac{\sqrt{2}(M_U)_{jj}}{v} + \frac{(M_U)_{jj}}{4\sqrt{2}\pi^2 v^3}\log\left(\frac{\Lambda_H}{\Lambda_{\rm P}}\right)\Big\{(a^E - a^U)\left[1 + a^U(a^E)^*\right]\delta_{ij}\sum_k (M_E^2)_{kk} \\
+(a^D - a^U)\left[1 + a^U(a^D)^*\right]\sum_k\left[3\delta_{ij}(M_D^2)_{kk} - 2(M_D^2)_{kk}K_{ik}K^*_{jk}\right]\Big\}\,, \\
\rho^D(\Lambda_H)_{ij} \simeq a^D\delta_{ij}\frac{\sqrt{2}(M_D)_{ii}}{v} + \frac{(M_D)_{ii}}{4\sqrt{2}\pi^2 v^3}\log\left(\frac{\Lambda_H}{\Lambda_{\rm P}}\right)\Big\{(a^E - a^D)\left[1 + a^D(a^E)^*\right]\delta_{ij}\sum_k (M_E^2)_{kk} \\
+(a^U - a^D)\left[1 + a^D(a^U)^*\right]\sum_k\left[3\delta_{ij}(M_U^2)_{kk} - 2(M_U^2)_{kk}K^*_{ki}K_{kj}\right]\Big\}\,.
\end{aligned}$$

where K is the CKM mixing matrix.

[†]S. Gori, H.E. Haber and E. Santos, arXiv:1703.05873 [hep-ph]. See also, C.B. Braeuninger, A. Ibarra and C. Simonetto, Phys. Lett. B **692**, 189 (2010).

The validity of the one-loop leading log approximation breaks down for large values of the alignment parameters.



Blue: region of the A2HDM parameter space where the prediction for all the off-diagonal terms of the ρ^Q matrices lies within a factor of 3 from the results obtained with the full running. Red: region where the one-loop leading log approximation differs significantly from the the results obtained by numerically solving the RGEs.

Remark: In our numerical analysis, we require that no Landau poles in the Yukawa couplings κ^Q and ρ^Q appear below $\Lambda = M_{\rm P}$. This constraint is reflected in the upper boundary of the red curve shown above.

The significance of the parameter $\tan\beta$ in the A2HDM

Since $\tan\beta$ is a basis-dependent quantity, it has no significance in the A2HDM. In the CP-conserving case, only $\beta-\alpha$ (which is basis independent) has significance. Indeed, $\tan\beta$ does not appear in the Yukawa couplings of the A2HDM.

In our analysis, we have neglected neutrino masses, so that alignment in the leptonic sector is preserved by RG running. Thus, it is convenient to define $\tan\beta$ via

$$a^E \equiv \tan\beta\,,$$

which is a real number of either sign. The significance of $\tan\beta$ is that in the Φ_1–Φ_2 basis, we have $h_2^E = 0$, although this is not enforced by a discrete symmetry. The Yukawa couplings to leptons then resemble those of a Type II or Type X 2HDM.

Phenomenological consequences

1. Flavor-changing top decays are too small to be seen at the LHC or at future colliders under consideration.

2. Higgs mediated contributions to neutral meson mixing ($B_{d,s}$–$\overline{B}_{d,s}$, K–$\overline{K}$ and D–$\overline{D}$ mixing) arise in our model.

3. Observable contributions to $B_{s,d} \to \mu^+\mu^-$ are possible. At present the SM predicted rates,

$$\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{SM}} = (3.65 \pm 0.23) \times 10^{-9},$$

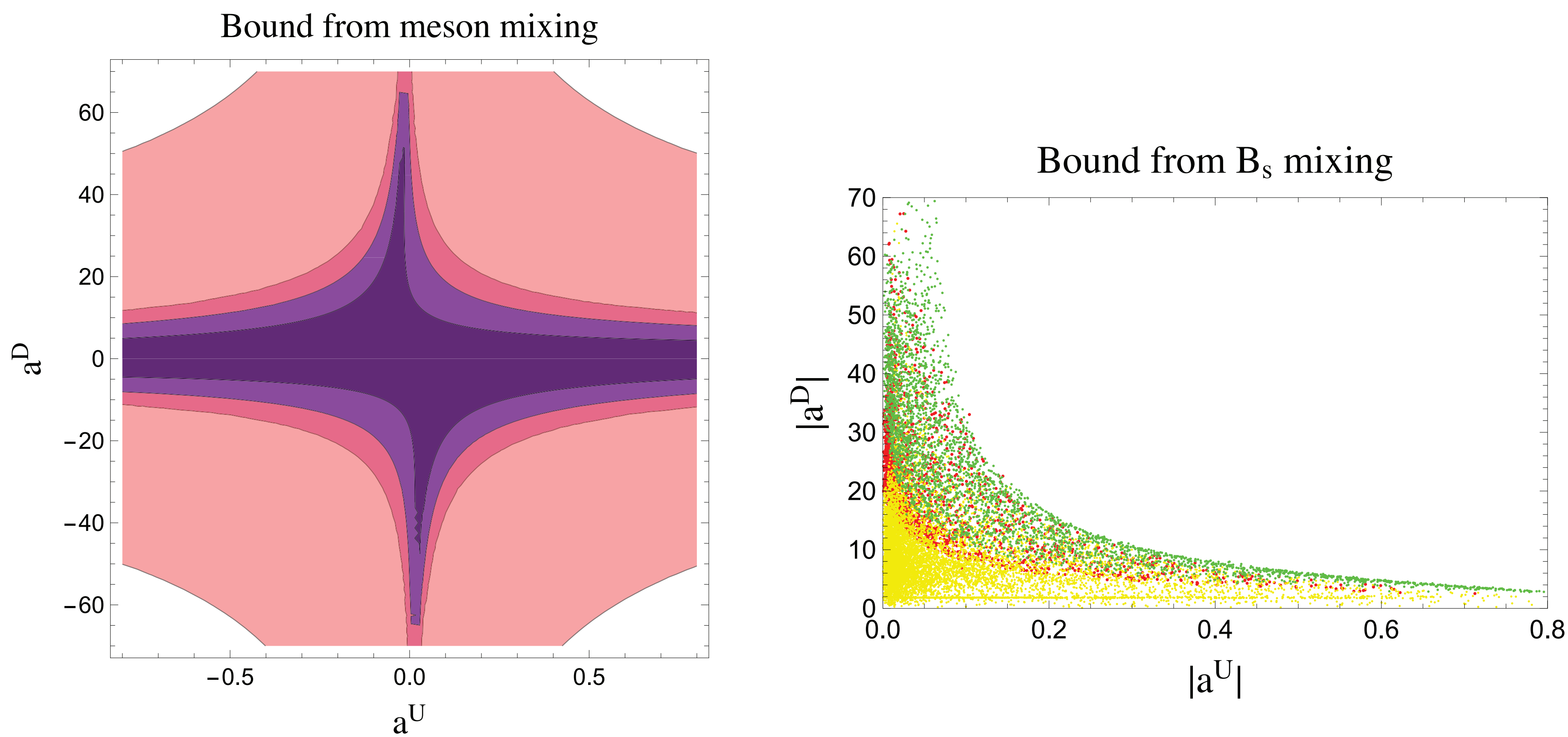
$$\mathrm{BR}(B_d \to \mu^+\mu^-)_{\mathrm{SM}} = (1.06 \pm 0.09) \times 10^{-10}.$$

are in good agreement with the combination of the LHCb and the CMS measurements at Run I for the B_s decay,

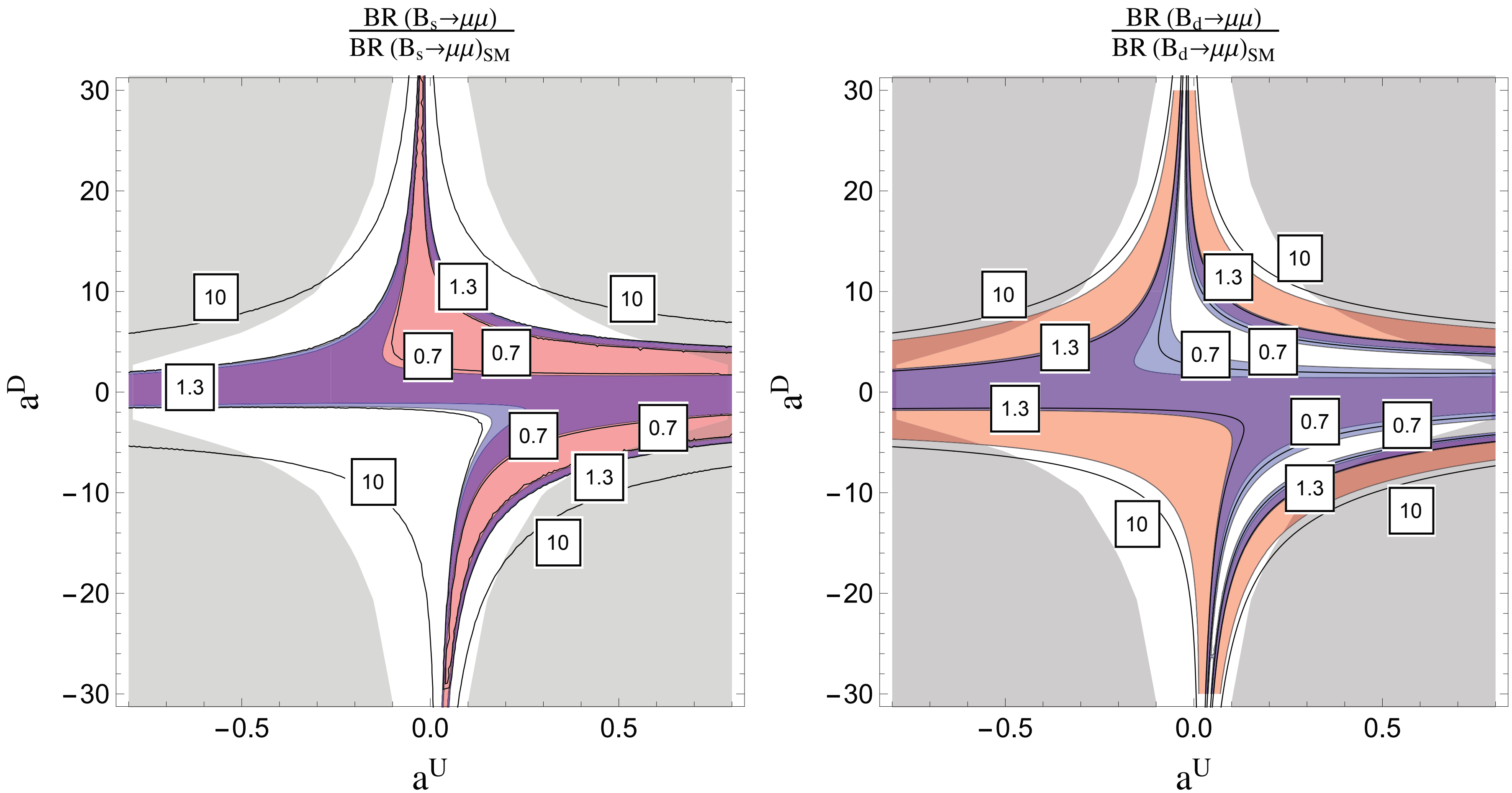
$$\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{exp}} = (2.8^{+0.7}_{-0.6}) \times 10^{-9},$$

$$\mathrm{BR}(B_d \to \mu^+\mu^-)_{\mathrm{exp}} = (3.9^{+1.6}_{-1.4}) \times 10^{-10}\,.$$

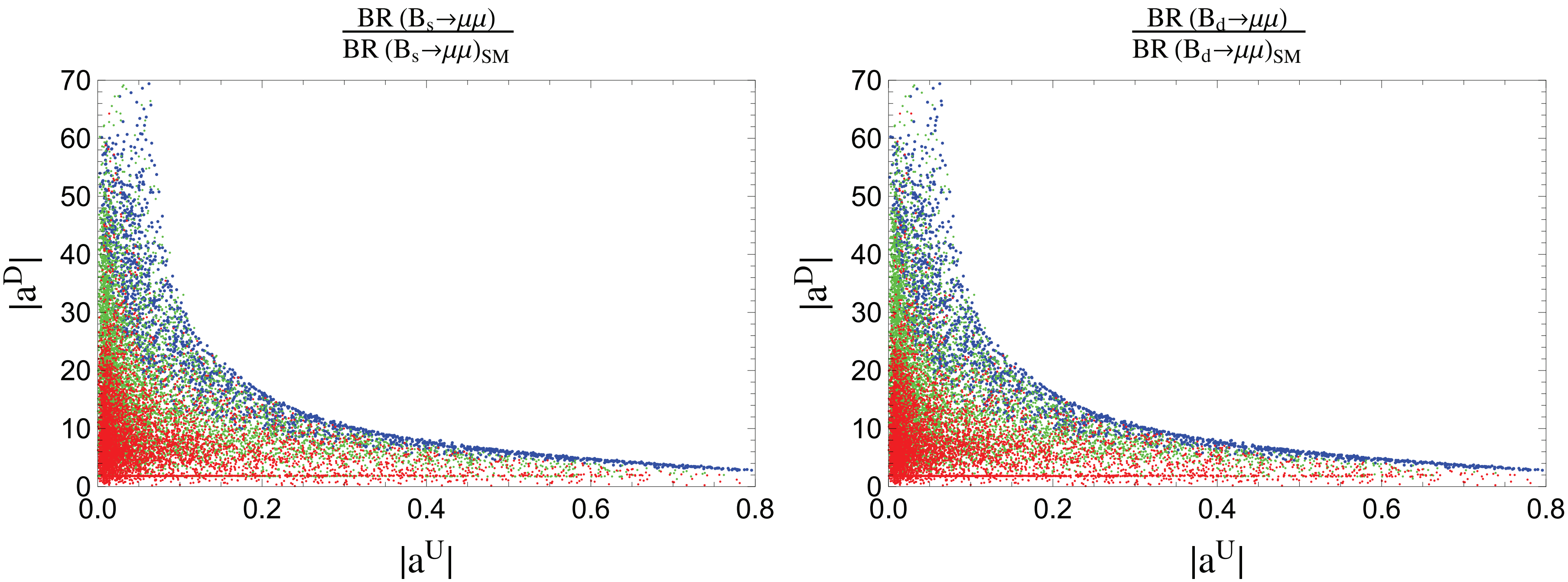
These data provide the most stringent constraints of the alignment parameters.



Bounds from meson mixing observables. Left panel: experimentally preferred regions, as computed in our model in the leading log approximation. The dark purple region is favored by the measurement of B_s mixing, the purple region by B_d mixing, and the dark pink (pink) region by the phase (mass difference) of the Kaon mixing system. D meson mixing does not give any interesting bound on the parameter space and it is not shown. Right panel: corresponding B_s results as obtained scanning the parameter space and using the full RG running. The yellow, red, and green points corresponds to a Wilson coefficient whose magnitude relative to the present bound from B_s mixing is $< 1/3, [1/3, \mathbf{1}], > \mathbf{1}$ relative to the value that yields the present bound from B_s mixing.



Leading log prediction for the branching ratios for $B_s \to \mu^+\mu^-$ (left panel) and $B_d \to \mu^+\mu^-$ (right panel) relative the the SM, as a function of a^U and a^D, with fixed $\tan\beta = 10$, $\cos(\beta - \alpha) = 0$, and $m_A = m_H = 400$ GeV. The regions in pink are allowed at the 2σ level by the present measurements. The purple shaded regions are anticipated by the more precise HL-LHC measurements, assuming a measured central value equal to the SM prediction. The gray shaded regions produce Landau poles in the Yukawa couplings below $M_{\rm P}$.



The branching ratio for $B_s \to \mu^+\mu^-$ (left panel) and for $B_d \to \mu^+\mu^-$ (right panel) relative to the SM, obtained via scanning the parameter space and using the full RG running, with fixed $\tan\beta = 10$, $\cos(\beta - \alpha) = 0$, and $m_A = m_H = 400$ GeV. The yellow, red, green and blue points corresponds to branching ratios normalized to the SM prediction $< \mathbf{0.4}, [\mathbf{0.4}, \mathbf{1.1}], [\mathbf{1.1}, 10], > 10$. In boldface we denote the range preferred by the LHCb and ATLAS measurements of $B_s \to \mu^+\mu^-$.

The red points shown in the left plot above correspond roughly to the regions allowed by the experimental measurements at the 2σ level.

4. Interesting constraints also arise in $B \to \tau\nu$. The present data yields

$$\mathrm{BR}(B \to \tau\nu)_{\mathrm{exp}} = (1.06 \pm 0.19) \times 10^{-4},$$

which is in a relatively good agreement with the SM prediction,

$$\mathrm{BR}(B \to \tau\nu)_{\mathrm{SM}} = (0.848^{+0.036}_{-0.055}) \times 10^{-4}.$$

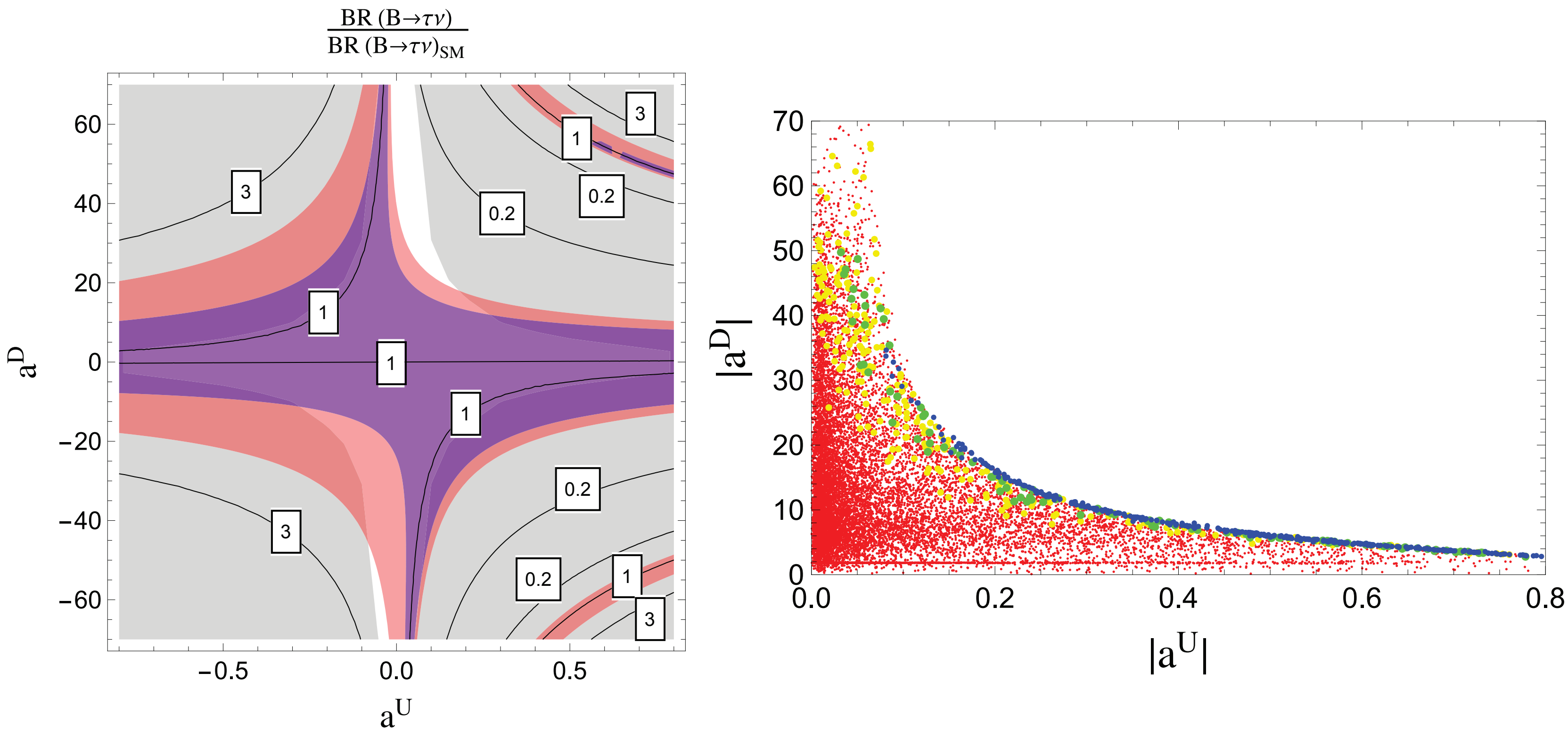
The branching ratio in the 2HDM relative to that of the SM is given by

$$\frac{\mathrm{BR}(B \to \tau\nu)}{\mathrm{BR}(B \to \tau\nu)_{\mathrm{SM}}} = \left| 1 - \frac{m_B^2}{m_b} \frac{v \tan\beta}{\sqrt{2} K_{ub} m_{H^\pm}^2} \sum_i \left[K_{ui} \rho_{3i}^{D*} + K_{ib}^* \rho_{i1}^{U*} \right] \right|^2 .$$

5. If a heavy CP-even Higgs boson H is discovered, then its branching ratios provide critical tests of the A2HDM approach.

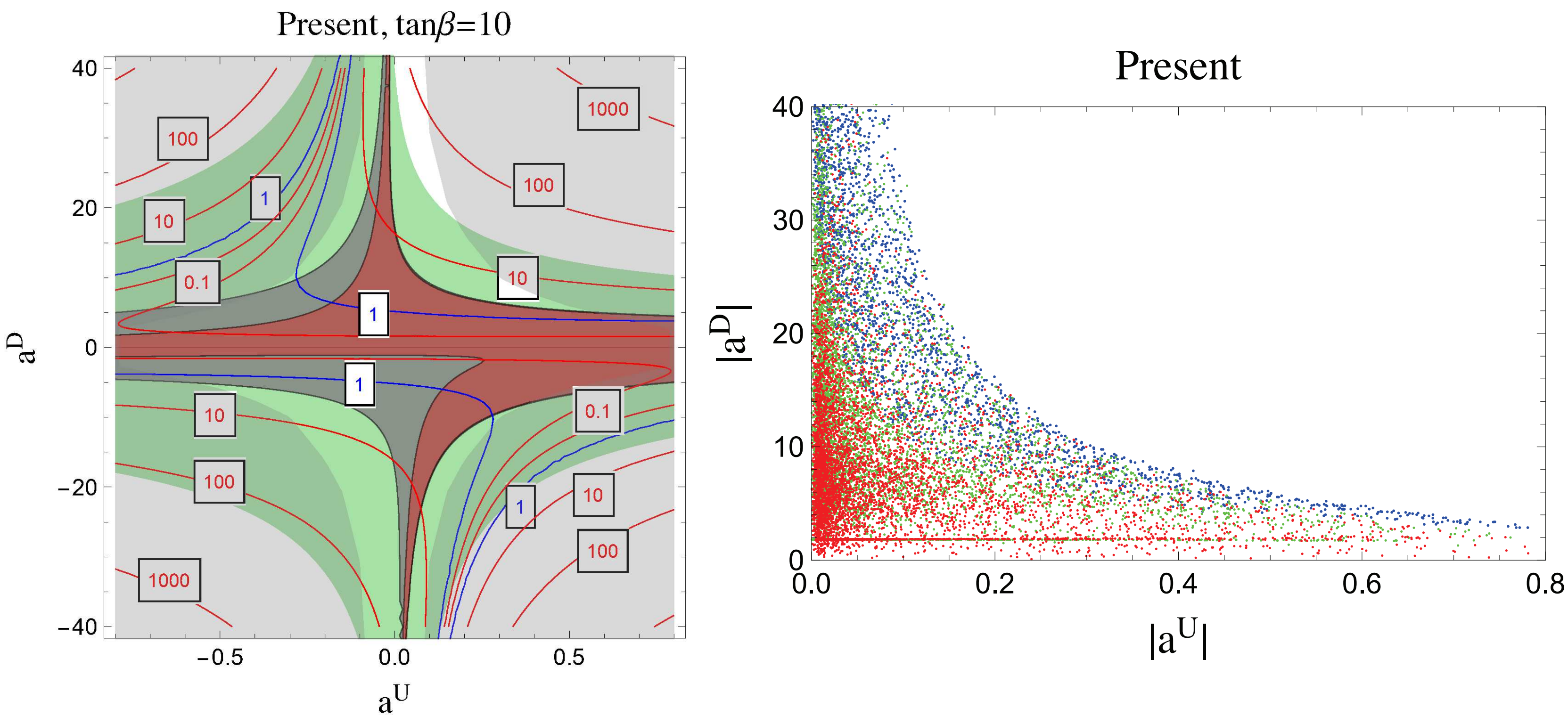
- Possible flavor non-diagonal decays, e.g. $H \to b\bar{s}$, $\bar{b}s$
- Non-standard ratios of BRs, e.g.

$$\frac{\mathrm{BR}(H \to \bar{b}b)}{\mathrm{BR}(H \to \tau^+\tau^-)} \neq \frac{3m_b^2}{m_\tau^2} .$$



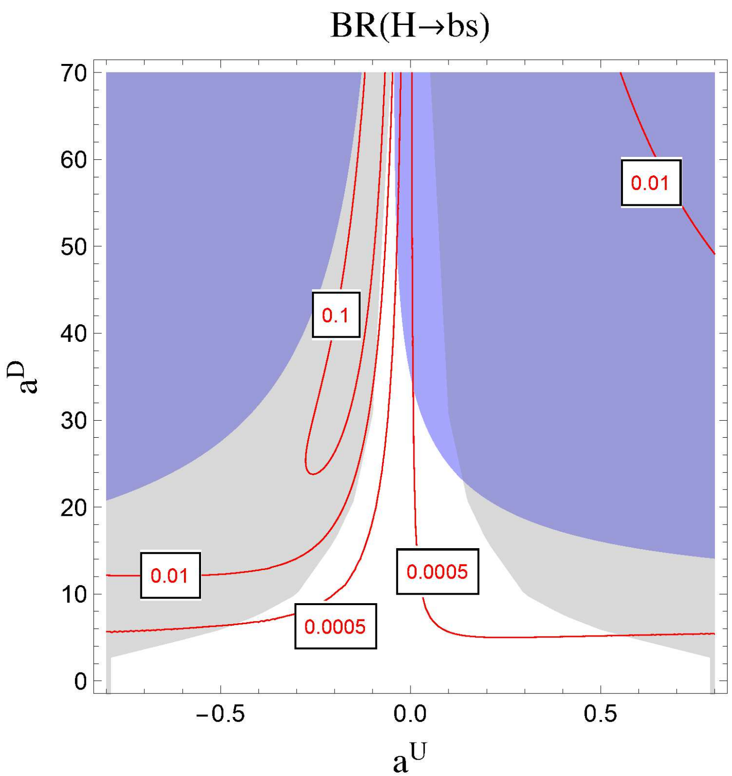
The ratio $\mathrm{BR}(B \to \tau\nu)/\mathrm{BR}(B \to \tau\nu)_{\mathrm{SM}}$ at fixed $\tan\beta = 10$ and $m_{H^\pm} = 400$ GeV. Left panel: leading log predictions, where the pink region is favored by the measurement of $B \to \tau\nu$. The purple region is anticipated by future measurement at Belle II, under the assumption that the central value of the measurement is given by the SM prediction. Right panel: result of the parameter space scan, using the full RG running. Yellow, red, green and blue points correspond to the ratios < 0.2, $[\mathbf{0.79}, \mathbf{1.71}]$, $[\mathbf{1.71}, 3]$, > 3, respectively. In boldface we denote the range preferred by the present world average for BR$(B \to \tau\nu)$.

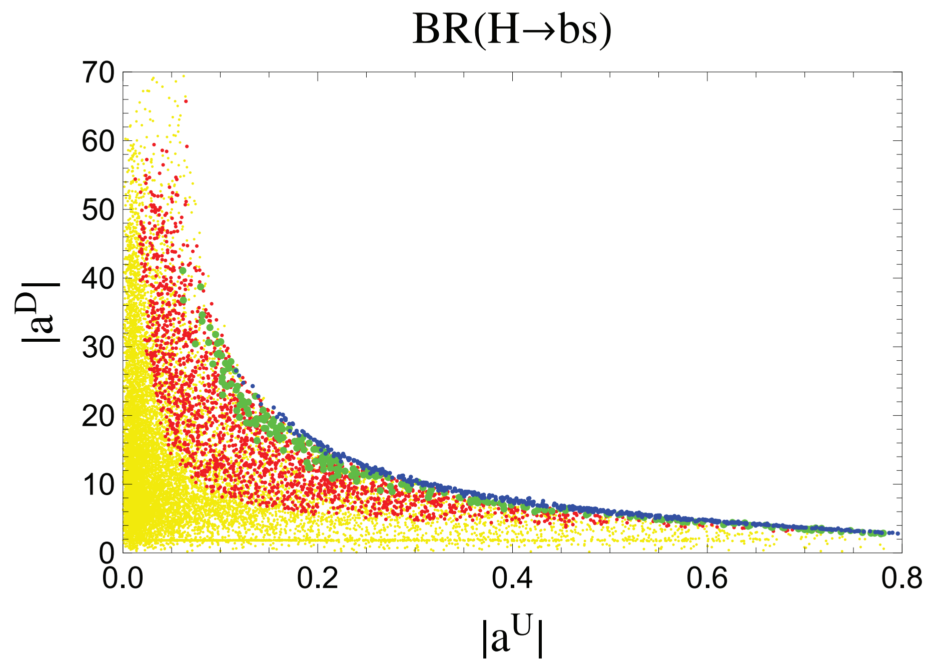
Summary Plots



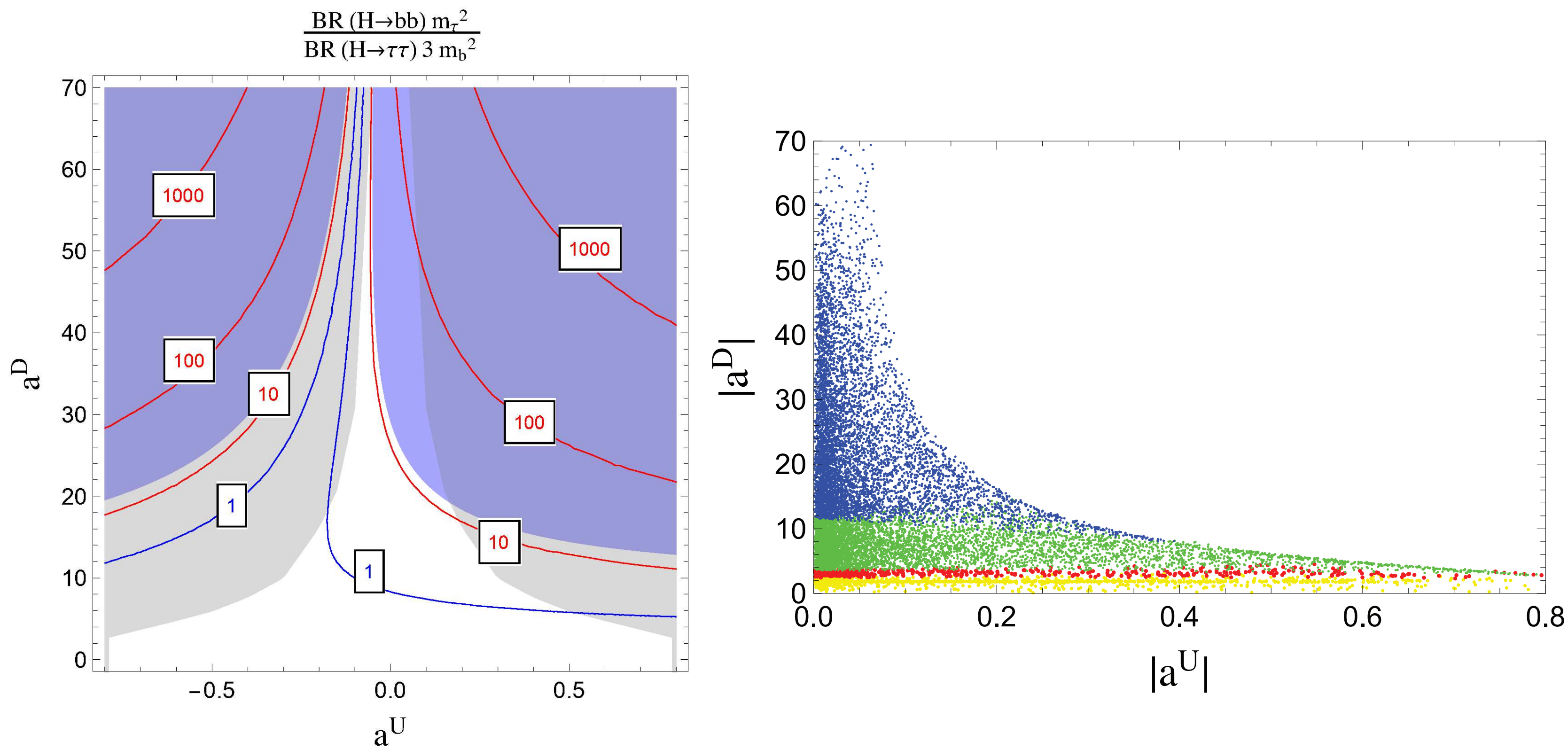
Summary of the present day constraints and predictions for the heavy Higgs phenomenology, with $\cos(\beta-\alpha)=0$, $\tan\beta=10$ and $m_A=m_H=m_{H^\pm}=400$ GeV. Left panel: Predictions of the leading log approximation. The contours represent the ratio $\mathrm{BR}(H\to b\bar{b})m_\tau^2/[\mathrm{BR}(H\to\tau^+\tau^-)3m_b^2]$. The reddish-brown regions are favored by all flavor constraints. Green, blue-gray and tan regions are favored by the measurement of $B\to\tau\nu B_s$ mixing and $B_s\to\mu^+\mu^-$, respectively. The gray shaded regions produce Landau poles in the Yukawa couplings below M_{P}. Right panel: Result of the parameter scan using full RG running. Blue points correspond to points allowed by the measurement of $B\to\tau\nu$, but not by the measurement of B_s mixing or $B_s\to\mu^+\mu^-$. Green points are allowed by the measurements of $B\to\tau\nu$ and of meson mixing but not by $B_s\to\mu^+\mu^-$. Red points are allowed by all constraints. In the solid white region, Landau poles in the Yukawa couplings are produced below M_{P}.

If heavy Higgs boson decays are observed





Assuming $\tan\beta = 10$, $\cos(\beta - \alpha) = 0$, and $m_H = 400$ GeV. Left panel: Leading log prediction for $\mathrm{BR}(H \to \bar{b}s,\, b\bar{s})$. The blue shaded regions have been probed by the LHC searches for $H, A \to \tau^+\tau^-$, $b\bar{b}$. The gray shaded regions produce Landau poles below the Planck scale M_{P}. Right panel: $\mathrm{BR}(H \to \bar{b}s,\, b\bar{s})$ obtained by scanning the parameter space and using the full RG running. Yellow, red, green and blue colors correspond to $\mathrm{BR} < 0.0005$, $[0.0005, 0.01]$, $[0.01, 0.1]$, and > 0.1 based on a full numerical scan.



Assuming $\tan\beta = 10$, $\cos(\beta - \alpha) = 0$, and $m_H = 400$ GeV. Left panel: Leading log prediction for the branching ratios of the heavy Higgs boson, H. The blue contours represent the prediction of a Type II 2HDM. The gray shaded regions produce Landau poles below the Planck scale $M_{\rm P}$. The blue shaded regions have been probed by the LHC searches for heavy scalars. Right panel: Branching ratios obtained by scanning the parameter space and using the full RG running. The yellow, red, green and blue points correspond to: upper left panel, $\mathrm{BR}(H \to \bar{b}b) m_\tau^2 / \mathrm{BR}(H \to \tau^+\tau^-) 3 m_b^2 < \mathbf{1}, [\mathbf{1}, 10], [10, 100], > 100$.

Conclusions

- The LHC Higgs data is consistent with a SM-like Higgs boson with suppressed Higgs-mediated FCNCs.

- It is tempting to anticipate the existence of an extended Higgs sector in light of the non-minimality of the SM.

- A non-minimal Higgs sector must exhibit two types of approximate alignments:
  - Higgs alignment, in which the observed Higgs boson mass eigenstate is approximately aligned value (in field space) in the direction of the scalar vacuum expectation.
  - Flavor alignment, in which the neutral Higgs-fermion Yukawa coupling matrices are approximately diagonal in the basis of diagonal quark and (charged) lepton mass matrices.
- Different mechanisms for achieving these alignments have been exhibited. Distinguishing among them will be an important task for the precision Higgs program at the LHC and any future collider. Ultimately, the discovery of additional scalars will be critical for further progress.