

Extended Higgs Sectors at Present And Future Colliders

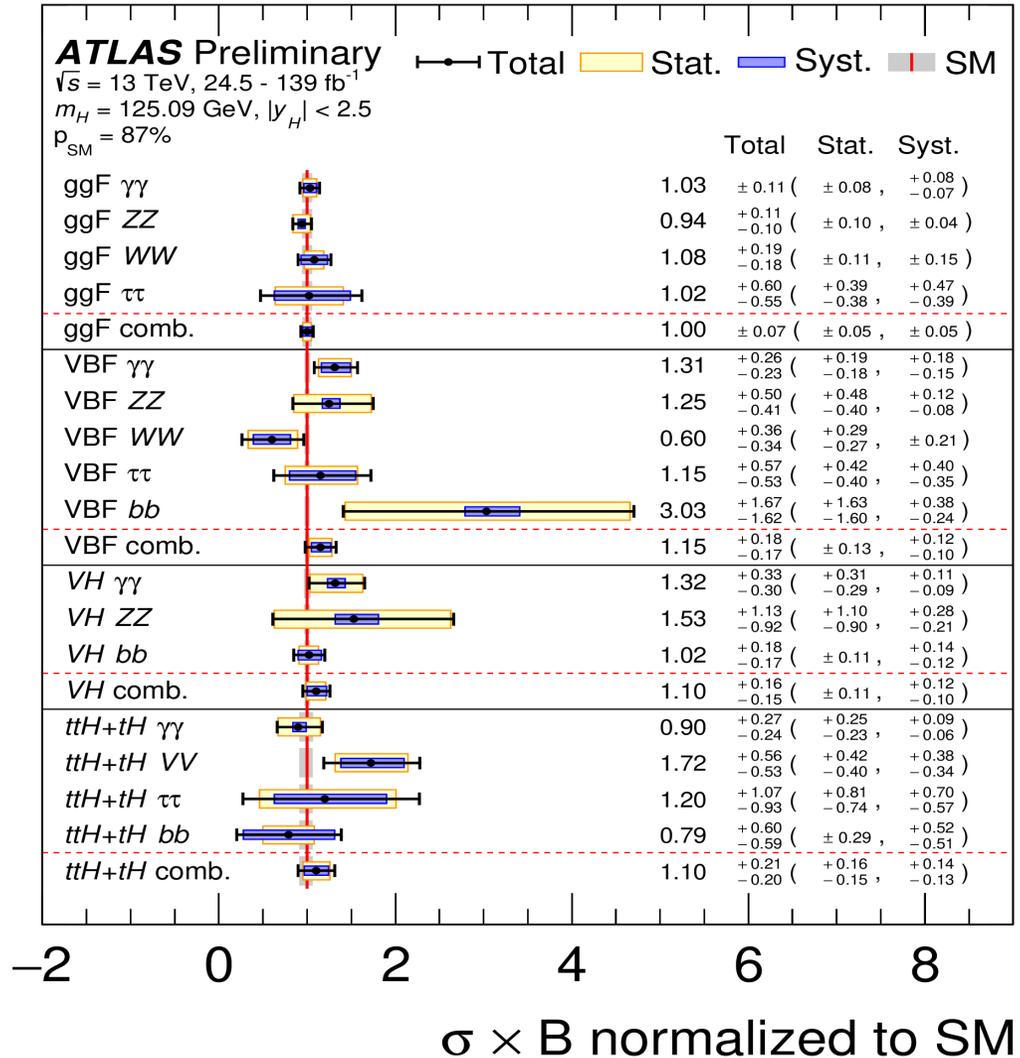


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Charged Higgs Online
Workshop

Outline

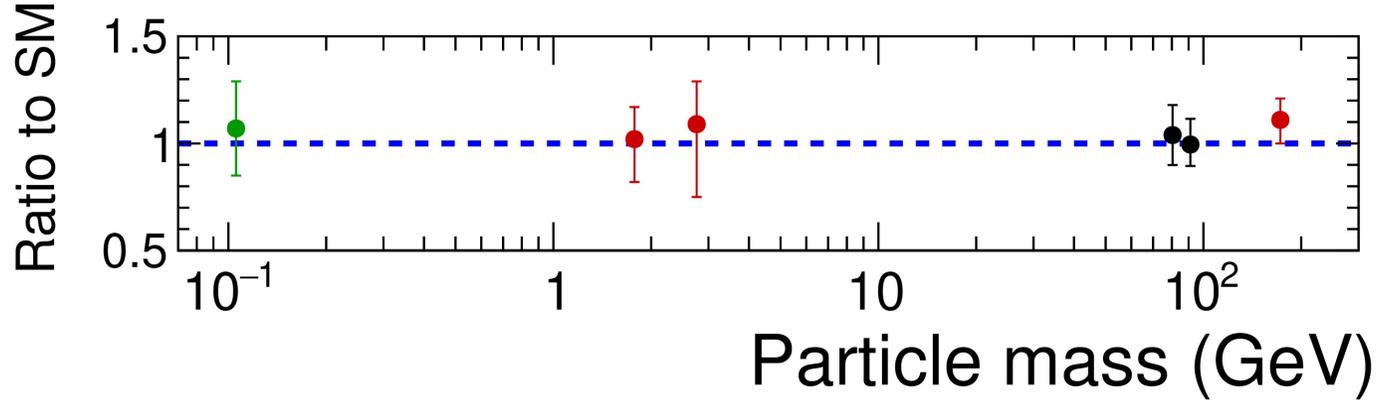
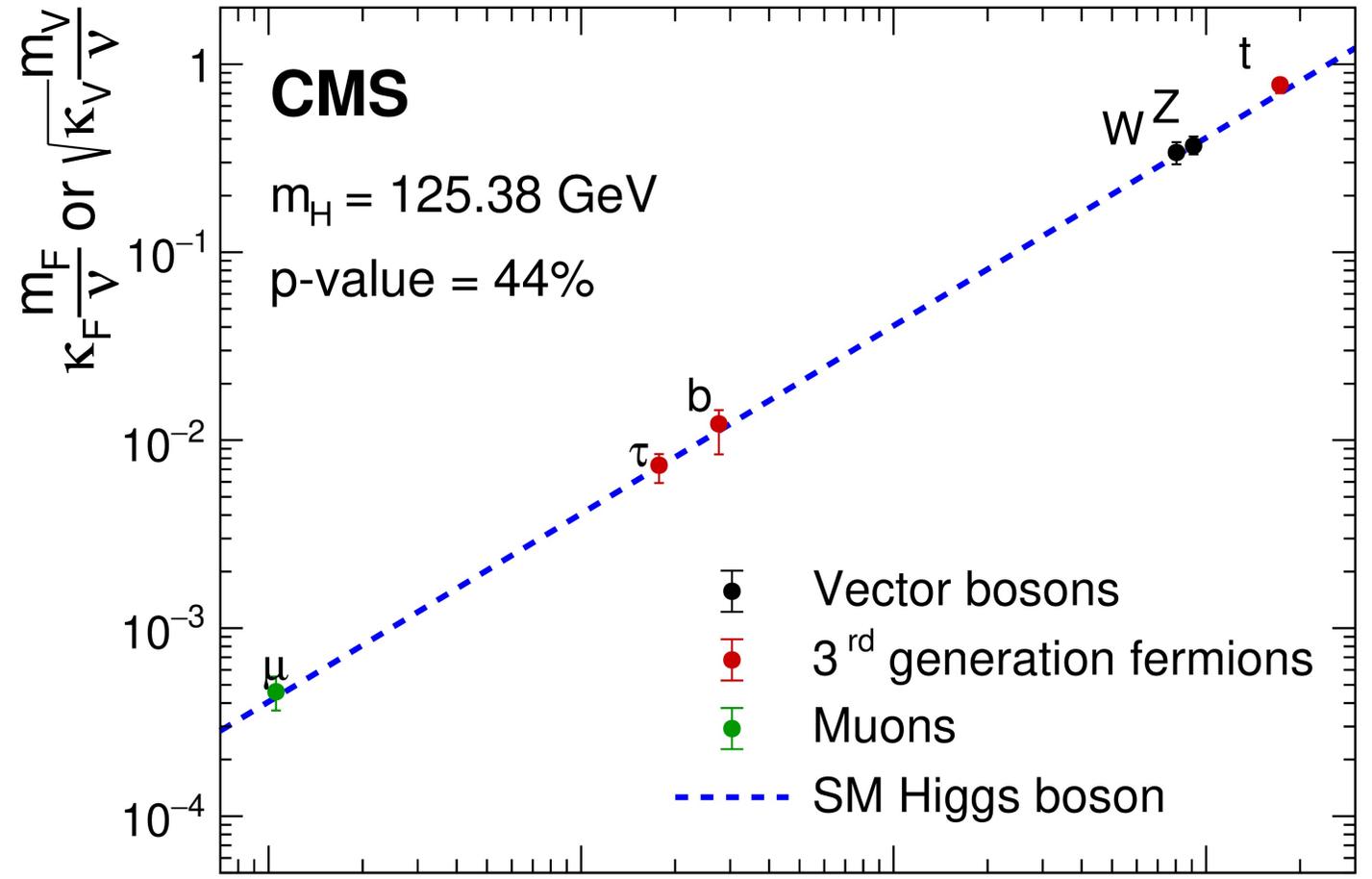
1. Motivating an extended Higgs sector
2. Constraints on Extended Higgs Sectors
 - The electroweak ρ parameter and the Georgi-Machacek model
 - A tale of two alignment mechanisms and the 2HDM
3. Fingerprinting nonminimal Higgs sectors at future colliders
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Nine years after the discovery of the Higgs boson, the data from Runs 1 and 2 of the LHC are well described by the Standard Model.



Taken from ATLAS collaboration, ATLAS-CONF-2020-027
 Cross sections times branching fraction for ggF , vector boson fusion (VBF), VH and $t\bar{t}H+tH$ production in each relevant decay mode, normalized to their Standard Model (SM) predictions. The values are obtained from a simultaneous fit to all channels. The cross sections of the ggF , $H \rightarrow b\bar{b}$, VH , $H \rightarrow WW^*$ and VH , $H \rightarrow \tau\tau$ processes are fixed to their SM predictions. Combined results for each production mode are also shown, assuming SM values for the branching fractions into each decay mode. The black error bars, blue boxes and yellow boxes show the total, systematic, and statistical uncertainties in the measurements, respectively. The gray bands show the theory uncertainties in the predictions. The level of compatibility between the measurement and the SM prediction corresponds to a p -value of $p_{\text{SM}}=87\%$, computed using the procedure outlined in the text with 16 degrees of freedom.

35.9-137 fb⁻¹ (13 TeV)



Nevertheless, given the current precision of the Higgs data, the possibility that the Higgs sector contains more than one physical scalar cannot be excluded.

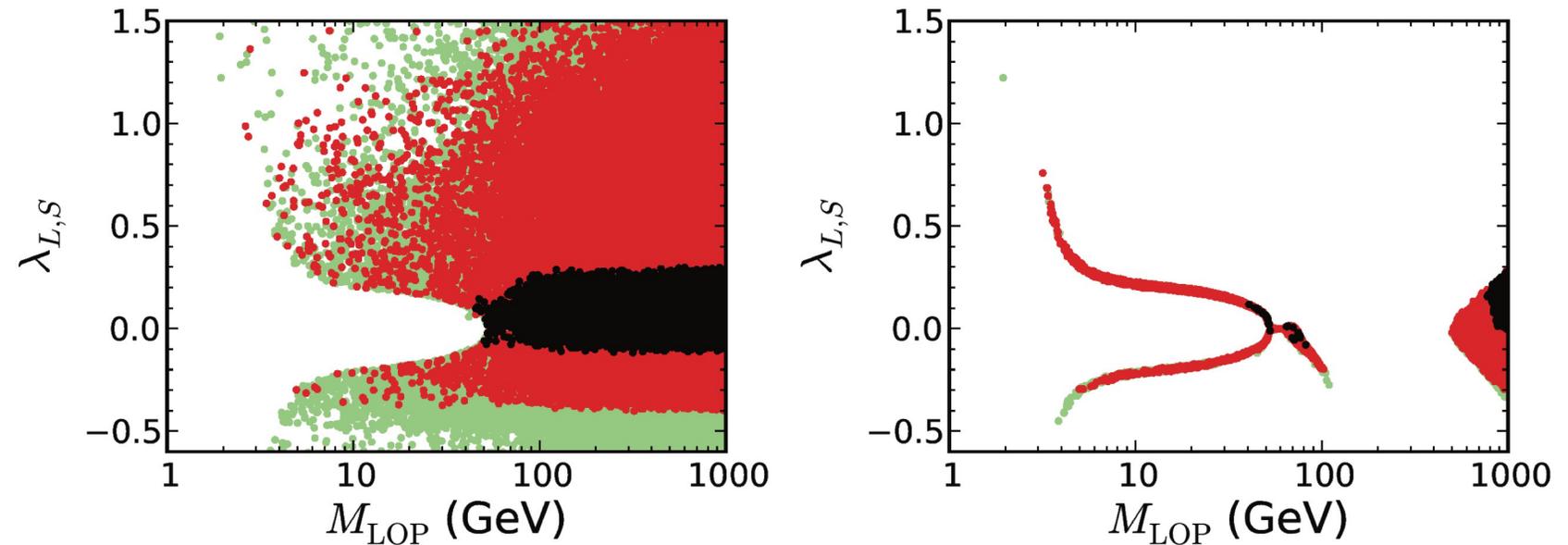
Indeed, the structure of the Standard Model (SM) is far from being of minimal form. For example, there are three generations of quarks and leptons whereas one generation would have been sufficient (“Who ordered that?”). So why shouldn’t the scalar sector be non-minimal as well?

Motivations for Extended Higgs Sectors

- Extended Higgs sectors can modify the electroweak phase transition and facilitate baryogenesis.
- Extended Higgs sectors can enhance vacuum stability.
- Extended Higgs sectors can provide a dark matter candidate.
- Extended Higgs sectors can be employed to provide a solution to the strong CP problem (\Rightarrow axion)
- 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).

A neutral scalar dark matter candidate—the inert doublet model (IDM)

The IDM is a 2HDM in which the scalar potential in a basis where $\langle H_1 \rangle = v/\sqrt{2}$ and $\langle H_2 \rangle = 0$ exhibits an exact \mathbf{Z}_2 discrete symmetry. All fields of the IDM—gauge bosons, fermions and the Higgs doublet field H_1 are even under \mathbf{Z}_2 . Only the Higgs doublet field H_2 is \mathbf{Z}_2 -odd. Hence, there is no mixing between H_1 and H_2 . In particular, the SM Higgs boson h resides in H_1 . The lightest \mathbf{Z}_2 -odd particle (LOP) residing in H_2 is a candidate for the dark matter.



The viable IDM parameter space projected on the $(M_{\text{LOP}}, \lambda_{L,S})$ plane imposing only the upper limit (left) and the upper and lower limits (right) of the WMAP range, $0.1018 \leq M_{\text{LOP}} h^2 \leq 0.1234$. The green points correspond to all valid points in the scan, while the red and black regions show the points which remain valid when the model satisfies stability and perturbativity up to a scale $\Lambda = 10^4$ GeV and the GUT scale $\Lambda = 10^{16}$ GeV, respectively. Taken from A. Goudelis, B. Herrmann and O. Stål, JHEP **1309** (2013) 106.

Note: deviations of h from SM Higgs properties can arise at one-loop (e.g., H^\pm loop corrections to $h \rightarrow \gamma\gamma$).

Extended Higgs Sectors are Highly Constrained

- The electroweak ρ parameter is very close to 1.
- One neutral Higgs scalar of the extended Higgs sector must be SM-like (and identified with the Higgs boson at 125 GeV).
- At present, only one Higgs scalar has been observed.
- Higgs-mediated flavor-changing neutral currents (FCNCs) are suppressed.
- Higgs sector CP-violation has not yet been observed (with implications for electric dipole moments).
- Charged Higgs exchange at tree level (e.g. in $\bar{B} \rightarrow D^{(*)} \tau^- \bar{\nu}_\tau$) and at one-loop (e.g. in $b \rightarrow s \gamma$) can significantly constrain the charged Higgs mass and the Yukawa couplings.

The ρ -parameter constraint on extended Higgs sectors

Given that the electroweak ρ -parameter is very close to 1, it follows that a Higgs multiplet of weak-isospin T and hypercharge Y must satisfy,¹

$$\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2 \theta_W} = 1 \quad \Longleftrightarrow \quad (2T + 1)^2 - 3Y^2 = 1,$$

independently of the Higgs vacuum expectation values (vevs). The simplest solutions are Higgs singlets $(T, Y) = (0, 0)$ and hypercharge-one complex Higgs doublets $(T, Y) = (\frac{1}{2}, 1)$. For example, the latter is employed by the two Higgs doublet model (2HDM).

More generally, one can achieve $\rho = 1$ by fine-tuning if

$$\sum_{T,Y} [4T(T + 1) - 3Y^2] |V_{T,Y}|^2 c_{T,Y} = 0,$$

where $V_{T,Y} \equiv \langle \Phi(T, Y) \rangle$ is the scalar vev, and $c_{T,Y} = 1$ for complex Higgs representations and $c_{T,Y} = \frac{1}{2}$ for real $Y = 0$ Higgs representations.

¹ Y is normalized such that the electric charge of the scalar field is $Q = T_3 + Y/2$.

Example: the Georgi-Machacek (GM) model (complex doublet, complex triplet, real triplet scalars)

$$(T, Y; c): \Phi=(\frac{1}{2}, 1; 1), X=(1, 2; 1), T=(1, 0; \frac{1}{2})$$

If $V_{1,2} = V_{1,0}$ then $\sum_{T,Y} [4(T(T+1) - 3Y^2)] |V_{T,Y}|^2 c_{T,Y} = 4(|V_{1,0}|^2 - |V_{1,2}|^2) = 0$, and it follows that $\rho = 1$.

One can write down a custodial symmetric scalar potential that yields $V_{1,2} = V_{1,0}$ at tree-level. However, due to custodial symmetry violating hypercharge gauge and Yukawa interactions, one finds that custodial symmetry violating terms in the scalar potential are generated at the loop level and are divergent and require counterterms. That is, a custodial symmetric scalar potential must be unnaturally fine-tuned. There are two options:

- Accept the fine-tuning of the scalar potential.
- Impose the custodial symmetric scalar potential at a very high energy scale (imposed by a mechanism to be determined by the (unknown) ultraviolet completion, and use RG evolution to permit (hopefully) small custodial violation at the electroweak scale.

A few phenomenological interesting features of the GM model:

- Doubly charged Higgs scalars
- Non-zero tree-level $H^\pm W^\mp Z$ vertex
- Possibility of an hVV coupling that is *larger* than the corresponding SM value

In the Georgi-Machacek model, the existence of doubly-charged Higgs bosons implies that

$$\sum_i g_{h_i W^+ W^-}^2 = g^2 m_W^2 + \sum_k |g_{\phi_k^{++} W^- W^-}|^2,$$

where the sum over i is taken over all CP-even Higgs bosons of the model. The presence on the last term on the right hand side above means that individual $h_i VV$ couplings can exceed the corresponding coupling of the SM.

Decoupling limit of the GM Model

Denote the doublet and triplet vevs by v_ϕ and v_χ , respectively. Then $v^2 \equiv v_\phi^2 + 8v_\chi^2 = (246 \text{ GeV})^2$. Define $\cos \theta_H \equiv v_\phi/v$. The scalar spectrum consists of multiplets that transform as a **5**, **3** and **1** under the custodial SU(2) symmetry of the scalar potential:

$$\{H_5^{\pm\pm}, H_5^\pm, H_5^0\}, \quad \{H_3^\pm, H_3^0\}, \quad \{H_1^0\}, \quad \{H_1'^0\},$$

where the 5-plet and triplet masses are denoted by m_5 and m_3 , respectively. The two custodial singlets mix to produce mass eigenstates,

$$h = H_1^0 \cos \alpha - H_1'^0 \sin \alpha, \quad H = H_1^0 \sin \alpha + H_1'^0 \cos \alpha.$$

In the decoupling limit, $m_5 \simeq m_3 \gg v$, and $\cos \alpha \simeq \cos \theta_H \simeq 1$. In this case, we can identify h as the SM-like Higgs boson, with coupling modifiers,^a

$$\kappa_V \simeq 1 + \frac{3M_1^2 v^2}{8m_3^4}, \quad \kappa_F \simeq 1 - \frac{M_1^2 v^2}{8m_3^4},$$

where the mass parameter M_1 appears as a coefficient of one of the two cubic terms in the scalar potential. M_1 can be as large as $\mathcal{O}(m_3)$. Note that κ_V is *larger* than 1, which signals the presence of doubly charged Higgs bosons in the scalar spectrum.

^aP.M. Ferreira, H.E. Haber, H.E. Logan and Y. Wu, in preparation.

SM-like Higgs boson with suppressed Higgs-mediated FCNCs: A tale of two alignment mechanisms

1. Higgs field alignment

In the limit in which one of the Higgs mass eigenstate fields is approximately aligned with the direction of the scalar doublet vacuum expectation value (vev) in field space, the tree-level properties of the corresponding scalar mass eigenstate approximate those of the SM Higgs boson.

2. Flavor alignment

The quark mass matrices derive from the Higgs-fermion Yukawa couplings when the neutral Higgs fields acquire vevs. Flavor alignment arises when the diagonalization of the quark mass matrices simultaneously diagonalize the neutral Higgs quark interactions, implying the absence of tree-level Higgs-mediated FCNCs.

The Higgs field alignment limit: approaching the SM Higgs boson

Consider an extended Higgs sector with n hypercharge-one Higgs doublets Φ_i and m additional singlet Higgs fields ϕ_i .

After minimizing the scalar potential, we assume that only the neutral Higgs fields acquire vacuum expectation values (in order to preserve $U(1)_{\text{EM}}$),

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

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

The Higgs basis

Define new linear combinations of the hypercharge-one doublet Higgs fields (the so-called *Higgs basis*). In particular,

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

and H_2, H_3, \dots, H_n are the other linear combinations of doublet scalar fields such that $\langle H_i^0 \rangle = 0$ (for $i = 2, 3, \dots, n$).

That is H_1^0 is **aligned** in field space with the direction of the Higgs vacuum expectation value (vev). Thus, if $\sqrt{2} \operatorname{Re}(H_1^0) - v$ is a mass-eigenstate, then the tree-level couplings of this scalar to itself, to gauge bosons and to fermions are precisely those of the SM Higgs boson, h^0 . This is the exact **alignment limit**.

A SM-like Higgs boson

In general, $\sqrt{2} \operatorname{Re}(H_1^0) - v$ is not a mass-eigenstate due to mixing with other neutral scalars. Nevertheless, a SM-like Higgs boson exists if either:

- the diagonal squared masses of the other Higgs basis scalar fields are all large compared to the mass of the observed Higgs boson (the so-called *decoupling limit*).

and/or

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

Higgs field alignment with or without decoupling

1. The decoupling limit

In the decoupling limit, there is a new mass parameter, $M \gg v$, such that all physical Higgs masses with one exception are of $\mathcal{O}(M)$. The Higgs boson, with $m_h \sim \mathcal{O}(v)$, is SM-like, due to approximate Higgs field alignment.

2. Higgs alignment limit without decoupling

In models of alignment with suppressed scalar mixing, the masses of all Higgs scalars, both SM-like and non-SM-like, can be of $\mathcal{O}(v)$. The absence (suppression) of scalar mixing is due to an exact (approximate) symmetry or the result of a finely tuned scalar potential.

Exhibiting Higgs field alignment in the 2HDM

The Higgs basis fields of the 2HDM are,

$$H_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}} \left(v + iG^0 + \sum_{k=1}^3 q_{k1} h_k \right) \end{pmatrix}, \quad H_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}} \sum_{k=1}^3 q_{k2} h_k \end{pmatrix},$$

where h_1 , h_2 and h_3 are three neutral scalars, and the quantities q_{k1} (real) and q_{k2} (complex), for $k = 1, 2, 3$, depend on mixing parameters that determine the neutral scalar mass eigenstates. The Goldstone bosons (G^\pm and G^0) are absorbed into the longitudinal modes of the gauge bosons W^\pm and Z , respectively. The scalar potential of the most general 2HDM is CP-violating, in which case the h_k are not states of definite CP.

The Higgs field alignment limit is most easily obtained by considering the VVH and Yukawa interactions:

$$\mathcal{L}_{VVH} = \left(gm_W W_\mu^+ W^{\mu-} + \frac{g}{2 \cos \theta_W} m_Z Z_\mu Z^\mu \right) \sum_k q_{k1} h_k$$

$$\mathcal{L}_{\text{Yuk}} = -\frac{1}{v} \sum_k \bar{D} \left\{ q_{k1} M_D + \frac{v}{\sqrt{2}} \left[q_{k2} \rho^{D\dagger} P_R + q_{k2}^* \rho^D P_L \right] \right\} D h_k$$

$$- \frac{1}{v} \sum_k \bar{U} \left\{ q_{k1} M_U + \frac{v}{\sqrt{2}} \left[q_{k2}^* \rho^U P_R + q_{k2} \rho^{U\dagger} P_L \right] \right\} U h_k$$

$$- \left\{ \bar{U} [K \rho^{D\dagger} P_R - \rho^{U\dagger} K P_L] D H^+ + \text{h.c.} \right\},$$

In the Higgs field alignment limit, tree-level FCNCs mediated by h_2 and h_3 are present due to the off-diagonal elements of ρ^U and ρ^D .

where $P_{R,L} \equiv \frac{1}{2}(1 \pm \gamma_5)$, $Q = U$ and D are three flavors of up and down quark fields, the M_Q are the 3×3 up and down-type diagonal quark mass matrices, K is the CKM mixing matrix and the ρ^Q are generic complex 3×3 matrices. Thus, in the Higgs field alignment limit where h_1 is the SM-like Higgs boson,

$$q_{11} = q_{22} = -iq_{23} = 1, \quad q_{21} = q_{31} = q_{12} = 0.$$

Flavor alignment to avoid tree-level Higgs-mediated FCNCs

1. In the 2HDM, choose the ρ^Q to be diagonal matrices.

This requirement, if implemented generically, is not stable under RG evolution.

The diagonality condition can be imposed either at

- the electroweak scale by fine-tuning [A. Pich and P. Tuzon, arXiv: [0908.1554](#)]
or at
- a very high energy scale, in which case tree-level Higgs-mediated FCNCs are generated at the electroweak scale and provide potential signals for discovery [S. Gori, H.E. Haber and E. Santos, [arXiv:1703.05873](#)]

2. In the 2HDM, impose a discrete symmetry on the Higgs Lagrangian such the the ρ^Q are diagonal. Different choices of the discrete symmetry yield the well-known Types I, II, III (or Y) and IV (or X) Yukawa couplings of the 2HDM.

In the CP-conserving 2HDM, the neutral scalar fields are denoted by the CP-even fields h and H and a CP-odd field A . To conform with the conventions of the 2HDM literature, we identify

k	scalar	q_{k1}	q_{k2}
1	h	$\sin(\beta - \alpha)$	$\cos(\beta - \alpha)$
2	H	$\cos(\beta - \alpha)$	$-\sin(\beta - \alpha)$
3	A	0	i

In the Higgs field alignment limit h is SM-like, and $q_{21}=q_{31}=q_{12}=0 \implies \cos(\beta-\alpha)=0$.

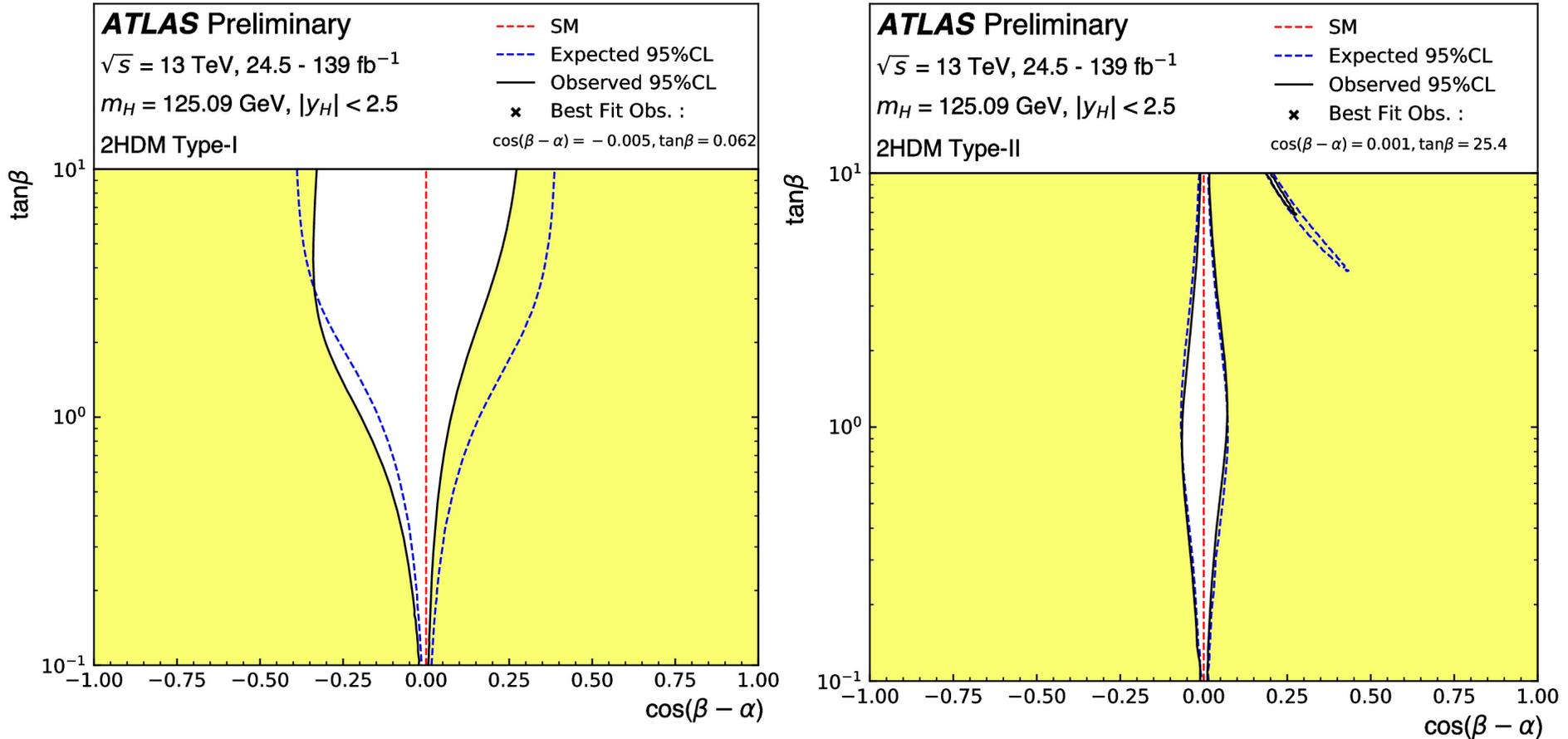
The Type I and II Yukawa couplings ρ^U and ρ^D are diagonal matrices

$$\frac{v}{\sqrt{2}}\rho^U = M_U \cot \beta, \quad \text{Types I and II,}$$

$$\frac{v}{\sqrt{2}}\rho^D = \begin{cases} M_D \cot \beta, & \text{Type I,} \\ -M_D \tan \beta, & \text{Type II.} \end{cases}$$

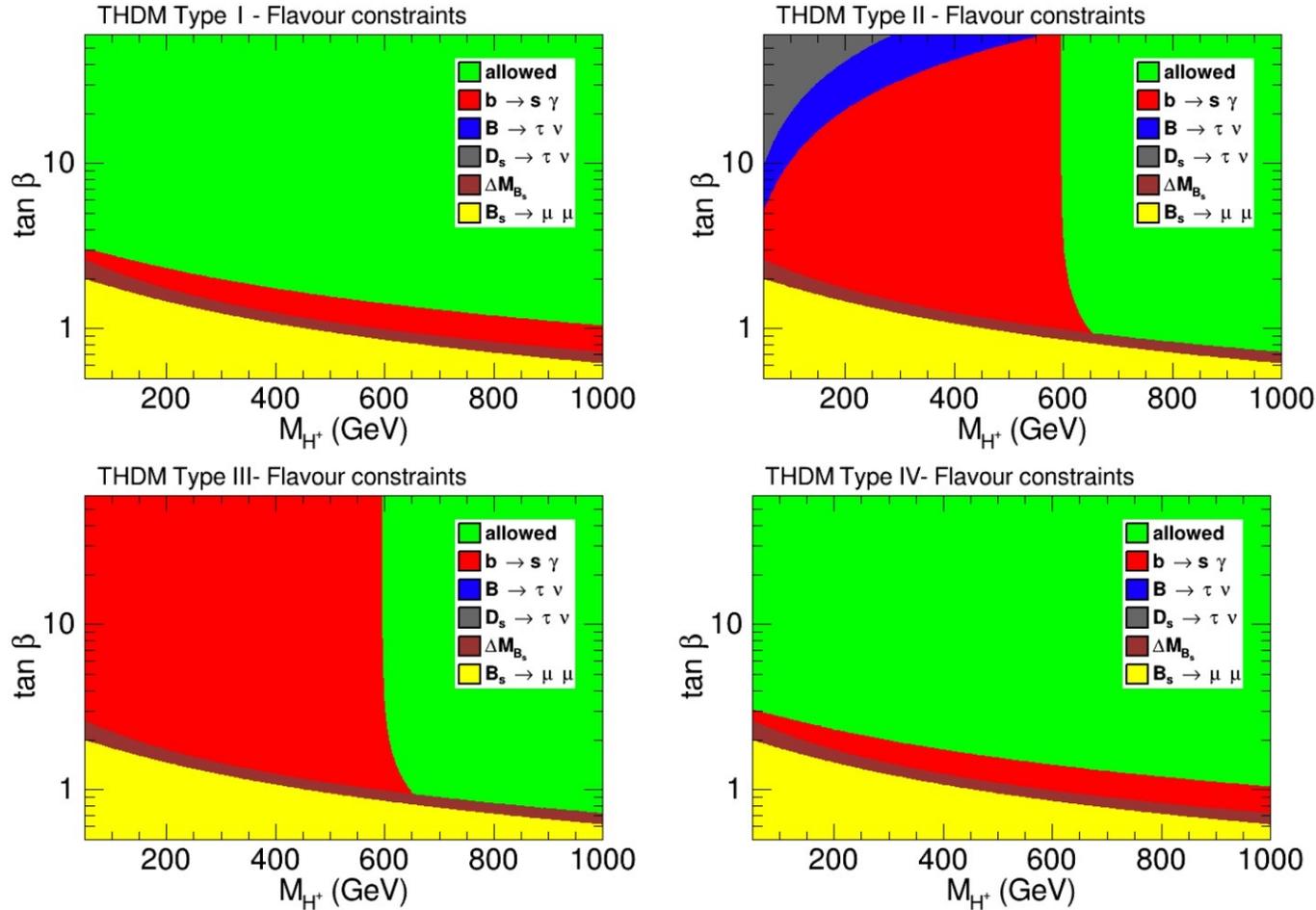
$\tan \beta = v_2/v_1$ is defined in the scalar field basis in which the discrete symmetries that define the Types I and II Yukawa couplings are manifestly realized. In this basis, α is the CP-even Higgs mixing angle.

LHC constraints on Higgs field alignment in the 2HDM



Regions of the $(\cos(\beta - \alpha), \tan \beta)$ plane of the 2HDM with Type-I and Type-II Yukawa couplings, excluded by fits to the measured rates of Higgs boson production and decays. Contours at 95% CL, defined in the asymptotic approximation by $-2 \ln \Lambda = 5.99$, are drawn for both the data and the expectation for the SM Higgs sector. Taken from ATLAS-CONF-2020-027 (29 July 2020).

Constraints on the 2HDM from flavor physics observables



Taken from A. Arbey,
F. Mahmoudi, O. Stal and
T. Stefaniak, arXiv:[1706.07414](https://arxiv.org/abs/1706.07414)

Remark: A more recent analysis
by M. Misiak, A. Rehman and
M. Steinhauser, arXiv:[2002.01548](https://arxiv.org/abs/2002.01548)
asserts that the 95% CL lower
bound on the charged Higgs mass
in the Type II (and III) 2HDM has
been strengthened to **800 GeV**.

Figure 8. Regions of the $(M_{H^+}, \tan\beta)$ parameter space excluded by flavour constraints at 95% C.L. for the different 2HDM Yukawa types. The colour coding corresponds to exclusion by different constraints, as described by the legend. The green region is consistent with all constraints. The obtained constraints are independent of the remaining 2HDM parameters.

Fingerprinting nonminimal Higgs sectors

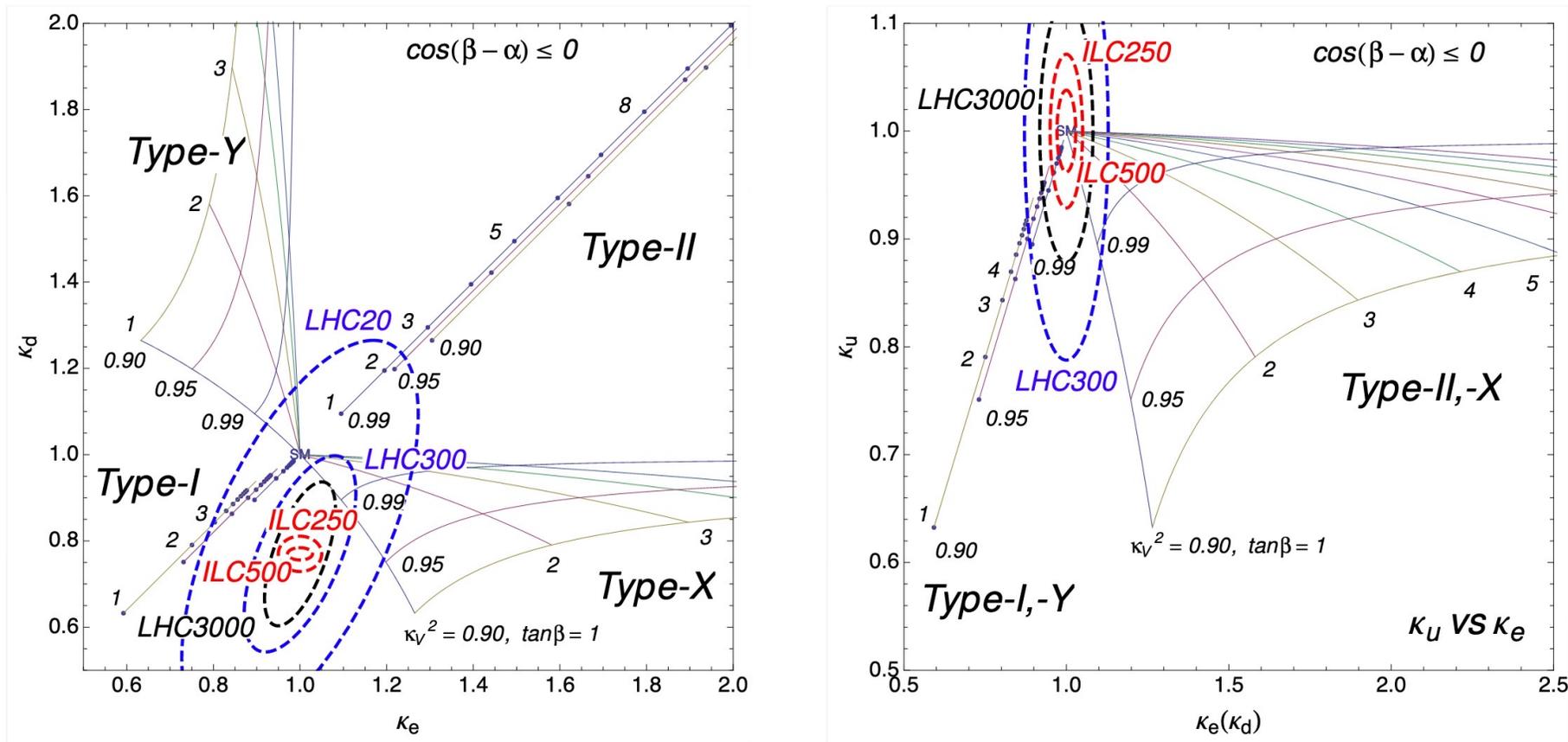


FIG. 10: The scaling factors for the Yukawa interaction of the SM-like Higgs boson in THDMs in the case of $\cos(\beta - \alpha) < 0$.

Taken from S. Kanemura, K. Tsumura, K. Yagyu and H. Yokoya, arXiv: [1406.3294](https://arxiv.org/abs/1406.3294)

In models with a universal shift in the Yukawa couplings, i.e. $\kappa_F = \kappa_U = \kappa_D$, one can distinguish among a number of different extended Higgs sectors:

	$\tan \beta$	κ_f	κ_V
Doublet-Singlet Model	—	$\cos \alpha$	$\cos \alpha$
Type-I THDM	v_0/v_{ext}	$\cos \alpha / \sin \beta = \sin(\beta - \alpha) + \cot \beta \cos(\beta - \alpha)$	$\sin(\beta - \alpha)$
GM Model	$v_0/(2\sqrt{2}v_{\text{ext}})$	$\cos \alpha / \sin \beta$	$\sin \beta \cos \alpha - \frac{2\sqrt{6}}{3} \cos \beta \sin \alpha$
Doublet-Septet Model	$v_0/(4v_{\text{ext}})$	$\cos \alpha / \sin \beta$	$\sin \beta \cos \alpha - 4 \cos \beta \sin \alpha$

TABLE V: The fraction of the VEVs $\tan \beta$ and the scaling factors κ_f and κ_V in the extended Higgs sectors with universal Yukawa couplings.

Remark: the septet scalars corresponds to $(T,Y)=(3,4)$, which also yields $\rho = 1$ without fine-tuning of the vevs.

Taken from S. Kanemura, K. Tsumura, K. Yagyu and H. Yokoya, arXiv: [1406.3294](https://arxiv.org/abs/1406.3294)

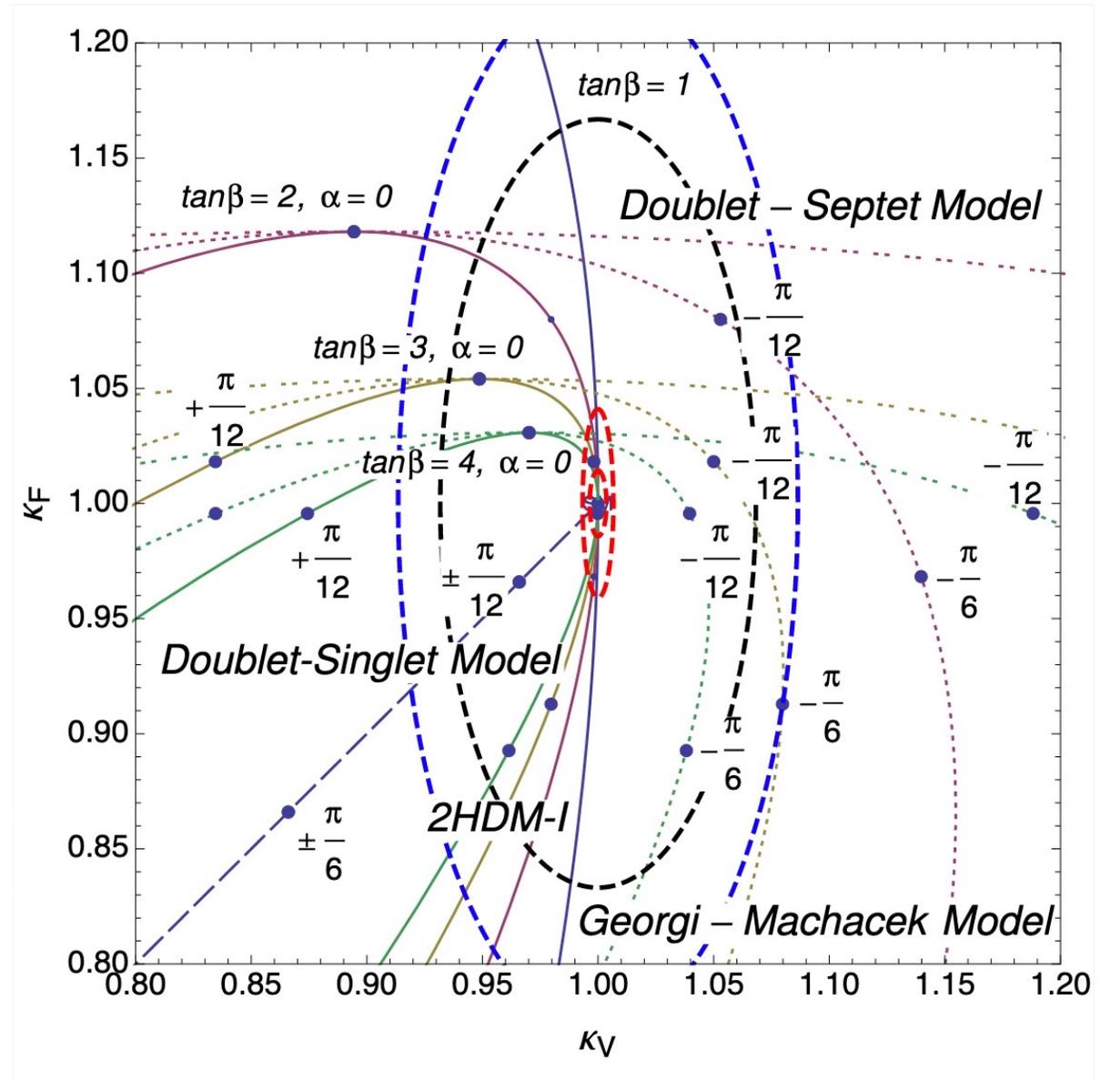


FIG. 12: The scaling factors κ_f and κ_V in models with universal Yukawa coupling constants.

CP violation originating from the scalar sector

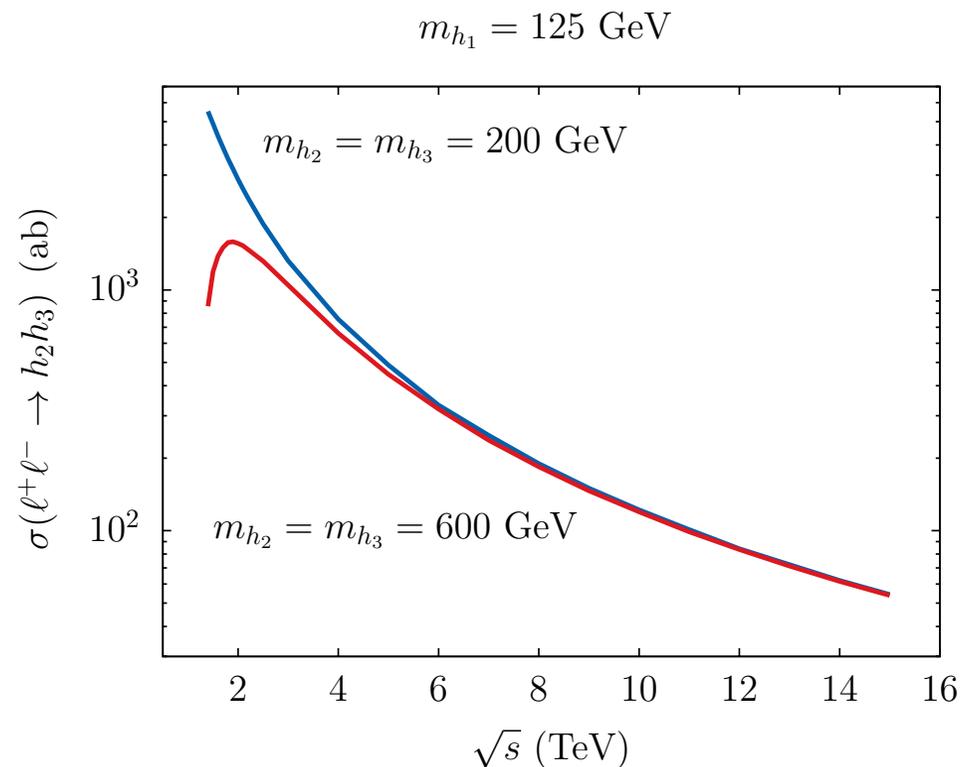
- Expected in any extended Higgs sector. Since CP-violation via the CKM matrix is already present, to turn off CP-violation effects that can arise via the scalar potential (or via the Yukawa couplings without additional symmetries) requires a fine-tuning of parameters [D. Fontes, M. Loschner, J.C. Romao and J.P. Silva, arXiv: [2103.05002](#)]
- Strongly constrained by experimental limits on the electric dipole moment of the electron [for recent work, see W. Altmannshofer, S. Gori, N. Hamer and H.H. Patel, arXiv: [2009.01258](#)]
- Interesting phenomenological features of the complex 2HDM
 - P-even, C-odd phenomena originating from the bosonic sector
 - P-odd, C-even phenomena originating from the Yukawa sector

A proposal to observe scalar sector CP violation (P-even, C-odd) at future colliders

In this example, we employ the 2HDM framework in the Higgs field alignment limit. This precludes the identification of CP violation through the observation of ZZh_1 , ZZh_k and Zh_1h_k vertices ($k=2$ or 3), since the ZZh_k vertex is absent, if $k=2$ or 3 , in the alignment limit.

Our proposal (H.E. Haber, V. Keus and R. Santos, in preparation) is to employ the observation of $h_2H^+H^-$, $h_3H^+H^-$ and Zh_2h_3 vertices. All three vertices are generically nonvanishing in the alignment limit. If CP is conserved, then h_2 and h_3 must have opposite sign CP quantum numbers, whereas H^+H^- can only couple to a CP-even scalar.

Parameter regimes exist in which both h_2 and h_3 can decay to H^+H^- with significant branching ratios (which can be as large or larger than the branching ratios into third generation fermion pairs). In such a scenario, the observation of h_2h_3 production and subsequent decays into H^+H^- would confirm the existence of P-even, C-odd phenomena in the scalar sector. This would be a program that could be pursued at multi-TeV lepton colliders such as CLIC or a future $\mu^+\mu^-$ collider.



Extended Higgs Sectors and Supersymmetry

1. The Minimal Supersymmetric Extension of the SM (MSSM)

The MSSM employs a 2HDM Higgs sector and provides a (potentially) natural framework for electroweak symmetry breaking. The observed Higgs mass of 125 GeV is a prediction of the MSSM as a function of MSSM parameters.

The most recent precision Higgs mass calculations suggest that the supersymmetry (SUSY) breaking scale M_S may be out of reach of LHC searches.

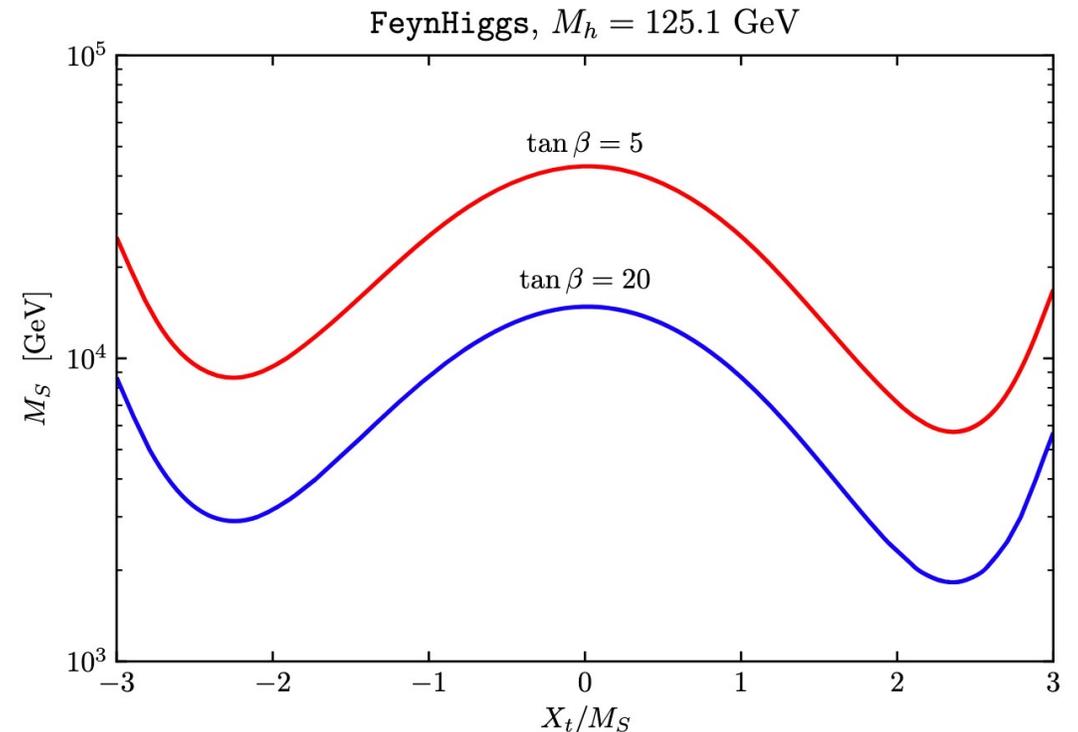


Fig. 2 Values of the SUSY mass parameter M_S and of the stop mixing parameter X_t (normalized to M_S) that lead to the prediction $M_h = 125.1$ GeV, in a simplified MSSM scenario with degenerate SUSY masses, for $\tan \beta = 20$ (blue) or $\tan \beta = 5$ (red)

Can the H , A and H^\pm be discovered at the LHC in the parameter range of $m_A \gtrsim 500$ GeV and $1 \lesssim \tan \beta \lesssim 5$?

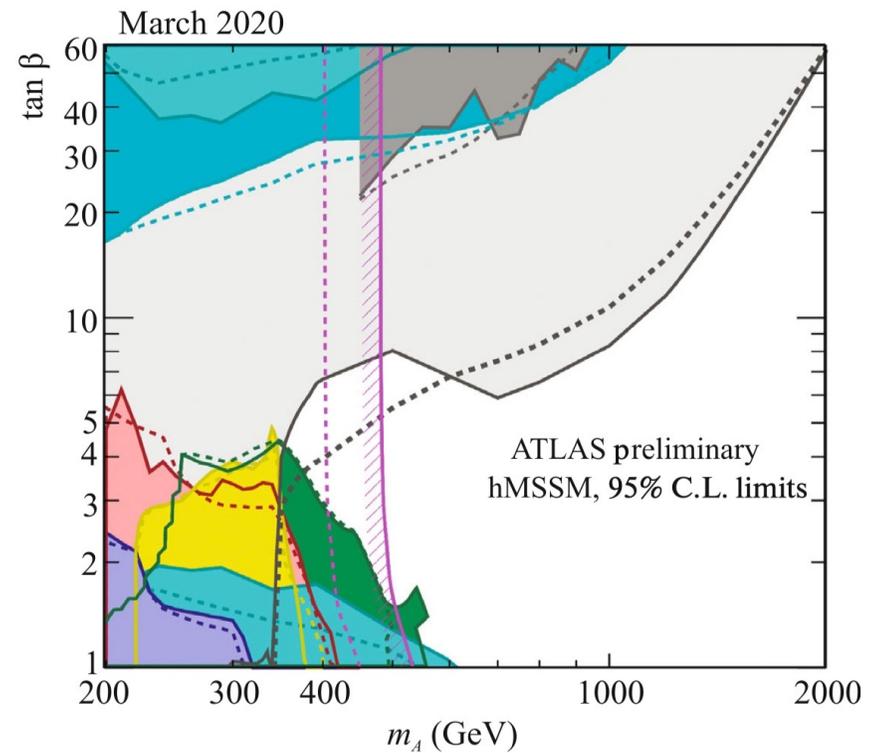
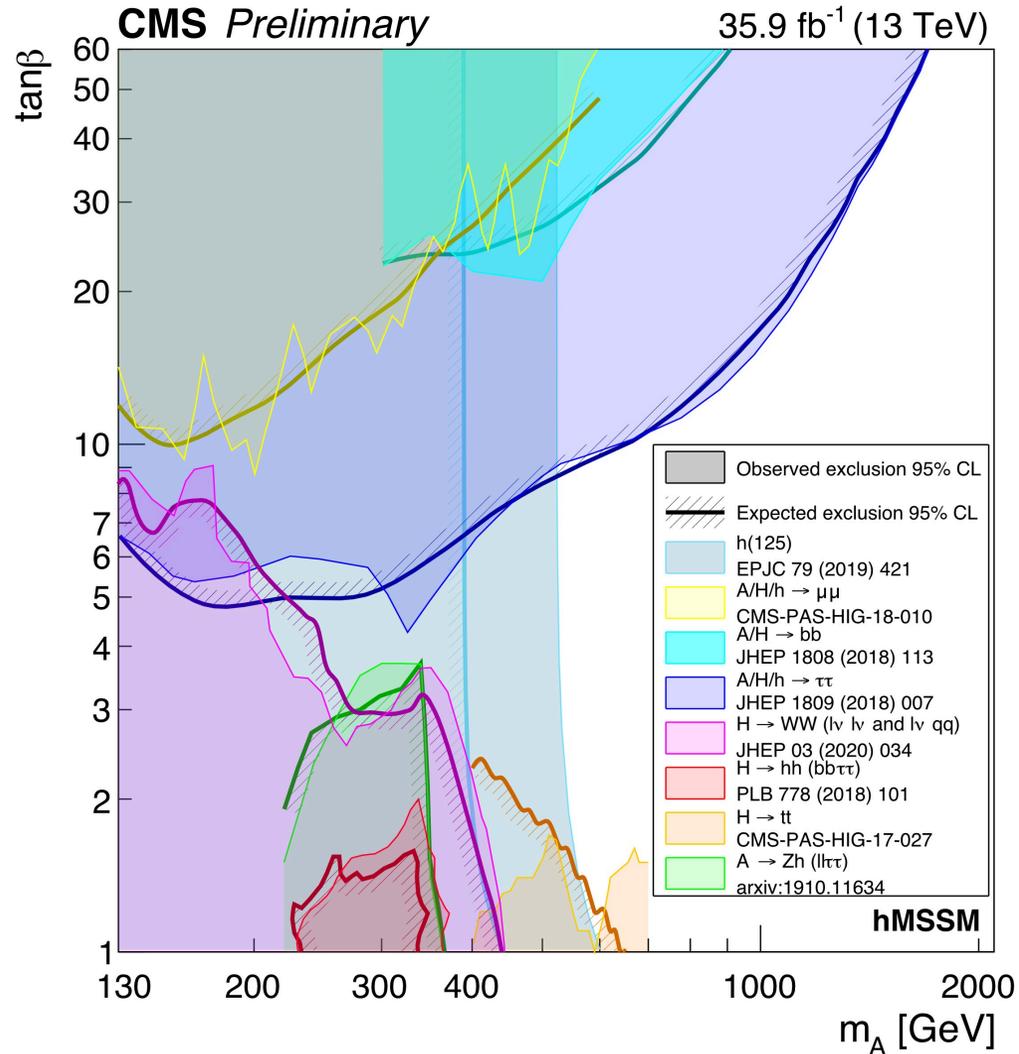


Fig. 12. (Color online) Regions of the $[m_A, \tan \beta]$ plane excluded in the hMSSM model via direct searches for heavy Higgs bosons and fits to the measured rates of observed Higgs boson production and decays [105]. Limits are quoted at 95% C.L. and indicated for the (solid lines) data and (dashed lines) expectation for the SM Higgs sector. The light shaded or hashed regions indicate the observed exclusions obtained in ATLAS experiment: (light grey) $H/A \rightarrow \tau\tau$ [53], (cyan) $H^+ \rightarrow \tau\nu$ [80], (dark cyan) $H^+ \rightarrow tb$ [81], (dark grey) $Hb \rightarrow bbb$ [71], (light red) $H \rightarrow ZZ \rightarrow 4l/ll\nu\nu$ [42], (yellow) $gg \rightarrow A \rightarrow Zh$ [106], (blue) $H \rightarrow WW \rightarrow lvlv$ [40], and (green) combination of the $H \rightarrow hh \rightarrow 4b, bbWW, bb\tau\tau, 4W, bb\gamma\gamma, WW\gamma\gamma$ decay channels [107] and the pink line shows the limit obtained with the fits to the measured rates of SM Higgs boson production and decay [78].

2. Non-minimal SUSY models

In the NMSSM, the superpotential contains a term $\lambda H_U H_D N$, where N is a singlet superfield. The parameter λ plays a significant role in determining the Higgs mass. Remarkably, approximate Higgs field alignment is achieved for $\lambda = \lambda_{\text{alt}}$.

This scenario provides a much richer phenomenology for future LHC searches.

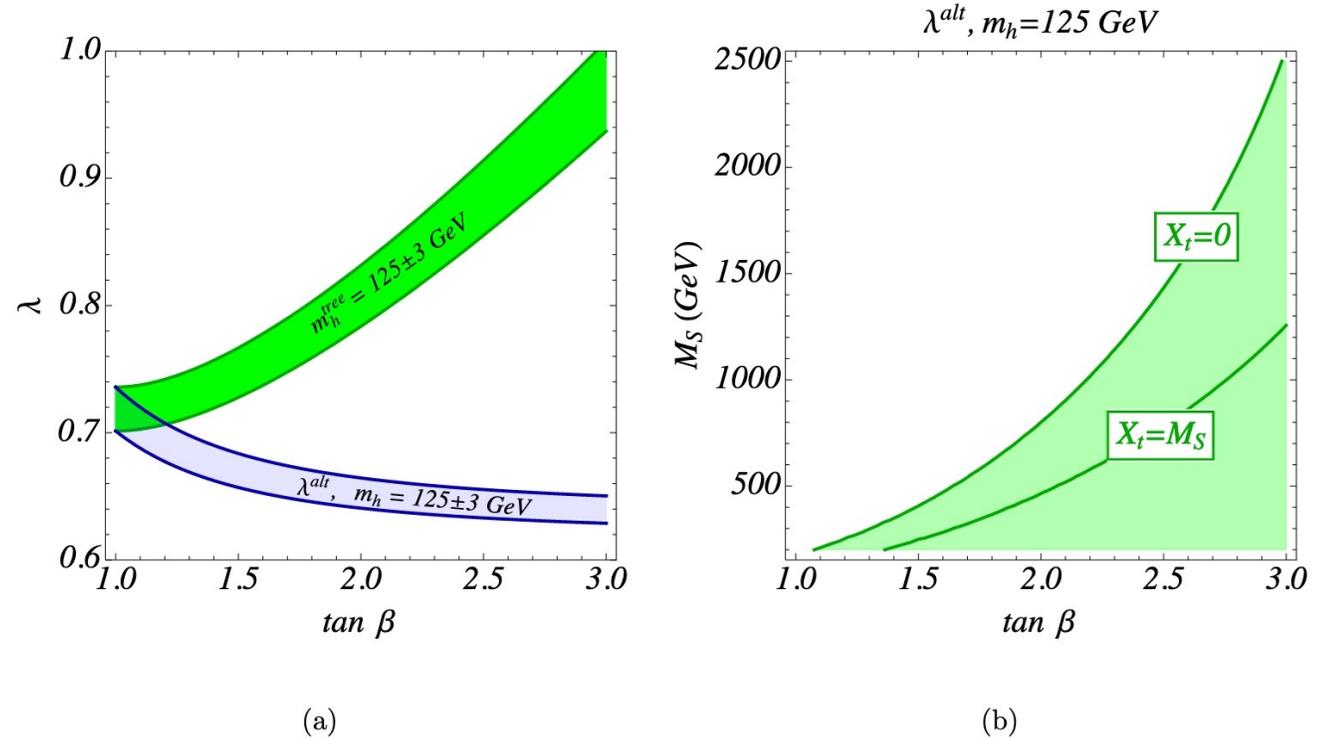


FIG. 2: Left panel : The blue shaded band displays the values of λ as a function of $\tan \beta$, necessary for alignment for $m_h = 125 \pm 3 \text{ GeV}$. Also shown in the figure as a green band are values of λ that lead to a tree-level Higgs mass of $125 \pm 3 \text{ GeV}$. Right panel : Values of M_S necessary to obtain a 125 GeV mass for values of λ fixed by the alignment condition and stop mixing parameter $X_t = 0$ and $X_t = M_S$. The dominant two-loop corrections are included.

Taken from M. Carena, H.E. Haber, I. Low, N. Shah and C.E.M. Wagner, [arXiv:1510.09137](https://arxiv.org/abs/1510.09137)