Looking for New Naturally Aligned Higgs Bosons at the LHC

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Based on (i) R. Battye, G. Brawn, A.P., JHEP1108 (2011) 020 (73p),
(ii) A.P., Phys. Lett. B706 (2012) 465; PRD93 (2016) 075012,
(iii) P.S.B. Dev, A.P., JHEP1412 (2014) 024,
(iv) P.S.B. Dev, A.P. et al, work in progress.

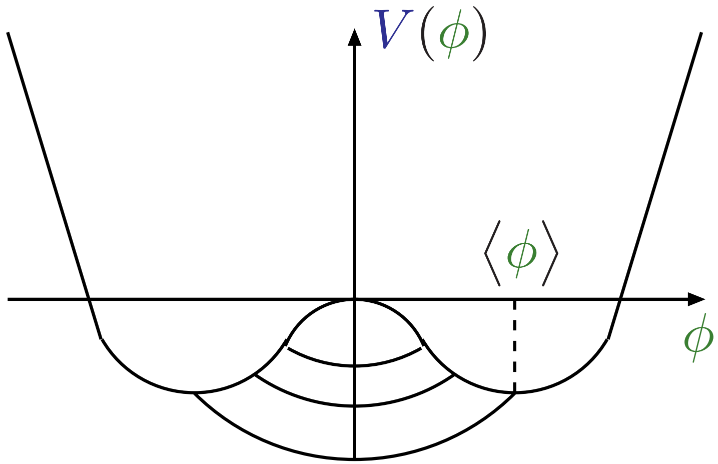
Outline:

- The Standard Theory of Electroweak Symmetry Breaking: SM
- The Two Higgs Doublet Model (2HDM) Potential
- SM Alignment in the 2HDM
- Symmetries of the 2HDM Potential
- Phenomenological Implications at the LHC
- Conclusions

• The Standard Theory of Electroweak Symmetry Breaking

Higgs Mechanism in the SM: $\mathrm{SU(3)}_{\rm colour} \otimes \mathrm{SU(2)}_L \otimes \mathrm{U(1)}_Y$

[P. W. Higgs '64; F. Englert, R. Brout '64.]



Higgs potential $V(\phi)$

$$V(\phi) \;=\; -m^2\phi^\dagger\phi \;+\; \lambda(\phi^\dagger\phi)^2\,.$$

Ground state:

$$\langle\phi\rangle \;=\; \sqrt{\frac{m^2}{2\lambda}}\begin{pmatrix}0\\1\end{pmatrix}$$

carries weak charge, but no electric charge and colour.

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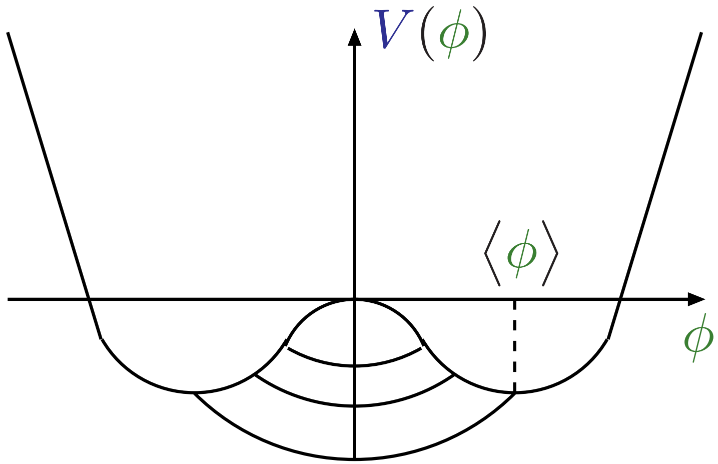

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Custodial Symmetry of the SM with $g' = Y_f = 0$ and $V(\phi)$:

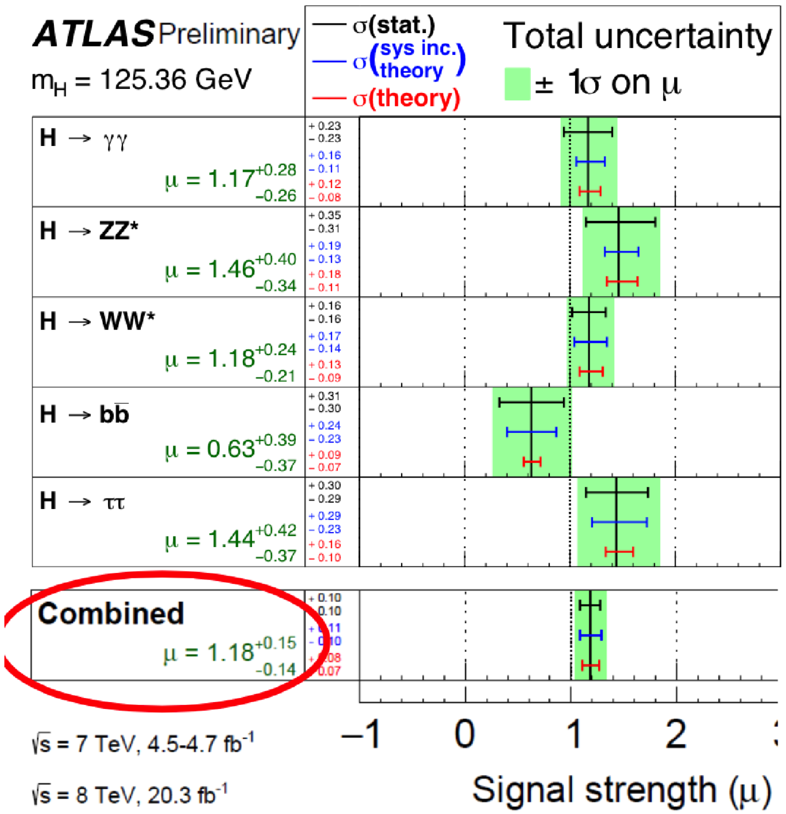
[P. Sikivie, L. Susskind, M. B. Voloshin, V. I. Zakharov '80.]

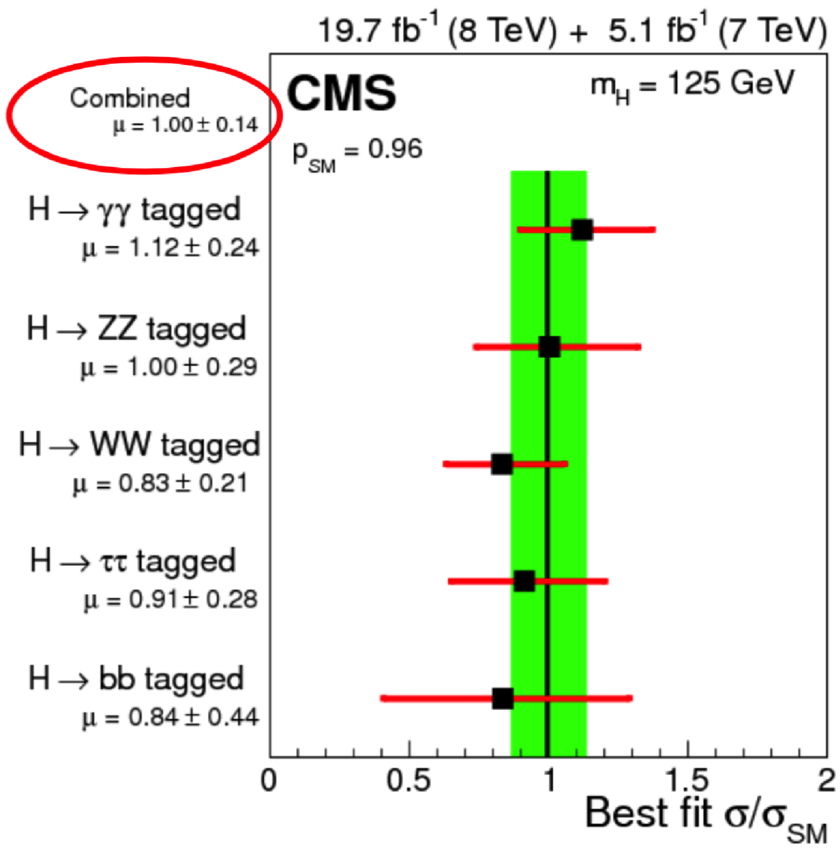
$$\mathbf{\Phi} \;\equiv\; \big(\phi\;,\; i\sigma^2\phi^*\big) \quad\mapsto\quad \mathbf{\Phi}' \;\equiv\; U_L\,\mathbf{\Phi}\,U_{\mathrm{C}}\;,$$

with $U_L \in \mathrm{SU}(2)_L$ and $U_{\mathrm{C}} \in \mathrm{SU}(2)_{\mathrm{C}}$, and $\mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_{\mathrm{C}}/\mathbb{Z}_2 \simeq \mathrm{S}\mathbb{O}(4)$.

Higgs Boson @ LHC: Signal Strength for Decay Modes

Signal strength: $\mu = \sigma_{observed}/\sigma_{SM}$





- Results consistent with SM

• The 2HDM Potential

[T. D. Lee '73]

$$\begin{aligned} \mathrm{V} \; = \; & -\mu_1^2(\phi_1^\dagger\phi_1) - \mu_2^2(\phi_2^\dagger\phi_2) - m_{12}^2(\phi_1^\dagger\phi_2) - m_{12}^{*2}(\phi_2^\dagger\phi_1) \\ & + \lambda_1(\phi_1^\dagger\phi_1)^2 + \lambda_2(\phi_2^\dagger\phi_2)^2 + \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) \\ & + \frac{\lambda_5}{2}(\phi_1^\dagger\phi_2)^2 + \frac{\lambda_5^*}{2}(\phi_2^\dagger\phi_1)^2 + \lambda_6(\phi_1^\dagger\phi_1)(\phi_1^\dagger\phi_2) + \lambda_6^*(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_1) \\ & + \lambda_7(\phi_2^\dagger\phi_2)(\phi_1^\dagger\phi_2) + \lambda_7^*(\phi_2^\dagger\phi_2)(\phi_2^\dagger\phi_1)\,. \end{aligned}$$

V has 4 real mass parameters and 10 real quartic couplings.

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& + \lambda_1(\phi_1^\dagger\phi_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) \\
& + \frac{\lambda_5}{2}(\phi_1^\dagger\phi_2)^2 + \frac{\lambda_5^*}{2}(\phi_2^\dagger\phi_1)^2 + \lambda_6(\phi_1^\dagger\phi_1)(\phi_1^\dagger\phi_2) + \lambda_6^*(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_1) \\
& + \lambda_7(\phi_2^\dagger\phi_2)(\phi_1^\dagger\phi_2) + \lambda_7^*(\phi_2^\dagger\phi_2)(\phi_2^\dagger\phi_1)\,.
\end{aligned}
$$

V has <u>4</u> real mass parameters and <u>10</u> real quartic couplings.

Remark on the *tree-level* **MSSM Higgs potential:**

$$
m_{12}^2 \;=\; -B\mu\,,\quad \lambda_1 \;=\; \lambda_2 \;=\; -\frac{1}{8}(g_w^2 + g'^2)\,,\quad \lambda_3 \;=\; -\frac{1}{4}(g_w^2 - g'^2)\,,
$$

$$
\lambda_4 \;=\; \frac{1}{2}g_w^2\,,\qquad \lambda_5 \;=\; \lambda_6 \;=\; \lambda_7 \;=\; 0\,.
$$

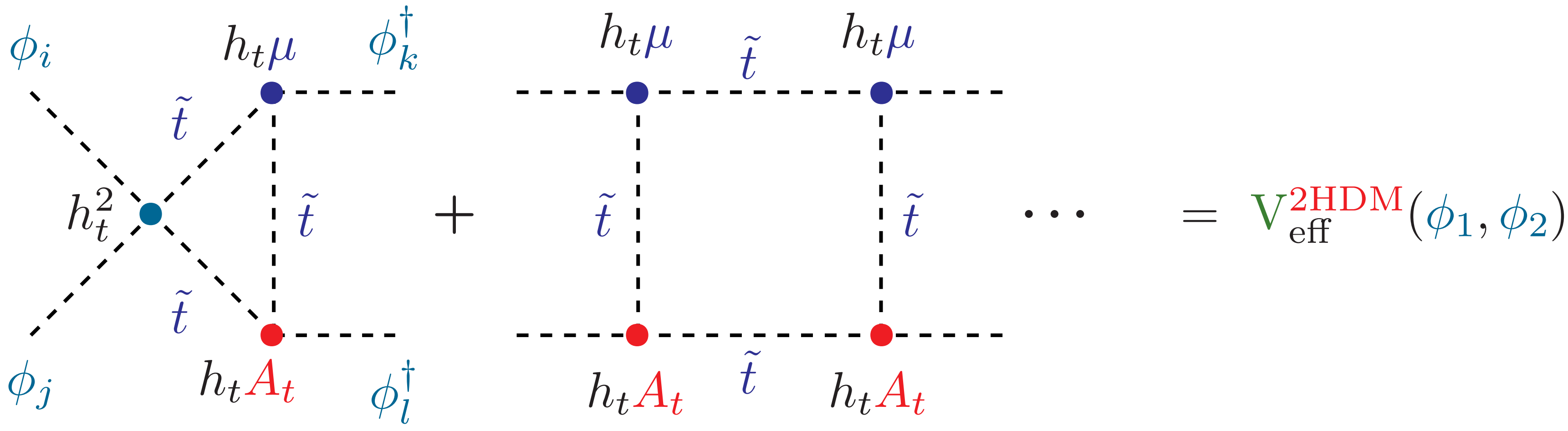
$\phi_2 \to e^{i\arg m_{12}^2}\,\phi_2 \;\Longrightarrow\;$ Tree-level Higgs potential is <u>invariant</u> under CP

Loop effects are **sizeable leading to a General 2HDM.**

[J. Ellis, G. Ridolfi, F. Zwirner '91;
Y. Okada, M. Yamaguchi, T. Yanagida '91;
H.E. Haber, R. Hempfling '91.]

Radiative Higgs-sector CP Violation:

[A.P. '98; A.P., C.E.M. Wagner '99]



CP-violating terms are $\propto\ \mathrm{Im}\,(\,\boldsymbol{m_{12}^{2*}\,\mu\,A_{t,b}}\,)\ \neq\ \mathbf{0}$

Latest version:

CPsuperH2.3: J. S. Lee, M. Carena, J. Ellis, A.P., C. E. M. Wagner, JHEP1602 (2016) 123.

• SM Alignment in the 2HDM

• Physical (CP-conserving) spectrum:

CP-even Higgs bosons $\boldsymbol{H}$ and $\boldsymbol{h}$;   CP-odd scalar $\boldsymbol{a}$;   charged scalars $\boldsymbol{h}^{\pm}$.

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• Higgs coupling to gauge bosons $V = W, Z$:

$$g_{HVV} \; = \; \cos(\beta - \alpha) \; , \qquad g_{hVV} \; = \; \sin(\beta - \alpha) \; ,$$

where $\tan\beta = \langle\phi_2\rangle/\langle\phi_1\rangle$ related to the diagonalization of the CP-odd mass matrix and the mixing angle α diagonalizes the CP-even mass matrix.

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• SM Alignment $\beta \to \alpha$:

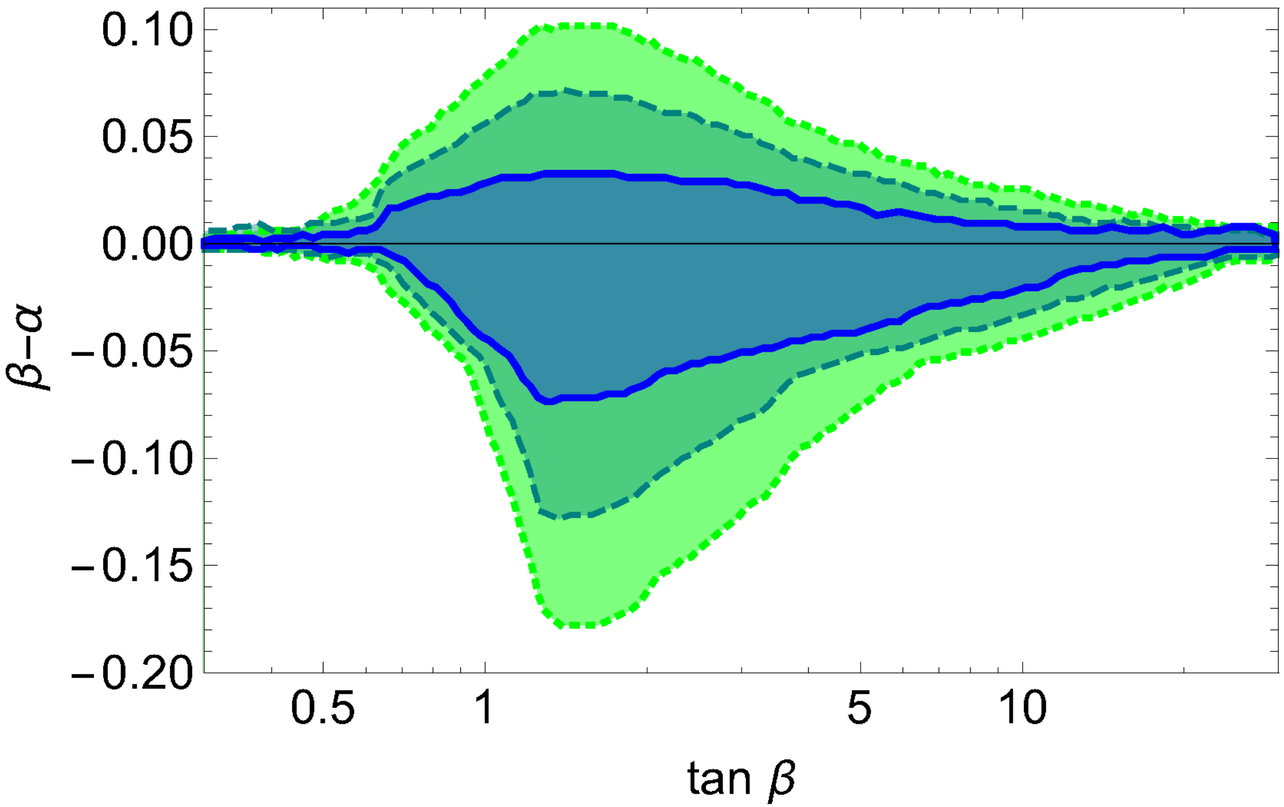
(i) Decoupling: $M_{h^\pm} \gg M_H$ [J. F. Gunion, H. E. Haber, Phys. Rev. D67 (2003) 075019.]

(ii) Fine-tuning: [P.S.B. Dev, A.P., JHEP1412 (2014) 024.]

$$\lambda_7 t_\beta^4 \;-\; (2\lambda_2 - \lambda_{345})t_\beta^3 \;+\; 3(\lambda_6 - \lambda_7)\, t_\beta^2 \;+\; (2\lambda_1 - \lambda_{345})t_\beta - \lambda_6 \;=\; 0$$

• **Global Fit to the SM Alignment** $\beta \to \alpha$:

[e.g. D. Chowdhury, O. Eberhardt, JHEP11 (2015) 052.]



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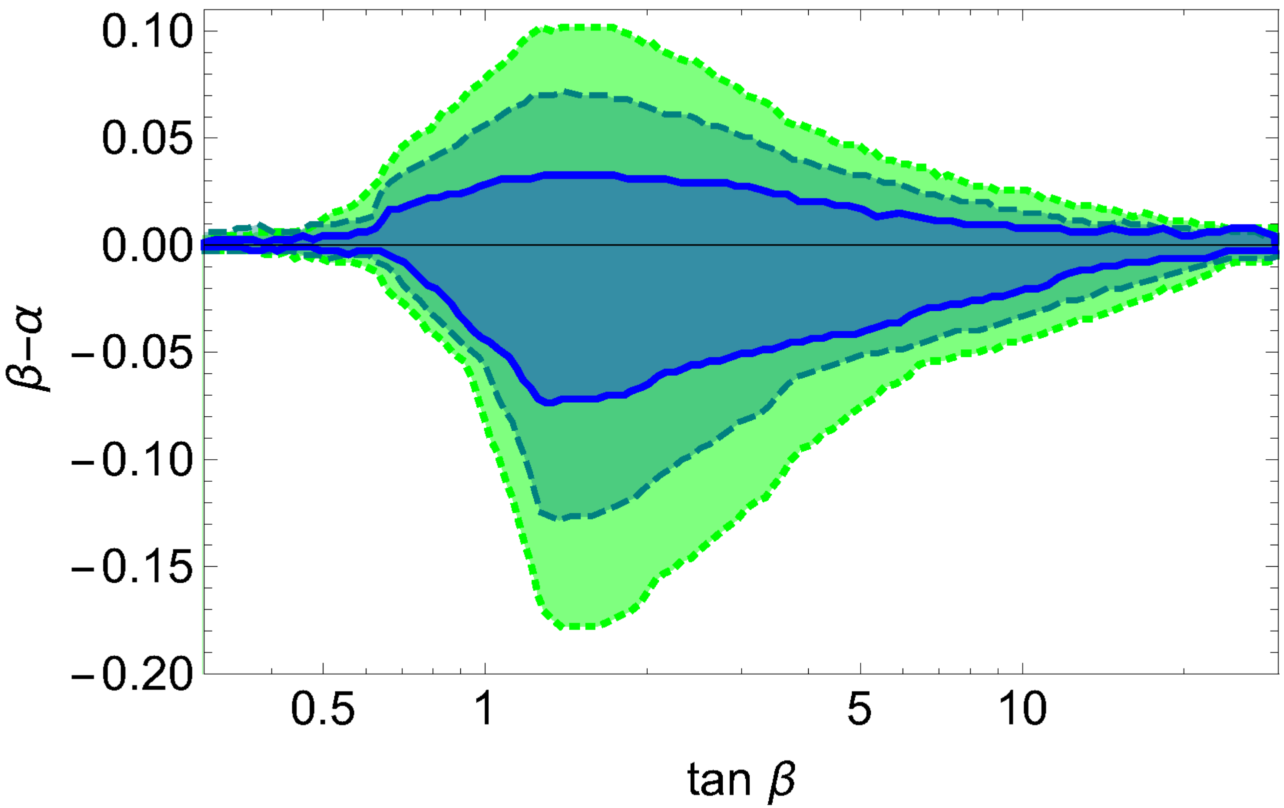

- **Natural Alignment** (*without* **decoupling** *or* **fine-tuning**):

[P.S.B. Dev, A.P., JHEP1412 (2014) 024.]

$$\boldsymbol{\lambda_1 = \lambda_2 = \lambda_{345}/2, \quad \lambda_6 = \lambda_7 = 0 .}$$

References (*an incomplete list on SM Alignment in the 2HDM*)

- **On the SM Higgs basis (also Decoupling of FCNC Effects):**
  H. Georgi and D. V. Nanopoulos, Phys. Lett. B82 (1979) 95.

- **Alignment via Decoupling:**
  J. F. Gunion, H. E. Haber, Phys. Rev. D67 (2003) 075019.

- I. F. Ginzburg, M. Krawczyk, Phys. Rev. D72 (2005) 115013.

- **Alignment via Fine-tuning:**
  P. H. Chankowski, T. Farris, B. Grzadkowski, J. F. Gunion, J. Kalinowski, M. Krawczyk, Phys. Lett. B496 (2000) 195

- A. Delgado, G. Nardini, M. Quiros, JHEP **1307** (2013) 054.

- M. Carena, I. Low, N. R. Shah, C. E. M. Wagner, JHEP1404 (2014) 015.

- **Natural Alignment without Decoupling and without Fine-tuning:**
  P.S.B. Dev, A.P., JHEP1412 (2014) 024.

References (*an incomplete list on symmetries in the 2HDM*)

- **Spontaneous CP Violation:** T. D. Lee, Phys. Rev. D **8** (1973) 1226.
- **Z_2 symmetry:** S. L. Glashow, S. Weinberg, Phys. Rev. D **15** (1977) 1958.
- **Inert Z_2 symmetry:** N. G. Deshpande, E. Ma, Phys. Rev. D **18** (1978) 2574.
- **PQ U(1) symmetry:** R. D. Peccei, H. R. Quinn, Phys. Rev. Lett. **38** (1977) 1440.
- **Custodial $SU(2)_L$-preserving symmetry:**
  P. Sikivie, L. Susskind, M. B. Voloshin, V. I. Zakharov, Nucl. Phys. B **173** (1980) 189.
- **Bilinear formalism:**
  M. Maniatis, A. von Manteuffel, O. Nachtmann, F. Nagel, EPJC **48** (2006) 805;
  C. C. Nishi, Phys. Rev. D **74** (2006) 036003 [Erratum-ibid. D **76** (2007) 119901].
- **$SU(2)_L \otimes U(1)_Y$-preserving symmetries:**
  I. P. Ivanov, Phys. Rev. D **75** (2007) 035001 [Erratum-ibid. D **76** (2007) 039902].
- **Hypercustodial $SU(2)_L$-preserving symmetries:**
  R. A. Battye, G. D. Brawn, A.P., JHEP1108 (2011) 020.
- **On completeness and uniqueness of classification:**
  A.P., Phys. Lett. B **706** (2012) 465.

• Symmetries of the 2HDM Potential

[R. A. Battye, G. D. Brawn, A.P., JHEP1108 (2011) 020.]

Introduce the $\mathrm{SU}(2)_L$-covariant 8D complex field multiplet

$$\mathbf{\Phi} \; = \; \begin{pmatrix} \phi_1 \\ \phi_2 \\ i\sigma^2\phi_1^* \\ i\sigma^2\phi_2^* \end{pmatrix} , \quad \text{with} \;\; U_L \in \mathrm{SU}(2)_L : \; \mathbf{\Phi} \; \mapsto \; \mathbf{\Phi}' \; = \; U_L\,\mathbf{\Phi} \; .$$

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$\mathbf{\Phi}$ satisfies the **Majorana constraint**

$$\mathbf{\Phi} \;=\; \mathrm{C}\,\mathbf{\Phi}^*\,,$$

where C is the **charge conjugation** 8D matrix

$$\mathrm{C} \;=\; \sigma^2 \otimes \sigma^0 \otimes \sigma^2 \;=\; \begin{pmatrix} \mathbf{0}_4 & \mathbf{1}_4 \\ -\,\mathbf{1}_4 & \mathbf{0}_4 \end{pmatrix} \otimes (-i\sigma_2)\,.$$

• The SO(1,5) Bilinear Formalism

Introduce the *null* 6-Vector

$$\mathrm{R}^{\mathrm{A}} \;=\; \mathbf{\Phi}^{\dagger}\,\Sigma^{\mathrm{A}}\,\mathbf{\Phi} \;=\; \left(\begin{array}{c} \phi_1^{\dagger}\phi_1 + \phi_2^{\dagger}\phi_2 \\ \phi_1^{\dagger}\phi_2 + \phi_2^{\dagger}\phi_1 \\ -i\left[\phi_1^{\dagger}\phi_2 - \phi_2^{\dagger}\phi_1\right] \\ \phi_1^{\dagger}\phi_1 - \phi_2^{\dagger}\phi_2 \\ \phi_1^{\mathsf{T}} i\sigma^2 \phi_2 - \phi_2^{\dagger} i\sigma^2 \phi_1^{*} \\ -i\left[\phi_1^{\mathsf{T}} i\sigma^2 \phi_2 + \phi_2^{\dagger} i\sigma^2 \phi_1^{*}\right] \end{array} \right),$$

with $\mathrm{A} = \mu,\ 4,\ 5$ and

$$\Sigma^{\mu} \;=\; \frac{1}{2}\left(\begin{array}{cc} \sigma^{\mu} & \mathbf{0}_2 \\ \mathbf{0}_2 & (\sigma^{\mu})^{\mathsf{T}} \end{array} \right) \otimes \sigma^0\,,$$

$$\Sigma^{4} \;=\; \frac{1}{2}\left(\begin{array}{cc} \mathbf{0}_2 & i\sigma^2 \\ -i\sigma^2 & \mathbf{0}_2 \end{array} \right) \otimes \sigma^0\,, \qquad \Sigma^{5} \;=\; \frac{1}{2}\left(\begin{array}{cc} \mathbf{0}_2 & -\sigma^2 \\ -\sigma^2 & \mathbf{0}_2 \end{array} \right) \otimes \sigma^0\,.$$

• The 2HDM Potential in the SO(1,5) Formalism

$$\mathrm{V} = -\frac{1}{2}\,\mathrm{M_A}\,\mathrm{R^A} + \frac{1}{4}\,\mathrm{L_{AB}}\,\mathrm{R^A}\,\mathrm{R^B}\,,$$

with

$$\mathrm{M_A} = \left(\mu_1^2+\mu_2^2\,,\quad 2\mathrm{Re}(m_{12}^2)\,,\quad -2\mathrm{Im}(m_{12}^2)\,,\quad \mu_1^2-\mu_2^2\,,\quad 0\,,\quad 0\right)\,,$$

$$\mathrm{L_{AB}} = \begin{pmatrix} \lambda_1+\lambda_2+\lambda_3 & \mathrm{Re}(\lambda_6+\lambda_7) & -\mathrm{Im}(\lambda_6+\lambda_7) & \lambda_1-\lambda_2 & 0 & 0 \\ \mathrm{Re}(\lambda_6+\lambda_7) & \lambda_4+\mathrm{Re}(\lambda_5) & -\mathrm{Im}(\lambda_5) & \mathrm{Re}(\lambda_6-\lambda_7) & 0 & 0 \\ -\mathrm{Im}(\lambda_6+\lambda_7) & -\mathrm{Im}(\lambda_5) & \lambda_4-\mathrm{Re}(\lambda_5) & -\mathrm{Im}(\lambda_6-\lambda_7) & 0 & 0 \\ \lambda_1-\lambda_2 & \mathrm{Re}(\lambda_6-\lambda_7) & -\mathrm{Im}(\lambda_6-\lambda_7) & \lambda_1+\lambda_2-\lambda_3 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}.$$

• The 2HDM Potential in the SO(1,5) Formalism

$$\mathrm{V} \;=\; -\,\frac{1}{2}\,\mathrm{M_A}\,\mathrm{R^A} \;+\; \frac{1}{4}\,\mathrm{L_{AB}}\,\mathrm{R^A}\,\mathrm{R^B}\;,$$

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• Unitary Field Transformations:

[A.P., Phys. Lett. B706 (2012) 465.]

$\mathrm{Sp}(4):\qquad \mathbf{\Phi} \;\mapsto\; \mathbf{\Phi}' \;=\; U\,\mathbf{\Phi}\,,$ with $U \in \mathrm{U}(4)$ and $UCU^{\mathsf{T}} = \mathrm{C}$

$\mathrm{SO}(5):\qquad \mathrm{R^I} \;\mapsto\; \mathrm{R'^I} \;=\; \mathrm{O^I{}_J}\,\mathrm{R^J}\,,$ with $\mathrm{O} \in \mathrm{SO}(5) \,\subset\, \mathrm{SO}(1,5)$

$\Longrightarrow \qquad \mathrm{SO}(5) \;\sim\; \mathrm{Sp}(4)/\mathbf{Z}_2$

• Symmetries of the $U(1)_Y$-Invariant 2HDM Potential

SO(5)-diagonally reduced basis: $\mathrm{Im}\,\lambda_5 = 0$ and $\lambda_6 = \lambda_7$.

The 2HDM potential exhibits a **total** of **13** accidental symmetries:

Symmetry	μ_1^2	μ_2^2	m_{12}^2	λ_1	λ_2	λ_3	λ_4	$\mathrm{Re}\,\lambda_5$	$\lambda_6 = \lambda_7$
$(Z_2)^2 \times SO(2)$	–	–	0	–	–	–	–	–	0
$O(2) \times O(2)$	–	–	0	–	–	–	–	0	0
✓ $\mathbf{O(3) \times O(2)}$	–	μ_1^2	0	–	λ_1	–	$2\lambda_1 - \lambda_3$	0	0
$Z_2 \times O(2)$	–	–	Real	–	–	–	–	–	Real
$(Z_2)^3 \times O(2)$	–	μ_1^2	0	–	λ_1	–	–	–	0
✓ $\mathbf{Z_2 \times [O(2)]^2}$	–	μ_1^2	0	–	λ_1	–	–	$2\lambda_1 - \lambda_{34}$	0
✓ **SO(5)**	–	μ_1^2	0	–	λ_1	$2\lambda_1$	0	0	0
$Z_2 \times O(4)$	–	μ_1^2	0	–	λ_1	–	0	0	0
$SO(4)$	–	–	0	–	–	–	0	0	0
$O(2) \times O(3)$	–	μ_1^2	0	–	λ_1	$2\lambda_1$	–	0	0
$(Z_2)^2 \times SO(3)$	–	μ_1^2	0	–	λ_1	–	–	$\pm\lambda_4$	0
$Z_2 \times O(3)$	–	μ_1^2	Real	–	λ_1	–	–	λ_4	Real
$SO(3)$	–	–	Real	–	–	–	–	λ_4	Real

✓: Natural SM Alignment $\mapsto$ [P.S.B. Dev, A.P., JHEP1412 (2014) 024.]

• Symmetry Breaking Scenarios and pseudo-Goldstone Bosons

[A.P., Phys. Lett. B706 (2012) 465.]

No	Symmetry	Generators $T^a \leftrightarrow K^a$	Discrete Group Elements	Maximally Broken SO(5) Generators	Number of Pseudo-Goldstone Bosons
1	$Z_2 \times O(2)$	T^0	D_{CP1}	–	0
2	$(Z_2)^2 \times SO(2)$	T^0	D_{Z_2}	–	0
3	$(Z_2)^3 \times O(2)$	T^0	D_{CP2}	–	0
4	$O(2) \times O(2)$	$T^3,\ T^0$	–	T^3	1 (a)
✓ 5	$Z_2 \times [O(2)]^2$	$T^2,\ T^0$	D_{CP1}	T^2	1 (h)
✓ 6	$O(3) \times O(2)$	$T^{1,2,3},\ T^0$	–	$T^{1,2}$	2 $(h,\ a)$
7	$SO(3)$	$T^{0,4,6}$	–	$T^{4,6}$	2 $(h^\pm)$
8	$Z_2 \times O(3)$	$T^{0,4,6}$	$D_{Z_2} \cdot D_{CP2}$	$T^{4,6}$	2 $(h^\pm)$
9	$(Z_2)^2 \times SO(3)$	$T^{0,5,7}$	$D_{CP1} \cdot D_{CP2}$	$T^{5,7}$	2 $(h^\pm)$
10	$O(2) \times O(3)$	$T^3,\ T^{0,8,9}$	–	T^3	1 (a)
11	$SO(4)$	$T^{0,3,4,5,6,7}$	–	$T^{3,5,7}$	3 $(a,\ h^\pm)$
12	$Z_2 \times O(4)$	$T^{0,3,4,5,6,7}$	$D_{Z_2} \cdot D_{CP2}$	$T^{3,5,7}$	3 $(a,\ h^\pm)$
✓ 13	$SO(5)$	$T^{0,1,2,\dots,9}$	–	$T^{1,2,8,9}$	4 $(h,\ a,\ h^\pm)$

✓: Natural SM Alignment $\mapsto$ [P.S.B. Dev, A.P., JHEP1412 (2014) 024.]

• Phenomenological Implications at the LHC

• Maximally Symmetric Two Higgs Doublet Model

[P.S.B. Dev, A.P., JHEP1412 (2014) 024.]

$$\mathrm{V} \;=\; -\,\mu^2\Big(|\Phi_1|^2+|\Phi_2|^2\Big)+\lambda\,\Big(|\Phi_1|^2+|\Phi_2|^2\Big)^2 \;=\; -\frac{\mu^2}{2}\,\mathbf{\Phi}^\dagger\,\mathbf{\Phi}\,+\,\frac{\lambda}{4}\,\big(\mathbf{\Phi}^\dagger\,\mathbf{\Phi}\big)^2$$

Symmetry Group: $G_{\mathbf{\Phi}} = \mathrm{SU}(2)_L \otimes \mathrm{Sp}(4)/\mathbf{Z}_2 \simeq \mathrm{SU}(2)_L \otimes \mathrm{SO}(5)$.

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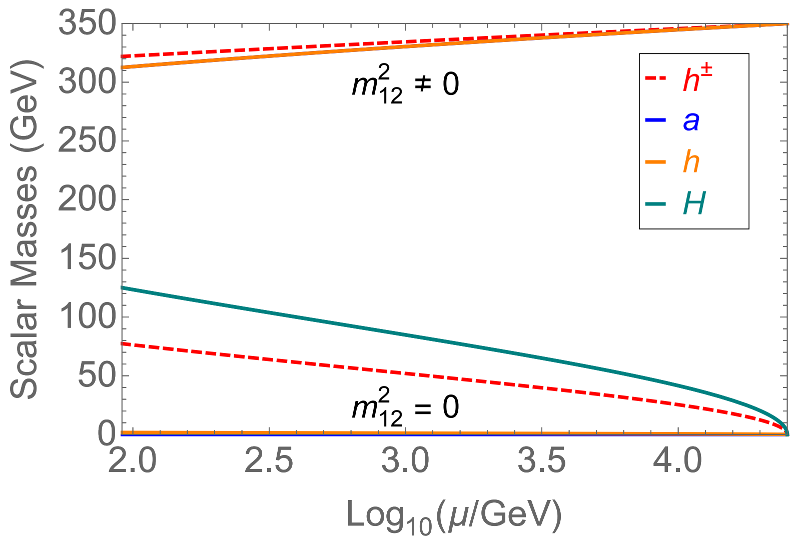
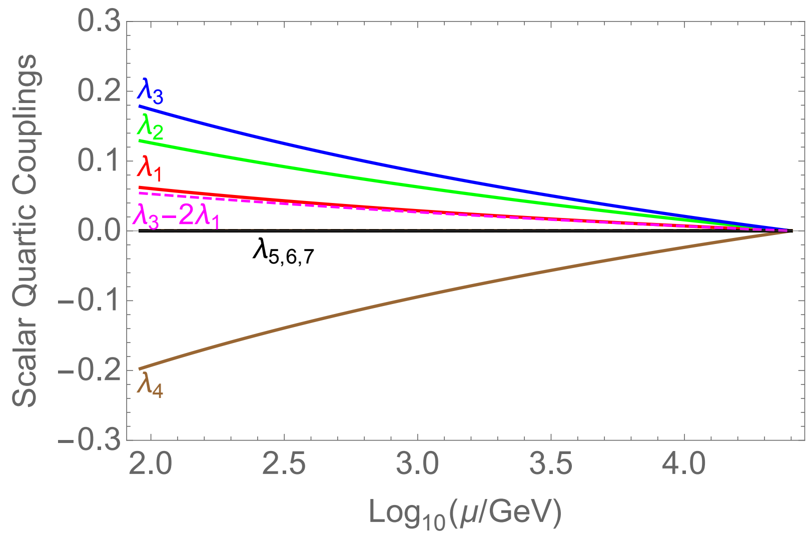
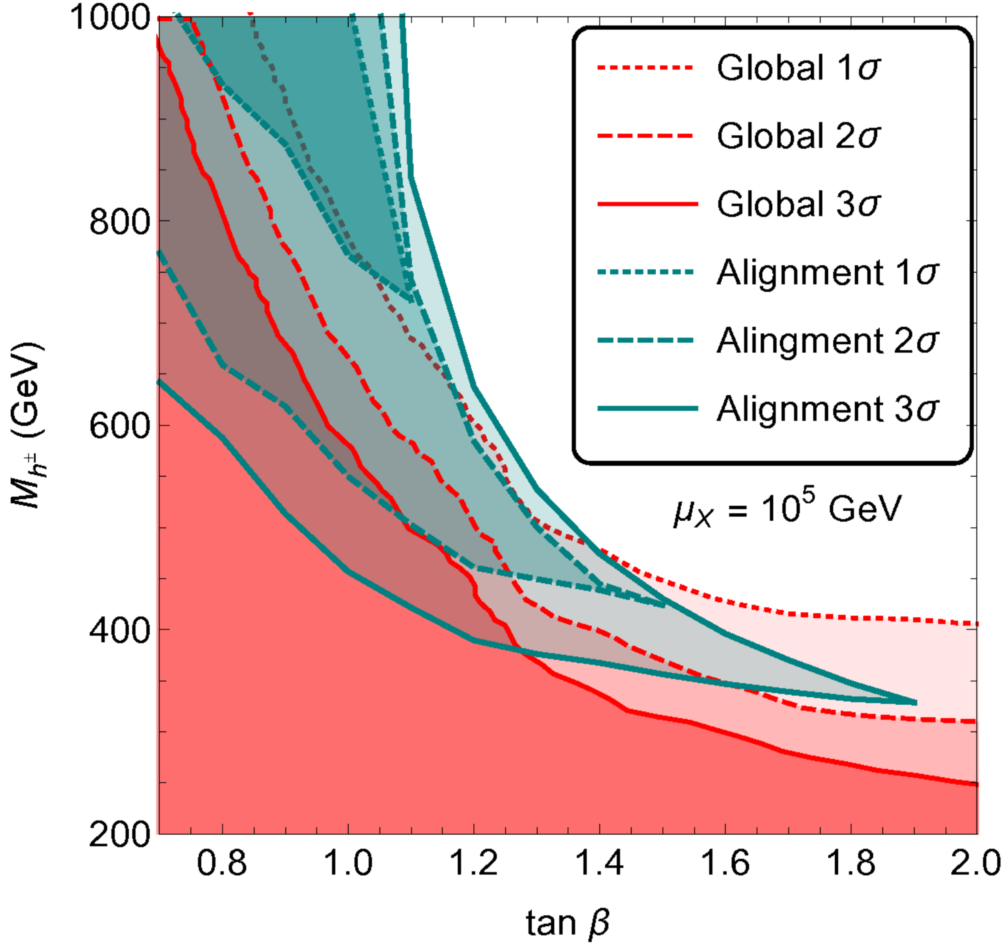
Breaking Effects: $-m_{12}^2\,\phi_1^\dagger\phi_2$, $\mathrm{U}(1)_Y$ coupling g', Yukawa couplings $h_{t,b}$.





Quasi-Degenerate Heavy Higgs Spectrum: $M_h^2 \;=\; M_a^2 + \lambda_5 v^2 \;\simeq\; M_{h^\pm}^2$

• **Constraints on** $(\tan\beta\,,\ M_{h^\pm})$ [P.S.B. Dev and A.P., JHEP1412 (2014) 024.]

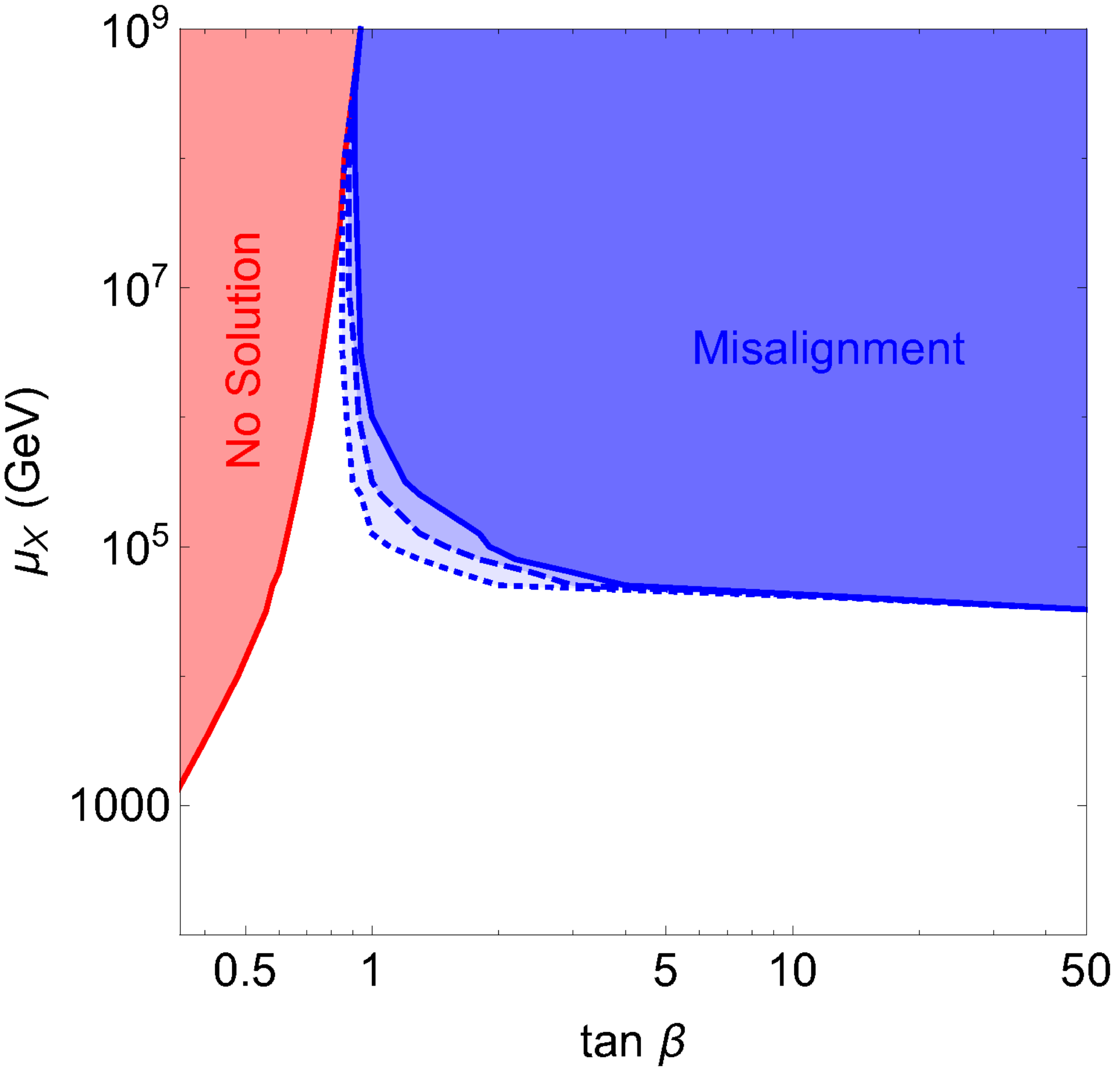


Constraints due to low-energy and LHC Higgs precision data.

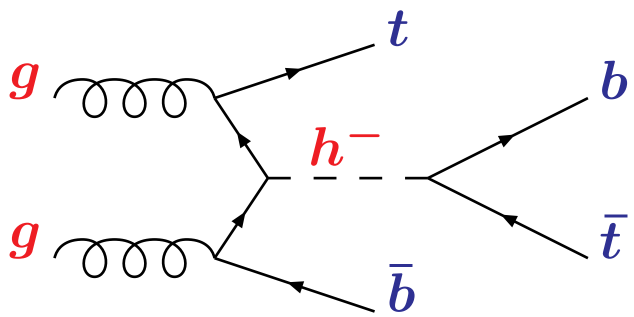
[See, e.g., J. Baglio, O. Eberhardt, U. Nierste, M. Wiebusch, PRD90 (2014) 015008;
K. Cheung, J.S. Lee, P.-Y. Tseng, JHEP1401 (2014) 085.]

• Misalignment Predictions

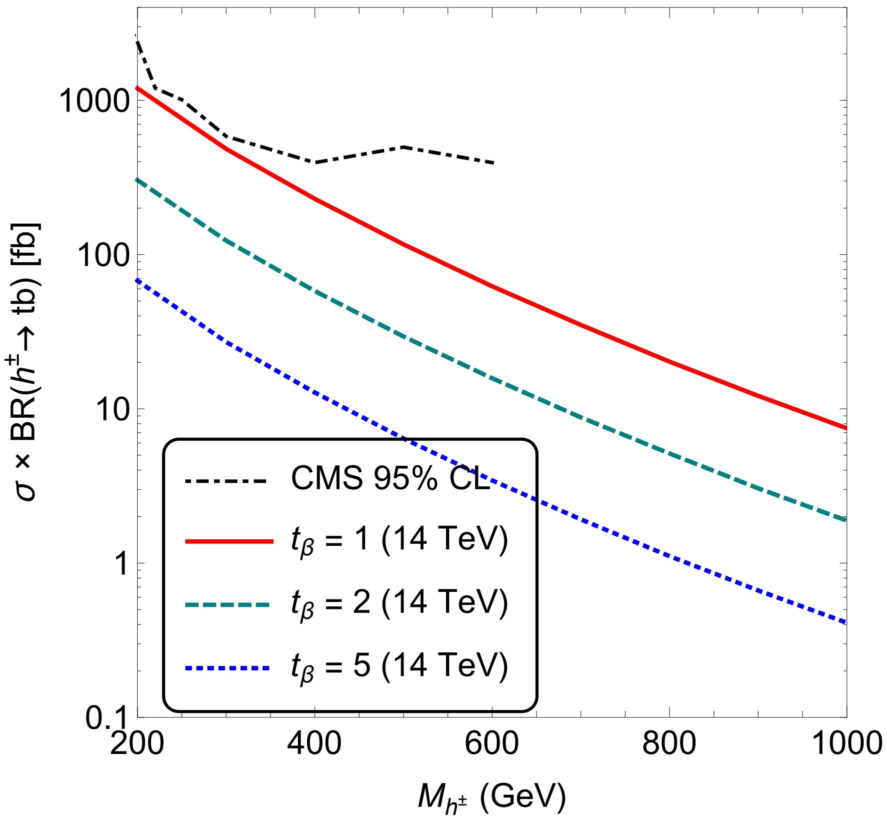
[P.S.B. Dev and A.P., JHEP1412 (2014) 024.]



• $gg \to t\bar{b}h^- \to t\bar{b}\bar{t}b$



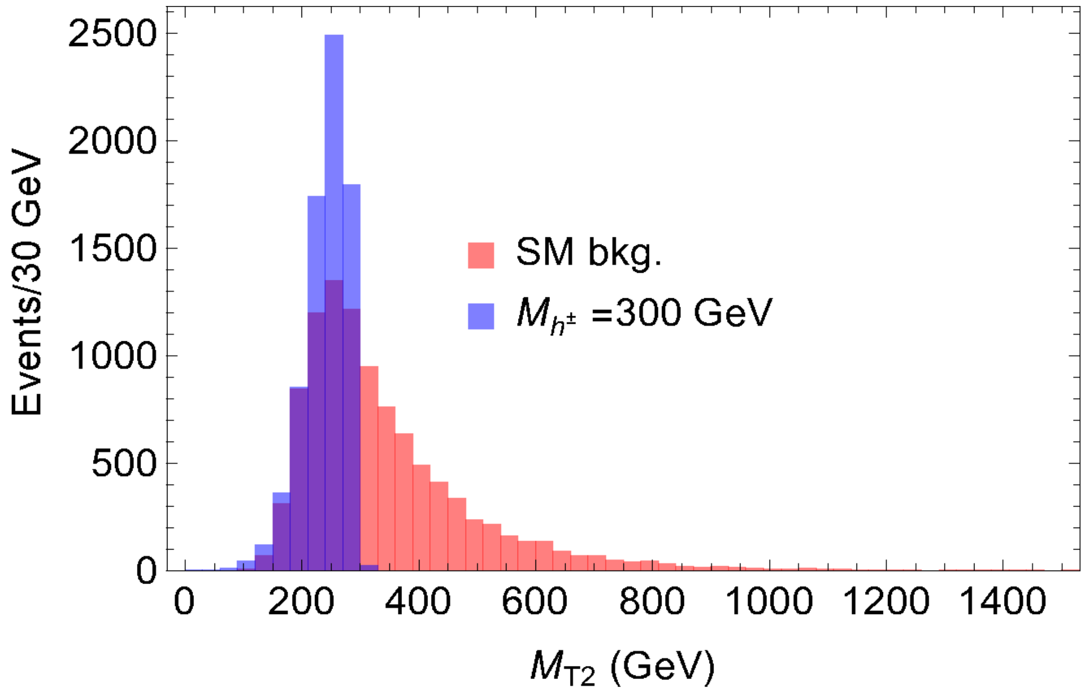
[CMS Collaboration, CMS-PAS-HIG-13-026;
P.S.B. Dev and A.P., JHEP1412 (2014) 024.]



$p_T^\ell > 20$ GeV,
$|\eta^\ell| < 2.5$,
$\Delta R^{\ell\ell} > 0.4$,
$M_{\ell\ell} > 12$ GeV,
$|M_{\ell\ell} - M_Z| > 10$ GeV,
$p_T^j > 30$ GeV,
$|\eta^j| < 2.4$,
$\not{E}_T > 40$ GeV.

• M_{T2} Variable for reconstructing $M_{h^\pm}$

[C. G. Lester and D. J. Summers, Phys. Lett. B463 (1999) 99.]



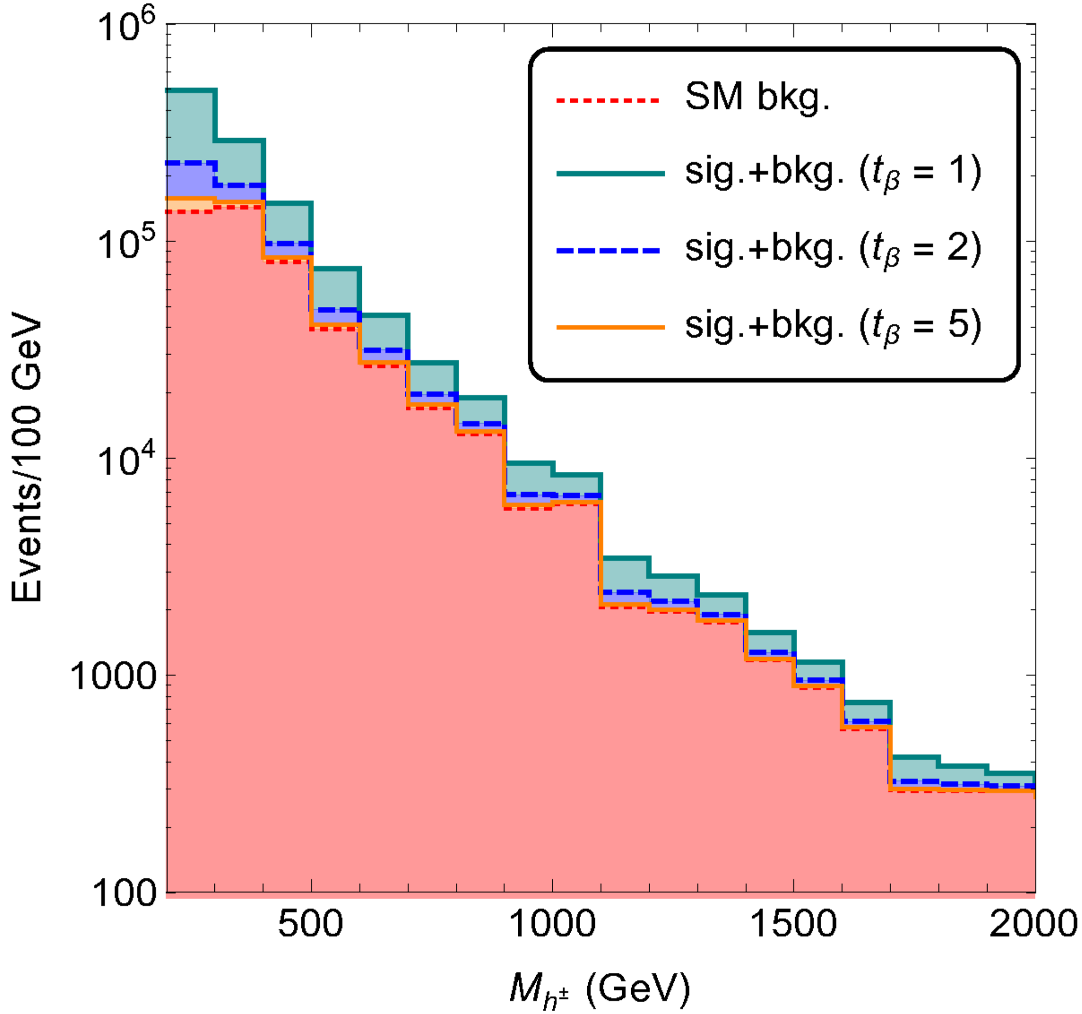
Decay chain: $gg \;\to\; h^\pm\, t\, b \;\to\; (\ell\nu_\ell bb)\,(\ell'\nu_{\ell'}b)\,b$

$$M_{T2} \;=\; \min_{\left\{\not{p}_{T_{\rm a}}+\not{p}_{T_{\rm b}}=\not{p}_T\right\}} \Big[\max\left\{m_{T_{\rm a}}, m_{T_{\rm b}}\right\}\Big] \;\lesssim\; M_{h^\pm}$$

$m_{T_{\rm a,b}}$: usual transverse masses for $\{{\rm a}\} = (\ell\nu_\ell bb)$ and $\{{\rm b}\} = (\ell'\nu_{\ell'}bb)$.

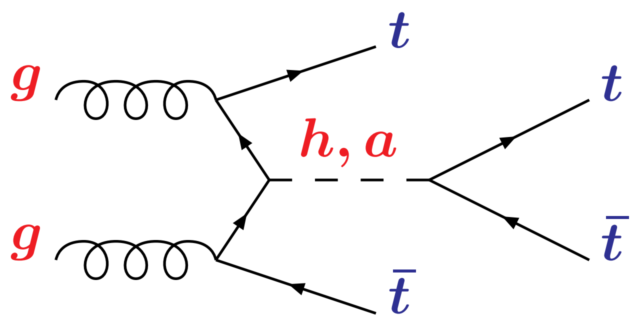
- **Predicted number of events for $h^{\pm}$ signal at $\sqrt{s} = 14$ TeV with 300 fb^{-1} integrated luminosity**

[P.S.B. Dev and A.P., JHEP1412 (2014) 024.]

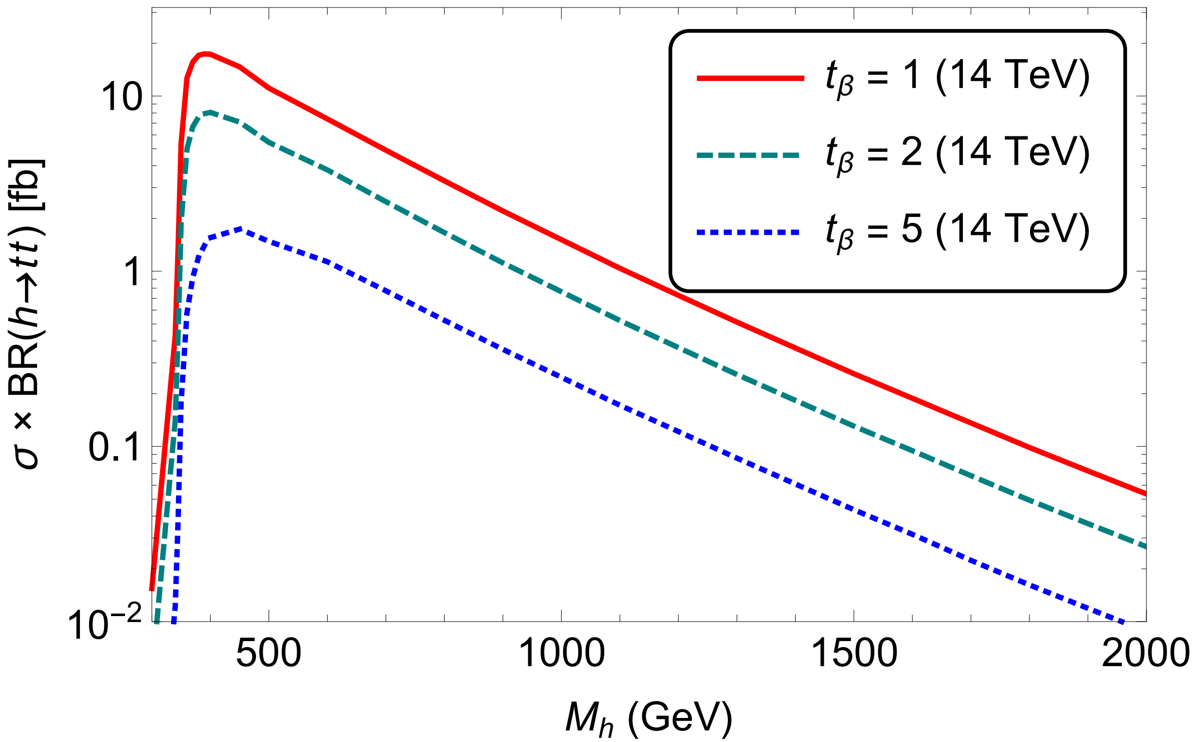


using `MadGraph5.aMC@NLO`.

- $gg \to t\bar{t}(h, a) \to t\bar{t}t\bar{t}$

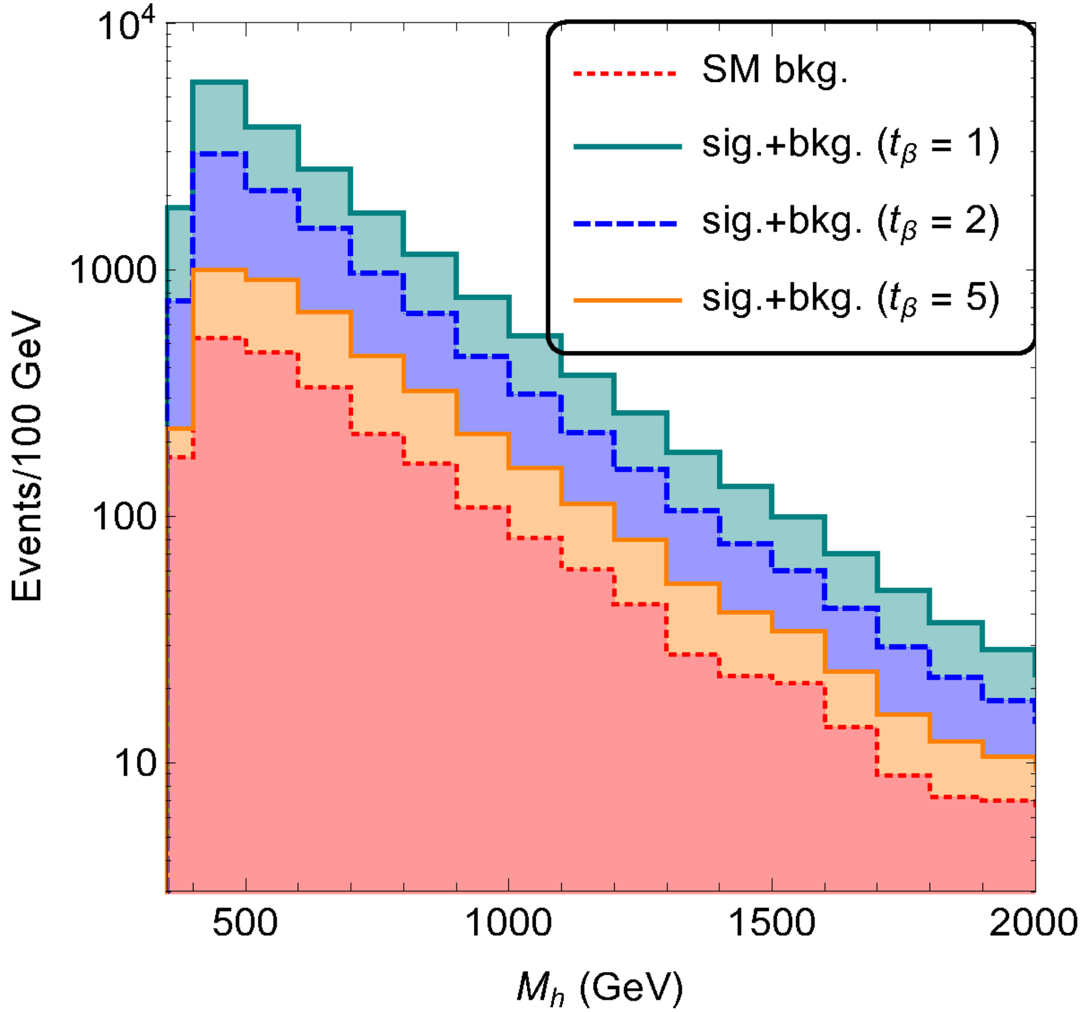


[P.S.B. Dev and A.P., JHEP1412 (2014) 024.]



- **Predicted number of events for h, a signal at $\sqrt{s} = 14$ TeV with 300 fb^{-1} integrated luminosity**

[P.S.B. Dev and A.P., JHEP1412 (2014) 024.]



using `MadGraph5.aMC@NLO`.

• Conclusions

- **The 2HDM potential may exhibit up to <u>13</u> *distinct* discrete and global symmetries as derived in the SO(1,5) bilinear formalism.**

- **Maximal Symmetry Group for nHDM Potentials:**

$$G_{\Phi} \;=\; \mathrm{SU}(2)_L \otimes \mathrm{Sp}(2n)/\mathbf{Z}_2 .$$

- **3 syms. lead to Natural Alignment in 2HDM ($\lambda_1 = \lambda_2 = \lambda_{345}/2$):**

  (i) $\mathrm{SO}(5)$; **(ii)** $\mathrm{O}(3) \times \mathrm{O}(2)$; **(iii)** $\mathrm{Z}_2 \times \mathrm{O}(2) \times \mathrm{O}(2)$.

- **The Aligned Heavy Higgs Sector is Gaugephobic.**

- **Two-loop RG Effects give rise to misalignment predictions leading to lower limits on the charged Higgs mass $M_{h^\pm}$.**

- **Probing New Aligned Higgs Doublets via the production channels:**

  (i) $gg \to t\bar{t}(h, a) \to t\bar{t}t\bar{t}$; **(ii)** $gg \to t\bar{b}h^- \to t\bar{b}\bar{t}b$.