

Back to the Future: CPX

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BSM from Colliders to the Early Universe

Chicago U./Fermilab, USA

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Outline:

- *Radiative Higgs-Sector CP Violation* in the MSSM
- **Maximal Symmetry** and Quartic Coupling Unification
- Natural Alignment in the 2HDM and Beyond
- Phenomenology at the LHC
- **Concluding Remarks**

- **Radiative Higgs-Sector CP Violation in the MSSM**

Lagrangian part describing the MSSM Higgs potential:

$$\begin{aligned}\mathcal{L}_V = & \mu_1^2(\Phi_1^\dagger\Phi_1) + \mu_2^2(\Phi_2^\dagger\Phi_2) + m_{12}^2(\Phi_1^\dagger\Phi_2) + m_{12}^{*2}(\Phi_2^\dagger\Phi_1) \\ & + \lambda_1(\Phi_1^\dagger\Phi_1)^2 + \lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1),\end{aligned}$$

with

$$m_{12}^2 = B\mu, \quad \lambda_1 = \lambda_2 = -\frac{1}{8}(g_w^2 + g'^2), \quad \lambda_3 = -\frac{1}{4}(g_w^2 - g'^2), \quad \lambda_4 = \frac{1}{2}g_w^2.$$

$\Phi_2 \rightarrow e^{i\arg m_{12}^2} \Phi_2 \implies$ Tree-level Higgs potential is invariant under CP !

Higgs-boson mass spectrum:

$$\phi_1 : \quad \text{CP} = +1$$

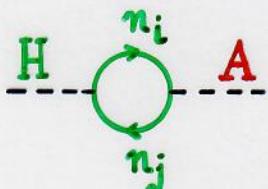
$$\phi_2 : \quad \text{CP} = +1$$

$$a : \quad \text{CP} = -1$$

- How to get the HA mixing ?

popular scenarios :

- Through Majorana fermions ($n = n^c$) in a 2HDM.



In the MSSM, $n_i \leftrightarrow$ neutralinos or charginos

$$\mathcal{L}_H = -\frac{g}{4M_W} \chi_H^u H \bar{n}_i [(m_i + m_j) \text{Re} C_{ij} + i \gamma_5 (m_j - m_i) \text{Im} C_{ij}] n_j$$

$$\mathcal{L}_A = \frac{i g}{4M_W} \chi_A^u A \bar{n}_i [\gamma_5 (m_i + m_j) \text{Re} C_{ij} + i (m_j - m_i) \text{Im} C_{ij}] n_j$$

$$\chi_H^u \sim \chi_A^u \sim \tan \beta = \frac{v_2}{v_1}$$

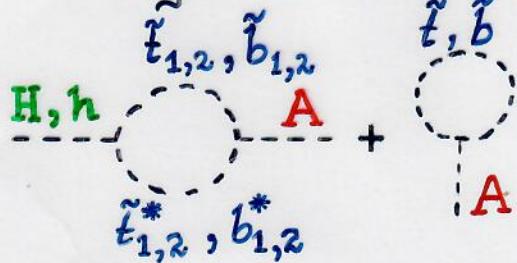
$$\text{CP violation} \implies C_{ij} \neq \pm C_{ij}^* \text{ or } \text{Im} C_{ij}^2 \neq 0$$

- Through soft-breaking (CP) terms in the Higgs potential of a 2HDM. [T.D.Lee, PRD 8 (73) 1226.]

$$V = V_{\text{CP}} + V_{\text{CP}}^{\text{soft}}$$

~~H_{1,2}~~ A The mixing occurs at tree level

- Through radiative effects of $\tilde{t}_1, \tilde{t}_2, \tilde{b}_1, \tilde{b}_2$ in MSSM



UV finite + large

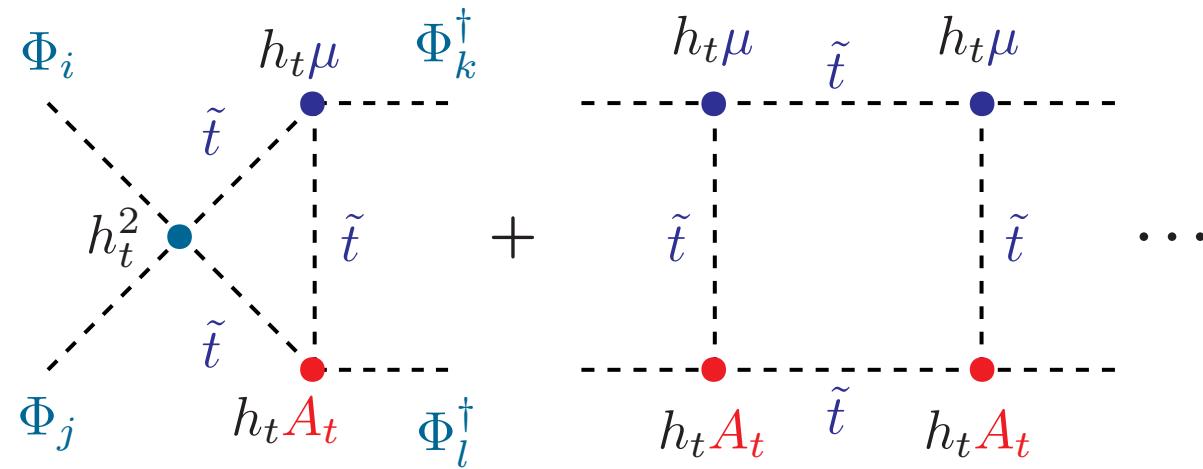
[A.P., PLB 435, 88 (1998)
PRD 58, 096010 (1998)]

⇒ CP violation in the Higgs sector can be induced through loop effects at the observable level

[A.P., PLB435 (1998) 88; A.P., C.E.M. Wagner, NPB553 (1999) 3.]

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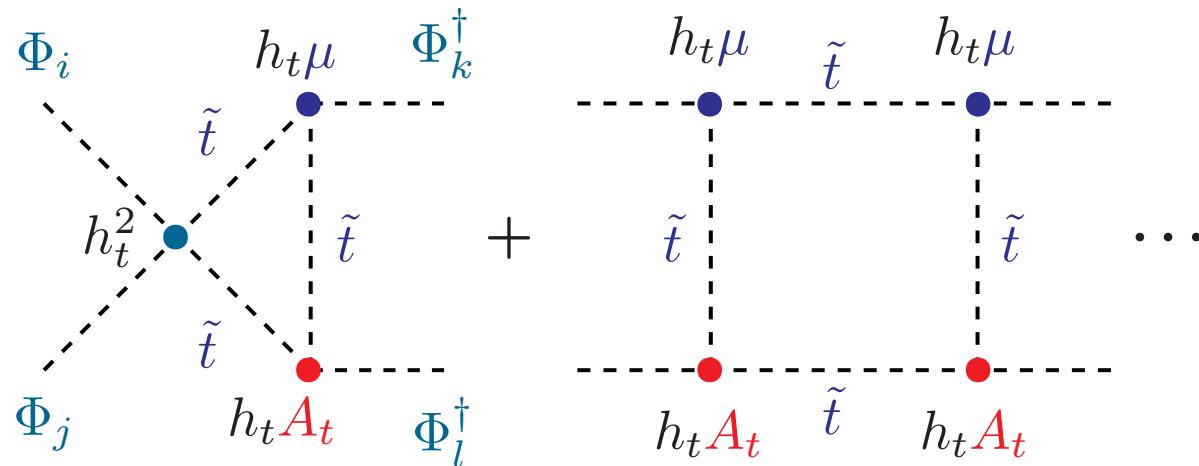
[A.P., PLB435 (1998) 88; A.P., C.E.M. Wagner, NPB553 (1999) 3.]



$$\propto \boxed{\text{Im} (m_{12}^{2*} \mu A_{t,b}) \neq 0}$$

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[A.P., PLB435 (1998) 88; A.P., C.E.M. Wagner, NPB553 (1999) 3.]



$$\propto \boxed{\text{Im} (m_{12}^{2*} \mu A_{t,b}) \neq 0}$$

Additional loop contributions from gluinos, charginos, Higgs bosons

[M. Carena, J. Ellis, A.P., C.E.M. Wagner, NPB586 (2000) 92; NPB625 (2002) 345;
 D.A. Demir, PRD60 (1999) 055006; S.Y. Choi, M. Drees, J.S. Lee, PLB481 (2000) 57;
 T. Ibrahim and P. Nath, PRD63 (2001) 035009;
 S.P. Martin, PRD66 (2002) 096001;
 M. Frank, T. Hahn, S. Heinemeyer, W. Hollik, H. Rzehak, G. Weiglein, JHEP0702 (2007) 047.]

The mixing of the three neutral Higgs bosons:

$$\begin{pmatrix} \phi_1 \\ \phi_2 \\ \textcolor{red}{a} \end{pmatrix} = \textcolor{red}{O} \begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix}$$

O : 3×3 orthogonal matrix describing the CP mixing of Higgs bosons.

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Higgs bosons with mixed CP parities are ordered according to their weights:

$$M_{H_1} \leq M_{H_2} \leq M_{H_3}$$

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At the 1-loop level, $M_{H_{1,2,3}}$ and O are predicted by the input parameters:

$$M_{H^+}(m_t), \quad \tan \beta(m_t),$$

$$\mu(Q_{tb}), \quad A_t(Q_{tb}), \quad A_b(Q_{tb}),$$

$$\widetilde{M}_Q^2(Q_{tb}), \quad \widetilde{M}_t^2(Q_{tb}), \quad \widetilde{M}_b^2(Q_{tb}).$$

$$M_{1,2,3}$$

Effective Higgs couplings to gauge bosons and fermions

$$H_i \begin{array}{c} \text{---} \\ \diagdown \end{array} Z_\mu : ig_w \frac{M_W^2}{M_Z} (c_\beta O_{1i} + s_\beta O_{2i}) g_{\mu\nu}$$

Z_ν

$$H_i(k) \begin{array}{c} \text{---} \\ \diagdown \end{array} W_\mu^\pm : \pm \frac{i}{2} g_w (c_\beta O_{2i} - s_\beta O_{1i} + i O_{3i}) (p - k)_\mu$$

$H^\mp(p)$

$$H_i(k) \begin{array}{c} \text{---} \\ \diagdown \end{array} Z_\mu : - \frac{i g_w M_Z}{2 M_W} \left[O_{3i} (c_\beta O_{2j} - s_\beta O_{1j}) - (i \leftrightarrow j) \right] (p - k)_\mu$$

$H_j(p)$

$$H_i \begin{array}{c} \text{---} \\ \bullet \\ \nearrow d \\ \searrow d \end{array} : - \frac{i g_w m_d}{2 M_W c_\beta} (O_{1i} - i s_\beta O_{3i} \gamma_5) + \dots$$

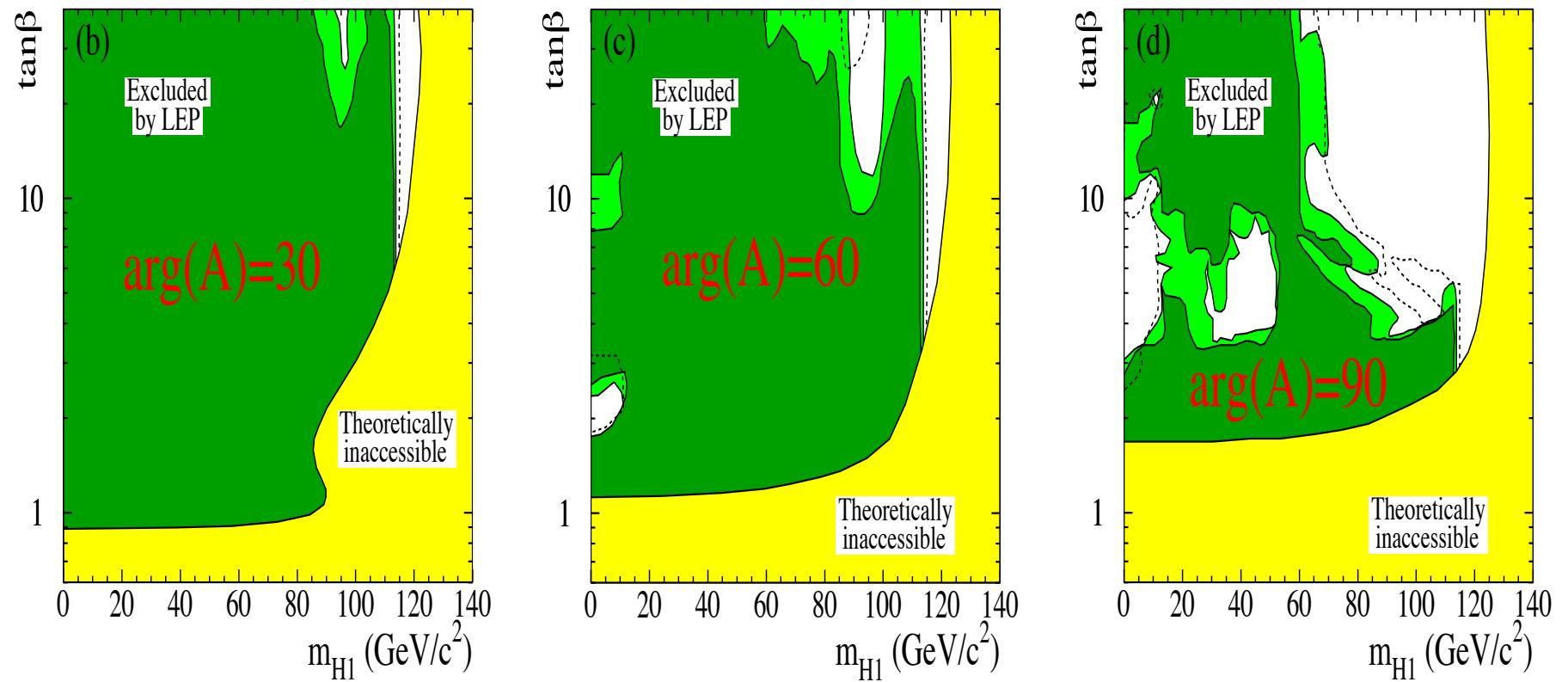
$$H_i \begin{array}{c} \text{---} \\ \bullet \\ \nearrow u \\ \searrow u \end{array} : - \frac{i g_w m_u}{2 M_W s_\beta} (O_{2i} - i c_\beta O_{3i} \gamma_5) + \dots$$

[**CPsuperH**: J.S. Lee, A.P., M. Carena, S.Y. Choi, M. Drees, J.R. Ellis, C.E.M. Wagner, CPC156 (2004) 283.]

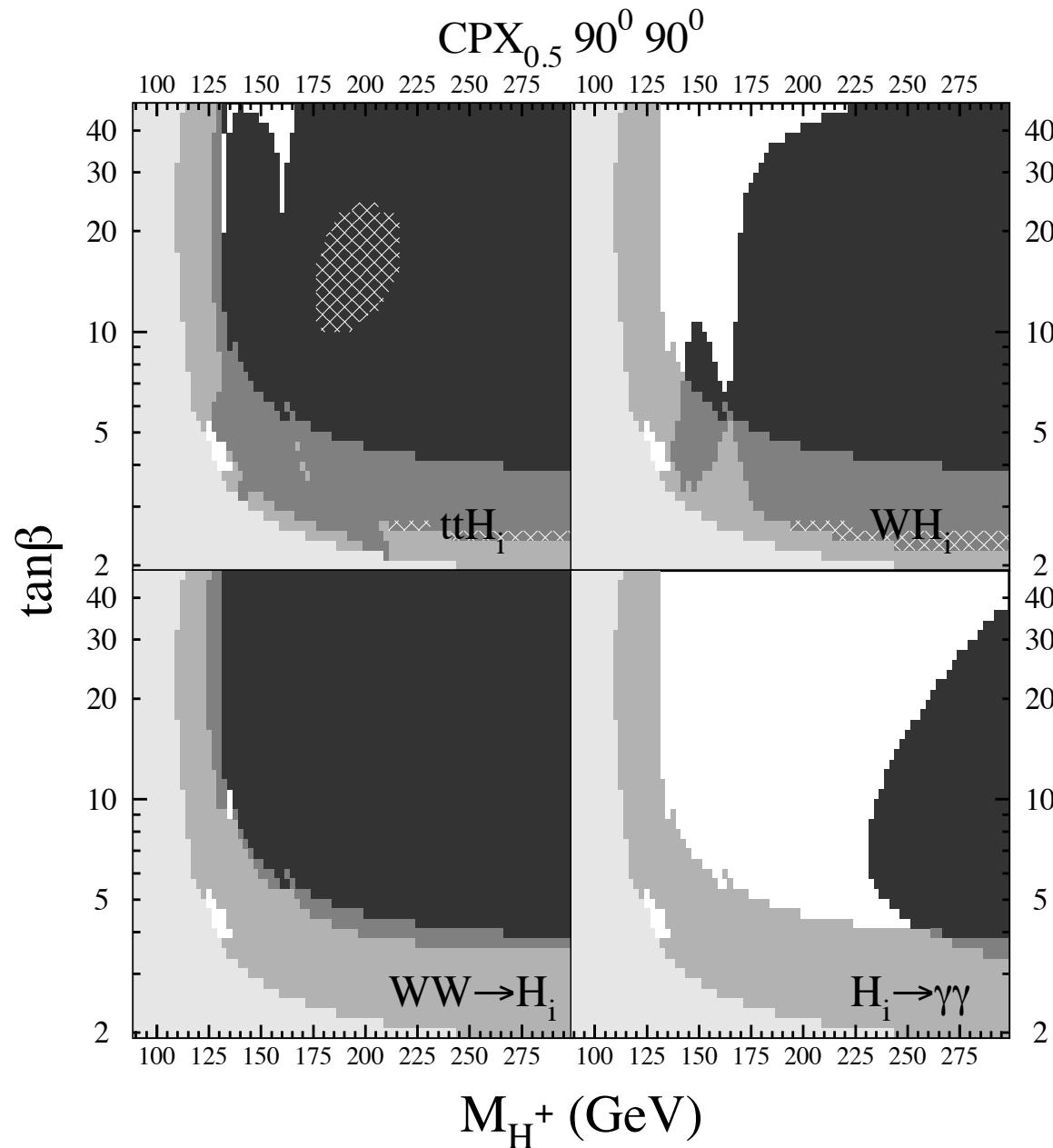
Elusive light CP-violating Higgs bosons at LEP2

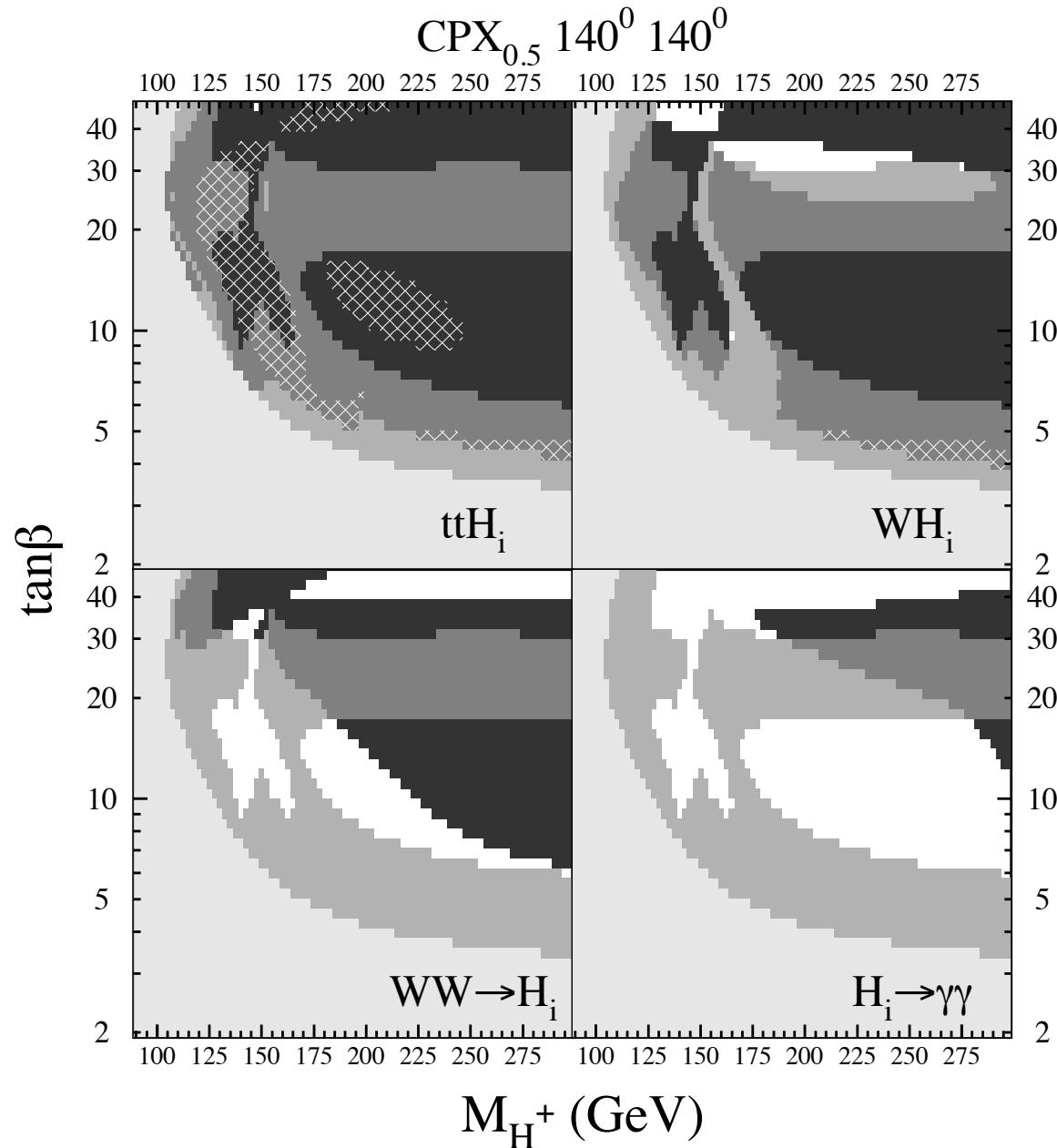
CPX scenario: $\mu = 4 M_{\text{SUSY}}$, $A_{t,b} = 2 M_{\text{SUSY}}$ ($m_t = 174.3$ GeV)

[M. Carena, J. Ellis, A.P., C.E.M. Wagner, PLB495 (2000) 155.]

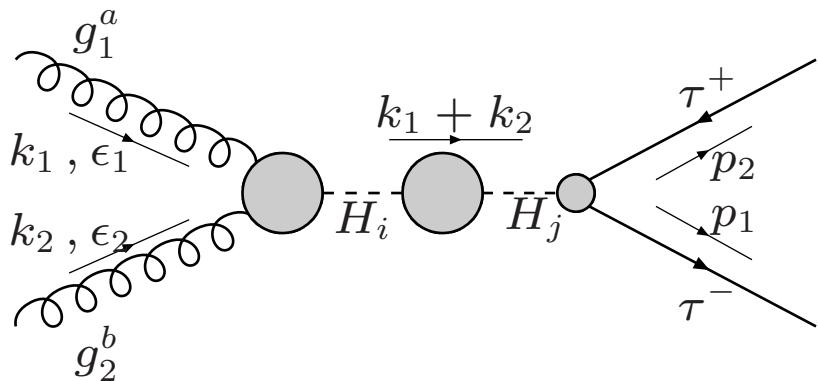


[Combined analysis from LEP collaborations, Eur. Phys. J. C 47 (2006) 547, uses **CPsuperH** + **FeynHiggs**]





CP Violation in Higgs Production → Mixing → Decay at the LHC



[A.P., NPB504 (1997) 61;
J. Ellis, J.S. Lee, A.P., PRD70 (2004) 075010]

Resummed Higgs-boson propagator matrix:

[M. Carena, J. Ellis, A.P., C. Wagner, NPB625 (2002) 345]

$$\Delta(\hat{s}) = \begin{pmatrix} \hat{s} - M_{H_1}^2 + i\text{Im}\widehat{\Pi}_{11}(\hat{s}) & i\text{Im}\widehat{\Pi}_{12}(\hat{s}) & i\text{Im}\widehat{\Pi}_{13}(\hat{s}) \\ i\text{Im}\widehat{\Pi}_{21}(\hat{s}) & \hat{s} - M_{H_2}^2 + i\text{Im}\widehat{\Pi}_{22}(\hat{s}) & i\text{Im}\widehat{\Pi}_{23}(\hat{s}) \\ i\text{Im}\widehat{\Pi}_{31}(\hat{s}) & i\text{Im}\widehat{\Pi}_{32}(\hat{s}) & \hat{s} - M_{H_3}^2 + i\text{Im}\widehat{\Pi}_{33}(\hat{s}) \end{pmatrix}^{-1}$$

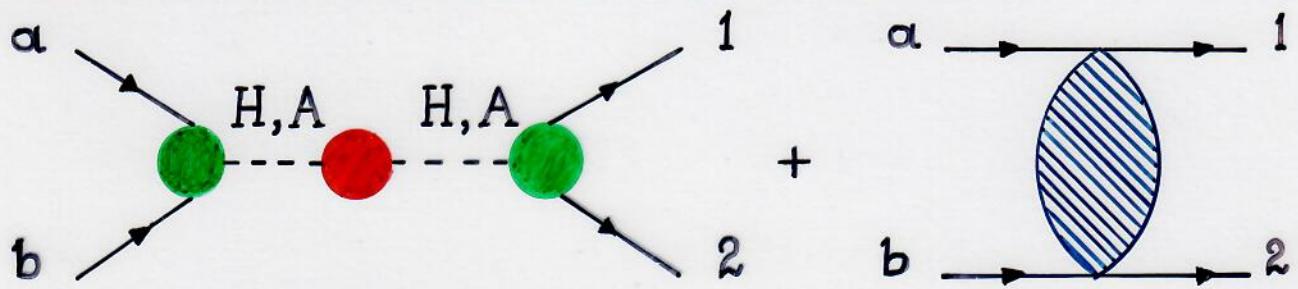
M_{H_i} : OS-renormalized mass in the Pinch Technique (PT) framework

$\text{Im}\widehat{\Pi}_{ij}(\hat{s})$: PT absorptive parts, with $\text{Im}\widehat{\Pi}_{ii}(\hat{s} = M_{H_i}) = M_{H_i} \Gamma_{H_i}$

PT is used to obtain a GFP-independent $\Delta(\hat{s})$, consistent with tree-like WIs and unitarity, i.e. cancellation of s^2 -dependent terms in $\text{Im}\widehat{\Pi}_{ij}^{VV,VH}(\hat{s})$.

[J. Papavassiliou, A.P., PRL75 (1995) 3060; PRL80 (1998) 2785; PRD58 (1998) 053002]

- **CP** violation in transition amplitudes



$$\mathcal{T} = \mathcal{T}^{\text{RES}} + \mathcal{T}^{\text{BOX}} = V_i^P \left(\frac{1}{s \mathbf{1} - \mathbf{H}(s)} \right)_{ij} V_j^D + \mathcal{T}^{\text{BOX}}$$

$$\mathcal{T}^{\text{CP}} = \bar{\mathcal{T}}^{\text{RES}} + \bar{\mathcal{T}}^{\text{BOX}} = \bar{V}_i^P \left(\frac{1}{s \mathbf{1} - \bar{\mathbf{H}}(s)} \right)_{ij} \bar{V}_j^D + \bar{\mathcal{T}}^{\text{BOX}}$$

$$V_i = |V_i| e^{i\delta_f} e^{i\varphi_w} \xrightarrow{\text{CP}} \bar{V}_i = |V_i| e^{i\delta_f} e^{-i\varphi_w}$$

δ_f : absorptive or final state phase

φ_w : weak phase

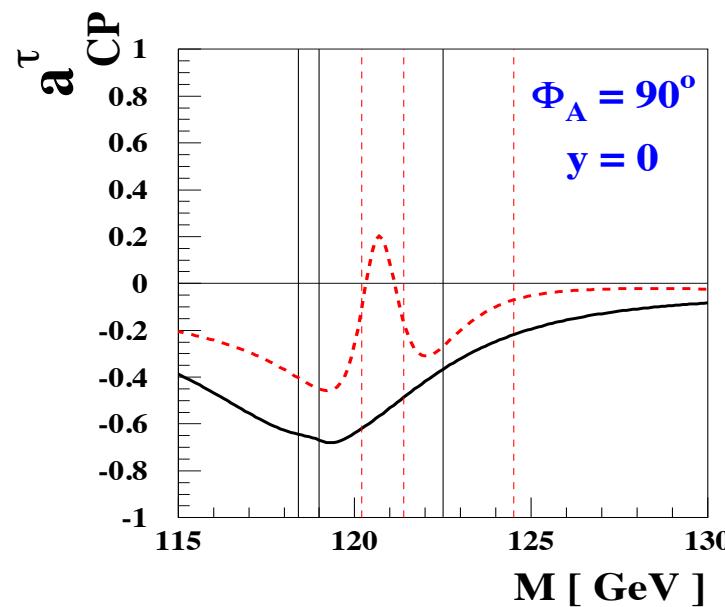
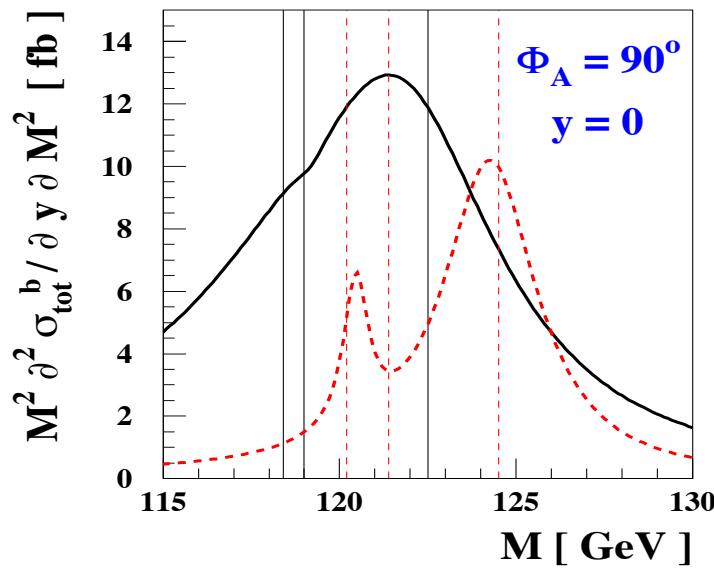
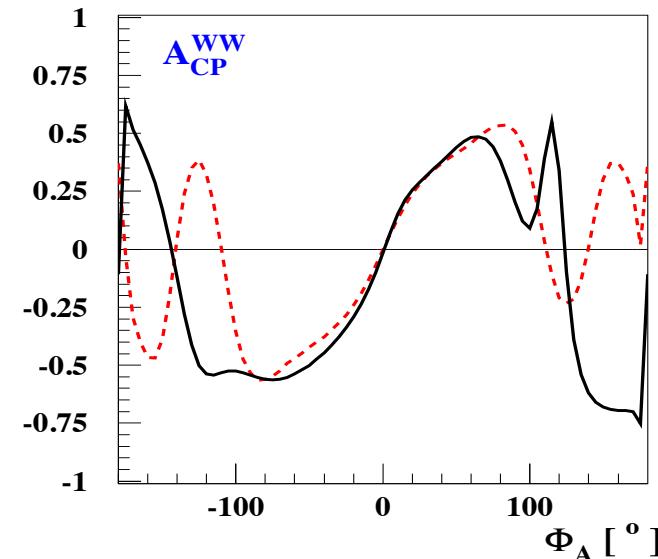
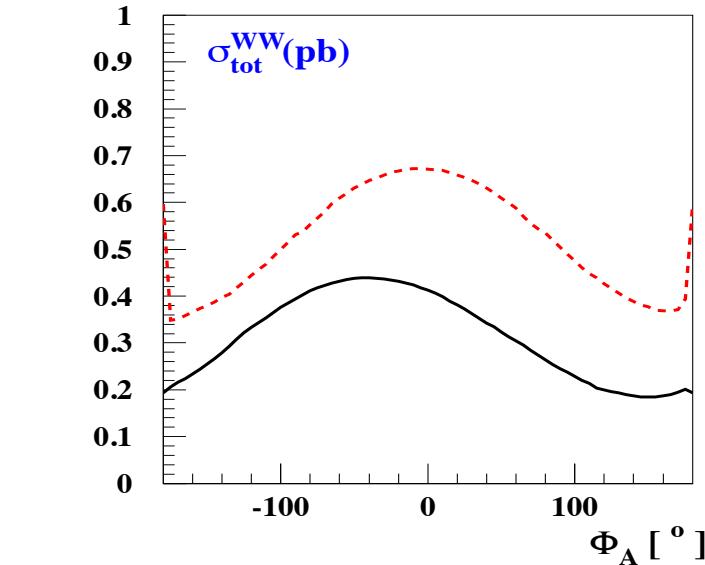
- $V_i^{\text{P,D}}$: **CP** in the production and decay amplitudes } ϵ' -type effect
- $H(s)$: **CP** in the mass matrix
 $H(s) \neq H^T(s)$ in a K^0 - \bar{K}^0 -like basis
 $H(s) \xrightarrow{\text{CP}} \bar{H}(s) = H^T(s)$ } ϵ -type effect

CP asymmetry :

$$A_{\text{CP}} = \frac{|\mathcal{T}|^2 - |\mathcal{T}^{\text{CP}}|^2}{|\mathcal{T}|^2 + |\mathcal{T}^{\text{CP}}|^2} = \frac{|\mathcal{T}^{\text{RES}}|^2 - |\bar{\mathcal{T}}^{\text{RES}}|^2}{|\mathcal{T}^{\text{RES}}|^2 + |\bar{\mathcal{T}}^{\text{RES}}|^2}$$

Resonant CP Violation at the LHC

[J. Ellis, J.S. Lee, A.P., PRD70 (2004) 075010; PRD71 (2005) 075007.]



- Maximal Symmetry and Quartic Coupling Unification

- Symmetries of the Two Higgs Doublet Model Potential

- $SU(2)_L \otimes U(1)_Y$ -preserving symmetries: 6

⇒ 1. CP, 2. Z_2 , 3. CP2, 4. $U(1)_{PQ}$, 5. $CP \times SO(2)$, 6. $SU(2)$

[I.P. Ivanov, PRD75 (2007) 035001; P.M. Ferreira, H.E. Haber, J.P. Silva, PRD79 (2009) 116004.]

- Hypercustodial $SU(2)_L$ -preserving symmetries: +7

⇒ 1. $Sp(2)$, 2. $CP \times Sp(2)$, 3. $Z_2 \times Sp(2)$, 4. $U(1) \times Sp(2)$,
5. $Sp(2) \times Sp(2)$, 6. $S_2 \times Sp(2) \times Sp(2)$, 7. $Sp(4)$

[R.A. Battye, G.D. Brawn, AP, JHEP1108 (2011) 020; AP, PLB706 (2012) 465;

N. Darvishi, A.P., PRD101 (2020) 095008.]

- Symmetries of the Three Higgs Doublet Model Potential

[N. Darvishi, A.P., PRD101 (2020) 095008, and references therein.]

- Symmetries: 40 = 19 [U(1)_Y] + 21 [Custodial]

- Maximally Symmetric Two Higgs Doublet Model

[P.S.B. Dev, AP '14; N. Darvishi, AP '19]

$$G_\Phi = \mathrm{SU}(2)_L \otimes \mathrm{Sp}(4)/\mathbb{Z}_2 \simeq \mathrm{SU}(2)_L \otimes \mathrm{SO}(5)$$

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

where

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

such that under **global field transformations**,

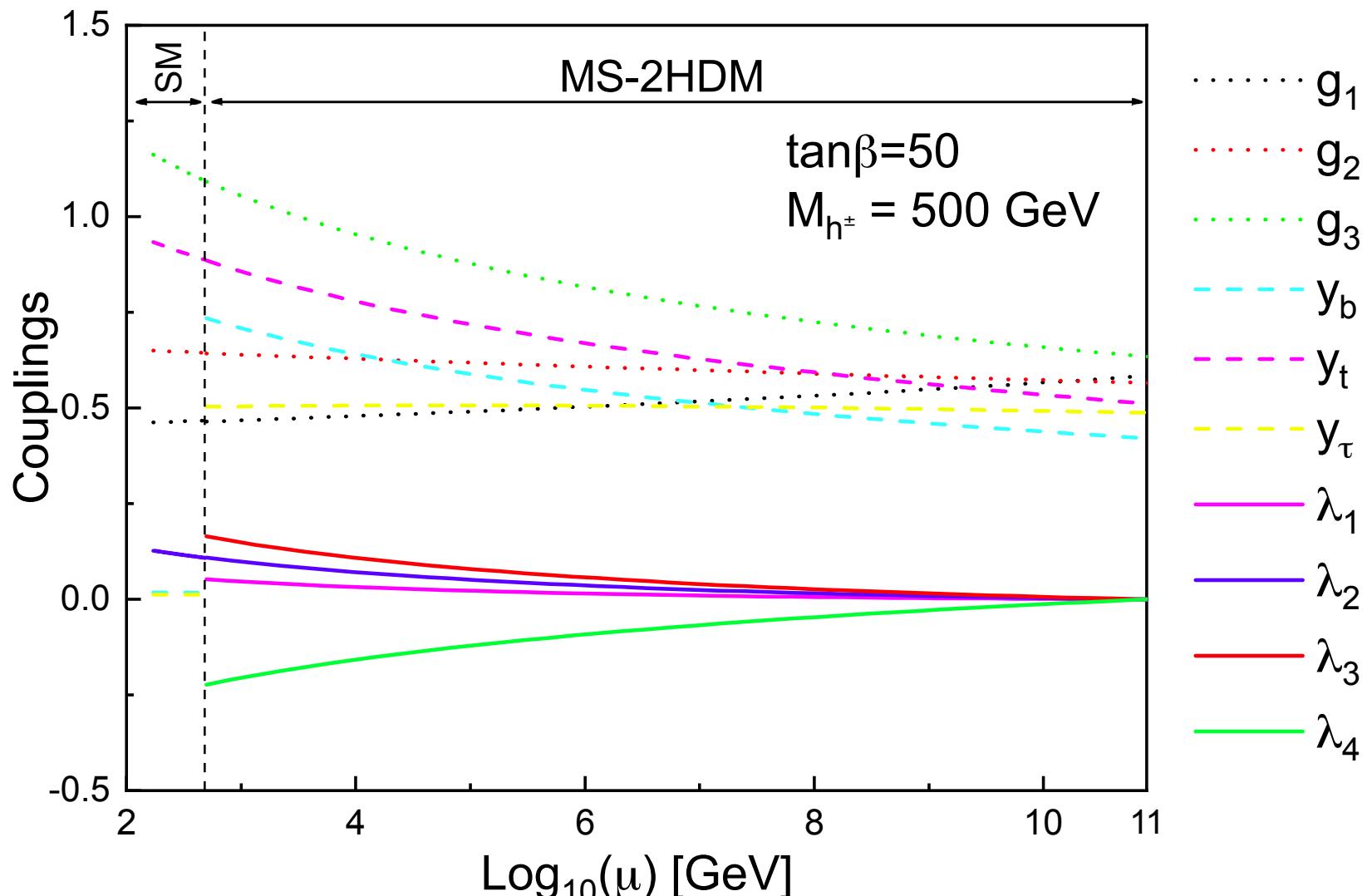
$$\mathrm{Sp}(4) : \Phi \mapsto \Phi' = U \Phi, \quad \text{with } U \in \mathrm{U}(4) \quad \& \quad UCU^\top = C \equiv i\sigma^2 \otimes \sigma^0$$

SU(2)_L gauge kinetic terms remain invariant.

Breaking Effects: $m_{12}^2 \phi_1^\dagger \phi_2$ (or M_{h^\pm}), $\mathrm{U}(1)_Y$ coupling g' , Yukawa's $\mathbf{Y}^{u,d}$.

- Quartic Coupling Unification (up to two loops)

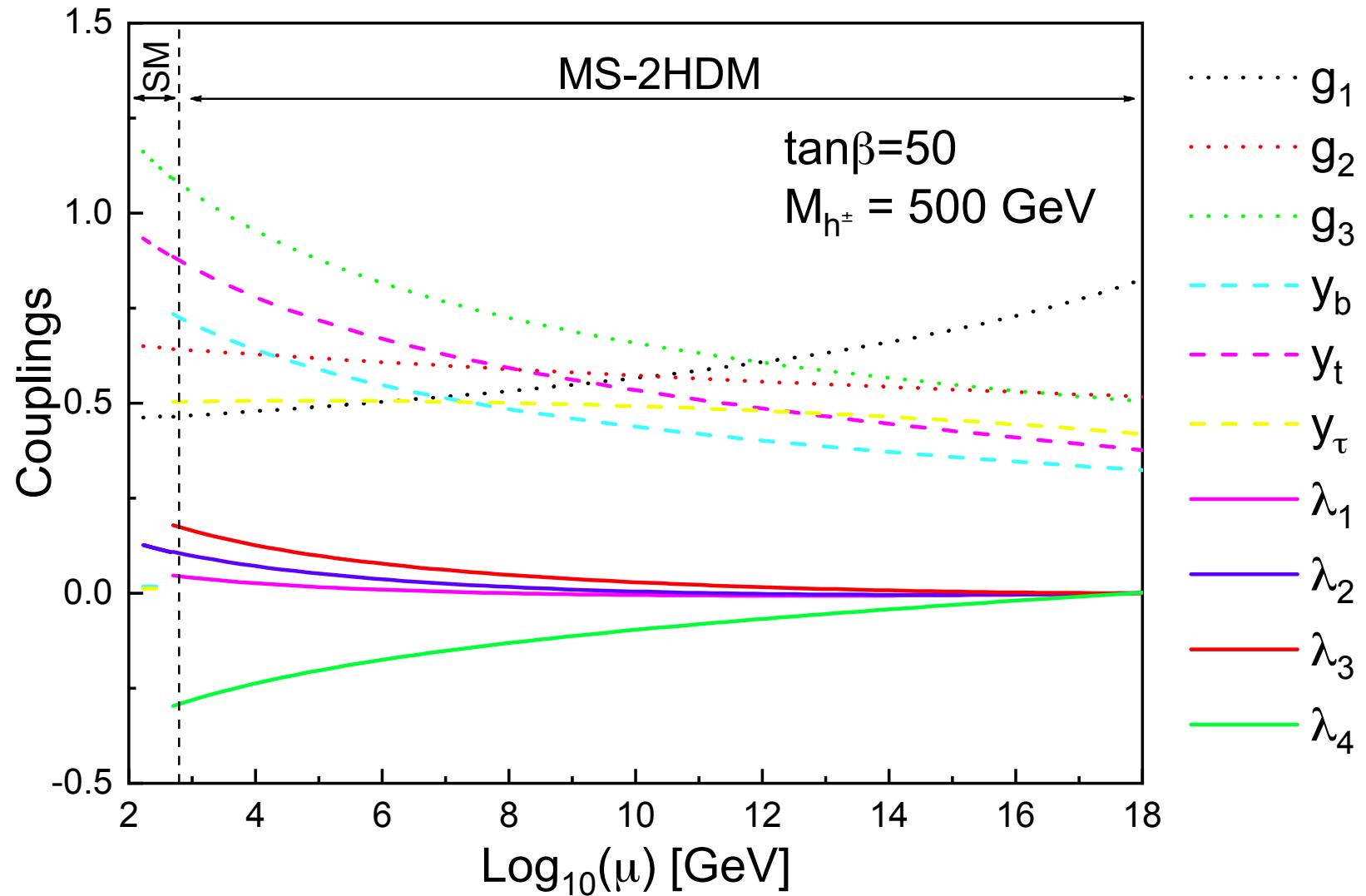
[N. Darvishi, AP '19]



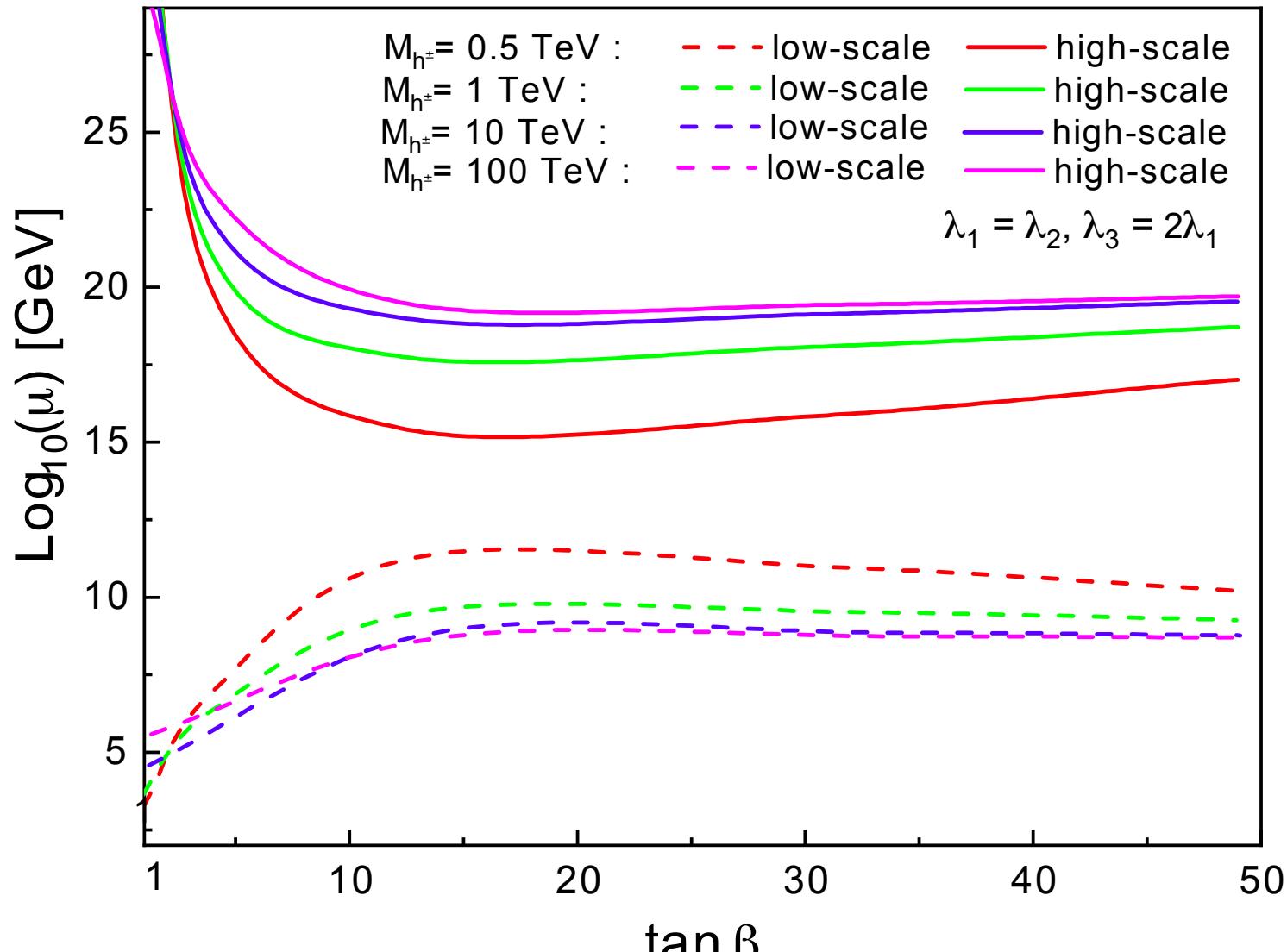
First conformal unification point: $\mu_X^{(1)} \sim 10^{11} \text{ GeV}$ (of order PQ scale)

Second conformal unification point: $\mu_X^{(2)} \sim 10^{18}$ GeV (of order m_{Pl})

[N. Darvishi, AP '19]



Low- and high-scale quartic coupling unification: $\tan \beta$ vs $\mu_X^{(1,2)}$



[N. Darvishi, AP '19]

- **Misalignment in the MS-2HDM**

CP-even mass matrix in Higgs basis:

$$\mathcal{M}_S^2 = \begin{pmatrix} \hat{A} & \hat{C} \\ \hat{C} & \hat{B} \end{pmatrix} \xrightarrow[\text{approx.}] {\text{seesaw}} M_H^2 \simeq \hat{A} - \frac{\hat{C}^2}{\hat{B}} \quad \& \quad M_h^2 \simeq \hat{B} \gg \hat{A}, \hat{C}$$

Light-to-heavy scalar mixing:

$$\theta_S \equiv \frac{\hat{C}}{\hat{B}} = \frac{v^2 s_\beta c_\beta [s_\beta^2 (2\lambda_2 - \lambda_{34}) - c_\beta^2 (2\lambda_1 - \lambda_{34})]}{M_a^2 + 2v^2 s_\beta^2 c_\beta^2 (\lambda_1 + \lambda_2 - \lambda_{34})} \ll 1$$

Higgs couplings to $V = W, Z$:

$$g_{HVV} \simeq 1 - \frac{1}{2} \theta_S^2, \quad g_{hVV} \simeq -\theta_S$$

Higgs couplings to quarks:

$$\begin{aligned} g_{Hu u} &\simeq 1 + t_\beta^{-1} \theta_S, & g_{Hd d} &\simeq 1 - t_\beta \theta_S, \\ g_{hu u} &\simeq -\theta_S + t_\beta^{-1}, & g_{hdd} &\simeq -\theta_S - t_\beta. \end{aligned}$$

Misalignment predictions in the MS-2HDM with low- and high-scale quartic coupling unification, assuming $M_{h^\pm} = 500$ GeV.

[N. Darvishi, AP '19]

Couplings	ATLAS	CMS	$\tan \beta = 2$	$\tan \beta = 20$	$\tan \beta = 50$
$ g_{HZZ}^{\text{low-scale}} $	[0.86, 1.00]	[0.90, 1.00]	0.9999	0.9999	0.9999
$ g_{HZZ}^{\text{high-scale}} $			0.9981	0.9999	0.9999
$ g_{Htt}^{\text{low-scale}} $	$1.31^{+0.35}_{-0.33}$	$1.45^{+0.42}_{-0.32}$	1.0049	1.0001	1.0000
$ g_{Htt}^{\text{high-scale}} $			1.0987	1.0003	1.0001
$ g_{Hbb}^{\text{low-scale}} $	$0.49^{+0.26}_{-0.19}$	$0.57^{+0.16}_{-0.16}$	0.9803	0.9560	0.9590
$ g_{Hbb}^{\text{high-scale}} $			0.8810	0.9449	0.9427

→ Misalignment predictions consistent with experiment

• Natural Alignment in the 2HDM and Beyond

- **n HDM potential** with m inert scalar doublets:

[P.S.B. Dev, AP '14,
AP '16]

$$V_{n\text{HDM}} = V_{\text{sym}} + V_{\text{inert}} + \Delta V_{\text{soft}},$$

- 3 continuous alignment symmetries in the **field space of the active EWSB sector** ($N_H = n - m$):

$$(i) \quad \text{Sp}(2N_H) \times \mathcal{D} \quad (ii) \quad \text{SU}(N_H) \times \mathcal{D} \quad (iii) \quad \text{SO}(N_H) \times \mathcal{CP} \times \mathcal{D},$$

where \mathcal{D} acts on the inert sector *only*.

- **Symmetry invariants:**

$$(i) \quad S = \Phi_1^\dagger \Phi_1 + \Phi_2^\dagger \Phi_2 + \dots = \frac{1}{2} \Phi^\dagger \Phi$$

$$(ii) \quad D^a = \Phi_1^\dagger \sigma^a \Phi_1 + \Phi_2^\dagger \sigma^a \Phi_2 + \dots$$

$$(iii) \quad T = \Phi_1 \Phi_1^\top + \Phi_2 \Phi_2^\top + \dots$$

- **Symmetric part of the scalar potential:**

$$V_{\text{sym}} = -\mu^2 S + \lambda_S S^2 + \lambda_D D^a D^a + \lambda_T \text{Tr}(T T^*) .$$

- Inert part of the scalar potential:

$$\begin{aligned}
 V_{\text{inert}} = & \widehat{m}_{\hat{a}\hat{b}}^2 \widehat{\Phi}_{\hat{a}}^\dagger \widehat{\Phi}_{\hat{b}} + \lambda_{\hat{a}\hat{b}\hat{c}\hat{d}} (\widehat{\Phi}_{\hat{a}}^\dagger \widehat{\Phi}_{\hat{b}})(\widehat{\Phi}_{\hat{c}}^\dagger \widehat{\Phi}_{\hat{d}}) + \lambda_{\hat{a}\hat{b}cd} (\widehat{\Phi}_{\hat{a}}^\dagger \widehat{\Phi}_{\hat{b}})(\Phi_c^\dagger \Phi_d) \\
 & + \lambda_{a\hat{b}\hat{c}d} (\Phi_a^\dagger \widehat{\Phi}_{\hat{b}})(\widehat{\Phi}_{\hat{c}}^\dagger \Phi_d) + \left[\lambda_{a\hat{b}cd} (\Phi_a^\dagger \widehat{\Phi}_{\hat{b}})(\Phi_c^\dagger \widehat{\Phi}_{\hat{d}}) + \text{H.c.} \right]
 \end{aligned}$$

$$Z_2^I : \quad \Phi_a \rightarrow \Phi_a \quad (a = 1, 2, \dots, N_H), \quad \widehat{\Phi}_{\hat{b}} \rightarrow -\widehat{\Phi}_{\hat{b}} \quad (\hat{b} = \hat{1}, \hat{2}, \dots, \hat{m})$$

- Soft-symmetry Breaking:

$$\Delta V_{\text{soft}} = m_{ab}^2 \Phi_a^\dagger \Phi_b$$

- Minimal Symmetry of Alignment in the Higgs basis:

$$Z_2^{\text{EW}} : \quad \Phi'_1 \rightarrow \Phi'_1, \quad \Phi'_{a'} \rightarrow -\Phi'_{a'} \quad (a' = 2, 3, \dots, N_H)$$

where m_{ab}^2 becomes diagonal.

\implies

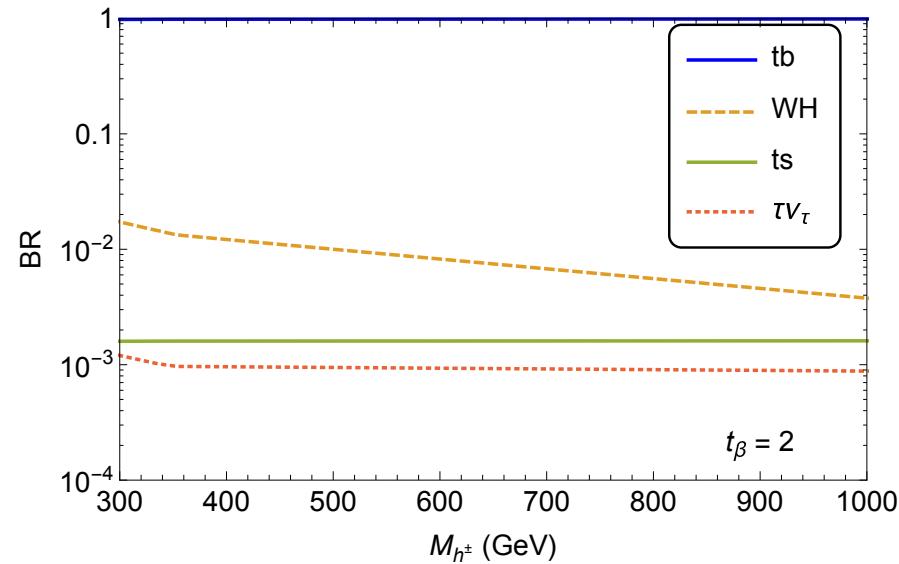
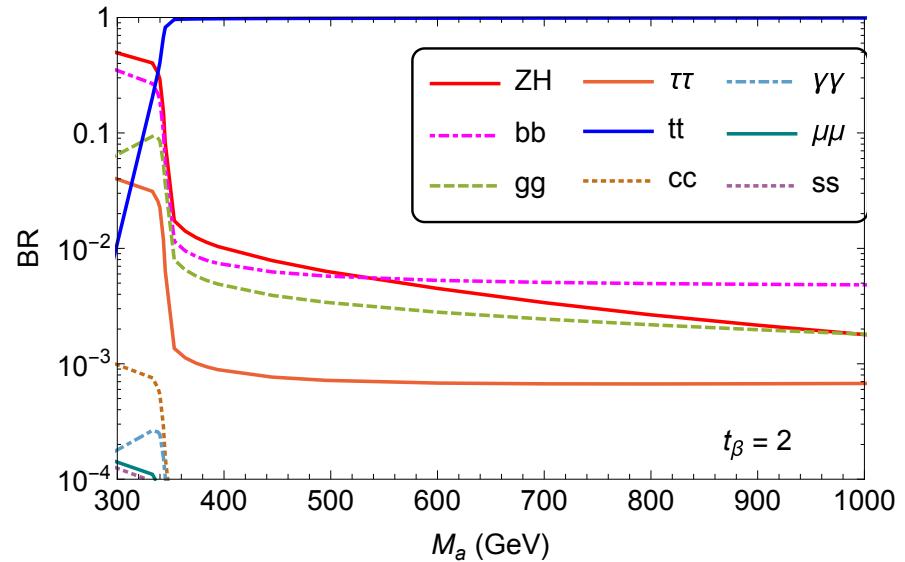
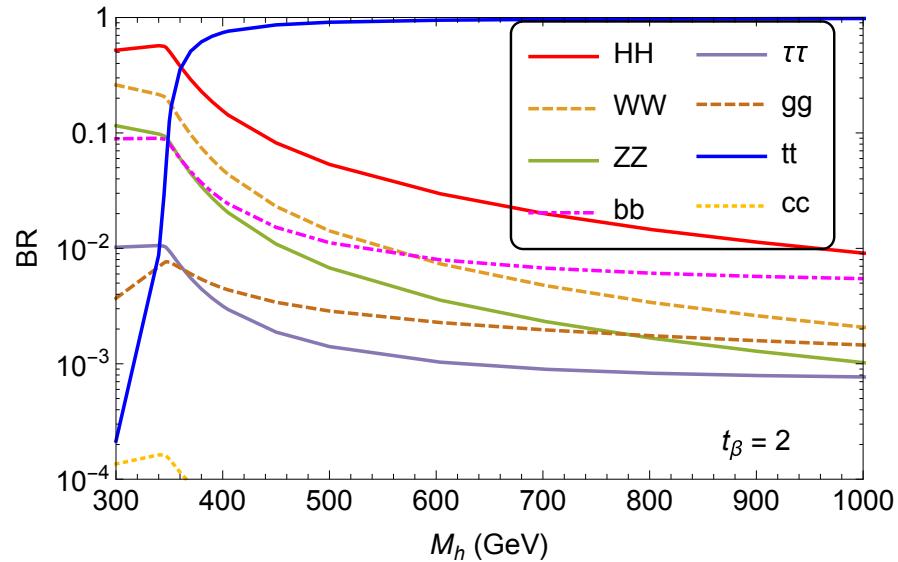
Minimal Alignment Symmetry: $Z_2^{\text{EW}} \times Z_2^I$

[AP '16]

• Phenomenology at the LHC

– Branching ratios in the MS-2HDM

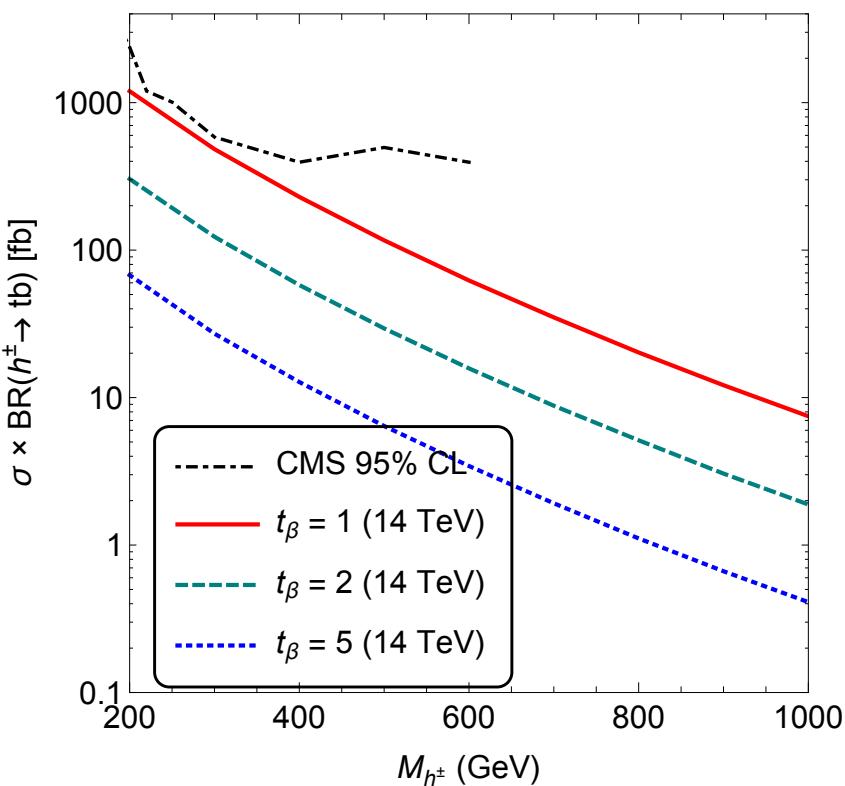
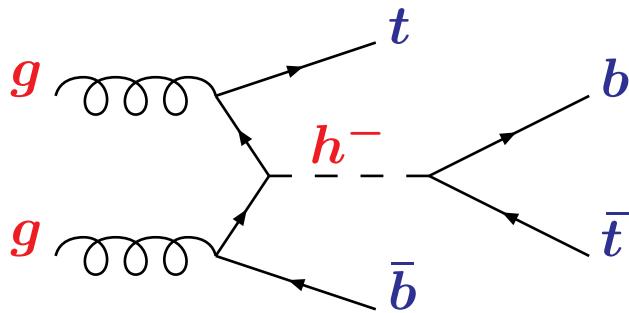
[Dev, AP '14]



- Discovery channels for aligned Higgs doublets:

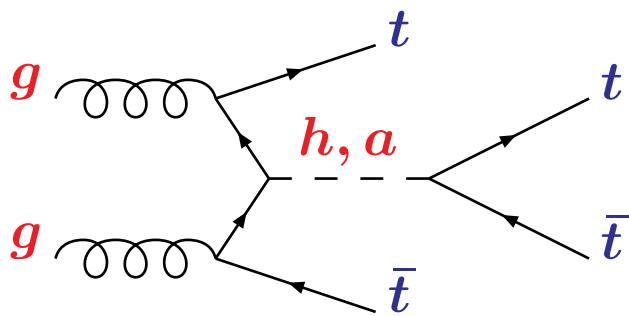
- $gg \rightarrow t\bar{b}h^- \rightarrow t\bar{b}\bar{t}b$

[Dev, AP '14]

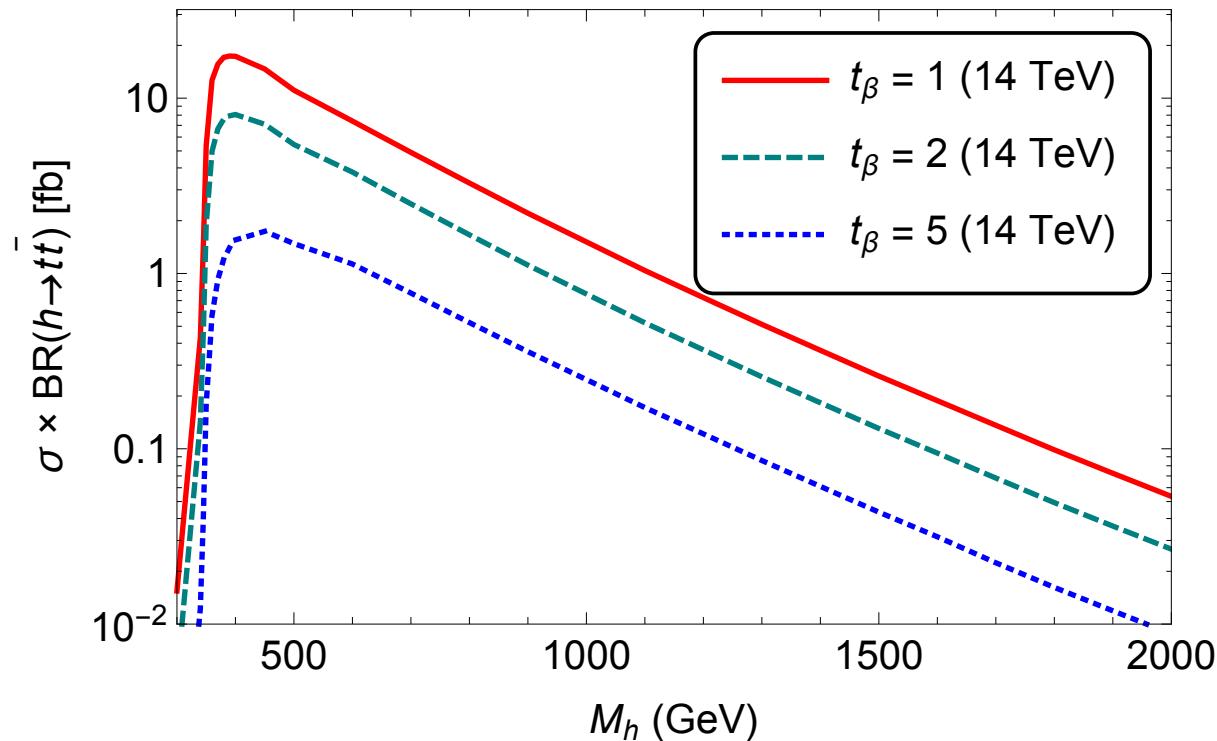


$p_T^\ell > 20$ GeV,
 $|\eta^\ell| < 2.5$,
 $\Delta R^{\ell\ell} > 0.4$,
 $M_{\ell\ell} > 12$ GeV,
 $|M_{\ell\ell} - M_Z| > 10$ GeV,
 $p_T^j > 30$ GeV,
 $|\eta^j| < 2.4$,
 $\cancel{E}_T > 40$ GeV.

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

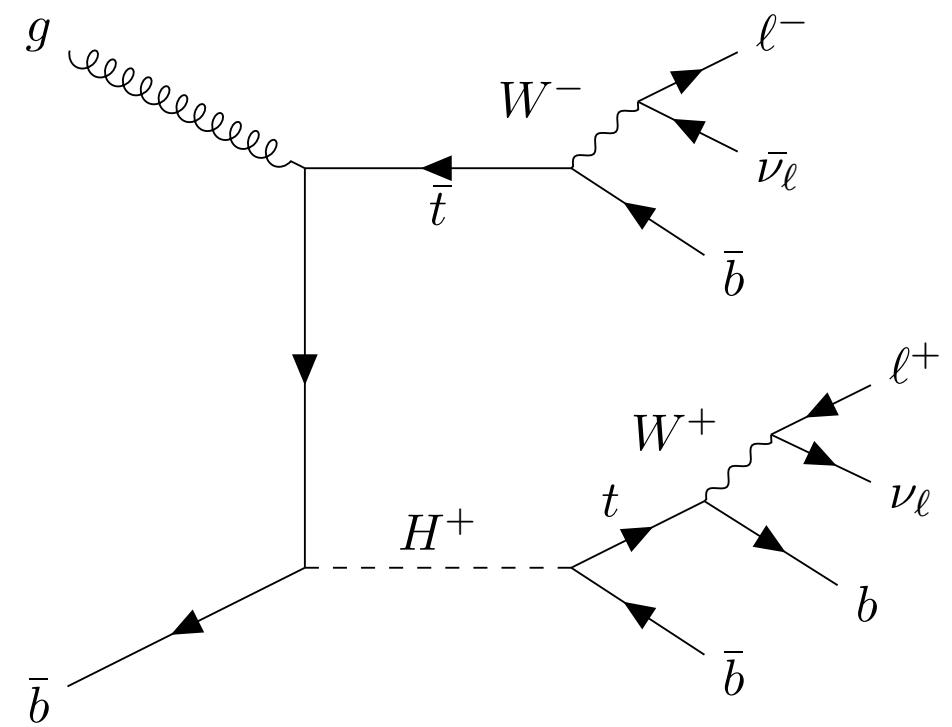
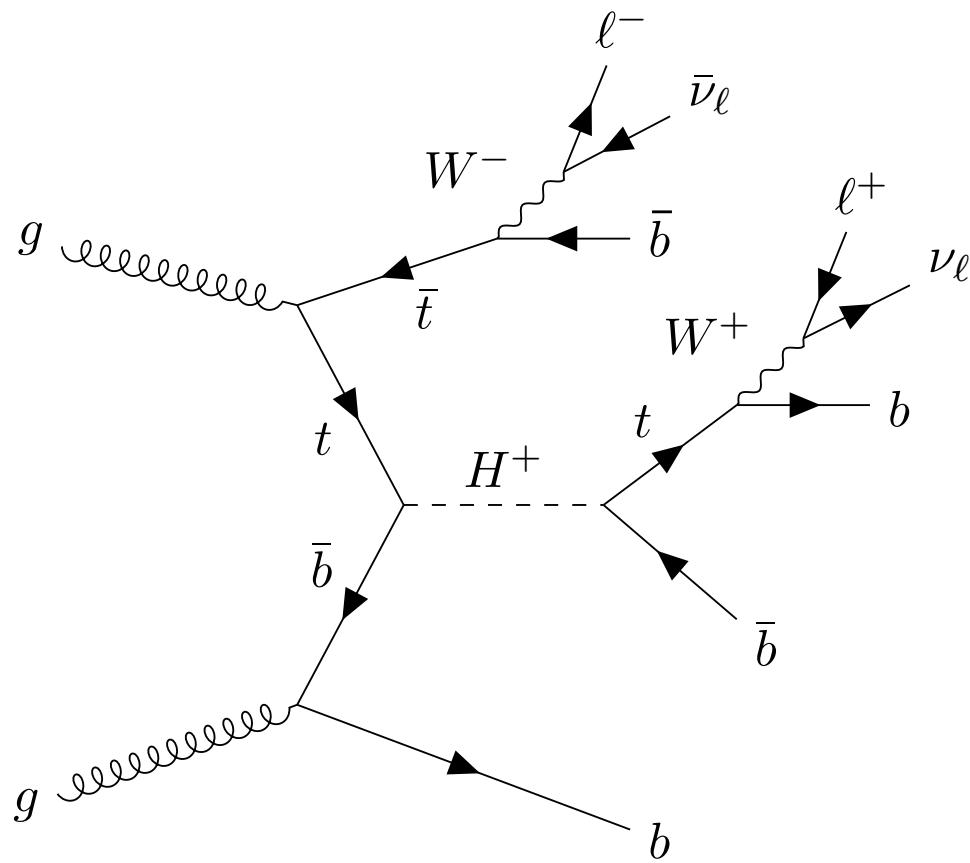


[Dev, AP '14]



– Realistic simulation analysis with a reconstruction BDT

[Emily Hanson, W. Klemm, R. Naranjo, Yvonne Peters, AP, PRD100 (2019) 035026]

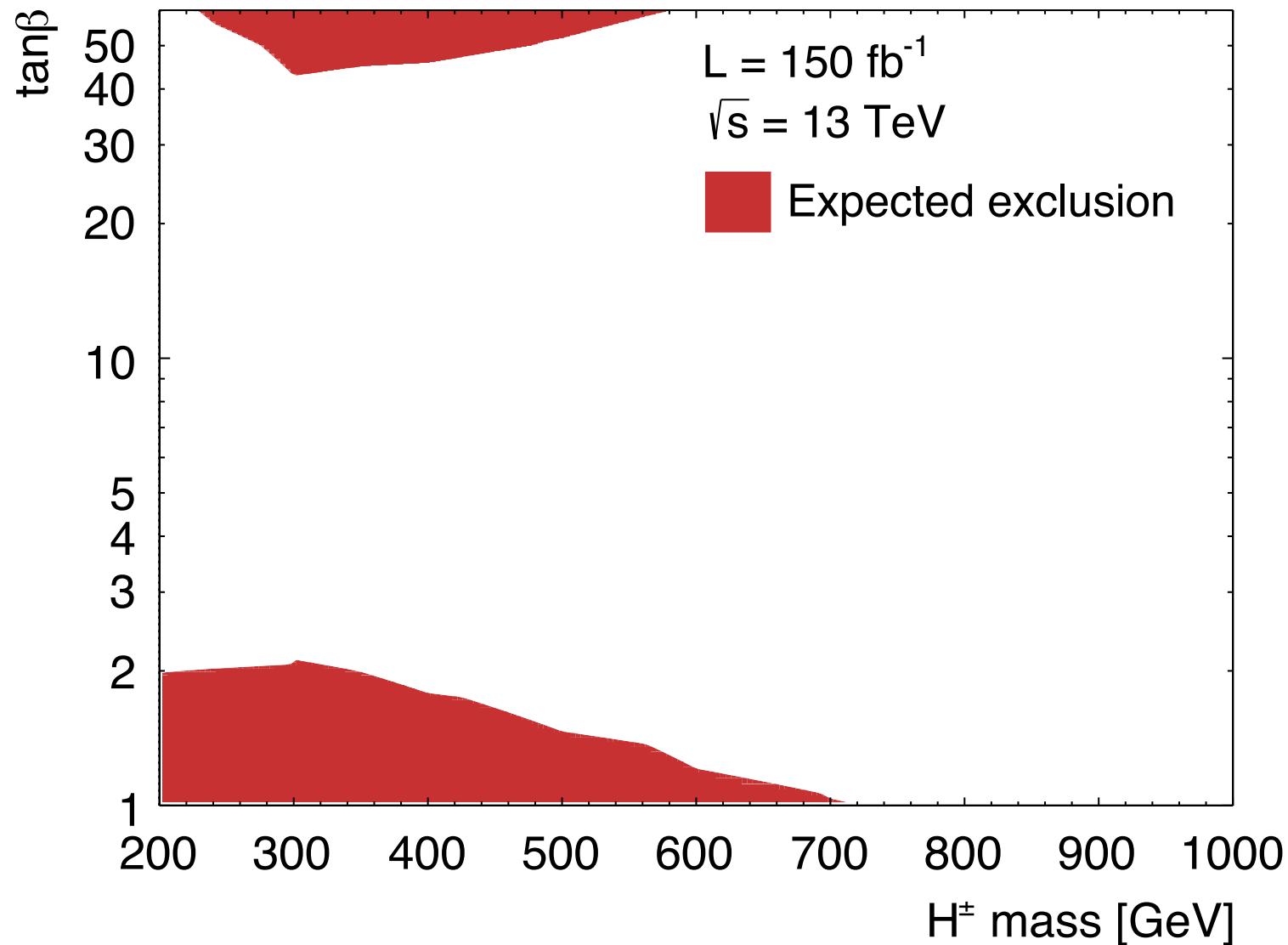


Reconstruction BDT trained on 57 observables:

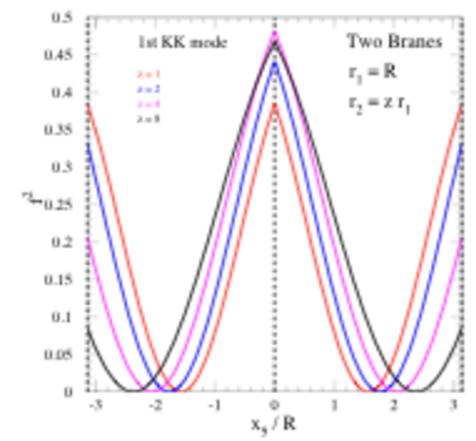
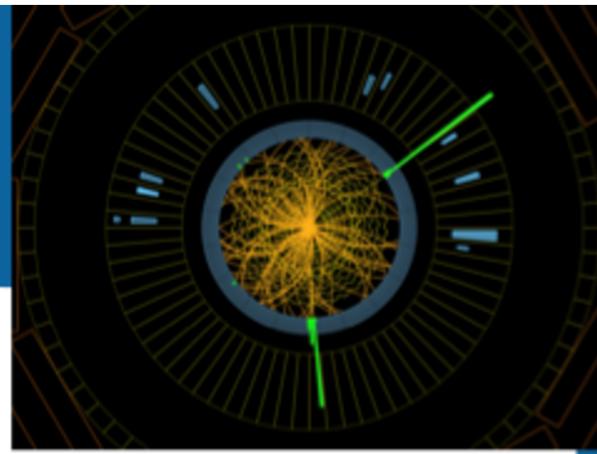
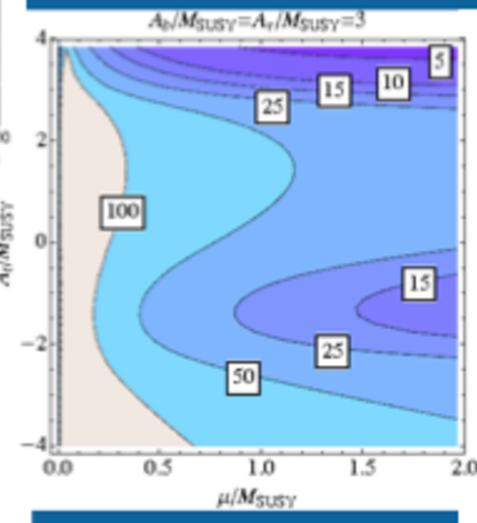
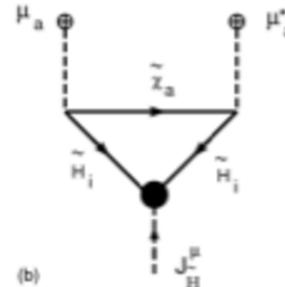
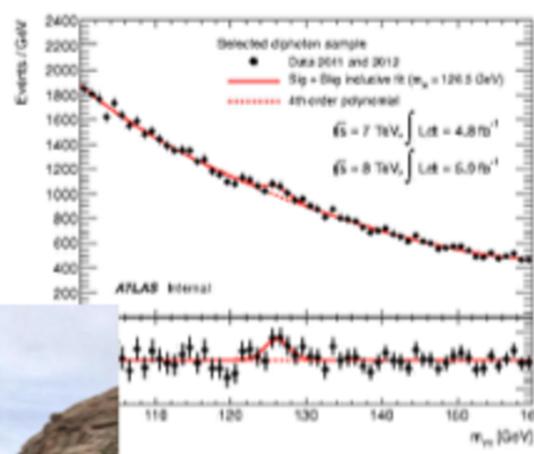
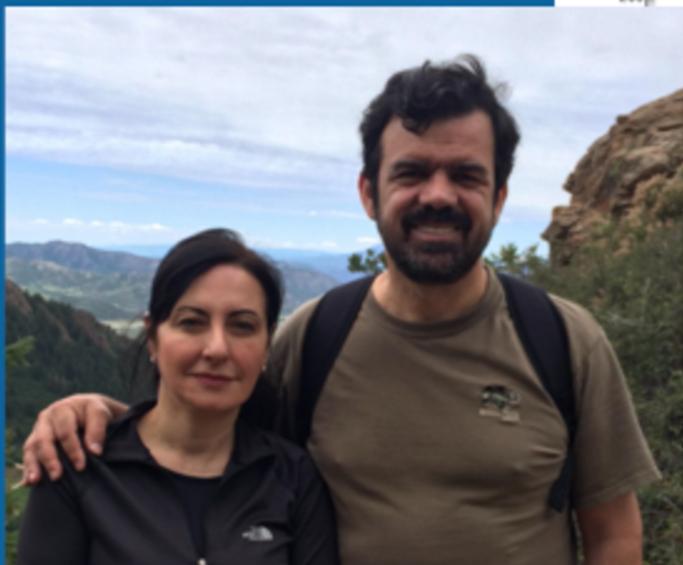
- $\Delta R(b_i, l^a)$, $\Delta\eta(b_i, l^a)$, $\Delta\phi(b_i, l^a)$, $p_T^{b_i + l^a}$, $m(b_i, l^a)$, where $i = tH, t$ and $a = +, -$
- $|m(l^+, b_{tH}) - m(l^-, b_t)|$ and $|m(l^-, b_{tH}) - m(l^+, b_t)|$
- $p_T^{b_j}$, where $j = tH, H, t$
- $\Delta R(b_{tH}, b_k)$, $\Delta\eta(b_{tH}, b_k)$, $\Delta\phi(b_{tH}, b_k)$, $p_T^{b_{tH} + b_k}$, $m(b_{tH}, b_k)$, where $k = H, t$
- $\Delta R(t_{H^a}, b_H)$, $\Delta\eta(t_{H^a}, b_H)$, $\Delta\phi(t_{H^a}, b_H)$, $p_T^{t_{H^a}, b_H}$, $m(t_{H^a}, b_H)$, where $a = +, -$
- $\Delta R(t_{H^a}, t_c)$, $\Delta\eta(t_{H^a}, t_c)$, $\Delta\phi(t_{H^a}, t_c)$, where $(H^a, t_c) = (H^+, \bar{t})$ or (H^-, t)
- $m(H^a) - m(b_H)$, where $a = +, -$
- $m(H^+) - m(\bar{t})$ and $m(H^-) - m(t)$
- $p_T^{H^\pm + t_{\text{other}}}$
- $m(H^\pm, t_{\text{other}})$

– Results

[Emily Hanson, W. Klemm, R. Naranjo, Yvonne Peters, AP, PRD100 (2019) 035026]



Thank you Marcela and Carlos



for the wonderful Physics

Back-Up Slides

- Quartic coupling unification in the MS-2HDM

[Dev, AP '14; N. Darvishi, AP '19]

Symmetry-breaking of $\text{Sp}(4)/\mathbb{Z}_2 \sim \text{SO}(5)$:

- Soft breaking (e.g. through m_{12}^2):

$$M_H^2 = 2\lambda_2 v^2, \quad M_h^2 = M_a^2 = M_{h^\pm}^2 = \frac{\text{Re}(m_{12}^2)}{s_\beta c_\beta}$$

Heavy Higgs spectrum is degenerate at tree level.

- Explicit breaking through RG running (two loops):

$$\begin{aligned} \text{Sp}(4)/\mathbb{Z}_2 \otimes \text{SU}(2)_L &\xrightarrow{g' \neq 0} \text{SU}(2)_{\text{HF}} \otimes \text{U}(1)_Y \otimes \text{SU}(2)_L \\ &\xrightarrow{\mathbf{Y}^{u,d}} \text{U}(1)_{\text{PQ}} \otimes \text{U}(1)_Y \otimes \text{SU}(2)_L \\ &\xrightarrow{\frac{m_{12}^2}{\langle \Phi_{1,2} \rangle}} \text{U}(1)_{\text{em}} \end{aligned}$$

A closer look at the RG evolution of λ_2

