Higgs as a Probe of New Physics

Tanmoy Mondal
BITS Pilani

Based on arXiv:2505.05104 in collaboration with Kei Yagyu

9 June 2025, HPNP 2025, Osaka University

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Higgs Precision as a Probe of Spontaneous CP Violation

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Why CP Violation ?

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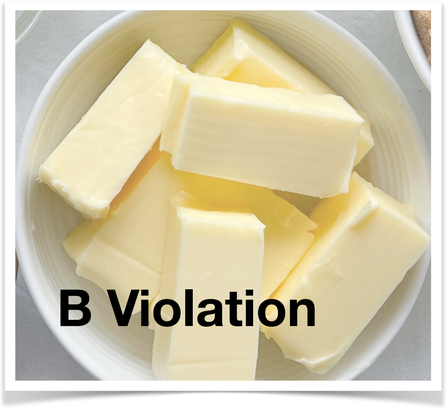

Why CP Violation ?

- Types of CP Violation
  - Explicit : $\mathscr{L}$ breaks CP, complex couplings
  - Spontaneous : $\mathscr{L}$ respects CP, Vacuum does not

T D Lee, PRD 8, 1226 (1973)

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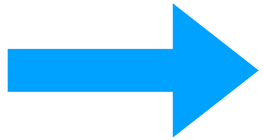
T D Lee, PRD 8, 1226 (1973)

- SM doesn't allow SCPV, 2HDM does
  - L. Lavoura and Joao P. Silva, PRD 50, 4619 (1994)
  - John F. Gunion and Howard E. Haber, PRD 72, 095002 (2005)
  - B. Grzadkowski, O. M. Ogreid, and P. Osland, PRD 94, 115002 (2006)

Spontaneous CP Violation in 2HDM

CPV arises **dynamically** from *vev*, not from complex parameters in the Lagrangian

$$\Phi_a = e^{i\xi_a}\begin{pmatrix} \omega_a^+ \\ \frac{1}{\sqrt{2}}(v_a + h_a + iz_a) \end{pmatrix}, \quad (a = 1,2),$$



$$\langle \Phi_1 \rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v\ c_\beta \end{pmatrix}, \qquad \langle \Phi_2 \rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v\ s_\beta\ e^{i\xi} \end{pmatrix},$$

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$$V = m_1^2|\Phi_1|^2 + m_2^2|\Phi_2|^2 - (m_3^2\Phi_1^\dagger\Phi_2 + \text{h.c.}) + \frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2$$
$$+ \left[\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2) + \lambda_6|\Phi_1|^2 + \lambda_7|\Phi_2|^2\right](\Phi_1^\dagger\Phi_2) + \text{h.c.}\,.$$

$\{m_i^2, \lambda_i\} \in \mathbb{R}$

Yukawa Interaction: $\mathscr{L}_Y = -\sum_{a=1,2}\left[\overline{\tilde{Q}_L}\,\tilde{Y}_d^a\,\Phi_a\,\tilde{d}_R + \overline{\tilde{Q}_L}\,\tilde{Y}_u^a\,\Phi_a^c\,\tilde{u}_R + \overline{\tilde{L}_L}\,\tilde{Y}_e^a\,\Phi_a\,\tilde{e}_R + \text{h.c.}\right], \qquad \tilde{Y}_f^a \in \mathbb{R}$

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In this talk: Higgs precision can make or break the SCPV 2HDM

Spontaneous CP Violation in 2HDM

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Non-decoupling

SCPV 2HDM : Scalar Sector

- Minimisation of the potential : $m_1^2, m_2^2, m_3^3 \Leftrightarrow v, t_\beta, t_\xi$
- Charged Higgs : $m_{H^\pm} = v\sqrt{\lambda_5 - \lambda_4}$
- Neutral Mass Matrix: $f(\lambda_i, t_\beta, t_\xi) \Rightarrow$ Diagonalise to get $m_{H_i}^2$

$$tr[\mathscr{M}] = \sum m_{H_i^2} = v^2(s_{2\beta}\, c_\xi\, (\lambda_6 + \lambda_7) + \lambda_2 s_\beta^2 + \lambda_1 c_\beta^2 + \lambda_5) \quad \& \quad det[\mathscr{M}] \propto \frac{v^6 s_\xi^2}{(t_\beta + 1/t_\beta)^2}$$

- Lower limit on ξ & lower+upper limit on t_β
- Unitarity, Perturbativity, Stability strongly contain the neutral scalar mass spectrum
- All the BSM masses are **below ~ 600** GeV

- Ulrich Nierste, Mustafa Tabet, Robert Ziegler, PRL 125, 031801 (2020)
- M. Nebot, F. J. Botella, and G. C. Branco, EPJC 79, 711 (2019)
- G. Barenboim, M. Gorbahn, U. Nierste, and M. Raidal, PRD 65, 095003(2002)

SCPV 2HDM : Scalar Sector

- We assumed Higgs alignment $\Rightarrow \lambda_{6/7} = f(\lambda_{1-5}, t_\beta, t_\xi)$

- The scalar trilinear couplings:

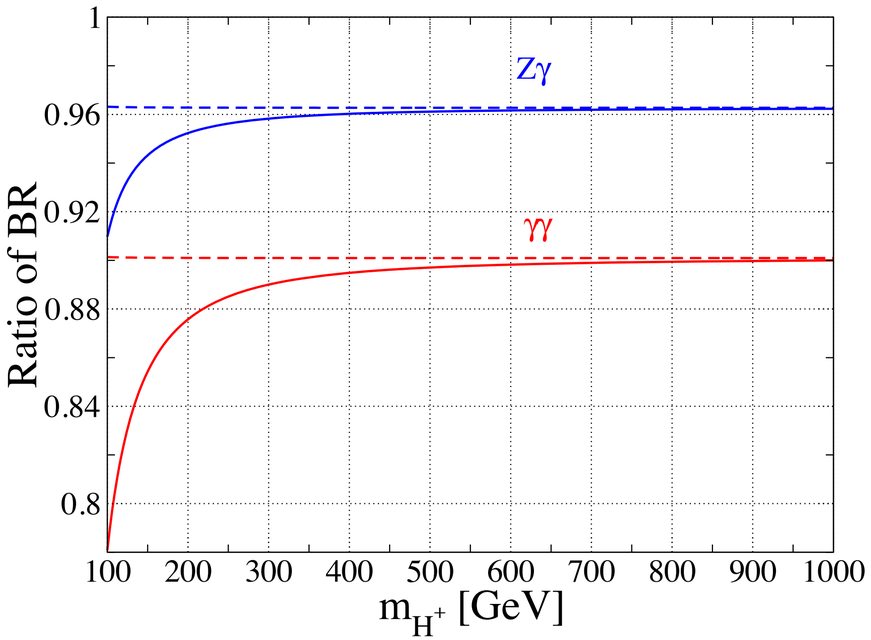
$$\lambda_{H^+H^-h} = -\frac{1}{v}(2m_{H^\pm}^2 + m_h^2), \qquad \lambda_{H_iH_ih} = -\frac{1}{2v}(2m_{H_i}^2 + m_h^2), \quad (i = 2,3)$$

$$\lambda_{H_{2/3}hh} = 0, \qquad \lambda_{hhh} = -\frac{m_h^2}{2v}$$

These affect $h \to \gamma\gamma, Z\gamma$ & λ_{hhh}

$$\Gamma(h \to \gamma\gamma) = \frac{\sqrt{2} G_F \, \alpha_{em}^2 \, m_h^3}{16\pi^3} \left| (t, W) + \frac{\lambda_{H^+H^-h}}{v} I_S \right|^2$$

SM part



SCPV 2HDM : λ_{hhh}

- The effective potential is given at one-loop : $V_{\rm eff} = V_0 + V_1 + V_{\rm CT} \longrightarrow \{m_i, \lambda_i\} \to \{\delta m_i, \delta\lambda_i\}$

$$V_1 = \frac{n_\phi}{64\pi^2} m_\phi^4(\varphi) \left[\ln\left(\frac{m_\phi^2(\varphi)}{\mu^2} \right) - c \right] + \cdots, \qquad (\phi = H^\pm,\, H_1,\, H_2,\, H_3)$$

- Preserve the correct vacuum and physical scalar masses: Renormalization conditions

$$\left. \frac{\partial (V_1 + V_{\rm CT})}{\partial \phi_i} \right|_{\phi = v} = 0 \quad \& \quad \left. \frac{\partial^2 (V_1 + V_{\rm CT})}{\partial \phi_i \partial \phi_j} \right|_{\phi = v} = 0$$

- In the alignment limit we get:

$$V_{{\rm eff},\, \varphi_1\varphi_1\varphi_1} = -\,3!\lambda_{h_1' h_1' h_1'} - \frac{1}{32\pi^2} \sum_\phi n_\phi \frac{\lambda_{\phi\phi h_1'}^3}{m_\phi^2}\,. \qquad (m_\phi^2)_{\varphi_1\varphi_i} = -\,\lambda_{\phi\phi h_1' h_i'} = -\,\frac{\lambda_{\phi\phi h_i'}}{v}$$

- S. Kanemura, S. Kiyoura, Y. Okada, E. Senaha, and C. P. Yuan, PLB 558, 157 (2003)
- S. Kanemura, Y. Okada, E. Senaha, and C. P. Yuan PRD 70, 115002 (2004)

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$$= \frac{1}{32\pi^2}\sum_{\phi=H^\pm,H_2,H_3} n_\phi \frac{(2m_\phi^2 + m_h^2)^3}{v^3 m_\phi^2}.$$

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SCPV 2HDM : Fermion sector

- To avoid FCNC typically Yukawa alignment is introduced.
- Then fermion mass matrices can be expressed by the real 3x3 matrices with an overall complex phase factor which can be absorbed in quark fields
- SCPV **Yukawa misalignment** is necessary to produce CKM phase.

$$\mathscr{L}_Y = -\left[\overline{Q_L^d}\left(\frac{\sqrt{2}M_d}{v}\Phi + \rho_d\Phi'\right)d_R + \overline{Q_L^u}\left(\frac{\sqrt{2}M_u}{v}\Phi^c + \rho_u\Phi'^c\right)u_R + \overline{L_L}\left(\frac{\sqrt{2}M_e}{v}\Phi + \rho_e\Phi'\right)e_R + \text{h.c.}\right],$$

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Yukawa couplings must be real

$$\rho_f = \frac{\sqrt{2}}{s_{2\beta}\,v}\left[\left(c_{2\beta} + \frac{i}{\tan(2I_f\xi)}\right)M_f - \left(1 + \frac{i}{\tan(2I_f\xi)}\right)(V_f^\dagger\, V_f^*\, M_f\, U_f^T\, U_f)\right]$$

$$\tilde{f}_L = V_f f_L$$
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- We assumed partial alignment : bottom & lepton sector is Yukawa aligned

$$\rho_{d,e} = \frac{\sqrt{2}M_{d,e}}{v}\zeta_{d,e}, \qquad \zeta_{d,e} = \frac{\tilde{\zeta}_{d,e}\,e^{i\xi} - t_\beta}{1 + t_\beta\,\tilde{\zeta}_{d,e}\,e^{i\xi}} = \begin{cases} -\tan\beta & \text{for } \tilde{\zeta}_{d,e} \to 0 \\ \cot\beta & \text{for } \tilde{\zeta}_{d,e} \to \infty \end{cases}$$

SCPV 2HDM : Constraints

Constraints

- Vacuum Stability, Unitarity, Oblique Parameters
- Flavour constraints via up type Yukawa coupling
- CPV phase ξ contributes to **Electric dipole moment (EDM)**

$$|d_e| \leq 4.1 \times 10^{-30} \mathrm{e} - \mathrm{cm}$$

- LHC Direct searches

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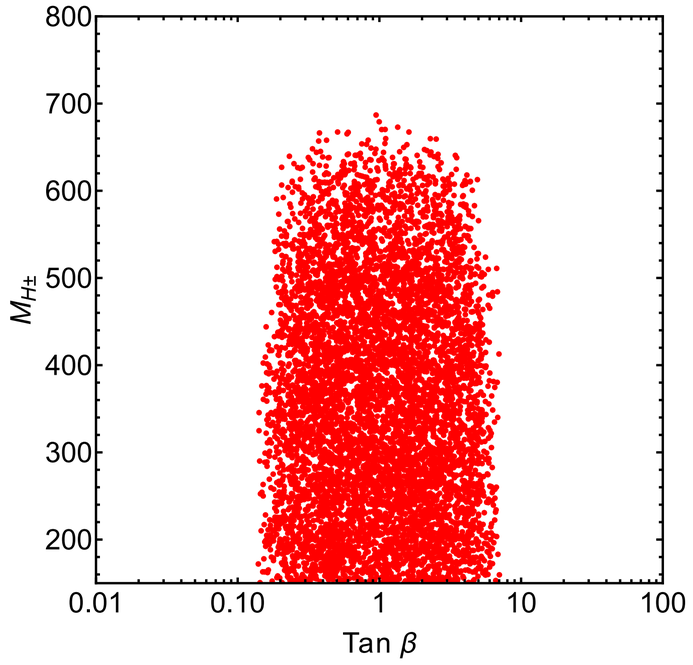
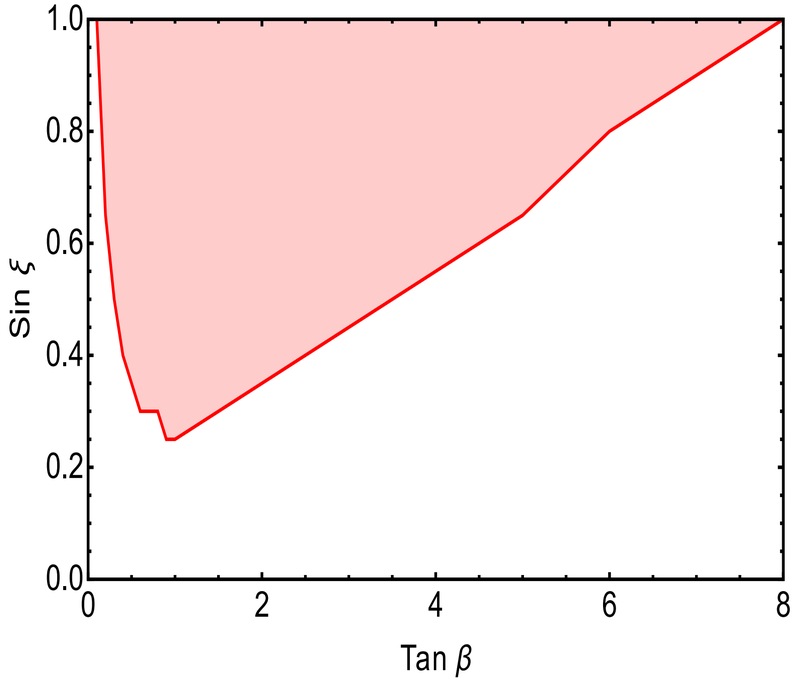
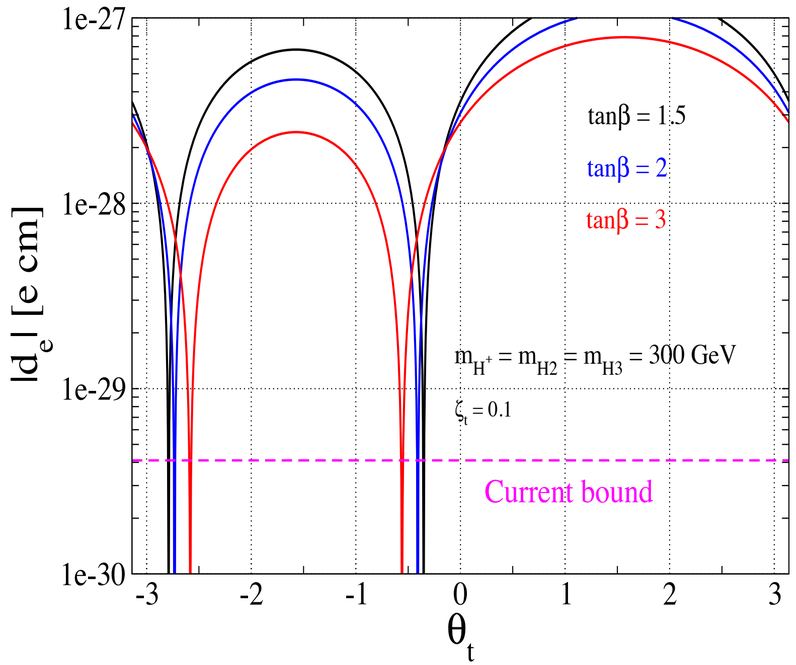






SCPV 2HDM & Higgs Precision Measurements

$$\Delta\kappa_\lambda = \frac{\Delta\lambda_{hhh}^{1-\text{loop}}}{(\lambda_{hhh}^{1-\text{loop}})_{\text{SM}}}$$

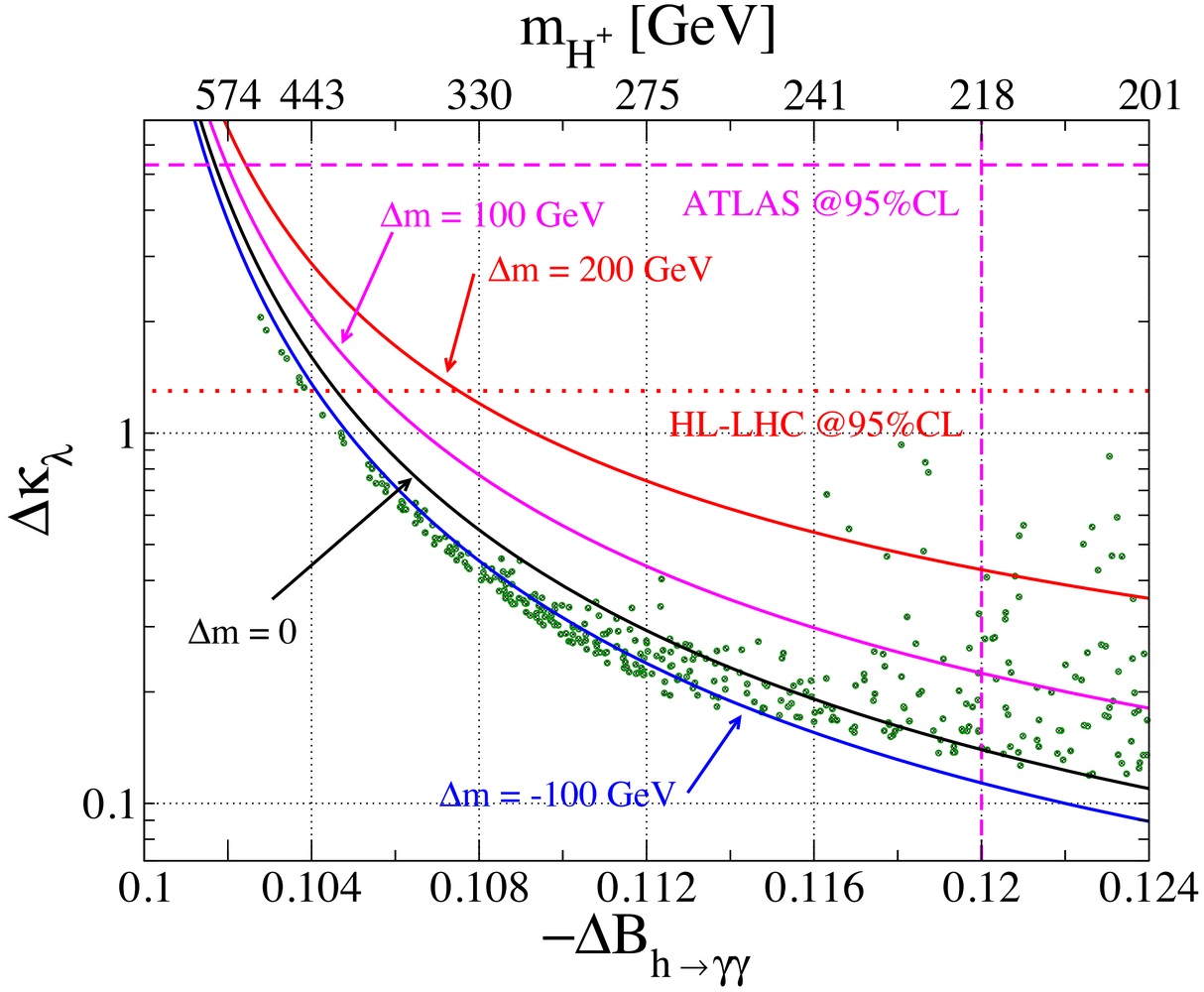
Current Limit : $-1.4 \leq \Delta\kappa_\lambda \leq 5.3$

Projected : $\Delta\kappa_\lambda < 1.3$

$$\Delta\mathscr{B}_{h\to\gamma\gamma} = \frac{\mathscr{B}_{h\to\gamma\gamma}^{\text{2HDM}}}{\mathscr{B}_{h\to\gamma\gamma}^{\text{SM}}} - 1,$$

ATLAS : $-0.12 \leq \Delta\mathscr{B}_{h\to\gamma\gamma} \leq 0.18$

Projected : $\Delta\mathscr{B}_{h\to\gamma\gamma}$@4 %



Tanmoy Mondal, Kei Yagyu, ArXiv: 2505.05104

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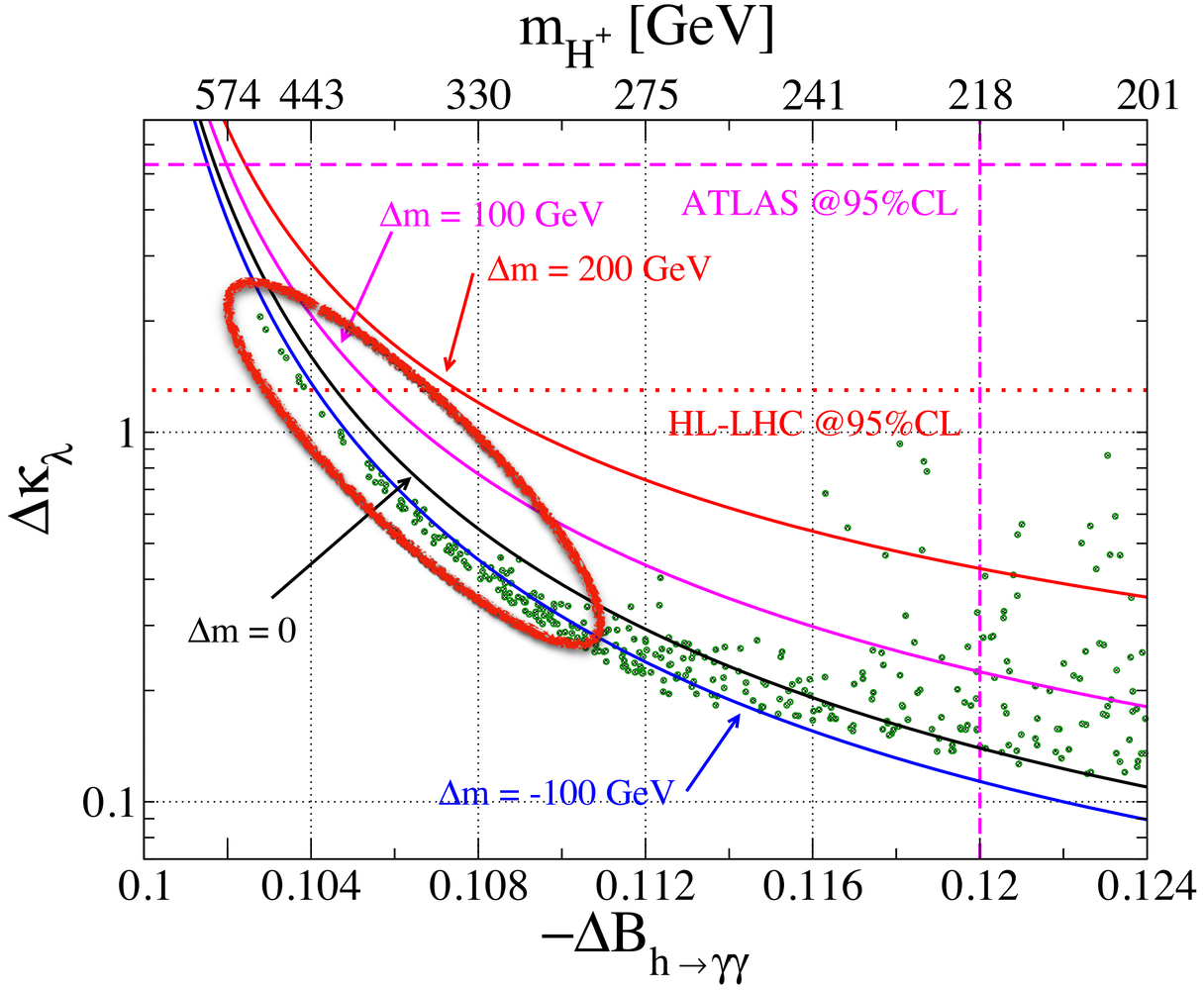

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SCPV 2HDM : Characteristic Phenomenology

- H_2 is always below $t\bar{t}$ threshold & mostly **decays to** tc

- H_3 and $H^\pm$ can decay via bosonic final states. Sometimes $H^\pm \to cb$ is also possible

$m_{H^\pm/H_2/H_3}$(GeV)	455 / 228 / 454	264 / 212 / 223	236 / 248 / 446	246 / 243 / 245
$\tan\beta$	2.61	3.12	2.51	2.53
$\tan\xi$	33.13	7.95	13.45	42.31
$\mathcal{B}_{H_2\to XY}$ (%)	tc : 82.93 $\tau\tau$: 4.70 tu : 3.88	tc : 96.85 $\tau\tau$: 1.03 tu : 0.62	tc : 99.04 $\tau\tau$: 0.23 tu : 0.21	tc : 99.56 – –
$\mathcal{B}_{H_3\to XY}$ (%)	H_2Z : 89.52 tt : 9.57 tc : 0.59	tc : 97.34 $\tau\tau$: 0.73 tu : 0.63	$H^\pm W^\mp$: 66.46 H_2Z : 25.98 tt : 3.78	tc : 99.5 – –
$\mathcal{B}_{H^\pm\to XY}$ (%)	$H_2W^\pm$: 78.1 tb : 21.23 cb : 0.65	tb : 56.78 cb : 43.11 $H_2W^\pm$: 0.06	cb : 61.28 tb : 38.67 $\tau\nu$: 0.03	cb : 77.95 tb : 22.03 –
$\sigma(pp\to H^\pm tb/H^\pm cb)$ (pb)	0.087/0.088	0.253/6.367	0.471/19.762	0.371/38.671
$\sigma(pp\to H_{2/3})$ (pb)	4.277 / 4.247	4.854 / 7.022	3.702 / 4.657	4.163 / 8.348

Tanmoy Mondal, Kei Yagyu, ArXiv: 2505.05104

Conclusion

- SCPV in 2HDM features non decoupling behaviour
- We estimated deviation in triple Higgs coupling and $H \to \gamma\gamma$
- Existing constraints forces a correlation between λ_{hhh} & $\mathcal{B}(H \to \gamma\gamma)$
- Existing data limits $m_{H^{\pm}} > 220\ GeV$
- Higgs-precision@HL-LHC will make or break SCPV in 2HDM
- We can also look for characteristic phenomenological signature of BSM scalars @ LHC

Thank You

Scan

Parameters	Range	Parameters	Range
$m_{H^\pm/H_2/H_3}\,(\mathrm{GeV})$	$200-800$	α	$-\pi/2-\pi/2$
$\tan\beta$	$1-8$	$\theta_{12/23/13}$	$0-\pi$
$\tan\xi$	$0.5-50$	$\delta_{12/23/13}$	$0-2\pi$
$\tilde{\zeta}_d$	$0-50$	$\tilde{\zeta}_e$	1

$$\rho_u^{ij}=\frac{\sqrt{2}}{s_{2\beta}v}\left[\left(c_{2\beta}+\frac{i}{t_\xi}\right)(M_u)_{ij}-\left(1+\frac{i}{t_\xi}\right)(VV^TM_uU_u^TU_u)_{ij}\right]$$

$$U_u=\begin{pmatrix}1&0&0\\0&c_{23}&s_{23}e^{-i\delta_{23}}\\0&-s_{23}e^{i\delta_{23}}&c_{23}\end{pmatrix}\begin{pmatrix}c_{13}&0&s_{13}e^{-i\delta_{13}}\\0&1&0\\-s_{13}e^{i\delta_{13}}&0&c_{13}\end{pmatrix}\begin{pmatrix}c_{12}&s_{12}e^{-i\delta_{12}}&0\\-s_{12}e^{i\delta_{12}}&c_{12}&0\\0&0&1\end{pmatrix}$$

Scalar Sector

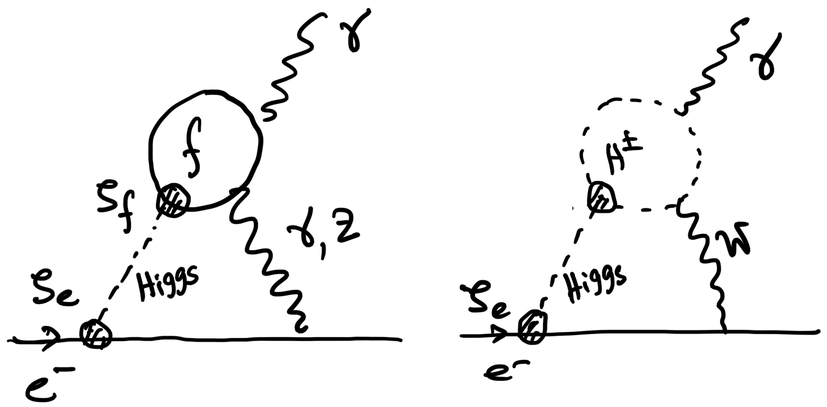
$$\mathscr{M} = v^2 \begin{pmatrix} \lambda_1 c_\beta^2 + \lambda_5 s_\beta^2 c_\xi^2 + \lambda_6 s_{2\beta} c_\xi [(\lambda_3+\lambda_4) - \lambda_5 s_\xi^2] c_\beta s_\beta + \lambda_6 c_\beta^2 c_\xi + \lambda_7 s_\beta^2 c_\xi & -(\lambda_5 s_\beta c_\xi + \lambda_6 c_\beta) s_\xi \\ \lambda_2 s_\beta^2 + \lambda_5 c_\beta^2 c_\xi^2 + \lambda_7 s_{2\beta} c_\xi & -(\lambda_5 c_\beta c_\xi + \lambda_7 s_\beta) s_\xi \\ & \lambda_5 s_\xi^2 \end{pmatrix}.$$

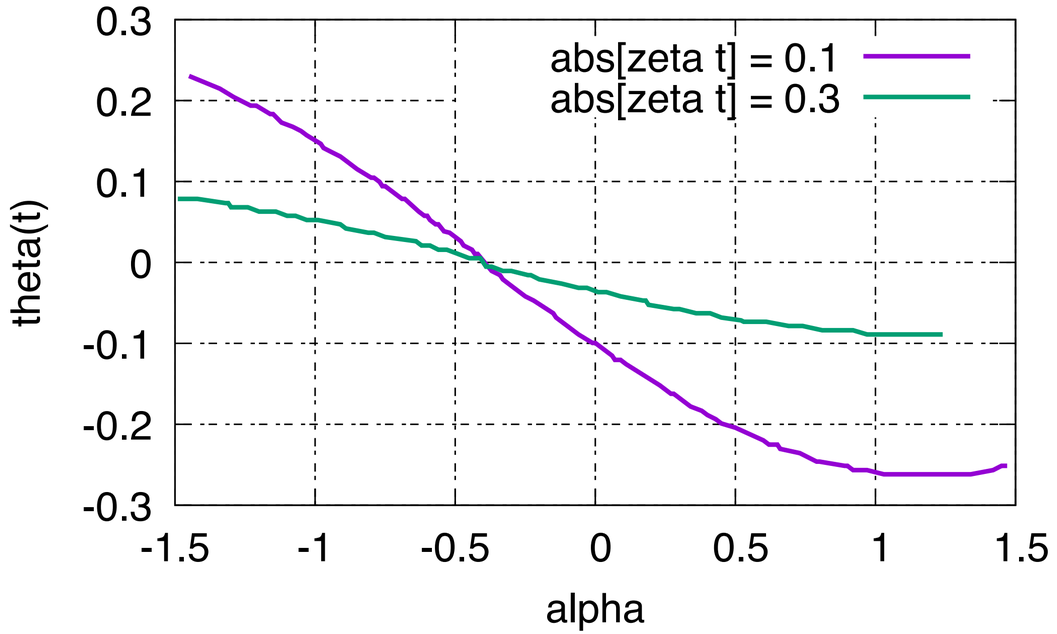
$$\mathscr{M}_{\rm HB} = \begin{pmatrix} c_\beta s_\beta 0 \\ -s_\beta c_\beta 0 \\ 0\ 0\ 1 \end{pmatrix} \mathscr{M} \begin{pmatrix} c_\beta - s_\beta 0 \\ s_\beta \quad c_\beta 0 \\ 0 \quad 0 1 \end{pmatrix}. \quad \Rightarrow \quad R^T \mathscr{M}_{\rm HB} R = \mathrm{diag}(m_{H_1}^2, m_{H_2}^2, m_{H_3}^2)\,. \qquad R \underset{\rm HA}{\longrightarrow} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_\alpha & -s_\alpha \\ 0 & s_\alpha & c_\alpha \end{pmatrix}.$$

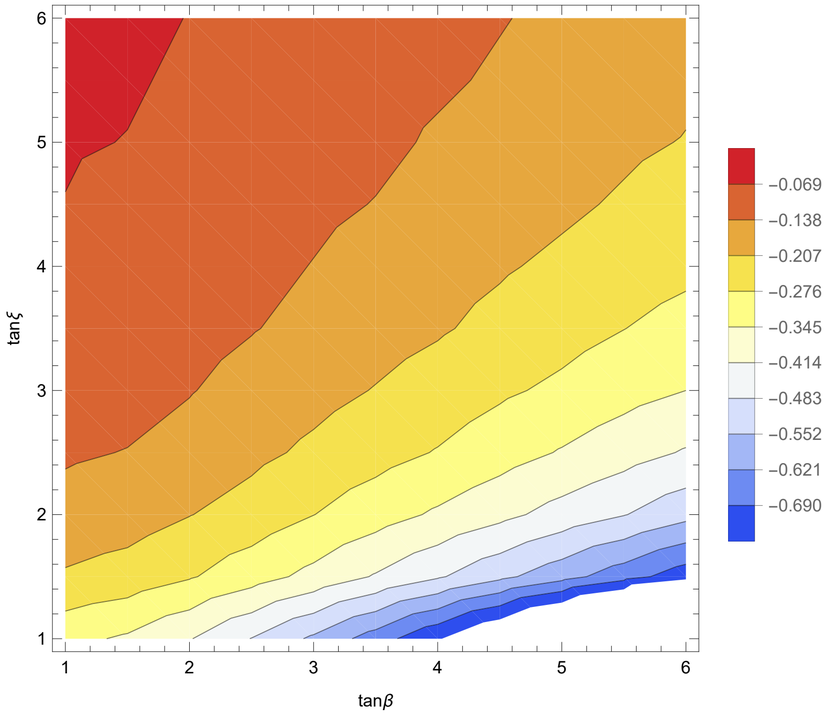
EDM

$$\lambda_{H^+H^-H_2} = -\frac{m_{H_2}^2}{v s_\beta c_\beta}(c_\alpha c_{2\beta} + s_\alpha \cot\xi),$$

$$\lambda_{H^+H^-H_3} = -\frac{m_{H_3}^2}{v s_\beta c_\beta}(c_\alpha \cot\xi - s_\alpha c_{2\beta})$$







Why CP Violation ?

Sakharov Conditions

- B Violation
- C & CP Violation
- Departure from thermal equilibrium

BSM : CPV phase in the CKM is too small

Where did all the antimatter go?

$$\frac{n_B}{s} \approx (8.6 \pm 0.1) \times 10^{-11}$$

Baryon Asymmetry

- Types of CP Violation
  - Explicit : $\mathscr{L}$ breaks CP, complex couplings
  - Spontaneous : $\mathscr{L}$ respects CP, Vacuum does not

T D Lee, PRD 8, 1226 (1973)

- SM doesn't allow SCPV, 2HDM does
  - L. Lavoura and Joao P. Silva, PRD 50, 4619 (1994)
  - John F. Gunion and Howard E. Haber, PRD 72, 095002 (2005)
  - B. Grzadkowski, O. M. Ogreid, and P. Osland, PRD 94, 115002 (2006)