ヒッグス物理で迫るCPの破れの起源

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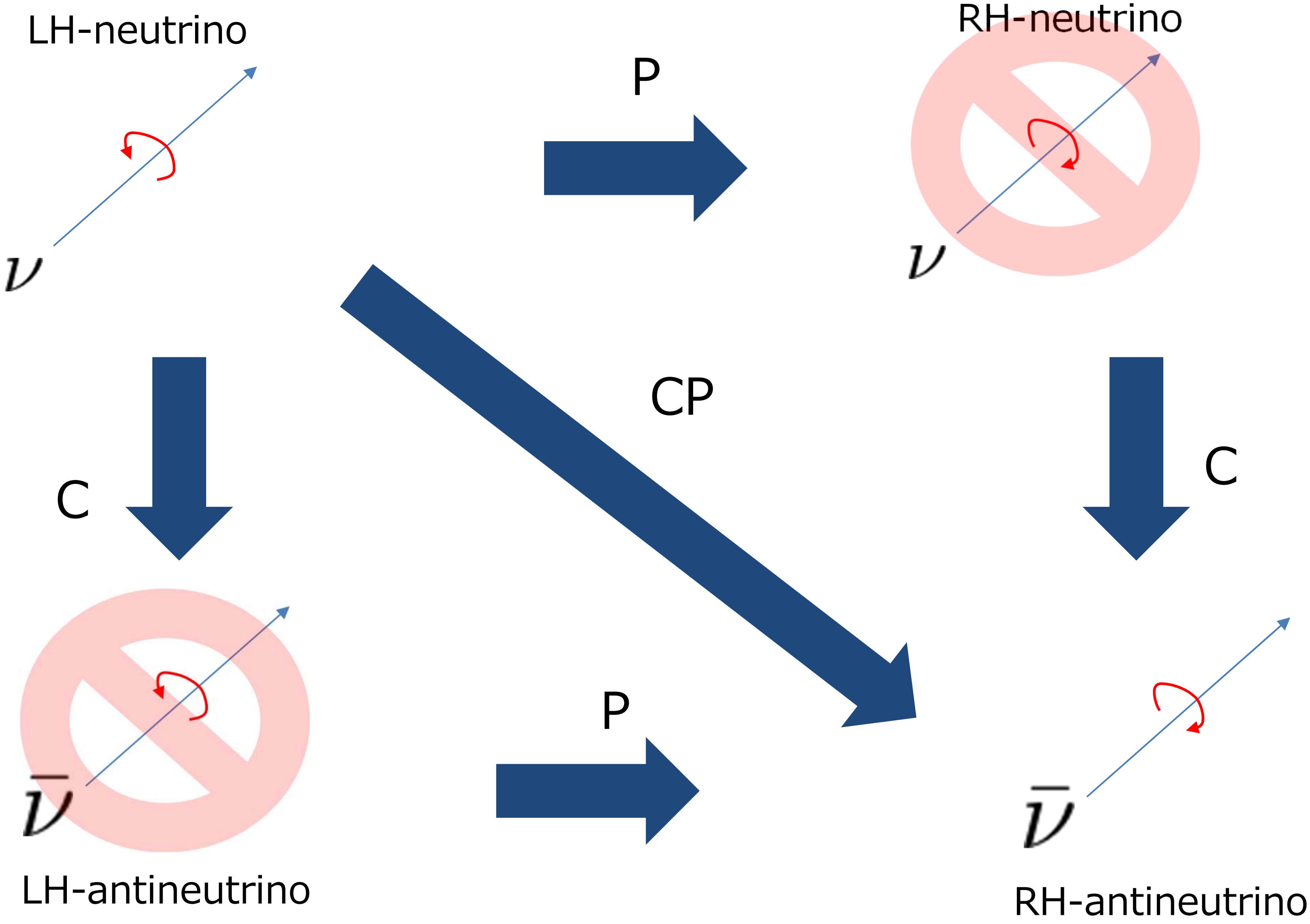
CP-transformation



LH-neutrino

RH-neutrino

P

CP

C

C

P

LH-antineutrino

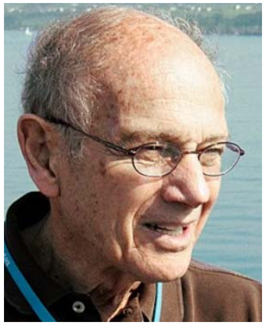
RH-antineutrino

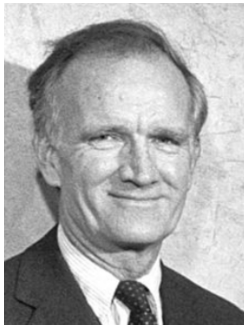
CP-violation

- CP-violation has been discovered by Kaon decays in 1964.

$$K_L \rightarrow \pi\pi\pi \qquad \text{CP-odd}$$

$$K_L \rightarrow \pi\pi \qquad \text{CP-even}$$


Cronin


Fitch

- In the SM, CPV can be explained by the Kobayashi-Maskawa phase (1973).

$$V_{\text{CKM}} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

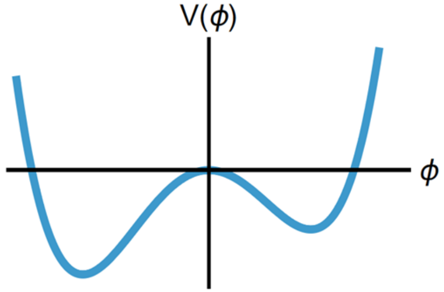

Kobayashi Maskawa

Question: What is the origin of the KM phase?

Origin of CP-violation

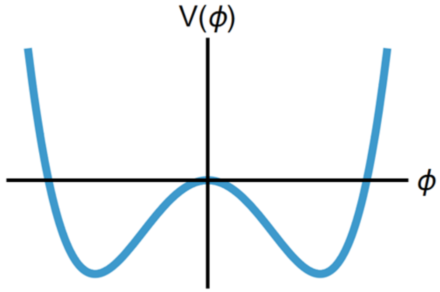
CPV

Explicit Breaking



SM

Spontaneous Breaking



Let us consider 2HDMs as a simple example of SCPV.

SCPV 2HDM: T. D. Lee (1973)

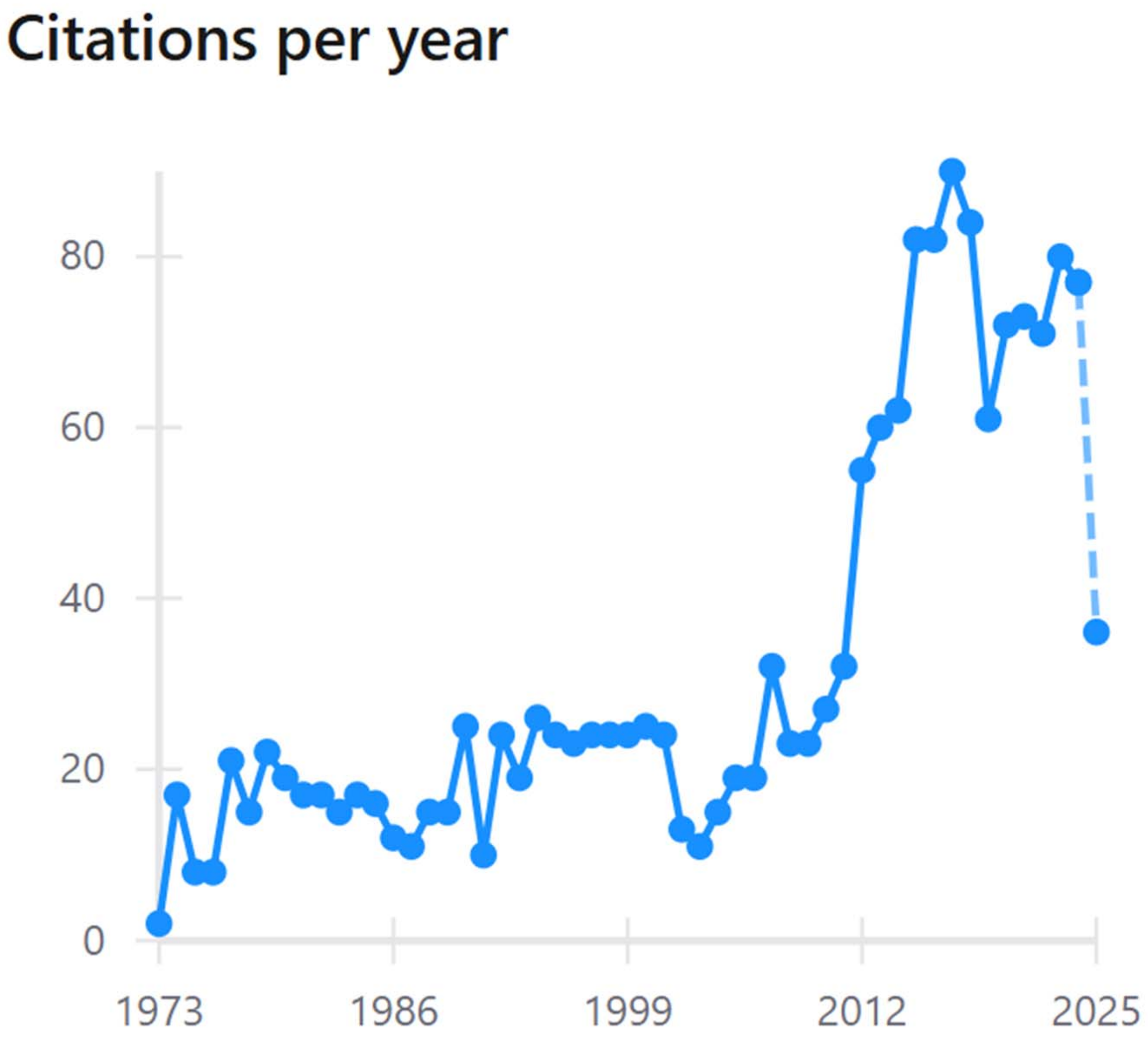
SCPV

- Inevitable non-decoupling Higgs sectors
- Flavor misalignment

A Theory of Spontaneous T Violation

T.D. Lee (Columbia U.)

1973



SCPV in 2HDMs

- VEVs $\langle\Phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_1\end{pmatrix}, \quad \langle\Phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_2 e^{i\xi}\end{pmatrix}$

- Potential

$$\begin{aligned} V = {} & \mu_1^2|\Phi_1|^2 + \mu_2^2|\Phi_2|^2 - (\mu_3^2\Phi_1^\dagger\Phi_2 + \text{h.c.}) \\ & + \frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 \\ & + \frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + \lambda_6|\Phi_1|^2(\Phi_1^\dagger\Phi_2) + \lambda_7|\Phi_2|^2(\Phi_1^\dagger\Phi_2) + \text{h.c.} \end{aligned}$$

$\mu_i^2,\ \lambda_j \in \mathbb{R}$

$$\xrightarrow[\text{VEV}]{} v_1 v_2\left(-\mu_3^2\cos\xi + \frac{\lambda_5}{4}v_1 v_2\cos 2\xi + \frac{\lambda_6}{2}v_1^3 v_2\cos\xi + \frac{\lambda_7}{2}v_1 v_2^3\cos\xi\right)$$

+ξ independent terms

$$\xrightarrow[\frac{\partial V}{\partial \xi}]{} v_1 v_2 \sin\xi\left(\mu_3^2 - \lambda_5 v_1 v_2\cos\xi - \frac{\lambda_6}{2}v_1^3 v_2 - \frac{\lambda_7}{2}v_1 v_2^3\right)$$

$$\frac{\partial V}{\partial \xi} = 0 \quad \Rightarrow \quad \boxed{\mu_3^2 = v_1 v_2\left(\lambda_5\cos\xi + \frac{\lambda_6}{2}v_1^2 + \frac{\lambda_7}{2}v_2^2\right), \quad \xi \neq n\pi}$$

Condition for SCPV

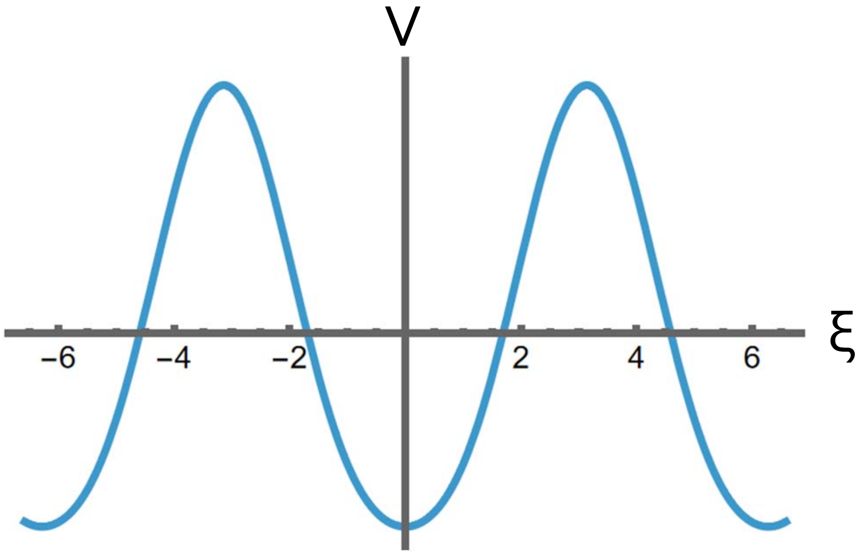
Vacuum Structure (Soft Z_2 case: $\lambda_6 = \lambda_7 = 0$)

$$V_{\rm vac} = v_1 v_2 \left(-\mu_3^2 \cos\xi + \frac{\lambda_5}{4} v_1 v_2 \cos 2\xi\right) + \text{const.}$$

$$\frac{\partial V_{\rm vac}}{\partial \xi} = v_1 v_2 \sin\xi \left(\mu_3^2 - \lambda_5 v_1 v_2 \cos\xi\right)$$

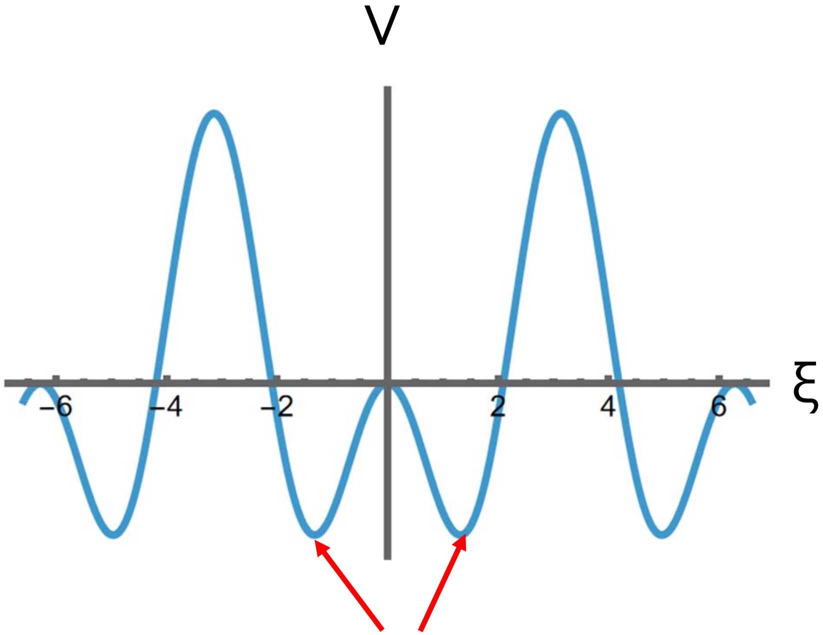
Vac. condition for SCPV: $\cos\xi = \dfrac{\mu_3^2}{v_1 v_2 \lambda_5}$

$\mu_3^2 > v_1 v_2 \lambda_5$



No CPV

$\mu_3^2 < v_1 v_2 \lambda_5$

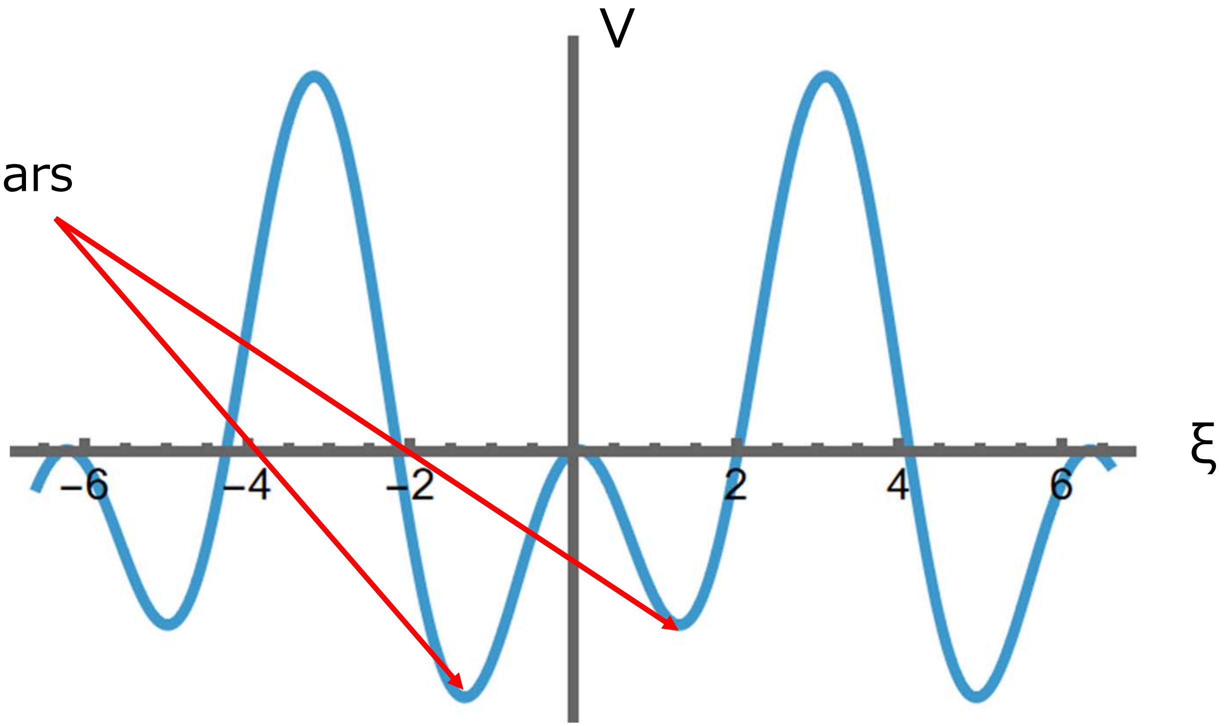


Degenerate CPV vacua → SCPV

Vacuum Structure (Soft Z_2 case: $\lambda_6 = \lambda_7 = 0$)

If we introduce an explicit CPV term e.g, $\mathrm{Im}[\mu_3^2] \neq 0$, potential becomes

$$V_{\mathrm{vac}} = v_1 v_2 \left(-\mu_3^2 \cos\xi + \frac{\lambda_5}{4} v_1 v_2 \cos 2\xi + \mathrm{Im}[\mu_3^2] \sin\xi \right) + \mathrm{const.}$$



Degeneracy disappears

→ Explicit CPV

We focus on SCPV 2HDM.

Potential

- Most general form with CP-invariance

$$\begin{aligned} V = {} & \mu_1^2|\Phi_1|^2 + \mu_2^2|\Phi_2|^2 - (\mu_3^2\Phi_1^\dagger\Phi_2 + \mathrm{h.c.}) \\ & + \frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 \\ & + \frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + \lambda_6|\Phi_1|^2(\Phi_1^\dagger\Phi_2) + \lambda_7|\Phi_2|^2(\Phi_1^\dagger\Phi_2) + \mathrm{h.c.} \end{aligned}$$

$$\mu_i^2,\ \lambda_j \in \mathbb{R}$$

- Higgs fields

NGBs

Charged Higgs

$$\begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & e^{i\xi} \end{pmatrix} \begin{pmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \Phi \\ \Phi' \end{pmatrix} \qquad \Phi = \begin{bmatrix} G^+ \\ \frac{1}{\sqrt{2}}(h_1' + v + iG^0) \end{bmatrix}, \quad \Phi' = \begin{bmatrix} H^+ \\ \frac{1}{\sqrt{2}}(h_2' + ih_3') \end{bmatrix}$$

Neutral Higgses

- Vacuum conditions

$$\mu_1^2 = -\frac{v^2}{2}(\lambda_1 c_\beta^2 + \lambda_3 s_\beta^2 - \lambda_4 s_\beta^2 - \lambda_5 s_\beta^2 + \lambda_6 s_{2\beta} c_\xi),$$

$$\mu_2^2 = -\frac{v^2}{2}(\lambda_2 s_\beta^2 + \lambda_3 c_\beta^2 + \lambda_4 c_\beta^2 - \lambda_5 c_\beta^2 + \lambda_7 s_{2\beta} c_\xi),$$

$$\mu_3^2 = \frac{v^2}{2}(\lambda_5 s_{2\beta} c_\xi + \lambda_6 c_\beta^2 + \lambda_7 s_\beta^2).$$

Mass formulae

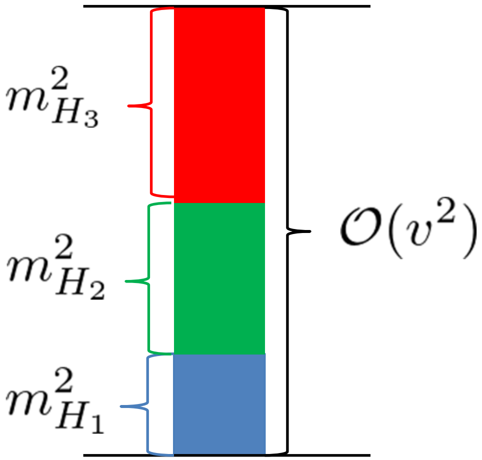
- Charged-Higgs mass

$$m^2_{H^\pm} = \frac{v^2}{2}(\lambda_5 - \lambda_4)$$

$$\begin{pmatrix} h'_1 \\ h'_2 \\ h'_3 \end{pmatrix} = R_{23}(\alpha_{23})R_{13}(\alpha_{13})R_{12}(\alpha_{12}) \begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix}$$

- Neutral Higgs masses (3×3 mass matrix)

$$\mathrm{tr}[\mathcal{M}] = \sum_{i=1,3} m^2_{H_i} = v^2[\lambda_1 c^2_\beta + \lambda_2 s^2_\beta + \lambda_5 + (\lambda_6 + \lambda_7) s_{2\beta} c_\xi]$$



➡ No decoupling limit

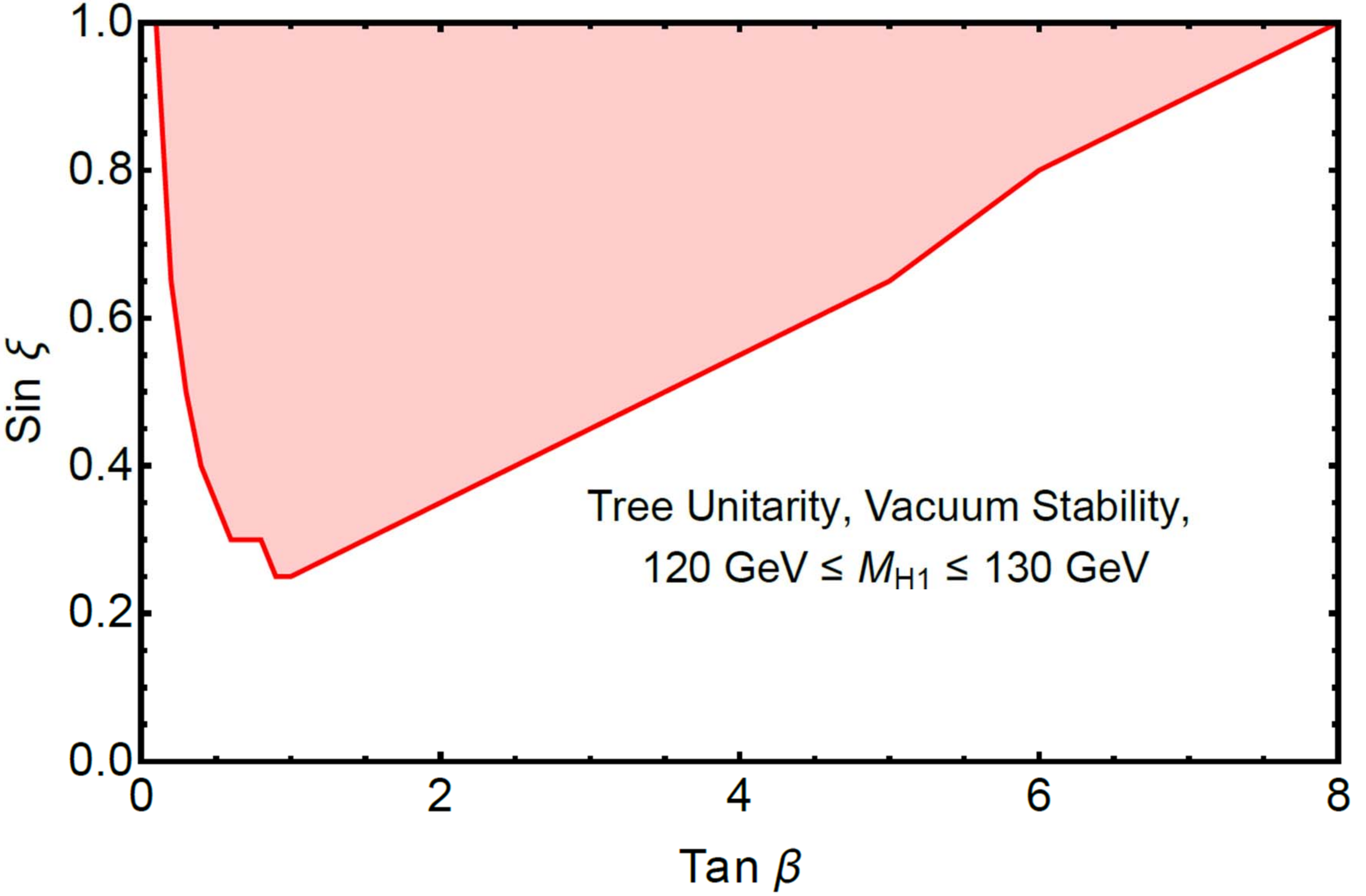
$$\mathrm{Det}[\mathcal{M}] = \prod_{i=1,3} m^2_{H_i} \propto \frac{v^6 s^2_\xi}{(t_\beta + 1/t_\beta)^2}$$

➡ Lower limit on |sin ξ|, lower and upper limit on tanβ .

- 10 Parameters : m_{H1}, m_{H2}, m_{H3}, $m_{H\pm}$, $\underline{\alpha_{23}, \alpha_{13}, \alpha_{12}}$, v, tanβ, sinξ.

→ (α,0,0) in the Higgs alignment limit

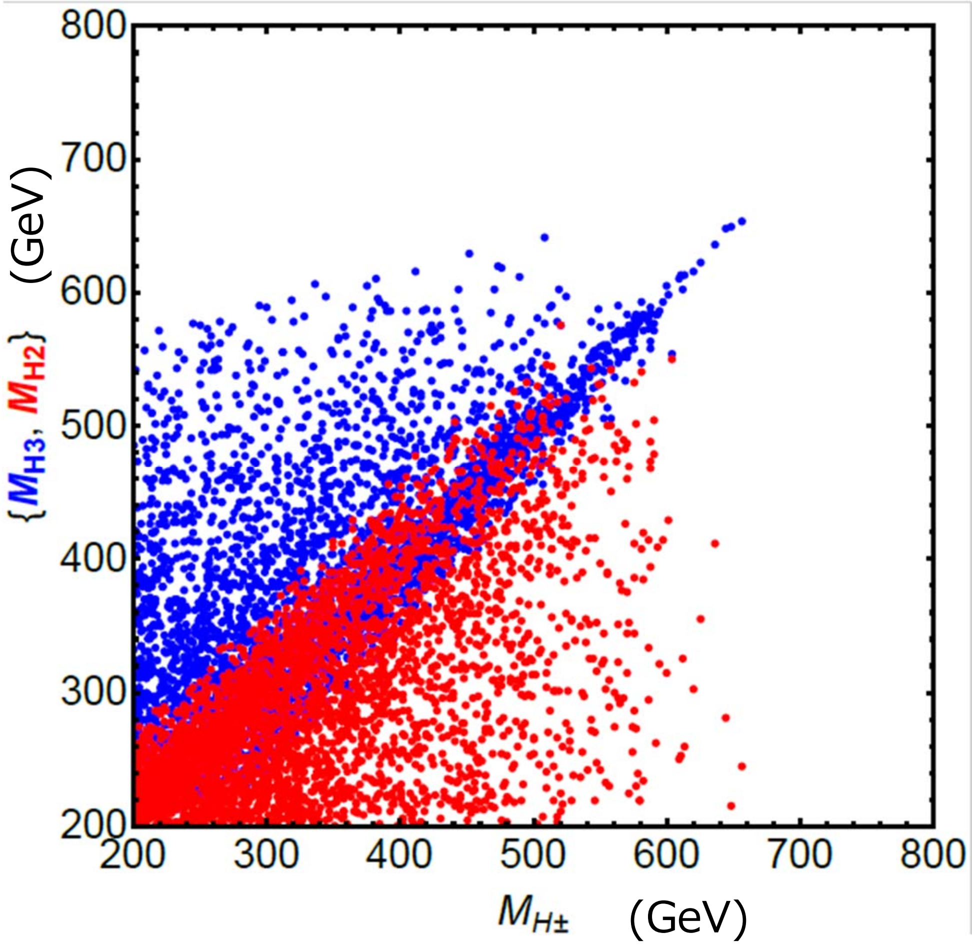
Limit on tanβ – sinξ plane



$$0.1 \lesssim \tan\beta \lesssim 10, \quad |\sin\xi| \gtrsim 0.3$$

Limit on $m_{H\pm}$ - $m_{H2,3}$ plane

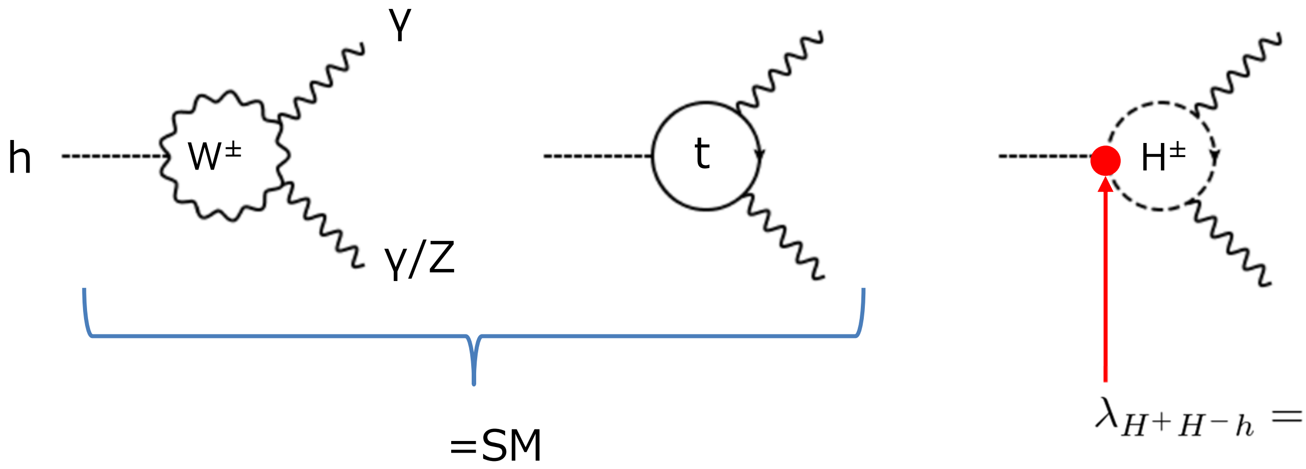
NLO unitarity bound: Nierste, Mustafa, Tabet, Robert, Ziegler (2020)



$$m_{H^\pm} \lesssim 650 \text{ GeV}, \quad m_{H_2} \lesssim 600 \text{ GeV}, \quad m_{H_3} \lesssim 700 \text{ GeV}$$

h → γγ/Zγ

- ☐ We take the Higgs alignment limit.

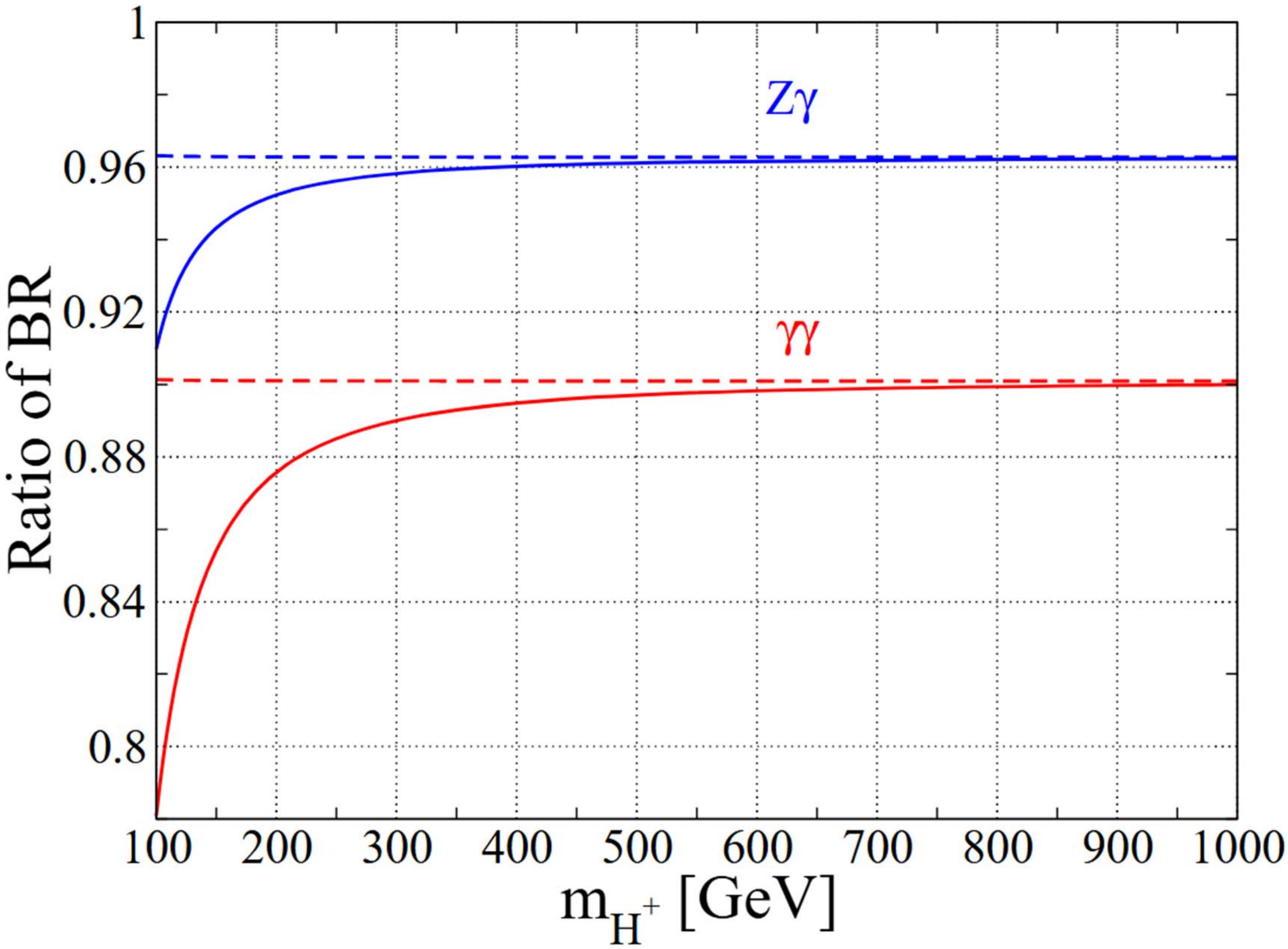


$$\lambda_{H^+H^-h} = \frac{1}{v}(2m_{H^\pm}^2 + m_h^2)$$

$$\Gamma(h \to \gamma\gamma) = \frac{\alpha_{\mathrm{em}}^2 m_h^3}{16\pi^3 v^2} \left| \underbrace{(W, t\text{-loop})}_{\sim 1.6} - \underbrace{\frac{1}{24}\frac{v\lambda_{H^+H^-h}}{m_{H^\pm}^2}}_{\sim 1/12} + \mathcal{O}\left(\frac{m_h^2}{m_{H^\pm}^2}\right) \right|^2$$

h → γγ/Zγ

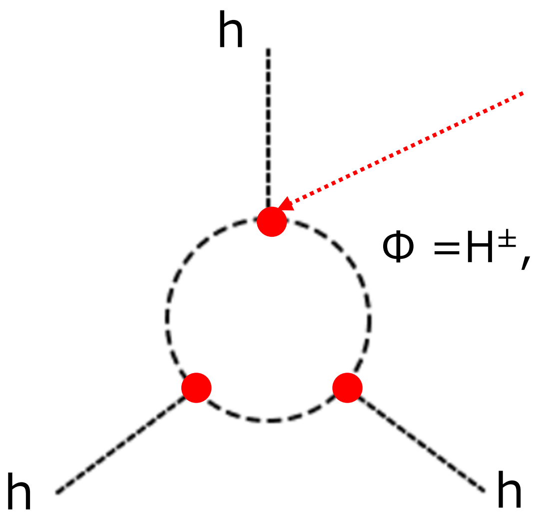
2-loop: Aiko, Braathen, Kanemura (2023)
Degrassi, Slavich (2023)



Self-coupling

1-loop: Kanemura, Okada, Senaha, Yuan (2004)

2-loop: Braathen, Kanemura (2019)



$\Phi = H^{\pm}, H_2, H_3$

$$\lambda_{\Phi\Phi h} = \frac{1}{v}(2m_\Phi^2 + m_h^2)$$

$$\lambda_{ABC} \equiv \frac{\partial^3 V}{\partial A \partial B \partial C}$$

$$\simeq \frac{1}{32\pi^2}\left(\frac{2\lambda^3_{H^+H^-h}}{m^2_{H^\pm}} + \frac{\lambda^3_{H_2H_2h}}{m^2_{H_2}} + \frac{\lambda^3_{H_3H_3h}}{m^2_{H_3}}\right)$$

$$\simeq \frac{1}{32\pi^2 v^3}\left(2m^4_{H^\pm} + m^4_{H_2} + m^4_{H_3}\right)$$

cf. 2HDM w/o SCPV

$$\frac{1}{32\pi^2 v^3}\left[2m^4_{H^\pm}\left(1 - \frac{M^2}{m^2_{H^\pm}}\right)^3 + m^4_{H_2}\left(1 - \frac{M^2}{m^2_{H_2}}\right)^3 + m^4_{H_3}\left(1 - \frac{M^2}{m^2_{H_3}}\right)^3\right]$$

The SCPV 2HDM predicts the maximal non-decoupling loop effect.

Yukawa interactions

- ☐ Up-type quark sector (down sectors are similar)

$$\mathcal{L}_Y = -\bar{Q}_L\Big(Y_1\tilde{\Phi}_1 + Y_2\tilde{\Phi}_2\Big)u_R + \text{h.c.}$$

$$= -\bar{Q}_L\left(\frac{\sqrt{2}}{v}\tilde{M}_u\tilde{\Phi} + \tilde{\rho}_u\tilde{\Phi}'\right)u_R + \text{h.c.}$$

Y_1, Y_2: Real matrices

where $$\tilde{M}_u = \frac{v}{\sqrt{2}}(Y_1\cos\beta + e^{-i\xi}Y_2\sin\beta), \quad \tilde{\rho}_u = -Y_1\sin\beta + e^{-i\xi}Y_2\cos\beta$$

Yukawa interactions

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$$\begin{aligned}\mathcal{L}_Y &= -\bar{Q}_L\left(Y_1\tilde{\Phi}_1 + Y_2\tilde{\Phi}_2\right)u_R + \text{h.c.}\\ &= -\bar{Q}_L\left(\frac{\sqrt{2}}{v}\tilde{M}_u\tilde{\Phi} + \tilde{\rho}_u\tilde{\Phi}'\right)u_R + \text{h.c.}\end{aligned}$$

Y_1, Y_2: Real matrices

where $\tilde{M}_u = \frac{v}{\sqrt{2}}(Y_1\cos\beta + e^{-i\xi}Y_2\sin\beta), \quad \tilde{\rho}_u = -Y_1\sin\beta + e^{-i\xi}Y_2\cos\beta$

- Biunitary transformation makes the mass matrix diagonal:

$$u_L \to V_u u_L, \quad u_R \to U_u u_R$$

$$\tilde{M}_u \to M_u = V_u^\dagger \tilde{M}_u U_u \ \ (\text{diagonal}) \qquad \tilde{\rho}_u \to \rho_u = V_u^\dagger \tilde{\rho}_u U_u$$

- Reality condition, $\mathrm{Im}[Y_1] = \mathrm{Im}[Y_2] = 0$, restricts the structure of ρ_u matrix.

$$\boxed{\rho_u = \frac{1}{\sqrt{2}c_\beta s_\beta v}\left[\left(c_{2\beta} + \frac{i}{t_\xi}\right)M_u - \left(1 + \frac{i}{t_\xi}\right)(V_u^\dagger V_u^* M_u U_u^T U_u)\right]}$$

Yukawa alignment

- ☐ If we impose the Yukawa alignment condition $Y_2 = \zeta_u Y_1 \quad (\zeta_u \in \mathbb{R})$

$$\tilde{M}_u = \frac{v}{\sqrt{2}} Y_1 \underbrace{(\cos\beta + e^{-i\xi}\zeta_u \sin\beta)}_{\text{complex parameter}}, \quad \tilde{\rho}_u = Y_1 \underbrace{(-\sin\beta + e^{-i\xi}\zeta_u \cos\beta)}_{\text{complex parameter}}$$

- We can diagonalize two matrices at the same time. 😃
- Complex phase can be removed by quark rephasing. 🙁

  → KM phase vanishes. So, we need Yukawa misalignment.

Yukawa alignment

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$$\tilde{M}_u = \frac{v}{\sqrt{2}} Y_1 \underset{\text{complex parameter}}{\underline{(\cos\beta + e^{-i\xi}\zeta_u \sin\beta)}}, \qquad \tilde{\rho}_u = Y_1 \underset{\text{complex parameter}}{\underline{(-\sin\beta + e^{-i\xi}\zeta_u \cos\beta)}}$$

  - We can diagonalize two matrices at the same time. 😃
  - Complex phase can be removed by quark rephasing. 🙁

    → KM phase vanishes. So, we need Yukawa misalignment

- ☐ We partially impose the Yukawa alignment for d/e sectors.

$$\rho_{d/e} = \frac{\sqrt{2} M_{d/e}}{v} \left(\frac{-t_\beta + \zeta_{d/e}\, e^{i\xi}}{1 + \zeta_{d/e}\, t_\beta\, e^{i\xi}} \right) \qquad V_{\mathrm{CKM}} = V_u^\dagger V_d$$

$$\rho_u = \frac{1}{\sqrt{2} c_\beta s_\beta v} \left[\left(c_{2\beta} + \frac{i}{t_\xi} \right) M_u - \left(1 + \frac{i}{t_\xi} \right) \left(V_{\mathrm{CKM}} V_{\mathrm{CKM}}^T M_u U_u^T U_u \right) \right]$$

Constraints on ρ_u

- ☐ Now, flavor violating interaction comes from ρ_u.

$$\rho_u = \frac{1}{\sqrt{2}c_\beta s_\beta v}\left[\left(c_{2\beta}+\frac{i}{t_\xi}\right)M_u - \left(1+\frac{i}{t_\xi}\right)\left(\underbrace{V_{\text{CKM}}V_{\text{CKM}}^T}_{\sim I+\epsilon\,(10^{-3}\text{-}10^{-4})} M_u U_u^T U_u\right)\right]$$

- Ex 1: U_u to be orthogonal with a phase factor

$$\rho_u = \frac{\sqrt{2}M_u}{v}\zeta_u + \mathcal{O}(\epsilon) \qquad \zeta_u = \frac{1}{s_{2\beta}}\left[c_{2\beta}+\frac{i}{t_\xi} - \left(1+\frac{i}{t_\xi}\right)e^{2i\theta_u}\right]$$

→ Yukawa alignment like scenario

- Ex 2: U_u to be (2,3) rotation, i.e.,

$$U_u = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & e^{-i\delta}\sin\theta \\ 0 & -e^{i\delta}\sin\theta & \cos\theta \end{pmatrix}$$

$$\rho_u = \frac{1}{\sqrt{2}c_\beta s_\beta v}\left[\left(c_{2\beta}+\frac{i}{t_\xi}\right)M_u - \left(1+\frac{i}{t_\xi}\right)\left(\underline{V_{\text{CKM}}V_{\text{CKM}}^T M_u U_u^T} U_u\right)\right]$$

$$m_t \begin{pmatrix} \mathcal{O}(r_u) & \mathcal{O}(\epsilon) & \mathcal{O}(\epsilon) \\ \mathcal{O}(\epsilon r_u) & \mathcal{O}(r_c) & \mathcal{O}(r_c) \\ \mathcal{O}(\epsilon r_u) & \mathcal{O}(1) & \mathcal{O}(1) \end{pmatrix} \qquad r_u = \frac{m_u}{m_t}, \quad r_c = \frac{m_c}{m_t}$$

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- ☐ Now, flavor violating interaction comes from ρ_u.

$$\rho_u = \frac{1}{\sqrt{2} c_\beta s_\beta v}\left[\left(c_{2\beta} + \frac{i}{t_\xi}\right) M_u - \left(1 + \frac{i}{t_\xi}\right)(\underbrace{V_{\rm CKM} V_{\rm CKM}^T}_{\sim I + \epsilon\, (10^{-3}\text{-}10^{-4})} M_u U_u^T U_u)\right]$$

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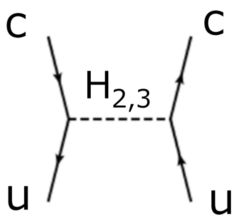


$$\rho_u = \frac{1}{\sqrt{2} c_\beta s_\beta v}\left[\left(c_{2\beta} + \frac{i}{t_\xi}\right) M_u - \left(1 + \frac{i}{t_\xi}\right)\underline{(V_{\rm CKM} V_{\rm CKM}^T M_u U_u^T U_u)}\right]$$

$|(\rho_u)_{12}(\rho_u)_{21}| < O(10^{-8})$

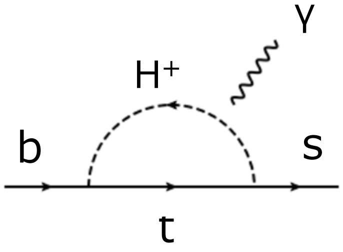
$$m_t \begin{pmatrix} \mathcal{O}(r_u) & \mathcal{O}(\epsilon) & \mathcal{O}(\epsilon) \\ \mathcal{O}(\epsilon r_u) & \mathcal{O}(r_c) & \mathcal{O}(r_c) \\ \mathcal{O}(\epsilon r_u) & \mathcal{O}(1) & \mathcal{O}(1) \end{pmatrix} \qquad r_u = \frac{m_u}{m_t}, \quad r_c = \frac{m_c}{m_t}$$

Constraints on ρ_u

☐ Now, flavor violating interaction comes from ρ_u.

$$\rho_u = \frac{1}{\sqrt{2}c_\beta s_\beta v}\left[\left(c_{2\beta}+\frac{i}{t_\xi}\right)M_u - \left(1+\frac{i}{t_\xi}\right)(\underline{V_{\mathrm{CKM}}V_{\mathrm{CKM}}^T}M_u U_u^T U_u)\right]$$

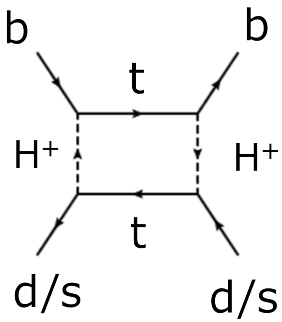
$\sim I + \varepsilon\ (10^{-3}\text{-}10^{-4})$



- Ex 1: U_u to be orthogonal with a phase factor

$$\rho_u = \frac{\sqrt{2}M_u}{v}\zeta_u + \mathcal{O}(\epsilon) \qquad \zeta_u = \frac{1}{s_{2\beta}}\left[c_{2\beta}+\frac{i}{t_\xi}-\left(1+\frac{i}{t_\xi}\right)e^{2i\theta_u}\right]$$

→ Yukawa alignment like scenario



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$$\rho_u = \frac{1}{\sqrt{2}c_\beta s_\beta v}\left[\left(c_{2\beta}+\frac{i}{t_\xi}\right)M_u - \left(1+\frac{i}{t_\xi}\right)(\underline{V_{\mathrm{CKM}}V_{\mathrm{CKM}}^T M_u U_u^T U_u})\right]$$

$|(\rho_u)_{13}|$, $|(\rho_u)_{23}| < O(10^{-2})$

$$m_t\begin{pmatrix} \mathcal{O}(r_u) & \mathcal{O}(\epsilon) & \mathcal{O}(\epsilon) \\ \mathcal{O}(\epsilon r_u) & \mathcal{O}(r_c) & \mathcal{O}(r_c) \\ \mathcal{O}(\epsilon r_u) & \mathcal{O}(1) & \mathcal{O}(1) \end{pmatrix} \qquad r_u = \frac{m_u}{m_t},\quad r_c = \frac{m_c}{m_t}$$

Constraints on ρ_u

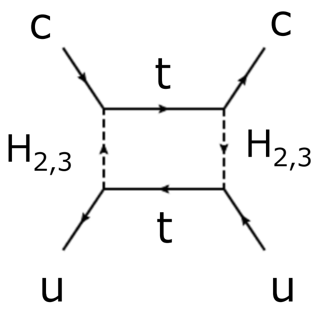
- Now, flavor violating interaction comes from ρ_u.

$$\rho_u = \frac{1}{\sqrt{2} c_\beta s_\beta v}\left[\left(c_{2\beta} + \frac{i}{t_\xi}\right) M_u - \left(1 + \frac{i}{t_\xi}\right)(\underbrace{V_{\mathrm{CKM}} V_{\mathrm{CKM}}^T}_{\sim I + \epsilon\,(10^{-3}\text{-}10^{-4})} M_u U_u^T U_u)\right]$$

・Ex 1: U_u to be orthogonal with a phase factor

$$\rho_u = \frac{\sqrt{2} M_u}{v} \zeta_u + \mathcal{O}(\epsilon) \qquad \zeta_u = \frac{1}{s_{2\beta}}\left[c_{2\beta} + \frac{i}{t_\xi} - \left(1 + \frac{i}{t_\xi}\right) e^{2i\theta_u}\right]$$

→ Yukawa alignment like scenario



・Ex 2: U_u to be (2,3) rotation, i.e.,

$$U_u = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & e^{-i\delta}\sin\theta \\ 0 & -e^{i\delta}\sin\theta & \cos\theta \end{pmatrix}$$

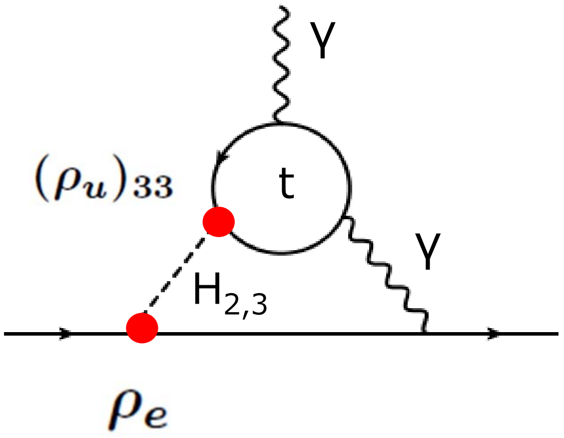
$$\rho_u = \frac{1}{\sqrt{2} c_\beta s_\beta v}\left[\left(c_{2\beta} + \frac{i}{t_\xi}\right) M_u - \left(1 + \frac{i}{t_\xi}\right)\underbrace{(V_{\mathrm{CKM}} V_{\mathrm{CKM}}^T M_u U_u^T U_u)}\right]$$

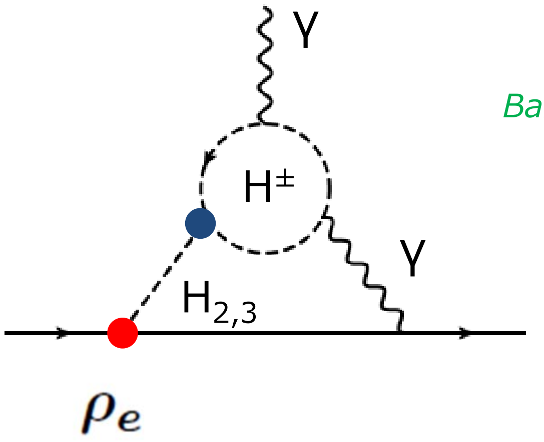
$|(\rho_u)_{31}(\rho_u)_{32}| < \mathcal{O}(10^{-2})$

$$m_t \begin{pmatrix} \mathcal{O}(r_u) & \mathcal{O}(\epsilon) & \mathcal{O}(\epsilon) \\ \mathcal{O}(\epsilon r_u) & \mathcal{O}(r_c) & \mathcal{O}(r_c) \\ \mathcal{O}(\epsilon r_u) & \mathcal{O}(1) & \mathcal{O}(1) \end{pmatrix} \qquad r_u = \frac{m_u}{m_t}, \quad r_c = \frac{m_c}{m_t}$$

EDM Constraints

☐ Barr-Zee diagrams give dominant contribution to the electron EDM.





Barr, Zee (1990)

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

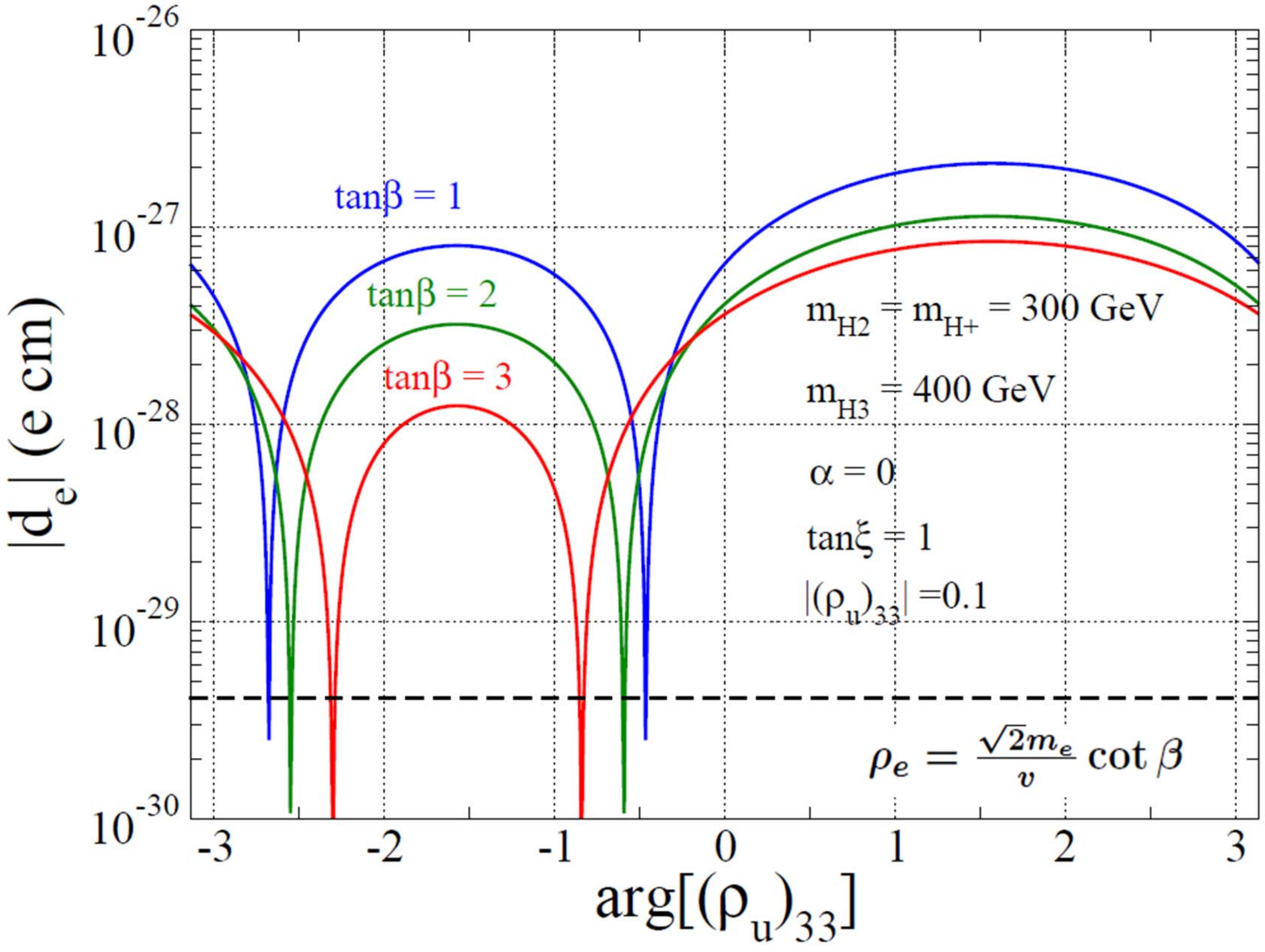
$$\lambda_{H^+H^-H_3} = -\frac{m_{H_3}^2}{v s_\beta c_\beta}(c_\alpha \cot\xi - s_\alpha c_{2\beta}),$$

$$\boxed{d_e \sim \left(\frac{1}{16\pi}\right)^2 \times e^3 G_F m_e \sim 10^{-27}\, e\,\mathrm{cm}}$$

$|d_e| \leq 4.1 \times 10^{-30}\, e\,\mathrm{cm}$ @ 90% CL

Roussy, et.al, arXiv: 2212.11841

EDM Constraints



Correlation b/w $\Delta\kappa_h$ and $h \to \gamma\gamma$

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

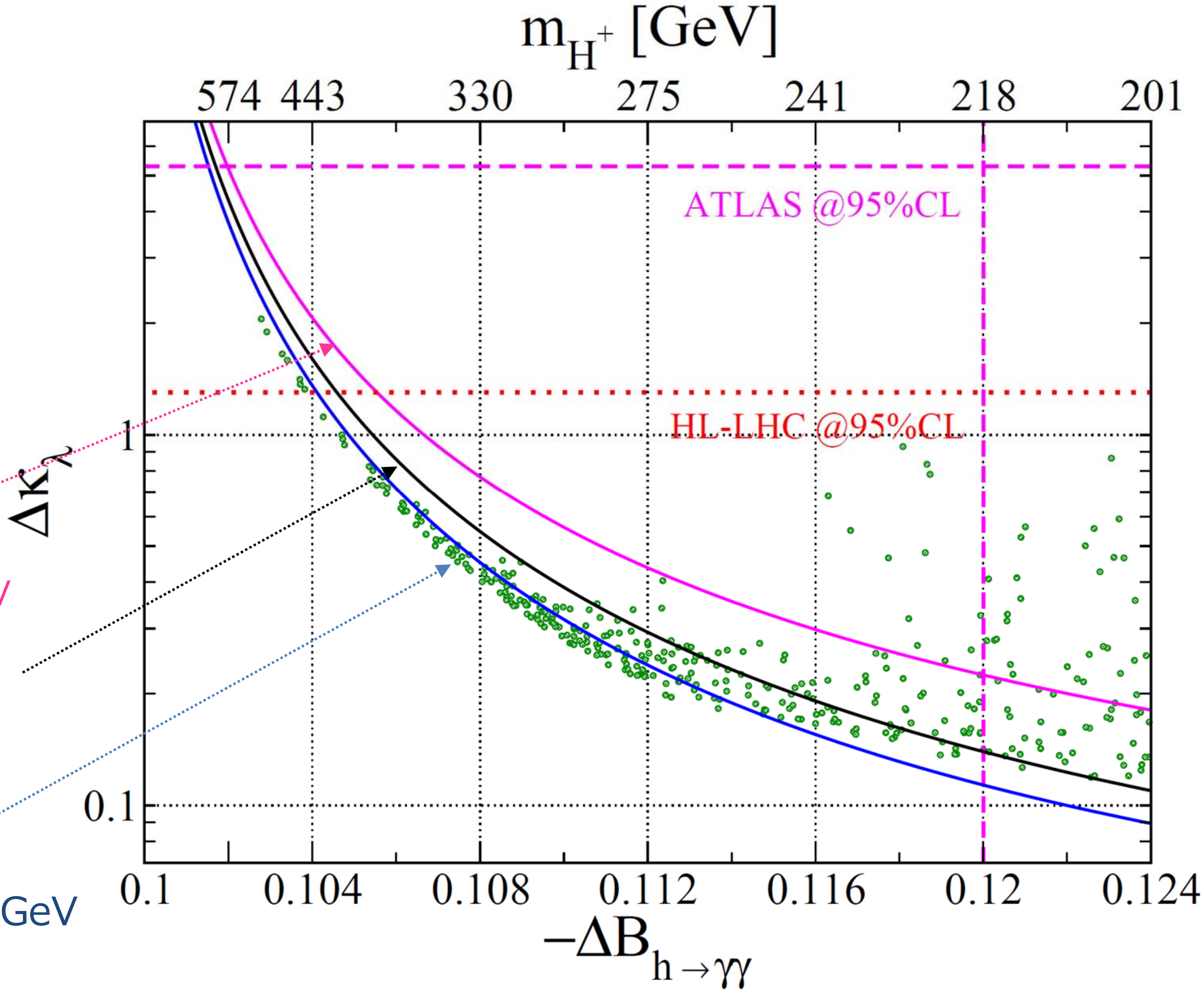
Current Limit : $-1.4 \leq \Delta\kappa_\lambda \leq 5.3$

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

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

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

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



$m_{H+} = m_{H3}$,

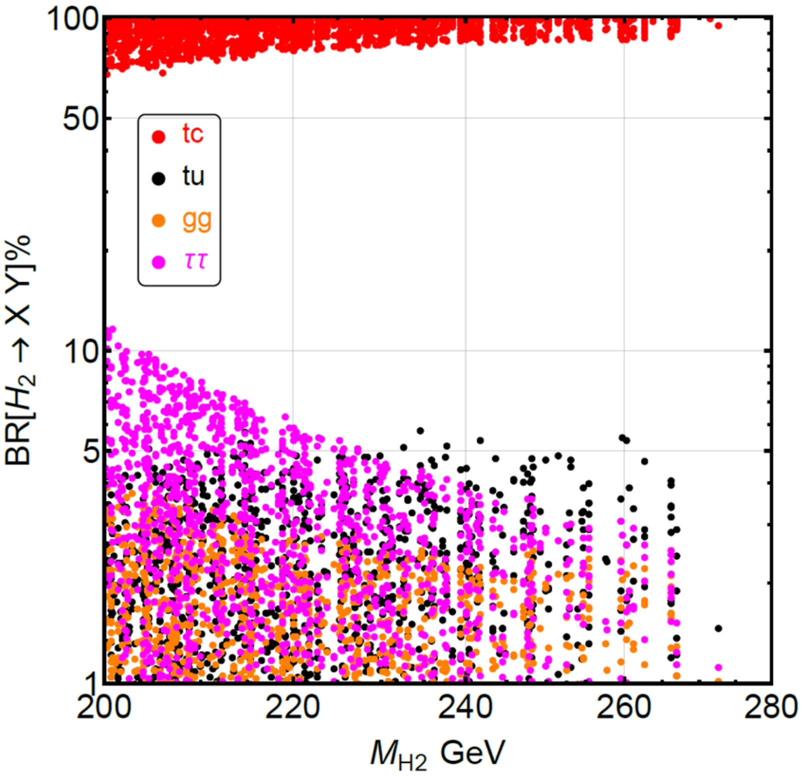
$m_{H3} - m_{H2}$ = 100 GeV

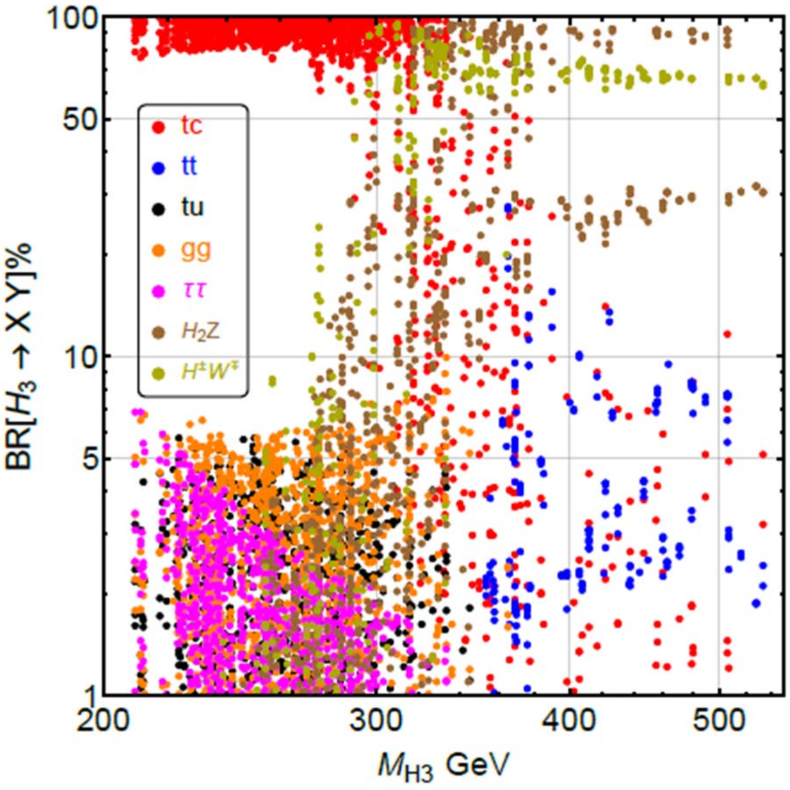
$m_{H+} = m_{H2} = m_{H3}$

$m_{H+} = m_{H2}$,

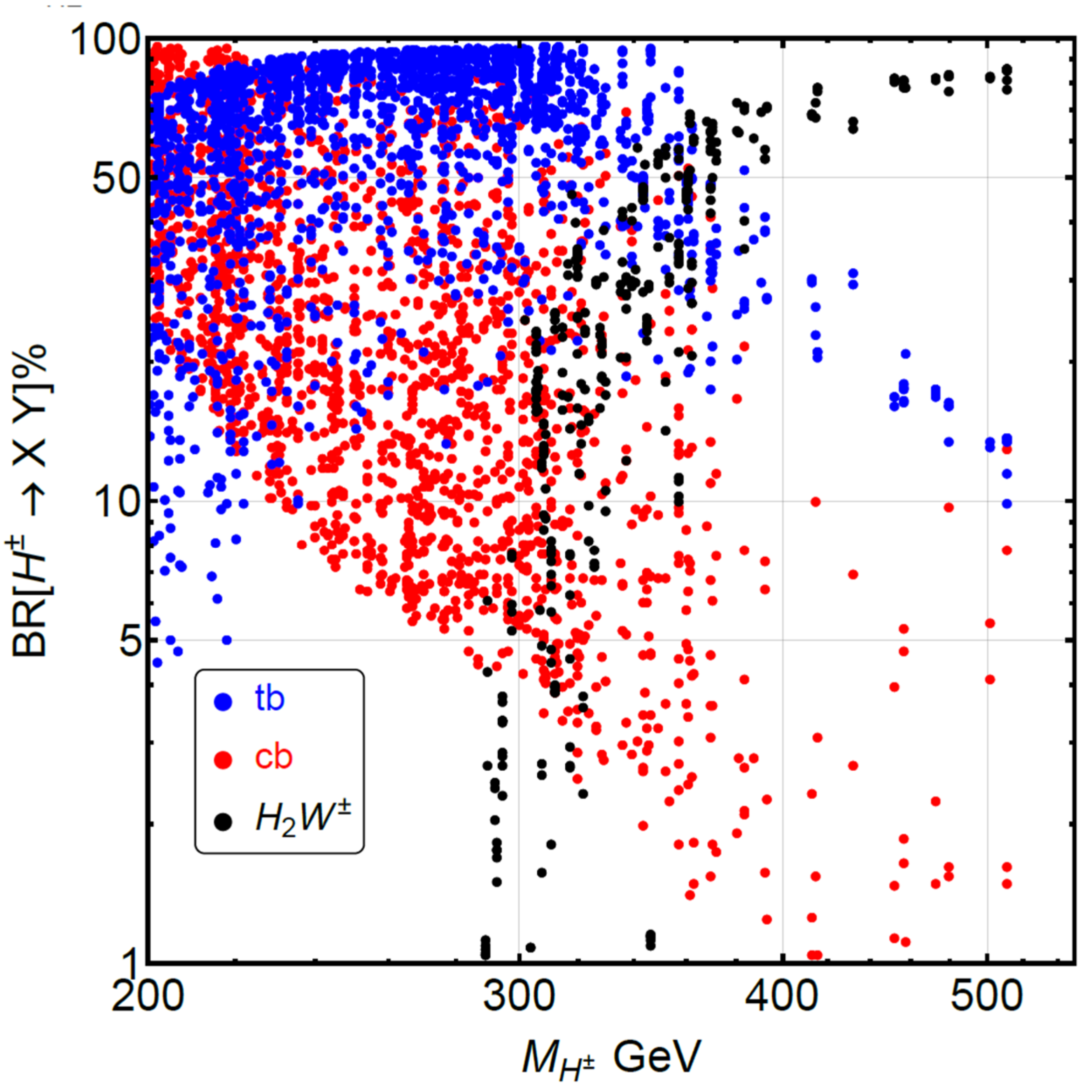
$m_{H3} - m_{H2}$ = 100 GeV

Decay BR of H_2 and H_3





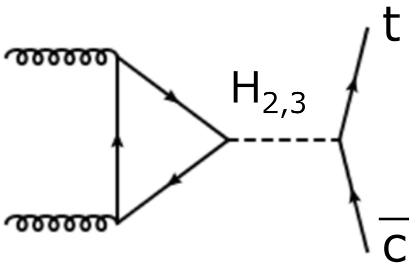
Decay BR of H±



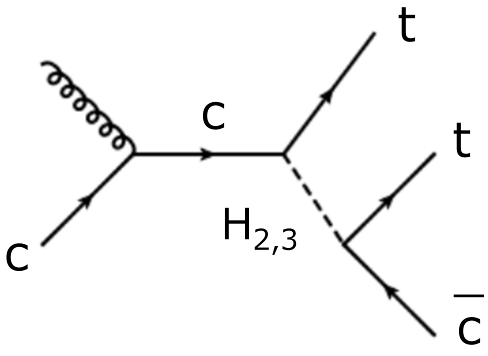
Collider signatures (on going)

- Characteristic signatures via multi-top events appear from $[\rho_u]_{32}$

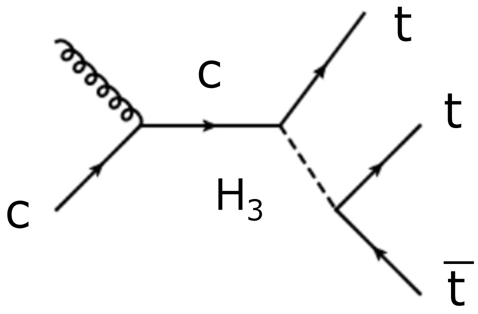
- Mono-top



- Di-top

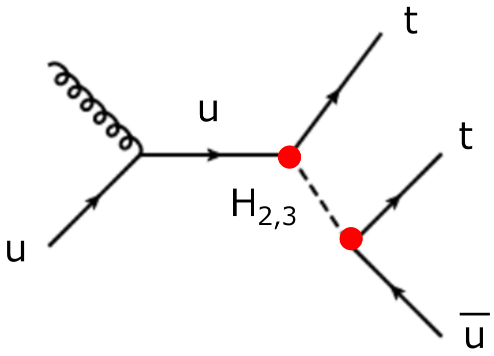


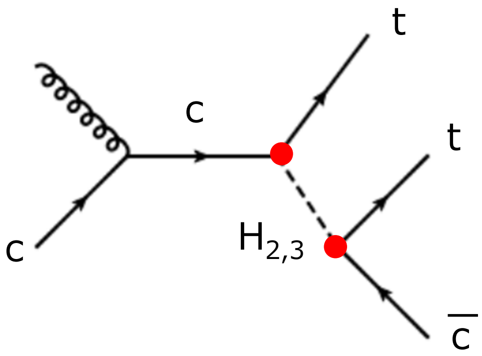
- Triple-top

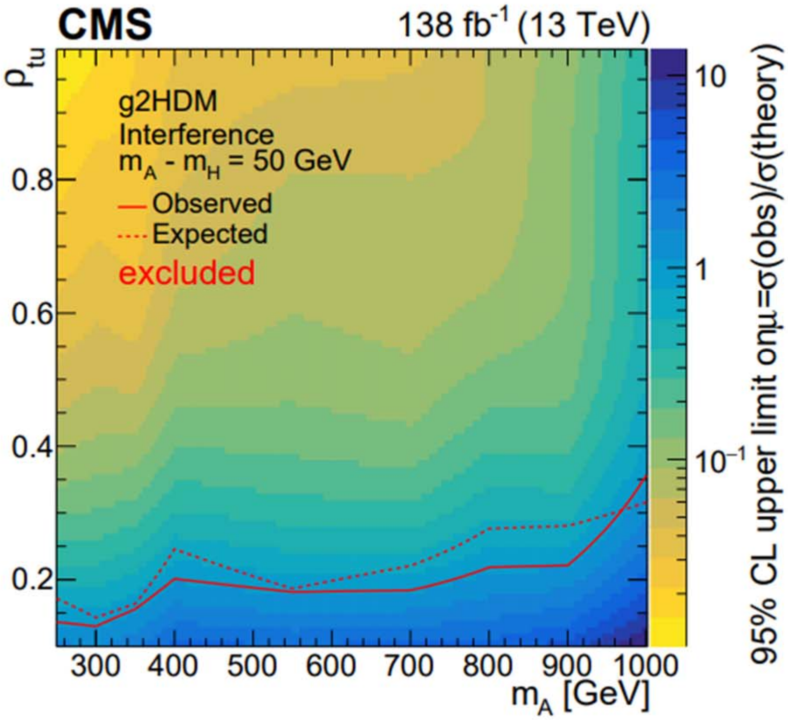


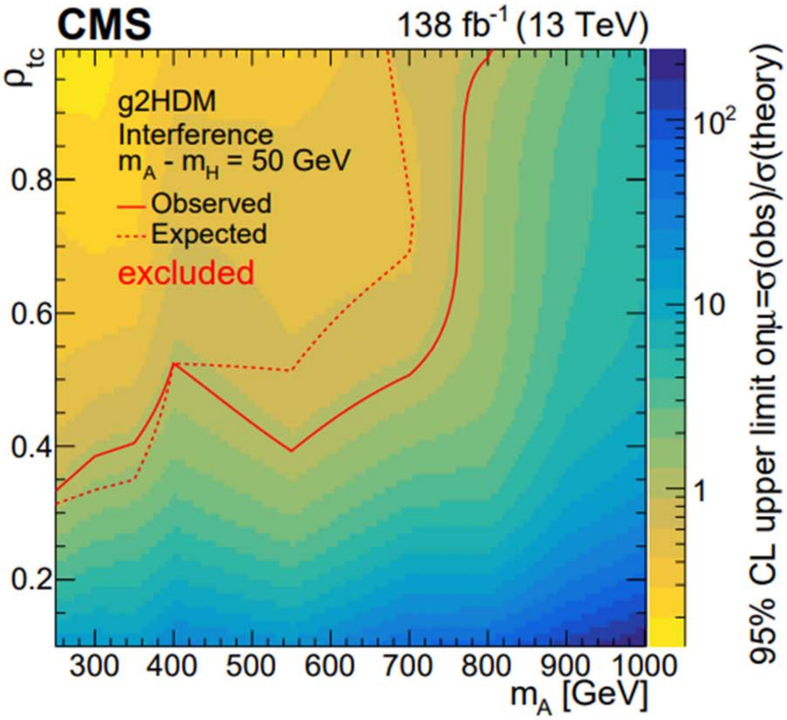
Smoking gun: Top number violating signatures w/ charm

Current bounds on ρ_{31} and ρ_{32}









Summary

SCPV 2HDM

- Inevitable non-decoupling Higgs sectors
- Flavor misalignment