Probing Spontaneous CP-violation through Precision Higgs Observables

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Collaboration with

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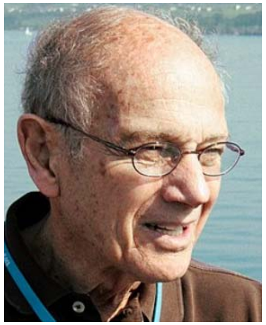
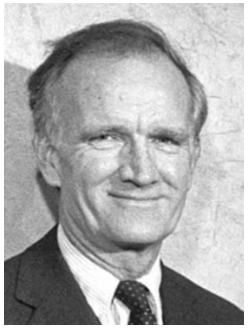
CP-violation

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

$K_L \to \pi\pi\pi$ CP-odd

$K_L \to \pi\pi$ CP-even


Cronin


Fitch

- In the SM, CPV can be explained by 3 gen. structure of quark sector (1973).

KM phase

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


Kobayashi Maskawa

Question: What is the origin of the KM phase?

Origin of CP-violation

☐ Explicit violation

- Lagrangian is not invariant under the CP transformation.
  (e.g., complex phases of the Yukawa coupling in the SM)

☐ Spontaneous violation

- Vacuum structure is not invariant under the CP transformation
  (Extended Higgs sectors)

Origin of CP-violation

☐ Explicit violation

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  (Extended Higgs sectors)

☐ Motivation to consider SCPV

- Why not?
- Dynamical explanation of CPV by vacuum structure
- Solution to strong CPV
- Connection to BAU (Naturally introduce extended Higgs)

SCPV in 2HDMs

- ☐ First proposed by T. D. Lee in 1973

WT. D. Lee

- ☐ Basis invariant CPV quantities

  Lavoura, Silva (9404276, PRD)

  Gunion, Haber (0506227, PRD)

  Necessary & sufficient conditions for SCPV in the 2HDM in a basis indep. way.

Howard E. Haber

- ☐ Vacuum structure

  Barroso, ferreira, Santos (0406231, PLB)

  Ivanov (0710.3490, PRD)

  If CPV vacuum exists, it must be a global minimum.

  Grsadkowski, Ogreid, Osland, (1609.04764, PRD)

  Nierste, Tabet, Ziegler (1912.11501, PRL), etc.

- ☐ Phenomenology at collider experiments

  To reproduce the KM phase, flavor misalignment is necessary.

R. Santos

In our work, we focus on the h(125) physics and flavor physics in the SCPV 2HDM.

Higgs potential

- 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

→ $\frac{\partial V}{\partial \xi} = 0$

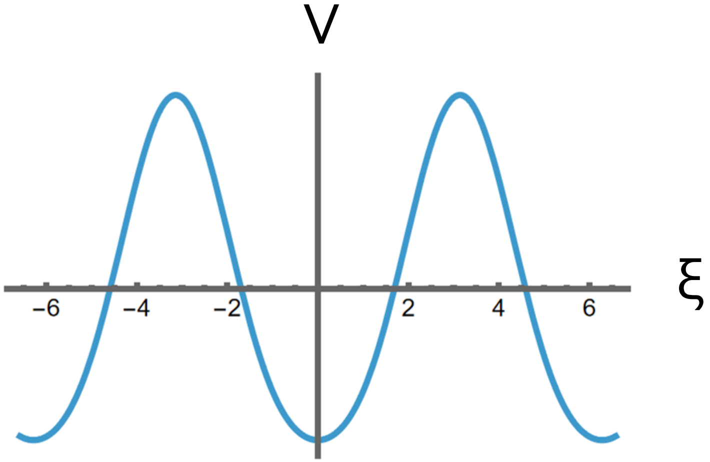
$$\boxed{\mu_3^2 = v_1 v_2\left(\lambda_5\cos\xi + \frac{\lambda_6}{2}v_1^2 + \frac{\lambda_7}{2}v_2^2\right), \quad \xi \neq n\pi}$$

Condition for SCPV

Shape of the potential ($\lambda_6 = \lambda_7 = 0$)

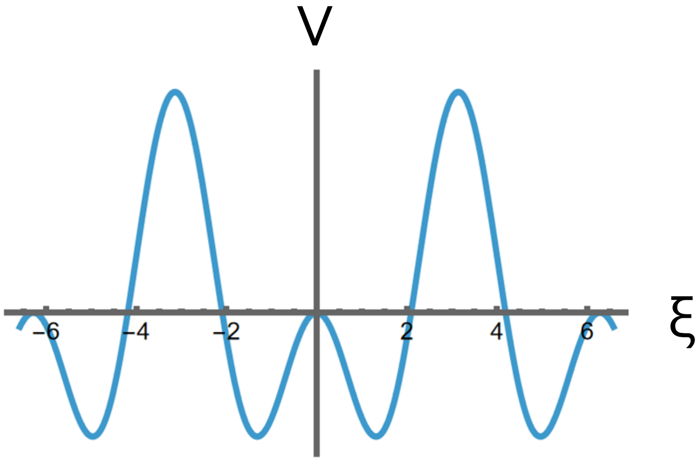
Condition for SCPV $\mu_3^2 = \lambda_5 v_1 v_2 \cos\xi$

CP-Conserving



$$|\mu_3^2| > v_1 v_2 \lambda_5$$

Spontaneous CPV



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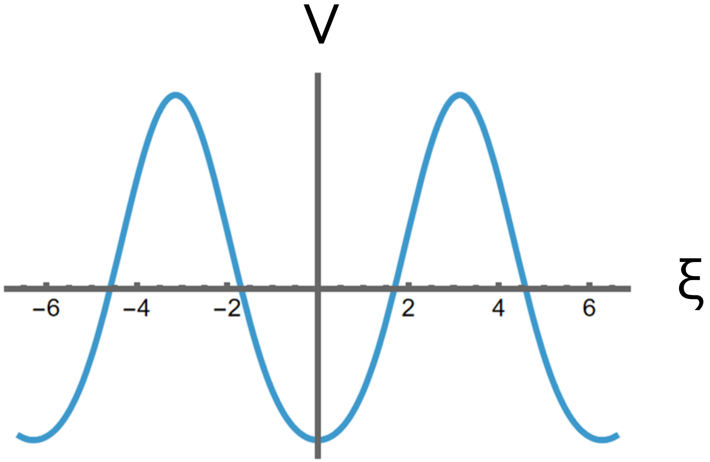

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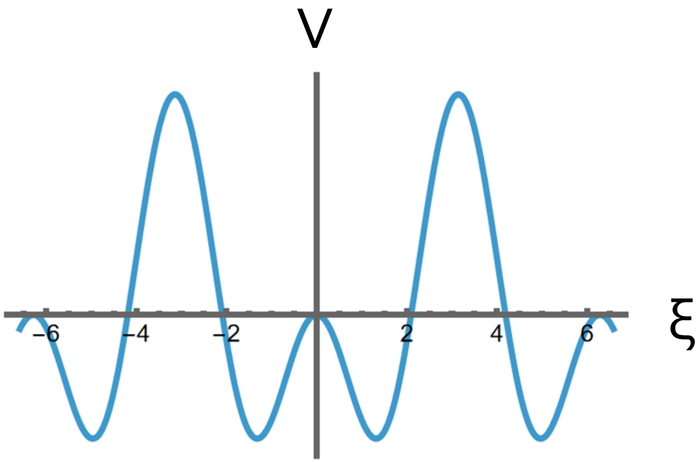
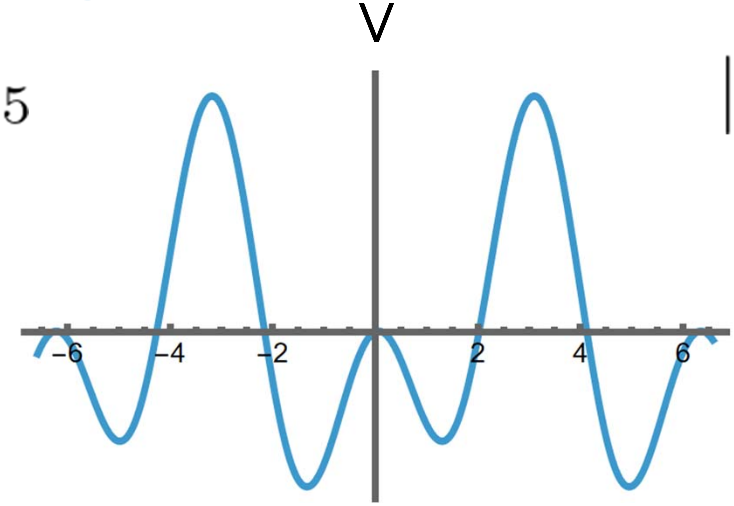


$$|\mu_3^2| < v_1 v_2 \lambda_5$$

Explicit CPV



$\mathrm{Im}[\mu_3^2] \neq 0$

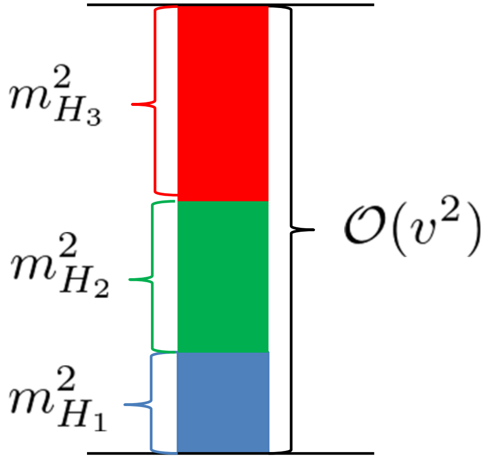
$$\mathrm{Re}\,[\mu_3^2] = \lambda_5 v_1 v_2 \cos\xi - \mathrm{Im}\,[\mu_3^2] \tan\xi$$

Nondecoupling Higgs

- Stationary conditions

$$\frac{\partial V}{\partial v_1} = \frac{\partial V}{\partial v_2} = \frac{\partial V}{\partial \xi} = 0 \quad \longrightarrow \quad \mu_i^2 = f_i(v, \lambda_j)$$

- Additional Higgs masses



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

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

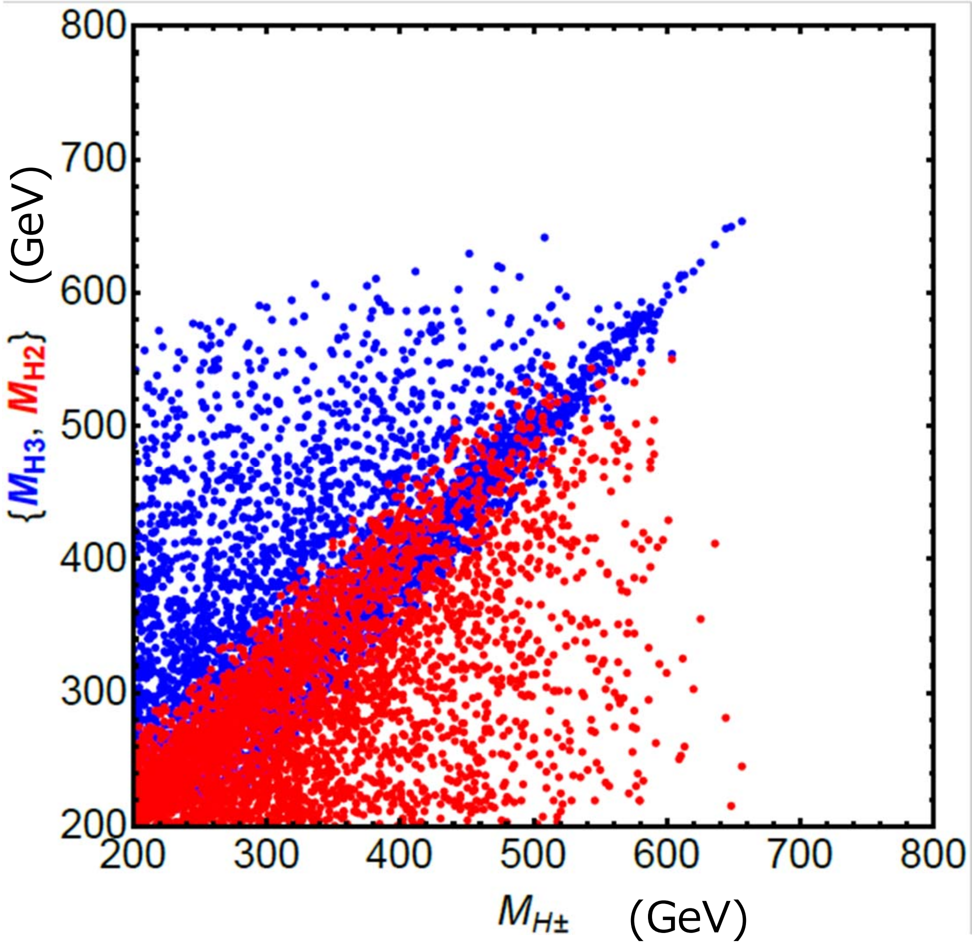
→ Upper limit on the additional Higgs masses

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

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

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

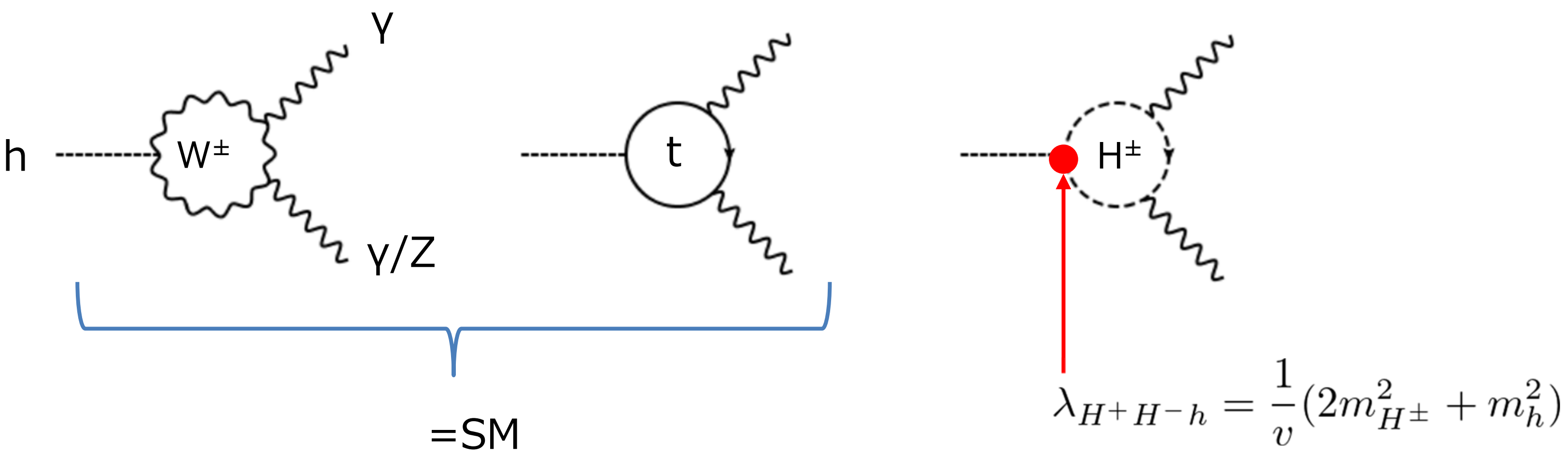
NLO unitarity bound: Nierste, Mustafa, Tabet, Robert, Ziegler (2020)



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

h → γγ/Zγ

- We take the Higgs alignment limit.



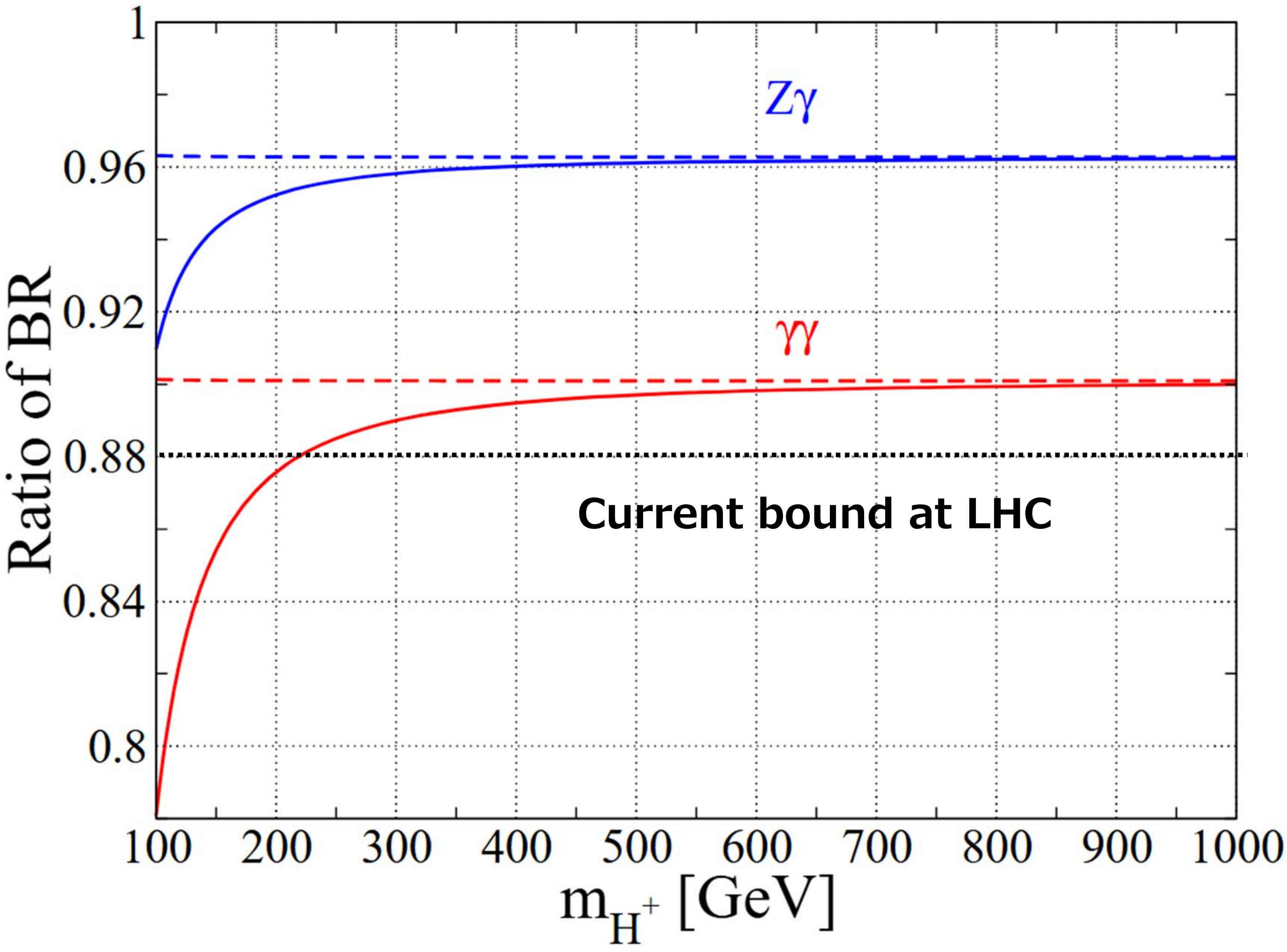
=SM

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

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

$h \to \gamma\gamma/Z\gamma$

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

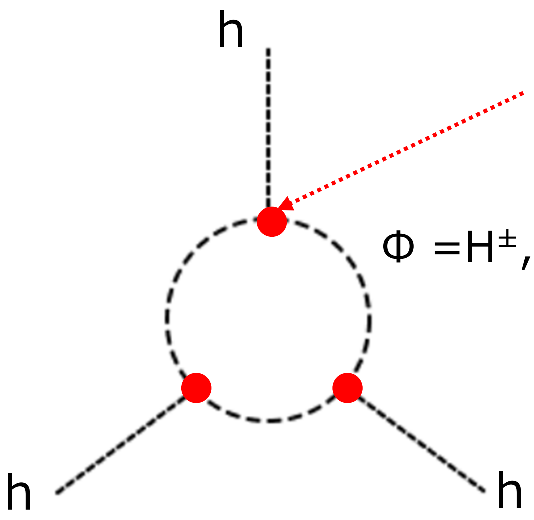


Current bound at LHC

Self-coupling

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

2-loop: Braathen, Kanemura (2019)



Φ =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

☐ Down-type quark Yukawa

$$\mathcal{L}_Y = -Y_1 \bar{Q}_L \Phi_1 d_R - Y_2 \bar{Q}_L \Phi_2 d_R + \mathrm{h.c.}$$

Y_1, Y_2: Real matrices

$$\rightarrow \quad M_d = \frac{v_1}{\sqrt{2}} Y_1 + \frac{v_2 e^{i\xi}}{\sqrt{2}} Y_2$$

If we impose the alignment condition, i.e., $Y_2 = \zeta Y_1$

$$M_d = \frac{Y_1}{\sqrt{2}} (v_1 + \zeta v_2 e^{i\xi})$$

(Real matrices) × (Overall phase)

→ KM phase disappears!

We need a Yukawa misalignment to reproduce the KM phase.

(This means Z_2 symmetry cannot be imposed to the SCPV 2HDM)

Partially Yukawa alignment

Mondal, Yagyu, 2505.05104

- We partially impose the Yukawa alignment to the (d, e) sectors.

Up-quarks

$$Y_1^u, \quad Y_2^u$$

General

Down-quarks

$$Y_2^d = \zeta_d \, Y_1^d$$

Charged-leptons

$$Y_2^e = \zeta_e \, Y_1^e$$

Yukawa aligned

- KM phase is reproduced.
- FCNCs from (d,e) sectors are forbidden.
- Yukawa-int. for up-sector is given by

U_u: Unitary matrix for RH up-quarks

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

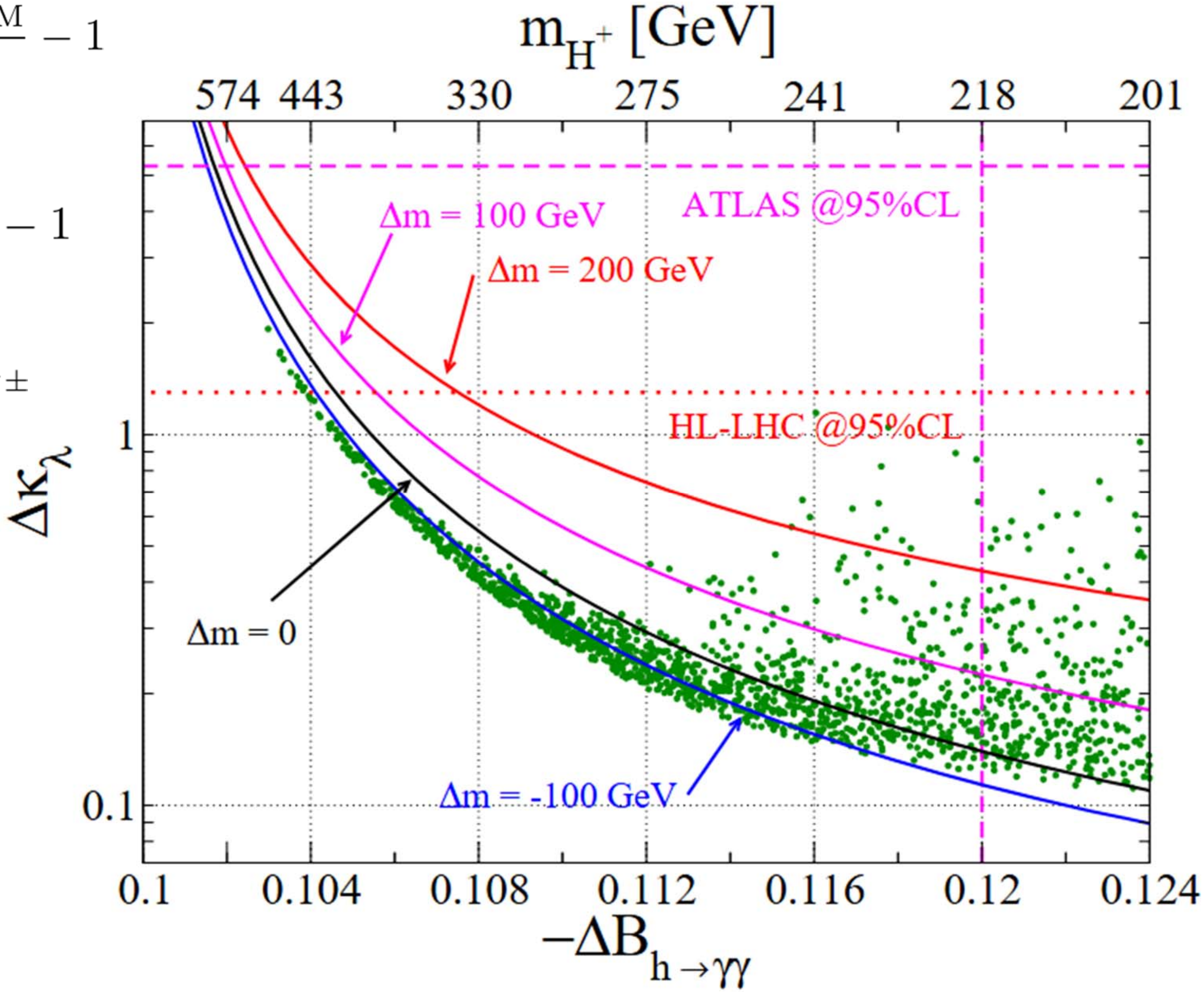
Correlation b/w $\Delta\kappa_\lambda$ and h → γγ

Mondal, Yagyu, 2505.05104

$$\Delta\kappa_\lambda \equiv \frac{(\lambda_{hhh}^{1-\text{loop}})_{\text{2HDM}}}{(\lambda_{hhh}^{1-\text{loop}})_{\text{SM}}} - 1$$

$$\Delta\mathcal{B}_{h\to\gamma\gamma} \equiv \frac{\mathcal{B}_{h\to\gamma\gamma}^{\text{2HDM}}}{\mathcal{B}_{h\to\gamma\gamma}^{\text{SM}}} - 1$$

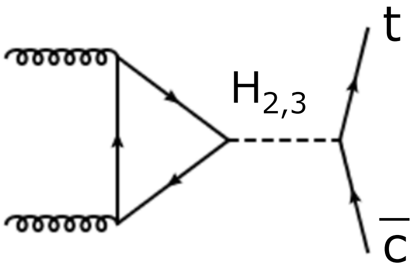
$$\Delta m = m_{H_2} - m_{H^\pm}$$



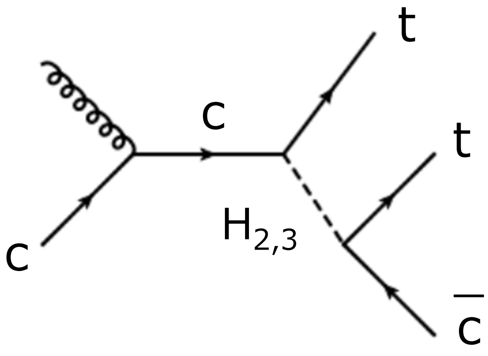
Collider signatures (on going)

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

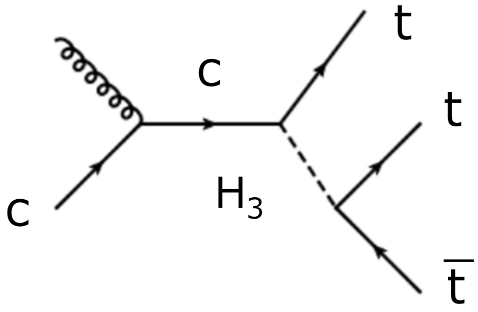
- Mono-top

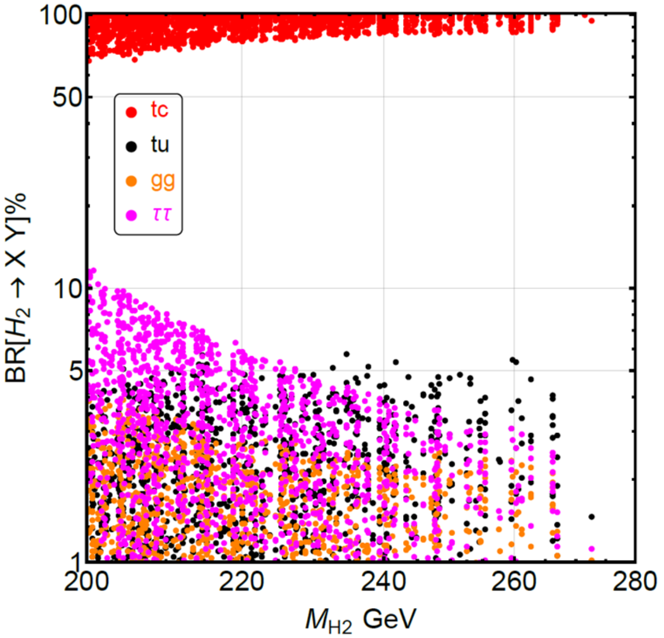


- Di-top



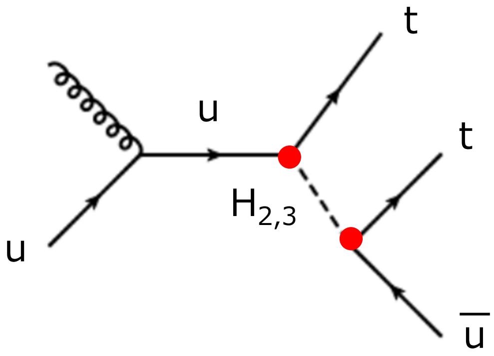
- Triple-top

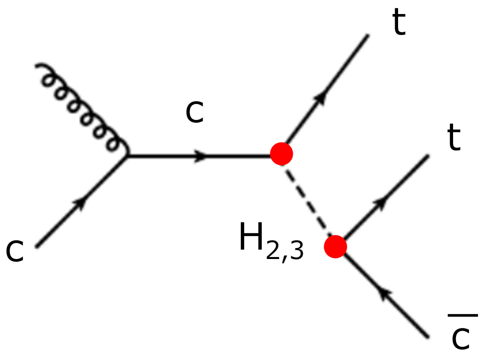


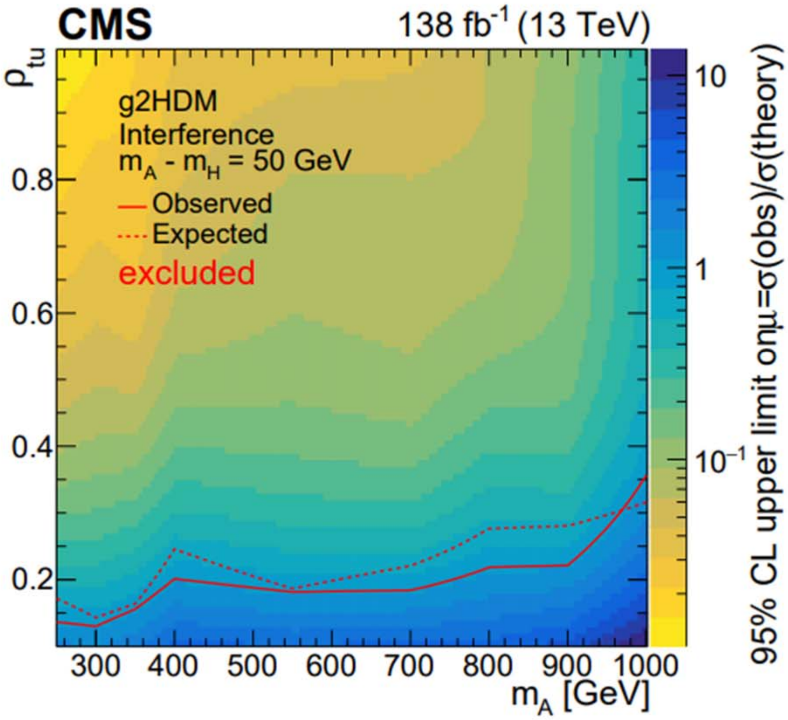


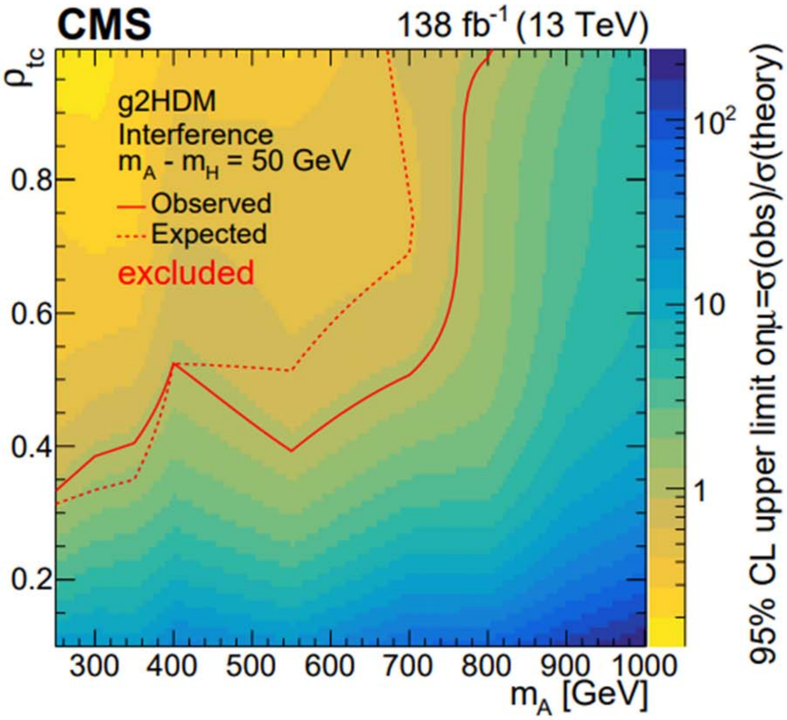
Smoking gun: Top number violating signatures w/ charm

Current bounds on ρ_{31} and ρ_{32}





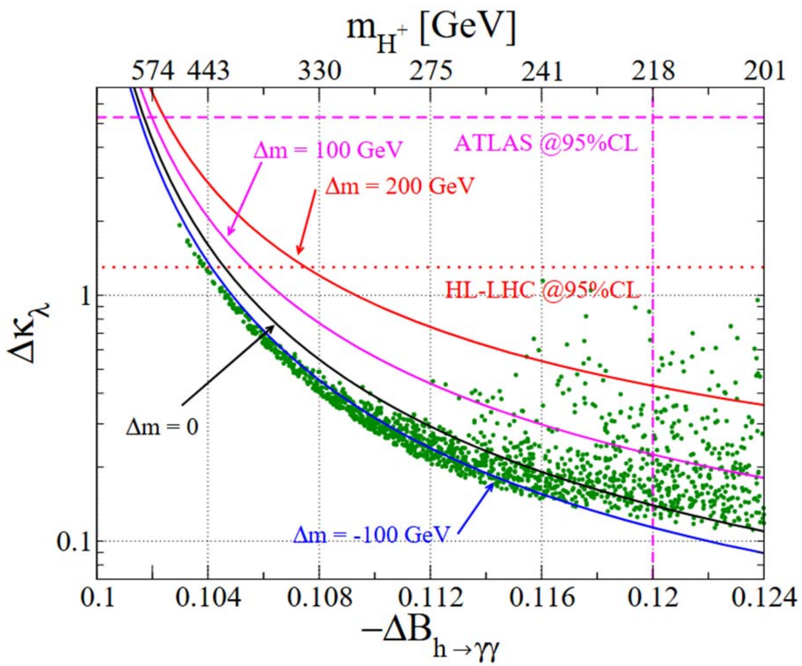


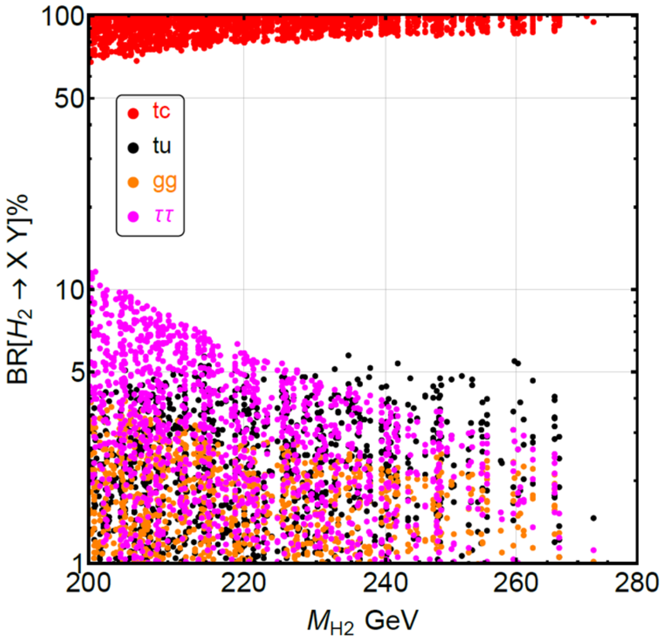


Summary

SCPV 2HDMs

- Inevitable non-decoupling Higgs sectors
- Flavor misalignment





HL-LHC could discover/kill the SCPV 2HDMs.

Backup Slides

Constraints on ρ_u

☐ Now, flavor violating interaction comes from ρ_u.

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

- 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.,

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

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$$r_u = \frac{m_u}{m_t}, \quad r_c = \frac{m_c}{m_t}$$

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

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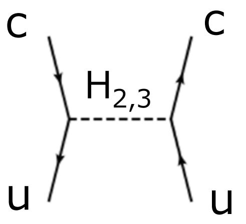

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$|(\rho_u)_{12}(\rho_u)_{21}| < O(10^{-8})$

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

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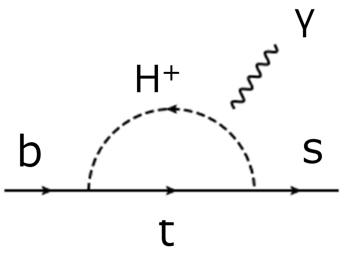
$\sim I + \varepsilon\ (10^{-3}\text{-}10^{-4})$



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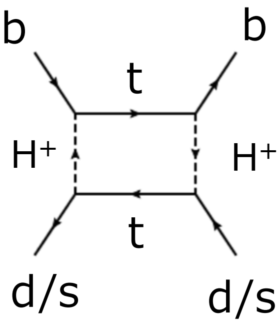
→ Yukawa alignment like scenario



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

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

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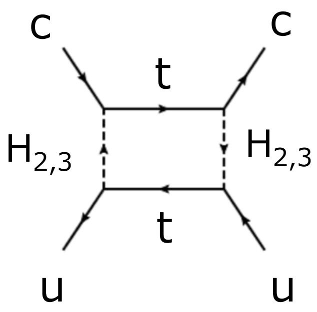
$$\rho_u = \frac{1}{\sqrt{2} c_\beta s_\beta v}\left[\left(c_{2\beta} + \frac{i}{t_\xi}\right) M_u - \left(1 + \frac{i}{t_\xi}\right)(\underbrace{V_{\mathrm{CKM}} V_{\mathrm{CKM}}^T}_{\sim I + \varepsilon (10^{-3}\text{-}10^{-4})} M_u U_u^T U_u)\right]$$

・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.,

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

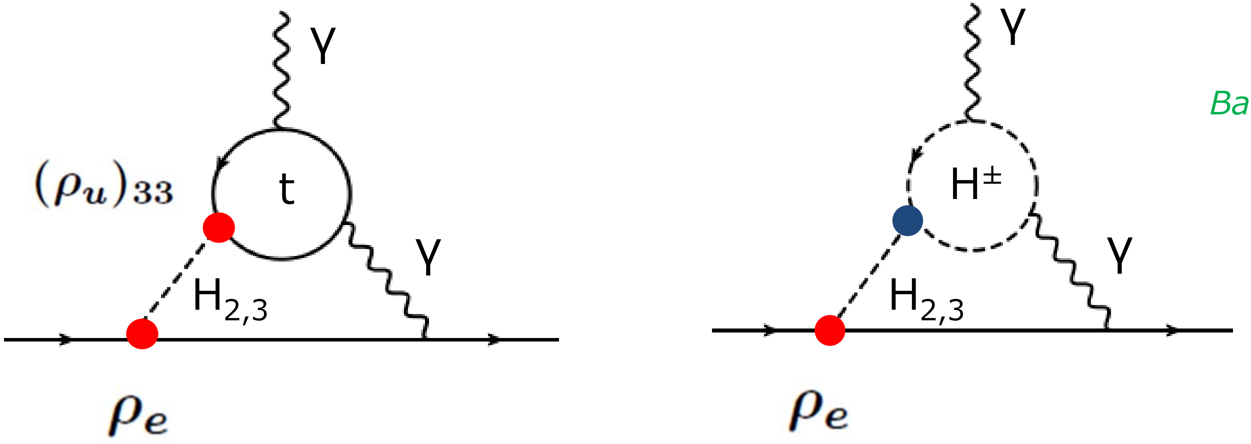
$$\rho_u = \frac{1}{\sqrt{2} c_\beta s_\beta v}\left[\left(c_{2\beta} + \frac{i}{t_\xi}\right) M_u - \left(1 + \frac{i}{t_\xi}\right)(\underline{V_{\mathrm{CKM}} V_{\mathrm{CKM}}^T M_u U_u^T U_u})\right]$$

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

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

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

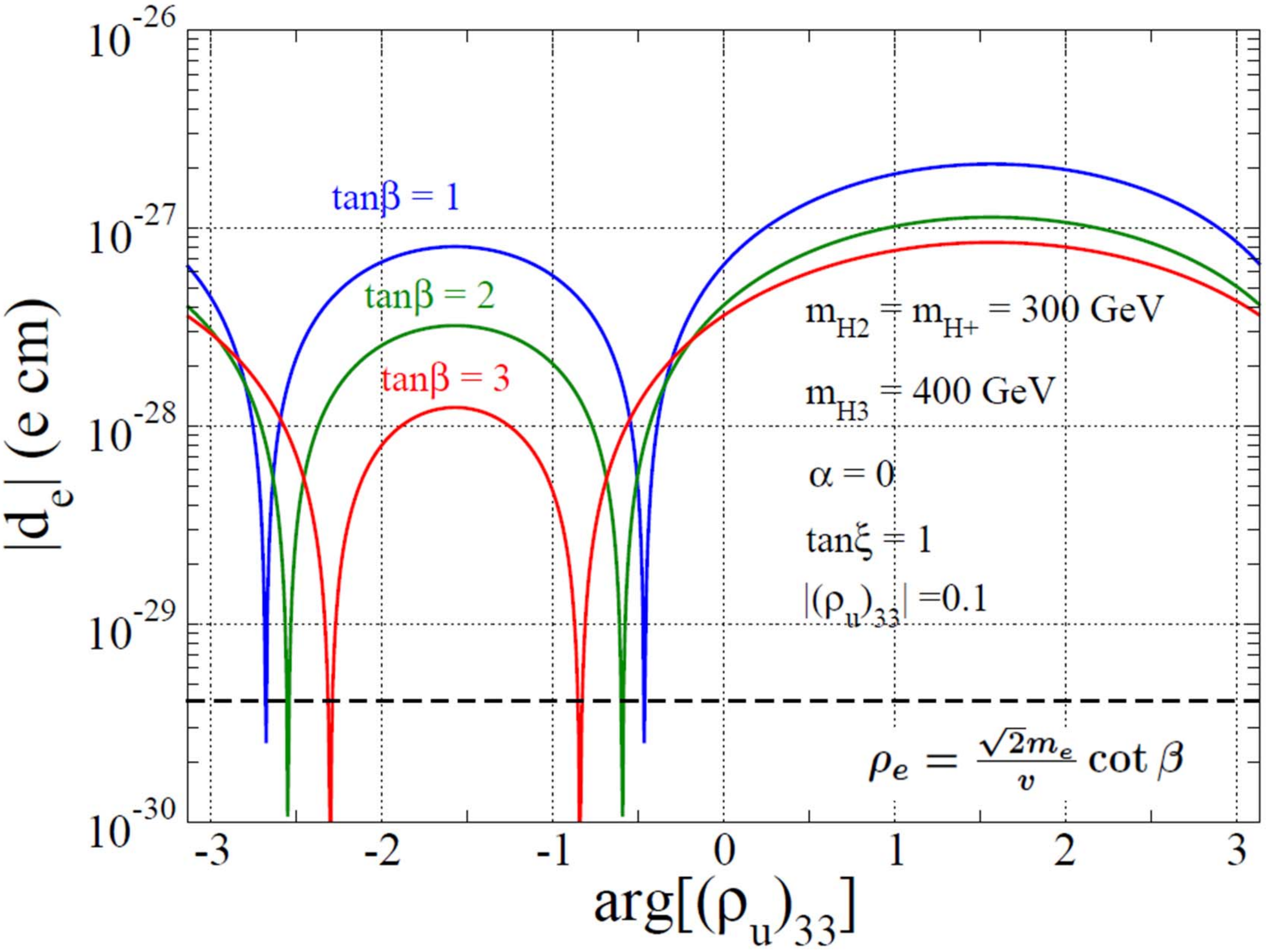
Scan

Parameters	Range	Parameters	Range
$m_{H^\pm/H_2/H_3}$(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

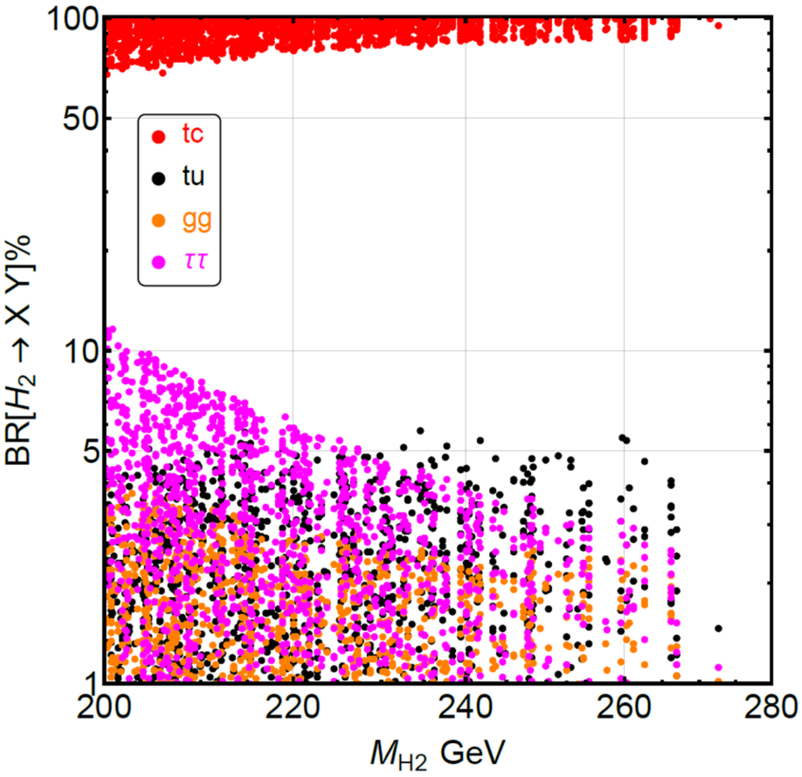
$$\rho_u^{ij} = \frac{\sqrt{2}}{s_{2\beta} v}\left[\left(c_{2\beta} + \frac{i}{t_\xi}\right)(M_u)_{ij} - \left(1 + \frac{i}{t_\xi}\right)(VV^T M_u U_u^T U_u)_{ij}\right]$$

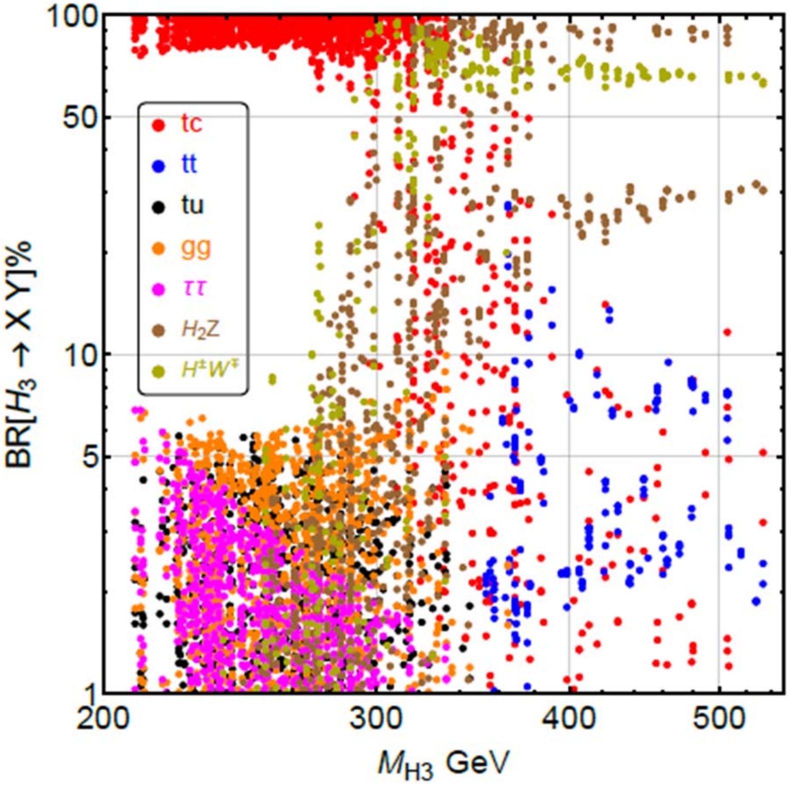
$$U_u = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23}e^{-i\delta_{23}} \\ 0 & -s_{23}e^{i\delta_{23}} & c_{23} \end{pmatrix}\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix}\begin{pmatrix} c_{12} & s_{12}e^{-i\delta_{12}} & 0 \\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

EDM Constraints

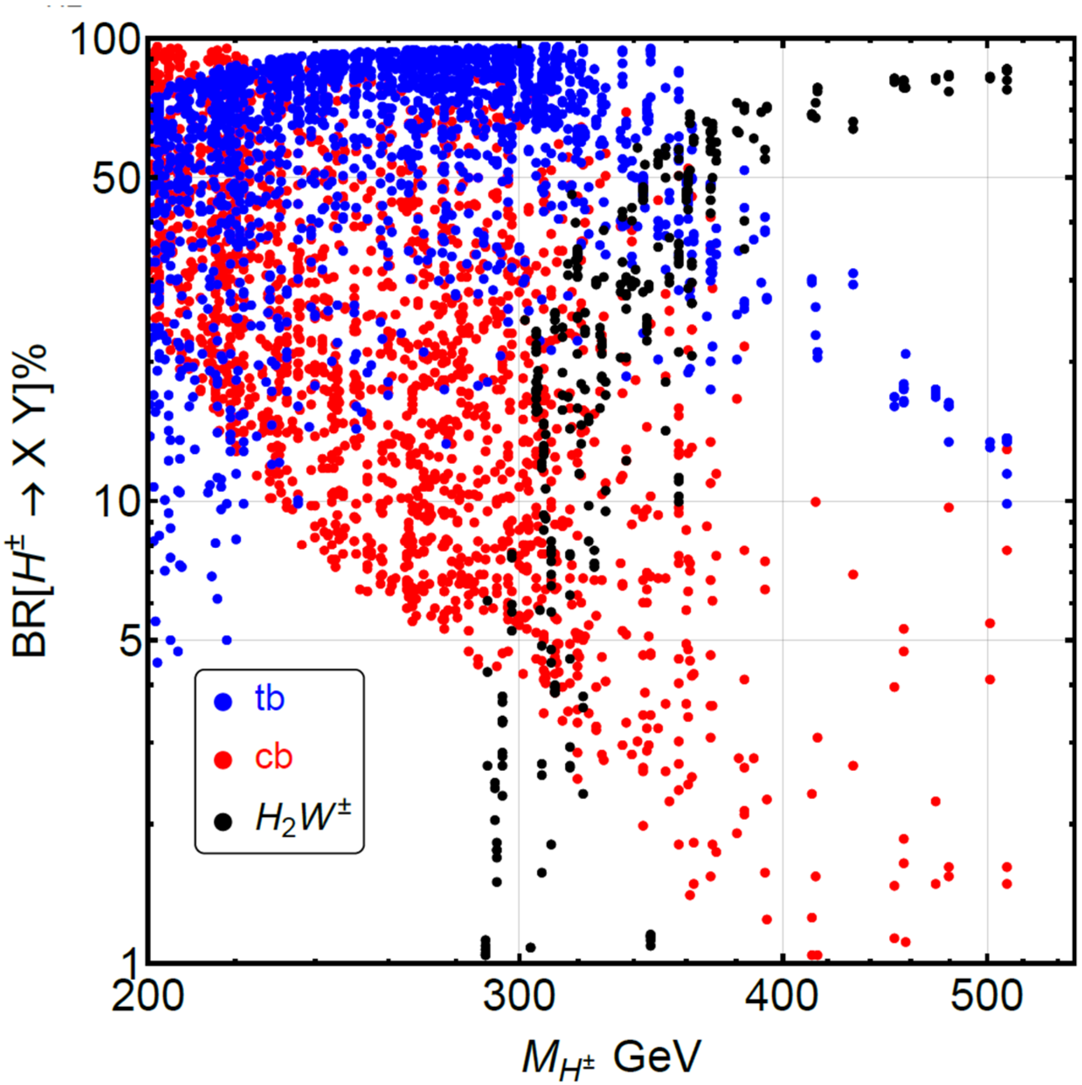


Decay BR of H_2 and H_3

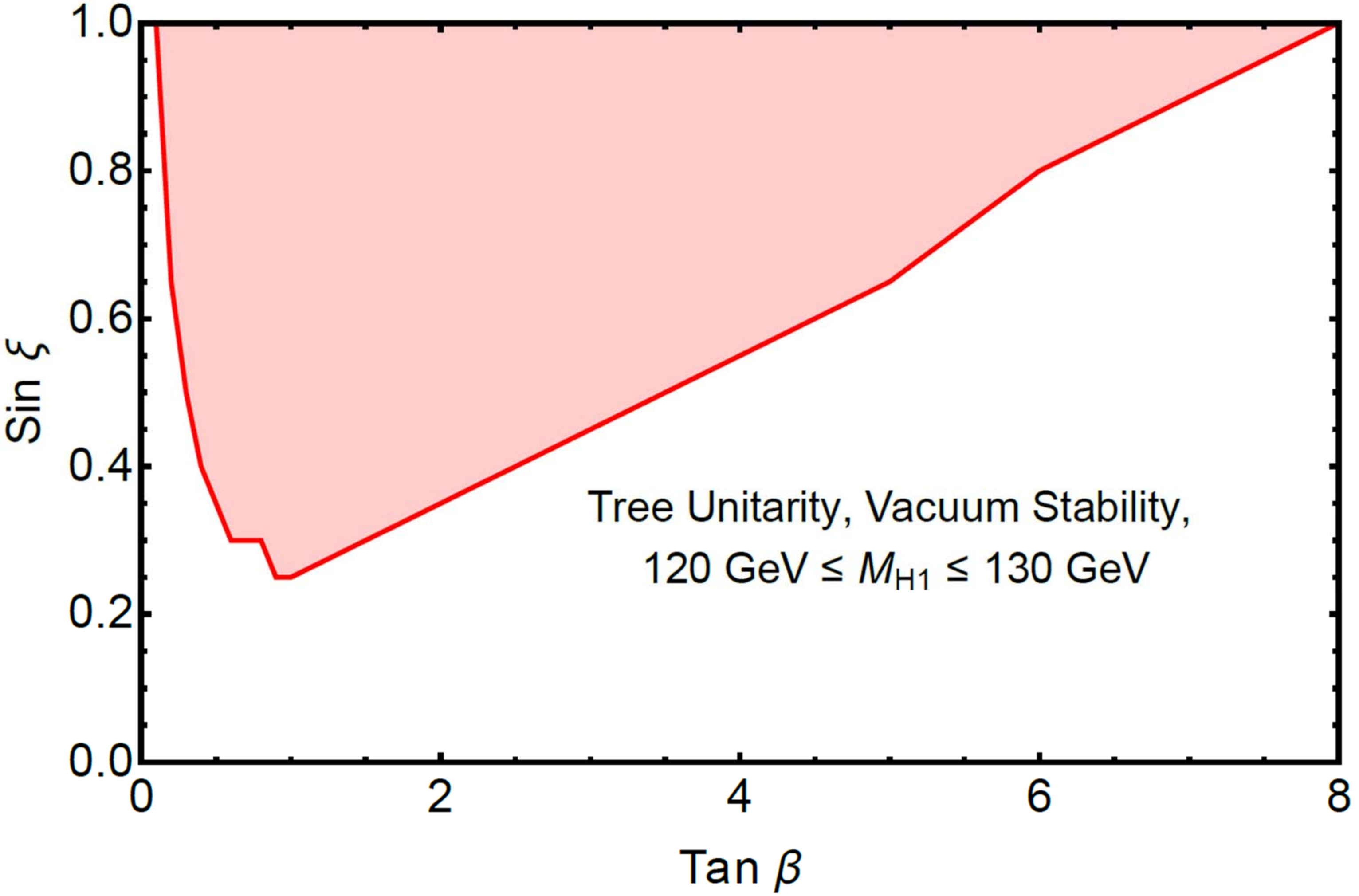




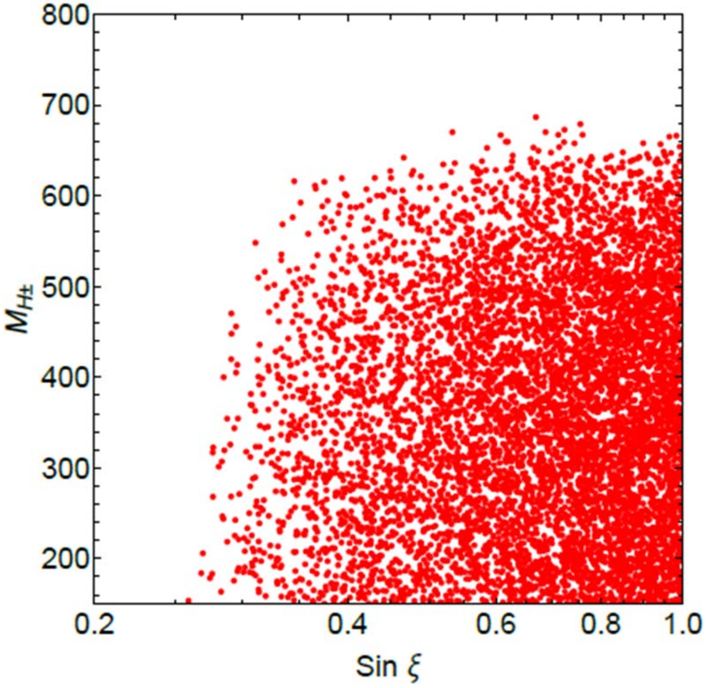
Decay BR of $H^\pm$

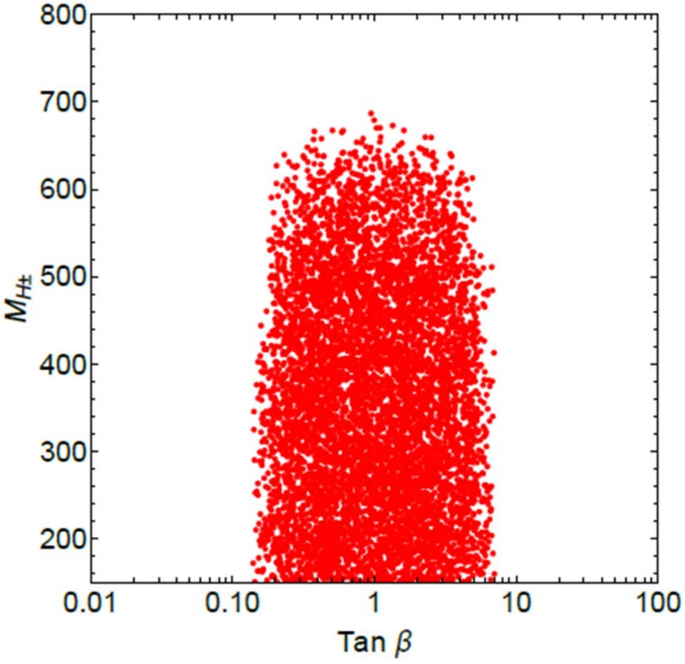


Limit on tanβ – sinξ plane



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


800
700
600
500
400
300
200
$M_{H\pm}$
0.2
0.4
0.6
0.8
1.0
Sin ξ


800
700
600
500
400
300
200
$M_{H\pm}$
0.01
0.10
1
10
100
Tan β