Large CP Violation
in the Complex Two-Higgs-Doublet Model
From the Electron EDM to Hidden CP Violation

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based on arXiv: 2512.17002 (Published in PRD)
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FLASY 2026

Gyeongju, Korea · 19 August 2026

Contents

I

Introduction

Why we need a new source of CP violation

Baryon-to-Photon Ratio (η_B): $\eta_B \equiv \dfrac{n_B - n_{\bar{B}}}{n_\gamma} \approx 6 \times 10^{-10}$

SM Prediction: $\eta_B^{\mathrm{SM}} \sim 10^{-20}$

Sakharov conditions

1 Baryon number violation

Satisfied in the SM

2 C and CP violation

CKM phase is too small

3 Out of thermal equilibrium

125 GeV Higgs gives
a smooth crossover

"Complex 2HDM"

New CP phase

One of the simplest extensions of the scalar sector

Viable strong first-order EWPT

II

Model

The C2HDM: fields, Z_2 symmetry and the potential

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \dfrac{v_1 + \rho_1 + i\eta_1}{\sqrt{2}} \end{pmatrix}, \qquad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \dfrac{v_2 + \rho_2 + i\eta_2}{\sqrt{2}} \end{pmatrix}, \qquad t_\beta = \frac{v_2}{v_1}, \quad v = \sqrt{v_1^2 + v_2^2}$$

A discrete Z_2 to avoid tree-level FCNC $\quad Z_2 : \quad \Phi_1 \to \Phi_1, \qquad \Phi_2 \to -\Phi_2$

The four Yukawa types follow from the right-handed fermion charges → four Yukawa types (I, II, X, Y)

$$V_\Phi = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left(m_{12}^2\, \Phi_1^\dagger \Phi_2 + \text{h.c.} \right) + \tfrac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \tfrac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2$$
$$+ \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \tfrac{1}{2}\left[\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \text{h.c.} \right]$$

$$\text{Hermiticity} \;\Rightarrow\; \text{all other terms are self-conjugate} \;\Rightarrow\; \text{only } m_{12}^2 \text{ and } \lambda_5 \text{ may be complex}$$

$$\underbrace{2\,\mathrm{Im}(m_{12}^2) = v_1 v_2\, \mathrm{Im}(\lambda_5)}_{\text{minimisation condition}} \;+\; \underbrace{\Phi_2 \to e^{i\xi}\Phi_2}_{\text{rephasing}} \quad\Longrightarrow\quad \arg\!\left(\lambda_5 (m_{12}^2)^{-2}\right) \;:\; \text{one physical phase}$$

* An exact Z_2 ($m^2_{12} = 0$) forces Im $\lambda_5 = 0$ — CP violation needs the symmetry to be **softly broken**

One physical CP phase — the source of CP violation

The Higgs basis isolates the physical CP-odd state

$$\begin{pmatrix}\mathcal{H}_1\\ \mathcal{H}_2\end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ -s_\beta & c_\beta\end{pmatrix}\begin{pmatrix}\Phi_1\\ \Phi_2\end{pmatrix}: \qquad \mathcal{H}_1 = \begin{pmatrix} G^\pm \\ \frac{1}{\sqrt{2}}(v + H^0 + iG^0)\end{pmatrix}, \qquad \mathcal{H}_2 = \begin{pmatrix} H^\pm \\ \frac{1}{\sqrt{2}}(R_2 + i\, I_2)\end{pmatrix}$$

$$I_2 = -s_\beta\,\eta_1 + c_\beta\,\eta_2 \ \ \text{(physical CP-odd state)}, \qquad G^0 = c_\beta\,\eta_1 + s_\beta\,\eta_2 \ \ \text{(Goldstone)}$$

ρ_1, ρ_2: CP-even

I_2: CP-odd

$$\mathcal{M}^2 = \begin{array}{c} \begin{array}{ccc} \rho_1 & \rho_2 & I_2 \\ \downarrow & \downarrow & \downarrow \end{array} \\ \begin{pmatrix} \bar{m}^2 s_\beta^2 + \lambda_1 v^2 c_\beta^2 & -(\bar{m}^2 - \lambda_{345}v^2)s_\beta c_\beta & -\frac{1}{2}\mathrm{Im}(\lambda_5)v^2 s_\beta \\ -(\bar{m}^2 - \lambda_{345}v^2)s_\beta c_\beta & \bar{m}^2 c_\beta^2 + \lambda_2 v^2 s_\beta^2 & -\frac{1}{2}\mathrm{Im}(\lambda_5)v^2 c_\beta \\ -\frac{1}{2}\mathrm{Im}(\lambda_5)v^2 s_\beta & -\frac{1}{2}\mathrm{Im}(\lambda_5)v^2 c_\beta & \bar{m}^2 - \mathrm{Re}(\lambda_5)v^2 \end{pmatrix} \end{array}$$

Im λ_5 fills the (ρ_1 , I_2) and (ρ_2 , I_2) entries — it mixes the CP-even fields with the CP-odd one

Neutral mixing: gauge and Yukawa couplings

$$\begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix} = \mathbf{R} \begin{pmatrix} \rho_1 \\ \rho_2 \\ I_2 \end{pmatrix}, \qquad \mathbf{R} = \begin{pmatrix} c_{\alpha_1} c_{\alpha_2} & s_{\alpha_1} c_{\alpha_2} & s_{\alpha_2} \\ -c_{\alpha_1} s_{\alpha_2} s_{\alpha_3} - s_{\alpha_1} c_{\alpha_3} & c_{\alpha_1} c_{\alpha_3} - s_{\alpha_1} s_{\alpha_2} s_{\alpha_3} & c_{\alpha_2} s_{\alpha_3} \\ -c_{\alpha_1} s_{\alpha_2} c_{\alpha_3} + s_{\alpha_1} s_{\alpha_3} & -c_{\alpha_1} s_{\alpha_3} - s_{\alpha_1} s_{\alpha_2} c_{\alpha_3} & c_{\alpha_2} c_{\alpha_3} \end{pmatrix}$$

- Normal scenario: M_{H1} = 125 GeV ($M_{H1} < M_{H2} < M_{H3}$)
- R_{i3} is the CP-odd fraction of H_i . Im $\lambda_5 \to 0$ gives $R_{13} = R_{23} = 0$ — CP is restored

Gauge couplings

$$c(H_i VV) = c_\beta R_{i1} + s_\beta R_{i2}\ , \qquad \sum_{i=1}^{3} c^2(H_i VV) = 1 \quad (\text{orthogonality of } \mathbf{R})$$

Yukawa couplings

$$\mathcal{L}_Y = -\sum_i \frac{m_f}{v} \bar{\psi}_f \left[\underline{c^e(H_i f f)} + i\, \underline{c^o(H_i f f)}\, \gamma_5 \right] \psi_f H_i \qquad \left(c^e \cdot c^o \neq 0 \ \Leftrightarrow\ \text{CP violation} \right)$$

$$\textbf{Type-I}: \quad c^e(H_i tt) = c^e(H_i bb) = c^e(H_i \tau\tau) = \frac{R_{i2}}{s_\beta}, \qquad c^o(H_i tt) = -c^o(H_i bb) = -c^o(H_i \tau\tau) = -\frac{R_{i3}}{t_\beta}$$

$$\textbf{Type-II}: \quad c^e(H_i tt) = \frac{R_{i2}}{s_\beta}, \quad c^e(H_i bb) = c^e(H_i \tau\tau) = \frac{R_{i1}}{c_\beta}; \qquad c^o(H_i tt) = -\frac{R_{i3}}{t_\beta}, \quad c^o(H_i bb) = c^o(H_i \tau\tau) = -t_\beta R_{i3}$$

Two global measures of CP violation

Gauge sector

$$\xi_V = 27 \prod_{i=1}^{3} c^2(H_i VV)$$

Yukawa sector

$$\text{Type-I}: \quad \zeta_t = \zeta_b = \zeta_\tau = \zeta_{23} = 2 \sum_i \left(R_{i2} R_{i3}\right)^2$$

$$\text{Type-II}: \quad \zeta_t = \zeta_{23} = 2 \sum_i \left(R_{i2} R_{i3}\right)^2, \qquad \zeta_b = \zeta_\tau = \zeta_{13} = 2 \sum_i \left(R_{i1} R_{i3}\right)^2$$

- **ξ_V is a product: it dies if any one H_i decouples from VV. ζ is a sum of squares: it survives even then**
- Both are normalised to [0, 1]
- we call $\xi_V > 0.1$ or $\zeta > 0.1$ “large CP violation”

The Higgs alignment limit, and why CPV avoids it

$$\text{Higgs alignment}: \quad \alpha_1 = \beta, \quad \alpha_2 = 0 \qquad \Longrightarrow \qquad c(H_1VV) = 1, \quad c(H_{2,3}VV) = 0$$

$$\mathrm{Im}\,\lambda_5 = 0 \quad \text{and} \quad \alpha_3 \in \{0, \pm\pi/2\} \qquad \Longrightarrow \qquad \textbf{exact alignment} \;\Leftrightarrow\; \textbf{CP conservation}$$

How far are we from it?

$$\delta_{H\text{-align}} = \sqrt{\frac{s^2_{\beta-\alpha_1} + s^2_{\alpha_2}}{2}}$$

- In the exact alignment limit H_1 has SM couplings and the heavy scalars decouple from VV
- The same limit forces Im $\lambda_5 = 0$, so the CP-odd state decouples and CP is exactly conserved
- **Sizeable CP violation therefore lives close to, but never at, alignment**
- This is why we quantify the distance with $\delta_{H\text{-align}}$, and why it appears on almost every plot from here on

Exact alignment ⇒ CP conservation. Large CPV and an exactly SM-like 125 GeV Higgs are in tension.

III

Results

A global scan under every current constraint

9 independent input parameters

$$m_{H_b} \in [130, 2000]\,\text{GeV}, \qquad M_{H^\pm} \in [90, 2000]\,\text{GeV}, \qquad t_\beta \in [0.5, 50],$$

$$\text{Re}(m_{12}^2) \in [0, 2\times 10^6]\,\text{GeV}^2, \quad \text{sign}(R_{a3}) \in \{\pm 1\}, \qquad R_{b3} \in [-1, 1],$$

$$c^2(H_a VV) \in [0.7, 1.0], \qquad |c(H_a t\bar{t})|^2 \in [0.6, 1.6].$$

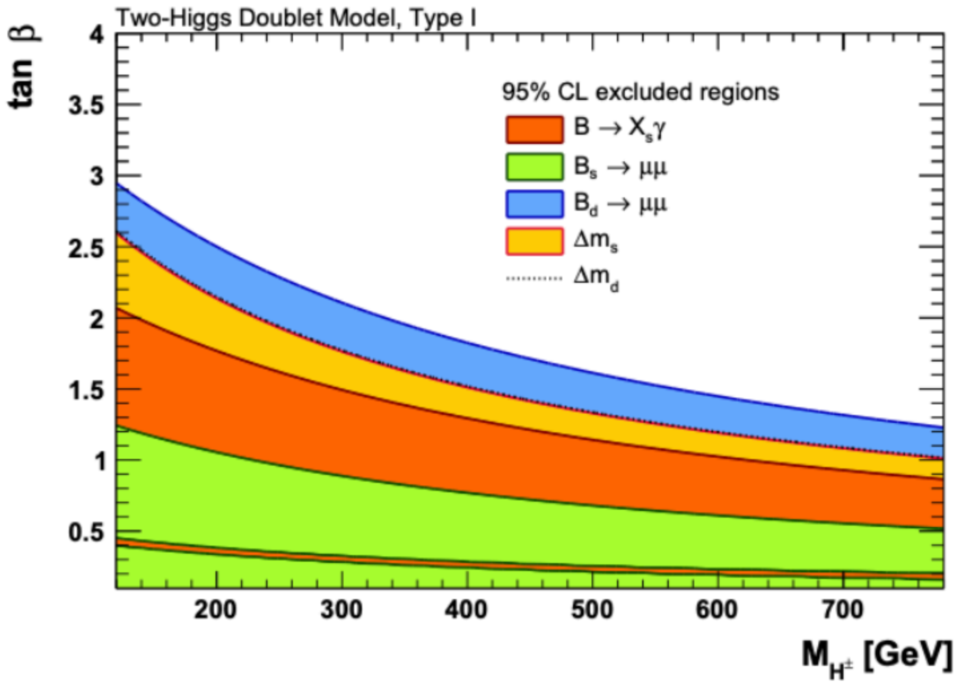
i	**Theory**	boundedness from below, perturbative unitarity, vacuum stability
ii	**EW + flavour**	S, T, U Oblique parameters; B-Physics
iii	**Higgs data**	HiggsSignals + HiggsBounds (HiggsTools 1.1.3); ATLAS bound $\alpha_\tau^{H_1} = 9^\circ \pm 34^\circ$
iv	**Electron EDM**	(two-loop Barr–Zee) JILA: $\lvert d_e\rvert < 4.1 \times 10^{-30}$ e·cm (90% C.L.)

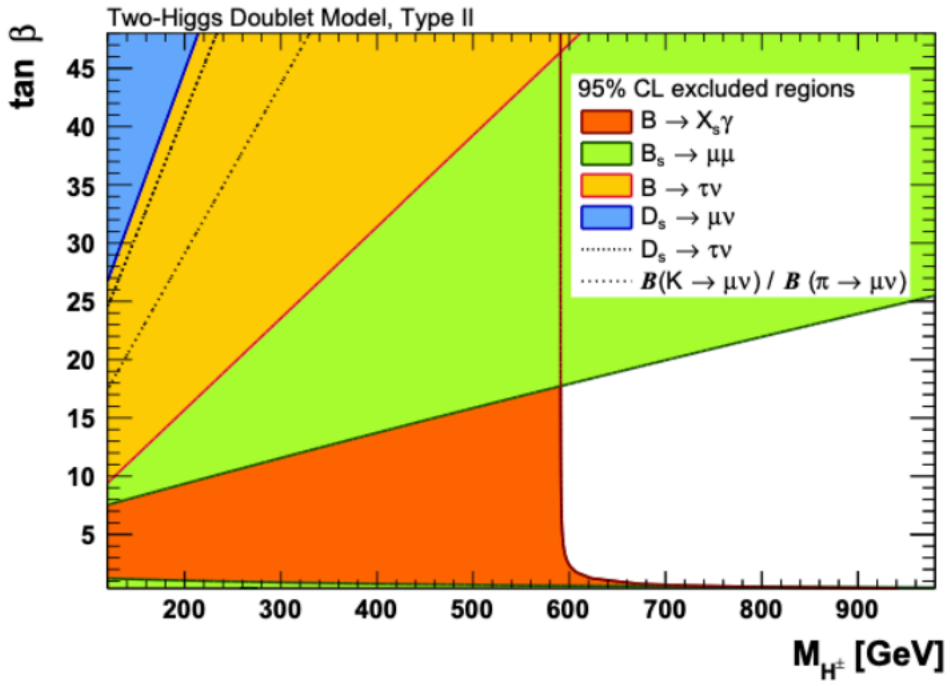
random scan with ScannerS v2.0.0

B-Physics constraint

ii	**EW + flavour**	S, T, U Oblique parameters; B-Physics

Type-I vs Type-II

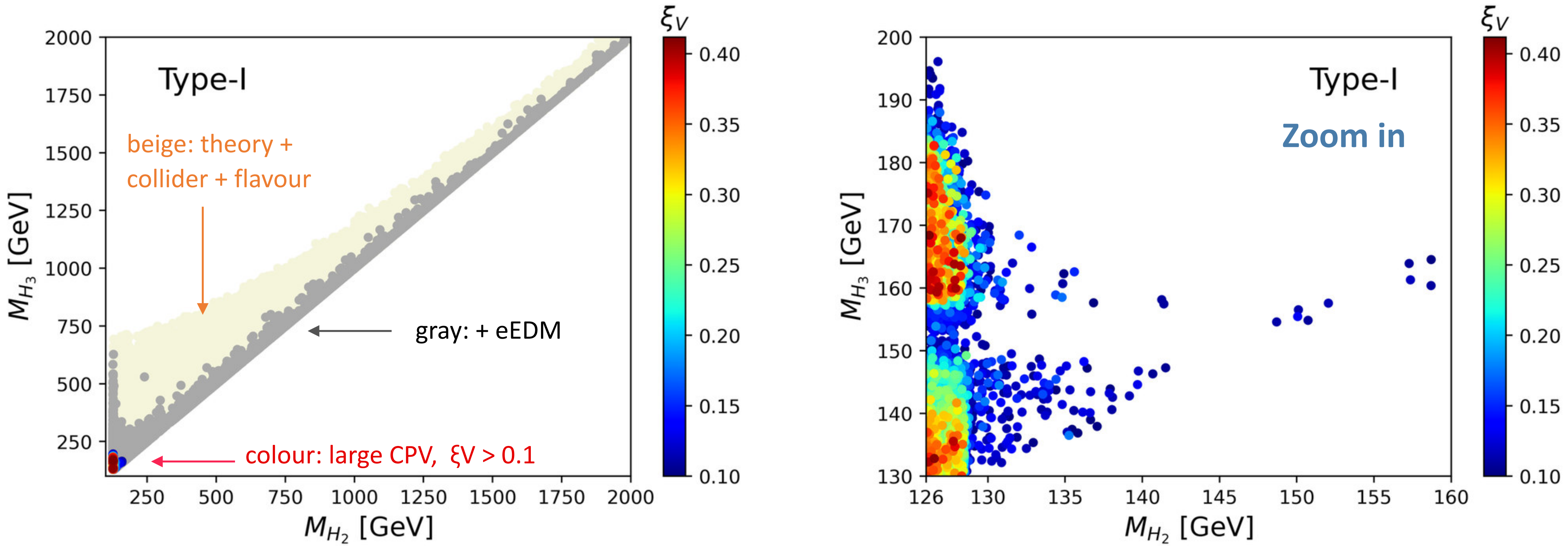




Haller et al. arXiv:1803.01853

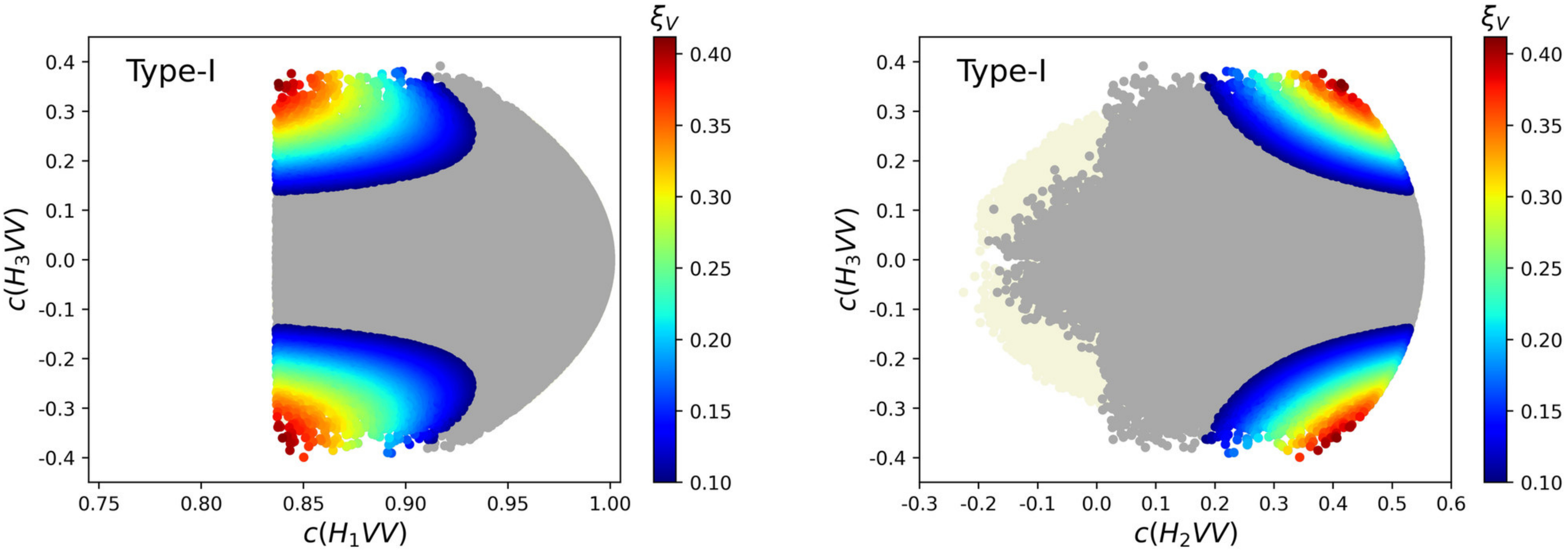
Type-I: large gauge CPV needs a light, degenerate spectrum

$$\boxed{\xi_V = 27\, c^2(H_1VV)\, c^2(H_2VV)\, c^2(H_3VV)}$$



Large CPV with $\xi_V > 0.1$: $\quad M_{H_2} \lesssim 149\,\mathrm{GeV}, \quad M_{H_3} \lesssim 195\,\mathrm{GeV}, \quad M_{H^\pm} \lesssim 229\,\mathrm{GeV}, \quad \tan\beta > 5.1$

Type-I: the gauge couplings make this testable

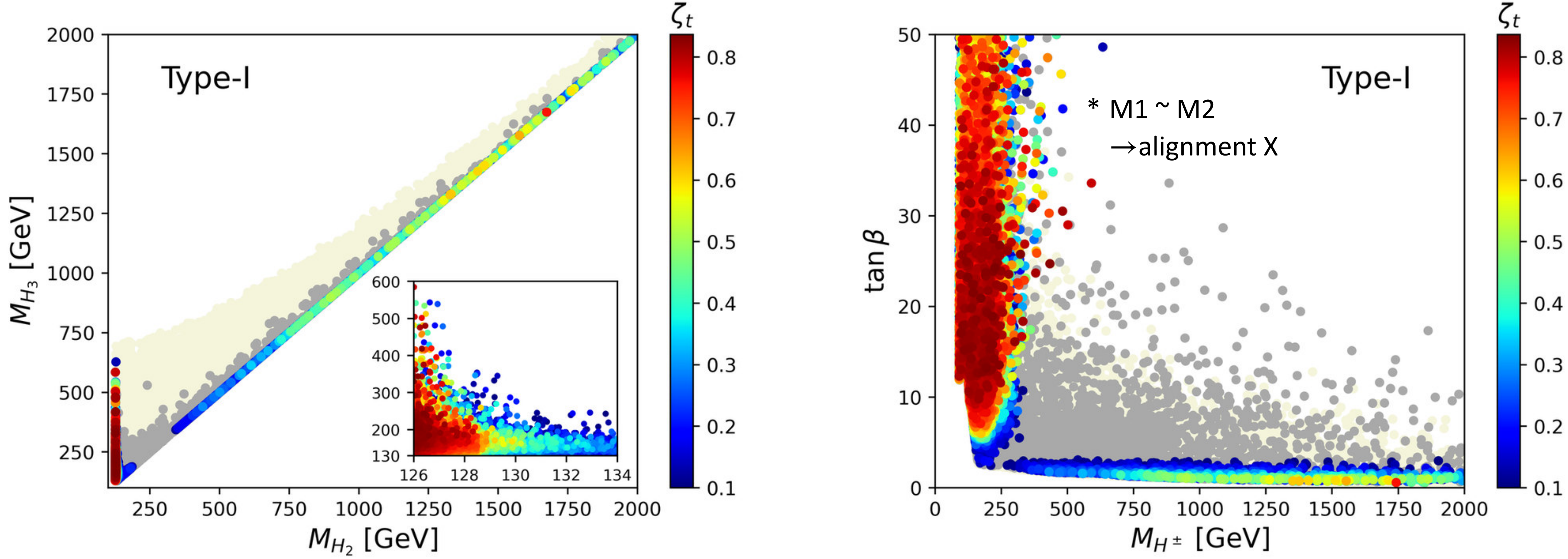


- Large ξ_V demands a visible deviation from alignment: $c(H_1VV) \lesssim 0.935$, $|c(H_2VV)| \gtrsim 0.2$, $|c(H_3VV)| \gtrsim 0.14$
- It also prefers a light charged Higgs: $M_{H\pm} < 229$ GeV with $\tan\beta > 5.1$

If κ_V is measured above 0.95, then ξ_V cannot exceed 0.1 → Higgs precision data probe CPV directly

Type-I: Yukawa CPV opens a second, heavy branch

$$\text{Type-I}: \quad \zeta_t = \zeta_b = \zeta_\tau = \zeta_{23} = 2\sum_i \left(R_{i2}R_{i3}\right)^2$$

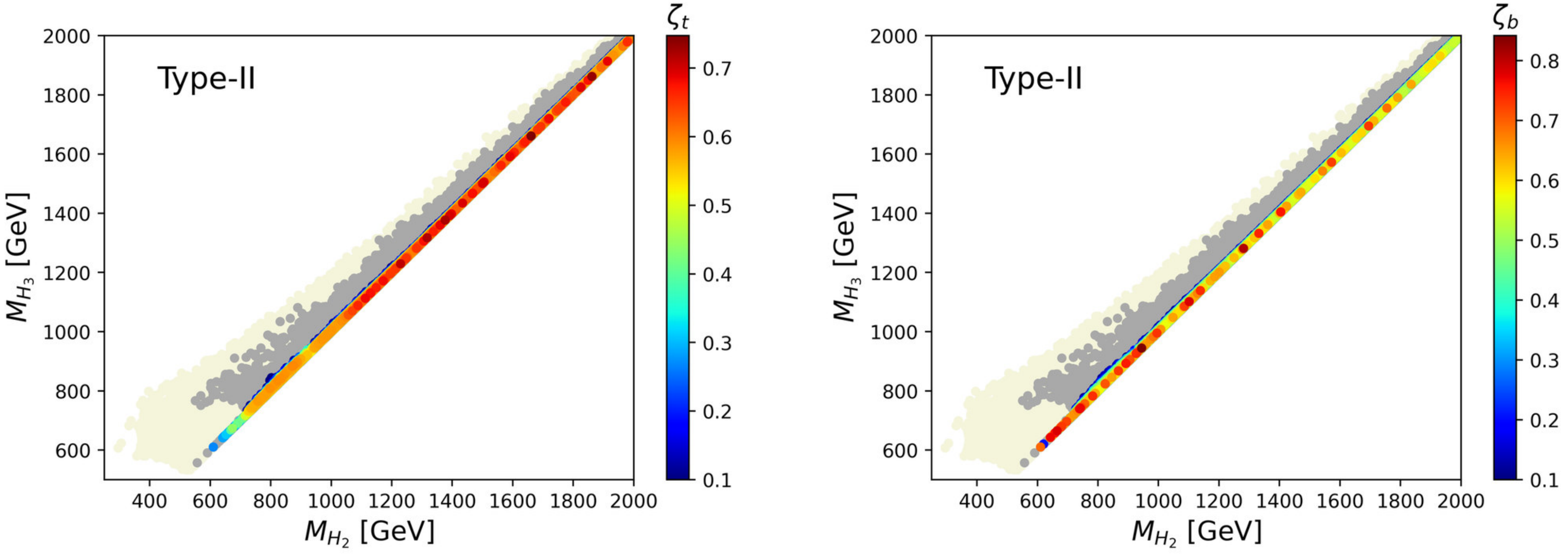


- ζ_t reaches 0.84 → larger than ξ_V, because ζ is a sum while ξ_V is a product
- Two clusters: a light $H_{2,3}$, $H^\pm$ with broad tanβ , and heavy $H_{2,3}$, $H^\pm$ up to 2 TeV but only for tanβ ≲ 3

If ζ_t > 0.6, still require M_{H2} < 129 GeV → back to near-degeneracy

Type-II: gauge CPV shuts down, Yukawa CPV survives

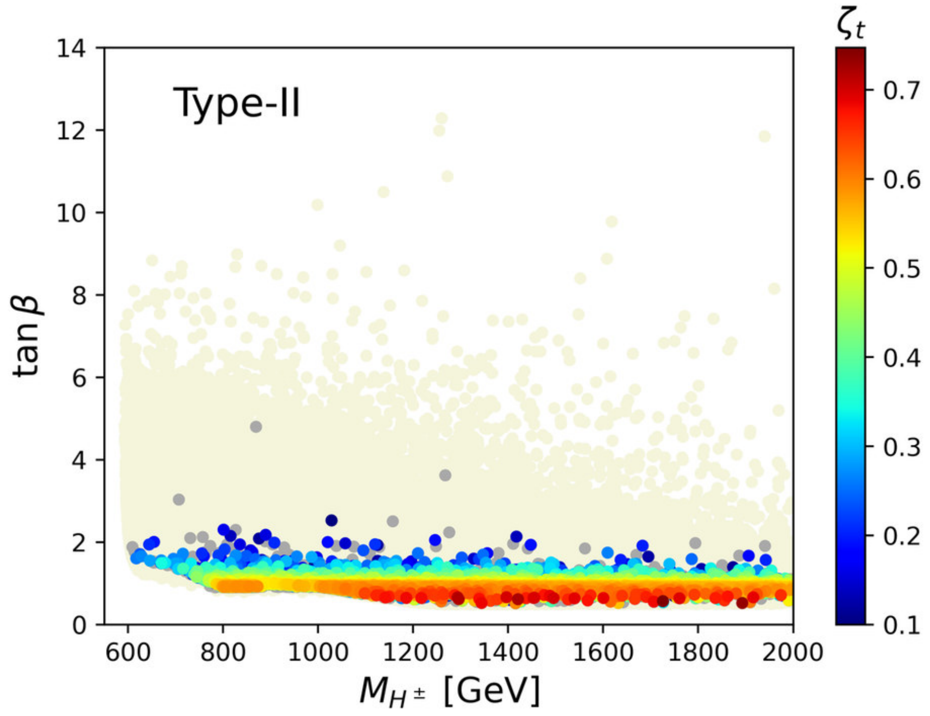
$$\text{Type-II}: \quad \zeta_t = \zeta_{23} = 2\sum_i \left(R_{i2}R_{i3}\right)^2, \qquad \zeta_b = \zeta_\tau = \zeta_{13} = 2\sum_i \left(R_{i1}R_{i3}\right)^2$$

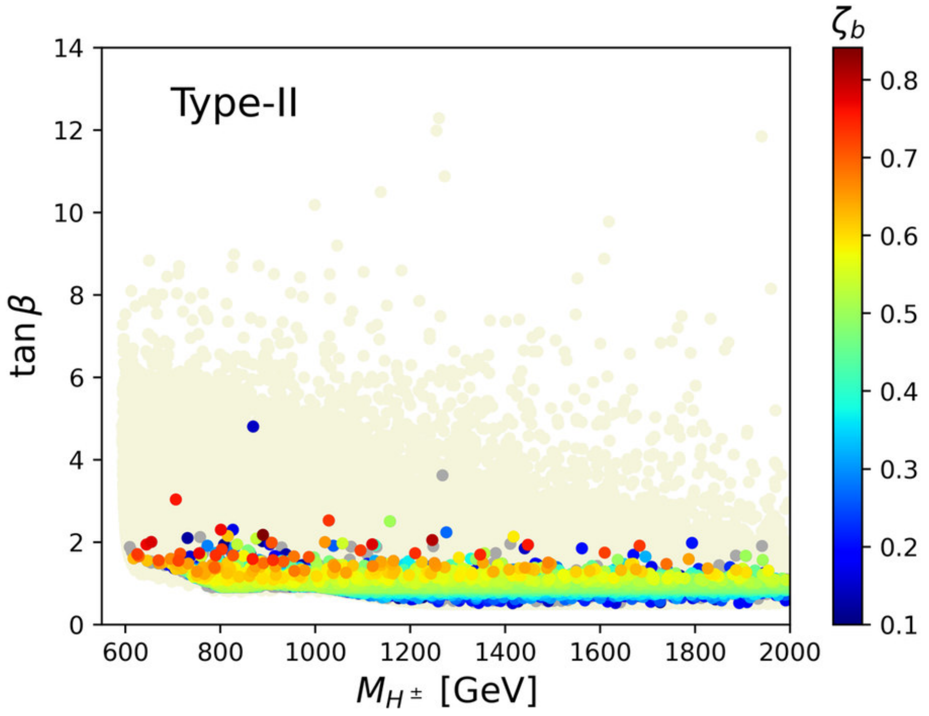


$$\xi_V < 3.3 \times 10^{-3}, \qquad \zeta_t \lesssim 0.75, \qquad \zeta_b \lesssim 0.84$$

- $B \to X_s\gamma$ pushes $M_{H^\pm}$ above ~580 GeV; the oblique parameters drag H_2 and H_3 up with it
- Large ζ_t or ζ_b then forces H_2 and H_3 to be almost mass-degenerate, all the way up to 2 TeV

Type-II: the electron EDM caps tanβ below 4





$$\text{Type-II}: \quad c^o(H_i ee) = -t_\beta R_{i3}\ , \quad c^e(H_i ee) = \frac{R_{i1}}{c_\beta} \qquad \Longrightarrow \qquad |d_e| \text{ grows with } t_\beta$$

$$\text{near alignment}: \qquad \zeta_{23} \simeq s^2_{2\alpha_3}\, c^2_\beta \quad (\zeta_t)\ , \qquad \zeta_{13} \simeq s^2_{2\alpha_3}\, s^2_\beta \quad (\zeta_b)$$

No tanβ enhancement of the heavy-Higgs couplings to b and τ is left in the large-CPV region

IV

Prospects

What eEDM values does the model actually predict?

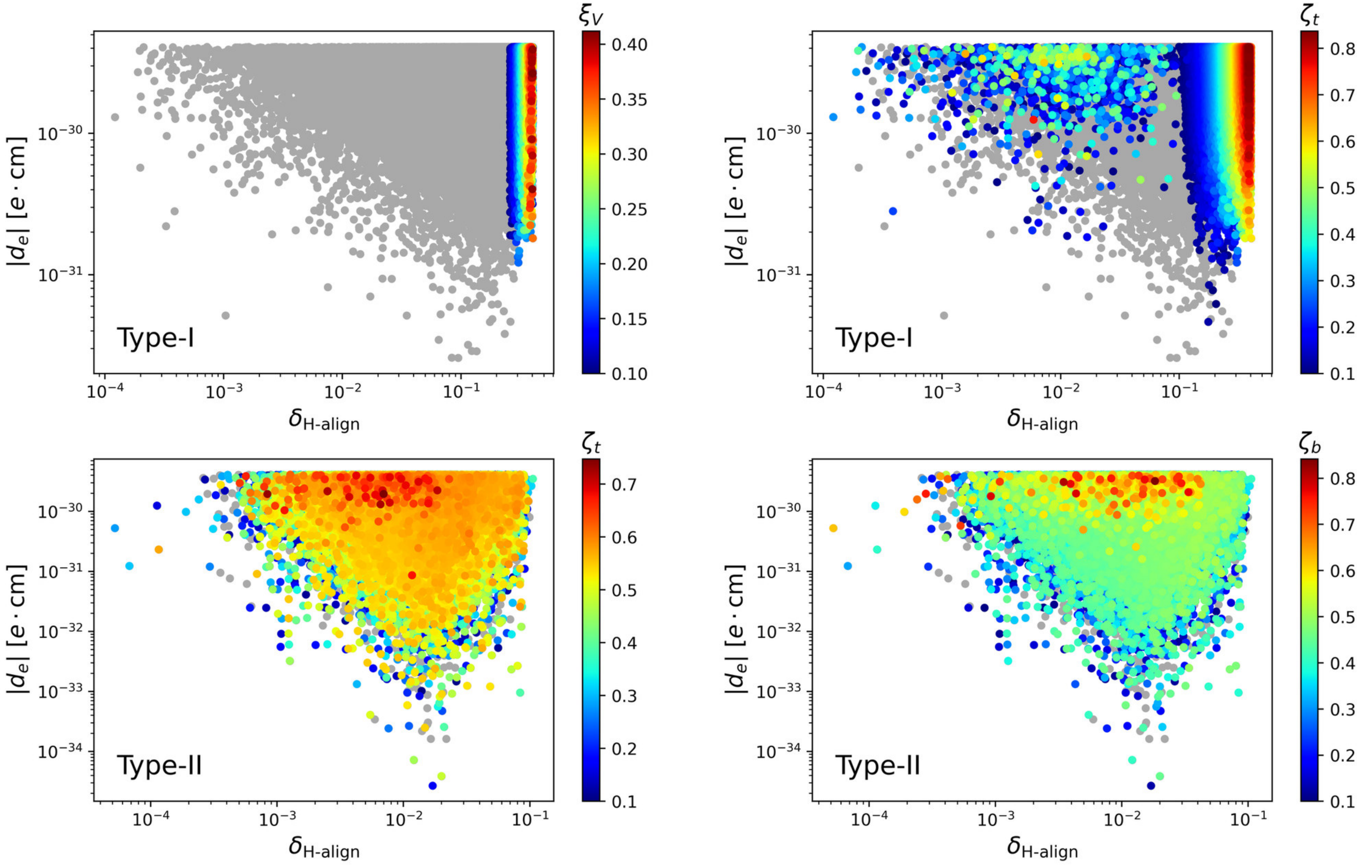
Type-I

- The closer to alignment, the larger the minimum $|d_e|$. Essentially the whole viable set sits above 10^{-31} e·cm.

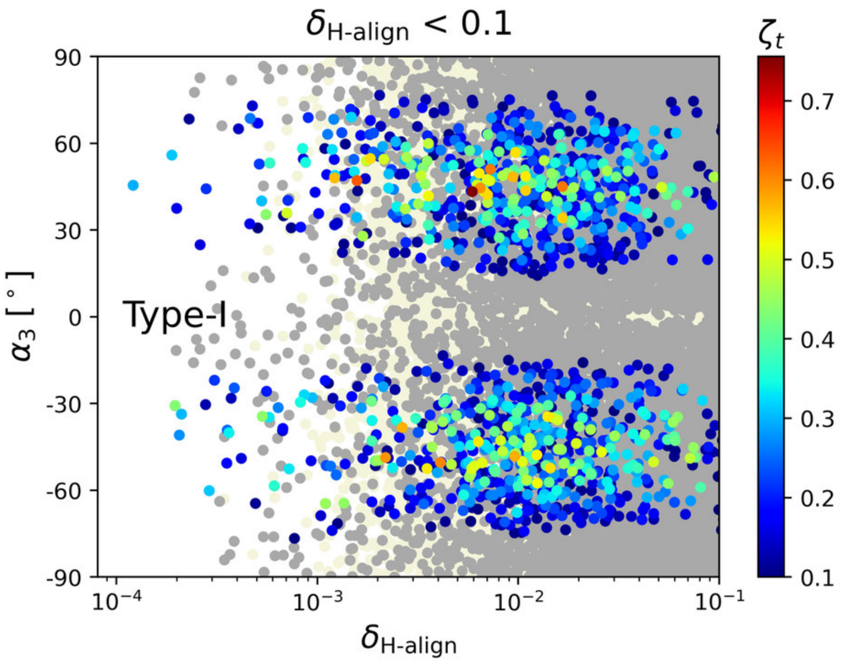
Type-II

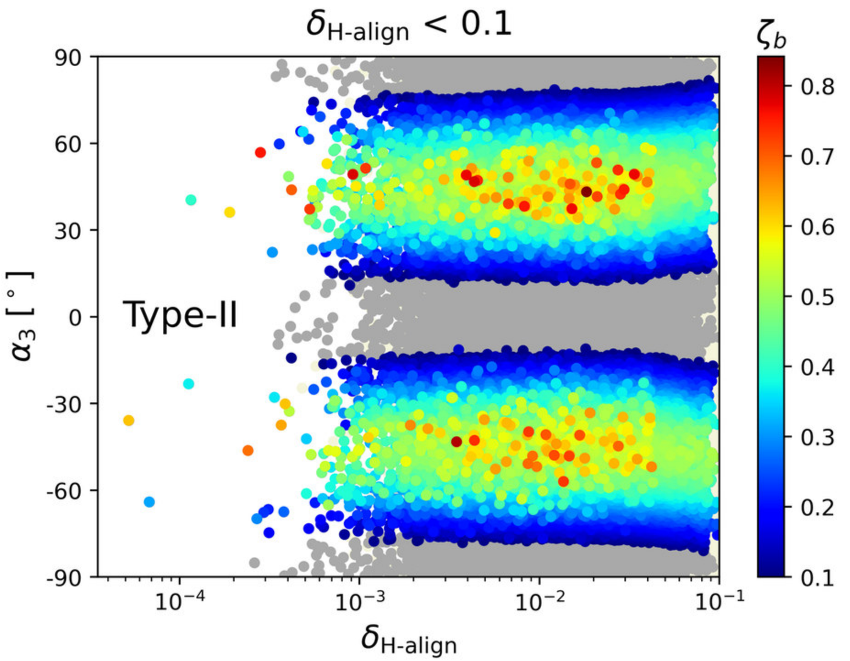
- $|d_e|$ tracks ζ_t and ζ_b directly, but destructive interference can push it down to 10^{-35} e·cm
  $\rightarrow$ no useful lower bound.

- **Next generation of ACME III, JILA, NL-eEDM will reach 10^{-31}–10^{-32} e·cm.**



Hidden CP violation in the alignment limit





$$\zeta_{23} \simeq s^2_{2\alpha_3} c^2_\beta, \qquad \zeta_{13} \simeq s^2_{2\alpha_3} s^2_\beta \qquad \Longrightarrow \qquad \text{maximal at} \quad \alpha_3 = \pm\pi/4$$

$$c(H_{2,3}VV) = \mathcal{O}(\delta_{H\text{-align}}) \to 0, \qquad [H_2 H_3 Z^\mu] \simeq \frac{g}{2c_W}(p_{H_2} - p_{H_3})^\mu \quad \text{robust}$$

CPV persists in the heavy sector even as H_1 becomes exactly SM-like

→ Probe it with Yukawa interactions of H_2 and H_3, as well as the robust H_2-H_3-Z coupling.

Summary

Type-I

ξ_V up to 0.4 and ζ_t up to 0.84, but only when H_2 is nearly degenerate with the 125 GeV Higgs. $|d_e| \gtrsim 10^{-31}$ e·cm, within reach of the next generation of EDM experiments.

Type-II

Gauge CPV is switched off ($\xi_V < 3.3 \times 10^{-3}$), yet the Yukawa sector reaches $\zeta_t \simeq 0.75$ and $\zeta_b \simeq 0.84$. Cancellations allow $|d_e|$ as low as 10^{-35} e·cm.

Hidden CPV

In the near alignment, invisible in H_1 couplings but reachable via Yukawa interactions of H_2 and H_3 with the H_2H_3Z vertex.

Thank you!

Backup

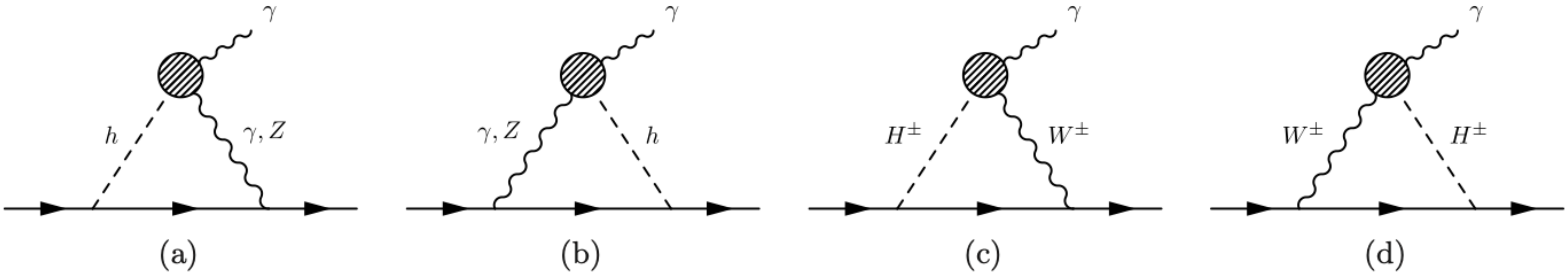
Type-I vs Type-II: the same phase, two different fates

	Type-I	Type-II
Z_2 charges	all f_R couple to Φ_2	u_R to Φ_2 ; d_R , e_R to Φ_1
gauge CPV ξ_V	up to 0.4	$< 3 \times 10^{-3}$ (switched off)
Yukawa CPV	$\zeta_t = \zeta_b$ up to 0.84	$\zeta_t \leq 0.75$, $\zeta_b \leq 0.84$
large CPV $\Rightarrow$ tanβ	$\tan\beta > 5.1$	$\tan\beta \lesssim 4$ (from the eEDM)
BSM scalar masses	$\lesssim$ 230 GeV	$\gtrsim$ 610 GeV
predicted $\lvert d_e \rvert$	$\gtrsim 10^{-31}$ e·cm	down to 10^{-35} e·cm

Same potential, same single CP phase. Only the Z_2 charges of the right-handed fermions differ

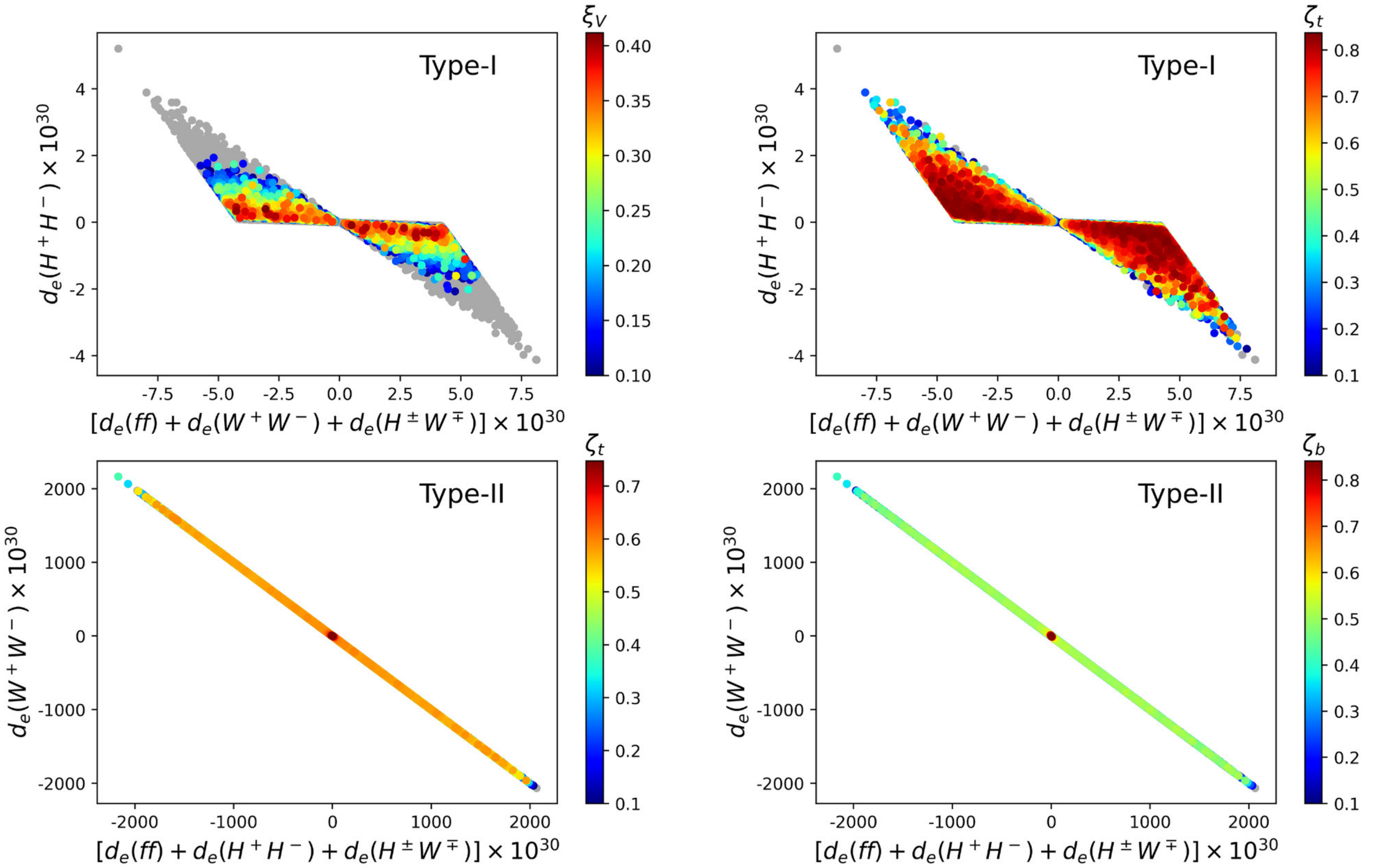
Diagrams of two-loop Barr–Zee to the eEDM in 2HDM

JHEP 01 (2014) 106 (arXiv:1311.4704)



Barr-Zee diagrams, which contribute to fermionic EDMs at two-loop level.

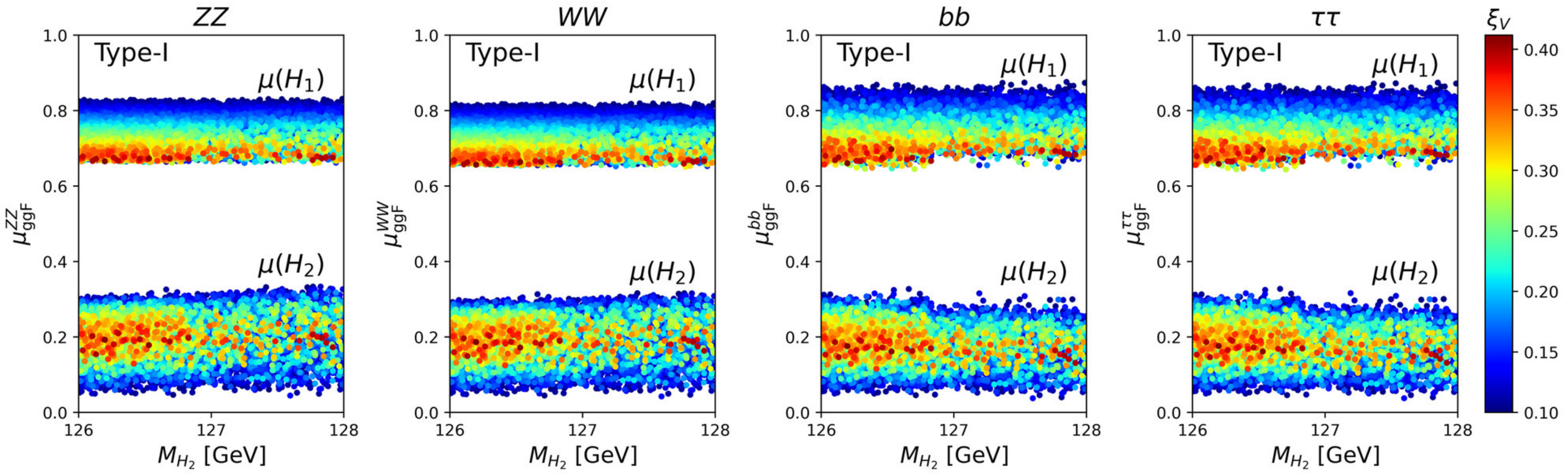
Anatomy of the two-loop Barr–Zee contributions to the eEDM



Type-I (upper): the H^+H^- loop has the opposite sign and partly cancels the rest.

Type-II (lower): terms overshoot by up to 10^3, so the W^+W^- loop must cancel them, yet at $\zeta \gtrsim 0.7$ each term is small by itself.

Type-I: two states hiding inside the 125 GeV peak

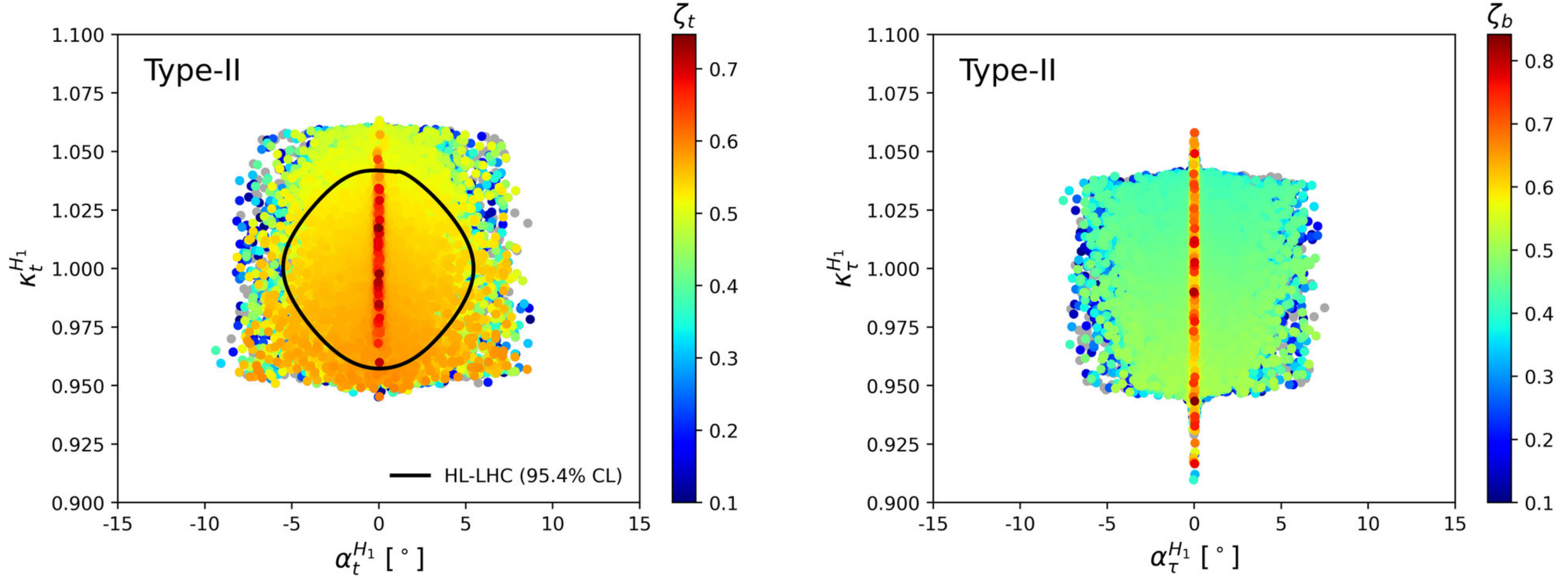


$$\mu(H_1) + \mu(H_2) \simeq 1$$

- Near-degenerate CPV scenario: $M_{H2} \in [126, 128]$ GeV and $\xi_V > 0.1$. $\mu(H_1) \simeq 0.67$–0.85, $\mu(H_2) \simeq 0.1$–0.3, sum $\simeq 1$

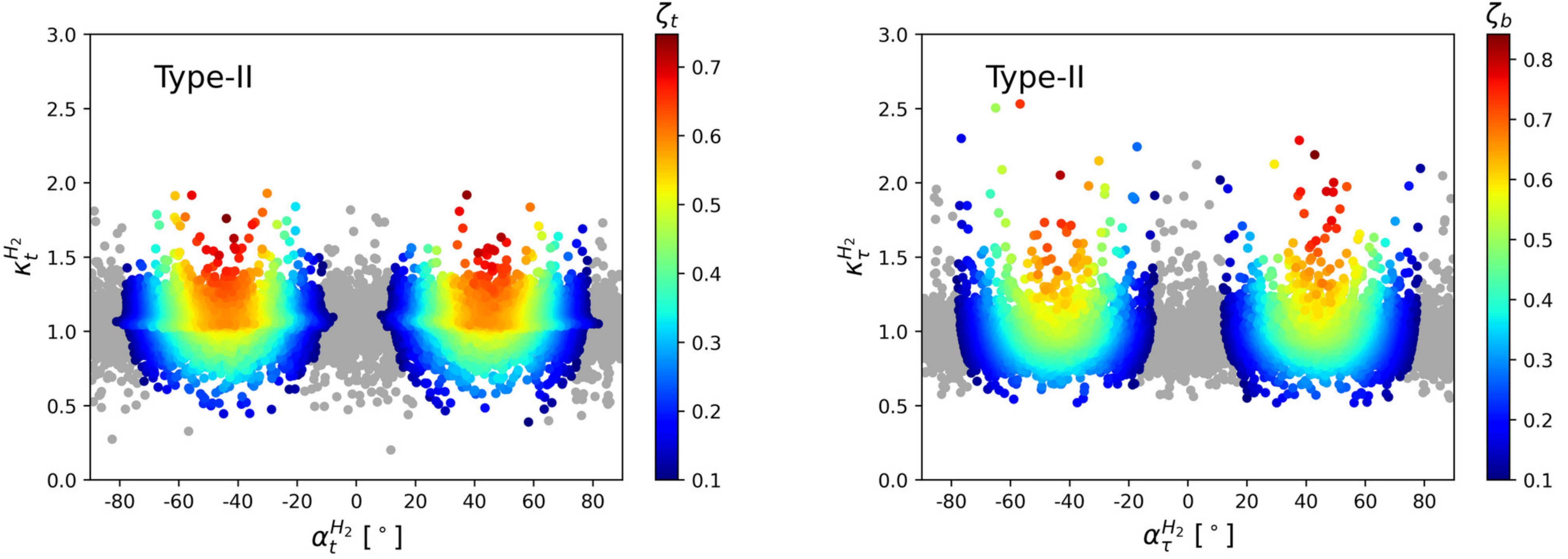
Type-II: H_1 alone will not reveal the CP violation

$$\mathcal{L} \supset -\frac{m_f}{v}\,\kappa_f^{H_i}\left[\cos\alpha_f^{H_i} + i\gamma_5 \sin\alpha_f^{H_i}\right]\bar{f} f\, H_i$$



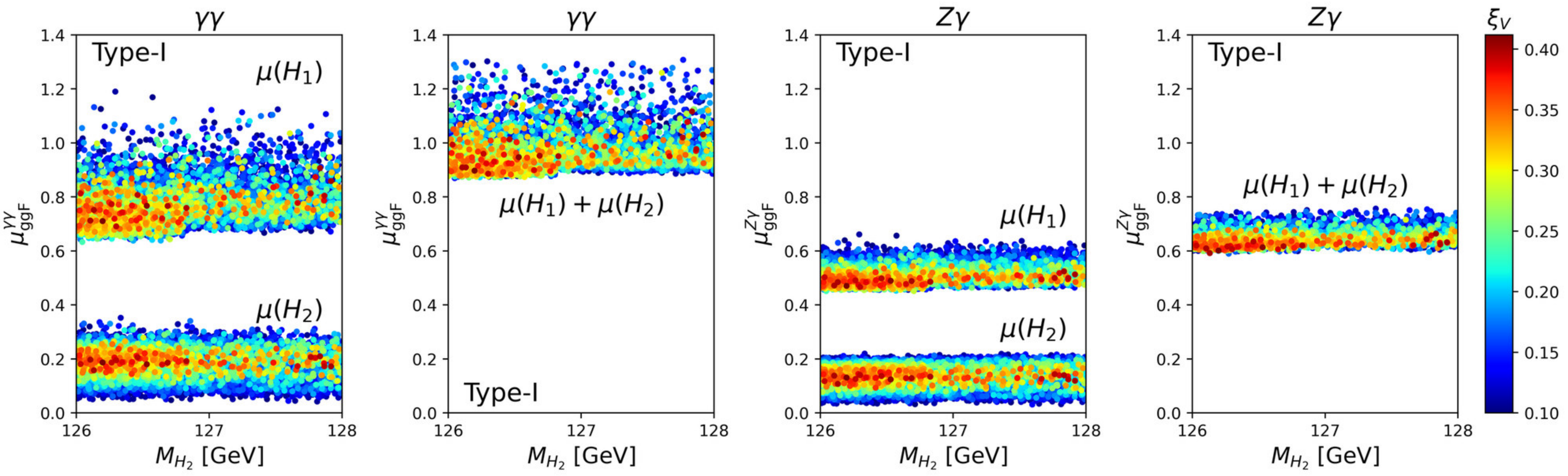
- Allowed CP-mixing angles are small: $|\alpha_t| \lesssim 8°$ and $|\alpha_\tau| \lesssim 7°$, with κ within 5–6% of the SM value
- Worse, the largest ζ_t values cluster at $\alpha_t \approx 0$. They look exactly like a CP-even SM Higgs

Type-II: the heavy scalars are maximally CP-mixed



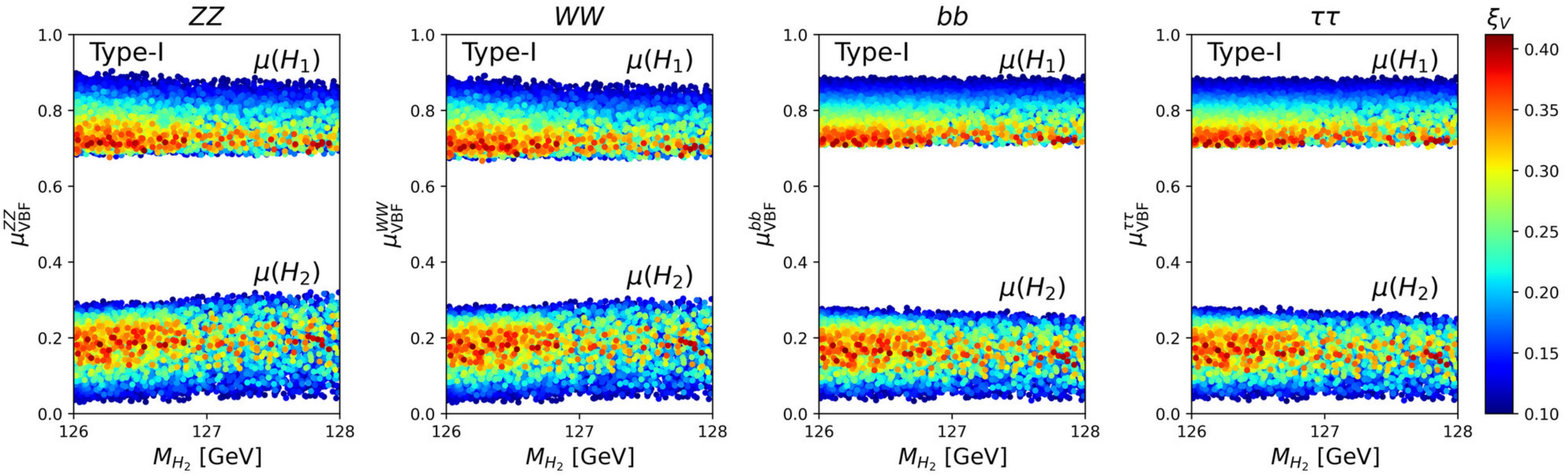
- As ζ_t and ζ_b grow, both α_t and α_τ of H_2 converge on ±45° → equal CP-even and CP-odd parts
- H_3 behaves in the same way, and the coupling strengths κ stay broadly SM-like

Type-I: γγ and Zγ signal strengths (ggF)



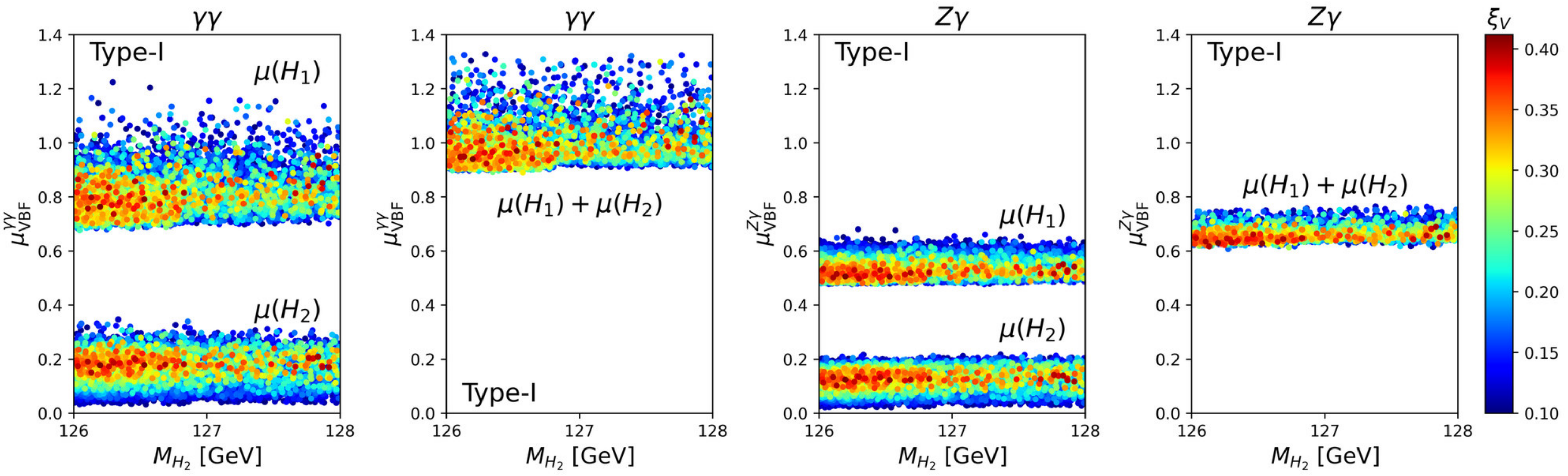
Combined μ(γγ) stays within the ATLAS value 1.05 ± 0.10. The combined μ(Zγ) is robustly suppressed below ~0.75.

Type-I: signal strengths from VBF



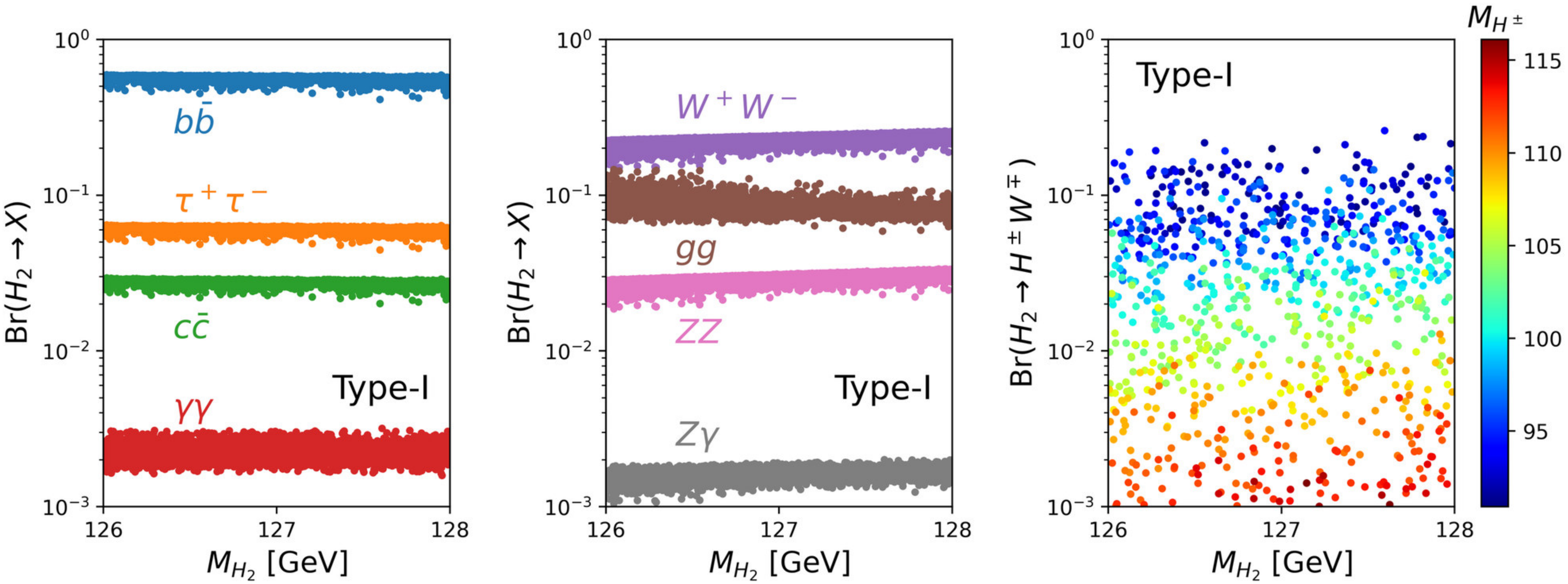
The same picture as gluon fusion: $\mu(H_1) + \mu(H_2) \simeq 1$, fixed by the coupling sum rule.

Type-I: γγ and Zγ from VBF



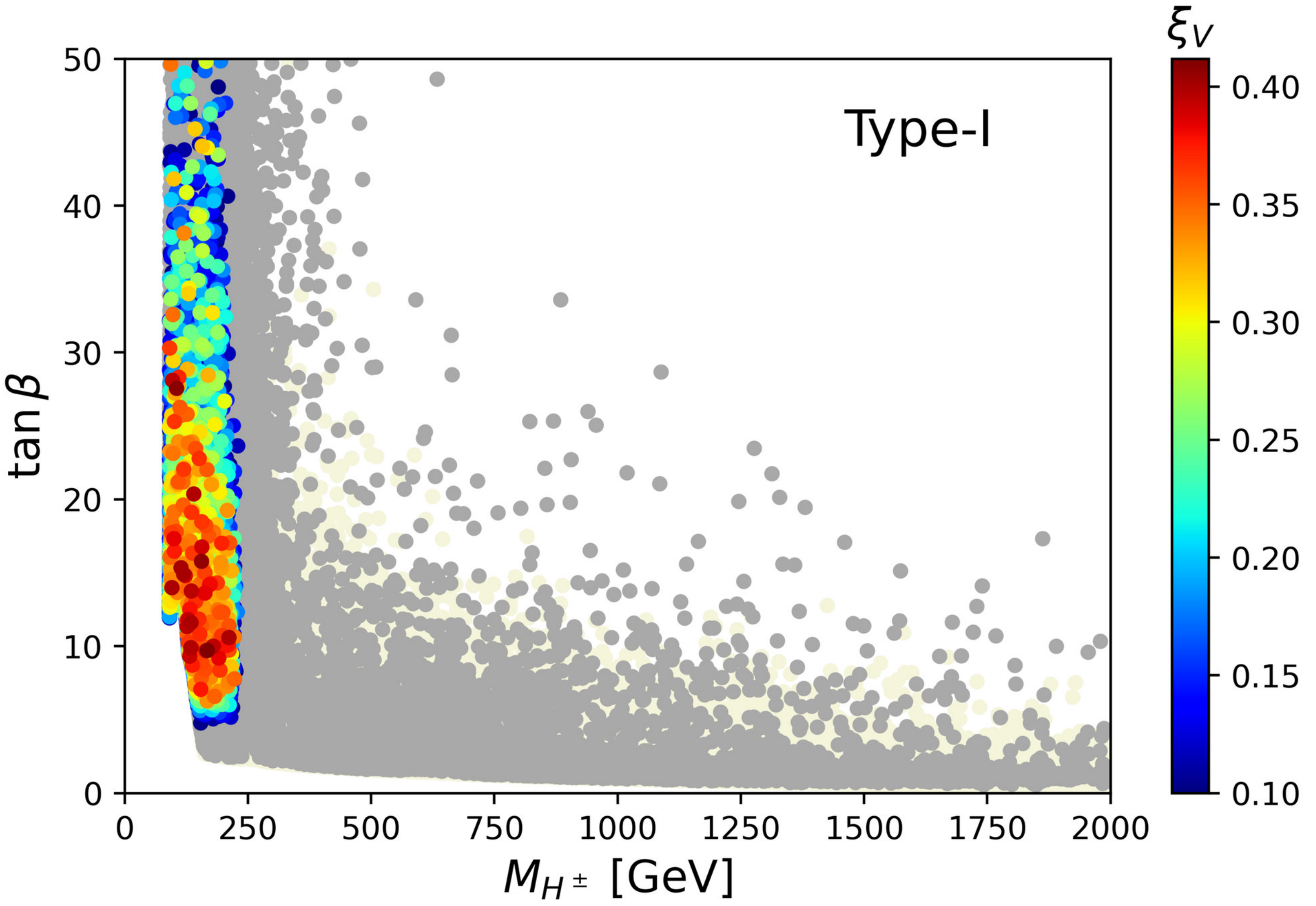
Same conclusion as for gluon fusion: the total γγ rate is SM-like, while the Zγ rate stays suppressed.

Type-I: branching ratios of H_2 (near-degenerate scenario)



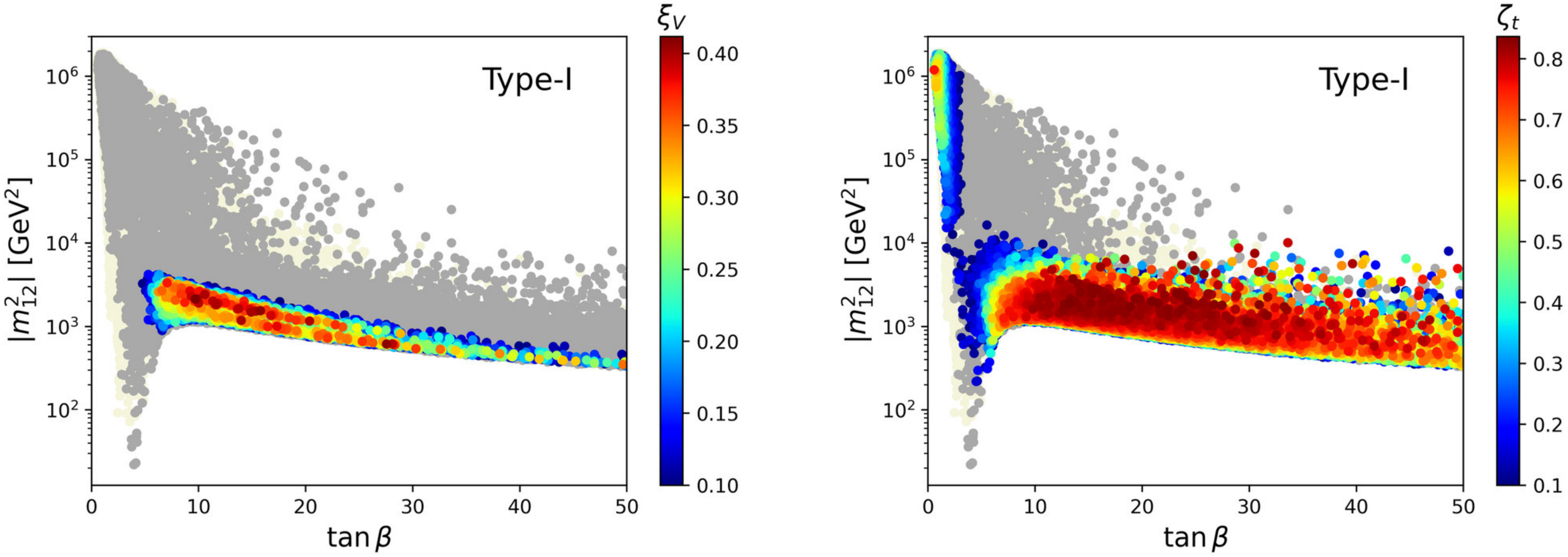
Almost SM-like, plus $H_2 \to H^\pm W^\mp$ when kinematically open. $\Gamma_{tot}(H_2) \in [0.16, 1.37]$ MeV.

Type-I: the ($M_{H\pm}$, tanβ) plane



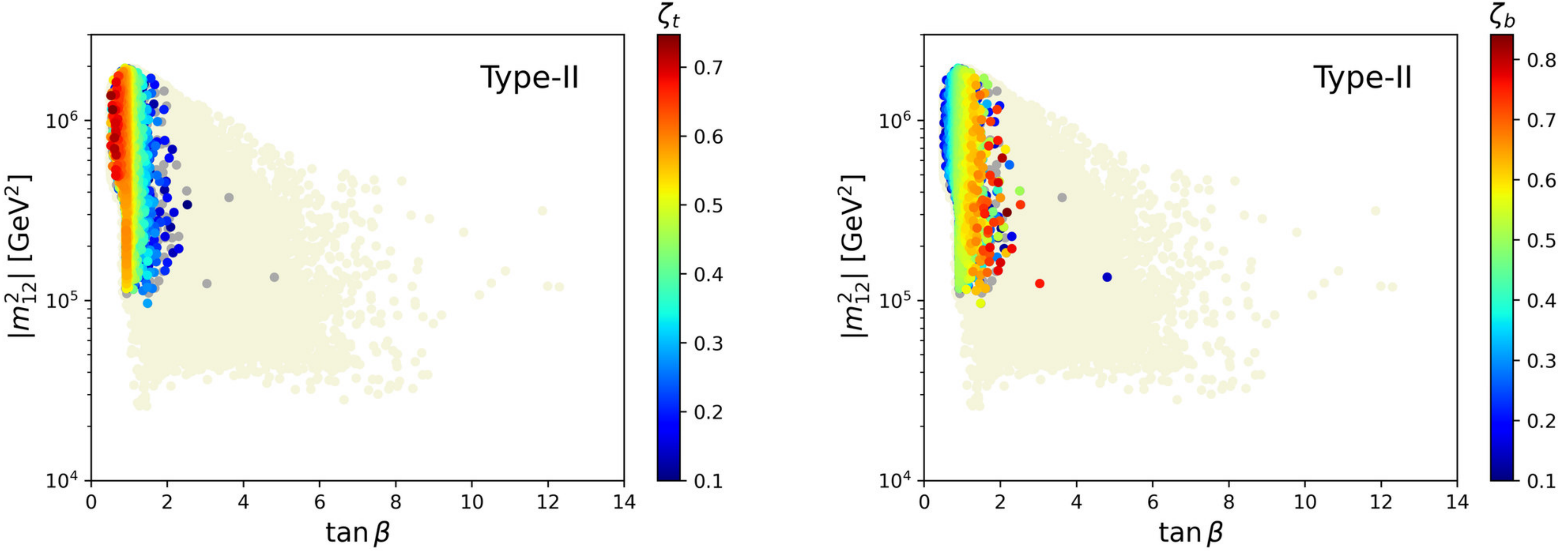
Large ξ_V selects $M_{H\pm}$ < 229 GeV and tanβ > 5.1.

Type-I: the soft Z_2-breaking scale



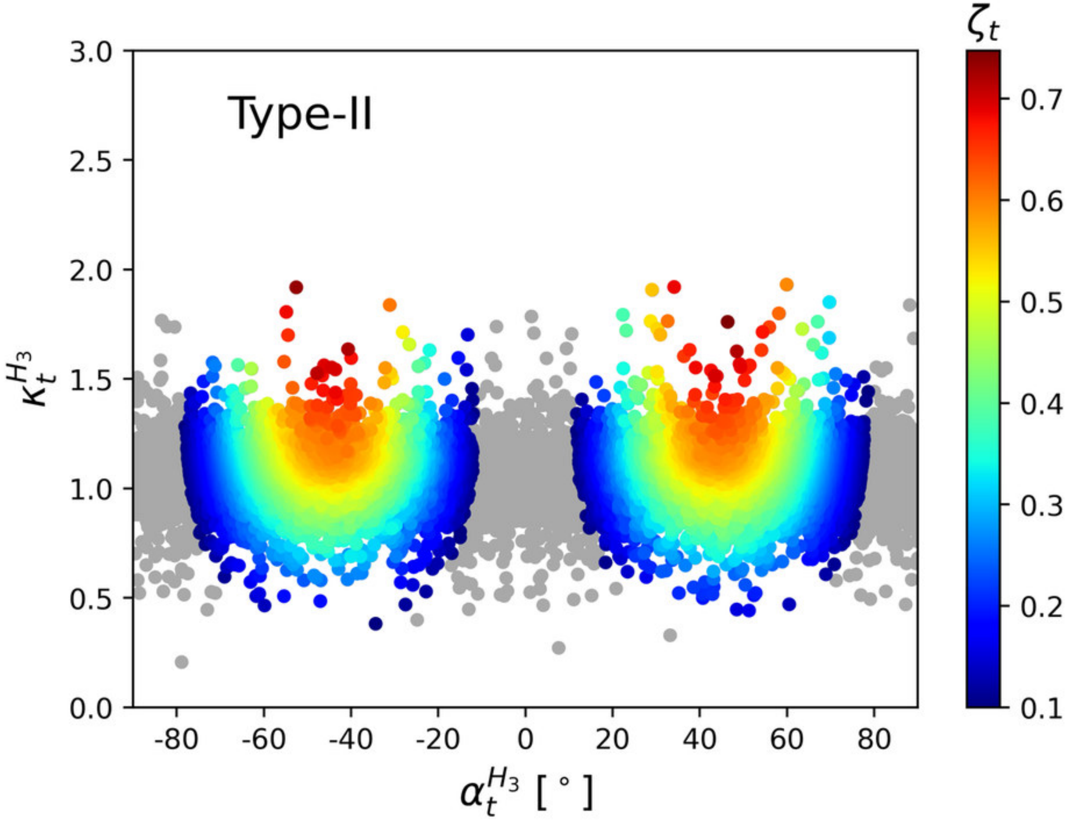
$\xi_V > 0.1$ picks a narrow band $|m^2_{12}| \sim 10^3$ GeV^2. $\zeta_t > 0.1$ allows two separate regions.

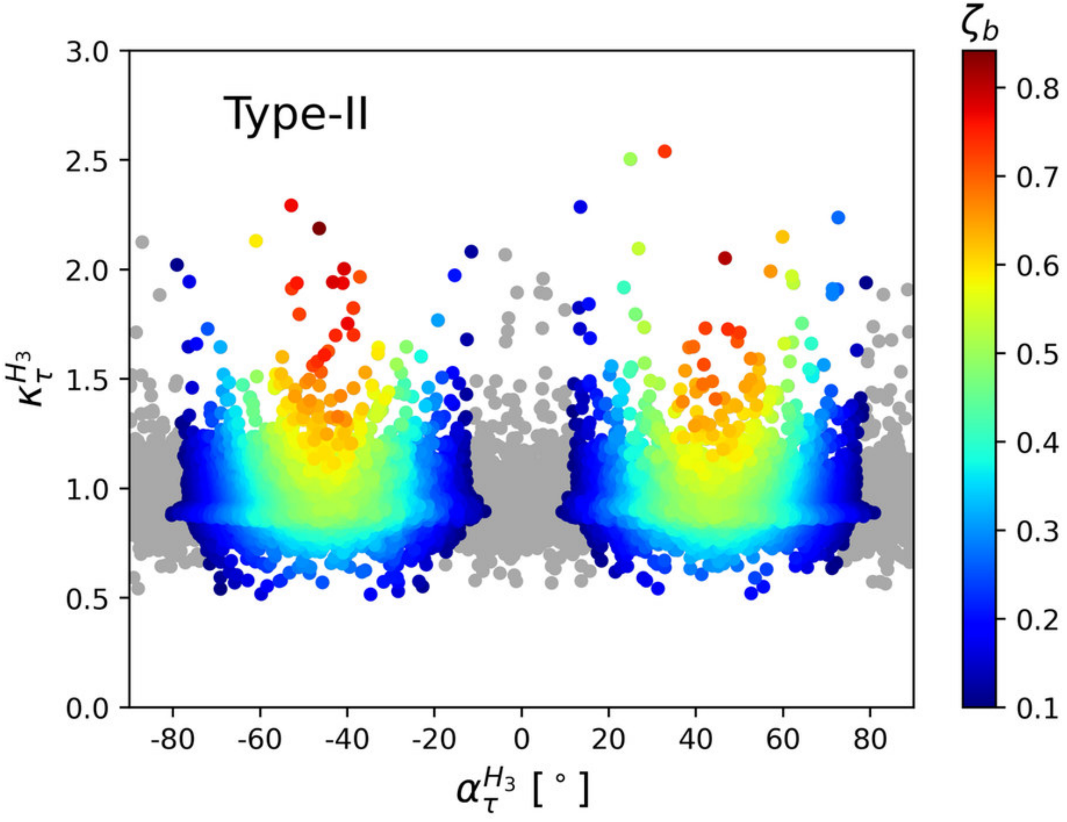
Type-II: the soft Z_2-breaking scale



Larger $|m^2_{12}|$ than in Type-I, following the heavier spectrum. The eEDM raises the lower bound.

Type-II: CP structure of the H_3 couplings





H_3 mirrors H_2 : the mixing angles converge on ±45° as the global CPV measures increase.

Heavy-Higgs Yukawa couplings in the alignment limit

$$\textbf{Type-I}: \quad c^e(H_2ff) = \frac{c_{\alpha_3}}{t_\beta}, \quad c^o(H_2tt) = -\frac{s_{\alpha_3}}{t_\beta}; \qquad c^e(H_3ff) = -\frac{s_{\alpha_3}}{t_\beta}, \quad c^o(H_3tt) = -\frac{c_{\alpha_3}}{t_\beta}$$

$$\textbf{Type-II}: \quad c^e(H_2bb) = -t_\beta c_{\alpha_3}, \quad c^o(H_2bb) = -t_\beta s_{\alpha_3}; \qquad c^e(H_3bb) = t_\beta s_{\alpha_3}, \quad c^o(H_3bb) = -t_\beta c_{\alpha_3}$$

in the exact alignment limit ($\alpha_1 = \beta$, $\alpha_2 = 0$)

- Even at exact alignment the $H_{2,3}$ Yukawa couplings keep their full α_3 dependence
- This is why hidden CP violation is observable at all: it survives in the fermionic couplings of the heavy states
- Type-II has the same structure, with the usual tanβ enhancement for b and τ

The α_3 dependence of the heavy-Higgs Yukawa couplings is the key to probing hidden CPV