Lepton Flavor Violation in CP4 3HDM

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New physics beyond the SM

The Standard Model is incomplete:

- Dark matter.
- Matter-antimatter asymmetry.
- Neutrino masses.

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A simple idea, several Higgs generations:

- 2HDM [T.D.Lee, 1973], [G.C.Branco et al, 2012].
- 3HDM [Weinberg, 1976],[Igor P. Ivanov, 2017] .
- Symmetries:
  - Can resolve some problems of the SM.
  - More phenomenology.
  - Reduce the number of free parameters.
  - Increase predictivity.

Symmetry can provides us an insight into CP violation, we can also have different form of CP transformation.

CP4 3HDM

In QFT, CP is not uniquely defined, with N scalar field ϕ_i, general CP (GCP) [G. Ecker et al, 1987], [The quantum theory of fields, Weinberg]:

$$\phi_i \xrightarrow{GCP} X_{ij}\, \phi_j^*$$

- Usual CP: $X = 1$.

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Apply CP transformation twice:

$$\phi_i \xrightarrow{GCP} X_{ij}\,\phi_j^* \xrightarrow{GCP} (X\,X^*)_{ij}\,\phi_j$$

- CP symmetry of order 2 (CP2): $X\,X^* = 1$.
- We have higher order CP symmetry if: $X\,X^* \neq 1$ but $(X\,X^*)^k = 1$ for $k > 1$.

CP4 3HDM

CP symmetry of order 4 : $(XX^*)^2 = 1$, $X = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & i \\ 0 & -i & 0 \end{pmatrix}$, $\phi_2 \to i\phi_3, \phi_3 \to -i\phi_2$

The scalar potential[Ivanov, Silva, 2015]:

$$\begin{aligned} V_0 = & -m_{11}^2(1^\dagger 1) - m_{22}^2(2^\dagger 2 + 3^\dagger 3) + \lambda_1(1^\dagger 1)^2 + \lambda_2[(2^\dagger 2)^2 + (3^\dagger 3)^2] \\ & + \lambda_{34}(1^\dagger 1)(2^\dagger 2 + 3^\dagger 3) + \lambda_{34}'(2^\dagger 2)(3^\dagger 3) - \lambda_4'[(2^\dagger 2)(3^\dagger 3) - (2^\dagger 3)(3^\dagger 2)] \\ & - \lambda_4[(1^\dagger 1)(2^\dagger 2) - (1^\dagger 2)(2^\dagger 1) + (1^\dagger 1)(3^\dagger 3) - (1^\dagger 3)(3^\dagger 1)] \\ V_1 = & \lambda_5(3^\dagger 1)(2^\dagger 1) + \lambda_8(2^\dagger 3)^2 + \lambda_9(2^\dagger 3)(2^\dagger 2 - 3^\dagger 3) + h.c. \end{aligned}$$

with complex λ_8, λ_9, here $1, 2, 3 \equiv \phi_1, \phi_2, \phi_3$.

The quark sector of the CP4 3HDM

Extending CP4 to quark sector: $\Psi_i \to Y_{ij}\Psi_j^{CP}$,

$$-\mathcal{L}_Y = \bar{q}_L \Gamma_a d_R \phi_a + \bar{q}_L \Delta_a u_R \tilde{\phi}_a + h.c.$$

is invariant under CP4 if:

$$(Y^L)^\dagger \Gamma_a Y^d X_{ab} = \Gamma_b^*, \quad (Y^L)^\dagger \Delta_a Y^u X_{ab}^* = \Delta_b^*$$

Four distinct solution of Yukawa coupling in the quark sector: A, B_1, B_2, B_3 .

Seven viable combinations for quark sector, limit FCNC with meson oscillation constraints then only two cases left: $(up, down) : (A, B_1), (B_1, B_2)$. [Zhao et al, 2302.03094]

How about Lepton sector in CP4 3HDM?

Misalignment Higgs decay

The Yukawa coupling in lepton sector:

$$-\mathcal{L}_Y = \bar{q}_L \Gamma_a e_R \phi_a + h.c.$$

In the Higgs basis:

$$\Phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h_1 \end{pmatrix}, \Phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2} w_2^+ \\ h_2 + i\eta_2 \end{pmatrix}, \Phi_3 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2} w_3^+ \\ h_3 + i\eta_3 \end{pmatrix}$$

Alignment: $h_{SM} = h_1$, no LFV decay.

Misalignment: $h_{SM} = \cos\epsilon \cdot h_1 + \cdots$

Numerical scan of case B_1: $\tan\beta = 1$

SM-like Higgs decay:

- Lepton flavor conserving decay:
  $h_{SM} \to ee, \mu\mu, \tau\tau$
  [ATLAS, 2020], [CMS, 2022] ;
- Lepton flavor violating decay:
  $h_{SM} \to e\mu, e\tau, \mu\tau$
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Two important parameters: $\tan\beta, \cos\epsilon$.

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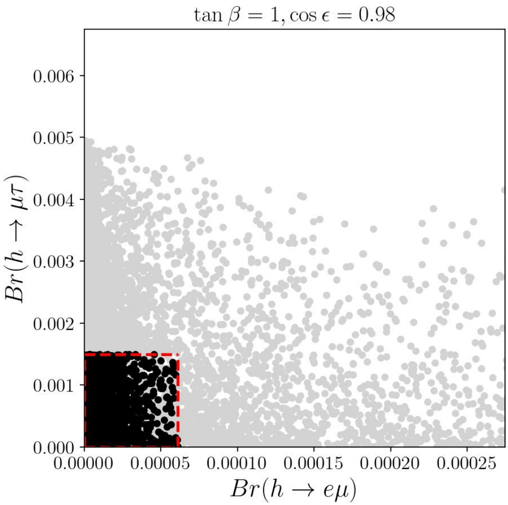
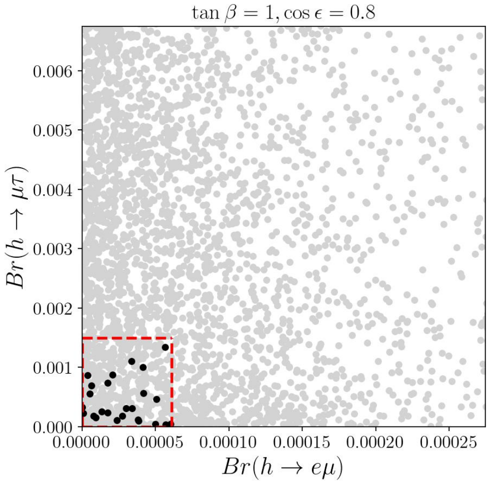


Numerical scan of case B_1: $\cos\epsilon = 0.8$



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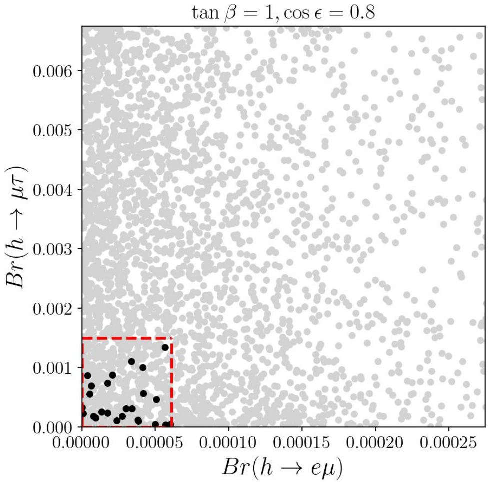
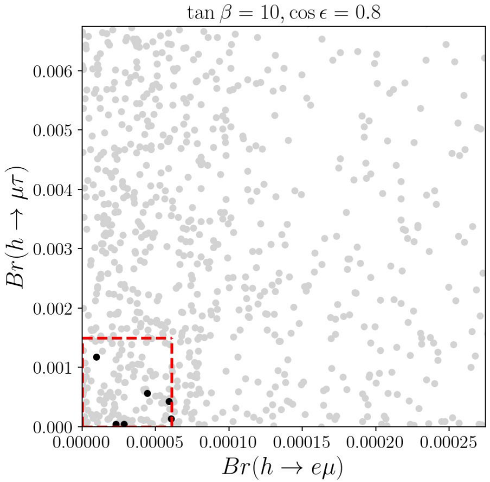
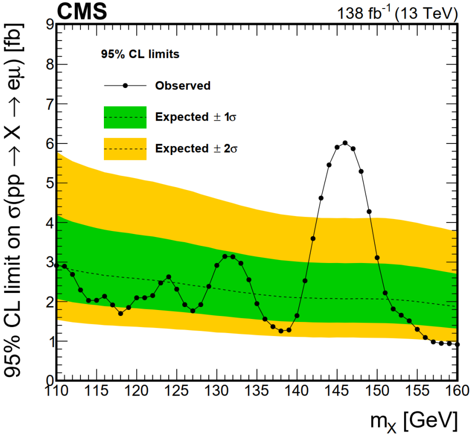




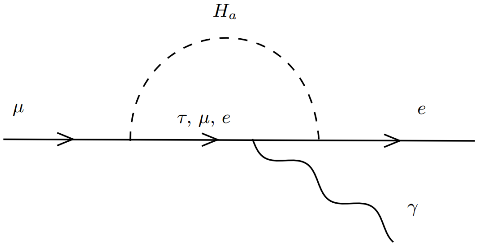
Additional Higgs boson LFV decay

- $H \to e^{\pm}\mu^{\mp}$ with local(global) significance of 3.8 (2.8) σ at 146 GeV. [CMS, 2023]



Other LFV process

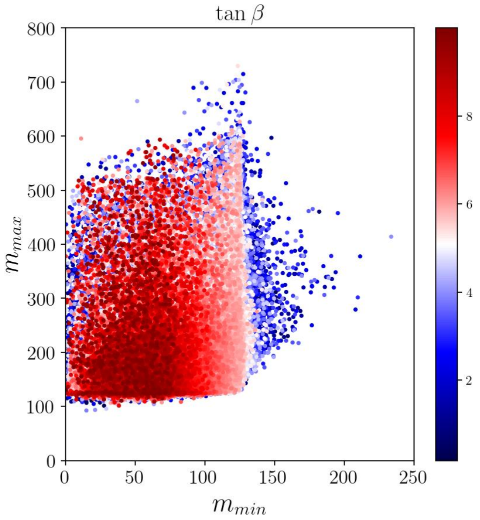
- Lepton decay: $\mathcal{B}(\mu^+ \to e^+\gamma) < 4.2 \times 10^{-13}$ [MEG, 2016].



Masses of four neutral Higgs boson play a important role.

The mass distribution of neutral Higgs

- With constraints: bound from below [Ferreira et al, 2018] and $|\lambda_i| < 5$.
- m_{min} is the minimum mass of four extra Higgs boson.
- m_{max} is the maximum mass of four extra Higgs boson.
- $\tan\beta = \sqrt{v_2^2 + v_3^2}/v_1$
- Units: GeV
- No decoupling



Outlook

Deeper looks into the CP4 3HDM scalar sector:

- implement unitarity constraints.
- test it against experimental measurements and searches (for example, HiggsSignals/HiggsBounds).

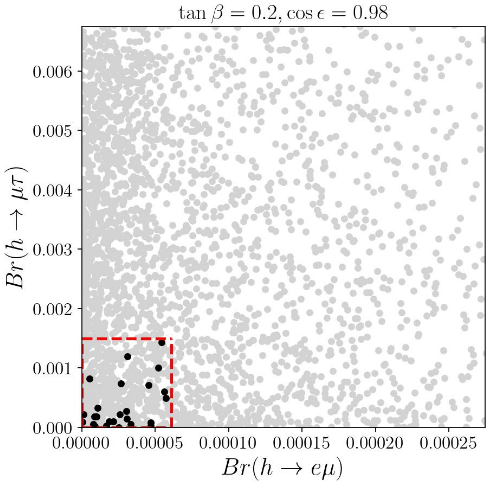
Check LFV signals induced by new Higgses:

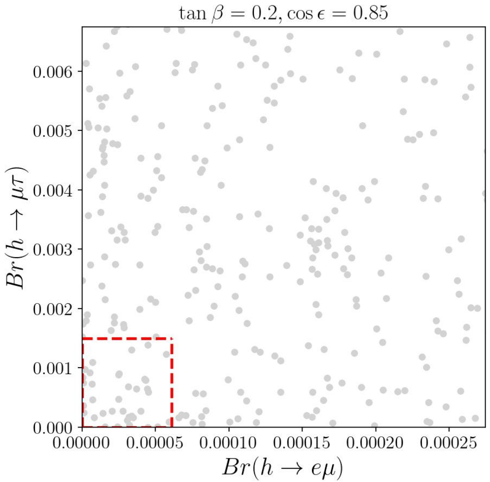
- explore $H \to \ell_i^+ \ell_j^-$
- compute $\mu \to e\gamma$

Add neutrinos and study CP4 based neutrino mass models.

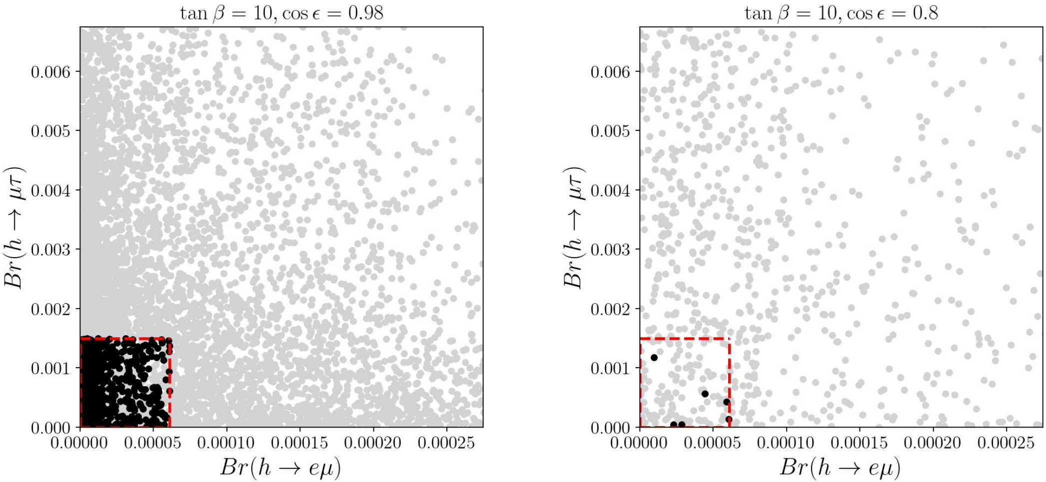
Thanks!

Numerical scan of case B_1: $\tan\beta = 0.2$





Numerical scan of case B_1: $\tan\beta = 10$



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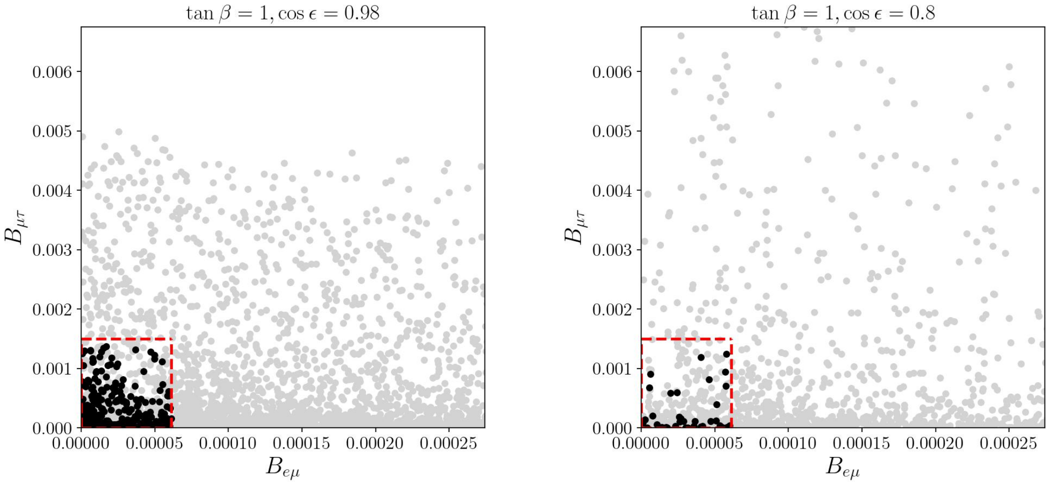
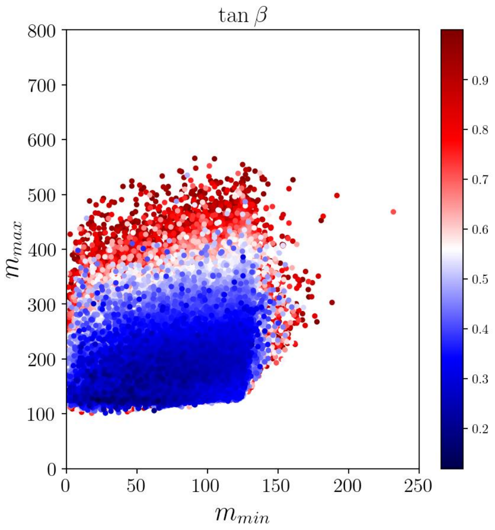
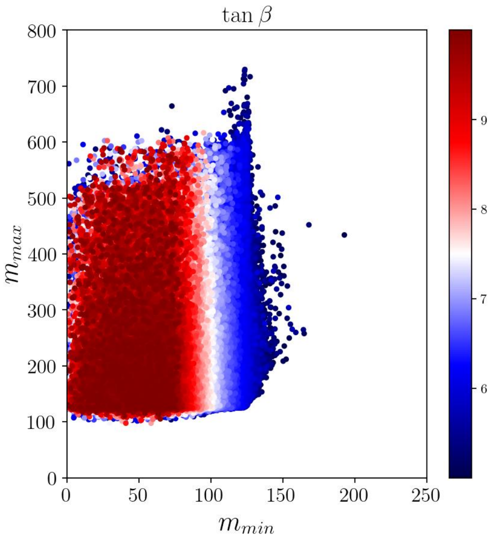
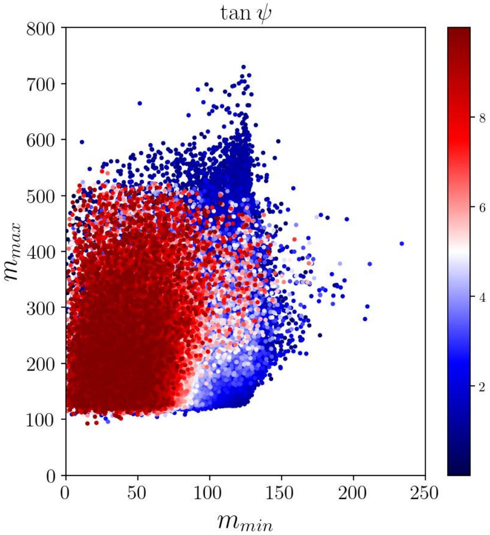
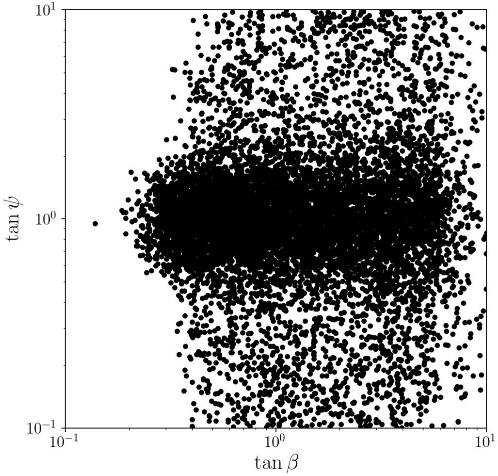
Numerical scan of case B_2: $\tan\beta = 1$




tan β
m_{max}
m_{min}
0
100
200
300
400
500
600
700
800
0
50
100
150
200
250
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9


tan β
m_{max}
m_{min}
0
100
200
300
400
500
600
700
800
0
50
100
150
200
250
6
7
8
9


tan ψ
800
700
600
500
400
300
200
100
0
0
50
100
150
200
250
m_max
m_min
8
6
4
2


10^1
10^0
10^-1
10^-1
10^0
10^1
tan ψ
tan β