Fermion mass hierarchy in an extended left-right symmetric model

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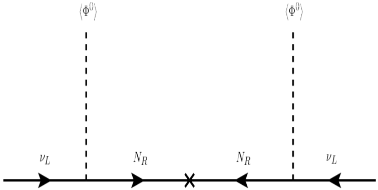
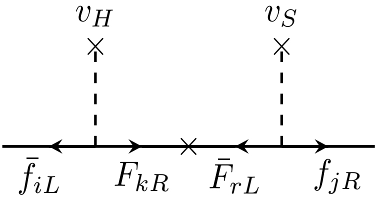
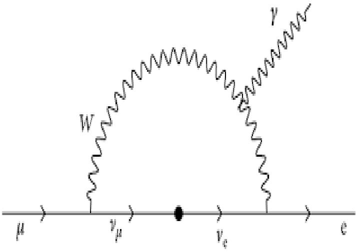
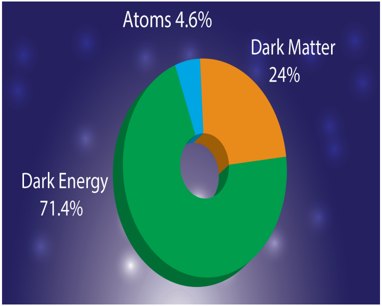


Type I seesaw mechanism

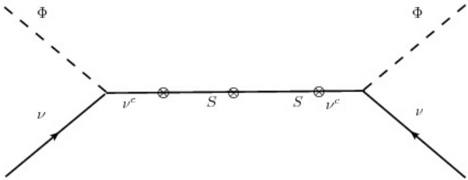


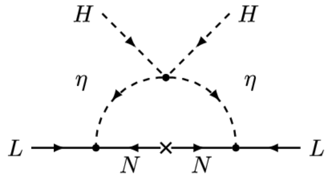
Universal seesaw mechanism





$Br_{SM}\left(\mu \to e\gamma\right) \sim \mathcal{O}\left(10^{-54}\right)$, $Br_{exp}\left(\mu \to e\gamma\right) < 4.2 \times 10^{-13}$





One loop Zhijian Tao radiative seesaw model (1996)

η and N are odd under a preserved Z_2

$$L\widetilde{\eta}N, \frac{\lambda_5}{2}\left(H^{\dagger}\cdot\eta\right)^2 + h.c$$

Inverse seesaw

$$-\mathcal{L}_{mass}^{(\nu)} = \frac{1}{2}\begin{pmatrix} \overline{\nu_L^C} & \overline{N}_R & \overline{S}_R \end{pmatrix} \mathbf{M}_\nu \begin{pmatrix} \nu_L \\ N_R^C \\ S_R^C \end{pmatrix} + H.c$$

$$\mathbf{M}_\nu = \begin{pmatrix} 0_{3\times 3} & \mathbf{m}_D & 0_{3\times 3} \\ \mathbf{m}_D^T & 0_{3\times 3} & \mathbf{M} \\ 0_{3\times 3} & \mathbf{M}^T & \mu \end{pmatrix}$$

$$\mu_{ij} << (m_D)_{ij} << (M)_{ij}$$

$$Q_{\nu_L}^{U(1)_L} = Q_{S_R}^{U(1)_L} = -Q_{N_R}^{U(1)_L} = 1$$

$$\widetilde{\mathbf{M}}_\nu = \mathbf{m}_D\left(\mathbf{M}^T\right)^{-1}\mu\mathbf{M}^{-1}\mathbf{m}_D^T$$

$$\mathbf{M}_\nu^{(1)} = -\frac{1}{2}\left(\mathbf{M}+\mathbf{M}^T\right) + \frac{1}{2}\mu$$

$$\mathbf{M}_\nu^{(2)} = \frac{1}{2}\left(\mathbf{M}+\mathbf{M}^T\right) + \frac{1}{2}\mu$$

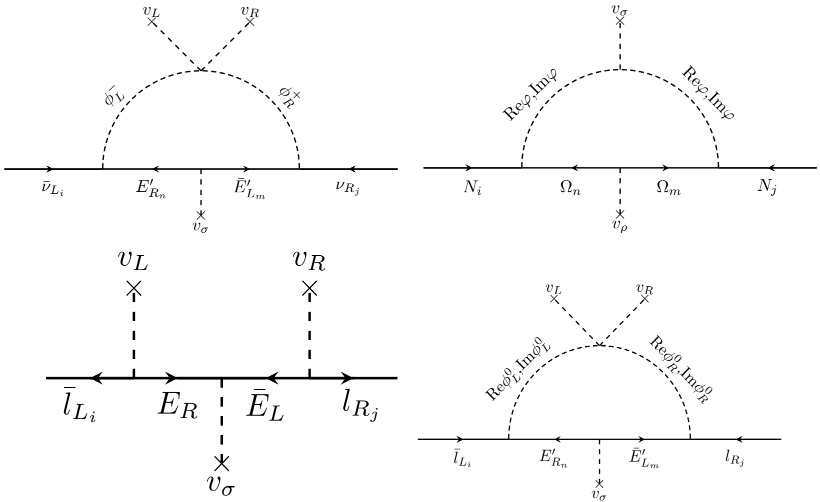
The model of this talk yields m_D and μ at 1-loop.

For three loop level μ, see Tessio De Melo talk of Saturday, JHEP **05**, 035 (2024).

An extended left-right symmetric model.

Model based on $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times U(1)_X$ with:

1. Tree level masses for t, b, c, τ from Universal Seesaw.
2. 1-loop masses for u, d, s, e, μ.
3. 3-loop ν masses from inverse seesaw, with 1-loop Dirac and Majorana submatrices.
4. Global $U(1)_X$ broken to preserved Z_2, with $(-1)^{X+2s}$ being the Z_2 charges.
5. No tree level FCNCs.



Here $i = 1, 2, 3$, $n, m = 1, 2$. Left (right) handed SM fermions are in $SU(2)_L$ ($SU(2)_R$) doublets. m_D and μ arise at 1 loop.

$$M_\nu = \begin{pmatrix} 0_{3\times3} & m_D & 0_{3\times3} \\ m_D^T & 0_{3\times3} & M \\ 0_{3\times3} & M & \mu \end{pmatrix}$$

	χ_L	χ_R	ϕ_L	ϕ_R	σ	ρ	φ
$SU(3)_C$	**1**	**1**	**1**	**1**	**1**	**1**	**1**
$SU(2)_L$	**2**	**1**	**2**	**1**	**1**	**1**	**1**
$SU(2)_R$	**1**	**2**	**1**	**2**	**1**	**1**	**1**
$U(1)_{B-L}$	1	1	1	1	0	0	0
$U(1)_X$	0	0	-1	-1	-2	-6	-1

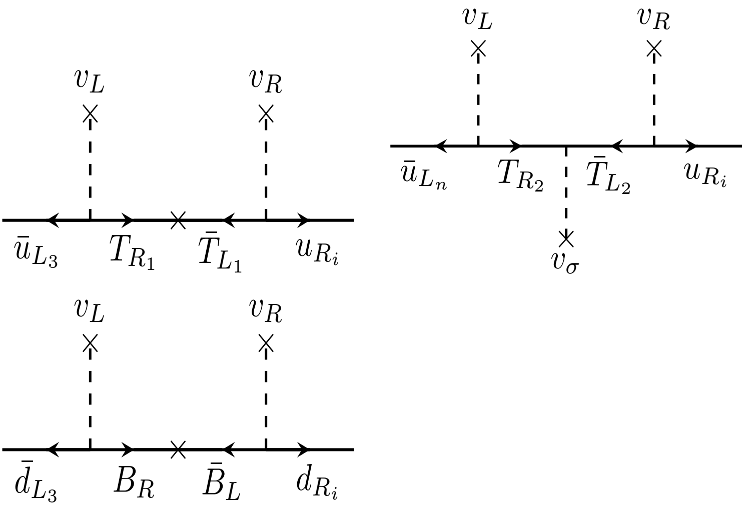
	Q_{L_n}	Q_{L_3}	Q_{R_i}	L_{L_i}	L_{R_i}	T_{L_n}	T_{R_1}	T_{R_2}	B_L	B_R	T'_L	T'_R	B'_{L_n}	B'_{R_n}	E_L	E_R	E'_{L_n}	E'_{R_n}	N_{R_i}	Ω_{R_n}
$SU(3)_C$	**3**	**3**	**3**	**1**	**1**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**1**	**1**	**1**	**1**	**1**	**1**
$SU(2)_L$	**2**	**2**	**1**	**2**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
$SU(2)_R$	**1**	**1**	**2**	**1**	**2**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
$U(1)_{B-L}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	-1	-1	$\frac{4}{3}$	$\frac{4}{3}$	$\frac{4}{3}$	$-\frac{2}{3}$	$-\frac{2}{3}$	$\frac{4}{3}$	$\frac{4}{3}$	$-\frac{2}{3}$	$-\frac{2}{3}$	-2	-2	-2	-2	0	0
$U(1)_X$	2	0	0	0	-2	0	0	2	0	0	-1	1	1	3	-2	0	-1	1	2	-3

Table: Fermion assignments under the $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times U(1)_X$ symmetry. Here $n = 1, 2$ and $i = 1, 2, 3$.

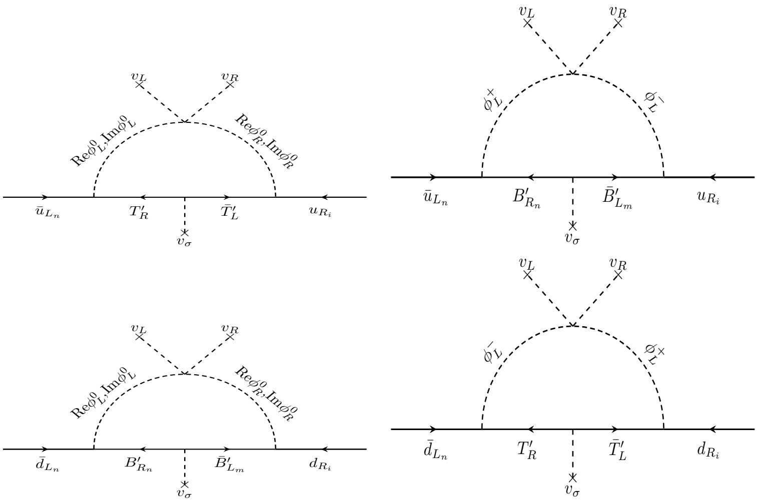
	χ_L	χ_R	ϕ_L	ϕ_R	σ	ρ	φ
$SU(3)_C$	**1**	**1**	**1**	**1**	**1**	**1**	**1**
$SU(2)_L$	**2**	**1**	**2**	**1**	**1**	**1**	**1**
$SU(2)_R$	**1**	**2**	**1**	**2**	**1**	**1**	**1**
$U(1)_{B-L}$	1	1	1	1	0	0	0
$U(1)_X$	0	0	-1	-1	-2	-6	-1

Table: Scalar boson charge assignments under the $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times U(1)_X$ symmetry.

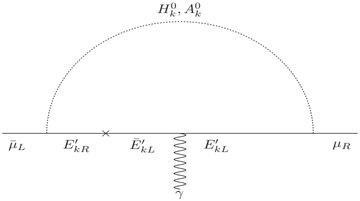
Global $U(1)_X$ broken to preserved Z_2, with $(-1)^{X+2s}$ being the Z_2 charges. The scalar dark matter candidate is the lightest among the $Re\varphi$, $Im\varphi$, $Re\phi_L^0$, $Re\phi_R^0$ fields.

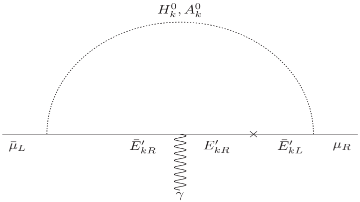


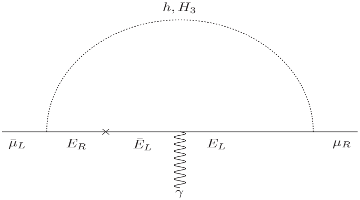
Here $i = 1, 2, 3$, $n = 1, 2$. Left (right) handed SM fermions are in $SU(2)_L$ ($SU(2)_R$) doublets.

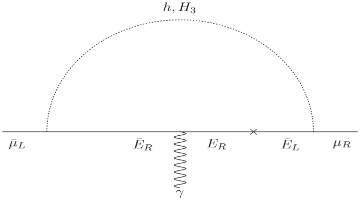


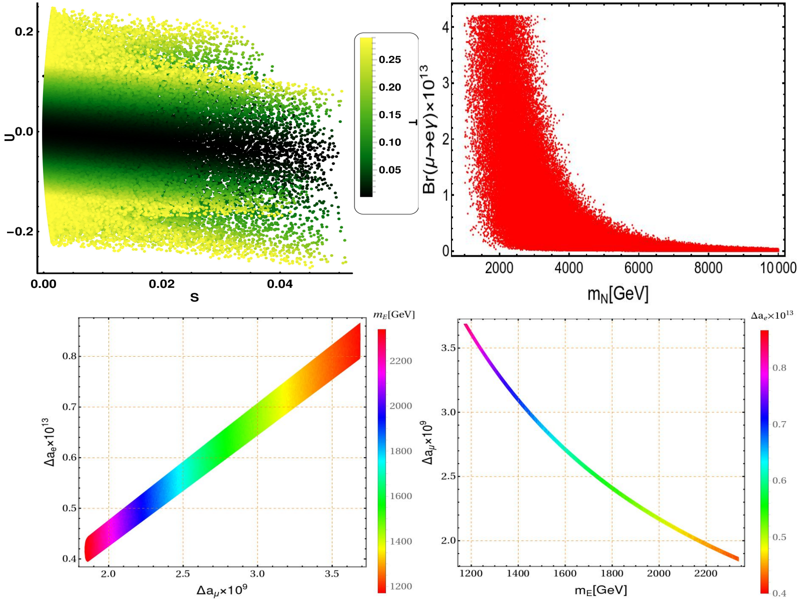
Here $i = 1, 2, 3$, $n, m = 1, 2$. Left (right) handed SM fermions are in $SU(2)_L$ ($SU(2)_R$) doublets.


H_k^0, A_k^0
$\bar{\mu}_L$
E'_{kR}
$\bar{E}'_{kL}$
E'_{kL}
μ_R
γ

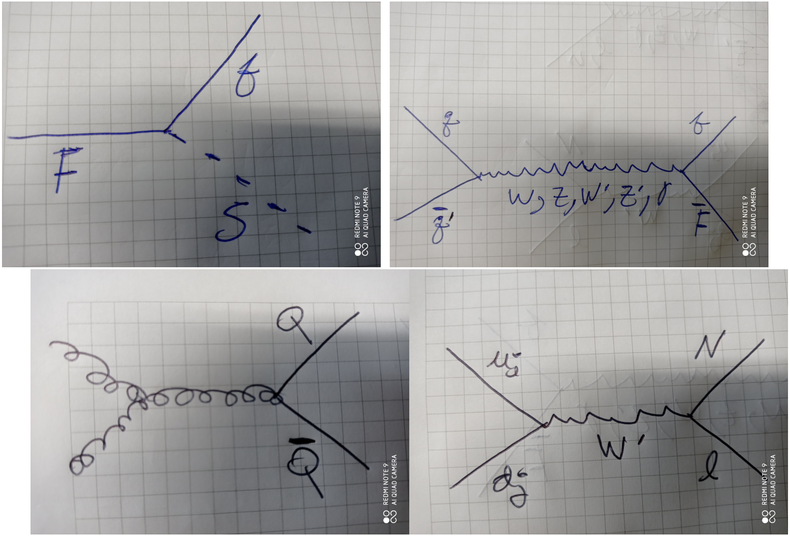

H_k^0, A_k^0
$\bar{\mu}_L$
$\bar{E}'_{kR}$
E'_{kR}
$\bar{E}'_{kL}$
μ_R
γ


h, H_3
$\bar{\mu}_L$
E_R
$\bar{E}_L$
E_L
μ_R
γ

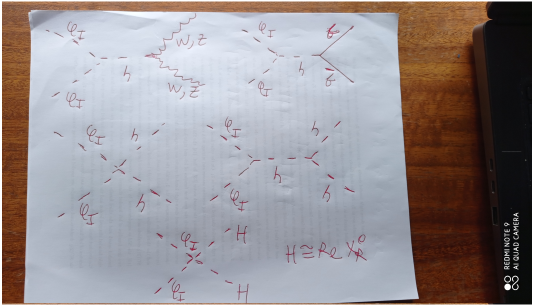

h, H_3
$\bar{\mu}_L$
$\bar{E}_R$
E_R
$\bar{E}_L$
μ_R
γ

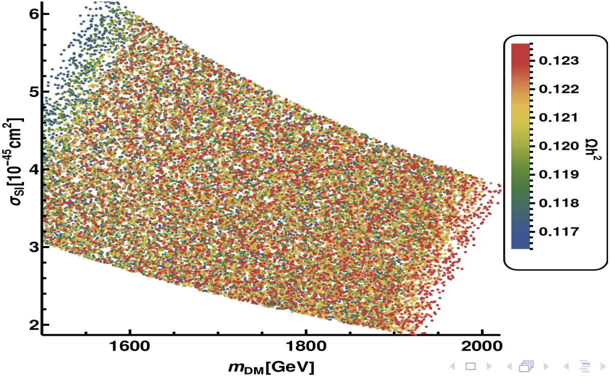


U
S
T
0.25
0.20
0.15
0.10
0.05
Br(μ→eγ)×10^13
m_N[GeV]
Δa_e×10^13
Δa_μ×10^9
m_E[GeV]
Δa_μ×10^9
m_E[GeV]
Δa_e×10^13



The sterile neutrinos have the following decay modes $N_a^{\pm} \to l_i^{\pm} W^{\mp}$, $N_a^{\pm} \to \nu_i Z$ and $N_a^{\pm} \to \nu_i S$, $N_a^{\pm} \to l_i^{+} l_j^{-} \nu_k$, $N_a^{\pm} \to l_i^{-} u_j \bar{d}_k$, $N_a^{\pm} \to b\bar{b}\nu_k$





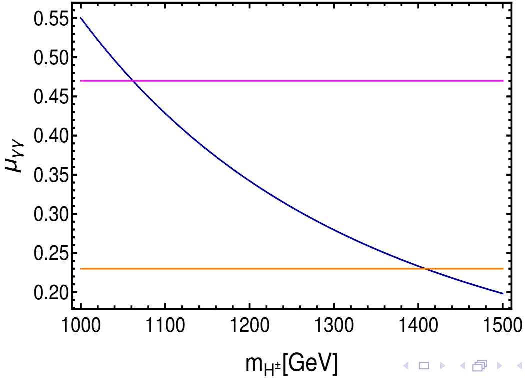
$\sigma_{SI}[10^{-45}\mathrm{cm}^2]$
m_{DM}[GeV]
Ωh^2
0.123
0.122
0.121
0.120
0.119
0.118
0.117

The 95 GeV diphoton excess has a signal strength given by:

$$\mu_{\gamma\gamma}^{(\mathrm{exp})} = \frac{\sigma_{\mathrm{exp}}\left(pp \to \sigma_R \to \gamma\gamma\right)}{\sigma_{SM}\left(pp \to h \to \gamma\gamma\right)} = 0.35 \pm 0.12\,, \qquad (1)$$

For the sake of simplicity, we set:

$$\begin{aligned} m_{T_2} &\simeq 20\mathrm{TeV}, \quad m_{T'} = m_{B_1'} = m_{B_2'} \simeq 4\mathrm{TeV}, \quad v_\sigma = 10\mathrm{TeV} \\ m_E &\simeq 1.7\mathrm{TeV}, \quad m_{E_1'} \simeq 3.8\mathrm{TeV}, \quad m_{E_2'} \simeq 3.3\mathrm{TeV}, \quad m_{H_1^\pm} = m_{H^\pm}, \\ m_{H_2^\pm} &= m_{H^\pm} + \delta, \quad \delta = 0.1\mathrm{TeV}, \quad C_{\sigma H_1^\pm H_1^\mp} = C_{\sigma H_2^\pm H_2^\mp} = 10\,\mathrm{TeV}, \end{aligned}$$



Conclusions

- Both tree-level and radiative seesaw mechanisms can be implemented for explaining the SM fermion mass hierarchy.
- Neutrino masses can be generated via radiative inverse seesaw.
- Dark matter stability can arise from a residual discrete symmetry.
- Fermion masses and mixings, DM, CLFV, oblique parameters, 95 GeV diphoton excess and $(g-2)_{e,\mu}$ anomalies can be accounted for.

Acknowledgements

Thank you very much to all of you for the attention.

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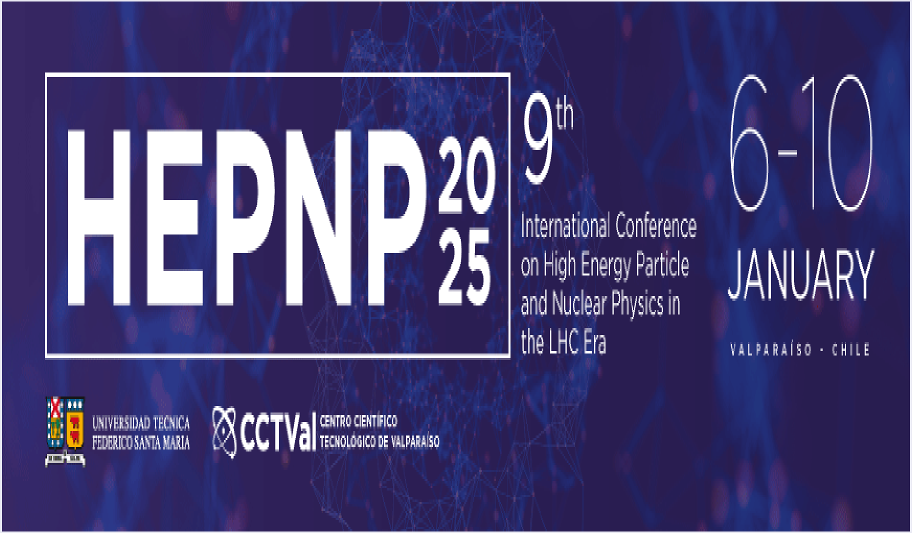
This talk is dedicated to the memory of Ivan Schmidt, a very nice person, friend and long-term collaborator.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Extra Slides

The one-loop contributions to the oblique parameters T, S and U are defined as:

$$T = \left.\frac{\Pi_{33}\left(q^2\right) - \Pi_{11}\left(q^2\right)}{\alpha_{EM}(M_Z)M_W^2}\right|_{q^2=0}, \qquad S = \frac{2\sin 2\theta_W}{\alpha_{EM}(M_Z)}\left.\frac{d\Pi_{30}\left(q^2\right)}{dq^2}\right|_{q^2=0},$$

$$U = \frac{4\sin^2\theta_W}{\alpha_{EM}(M_Z)}\left.\left(\frac{d\Pi_{33}\left(q^2\right)}{dq^2} - \frac{d\Pi_{11}\left(q^2\right)}{dq^2}\right)\right|_{q^2=0}$$

where $\Pi_{11}(0)$, $\Pi_{33}(0)$, and $\Pi_{30}\left(q^2\right)$ are the vacuum polarization amplitudes with $\{W_\mu^1, W_\mu^1\}$, $\{W_\mu^3, W_\mu^3\}$ and $\{W_\mu^3, B_\mu\}$ external gauge bosons, respectively, and q is their momentum. The experimental values of T, S and U are:

$$T = -0.01 \pm 0.10, \qquad S = 0.03 \pm 0.12, \qquad U = 0.02 \pm 0.11\,. \quad (2)$$

The scalar sector yields the prediction $m_{H_i^0} = m_{A_i^0}$ $(i = 1, 2)$ and $\theta_H = -\theta_A$. In our numerical analysis we have varied $m_{H_1^0}$, $m_{H_2^0}$, θ_H, θ in the ranges 1 TeV $\leqslant m_{H_i^0} \leqslant$ 3 TeV $(i = 1, 2)$, 0.9×10^{-2} rad $\leqslant \theta_H \leqslant 1.1 \times 10^{-2}$ rad and 0.9×10^{-3} rad $\leqslant \theta \leqslant 1.1 \times 10^{-3}$ rad, respectively.