LFV decays $Z \to l_i^{\pm} l_j^{\mp}$, $h \to l_i^{\pm} l_j^{\mp}$ and $l_j \to l_i \gamma\gamma$ in the U(1)xSSM

河北大学

刘明月，赵树民，王艺潼

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目　录

1、The lepton flavor violation (LFV)

The breaking theory of electric weak symmetry and neutrino oscillation experiment show that lepton flavor violation exists both theoretically and experimentally. However, the lepton number is conserved in the SM. It is necessary to expand the SM. Any sign of LFV can be regarded as evidence of the existence of new physics.

We study the LFV of the $l_j \to l_i\gamma\gamma$, $Z \to l_i^{\pm} l_j^{\mp}$ and $h \to l_i^{\pm} l_j^{\mp}$ in the $U(1)_X SSM$. At the analytical level, we can find many parameters that have direct influence on LFV.

$l_j \to l_i\gamma\gamma$

decay modes	$\mu \to e\gamma\gamma$	$\tau \to \mu\gamma\gamma$	$\tau \to e\gamma\gamma$
Upper Limit	7.2×10^{-11}	5.8×10^{-4}	2.5×10^{-4}

$Z \to l_i^{\pm} l_j^{\mp}$

decay modes	$Z\to e\mu$	$Z\to e\tau$	$z\to \mu\tau$
Upper Limit	7.5×10^{-7}	9.8×10^{-6}	1.5×10^{-5}

$h \to l_i^{\pm} l_j^{\mp}$

decay modes	$h\to e\mu$	$h\to e\tau$	$h\to \mu\tau$
Upper Limit	6.2×10^{-5}	4.7×10^{-3}	2.5×10^{-3}

$l_j \to l_i\gamma$

decay modes	$\mu \to e\gamma$	$\tau \to \mu\gamma$	$\tau \to e\gamma$
Upper Limit	4.2×10^{-13}	4.4×10^{-8}	3.3×10^{-8}

2、The U(1)xSSM

U(1)xSSM is the U(1) extension of MSSM. To obtain this model, three singlet Higgs superfields and right-handed neutrinos are added to MSSM.

Its local gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_X$.

The particle content and charge assignments for U(1)xSSM:

Superfields	$\hat{q}_i$	$\hat{u}_i^c$	$\hat{d}_i^c$	$\hat{l}_i$	$\hat{e}_i^c$	$\hat{\nu}_i$	$\hat{H}_u$	$\hat{H}_d$	$\hat{\eta}$	$\hat{\bar{\eta}}$	$\hat{S}$
$SU(3)_C$	3	$\bar{3}$	$\bar{3}$	1	1	1	1	1	1	1	1
$SU(2)_L$	2	1	1	2	1	1	2	2	1	1	1
$U(1)_Y$	1/6	-2/3	1/3	-1/2	1	0	1/2	-1/2	0	0	0
$U(1)_X$	0	-1/2	1/2	0	1/2	-1/2	1/2	-1/2	-1	1	0

The superpotential

$$W = l_W \hat{S} + \mu \hat{H}_u \hat{H}_d + M_S \hat{S}\hat{S} - Y_d \hat{d}\hat{q}\hat{H}_d - Y_e \hat{e}\hat{l}\hat{H}_d + \lambda_H \hat{S}\hat{H}_u \hat{H}_d$$
$$+ \lambda_C \hat{S}\hat{\eta}\hat{\bar{\eta}} + \frac{\kappa}{3}\hat{S}\hat{S}\hat{S} + Y_u \hat{u}\hat{q}\hat{H}_u + Y_X \hat{\nu}\hat{\bar{\eta}}\hat{\nu} + Y_\nu \hat{\nu}\hat{l}\hat{H}_u.$$

The Higgs superfields

$$H_u = \begin{pmatrix} H_u^+ \\ \frac{1}{\sqrt{2}}\left(v_u + H_u^0 + iP_u^0\right) \end{pmatrix}, \qquad H_d = \begin{pmatrix} \frac{1}{\sqrt{2}}\left(v_d + H_d^0 + iP_d^0\right) \\ H_d^- \end{pmatrix},$$

$$\eta = \frac{1}{\sqrt{2}}\left(v_\eta + \phi_\eta^0 + iP_\eta^0\right), \qquad \bar{\eta} = \frac{1}{\sqrt{2}}\left(v_{\bar{\eta}} + \phi_{\bar{\eta}}^0 + iP_{\bar{\eta}}^0\right),$$
$$S = \frac{1}{\sqrt{2}}\left(v_S + \phi_S^0 + iP_S^0\right).$$

The soft SUSY breaking terms

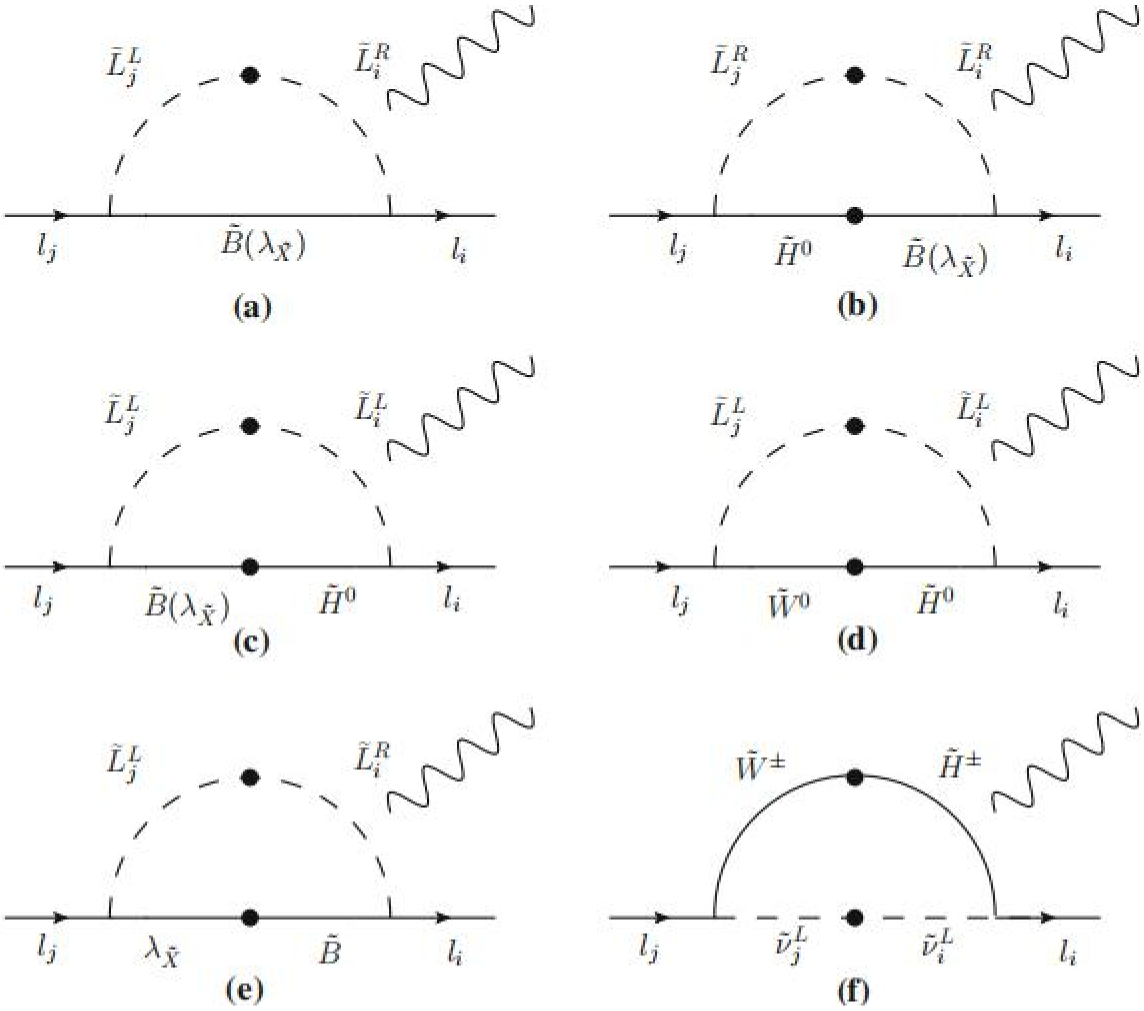
$$\mathcal{L}_{soft} = \mathcal{L}_{soft}^{MSSM} - B_S S^2 - L_S S - \frac{T_\kappa}{3} S^3 - T_{\lambda_C} S \eta \bar{\eta} + \epsilon_{ij} T_{\lambda_H} S H_d^i H_u^j$$
$$-T_X^{IJ} \bar{\eta} \tilde{\nu}_R^{*I} \tilde{\nu}_R^{*J} + \epsilon_{ij} T_\nu^{IJ} H_u^i \tilde{\nu}_R^{I*} \tilde{l}_j^J - m_\eta^2 |\eta|^2 - m_{\bar{\eta}}^2 |\bar{\eta}|^2$$
$$-m_S^2 S^2 - (m_{\tilde{\nu}_R}^2)^{IJ} \tilde{\nu}_R^{I*} \tilde{\nu}_R^J - \frac{1}{2}\left(M_X \lambda_{\tilde{X}}^2 + 2 M_{BB'} \lambda_{\tilde{B}} \lambda_{\tilde{X}}\right) + h.c \quad .$$

The covariant derivatives of U(1)xSSM

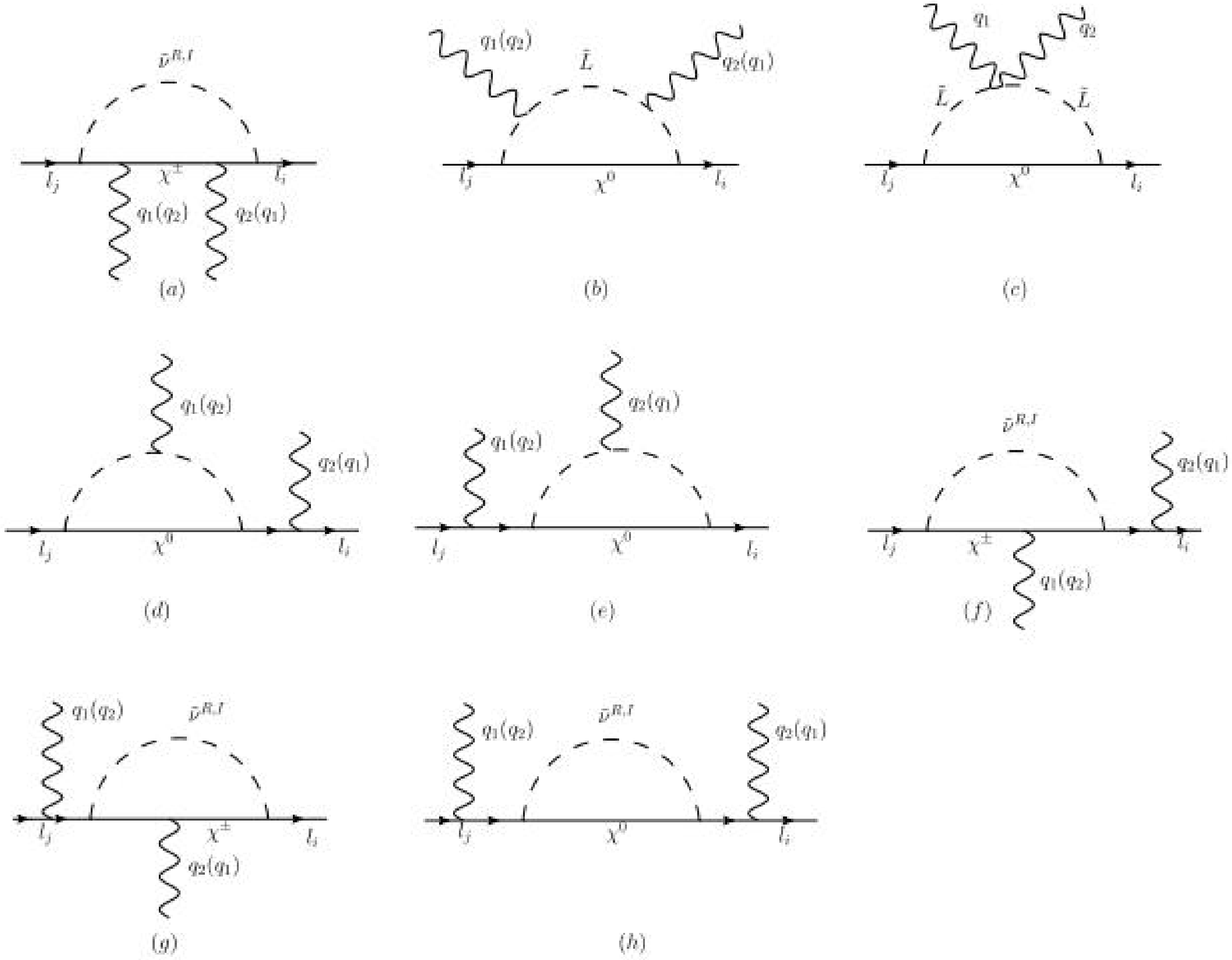
$$D_\mu = \partial_\mu - i\left(Y, X\right)\begin{pmatrix} g_Y, & g'_{YX} \\ g'_{XY}, & g'_X \end{pmatrix}\begin{pmatrix} A'^Y_\mu \\ A'^X_\mu \end{pmatrix}$$

3、$l_j \to l_i\gamma$ and $l_j \to l_i\gamma\gamma$

3.1、 Feynman diagrams of $l_j \to l_i\gamma$



3.2、 Feynman diagrams of $l_j \to l_i\gamma\gamma$



3.3、decay width

Let the Euler angles are (α, β, γ) to determine the final system with respect to the initial orientation of the particles

$$d\Gamma = \frac{1}{(2\pi)^5}\frac{1}{16M}|\mathcal{M}|^2 dE_1 dE_3 d\alpha d(\cos\beta) d\gamma.$$

⬇

$$d\Gamma = \frac{1}{(2\pi)^3}\frac{1}{8M}|\mathcal{M}|^2 dE_1 dE_3.$$

the decay width and branching ratio

$$\Gamma(l_j \to l_i\gamma\gamma) = \frac{1}{(2\pi)^3}\frac{1}{8M}\int |\mathcal{M}|^2 dE_1 dE_2,$$

$$Br(l_j \to l_i\gamma\gamma) = \frac{\Gamma(l_j \to l_i\gamma\gamma)}{\Gamma_{l_j}}.$$

3.4、Numerical results

Experimental limitations considered

1. the lightest CP-even Higgs mass m_{h^0} = 125.25 GeV
2. The latest experimental results of the mass of the heavy vector boson Z' is $M_{Z'} > 5.1$ TeV
3. The limits for the masses of other particles beyond SM.
4. The bound on the ratio between $M_{Z'}$ and its gauge coupling g_X is $M_{Z'}/g_X \geq 6$ TeV at 99% CL
5. The constraint from LHC data, $\tan\beta_\eta < 1.5$
6. The scalar lepton masses larger than 700 GeV and chargino masses larger than 1100 GeV

we adopt the following parameters in the numerical calculation

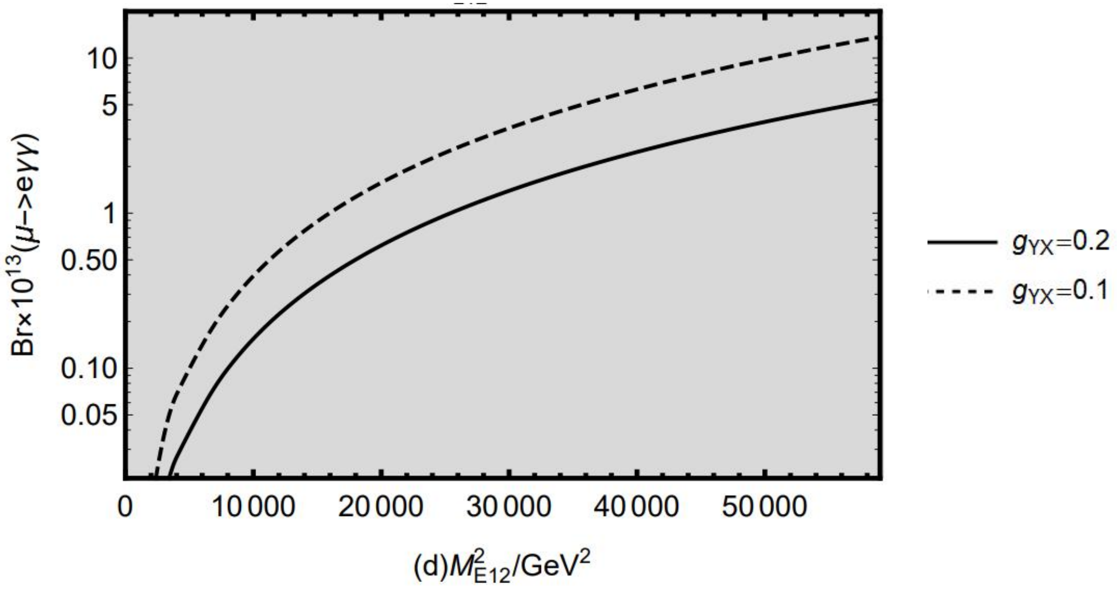
$$\mu = M_{BL} = T_{\lambda_C} = T_{\lambda_H} = T_\kappa = 1 \text{ TeV}, \quad M_{BB'} = M_S = 0.4 \text{ TeV},$$

$$\lambda_H = 0.1,\ l_W = B_\mu = B_S = 0.1 \text{ TeV}^2, \quad T_{Xii} = -1 \text{ TeV},$$

$$\kappa = 0.1, \quad Y_{Xii} = 1 \text{ TeV}(i = 1,2,3),\ M^2_{\tilde{E}ii} = 0.8 \text{ TeV}^2,$$

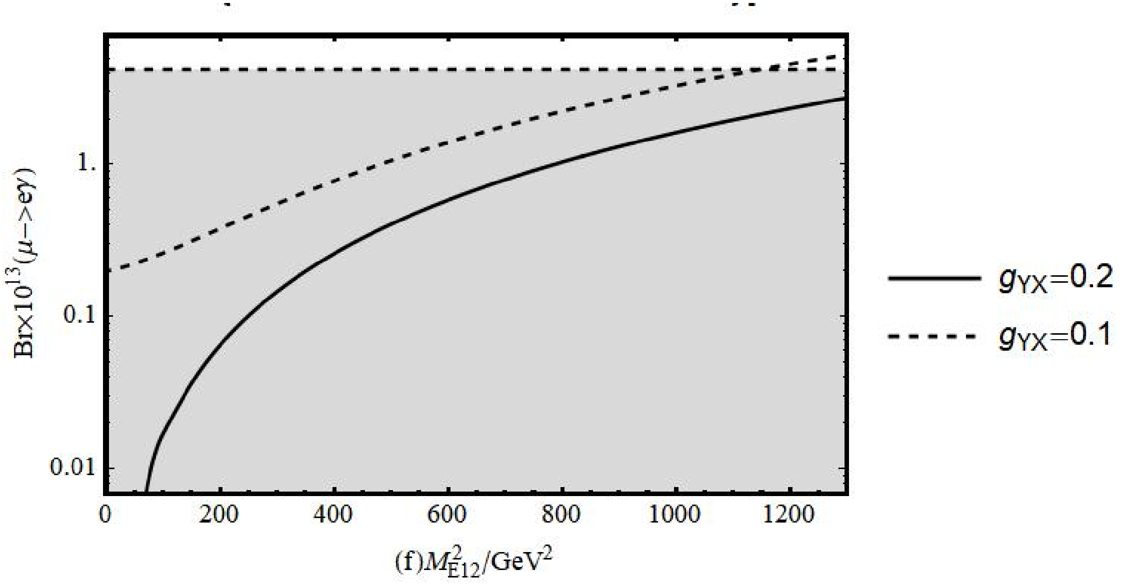
$$M^2_{\tilde{\nu}ii} = 0.3 \text{ TeV}^2, \quad T_{\tilde{e}ii} = 0.5 \text{ TeV},\ \lambda_C = -0.25.$$

μ → eγγ



10
5
1
0.50
0.10
0.05
Br×10^13(μ->eγγ)
0
10 000
20 000
30 000
40 000
50 000
(d)M^2_E12/GeV^2
g_YX=0.2
g_YX=0.1

μ → eγ



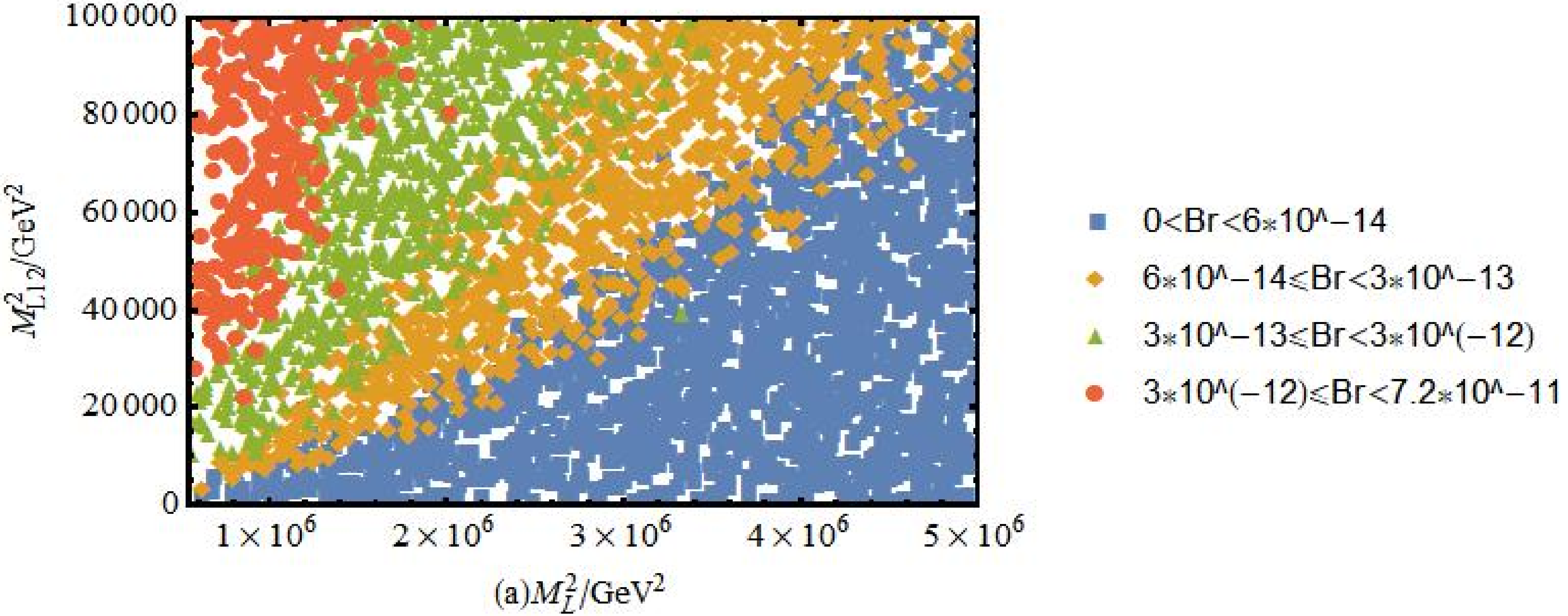
1.
0.1
0.01
Br×10^13(μ->eγ)
0
200
400
600
800
1000
1200
(f)M^2_E12/GeV^2
g_YX=0.2
g_YX=0.1

Scanning parameters

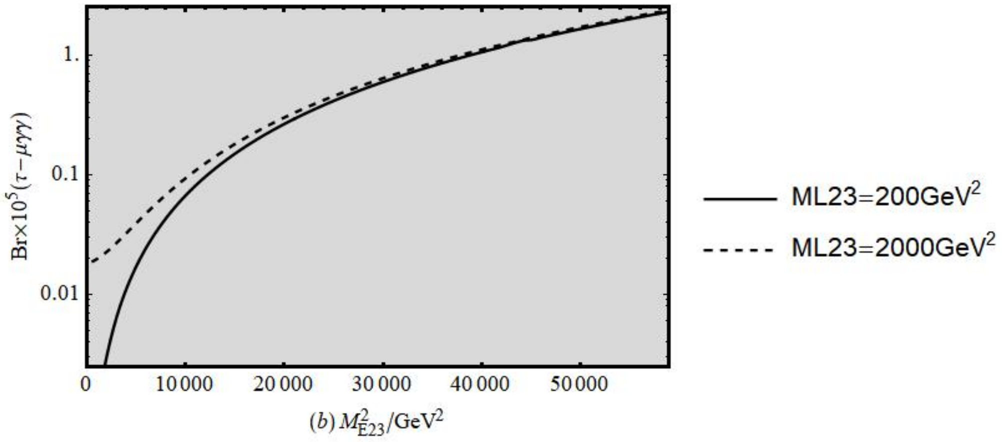
Parameters	$\tan\beta$	g_X	g_{YX}	λ_H	λ_C	μ/GeV	M_2/ GeV	$M_{\tilde{L}}^2$/ GeV^2	$M_{\tilde{\nu}}^2$/ GeV^2
Min	5	0.3	0.01	0.1	-0.3	1000	700	4×10^5	3×10^5
Max	50	0.6	0.2	0.3	-0.1	1300	2500	5×10^6	5×10^6

$\mu \to e\gamma\gamma$

Parameters	$M_{\tilde{L}12}^2$/ GeV^2	T_{e12}/ GeV	$T_{\tilde{\nu}12}$/ GeV
Min	0	- 400	- 400
Max	10^5	400	400

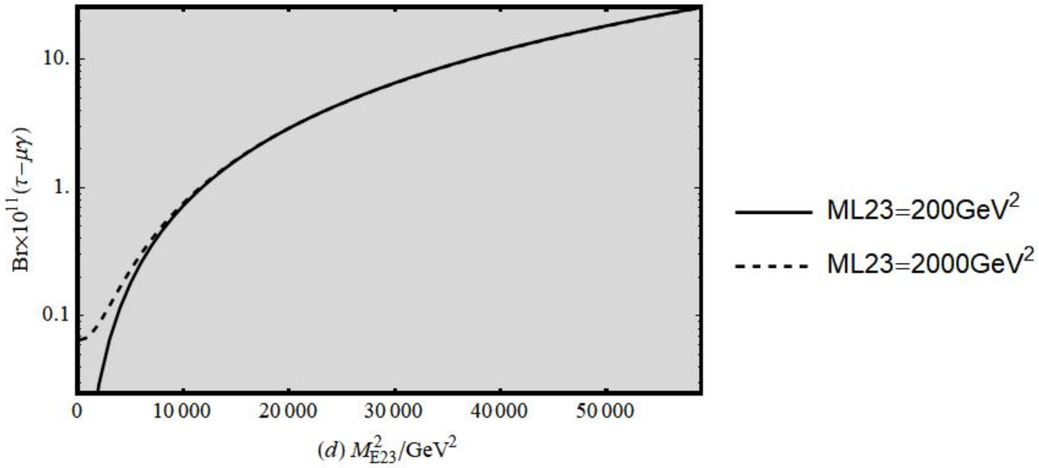

100 000
80 000
60 000
40 000
20 000
0
M^2_{L12}/GeV^2
1×10^6
2×10^6
3×10^6
4×10^6
5×10^6
(a)M^2_L/GeV^2
0<Br<6*10^−14
6*10^−14≤Br<3*10^−13
3*10^−13≤Br<3*10^(−12)
3*10^(−12)≤Br<7.2*10^−11

τ → μγγ



1.
0.1
0.01
Br×10^5(τ−μγγ)
0
10 000
20 000
30 000
40 000
50 000
(b) M^2_{E23}/GeV^2
ML23=200GeV^2
ML23=2000GeV^2

τ → μγ

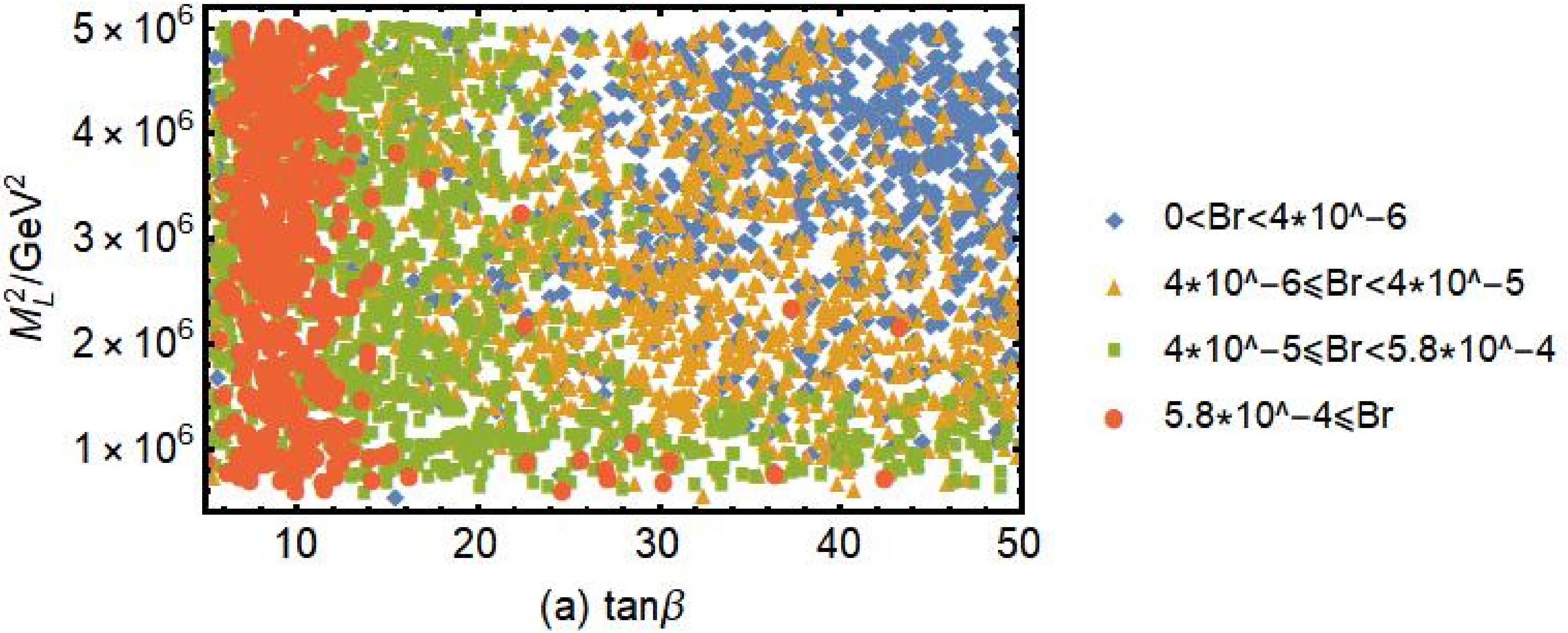


10.
1.
0.1
Br×10^{11}(τ−μγ)
0
10 000
20 000
30 000
40 000
50 000
(d) M^2_{E23}/GeV^2
ML23=200GeV^2
ML23=2000GeV^2

Parameters	$\tan\beta$	g_X	g_{YX}	λ_H	λ_C	μ/GeV	M_2/ GeV	$M_{\tilde{L}}^2$/ GeV^2	$M_{\tilde{\nu}}^2$/ GeV^2
Min	5	0.3	0.01	0.1	-0.3	1000	700	4×10^5	3×10^5
Max	50	0.6	0.2	0.3	-0.1	1300	2500	5×10^6	5×10^6

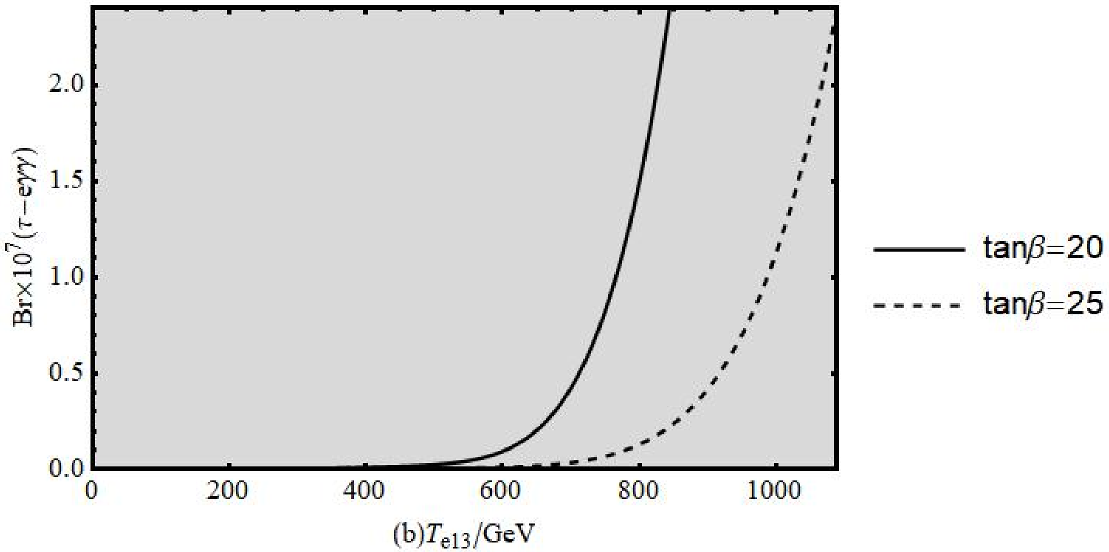
$\tau \to \mu\gamma\gamma$

Parameters	$M_{\tilde{L}23}^2$/ GeV^2	T_{e23}/ GeV	$T_{\tilde{\nu}23}$/ GeV
Min	0	- 400	- 400
Max	10^5	400	400



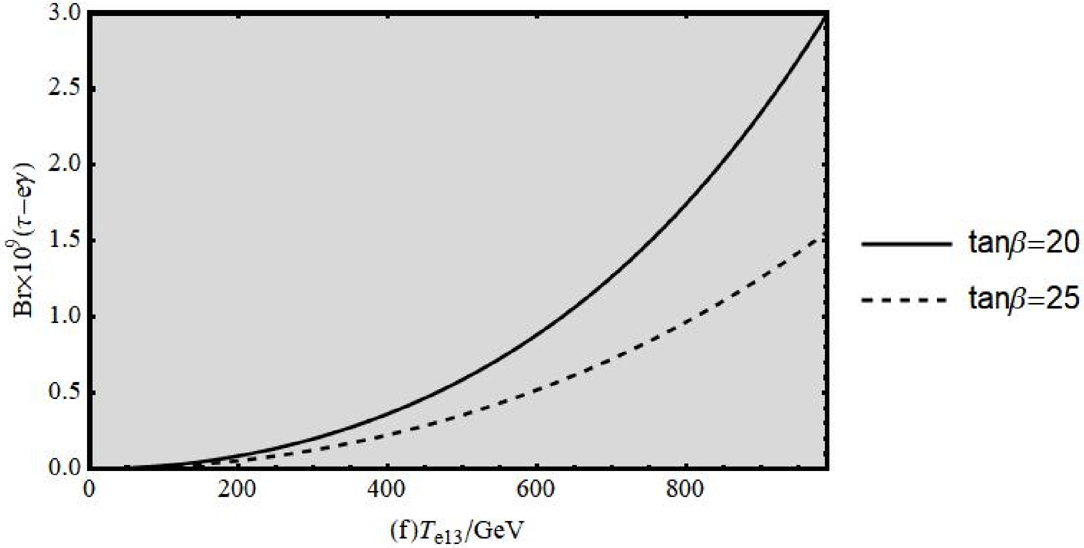
5×10^6
4×10^6
3×10^6
2×10^6
1×10^6
M_L^2/GeV^2
10
20
30
40
50
(a) $\tan\beta$
0<Br<4*10^-6
4*10^-6⩽Br<4*10^-5
4*10^-5⩽Br<5.8*10^-4
5.8*10^-4⩽Br

τ → eγγ



Br×10^7(τ−eγγ)
0.0
0.5
1.0
1.5
2.0
0
200
400
600
800
1000
(b)T_e13/GeV
tanβ=20
tanβ=25

τ → eγ

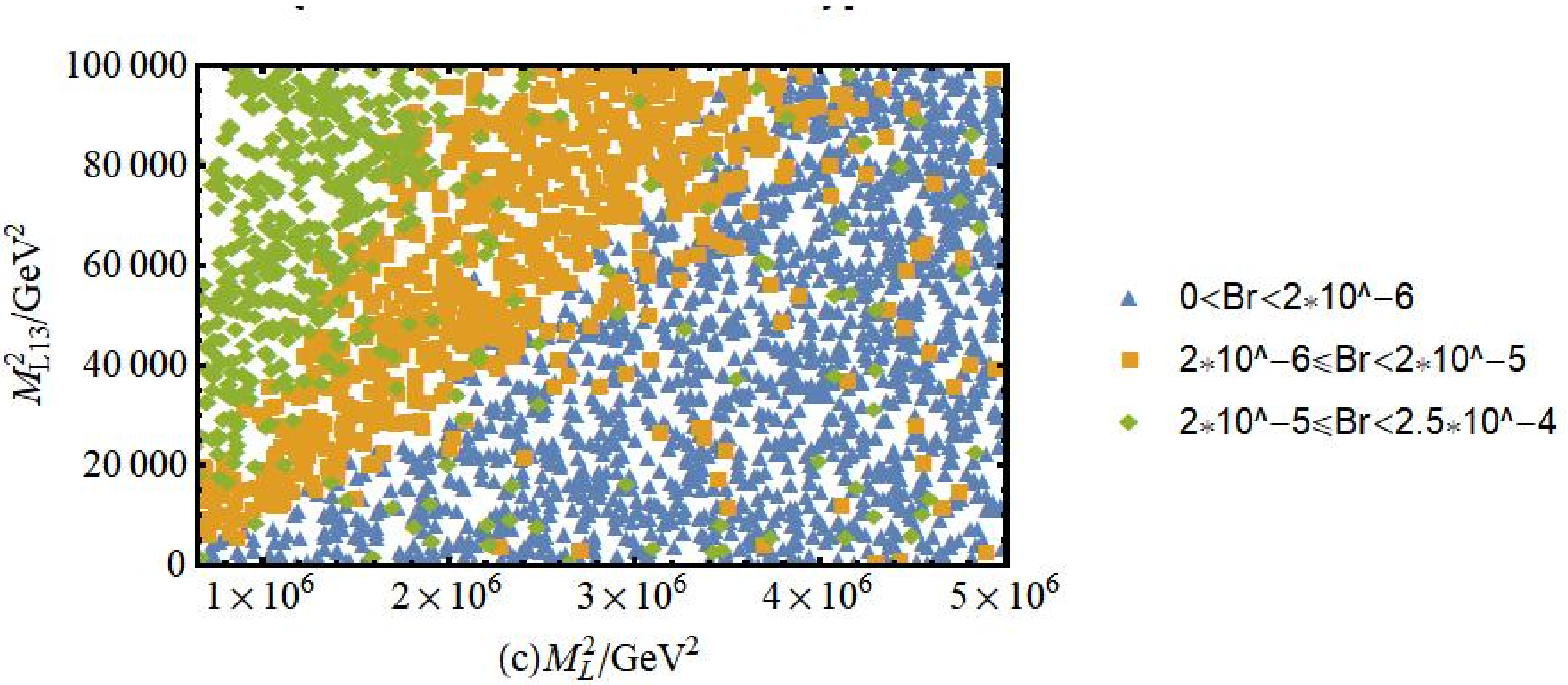


Br×10^9(τ−eγ)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
0
200
400
600
800
(f)T_e13/GeV
tanβ=20
tanβ=25

Parameters	$\tan\beta$	g_X	g_{YX}	λ_H	λ_C	μ/GeV	M_2/ GeV	$M_{\tilde{L}}^2$/ GeV^2	$M_{\tilde{\nu}}^2$/ GeV^2
Min	5	0.3	0.01	0.1	-0.3	1000	700	4×10^5	3×10^5
Max	50	0.6	0.2	0.3	-0.1	1300	2500	5×10^6	5×10^6

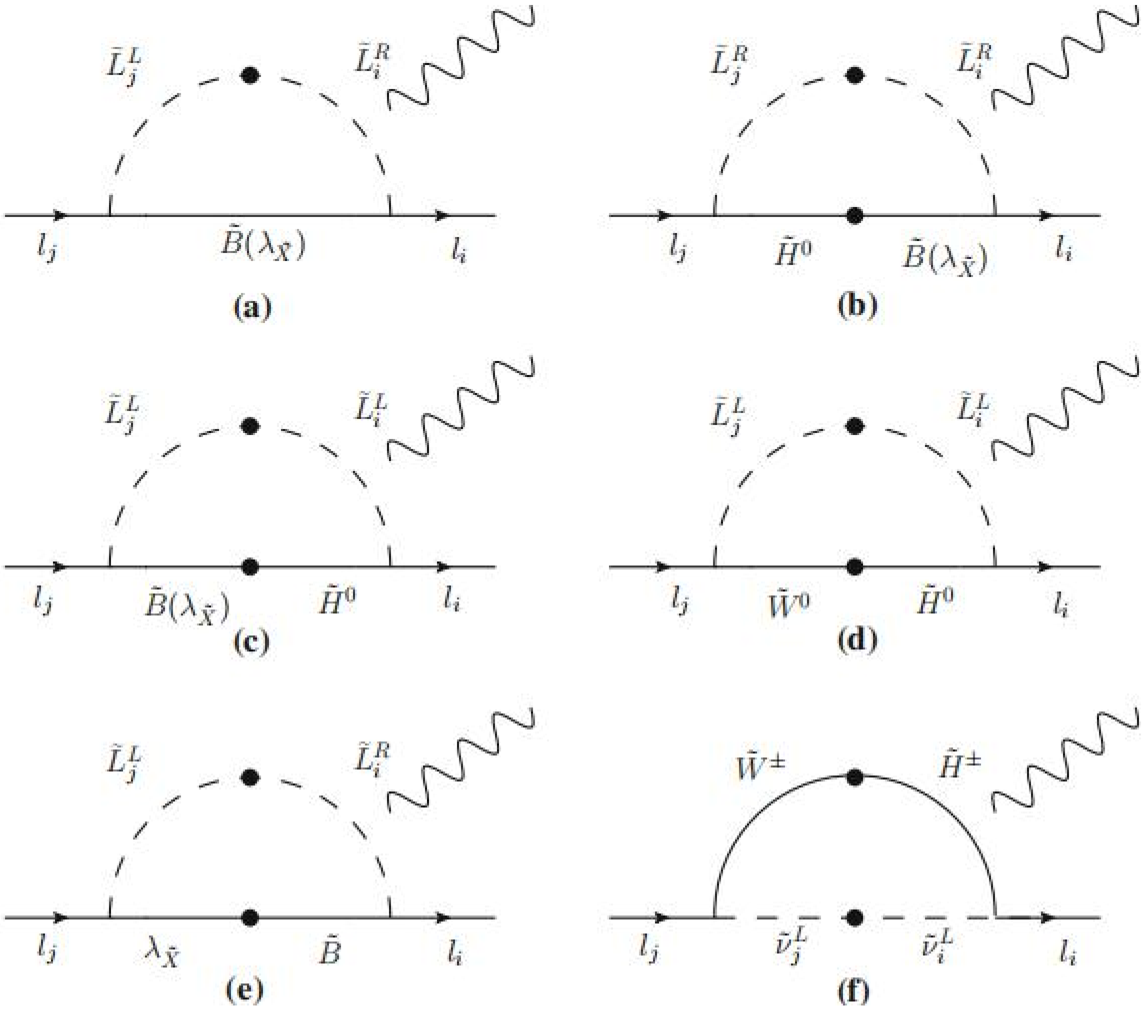
$\tau \to e\gamma\gamma$

Parameters	$M_{\tilde{L}13}^2$/ GeV^2	T_{e13}/ GeV	$T_{\tilde{\nu}13}$/ GeV
Min	0	- 400	- 400
Max	10^5	400	400


100 000
80 000
60 000
40 000
20 000
0
M^2_{L13}/GeV^2
1×10^6
2×10^6
3×10^6
4×10^6
5×10^6
(c)M^2_L/GeV^2
0<Br<2*10^-6
2*10^-6⩽Br<2*10^-5
2*10^-5⩽Br<2.5*10^-4

4、$Z \to l_i^{\pm} l_j^{\mp}$ and $h \to l_i^{\pm} l_j^{\mp}$

4.1、 Feynman diagrams of $Z \to l_i^{\pm} l_j^{\mp}$



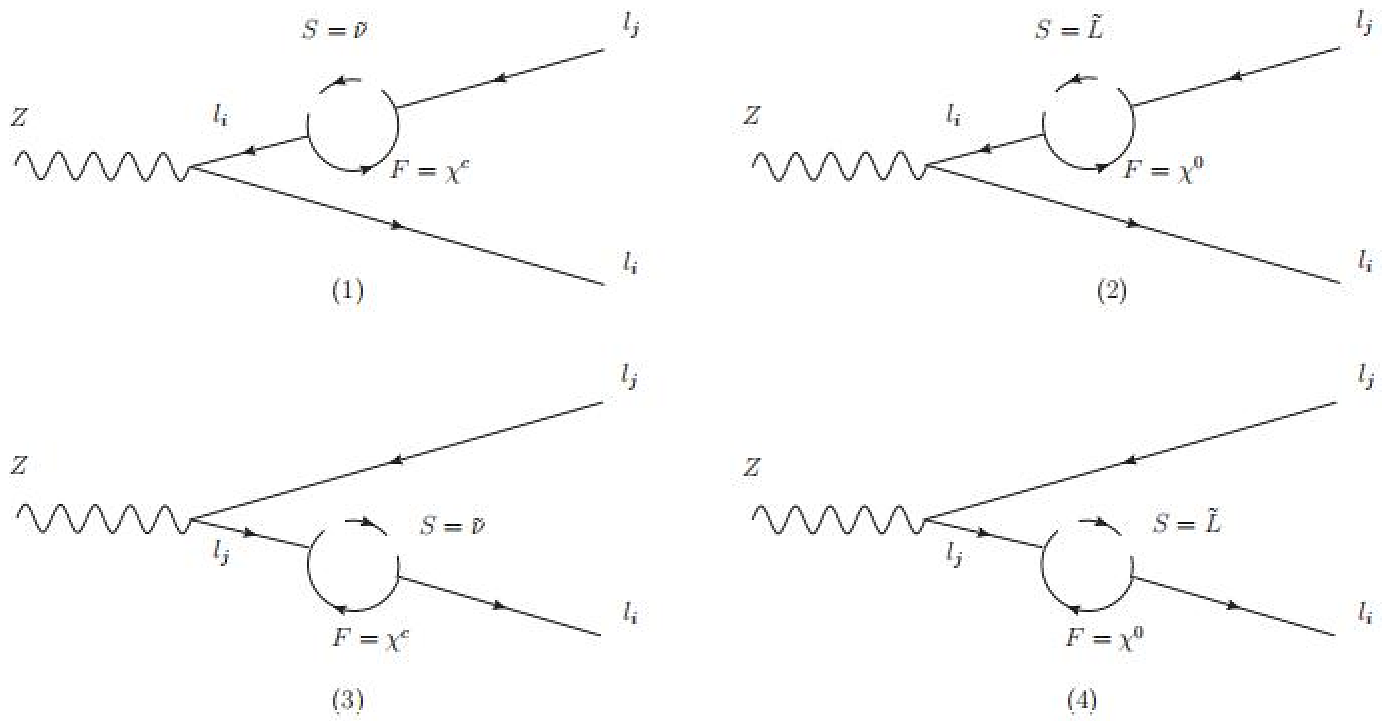


FIG. 2: Feynman diagrams for the processes $Z \to l_i^{\pm} l_j^{\mp}$ in the $U(1)_X$SSM, which denote self-energy diagrams contributing to $Z \to l_i^{\pm} l_j^{\mp}$ from loops.

4.2、Numerical results

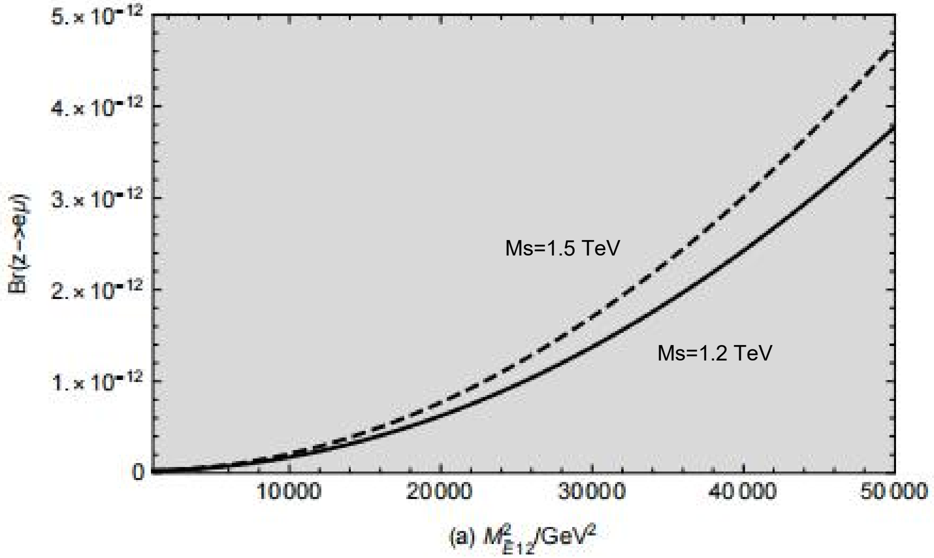
we adopt the following parameters in the numerical calculation

$$g_X = 0.3,\ g_{YX} = 0.1,\ \lambda_H = 0.1,\ \lambda_C = -0.2,\ \sqrt{v_\eta^2 + v_{\bar{\eta}}^2} = 17\ \text{TeV},$$

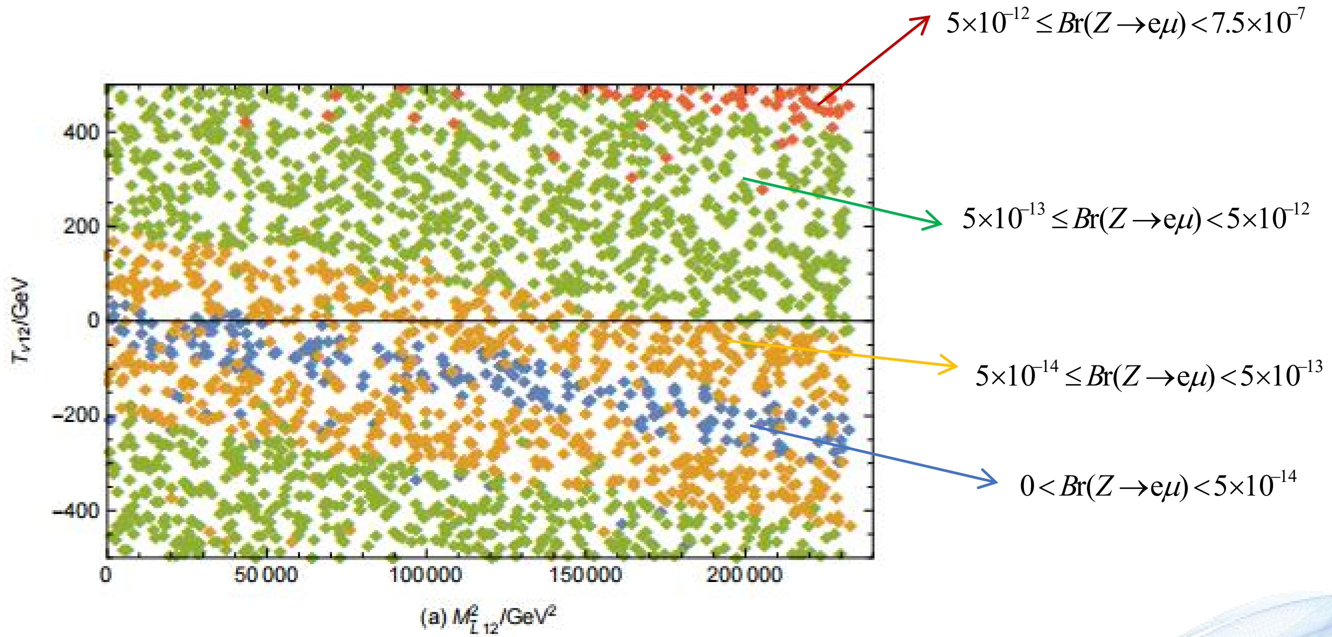
$$\mu = M_{BL} = T_{\lambda_H} = T_{\lambda_C} = T_\kappa = 1\ \text{TeV},\ M_{BB'} = 0.4\ \text{TeV},\ \kappa = 0.1,$$

$$l_W = B_\mu = B_S = 0.1\ \text{TeV}^2,\ T_{Xii} = -1\ \text{TeV},\ Y_{Xii} = 1,\ (i = 1, 2, 3).$$

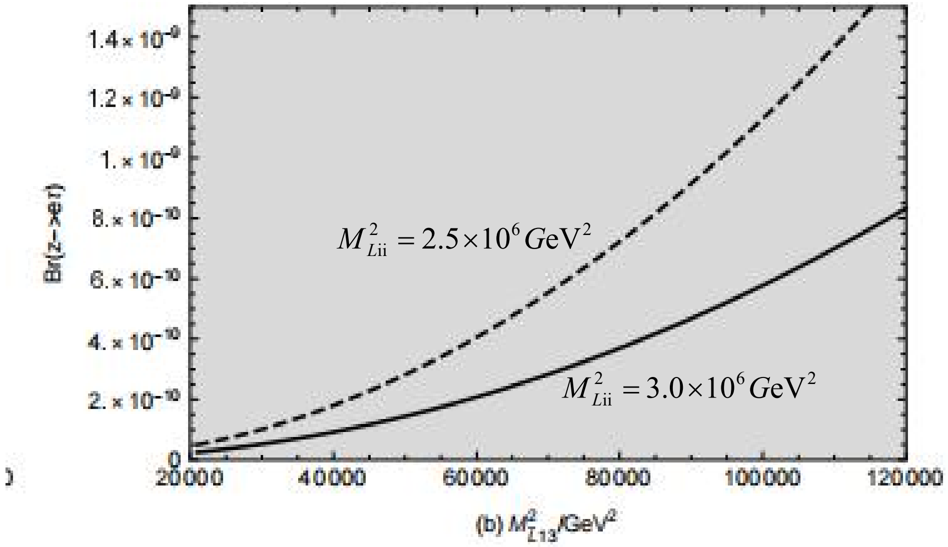
Z → eμ



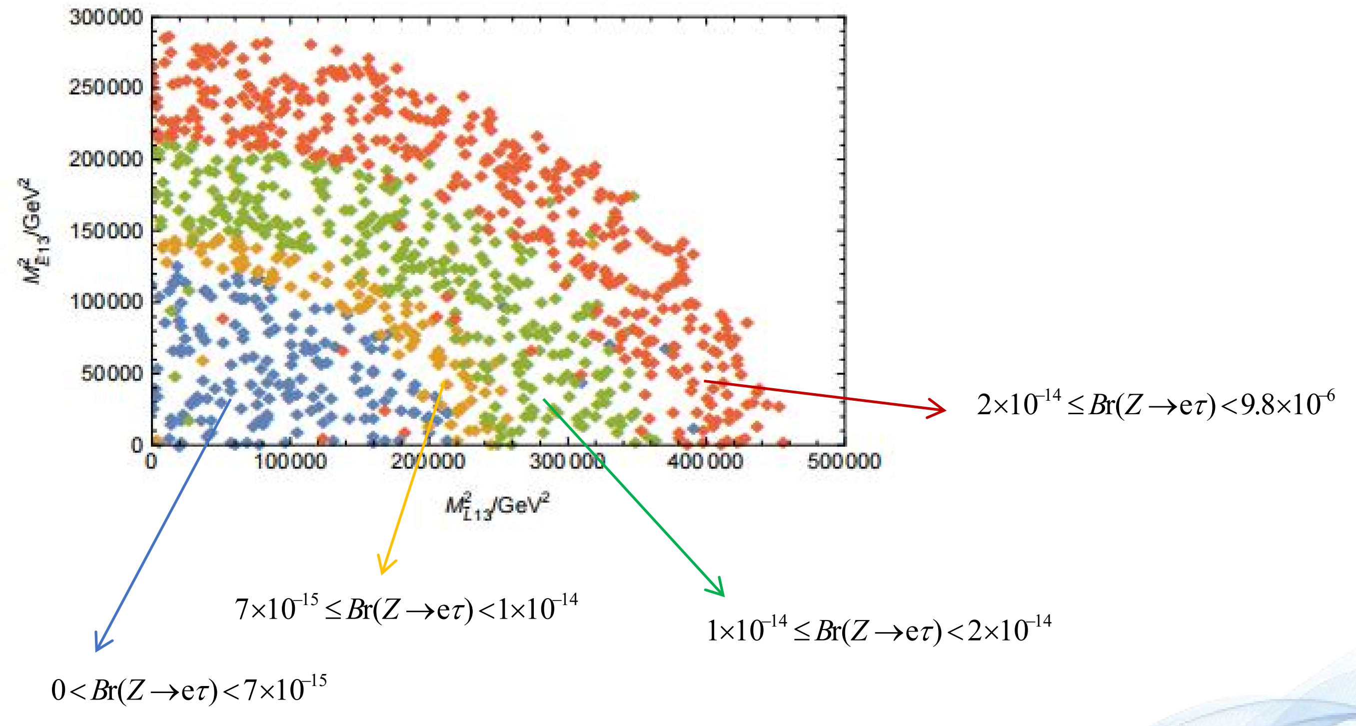
Parameters	Min	Max
$M^2_{\tilde{L}12}/\mathrm{GeV}^2$	0	10^6
$M^2_{\tilde{E}12}/\mathrm{GeV}^2$	0	10^6
$M^2_{\tilde{\nu}12}/\mathrm{GeV}^2$	0	10^6
T_{e12}/GeV	-300	300
$T_{\nu12}/\mathrm{GeV}$	-500	500
$M^2_{\tilde{L}ii}/\mathrm{GeV}^2$	2×10^5	10^9
$M^2_{\tilde{E}ii}/\mathrm{GeV}^2$	2×10^5	10^9
$M^2_{\tilde{\nu}ii}/\mathrm{GeV}^2$	1×10^5	10^9
T_{eii}/GeV	-3000	3000
$T_{\nu ii}/\mathrm{GeV}$	-3000	3000
$\tan\beta$	1	50
M_1/GeV	200	3000
M_2/GeV	600	3000



Z → eτ

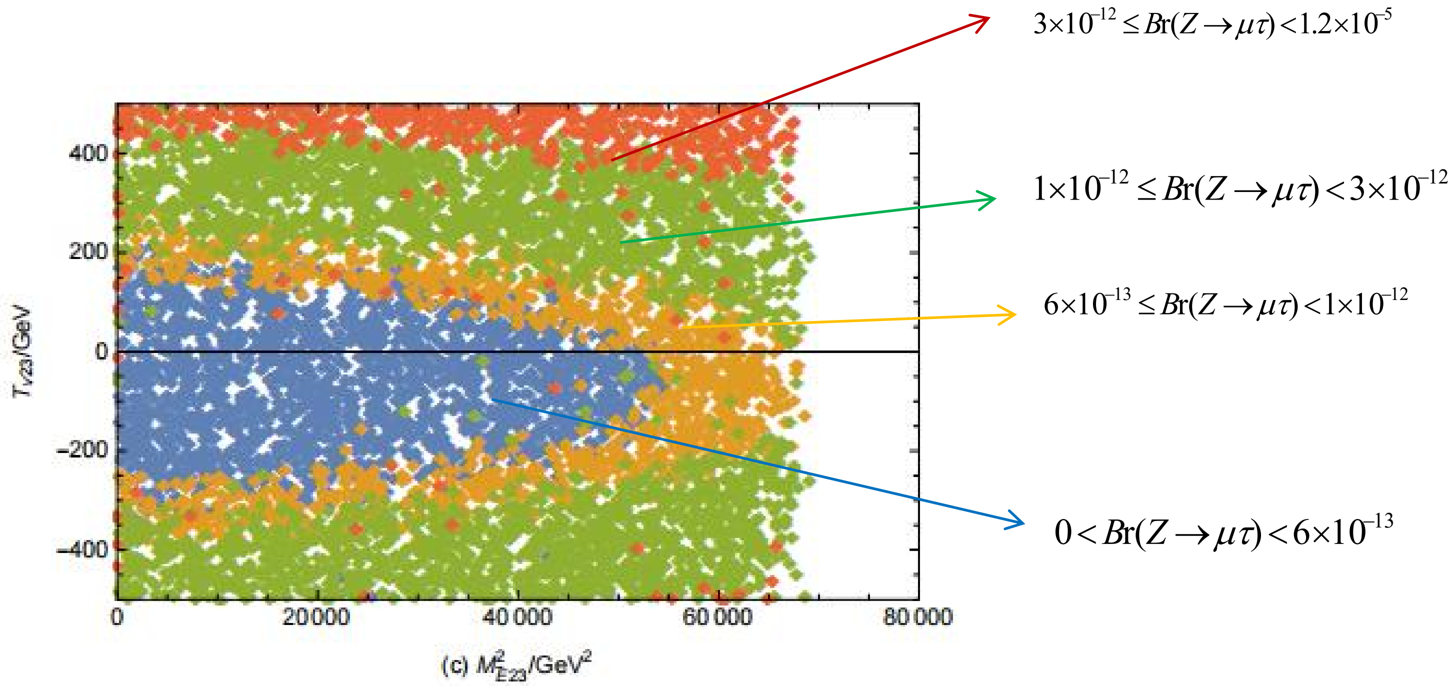


Parameters	Min	Max
$M^2_{\tilde{L}13}/\mathrm{GeV}^2$	0	10^6
$M^2_{\tilde{E}13}/\mathrm{GeV}^2$	0	10^6
$M^2_{\tilde{\nu}13}/\mathrm{GeV}^2$	0	10^6
T_{e13}/GeV	−300	300
$T_{\nu13}/\mathrm{GeV}$	−500	500



Z → μτ

Parameters	Min	Max
$M^2_{\tilde{L}23}/\text{GeV}^2$	0	10^5
$M^2_{\tilde{E}23}/\text{GeV}^2$	0	10^5
$M^2_{\tilde{\nu}23}/\text{GeV}^2$	0	10^5
T_{e23}/GeV	-300	300
$T_{\nu23}/\text{GeV}$	-500	500
$M^2_{\tilde{L}ii}/\text{GeV}^2$	2×10^5	10^8
$M^2_{\tilde{E}ii}/\text{GeV}^2$	2×10^5	10^8
$M^2_{\tilde{\nu}ii}/\text{GeV}^2$	1×10^5	10^8
T_{eii}/GeV	-3000	3000
$T_{\nu ii}/\text{GeV}$	-3000	3000



4.2、 Feynman diagrams of $\mathrm{h} \rightarrow l_i^{\pm} l_j^{\mp}$

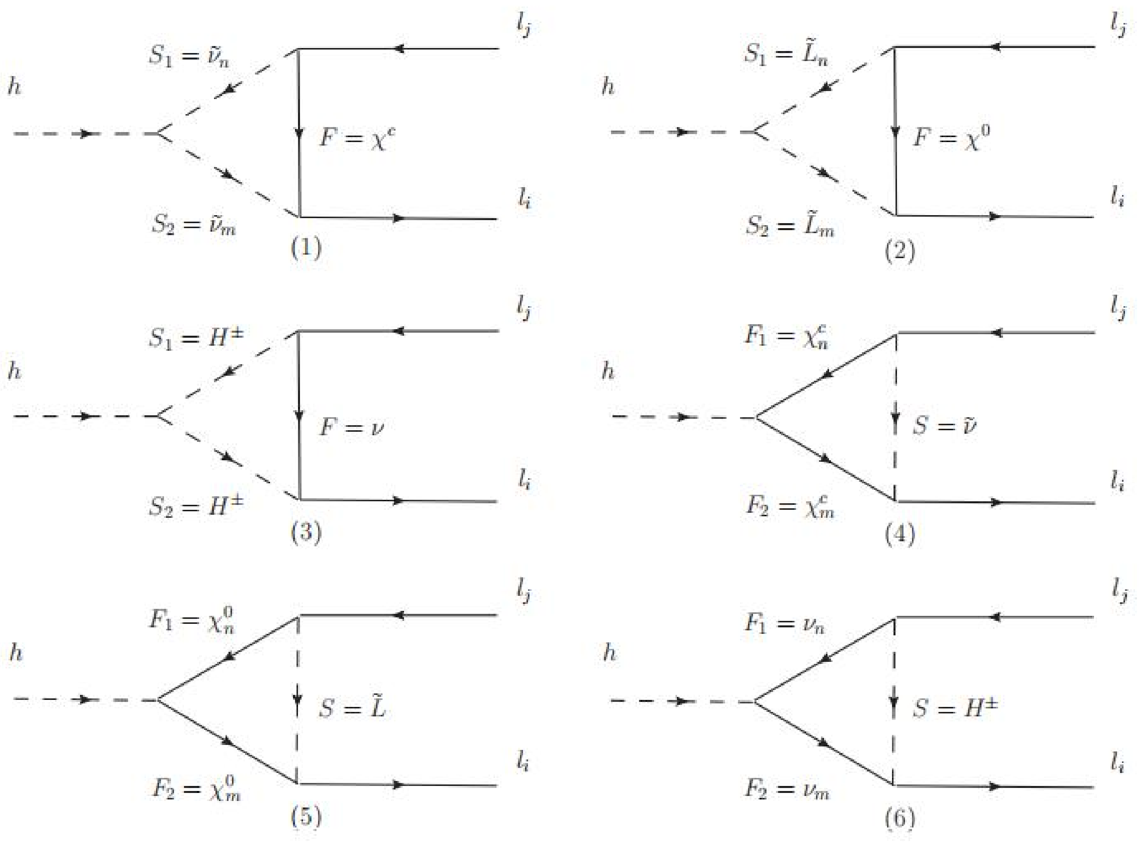


FIG. 3: Feynman diagrams for the processes $h \rightarrow l_i^{\pm} l_j^{\mp}$ in the $U(1)_X$SSM, which denote the contributions of vertex diagrams for $h \rightarrow l_i^{\pm} l_j^{\mp}$ from loops.

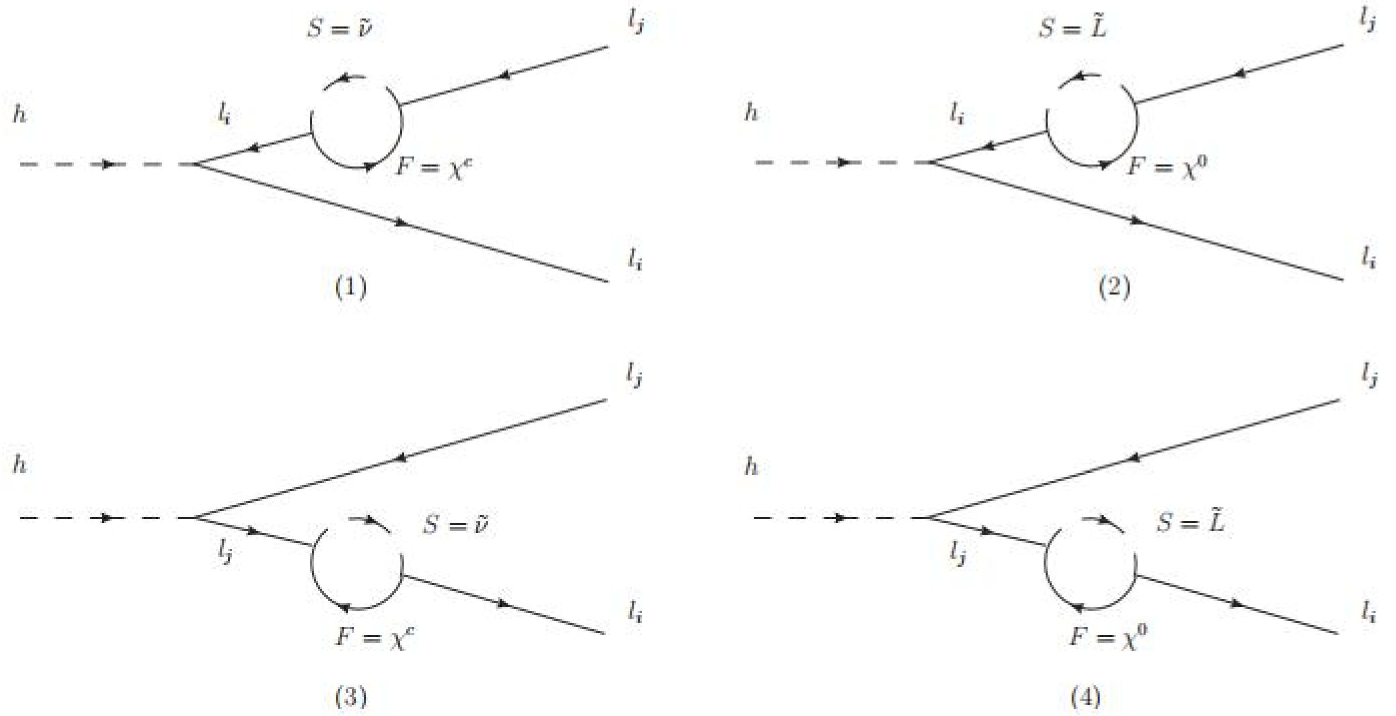
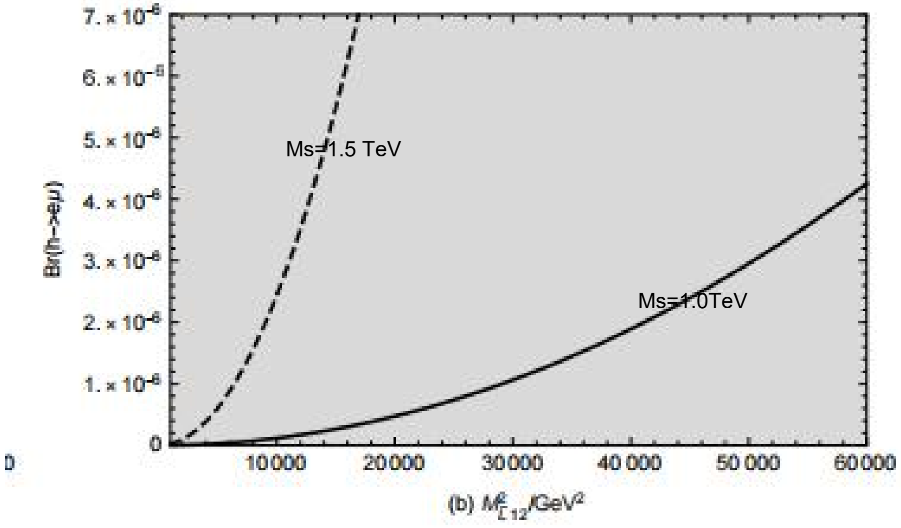
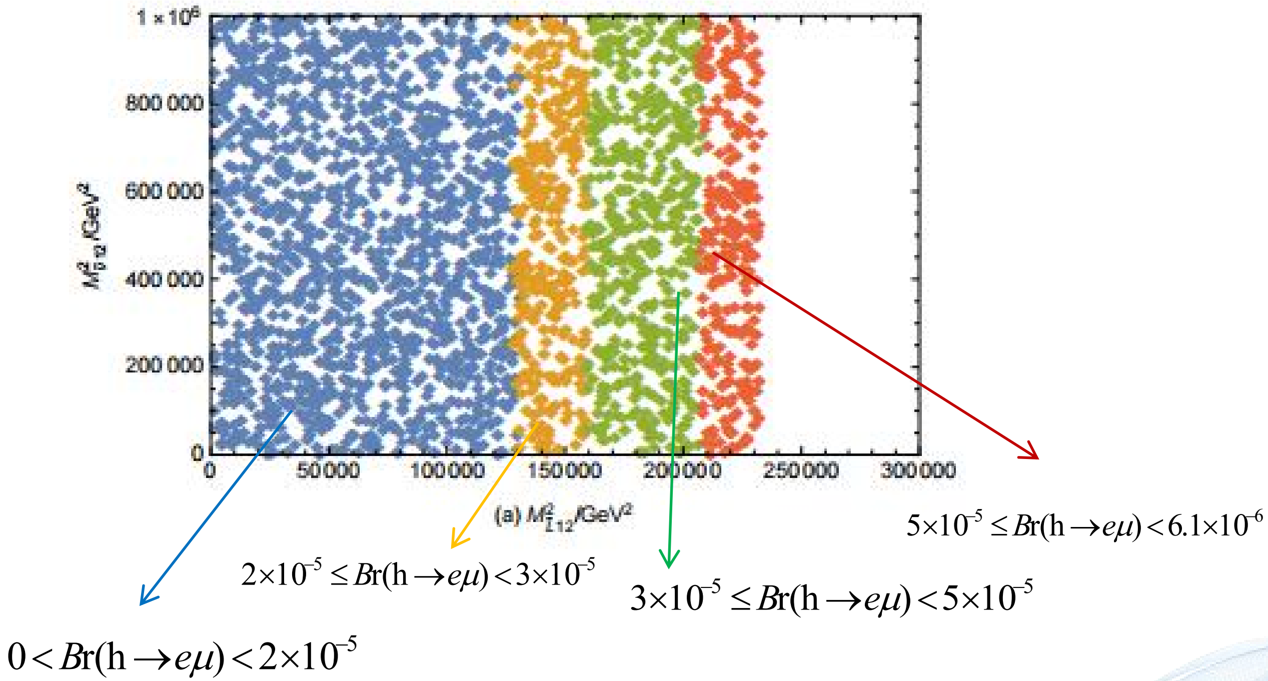


FIG. 4: Feynman diagrams for the processes $h \to l_i^{\pm} l_j^{\mp}$ in the $U(1)_X$SSM, which denote self-energy diagrams contributing to $h \to l_i^{\pm} l_j^{\mp}$ from loops.

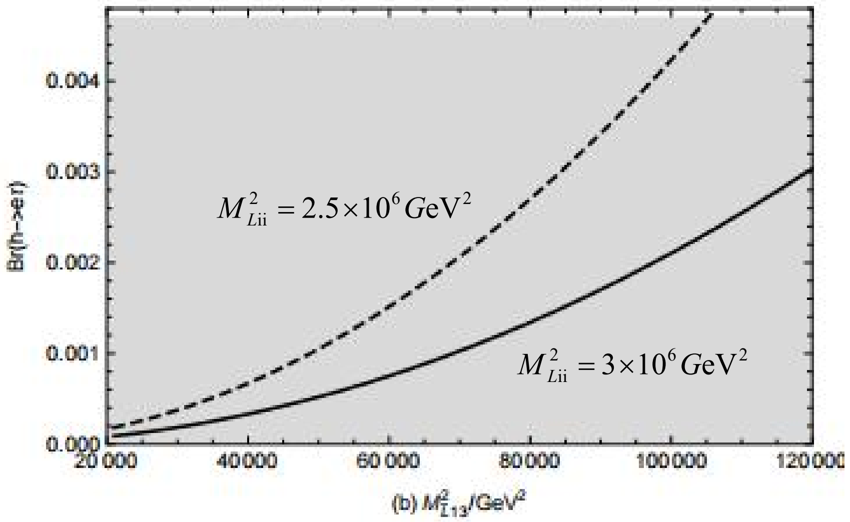
h → eμ



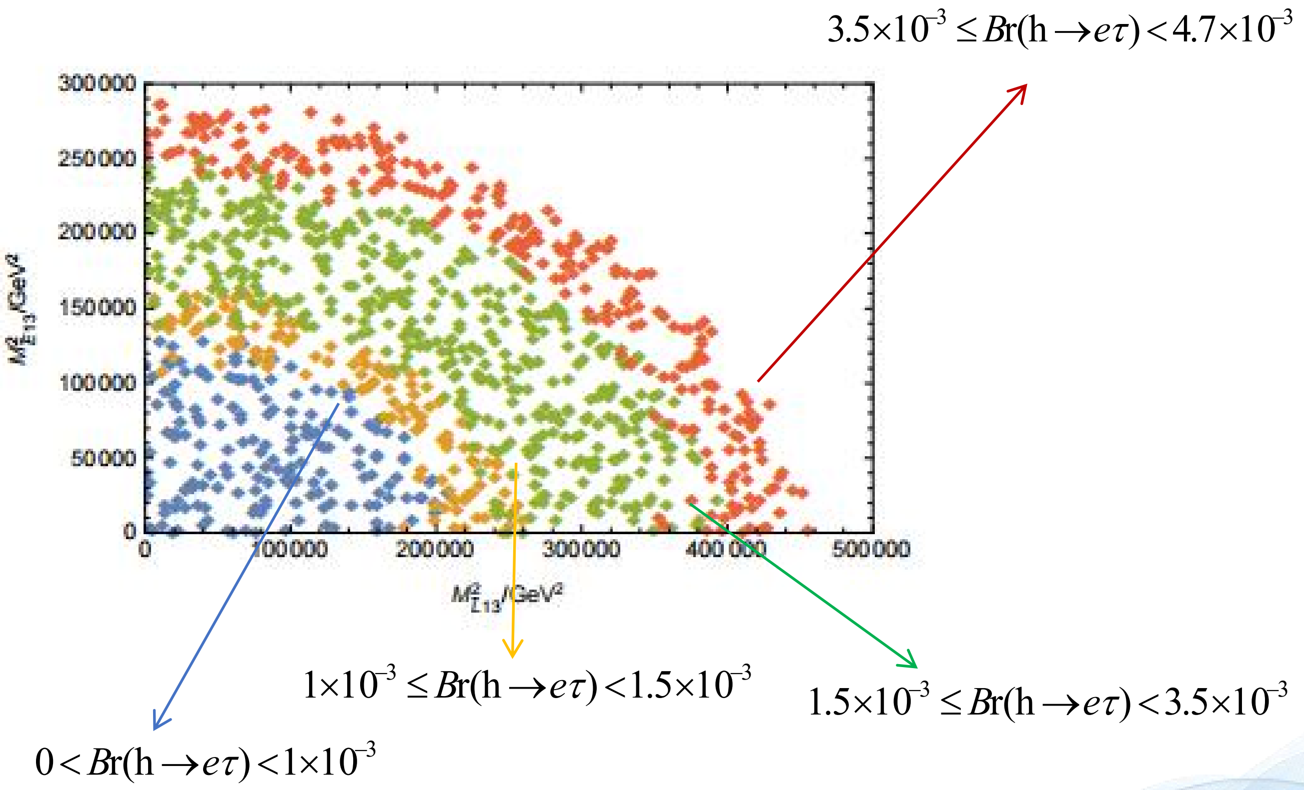
Parameters	Min	Max
$M^2_{\tilde{L}12}/\mathrm{GeV}^2$	0	10^6
$M^2_{\tilde{E}12}/\mathrm{GeV}^2$	0	10^6
$M^2_{\tilde{\nu}12}/\mathrm{GeV}^2$	0	10^6
T_{e12}/GeV	−300	300
$T_{\nu12}/\mathrm{GeV}$	−500	500
$M^2_{\tilde{L}ii}/\mathrm{GeV}^2$	2×10^5	10^9
$M^2_{\tilde{E}ii}/\mathrm{GeV}^2$	2×10^5	10^9
$M^2_{\tilde{\nu}ii}/\mathrm{GeV}^2$	1×10^5	10^9
T_{eii}/GeV	−3000	3000
$T_{\nu ii}/\mathrm{GeV}$	−3000	3000
$\tan\beta$	1	50
M_1/GeV	200	3000
M_2/GeV	600	3000



h → eτ

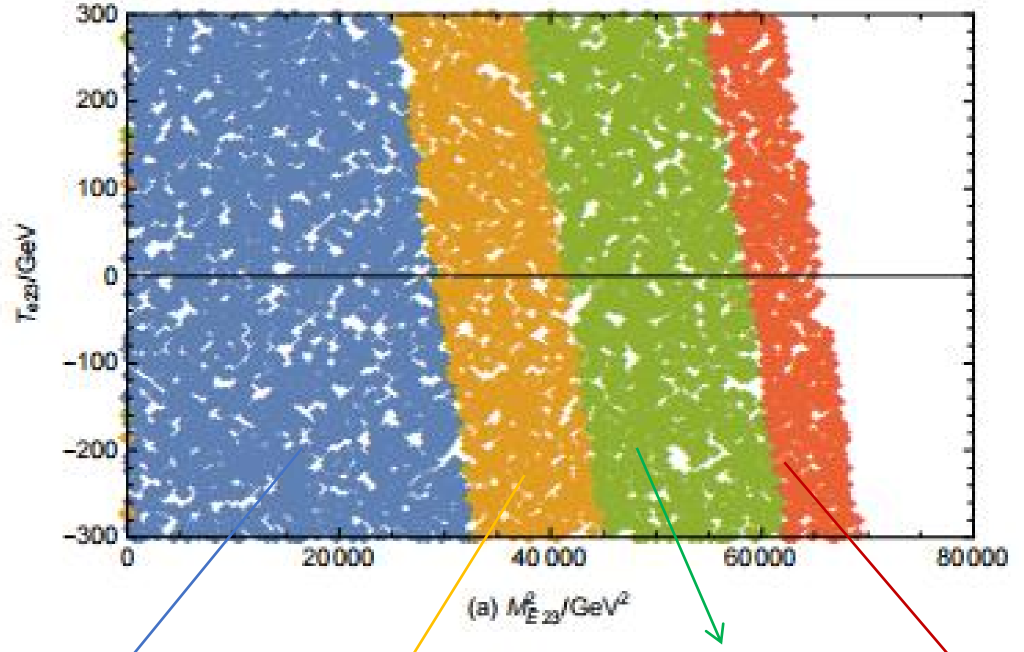


Parameters	Min	Max
$M^2_{\tilde{L}13}/\mathrm{GeV}^2$	0	10^6
$M^2_{\tilde{E}13}/\mathrm{GeV}^2$	0	10^6
$M^2_{\tilde{\nu}13}/\mathrm{GeV}^2$	0	10^6
T_{e13}/GeV	-300	300
$T_{\nu13}/\mathrm{GeV}$	-500	500



h → μτ

Parameters	Min	Max
$M^2_{\tilde{L}23}/\mathrm{GeV}^2$	0	10^5
$M^2_{\tilde{E}23}/\mathrm{GeV}^2$	0	10^5
$M^2_{\tilde{\nu}23}/\mathrm{GeV}^2$	0	10^5
T_{e23}/GeV	-300	300
$T_{\nu23}/\mathrm{GeV}$	-500	500
$M^2_{\tilde{L}ii}/\mathrm{GeV}^2$	2×10^5	10^8
$M^2_{\tilde{E}ii}/\mathrm{GeV}^2$	2×10^5	10^8
$M^2_{\tilde{\nu}ii}/\mathrm{GeV}^2$	1×10^5	10^8
T_{eii}/GeV	-3000	3000
$T_{\nu ii}/\mathrm{GeV}$	-3000	3000



$1\times10^{-3} \le Br(h\to\mu\tau) < 2\times10^{-3}$

$0 < Br(h\to\mu\tau) < 5\times10^{-4}$

$2\times10^{-3} \le Br(h\to\mu\tau) < 2.5\times10^{-3}$

$5\times10^{-4} \le Br(h\to\mu\tau) < 1\times10^{-3}$

5、Summary

- We study the LFV of the $l_j \to l_i\gamma$, $l_j \to l_i\gamma\gamma$, $Z \to l_i^{\pm} l_j^{\mp}$ and $h \to l_i^{\pm} l_j^{\mp}$ in the $U(1)_X SSM$. In the numerical calculation, we take many parameters as variables, We find the branching ratios depend on the slepton flavor mixing parameters.

- ① Fully satisfying the experimental constraints, we get that the branching ratio of $\mu \to e\gamma\gamma$ can reach 10^{-12}, $\tau \to \mu\gamma\gamma$ can reach 10^{-4} and $\tau \to e\gamma\gamma$ can reach 10^{-5}.

  ② we get that the branching ratio of $Z \to e\mu$ can reach 10^{-11}, the branching ratios of $Z \to e\tau$ and $Z \to \mu\tau$ can reach 10^{-9}.

  ③The branching ratio of $h \to e\mu$ can reach 10^{-5}, the branching ratios of $h \to e\tau$ and $h \to \mu\tau$ can reach 10^{-3}.

- The non-diagonal elements which correspond to the generations of the initial lepton and final lepton are main sensitive parameters and LFV sources.

Thank you