The lepton flavor changing processes: $\gamma\gamma \to \ell_i \bar{\ell}_j$ in HTM

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Motivation of the New Physics

Though the 125GeV higgs-like found, still large space for new physics:

1. neutrino masses
2. Dark matter
3. fine-tuning, too many handed-put parameters put by hand
4. SM in any case, an effective energy, new physics should exist
5. flavor problem
6. Triviality bounds and vacuum stability bounds. Triviality bounds needs light higgs. Triviality bounds $\Lambda_\infty \simeq v \times (5 \times 10^5)^{\frac{246^2}{m_h^2}}$. Vacuum stability bounds $m_H \leq 129.5 + 1.4\frac{m_t(GeV)-173.1}{0.7} - 0.5\frac{\alpha_s(M_z)-0.1184}{0.0007}$.

Contents

the Higgs Triplet Model

a $I = 1,\ Y = 2$ complex $SU(2)_L$ isospin triplet of scalar fields is added to the SM Lagrangian. Such a model can provide a Majorana mass for the observed neutrinos without the introduction of a right-handed neutrino

$$\mathcal{L} = h_{ij}\psi_{iL}^{T} C i\tau_2 \Delta \psi_{jL} + h.c \tag{1}$$

$$\Delta = \begin{pmatrix} \Delta^{+}/\sqrt{2} & \Delta^{++} \\ \Delta^{0} & -\Delta^{+}/\sqrt{2} \end{pmatrix} \tag{2}$$

$$m_{ij} = 2h_{ij}\langle\Delta^{0}\rangle = \sqrt{2}h_{ij}v_{\Delta} \tag{3}$$

V_{MNS}- Diagonalizing mass matrix of 3 Dirac neutrinos and the cou

$$V_{MNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \quad (4)$$

Majorana neutrinos: $V = V_{MNS} \times diag(1, e^{i\varphi_1/2}, e^{i\varphi_2/2})$,

Rewritten m_{ij} in the basis of the three diagonal Dirac neutrino masses by the MNS (Maki-Nakagawa-Sakata) matrix VMNS,

$$h_{ij} = \frac{m_{ij}}{\sqrt{2}v_\Delta} = \frac{1}{\sqrt{2}v_\Delta} \left[V_{MNS} diag(m_1, m_2 e^{i\phi_1}, m_3 e^{i\phi_2}) V_{MNS}^T\right]_{ij} \quad (5)$$

Explicit form of h_{ij}-1

$$
\begin{aligned}
h_{ee} &= \frac{1}{\sqrt{2}v_\Delta}\left(m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{i\phi_1} + m_3 s_{13}^2 e^{-2i\delta} e^{i\phi_2}\right), \\
h_{e\mu} &= \frac{1}{\sqrt{2}v_\Delta}\Big\{m_1(-s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta})c_{12}c_{13} \\
&\quad + m_2(c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta})s_{12}c_{13}e^{i\phi_1} + m_3 s_{23}c_{13}s_{13}e^{-i\delta}e^{i\phi_2}\Big\}, \\
h_{e\tau} &= \frac{1}{\sqrt{2}v_\Delta}\Big\{m_1(s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta})c_{12}c_{13} \\
&\quad + m_2(-c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta})s_{12}c_{13}e^{i\phi_1} + m_3 c_{23}c_{13}s_{13}e^{-i\delta}e^{i\phi_2}\Big\},
\end{aligned}
$$

Explicit form of h_{ij}-2

$$
\begin{aligned}
h_{\mu\mu} &= \frac{1}{\sqrt{2}v_\Delta}\Big\{m_1(-s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta})^2 \\
&+ m_2(c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta})^2e^{i\phi_1}+m_3s_{23}^2c_{13}^2e^{i\phi_2}\Big\}, \\
h_{\mu\tau} &= \frac{1}{\sqrt{2}v_\Delta}\Big\{m_1(-s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta})(s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta}) \\
&+ m_2(c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta})(-c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta})e^{i\phi_1}+m_3c_{23}s_{23}c_{13}^2e^{i\phi_2}\Big\}, \\
h_{\tau\tau} &= \frac{1}{\sqrt{2}v_\Delta}\Big\{m_1(s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta})^2+m_2(-c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta})^2e^{i\phi_1} \\
&+ m_3c_{23}^2c_{13}^2e^{i\phi_2}\Big\}.
\end{aligned}
\tag{6}
$$

The 9 parameters involved in h_{ij}

h_{ij}–9 parameters, Δm^2_{21}, Δm^2_{31} , m_0, three mixing angles (θ_{12}, θ_{13}, θ_{23}), and three complex phases (δ, ϕ_1, ϕ_2)

$$\Delta m^2_{21} \equiv m^2_2 - m^2_1 \simeq 7.9 \times 10^{-5}\mathrm{eV}^2\,, \quad |\Delta m^2_{31}| \equiv |m^2_3 - m^2_1| \simeq 2.7 \times 10^{-3}\mathrm{eV}^2\,, \tag{7}$$

$$\sin^2 2\theta_{12} \simeq 0.86\,, \qquad \sin^2 2\theta_{23} \simeq 1\,, \qquad \sin^2 2\theta_{13} \simeq 0.089\,. \tag{8}$$

Take $\delta = 0$;

Normal hierarchy: $m_1 < m_2 < m_3$;

Inverted hierarchy: $m_3 < m_1 < m_2$

m_0 and four cases of ϕ_1, ϕ_2

ArXiv: 0911.5291 shows that the upper limit of $\sum m_\nu \leq 0.28$ eV ($95\%\ CL$) on the sum of the neutrino masses assuming a flat ΛCDM cosmology. We take $0 \leq m_0 \leq 0.3$ eV

Case I ($\varphi_1 = 0, \varphi_2 = 0$);

Case II ($\varphi_1 = 0, \varphi_2 = \pi$);

Case III ($\varphi_1 = \pi, \varphi_2 = 0$);

Case IV ($\varphi_1 = \pi, \varphi_2 = \pi$)

phenomenological constraints on the parameters h_{ij}

$\mu \to e\gamma$, $\tau \to e(\mu)\gamma$, $\mu \to eee$, and $\tau \to lll$ etc., in hep-ph/9511297,0304254,0304069, etc., give $h_{ij} \leq 1$, or much smaller than 1

Especially for h_{ee} and $h_{e\mu}$, quite small, close to 0 — we will consider the limits: $h_{ee} = h_{e\mu} = 0$,

parameter v_Δ and the scalar masses $m_{\phi^{\pm\pm}}$ and $m_{\phi^{\pm}}$

In general, m_ϕ in the order of hundred GeV. So we here assume the scalar mass m_ϕ is less than 1 TeV and to investigate the dependence of the cross sections on it, 3 classical values: $m_\phi = 200,\ 500,\ 1000$ GeV are taken

—— small neutrino masses make small v_Δ necessary and natural

—— adjusting various parameters in the most general form of the Higgs potential make Small v_Δ possible

——two possible realization, I, the lepton number is explicitly violated at very low energy scale M_S, resulting in a tiny v_Δ[0509152]

II, even if the energy scale M_S is not so tiny, i.e, $M_S \sim v$ $(v = 246$ GeV),

v_Δ can be naturally small, which is denoted as a "type II seesaw mechanism" [0904.3640].

WE choose v_Δ at the order of the typical neutrino mass upper limit, i.e, $v_\Delta \sim 1$ eV.

$$M = v_\Delta \approx eV << v_\phi. \tag{9}$$

In calculation, $v_\Delta = 1$ eV taken.

scalar masses in the range of a few of hundred GeV, We take degenerate masses unless with otherwise statement, i.e, $m_{\phi^{\pm\pm}} = m_{\phi^\pm} = m_\phi$

The Amplitude and the Cross Section of the processes

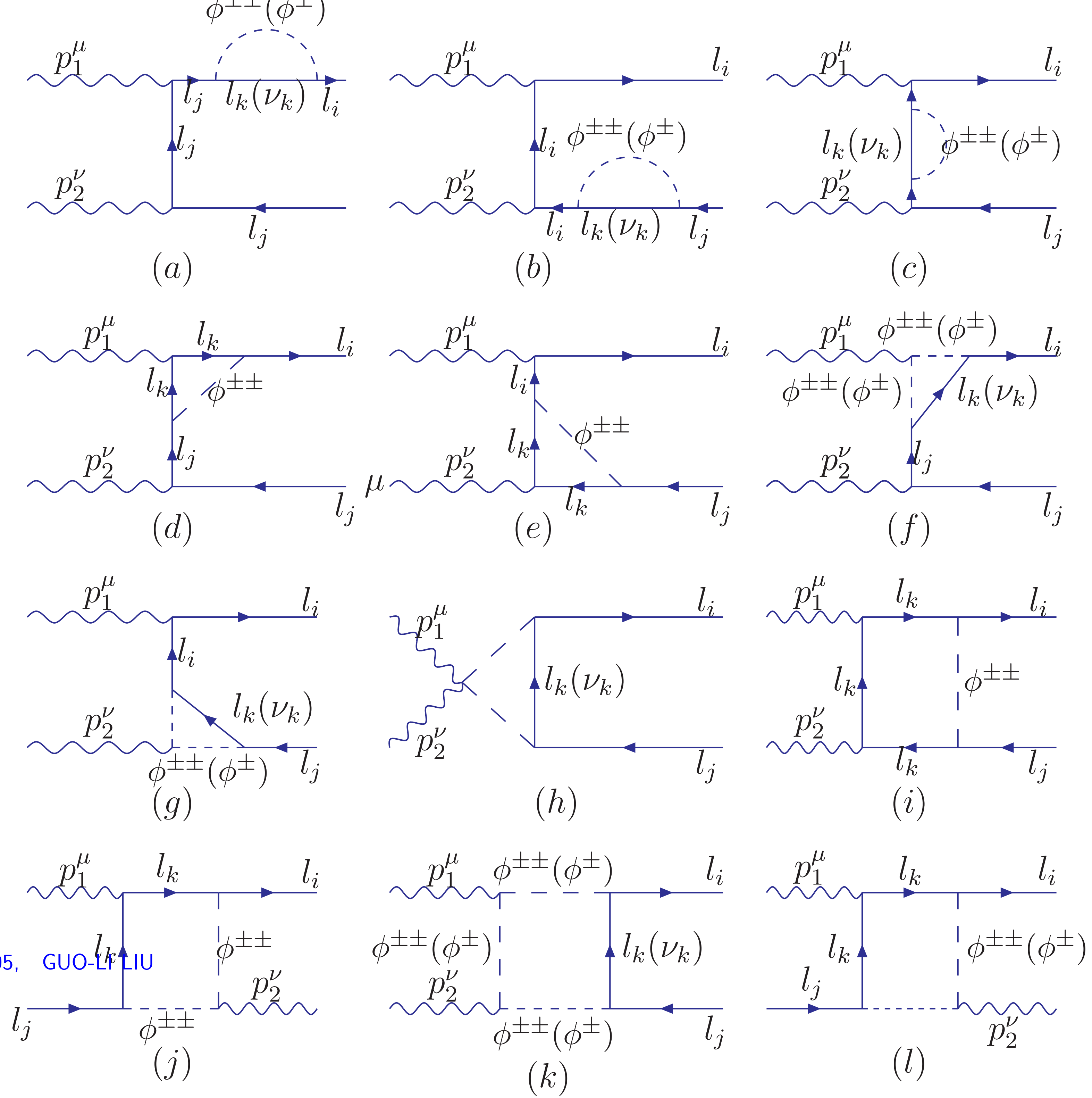
$$\mathcal{M} = \frac{1}{2}\,\bar{u}_\tau \Gamma^{\mu\nu} P_L v_\mu\ \epsilon_\mu(\lambda_1)\epsilon_\nu(\lambda_2) \tag{10}$$

$$N_{\gamma\gamma\to\ell_i\bar{\ell}_j} = \int d\sqrt{s_{\gamma\gamma}}\frac{d\mathcal{L}_{\gamma\gamma}}{d\sqrt{s_{\gamma\gamma}}}\hat{\sigma}_{\gamma\gamma\to\ell_i\bar{\ell}_j}(s_{\gamma\gamma}) \equiv \mathcal{L}_{e^+e^-}\sigma_{\gamma\gamma\to\ell_i\bar{\ell}_j}(s)\ , \tag{11}$$

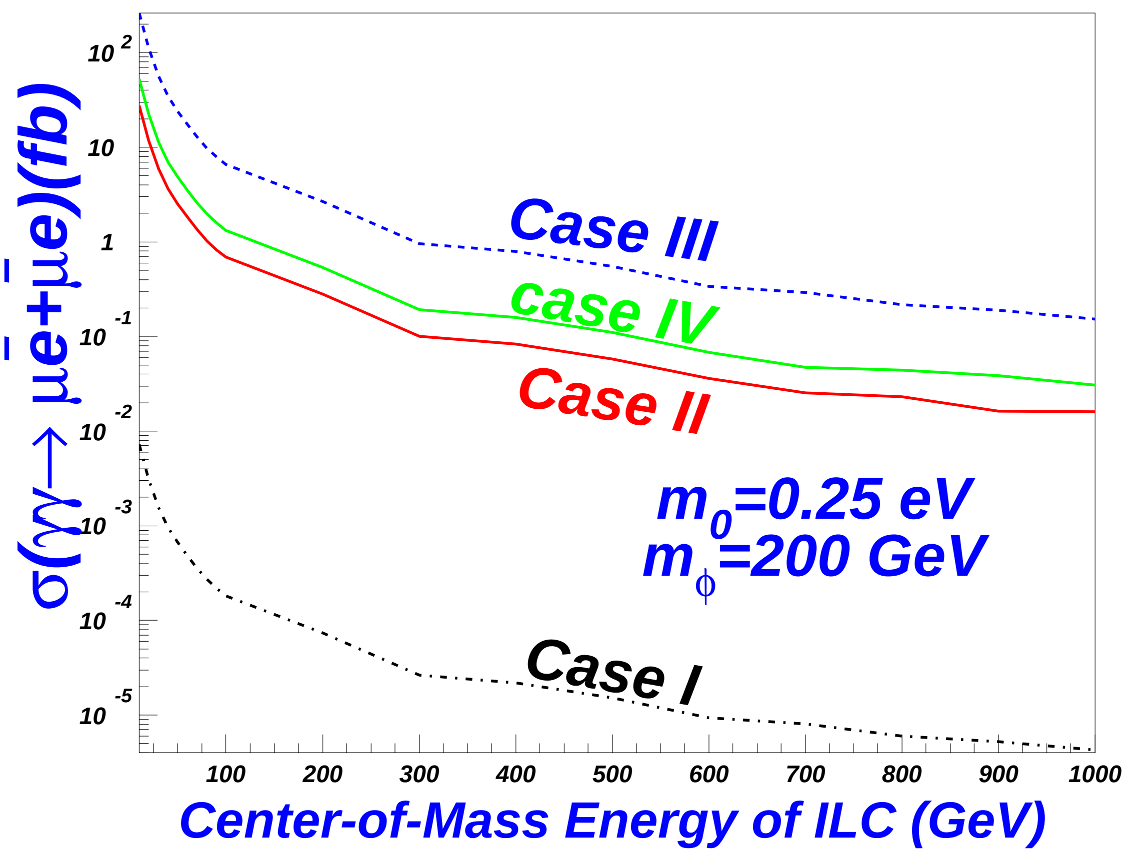
$$\sigma_{\gamma\gamma\to\ell_i\bar{\ell}_j}(s) = \int_{\sqrt{a}}^{x_{max}} 2zdz\hat{\sigma}_{\gamma\gamma\to\ell_i\bar{\ell}_j}(s_{\gamma\gamma} = z^2 s)\int_{z^2/x_{max}}^{x_{max}}\frac{dx}{x}F_{\gamma/e}(x)F_{\gamma/e}(\frac{z^2}{x}) \tag{12}$$

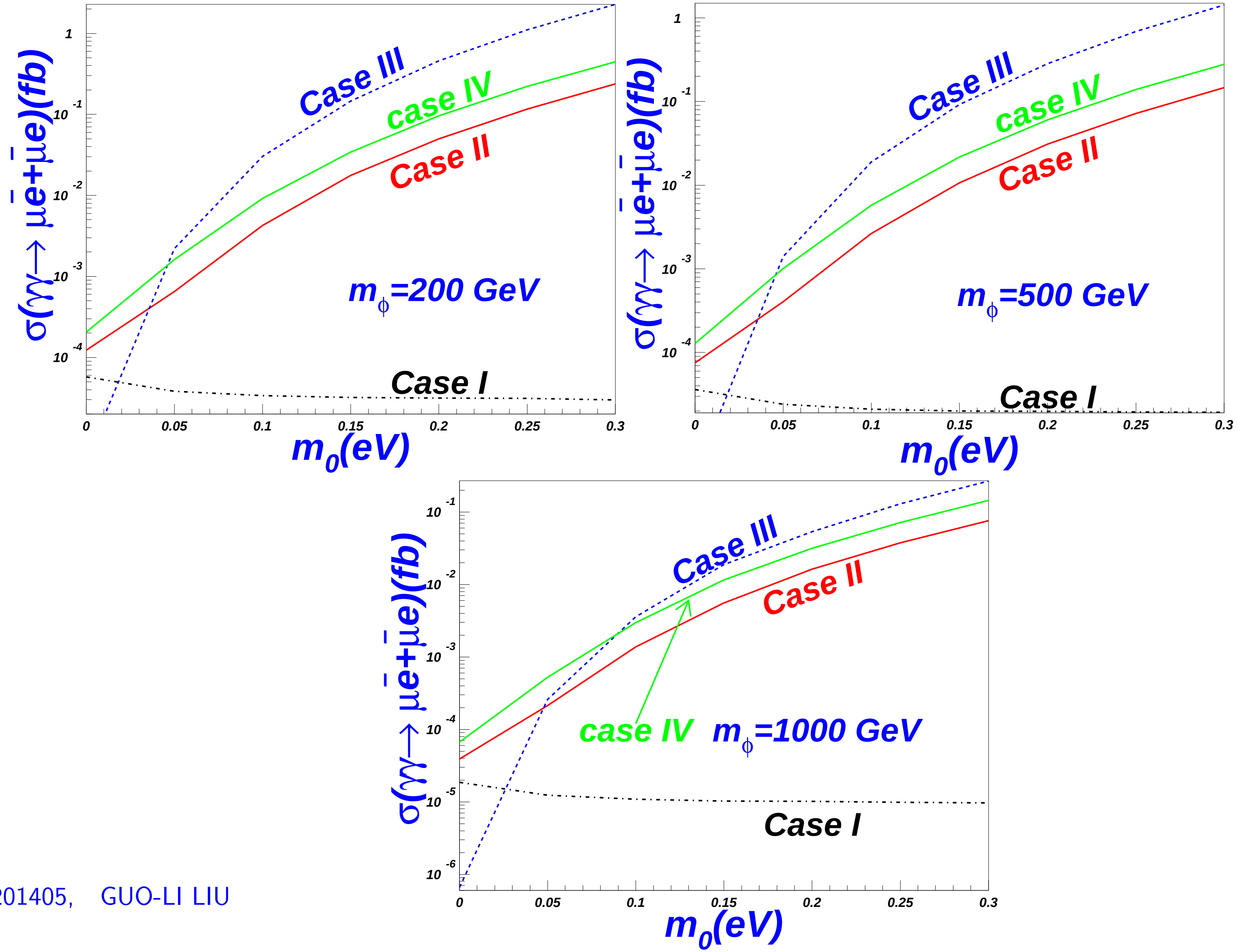
$$F_{\gamma/e}(x) = \frac{1}{D(\xi)}\left[1 - x + \frac{1}{1-x} - \frac{4x}{\xi(1-x)} + \frac{4x^2}{\xi^2(1-x)^2}\right] \tag{13}$$

Feynman diagrams

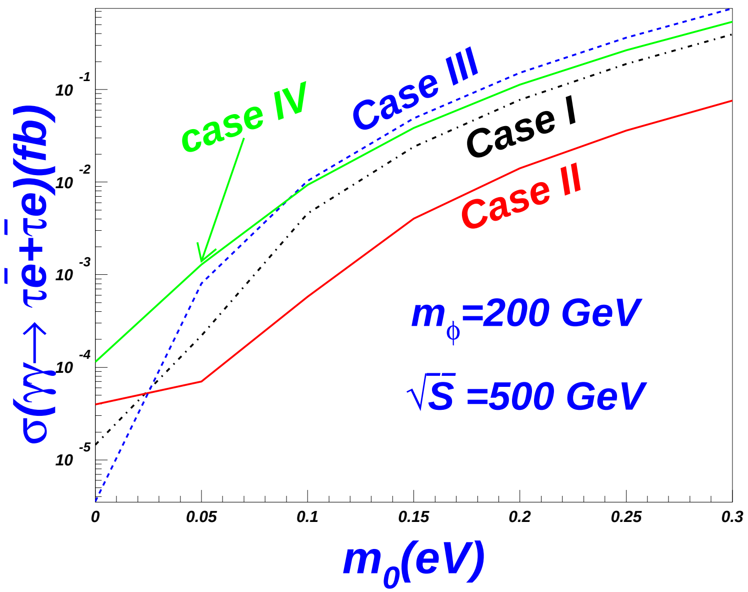

(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
(j)
(k)
(l)

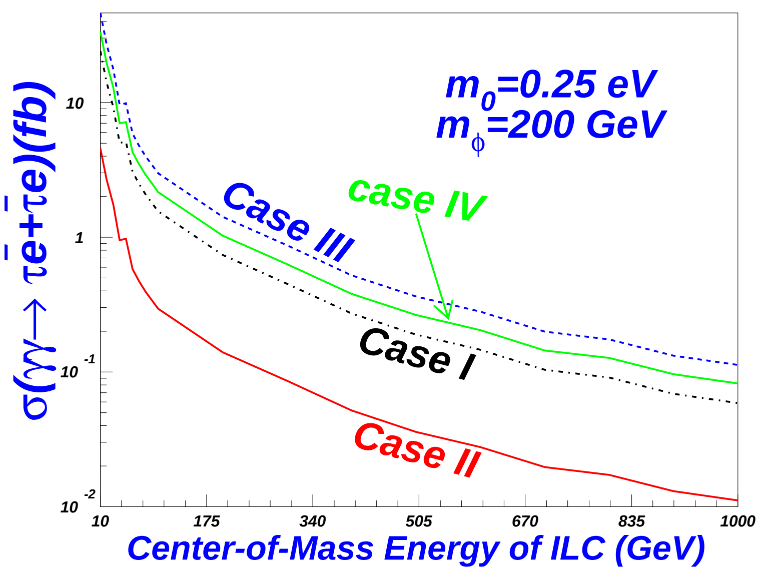
numerical calculation—- Normal Hierarchy

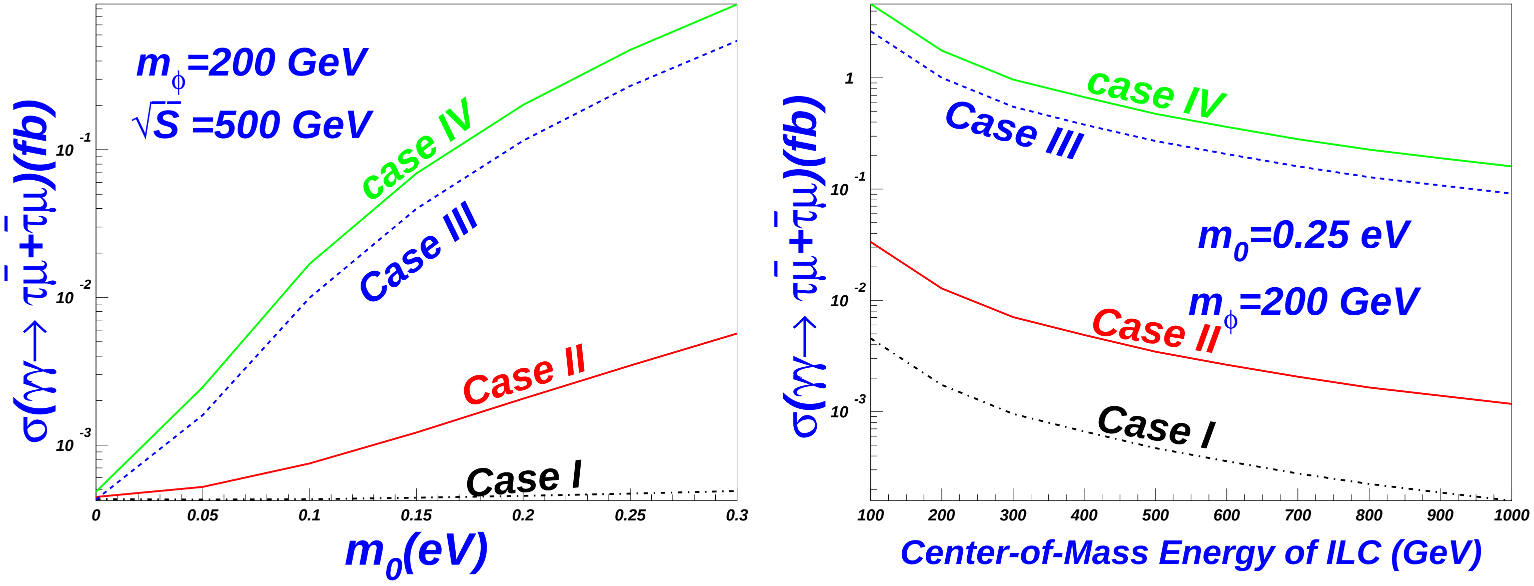




σ(γγ→ μ̄e+μē)(fb)
m0(eV)
Case III
case IV
Case II
Case I
mφ=200 GeV
mφ=500 GeV
mφ=1000 GeV

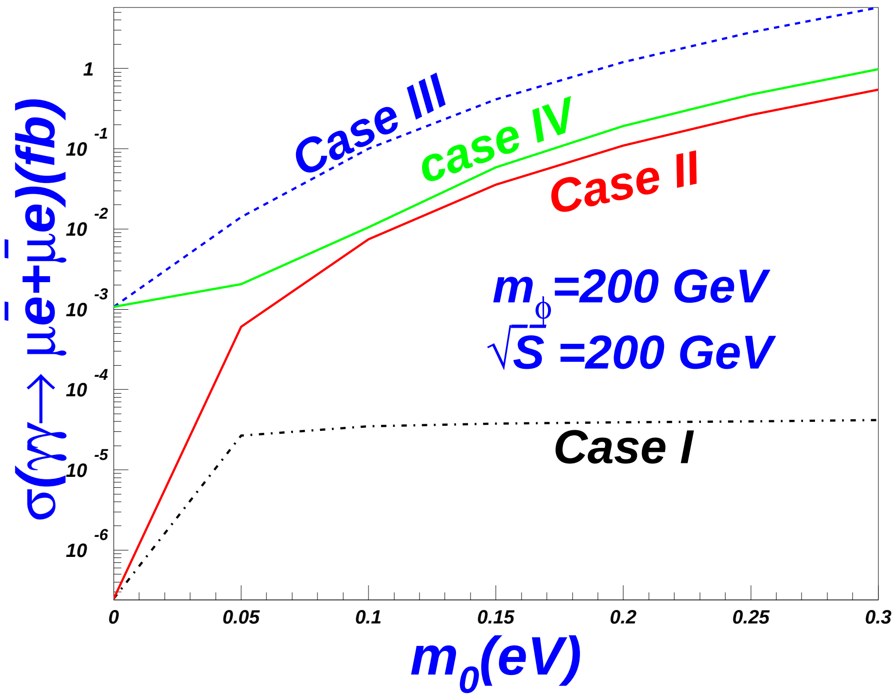

case IV
Case III
Case I
Case II
m_ϕ=200 GeV
$\sqrt{S}$ =500 GeV
$\sigma(\gamma\gamma\to\tau\bar{e}+\bar{\tau}e)$(fb)
m_0(eV)

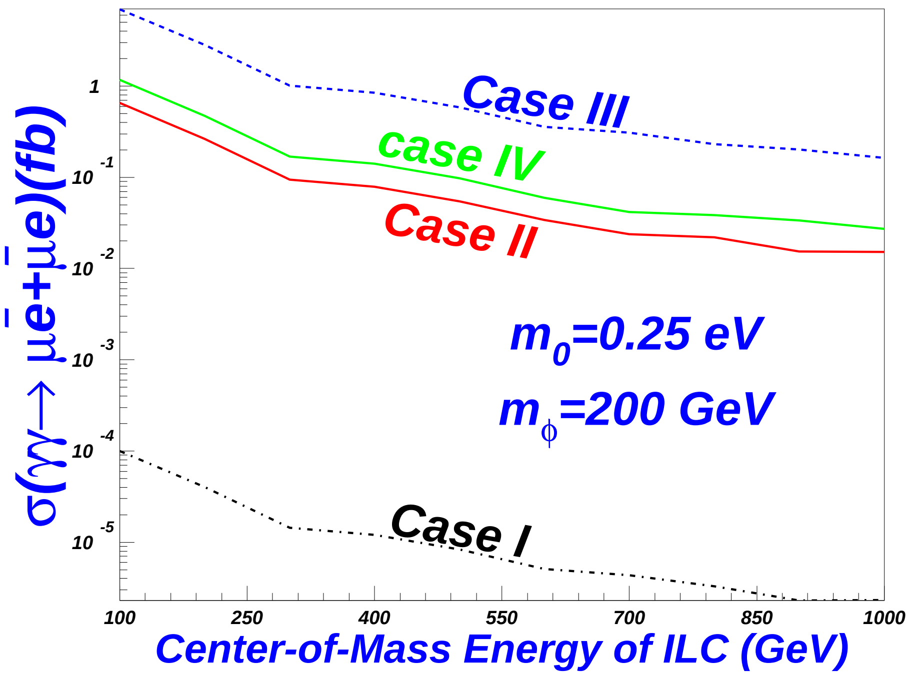

m_0=0.25 eV
m_ϕ=200 GeV
Case III
case IV
Case I
Case II
$\sigma(\gamma\gamma\to\tau\bar{e}+\bar{\tau}e)$(fb)
Center-of-Mass Energy of ILC (GeV)

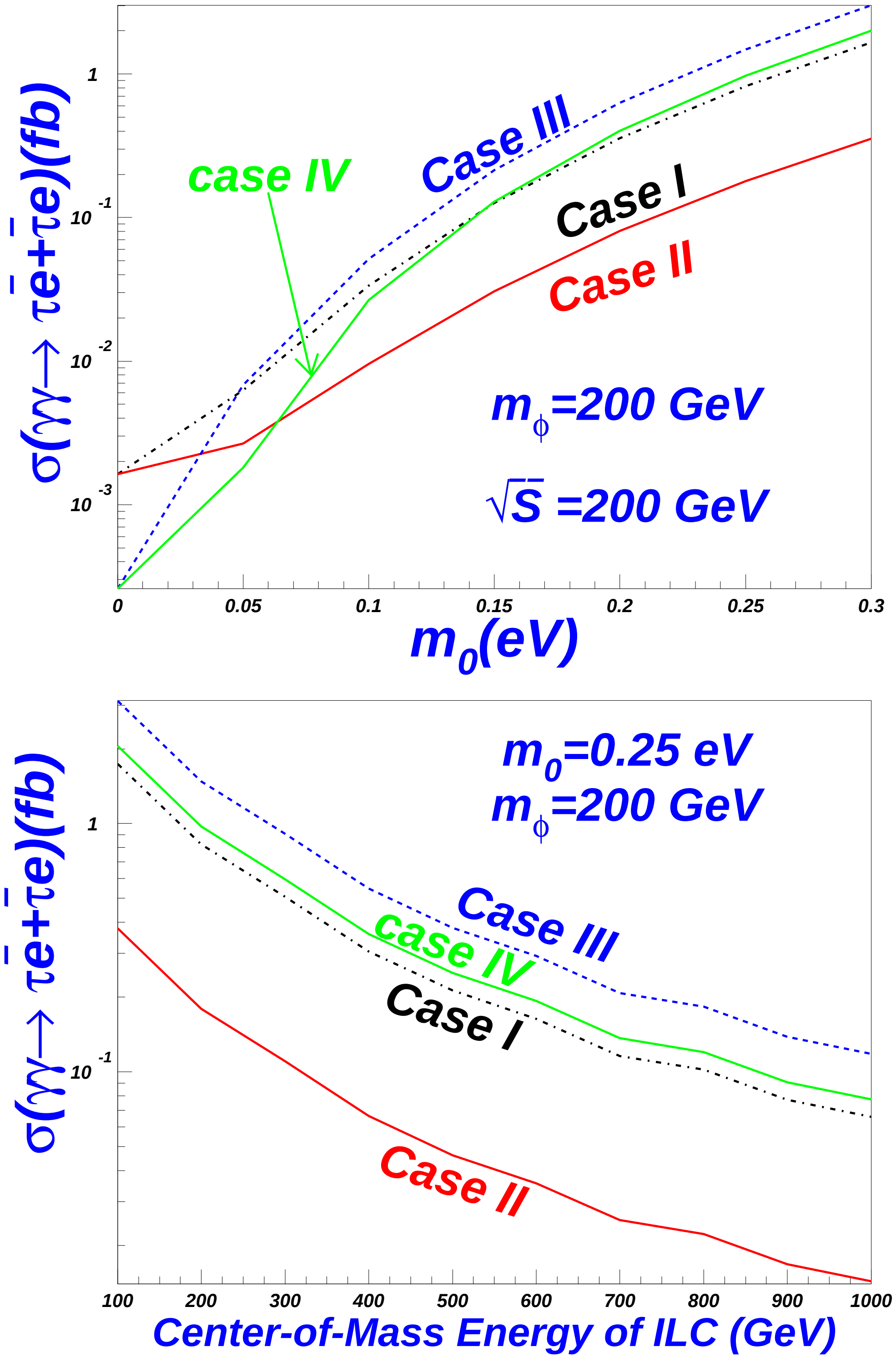


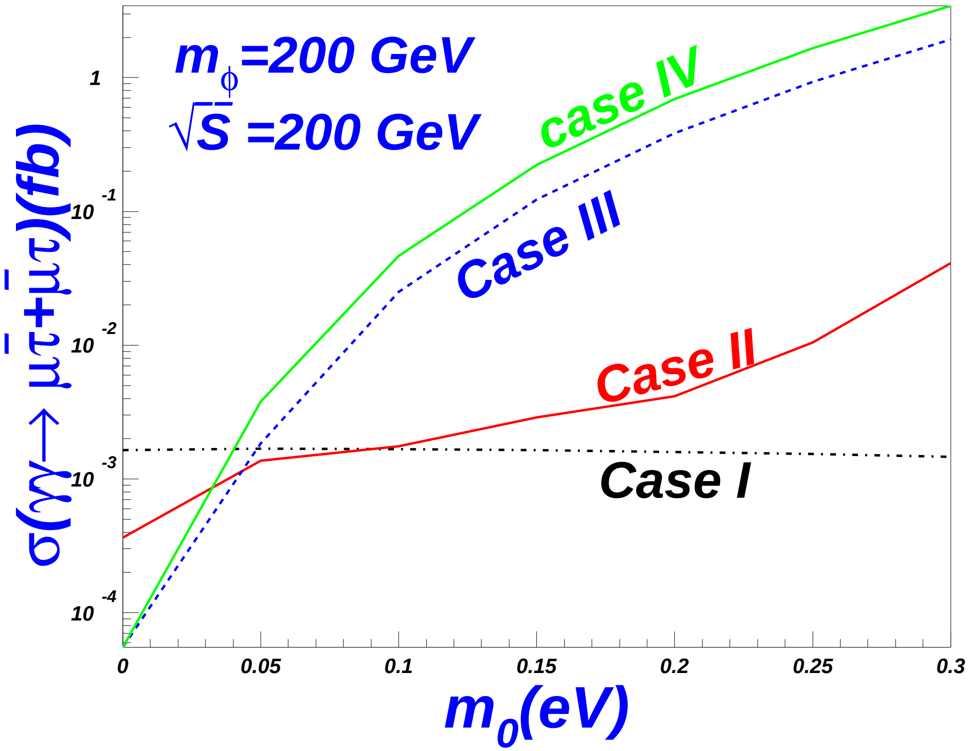
mφ=200 GeV
√S =500 GeV
case IV
Case III
Case II
Case I
σ(γγ→ τμ̄+τ̄μ)(fb)
m0(eV)
0
0.05
0.1
0.15
0.2
0.25
0.3
10 -1
10 -2
10 -3
case IV
Case III
m0=0.25 eV
mφ=200 GeV
Case II
Case I
σ(γγ→ τμ̄+τ̄μ)(fb)
1
Center-of-Mass Energy of ILC (GeV)
100
200
300
400
500
600
700
800
900
1000

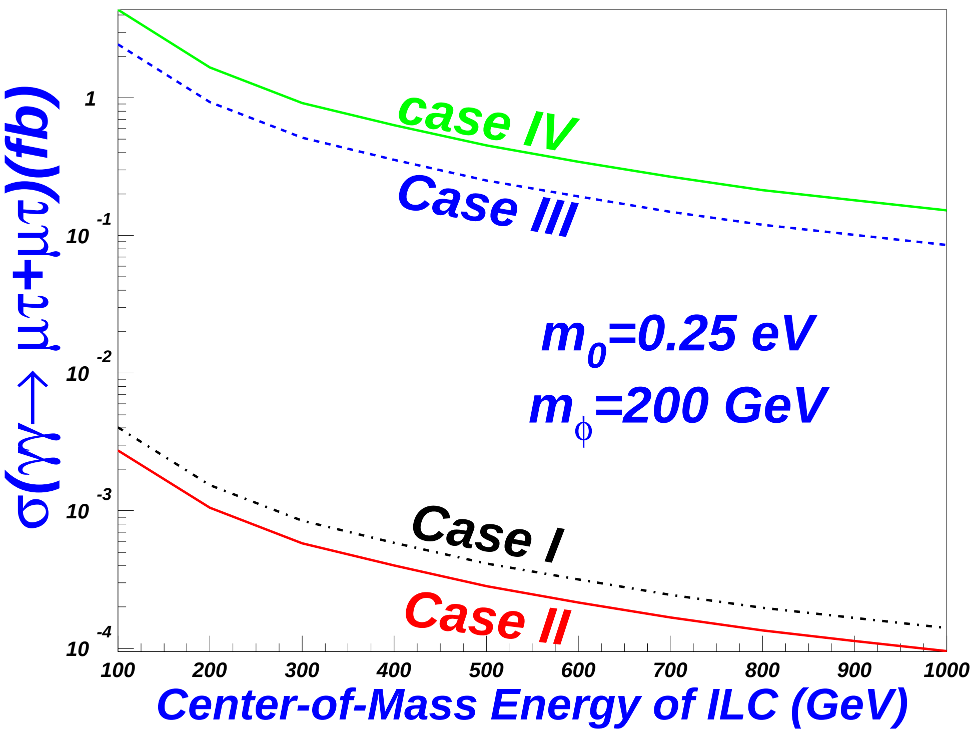
Inverted hierarchy



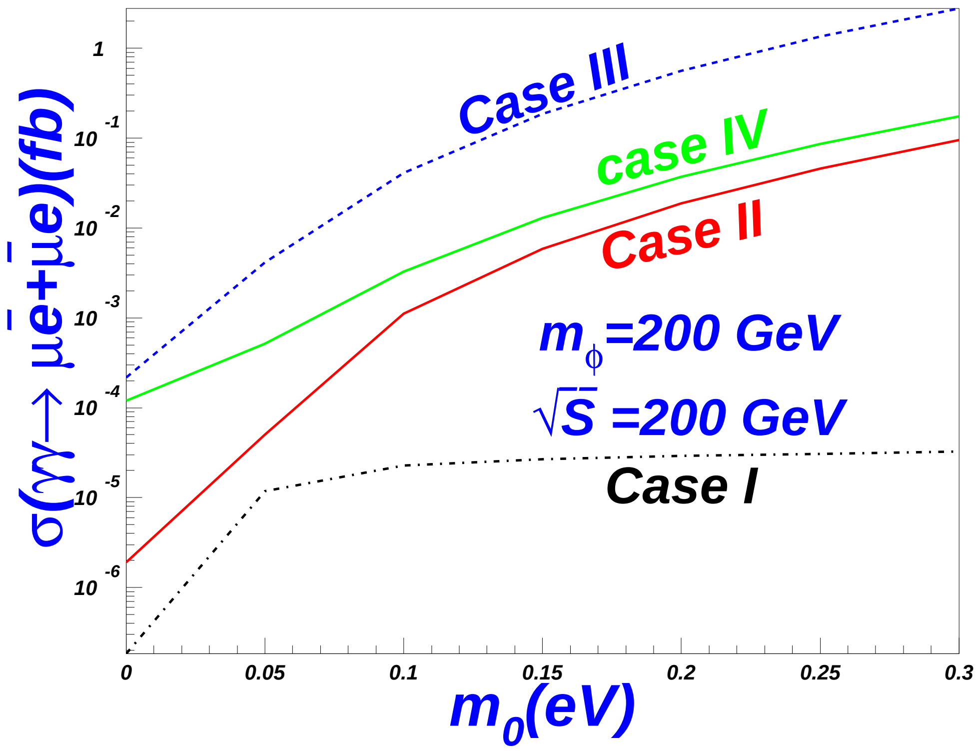



σ(γγ → τē+τ̄e)(fb)
case IV
Case III
Case I
Case II
m_φ=200 GeV
√S =200 GeV
m_0(eV)
σ(γγ → τē+τ̄e)(fb)
m_0=0.25 eV
m_φ=200 GeV
Case III
case IV
Case I
Case II
Center-of-Mass Energy of ILC (GeV)

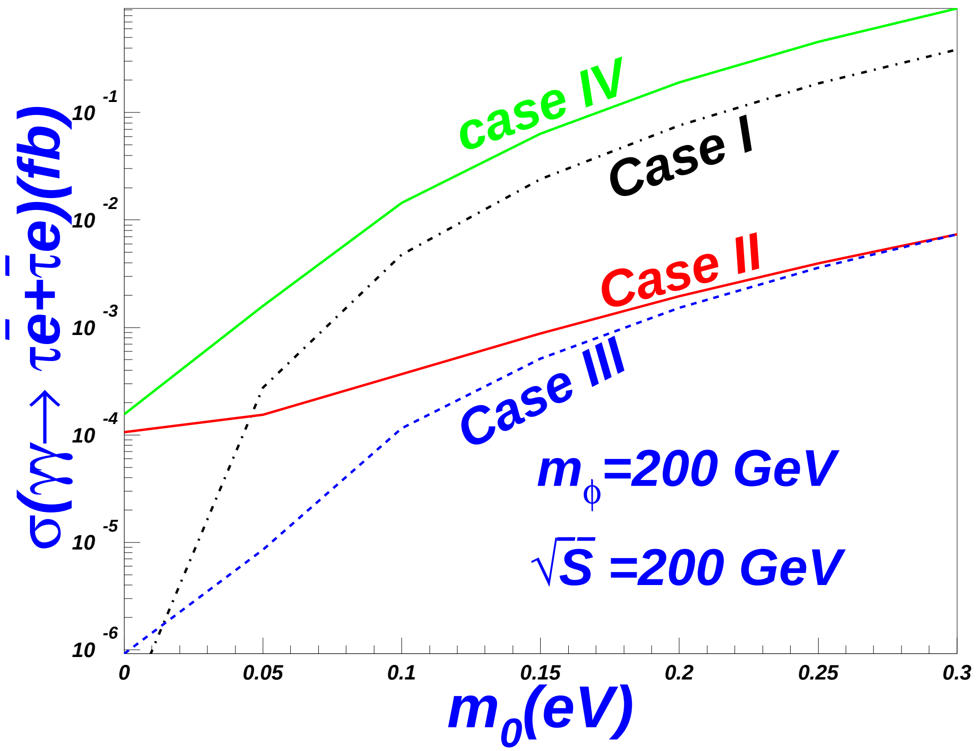

m_φ=200 GeV
√S =200 GeV
case IV
Case III
Case II
Case I
σ(γγ→ μτ̄+μ̄τ)(fb)
m_0(eV)


case IV
Case III
m_0=0.25 eV
m_φ=200 GeV
Case I
Case II
σ(γγ→ μτ̄+μ̄τ)(fb)
Center-of-Mass Energy of ILC (GeV)

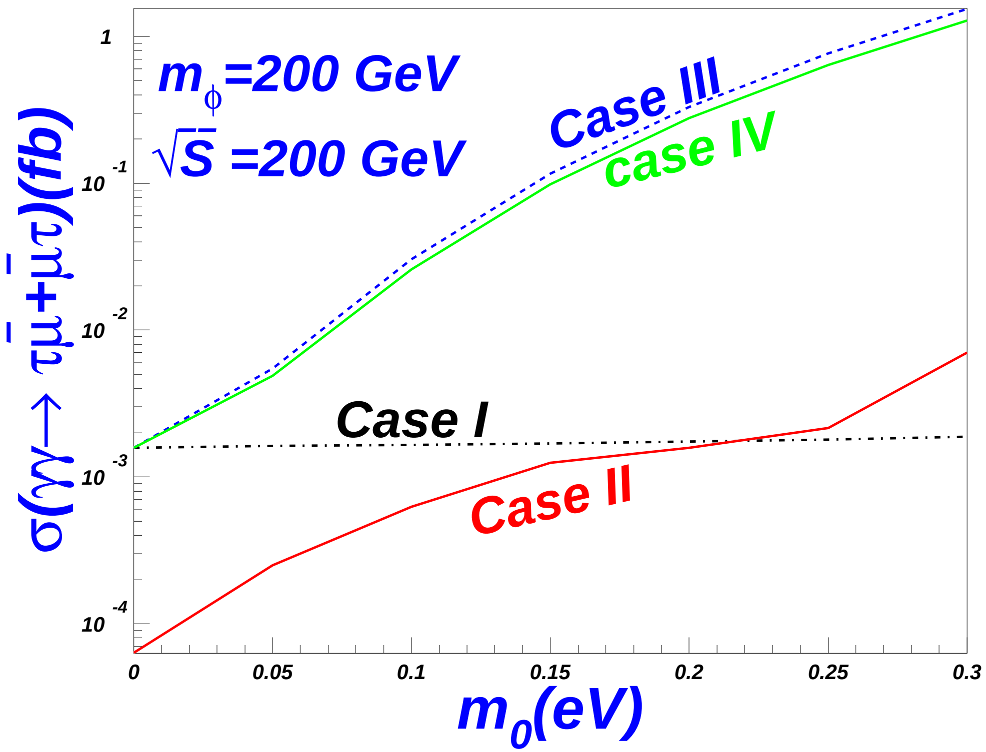
$h_{e\mu} = h_{ee} \approx 0$ constraints



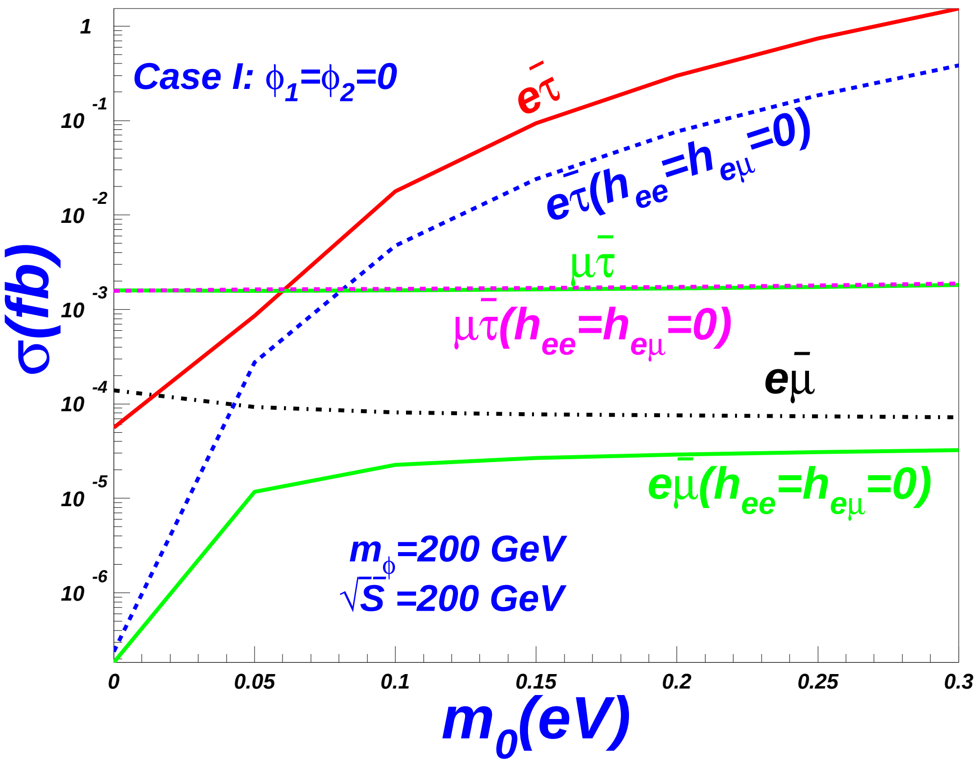
$h_{e\mu} = h_{ee} \approx 0$ constraints

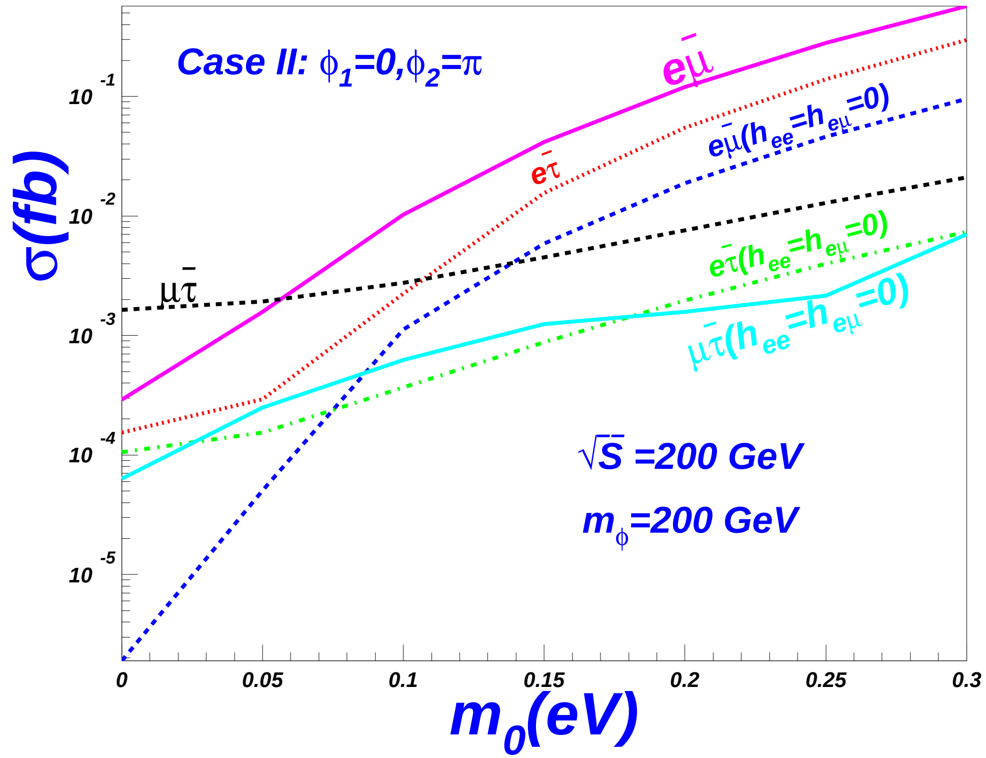


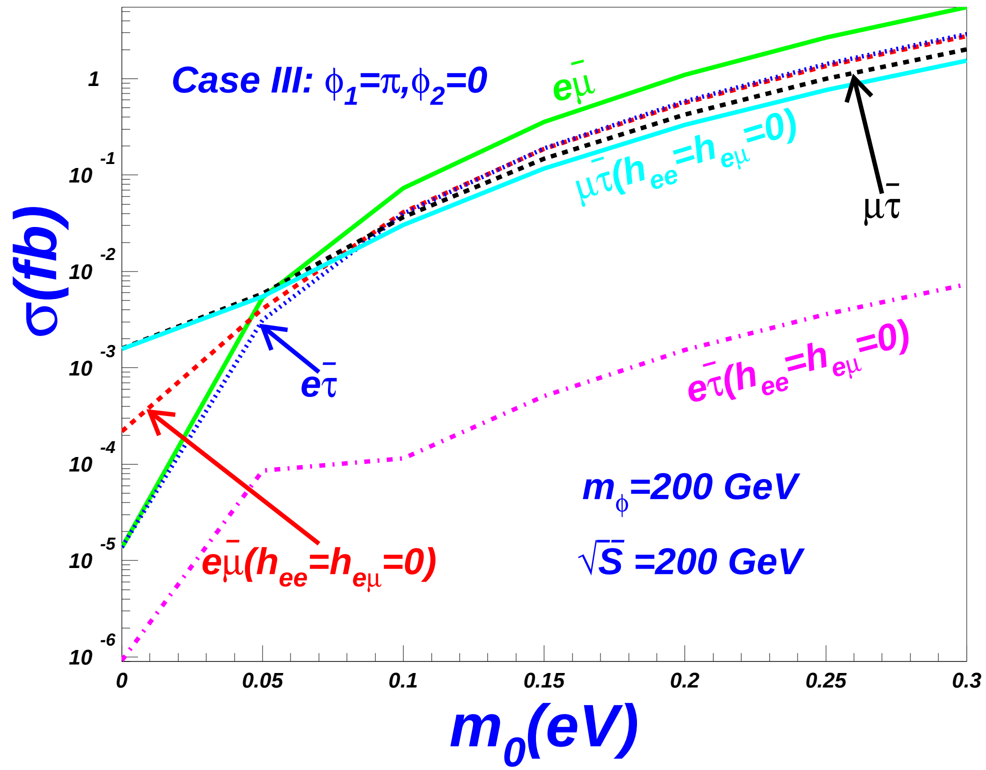
$h_{e\mu} = h_{ee} \approx 0$ constraints

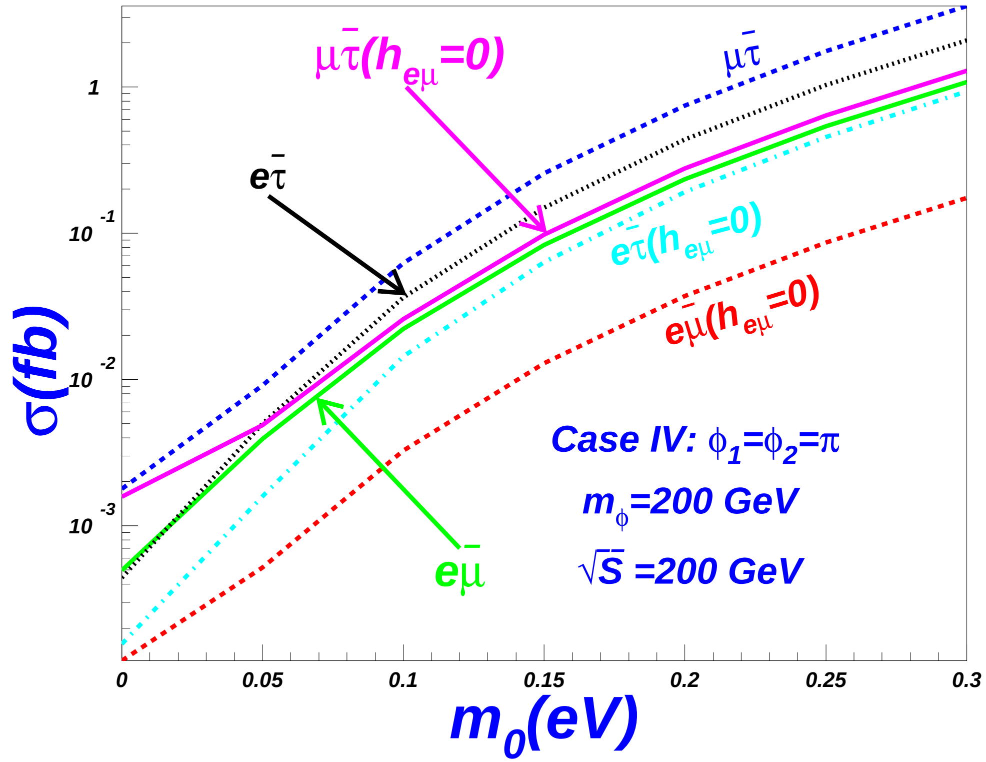


compare the results with and without the constraints $h_{e\mu} = h_{ee} = 0$




Case II: ϕ1=0,ϕ2=π
eμ̄
eτ̄
eμ̄(hee=heμ=0)
μτ̄
eτ̄(hee=heμ=0)
μτ̄(hee=heμ=0)
√S =200 GeV
mϕ=200 GeV
σ(fb)
m0(eV)


Case III: ϕ1=π,ϕ2=0
eμ̄
μτ̄(hee=heμ=0)
μτ̄
eτ̄
eτ̄(hee=heμ=0)
eμ̄(hee=heμ=0)
mϕ=200 GeV
√S =200 GeV
σ(fb)
m0(eV)



$\mu\bar{\tau}(h_{e\mu}=0)$
$\mu\bar{\tau}$
$e\bar{\tau}$
$e\bar{\tau}(h_{e\mu}=0)$
$e\bar{\mu}(h_{e\mu}=0)$
$e\bar{\mu}$
Case IV: $\phi_1=\phi_2=\pi$
m_ϕ=200 GeV
$\sqrt{S}$ =200 GeV
$\sigma(fb)$
$m_0(eV)$
1
10^{-1}
10^{-2}
10^{-3}
0
0.05
0.1
0.15
0.2
0.25
0.3

Permitted ranges of the cross sections of $\gamma\gamma \to l_i l_j$, obtained by varying $-\pi < \phi_1, \phi_2 < \pi$ for s

m_0 (eV)	Normal Hierarchy		
	$\mu\bar{e}$	$\tau\bar{e}$	$\tau\bar{\mu}$
0.25	(0.001,6.30)	(0.0008,1.53)	(0.002,3.66)
0.15	(0,0.186)	(0.000001,0.06)	(0.00006,0.53)
0.05	(0,0.004)	(0,0.002)	(0.00002,0.014)
0.00	(0,0.0002)	(0,0.000)	(0,0.0017)

m_0 (eV)	Inverted Hierarchy		
	$\mu\bar{e}$	$\tau\bar{e}$	$\tau\bar{\mu}$
0.25	(0.000013,1.38)	(0.0003,0.44)	(0.002,1.83)
0.15	(0.000004,0.20)	(0.000003,0.04)	(0.002,0.53)
0.05	(0.000001,0.0056)	(0.000002,0.002)	(0.00004,0.014)
0.00	(0,0.0003)	(0,0.0002)	(0.00004,0.002)

background analysis and the signal detection

The background for $\gamma\gamma \to \ell_i\bar{\ell}_j$ comes from $\gamma\gamma \to \tau^+\tau^- \to \tau^-\nu_e\bar{\nu}_\tau e^+$, $\gamma\gamma \to W^+W^- \to \tau^-\nu_e\bar{\nu}_\tau e^+$ and $\gamma\gamma \to e^+e^-\tau^+\tau^-$

kinematical cuts: $|\cos\theta_\ell| < 0.9$ and $p_T^\ell > 20$ GeV $(\ell = e, \mu)$, to enhance the ratio of signal to background

With these cuts, the background cross sections from $\gamma\gamma \to \tau^+\tau^- \to \tau^-\nu_e\bar{\nu}_\tau e^+$, $\gamma\gamma \to W^+W^- \to \tau^-\nu_e\bar{\nu}_\tau e^+$ and $\gamma\gamma \to e^+e^-\tau^+\tau^-$ at $\sqrt{s} = 500$ GeV are suppressed respectively to 9.7×10^{-4} fb, 1.0×10^{-1} fb and 2.4×10^{-2} fb

This is based on hep-ph/0409240

To get the 3σ observing sensitivity with 3.45×10^2 fb^{-1} integrated luminosity

From the above figures, we can see that under the current bounds from $\ell_i \to \ell_j \gamma$ and $\mu(\tau) \to 3e$, the LFV couplings can be large enough to enhance the productions $\gamma\gamma \to e\bar{\tau}, \mu\bar{\tau}$ to the 3σ sensitivity and may be detected in the future ILC colliders.

Comparision with different models

Theoretical predictions for the $\ell_i\bar{\ell}_j$ $(i \neq j)$ productions at $\gamma\gamma$ collision at the ILC. The predictions beyond SM are the optimum values. The collider energy is 500 GeV.

	SUSY	TC2	LHT	HTM
$\sigma(\gamma\gamma \to \tau\bar{\mu})$	$\mathcal{O}(10^{-2})$ fb	$\mathcal{O}(1)$ fb	$\mathcal{O}(1)$ fb	$\mathcal{O}(10^{-1})$ fb
$\sigma(\gamma\gamma \to \tau\bar{e})$	$\mathcal{O}(< 10^{-1})$ fb	$\mathcal{O}(1)$ fb	$\mathcal{O}(10^{-1})$ fb	$\mathcal{O}(10^{-1})$ fb
$\sigma(\gamma\gamma \to \mu\bar{e})$	$\mathcal{O}(< 10^{-3})$ fb	$\mathcal{O}(10^{-3})$ fb	$\mathcal{O}(10^{-1})$ fb	$\mathcal{O}(10^{-1})$ fb

summary

1. constraint φ_1 and φ_2

2.constraint neutrino mass

3. may be probed in the future collider, may be a NP signal according to the bg analysis, may be found at the ILC

4. Like that in other models, may be a powerful detection of NP

The end

THANK YOU!