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Di-Higgs decay of stoponium at future $\gamma\gamma$ collider

Hayato Ito, Takeo Moroi, Yoshitaro Takaesu

• Assume :

mass

others

$\tilde{t}_1$ - NLSP

$\tilde{\chi}_1^0$ - LSP

masses are measured

• $m_h = 125\,\text{GeV}$ is realized in MSSM (A_t and $m_{\tilde{t}_2}$)

already discovered

• $\tilde{t}_1 - \tilde{t}_1^*$ forms a bound state "stoponium $\sigma_{\tilde{t}}$" $[J^{PC} = 0^{++}]$ ①

⇒ utilize $\gamma\gamma$-collider ② to determine other SUSY parameters ④

observe σ and ③

① $\tilde{t}_1 - \tilde{t}_1^*$ from threshold production may form stoponium bound state

$p_{\tilde{t}} \sim 0$ and forms $\sigma_{\tilde{t}}$

$\Gamma_{\tilde{t}}^{total} \lesssim E_{binding}$ and $\Gamma_{\sigma_{\tilde{t}}}^{total} \sim \Gamma_{\sigma_{\tilde{t}} \to gg}$

$E_{Hydrogen} \sim m_e \alpha^2$

$m_{\tilde{t}_1} \cdot \alpha_s^2 = O(1)\,\text{GeV}$

$= \frac{4\alpha_s^2}{3} \cdot \frac{|R(0)|^2}{m_{\sigma_{\tilde{t}}}^2}$

$\sim 0.2\,\text{GeV}$

$R = \sqrt{4\pi}\,\psi$

$\therefore$ $\Gamma_{\tilde{t}} \lesssim O(1)\,\text{MeV}$ $\sim O(\text{MeV})$

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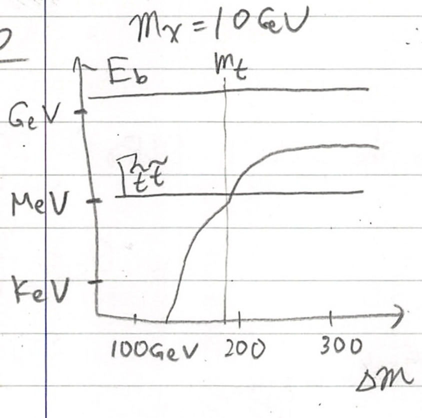
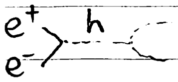


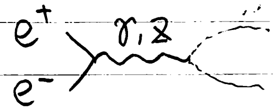
satisfied if $\tilde{t} \to t + \tilde{\chi}$, $\tilde{t} \to b + \tilde{W}$ are closed

[and thus $\tilde{t} \to c\,\tilde{\chi}$, $\tilde{t} \to b f f \tilde{\chi}$]

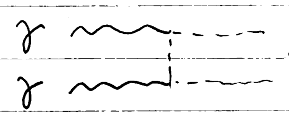
◦ Stoponium production



~ 0



stoponium (1P) $\propto \alpha_s^5 \alpha^2 \sim 0$

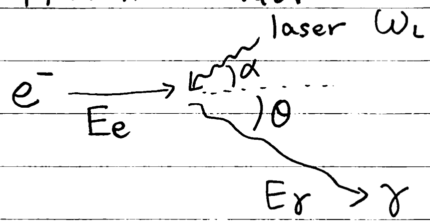


stoponium (1S) $\propto \alpha_s^3 \alpha^2 \sim 1\,\mathrm{fb}$ @ $m_{\tilde{t}} = 400\,\mathrm{GeV}$

$\Rightarrow$ photon collider

$\omega_L = 1.06\,\mu m$
$= 1.17\,eV$
[Nd^{3+} in glass/garnet]

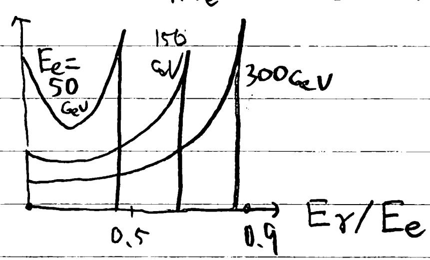
② Photon Collider



For $x \gtrsim 4.8$,
$\gamma\gamma \to e^+e^-$ occurs
and xs is reduced.

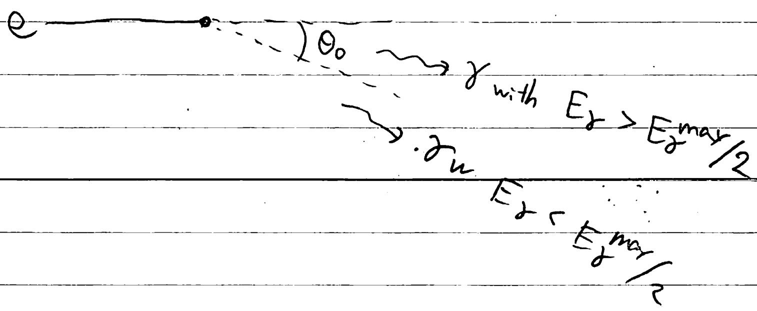
with $x = \frac{4 E_e \omega_L}{m_e^2} \cos^2\frac{\alpha}{2}$, $E_\gamma \leq E_\gamma^{max} = \frac{x}{x+1} E_e$

(~~205 GeV for $E_e = 250$ GeV~~
~~450 GeV for $E_e = 500$ GeV~~)



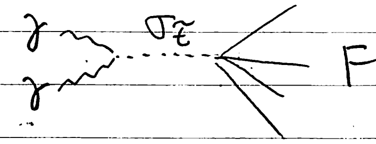
and the angle is $\theta(E_\gamma) = \sqrt{\frac{E_\gamma^{max} - E_\gamma}{E_\gamma}}\,\theta_0$

w. $\theta_0 = \frac{m_e}{E}\sqrt{1+x}$
$\sim O(10^{-6})\,\mathrm{rad}$



※ due to small bunch size @ LC, one can focus laser to the e^- beam
so that conversion rate $k \sim 1$ if one uses $1 \sim 5$ J beam

○ cross section



$$\Rightarrow \mathcal{M} = \mathcal{M}(\gamma\gamma\to\sigma)\frac{i}{s-m_\sigma^2+im_\sigma\Gamma_\sigma}\times\mathcal{M}(\sigma\to F)$$

$$\therefore d\sigma = \frac{1+\xi_2\xi_2'}{2}\,d\sigma(\gamma_+\gamma_+\to\sigma_{\tilde{\ell}}\to F)$$

$$= \frac{1+\xi_2\xi_2'}{2}\times\frac{1}{2S_{\gamma\gamma}}\int d\Pi_f\left|\mathcal{M}(\gamma_+\gamma_+\to\sigma)\frac{i}{s-m_\sigma^2+im_\sigma\Gamma_\sigma}\mathcal{M}(\sigma\to F)\right|^2$$

$$\simeq \frac{1+\xi_2\xi_2'}{2}\,\frac{1}{(s-m_\sigma^2)^2+m_\sigma^2\Gamma_\sigma^2}\cdot 8\pi m_\sigma\Gamma(\sigma\to\gamma\gamma)\,\frac{1}{2S_{\gamma\gamma}}\,2m_\sigma\Gamma(\sigma\to F)$$

$$\Gamma(\sigma\to\gamma\gamma) = \frac{1}{2m_\sigma}\int d\Pi_2\sum_{pol}|\mathcal{M}|^2 = \frac{1}{16\pi m_\sigma}\left[|\mathcal{M}_{++}|^2+|\mathcal{M}_{--}|^2\right]$$

$$\therefore |\mathcal{M}_{++}|^2 \sim 8\pi m\Gamma$$

Breit-Wigner approx

ξ_2 is the stokes parameter of photon

$$\mathcal{S} = \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} = \begin{pmatrix} \xi_0 \\ \xi_1 \\ \xi_3 \\ \xi_2 \end{pmatrix}$$

ξ_0 — total intensity

ξ_1, ξ_3 } linear polarization → irrelevant because γ is expected as axial-symmetric

ξ_2 — circular polarization

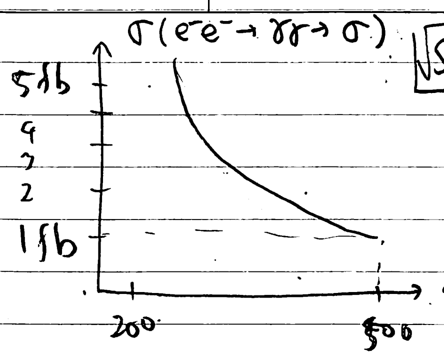
or in density matrix form.

$$|\gamma_\pm\rangle\langle\gamma_\pm| = \frac{1}{2}\begin{pmatrix} 1+\xi_2 & -\xi_3+i\xi_1 \\ -\xi_3-i\xi_1 & 1-\xi_2 \end{pmatrix}$$

$$\int_0^\infty ds\,\frac{1}{(s-m^2)^2+m^2\Gamma^2} \sim \frac{\pi}{m\Gamma}$$

$$\therefore \sigma(e^-e^-\to\gamma\gamma\to\sigma\to F)$$

$$\simeq \underbrace{\frac{1}{L_{ee}}\int_0^{E_\gamma^{max}/E_e} dy\,dy'\,\frac{d^2L_{\gamma\gamma}}{dy'dy}}_{ee\to\gamma\gamma\text{ conversion}}\;\underbrace{\frac{1+\xi_2(y)\xi_2'(y')}{2}}_{\text{determined by } y,\,y'\text{ and } e^-\text{-polarization}}\;\underbrace{\frac{8\pi\,\Gamma(\sigma\to\gamma\gamma)\Gamma(\sigma\to F)}{(S_{ee}yy'-m_\sigma^2)^2+m_\sigma^2\Gamma_\sigma^2}}_{\gamma\gamma\to F\text{ "resonance"ness}}$$



$\boxed{\sqrt{S_{ee}} = 1.26\,m_\sigma}$ - tuned

$$\sum \rho^{ac}\rho'^{bd}\mathcal{M}_{ab}\mathcal{M}_{cd}^*$$

w. $\mathcal{M}_{++} = \mathcal{M}_{--}$

$\mathcal{M}_{+-} = \mathcal{M}_{-+} = 0$

$$= |\mathcal{M}_{++}|^2\left[\frac{1+\xi_2\xi_2'}{2} + \underbrace{\frac{\xi_3\xi_3'-\xi_1\xi_1'}{2}}_{\to 0}\right]$$

depend on
A_t, $m_{\tilde{t}_2}$, $t\beta$
μ etc...

$\sigma_{\gamma\gamma\to WW} = 60\,pb$
@ $\sqrt{s_{\gamma\gamma}} = 200\,GeV$

① Decay ?

		"rough" value	
$\sigma_{\tilde{t}} \to$	gg	$> 50\%$	→ nice for discovery but uninteresting
	WW	$\sim 10\%$	SM bkg (no information on SUSY params)
	ZZ	$\sim 5\%$	
	hh	~ 1–10%	← of interest.
	tt	$\sim 1\%$	
	$\tilde{\chi}^0_1\tilde{\chi}^0_1$	$\sim 1\%$	
	$\gamma\gamma$	$\sim 0.3\%$	
	$Z\gamma$	$\sim 0.2\%$	

$$\sigma(ee \to \gamma\gamma \to \sigma \to hh) \sim O(0.1)\,fb$$

Sho Iwamoto

No. 5

Date . .

$\Delta E \sim \left(\frac{2}{\sqrt{E}} \oplus 0.5\right)\%$ EM cal

$\Delta E \sim \left(\frac{50}{\sqrt{E}} + 3\right)\%$ Had cal

∘ Event Selection $\sqrt{s_{ee}} \leq 1\,\mathrm{TeV}$ $\int \mathcal{L} = 1\,\mathrm{ab}^{-1}$ $O(100)$ evts

($\gamma\gamma \to \sigma \to hh \to 4b$)

① ∘ 4J30 w. $|\eta| < 2.0$

① ∘ $-60\,\mathrm{GeV} < M_{4J} - m_\sigma < 40\,\mathrm{GeV}$ $[M_\sigma \simeq 2m_{\tilde{t}}]$

② ∘ 3b

③ ∘ for $M_{1,2}$ minimizing $(M_1 - m_h)^2 + (M_2 - m_h)^2$ ($|M_1 - m_h| < |M_2 - m_h|$)

$M_1 - m_h \in [-20, 5]\,\mathrm{GeV}$

$M_2 - m_h \in [-25, 5]\,\mathrm{GeV}$ for MP1

$[-20, 5]\,\mathrm{GeV}$ for MP2,3,4

④ $\min(\Delta R_1, \Delta R_2) \leq 1.4$

$\max(\Delta R_2, \Delta R_1) \leq 1.8$ when $\Delta R_i = \Delta R(\text{jets in } M_i)$

∘ Signal — MG5 + phy. del.

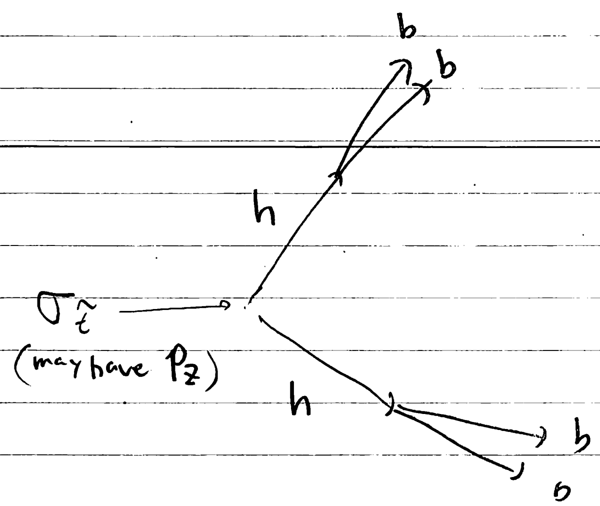
∘ BKG

- hh
- 4b
- 2b2c
- 4c
- 2b2q
- tt

} as signal

- ZZ
- WW
- WWZ

} as signal



$S_{\gamma\gamma} = z^2 S_{ee}$

$E_{lab} = E_{\gamma_1} + E_{\gamma_2}$

$= E_{h_1} + E_{h_2}$

$= \left(y + \frac{z^2}{y}\right) E_{ee}$

∘ $\gamma\gamma \to hh \to 4b$ BKG

$$\sigma_{cut} = Br(h\to bb)^2 \sum_{\substack{\lambda\lambda' \\ =\pm 1 \\ +-}} \int_0^{y_m} dz \int_{z^2/y_m}^{y_m} dy \frac{1}{L_{ee}} \frac{d^2 L_{\gamma\gamma}}{dz\,dy} \left(\frac{1+\xi_2 \xi_2'}{2}\right)$$

$$\int_0^1 d\cos\theta^* \frac{d\sigma_{\lambda\lambda'}(\gamma\gamma\to hh)}{d\cos\theta^*} \varepsilon_{\lambda\lambda'}(z, y, \theta^*)$$

w. θ^* in CM frame of $\gamma\gamma$ (=hh)

Small dependence on θ^*

⇒ averaged

(this approximation has < 15% precision...)

they could do w/o approx
but perhaps they didn't know
how to calculate...

∘ $\gamma\gamma \to ZZ$ BKG

only employ ①②③ and calculate σ_{cut}'s upper bound
w/o MC simulation (i.e. w. analytics)

not very
important

$m_{\tilde{t}}$/GeV	250	300	350	400
$\sqrt{s_{ee}}$/GeV	625	750	875	1000
$\sigma(\to hh)$/fb	0.34	0.26	0.2	0.18
N_{sig}	109	83	70	58
4J w. m_σ	33	29	23	22
3b	27	23	19	18
$\sim m_h$	18	15	13	13
ΔR	14	14	13	13
hh	2.2	2.1	1.7	1.4
ZZ	<0.8	<0.5	<0.3	<0.7
others	1.0	0.7	0.3	0.2
tot	3.9	3.2	2.3	2.3

4J30

~~4J~~30

7

higgs less boosted

$Z_0 > 5$ for all points.

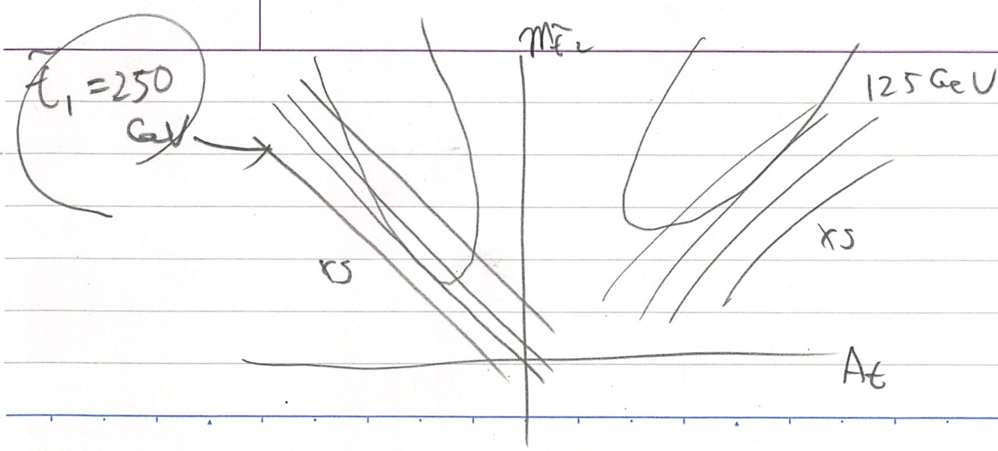
we knew $m_{\tilde{t}}$, $m_{\tilde{\chi}_0}$ only.

$\Rightarrow$ we will know $\sigma \propto \underbrace{\Gamma(\sigma_{\tilde{t}} \to \gamma\gamma)}_{\text{Just QED}} \times \underbrace{\Gamma(\sigma_{\tilde{t}} \to hh)}_{\text{function of } \theta_{\tilde{t}},\ \alpha,\ \beta}$

new constraint

tuned s.t. 125.7 GeV

$m_{\tilde{t}_2}^{true}$	3480	3810	4110	4080
A_t^{true}	-4770	-4940	-5460	-5670
$m_{\tilde{t}_2}^{upper}$	3.8	4.2	4.6	4.7
$\lvert A_t \rvert^{upper}$	5.1	5.7	6.2	6.5



parameter scan w.r.t.

$t\beta$, μ, $M_{\tilde{g}}$

$M_{\tilde{\tau}}$, $M_{\tilde{b}_R}$, $A_b = A_\tau$

$A_{1st/2nd}$, M_{others}