$\gamma\gamma$, $e\gamma$ and e^-e^- Options

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Abstract. In this review, we discuss on the possibilities of physics and experiments other than the e^+e^-interaction, i.e., $\gamma\gamma$, $e\gamma$ and e^-e^- interaction, putting emphasis on luminosities and physics opportunities with these options. We briefly discuss on technical issues on the options as well.

INTRODUCTION

It is needless to say that the electron(and the positron) beam for the e^+e^- linear collider is the highest energy and the most intense electron beam. So that it natural to think of using the beam as the source of more general interaction in addition to the e^+e^- interaction. The simplest case is to replace the positron beam of the e^+e^- collider with the electron beam. The facility is then a high energy e^-e^- collider. The other possibility is to convert the electron beam to the photon beam by the backward Compton scattering. In this case, it is a $\gamma\gamma$ collider or an $e\gamma$ collider.

The feasibility of these 'optional' interaction has been studied for years [1–4], however, it was not explored as the level performed in the e^+e^- interaction yet and are still not familiar with many peoples in the linear collider community. Therefore, in this report, we try to give general idea of how these options look like, particularly; 1) how the luminosities and polarization look like, 2) what kind of topics can be studied with provided luminosities, 3) how far the interaction region away from the e^+e^-collider, then hopefully, try to promote more attention to these options.

LUMINOSITIES

$\gamma\gamma$ Collider

In $\gamma\gamma$ colliders, photon beams are generated by the inverse Compton scattering of electron and laser beams just before the interaction point. The maximum energy

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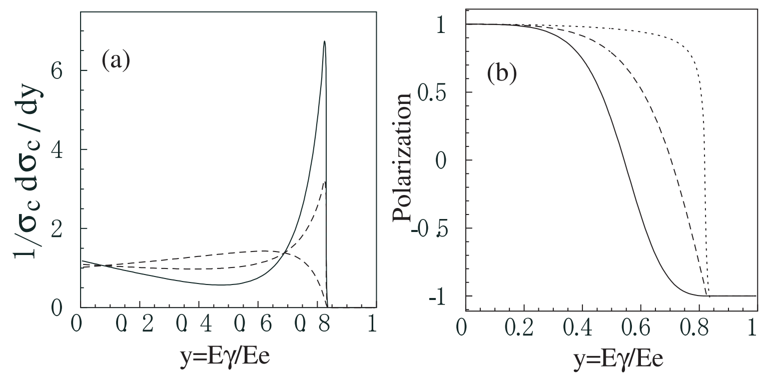

FIGURE 1. Calculated energy and polarization of back-scattered photons by laser-Compton scattering for different combination of the laser and the electron beam polarization, i.e., $P_L P_e = -1$ (solid), $P_L P_e = 0$ (dashed) and $P_L P_e = 1$ (dotted), respectively.

of the generated photon is expressed as;

$$E_\gamma|^{max} = \frac{x}{x+1} E_e. \tag{1}$$

Here, x is a kinematics parameter of the Compton scattering defined as

$$x = \frac{4E_e \omega_L}{m_e^2} \cos^2(\theta/2), \tag{2}$$

where E_e, ω_L and θ are the electron energy, laser photon energy and angle between the electron beam and the laser beam. The calculated photon energy spectrum generated by the backward Compton scattering is shown in fig. 1.

As seen from the figure, the energy distribution of the photons depends on the polarization of the electrons and the laser beam, *i.e.*, one can obtain a broad energy distribution or peaked distribution by controlling the polarization. Usually, x in equation (1) is restricted to be smaller than $2(1+\sqrt{2}) \approx 4.83$ to avoid pair creation process by the collision of the Compton photon and the laser photon, corresponding to the maximum photon energy of about 80% of the electron energy.

With typical parameters of the photon collider, the average number of Compton interactions of an electron in a laser pulse is assumed to be 1 which corresponds to the conversion efficiency $k \approx 0.63$. In most cases, we are interested in the high energy part of the spectrum and if we take high energy part of the spectrum, the effective conversion efficiency k' can be regarded as $k' \approx 0.3$. Therefore, the high energy part of luminosity of the $\gamma\gamma$ collider is expressed approximately as;

$$L_{\gamma\gamma} = k'^2 L_{ee} \approx 0.3^2 L_{ee} \approx 0.1 L_{ee}, \tag{3}$$

where L_{ee} is the geometric luminosity of $e^- e^-$ collisions. It should be noted that the geometric luminosity is not necessary to be the same as the e^+e^- collider. Since the effect of the beam beam interaction is less serious than e^+e^- interaction, the geometric luminosity is possibly higher that the e^+e^-collision.

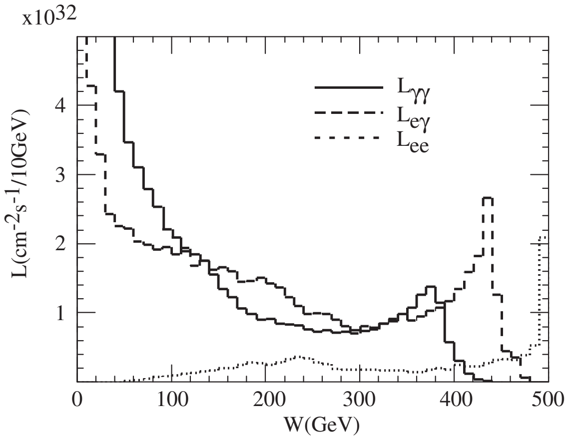

FIGURE 2. Luminosity distributions simulated by CAIN, the solid, dashed and dotted lines are luminosities of $\gamma\gamma$, $e\gamma$ and e^-e^- collisions, respectively, and W is their center-of-mass energies.

More precise estimation of the luminosity spectrum can be performed using numerical simulation with a specific parameters of the electron and the laser beam. The luminosity distributions simulated using CAIN [5], a simulation program for the laser-electron and the beam-beam interaction, with a $\gamma\gamma$ option of the JLC is shown in fig. 2. We have $\gamma\gamma$, $e\gamma$ and e^-e^- interaction simultaneously and low energy interaction caused by beamstrahlung photons.

e^-e^- Collider

The collision of the same sign beam suffers from the anti-pinch effect due to the repulsive force between them. It requires a careful tuning of the beam parameters because small beam just size increases the beamstrahlung but may not gain the luminosity. The discussion on the optimization of the luminosity of the e^-e^- collider is found in [6]. According to the discussion, the typical luminosity of the e^-e^-collider is around 30% of the e^+e^-collider. A simulated luminosity distribution is show in fig.3. As an example of the parameter, a parameter set for JLC/NLC (ISG-B) [7] e^+e^- collider was used with replacing a positron beam to the electrons. In this particular case, the luminosity was about 20% of the those of the e^+e^- luminosity of the same parameters.

Physics with $\gamma\gamma$, $e\gamma$ and e^-e^-Interactions

There are many possibilities to be explored with $\gamma\gamma$, $e\gamma$ and e^-e^- interactions and it is not possible cover everything in this report. Here we describe some example which could give new or additional information to which we expect with the e^+e^- interaction.

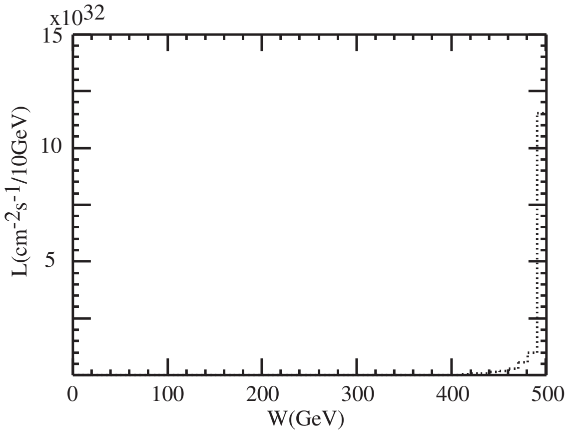

FIGURE 3. Luminosity distributions for e^-e^-collider mode simulated by CAIN

Two Photon Decay Width of the light Higgs Bosons

The study of Higgs boson, particularly measurement of the two photon decay width, primarily motivates the $\gamma\gamma$ collider [9,10]. As discussed in the previous section, the luminosity distribution of the $\gamma\gamma$ collider is not monochromatic, so that convolution of the spectrum with the production cross section is necessary to estimate number of expected event . An estimation with the JLC $\gamma\gamma$ option shows about 5,000 events can be expected in a year of the operation.

The light Higgs boson in the Standard Model mainly decays into a $b\bar{b}$ pair, and b hadrons can be tagged effectively by current b-tagging technology [11]. Therefore, $b\bar{b}$ events are the best signal of the intermediate-mass Higgs bosons. The main backgrounds are $\gamma\gamma \to q\bar{q}$ processes and are dominantly produced by the initial photon collision in the $J_z = 2$ angular momentum state, while the Higgs boson signals are only accessible by the $J_z = 0$ collisions [12,13]. This feature allows good background suppression by controlling beam polarization. The feasibility of a measurement of the two-photon decay width of the Higgs boson has been studied by by several groups [13–16]. An expampel of the mass plot of the signal and background is shown in Fig. 4 [1].

It has been shown by both of recent work, [15], [16], statistical accuracy on measurement of $\Gamma(h \to \gamma\gamma)Br(h \to b\bar{b})$ is estimated to be about 2%. The $Br(h \to b\bar{b})$ can be measured by the e^+e^- collision with the accuracy of 2% for 120 GeV Higgs boson [17] so that $\Gamma(h \to \gamma\gamma)$ is obtained with 3% accuracy.

Measurement of CP Nature of the Higgs Boson

Using the linear polarization of the photon beam, it is possible to measure asymmetry of the Higgs boson production as;

$$A_{CP} \equiv \frac{\sigma_{\parallel} - \sigma_{\perp}}{\sigma_{\parallel} + \sigma_{\perp}} \tag{4}$$

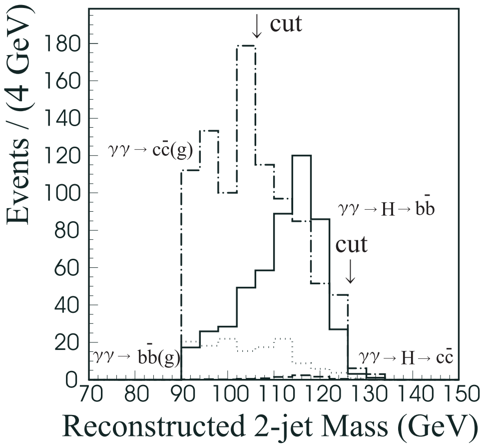

FIGURE 4. Mass distributions for Higgs signal and heavy quark background for $m_h = 120$GeV from [1]

which directly reflects CP nature of the produced Higgs boson, where $\sigma_{\parallel}(\sigma_{\perp})$ is the production cross section of the Higgs boson when the polarization of the initial photons are set in parallel(perpendicular) each other. In the real situation, the photon beam is not 100% polarized and the observed asymmetry is smeared. This process may be the best way to observe CP nature of the Higgs boson with by the linear collider including e^+e^- mode, however, a realistic simulation study is yet to be performed.

Selectron Production by $e\gamma$ Collisions

In $e\gamma$ interaction, single production of selectron ,$e\gamma \to \tilde{e}\tilde{\chi}^0$, is advantageous over e^+e^- interactions. Assuming $\tilde{\chi}^0$ as the LSP, the process has a lower mass threshold of $m_{\tilde{e}_R} + m_{\tilde{\chi}^0_1}$ than that of $2m_{\tilde{e}_R}$ for the selectron pair production at e^+e^- colliders. Figure 5 shows the selectron mass dependence of the total cross section [18]. We see large cross section for $e\gamma \to \tilde{e}_R\tilde{\chi}^0_1$, even if the selectron is rather heavy, $m_{\tilde{e}_R} \geq \sqrt{s}/2$. It is also seen that the cross section depends on the beam polarization and is effective to enhance selectron signals.

Another important property of the process is the simple dependence of the cross section on the SUSY parameters. The cross section is proportional to the bino component (N_{11}) of the lightest neutralino, $\tilde{\chi}^0 = N_{11}\tilde{B} + N_{12}\tilde{W} + N_{13}\tilde{H}^0_1 + N_{14}\tilde{H}^0_2$. Arbitrary SUSY parameters appearing in the cross section are only $m_{\tilde{e}_R}$, $\tilde{\chi}^0$ and $|N_{11}|$. This situation is different from selectron pair production at e^+e^- colliders where all masses and many mixing angles of the neutralinos contribute to the cross section. If we know $m_{\tilde{e}_R}$ and $\tilde{\chi}^0$ from an analysis of the process $e^+e^- \to \tilde{e}^+_R\tilde{e}^-_R$ [19] or $e^-e^- \to \tilde{e}^+_R\tilde{e}^-_R$ (see below) we could determine $|N_{11}|$ by a measurement of the total cross section for $e\gamma \to \tilde{e}_R\tilde{\chi}^0$.

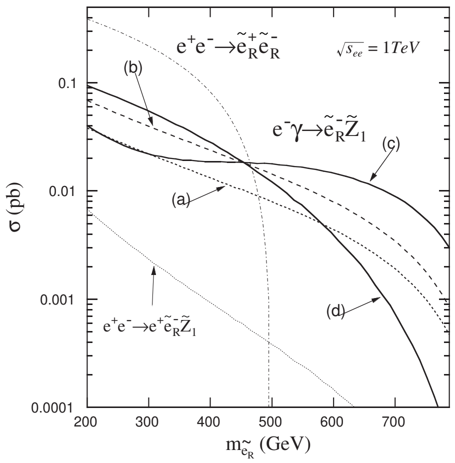

FIGURE 5. Selectron mass dependence of the total cross sections for each initial beam polarization from [1], $(\lambda_1, \lambda_2, P_2^c) = (0, 0, 0)$ (a), $(+1/2, 0, 0)$ (b), $(+1/2, +1/2, -1)$ (c) and $(+1/2, -1/2, +1)$ (d). $\sqrt{s_{ee}} = 1\text{TeV}$ and $m_{\tilde{\chi}_1^0} = m_{\tilde{B}} = 100GeV$.

Selectron in e^-e^-Collisions

The e^-e^- interaction has a unique feature for threshold behavior of the production of the selectrons. In the case of the same helicity selectron production in the e^+e^-collision as $e^+e^- \to \tilde{e}_R^+\tilde{e}_R^-$, it is suffred from β^3 behavior at the threshold. On the contrary, in the e^-e^-collision, the process $e^-e^- \to \tilde{e}_R^-\tilde{e}_R^-$ has β shape at the threshold. It is because total angular momentum $J = 0$ in the e^-e^-initial state so that $\tilde{e}_R^-\tilde{e}_R^-$ is produced in s-state. The production cross section of the right handed selectron near the threshold is shown in fig. 6 for both e^+e^- and e^-e^- collisions [20]. It is clear that the e^-e^-collision has advantage over the e^+e^-collision at the threshold behavior of the production cross section which allows a precise determi-

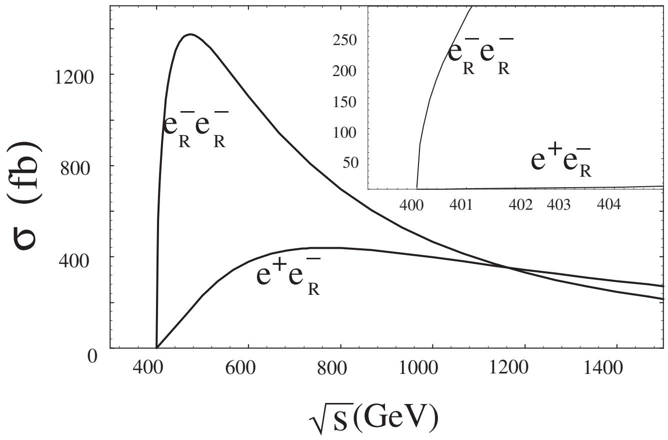

FIGURE 6. Threshold behavior of the production cross section of right handed selectron pairs in e^+e^- and e^-e^- collision for $m_{\tilde{e}_R} = 200GeV$, from [20]

nation of the mass of the $\tilde{e}_R$ by the energy scan [20]. It needs to be noted that the initial state radiation and the beamstrahlung deteriorate the threshold behavior just as we expected threshold scan of $t\bar{t}$ process in e^+e^-collision. A realistic estimate of the feasibility is necessary for more precise discussion.

W bosons

The sensitivity for the anomalous couplings of W bosons, $\delta\kappa_\gamma, \lambda_\gamma$, of high energy $\gamma\gamma$ and $e\gamma$ interaction has been discussed by several authors. [21–23] All these studies pointed out that both $\gamma\gamma$ and $e\gamma$ interaction play a complementary role to e^+e^- interaction for this measurement.

The cross section of W pair production in the $\gamma\gamma$ collision is about 90pb for $\sqrt{s_{\gamma\gamma}} > 200$ GeV and is almost independent of the $\gamma\gamma$ center-of-mass energy. This cross section is $\mathrm{O}(10-10^2)$ higher than the fermion pair production, and is also $\mathrm{O}(10-10^2)$ higher than the W pair production in the e^+e^- collision. However, it has to be mentioned that even the total cross section of the W boson pair production is large in high energy $\gamma\gamma$ interaction, the amplitude for $W_T W_T$ production is more and more dominant in higher energy. Since the information of the anomalous coupling is included in the longitudinal W boson amplitude, going to higher energy does not improve the sensitivity to the anomalous coupling [21]. In this sense, e^+e^-mode is advantageous in higher energy, however, at $\sqrt{s} \approx 500GeV$, $\gamma\gamma$ mode is still useful to explore the anomalous coupling of W bosons.

For e^+e^- interaction, the feasibility of the measurement has been investigated by Monte Carlo simulation including detector effect [24]. Since effect of the luminosity) distribution and polarization is more important for the $\gamma\gamma$ and the $e\gamma$ options, it has to be taken into account to estimate sensitivity for the precise measurement. The feasibility of a measurement of the W pair production cross section in the $\gamma\gamma$ collision and its sensitivity to the anomalous coupling of the W boson to the photon have been investigated by the Monte Carlo simulation [25]. It showed that about 11,000 events/10fb^{-1} can be detected using 4 jet decay of the W boson pairs. For the obtained number of events, the sensitivity to the anomalous coupling, $\delta\kappa_\gamma$ and λ_γ, were examined as shown in fig. 7. As can be seen from the figure, the feasibility for a measurement of the anomalous coupling of the W boson by $\gamma\gamma$ colliders is comparable to that from e^+e^-colliders and is complementary. This feasibility is derived only from measurement of the total cross section, and improvements are expected by a comprehensive angular analysis using the decay property of the W boson.

It has been recently pointed out that $\gamma\gamma \to W^+W^-$, process is a good place to study the gravity in extra-dimensions [29]. Using this process it is estimated to be explore M_s up to $11\sqrt{s}$ while it is about $4-5\sqrt{s}$ in other channel like $e^+e^- \to f\bar{f}$. Once we perform the analysis for the anomalous coupling, it can be applied to the extra-dimension.

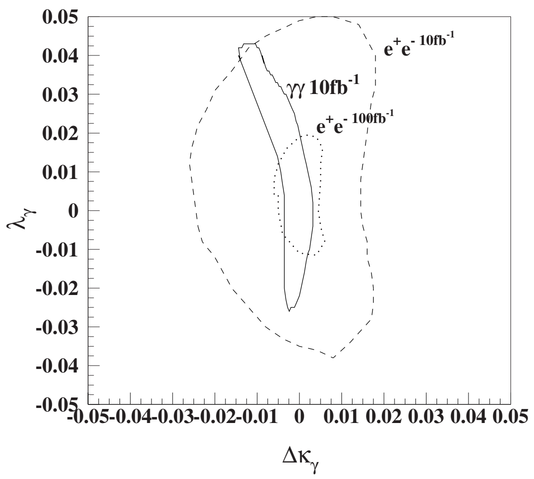

FIGURE 7. Expected 90% limit in W's anomalous coupling parameter $\delta\kappa_\gamma$, λ_γ. An estimation with an e^+e^- collision is also shown by the dotted and dashed lines. The total integrated luminosity is assumed to be 10fb^{-1}.

Precise Determination of Weiberg Angle by e^-e^- Interaction

The use of polarized beam for the precise measurement has been well verified by the SLD experiment [26]. The precise measurement of the Møller scattering at the e^-e^- interaction has the advantage for this purpose [27]. Since both beams can be polarized in the e^-e^- mode, the polarization is effectively higher as;

$$P_{eff} = \frac{2P_e}{1+P_e^2} \tag{5}$$

here the same degree of polarization for both beams are assumed. With currently achieved 77% electron beam polarization [28], it is already reach 97% and if we assume 90% polarization for the electron beam in the future, it goes up to 99%. This allows e^-e^- interaction to measure A_{LR} with double beam polarization. Because Møller is a t-channel process, the Q^2 depends on the scattering angle as $Q^2 = ys$, where y is a kinematical parameter related with the scattering angle with respect to the beam axis as;

$$y = \frac{1-\cos\theta}{2}. \tag{6}$$

Figure 8 shows a potential of e^-e^- interaction for the measurement of the Weinberg angle at $\sqrt{s} = 1TeV$ [27]. It is seen that single measurement gives the $sin^2\theta_W$ at several Q^2 and its precision is better for lower Q^2 corresponding to the small angle scattering.

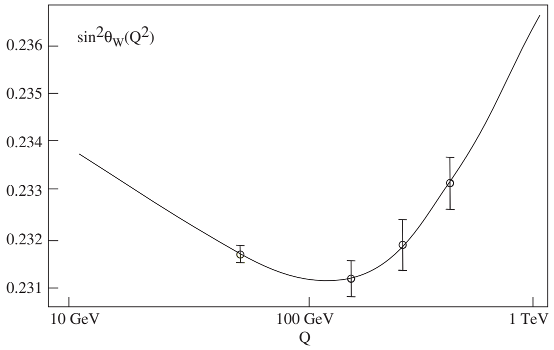

FIGURE 8. Running of $sin^2\theta_W(Q^2)$ compared with potential future e^-e^-collider measurements at $\sqrt{s} = 1TeV$ from [28].

Technical Issues

The $\gamma\gamma$ and the $e\gamma$ collider needs TW laser pulses synchronized with the electron beam. It adds technical issues to be solved in addition to the e^+e^- collider, i.e.,

- Development of high-repetition/high-power lasers.
- Optical system forlaser pulses.

The development of the laser is the important issue however, it is likely that we can count on general R&D of the commercial use laser for most of key technology, while optics layout in the interaction region is the issue we have to solve for ourselves. The issue on the interaction region are:

- Take TW laser pulses in and out from the interaction region without hitting anywhere.
- Protect detectors from the beam-beam backgrounds.
- Extract spent electron beam.

An example of the interaction region layout in $\gamma\gamma$ collider is shown in fig. 9 [2]. It consists of mask system which protects the vertex and the central drift chamber from neutron, electron and photon background caused by the beam-beam interaction. The third point is important because the energy of the electron after the Compton scattering is as low as a few GeV and are kicked away by the beam-beam interaction much larger than those in the e^+e^- collider. It makes the design of the electron beam extraction line more difficult. Schematics of the interaction region is discussed in previous reports [1–3], however it was still a level of conceptual drawing.

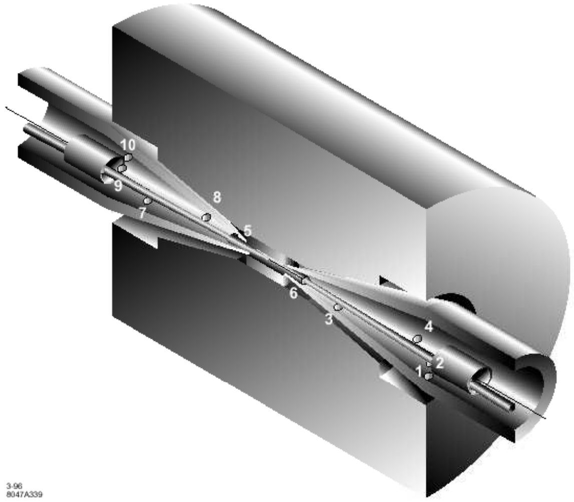

FIGURE 9. Example of the interaction region layout in $\gamma\gamma$ collider. [2]

Summary

The $\gamma\gamma$, $e\gamma$and e^-e^-options have interesting topics which hardly accessible by or complementary to the e^+e^- interactions. An comparison of the feasibility by the options are shown in table 1.

There is not a single scenario expected in physics in TeV region and we do not know which one will be realized (or non of them might not be true). It means that we have to prepare ways to explore TeV region as much as possible if it is affordable and feasible. In this sense we have to continue the R&D of options and it has to be ready at the time we need them. Particularly for the $\gamma\gamma$ and the $e\gamma$ operation of the linear collider, technical issues such as development of the high peak and average power laser or the optics layout around the interaction region are yet to be solved and we have to be make it clear to proceeds the linear collider project.

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TABLE 1. Possible topics studied by the linear collider.

Scenario	e^+e^-	$\gamma\gamma/e\gamma$	e^-e^-
Light Higgs			
	Discovery	$\Gamma(h \to \gamma\gamma)$	
	Br		
	Coupling	CP linear pol.	
	$\Gamma(h \to all)$		
Heavy Higgs			
	Discovery	higher reach	
	Coupling	CP	
		H/A int. [30]	
SUSY			
	Discovery	$\tilde{e}$ with $e\gamma$	$\tilde{e}$
	Spectroscopy		
Precision			
meaurement	W oupling	W coupling	
	WW scatt.		WW scattering
	Contact int.		Contact int.
	$sin^2\theta_W$		Weinberg angle
	Top threshold	pol. top	
	TOP CP		
Extra-dimension			
	$M_s \leq 6\sqrt{s}$	$M_s \leq 11\sqrt{s}$	$M_s \leq 6\sqrt{s}$

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