SUMMARY AND OUTLOOK: PHYSICS*

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This article presents a personal summary of the physics case for a photon collider at the ILC and the necessary steps to get this machine.

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1. The photon linear collider in the ILC project

Within the ILC project the Photon Linear Collider (PLC) is an option [1]. This means that it is not in the baseline design that will be constructed in the beginning, however previsions will be foreseen to install it later if it is technically feasible and physics requires it. For the $\gamma\gamma$ community this means that it has to show that the PLC is technically feasible [2] and that the physics case needs to be prepared.

To convince the community that the PLC is worth building one has to study scenarios in which the PLC adds significantly to the ILC program and to show that the PLC is superior to spending the same money for e^+e^- upgrades such as higher energy or larger luminosity.

A possible timeline is shown in figure 1. This timeline assumes that the physics case for the PLC can be made as soon as two years after ILC starts data taking.

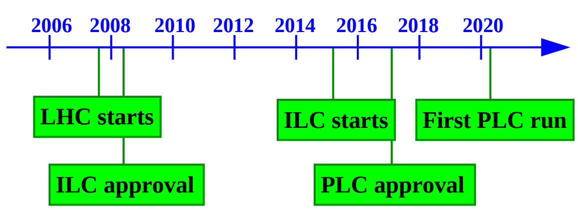

Fig. 1. Possible timeline for the PLC.

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2. Generalities about photon linear colliders

At a PLC all charged particles can be pair-produced that are kinematically accessible. The cross section is generally determined by QED and thus "boring". This however allows for an easy measurement of branching ratios. Cross sections are typically large, about an order of magnitude larger than in e^+e^-, however backgrounds are large as well.

Higgs particles are produced singly via loops in an s-channel process. The mass reach for them is thus larger than in the e^+e^- mode where they can only be produced in pairs.

A significant disadvantage of the PLC is the variable beam energy. It makes mass measurements more difficult than in the e^+e^- mode and also the energy-momentum conservation in the event reconstruction can only be used in the transverse plane. Also, because of the high $\gamma\gamma$ luminosity at low energies there is about one pile-up event per bunch crossing. These features make experimentation at the PLC somewhat similar to that in hadron colliders.

3. Higgses at the photon linear collider

With our present knowledge Higgs physics is certainly the strongest point at the PLC. Higgs production proceeds only via loops which makes the cross section very sensitive to new physics effects. For a light Higgs, decaying into $b\bar{b}$, several existing studies show that a 2% measurement of the $H\gamma\gamma$ coupling is possible [3, 4]. This coupling depends on the coupling of the Higgs to all charged particles as well as on the CP violating phases of the Higgs mixing angles (see Fig. 2 left) [5]. However, the partial width $\Gamma_{\gamma\gamma}$ alone cannot distinguish between the different effects.

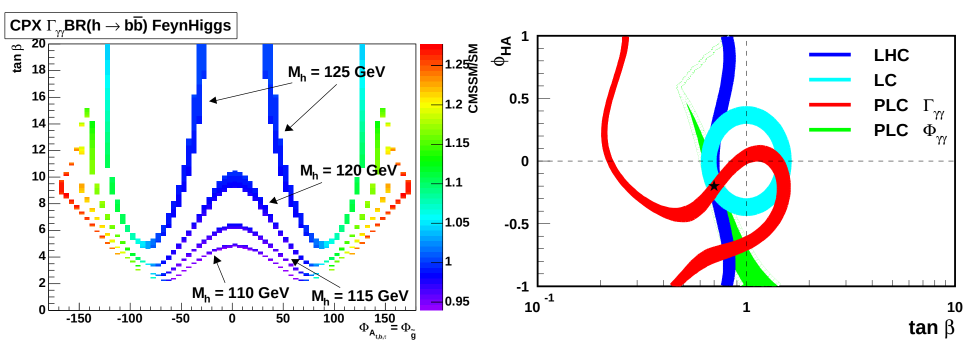

Fig. 2. Left: Dependence of the partial width $\Gamma(H \to \gamma\gamma)$ on the CP violating phase of the Higgs mixing angles [5]. Right: Combined analysis of the Higgs results from LHC, ILC and PLC for a two Higgs doublet model with CP violation [7].

For heavier Standard-Model like Higgses the CP mixing can be reconstructed from the decay angles in $\gamma\gamma \to H \to ZZ$ events [6]. This analysis is highly complementary to LHC and ILC and all three may be needed for a final parameter determination (see Fig. 2 right) [7].

3.1. Heavy MSSM-Higgses at the photon linear collider

In the MSSM the ZZH coupling vanishes for large A masses and the heavy Higgses can only be produced in e^+e^- via the pair production process $e^+e^- \to HA$. In addition for large A masses the H, the A and the charged Higgses $H^\pm$are almost mass degenerate. The mass reach at the e^+e^- ILC collider is thus $m_H, m_A < 0.5\sqrt{s}$. On the contrary, in $\gamma\gamma$ also the heavy Higgses can be produced singly so that the mass reach there is $m_H, m_A < 0.8\sqrt{s}_{ee}$. Also the LHC has difficulties to see heavy MSSM Higgses with $m_A > 200\,\mathrm{GeV}$ and intermediate $\tan\beta$ so that the photon collider has a unique discovery window.

For $\sqrt{s}_{ee} = 500\,\mathrm{GeV}$ it has been shown already that the PLC can indeed see the heavy Higgses if the beam energy can be a priori optimised to the Higgs mass [8]. It needs to be shown that this is also possible at $\sqrt{s}_{ee} = 1\,\mathrm{TeV}$ with less optimistic assumptions on the beam energy.

To study the properties of the heavy Higgses a major problem is the separation of the H and the A. A theory analysis has shown that this may be possible with a threshold scan [9], however this study needs to be repeated with a full experimental simulation of the mass resolution and the photon spectra.

If there is CP violation in the Higgs system, then it is especially probable that the A and the H mix. The PLC is then particularly suited to measure CP violation. Two initial state polarisation asymmetries can be defined that are sensitive to different aspects of CP violation [10]:

$$\mathcal{A}_{\mathrm{lin}} = \frac{\sigma_\parallel - \sigma_\perp}{\sigma_\parallel + \sigma_\perp}$$

with linear photon polarisation and

$$\mathcal{A}_{\mathrm{hel}} = \frac{\sigma_{++} - \sigma_{--}}{\sigma_{++} + \sigma_{--}}$$

with circular photon polarisation.

Detailed experimental studies are urgently needed to estimate the experimental sensitivity. The separation of the heavy Higgs states is easier in the CP violating case, since the mixing tends to increase the mass difference and maybe not even needed for $\mathcal{A}_{\mathrm{hel}}$. However to have $\mathcal{A}_{\mathrm{hel}} \neq 0$ the mixing angle has to be complex. $\mathcal{A}_{\mathrm{lin}}$ is experimentally more challenging. For large

$\sqrt{s}$ the maximally reachable linear polarisation is 30% leading to small signals. At the same time the circular polarisation is $< 80\%$ which increases the background and the energy spectrum is less peaked. On the other hand $\mathcal{A}_{\rm lin} \neq \pm 1$ also for real mixing angles.

Another interesting possibility is the measurement of $\tan\beta$ with $\tau\tau$ fusion ($\gamma\gamma \to \tau\tau\mathcal{H}$, $\mathcal{H} = H, A$) [9]. The cross section is proportional to $\tan^2\beta$ and $\mathcal{O}(100)$ events/year can be expected. It has, however, to be verified experimentally that the τ's can be tagged with high efficiency when the tracks are overlapping with pile-up and that there is no significant accidental overlap of a $\mathrm{b\bar{b}}$ event at intermediate centre of mass energy, where the polarisation is small, and a $\tau\tau$ event or misidentified hadronic pile-up.

4. Supersymmetry

Supersymmetric particles are pair produced in the $\gamma\gamma$ collider and the kinematic reach is therefore slightly smaller than in the e^+e^- one. However there is a discovery window in $\mathrm{e}\gamma$ running [11]. The kinematic reach for the process $e\gamma \to \tilde{e}\tilde{\chi}_1^0$ is $m(\tilde{e}) + m(\tilde{\chi}_1^0) < 0.9\sqrt{s}_{ee}$. If the $\tilde{e} - \tilde{\chi}_1^0$ mass difference is large, this may be superior to the e^+e^- reach being of $0.5\sqrt{s}_{ee}$ for the selectron. The situation is especially favourable for the $\tilde{e}_{\rm R}$ which is expected to be the lighter one. The $\tilde{e}_{\rm R}$ is produced with a right-handed electron beam for which the process $e\gamma \to W\nu$ is absent (for 100% polarisation) and for which $e\gamma \to Ze$ is suppressed. A simulation study has shown that at $\sqrt{s}_{ee} = 500\,\mathrm{GeV}$ this channel is indeed visible [12]. A study for $\sqrt{s}_{ee} = 1\,\mathrm{TeV}$ is still missing.

In the $\gamma\gamma$ mode the production cross sections are generally large. However the background, especially from W-pair production, is also large and, because of the variable beam energy, difficult to reject. On the other hand the production cross sections can be calculated in QED so that the event rate in a given channel directly measures the branching ratio in this channel. Simulation studies have been done for slepton [13] and chargino [14] production. Although the final purity is in some cases only in the 10% region, the branching ratio measurements of a few percent accuracy are possible because of the large cross section, if the background can be understood. For the chargino analysis the branching ratio $\tilde{\chi}_1^+ \to \tilde{\chi}_1^0 W$ has been injected into the SUSY parameter fit of [15] and for $\tan\beta$ and the mixing parameter in the $\tilde{\tau}$ sector, X_τ, an improvement of about a factor two has been observed. It should, however, be noted that up to now no observables related to superpartner decays from e^+e^- are used.

5. Coupling measurements

It is often remarked that the PLC is, because of the large cross sections, a good place to measure couplings of the photon to charged particles, especially W-bosons. It should, however, be noted that in e^+e^- the W-pair cross section is relatively small due to gauge cancellations, which get destroyed by any anomalous coupling, increasing enormously the sensitivity. Detailed studies have been done in the $e\gamma$ and $\gamma\gamma$ mode [16, 17]. Because of the varying beam energy only the hadronic W-decay modes are used. This is however not such a large problem as in e^+e^- because in $\gamma\gamma$ no forward backward asymmetry exists. As shown in figure 3 the sensitivity is similar to e^+e^-, but of course the WWZ couplings are not accessible in $\gamma\gamma$.

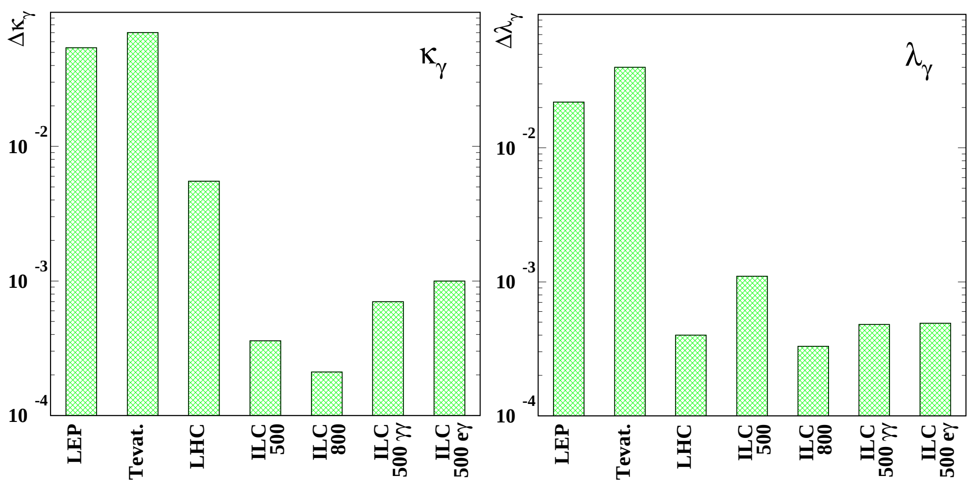

Fig. 3. Sensitivity to anomalous $WW\gamma$ couplings at different machines.

The anomalous $t\bar{t}\gamma$ couplings have been studied as well [18]. Also here the sensitivity to the real parts of the couplings is slightly worse than in e^+e^-, but the imaginary parts are only accessible in $\gamma\gamma$.

6. Conclusions

Building on the physics case discussed here, the rest of the linear collider community has to be convinced that the PLC is worth the effort and one should not forget that the $\gamma\gamma$ collider takes resources from the e^+e^- machine.

For a light Higgs the possibilities are well established. The physical relevance of these measurements has to be shown for the different physics scenarios and they have to be compared to the competing options like GigaZ or high energy running.

For heavy MSSM Higgses at the PLC there is a window of opportunity in the region $0.5\sqrt{s} < m_H < 0.8\sqrt{s}$. One has to discuss which indirect indications will be strong enough to motivate the search. Are we able to separate the heavy Higgs states and can we perform the CP measurements which are unique for the photon collider? Both questions need an answer from simulation studies.

In SUSY there is a discovery window in $e\gamma$ for a large $\tilde{e} - \tilde{\chi}_1^0$ mass difference. In this case neutralinos and charginos should have been seen in e^+e^- and from neutralino pair production one should have a sign that the selectron mass is in the relevant range. In the $\gamma\gamma$ collider clean branching ratio measurements are possible, however no studies from e^+e^- exist up to now to compare to.

Coupling measurements at the PLC are comparable to the e^+e^- ones for the photon couplings, however the couplings to the Z are not accessible. They will become interesting once effects are found in e^+e^-.

Of course there are many interesting measurements possible for QCD, which have not been discussed here. However on their own they will probably not motivate the construction of a photon collider.

It is our task to convince the community that a photon collider is needed. We are on the right track, but there is still a lot to be done. We should not expect approval before supporting results from the LHC and the ILC are present, but we have to make sure that we are ready then.

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